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NEW INJECTION BEAMLINE FOR TRIUMF CYCLOTRON*

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Abstract

The TRIUMF ion source and injection system beamline is used to transport the 300 keV H$^-$ beam from the ion source to the injection into the 500 MeV cyclotron. The vertical section of the beamline, upgraded in 2011, is very robust and reliable, while the horizontal section, now 50 years old, is very demanding in maintenance, and it presents a high risk of downtime due to ageing. The horizontal beamline is being re-designed with well-proven optical concepts, and modern UHV technologies already used in the vertical section, and in the ARIEL RIB transport system; this will produce a more efficient system that is easier to maintain and tune. The beamline will use electrostatic optical modules like matching, periodic, and 90-degree achromatic bend sections; updated elements include bunchers, a high-energy pulser, a 5:1 selector, and a new set of diagnostics. A crucial aspect of the new beamline is a magnetic shield, to compensate the cyclotron's stray field, comprised of a μ-metal in-vacuum liner allowing HV feedthroughs and diagnostics insertion without breaking the shield's continuity. The new injection beamline will be controlled via EPICS. This paper presents the status of the project.

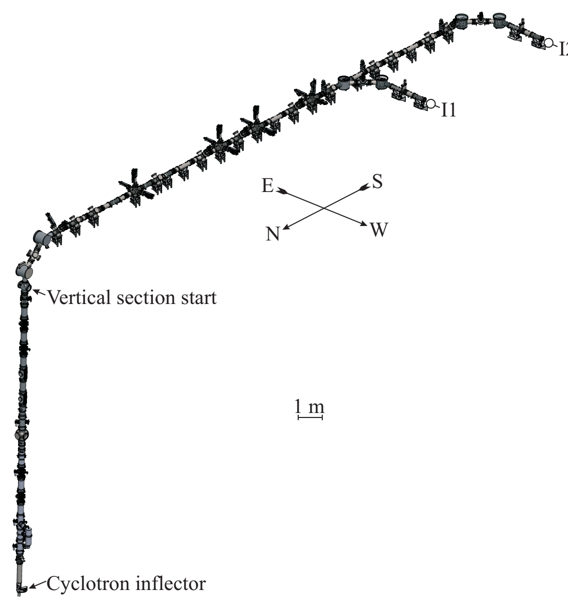

Figure 1: New injection beamline 3D model (including existing vertical section).

INTRODUCTION

The ion source and injection system is an electrostatic beamline that transports a 300 keV H$^-$ beam from the ion source terminal to the injection point, the inflector, of TRIUMF 500 MeV cyclotron [1]. At the moment a single ion source terminal, I1, is in operation since 1974, while a second terminal, I2, is being developed. One of the project requirements is having the capability of feeding the H$^-$ beam into the new transport section from two redundant terminals.

The beamline, from the ion source terminal to the inflector, is divided into a horizontal and a vertical section for practical purposes. The vertical section of the beamline was upgraded and commissioned in 2011 [2,3], and, since then, it operates very reliably. The horizontal beamline, which still is the original installation, needs to be updated as well since it requires significant routine maintenance, and it presents a high risk of downtime due to ageing equipment (optics, diagnostics, vacuum, etc.). The overall layout of the new horizontal installation is represented in Fig. 1.

The re-design is taking advantage of the recent experience with the ARIEL RIB transport system [4], which is also a complex of electrostatic beamlines. New technologies are to be adopted including metal seals (ConFlat® flanges), and ultra-high vacuum (UHV) materials and assembly procedures in order to reach a lower pressure (10^{-8} Torr) with respect to the present installation, and hence reduce beam losses due to residual gas interaction.

The new injection beamline is planned to be controlled via EPICS like all the ISAC/ARIEL accelerator systems. The vacuum system of the present installation has already been migrated to EPICS. It is foreseen though that some cross talking with the original Central Control System (CCS) will still be necessary to exchange information and/or interlock signals from the cyclotron.

BEAM OPTICS

Basic beam transport requirements for the horizontal injection beamline are specified in table 1.

The injection beamline consists of electrostatic optics modules such as periodic sections, 90-degrees achromatic bend sections and matching sections. The electrostatic optical elements (quadrupole, bender and steerer) have been modelled in OPERA® to calculate the realistic electric fields to be used in the beam dynamics simulations.

The ion beam transport calculations have been performed for the given beamline layout (see figure1) at the I1 and I2 injection terminals. The position of the ion source at I1

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Table 1: Summary of Basic Beam Transport Requirements

Parameter	Requirement
Beam species	H^-
Beam energy	300 keV
Maximum beam current	1 mA
Beam emittance at 300 keV	12.0 µm
Pulser Frequency	375 Hz–1.126 kHz
Beam duty cycle	0.1% – 99.0%
Bunching frequency	23.06 MHz
Localized maximum beam loss	<10 µA
Vacuum	$\ll 1 \times 10^{-7}$ torr

and I2, as well as the horizontal section with respect to the vertical section has been measured and fixed. This gives a constraint on the new horizontal beamline layout and its total length, which is approximately 34 m.

