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IMPROVEMENT OF THE EFFICIENCY OF THE TRIUMF CHARGE STATE BOOSTER (CSB)

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Abstract

The Electron Cyclotron Resonance Ion Source (ECRIS) is a versatile and reliable ion source to charge-breed rare isotopes at the TRIUMF's Isotopes Separation and Acceleration (ISAC) facility. Significant research work has been done by different groups worldwide to improve the efficiency and performance of the ECRIS. The most recent result of these activities is the implementation of the two-frequency plasma heating. At the ISAC facility of TRIUMF, a 14.5 GHz PHOENIX booster which has been in operation since 2010 was recently upgraded to accommodate the two-frequency heating system using a single waveguide to improve its charge breeding efficiency. Besides, a program has been launched to improve and optimize the extraction of charge bred isotopes in terms of beam emittance. A detailed investigation of the effect of the two-frequency heating technique on the intensity, emittance, and the efficiency of the extracted beam is presently being conducted and the status will be presented.

INTRODUCTION

Different techniques and methods have been explored and employed to improve the performance and efficiency of the Electron Cyclotron Resonance Ion Source (ECRIS) since it was first developed. Examples are plasma-wall coating, biased disks, the increase of the magnetic field strength which allows increasing the RF-frequency, and operation of the ECRIS in two frequencies mode. The operation of the ECRIS with these techniques listed above has demonstrated increased performance of the ECRIS in view of the application as a charge state booster [1-4]. Investigations of the 1+ to n+ conversion processes in the community demonstrated that the efficiency of the process and quality of the highly charged ion beam produced by a Charge State Booster (CSB) can be significantly enhanced by optimizing the plasma conditions and the beam formation in the extraction region [5]. However, the 1+ to n+ conversion rate depends on the flexibility of the injection optics, the plasma conditions, and the beam formation upon ion extraction. TRIUMF embarks on further investigations of ECRIS performance as an ECRIS is used at TRIUMF to boost the charge state of rare isotopes before injection into the linear accelerator (LINAC) of ISAC for post-acceleration.

THE TRIUMF ECRIS CSB

The 14.5 GHz PHOENIX booster of TRIUMF from PANTECHNIK was originally designed as a conventional single-frequency-plasma-heating source. The booster is equipped with a three-electrode extraction system with an aperture radius of 3 mm and an extraction gap of 25 mm. This source has been installed and commissioned in 2010 [6]. The typical operating parameter of the source is listed in Table 1. To optimize the charge breeding results, the plasma chamber wall, the injection, and the extraction electrodes were coated/replaced in 2012 with aluminum/aluminum electrodes to reduce the intensity of the background ions that are introduced into the bulk plasma through plasma-wall interaction. As reported in [7], the intensity of some of the background ions was reduced by about 2 orders of magnitude with aluminum wall coating.

Table 1: Typical Operating Parameters of the TRIUMF CSB

Parameters	Values
Beam energy	11.27*Q keV
Binj	1.15 T
Bmin	0.35 T
Bext	0.87 T
Becr	0.52 T
Br	1.2 T
ECR frequency	14.5 GHz

The preliminary result obtained after the implementation of a two-frequency RF-system is a topic that will be addressed in this paper. A program to improve the beam quality of the CSB has been started. It comprises simulations of the injection and the extraction systems using the code IGUN©. Besides, the result of the magnetic field distribution of the booster that was modelled and simulated in OPERA in preparation for the extraction system simulation in IGUN© will be presented as well.

TWO FREQUENCY OPERATION

The TRIUMF charge state booster (CSB) was recently upgraded to implement the two-frequency heating technique using a single waveguide because the booster was not originally designed to accommodate the conventional two-waveguide approach. The layout of the new rf system upgrade is shown in Fig. 1. The output signals of the two rf signal generators (from BNC with model numbers 845 and 845-20) both with a frequency range of 9 kHz – 20 GHz and output power between -30 – 20 dBm are combined using a high-frequency microwave power combiner (from Mini-circuits with model number ZX10-2-183-S+) with a frequency range of 1.5 – 18 GHz. The combined microwave is fed to a newly installed travelling wave tube amplifier (TWTA) (from CPI with model number VZM6993J4) with a maximum output power of 400 W and a frequency range of 8 – 18 GHz. The amplified microwave

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is fed into the booster through WR-65 waveguide with a frequency range of 12 – 18 GHz.

