Magnet system design for the new 18 GHz ECR ion source at GSI

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Abstract. In order to increase intensities and charge states of available ion species, a new room-temperature ECR Ion Source (ECRIS) operating at 18 GHz is currently under development at GSI. The new ECRIS is based on a Heavy Ion Ion Source Injector (HIISI), developed at the Department of Physics, University of Jyväskylä (JYFL), and features three normal conducting coils and a permanent magnet hexapole for plasma confinement. The latter has to be installed inside a refrigerated hexapole chamber, allowing to achieve the required radial confining field and avoiding demagnetization of permanent magnets. Computer simulations are carried out with Opera software package for two Halbach hexapole arrangements and the resulting three-dimensional magnetic fields are compared. The demagnetization of permanent magnets due to the superposition of fields generated by the coils and the hexapole is also simulated for both arrangements.

1. Introduction

The 14.5 GHz CAPRICE ECR Ion Source (ECRIS) installed at the High Charge State Injector (HLI) of GSI provides highly charged ion beams of various gaseous and metallic elements for the accelerator facility. Since its commissioning in 1992, the source has undergone a number of upgrades allowing to improve stability and intensity of the accelerated ion beams. Recently, an optical emission spectrometer and a microwave shielding grid have been applied for routine operation which improved the long time stability and reproducibility of the ^{48}Ca beam [1].

In order to benefit from the technological advances of ECRIS development and from increased intensities and available charge states of heavy ion beams for the FAIR facility, a new ECRIS is currently under development. In accordance with semi-empirical ECR scaling laws, higher intensities require higher plasma densities, which implies an increase of the microwave frequency and of the confining magnetic field.

The new 18 GHz ECRIS is based on the design of Heavy Ion Ion Source Injector (HIISI) developed at the Department of Physics, University of Jyväskylä (JYFL) [2]. Its design incorporates a number of innovative technical solutions allowing to reach the required magnetic field configuration with nonsuperconducting coils and permanent magnets.

2. Magnet system design

The new ECRIS will be based on a room-temperature magnet system. The axial magnetic field is produced by three normal conducting coils. The reverse direction of current in the middle

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Table 1. Design parameters of the magnet system of the new ECRIS.

Parameter	Value
Magnetic field at injection B_{inj}	2.8 T
Magnetic field at center B_{min}	0.45 T
Magnetic field at extraction B_{ext}	1.3 T
Nominal currents of coils (Inj. / Center / Ext.)	1000 A / -300 A / 820 A
Inner radius of the hexapole	58 mm
Outer radius of the hexapole	120 mm
Length of the hexapole	420 mm

coil allows to adjust the minimum magnetic field at the center. The radial plasma confinement is provided by a permanent magnet hexapole, which has a Halbach structure with 36 segments. Table 1 summarizes the main parameters of the magnet system.

In order to maximize the radial confining field, NdFeB permanent magnets of grade N45SH have been chosen [3]. This material is characterized by the following nominal values of remanence and coercivity at 20 °C : $B_{\mathrm{rem}} = 1.35\,\mathrm{T}$ and $H_{\mathrm{cJ}} = 1592\,\mathrm{kA/m}$, respectively.

2.1. Hexapole arrangements

a) b)

