# Improvement of the Efficiency and Beam Quality of the TRIUMF Charge State Booster

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**Abstract**. An Electron Cyclotron Resonance Ion Source is used as the charge state booster (CSB) at the Isotope Separator and Accelerator facility (ISAC) of TRIUMF. Since its commissioning in 2010, the source has been used to charge breed radioactive ions ranging from potassium to erbium operating in single-frequency heating mode. Under this regime, the single charge state efficiency of the booster was measured up to 6 % for noble gases and the maximum charge state of Cesium that can be measured is 27+. The rf system of the source was recently upgraded to implement the two-frequency heating using a single waveguide. Preliminary operation of the booster in a two-frequency heating mode shifted the maximum charge state of Cesium that can be measured to 30+. Another point of improvement that is being addressed is the beam extraction system of the booster. A quadrupole scan technique using a thick lens approach has been developed to measure the emittance of the extracted beam and to analyze the quality of the extraction system. Overall, the system of the CSB is currently being optimized in preparation for the detailed determination of the effect of the two-frequency heating on the beam output.

## 1. Introduction

At the ISAC facility of TRIUMF, radioactive isotope beams (RIBs) with atomic mass $A > 30$ require charge breeding before being injected into the linear accelerator (LINAC) for post-acceleration. The first stage of post-acceleration, which is the radiofrequency quadrupole, was designed to accept RIBs at $A/Q \leq 30$, the second and third stages of post-acceleration, which are drift-tube linac and superconducting radiofrequency linac, were designed to accept RIBs at $A/Q \leq 7$. For charge breeding purposes at the ISAC facility, an ECRIS is used. Since it was commissioned in 2010 [1], only aluminum coating of the plasma chamber wall and the modification and replacement of the injection and extraction electrodes using aluminum have been done. This did improve the performance of the source by reducing the intensity of some background ions by about two orders of magnitude [2]. To further improve the overall performance of the TRIUMF charge state booster (CSB), two-frequency heating is being implemented using a single waveguide.

Furthermore, besides improving the performance of the ECRIS as a highly charged ions generator, optimization of the extraction system for better beam quality upon extraction is critical. Previous investigation of the extraction system of the ECR ion source [3] revealed that magnetic field greatly influences the beam emittance, and simulation codes are usually employed to systematically investigate and optimize the extraction system for good beam quality. Systematic investigation of the

extraction system of the TRIUMF CSB using IGUN© code [4] has been embarked on. The plasma and the extraction parameters are being studied to understand their influence on the extracted beam. The insights gained from this systematic investigation will allow optimizing the extraction system of the CSB for better beam quality.
In this paper, the results of measurements of the extracted beam from the CSB during operation with the single frequency heating will be presented and compared with the preliminary result obtained after the implementation of the two-frequency heating. In addition, the results of the systematic investigation of the influence of extraction voltage and magnetic field on the beam emittance simulated in IGUN© compared with measurement are also reported.

## 2. The TRIUMF Electron Cyclotron Resonance Ion Source Charge State Booster
The TRIUMF CSB is a 14.5 GHz PHOENIX ECRIS from PANTECHNIK and was originally designed for single-frequency microwave plasma-heating to produce highly charged ions. The CSB is equipped with a three-electrode extraction system. The plasma chamber, the injection electrode and the extraction electrode are coated with pure aluminum. The TRIUMF CSB is routinely operated with helium as a support gas. Two cryo-pumps are connected to the booster at the injection and the extraction regions to achieve a low-pressure vacuum in the order of $10^{-8}$ *Torr* during operation. For axial plasma confinement, magnetic fields are generated axially by a set of three solenoid coils while radial confinement is achieved using the magnetic fields generated by hexapole permanent magnets. For the selection of the desired charge-bred ions, a Nier-type spectrometer [5] (combination of magnetic dipole and two electrostatic benders) is used. The typical operating magnetic field of the CSB are Binj = 1.14 T at I = 1050 A, Bmin = 0.35 T at 250 A, Bext = 0.87 T at I = 750 A.

## 3. Experimental Set-up and measurements
For all the results presented in this paper, the TRIUMF CSB high voltage bias was set to 10 kV. The puller electrode voltage was varied and the 2rms emittance of the CSB was determined via the Quadrupole Scan Technique (QST). For the single-frequency operation, the travelling wave tube amplifier power was set to 350 W. For the operation of the two-frequency heating, it was implemented using a single waveguide because the ECRIS CSB was not designed to accommodate two separate waveguides. A low-power, high-frequency combiner was used to add two microwave signals operating at two separate frequencies. The combined signal was fed into a broadband travelling wave tube amplifier (TWTA), and the combined RF power is transported into the plasma chamber via a WR-62 waveguide.

