A surface-electrode quadrupole guide for electrons

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Für meine Eltern und Susanne

Zusammenfassung

Thema dieser Arbeit ist der Entwurf und die experimentelle Realisierung eines Quadrupolleiters für freie Elektronen. Dieser basiert auf einer miniaturisierten, planaren Elektrodenkonfiguration und wird mit einem Mikrowellensignal betrieben. Der Elektroneneinschluß findet im Nahfeld der Mikrowellenanregung statt. Dort lassen sich hohe elektrische Feldgradienten mit moderaten Spannungen erzeugen, ohne Resonatoren zur Spannungsüberhöhung verwenden zu müssen. Der Einsatz von mikrofabrizierten Elektrodengeometrien erlaubt es, vielfältige Potentiallandschaften zu erzeugen, die auf kleinen Skalen strukturiert werden können. Dies eröffnet die Perspektive, neuartige Quantenexperimente mit freien Elektronen zu realisieren.

Im Rahmen dieser Arbeit wurde ein Experiment entworfen, aufgebaut und ausgeführt, das zum ersten Mal den Einschluß freier Elektronen in einem miniaturisierten Quadrupolleiter demonstriert. Langsame Elektronen mit Energien von einem bis zu zehn Elektronenvolt werden hierzu entlang einer gebogenen Elektrodenstruktur geführt. Um das Fallenpotential zu charakterisieren, wurde die Stabilität der Elektronenbewegung in Abhängigkeit der Treiberparameter und der Elektronenenergie untersucht. Die Ergebnisse stimmen qualitativ gut mit numerischen Simulationen der Teilchentrajektorien überein, was zu einem tieferen Verständnis der Elektronendynamik im Leiterpotential führt.

In der vorliegenden Arbeit wird außerdem der Entwurf der verwendeten Elektrodengeometrie detailliert beschrieben. Dies beinhaltet die Entwicklung einer optimierten Einkoppelstruktur, welche es erlaubt, Elektronen unter geringer transversaler Anregung in das Quadrupolpotential einzuspeisen. Ich beschreibe auch eine mögliche Erweiterung des momentanen Aufbaus um Strukturen, deren Länge vergleichbar mit oder größer als die Wellenlänge des Treibersignals ist. Dies läßt sich mit einer modifizierten Elektrodengeometrie erreichen, die aus erhöhten Signalleitern über einer geerdeten Fläche besteht.

Ein Beispiel für die vielfältigen Potentiale für Elektronen, die mit mikrostrukturierten Elektrodengeometrien erzeugt werden könnten, sind Strahlteiler zum Aufspalten und anschließenden Zusammenführen eines eingeschlossenen Elektronenstrahls. Außerdem sollte es möglich sein, Elektronen in niedrigliegenden quantenmechanischen Zuständen des transversalen Potentials zu präparieren, indem der einfallende Elektronenstrahl an die Wellenfunktionen der geführten Elektronen angepaßt wird.

Abstract

This thesis reports on the design and first experimental realization of a surface-electrode quadrupole guide for free electrons. The guide is based on a miniaturized, planar electrode layout and is driven at microwave frequencies. It confines electrons in the near-field of the microwave excitation, where strong electric field gradients can be generated without resorting to resonating structures or exceptionally high drive powers. The use of chip-based electrode geometries allows the realization of versatile, microstructured potentials with the perspective of novel quantum experiments with guided electrons.

I present the design, construction and operation of an experiment that demonstrates electron confinement in a planar quadrupole guide for the first time. To this end, electrons with kinetic energies from one to ten electron-volts are guided along a curved electrode geometry. The stability of electron guiding as a function of drive parameters and electron energy has been studied. A comparison with numerical particle tracking simulations yields good qualitative agreement and provides a deeper understanding of the electron dynamics in the guiding potential.

Furthermore, this thesis gives a detailed description of the design of the surfaceelectrode layout. This includes the development of an optimized coupling structure to inject electrons into the guide with minimum transverse excitation. I also discuss the extension of the current setup to longitudinal guide dimensions that are comparable to or larger than the wavelength of the drive signal. This is possible with a modified electrode layout featuring elevated signal conductors.

Electron guiding in the field of a planar, microfabricated electrode layout allows the generation of versatile and finely structured guiding potentials. One example would be the realization of junctions that split and recombine a guided electron beam. Furthermore, it should be possible to prepare electrons in low-lying quantum mechanical oscillator states of the transverse guiding potential by matching an incoming electron beam to the wave functions of these states.

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Introduction

Observations of the wave nature of elementary particles belong to the most fascinating experiments in physics, and free electrons have played a key role in such fundamental studies. An early example is the famous experiment of Davisson and Germer [1] that, for the first time, directly proved the wave nature of matter by demonstrating diffraction of a free electron beam from a nickel crystal lattice. In the 1950s, the development of the biprism allowed coherent splitting of the wavefront of impinging electrons and the observation of Fresnel interference with massive particles [2]. This was followed by electron interference originating from the diffraction at several vertical thin slits [3], which represents the matter-wave analogon of Young's double slit experiment. Although rarely recognized at the time of its publication, it has been elected to be the most beautiful experiment in physics by a survey published in *Physics World* [4]. In the following decades, other fundamental quantum mechanical aspects like the Aharanov-Bohm effect [5, 6] or Hanbury Brown-Twiss anticorrelations [7] have been observed with free electron beams.

An achievement that enabled wholly new types of experiments was the three-dimensional confinement of electrons in the electromagnetic field of a Penning trap [8]. It binds the movement of electrons by combining a homogeneous magnetic field with a superimposed electrostatic quadrupole field. An electron confined in a Penning trap has been the first individually trapped single particle [9], later visualized by Hans Dehmelt as an artificial atom binding an electron to the trap apparatus (placed on earth) and therefore termed *Geonium* [10]. Penning traps allow the measurement of fundamental physical quantities to highest precision, a prominent example of which is the determination of the electron's anomalous magnetic moment [11], which provides the most accurate value of the fine structure constant today.

This thesis is concerned with the confinement of a freely propagating electron beam in a transverse guiding potential, which is motivated by recent experiments on laser triggered electron emission from nano-scale metal tips [12]. Such a confinement would add continuous spatial control to precisely timed electrons. However, one significant drawback of using magnetic fields for this purpose is that they cause complicated electron dynamics in the transverse plane and are additionally hard to pattern on small length scales. Thus, it is difficult to generate versatile potential landscapes for the guiding of transversally confined electrons.

A more promising approach is the confinement of electrons in purely electric fields, like they are used in the alternating quadrupole configuration of Paul traps [13]. Omitting the magnetic field of a Penning trap opens the possibility to more freely shape the confining potential by implementing microstructured electrode geometries. Following the recent success of quantum manipulation experiments in surface-electrode traps for ions [14–17], these devices would enable the realization of versatile miniaturized electron guides. Besides steering and deflecting electrons, junctions that join several guiding potentials [18, 19] may allow the splitting and recombination of a confined electron beam. Apart from ion traps, microfabricated conductor structures have also proven to be extremely useful in the realization of magnetic traps for neutral atoms [20].

Interestingly, the confinement of electrons in an alternating electric quadrupole potential has rarely been considered. This is probably due to the fact that the large charge-tomass ratio of electrons demands high drive voltages as well as high drive frequencies in the microwave regime. Previous work on the deflection and guiding of electrons in electric microwave fields has been carried out both theoretically and experimentally in the context of plasma confinement for fusion research in the 1960s, see [21] for a review. These experiments incorporated three-dimensional resonating or helical electrode structures, which impede a microscopic shaping of the guiding potential. A later experiment stored electrons in the alternating electric field of a combined Paul and Penning trap, where they were confined together with H_2^+ ions to demonstrate the potential use of the apparatus for anti-hydrogen production [22]. To generate the high microwave powers that were needed in this experiment, it has likewise been integrated into a macroscopic coaxial resonator.

This thesis presents the experimental realization of electron confinement in the purely electric field of a miniaturized quadrupole guide. The device is operated at microwave frequencies and is based on electrodes fabricated on a planar chip substrate. Strong electric field gradients and deep guiding potentials can be generated without resorting to resonating structures or high drive powers by confining the electrons in the near-field of the microwave excitation. Furthermore, the choice of a planar geometry is ideally suited to feed the electrode structure by on-chip microwave transmission lines.

In the course of this dissertation, a proof-of-principle experiment has been designed, built and conducted. Low energy electrons at a few electron-volts kinetic energy are injected into a quadrupolar guiding potential, where they are tightly confined in the radial direction and are free to propagate longitudinally. Successful guiding is demonstrated by a spatial deflection of the confined beam along a curved guiding structure. This combines, for the first time, the advantages of a propagating electron beam with the precise control of a continuous transverse potential, which is difficult to achieve with magnetic fields.

An interesting feature of a quadrupole guide, as it is presented in this thesis, is the fact that the quantum mechanical ground state wave function of an electron in the harmonic guiding potential has a lateral extend that is well resolvable with conventional electron optics. This could allow the direct injection of incoming electrons into low-lying oscillator states. A well defined motional quantum system would result, which does not require cooling of the particles involved. I will shortly sketch the basic principle of this scheme at the end of Chapter 1.

The present study furthermore evaluates the stability of electron trajectories with respect to the depth and the ponderomotive stability of the guiding potential. Guiding can be observed over a wide range of parameter settings, and a comparison with simulated electron trajectories yields good qualitative agreement. From the simulated trajectories, the factors that limit the performance of the current setup can be identified. As an important step towards future guiding experiments, I present the design of an improved coupling structure.

Additionally, a study of the microwave transmission line properties of surface-electrode structures that are used both in the present experiment and in ion trapping setups has been carried out. I discuss an electrode design that will overcome the current technical limitation to electrically short electrode structures and will allow the realization of, in principle, arbitrarily long electron guides.

This dissertation is organized as follows:

Chapter 1 reviews the basic principles of charged particle confinement in alternating quadrupole potentials and derives the operation parameters for electron guiding. At the end of this chapter, I propose a possible extension of the guiding setup to prepare electrons in low-lying quantum mechanical oscillator states of the transverse harmonic potential.

Chapter 2 describes the electrode design of the electron guide with an emphasize on the optimization of the coupling structure at the guide entrance. I also discuss the transmission line properties of the five-wire structure presently used as well as possible extensions to electrode geometries that are longer than the drive wavelength.

Chapter 3 details the experimental setup that was designed, constructed and implemented during this dissertation.

Chapter 4 presents the first demonstration of electron guiding in a surface-electrode structure. I will give a detailed characterization of the guiding stability in terms of drive parameters and electron energies as well as a characterization of the coupling structure. The experimental results are compared to numerical particle tracking simulations. I also discuss the next experimental steps towards an improved second generation setup.

Chapter 5 concludes with an outlook on possible future experiments.

Manuscripts published in peer-reviewed journals

- Microwave Guiding of Electrons on a Chip
 J. Hoffrogge, R. Fröhlich, M. A. Kasevich and P. Hommelhoff *Physical Review Letters* 106, 193001 (2011)
 (selected as Editor's Suggestion and for a Viewpoint in *Physics* [23])
- Planar microwave structures for electron guiding J. Hoffrogge and P. Hommelhoff New Journal of Physics 13, 095012 (2011)

Chapter 1

Theory of Paul traps

The development of radio-frequency traps for charged particles began with the pioneering work of Wolfgang Paul and co-workers in the 1950's. They adapted the principle of electromagnetic lenses from atomic and molecular beam experiments to the stable confinement of charged particles in time-varying electric fields. This led to the development of linear quadrupole devices for two-dimensional confinement [24, 25] as well as three-dimensional ion traps, originally termed *Ionenkäfige* [26].

While the linear quadrupole guide is still the basis of many mass spectrometers [27, 28], traps providing confinement in all three dimensions have evolved to a valuable tool in atomic and molecular physics. Paul traps, along with Penning traps, allowed for the first time the storage and observation of an ensemble of laser-cooled atomic ions [29, 30] leading to the isolation of a single trapped ion in the early 1980's [31, 32]. Atoms put to rest in a confining potential are an ideal starting point for sensitive experiments such as basic quantum optical measurements or accurate optical clocks [17, 33, 34]. Using Paul traps, it is furthermore possible to manipulate trapped ions on the level of single motional quanta [17, 35], which has been pioneered by David Wineland who therefore shared the Nobel Prize in Physics in 2012. These techniques are also a key ingredient for the envisioned realization of quantum computers [36, 37] or quantum simulators [38, 39] with trapped ions.

The working principles and applications of quadrupole traps and guides have been reviewed in several publications, see for example [13, 40, 41]. In the following, I summarize the most important aspects that govern the dynamics of charged particles in linear quadrupole guides to deduce the operating conditions needed for electron confinement. While typical ion traps operate at drive frequencies from several ten to a few hundred megahertz [42], stable confinement of lightweight electrons requires notably higher drive frequencies that lie well in the microwave region.

The chapter concludes with a possible application of the novel quadrupole guides for electrons demonstrated in this thesis. In particular, I consider the quantum mechanical ground state of an electron in the harmonic guiding potential, which has a lateral extension of roughly one hundred nanometers and is therefore well resolvable with conventional electron optics. Consequently, it should be possible to directly prepare electrons in low lying oscillator states of the transverse guiding potential.



Figure 1.1: Paul trap geometries. a) Cross-sectional electrode layout of a three-dimensional Paul trap generated by a ring electrode and two end cap electrodes. b) Linear quadrupole guide providing two-dimensional confinement in the xz-plane. Pictures adapted from [13].

1.1 Charged particle dynamics in quadrupole guides

The confinement of a charged particle in a quadrupole guide relies on the time-averaged force exerted by an alternating electric field. In the simplest case, the underlying electric potential $\Phi(x, y, z, t)$ is quadrupolar

$$\Phi(x, y, z, t) = [V_{dc} + V_0 \cos(\Omega t)] \frac{\alpha x^2 + \beta y^2 + \gamma z^2}{2}, \qquad (1.1)$$

with static and oscillating components of amplitude V_{dc} and V_0 , respectively. Φ has to fulfil Laplace's equation $\nabla^2 \Phi = 0$, which restricts the geometrical parameter space to

$$\alpha + \beta + \gamma = 0. \tag{1.2}$$

One popular choice is $\alpha + \beta = -\gamma$, leading to three-dimensional confinement in the oscillating field. This potential is generated by a hyperbolically shaped ring electrode closed at each end by two, also hyperbolical, end cap electrodes [26], see Fig. 1.1 a). Another choice is $\alpha = -\gamma$, $\beta = 0$. It results in a two dimensional quadrupole potential in the transverse direction (*xz*-plane), which is homogeneous along the *y*-coordinate. Such a linear quadrupole guide is ideally realized by four hyperbolically shaped electrodes as shown in Fig. 1.1 b), where one of the pairs of opposing electrodes in the *x*- and *z*-direction is held at positive potential and the other pair at a negative potential of the same magnitude. It provides confinement in the radial directions, whereas a particle is free to move axially. This geometry forms an integral part of most quadrupole mass spectrometers and is also preferred in ion trapping experiments due to its geometrical simplicity. There, threedimensional confinement may be achieved by superimposing a confining static potential in the axial direction [43–45]. In the following, I will exclusively study the latter geometry. In the electron guiding experiment, the structure is open and homogeneous along the longitudinal direction, thus providing only two-dimensional confinement.

Setting the coordinate origin to the center between the electrodes, the potential of a



Figure 1.2: a) Hyperbolic quadrupole potential generating a saddle point at the center. b) Stability diagram of a linear quadrupole guide. The curves (a_x, q_x) with negative slope represent constant values of β_x , those with positive slope constant β_z . The lowest stability region is bounded by the values (a_i, q_i) , where $\beta_i \in \{0, 1\}$ holds. As $q_x = -q_z$ and $a_x = -a_z$, the stability diagram is symmetric with respect to the (a = 0)-axis. Picture taken from [35].

quadrupole guide may be written as

$$\Phi(x, y, z, t) = [V_{dc} + V_0 \cos(\Omega t)] \frac{(x^2 - z^2)}{2R_0^2},$$
(1.3)

corresponding to $\alpha = -\gamma = 1/R_0^2$ in Eq. (1.1). Here, R_0 is the minimum distance from the guiding center to the electrode surfaces. In the static case, Eq. (1.3) generates a saddle point of $\Phi(x, y, z, t)$ at (0, y, 0) where a charged particle is harmonically confined in one radial direction and repelled in the other, see Fig.1.2 a). By changing the sign of the voltages applied to the electrodes, a time-averaged restoring force may emerge. Due to the curvature of the electric potential, the particle can experience a larger restoring force far away from the center and a smaller defocussing force next to it, provided that an appropriate drive frequency is chosen. This is analogous to the principle of *strong focusing* in particle optics [46, 47], where a particle passes through a set of electromagnetic lenses that alternately focus and defocus it in one radial direction. By adjusting the focal lengths and spacings of the lenses in the right way, one can achieve that the particle passes a defocussing lens closer to the optical axis than the previous, focusing one, leading to a net convergence towards the center.

The equations of motion of a particle of charge Q and mass M in the potential of Eq. (1.3) decouple in the x- and z-direction and are given along x by [40]

$$\frac{d^2x}{d\xi^2} + [a - 2q\cos(2\xi)]x = 0 \tag{1.4}$$

with

$$\xi = \frac{\Omega t}{2}, \quad a = \frac{4Q}{M} \frac{V_{dc}}{\Omega^2 R_0^2} \tag{1.5}$$

and

$$q = \frac{2Q}{M} \frac{V_0}{\Omega^2 R_0^2}.$$
 (1.6)

In the z-direction, the same equations hold with modified parameters $a_z = -a$ and $q_z = -q$. Eq. (1.4) is the standard form of the Mathieu differential equation. Solutions to Eq. (1.4), for which the particle trajectory $x(\xi)$ is bounded for all times, are called stable and may be written as [40]

$$x(\xi) = A \sum_{n=-\infty}^{+\infty} C_{2n} \cos\left[(2n \pm \beta)\xi\right] + B \sum_{n=-\infty}^{+\infty} C_{2n} \sin\left[(2n \pm \beta)\xi\right].$$
 (1.7)

The integration constants A and B are set by the initial conditions, whereas the so-called characteristic exponent $\beta(a, q)$ and the amplitudes $C_{2n}(a, q)$ depend on a and q only and can be determined from continuous fraction expressions [35]. Stable solutions to Eq. (1.7) exist for real values of $\beta(a, q)$ that are not an integer [40]. The corresponding values of (a, q) form connected regions in the a-q-plane, which are bounded by lines where $\beta(a, q)$ takes integer values. Fig. 1.2 b) depicts the lowest stability region between $\beta = 0$ and $\beta = 1$. There, the exponent $\beta_z(a_z, q_z)$ arising from the motion in the z-direction has also been included. It follows from $a_z = -a$, $q_z = -q$ and the fact that the stability regions are symmetric with respect to the (q = 0)-axis that this can be done by mirroring the stability pattern of β along the (a = 0)-axis. In the experiments, I will exclusively study situations with $V_{dc} = 0$, leading to $a = a_z = 0$. The maximum value of q in the lowest stability region then amounts to $q_{max} = 0.908$.

It can be seen from Eq. (1.7) that the motional spectrum of the charged particle is composed of harmonic components oscillating at frequencies

$$\omega_n = (2n \pm \beta)\Omega/2. \tag{1.8}$$

Since integer values of β are excluded, the particle exhibits no motional component at multiples of the drive frequency Ω , which could be resonantly excited by an energy transfer from the driving field to the particle motion.

1.2 Secular approximation

In the limit of small a and q, the characteristic exponent β may be approximated by

$$\beta \approx \sqrt{a+q^2/2}.\tag{1.9}$$

Note that this approximation already breaks down for $q \approx 0.4$ [48], which is about half of the value of q_{max} at a = 0. In this limit, the motion of Eq. (1.7) can be approximated to lowest order by

$$x(t) \approx C \cdot \left[1 - \frac{q}{2}\cos\left(\Omega t\right)\right] \cos\left(\frac{\beta}{2}\Omega \cdot t\right).$$
 (1.10)

It follows from $\cos(a)\cos(b) = 1/2[\cos(a+b) + \cos(a-b)]$, that Eq. (1.10) describes the sum of three harmonic oscillations. The first has a slower frequency of $\omega = \beta \Omega/2$ and the other two form positive and negative sidebands $\Omega \pm \omega$ of the drive frequency Ω . The slow motion at ω is conventionally termed *secular motion*, whereas the components near the drive frequency are called *micromotion*. At $V_{dc} = 0$, i.e. at a = 0, the secular frequency can be written as

$$\omega \approx \frac{q}{\sqrt{8}} \Omega = \frac{Q}{\sqrt{2}M} \frac{V_0}{\Omega R_0^2}.$$
(1.11)



Figure 1.3: Particle trajectory (1-D) in the x-direction in an ideal linear quadrupole guide following Eq. (1.10). a) has been calculated for a q-parameter of q = 0.1, whereas b) features q = 0.3. The particle performs larger oscillations at the secular frequency with the faster micromotion of smaller amplitude superimposed. At larger q, both the relative amplitude of the micromotion and the ratio between the secular and the micromotion frequency become larger.

For typical values of $q \approx 0.3$, this means that the secular frequency ω is about one tenth of the drive frequency Ω .

Fig. 1.3 depicts typical trajectories for two different values of q. The components that result from the secular and the micromotion are clearly discernible with their relative amplitudes being given by q/4.

1.3 Adiabatic approximation

The secular approximation at small q may be generalized to an arbitrary electric field [41, 49]. This assumes that the variation of the field is small over the distance that the particle travels within one oscillation period of the driving field $T = 2\pi/\Omega$. It is then possible to average the particle's motion over the fast oscillations near the drive frequency Ω . This yields equations of motion that are governed by an effective pseudopotential, which is given by

$$\Psi = \frac{Q^2}{4M\Omega^2} \left| \nabla \Phi \right|^2. \tag{1.12}$$

This description also emphasizes the fact that the force that is exerted on the particle is independent of the sign of its charge Q. For the hyperbolic potential of Eq. (1.3), this results in

$$\Psi(x,z) = \frac{Q^2 V_0^2}{4M\Omega^2 R_0^4} \left(x^2 + z^2\right),\tag{1.13}$$

reproducing the oscillations in a harmonic potential with frequency ω given by Eq. (1.11). Additionally, the depth of the pseudopotential U may be quantified by the value of Ψ on the electrode surfaces:

$$U = \frac{Q^2}{4M} \frac{V_0^2}{\Omega^2 R_0^2} = \frac{Q}{8} q \cdot V_0.$$
(1.14)

The pseudopotential description of Eq. (1.12) is especially handy to study particle motion in an arbitrary electric field. Provided that the field variation is slow enough, the particle will always adiabatically follow the gradient of an alternating electric field towards regions of (local) field minima. The potential of Eq. (1.12) represents the kinetic energy of the particle's motion at the drive frequency. It is also called *ponderomotive* energy in the context of plasma physics [50] and the theory of high-harmonic generation in atomic gas jets. I will make use of Eq. (1.12) in the optimization of the electron coupling structure reported on in Section 2.2.

1.4 Drive parameters for electron confinement

For the design of Paul traps, it is handy to express the secular frequency ω and the potential depth U in terms of the Mathieu stability parameter q, which is summarized again for convenience:

$$q = \frac{2Q}{M} \frac{V_0}{\Omega^2 R_0^2}$$
$$\omega = \frac{Q}{\sqrt{2}M} \frac{V_0}{\Omega R_0^2} = \frac{1}{\sqrt{8}} q \cdot \Omega$$
$$U = \frac{Q^2}{4M} \frac{V_0^2}{\Omega^2 R_0^2} = \frac{Q}{8} q \cdot V_0.$$

Fixing q and therefore the amount of micromotion results in ω and U being proportional to the drive frequency Ω and the drive voltage V_0 . Choosing both ω and U freely then requires a structure size R_0 that is compatible with the desired q. Similarly, a fixed structure size and stability parameter q mean that only one of the two parameters ω or U may be chosen freely. It also follows that reducing R_0 allows the implementation of a higher drive frequency Ω while keeping V_0 and q constant, which in turn results in a higher secular frequency ω at constant U. Since ω defines the timescale of motional quantum gates [51], miniaturized structures are especially interesting for quantum information processing applications [52–54].

Due to the electron's large charge-to-mass ratio e/m_e , typical operating conditions for electron guiding vary significantly from the ion trapping case. For example, an ion trapping experiment that works with ²⁵Mg⁺ ions and incorporates a structure size of $R_0 = 500 \,\mu\text{m}$, a stability parameter of q = 0.2 and a potential depth of $U = 1 \,\text{eV}$ would require a drive frequency of $\Omega = 2\pi \cdot 13 \,\text{MHz}$. This results in a secular frequency of $\omega = 2\pi \cdot 900 \,\text{kHz}$.

Since the ratio between the mass of a ${}^{25}\text{Mg}^+$ ion and an electron amounts to approximately 44 000, an electron guide that implements the same R_0 , q and U has to be operated at $\Omega = 2\pi \cdot 2.7 \text{ GHz}$. However, the resulting secular frequency now is also significantly higher with $\omega = 2\pi \cdot 200 \text{ MHz}$.

