

AN ELECTROSTATIC QUADRUPOLE DOUBLET WITH AN INTEGRATED STEERER

Carsten P. Welsch¹, Manfred Grieser, Joachim Ullrich, MPI-K, Heidelberg Germany
Christian Gläßner, IAP, Goethe Universität Frankfurt/Main, Germany

Abstract

Electrostatic storage rings have proven to be a valuable tool for atomic and molecular physics [1], [2]. Due to the mass independence of the electrostatic rigidity, different kinds of ions with the same charge/energy ratio from light protons to very heavy bio molecules can be stored with the same field setup. The transverse dimensions of the circulating beam are controlled by electrostatic quadrupole doublets or triplets. It is essential that the fields in these lenses can be adjusted independently one from another to allow an exact control of the stored ions. In this paper, first an overview of the principle of electrostatic lenses is given. After a short discussion of fringe field effects, the results of field calculations are presented and the final layout of an electrostatic quadrupole doublet with an integrated steerer as it will be used in future electrostatic storage rings in Frankfurt and Heidelberg is discussed.

OVERVIEW

General Remarks

During the last decades, experiments with ions at high energies in magnetic storage rings and at rest in electrostatic traps have contributed substantially to the understanding of complex many particle systems. With the high repetition rates of storage rings combined with the newest imaging techniques, even single particles could be analyzed with great precision.

However, the energy range best suited for many fields like e.g. selective fragmentation of heavy bio molecules could not be covered with these machines. Recently developed electrostatic storage rings demonstrated the advantage of these machines [3] which are a central part of future facilities [4], [5].

The initial divergence of an ion beam in a storage ring automatically leads to a growth of the beam size. If no counteracting forces are applied, the particles soon hit the walls and get lost. In order to control the size of the circulating beam in the transverse dimensions, electrostatic quadrupole lenses can be used.

These elements are always focusing in one transverse plane, while being defocusing in the other one. By combining at least two quadrupoles, an overall focusing effect in both transverse planes can be achieved.

Forces on Charged Particles

If a voltage U_0 is applied to an ideal quadrupole with an aperture radius r_{ap} , the force pushing particles with charge q back towards the design orbit rises linear with the distance r from the design orbit. The equation of motion is that of a harmonic oscillator $r'' \pm k \cdot r = 0$ with

$$k = \frac{q \cdot U_0}{E_{Kin} \cdot r_{ap}^2} \quad (1)$$

The kinetic energy E_{Kin} of the ions therefore directly determines the focusing strength of a quadrupole [6].

The difference between the effects of magnetic and electrostatic quadrupoles on the circulating beam can be seen by comparing the effects of electric and magnetic fields on charged particles:

$$\rho \cdot E = \frac{2 \cdot E_{Kin}}{q} \quad (2)$$

$$\rho \cdot B = \frac{1}{q} \cdot \sqrt{2 \cdot m \cdot E_{Kin}} \quad (3)$$

In the electrostatic case (2), the necessary electric field E to bend a particle with charge q a radius r is proportional to the kinetic energy E_{Kin} , while in a magnet with field B the bending radius is proportional to the square root of the particles' mass m and its kinetic energy. This explains why high energy storage rings solely use magnetic fields to bend and focus ion beams.

However, in the low energy regime, the focusing efficiency of electrostatic lenses is advantageous and relatively low fields have to be used to control the particles. Due to the mass independence of the electrostatic rigidity, even heavy particles can be stored.

Effective Length

In a first approximation, the fields are always assumed to rise and fall abruptly at the entrance and exit of an optical element. However, fringe fields always exist and lead to additional changes in the particles' trajectories. By adding grounded shields at the entrance and exit of a quadrupole doublet, these fringe fields can be minimized, as illustrated in Fig. 1.

