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FIRE—the Frankfurt Ion stoRage Experiments

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Abstract

Existing electrostatic storage rings have proven to be a valuable tool for molecular and atomic physics in the low-energy regime. At the new Stern-Gerlach Center of Frankfurt University a small machine for ion energies up to 50 keV will be build up. It will serve as a tool to analyze the structure and dynamics of many particle systems from atoms to complex organic biomolecules. It will be possible to prepare the particle beams of interest in novel and unique ways. In direct comparison to traditional setups, the luminosity of the measurements will be improved by many orders of magnitude.

In combination with the newest reaction microscopes, the *F*rankfurt *I*on sto*R*age *E*xperiments (FIRE) will allow analysis of many particle fragmentation processes of atoms and molecules with unrivaled resolution and completeness. In contrast to experiments with traps, an electrostatic storage ring has the advantage of being able to record the momenta of all neutral fragments.

This paper gives an overview of the design parameters, the optical elements used and the project status.

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1. Overview

1.1. General remarks

Typically operating at energies of some 10 keV, electrostatic rings [1,2] can be seen as a cross between ‘classical’ magnetic rings and electrostatic traps. The difference between a magnetic and an electrostatic storage ring can easily be seen when the field on axis is expanded into a Taylor series

$$\begin{array}{llllll} \frac{q}{p}B_z(x,z,s) & =\frac{q}{p}B_{z0} & +\frac{q}{p}\frac{\mathrm{d}B_z}{\mathrm{d}x}x & +\frac{1}{2!}\frac{q}{p}\frac{\mathrm{d}^2B_z}{\mathrm{d}x^2}x^2 & +\cdots \\ & =\frac{1}{R} & +kx & +\frac{1}{2!}mx^2 & +\cdots \\ & \textit{Dipole} & \textit{Quadrupole} & \textit{Sextupole} & \end{array} \qquad (1)$$

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The different multipoles correspond to the magnetic fields and its derivatives multiplied by the charge over momentum ratio. In the electrostatic case, the same considerations lead to

$$\begin{array}{llll} \frac{q}{mv^2}E_x(x,z,s) & & & \\ = \frac{q}{mv^2}E_{x0} & +\frac{q}{mv^2}\frac{\mathrm{d}E_x}{\mathrm{d}x}x & +\frac{1}{2!}\frac{q}{mv^2}\frac{\mathrm{d}^2E_x}{\mathrm{d}x^2}x^2 & +\cdots \\ = \frac{1}{R} & +kx & +\frac{1}{2!}mx^2 & +\cdots \\ \textit{Dipole} & \textit{Quadrupole} & \textit{Sextupole} & \end{array} \tag{2}$$

In the electrostatic case, the different multipoles are expressed by the electric field and its derivatives multiplied with the charge over energy ratio, i.e. that particle motion is completely independent of the ions' mass.

In other words, different ions from light protons to heavy bio molecules with the same kinetic energy and charge can be stored with identical field setups. This is a clear advantage for experiments—the fields can be adjusted with an intense, well-known beam and then the injection is changed to the weaker beam of interest.

1.2. Project goals

During the last 10 years, research in the fields of traps and storage rings has contributed substantially to the analysis of complex many particle systems. Atoms, molecules and even large bio systems can be prepared in interesting quantum mechanical states and analyzed with high resolution. With high repetition rates, even single objects can be analyzed with great precision.

In order to transfer these advantages to studies of dynamic many particle correlations, an electrostatic storage ring is the ideal tool. In such a machine, molecules can be fragmented and detected by state of the art imaging techniques with high momentum resolution. In a final step, the measurement of dynamic correlations in the 10-attosecond regime can be envisioned. In traps, where ions are controlled by non-linear electric and magnetic fields, such precision measurements are hardly possible. In a storage ring, which can be seen as an infinite trap, measurement of all momenta with highest precision can be done.

During the last 15 years the development of COLTRIMS [3] and multi-fragment imaging techniques [4] was one of the central research fields at IKF, Frankfurt. Based on this experience, an in-ring reaction microscope could greatly improve present experimental resolutions.

2. Ring lattice

In general, the layout principles of an electrostatic storage ring are no different from its magnetic counterparts. In particular, it is not limited to some specific designs. Previous work [5] showed that classical ring shapes can be realized as well as racetrack shaped machines or even double rings [6].

FIRE will use a round machine of roughly 7 × 7 m side length as shown in Fig. 1. The design energy of the machine is 50 keV, which is also the maximum energy of the existing ECR ion source that will be used for first experiments [7].