Before the two-frequency heating technique was implemented on the CSB, a bench test was conducted to ensure the two frequencies launched from the signal generators are fed into the plasma of the ECRIS. The frequencies of 13.65 GHz and 14.5 GHz were set on the signal generators, the launched microwaves were added using the power combiner, the output of the combiner was fed into the TWTA, and an attenuated sample from the TWTA was recorded on a low-power-high-frequency spectrum analyzer.

Figure 2 shows a picture of the spectrum analyzer screen showing the two distinct frequencies launched from the signal generators.

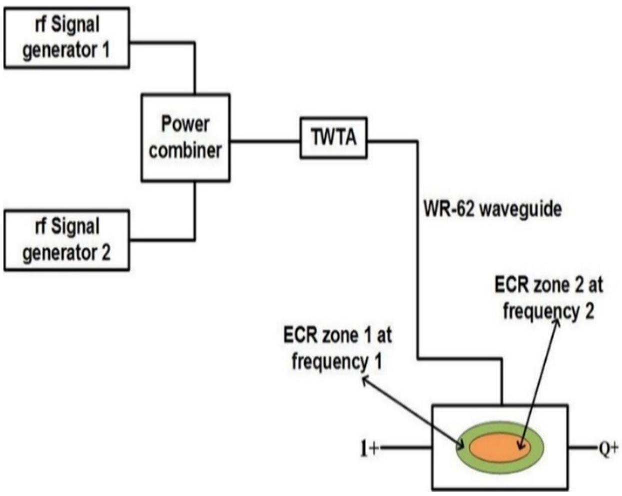

Figure 1: Layout of the TRIUMF two-frequency heating technique.

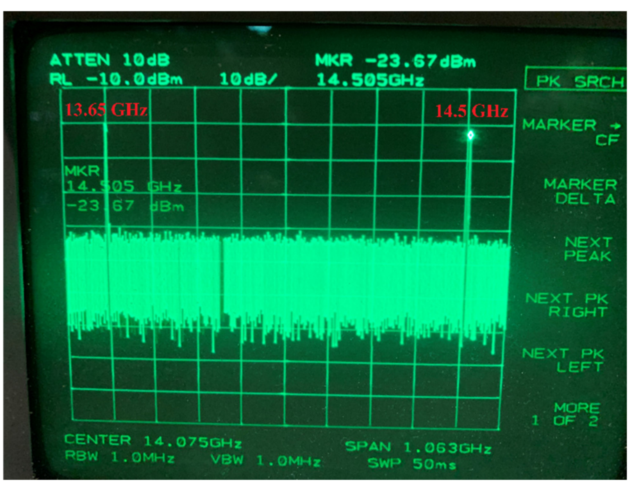

Figure 2: An image of a spectrum analyzer showing the combined microwaves of two frequencies 13.65 GHz and 14.5 GHz launched from the signal generators.

The effect of feeding microwaves with two frequencies into the plasma chamber was investigated by the influence on the extracted charge bred ion current.

INITIAL CHARGE BREEDING RESULT

A Cesium (Cs) test ion source (CTIS), located upstream of the booster for injection and extraction optics tuning, was used to inject a 1+ beam of Cs of about 11 nA into the booster. The booster and the extraction system were optimized for the extraction of Cs^{29+}. One of the rf signal generator's frequency was set to 13.65 GHz while the other signal generator was set to a frequency of 14.5 GHz. The TWTA output power was set to 150 W, the operating parameters listed in Table 1 were used and the Cs charge state distribution (CSD) was measured. The measured charge state distribution was compared with the charge state distribution recorded for the single frequency heating of the replaced rf system.