Consequently, a typical electron guide that is based on an alternating quadrupole field has to be operated at microwave frequencies. To realize such a device, we make use of a planar electrode geometry fabricated on a flat substrate. This allows to interface the guiding electrodes with a planar microwave transmission line to efficiently feed the guide. This design is described in more detail in Ch. 2. Note, however, that surface-electrode geometries like they have been used in this thesis provide smaller potential depths U than three-dimensional structures, see Sec. 2.1.2. Typically, U is reduced by a factor of 100 compared to an ideal geometry.

The high secular frequencies that can be achieved in a microwave guide for electrons are additionally interesting in the context of the envisioned preparation of low-lying quantum states of the transverse potential, as described in Sec. 1.6. The resulting larger energy spacing of the quantum states should make it easier to resolve individual states by collimating the incoming electron beam. Also, electrons in tight potentials are less susceptible to heating by electric field noise, see the following Section.

1.5 Estimation of heating rates

A limiting factor in all quantum manipulation experiments with trapped ions is heating of the confined particles by electric field noise [15, 55]. The heating rates that are observed in miniaturized ion traps are orders of magnitude higher than what is estimated from conventional noise sources like Johnson noise in the trap electrodes. Thus, this heating is often termed *anomalous* in ion trapping publications. Although such heating is not relevant for the experiments presented in this thesis, it is interesting to see whether it might become an issue in future experiments that aim at more refined control over guided electrons.

The heating rate \dot{n} of a confined particle of mass M and charge e, measured in motional quanta per second, is given by [56]

$$\dot{n} = \frac{e}{4M\hbar\omega} S_E(\omega), \qquad (1.15)$$

with $S_E(\omega)$ being the spectral noise density of the electric field above the electrodes at transverse frequency ω . $S_E(\omega)$ has been found to scale with transverse frequency and trap-to-electrode distance like $1/\omega$ and $1/R_0^4$ [55, 57–59]. It can be significantly reduced by either cleaning the trap electrodes by argon-ion-beam bombardment [59] or by cooling them to cryogenic temperatures [56, 57]. This confirms the assumption that anomalous heating is caused by thermally activated, fluctuating patch potentials that originate from adsorbed surface contaminants.

The lowest electric field noise spectral densities $S_E(\omega)$ that have been measured in cryogenic [56] or ion-beam cleaned, room temperature setups [59] amount to $S_E(\omega) \approx 3 \cdot 10^{-14} \,\mathrm{V}^2/\mathrm{m}^2/\mathrm{Hz}$ at $\omega = 2\pi \cdot 1 \,\mathrm{MHz}$ and $R_0 = 100 \,\mu\mathrm{m}$. For a ${}^9\mathrm{Be^+}$ ion, this corresponds to a heating rate of $\dot{n} = 15 \,\mathrm{quanta/s}$. As the transverse frequencies ω for electron guiding are about a factor of hundred higher than for ion trapping, the heating rates scale favorably, despite of the lower electron mass. The noise spectral density mentioned above corresponds to a heating rate of $\dot{n} = 24 \,\mathrm{quanta/s}$ for electrons confined at $\omega = 2\pi \cdot 100 \,\mathrm{MHz}$ and $R_0 = 100 \,\mu\mathrm{m}$, which is comparable to the ion trapping case at $\omega = 2\pi \cdot 1 \,\mathrm{MHz}$. For the guide implemented in this thesis ($\omega = 2\pi \cdot 100 \,\mathrm{MHz}$ and $R_0 = 500 \,\mu\mathrm{m}$) the heating rate even reduces to $\dot{n} = 0.04 \,\mathrm{quanta/s}$.

Experimentally relevant time scales are typically on the order of the oscillation cycle of the confined particles. These time scales are consequently expected to be significantly smaller in electron guiding experiments than in similar ion trapping setups. Thus, anomalous heating should not become a problem in future experiments.

1.6 Proposed scheme for ground state injection

An intriguing application of an electron guide would be the preparation of electrons in low-lying quantum mechanical oscillator states of the secular guiding potential. Since the full electric potential varies in time, no stationary quantum mechanical states exist. However, it is still possible to define quasistationary states with wave functions that closely resemble the eigenstates of the harmonic secular potential and exhibit only a small periodic modulation at the drive frequency [35]. At low values of q, the latter can be neglected in most cases. Since the spatial extent of the secular wave function of an electron in the guide is on the order of several hundred nanometers, a direct injection of electrons into the transverse ground state of motion should be possible with realistic electron beam properties. This would realize a well-defined motional quantum system of electrons without the need for cooling of the particles involved. As this future goal is one of the main motivations of the experiments presented in this thesis, the following will sketch the basic idea for later reference.

The extensions of the Gaussian wave function of an electron in the ground state of a harmonic oscillator potential in position and momentum space are given by [60]

$$\Delta x = \sqrt{\frac{\hbar}{2m_e\omega}} \text{ and}$$

$$\Delta p = \sqrt{\frac{1}{2}\hbar m_e\omega} .$$
(1.16)

 Δx and Δp fulfill the lower limit of Heisenberg's uncertainty relation $\Delta x \Delta p \geq \hbar/2$. In a technically feasible case ($\omega = 2\pi \cdot 500$ MHz, corresponding to $\Omega = 2\pi \cdot 14$ GHz at q = 0.1), the transverse extension amounts to $\Delta x = 130$ nm. This is well resolvable with conventional electron optics. In principle, it should therefore be possible to match a free electron wave packet impinging on the guide's center to the quantum mechanical ground state in the transverse potential, provided that the spread of the momentum space wave packet can also be adapted to that of the confined particle.

Assuming phase-space preserving electron optics, one prerequisite for this scheme is that the initial wave packet features the minimum position and momentum spread allowed by the Heisenberg relation. This can be assumed for electrons originating from a singleatom-tip field emitter [61, 62], which consists of a sharp pyramid of Nobel atoms on top of a conventional tungsten field emission tip. These devices emit electrons from the topmost atom only and produce a fully coherent electron beam [63]. From the small source size and divergence angle of the emitted beam, one can conjecture that a single-atom-tip indeed generates Heisenberg limited electron wave packets [63].

The second element of an electron source suitable for ground state injection, as schematically sketched in Fig. 1.4, would then be an electron lens, which refocuses the electron wave packet emitted from a single-atom source, so that it matches the spatial and momentum spread of the guided electron wave function. Here, a miniaturized electrostatic immersion lens [64, 65] would be suited to keep spherical and chromatic aberrations small, as these scale linearly with the structure size [66].

The requirements on the focusing properties of the electron lens may be estimated by converting the transverse momentum spread Δp of the ground state wave function to the



Figure 1.4: Proposed scheme for injecting electrons into the quantum mechanical ground state of a quadrupole guide. Electrons that are emitted from a Heisenberg limited point source of electrons are imaged by a miniaturized, electrostatic immersion lens featuring low aberrations. A significant population of the ground state of the secular potential should be achievable by matching the position and momentum wave functions of an incoming free electron to the harmonic oscillator ground state.

divergence angle ϵ of a classical electron beam. This can be done by equating Δp with the width of the (Gaussian) distribution of transverse momenta of the electrons in the beam. For an electron kinetic energy of E_{kin} and a total momentum $p = \sqrt{2m_e E_{kin}}$, the full divergence angle ϵ of such a beam is given by

$$\epsilon = 2\sin^{-1}\left(\frac{\Delta p}{2p}\right) = 2\sin^{-1}\left(\sqrt{\frac{\hbar\omega}{16E_{kin}}}\right).$$
(1.17)

At large distances from the focus of the lens, the beam will well approximate the evolution of the lateral extension of a single electron wave packet with a focal width of Δp [60]. As will be shown in the experimental section (Ch. 4), it is possible to efficiently guide low energy electrons at $E_{kin} = 1 \text{ eV}$ in our structures. This leads to $\epsilon = 0.7 \text{ mrad}$ if one assumes a transverse secular frequency of $\omega = 2\pi \cdot 500 \text{ MHz}$ in the guide.

First investigations on miniaturized electrostatic lens systems with sub-micron apertures indicate that an electron beam fulfilling the requirements mentioned above should be feasible, although the necessary beam collimation is definitely challenging to realize [67]. But even for an electron beam, which does not exactly reproduce the wave function of the ground state, only a minor fraction of the electrons will be reflected at the guide entrance as long as the deviation from the optimum parameters is not too large. This should still yield a high probability to prepare electrons in the lowest motional oscillator state. Additionally, one could think of lowering the potential depth adiabatically along the guide until only the lowest oscillator state is confined. This would effectively filter the ground state from an ensemble of transverse oscillator states.

Chapter 2 Guide design

In the following, I outline the basic electrostatic properties of planar guiding structures and their implications on guiding parameters such as transverse frequency and potential depth. After a brief characterization of the guiding potential of a five-wire structure, as it is implemented in this thesis, I proceed with the description of a special electrode layout that is used to couple electrons into and out of the guide. Finally the microwave transmission line properties of the five-wire design are analyzed, and the realization of guiding structures with a longitudinal extension that is larger than the drive wavelength is discussed.

2.1 Surface-electrode traps

As mentioned in Sec. 1.1, a pure quadrupole potential with vanishing higher order multipole moments is realized with electrodes that are shaped to match the hyperbolic equipotantial surfaces [13, 41]. This electrode configuration has the disadvantage of rather difficult fabrication due to its complicated shape. Additionally, it offers only limited optical access to the trapping region, which particularly affects its usability in ion trapping experiments. However, any electrode geometry that generates a saddle point of the electric potential is in principle capable to dynamically confine charged particles. The lowest order coefficient of a multipole expansion around the saddle point will be quadrupolar and the particle's trajectory in the vicinity of that point can again be approximated by that in a harmonic pseudopotential, provided that all higher order terms stay sufficiently small. This allows particle confinement even in unusual geometries like the ring trap of Straubel [68]. To overcome the limitations of hyperbolic designs mentioned above, most modern ion traps incorporate a modified electrode structure, such as, for example, circular rods [44, 69, 70] or linear blades [48, 71].

During the last few years, several groups have developed a new type of linear ion traps that consists of planar electrodes placed on a flat substrate [14, 18, 56, 58, 72–82]. Typically, the electrode patterns of these surface-electrode traps are fabricated using semiconductor microfabrication processes like photolithography, electroplating or various etching techniques [55]. It is therefore possible to realize complex trap structures, which can be quite easily scaled to larger arrays [83]. Additionally, micron sized electrode patterns allow for small distances R_0 between the trap center and the electrodes that typically



Figure 2.1: Conductor layout of the electron guide with pseudopotential superimposed. The microwave signal is applied to the two red wires and the blue ones are grounded. The upper dimensions indicate the physical width of the central wire c, the signal wires w and the gaps between the electrodes g. The lower dimensions are virtual values that are used in the gapless-plane approximation, see Sec. 2.1.1. The color plot shows the resulting pseudopotential with the guiding minimum visible as a blue spot at a height R_0 above the central wire.

range from several tens to several hundreds of micrometers. This means that traps with high transverse frequencies and variations of the pseudopotential on the micrometer scale can be realized, which is a key ingredient for quantum logic applications like, for example, the coupling of ions in separated traps via the Coulomb force [15, 16]. It also facilitates the implementation of interfaces to other structures that are integrated in the chip layout, such as optical components [84–87], superconductors in a cryogenic environment [82, 88] or microwave transmission lines to drive hyperfine transitions of ions trapped above the surface [89, 90].

As discussed in Sec. 1.4, the confinement of electrons requires high drive frequencies in the range from about 1 GHz up to several 10 GHz. Planar electrode structures are, besides the advantages just mentioned, well suited for this frequency range as they can be directly interfaced with planar microwave transmission lines on the same substrate.

A sketch of the layout of our surface-electrode guide is depicted in Fig. 2.1. The guide consists of a symmetric pattern of five conductors with rectangular cross section. The center and the outer wires are grounded and enclose the signal wires, where the microwave voltage is applied to. The two outermost grounded wires extend all the way out to the substrate edges and form a grounded plane that covers the entire remaining substrate surface. The pseudopotential of Eq. (1.12), which is generated by this electrode structure, is also depicted in Fig. 2.1. The potential minimum at the center of the guide is situated at a distance R_0 above the electrode surface.

2.1.1 Approximations

The following summarizes the approximations that have been applied to facilitate the design of the electrode structure. They are mainly based on the assumption that certain physical dimensions of the guide are smaller than the drive wavelength λ . This always holds for the lateral extension L = c + 2w + 4g, see Fig. 2.1, of the electrode structure at the drive frequencies implemented in the following. For electrode configurations with longitudinal extensions that are also much smaller than λ , it is therefore save to neglect microwave propagation effects altogether and to consider the electrodes as being homogeneously charged at every instant of time. For ion traps at drive frequencies ranging from about 10 MHz to 240 MHz [42] and with overall dimensions of several centimeters, this condition is generally met. The time variation of the field above the electrodes can then be separated from its spatial variation. In the *quasi-static approximation*, the latter is given by the electrostatic potential that is generated by the trap electrodes set to the voltage amplitude of their time varying excitation.

As the drive frequency for electron guiding is up to two orders of magnitude higher, the longitudinal extension of the guiding structures can become comparable to or larger than the wavelength. But even in this case, a quasi-static approximation is applicable as long as the electrode layout is translationally invariant and $L \ll \lambda$ holds, see Sec. 2.3.1. In this case, the electric field that is generated by the microwave excitation on the electrodes can be considered to lie entirely in the transverse plane perpendicular to the guide axis (the *xz*-plane in Fig. 2.1). It can then again be determined by an electrostatic calculation in this plane, see Sec. 2.3.2 and [91]. In analogy to the pure transverse electric modes (TEM) of a waveguide, this approximation is called *quasi-TEM approximation*. For the purpose of deriving the basic guiding parameters of an idealized and axially homogeneous guiding structure, it is therefore sufficient to model the cross-sectional cut through the electrodes, like it is also done in the design of linear ion traps.

In most cases, the size of the gaps g between the electrodes will be much smaller than the distance between the electrodes and the trap center R_0 . Likewise, the metalized area around the electrodes will be much larger than R_0 . It is then justified to model the electrodes without gaps and being embedded in an infinite grounded plane [92–94]. This gapless-plane approximation changes the guiding parameters only to second order in g [93] and is justified in most practical circumstances [94]. The junctions between the individual electrodes are placed in the middle of the electrode gaps, which yields modified electrode dimensions c' = c + g and w' = w + g.

2.1.2 Conformal mapping

The cross sectional electrode layout of most surface-electrode trap designs can be derived [92] by projecting a circular electrode pattern to the chip plane via a Möbius map, as illustrated in Fig. 2.2. This conformal map is constructed such that fixpoints lie at the trap center and in the electrode plane directly below the trap center. Furthermore, it preserves the number of vanishing lowest-order multipole coefficients of an expansion of the potential around the trap center and scales the first non-vanishing order by a multiplicative factor only [92]. Paul traps usually utilize a potential that is quadrupolar to lowest order. The simplest way to create a potential with vanishing monopole and dipole components with an annular electrode pattern is to distribute four electrodes along the circumference of the ring. Additionally, opposing electrodes must have the same width and be at the same potential.

The two configurations shown in Fig. 2.2 represent two special cases, commonly termed



Figure 2.2: Möbius map used in [92] to derive basic properties of surface-electrode potentials from a circular electrode pattern in the complex plane. The guide center is located at the origin and the electrode plane is indicated by the horizontal line at $\Re(c) = R_0$. The microwave voltage is applied to the red electrodes, whereas the black sections of the circle or the electrode plane are grounded. A point P on the circle is mapped to a point P' that is constructed by the intersection of the electrode plane with the circle tangent through P. The microwave electrodes have an angular width ϑ_w and their position on the circle is given by a rotation angle ϑ_0 . Structures with $\vartheta_0 = \vartheta_w/2$, as in a), produce electrode patterns that consist of four wires (including the side planes). b) shows a special variant of a five-wire design, which is symmetric with respect to the real axis and is characterized by $\vartheta_0 = \pi/2$.

the four-wire trap and the five-wire trap. Note, that the ground planes on either side of the structure are counted as individual electrodes. In the four-wire configuration, an electrode junction is situated below the trap center and the electrodes to the left and to the right are held at different potential. The five-wire configuration features a central wire below the trap center and two adjacent electrodes at different potential. Fig. 2.2 b) shows a special variant of a five-wire design, where the pseudopotential minimum is located above the center of the middle wire, which leads to a symmetric voltage distribution around the vertical axis. This design has also been chosen for the electron guide.

To characterize a surface-electrode geometry, it is convenient to reference its potential depth U_{SE} and transverse angular frequency ω_{SE} to the values generated by a pure quadrupole potential, see Eq. (1.3). To this end, the quadrupole moment $\alpha = 1/R_0^2$ at the guiding center of the surface geometry is expressed in terms of that of the ideal geometry via $\alpha' = \eta/R_0^2$, yielding an effective quadrupole strength η . With Eqs. (1.6) and (1.11), this leads to a modified guide stability q_{SE} and transverse angular frequency ω_{SE} of

$$q_{SE} = \eta \cdot \frac{2e}{m_e} \frac{V_0}{\Omega^2 R_0^2} \tag{2.1}$$

$$\omega_{SE} = \eta \cdot \frac{e}{\sqrt{2}m_e} \frac{V_0}{\Omega R_0^2} = \frac{q_{SE}}{\sqrt{8}} \Omega.$$
(2.2)

Note that the relationship $q_{SE} = \sqrt{8} \omega_{SE} / \Omega$ from Eq. (1.11) still holds.

The potential depth U is normally given by the maximum value of the pseudopotential Ψ in the direction of weakest confinement, which is the z-axis in the case of our guide

design, see Fig. 2.1. U is therefore determined by the layout of the electrodes that generate the guiding field and can not directly be related to the relative strength η of the electric quadrupole potential at the guiding minimum. The relative change in potential depth, when compared to the ideal hyperbolic guide, Eq.(1.14), is quantified by a geometric relative potential depth u defined via

$$U_{SE} = u \cdot \frac{e}{4m_e} \frac{V_0^2}{\Omega^2 R_0^2} = \frac{u}{\eta} \frac{q_{SE}}{8} V_0.$$
(2.3)

According to the last term, the ratio u/η can be interpreted as the efficiency of a surfaceelectrode configuration, as it determines the increase in drive voltage V_0 that is needed to realize a specific U_{SE} at given ponderomotive stability q_{SE} .

We sender has shown in [92] that the maximum achievable potential depth is independent of the rotation angle ϑ_0 (see Fig. 2.2) of the signal electrodes and therefore can be realized in both four-wire and five-wire designs. It is characterized by a scaling factor of $u_{max} = 0.0091$, and the potential depth of any surface-electrode guide can therefore be at best $\approx 1\%$ of that of the ideal quadrupole configuration. The reduction of the maximum transverse frequency is less dramatic and the best value obtainable amounts to $\eta_{max} = 0.318$. This value is independent of rotation θ_0 and is realized by a configuration with half of the sphere held at non-zero potential, corresponding to $\vartheta_w = \pi/2$ in Fig. 2.2. Furthermore, one can analytically show that only the four-wire configuration with electrodes of equal arc length ($\vartheta_0 = \pi/4$, $\vartheta_w = \pi/2$) realizes the maximum potential depth and transverse frequency at the same time.

In total, the variations in potential depth and transverse frequency with the electrode width (ϑ_w in Fig. 2.2) are rather small around the optimum value $\vartheta_w = \pi/2$ and approximately scale like $\eta \propto \sin(\vartheta_w)$ and $u \propto \sin^2(\vartheta_w)$ [92]. Therefore, the choice of a particular geometry will be influenced more by experimental constraints than by the optimum potential depth or transverse frequency achievable.

2.1.3 Five-wire configuration

The electron guiding setup is based on a symmetric five-wire design. It makes the guide compatible with future implementations of electrode junctions joining three or more guiding volumes [18, 19], which is needed for the envisioned realization of beamsplitter structures for guided electrons. A symmetric electrode pattern is conceptionally simpler than an asymmetric design and has the additional advantage that the location of the potential minimum above the center of the middle wire leads to optimal geometric shielding of exposed dielectrics in the gaps between the conductors [83]. This configuration is rarely used for ion traps, because the two principal axes of the quadrupole potential are oriented in the horizontal and vertical direction. This means that the vertical motion of an ion can not be cooled by a laser beam traveling parallel to the chip surface. Although the trap axes may be rotated by a suitable DC bias electric field [81, 95], almost all ion traps incorporate four-wire or asymmetric five-wire designs with unequal RF electrode widths.

The principal guiding parameters of the symmetric five-wire layout can be derived analytically due to its high symmetry [93, 96, 97]. The potential minimum forms at a distance of

$$R_0 = 1/2 \cdot \sqrt{c'^2 + 2c'w'} \tag{2.4}$$



Figure 2.3: a) Vertical cut through the pseudopotential experienced by an electron above a planar five-wire structure. The electrodes extend homogeneously in the direction perpendicular to the image plane. The microwave signal is applied to the red electrodes, whereas the blue structures are grounded. The substrate ($\epsilon_r = 3.66$) is shown in green. Electrode widths are $c = 350 \,\mu\text{m}$ for the center one and $w = 750 \,\mu\text{m}$ for the microwave electrodes. The gaps are $g = 110 \,\mu\text{m}$ wide and the wires are electroplated to a thickness of $T = 35 \,\mu\text{m}$. b) and c): The blue lines represent the pseudopotential along horizontal and vertical cuts through the guiding minimum, whereas the green lines show parabolic fits to the potential around the minimum.

from the electrode surface with c' = c+g and w' = w+g being the width of the central and the signal wires in the gapless-plane approximation, see Fig. 2.1. Furthermore, the maximum trap depth is realized for $c'/R_0 = 0.692$ and $w'/R_0 = 2.544$. For this configuration, the effective quadrupole strength is $\eta = 0.309$, only slightly smaller than the optimum value $\eta_{max} = 0.318$.

For the first proof-of-concept experiment described here, a distance of $R_0 \approx 500 \,\mu\text{m}$ between the potential minimum and the electrode surface was chosen. Technical constraints in the fabrication of the guiding structure by a commercial printed circuit board (PCB) manufacturer limited the electrode width to $(c, w) \geq 350 \,\mu\text{m}$ and the gap between the conductors to $g \geq 110 \,\mu\text{m}$. The center and microwave electrode width was therefore set to $c = 350 \,\mu\text{m}$ and $w = 750 \,\mu\text{m}$. Taking into account a gap width of $g = 110 \,\mu\text{m}$, this results in gapless-plane parameters of $c' = 460 \,\mu\text{m}$ and $w' = 860 \,\mu\text{m}$. The deviation from the optimum values ($\tilde{c}' = 350 \,\mu\text{m}$ and $\tilde{w}' = 1270 \,\mu\text{m}$) does not lead to a significant reduction in transverse frequency or potential depth.

Fig. 2.3 shows a numerical calculation of the pseudopotential above our guiding structure, including the effect of finite gaps between the electrodes. Any grounded enclosure around the guiding region is assumed to be placed sufficiently far away not to influence the guiding potential, compare also Sec. 2.1.5. As outlined in Sec. 2.1.2, the guide-to-electrode distance is given by the electrode dimensions only and equals $R_0 = 496 \,\mu\text{m}$. The relative quadrupole strength can be inferred from a parabolic fit to the pseudopotential along horizontal and vertical cuts through the guiding minimum, which leads to $\eta = 0.31$. The relative trap depth amounts to u = 0.0079 and is given by the value of the pseudopotential at the saddle point at $z \approx 950 \,\mu\text{m}$, see Fig. 2.3 c). In total, these values deviate by only

q	$\omega/2\pi$	U	$\Omega/2\pi$	V_0	R_0	λ_0
0.3	$113\mathrm{MHz}$	$29\mathrm{meV}$	$1.05\mathrm{GHz}$	$30\mathrm{V}$	$496\mu\mathrm{m}$	$286\mathrm{mm}$
0.1	$46\mathrm{MHz}$	$5\mathrm{meV}$	$1.3\mathrm{GHz}$	$15\mathrm{V}$	$496\mu\mathrm{m}$	$231\mathrm{mm}$
0.1	$102\mathrm{MHz}$	$24\mathrm{meV}$	$2.8\mathrm{GHz}$	$72\mathrm{V}$	$496\mu\mathrm{m}$	$107\mathrm{mm}$
0.03	$113\mathrm{MHz}$	$29\mathrm{meV}$	$10.5\mathrm{GHz}$	$300\mathrm{V}$	$496\mu\mathrm{m}$	$29\mathrm{mm}$
0.1	$500\mathrm{MHz}$	$23\mathrm{meV}$	$14\mathrm{GHz}$	$72\mathrm{V}$	$100 \mu \mathrm{m}$	$21\mathrm{mm}$
0.1	$1\mathrm{GHz}$	$23\mathrm{meV}$	$28\mathrm{GHz}$	$72\mathrm{V}$	$50\mu{ m m}$	$11\mathrm{mm}$

Table 2.1: Compilation of drive parameters required to realize various transverse frequencies according to Eqs. (2.1) to (2.3) with $\eta = 0.31$ and u = 0.0079. λ_0 denotes the free space wavelength at the drive angular frequency Ω . The first three lines correspond to drive parameters accessible with the current laboratory equipment and the first line represents the experimentally realized configuration.

about 1% from the gapless plane approximation ($R_0 = 501 \,\mu\text{m}$, u = 0.0080, $\eta = 0.315$) and are slightly smaller than those of the optimum four-wire configuration with $u_{opt} = 0.0091$ and $\eta_{opt} = 0.318$.