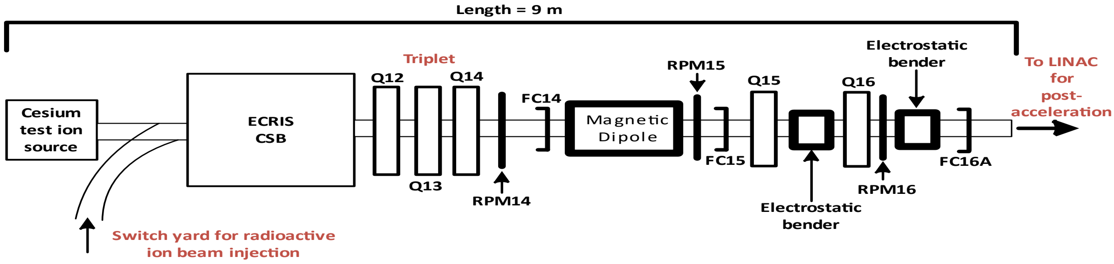


Figure 1: Schematic of the TRIUMF ECRIS CSB Beamline

Figure 1 shows the layout of the injection and extraction beamlines of the TRIUMF CSB. The Cesium test ion source, located upstream of the CSB, is used for injection, plasma and extraction system tuning. Extracted ions from the CSB are overall focused by the triplet Q12, Q13 and Q14, while the profile and the total current of the extracted beam from the CSB are monitored by the RPM-14 and Faraday cup FC14 respectively. The combination of magnetic dipole and two electrostatic benders act as a Nier-type spectrometer for the selection of the desired highly charged ions before injection into the linac for post-acceleration. The beam current measured on the Faraday cup FC16A is considered to have fewer background ions of similar A/q.

Singly charged Cesium ion beam of about 22 $nA$ was injected from the test ion source, and the frequency of the microwave was tuned to determine the frequency that produces the maximum intensity of $Cs^{24+}$ monitored on FC16A. The extraction system of the CSB, the adjacent beam transports up to the Faraday cup FC16A were optimized for the extraction and transport of the $Cs^{24+}$ beam. The difference between the high voltage bias of the test ion source and the CSB, the delta-V value, was varied to determine the voltage at which the injected ions were efficiently captured by the plasma. During the variation of the delta-V, the intensities of $Cs^{+}$, $Cs^{18+}$, $Cs^{21+}$ and $Cs^{23+}$ were monitored on the Faraday cup FC16A. Figure 2 (left) shows the normalized current of $Cs^{+}$, $Cs^{18+}$, $Cs^{21+}$ and $Cs^{23+}$ plotted against delta-V. It can be seen from the plot that as the delta-V increases the intensities of $Cs^{18+}$, $Cs^{21+}$ and $Cs^{23+}$ increase until delta-V reaches 13.0 V where the intensities of the Cesium charge state are maximum. However, further increase of delta-V leads to a reduction in the intensities of the charge state. This behaviour indicates that below delta-V = 13.0 V, $Cs^{+}$ ion beam injected into the CSB is strongly repelled by the positive potential of the plasma but efficiently captured when delta-V reaches 13.0 V and passed through the plasma without being captured at delta-V greater than 13.0 V. The plasma potential seems to be of the order of 13 V. On the other hand, the intensity of $Cs^{+}$ extracted increases linearly between 10 V and 20 V which indicates that some or all of the $Cs^{+}$ ions injected were captured by the plasma but were repelled below 10 V and not captured above 20 V, the behaviour that is evident in the shape of the distribution of the intensity of $Cs^{18+}$, $Cs^{21+}$ and $Cs^{23+}$.

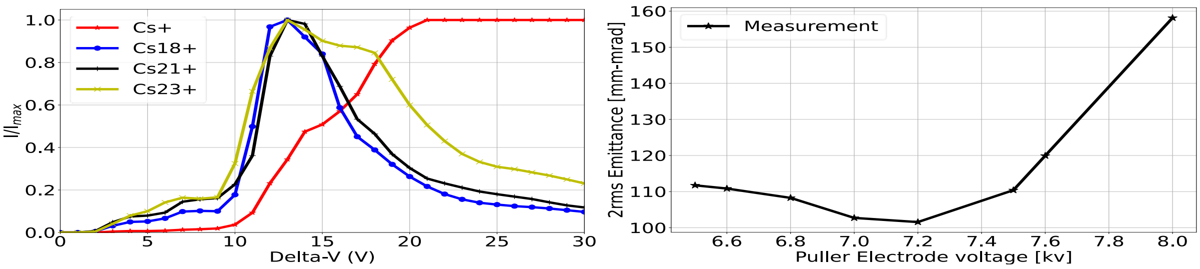


Figure 2: (left) Normalized Beam intensities of some selected Cesium charge states versus Delta-V. (right) 2rms Emittance of the total current extracted from the TRIUMF ECRIS CSB using Quadrupole Scan Technique

