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# SIMULATION STUDIES OF THE PARTICLE DYNAMIC IN BEAM: INTERNAL TARGET AND BEAM-BEAM INTERACTIONS IN THE FIGURE-8 STORAGE RING(F8SR)

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*Abstract*

The Figure-8 storage ring (F8SR) concept for fusion reaction research in context of astrophysics is under development at Frankfurt University. In contrast to traditional storage rings, a guiding longitudinal magnetic field is used for confinement of very low energy charged particle beams continuously with high transverse momentum acceptance. Due to the strong magnetic field level (B=6 T), low energy proton and ion beams (W < 1MeV) of several amperes can be confined. Many characteristic and unique features (e.g. injection system, collider mode) and key components were developed in the past. The current developments are concentrated on the design of a beam-target area and detectors. Particle-in-cell (PIC) simulation of high current beam propagation through a target area and interaction with an internal gas target will be presented and discussed. Possible space charge compensation through confined electrons will be assessed. Investigation of the large target area for colliding beam mode will be presented and discussed as well.

## INTRODUCTION

The Figure-8 storage ring (F8SR) (Fig.1) uses a concept of the charge particle confinement in a guiding longitudinal magnetic field of 6-7T. The 3D-geometry of an array of solenoidal coils creates a true 3D-trap for charged particles and it is known from Project *Matterhorn* under the name *Stellarator* [1, 2].

Comparing with the closed plasma fusion device, we introduced very similar confinement structure with an injection channel for high current beams. Objectives are to study transition of the ion beam into the non-neutral plasma state through the collision on target atoms and ions, fusion cross sections measurement and investigation of space charge compensation and electron screening effects. Ions are carrier of the energy alone from an initial state and not the electrons. This means, that electric proton current is relative negligible (~10A, in this non-relativistic case) comparing with the electron currents in plasma fusion devices (kA range).

Because of a larger momentum of ions, the beam drifts in the vertical axis up and down in toroidal bends (centripetal force RxB and B-gradient drifts). Beam momentum causes also a shift of the closed orbit away from the magnetic axis and magnetic surfaces, as demonstrated in Fig. 2. Co-moving (parallel with magnetic field) and counter-moving beams separates their orbits in bends and straight sectors Ix and Da (see Fig.1), while overlaps and crossing in experimental areas Ex-1 and Ex-2, schematically shown in Fig. 3.

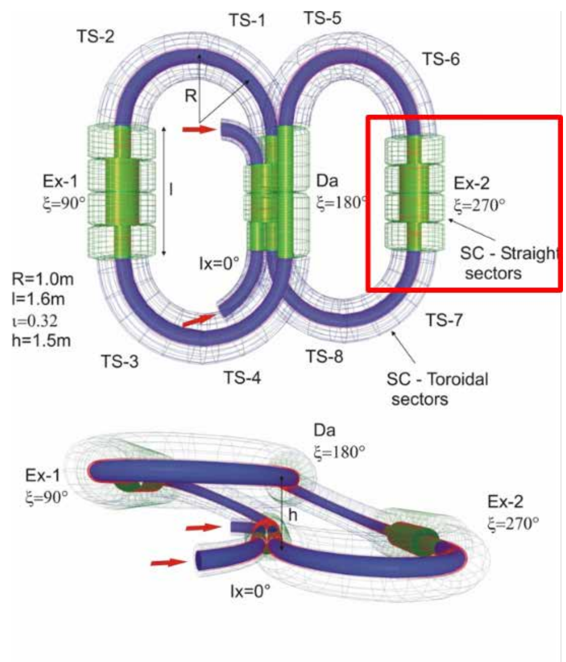


Figure 1: Proposed Figure-8 storage ring for low energy high current ion beams [3,4]. Experimental area of interest is depicted by red square.

An injection system consisting of an adiabatic magnetic channel, ExB kicker system, and corrector coils, were developed and investigated theoretically and experimentally in the past [3, 4]. Now, it is important to balance the momentum transfer and momentum spread of the intense ion beam caused by interaction within dedicated experimental area of the ring.