The potential shown in Fig. 2.3 has been computed with an angular drive frequency of $\Omega = 2\pi \cdot 1 \text{ GHz}$ and a voltage amplitude of $V_0 = 30 \text{ V}$, which are typical values used in the experiments. This leads to a guiding potential with a transverse frequency of $\omega = 2\pi \cdot 118 \text{ MHz}$, a potential depth of U = 32 meV and a stability parameter of q = 0.33.

2.1.4 Guiding at higher trap stability

For future experiments, it would be desirable to operate the guide at lower stability parameters q (see Sec. 4.3.3) and/or at higher transverse frequencies ω . The basic scaling of these values can be deduced from Eqs. (2.1) and (2.2). Fixing both the transverse angular frequency ω and the guide stability q determines the angular drive frequency Ω . Accordingly, the choice of the drive voltage V_0 and trap stability q sets the trap depth U. Tuning the guide-to-electrode distance R_0 allows to set both ω and U independently at fixed q. Table 2.1 compiles settings that might be interesting for future designs. For direct injection of electrons into the transverse quantum mechanical ground state of the guide, a transverse angular frequency higher than the demonstrated $\omega \approx 2\pi \cdot 100 \text{ MHz}$ is desirable. This avoids that the transverse collimation that is needed to match the ground state wave function becomes too small, see Eq. (1.17). Note that a transverse angular frequency of $\omega = 2\pi \cdot 1 \text{ GHz}$ at q = 0.1 requires a drive at $\Omega = 2\pi \cdot 28 \text{ GHz}$, regardless of the potential depth. This is a frequency value that is challenging to handle experimentally and demands special microwave components like K-type connectors and low-loss cables. As both q and ω scale linearly with Ω , either guide stability or transverse frequency can be traded in for lower drive frequency. For a potential depth of U = 23 meV, the voltage amplitude on the electrodes is at moderate V = 72 V at q = 0.1 and the guide-to-electrode distance stays between $R_0 = 50 \,\mu\text{m}$ and $R_0 = 500 \,\mu\text{m}$. For drive frequencies $\Omega \gtrsim 2\pi \cdot 3 \,\text{GHz}$, the free space wavelength λ_0 approaches the longitudinal extension of the present guiding structures so that an operation in a standing wave configuration is no longer possible and one has to realize electrically long structures, see Sec. 2.3.

2.1.5 Influence of a grounded top plane

So far, only setups have been discussed in which the guiding region is limited in the vertical direction by a grounded plane at $z \to \infty$. Introducing a grounded plane at a finite height $z = h_{gpl}$ above the conductors can increase the potential depth and outperforms optimizations of the pure in-plane electrode pattern [73, 98]. Although we did not use a grounded plane at distances that significantly influence the guiding parameters in the experiments reported on here, a study of the possible modifications is interesting for future experimental implementations.

Zhou *et. al.* have investigated the effect of a grounded top plate at finite distances above a symmetric five conductor pattern both analytically and numerically [98]. However, they reference their findings to the width of the center conductor c and not to the guiding height R_0 . Consequently, their results concerning the potential depth represent the maximum absolute value U that can be achieved for given conductor dimensions w/c, drive voltage V_0 and drive frequency Ω . With decreasing h_{gpl} , the guiding height R_0 also decreases and this leads to an increase in U for all geometries, regardless of their relative potential depth u, see Eq. (2.3). The optimization of U reported in [98] is therefore only partially caused by the presence of a grounded plane.

In Fig. 2.4, we show results of an optimization of h_{gpl} with the aim to maximize the relative potential depth u, yielding a result that is independent of the guide-to-electrode distance R_0 . The data have been derived from a finite-element simulation of a five-wire structure in the gapless-plane approximation. Fig. 2.4 a) shows the optimum height \tilde{h}_{gpl} of a grounded plane above the conductors, at which u is maximized, plotted against the ratio of signal to center conductor width w/c. For $w/c \gtrsim 5$, the optimum configuration $\tilde{h}_{gpl} \approx 2.5c$ is singly set by the distance of the ground plane from the conductors, and an increase of w at constant h_{gpl} does not affect the guiding field above the center conductor any more. Consequently, all geometric parameters u, R_0 and η converge, as can be seen from Figs. 2.4 b) to d). The maximum relative potential depth amounts to $u_{max} \approx 0.05$, which is about five times higher than the best value u = 0.0091 at $h_{gpl} \to \infty$. The relative quadrupole strength η , shown in Fig. 2.4 d), also increases with a grounded plane at the optimum distance \tilde{h}_{gpl} , although the gain is only about 25%.

Figs. 2.4 e) to g) additionally display the relative change of u, R_0 and η with w/c, referenced to the values without grounded plane, u_0 , $R_{0,0}$ and η_0 . Due to the decrease in u_0 for electrode widths that exceed the optimum w/c = 3.68, u/u_0 increases more steeply for higher w/c.

When choosing the drive parameters of a guiding experiment, it is often advisable to fix the guide stability q first, as this value determines how well the electron motion can be approximated by the time-averaged pseudopotential and ultimately limits electron guiding, see Sec. 4.2. Following Eq. (2.3), the potential depth U is then given by the ratio u/η , which is plotted in Fig. 2.4 h). Assuming constant q, an adjustment of the top plane distance h_{gpl} to yield maximum u/η can be useful in two ways. First, a given value of U can be achieved by a lower guide voltage V_0 . Usually, the smaller V_0 compensates the changes



Figure 2.4: Optimum height \tilde{h}_{gpl} of a grounded plate above the conductors and influence on guiding parameters. a): \tilde{h}_{gpl}/c for maximum relative potential depth u as a function of relative signal conductor width w/c. b) to d): Values of u, R_0 and η against w/c with $h_{gpl} = \tilde{h}_{gpl}$ from a). e) to g): Relative variation of the same parameters compared to a geometry without grounded plane characterized by u_0 , $R_{0,0}$ and η_0 . h): Relative variation of the ratio u/η with w/c at $h_{gpl} = \tilde{h}_{gpl}$. The optimum ratio w/c = 3.68 that yields a maximum u without grounded top plane is marked in all plots by a red vertical line.

in R_0 and η that arise from the presence of the top plate, and q stays approximately constant without need for a large variation in drive frequency Ω . Secondly, when keeping the drive voltage V_0 constant, a higher potential depth can be realized at given q. However, as the ground plane causes a higher η and smaller R_0 , the drive frequency Ω has to be increased to keep q constant. Additional care has then to be taken that the overall size of the guiding structure is still compatible with the reduced drive wavelength.

For the five-wire structure used in the present experiments, a value of w/c = 1.87 leads to an optimum ground plane height of about $\tilde{h}_{gpl} = 1.89c$. This increases the relative quadrupole strength η and relative potential depth u to $\eta = 0.37$ and u = 0.040, while it lowers the guiding height to $R_0 = 305 \,\mu\text{m}$. With a fixed $V_0 = 30 \,\text{V}$ and q = 0.3, the potential depth rises from $U = 29 \,\text{meV}$ to $U = 121 \,\text{meV}$. At the same time, the drive frequency has to be increased from $\Omega = 2\pi \cdot 1.05 \,\text{GHz}$ to $\Omega = 2\pi \cdot 1.88 \,\text{GHz}$.

One potential drawback of geometries with finite h_{gpl} is the increased anharmonicity of the guiding potential, which eventually leads to dynamical instabilities of the electron motion in longer guides [99]. In the first implementation of an electron guide reported on here we used a shielding cover at a comparatively large distance of $h_{gpl} = 10$ mm, which leaves the guiding potential essentially unperturbed.

2.1.6 Influence of static bias voltages

In principle, the trap depth can be further increased by applying a static negative voltage to the top plane [73]. However, this shifts the guiding center away from the position, at which the microwave potential is zero, thus increasing micromotion [100]. On the contrary, biasing the signal electrodes with a static positive voltage generates an additional quadrupole field with its field zero overlapping with the microwave null. Following from the conformal map described in Sec. 2.1.2, a positive voltage corresponds to a configuration that confines electrons in the vertical direction and repels them horizontally. This effectively deepens the guide [92], since the pseudopotential well is about ten times higher in the horizontal than in the vertical direction, see Fig. 2.3. However, the guide stability of Eq. (1.5) is also modified and is now characterized by $a \neq 0$, consequently limiting the stability at low q, see Fig. 1.2.

2.2 Coupling structure

In the experiments, electrons are injected into the guide at the edges of the substrate. There, the homogeneity of the electrodes is broken and the resulting fringing fields disturb the guiding potential. Therefore, the electrode pattern at the end of the electrodes has been optimized numerically to achieve a smooth extension of the guide's potential minimum into the field free region in front of the substrate. Similar optimizations of the electrode shape are also used in the design of ion traps, for example to minimize the pseudopotential at junctions connecting three trapping volumes [18, 19].

The principal aim of the optimization is to reduce the transverse excitation of an electron entering the guide. This enhances the guiding efficiency in the present experiments and is also a prerequisite for ground state injection as described in Sec. 1.6. Because of the electrode symmetry with respect to the vertical cut plane along the guiding minimum

(x = 0 plane), the horizontal pseudopotential gradient within this plane is always zero and electrons that travel near the guiding axis experience only a small horizontal force. Considering a lateral deflection, it therefore suffices that the optimization routine evaluates forces in the vertical direction.

All optimizations have been performed by systematically varying the electrode shape while preserving symmetry with respect to the yz-plane. During the course of this thesis, two different coupling structures have been designed. The first design, see Sec. 2.2.1, has been derived by minimizing the transverse component of the electric microwave field along the guide axis. It resulted in a reduction of the transverse field by a factor of 20 compared to a reference design ending in straight wires. However, when numerical particle tracking simulations are compared with the experiment, see Sec. 4.3.3, the transverse excitation is still found to be quite large. The second design, reported on in Sec. 2.2.2, directly minimizes the transverse gradient of the pseudopotential, thus reducing the vertical force that is exerted on an electron in the time averaged picture. Compared to the first design, simulations indicate a further reduction of the amplitude of the transverse motion by a factor of about 10.

In the optimizations, the electric field is computed in the quasi-static approximation, see Sec. 2.1.1. This is justified for both designs discussed in the following. They feature a longitudinal extension of 3 mm and 10 mm, respectively, which is much smaller than the on-substrate wavelength of $\lambda \approx 200$ mm at typical drive frequencies of $\Omega = 2\pi \cdot 1$ GHz. Since the optimizations have been additionally performed with models that implement the gapless-plane approximation, I also discuss the effect of finite electrode gaps at the end of this section.

2.2.1 First generation design: Minimization of the transverse electric field

This subsection is based on the Supplemental Material published together with [101].

The first coupling structure that has been developed in the course of this thesis and the one that has been used in all of the experiments reported on in the following, has been optimized by minimizing the maximum value of the transverse electric field along the guide axis. Since the horizontal electric field is zero due to electrode symmetry, this amounts to a reduction of the vertical electric field component E_z . As long as this procedure leads to an extremum of the total field magnitude |E| on the guiding axis, the vertical pseudopotential gradient $(\partial/\partial z) \Psi = (\partial/\partial z) |E|^2$ is also zero so that no force is exerted on the electron in the time averaged picture. However, a gradient force in the vertical direction, which originates from a vertical variation of the longitudinal field component E_y , is not accounted for.

Fig. 2.5 a) shows the finite element model that has been used for the electrostatic field calculation. Upon optimization, the positions of twelve points at the edges of the signal conductors, which are shown as black dots in Fig. 2.5, are laterally varied while preserving symmetry with respect to the vertical plane through the guide's center. The model also includes an aperture plate, which is placed at a distance of 500 μ m in front of the guide, to account for the last element of the electron gun. The exit hole is situated at the guiding height R_0 above the electrode plane and has a diameter of 400 μ m. On the substrate, the



Figure 2.5: Coupling structure. a) Electrode pattern at the edges of the substrate with aperture in the back. The shape of the electrodes has been numerically optimized by lateral variation of twelve points at the edges of the signal electrodes, as indicated by black dots. b) Optimization result. Finite element simulation of the magnitude of the radial electric field in a vertical cut through the guide center at the beginning of the structure. c) Field of electrodes that end in straight lines. The line of minimum radial field bends down between the end of the guide and the coupling aperture.

signal conductors extend all the way out to the substrate edge in front of the coupling aperture.

The electric field above the electrodes is calculated with the electrostatic field solver of the COMSOL package, while the optimization is performed with MATLAB's built-in Nelder-Mead Simplex algorithm.

The result of this optimization is presented in Fig. 2.5 b), where the magnitude of the transverse electric field is shown in a vertical plane that is orientated along the guide and cuts through the potential minimum. Here, a minimum of the absolute value $|E_z|$ of the transverse electric field extends in a horizontal line from the guide through the aperture. The maximum vertical field on the guide axis has been reduced by the optimization to $E_z(\max) = 6 \text{ V/m}$, a factor of 20 lower than for a geometry ending in straight electrodes. For comparison, the field of this straight electrode configuration is plotted in Fig. 2.5 c). There, the potential minimum bends down between the substrate and the aperture plate, which leads to a maximum transverse field of $E_z(\max) = 120 \text{ V/m}$ on the guide axis.

One weakness of the electrostatic model used here is the fact that the signal electrodes extend all the way out to the substrate edges. After completion of the guide design, it turned out that it is impossible to pattern the electrode structure directly at the edges, neither by the printed circuit board technique nor by photolithography. On the fabricated substrates, the signal electrodes are therefore recessed from the substrate edge introducing a thin grounded strip perpendicular to the guiding electrodes, see Sec. 3.1. The disturbance of the pseudopotential that is introduced by this additional feature is small enough to


Figure 2.6: a) Reference electrode pattern before optimization. Signal electrodes are shown in blue, the entire white plane is grounded. The model includes a grounded plane at y = 0, at a distance d from the tip of the electrodes. During optimization, the position of the black dots is laterally varied, while the gradient W is integrated at a height $z = R_0$ along the red line of length L_i . b) Vertical normalized gradient W for four initial structures with different taper length L and gun-to-electrode distance $d = R_0$.

be neglected in experiments that use a rather diffuse thermal electron beam, see Ch. 4. However, it will be an issue in future experiments that require an increased control over the electron trajectories. The second generation coupler design, which is described in the following Section, therefore uses a model that includes a grounded strip in front of the electrodes.

2.2.2 Second generation design: Minimization of the transverse potential gradient

Numerical particle tracking simulations in the electric field of the coupling structure of the previous Section still indicate a substantial transverse excitation of electrons at the guide entrance, see Secs. 2.2.3 and 4.3.3. To further reduce this excitation, a new coupler has been designed by using a different optimization objective.

Description of the optimization model

The optimization directly minimizes the vertical gradient $\partial_z \Psi$ of the pseudopotential of Eq. (1.12) on a straight line at height R_0 along the guiding center. The longitudinal gradient as well as the absolute value of the pseudopotential Ψ have not been considered. In the following, $\partial_z \Psi$ will be parametrized by a normalized gradient W, which is given by

$$\frac{\partial}{\partial z}\Psi = \frac{e^2 V_0^2}{4m_e \Omega^2 R_0^2} \cdot \frac{W}{R_0}$$
(2.5)

and represents the dimensionless vertical gradient of $|E|^2$ computed for $V_0 = 1$ V and $R_0 = 1$ m.

Fig. 2.6 a) depicts a continuously tapered reference electrode pattern that has been derived by scaling the width of the signal electrodes w from an initial value of $w = 2R_0$ down towards zero, while adjusting the width of the center electrode according to $c = \sqrt{4R_0^2 + w^2} - w$. Assuming an adiabatic tapering, this would give a constant guiding height R_0 (see Eq. (2.4)). The last element of the electron gun in front of the guide is represented by a grounded plane at y = 0, which is implemented by including mirror charge electrodes at negative y that are not shown in Fig. 2.6 a). This neglects the effect of fringing fields at the hole of the aperture.

During optimization, the position of several points on the electrode edges are varied laterally, while the merit function of the optimization procedure is the integral of $|W|^2$ along a line at height R_0 , which starts at the aperture plate at y = 0 and extends over a distance L_i along the guide axis. The optimization model features a taper that ends in a single point. Optimizations with a blunt structure with two end points yielded larger residual gradients W and resulted in the two points being separated by the minimum distance that was still compatible with the optimization constraints. All optimization points are connected by straight lines, which facilitates the calculation of the pseudopotential. Additionally, testing a geometry with rounded corners did not give better results.

The electrodes are modeled in the gapless-plane approximation and cover the entire horizontal plane at z = 0. The normalized gradient W is computed by using the MATHE-MATICA package *SurfacePattern* developed by Roman Schmied [102, 103]. The optimization itself is performed by the Nelder-Mead optimization algorithm of MATHEMATICA.

As a reference, Fig. 2.6 b) depicts the normalized vertical gradient W of the continuously tapered design for four different taper lengths L. With increasing L, the maximum vertical gradient decreases from $W = 13 \cdot 10^{-3}$ at $L = 8R_0$ to $W = 6 \cdot 10^{-3}$ at $L = 20R_0$. Generally, the gradient W depends on the taper length L, the number of taper segments Nand the gun-to-electrode distance d. To minimize the initial gradient W before optimization as well as field disturbances caused by the electron gun, it would be advisable to allow for as large L and d as possible. However, they are restricted by the drive wavelength and the working distance of the electron lens, respectively. The maximum segment number was limited to N < 20 by the computing power available. In addition, the optimization result has also been found to vary with the interval L_i , over which the integration of the vertical gradient is performed. Shorter or larger values of L_i resulted in a reduced W at the beginning or the end of the taper, respectively. To facilitate the computation and to obtain geometries for different constraints on L and d, optimization runs have been performed for several sets of L, d, N and L_i . This also allowed to study the effect of the individual parameters separately, as I will discuss in greater detail in the following.

Segment length

The segment length $\Delta = L/N$ between the optimization points sets the maximum level of detail of the taper structure. Decreasing Δ leads to a smoother variation of the normalized gradient W and smaller maximum values of W. On the other hand, the fabrication process sets a lower limit on Δ .

Fig. 2.7 shows optimized electrode layouts for two configurations with taper length $L = 20R_0$ and a segment length of $\Delta = 2R_0$ and $\Delta = R_0$, along with the corresponding normalized gradients W. For $\Delta = 2R_0$, the maximum gradient in the taper region



Figure 2.7: Optimized geometries for a taper length of $L = 20R_0$ and a segment length of a) $\Delta = 2R_0$ and b) $\Delta = R_0$. The gun-to-electrode distance is in both cases $d = 4R_0$ and the transverse pseudopotential gradient has been optimized in the interval $[0 \dots 33R_0]$. c): Vertical normalized gradient W for the structures shown in a) and b). Both geometries reduce W in the taper region up to about $y = 30R_0$. The residual gradient at $y \approx 35R_0$ can not be reduced by a variation of the taper segments and approximately amounts to the value of W without optimization.

 $|W|_{max} \approx 3 \cdot 10^{-4}$ is limited by the segment length and varying the taper length L did not yield smaller values of W. A reduction of the segment length to $\Delta = R_0$ leads to a decrease of the vertical gradient in the taper region by a factor of roughly ten. W is then limited by its values at $y \gtrsim 30R_0$, which can not be influenced by a variation of the taper structure, which ends at $y = 24R_0$. A further decrease of W then would require a larger taper length L.

An increased number of optimization points additionally reduces the influence of a segment variation at the beginning of the taper on the gradient W at the end of the taper and vice versa. This allows the independent minimization of the gradient at the coupling aperture and at the transition from the taper to the guide. Consequently, the optimization result at shorter $\Delta = L/N$ is less sensitive to changes in other optimization parameters like integration length L_i or guide-to-electrode distance d.

The structure of Fig. 2.7 b) with $L = 20R_0$ and N = 20 generates the smallest vertical pseudopotential gradient of all configurations studied. Increasing L at constant L/Npossibly allows a further reduction of the transverse gradient, especially at $y > 30R_0$. However, due to the increased computing power that is needed to optimize at higher N, no further calculations have been carried out so far. Additionally, a significant increase in taper length would be incompatible with the standing wave microwave excitation (see Sec. 3.2.2) that is used in the experiments reported on here.

Another option, that might improve the optimization results but that has not yet been implemented, would be to allow for variable distances between the segments during the optimization in order to concentrate the optimization points in critical regions.

Taper length

The optimized structures of Fig. 2.6 still show a residual gradient W behind the transition from the taper to the guide ($y \gtrsim 30R_0$). A reduction of W in this area can not be achieved by a lateral variation of the taper's electrode shape, but requires a longitudinal extension of the taper.

Fig. 2.8 a) shows the normalized gradient W for two optimized geometries with different taper lengths $L = 16R_0$ and $L = 20R_0$ and a constant segment length of $\Delta = 2R_0$. The variation of W is essentially the same for both geometries up to a longitudinal distance of $y \approx 15R_0$ from the coupling aperture. At the transition to the guiding potential in the region $y \gtrsim 15R_0$, the longer electrode pattern with $L = 20R_0$ features a smaller W. Fig. 2.9 shows the corresponding electrode patterns, together with additional layouts for shorter L. Adding more segments at higher L barely changes the thin electrode structure at the beginning of the taper.

In all geometries shown in Fig. 2.9, the values of the local maxima of W in the taper region are limited by the segment length $\Delta = 2R_0$, and an increase in taper length L does not change the gradient at the beginning of the taper any more. For fixed Δ , it therefore does not make sense to increase L above a certain value, and the segment length $\Delta = L/N$ determines the reasonable maximum L or vice versa. For $L \approx 20R_0$ we find that a segment length of $\Delta = R_0$ generally gives good results with maximum gradients in the taper region that are on the order of or smaller than the residual gradient behind the taper ending, see for example Fig. 2.7 b).

Concerning the gradient at the far end of the taper, it would be desirable to realize a



Figure 2.8: Dependence of the normalized vertical gradient W after optimization on a) the taper length L and b) the integration length L_i . The corresponding taper geometries are shown in Fig. 2.9. All models have a segment length of $\Delta = 2R_0$ and a gun-to-electrode distance of $d = 4R_0$. In a), the optimization has been performed over the common interval $[0 \dots 33R_0]$, whereas the models of b) feature the same taper length of $L = 16R_0$.

taper as long as possible. However, this has to be traded off against the fact that a too large value of L would be incompatible with the quasi-static approximation that underlies the optimization routine.

Integration length

The optimization result is also influenced by changes in the length L_i of the interval $[0; L_i]$, over which W is integrated during optimization. Although L_i is no physical parameter of the taper geometry, it modifies the optimization results. Different runs have been performed in which the integration started at the coupling electrode and stopped at varying longitudinal distances L_i . A smaller value of L_i leads to a predominant minimization of the gradient at the beginning of the taper, whereas a larger L_i also reduces W at the end of the guide. For a too short taper or for too few optimization points N, a reduction at the end of the taper can only be realized at the cost of an increase at the beginning.

For some geometries, a change of L_i leads to a qualitatively different optimized taper layout. One example are the two structures of Figs. 2.9 c) and e) with $L = 16R_0$, $\Delta = 2R_0$ and an integration length of $L_i = 33R_0$ and $L_i = 100R_0$, respectively. The resulting maximum gradient W, plotted in Fig. 2.8 b), decreases with an increase in integration length by about 30%. In addition to the smaller peak value at the end of the taper, the extended integration also reduced the magnitude of W at the beginning of the taper.

The influence of L_i on the optimization result depends on the specific choices of N and L, so each result should be checked at different L_i . Generally, the sensitivity on L_i seems to decrease with larger L and Δ and the changes in the residual gradient that have been observed at different L_i amounted to less than a factor of five.



Figure 2.9: Optimized geometries for varying taper length L. a)-d): Structures with $L = 8R_0$ up to $L = 20R_0$. The segment length in all models amounts to $L/N = 2R_0$, while the gun-to-electrode distance is $d = 4R_0$ and the integral of the normalized gradient W has been minimized in the interval $[0 \dots 33R_0]$. e): Optimization result for the parameters of c), but with an integration interval of $[0 \dots 100R_0]$. Note that the vertical axis is slightly compressed compared to a) to d). The normalized gradients of c) to e) are plotted in Fig. 2.8.



Figure 2.10: Normalized gradient W plotted against longitudinal distance y for varying gun-to-electrode distances d. The electrode pattern has been optimized in a model without aperture plate. Introducing an aperture at decreasing distances d from the beginning of the taper (at y = 0) leads to an increase of the vertical gradient W. For comparison, the gradient of the model without aperture is shown in blue.

Gun-to-electrode distance

The influence of the grounded coupling aperture on the taper field decreases with increasing distance d between the aperture and the electrode pattern. It is therefore interesting to see, for which minimal value of d the presence of the electron gun can be neglected both during optimization and in the experiment. This critical distance d can be inferred from Fig. 2.10 where the normalized gradient W is plotted for d ranging from $d = 50R_0$ to $d = 10R_0$. The electrode pattern that has been used in these computations has been optimized in a model with no coupling aperture at all and $L = 16R_0$, N = 16 and $L_i = 30R_0$. The presence of the coupling aperture starts to disturb the taper potential for distances smaller than about $d \approx 30R_0$.