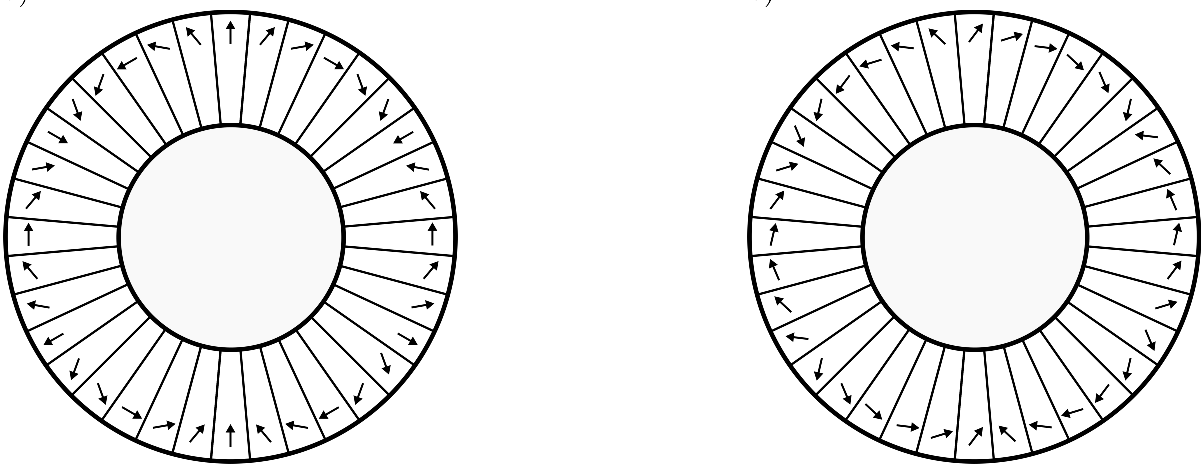

Figure 1. Magnetization directions for typical (a) and offset-Halbach (b) hexapoles. Arrows show magnetization direction of each permanent magnet block.

In this work, two Halbach hexapole arrangements are compared with each other. The first hexapole arrangement which corresponds to a typical Halbach structure is shown in Figure 1 a. The second arrangement studied is a so-called offset-Halbach arrangement (see Figure 1 b) introduced in [4]. In the latter design, the magnetization direction of each of the 36 magnet segments is chosen in a way that the magnetic poles are located between the magnet pieces.

Three-dimensional simulations of the complete magnetic system were performed using the Opera software package [5]. Thus, the resulting magnetic field map represents a superpostion of the solenoid and hexapole fields. All the simulations were done with the magnet grade N45SH and the coil currents given in Table 1. The influence of the offset angle on the configurations of magnetic and demagnetizing fields is discussed in the following.

2.2. Magnetic field structure

The magnetic field along the axis of the plasma chamber is mainly determined by the coil currents. Therefore, as expected, both arrangements provide identical axial magnetic field profile which is shown in Figure 2. The maximum axial magnetic fields are about 2.8 T and 1.3 T at the injection and the extraction, respectively.

Figure 3 shows the radial field profiles obtained for both arrangements. The longitudinal coordinate (z) corresponds to the middle of the hexapole assembly. One can see, that the offset-Halbach structure allows to reach a higher magnetic field at the inner wall of the plasma chamber (see also Figure 4). The maximum radial magnetic fields achieved with typical and offset-Halbach are 1.21 T and 1.31 T, respectively. Figure 6 shows the radial magnetic field at the magnetic pole along the axial direction for both arrangements. One can note, that the field profiles provided by both structures are identical, with overall higher radial magnetic field produced by the offset-Halbach hexapole at injection ($z < 216$ mm) and extraction ($z > 216$ mm) sides. The hexapole design without offset provides a more homogeneous field at the inner surface of the plasma chamber with the maximum $|B| = 1.31$ T (see Figure 5). The absolute value of the magnetic field at the inner surface of the plasma chamber which is produced by the offset-Halbach hexapole is higher ($|B| = 1.39$ T). This design also provides a field profile in which the peak magnetic field periodically occurs in narrow regions. Three-dimensional views of the magnetic field structure for both hexapole arrangements are shown in Figure 7.

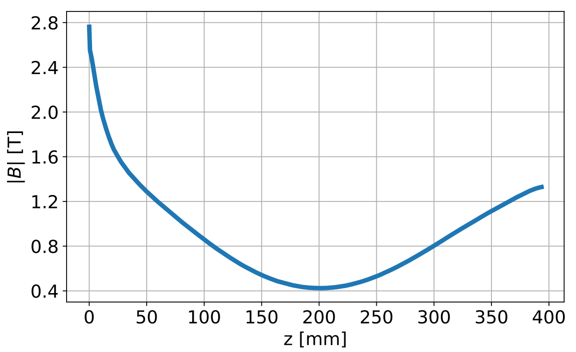

Figure 2. Axial magnetic field. The coordinates $z = 0$ mm and $z = 394$ mm correspond to the injection and extraction ends of the plasma chamber, respectively.

