ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-TUA1

# DESIGN OF A NEW IRON PLUG FOR THE TRIUMF ECRIS CHARGE STATE BOOSTER CONFERENCES*

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*Abstract*

This paper presents a solution to address the issue of asymmetric dipole fields in the injection region of the TRIUMF electron cyclotron resonance ion source PHOENIX booster. The asymmetric fields arise from a wide gap in the injection soft iron plug of the booster, which allows the connection of the RF waveguide to the plasma chamber. Simulations and experimental measurements have revealed that singly charged ions, injected for charge breeding, experience deflection and get lost due to the asymmetric magnetic fields instead of being effectively captured by the plasma, thereby diminishing the efficiency of the charge state booster. To address this problem, an iron plug with an enlarged inner diameter, which allows the RF waveguide to connect to the plasma chamber, was designed. This redesign necessitated modifications to the injection electrodes and plasma chamber, including repositioning the waveguide and gas-inlet windows. By implementing these changes, the TRIUMF charge state booster is anticipated to achieve efficiency levels comparable to other PHOENIX boosters.

## INTRODUCTION

The Electron Cyclotron Resonance Ion Source (ECRIS) has been used at TRIUMF's Isotope Separator and Accelerator (ISAC) facility since 2010 [1] to charge-breed exotic isotopes, particularly those with an atomic mass greater than 30. This is essential to match the mass-to-charge (A/Q) ratio of the linear accelerator (LINAC) before post-acceleration, enabling the use of these isotopes in nuclear physics and astrophysics research. The ECRIS is a highly efficient ion source that operates continuously and can produce highly charged ions at high intensities. It offers several advantages over the electron beam ion source (EBIS), including low-maintenance requirements and a prolonged operational lifespan. Systematic investigations conducted at TRIUMF [2, 3] have shown that the ECRIS charge state booster (CSB) performance can be significantly enhanced by optimizing and improving various components, such as the injection optics, injection system, RF power and frequency, magnetic field, plasma parameters, extraction system and optics. Research activities have commenced at TRIUMF to improve the performance of the CSB based on the results of these investigations. The superior two-frequency heating technique using a single waveguide was recently implemented, and the associated transport optics and the extraction system were optimized. The global efficiency of the booster for cesium charge states between $20^+$ and $32^+$, increased from 34 % under single-frequency heating operation to 41 % under two-frequency heating [2]. While this improvement is substantial compared to previous performance results, it's important to note that the efficiency still needs to improve compared to other PHOENIX boosters. For instance, the LPSC booster has reported a remarkable global efficiency of up to 92 % [4]. This comparison highlights the potential for further enhancements of the TRIUMF booster. Furthermore, during the systematic investigations, it was discovered that the wide gap created in the injection soft iron plug to connect the waveguide to the plasma chamber creates an asymmetry in the magnetic field in the plasma chamber that steers ions to the electrodes and chamber wall during injection, thus reducing the charge breeding efficiency. To address this problem, a new soft iron plug was designed. The redesign led to modifying the injection electrodes and plasma chamber and repositioning the waveguide and gas-inlet windows. The paper presents the results of designing a new soft iron plug, magnetic field simulation of the CSB, and RF modelling of the plasma chamber without plasma.

## THE TRIUMF PHOENIX BOOSTER AND EFFECT OF A GAP IN THE INJECTION SOFT IRON PLUG

The TRIUMF ECRIS PHOENIX booster, initially developed by Pantechnik for single-frequency heating operation at 14.5 GHz, has recently been upgraded to support two-frequency heating using the existing single waveguide. Refer to [2, 3] for detailed information about the two-frequency heating setup. The single charge state efficiency of the CSB under the single-frequency heating operation has been measured up to 8.8 % for $^{133}Cs^{23+}$ and up to 9.1 % for $^{133}Cs^{26+}$ under the two-frequency heating operation [3]. The source utilizes three room-temperature solenoid coils and hexapole permanent magnets to generate axial and radial magnetic field distributions for plasma confinement. ARMCO™ soft iron plugs are installed in the injection and extraction regions to enhance the injection and extraction magnetic fields. However, a wide gap was created in the injection iron plug to allow the waveguide and water cooling lines to be connected to the plasma chamber. Figure 1 shows the injection iron plug as designed by Pantechnik. To investigate the effect of the wide gap, the geometry of the CSB was modelled in OPERA 3D [5], and the trajectories of an ion beam were calculated and visualized using the ray tracing package of the software. The simulations, which considered only the magnetic fields created by the three solenoids and hexapole of the ion source (excluding plasma space charge and electric fields from the injection system), revealed significant beam deflection. Figure 2 shows the trajectories of $^{133}Cs^+$ ion beam, initially travelling parallel to the beam axis. The

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beam begins to deviate from its intended path at approximately −300 mm, eventually moving perpendicular to its original direction, indicating the presence of a dipole field near the injection region.