While this increase of the transverse gradient can be avoided by including the aperture in the optimization model, the solutions that are obtained in this way are specific to a certain value of d. In the experiment, d is limited by the focal length f of the coupling electron lens. At $L = 16R_0$ and $\Delta = 2R_0$, f should therefore amount to $f \gtrsim 30R_0$ in order to obtain a configuration that is independent of d.

Fabrication tolerances

The tapers, that produce small gradients W, start with a very fine electrode pattern in the region from $y = 4R_0$ to $y = 8R_0$, see for example Fig. 2.7 b). Simulations show that these features are essential to reduce W at the beginning of the guide. For instance, removing the electrodes between the first three optimization points leads to an increase of the maximum gradient by a factor of 30. Moreover, optimizing a structure, that starts with a blunt termination with fixed lateral width, fails to produce values of $|W|_{max}$ as small as that of structures starting in a single point. The necessity of placing fine features at the beginning of the guide additionally appears to be independent of the gun-to-electrode distance. The optimization of a model without aperture plane also led to thin electrodes that nearly touch each other at the beginning of the taper.

These small features pose a challenge regarding fabrication. The tolerances required for the electrode pattern of Fig. 2.7 b) can be estimated from a variation of the width of the center or signal conductor at one optimization point. It turns out that the magnitude of W is especially sensitive to lateral shifts of conductor edges near the guide center. There, a relative variation of $\Delta x \approx 0.01R_0$ leads to an increase of $|W|_{max}$ that is on the order of the residual pseudopotential gradient at the transition from the taper to the guide. For a guiding height of $R_0 = 500 \,\mu\text{m}$, as it is employed in the present experiments, this amounts to $\Delta x \approx 5 \,\mu\text{m}$, which should still be compatible with photolithographic processes [104].

2.2.3 Comparison of different optimization results

Fig. 2.11 compares the electrode pattern and the normalized vertical gradient W at the guide axis for three different taper geometries. All gradients have been computed in the gapless-plane approximation with the last element of the electron gun represented by a grounded vertical plane at y = 0. The plots have additionally been scaled to the experimentally implemented guiding height of $R_0 = 500 \,\mu\text{m}$.

As a reference, results for the structure from Sec. 2.2.1 (termed *MWGuide1* in the following) are shown in Figs. 2.11 a) and b). Since it has been derived by minimizing the transverse electric field and not the gradient W itself, it features a comparatively high maximum gradient of $|W|_{max} \approx 0.007$.

Figs. 2.11 c) to f) depict taper layouts that result from the explicit minimization of the integral of $|W|^2$ along the guide axis. Compared to *MWGuide1*, the underlying straight guiding structure features a thinner center conductor of $c = 414 \,\mu\text{m}$ and wider signal conductors of $w = 1 \,\text{mm}$, which does not change the guiding height, but leads to a deeper and stiffer guiding potential ($\eta = 0.32$ and u = 0.0088). The geometry of Fig. 2.11 c) has a gun-to-electrode distance of $d = 2 \,\text{mm}$ and a taper length of $L = 8 \,\text{mm}$, which both is slightly larger than in *MWGuide1*. The segment length amounts to $\Delta = 1 \,\text{mm}$. An optimization of the normalized gradient W yields a maximum of $|W|_{max} \approx 4 \cdot 10^{-4}$, more than an order of magnitude smaller than the gradient of *MWGuide1*. A further reduction to $|W|_{max} \approx 2 \cdot 10^{-4}$ can be achieved by optimizing with a segment length of $\Delta = 500 \,\mu\text{m}$ and a taper length of $L = 10 \,\text{mm}$, see Figs. 2.11 c) and f).

Figs. 2.12 a), c) and e) show the pseudopotential Ψ of the taper layouts of Fig. 2.11 in a vertical cut through the guide axis. They have been calculated for a drive frequency of $\Omega = 2\pi \cdot 2.8$ GHz, a drive voltage of $V_0 = 72$ V and a distance of $R_0 = 500 \,\mu\text{m}$ between guide and electrodes. This yields a stability parameter of q = 0.1 for all structures, while the transverse frequency and the potential depth amount to $\omega = 2\pi \cdot 100$ MHz and $U = 23 \,\text{meV}$ for MWGuide01 and to $\omega = 2\pi \cdot 104$ MHz and $U = 26 \,\text{meV}$ for the two other designs.

The run of the pseudopotential minimum can be inferred from the inner equipotential line at $\Psi = 10 \text{ meV}$. The layout of *MWGuide01* produces a potential minimum that bends down by about 10 µm before ending in a transition region with a pseudopotential



Figure 2.11: Electrode pattern (left) and corresponding pseudopotential gradients at $z = R_0$ (right) for different coupling structures. The electrode layout of a) and b) has been derived by minimizing the transverse electric field on the guide axis, see section 2.2.1, while the patterns of c) to f) minimize the vertical pseudopotential gradient. c) and d): Taper with a length of $L = 16R_0$, a gun-to-electrode distance of $d = 4R_0$ and a segment length of $\Delta = 2R_0$. Due to constraints imposed by the fabrication process, the structure does not end in a single point, like in Fig. 2.9 c), but features a blunt end with a width of $\Delta x = 20 \,\mu\text{m}$. This did not significantly alter the shape of the optimized electrode pattern. e) and f): $L = 20R_0$, $d = 4R_0$ and $\Delta = R_0$, cf. Fig. 2.7. All spatial dimensions have been scaled to yield a guiding height of $R_0 = 500 \,\mu\text{m}$.



Figure 2.12: Pseudopotential in the vertical plane along the guiding center at x = 0 (left) and electron trajectories in this plane (right) for the coupling structures shown in Fig. 2.11. The inner equipotential line in the plots on the left represents a pseudopotential of $\Psi = 10 \text{ meV}$, while the outer ones are logarithmically spaced from $\Psi = 10 \text{ eV}$ to $\Psi = 316 \text{ eV}$. All potential plots and trajectories have been computed with a drive frequency of $\Omega = 2\pi \cdot 2.8 \text{ GHz}$, a drive voltage of $V_0 = 72 \text{ V}$ and an electron kinetic energy of $E_{kin} = 1 \text{ eV}$. a) and b): *MWGuide1* from Sec. 2.2.1. c) and d): Structure with minimized transverse pseudopotential gradient and a taper length of L = 8 mm, a gun-to-electrode distance of d = 2 mm and a segment length of $\Delta = 1 \text{ mm}$. e) and f): The same for L = 10 mm, d = 2 mm and $\Delta = 0.5 \text{ mm}$.

maximum in front of the electron gun (y < 3 mm). There, the equipotential lines run fairly upright with a slightly falling inclination. The drop of the pseudopotential minimum for y < 15 mm causes the increase of the vertical potential gradient W that is observed in the cut of Fig. 2.11 b), where W has been evaluated at a constant height of z = 500 µm. The pseudopotential minimum of structures that have been optimized with respect to W approximately runs at a constant height of $z = R_0 = 500 \text{ µm}$. Towards the electron gun, several isolated minima appear in the transition region at y < 10 mm, before the potential again forms a maximum in front of the aperture plane. There, the nearly vertical equipotential lines reflect the small vertical potential gradient along z = 500 µm.

Particle tracking

Numerical particle tracking of electrons in the simulated electric field directly verifies the influence of a reduced gradient W on the electron trajectories at the guide entrance, as can be seen from Figs. 2.12 b), d) and f). The trajectories have been computed in a quasi-static approximation with a sinusoidal variation applied to the static field that has been computed from a gapless-plane model. This is justified for all structures of Fig. 2.12 at a drive frequency of $\Omega = 2\pi \cdot 2.8 \text{ GHz}$ (free space wavelength of $\lambda = 110 \text{ mm}$). The guiding parameters are the same as in the pseudopotential plots of the left column of Fig. 2.12.

Since the pseudopotential minimum of MWGuide01 bends down at the beginning of the taper, electrons starting at $z_0 = 500 \,\mu\text{m}$ first get deflected downwards, which leads to a subsequent oscillation in the harmonic guiding potential with an amplitude of $\Delta z = 6 \,\mu\text{m}$. This oscillation can be reduced by lowering the starting height to $z_0 = 490.5 \,\mu\text{m}$. The electrons then follow the potential minimum in the entire taper region, which results in a reduced oscillation amplitude of $\Delta z = 1 \,\mu\text{m}$. Note however, that the necessary reduction of z_0 depends on the kinetic energy of the electrons. An improvement of the coupling behavior by adjusting the vertical position of the electron gun will therefore only be possible for electrons of a specific velocity class.

Owing to the straighter run of the potential minimum of the two other structures of Fig. 2.12, the excitation of an incoming electron is smaller and amounts to $\Delta z = 1 \,\mu\text{m}$ and $\Delta z = 0.5 \,\mu\text{m}$, respectively. Moreover, the electrons that experience the smallest deflection in the transition region start at $z_0 = 500 \,\mu\text{m}$ and the oscillation amplitude is largely independent of electron kinetic energy.

The initial excitation of an electron with fixed kinetic energy is given by the magnitude of the pseudopotential Ψ in the transition region, which in turn is proportional to the trap depth U. Scaling the drive frequency to $\Omega' = C \cdot \Omega$ and the electrode size to $R'_0 = 1/C \cdot R_0$, while keeping the drive voltage V_0 constant, changes the transverse frequency to $\omega' = C \cdot \omega$ without changing U and q, see Eqs. (1.6), (1.11) and (1.14). The amplitude of the vertical electron excitation in the coupling region then scales like $\Delta z' = 1/C \cdot \Delta z$, which leads to a reduced oscillation in a smaller and stiffer guiding potential (C > 1).

Implications for ground state guiding

Concerning the direct coupling of electrons into the transverse ground state of motion, see Sec. 1.6, the quantum mechanical excitation at the coupling structure can be estimated from a comparison of the classical electron motion to that of a coherent oscillator state $|\alpha\rangle$ in the guiding potential. $|\alpha\rangle$ is given by [60]

$$|\psi(t=0)\rangle = |\alpha\rangle = \exp^{-|\alpha|/2} \sum_{n} \frac{\alpha^{n}}{\sqrt{n!}} |n\rangle, \qquad (2.6)$$

with $|n\rangle$ being the harmonic oscillator energy eigenvectors and α a complex amplitude. The mean phonon occupation number of this state is

$$\langle n \rangle = |\alpha|^2 \,. \tag{2.7}$$

Its expectation values $\langle Z \rangle(t)$ in position and $\langle P_Z \rangle(t)$ in momentum space oscillate sinusoidally and are given by

$$\langle Z \rangle (t) = \sqrt{\frac{2\hbar}{m_e \omega}} \cdot \Re \left[\alpha \left(t \right) \right]$$
 (2.8)

$$\langle P_Z \rangle (t) = \sqrt{2m_e \hbar \omega} \cdot \Im [\alpha (t)].$$
 (2.9)

Equating the classical oscillation amplitudes of the electron position and momentum with the amplitudes of $\langle Z \rangle(t)$ and $\langle P_Z \rangle(t)$ yields via Eq. (2.7) the mean occupation number of the coherent state, the expectation values of which most closely reproduce the classical motion.

With this estimate, the trajectories of Fig. 2.12 may be related to a mean occupation number $\langle n \rangle$. For *MWGuide01*, this leads to $\langle n \rangle = 390$ and $\langle n \rangle = 5$, when considering the trajectories starting at $z = 500 \,\mu\text{m}$ and $z = 490.5 \,\mu\text{m}$, respectively. The structures, that feature a minimized gradient W on the guiding axis, give rise to $\langle n \rangle = 5$ in the shorter and $\langle n \rangle = 1.3$ in the longer taper.

Besides using structures that produce smaller potential gradients, $\langle n \rangle$ can be further reduced by scaling the electrode pattern. As mentioned above, an increase of transverse frequency ω by a factor of C at constant q and U reduces the oscillation amplitudes Δz and Δp_z by a factor of 1/C. According to Eqs. (2.7) to (2.9), this in turn lowers the mean occupation number to $\langle n \rangle' = 1/C \langle n \rangle$.

Although these values have been derived by starting with a perfectly collimated electron beam on axis and neglecting fabrication imperfection, electrode gaps and fringing fields at the coupling aperture, it still appears feasible to obtain mean occupation numbers below $\langle n \rangle = 10$ using the structure of Fig. 2.11 c) at $\Omega = 2.8$ GHz and $V_0 = 72$ V. Since the concept of a classical oscillation is no longer meaningful at such low $\langle n \rangle$, the calculations presented in this thesis can only serve as a starting point for future quantum mechanical simulations and experiments.

2.2.4 Influence of electrode gaps

All optimizations in this section have been performed in the gapless-plane approximation, see Sec. 2.1.1. To study the remaining influence of electrode gaps on the coupling field, the optimized electrode structure has been modeled with gaps of varying width g.

Fig. 2.13 compares the transverse electric field E_z on the guiding axis and particle trajectories for different values of g. The electric field of the models with finite g have been calculated using the commercially available boundary element method (BEM) solver CPO,



Figure 2.13: Vertical electric field on the guiding axis and electron trajectories for varying electrode gap width g, computed for the electrode structure *MWGuide1*, see Sec. 2.2.1. a) Vertical component of the electric field E_z . The individual heights z, the cut has been taken at, are given in the figure legend. b) Electron trajectories at a longitudinal kinetic energy of 1 eV for $\Omega = 2\pi \cdot 2.8$ GHz and $V_0 = 72$ V. The trajectories for $g = 40 \,\mu\text{m}$ and $g = 110 \,\mu\text{m}$ overlap. For each value of g, the electrons are released at the respective guiding height R_0 , which is given by $R_0 = 502.5 \,\mu\text{m}$, $R_0 = 496.5 \,\mu\text{m}$ and $R_0 = 500.5 \,\mu\text{m}$ for $g = 40 \,\mu\text{m}$, $g = 110 \,\mu\text{m}$ and g = 0.

while that for g = 0 is determined with the MATHEMATICA code of the previous Section. Since the guiding height R_0 changes with g, the cuts for the different models in Fig. 2.13 have been taken at different vertical positions $z = R_0$.

In the taper region ($y \leq 3 \text{ mm}$), the models with g = 0 and g = 40 µm yield nearly the same vertical field E_z , while an increase to g = 110 µm gives an approximately 25% larger E_z . This illustrates the fact that an increase of g predominantly shifts the guiding minimum towards the electrode surface, while keeping the guiding field approximately constant. For y > 3 mm, the models with finite gap width closely agree. The slight difference in E_z compared to the gapless model can be partly attributed to a too large transverse grid spacing in this part of the BEM models, where a limited total number of segments prohibited a refinement until convergence is reached.

The electron trajectories for all three gap widths agree within the numerical accuracy of the simulation, which confirms that the gapless-plane approximation is valid. The small differences between the traces with finite g and g = 0 can again be attributed to numerical imperfections of the BEM field calculation behind the coupling region.

2.3 Microwave transmission line properties

So far, the electric field above the guiding electrodes has only been treated quasi-statically, neglecting microwave propagation effects on the electrodes. This is justified for structures that are electrically short, meaning that their overall extension in all spatial directions is much smaller than the wavelength λ of the driving field. This assumption is easily fulfilled in ion trapping experiments with electrode sizes of several centimeters and operation at drive frequencies below a few hundred megahertz. For electron guiding structures that are driven at microwave frequencies it may still hold for sub-components like the coupling

structures discussed in Sec. 2.2, but especially the longitudinal extension of the guide can become comparable to λ , which amounts to $\lambda \approx 200 \text{ mm}$ at $\Omega = 2\pi \cdot 1 \text{ GHz}$.

This has been avoided in the experiments presented in this thesis by keeping the whole electrode structure shorter than $\lambda/4$, see Sec. 3.1.1. Nevertheless, it is desirable to levitate this restriction in future experiments to be able to guide electrons over longer distances. For longer guides, the variation of the voltages on the conductors in both time and space has to be considered. In the limit that the lateral extensions of the electrodes are small compared to λ , the guide can be viewed as a microwave transmission line supporting a propagating voltage excitation.

This allows the realization of electrically long guiding structures by confining co- or counter-propagating electrons in a traveling microwave field. In this scheme, the microwave signal is coupled to the electrodes at one end of the guide and coupled out again at the other end, thus avoiding the formation of a standing wave. As the speed of low energy electrons at several electron volts is two orders of magnitude smaller than the velocity of the microwave signal ($v \approx c/\sqrt{\epsilon_r}$, with $\epsilon_r \approx 3$ being the relative permittivity of the surrounding material), the moving electrons still experience a (Doppler shifted) oscillating transverse field, albeit at a slightly reduced (or increased) frequency as compared to the stationary case. Thus the pseudopotential picture sketched in Sec. 1.3 still holds.

One prerequisite for this concept is that the voltage excitation that is used for electron guiding can propagate without distortion along the electrodes. A general transmission line structure that consists of N individual conductors supports n = (N - 1) traveling eigenmodes, each of which is characterized by a specific set of electrode voltages. As the eigenmodes generally propagate at different phase velocities and experience unequal damping, a guiding potential that is composed of several eigenmodes may get distorted upon traveling along the guide. As a side-effect, the superposition can not completely be coupled out at the distant end, which leads to an additional standing wave component on the guide. To realize electrically long electron guides, it is therefore essential to study the decomposition of the voltage pattern of the guiding potential into the eigenmodes of the electrode structure.

This section, which has also been published in [105], therefore first summarizes the modal analysis of multiconductor transmission line structures [91, 106], which is then applied to analyze the five-wire configuration of Sec. 2.1.3. It is found that it generally does not support the guiding voltages as a traveling eigenmode. This can be altered by using an electrode layout that connects all grounded conductors over the entire guiding length, like, for example, a coupled microstrip configuration.

2.3.1 Transmission line theory of multi conductor lines

In the following, a uniform transmission line similar to the structure shown in Fig. 2.1 is considered. It consists of electrodes with a constant cross section in the xz-plane and infinitely extends in the y-direction, which is also the direction of propagation. The electric and magnetic field of a microwave excitation propagating on such a line and oscillating at an angular frequency Ω is usually described in complex phasor notation as

$$\mathbf{E}(x, y, z, t) = (\mathbf{E}_t(x, z) + E_y(x, z)\,\hat{\mathbf{y}}) \cdot \exp(i\Omega t - \gamma y), \mathbf{B}(x, y, z, t) = (\mathbf{B}_t(x, z) + B_y(x, z)\,\hat{\mathbf{y}}) \cdot \exp(i\Omega t - \gamma y),$$
(2.10)



Figure 2.14: Lumped circuit model of a two conductor line. The voltage drop V(y+dy) - V(y) and current change I(y+dy) - I(y) over an infinitesimal line segment is given by the per-unit-length resistance R, inductance L, shunt capacitance C and shunt conductance G.

where γ is the propagation constant. The electric and magnetic fields have been decomposed into transverse components $\mathbf{E}_t(x, z)$ and $\mathbf{B}_t(x, z)$ in the *xz*-plane and longitudinal components $E_y(x, z)$ and $B_y(x, z)$ along the guide.

The longitudinal electric field can be further decomposed into two components [107]. The first is caused by ohmic losses in the conductors that give rise to a small electric field along the propagation direction. The second arises at the interface between two dielectrics, where the electric field normal to the boundary is discontinuous. On a waveguide, which consists of perfectly conducting electrodes and is surrounded by a homogeneous dielectric, the longitudinal electric field vanishes and the structure supports a pure transverse electric (TEM) mode.

However, for low-loss transmission lines with lateral dimensions and substrate thicknesses that are much smaller than the drive wavelength, the electromagnetic field around the conductors is mainly transverse with only a small longitudinal component. It can thus be approximated by a quasi-TEM mode, which neglects the longitudinal field components altogether [91]. Although the TEM behavior can be obtained as lowest order of an expansion of the field and propagation constant in powers of Ω [108], it is difficult to quantify distinct conditions, where higher order terms vanish and a quasi-TEM description is valid. Generally, it should be justified for structures with lateral extents that are smaller than $\lambda/10$, provided that ohmic losses and the variations of the dielectric function over the entire mode volume are small [109]. This is the case for all structures that are considered in this thesis. The quasi-TEM assumption allows the definition of unique voltages V_i and currents I_i on the transmission line, which are the sources of the electric and magnetic field in the plane perpendicular to the propagation direction [91].

Two conductor lines

For the simplest case of a uniform two-wire line and propagation in the y-direction, one defines a line voltage $V(y,t) = V_0(y) \exp(i\Omega t)$ of the signal line with respect to the ground conductor. Analogous, a line current $I(y,t) = I_0(y) \exp(i\Omega t)$ is assumed to propagate in the signal line and to return on the ground conductor. The voltage and current drop, (d/dy) V(y,t) and (d/dy) I(y,t), over an infinitesimal piece of wire is then given by the

transmission line equations (also called Telegrapher's equations) [110]

$$\frac{d}{dy}V_0(y) = -(R+i\Omega L)I_0(y) = -ZI_0(y)
\frac{d}{dy}I_0(y) = -(G+i\Omega C)V_0(y) = -YV_0(y),$$
(2.11)

with the complex impedance Z and admittance Y derived from a lumped circuit model, see Fig. 2.14. Here, C describes the capacity between the wires, L their mutual inductance, while R is the resistance of the wires and G the shunt conductance due to dielectric loss in the surrounding medium.

The line voltage V(y,t) and current I(y,t) are then given by

$$V(y,t) = V_0 \cdot \exp(-\gamma y + i\Omega t)$$

$$I(y,t) = I_0 \cdot \exp(-\gamma y + i\Omega t) = V_0/Z_0 \cdot \exp(-\gamma y + i\Omega t).$$
(2.12)

The characteristic impedance $Z_0 = [(R + i\Omega L)/(G + i\Omega C)]^{1/2}$ connects the voltage and current amplitudes V_0 and I_0 , while the propagation constant $\gamma = \alpha + i\beta = [(R + i\Omega L) \cdot (G + i\Omega C)]^{1/2}$ is composed of the attenuation constant α and the phase constant β . In the limit of small resistive and dielectric losses, the characteristic impedance and propagation constant can be approximated by $Z_0 = \sqrt{L/C}$ and $\alpha = 0$, $\beta = \Omega\sqrt{LC}$.

Multiconductor lines

In the general case of a uniform transmission line in the y-direction that consists of N conductors, there are n = (N-1) degrees of freedom for the voltages $V_k(y,t) = V_k(y) \exp(i\Omega t)$, $k = 1 \dots n$, of each single wire with respect to an arbitrarily chosen reference conductor. Similarly, n independent currents $I_k(y,t) = I_k(y) \exp(i\Omega t)$ can be defined that propagate on each wire and return on the reference electrode. The transmission line equations of Eq. (2.11) then generalize to [91]

$$\frac{d}{dy} \begin{bmatrix} V_1(y) \\ \vdots \\ V_n(y) \end{bmatrix} = - \begin{bmatrix} Z_{11}(y) & \dots & Z_{1n}(y) \\ \vdots & & \vdots \\ Z_{n1}(y) & \dots & Z_{nn}(y) \end{bmatrix} \begin{bmatrix} I_1(y) \\ \vdots \\ I_n(y) \end{bmatrix},$$

$$\frac{d}{dy} \begin{bmatrix} I_1(y) \\ \vdots \\ I_n(y) \end{bmatrix} = - \begin{bmatrix} Y_{11}(y) & \dots & Y_{1n}(y) \\ \vdots & & \vdots \\ Y_{n1}(y) & \dots & Y_{nn}(y) \end{bmatrix} \begin{bmatrix} V_1(y) \\ \vdots \\ V_n(y) \end{bmatrix}.$$
(2.13)

The per-unit-length impedance and admittance matrices are defined by $Z = R + i\Omega L$ and $Y = G + i\Omega C$, and the transmission line parameters C, L, R and G are matrices with coefficients being defined for each conductor pair.

Eqs. (2.13) can be solved by transforming the voltages $\mathbf{V}(y)$ and currents $\mathbf{I}(y)$ on the line to modal coordinates as described in [111], which is summarized in the following. A

second differentiation of Eq. (2.13) leads to

$$\frac{d^2}{dy^2} \mathbf{V}(y) = ZY \mathbf{V}(y)$$

$$\frac{d^2}{dy^2} \mathbf{I}(y) = Y Z \mathbf{I}(y).$$
(2.14)

The transformation to mode voltages $\mathbf{V}_m(y)$ and currents $\mathbf{I}_m(y)$,

$$\mathbf{V}(y) = T\mathbf{V}_m(y)
\mathbf{I}(y) = W\mathbf{I}_m(y),$$
(2.15)

is chosen in a way that the matrices T and W diagonalize ZY and YZ, respectively:

$$T^{-1}ZYT = W^{-1}YZW = \gamma^{2} = \begin{bmatrix} \gamma_{1}^{2} & 0 \\ & \ddots & \\ 0 & & \gamma_{n}^{2} \end{bmatrix}.$$
 (2.16)

Since the matrices Z and Y are symmetric, the eigenvalues of ZY and $YZ = (ZY)^T$, with ()^T denoting the transposed matrix, are the same. This decouples Eq. (2.14) into n differential equations for the components of $\mathbf{V}_m(y)$ and $\mathbf{I}_m(y)$.