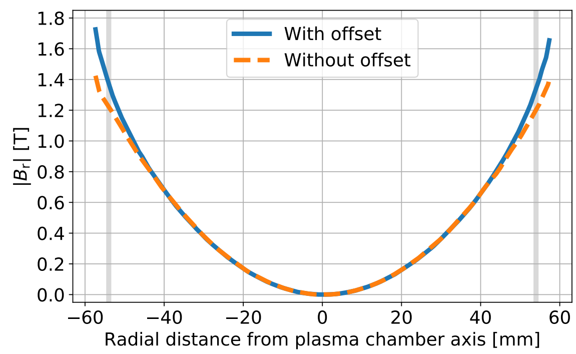

Figure 3. Radial component of magnetic field along radius ($z = 210$ mm). The shaded area marks inner wall of the plasma chamber ($r = 53.5$ mm).

2.3. Demagnetization analysis

A superposition of fields generated by the coils and the hexapole can cause a partial demagnetization of permanent magnets. This phenomenon occurs when the amplitude of the demagnetizing field exceeds the coercivity of a permanent magnet block and its direction is opposite to the magnetization direction of this segment.

In present analysis, a 30 % safety margin is taken for the coercivity of the permanent magnets in order to avoid partial demagnetization of the permanent magnet material. Therefore, the amplitude of the demagnetizing field should not exceed a value of 1.1 kA/m. The demagnetization analysis shows that the offset-Halbach arrangement experiences a larger

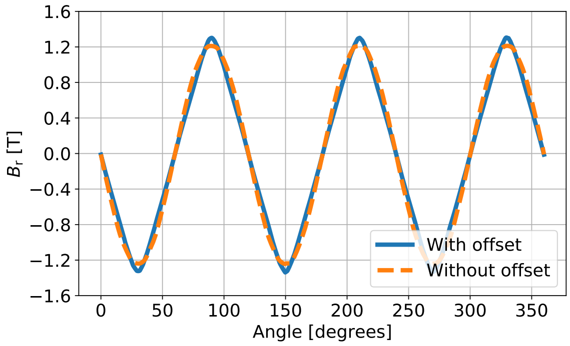

Figure 4. Radial component of magnetic field at the surface of the plasma chamber inner wall ($r = 53.5$ mm, $z = 210$ mm).

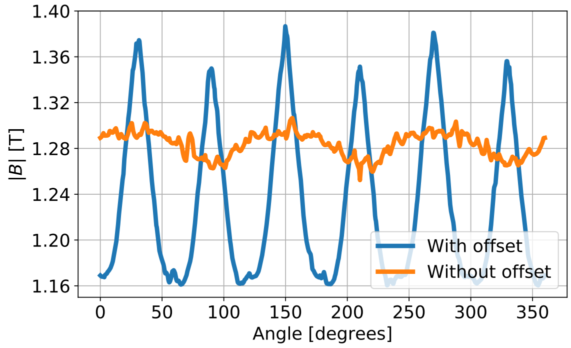

Figure 5. Magnetic field at the surface of the plasma chamber inner wall ($r = 53.5$ mm, $z = 210$ mm).

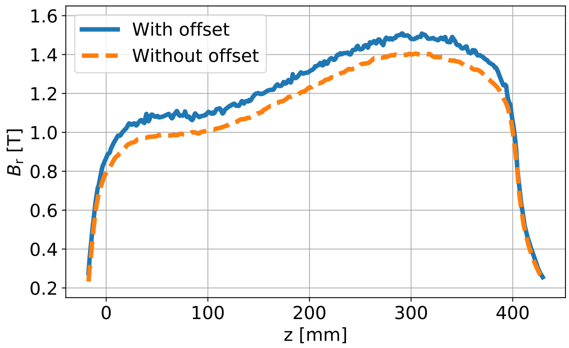

Figure 6. Radial component of the magnetic field at the inner surface of the plasma chamber along the axial direction ($r = 53.5$ mm).

a) b)