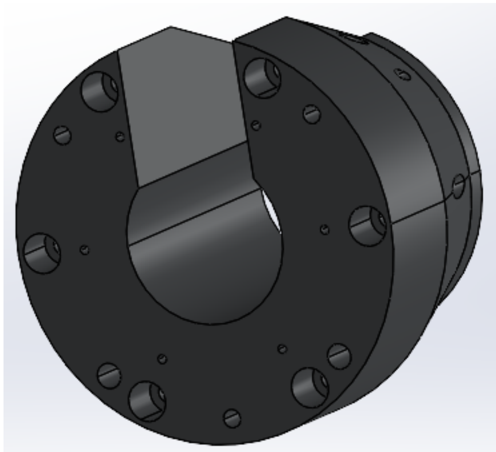


Figure 1: Injection soft iron with a gap to accommodate the RF waveguide to the plasma chamber. It has an inner diameter of 80 mm,outer diameter of 194 mm, and length of 142 mm.

The impact of the dipole field was further confirmed through experimental observations. In the experiment, the plasma was extinguished by switching off the RF power, and the magnetic field in the injection region was switched off while the center and extraction fields remained active. Subsequently, a beam of $^{133}Cs^{+}$ ions with an intensity of approximately 10 nA was injected into the booster. Downstream of the booster, the nearest Faraday cup recorded a current of about 3 nA. However, upon switching on the injection magnetic field, the measured current on the Faraday cup decreased to approximately 0.1 nA, consistent with the simulation results presented in Fig. 2.

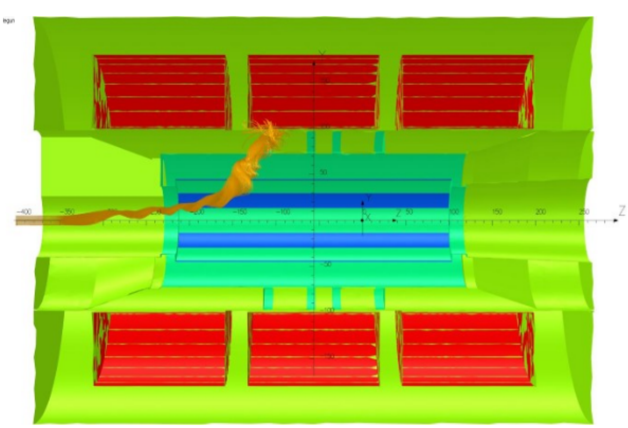


Figure 2: Simulation of ion beam deflection induced by the dipole magnetic field component at the injection region of the TRIUMF CSB. The plots in red are the solenoid coils, while the blue plots are the hexapole magnets.

Further analysis of the measured transverse magnetic fields ($B_x$ and $B_y$) and the longitudinal field ($B_z$) around the injection region revealed that the transverse components are not zero (Fig. 3). Particularly, the $B_y$ component (blue plot) peaked at around 1 kG at a distance of −210 mm, representing approximately 10 % of the main $B_z$ field (10 kG). At this location, due to the deceleration caused by the injection electrodes, the injected singly charged ions had low energy (a few tens of eV). If we assume that $^{133}Cs^{+}$ beam has an energy of about 10 eV at this location, then the calculated Larmor radius for 1 kG field is 53 mm, which significantly exceeds the 20 mm aperture of the last injection electrode of the CSB. This suggests significant ion loss during injection, explaining the observed low efficiency compared to the LPSC booster.

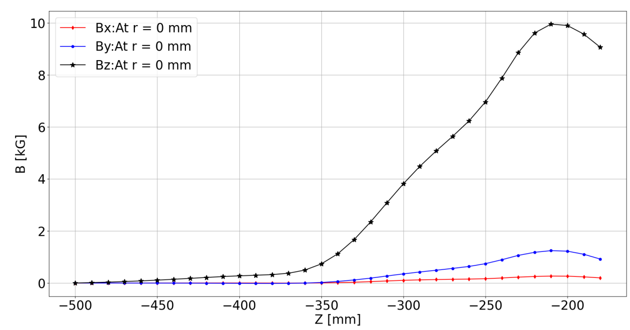



Figure 3: Spatial distribution of magnetic field components around the CSB injection region. The $B_y$ component is up to 1 kG around −210 mm.

