THE INJECTION SEPTUM MAGNET FOR THE COLLECTOR RING (FAIR)*

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Abstract

Collector Ring [1] is one of the key installations of the FAIR project (Darmstadt, Germany). It is dedicated for stochastic cooling of incoming beams of antiprotons and rare ions. Additionally there is a mode of operation for experiments in the ring. Beams for all modes of operation are injected through one transfer channel. Extremely high acceptance of the ring (240 mm*mrad) leads to large apertures of all magnetic elements including the septum magnet. Meanwhile planned parameters of the magnetic field and magnetic field quality are comparatively strict. The present state of the design of the pulsed injection septum for the CR is presented in this article together with the concept of the injection system.

THE SCHEME OF INJECTION

The cycle of the Collector ring operation for the antiprotons consists of injection, cooling and extraction. The full cycle takes 10 seconds. The analogous cycle for the rare isotope beams takes only 1.5 seconds. Additionally there are options of the RIBs injection for further experiments in the so-called isochronous lattice [2]. All beams that are cooled and later extracted have the rigidity of 13 T·m. The isochronous mode experiments are planned for the discrete set of beam energies: $\gamma=1.84$, $\gamma=1.67$, $\gamma=1.43$. Each regime of the RIBs has one lattice option. For better flexibility for antiprotons two lattices are foreseen – with positive and negative slip-factor η. The full list of all mentioned regimes is shown in the Table 1.

Table 1: The list of the CR operation regimes

The particles type	*The lattice name*	*The cycle length*	*Emittance*
P-bars	P-bar 1	10 sec	240 mm·mrad
P-bars	P-bar 2	10 sec	240 mm·mrad
RIB	RIB	1.5 sec	200 mm·mrad
RIB	ISO 1.84	-	100 mm·mrad
RIB	ISO 1.67	-	100 mm·mrad
RIB	ISO 1.43	-	100 mm·mrad

In all regimes of operation the injecting beam comes from the TCR1 channel [3]. The angle between the channel and the CR orbit is 7.842538º. This angle is mainly compensated by the Injection Septum (IS). The final compensation is done by the fast kicker magnets (KM) [4]. The kicker magnets are grouped by three in two sections with the magnetic length of 60 cm and the maximum magnetic field of 0.054 T. After KM the injected beam trajectory coincides with the main CR orbit.

The distance between the end of the IS and the KM is about 15m. Three quadrupole magnets are placed in this region that produce enough betatron phase advance for the proper angle compensation in KM. In this region beam moves by the trajectory shifted from the main orbit so all the structure elements here have an enlarged aperture. The horizontal aperture in the CR01QS01, CR01QS02 and CR04QS02 quads is 270 mm. The scheme of the injection region is shown at the Figure 1.

INJECTION SEPTUM MAGNET DESIGN

As it is mentioned above the task of the septum magnet is to compensate the angle between the TCR1 channel and the orbit of the CR. Taking into account that the angle that can be later compensated with the KM varies from 8 to 13 mrad for the different modes of operation the angle of the injection septum should be ≈128 mrad. This angle is gained by the three pulsed magnets of similar desing that all together are called Injection Septum.

The principal scheme of the IS magnet is the following: pulsed magnetic field, several turns of the primary coil winded around the yoke of the magnet; the secondary coil is combined with the septum electrode; the straight ceramic vacuum chamber is used to avoid the heat losses during the pulse.

The basic layout of the IS magnet together with the injecting and circulating beams cross-sections are shown at the Figure 2. Beams sizes and positions are shown for the point at the exit of the last magnet by the way of the beam. Additionally the flange that combines the vacuum chamber of the IS and of the CR is shown. At the top and the bottom of the yoke two special cleats that tighten the laminated yoke in longitudinal direction are provided. The 3D model of the set of 3 IS magnets together with the vacuum chamber is shown at the Figure 3. Parameters of the IS magnet are provided in the Table 2.

The magnetic field and the magnetic length of the IS magnets are mainly limited by the following factors: the length of the injection straight section which is 5 meters and parameters of the power source.

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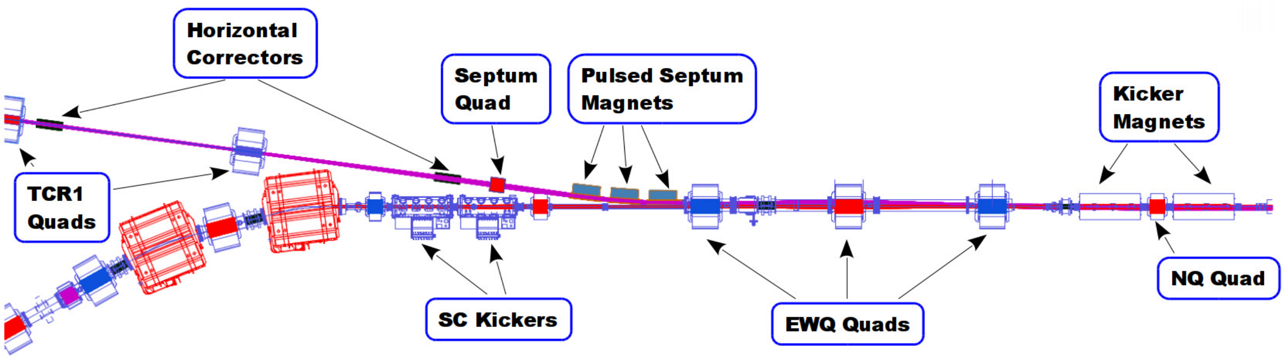

Figure 1: The scheme of the injection region together with the TCR1 transfer channel.

