

BEAM ACCUMULATION IN A STELLARATOR TYPE STORAGE RING

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Abstract

The stellarator-type storage ring for multi- Ampere proton and ion beams with energies in the range of 100 AkeV to 1AMeV was designed. The main idea for beam confinement with high transversal momentum acceptance was presented in EPAC06 [1] and EPAC08. Stable beam transport in opposite direction is possible through the same aperture with two crossing points along the structure. Elsewhere the beams are separated by the $R \times B$ drift motion in curved sections. The space charge compensation through the trapped or circulated electrons will be discussed. This ring is typically suited for experiments in plasma physics and nuclear astrophysics. Here we present the complete simulations for optimization of ring geometry, a stable beam confinement and developments in injection system.

INTRODUCTION

At Frankfurt University a storage ring for low energy high current density ion beams is proposed. A main longitudinal magnetic field component will provide quite homogenous transverse beam focusing conditions along the whole structure. The main advantage of a stellarator type ring against the traditional one is the higher transverse momentum acceptance which opens a possibility to accumulate high beam currents. The maximum density of confined particles depends on the focusing magnetic field and is given by the Brillouin flow density limit (Fig. 1).

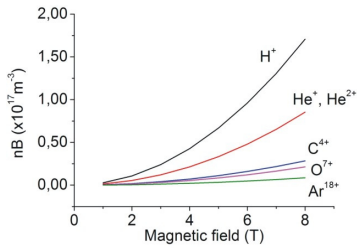


Figure 1: Brillouin flow density limit.

The maximum proton beam density $n=10^{17} \text{ m}^{-3}$ at a beam energy $W \sim 150 \text{ keV}$ confined by a magnetic field $B \sim 6 \text{ T}$ corresponds to the current density $j=8 \cdot 10^4 \text{ A m}^{-2}$. Assuming a beam radius $r \sim 0.01 \text{ m}$, the stored beam current will be 25 A .

Moreover, a stable beam transport in opposite direction is possible through the same aperture. Due to the sections with curved magnetic fields the beam will experience the $R \times B$ drift. To overcome this instability the figure-8 configuration was adopted in Frankfurt. The opposite $R \times B$ drifts along both loops will cancel each other. Additionally, the closed magnetic flux surfaces are

provided at the same time, which improve the particle confinement. The main limitation is the beam drift in a first half of the storage ring, which is proportional to the ratio of the curvature drift to the longitudinal velocity. Scaling properties of the ratio for the different charge states and different species are shown on Fig. 2. Design values are denoted by a dashed line.

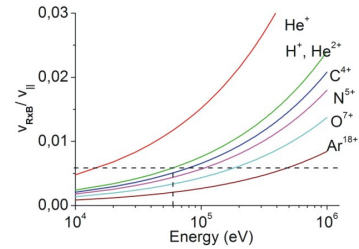


Figure 2: Ratio of the curvature drift velocity to the longitudinal velocity as a function of beam energy, at $B=6 \text{ T}$, $R=1 \text{ m}$.

NUMERICAL SIMULATION

For the long term numerical simulation of the charged particle motion in curved magnetic fields, it is convenient to introduce the so called magnetic flux coordinate system. It helps to overcome high frequency particle gyration by the use of the guiding centre method. Important role is played here by a magnetic scalar potential $\chi = \int \vec{B} \cdot d\vec{l}$, where the integration path follows magnetic field lines. The magnetic flux ψ is used as a radial coordinate and $\alpha \in [0,1]$ as a poloidal coordinate in a transversal plane (Fig. 3). Magnetic field at the position (ψ, α, χ) can be expressed in a contravariant form as

$$\vec{B} = \vec{\nabla} \alpha \times \vec{\nabla} \psi \quad (1)$$

and in covariant form as

$$\vec{B} = \vec{\nabla} \chi \quad (2)$$

For better and useful description geometrical coordinate system (ψ_N, θ, ξ) is also involved (Fig. 4). Here, $(\theta, \xi) \in [0, 2\pi]$ are poloidal and toroidal angle respectively. $\psi_N \in [0,1]$ is normalized flux in our case defined as $\psi_N = \psi / \psi_{\max}$, where $\psi_{\max}$ is flux enclosed by the last outer magnetic flux surface.

Dependence between these two curved orthogonal coordinate systems can be expressed for longitudinal coordinate by

$$\chi = g \cdot \xi, \quad (3)$$

where g is a constant proportional to the poloidal current in the external coils. Relation between the poloidal coordinates is expressed by equation

$$2\pi\alpha = (\theta - \iota\xi), \quad (4)$$

where ι denotes a poloidal helical twist of field lines along the geometrical path.