Solving for $\mathbf{V}_m(y)$ and $\mathbf{I}_m(y)$ and transforming back to the original, coupled basis leads to the solutions

$$\mathbf{V}(y) = \sum_{i=1}^{n} v_i \mathbf{T}_i \exp(-\gamma_i y)$$

$$\mathbf{I}(y) = \sum_{i=1}^{n} i_i \mathbf{W}_i \exp(-\gamma_i y).$$

(2.17)

A general voltage and current excitation $\mathbf{V}(y)$ and $\mathbf{I}(y)$ of the transmission line can therefore be written as a linear superposition of the voltage and current vectors \mathbf{T}_i and \mathbf{W}_i , which represent eigenmodes of the structure that travel with propagation constants $\gamma_i = \alpha_i + i\beta_i$. The vectors \mathbf{T}_i and \mathbf{W}_i denote the voltage and current excitations of the *i*-th mode in the original, coupled basis. They are given by the *i*-th column of the transformation matrices T and W, while one of the amplitudes v_i or i_i is determined by the initial conditions at the feeding point. The other amplitude is then determined by a characteristic impedance matrix Z_0 via $\mathbf{V}(y) = Z_0 \mathbf{I}(y)$, which is given by

$$Z_0 = T\gamma^{-1}T^{-1}Z.$$
 (2.18)

As the \mathbf{T}_i and \mathbf{W}_i represent a complete set of (N-1) linearly independent vectors, every excitation of the line can be represented as a linear combination of the fundamental modes. Due to the, in general, different α_i and β_i , such a superposition will dephase while it propagates along the line so that the originally applied excitation will become increasingly distorted with increasing distance from the feeding point. As guiding of electrons above a five electrode structure relies on one specific voltage distribution on the wires (see Fig. 2.3), which is not necessarily an eigenmode of the structure, a dephasing of the constituting modes will lead to an unwanted distortion of the harmonic pseudopotential and finally to the loss of electrons.

2.3.2 Calculation of transmission line matrices

To calculate the eigenmodes of the five-wire structure used in the present experiments, the transmission line matrices C, L, R and G have to be determined from the electromagnetic field around the conductors. For quasi-TEM modes, these fields can be derived from static calculations in the plane perpendicular to the propagation direction [91]. C and G are determined from an electrostatic simulation with the conductor voltages as source terms, whereas L and R may be derived from the magneto-quasistatic field that is caused by longitudinal currents running along the conductors.

High-frequency and low-loss approximation

The calculation can be simplified at high frequencies by separating the inductance matrix L in components arising from the fields inside and outside the conductors, conventionally named internal and external inductance, L_i and L_e [91, 109]. The external inductance is frequency independent and can be obtained from $L_e = 1/c^2 \cdot C_0^{-1}$. Here, c is the speed of light and C_0 the capacitance matrix computed with all dielectric media replaced by vacuum [112]. At frequencies, where the skin depth

$$\delta_s = \sqrt{\frac{2\rho}{\Omega\mu}} \tag{2.19}$$

 $(\rho \text{ and } \mu \text{ being the specific resistance and magnetic permeability of the electrodes})$ is much smaller than the lateral extensions of the electrodes, a magnetic field inside the conductors is only present in thin strips of width δ_s along the electrode edges. The internal inductance L_i can then be neglected compared to L_e . For a drive frequency of $\Omega = 2\pi \cdot 1 \text{ GHz}$ and gold coated electrodes ($\rho = 1.7 \cdot 10^{-8} \Omega \text{m}$), the skin depth amounts to $\delta_s = 2.1 \,\mu\text{m}$. As this is much smaller than the transverse dimensions of the electrodes, the skin effect is well developed in our case.

Furthermore, in the case of small resistive and dielectric losses ($G \ll \Omega C$ and $R \ll \Omega L$), the mode voltages \mathbf{T}_i , as well as the impedance matrix Z and the phase constants β_i , can be approximated by those of a loss-free model with R = 0, $L = L_e$ and G = 0. The impedance and admittance matrices of Eq. (2.13) consequently reduce to $Z = i\Omega L$ and $Y = i\Omega C$ [113]. In a second step, the attenuation constants α_i may be determined by a perturbation approach like the surface impedance concept [114]. This assumes that the modal currents derived from the lossless model propagate in thin strips with a width of $\delta_s/2$ at the electrode edges.

In the low-loss limit, the mode voltages can therefore be determined by computing the two capacitance matrices C and C_0 only.

Experimentally relevant field components

While the above-mentioned approximations are useful to determine the transmission line parameters of a specific electrode structure, care has to be taken when the voltages and currents calculated from a quasi-static approximation are used to compute the electromagnetic field above the transmission line. Regarding the magnetic field, the inhomogeneous current distribution over the conductor cross-section due to mutual inductance and the



Figure 2.15: Cross sectional substrate layout of the five wire structure from 2.3.

skin effect has to be taken into account, which results in the currents concentrating at the edges and especially in the corners of the electrodes [91]. This becomes relevant in experiments that rely on a detailed knowledge of the magnetic field above the microwave structures to, for example, realize state selective potentials for neutral atoms [115] or drive hyperfine transitions in trapped ions [89, 90]. In the case of electron guiding, however, only the electric field above the conductors is of interest. For quasi-TEM modes, the transverse electric field inside the conductors is negligible and the electric potential can safely be assumed to be constant over the entire conductor surface [116]. This allows to directly use the fields that have been derived from an electrostatic analysis for a calculation of the guiding potential.

2.3.3 Normal modes of the five-wire configuration

Fig. 2.15 schematically depicts the cross-sectional layout of the five-wire guiding substrate used in this thesis. As the two grounded outer electrodes are connected to the groundplane on the bottom side of the substrate, the structure represents a four-conductor system. Taking the connected groundplanes as the reference electrode, one obtains three degrees of freedom for the voltages on the center electrode and the two microwave electrodes. This results in three different traveling eigenmodes, which have been computed from the lossfree model by determining the capacitance matrices C and C_0 . Their entries $C_{ij} = Q_j/V_i$ have been calculated by a *finite-element-method* simulation in the transverse plane by applying a voltage V_i to the *i*-th conductor and determining the charge Q_j accumulating on the *j*-th conductor [91].

Fig. 2.16 shows the electric potential of the eigenmodes together with the directions of the electric field indicated by black arrows. In addition, the voltages of the individual conductors are given. The modes can be grouped into two symmetric and one antisymmetric mode with respect to the center conductor. The first symmetric mode consists of a voltage vector $\mathbf{T}_1 = [0.535 \ 0.654 \ 0.535]$ V, where the first vector component denotes the voltage on the left microwave conductor, the second component the center conductor voltage and the third component the voltage on the right microwave conductor. This mode propagates with a phase constant of $\beta_1 = 31.3 \text{ m}^{-1}$. The second mode is characterized by $\mathbf{T}_2 = [0.278 \ -0.919 \ 0.278]$ V and a phase constant of $\beta_2 = 29.9 \text{ m}^{-1}$. Additionally, a third, antisymmetric mode exists with $\mathbf{T}_3 = [0.707 \ 0 \ -0.707]$ V and $\beta_3 = 30.3 \text{ m}^{-1}$.

To check whether the low-loss approximation mentioned above applies, the resistance R_{22} of the central wire is compared to the product $\Omega L_{e,22} = 2700 \,\Omega/\text{m}$ obtained from the electrostatic calculation. In the skin-effect regime, where the currents essentially flow at the surface of the conductors, their resistance can be approximated by a surface resistance



Figure 2.16: Mode structure of the five-wire line from Fig. 2.3. The colors represent the electric potential for the three modes that are supported by the structure. Additionally, the direction of the local electric field is indicated by black arrows and the voltages of the three inner electrodes are given. The two outer conductors are held at ground potential (0 V). The guiding field of Fig. 2.3 is generated by a superposition of the two symmetric modes (upper plots).



Figure 2.17: Simulated electron trajectories in a guiding field composed of a superposition of the two eigenmodes of Fig. 2.16 a) and b) with amplitudes $v_1 = 1.37 \cdot 30$ V and $v_2 = 0.97 \cdot 30$ V and a drive frequency of $\Omega = 2\pi \cdot 1$ GHz. The electron is released with a horizontal and vertical offset of $\Delta x = 10 \,\mu\text{m}$ and $\Delta z = -3.5 \,\mu\text{m}$ from the guiding center at $(x = 0, z = 496 \,\mu\text{m})$. a): Trajectory at the feeding point where both modes oscillate in phase. The drive parameter correspond to $\omega = 2\pi \cdot 117$ MHz and q = 0.33. b): Trajectory at a longitudinal position of y = 10 cm behind the feeding point, taking the different propagation constants γ_1 and γ_2 of the two modes into account. The superposition no longer generates a guiding field with a zero at $z = R_0$, which results in a vertical excitation of the electron. Note the different scales of the vertical axes in a) and b).

 $R_S = \rho/\delta_s$ [110]. Assuming a homogeneous current distribution across the conductor surface, the resistance of the center conductor may be approximated by $R_{22} = R_S/2/(w + T) = 12 \,\Omega/\text{m}$ at $\Omega = 2\pi \cdot 1 \,\text{GHz}$, verifying the applicability of the low-loss approximation.

Additionally, the phase and attenuation constants including both dielectric and ohmic losses have been calculated with the port mode routine of a full wave microwave simulation package¹. With a loss tangent of $\tan \delta = 0.0037$ of the substrate and a conductivity of $5.9 \cdot 10^7 \,\text{S/m}$ of the gold layer, one obtains $\alpha_1 = 0.17 \,\text{m}^{-1}$ and $\alpha_2 = 0.27 \,\text{m}^{-1}$, whereas the phase constants agree within 1% with the results of the loss-less quasi-TEM calculation.

It can be inferred from Fig. 2.16 that the voltage configuration $\mathbf{V} = V_0 \begin{bmatrix} 1 & 0 & 1 \end{bmatrix}$ used for electron guiding is not proportional to an eigenmode of the structure, but has to be composed as a linear combination of the two symmetric modes via $\mathbf{V} = V_0 (1.37 \, \mathbf{T}_1 + 0.97 \, \mathbf{T}_2)$. The difference in phase constants of these two modes leads to a relative dephasing, which accumulates to 8° after a propagation length of $L = 10 \, \text{cm}$. To demonstrate the effect on electron trajectories in the guiding field, Fig. 2.17 presents results of a numerical particle tracking simulation in the time-dependent transverse electric field. A single particle is released with a lateral and vertical offset of $\Delta x = 10 \, \mu\text{m}$ and $\Delta z = -3.5 \, \mu\text{m}$ from the guide center. The trajectory of Fig. 2.17 a) has been simulated for an in-phase oscillation of the two modes, like it would be present at the feeding point. The particle performs harmonic oscillations in the time averaged pseudopotential with amplitudes equating its initial deflection. Fig. 2.17 b) has been simulated with a phase shift and attenuation of the two constituent modes that would result from a propagation length of $L = 10 \, \text{mm}$. The peak-to-peak amplitude of the electron's motion in the vertical direction increases to about

¹CST Microwave Studio



Figure 2.18: Pseudopotential of a coupled microstrip structure. The signal conductors (red) are fabricated on insulating posts (shown in green) above a continuous grounded plane (blue). The microwave electrodes are 570 µm wide with a spacing of 750 µm and a thickness of 20 µm. The height of the posts is 200 µm. The pseudopotential has been calculated for a drive frequency of $\Omega = 2\pi \cdot 1.02$ GHz and a microwave amplitude of 30 V. Guiding parameters are $\omega = 2\pi \cdot 144$ MHz, U = 53 meV and q = 0.4.

 $250 \,\mu\text{m}$. As the pseudopotential picture no longer holds for such a distorted microwave field, the presently used five-wire structure is not suited for realizations of electrically long guiding structures that support a traveling microwave excitation and provide a harmonic pseudopotential with well defined motional quantum states [35].

2.3.4 Electrically long guiding structures

To avoid a distortion of the guiding potential due to dephasing of the normal modes, the overall length of the five-wire structure used throughout this thesis is kept electrically short, see Sec. 3.1.1. For future implementations of a microwave guide that features larger lateral extensions or is operated at higher drive frequencies, it is interesting to realize electrically long devices.

One possibility to avoid a dephasing of the constituent modes would be to tune the substrate thickness H to yield equal phase constants β_i for the modes in question. Since the different values of β_i arise from different portions of the modal electric fields that travel inside and outside the dielectric substrate, a value of H should exist, where β_1 equals β_2 . This method, however, relies on an exact simulation of the eigenmodes and their phase constants as well as on tight fabrication tolerances. Furthermore, it does not take an unequal damping of the two modes into account.

A more robust solution is an electrode layout that supports the desired voltage configuration as a normal mode. This can be accomplished, for example, by a coupled microstrip structure [117] with elevated microwave conductors that are fabricated on insulating posts above a connected ground plane, see Fig. 2.18. A similar structure has already been proposed [118] and demonstrated for ion trapping experiments [119]. Although such a structure is slightly more complicated to fabricate due to the two metalization layers, it still offers the possibility of microscopic patterning that is needed for the realization of more complex guiding geometries. Because the number of free voltages is reduced to two, the device supports only two normal modes, an even mode with both signal electrodes at the same potential with respect to the ground plane and an odd mode with the electrode voltages being equal in amplitude but having opposite signs. The even excitation can be used for electron guiding. It generates a pseudopotential minimum in the center plane between the electrodes similar to the planar five-wire case. For the dimensions shown in Fig. 2.18, the guiding minimum forms at a distance of 500 μ m from the signal electrodes. The effective quadrupole strength $\eta = 0.39$ and the relative potential depth u = 0.014 are slightly higher than in the planar five-wire configuration.

Chapter 3

Experimental setup



Figure 3.1: Photograph of the guiding region with trajectories of guided and unguided electrons indicated in orange and blue, respectively. A thermal electron gun is visible in the upper right corner of the picture, while an imaging multi-channel-plate (MCP) detector, capable of single electron detection, is located to the left. In the center, the microwave substrate featuring bent guiding electrodes is visible.

For the first demonstration of electron guiding in a surface-electrode quadrupole guide, a proof-of-principle experiment has been designed and constructed. It relies on a bent electrode structure, which deflects guided electrons by about 30°. Fig. 3.1 depicts a top view of the setup, together with a sketch of guided and unguided electron trajectories. Electrons are laterally coupled to the guide at one edge of the substrate, follow the curved electrode geometry and leave the guide at the other substrate edge. Unguided electrons, however, spread out from the source and cross the substrate in straight lines. Consequently, the signature of successful electron guiding is a collimated and horizontally deflected electron beam appearing on the detector.

The guiding structure has an overall length of 37 mm, which is much shorter than the on-substrate wavelength of $\lambda = 200 \text{ mm}$ at a drive frequency of $\Omega = 2\pi \cdot 1 \text{ GHz}$. This enables the excitation with a standing voltage wave and minimizes the influence of microwave propagation effects on the guiding potential. The transverse frequency of the guiding potential amounts to about $\omega = 2\pi \cdot 100 \text{ MHz}$, which means that low energy electrons with a kinetic energy of $E_{kin} = 1 \text{ eV}$ perform roughly seven secular oscillation cycles while traveling along the guide.

The experiments presented in this thesis have been performed with a thermionic electron gun, which produces an electron beam that is $20 \,\mu\text{m}$ in diameter and has a full divergence angle of about 4°. This is sufficient to couple most electrons into the guide to demonstrate its basic working principle and characterize the guiding potential.

The following Chapter presents key components of the setup in greater detail, including the guiding substrates and the construction of the electron gun.

3.1 Guiding substrates

The principle design requirement concerning the guiding electrodes was the compatibility with a printed-circuit-board (PCB) manufacturing process, which is commonly used to produce electronic circuit boards. This allows the fabrication by a commercial supplier and enables fast turn-around times. For the same reasons, PCB designs have also been used in several ion trapping experiments [74, 77–80, 120–123]. However, they are restricted to minimum structure sizes of about one hundred to several hundred micrometers, which in turn limits typical guide-to-electrode distances to the same value. Additionally, the width of the gaps between individual electrodes has to be on the same scale. Wide gaps may lead to a perturbation of the guiding potential by static charges that accumulate on the exposed dielectric substrate between the electrodes. These limitations may be overcome by more elaborate and time consuming techniques like, for example, photolithographic patterning, which is nowadays the prevailing fabrication method for surface-electrode ion traps [55]. Another possibility to avoid the charging issue is milling away the substrate in the space between the electrodes. This is a viable option for ion traps and has been implemented in most PCB-based designs so far [74, 120]. However, it is difficult to realize with the elongated guide layout used in this thesis and requires even larger gap widths on the order of 500 μ m to be compatible with standard mill sizes. The proof-of-principle design described here therefore relies on reducing the gap width as far as possible without resorting to substrate milling.

3.1.1 Layout

As detailed in Sec. 2.1.3, the guide is designed for a guide-to-electrode distance of $R_0 = 500 \,\mu\text{m}$ with a central electrode width of $c = 350 \,\mu\text{m}$ and a microwave signal conductor width of $w = 750 \,\mu\text{m}$, see Fig. 2.3. This makes the structure also compatible with plated-through holes that contact the electrodes from the bottom side of the substrate and have a minimum diameter of 300 μm . The gap width between the electrodes amounts to $g = 110 \,\mu\text{m}$, which is the minimum value that can be fabricated by the PCB manufacturer¹.

In later designs, the trenches between the electrodes have been laser-cut², yielding a v-shaped profile with a gap width of $g = 15 \,\mu\text{m}$ at the bottom and $g = 70 \,\mu\text{m}$ at the

¹Multi Circuit Board Ltd., Brunnthal

²produced by *Micreon GmbH*, Hannover



Figure 3.2: Overview over the electrode layout of the microwave chip. The bent guiding electrodes are fabricated on the top layer of the substrate, while the feeding line is located on the bottom side. Connection between the feeding line and the guide is achieved by eight plated-through holes as indicated in the inset.

top. Together with an electrode thickness of $T = 40 \,\mu\text{m}$, this results in a high aspect ratio T/g = 2.7 of electrode height over gap width, which should yield a good shielding of the guided electrons from charges accumulating on the substrate [83]. Finite element simulations indicate a reduction of the static electric field that is generated by these charges at the center of the guide by a factor of over 500, when the gap width is decreased from $g = 110 \,\mu\text{m}$ to $g = 15 \,\mu\text{m}$. In surface-electrode ion trap experiments, aspect ratios between one and two are typically found to be sufficient even for sensitive quantum experiments, like the cooling of an ion to thermal excitations near the quantum mechanical ground state [15, 59, 89]. While substrates with laser cut electrodes already have been fabricated, all experiments reported on in this thesis feature electrode layouts with $g = 110 \,\mu\text{m}$.

Fig. 3.2 displays a schematic top view of the bent guide design. The guiding electrodes are placed on the top surface of a microwave compatible dielectric substrate. To avoid complications arising from traveling wave effects on the electrodes, as discussed in Sec. 2.3, their overall length of L = 37 mm is kept electrically short with respect to the wavelength of the drive field, which amounts to $\lambda \approx 200$ mm at $\Omega = 1$ GHz. The guide consists of a circular segment in the center that has a radius of 40 mm and an opening angle of 30° , resulting in an arc length of 21 mm. At both ends of the curve, a straight guiding section with a length of 5 mm connects to the two tapered coupling structures, each 3 mm long and located directly at the substrate edges. The experiments presented in this thesis exclusively implement the first generation taper design presented in Sec. 2.2.1.

The inset of Fig. 3.2 illustrates the connection of the guiding electrodes to the microwave feeding line on the bottom side, fabricated as a coplanar waveguide (CPW) transmission line with an impedance of 50Ω . The microwave signal is coupled in at the right



Figure 3.3: Photograph of guiding substrates. a): Bent structure with the guiding electrodes in the center featuring a gap width of $g = 110 \,\mu\text{m}$. An SMA coupler that connects the feeding line on the bottom side is visible to the right as well as plated-through connections from the bottom to the top layer in the center. This substrate has been used as demonstration device after removing it from the experiment. b) and c): top and bottom side of a straight substrate with a minimum gap width of 15 μ m between the guiding electrodes on the top. The feeding line on the bottom side shows a tapered section to match the signal conductor width at the coupler to the spacing of the central vias without causing reflections.

side of the substrate and the feeding line connects to the signal electrodes by two platedthrough holes in the center. There, six additional holes provide connection between the ground plane of the CPW and the grounded center wire of the guide as well as the outer grounded planes of the top layer.

3.1.2 Fabricated substrates

Fig. 3.3 shows photographs of the guiding chips that have been produced by the PCB manufacturer. They are based on a Rogers RO4350B microwave substrate, which features low dielectric losses $(\tan(\delta) = 0.0031 \text{ at } 2.5 \text{ GHz})$ and a relative dielectric constant of $\epsilon_r = 3.66$. It has been proven to be compatible with ultra-high vacuum environments in several ion trap experiments [74, 78, 80, 120–122]. The conductors are made from gold plated copper with an overall thickness of $T \approx 40 \,\mu\text{m}$. The electrochemically deposited gold layer is about 0.1 μm thick with an underlying, relatively thick (4 μm) bond coating made from nickel. No magnetic fields that might arise from the nickel coating could be measured down to a sensitivity limit of $200\mu\text{G}$. However, the gold layers have been found to be prone to scratches and will therefore be replaced by electroplated gold layers of about 2 μm thickness in future designs.

Fig. 3.3 a) depicts the bent guiding substrate, which is equipped with an edge-mount



Figure 3.4: Schematic overview of the microwave setup. Scattering parameter measurements have been performed between the positions marked by the encircled numbers. The 16 dB attenuator between generator and amplifier protects the amplifier by limiting the maximum power that can be fed to its input.

SMA connector³ for feeding. In the center, the eight connections to the feeding line and the ground plane on the bottom side can be seen. The substrate side planes at the beginning and the end of the guide are also electroplated to avoid charging. During manufacturing, the substrate has been held at four positions that have been covered by a conductive carbon paste and are visible as two black notches at either side. Later designs avoid the placement of holding bars at these positions.

Figs. 3.3 b) and c) show a straight version of the electrode design that additionally features laser cut trenches with a reduced gap width of $15 \,\mu\text{m}$. It allows to solely study the guide's ponderomotive stability by eliminating losses arising from the centrifugal force on the electrons in the curved section, see Sec. 4.2.4.

3.2 Microwave equipment

Fig. 3.4 shows an overview of the microwave setup that is used to generate the drive voltage V_0 on the electrodes. We directly feed the microwave signal to the guiding electrodes without using narrow-band resonating structures [124]. This allows scanning the drive frequency over a broad range to explore the limits of guiding stability, see Sec. 4.2.

3.2.1 Signal generation

In the experiment, the output of a microwave signal generator⁴ is boosted by a broadband microwave amplifier⁵ with a frequency range of 700 MHz-2500 MHz and saturated output power of 40 W before it is fed to the vacuum chamber via a SMA feedthrough. To protect the amplifier input, a -16 dB attenuator is placed between the generator and the amplifier, which damps the maximum generator output power to the maximum input power of the amplifier. A directional coupler⁶ between the amplifier and the vacuum chamber extracts

 $^{^3}Rosenberger$ 32 K 145-400 L5

 $^{^{4}}Agilent E5257C$

 $^{^{5}}Mini$ -Circuits ZHL-30W-252+

 $^{^{6}}MECA$ Electronics Inc. 750-S-20-1500V

a fraction of -20 dB of the microwave signal that leaves the amplifier and thus enables monitoring its output power. To provide a DC ground for the guiding electrodes and to be able to apply a DC voltage to the electrodes, the coupler is followed by a bias-tee⁷.

Since the guiding substrate represents an open termination of the feeding line, a standing wave excitation forms between the substrate and the output of the amplifier. The reflected power is internally dumped in the amplifier, which is specified to withstand the full CW output power reflected back into its output port. In the experiment, we nevertheless encountered a failure of the output amplifier stage twice, which possibly may be attributed to overheating due to back-reflected microwave power. Therefore, we will switch to another model⁸ offering a higher output power of 70 W in future experiments.

The guide voltage is derived from the output frequency $F = \Omega/(2\pi)$ and power P_1 of the signal generator by taking the frequency response of the microwave circuitry into account. The latter is obtained from scattering parameter (s-parameter) measurements Sij, which specify the ratio between the power P_i measured at one point of the network and the input power P_j fed to another node. In the experiments, the amplifier is operated near output saturation so that its gain S32 depends on the input power P_2 . This demands measurements at varying and, most notably, high input powers P_2 . The resulting high power levels P_7 on the guiding electrodes then inhibit a direct measurement of the complete frequency response S71 of the system. S71 is therefore determined by adding up different measurements of subsections of the microwave network via S71 = S21 + S52 - S53 + S73. Here, S21 describes the attenuation of the circuitry between generator and amplifier. S52 characterizes the amplifier gain by relating the fraction of the output power that is branched off by the directional coupler, P_5 , to the input power P_2 of the amplifier. With the known frequency response of the directional coupler S53, S52 can be reduced to the frequency response of the amplifier alone, which is given by S32 = S52 - S53. As the s-parameters Sij are commonly measured in decided, a multiplication of power ratios corresponds to an addition of the corresponding s-parameters. In the following, the frequency response of key components of the setup will be studied in more detail.