To simplify the design of the power source and reduce the stored energy the magnetic field has to be as low as possible. This is moreover important as soon as due to the huge beam sizes the volume occupied by the magnetic field is large enough. After the optimization the final parameters are: the magnetic length of each IS magnet is 952 mm, the maximum magnetic field is 0.6 T.

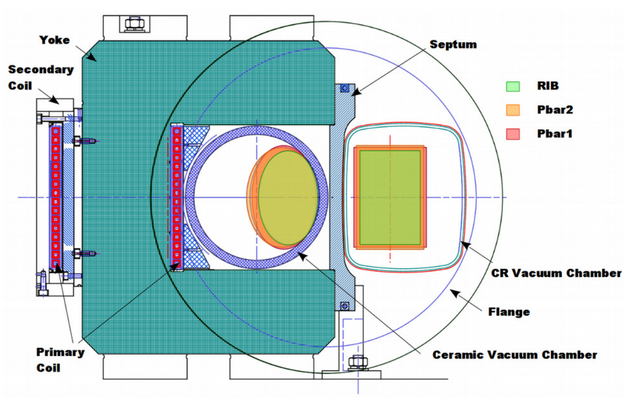

Figure 2: The basic layout of the ISM dipole.

The gap of the magnet is defined by the vacuum chamber. To avoid huge heat losses due to the eddy fields in the walls of the vacuum chamber the ceramic chamber is used. For the cost saving purpose there was selected vacuum chamber with round cross-section of the biggest diameter from the list of FREATEC standard cameras. The selected camera is straight and has the outer diameter of 170 mm and the wall thickness of 10 mm.

The septum electrode is specially shaped to increase it's strength while preserving the gap between the injecting and the circulating beam. The CR vacuum chamber follows this shape and has the thickness of 3 mm. The minimal thickness of the copper septum electrode is defined by the requirement to reduce the influence of the magnetic field in the septum magnet on the circulating beam. In the most thin point it is 15 mm that is about 4 skin layers for the pulse length of 3 ms.

The power source is connected to the primary coil that is winded over the yoke. The coil has 16 turns of the copper wire with cross-section of 9.5x9.5 mm^2 with the round (∅ = 5mm) channel for the water cooling. The secondary coil has one turn. It envelopes the primary coil at the outer part of the yoke to reduce the magnetic field level outside of the yoke. On the sides of the yoke there are electrodes connecting the envelope to the septum electrode. This scheme allows to have the solid septum electrode that is able to stand the mechanical stress during the pulse. Together with the primary coil the secondary coil forms the magnetic field in the gap.

Table 2: The list of the IS magnet parameters

Parameter	*Value*
Width and height of the gap	180/173 mm
Magnetic field	0.6 T
Effective length	0.952 m
Angle	0.04233 rad
Bending radius	21.666 m
Inductance	0.383 mH
Capacity	0.595 mF
Voltage	4300 V
Current	5162 A
Pulse duration, period	3 ms
Energy losses per cycle	1500 J
Vacuum chamber thickness	10 mm
Septum electrode thickness	15 mm

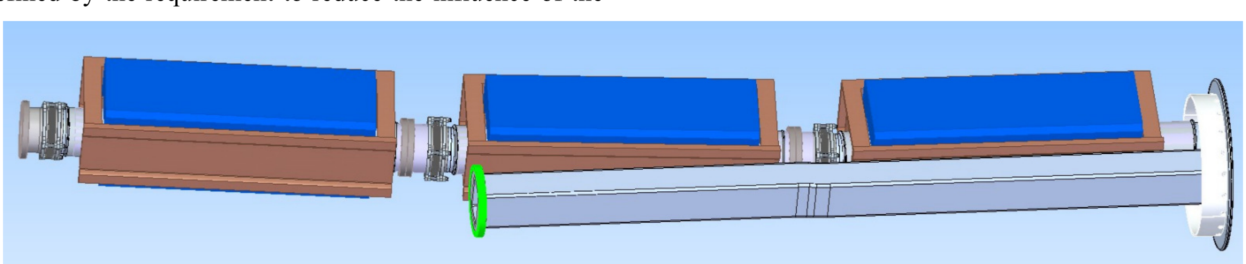

Figure 3: The set of all three magnets dipoles of the IS together with the vacuum chambers.