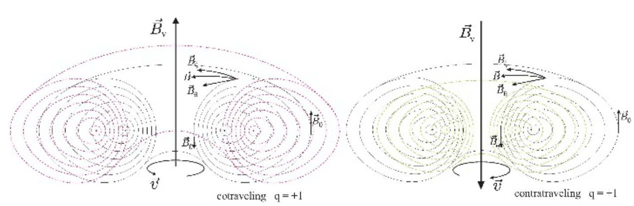


Figure 2: Momentum surfaces for co-traveling and contra-traveling particles [3, 4]

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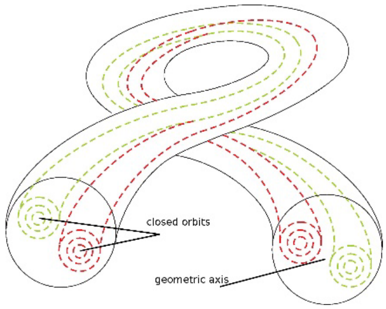


Figure 3: Momentum surfaces for co-traveling and contra-traveling particles. [3, 4]

## SIMULATION

Cylindrical 3D-PIC multi-particle tracking code was written in C++ and implemented on the FUCHS cluster of Goethe University, Frankfurt/Main, Germany [5]. Magnetic field was calculated separately with Biot-Savart solver from a given solenoidal coil configuration. Result is shown in the Fig 4 for the area of interest (Ex-2 section of the F8SR) Magnetic field vary from 6T in the main ring to the 3.5T in the experimental area and constitutes therefore so called magnetic bottle. The length of the interaction region is approximately L=1.6m in this simulation.

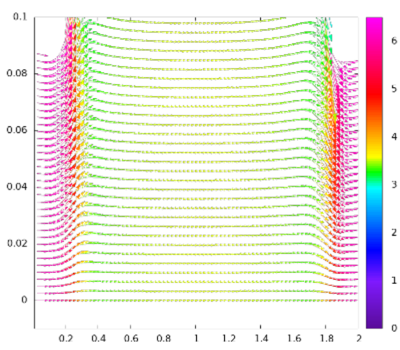


Figure 4: Magnetic field configuration used by proton beam tracking simulation.

Computational cylindrical grid (with overall number of knots $N_r$=85, $N_\theta$=65, $N_z$=2250) was distributed on 15 processors and electric field was calculated by global BiCGSTAB iteration method. Steps in radial and longitudinal direction were chosen to be of dr=0.0024 m, dz=0.001 m.

First studies were concentrated on the proton beam tracking simulation through the experimental area without collision. Particles were redeployed after passing whole area on the beginning at z=0. Initial kinetic energy was set W=150 keV, beam current I=1A, radius of the beam r=0.01m and momentum spread Δp/p ±10%. Ground potential was set at r=0.1m for the ring and r=0.2 m in the experimental area. Calculated beam potential reached 14kV level as showed in Fig. 5. The maximum ExB drift velocity is then E/B=$2\cdot10^5$ m/s, which is on 5% level of the longitudinal velocity. No particles reflection was observed.

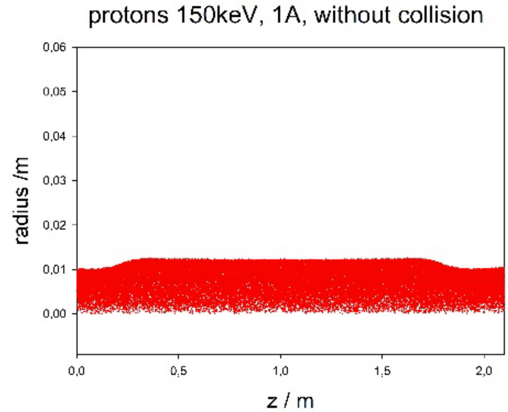


Figure 5: Proton beam distribution at Δt=0.8 μs. There was no observation of the reflected particles.

Collisional transport is depicted in Fig. 6. Neutral target gas density n=$10^{19}$ $m^3$ was assumed in simulation. Homogenous elastic scattering without back-scattering was set for the first investigation for simplicity and easier evaluation of reflection properties of the magnetic bottle. Creation of the halo distribution can be observed in approximately r=0.04 m radius.