The envisaged experiments at the new Stern-Gerlach Center at Frankfurt University require good access to the straight sections to be able to merge laser or electron beams with the circulating ion beam. This can be achieved by splitting up the

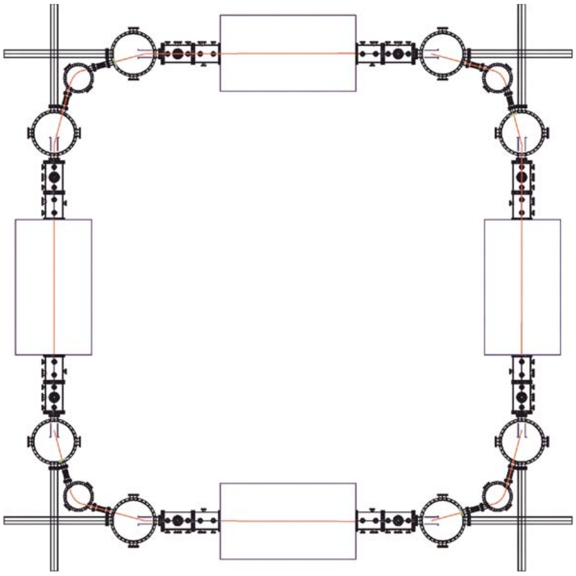

Fig. 1. Overview of the ring of FIRE.

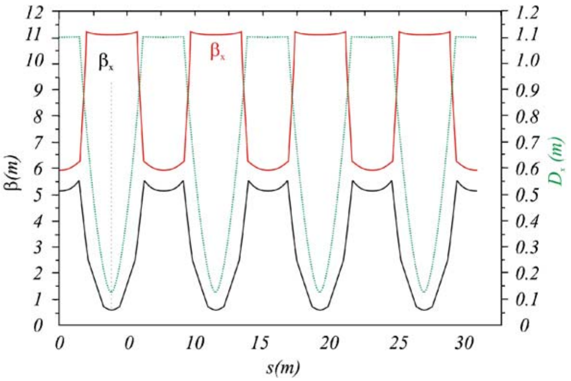

Fig. 2. Calculated lattice functions.

90° bend in the corner sections into two 15° parallel plate deflectors and a 60° cylinder deflector. This layout guarantees easy injection into the machine by pulsing the high voltage of the parallel plate deflector and allows the detection of neutral particles created along the straight sections at the same time.

Transverse focusing of the beam is done with pairs of electrostatic quadrupoles placed at symmetric positions around the machine. A double symmetric lattice was chosen to limit the number of independent voltage supplies and to simplify manufacturing of all the components.

The calculated lattice functions in both transverse planes are shown in Fig. 2.

It should be pointed out that the horizontal beta function β_x is at its minimum value inside the 60° bend, where the mechanical aperture reaches also its minimum, while the beta function is largest in the straight section where larger beams can be handled without a problem. The design parameters of the machine are shown in Table 1.

3. Optical elements

Entirely electrostatic elements are used in the storage ring. Therefore, all of the fields are completely mass-independent and as long as charge state and energy of the beam remain constant, the fields can be left unchanged, no matter which kind of ions are stored. Furthermore, spin polarized or otherwise prepared beams will not be affected by the rings' fields.

Table 1
Machine parameter

Maximum energy	50 keV
Circumference	30.68 m
Length of straight sections	2 m
Injection	Single turn
$\beta_{x,\max}$	5.53 m
$\beta_{y,\max}$	11.22 m
Q_x	2.91
Q_y	0.51

3.1. Parallel plate deflector

Parallel plate deflectors will be used for injection and beam bending. The ions follow a parabolar trajectory in this element and the maximum bending angle depends on the plate distance d, electrode length l and achievable fields.

$$\alpha = \arctan\left(\frac{qUl}{E_{Kin}\, d}\right). \tag{3}$$

In order to reach a good angular resolution, it was decided to put the 200 mm long electrodes at a distance of 100 mm. The maximum voltages for a beam of 50 keV will be ±6.5 kV.

In collision experiments along the straight sections of the storage ring, fragmentation of heavy molecules might occur and it is of particular interest to not only detect the neutral particles at the end of the straights, but also light particles created. If one assumes that all fragments keep their initial longitudinal velocity, the energy of the fragments scales with their mass ratio. An ideal particle will still pass the quadrupoles in their center and will not suffer addition deflection, but the bending angle in the parallel plate deflector will be increased drastically. As a result, the light fragments will hit the deflector plates and get lost.

Therefore, earlier designs were changed and a central mesh of 80 mm height was integrated in the plates as shown in Fig. 3. The design parameters of the electrostatic parallel plate deflector are shown in Table 2.