### 3.1. Emittance versus Puller electrode voltage

The Quadrupole scan technique (QST) was deployed via scanning through a range of focusing strength of a quadrupole and measuring the beam size at a given drift length downstream of the quadrupole, and by using the Twiss parameters transformation, the shape and the orientation of the emittance phase space can be determined at any location in the beam transport. The technique is well understood, and it has been used in several accelerator facilities [6]. Using the QST, the 2rms emittance of the CSB was measured as a function of the puller electrode voltage by scanning the strength of the quadrupole (Q14) of the triplet located after the extraction system and measuring the beam size on the profile monitor RPM-14 (see Figure 1). The puller electrode voltage was varied between 6.5 and 8.0 kV. Figure 2 (right) shows the plot of the 2rms emittance versus the puller electrode voltage. As seen, at 6.5 kV, the emittance was measured to be 111.7 mm-mrad, and as the puller electrode voltage is increased, the beam emittance decreases to 101.3 mm-mrad at 7.2 kV which is the minimum emittance. However, with a further increase in the voltage on the puller electrode, the beam emittance increased until it reached 156.9 mm-mrad at 8.0 kV. The behaviour of the emittance as the puller electrode voltage is changed suggests that the plasma boundary changed from the concave shape (low density, high extraction field) at 6.5 kV to a planar shape (moderate density, matched extraction field) at 7.2 kV and then convex shape (high density, low extraction field) at 8.0 kV, which has been observed in IGUN simulations of the extraction system.

### 3.2. Single Frequency Heating compared with the Preliminary result of Two-frequency heating

For the single frequency heating, the TWTA power was set to 350 W at a frequency of 14.5 GHz, while for the two-frequency heating, the CSB was operated at an additional rf frequency of 13.95

GHz. Meanwhile, regardless of the power settings on the signal generators, the same amplification gain was applied by the TWTA, thus the output power of the amplifier was set to 150 W for the two-frequency heating. Figure 3 (left) shows the mass spectrum of the CSB with and without Caesium between A/q of 3 and 10 with operation with single frequency heating. This A/q region is mostly dominated by residual ions from Carbon, Nitrogen and Oxygen. The peaks of the Caesium charge states are indicated by the arrows and the maximum charge state of Caesium that can be measured in the single frequency heating mode is 27+.

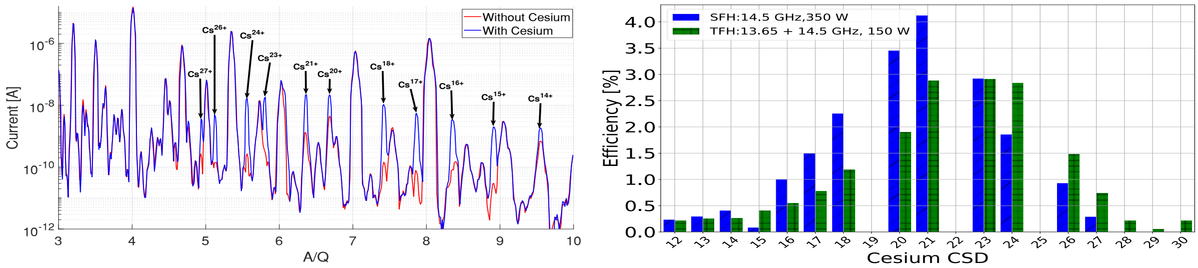


Figure 3: (left) Mass Spectrum of the CSB with and without Caesium. (right) The efficiency of Caesium charge state in single and two-frequency heating modes

In Figure 3 (right), the efficiency of Caesium in single frequency heating mode is compared with the efficiency of Caesium in a preliminary (not optimized) measurement of the two-frequency heating mode. Although, the charge state booster and the adjacent beam transport shown in Figure 1 were not properly optimized for the two-frequency heating, the maximum charge state of Caesium that can be measured shifted from 27+ for single-frequency heating to 30+ for two-frequency heating. In addition, while $Cs^{21+}$ has the maximum efficiency of 4.1 % in the single-frequency heating mode, the maximum efficiency shifted to $Cs^{23+}$ in the two-frequency heating regime with an efficiency of 2.9 %. Meanwhile, during the operation of the CSB in the two-frequency heating mode, the TWTA got damaged while performing frequency tuning. There was a high power reflection from the plasma and damaged the tube of the TWTA, and further measurements and optimization of the CSB using this approach of the two-frequency heating could not proceed further.