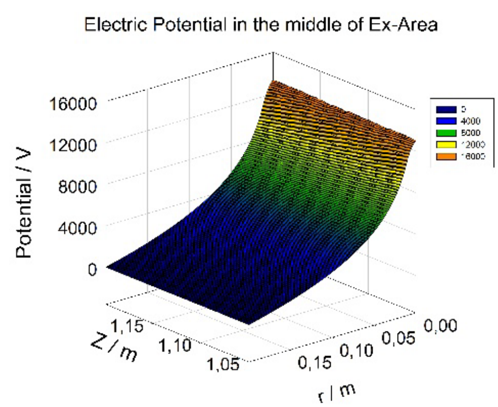


Figure 6: Calculated beam potential for I=1A, 150 keV proton beam

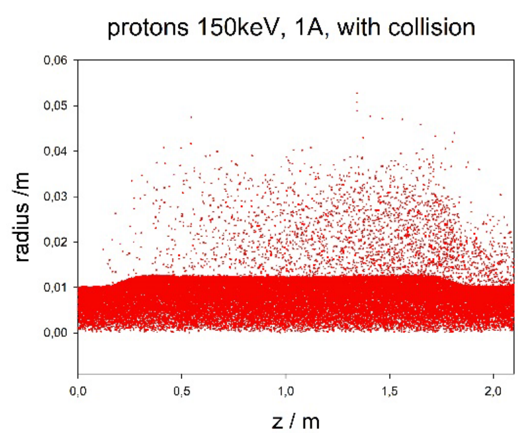


Figure 6: Proton beam distribution at Δt=0.8μs in collisional transport. Reflected particles are observed.

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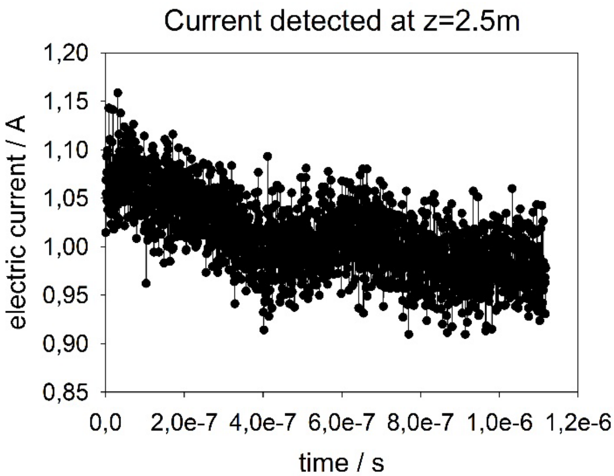


Figure 7: Electric current detected at z=2.5m dependent on simulation time.

Electric current was detected at the end of the experimental area at z=2.5 m and signal for collisional transport is showed in Fig. 7. Slow decreasing in the electric current is demonstrated in 1 μs, which is equivalent to the trapping efficiency of the magnetic bottle and diffusion current.

## CONCLUSION

F8SR will be stellarator-like storage ring for ultra-high intensity ion beams. In the case of protons, the beam energy is adjustable between 100-500 keV. Because of the closed confinement it enables the possibility to study cross sections for neutron-free fusion reactions. Experimental areas are planned for beam-beam interaction or beam interaction with internal gas or plasma targets.

For the simulation of momentum transfer the null momentum method was used [6]. The scattering angle was adjusted to be homogenous and back-scattering was disabled. This strategy was chosen to evaluate the longitudinal momentum of those particles, trapped in the Experimental area due to the magnetic bottle configuration. The momentum spread of the beam increases from 10% at the entrance to 45% downstream of the experimental area. The life-time of the beam is affected by transversal diffusion driven by the momentum spread. Therefore, future studies are planned to investigate beam dynamics with statistical increase of intrinsic momenta.

The particles captured in the experimental area are the reason for a transverse diffusion current, which lead to an interaction with dedicated energy absorber and charge neutralisation.

For an increase of the fusion reaction rates, the experimental areas can be expanded. Therefore, it is planned to investigate influence of the length of the interaction region in a future.

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