At the Figure 4 the magnetic flux distribution for the cross-section in the middle of the IS magnet is shown. To reach the design parameters of the magnetic field quality some tiny shims should be used at the pole profile. Fortunately due to the round shape of the vacuum chamber it doesn't lead to the increase of the gap. The yoke is made of laminated steel plates with thickness of 1 mm and the filling factor of 98%.

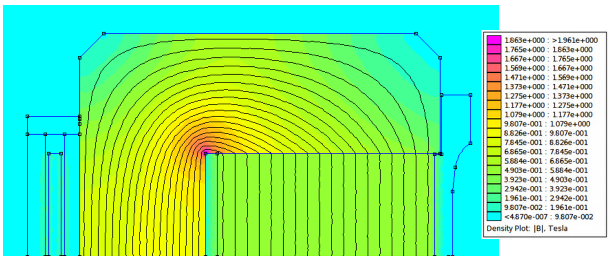

Figure 4: The magnetic flux distribution in the IS magnet.

INJECTION OPTIMIZATION

Due to the round in cross-section and longitudinally straight IS vacuum chambers the IS magnets are the bottleneck for the injecting beam. To improve the gain of the particles in the ring some additional optimization of the beam optics is provided.

Together with the angle between the TCR1 and the CR the trajectory of the injecting beam is defined by the following factors: the KM maximum bending angle, the magnetic field gradients and apertures in the quadrupole magnets of the injection region, the shift of the septum magnet from the CR orbit, the maximum magnetic field in the septum magnet, the sizes of the injecting and circulating beams. Schematically these limitations are shown at the Figure 5.

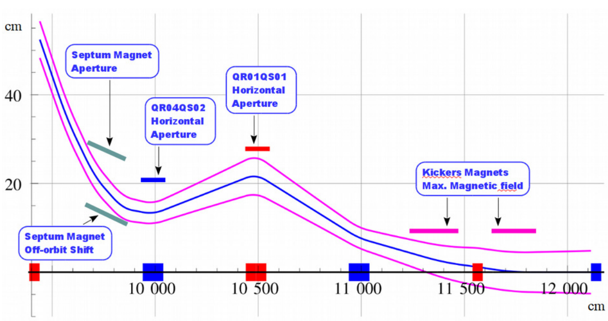

Figure 5: The schematic presentation of the injecting beam with limitations of the structure.

Within the development of the injection optics all parameters were optimized to find the "optimal" injection trajectory that is equally shifted from the mentioned above limits. Additionally possible deviations from this trajectory were studied to define the safety margins. At the Figure 6 beam cross-sections at the entrance of the first and at the exit of the last IS magnets are shown for the PBAR1 regime where the green ellipse corresponds to the "optimal" trajectory while the blue and orange ellipses represent the possible beam deviation from it. The maximum orbit deviation is limited to just 9 mm which is about 10% of the beam size. Fortunately each IS magnet has the individual power source which gives additional tuning possibilities.

Also it is possible to increase the IS acceptance by the optimization of the beam shape. Due to the axial symmetry of the conversion target and the magnetic horn the beam has the round shape in the cross section at the beginning of the channel [5]. But due to the different phase advances in vertical and horizontal oscillation planes the beam becomes rectangular elsewhere. However with additional condition for the phase advance ($\Delta\psi_{x,y} = n\cdot\pi$, where n is integer) the beam shape can be made round again and matched to the round vacuum chamber .

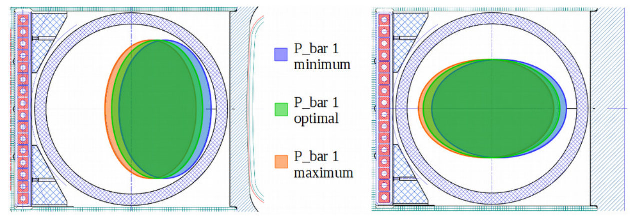

Figure 6: The beam cross-sections for the first (right) and last (left) IS magnets by the flight of the beam.

Such lattice for the p-bar transfer line is developed. The corresponding phase advances of the horizontal and vertical betatron oscillations are shown at the Figure 7. The phase advances between the beginning of the channel and the exit of the IS are $\Delta\psi_x/2\pi$ =2.0, and $\Delta\psi_y/2\pi$ =1.5.

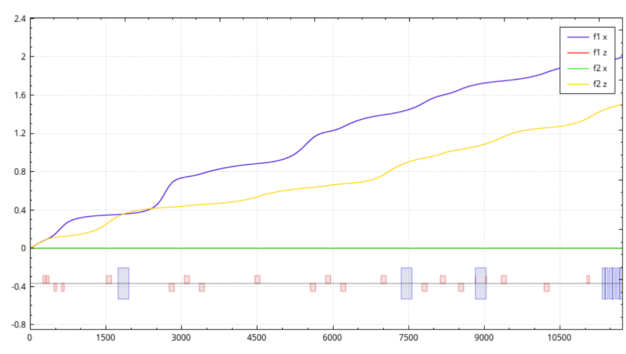

Figure 7: The betatron phase advances in the p-bar channel.

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