DESIGN STUDIES ON A NOVELL STELLARATOR TYPE HIGH CURRENT ION STORAGE RING

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Abstract

A high current storage ring for the accumulation of ion beams provided by a new 150 kV terminal is under investigation at Frankfurt University. The configuration based on a toroidal magnetic field looks promising for the storage of intense low energy ion beams, especially when concerning the various potential concepts for space charge compensation.

The theory of thermal and applied plasma confinement on magnetic surfaces is translated to numerical simulations on circulating ion beams. The space charge effects and stability conditions are studied and will be presented.

Various injection techniques based on crossed field-drifts are investigated. Accordingly test experiments are prepared based on two 30 degree toroidal sectors at a major radius of 1.3m with a maximum toroidal on axis magnetic field of 0.6T.

INTRODUCTION

In the previous paper[1] the idea of a novel type high current ion storage ring was presented. Here the longitudinal magnetic field is considered as a main focusing force with the possibility of confining both stored ions as well as space charge compensating electrons.

Various scenarios can be tested: Circulating e-beams against trapped compensation electrons. One main difficulty to be overcome are the FxB drifts. For drift compensation the structure is folded in a figure-8 like form, which could be realised with identical toroidal sectors and with solenoids, which provide straight sections. Single particle motions showed to be quite robust in such an array[1].

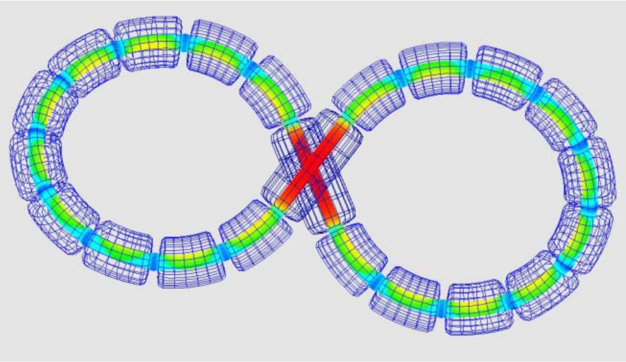

Figure 1.: Schematic view of the ring structure built by identical toroidal and solenoidal sectors. Colour coding on the folded surface inside gives the B-field profile.

Due to the 3D-geometry of the ring (conventional rings are designed in a 2D-plane) and to the occurrence of torsion, the magnetic field lines aren’t simply closed. They lie on the folded surfaces and make along the ring circumference the poloidal rotation ι (ratio of poloidal/toroidal turns ~ 0.2-0.6, ι ~ 4α, where α is a slope of the bending section according to the horizontal plane). In some respects the situation is similar to plasma physics but there are also characteristic differences.

The energy (W_i ~ 150keV) is stored in ions mainly and not in electrons. The proposed beam currents (around 10A) are by far less compared to plasma currents (> 10kA) in tokamaks and stellarators. Therefore self induced magnetic fields (Eq. 1, at an assumed beam radius a ~ 0.02m) are very small and don’t disturb the rotational transformation coming from external coils (B_{ext} ~ 5T, for the envisaged ring).

$$B_{self} = \frac{\mu_0 I}{2\pi a} = 10^{-4}\mathrm{T}. \qquad (1)$$

This kind of instabilities common in plasma physics will not appear.

On the other side the influence of mirror charges by high charge densities ($n \sim 10^{16}\ \mathrm{m}^{-3}$) combined with the ExB drift could lead to the diocotron-type[2] instability.

The Brillouin flow current limit is given by (Eq. 2)

$$n_B = \frac{\varepsilon_0 B^2}{2m} \sim 10^{16}\,\mathrm{m}^{-3}. \qquad (2)$$

In the low density limit, where parallel motion dominates over diocotron perpendicular dynamics ($\tau_\perp/\tau_\parallel = 2\pi a/(E/B)/2\pi R/(\iota v) >> 1$) this instability will not appear. To avoid the same instability in the high density limit the hollowness of the beam as well as the beam temperature (possibility of spatial Landau damping) must be controlled.

The collective behaviour of the beam with compensating particles will be studied with the in house developed codes running on the parallel computing cluster of the Center for Scientific Computing (CSC), Frankfurt University.