3.2. Cylinder deflector

The main bending will be done in a 60° cylinder deflector placed in each of the corner sections

Fig. 3. 15° Parallel plate deflector with central mesh.

of central radius r_C. The potential distribution between the plates at radius R_1, R_2 is given by

$$\varphi(\rho) = \int_{R_1}^{\rho} \frac{2U_0}{\ln(\frac{R_2}{R_1})} \frac{1}{\rho} \mathrm{d}\rho = \frac{2U_0}{\ln(\frac{R_2}{R_1})} \ln\left(\frac{\rho}{R_1}\right) + C. \quad (4)$$

The equation of motion can be determined directly by writing down the Lagrange function and applying Euler–Lagrange equations

$$\begin{aligned} L &= E_{Kin} - E_{Pot} = \tfrac{1}{2}mv^2 - q\varphi(\rho) \\ &= \frac{m}{2}\left[\left(\frac{\mathrm{d}\rho}{\mathrm{d}t}\right)^2 + \rho^2\theta^2 + \left(\frac{\mathrm{d}z}{\mathrm{d}t}\right)^2\right] \\ &\quad - \frac{2qU_0}{\ln(\frac{R_2}{R_1})} \ln\left(\frac{\rho}{R_1}\right) + U_0, \end{aligned} \quad (5)$$

$$\frac{\mathrm{d}^2 r}{\mathrm{d}s^2} + \frac{2}{R_0^2} r = 0. \quad (6)$$

Table 2
Design parameters of the electrostatic parallel plate deflector

Electrode height	160 mm
Electrode length	200 mm
Plate distance	100 mm
Mesh height	80 mm
Design angle	15°
Max. voltage	±6.5 kV

Table 3
Design parameters of the 60° electrostatic cylinder deflector

Electrode height	100 mm
Central radius	250 mm
Plate distance	30 mm
Shield distance	10 mm
Design angle	60°
Max. voltage	±6.0 kV

While the vertical motion corresponds to that of a field free drift region, the equation of motion (linear approximation) in the horizontal plane is that of a harmonic oscillator. This focusing helps to minimize the beam dimensions inside the cylinder deflector, where the mechanical aperture is smallest.

The cylinder deflectors' parameters as it will be used in the Frankfurt storage ring are summarized in Table 3.

3.3. Quadrupole doublets

Since quadrupole lenses are always focusing in one transverse plane, while being defocusing in the other, at least two of them have to be used together to achieve an overall focusing effect. The ideal hyperbolic surface of the electrodes is approximated by cylindrical electrodes of $r = 1.147 r_{\mathrm{Aperture}}$.

In contrast to existing designs, the two lenses are completely decoupled by grounded shields placed at the entrance and exit of the element as well as between the two quadrupoles. This allows independent control of each focusing element. Furthermore, it gives the possibility to insert a small vertical steerer for closed orbit correction between the lenses. Fig. 4 shows the doublet with an integrated steerer as it will be used in the Frankfurt electrostatic ring.

The quadrupoles allow a very flexible handling of the beam. Depending on the experimental requirements, a strongly focussed or parallel beam in the experimental region can be achieved. Different stable working points for the operating modes exist.

Fig. 4. Electrostatic quadrupole doublet with an integrated steerer as it will be used in the Frankfurt ion storage ring.

The design parameters of the quadrupole doublets are given in Table 4.

4. Diagnostic elements and control system

Mechanical scrapers and electrostatic pick-ups are the main diagnostic elements used in the storage ring. The beam position and intensity can be recorded non-destructively and gives a clear idea about the lifetime and longitudinal behavior of the stored beam. In addition, single particle detectors at the end of the straight sections and around the bending elements are used to detect neutral particles created and collision fragments.

External and in-ring experiments will have their own diagnostic and complement these elements.

A LabView based Group3 system was developed to control all voltages, diagnostic elements and the injection into the machine. Hardware requirements are rather low and the system can be easily adjusted and new modules added. At present, all necessary components have been integrated and successfully tested [8].

Table 4
Design parameters of the electrostatic quadrupole doublet with an integrated steerer

Electrode length	100 mm
Maximum voltages	±3 kV
Aperture radius	25 mm
Distance of shields from quadrupoles	10 mm
Distance between lenses	90 mm
Steerer length	50 mm
Steerer plate distance	60 mm

5. Status and outlook

Since the requirements of a storage ring are completely different from earlier work at IAP and IKF, a quarter ring section was built up at IAP to test all necessary components. All optical and diagnostic elements were designed and manufactured as prototypes, the layout of the control and vacuum system was finished and all components were integrated recently. Vacuum measurements are ongoing and a first test beam is expected until summer 2004.

The next steps will be to build up the vacuum system of the complete machine in parallel to the injection channel and first experiments. The ring of FIRE will allow novel experiments in atomic, nuclear and molecular physics and will take a central role on the Stern-Gerlach Center.

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