## DESIGN OF A NEW INJECTION SOFT IRON PLUG

A new soft iron plug has been designed to address the dipole magnetic field component issue at the injection region of the CSB caused by the gap. This was achieved by increasing the inner diameter of the iron from 80 mm to 120 mm, providing sufficient space for the waveguide connection, support gas connector, and cooling line connectors without requiring a gap. Figure 4 presents a 3D drawing of the newly designed soft iron plug. Consequently, the

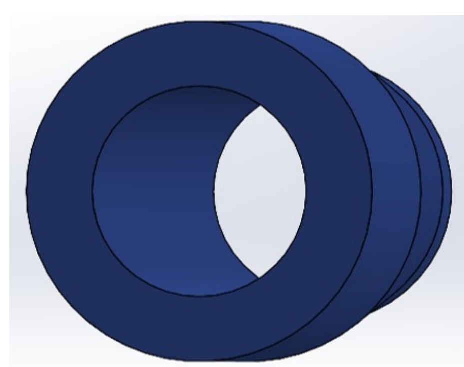


Figure 4: SolidWorks engineering drawing of the newly designed injection soft iron component. It has an inner diameter of 120 mm,outer diameter of 194 mm, and length of 142 mm.

26th Int. Workshop Electron Cyclotron Resonance Ion Sources ECRIS2024, Darmstadt, Germany JACoW Publishing
ISBN: 978-3-95450-257-8 ISSN: 2222-5692 doi:10.18429/JACoW-ECRIS2024-TUA1

soft iron plug redesign impacted the injection system and the portion of the plasma chamber where the waveguide is connected, prompting a redesign of these components. It is worth noting that only the portion of the plasma around the injection region was modified. The main chamber where the bulk of the plasma is expected to be confined remains unchanged. The inner diameter of this injection portion of the chamber was reduced from 62 mm to 55 mm to have enough space for the waveguide. Additionally, the waveguide and gas-inlet windows were repositioned during this process. Figure 5 shows a cross-sectional view of the new soft iron plug with the injection electrodes and the injection portion of the plasma chamber.

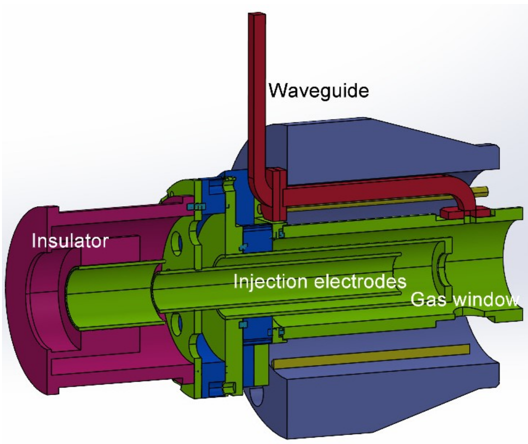



Figure 5: Cross-sectional view illustrating the newly designed injection soft iron component integrated with the redesigned injection system and a segment of the plasma chamber.

## DISCUSSION

The CSB was modelled using OPERA 3D software, featuring the newly designed injection iron plug. The magnetic field was calculated, and it was found that increasing the inner diameter of the iron plug increased the air volume around it. This change impacted the magnetic field lines of the solenoid at the injection region. With the original iron plug, a current of 1050 A on the injection solenoid could produce a magnetic field strength of up to 1.0 T at the injection region. However, with the newly designed iron plug, a higher current of about 1107 A was required to achieve the same 1.0 T magnetic field. Fortunately, the power supply of the solenoid coil was rated to supply current up to 1300 A, which allowed for compensation of the reduced magnetic field. As shown in Fig. 6, removing the gap eliminated the transverse asymmetric field, thus preventing deflection of the injected ion beam, in contrast to Fig. 2. Figure 7 compares the transverse fields of the original soft iron design by Pantechnik with the new design. The results indicate that the transverse field associated with the gapped soft iron (blue plot) was eliminated in the new design (green plot).