3.2.2 Voltage amplitude on substrates

As the guiding electrodes are not connected to the grounded part of the substrate, they form an open termination of the feeding line with a capacitance defined by the gap width g. The resulting standing wave on the guide and the feeding line has its maximum voltage amplitude at both ends of the guiding electrodes with the voltage dropping slightly towards the connecting holes in the center. On the feeding line, the voltage amplitude further decreases until it reaches a first node at a frequency dependent distance from the center connectors. The voltage on the feeding line is higher at the connection to the inner signal electrode of the guide than at the connection to the outer electrode. Consequently, the inner electrode is at a slightly higher voltage than the outer one.

Fig. 3.5 depicts the resulting peak electric field forming at a distance of 500 μ m above the top and below the bottom side of the substrate. The data has been derived from a numerical full-wave simulation that implements the *finite-integration-technique (FIT)*

⁷MECA Electronics Inc. 200-S-FF-2

⁸Microwave Amps Ltd. AM6-0.5-2.5-48-48



Figure 3.5: Electric field distribution above and below the substrate. Simulated electric field amplitude for a feeding power of $P_6 = 1$ W and a drive frequency of $F = \Omega/(2\pi) = 1$ GHz in a plane at $\Delta z = R_0 = 500 \,\mu\text{m}$ above the top electrode surface (a) and at a distance of $\Delta z = -500 \,\mu\text{m}$ below the bottom surface (b). In a), the four positions, at which the electrode voltage has been measured, are also indicated.

method⁹. A substrate input power of $P_6 = 1$ W and a drive frequency of F = 1 GHz has been assumed. Both an increase of the peak electric field towards the end of the guiding electrodes and a slight asymmetry between the inner and the outer conductor are visible. For a drive frequency of F = 1 GHz, the first voltage node on the feeding line forms at a distance of about 11 mm from the center connectors.

The voltage asymmetry on the guiding electrodes becomes more clearly visible in Fig. 3.6 a) which compares the frequency dependence of the simulated peak voltages at the four positions labeled in Fig. 3.5 a) for an input power of $P_6 = 1$ W. Starting from a nominal peak voltage of 20 V at low frequencies, the guide voltage continuously decreases with increasing drive frequency F until a resonance forms between F = 2.06 GHz and F = 2.15 GHz. There, a quarter of the wavelength on the guiding electrodes equals the distance from the center to the end of the guide and the first antinode forms directly at the connectors.

Both the voltage drop between the outer and the inner conductor at the same lateral position as well as the voltage drop from the end towards the center of the individual conductors emerge above $F \approx 1 \,\text{GHz}$. At this frequency, the relative voltage difference $\Delta V_0/V_0$ between the end and the center of the outer conductor amounts to 15%, yielding a 30% variation of potential depth U and a 15% variation of transverse frequency ω and stability parameter q along the guide. The relative voltage drop between the outer and inner conductor at the same lateral position of around 6% is considerably smaller. It leads to a slight horizontal shift of the guiding minimum by 20 µm towards the outer conductor. Additionally, the potential depth obtained from *FEM* simulations decreases by about 10% while the transverse frequency stays essentially constant. At one lateral position, the

⁹CST Microwave Studio



Figure 3.6: Simulated and measured voltages on the guiding electrodes. a) Frequency dependence of the simulated peak microwave voltage V_0 at the positions indicated in Fig. 3.5 a). Voltages at the end and the center of the inner (outer) conductor are printed in black and red (green and blue). b) Comparison between simulated and measured V_0 at the end of the inner conductor (meas.: red; sim.: blue) and the center of the outer conductor (meas.: green; sim.: black). All voltages have been referenced to a power of $P_6 = 1$ W fed to the substrate.

voltage differences that arise on the electrodes therefore perturb the guiding potential only slightly. Their main effect is a continuous variation of the guiding parameters along the guide, which is small enough not to inhibit electron guiding. In fact, numerical trajectory simulations that neglect voltage differences on the electrodes altogether show good agreement with experimental guiding data, see Sec. 4.3, and suggest that the demonstration experiment is currently not sensitive to microwave voltage differences on the electrodes.

Fig. 3.6 b) compares the simulation to a measurement of the electrode voltages with a high impedance probe¹⁰, which has been calibrated against a 50 Ω -probe¹¹. The measured voltages agree quite well with the simulations, which show a slightly higher V_0 and a shift of the resonance position to higher frequencies. This can be attributed to a not fully converged grid spacing in the simulations.

Fig. 3.7 illustrates the effect of different gap widths g on the electrode voltage. Reducing the gap width from $g = 110 \,\mu\text{m}$ to $g = 40 \,\mu\text{m}$ leads to a decrease of the guide voltage by about 20% due to an increased capacitance of the guiding structure. The position of the resonance does essentially not change. These results are also confirmed by numerical simulations at reduced g.

3.2.3 Power correction for the entire system

As mentioned above, saturation of the microwave amplifier at the high power levels that are used in the experiment demands a characterization of the frequency response at all generator output powers P_1 . However, the limited maximum input power of the highimpedance probes, with which the voltage on the electrodes has been determined, prevents a direct measurement of the frequency response S71 from the generator to the substrate

¹⁰Hameg HZ553

 $^{^{11}}GGB$ Industries Inc. Picoprobe model 40A-GSG-660/40A-GSG-660-D-1320



Figure 3.7: Influence of gap width on electrode voltage. Measured frequency dependence of the peak electrode voltage V_0 at the end of the inner conductor for gap widths of $g = 110 \,\mu\text{m}$ (red) and $g = 40 \,\mu\text{m}$ (blue). All voltages have been referenced to a power of $P_6 = 1 \,\text{W}$ fed to the substrate.

at higher P_1 . S71 is therefore split into at least three individual measurements. The amplifier gain is characterized at all power levels via the power that is branched off by the directional coupler, yielding S51. A separate measurement of the coupling ratio S53 and the loss S73 between amplifier and electrodes at low powers characterizes the circuitry following the amplifier.

Because of the formation of a standing wave between the substrate electrodes and the amplifier, the most exact correction is obtained when performing the s-parameter measurements with the substrate attached in every measurement step. The values of S51 and S53 are sensitive to the characteristics of the cables implemented behind the amplifier, but have been found to be independent of the gap width g of the substrate. Using a measurement of the entire frequency response S73 from the amplifier to the substrate, the combined scattering parameter S71 = S51 - S53 + S73 agrees very well with a direct measurement of S71 at low power levels, see Fig. 3.8 a). On the contrary, composing S71 = S51 - S53 + S76 + S63 from the s-parameters of the cables S63 and the substrate S76, which have been measured with the circuitry opened at position 6, fails to fully capture the frequency response. For the evaluation of the guiding experiments we nevertheless have to rely on the latter decomposition since no measurement of S73 has been available, see Sec 4.2.1.

Fig. 3.8 b) shows the resulting maximum guide voltage at $P_1 = 15 \text{ dBm}$, which corresponds to an amplifier input power of $P_2 = -1 \text{ dBm}$. Both the highest voltage, which is present at the end of the inner conductor, and the lowest voltage, present at the center of the outer conductor, are shown. They are additionally compared to the voltage at the end of the inner conductor that could be generated without gain saturation of the amplifier. At F = 1 GHz, its equivalent power level would be about 3.6 dB higher. Additional wiggles that appear across the whole frequency range in saturation illustrate the need to correct with measurements that are taken at the actual drive power, see also Sec. 4.2.1.

As can be seen from the stability measurements presented in Fig. 4.3, guiding at drive frequencies above $F \approx 1$ GHz is presently limited by the voltage V_0 available. One obvious



Figure 3.8: a) Frequency response of the microwave circuitry for three different decompositions of S71 and a substrate with $g = 40 \,\mu\text{m}$. All data have been taken at the center of the outer conductor, representing the lowest power levels across the electrodes. b) Peak electrode voltage at the maximum input power $P_1 = 15 \,\text{dBm}$ for a substrate with $g = 110 \,\mu\text{m}$. The red and blue data have been measured at the end of the inner and the center of the outer conductor, respectively. The thin green line indicates the voltage that would be present at the first position without gain saturation of the amplifier.

improvement would be to impedance match the guiding structure to the 50 Ω feeding line with, for example, a quarter-wave section [110]. This has not been done in the current design and would probably allow higher V_0 . In a standing wave configuration, a higher V_0 can in principle also be generated by enclosing the guiding electrodes in a CPW microwave resonator formed by an open termination of the feeding line at a distance of half the drive wavelength [90, 107]. A quarter-wave resonator with a shorted termination at one end would not be practical as it has to be fed at the open end, which necessarily lies at the guiding electrodes. A half-wave resonator would represent the planar analog to the helical resonator tank circuits implemented in RF ion traps [124]. Besides the voltage step-up, a narrow-band resonator would additional filter the drive signal and thus reduce the amplifier noise that is fed to the electrodes.

3.3 Experimental chamber

The guiding experiments have been performed in a vacuum chamber, which provides a background pressure of a about $2 \cdot 10^{-7}$ mbar. This is low enough for the operation of a microchannel plate (MCP) detector for single electron detection but does not require a time consuming bake-out procedure of the chamber after venting.

3.3.1 Guiding region

Fig. 3.9 depicts the guiding experiment assembly with the microwave substrate in the center. The electron gun is mounted on a vacuum compatible three-dimensional translation stage¹² for precise positioning in front of the guide entrance. The electron gun is a first

¹²New Focus 9066-XYZ-M-R-V stage with model 8353-V Picomotor actuators



Figure 3.9: Overview over the experimental setup. The electron guide in the center is fed by a coaxial cable entering from below. To the right of the guide, a first version of the electron gun described in Sec. 3.4 is visible. It is mounted on positioning stages providing three-dimensional alignment. The imaging MCP detector on the left is placed in front of a hole in the surrounding magnetic shielding box to provide optical access by a CCD camera from behind. version of the thermionic emitter described in Sec. 3.4 and has been replaced for most experiments reported on in this thesis.

A Chevron-type MCP detector¹³ is located behind the guide exit. It features a phosphor screen behind the MCP plates to image the amplified electron signal. Its gain is specified to be $7.6 \cdot 10^6$ at a maximum plate voltage of 2000 V. A wire grid can be mounted between guide and detector to accelerate the electrons towards the MCP for better detection efficiency. For the guiding experiments presented in this thesis, the grid has always been removed to avoid a disturbing lens action of its openings.

The microwave signal is fed to the substrate by vacuum compatible SMA cables, which are visible in the lower part of the picture. They are made from PTFE insulated RG-316/U cables¹⁴ that are equipped with gold coated SMA connectors¹⁵. A rubber sealing ring has been removed from the male connectors to make them vacuum compatible. Since the RG-316/U cables showed several failures due to overheating, they have been replaced by RG-142 type cables¹⁶, which also reduced cable losses from $1.9 \,\mathrm{dB/m}$ to $0.4 \,\mathrm{dB/m}$ (at $1 \,\mathrm{GHz}$) in later experiments.

The electron gun is manually positioned in front of the guide entrance. Since no rotating actuators have been included in the setup, this sets the horizontal tilt of the electron gun with respect to the guide's axis. Careful alignment with the gun nearly touching the substrate edge yields an estimated residual tilt uncertainty of less than 1°. Angular alignment in the vertical plane is guaranteed by the planarity of the substrate holder and the gun mounting stage. The distance of the electron gun to the guiding electrodes Δy is measured from above and set to $\Delta y = 0.5$ mm. It has been found that a coarse lateral alignment of the exit aperture in front of the guide is sufficient. In most cases, an initial electron signal can be obtained by tuning the drive voltage V_0 at a drive frequency around $\Omega = 2\pi \cdot 1.1$ GHz without need for scanning the gun position. The optimum lateral position of the electron gun in front of the guide is then determined by maximizing the guiding signal.

Electric and magnetic shielding

Since the guiding experiments are performed with low-energy electrons at a kinetic energy of a few electron volts, it is essential to shield them from any dielectric surface that may charge during the experiment, thus producing perturbing electric fields. Therefore, the entire guiding region is enclosed by a cover made from gold-coated copper sheet, see Fig. 3.10 a). It closely contacts to additional covers that are mounted in front of the MCP detector and around the electron gun. For better visibility, all covers have been removed in Fig. 3.9. The cover around the guide is additionally equipped with an isolated goldcoated copper plate mounted horizontally at 10 mm above the guide. There, an additional bias voltage can be applied to in order to compensate a charging of remaining surface contaminants on the electrodes and of the dielectric substrate between the electrodes.

The entire setup is placed inside a mu-metal box^{17} for magnetic shielding, which is

 $^{^{13}} PHOTONIS$ APD 2 PS 40/12/10/12 46:1 P20

 $^{^{14}}Allectra$ 312-PTFE50-D

 $^{^{15}}Rosenberger$ 32 S 127-302 L5 and 32 S 127-302 L5

 $^{^{16}} B\ddot{u}rklin~OHG$ 96 F 700

¹⁷made by *Meca Magnetic*, Amilly, France


Figure 3.10: Photographs of the electrical shielding and the vacuum chamber. a) The entire guiding region is shielded by caps made from gold-coated copper sheets that fit to the electron gun, around the electron guide and the MCP detector. Inside the cap above the guiding region, an electrically insulated plate is mounted that is situated 10 mm above the electrodes and can be biased with a static voltage, which is applied to the screw visible in the center. b) Experimental chamber with key components, see text.

visible in Fig. 3.9 and can be closed with a lid. It has several smaller holes for electrical connections and a larger one for optical access to the phosphor screen at the back of the MCP detector. The shielding has been measured to reduce the ambient static magnet field at the guide's position by a factor of over 200 to 2 mG and magnetic field fluctuations to below 0.2 mG. The influence of a residual magnetic field on the confined electrons can be estimated by equating the magnitude of the Lorentz force F = evB on an electron with velocity v in a perpendicular external magnetic field B with the restoring force in an harmonic oscillator potential with frequency ω , $F = -m_e \omega \Delta x$. In the ambient earth magnetic field $B \approx 500 \,\mathrm{mG}$ and assuming an electron energy of $E_{kin} = 1 \,\mathrm{eV}$, this yields a transverse displacement of $\Delta x \approx 12 \,\mu\mathrm{m}$, which reduces to $\Delta x \approx 50 \,\mathrm{nm}$ with the shielding employed. Since even the deflection in the unshielded field is well below the transverse extend of the guiding region, see Fig. 2.3, it will not inhibit electron guiding. A shielding of ambient magnetic fields is therefore not critical in the present experiment. However, it may become necessary in future setups that demand more precise control over the electron trajectories or aim to populate low-lying oscillator states of the transverse potential.

3.3.2 Vacuum system

The entire setup shown in Fig. 3.9 is placed in an ultra-high vacuum chamber that is based on a horizontally mounted CF-250 tube with a length of 350 mm, see Fig. 3.10 b). A vacuum window that is mounted to a CF-150 flange allows optical access to the detector, which is imaged by a CCD camera. The chamber is pumped by a turbo-molecular pump¹⁸ with a pumping speed of 3401/s. The CF-250 flange that provides the main access to the

 $^{^{18}}Leybold$ Turbovac 340M

chamber is sealed with a reusable Viton gasket. The background pressure in the experimental chamber usually falls to $2 \cdot 10^{-7}$ mbar after several hours of pumping without need for a vacuum bake-out. Several additional flanges mounted to the side of the chamber accommodate a Bayard-Alpert pressure gauge¹⁹ and various electrical connections, including a double-sided SMA feedthrough for the microwave signal.

All parts that are placed into the chamber are thoroughly cleaned prior to mounting. Best results have been achieved by first cleaning the machined parts with a non-foaming soap²⁰ in an ultrasonic cleaner to remove the major part of remaining grease. This has also proven to be very effective to reduce residuals deposited during laser cutting of the electrodes, see Sec. 3.1.2. The parts are subsequently cleaned, again in an ultrasonic cleaner, with acetone, followed by isopropanol, and are finally blown dry. Great care has been taken to keep the electron gun and the guiding region absolutely free from dust particles that may charge during the experiment. To this end, the gun and the interior of the mu-metal shielding box are assembled under a flowbox providing a laminar downward flow of filtered air.

3.4 Thermionic electron gun

The experiments presented in this thesis have been performed with an electron beam from thermionic electron guns. In contrast to field emission guns, contamination of the emitting surface is not an issue, which allows to run the experiment at modest vacuum background pressures in the range of several 10^{-7} mbar. The primary design requirement of the electron gun has been its capability to produce a low-energy electron beam at 1 eV to 10 eV longitudinal energy with a beam diameter of 50 µm at the gun exit and a full beam divergence angle below 4° FWHM at 1 eV. This translates to a beam diameter of 85 µm at the guide entrance, which is located 500 µm in front of the electron gun. This is sufficient to efficiently couple electrons into the guide, compare Fig. 2.3.

The electron gun is based on the widely used Erdman-Zipf design [125], which has been modified to accommodate additional exit apertures to geometrically confine the electron beam. In future experiments, that aim at injecting electrons into the transverse ground state of motion, a much smaller spot size and better beam collimation is needed, see Sec. 1.6. The thermionic gun will therefore be replaced by a gun that is based on a single-atom-tip field emitter, which is currently developed in our group.

3.4.1 Construction

Fig. 3.11 shows a cross sectional view of the electron gun. It consists of rectangular elements with a central bore accommodating the beam pass. The gun employs a thermionic hairpin emitter that is placed behind a grid aperture (element 1). The aperture is followed by an einzel lens (elements 2 to 4) in order to collimate the beam. The two last elements (5 and 6) of the gun are grounded and hold the exit apertures. The final electron kinetic energy is set by the voltage V_F that is applied to the filament with respect to this last element.

 $^{^{19}}Leybold$ IE 20

 $^{^{20}} Merz \ Hygiene$ Edisonite Super



Figure 3.11: Thermionic electron gun used in the guiding experiments. a) Cross sectional view. Element 1 accommodates the filament mount with a hairpin emitter (not shown), which is spot welded onto two rods. The ceramic body of the lens mount can be laterally moved by set screws to center the filament precisely in front of the grid aperture, which is also attached to element 1. Elements 2 to 4 form an einzel lens, which is used to collimate the electron beam. Elements 5 and 6 hold two additional apertures that clip and collimate the electron beam to the desired values. The voltages applied to the individual elements are indicated. b) Photograph of the assembled electron gun.

The lens elements have a central bore of 6 mm and a spacing of 0.6 mm between them. Between each two elements, three sapphire balls with a diameter of 2 mm are placed in conical depressions to isolate and align the parts. The whole assembly is held together by four threaded rods. The central lens bore and the depressions for the sapphire balls have been machined on a CNC mill without removing the work piece from the jig to allow a relative alignment precision of below $10 \,\mu m$. Care has been taken to shield the beam path from any dielectrics by setting back the trench between the elements using matching circular pockets and extrusions around the lens bore, see Fig. 3.11 a). All gun elements are made from titanium to eliminate disturbing magnetic fields and have been gold-coated for better conductivity. All other components of the electron gun, like screws and electrical connectors, are also made from non-magnetic materials. The homemade filament consists of a 0.1 mm diameter tungsten wire that is bent to hairpin shape and spot welded onto a Hitachi filament mount²¹. The mount can be laterally moved by four set screws for precise positioning of the filament in front of the exit aperture²², which has a hole diameter and plate thickness of 0.6 mm. The longitudinal spacing between filament and grid can be adjusted by moving the rear part of the filament holder via a fine thread. Typically, the filament is placed $100 \,\mu\text{m}$ behind the grid aperture.

A major problem with low-energy electron guns are stray potentials that are caused by charges accumulating on contaminations of the inner surfaces of the lenses, especially of the apertures. This is unavoidable at background pressures of 10^{-7} mbar. To keep the electrons near the optical axis and away from the electrode surfaces, the design implements

²¹*Hitachi High-Technologies*, part number 777-0179

²²*Plano GmbH*, part number A09616P

a strong einzel lens with a grounded central element, which focuses the beam upon entering the lens. In the original design, the beam is defined by the grid aperture acting as pupil and the filament being imaged as a real object. This eliminates the need for a second aperture to clip the beam, which would be prone to unwanted charging. However, the resulting beam diameter of about 1 mm is way too large for the presented experiments. The final beam is therefore clipped within the electron gun by up to two additional apertures with a hole diameter of several ten micrometers and a distance of 11 mm between them. Although this leads to some performance degradation due to charging of the exit apertures, the gun is still usable for the experiments presented in this thesis.

3.4.2 Performance

During operation, the grid aperture at V_G is positively biased with respect to the filament in order to accelerate the electrons towards the einzel lens that is formed by elements 2 to 4 in Fig. 3.11. The two outer lens elements are held at a positive voltage V_L , while the middle one is grounded. In the experiment, the electron gun can be operated at electron energies down to $E_{kin} = 1 \text{ eV}$ and typical gun voltages then are $V_F = -1 \text{ V}$, $V_G = -0.3 \text{ V}$ and $V_L = 4 \text{ V}$. The grid voltage deviates from the value $V_G = 0.9V_F$ reported in [125], which may be attributed to the smaller filament to grid distance of 100 µm and the use of a different filament type.

Measured full opening angels of the electron beam at $E_{kin} = 1 \text{ eV}$ are about $\alpha = 4^{\circ}$ (FWHM) if only one clipping aperture with a diameter of $D_6 = 50 \,\mu\text{m}$ is mounted to the last gun element and the electron beam is collimated by the einzel lens. Adding an additional aperture with $D_5 = 20 \,\mu\text{m}$ to the second to last element collimates the beam to below $\alpha = 2^{\circ}$ (FWHM). Typical beam currents with two apertures are about 30 fA at $E_{kin} = 1 \,\text{eV}$. This is much less than the emission currents that are reported for higher beam energies and no clipping of the final beam [125]. However, it is more than sufficient for the present experiments that implement a MCP detector, which is capable of single electron detection.

In operation, the beam current reduces by about 10% during the first 60 minutes. This behavior is also observed with a thermalized gun, where the electron beam has been blocked by a negative grid bias voltage while the filament has been heated for several hours. This excludes a thermal cause for the observed drift. It most probably originates from a charging of the grid aperture that results in a shift of the beam position away from the holes in the exit apertures. A decrease of the beam current can be avoided by adjusting the lens voltage to produce a larger beam diameter at the exit apertures, so that the holes are still covered by the beam after a drift of its position.

Chapter 4 Electron guiding

This chapter presents the first experimental demonstration of electron guiding in a surfaceelectrode quadrupole guide. The experimental signature of successful guiding is a deflection of electrons traveling along a curved potential minimum above the electrodes. When the guiding parameters or the energy of the incoming electron beam are changed, characteristic variations of the beam shape behind the guide can be observed. By systematically scanning the power and frequency of the drive signal, it is possible to determine the parameter range of stable electron guiding. For the curved guide, the signal is bounded towards low power levels by a minimal potential depth U and towards high power levels by a maximum stability parameter q. Comparing the stability region of the bent guide to that of a straight geometry at various kinetic energies confirms that the loss at small Uarises from an insufficient compensation of centrifugal forces in the guiding potential above the electrodes yields good qualitative agreement with the experimental results and allows to infer the main loss mechanisms, which are currently limiting the experiment.

4.1 Demonstration of electron guiding

As described at the beginning of Ch. 3, we inject electrons into the guide at one edge of the substrate, guide them along a curved trajectory and image them on a MCP detector that is placed directly behind the exit of the guide. Successful guiding is then detected by a spatial separation of guided and unguided electrons as well as by a collimation of the guided part, compare Fig. 3.1.

Fig. 4.1 presents images that have been recorded with the MCP detector for varying experimental parameters and an electron energy of $E_{kin} = 1 \text{ eV}$. The guide is operated at a drive frequency and voltage of $\Omega = 2\pi \cdot 1.03 \text{ GHz}$ and $V_0 = 19 \text{ V}$, which results in a transverse frequency of $\omega = 2\pi \cdot 73 \text{ MHz}$, a potential depth of U = 12 meV and a ponderomotive stability parameter of q = 0.20. This yields a clear signal of guided electrons at the position of the guide exit. Additionally, the signal from guided electrons appears much brighter and far better collimated than the rather diffuse spot of unguided electrons that is visible when the guide is turned off. This indicates that the guiding potential is able to compensate for the residual divergence of the electron beam as well as for a deflection of the comparatively slow electrons in stray electric fields above the



Figure 4.1: Electron guiding signal at $E_{kin} = 1 \text{ eV}$ for different guide settings $f = \omega/(2\pi)$, U, q and compensation voltages V_{top} . The origin of the coordinate system is placed at the position of the guide exit, as inferred from a), and marked by a red cross. The height of the substrate surface is indicated by a red horizontal line. Deepening the guiding potential leads to a larger spot of guided electrons that is slightly shifted to the left. Applying a cover plate bias V_{top} leads to a larger as well as to a more intense guiding signal that is now shifted downwards compared to $V_{top} = 0$. A faint signal of electrons that exit the guide in the upward direction while traversing the substrate is visible above and to the right of the guided electrons. It connects to a diffuse spot in the upper right part of the image that is caused by electrons that are not coupled to the guide at the entrance side of the substrate. The detected intensities are normalized to the maximum absolute pixel count of the camera and all guide settings have been derived from the electrode voltage measured at the end of the inner conductor, see Fig. 3.5 a). The MCP gain setting is the same for all plots and the absolute electron currents are about half of that of Fig. 4.2 for $E_{kin} = 4 \text{ eV}$.