The replaced rf system comprises a signal generator and a CPI travelling wave tube amplifier (TWTA). The TWTA has a narrow frequency bandwidth between 13.75 – 14.5 GHz. However, because of the upper band of the TWTA's frequency coincides with the designed frequency of the booster, the TWTA was routinely operated at an rf frequency of 14.46 GHz to preserve the life of the TWTA. With the replaced rf system, a 1+ beam of Cs of about 9 nA was injected into the booster, the rf frequency was set to 14.46 GHz and rf power was set to 200 W, while the beam optics and the booster were tuned for the extraction of Cs^{27+}. The two distinct measurements were compared solely to test the newly installed two-frequency heating system as the booster was not well optimized for the operation of the two-frequency heating. The optimization of the booster for two-frequency heating is ongoing. Meanwhile, the Cs charge states could be detected up to 29+ with the two-frequency heating compared to the single frequency heating with Cs charge state up to 27+. More systematic measurements will follow soon.

MAGNETIC FIELD SIMULATIONS

The extraction system of the TRIUMF CSB is currently being investigated by the simulation to further improve the performance of the booster. The correct magnetic field at the extraction region of the booster is an integral part of the extraction system simulation of the ECRIS. It has been reported in [8] that the decreasing axial magnetic field at the extraction region is the dominant cause of an increased emittance of the extracted beam from the ECRIS.

The magnetic field of the TRIUMF CSB has been modelled and simulated in OPERA and benchmarked against the measured field of the GANIL SPIRAL1 booster [9] that is similar to TRIUMF ECRIS CSB. The magnetic field configuration of the booster is composed of three solenoid coils (injection, middle and extraction coils) and a hexapole permanent magnet. The booster is typically operated with the solenoid coil current of 1050 A, 250 A, and 750 A defined on the injection, middle, and extraction coils, respectively. The solenoid coils and the hexapole permanent magnet are encapsulated in an ARMCO soft iron case. There are also ARMCO soft iron plugs at the injection and the extraction regions of the booster to shield stray fields. Besides, two ARMCO soft iron rings are installed around

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the hexapole magnet at the center of the booster to properly define the ECR zone in the plasma chamber.

Figure 3 shows the OPERA 3D model of the CSB and Fig. 4 shows the axial magnetic field distributions for different relative permeability values. Figure 5 shows the axial magnetic field distribution of TRIUMF CSB compared with the GANIL SPIRAL1 CSB measured field. The simulated field matched the measured field. The simulated magnetic field of the TRIUMF CSB will be benchmarked against Hall probe measurement in the future.

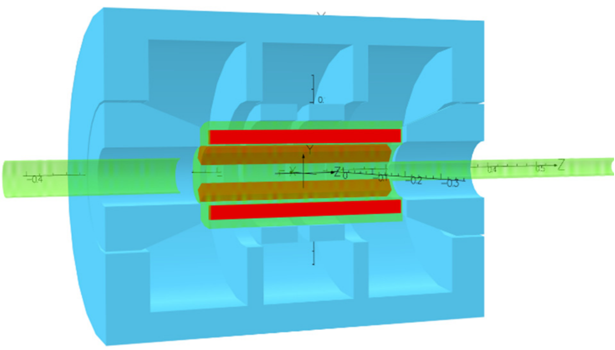

Figure 3: OPERA 3D model of the TRIUMF CSB.

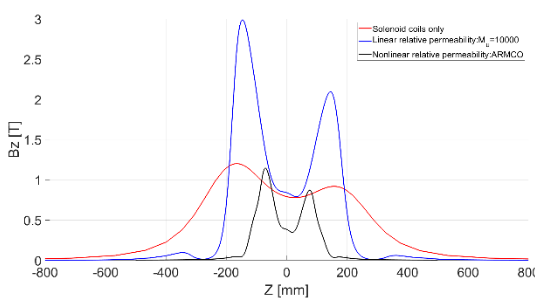

Figure 4: Axial magnetic field distribution of the TRIUMF CSB for different relative permeability values (the blue plot is the magnetic field with linear relative permeability, the black plot is the magnetic field with nonlinear relative permeability, and the red plot is the solenoid coils field only). Coil current (1050/250/750 A).