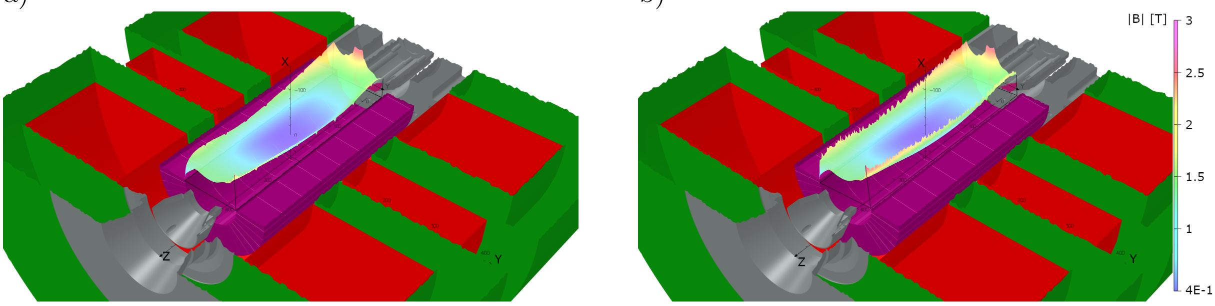

Figure 7. Magnetic field structure along the axial direction for typical (a) and offset-Halbach (b) magnetization directions.

demagnetizing field. From Figure 8 one can note that the maximum amplitude of the demagnetizing field is 1.49 kA/m and 1.74 kA/m for typical and for offset-Halbach hexapole, respectively. However, a smaller volume of permanent magnet material is subjected to the demagnetization with the latter design. The volume of permanent magnet material which is exposed to demagnetizing field exceeding 1.1 kA/m is 306 cm^3 for the offset-Halbach arrangement, compared to 428 cm^3 for the typical one. It should be noted that these values correspond to 2 and 3 percentage of the total permanent magnet volume, respectively.

The hexapole chamber is refrigerated to avoid demagnetization of permanent magnets by increasing coercivity of the magnet material. In addition to the cooling of the permanent

a) b)

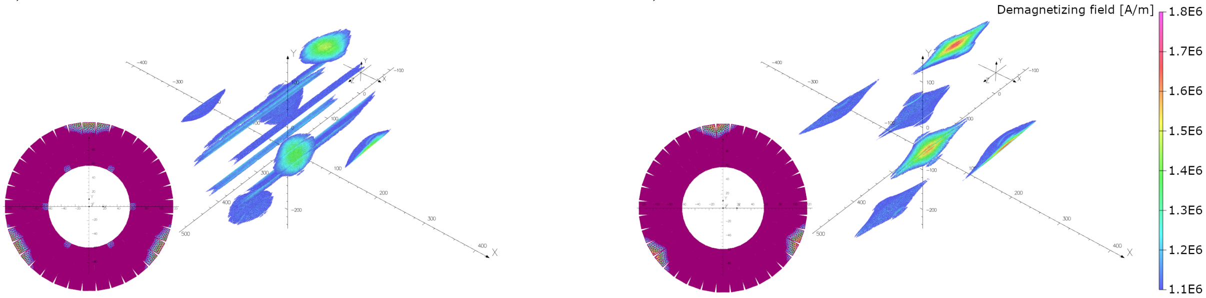

Figure 8. Demagnetizing field which exceeds a value of 1.1 kA/m for typical (a) and offset-Halbach (b) magnetization directions. Note that only the regions where the field is higher than the threshold value are shown. Transverse cross-section views show the largest demagnetizing field from injection side.

magnets, a material grade with higher coercivity can be used at those regions of the hexapole which experience the largest demagnetizing field. For example, a permanent magnet hexapole of the AISHa (Advanced Ions Source for Hadrontherapy) consists of two concentric rows of permanent magnet blocks to compensate for the demagnetizing field at the injection and extraction sides [6]. The analysis indicates that partially demagnetized regions are located along both the inner and outer radii of the typical hexapole assembly. Consequently, more hexapole segments would have to be replaced in this arrangement.

3. Conclusion

In this work, two Halbach hexapole arrangements were investigated with the Opera software package in terms of the produced magnetic and demagnetizing fields. It was found that a so-called offset-Halbach hexapole arrangement provides a 7 % increase of the radial magnetic field compared to a structure without offset, thereby allowing maximize the required radial confining field. Using offset-Halbach stucture allows to reduce the amount of material which is exposed to demagnetization by one percentage point. These features make the offset-Halbach arrangement a more attractive design for the permanent magnet system of the new ECRIS.

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