Figure 4.2: Electron guiding signal at $E_{kin} = 4 \,\mathrm{eV}$ for different guide settings $f = \omega/(2\pi)$, U, q and compensation voltages V_{top} . The guide exit and the substrate are marked as described in Fig. 4.1. The loss signal is visibly larger and more intense than that observed for $E_{kin} = 1 \,\mathrm{eV}$ in Fig. 4.1. With a negative voltage V_{top} applied to the cover electrode, unguided electrons that become deflected downwards hit the detector below the height of the substrate surface. The signal with the guide turned off, see c), shows arc-like shadows (indicated by vertical arrows) directly above the substrate, which are caused by a deflection of electrons due to charges accumulating in the trenches between the electrodes. Additionally, a shadow that is caused by a larger, charged spot is visible at the right edge of the beam (horizontal arrow). Note that the unguided electron signal in c) appears more to the right when compared to the loss electrons that originate from the beginning of the guide and are visible at $x' = 10 \,\mathrm{mm}$ in a). This could either indicate a slight horizontal tilt of the electron gun with respect to the guide axis or could be attributed to the charged spot at the right. The detected intensities are normalized to the maximum absolute pixel count of the camera and all guide settings have been derived from the electrode voltage measured at the end of the inner conductor, see Fig. 3.5 a). The MCP gain setting is the same for all plots and the absolute electron currents are about twice that of Fig. 4.1 for $E_{kin} = 1 \,\mathrm{eV}$. Due to the higher longitudinal energy of the electrons, the lateral shift acquired between the guide exit and the detector plate is smaller and the signal is generally less diffuse than at $E_{kin} = 1 \text{ eV}$. The substrate features gaps of width $g = 110 \mu \text{m}$.

chip surface. The images also show a small signal of electrons that are not guided over the entire distance and leave the guide by passing across the saddle point in the upward direction. This signal extends from the guide exit towards the position where the electrons that cross the substrate in straight trajectories hit the detector when no microwave power is applied to the guide.

The amount of guided electrons raises by about 35% when the electrode voltage is increased to $V_0 = 28$ V at constant drive frequency $\Omega = 2\pi \cdot 1.03$ GHz to yield $\omega = 2\pi \cdot 105$ MHz, U = 25 meV and q = 0.29. Owing to the stiffer and deeper potential, the maximum transverse momentum of guided electrons increases and the guiding signal becomes larger and more diffuse.

Increasing the kinetic energy of the electrons from $E_{kin} = 1 \text{ eV}$ to $E_{kin} = 4 \text{ eV}$ generally leads to higher loss both at the entrance of the guide and during guiding, see Fig 4.2. This means that no guiding is observed at $\Omega = 2\pi \cdot 1.03 \text{ GHz}$ for drive voltages below about $V_0 = 25 \text{ V}$. The guiding signal at $V_0 = 28 \text{ V}$ (Fig. 4.2 a)) shows a considerable amount of loss electrons between the position of the guide exit and the electron gun. The main reason for the loss during guiding is the centrifugal force on the electrons. At higher kinetic energies, it can not be compensated by the guiding potential and the electrons leave the guide in the vertical direction, where the confinement is weakest. Since not only the longitudinal, but also the transverse momentum of electrons exiting the electron gun increases at higher E_{kin} , a part of them is already lost in the straight section at the beginning of the guide and contributes to a higher loss signal at the position of the guide entrance. The outward shift of the electrons in the curved potential also leads to a slight horizontal shift of the guiding signal when compared to that obtained at $E_{kin} = 1 \text{ eV}$. Furthermore, the signal is surrounded by a spiral-like signature of electrons that are guided with high transverse excitation along the full length of the guide.

The data presented above has been taken with only one aperture of diameter $D_6 = 50 \,\mu\text{m}$ mounted to the last element of the electron gun. A measurement of the electron current at the exit of the guide with the second aperture ($D_5 = 20 \,\mu\text{m}$) additionally attached yields a value of roughly 100 fA at $E_{kin} = 1.5 \,\text{eV}$ and drive parameters corresponding to $\omega = 2\pi \cdot 110 \,\text{MHz}$, $U = 28 \,\text{meV}$ and q = 0.31. Since this current is about the same as that measured directly at the exit of the electron gun, one can conclude that all electrons that emerge from the gun are coupled to and conducted along the guide. This is additionally supported by the fact that no loss electrons are visible in the measurement. The observed current amounts to an electron density of less than 0.1 electron populating the guide at the same time so that space charge effects may safely be neglected in the current experiments.

Influence of substrate charging

With no microwave power applied, the electron signal at $E_{kin} = 4 \text{ eV}$ exhibits sharp, arclike structures close to the electrode surface where no electrons are detected, see Fig. 4.2 c). In other images, a maximum of four arcs becomes visible, which indicates that the deflection of electrons is caused by a negative charging of the substrate in the gaps between the electrodes.

Since the charging of the substrate increases during measurements, the electron signal continuously decreases with time. After 45 minutes of measurement, the signal from the electron gun with the guide switched off has been reduced by about 30%. The decrease of

the guiding signal at optimum drive parameters is considerably less, which indicates that the guiding potential can compensate the forces that are excerted by the stray charges. However, depending on the amount of charges present, a considerable reduction of the guiding signal can be observed for comparatively shallow guiding potentials at small U.

Influence of a cover plate bias voltage

The accumulation of negative charges on the substrate can be compensated to first order by applying a negative bias voltage V_{top} to the top plate covering the guiding region at a height of 10 mm. However, such a bias voltage also deepens the guide and prevents electrons from escaping in the upward direction where the guiding potential is shallowest, compare Fig. 2.3 c). Determining the optimum bias voltage by maximizing the guiding signal therefore leads to a higher V_{top} than it would be necessary for pure stray charge compensation. For the experiments presented in Figs. 4.1 and 4.2, the brightest signal could be obtained at a compensation voltage of $V_{top} = -1.5$ V, which resulted in a 100% relative increase of the guiding signal at $E_{kin} = 1 \text{ eV}$ and U = 12 meV. With the bias voltage applied, a slight downward shift of the guiding signal is observed, which is most probably caused by a deflection of the beam after it has exited the guide and travels in the fringing fields of the cover plate between substrate and detector. When the bias voltage is adjusted to yield the maximum signal intensity, guiding is observed for electron energies up to about $E_{kin} = 10 \text{ eV}$.

4.2 Guide stability

Since we do not use a resonator to amplify and filter the microwave signal fed to the electrodes [124], we can freely vary the drive frequency Ω and electrode voltage V_0 within the bandwidth limits of the microwave equipment, see Sec. 3.2. To characterize the quadrupole guide, the drive parameters are systematically scanned, while the intensity of the electron signal behind the guide is recorded.

4.2.1 Stability scans

Fig. 4.3 shows the result of such a parameter scan performed at a kinetic energy of $E_{kin} = 1 \text{ eV}$ with the bent substrate. For each drive frequency Ω , the voltage range V_0 , at which guiding is observed, is limited both from below and from above. The lower bound roughly follows a line of constant potential depth U_{min} or, equivalently, constant transverse angular frequency ω_{min} . The upper bound can be approximated by a constant stability parameter q_{max} . Following Eqs. (1.14) and (1.6), a fixed U or q only determines the slope or the curvature of the lower or upper line, respectively. Nevertheless, both one-parameter approximations reproduce the boundaries of the guiding signal quite accurately.

As will be detailed in Sec. 4.3.2, the lower bound on the guiding signal represents the pseudopotential depth U_{min} , at which the ponderomotive force on the electrons just compensates for the centrifugal force that is caused by their movement along the bent guiding minimum. The maximum stability parameter q_{max} represents the drive settings where the trajectories in the time varying microwave potential become unstable.



Figure 4.3: Beam intensity at the guide exit (color-coded) of the bent substrate. The signal is plotted against microwave drive frequency $F = \Omega/(2\pi)$ and peak microwave voltage V_0 at the end of the inner conductor (a) and at the center of the outer conductor (b), compare Fig. 3.5. The guiding signal is limited from above by a parabolic curve, which represents drive settings that yield a constant stability parameter q_{max} . A lower limit is approximately given by a straight line, which indicates a constant potential depth U_{min} . Since the voltage V_0 is not constant along the electrodes, see Sec. 3.2.2, Figs. a) and b) plot the signal intensity against the highest and lowest voltages present. The upper bound on U_{min} from a) approximates the lower edge of the stability region better than the smaller U_{min} in b). Likewise, the lower bound on q_{max} , derived from b), better approximates the upper edge of the guiding signal. Dark blue areas in the upper right and lower left part of the plots indicate parameter settings where no measurements have been performed. Electron kinetic energy is $E_{kin} = 1 \text{ eV}$, no bias voltage has been applied to the cover plate. The substrate features a gap width of $g = 110 \,\mu\text{m}$.

4.2 Guide stability

The following two paragraphs summarize the technical details of the scattering parameter correction that underlies the stability plots presented in this Section.

Influence of applied scattering parameter correction

Since the peak voltage V_0 varies along the guiding electrodes, see Sec. 3.2.2, the pseudopotential parameters U_{min} and q_{max} that limit the guiding signal are not uniquely defined. Assuming that guiding is no longer possible when U falls below or when q rises above a certain value, U_{min} and q_{max} should be derived from those values of V_0 that give the largest U_{min} or the smallest q_{max} .

These extrema can be inferred from the two graphs in Fig. 4.3 which plot the guiding signal against the highest and lowest voltage V_0 along the electrodes. It is confirmed that the larger U_{min} better approximates the lower edge of the guiding region while the smaller q_{max} better fits the upper border. Regarding U_{min} , the two different evaluations lead to a difference of about 30%, while the values of q_{max} vary by about 10%.

In the following, I will mainly examine changes of U_{min} and all signal intensities will be plotted against the largest V_0 , which is present at the end of the inner conductor. Consistently using this value also allows an at least qualitative discussion of changes in q_{max} .

The edges of the stability region in Fig. 4.3 do not exactly follow the bounding lines of U_{min} and q_{max} but show some wiggles at the upper and lower border. These can largely be attributed to a not fully corrected frequency response of the wiring. As mentioned in Sec. 3.2.3, the scattering parameter S73 of the components between the substrate and the amplifier should be determined from a single measurement in order to correctly account for the standing wave that is forming in this section. However, for the setup that has been used to take the data of Fig. 4.3, no such measurement is available. Instead, the separately measured contributions of the wiring S63 and the substrate S76 have been summed to determine S73 = S76 + S63. The wiggles increase even more when the standing wave on the feeding line is ignored altogether by using measurements of the amplifier gain (S52) and the coupling ratio (S53) that have been performed with the substrate replaced by a matched load.

Resonances with loss of guiding

The data of Fig. 4.3 shows a sharp loss of guiding at a well defined drive frequency of $\Omega_l = 2\pi \cdot 1.045 \,\text{GHz}$. Such features are observed in all data that have been taken with the bent guiding structure. Furthermore, the frequency, at which the loss occurs, depends on the gap width g between the guiding electrodes. Replacing the substrate with $g = 110 \,\mu\text{m}$ by a substrate with $g = 40 \,\mu\text{m}$ shifts the loss frequency to $\Omega_l = 2\pi \cdot 0.935 \,\text{GHz}$. The loss is therefore most likely caused by an abrupt change of the substrate voltage at Ω_l that is not captured by the scattering parameter measurements presented in Sec. 3.2.3. This interpretation is additionally supported by the fact that Ω_l changes when the length of the cable that connects the substrate to the amplifier is varied. What is more, no loss of guiding occurs when the straight guide design is used, see Sec. 4.2.4 below. Instead, one can even observe an increased signal at a drive frequency of $\Omega = 2\pi \cdot 1.09 \,\text{GHz}$, which hints at a resonance causing a higher V_0 in this case.

The loss of guiding can moreover be correlated with a higher amplifier output power, since the resonance becomes wider and more pronounced with increasing voltage levels V_0 . This is especially visible in data that is taken with an additional bias voltage applied to the cover plate, which allows guiding at lower voltage levels, see for example Fig. 4.5 b). There, guiding is still observed at $\Omega_l = 2\pi \cdot 1.045$ GHz and small V_0 , but the signal vanishes at voltages above about $V_0 = 30$ V. A possible explanation for this behavior would be an increase of microwave power at harmonics of the drive frequency at Ω_l that occurs at high output powers when the amplifier approaches saturation. However, no particularly high power level of one of the first five harmonics could be experimentally observed at Ω_l . A box resonance of the conductive shielding structure around the guiding region could also be ruled out, as Ω_l does not change when the shielding cap is removed.

Instabilities of the electron trajectories, like nonlinear resonances due to higher order multipole moments of the guiding potential [126, 127], are also unlikely to cause the observed loss. They should occur at constant transverse angular frequencies ω and therefore would follow lines of constant U in an Ω -V₀ plot, instead of being visible at fixed drive frequency Ω_l . Furthermore, these mechanisms would require that an electron performs much more than approximately five transverse oscillations in the guiding potential, as it is the case in the present experiment (compare Sec. 4.3.3).

4.2.2 Guiding at variable kinetic energy

Fig. 4.4 shows the guide stability for three different electron kinetic energies in the bent guide. In total, we observe electron guiding up to electron energies of about 10 eV. This value strongly depends on the amount of substrate charging present and on the compensation voltage V_{top} applied to the top plate, see the next section. Since the centripetal force that has to be exerted on the electrons by the guiding potential increases with kinetic energy E_{kin} , U_{min} increases from approximately $U_{min} = 21 \text{ meV}$ to about $U_{min} = 33 \text{ meV}$ when changing E_{kin} from $E_{kin} = 1.9 \text{ eV}$ to $E_{kin} = 5 \text{ eV}$. No significant change of q_{max} is observed, which stays approximately constant at around $q_{max} = 0.55$.

4.2.3 Guiding with biased cover plate

As mentioned in Sec. 4.1, a negative bias voltage V_{top} that is applied to the cover plate above the guiding region compensates for charges accumulating on the substrate and additionally deepens the guide. Fig. 4.5 illustrates the effect of a cover plate bias on guiding stability by comparing two measurements with $V_{top} = 0$ V and $V_{top} = -1.5$ V. On the one hand, applying V_{top} leads to an overall increase of the electron signal with an approximately 10% higher maximum count rate than without bias. On the other hand, the additional contribution to vertical potential depth reduces the value of U_{min} that is inferred from the dynamic drive parameters alone. With $V_{top} = -1.5$ V, guiding is possible at drive settings that would correspond to $U_{min} = 5$ meV in the unbiased case. Again, the signal at the upper border of the stability region approximately stays constant resulting in $q_{max} = 0.48$. This is slightly lower than the value obtained in the measurements at different kinetic energies presented in Sec. 4.2.2, which presumably have been taken with a higher static charging of the substrate. Generally, the values of U_{min} and q_{max} are not comparable between different charging levels.



Figure 4.4: Dependence of minimum potential depth U_{min} on the kinetic energy E_{kin} of the guided electrons. To better visualize changes in the limiting guiding parameters U_{min} and q_{max} , the integrated intensity in the guiding region (color-coded) is plotted against the stability parameter q and potential depth U. The approximate value of U_{min} is indicated by a red horizontal line. Deviations of the lower border of the stability region from this line can be attributed to an insufficient characterization of the frequency response S73 of the section between amplifier and substrate. The color scale of each plot is normalized to the maximum count rate at the corresponding energy E_{kin} and the bias to the cover plate has been $V_{top} = -0.5$ V for all measurements. Since the measurements have been performed at regularly spaced values of Ω and V_0 , the data points appear irregularly distributed in a q-U plot.



Figure 4.5: Stability plots taken with (b) and without (a) a top plate bias voltage of $V_{top} = -1.5$ V. The signal intensity has been plotted against the microwave frequency $F = \Omega/(2\pi)$ and voltage V_0 at the end of the inner conductor. The electron kinetic energy in both cases amounts to $E_{kin} = 1$ eV. A constant dark count rate has been subtracted from both plots to enhance the signal to noise ratio. Since the MCP gain has been identical, the relative count rates are directly comparable among these two measurements.

4.2.4 Guiding with straight substrate

All stability plots presented so far have been taken with the bent guiding structure. To examine the ponderomotive stability without centrifugal force on the electrons, a straight electrode geometry has been fabricated and studied. Since guided electrons are not spatially separated from unguided ones, they appear as a bright, collimated spot that is embedded in a diffuse background signal of loss electrons. This allows to determine the strength of the guiding signal by integrating the spot intensity only. Resulting stability plots for electron energies of $E_{kin} = 1 \text{ eV}$ and $E_{kin} = 2 \text{ eV}$ are shown in Fig. 4.6.

Since no lateral force has to be exerted onto the electrons in the straight potential minimum, guiding at $E_{kin} = 1 \text{ eV}$ can be observed for all potential depths. As can be inferred from Fig. 4.6 b), the guiding signal nevertheless vanishes at low U for higher kinetic energies. This can be attributed to a slight tilt of the electron gun that leads to electron loss in the transverse direction at very low U, which would also explain the experimental observation that unguided electrons predominantly appear to the right of the guiding signal. The maximum stability parameter $q_{max} = 0.63$ for $E_{kin} = 1 \text{ eV}$ is larger than in the bent geometry since the electrons stay closer to the guiding minimum, where they oscillate at a smaller micromotion amplitude. At $E_{kin} = 2 \text{ eV}$, electrons entering the guide at an angle experience larger micromotion oscillations at their more distant turning points and a coupling of lateral and vertical motion in the anharmonic guiding potential results in a slight reduction of q_{max} .

At a drive frequency of $\Omega \approx 2\pi \cdot 1.1$ GHz, the signal significantly increases, most likely due to a voltage increase that is not captured by the s-parameter measurements, similar to the effects discussed in Sec. 4.2.1.



Figure 4.6: Stability plots taken with a straight guiding structure at electron kinetic energies of a) $E_{kin} = 1 \text{ eV}$ and b) $E_{kin} = 2 \text{ eV}$ with no bias voltage applied to the cover plate. Since no measurements of the electrode voltage on the straight substrate have been available, the guiding signal is plotted against V_0 determined from a *FIT*-simulation of its frequency response S76, compare Sec. 3.2.2. The color scale in a) has been clipped at $6 \cdot 10^4$ counts to reduce the effect of a sharp increase of the guiding signal to $1.6 \cdot 10^5$ at $F = \Omega/(2\pi) \approx 1.1 \text{ GHz}$. Dark blue regions in the lower left and the upper right part of the plots indicate parameter settings where no data has been taken.

4.3 Comparison to simulated electron trajectories

To further analyze the experimental guiding signal, it is compared to numerical particle tracking simulations with a commercial software package¹ that implements the *boundary-element-method* (*BEM*). Although the simulations completely neglect microwave propagation effects, they reproduce the experimentally obtained stability plots and detector signals quite accurately.

4.3.1 Model

The simulation model shown in Fig. 4.7 reproduces the bent guiding structure with $g = 110 \,\mu\text{m}$ wide gaps between the electrodes. The first section has also been used to study the influence of finite electrode gaps on the coupling pseudopotential in Sec. 2.2.4. The simulation approximates the guiding electric field only quasi-statically by determining the electrostatic field above the electrodes and sinusoidally modulating the field amplitude in phase across the entire simulation domain. Similar to the field simulation used for optimizing the coupling structure (Sec. 2.2), this neglects voltage and phase variations arising from a microwave standing wave forming on the electrodes. While these variations are not relevant to the tapered electrode section in the coupling region with their length being much smaller than the drive wavelength λ , voltage differences become noticeable across the entire guiding electrodes at one lateral position only amounts to about 6%, see Sec. 3.2.2, a quasistatic simulation should still give a good estimate of the guiding properties. This is confirmed by the good agreement between experimental and simulated

¹ Charged particle optics, CPO



Figure 4.7: Top view of the *BEM*-model implemented in CPO to simulate the guide stability and the detector signal. The guide entrance is located to the left with the exit aperture of the electron gun modeled as a cylindrical tube connecting to a punched disc. The detector plate (not visible) is placed 10 mm behind the exit of the guide on the right. Red electrodes are grounded and the oscillating drive voltage is applied to the green and blue electrodes. The mesh shown is the finest partition possible due to a limited total segment number in CPO.

data presented in the following sections and indicates that the current demonstration experiment is not limited by microwave voltage differences on the electrodes.

The simulation domain encompasses the entire bent guiding electrodes including the tapers at both substrate edges. The exit aperture of the electron gun is represented by a grounded annular disc at the beginning of the guide and the detector plane is situated approximately 10 mm behind the exit of the guide. Due to a technical restriction regarding the segment density at the gun aperture, the opening diameter of the exit aperture of 120 μ m is larger than the experimental value of 50 μ m. This eventually leads to a reduced lens action of the aperture in the simulations. In total, 25 rays are simulated that represent the envelope of an electron beam with a full opening angle of 1.53°. They are released at 17 different instances in time equally distributed over one full microwave oscillation period. The detector signal is than averaged over all starting phases and the simulation is evaluated for several voltage amplitudes V_0 and drive frequencies Ω yielding different values of U and q.

4.3.2 Simulated stability plots

Stability plots that have been obtained from particle tracking simulations in the time varying guiding potential are shown in Fig. 4.8. The plots qualitatively agree with the experimental results from Fig. 4.4. The guiding region is likewise bounded towards large stability parameters q and low potential depths U. The value of $q_{max} = 0.6$ is approximately independent of kinetic energy E_{kin} and a little larger than in the experiments. The minimum potential depth is again energy dependent and raises approximately linearly from $U_{min} = 7 \text{ meV}$ at $E_{kin} = 1 \text{ eV}$ to $U_{min} = 42 \text{ meV}$ at $E_{kin} = 5 \text{ eV}$.

For higher electron energies the simulated data show a coupling of the two loss mechanisms at high q and low U. When q approaches q_{max} at $U \approx U_{min}$, the guiding potential can not compensate for a reduced guide stability and the signal intensity decreases faster than it is the case for a larger potential depth.

The linear increase of U_{min} with E_{kin} confirms the interpretation of U_{min} being the potential depth that just counteracts the centrifugal force on an electron in a bent guide. A rough estimate of U_{min} can be obtained by equating the centrifugal force on an electron $F_c = 2E_{kin}/r$ on a circular orbit of radius r = 40 mm with the restoring force in an harmonic oscillator potential at a predefined distance dx from the guide center, $F_{HO} = 0.5 m \omega_{min}^2 dx$. Consequently, the minimum transverse frequency ω_{min} is proportional to $\sqrt{E_{kin}}$ and it follows $U_{min} \propto \omega_{min}^2 \propto E_{kin}$. Fig. 4.9 compares the experimental and simulated values of U_{min} with those obtained by this rough estimate. By fitting the simulated data, a maximum displacement of $dx = 70 \,\mu\text{m}$ results, which is well inside the harmonic region of the transverse potential, see Fig. 2.3. While the simulated values for U_{min} follow the theoretical curve, the experimental data deviate noticeably. This can be attributed to experimental imperfections like gap charging or a decentered electron gun, which would especially deflect slow electrons at the guide entrance.

4.3.3 Simulated electron trajectories

Fig. 4.10 shows a side-view of electron trajectories in the bent guiding structure for various guide settings to illustrate different loss mechanisms encountered in the experiment. Sev-



Figure 4.8: Simulated stability plots at variable kinetic energies showing the fraction of electron trajectories that hit the detector plane at the position of the guide exit (colorcoded) for four different initial energies E_{kin} . The approximate value of minimum potential depth U_{min} is indicated by a horizontal dashed line. The rounded lower right corners of the stability region at higher E_{kin} indicate a coupling of the loss mechanisms at high stability parameter q and low potential depth U when both parameters approach their limiting values at the same time. The simulation models the geometry used in the measurements of Fig. 4.4.



Figure 4.9: Energy dependence of the minimum potential depth U_{min} needed for electron guiding in a bent electrode structure. The plot compares the experimental data of Fig. 4.4 to the simulated values. A linear fit on the simulated data is included, which is based on the assumption that the restoring force in the guiding potential counteracts the centrifugal force on the electrodes. It yields a maximum lateral deflection of $\Delta x = 70 \,\mu\text{m}$, see text.

eral rays have been traced that start from a circular disc at the exit aperture of the electron gun and form an electron beam with a full opening angle of 1.53° and a virtual pupil of $20 \,\mu\text{m}$ in diameter. Furthermore, the electron trajectories start at varying instances during one oscillation period of the drive field, which accounts for microwave-phase dependent effects.

The data in Fig. 4.10 a) and b) have been simulated with a comparably small trap depth U so that no guiding is possible at an electron energy of $E_{kin} = 3 \text{ eV}$. As one might expect, the electrons leave the guide at the beginning of the curved segment at y = 0. A comparison of the trajectories that start with an initial phase shift of 180° with respect to the microwave drive field shows that the electrons experience a phase dependent deflection when passing the exit aperture, which depends on the instantaneous direction of the electric field. In the comparably strong fringing fields at the guide entrance, the fast oscillations near the drive frequency Ω dominate the electron motion and a time-averaged description in the ponderomotive potential is not applicable.

For a higher potential depth, this initial kick upon entering the guide causes a phase dependent electron loss, as can be inferred from the individual trajectories shown in Figs. 4.10 c) and d). Electrons entering the curved section of the guide while performing an oscillation half cycle directed downwards stay in the guiding potential throughout its entire length. Those performing an upward oscillation are ejected while traveling along the curved part of the guide.

