Abstract
The stellarator-type storage ring for multi-Ampere proton and ion beams with energies in the range of 100 kkeV to 1 AMeV 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 RxB 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).

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 $\chi = \int \nabla \cdot \vec{B} \cdot dl$, where the integration path follows magnetic field lines. The magnetic flux $\psi$ 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 $(\psi, \alpha, \chi)$ can be expressed in a contravariant form as

$$\vec{B} = \nabla \alpha \times \nabla \psi$$

and in covariant form as

$$\vec{B} = \nabla \chi$$

For better and useful description geometrical coordinate system $(\psi_n, \theta, \xi)$ 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

\[ \chi = g \cdot \xi, \]  

(3)

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

\[ 2\pi\alpha = (\theta - t\xi), \]  

(4)

where \( t \) 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 \( \chi \) 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.

![Beam Dynamics and Electromagnetic Fields](image-url)

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>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending Radius R</td>
<td>1000 mm</td>
</tr>
<tr>
<td>Aperture d</td>
<td>200 mm</td>
</tr>
<tr>
<td>Crossover vertical distance h</td>
<td>1500 mm</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>5-7 T</td>
</tr>
<tr>
<td>Length of straight sectors L</td>
<td>1600 mm</td>
</tr>
<tr>
<td>Rotational transformation t</td>
<td>0.33-0.25</td>
</tr>
<tr>
<td>Beam energy (protons)</td>
<td>150 keV</td>
</tr>
</tbody>
</table>
In accordance with the recent simulation results new experimental straight sectors were designed at ξ=90° and ξ=270° positions (Fig. 6).

The toroidal and the solenoidal sectors provide at the same time transverse beam focusing, bending force and rotational transform ι 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.

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.

**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**