DESIGN CODES

To study the mentioned effects a set of codes was developed and implemented on the CSC parallel cluster with 64 Opteron processors. First of all the magnetic field is mapped in a special manner through the whole structure.

After this the magnetic coordinate system (Ψ - toroidal flux enclosed by surface and actual radial coordinate, θ - poloidal angle, ξ - toroidal angle) is calculated through Fourier transformation and decomposition of the space frequencies. The decomposition of the high frequency cyclotron oscillation from the particle motion is necessary.

Also the metric coefficients for Poisson solver are calculated. A FDTD symplectic solver with drift approximation is used to calculate the new position of the particles in given fields and coordinate system.

Here up to 10^7 macro particles of different species are possible. 10 processors are used for the Poisson solver, with 20x60x100 mesh points each. In every step the boundary data are exchanged and the potential profile is solved by an iteration method (BiCGSTAB – Bi-Conjugate Gradient Method – Stabilized). To save computational memory the sparse matrix format is used.

At present the code is tested and prepared for the first studies.

THE INJECTION STUDIES

One of the major tasks is to inject ions efficiently into the magnetic ring. Entering into a magnetic field region causes reflection and distortion at fringing fields.

Taking advantage of drift motions in curved fields and crossed electro-magnetic fields is the injection strategy under investigation.

The proposed experimental setup is shown in the following block diagram (Fig.2). The auxiliary field helps to provide homogenous curved magnetic field lines used for beam injection.

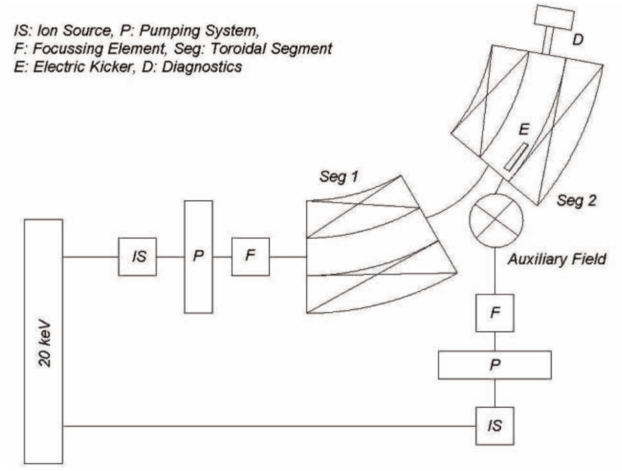

Figure 2: Block diagram for the experimental setup. IS: Ion Source, P: Pumping Element, F: Focusing Element, Seg: Toroidal Segments, E: Electric kicker, D: Diagnostics.

The parameters for the test experiment are given in the table 1.

Table 1: Parameters for test setup

Quantity	Value
Magnetic field (B_{tor})	0.6 Tesla
Energy	20 keV
Major radius of Toroidal Segments	1300 mm
Minor radius of Toroidal Segments	100 mm

The dynamics of charged particle beams in a magnetic field is simply described by the Lorentz force equation

$$\frac{d\vec{r}_i}{dt} = v_i ; \frac{d(m\vec{v}_i)}{dt} = q(\vec{E} + \vec{v}_i \times \vec{B}) \quad (3)$$

The electric field consists of external plus the self fields simulated by a PIC code.

To enter the magnetic field we make use of a curved auxiliary magnetic field. The curved magnetic field causes the drift velocity given by

$$\vec{v}_R = \frac{1}{q}\frac{\vec{R}\times\vec{B}}{B^2} \quad (4)$$

where $\vec{R}$ is the radius vector describing the curvature of the magnetic field lines.

It is obvious that magnetic field lines leaving the torus ring would cause particle losses of the circulating beam. In the proposed scheme the reversed process is used for particle injection.