¹carsten.welsch@mpi-hd.mpg.de

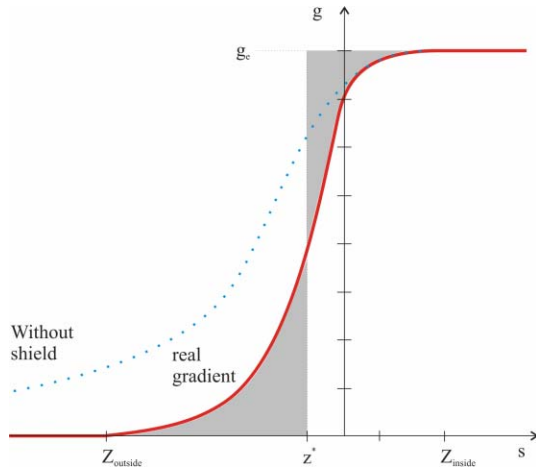


Figure 1: Illustration of the effective field length and fringe field reduction by grounded shields.

The remaining effects by these fields can be expressed by defining the effective length of a quadrupole [8]

$$Z_{eff} = \int_{-\infty}^{\infty} \frac{g}{g_0} ds \quad (2)$$

where g_0 is the gradient in the center of the quadrupole. In other words, one integrates over all gradients along the design orbit s through the quadrupole. The effective length corresponds to the length of an idealized quadrupole, i.e. box potential, with the same focusing effect. Fringe fields can be calculated analytically to high order and their effects can be included in the beam dynamics programs where the layout of the complete storage ring is done. The design parameters of the quadrupole lenses of the future cryogenic storage ring at MPI-K, Heidelberg, are shown in Table 1.

Table 1: Parameters of the CSR quadrupole-steerer combination

Parameter	Value
Electrode length	200mm
Maximum voltages	+/- 10 kV
Aperture radius	50 mm
Distance of shields from quadrupoles	10 mm
Distance between lenses	150 mm
Steerer length	100 mm
Steerer plate distance	120 mm

DECOUPLED LENSES

During operation of a storage ring, it is very important that all the fields in the machine can be adjusted independently. Fig. 2 shows the electric field as calculated with the program MAFIA at 1 cm distance from the central orbit in an electrostatic quadrupole

doublet of 250 mm length. While the voltages in the first quadrupole are kept at 3 kV all the time, the voltages in the second lens start at 3 kV and are increased in steps of 200 V.

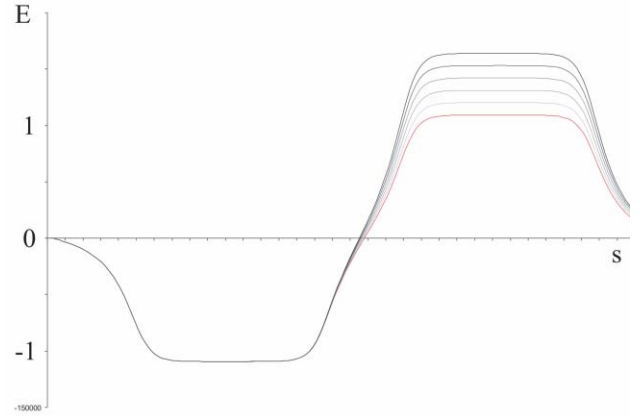


Figure 2: Distribution of electric field (arbitrary units) at $x=10\text{mm}$ from central axis. The voltage on the right lens is increased by steps of 200 V while the voltage on the left quadrupole stays constant at 3 kV.

It can clearly be seen that the intersection with the x -axis and thus the effective length of both lenses changes with an increasing difference in the voltages. This coupling between the two focusing elements leads to unwanted effects during the operation of the storage ring. Changing the voltage in one quadrupole would automatically modify the second lens as well.

To counteract this coupling, grounded shields were installed between the electrodes at a distance of 10 mm. Fig. 3 shows the direct comparison between the calculated fields with and without additional shields.