The modification of the injection region in the plasma chamber necessitated a careful assessment of its impact on

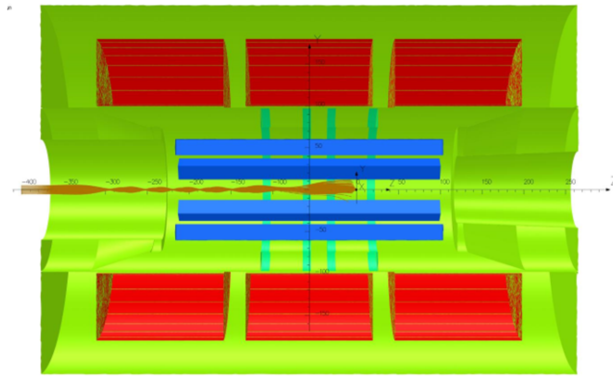


Figure 6: Ion beam trajectories at the injection region of the CSB incorporating the newly designed iron plug. The simulation illustrates how the modified plug influences the beam's path. The plots in red are the solenoid coils, while the blue plots are the hexapole magnets.

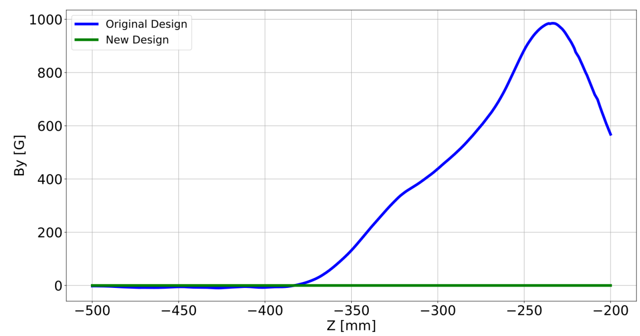
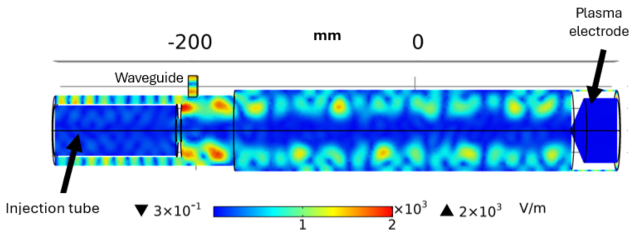
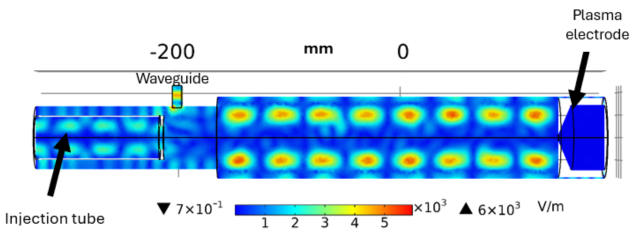



Figure 7: Comparison of the transverse magnetic field ($B_y$ component) at the injection region for two iron plug designs. The blue curve shows the $B_y$ component resulting from the gap in the original Pantechnik-designed iron plug. The green curve shows the elimination of this field when the gap is removed in the new design.

the RF electromagnetic modes essential for plasma heating. Despite the localized changes, their potential effects on the entire system could not be overlooked. To evaluate these effects, the redesigned plasma chamber (without plasma) was modelled using COMSOL multi-physics software [6] to simulate the electromagnetic modes. The original chamber, designed for electromagnetic waves at a frequency of 14.5 GHz, was a reference point for comparison. Simulation results, as illustrated in Fig. 8a, revealed a localized field island at the injection region (around −200 mm) in the original plasma chamber. The electric field in this region does not contribute to plasma heating. Interestingly, this field island disappeared in the modified geometry. This suggests that the changes made to the plasma chamber around the injection region improved wave propagation, resulting in more uniformly distributed modes, as shown in Fig. 8b. These findings indicate that the minor modifications avoided negative impacts on the RF electromagnetic modes and potentially enhanced the overall electromagnetic field distribution in the plasma chamber. This improvement could lead to more efficient plasma heating, which is crucial for increased efficiency.




(a) Existing plasma chamber




(b) Modified plasma chamber

Figure 8: These figures illustrate electromagnetic wave propagation simulations at 14.5 GHz in two plasma chamber configurations. The left portion of each figure shows the injection tube, while the right depicts the plasma electrode. Electromagnetic waves are launched from a waveguide positioned at the top of the injection tube, approximately −200 mm on the top horizontal axis. The simulations demonstrate that the modified chamber could still excite the modes required to sustain the plasma.

## CONCLUSION

The new soft iron plug and other modified components have undergone a design review and are currently being manufactured by Pantechnik. After the modified components are installed, the efficiency of the TRIUMF PHOENIX CSB is expected to improve significantly, bringing the source to the same performance as its counterpart in LPSC.

## ACKNOWLEDGEMENTS

The authors would like to express their gratitude for the grant from the Natural Sciences and Engineering Research Council (NSERC) of Canada and the support from TRIUMF.

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