## 4. Extraction system simulation

To improve and optimize the emittance of the extracted beam from the TRIUMF CSB, its extraction system was simulated for the first time with IGUN© code. To gain the required input parameter, the magnetic field distribution of the CSB was modelled and simulated in OPERA and then benchmarked against the measured magnetic field distribution of the GANIL charge state booster [7], a twin source of the TRIUMF CSB.

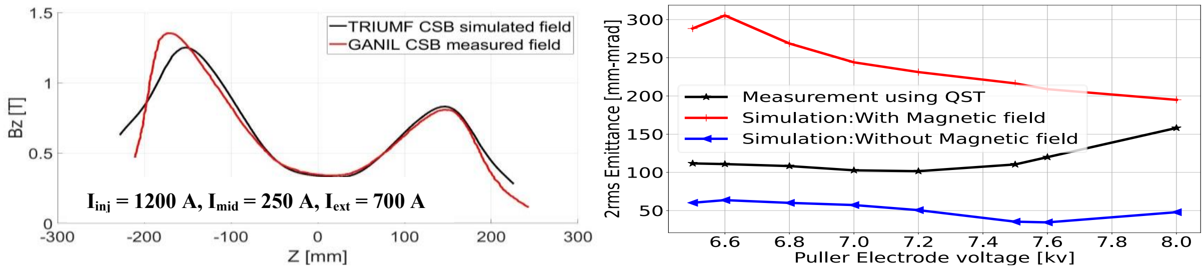


Figure 4: (left) Simulated magnetic field distribution of the TRIUMF CSB compared with the GANIL CSB measured field. (right) Comparison of the measured 2rms emittance with simulated 2rms emittance with and without the magnetic field

Figure 4 (left) compares the TRIUMF CSB simulated magnetic field distribution with the measured field of the GANIL CSB. The two fields are not matched at the injection region because the injection iron plug of the GANIL CSB is different from the TRIUMF CSB. The coils and other iron parts are similar. Since the simulated magnetic field of the TRIUMF CSB agreed with the measured magnetic field of the GANIL CSB at the extraction region, therefore the magnetic field values were imported into IGUN for the extraction system simulations. In the simulation, the difference between the biased voltage of the CSB and the voltage on the puller electrode which is defined as the extraction voltage was varied and beam emittance with and without magnetic field was calculated. The simulated emittances were compared with the measured 2rms emittance (black plot) of the CSB. As shown in Figure 4 (right), the measured emittance of the CSB does not agree with the simulated emittance assuming the magnetic field determined via OPERA (red plot). To gather information about the influence of the magnetic field on the beam formation, the magnetic field in the simulation was switched off and the extraction voltage was varied again, and the simulated emittance without magnetic field was calculated (blue plot). As it can be seen in Figure 4 (right), the emittance without the magnetic field is smaller compared with the case with the magnetic field. It demonstrates the strong influence of the magnetic field distribution in the extraction region on the beam emittance. The measurement reveals values somewhere in between these cases, which indicates that the magnetic field of the CSB is not yet correctly modelled with the geometry data available. Therefore it is planned to map the magnetic field distribution of the CSB in the near future.

## 5. Conclusion and Outlook

The research campaign and the deployment of techniques to improve the efficiency and beam quality of the TRIUMF charge state booster are in full swing. The implementation of the two-frequency heating of the plasma of the CSB indicated a significant increase in the electron energy and current density of the booster by measuring the charge state of Cesium up to 30+. A new approach to implement the two-frequency heating has been started. The new approach will involve using two separate TWTAs, a power combiner and a circulator to prevent reflected power from the plasma from damaging any of the RF components. It will be possible to individually adjust the power of each frequency of the microwave for better propagation into the plasma. Investigation of the effect of frequency gap and frequency range on the intensity of the maximum charge state will be conducted. Furthermore, the CSB will be opened during the next shutdown to directly measure its axial magnetic field distribution for benchmarking against the simulated magnetic field. Measuring the magnetic field will be beneficial for the optimization of the extraction system of the booster which is being modelled in IGUN©.

## 6. Acknowledgement

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