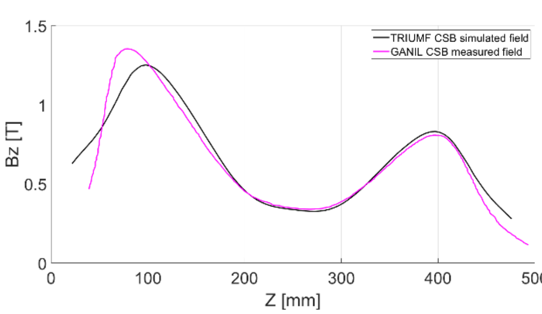

Figure 5: Axial magnetic field distribution of the TRIUMF CSB simulated in OPERA compared with the measured field of GANIL SPIRAL1 CSB. Coil current (1200/250/700 A).

EXTRACTION SYSTEM SIMULATIONS

The extraction system of the TRIUMF ECRIS CSB is being simulated with the code IGUN© to systematically investigate the effect of extraction parameters such as magnetic field, extraction voltage, extraction aperture, and extraction gap on the emittance of the extracted ions to further improve the performance of the booster.

The first simulations used the intrinsic routine of IGUN© to calculate solenoid fields, meanwhile, the calculation does not include the iron yoke or the permanent magnets. Besides, a magnetic field distribution on-axis can be calculated by a different code like OPERA and then import in to the IGUN© code for extraction system simulation. To compare the effect of the magnetic field in the extraction region of the CSB, simulations have been performed with the IGUN-calculated magnetic field and the OPERA-calculated magnetic field. The field distribution for both cases is shown in Fig. 6. It can be seen that with the OPERA-calculated field, the peak of the magnetic field at the injection, middle and extraction is narrow and well-defined while magnetic field distribution calculated with IGUN is broad. This is because the magnetic materials around the solenoid coils are defined and included in the OPERA simulation but not in the IGUN simulation.

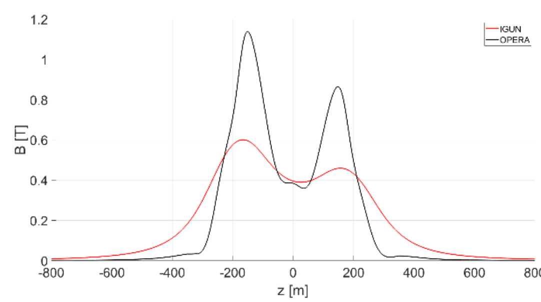

Figure 6: The IGUN-calculated field compared with the OPERA-simulated field. Coil current (1050/250/750 A).

The parameters of the simulated beam in IGUN© code are $^{16}O^{5+}$ with a beam energy of 11.27*Q keV, electron plasma temperature, Te=5 eV, and ion temperature, Ti=0.2 eV. The currents of the solenoid coils are as defined above. The results of the simulation show that the trajectories of the ions simulated with the only solenoid field calculated by the IGUN have less divergent angle compared with the trajectories of the ions simulated with the OPERA-calculated field as shown in Fig. 7. The ions simulated with the OPERA-calculated field have high divergence because of the reduced magnetic field at the end of the extraction system compared with the case of the IGUN-calculated field. The reduced field strength imposes a weaker focusing on the extracted beam resulting in larger beam size. This reduced field strength is caused by the ARMCO soft iron case around the solenoid coils that shield the stray fields.

As the effect of the magnetic field on the beam quality is understood and we have a realistic magnetic field distribution available from OPERA, a systematic parameter scan of voltages using IGUN© can be performed.