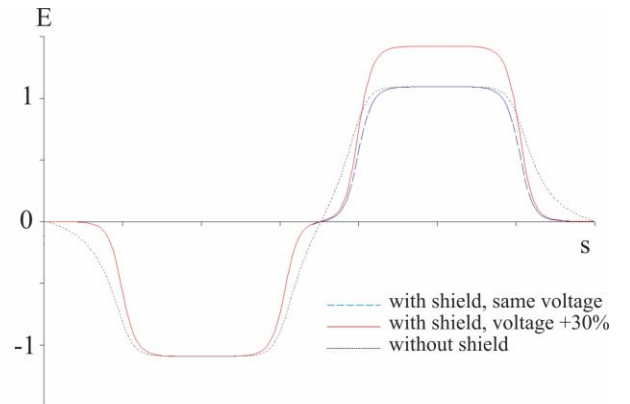


Figure 3: Field distribution (arbitrary units) in an electrostatic quadrupole doublet with and without additional shields.

The fringe fields can clearly be reduced and – more important – the coupling between the two quadrupoles vanishes. Even though the voltage of the right quadrupole was increased +30% compared to the left lens, the field distribution of the latter is not affected.

INTEGRATED STEERER

In addition to the design fields in a storage ring, field errors can never be avoided completely. Either limitations in manufacturing accuracy or positioning inaccuracies change the motion of the stored ions. Therefore, existing electrostatic storage rings use an additional parallel plate deflector to correct these misplacements in the vertical direction. Typically, this element is operated with small voltages in the order of some 10 V and placed in the corner section of the machines. Unfortunately, the corner sections are the regions of highest interest for detecting collision fragments or reaction products. The corrector clearly limits the available space and it would be ideal to place it at a position where it is less disturbing.

Thanks to the grounded shields, the region between the two quadrupole is field free. By separating the lenses a little bit further, there is enough room to fit a steerer within the quadrupole doublet. In the present design, the quadrupoles are separated a distance of 150 mm from each other, with the shields 10 mm away from them. A 100 mm long parallel plate deflector with a distance of 120 mm between the plates is placed between the two focusing elements as shown in Fig. 4.

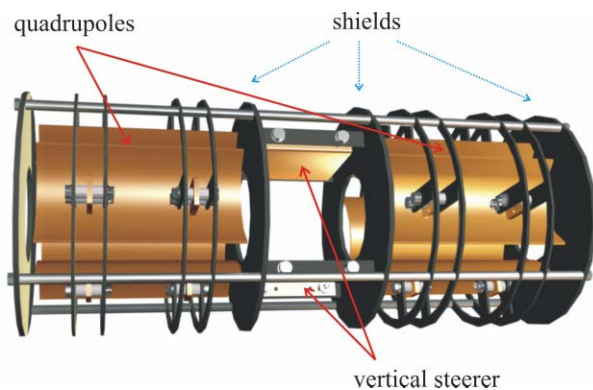


Figure 4: An electrostatic quadrupole with an integrated steerer.

Computations with the program MAFIA showed that even voltages of up to +/- 100 V applied to the steerer do not disturb the field distribution inside the quadrupoles which means that the correction of the ion orbit can be adjusted independently. By changing the voltages on the steerer, unwanted vertical displacements of the beam can be compensated effectively.

CONCLUSION

Besides their application in beam transport sections, electrostatic quadrupoles are used to control the transverse dimensions in electrostatic storage rings. To successfully control the beam, it is very important that the two lenses within a doublet can be adjusted independently. It has been shown that this can be achieved by placing additional grounded shields between the quadrupoles. Adjusting the voltages on one quadrupole in this case no longer affects the effective length of the second.

By placing an additional steerer between the two quadrupoles, a very compact optical element was designed, that allows the insertion of diagnostic elements and detectors in the corner sections. This combined element will be used in the future CSR in Heidelberg [9] as well as in the electrostatic storage ring of FIRE [10] in Frankfurt.

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