Lowering the q-parameter should reduce the phase dependent deflection in the coupling field as the motion of the electrons averages over the oscillating microwave field more efficiently. However, even for an about ten-fold reduction to q = 0.035, corresponding to $\Omega = 2\pi \cdot 8.74 \text{ GHz}$ and $V_0 = 242 \text{ V}$, a phase dependent focusing at the gun exit is still visible in Figs. 4.10 e) and f). The strong electric field that emerges at the exit



Figure 4.10: Side view of electron trajectories in the bent guide for different electron energies E_{kin} , guide stability q, potential depth U and start phases Φ_0 . The exit aperture is indicated in black and ends at y = -8.5 mm. The 3 mm long taper starts at y = 8 mm and is followed by a straight section. At a lateral position of y = 0, the curved part of the guide starts, which ends at $y \approx 26$ mm. The substrate surface is again situated at z = 0. For better visibility, each individual ray is plotted in a different color. Note that the trajectories appear compressed when the electrons turn towards the observer.

aperture diabatically defocuses or focuses the electron beam passing the aperture in less than one oscillation period. An initial defocussing results in larger oscillation amplitudes in the guiding field and eventually to electron loss on extremal trajectories. The effect is supposed to be reduced for higher drive frequency Ω or lower electron energy E_{kin} , as well as for electron guns with a smaller exit aperture.

In Figs. 4.10 a) to f), the two different frequency components of the secular and the micromotion are clearly discernible. In all cases, electron loss is finally caused by a potential too shallow to confine the beam and all electrons leave the guide at approximately the same lateral position within one secular oscillation cycle. For comparison, Fig. 4.10 g) has been simulated at much lower guide stability (q = 0.8) and at an electron energy of $E_{kin} = 1 \text{ eV}$. Here, the micromotion amplitude is much larger and causes the electrons to leave the guide at various lateral positions within one oscillation period of the microwave driving field. Even at positions far away from the fringing fields of the couplers, the electron dynamics is dominated by the fast oscillations at the drive frequency and can therefore not be described in the time-averaged ponderomotive picture.

From Fig. 4.10, two main shortcomings of the current design may be deduced. The first is the operation at rather high stability parameters q that cause a phase dependent deflection of the entire electron beam at the guide entrance, see Figs. 4.10 a) to d). This behavior has been observed at all values of q above approximately q = 0.2 and is limiting at electron energies above about $E_{kin} = 3 \text{ eV}$. Note that for $E_{kin} \approx 1 \text{ eV}$ and U = 30 meV, both the experiment and the simulation show nearly complete guiding even at q = 0.3. A second, closely related issue is the fringing field at the guide entrance that is still comparatively large, despite the reduction achieved by the taper design described in Sec. 2.2.1. It causes a phase dependent deflection of individual electron rays at the guide entrance even for (unrealistically) low q-parameters of q = 0.035, see Figs. 4.10 e) and f). This results in a phase dependent 'breathing' of the electron beam entering the guide and causes increased losses for phases, at which the radial deflection is largest.

4.3.4 Simulated detector signal

To match the simulated electron trajectories to the experiment, the corresponding detector signals may be compared. Fig. 4.11 shows the dependence of the simulated signal on the kinetic energy of the electrons at a stability parameter of q = 0.29 and a potential depth of U = 25 meV, which corresponds to the experimental parameters in Figs. 4.1 b) and 4.2 a). For these settings, the simulation yields guiding up to electron energies of about $5 \,\mathrm{eV}$, roughly the same as in the experiment. While the simulation for $E_{kin} = 1 \,\mathrm{eV}$ shows no loss of electrons, an extended loss signal is visible at $E_{kin} = 3 \,\mathrm{eV}$, which further increases for $E_{kin} = 4 \,\mathrm{eV}$. At $E_{kin} = 6 \,\mathrm{eV}$, the guiding signal has disappeared completely and all lost electrons are observed at the lateral position of the guide entrance. The data at $E_{kin} = 3 \,\mathrm{eV}$ and $E_{kin} = 4 \,\mathrm{eV}$ show the characteristic spiraling structure of lost electrons, which is also observed in the experiment, see Fig. 4.2 a). Furthermore, the position of the guiding signal at $E_{kin} = 4 \,\mathrm{eV}$ is slightly shifted towards the outer conductor when compared to that at $E_{kin} = 1 \,\mathrm{eV}$, which is in agreement with the experiment. Generally, the losses in the experiment are larger than in the simulation where, for example, no loss signal may be observed at $E_{kin} = 1 \,\mathrm{eV}$. This can be easily attributed to experimental imperfections like a more divergent electron beam, a decentered electron gun or substrate



Figure 4.11: Change of the simulated electron signal with increasing energy. The trajectories have been calculated at a drive frequency of 1030 MHz and an electrode peak voltage of $V_0 = 27.7$ V. This yields q = 0.29 and U = 25 meV, which is the same as in Figs. 4.1 b) and 4.2 a). The colors encode the phase of the driving field at the release time of the electron. The substrate surface coincides with the lower border of the plot frame at z = 0.

charging.

To visualize the phase dependent effects discussed in Sec. 4.3.3, simulations that start at different phases of the microwave cycle have been combined in Fig. 4.11. Phase dependent loss is especially observed at $E_{kin} = 3 \text{ eV}$, where the guiding and loss signals are composed of electrons that start with an initial relative phase shift of 180° . A side view of the corresponding trajectories is shown in Figs. 4.10 c) and d). For this electron energy, a guiding potential with U = 25 meV can not compensate all initial deflections at the guide entrance.

Figs. 4.12 and 4.13 further compare the dependence of simulated and measured electron signals on the trap depth U and the stability parameter q, respectively. Electron loss is generally higher in the experiment than in the simulations. This applies both to the loss at small U and at high q. Comparable detector signals consequently occur at slightly different drive parameters. At U = 20 meV, for example, similar signals are obtained at q = 0.38 in the experiment and q = 0.6 in the simulations, which again may be attributed to experimental imperfections that have not been accounted for in the simulations. Apart from the different loss contributions, the experimental signal patterns match the simulated structures quite well. The height above the electrodes, at which the guided electrons hit the detector, is approximately the same. This also holds for the horizontal distance between the guide center and the gun exit over which lost electrons can be observed.

As can be seen from Fig. 4.12, the guiding signal builds up in a characteristic way with increasing U. For very small U, all electrons are lost at the beginning of the guide and the signal appears to the right of the detector. When U increases, the electrons are



Figure 4.12: Dependence of the experimental and simulated detector signals on potential depth U at $E_{kin} = 1 \text{ eV}$. In the simulations, the substrate is located at z' = 0. For the experimental data, the coordinate system is vertically shifted and the substrate is indicated by a red line. Both the experimental and simulated data show a similar signal structure. The guiding signal appears at approximately the same height above the substrate and the lateral extent of the loss signal is roughly the same. Due to experimental imperfections, loss is generally higher in the experiment and the experimental signal at U = 20 meV (g) roughly corresponds to the simulations at U = 10 meV (b).



Figure 4.13: Dependence of the experimental and simulated detector signals on the stability parameter q at an electron energy of $E_{kin} = 1 \text{ eV}$. In the simulations, the substrate is located at z' = 0. For the experimental data, the coordinate system is vertically shifted and the substrate is indicated by a red line. Since losses are higher in the experiment, the experimental and simulated data have been taken with slightly different q-parameters to yield similar signal patterns.



Figure 4.14: Change of the simulated electron signal with a vertical shift of the electron gun. a) Detector signal simulated with a centered electron gun. b) Electron gun shifted downwards by $\Delta z = -100 \,\mu\text{m}$. Both simulations have been performed with $E_{kin} = 1 \,\text{eV}$, q = 0.15 and $U = 10 \,\text{meV}$. The phase of the microwave drive cycle with respect to the release time of the electron is indicated by the colors of the individual data points.

able to propagate ever longer distances in the guide and the loss signal extends towards the position of the guide exit until the guided spot appears. For even higher U, the loss signal first weakens at the gun exit and finally vanishes completely. With increasing U, neither the experiment, nor the simulations show a significant variation of the size of the guiding signal, as one might expect from a higher transverse potential depth and frequency. Instead, both data show a slight shift of the position of the guiding signal towards the inner conductor, which indicates that the electrons are guided closer to the potential minimum.

Fig. 4.13 compares two electron signals, which show electron loss that is predominantly caused by a too large stability parameter q instead of a limited potential depth U. While the loss signal at small U appears as a well defined line that extends from the gun exit towards the guide, a high q results in a diffusive electron signal that is smeared out in the upward direction. As can be seen from the trajectories presented in Fig. 4.10 g), this is due to the fact that the electrons exit the guide within one microwave cycle when they experience an abrupt deflection in the oscillating guiding field.

Signal with shifted electron gun

The particle tracking simulations also allow a study of the effect of different experimental imperfections on the guiding signal. As an example, Fig. 4.14 compares the simulated signals at an electron energy of $E_{kin} = 1 \,\text{eV}$ for two positions of the electron gun. It is either centered at the guide entrance or shifted downwards by $\Delta z = -100 \,\mu\text{m}$. The shift causes an increased electron loss during guiding, which has a pronounced kink at a lateral position of $x' = 45 \,\text{mm}$ and is not visible in the loss signal from a centered electron gun, compare also Fig. 4.11. A similar feature also appears in the experimental data of Fig. 4.2 a), which hints on a slightly decentered gun in the corresponding experimental configuration. By shifting the electron gun in front of the guide and comparing the electron signal with the simulated detector images, it is now possible to accurately center the exit aperture at the guide entrance.



Figure 4.15: Comparison of the width of the coupling region of a substrate with (red) and without (blue) the tapered structure shown in Fig. 2.5. a) Dependence of the signal intensity on a lateral shift Δx of the electron gun. The vertical position was set to the value yielding maximum signal intensity for a horizontally centered gun, which corresponds to $\Delta z = 0$ for the structure with taper and $\Delta z = 350 \,\mu\text{m}$ for that without. b) Signal intensity versus a vertical shift Δz of the gun at $\Delta x = 0$. With increasing Δx , the electron gun has been moved from the outer towards the inner conductor whereas the z-axis points upwards, see Fig. 3.9. The electron gun position in front of the guide has been measured as relative displacements from positions of maximum signal intensity in the tapered structure. For better comparison, the intensities of the traces have been normalized. The signal without taper is approximately a factor four smaller than that with tapered coupler.

4.4 Electron injection into the guide

To study the effectiveness of the coupling taper of Sec. 2.2.1, the coupling behavior has been measured for two bent guides. One guide has a taper at both ends, see Fig. 3.2, the other has both ends ending in straight wires. The measurements show that the coupling efficiency is significantly larger for the tapered design, with the fraction of guided electrons being about four times higher than for the design without taper.

Besides the higher coupling efficiency, the introduction of a taper also increases the coupling area. Fig. 4.15 compares the dependence of the guiding signal on the transverse position of the electron gun in front of the guide for both designs. The tapered guide exhibits a coupling region with a full width at half maximum of 490 μ m and 530 μ m in the horizontal and the vertical direction, respectively. This is twice the size of the coupling region of the design with straight ends, which extends over 260 μ m and 250 μ m. The horizontal scan additionally shows a slight asymmetry with a higher signal when the electron gun is positioned to the left of the coupling center. This might indicate that the electrons are more efficiently guided along the curved guiding center when they start with a transverse motion that follows the later deflection in the guide. Another possible explanation would be a slight horizontal tilt of the electron gun in front of the guide, which has been positioned by hand, see Sec. 3.3.1.

In the vertical direction, the tapered design shows a significantly larger asymmetry of the guiding signal than in the horizontal direction. The signal drops faster when the electron gun is shifted downwards from the center towards the substrate. This is most likely caused by the anharmonicity of the vertical guiding potential, which provides stronger confinement towards the electrode plane, see Fig. 2.3 c). A comparably small downward shift of the gun injects electrons at positions where the pseudopotential exceeds the potential depth U, which leads to a subsequent loss of the electrons in the upward direction. The observation that the coupling region is slightly larger than the vertical extension of the guiding potential in Fig. 2.3 c) indicates that the taper widens the entrance to the guide. In addition to the smaller coupling region, the vertical position of the coupling center without taper is about 350 μ m higher than for the tapered coupler. Additionally, the guiding signal exhibits virtually no asymmetry along the position scan.

The effect of the taper structure does not depend on the layout of the guide that follows the coupling region and stays the same when the bent, tapered guide is replaced by a straight one. The enhanced coupling efficiency and the larger coupling area confirm that the taper optimization presented in Sec. 2.2.1 efficiently reduces the fringing fields at the guide entrance.

4.5 Conclusion and next experimental steps

The results presented in this chapter demonstrate the feasibility of electron guiding in a microwave quadrupole guide based on a surface-electrode geometry. In the experiment, low energy electrons with a kinetic energy of 1 eV to 10 eV have been guided in two different electrode geometries that realize a bent and a straight guiding potential.

In the bent guide, best results are obtained at low energies around $E_{kin} = 1 \text{ eV}$ and a potential that has a depth of $U \approx 33 \text{ meV}$ and a transverse frequency of $\omega \approx 2\pi \cdot 110 \text{ MHz}$. Virtually all electrons emerging from the thermionic electron gun are then injected into and conducted along the guide. Future experiments that implement similar guide dimensions and transverse excitations due to, for example, a curved guide geometry should therefore aim at comparable values of drive parameters and kinetic energies.

A map of the dependence of the coupling behavior on a lateral shift of the electron gun shows that the tapered electrode structure of Sec. 2.2.1 increases the coupling efficiency by a factor of four over a structure with straight ends. Simultaneously, the extend of the coupling area in the horizontal and vertical direction approximately doubles.

A systematic variation of the frequency and power of the microwave signal that is applied to the electrodes allows to measure the stability of the electron guide against variations in guiding potential depth U and ponderomotive stability q. For the bent geometry, it is found that a minimum potential depth is required to counteract the centrifugal force on the electrons in the curved guide.

The experimentally observed stability diagrams and detector images show good qualitative agreement with results that are obtained from numerical simulations of electron trajectories in the guide. This allows to identify limiting loss mechanisms from the simulations. The performance of the guide is currently limited by a microwave-phase dependent deflection of electrons upon entering the guide. This is caused by comparatively high ponderomotive stability factors q, which are required to obtain a sufficiently deep guiding potential, and by still too large fringing fields at the guide entrance.

To minimize the excitation of electrons entering the guide, it is therefore desirable to reduce the residual field at the guide entrance and to operate at higher guide stability, corresponding to lower ponderomotive stability parameters q. In the following, I outline



Figure 4.16: Photograph of a printed circuit board substrate featuring the optimized taper structure of Sec. 2.2.2. The trenches between the electrodes have been laser cut with a gap width of $g \approx 15 \,\mu\text{m}$, compare Sec. 3.1.2

the next technical steps towards this goal.

Improvements on the tapered coupling structure

First steps to reduce the fringing fields by redesigning the taper structure at the guide entrance have already been described in Sec. 2.2.2, and a printed-circuit-board substrate with the new layout has been fabricated. Fig. 4.16 a) shows a photograph of the coupling structure, which has been structured by the same laser-cut process as the straight substrate of Fig. 3.3 b). Compared to the structure used in the experiments reported on in this thesis, a significant reduction of the initial excitations can be expected from the particle tracking simulations presented in Sec. 2.2.2. Due to the broken symmetry of the surface-electrode structure, it is considered unlikely that a further significant reduction of the fringing field can be obtained without resorting to three-dimensional electrode structures. These could allow the implementation of special aperture designs that are also used at the ends of quadrupole analyzers [128]. However, feeding the drive signal to such a three-dimensional structure poses significant challenges.

Triggering the electron beam in phase with the microwave drive frequency would allow a further investigation of the phase-dependent deflection at the guide entrance. The electron gun presented in Sec. 3.4 has therefore been extended with a deflection unit that is driven by a 100 MHz signal and streaks the electron beam that exits the collimation lenses across an additional exit aperture. With an aperture diameter of 20 μ m, this should yield sub 100 ps electron pulses, short enough to resolve a drive signal at $\Omega = 2\pi \cdot 1 \text{ GHz}$. The arrival time of the electron pulses will be scanned across the microwave cycle by locking the deflector to the microwave signal source and adjusting the phase shift between the two signals.

Substrate charging

As described in Sec. 4.1, the guiding signal is affected by a charging of the substrate in the gaps between the electrodes. While this did not generally inhibit electron guiding, it severely limited the guiding stability at the edges of the stability regions. Depending on the amount of charges present, guiding was sometimes not possible without compensating stray fields and deepening the guide with the cover electrode. Accumulated charges are assumed to especially affect the electron trajectories in the coupling region, where the transverse confinement is still comparatively weak.

So far, no systematic characterization of charging effects has been carried out. It would be interesting to compare the time-variation of the guiding signal for substrates with different gap widths. Compared to the substrates with wide gaps that have been used in this thesis, the laser cut designs should result in a significant reduction of charging effects. However, the laser cutting also deposits burned residues on the electrodes that are hard to remove. Even better results can be expected from lithographically patterned substrates that feature much cleaner electrode edges and even higher aspect ratios. As a test, the bent guiding structure has also been lithographically fabricated with an electrode thickness of 17 μ m and a gap width of 20 μ m by a commercial supplier.

For future designs, however, the development of an in-house lithographic fabrication process is highly desirable. This would offer much more flexibility regarding electrode geometries and dimensions, combined with faster turn-around times. Towards this goal, the realization of small plated-through holes to connect the guiding electrodes from the backside will be a key component.

Operation at higher guide stability with electrically long structures

The phase dependent dynamics in the coupling region can be avoided by operating the guide at higher ponderomotive stability, thus lower q. Keeping ω and U constant, this requires, according to Eq. (1.6), higher drive frequencies Ω and drive voltages V_0 . The reduced wavelength at higher Ω then prevents an operation in the standing wave configuration described in Sec. 3.2.2. A possible solution would be a traveling wave excitation on the guiding electrodes with the electrons co- or counter-propagating above, as has been detailed in Sec. 2.3.

A first test and technical demonstration of the concept could possibly be realized with the printed-circuit-board process used in this thesis. To guarantee that the center conductor is at ground potential over the entire guiding length, it can be connected to the underlying grounded plane by periodically placed plated holes. At both ends of the guide, the source and drain line can be connected to the coupling tapers from below. Since the impedance of the five-wire structure will roughly amount to 25Ω , the feeding line has to be connected via impedance matching $\lambda/4$ sections to the guide in order to prevent a back-reflection at the feeding point and especially at the coupler at the far end of the guide.

A first test setup could incorporate the existing microwave equipment at 1 GHz drive frequency. A traveling wave excitation definitely prevents to use a resonating structure for voltage enhancement. Thus, one would have to resort to microwave amplifiers with higher output power in order to increase the drive frequency and voltage for higher guide stability at constant potential depth.

Development of a field-emitter electron gun

Besides the improvements on the guiding potential, another prerequisite to approach the quantum regime, as sketched in Sec. 1.6, is a better collimated electron gun with a much smaller beam diameter. The beam diameter of the thermionic gun that has been used throughout this thesis causes electrons that enter the potential at the edge of the beam to perform large oscillations in the guiding potential, see Fig. 4.10 e). In order to generate an electron beam with a spot size and divergence that is compatible with ground state injection, a new gun design is currently implemented in our group, which combines a field emitter tip with micron-sized lens elements similar to the device demonstrated in [65].

Apart from ground state injection, it is also very interesting to test the coupling behavior of the different taper designs with a smaller electron beam. This should enable to resolve the secular motion in the guiding structure by shifting the electron gun away from the coupling center and observing the resulting beam steering behind the guide.

Chapter 5 Conclusion and outlook

This thesis presented the first realization of a microwave quadrupole guide for electrons that is based on a surface-electrode design. Crucial to the success of the experiment is the use of a miniaturized electrode geometry on a planar substrate, which allows guide operation at microwave drive frequencies around 1 GHz. The electrons are confined and guided by the high field gradients that are present in the microwave near-field at a height of 500 μ m above the electrode surface

In the experiment, low energy electrons with kinetic energies below 10 eV are injected into the guiding potential at one edge of the substrate. After propagating a distance of several centimeters in the transversally confining potential, they exit the guide at its opposing end and are imaged by an electron detector. Two different electrode geometries have been realized that generate a curved and straight guiding potential, respectively. In the bent geometry, guided electrons get horizontally deflected and become spatially separated from the unguided portion of the electron beam. An additional signature of electron guiding is a collimation of the confined electron beam. This permits to distinguish between guided and unguided electrons also in the case of the straight geometry, where both signals overlap. At low energies around one electron-volt, all electrons that are emitted by the electron gun are guided and detected. Without the guiding potential applied, most of the electrons would not reach the detector due to deflection from stray electric fields above the electrode surface.

At the entrance and the exit of the guide, a numerically optimized electrode structure is implemented, which reduces the effect of fringing fields on the electron trajectories. This has been confirmed experimentally by measuring the change of the guiding signal upon a lateral shift of the electron gun in front of the guide. Compared to a structure ending in straight wires, the optimized geometry yields a four times higher coupling efficiency and a twice as large extent of the coupling area.

A systematic variation of the frequency and power of the microwave signal applied to the guiding electrodes determines the settings that lead to stable trajectories in the guiding potential. In general, stable guiding is found to additionally depend on the electron energy and the amount of static charges accumulating on the substrate between the electrodes. A comparison of the experimental stability plots and detector signals with numerical particle tracking simulations shows good qualitative agreement. This allows to identify an initial, microwave-phase dependent excitation at the exit aperture of the electron gun as the dominant loss mechanism. An improved coupling structure has been designed, which promises to reduce the excitation of an electron that enters the guide on-axis by a factor of 10, when compared to the geometry used in the proof-of-concept experiments of this thesis.

Furthermore, a microwave transmission line analysis of the current five-wire electrode layout has been performed. This is relevant for the realization of electrically long guiding structures with a length that is comparable to or larger than the drive wavelength. It is found that longer guides can be realized with a modified electrode structure that features elevated signal conductors and a connected ground plane.

Outlook

The prospect of injecting electrons into the quantum mechanical ground state of the guide has been one main motivation of this thesis. As detailed in Sec. 1.6, this should be possible with a well collimated electron beam from a field emission electron gun that exhibits low aberrations. Such a device is currently being developed in our group. In ion traps, a general limiting factor for quantum manipulation experiments is heating of the ions, which can most likely be attributed to fluctuating electric fields that originate from surface contaminants. This is particularly an issue in surface-electrode design as the heating rate increases with decreasing trap to electrode distance. As has been detailed in Sec. 1.5, the electric noise densities that are measured in ion traps yield electron heating rates that should be sufficiently small for quantum experiments.

The surface-electrode design presented in this thesis offers the possibility to realize electron guiding potentials of much richer shape than the straight guides currently implemented. One extension would be a junction that splits a propagating electron beam. Although the conjecture has been stated that no crossing that supports a true pseudopotential zero can be generated by a planar electrode layout [92], a significant reduction of unwanted field components in the splitting region has been achieved [19, 83] by optimization routines that are similar to those used for the coupler design of Sec. 2.2. If a coherent splitting and subsequent propagation of confined electrons could be implemented, interference of guided, low-energy electrons could be studied. Due to the presence of the confining electric fields, this possibly requires the ground-state guiding mentioned above.

Another possibility to extend the guiding potential would be to decelerate confined electrons by applying a static voltage to additional electrodes located nearby the guide. It would be interesting to see by how much the electron energy in the guide can be reduced, thus generating an extremely slow, but at the same time well collimated electron beam. One could even think to close the guide longitudinally and confine electrons in a linear Paul trap. Stopping of the electrons could be achieved with a diabatically switched longitudinal potential and subsequent axial confinement. A static, harmonic stopping potential with a trap frequency of 100 MHz, similar to the secular frequencies in the guide, would require switching times of several nanoseconds, which is technically feasible.

The microwave guide could also be combined with laser triggered field emitters [12, 129, 130]. This would enable precise spatial and temporal control over the electrons for controlled interaction experiments with two electrons traveling in neighboring guides and interacting via their charge. Compared to the recently demonstrated Coulomb coupling of trapped ions [15, 16], the coupling strength increases for electrons due to their smaller mass by about four orders of magnitude. Thus, electron-electron interactions could be

studied for wider particle separations or with electrons confined in tighter potentials. Also, interfacing the electrons with other quantum systems like electrons in solids or signals in microwave cavities [131] could be possible.

Recently, a proposal for non-invasive electron microscopy has been published [132]. It suggests to confine electrons in a ring-shaped double well potential, which is generated by two closely spaced microwave guides similar to those used in this thesis. If the electrons were prepared in a localized quantum state of one potential well, an object in the other well would inhibit tunneling between the two potentials due to the quantum Zeno effect. Thus, the object could be detected although the probability of a direct interaction with the electrons nearly vanishes.

Another direction of future research could be the study of low-energy electron scattering from charged or neutral atoms. To this end, the guide could be, for example, overlapped with a (magneto-) optical trap for neutral atoms. Even the interaction with ions that are likewise confined in a radio-frequency trap might be possible, provided that the drive frequency is made sufficiently different from that of the electron guide. Here, three orders of magnitude should be easily achievable. Since the electrons are confined in a purely electric field, their spin can furthermore be freely manipulated and possibly be used as an experimental resource. In total, the microwave confinement of electrons that has been demonstrated in this thesis is expected to enable various, wholly new types of experiments with guided, low-energy electrons.

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