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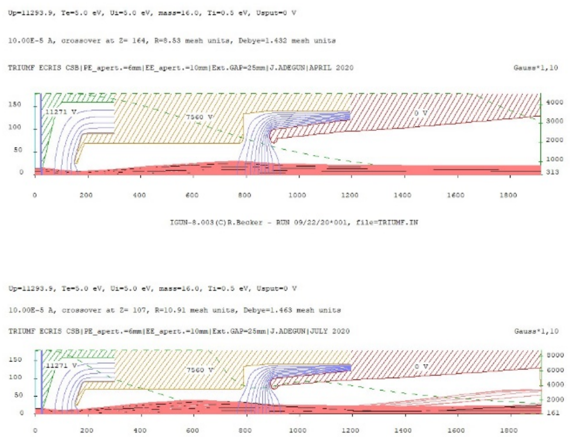

Figure 7: The extraction system of the TRIUMF CSB. The green dash line is the magnetic field. (Top picture is the extraction system simulation with IGUN-calculated field while the bottom picture is the extraction system simulation with OPERA-calculated field).

CONCLUSION AND OUTLOOK

The two-frequency heating system has been implemented at the TRIUMF CSB and the first beam test with two-frequency heating could be performed. The initial result obtained from the source with this operation suggests that the two-frequency heating has a significant effect on the plasma heating and therewith on the charge breeding performance of the booster. Also, a systematic investigation of extraction property using simulations has been started. Therefore, the magnetic field distribution of the CSB has been modelled and simulated in OPERA in preparation for the systematic parameter scans with the extraction system simulation to further improve the beam emittance of the TRIUMF CSB. The magnetic field distribution simulated has been benchmarked against the measured field of the GANIL SPIRAL1 charge state booster, and the simulated field matched the measured field very well.

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REFERENCES

[1] R. Vondrasek *et al.*, "ECRIS operation with multiple frequencies," in *AIP Conference Proceedings*, 2005, vol. 749, pp. 31–34.

[2] S. C. Jeong et al., "KEKCB-18 GHz ECR charge breeder at TRIAC," *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms*, vol. 266, no. 19–20, pp. 4411–4414, 2008.

[3] Z. Q. Xie, "State of the art of ECR ion sources," *Proc. IEEE Part. Accel. Conf.*, vol. 3, 1998.

[4] A. G. Drentje, A. Kitagawa, T. Uchida, R. Rácz, and S. Biri, "Experiments with biased side electrodes in electron cyclotron resonance ion sources," *Rev. Sci. Instrum.*, 2014, vol. 85, no. 2.

[5] R. Vondrasek, A. Levand, R. Pardo, G. Savard, and R. Scott, "Charge breeding results and future prospects with electron cyclotron resonance ion source and electron beam ion source (invited)," *Rev. Sci. Instrum*., vol. 83, no. 2, 2012.

[6] F. Ames, R. A. Baartman, P. G. Bricault, K. Jayamanna, and T. Lamy, "Commissioning of the ECRIS Charge State Breeder at TRIUMF", in *Proc. 19th Int. Workshop on ECR Ion Sources (ECRIS'10)*, Grenoble, France, Aug. 2010, paper WECOBK01, pp. 178-180.

[7] F. Ames, R. A. Baartman, P. G. Bricault, K. Jayamanna, and A. Mjøs, "Operation of an ECRIS Charge State Breeder at TRIUMF", in *Proc. 20th Int. Workshop on ECR Ion Sources (ECRIS'12)*, Sydney, Australia, Sep. 2012, paper THYO01, pp. 163-166.

[8] M. A. Leitner, D. C. Wutte, and C. M. Lyneis, "Design of the extraction system of the superconducting ECR ion source VENUS," in *Proceedings of the IEEE Particle Accelerator Conference,* 2001, vol. 1, pp. 67–69.

[9] A. Annaluru, "Beam optics transport and fundamental processes involving a charge breeder in the upgraded SPIRAL 1 facility," University of Caen Normandy, 2019.