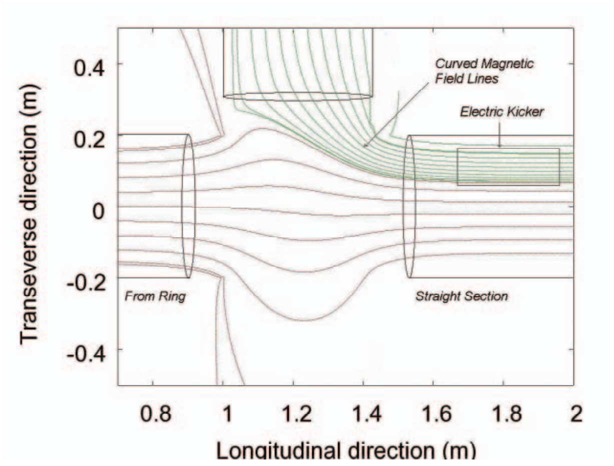

Figure 3: Field lines near injection section.

By installing an auxiliary magnet we can create a curved field region with field lines entering into the main ring aperture. Successively, by an electric kicker installed within the main ring aperture a transfer to the original magnetic ring field is achieved

The angle of injection depends on the ratio of the auxiliary field to the main toroidal field. This is shown in the following graph (Fig. 4).

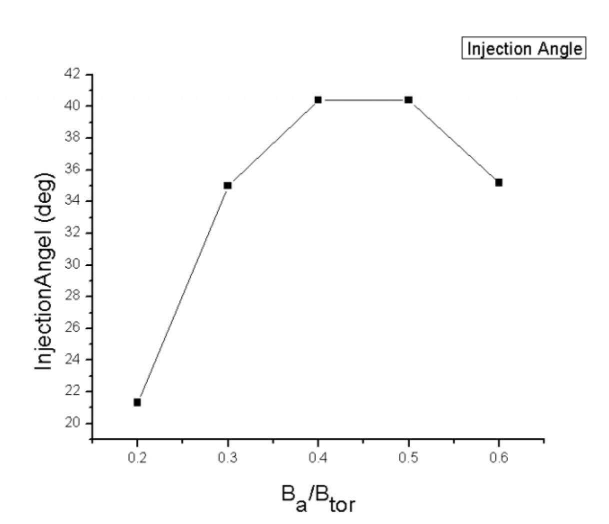

Figure 4: Injection angle with respect to the horizontal plane depending on the auxiliary field strength B_a.

The electric kicker will be used to move the injected beam from the auxiliary field lines to the main (ring) field lines by the crossed electromagnetic drift (ExB drift).

In external magnetic fields the equation (3) leads to a drift velocity

$$\vec{v}_E = \frac{\vec{E}\times\vec{B}}{B^2} \tag{5}$$

which is charge independent, so that the displacement can be controlled by solely the external electric field for a given magnetic field.

At a beam energy of 20keV and in a magnetic field of 1Tesla a deflection of 0.07m with an electric field of E=10kV/cm can be achieved within a plate length of 0.14m.

The following figure (Fig. 5) shows an example of beam displacement after passage of 12 turns along solenoidal magnetic channel.

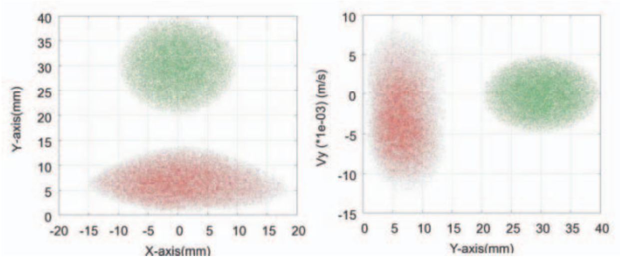

Figure 5: X-Y plane on left, Y-Vy on right (Green is input whereas red is deflected beam).

The effect of the auxiliary field and of the kicker on the ring beam is being simulated and will be tested experimentally also. The test setup is funded. Main components are under construction.

CONCLUSION AND OUTLOOK

Design studies on the high current storage ring at Frankfurt University are presented. Multi particle, multi species PIC codes are prepared and tested.

The experiments on toroidal segments will start end of this year, which will test the reliability of the simulation codes. Our experimental and numerical studies will be concentrated on beam injection and space charge compensation mainly.

REFERENCES

[1] M. Droba, et. al., “High Current Ion Beams at Frankfurt University”, EPAC’04, Lucerne, July 2004, p. 1198, http://www.jacow.org.

[2] S. N. Bhattacharyya , “The diocotron spectrum of a toroidal non-neutral plasma”, Phys. of Plasmas, December 2000, Vol. 7, 12, pp. 4805-4811.