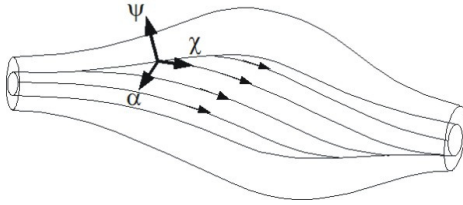


Figure 3: Magnetic flux coordinates.

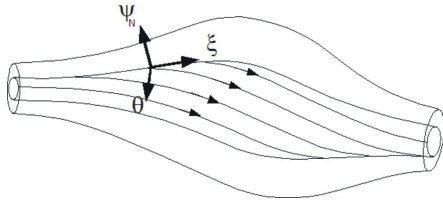


Figure 4: Geometrical coordinate system.

Construction of the numerical mesh and mapping of important parameters to the mesh points is done generally in two steps. First the magnetic potential χ is calculated along the magnetic field line and is used as a longitudinal coordinate. The magnetic field is numerically integrated from a given coil setting in a global Cartesian coordinate system through Biot-Savart formula. The position (x, y, z) and magnetic field are stored along the field line in terms of $d\chi$. Consequently the stored data are decomposed through the FFT (Fast Fourier Transformation) to the 1D frequency space.

Here, two main frequencies responsible for poloidal and toroidal rotation are identified and set as a new 2D orthogonal basis. The main mesh, which is identical with a magnetic flux surface, is calculated from stored positions by the use of 2D backward FFT.

Particle-in-cell (PIC) code was written to represent particle density on mesh points and space charge forces between the macroparticles. Electric potential is solved numerically on mesh using iteration method BiCGSTAB (Bi-Conjugate Gradient Stabilized method). Whole simulation code was implemented on parallel cluster of CSC (Center for Scientific Computation Frankfurt) and typically 32 processors are used. The particle motion of the guiding centre is given by Drift Hamiltonian and the

derived equations of motion [2], which are transformed to the numerical approach. An example of simulation results are shown on Fig. 5.

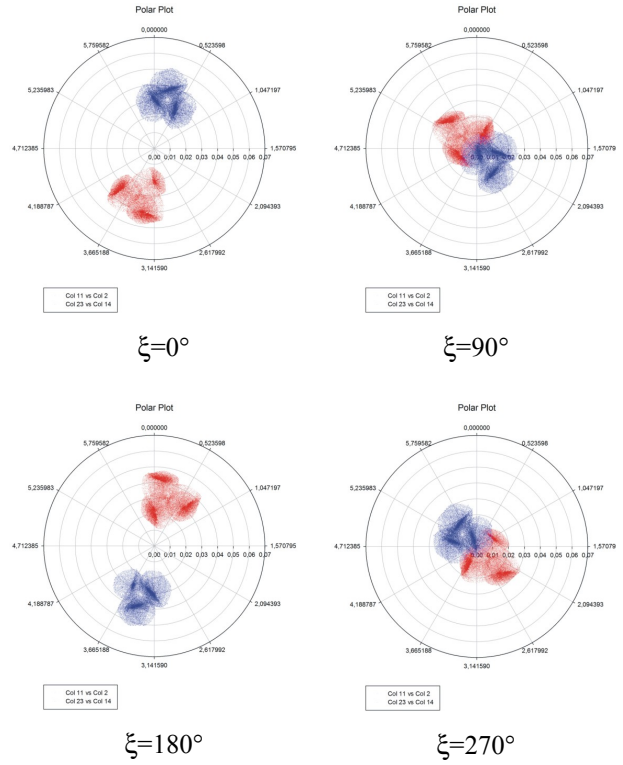


Figure 5: Clockwise (red) and anticlockwise (blue) moving beams in 4 cross sectional areas of the *figure-8* storage ring. Three revolutions of the particle beams at low current condition around the structure are shown.

The $\xi=0^\circ$ and $\xi=180^\circ$ are positions defined at the crossover of the *figure-8* structure. At $\xi=90^\circ$ and $\xi=270^\circ$ are the beams overlapping and this interesting areas in the middle of the loops were chosen for experiments.

DESIGN ASPECTS

The Frankfurt approach is based on the *figure-8* shape geometry. It is optimized with respect to the beam dynamics and to the technical design requirements. Main parameters are written in Tab.1.

Table 1: *Figure-8* Specifications

Parameter	
Bending Radius R	1000 mm
Aperture d	200 mm
Crossover vertical distance h	1500 mm
Magnetic field B	5-7 T
Length of straight sectors L	1600 mm
Rotational transformation ι	0.33-0.25
Beam energy (protons)	150 keV

In accordance with the recent simulation results new experimental straight sectors were designed at $\xi=90^\circ$ and $\xi=270^\circ$ positions (Fig. 6).

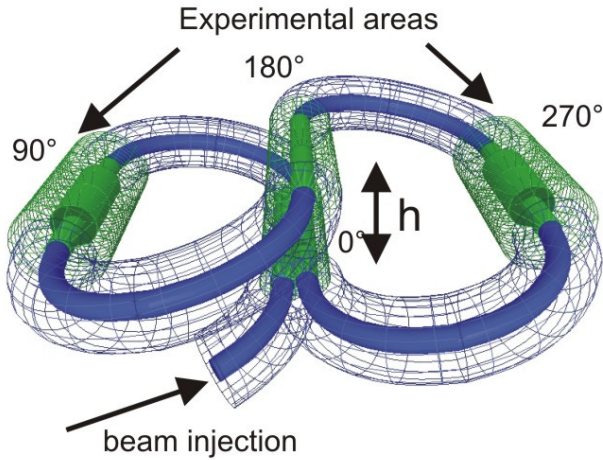


Figure 6: Figure-8 storage ring with new experimental areas.

The toroidal and the solenoidal sectors provide at the same time transverse beam focusing, bending force and rotational transform of the magnetic field lines. The distance between two segments with the related longitudinal field drop is optimized for an acceptable effect on beam transport. Some space for access to the beam is needed which is mainly defined by the envisaged beam diagnostics and experiments. Correction coils of circular shape were designed at special positions to minimize the on axis field variation. The positive effect of correction coils is shown in Fig.7.

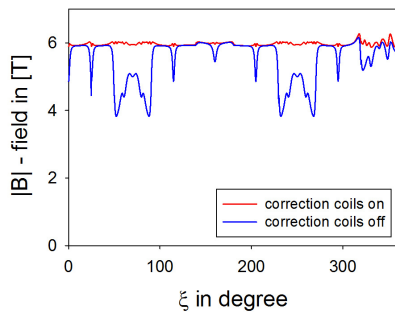


Figure 7: Magnetic field variation with correction coils switched on (red), and off (blue) along the geometrical axis.

The straight sections are designed to provide some flexibility (Fig. 8). The coils with larger aperture (coils with aperture $2d$) can be moved along the beam axis for better access during the installations of experimental setup.

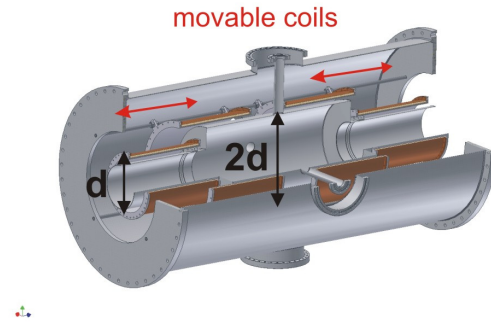


Figure 8: Experimental area with coil settings and cryostat design.

Tuning of the magnetic flux structure and the beam orbit correction can be provided by axial solenoid positioning and by variable external current levels at all bents. Different magnetic settings can be tested especially magnetic bottle, or as an extreme case a field reversed configuration. The additional confinement of the trapped electrons is numerically studied and will be investigated experimentally in the future.

The first sector at $\xi=0^\circ$ will be used for beam injection. A special injection technique is required to reach the acceptance area of the ring while not perturbing the magnetic field. An optimized magnetic channel is designed to bring the injected beam close enough to the magnetic ring flux. Finally, an $\mathbf{ExB}$ kicker is needed to move the injected beam from the injection channel to the main magnetic field lines. At a longitudinal magnetic field of 5 T , an electric field of about 2 MV/m is required over the distance of 1.4 m for a proton beam at 150 keV . The kinetic energy of the injected beam at the input and output of the kicker system is conserved but the transversal momentum spread increases if kicker fields, geometry and injection energy are mismatched.

OUTLOOK

The figure-8 storage ring will be suited for experiments in plasma physics and nuclear astrophysics. Two 30° room temperature toroidal magnets have been constructed and beam transport experiments have been started [3] with the aim to develop multi-turn beam injection schemes and to compare the beam measurements with simulation results.

REFERENCES

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