The beam envelope calculations have been performed from the beam waist at the exit of the 300 keV I2 terminal accelerating column up to the common periodic section for I2 and I1, and then up to the vertical beamline. The optics out of the I1 terminal is a copy of the I2 section. In these envelope calculations, the space-charge effect is taken into account for a 295 keV ion beam with a current up to 1 mA.

Figure 2 shows the calculated beam envelope from the I1 terminal through the horizontal injection beamline, up to the exit of the 90° vertical bend section. A 90° bend is achieved by means of two 45° electrostatic benders, and eight quadrupoles to maintain achromaticity. The second 45° bender of the I1 horizontal bend section is hollow to allow the beam from I2 to pass straight through, when the high voltage on this bender is turned off.

The beamline downstream of the I1 horizontal bend section is a common beamline for transporting the H^- beam from either the I1 or I2 terminal. Switching transport from one to the other terminal requires a polarity switch in the last quadrupole of the I1 horizontal bend section.

The concept of the optical modules is similar to the optics modules in the existing beamline, however, the length of the optical module differs from the existing one. Each periodic section has a 45° phase advance.

Longitudinal Beam Dynamics

The main feature of the longitudinal dynamics is the buncher, operating at the fundamental frequency of 23 MHz, to bunch at the cyclotron injection. The current configuration has two (double-drift) double-gap single-harmonic bunchers 4 m apart, the second operating at 46 MHz. In the new installation we are using only one "single-gap" multi-harmonic buncher ($\beta\lambda = 0.33$ m for the fundamental), like in the ISAC facility or in other laboratories [5]. The "single-gap" is referred to the space between two conical RF electrodes, but, unavoidably, there are two additional gaps between each electrode and the respective ground side, which are designed to efficiently optimize the TTFs considering all harmonics while fitting within the available insertion distance of 35 cm.

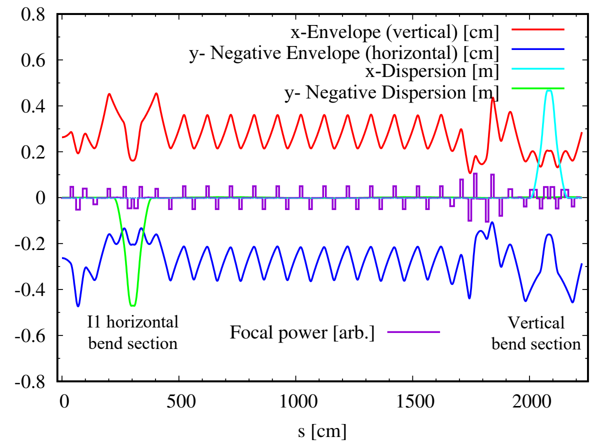

Figure 2: Calculated beam envelope (2RMS, positive for x, negative for y) for an extracted beam of 1 mA 295 keV H^- beam from the I1 terminal through the section of horizontal injection beamline with $\varepsilon_{4\mathrm{rms}}$ =6 µm.

Multi-particle simulations have been conducted, using realistic fields calculated in COMSOL®, to compare the new approach versus the current configuration. The longitudinal phase, displayed in Fig. 3, shows that the multi-harmonic buncher (right) perform as well as two separate bunchers (left). Furthermore a single buncher reduces operational overhead.

To maintain the current capabilities, a 300 keV high-voltage pulser operating at 3 kHz is going to be installed to generate macro-pulses at the experimental stations, and, in addition, an updated 4.6 MHz chopper to increase bunches separation is foreseen. The chopper selects one out of five bunches (5:1 selector) using a sine-wave mode similarly to the ISAC MEBT chopper [6].

STRAY FIELD COMPENSATION

One of the major issues to be addressed is the fact that the beamline is located in the cyclotron's stray magnetic field. This background field has been measured [7], and it follows fairly close the theoretical model of a single coil loop [8].

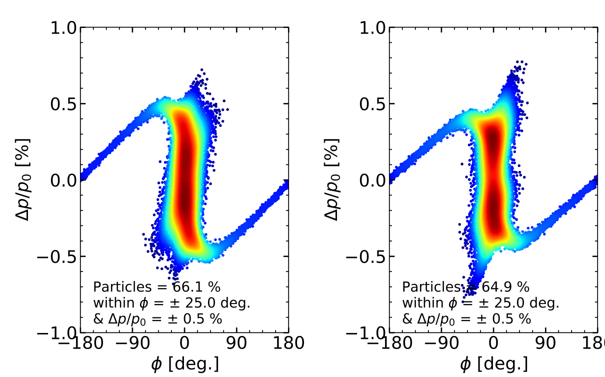

Figure 3: Longitudinal phase space at the cyclotron injection for the current double-drift (left) and for new single multi-harmonic buncher (right) configuration.

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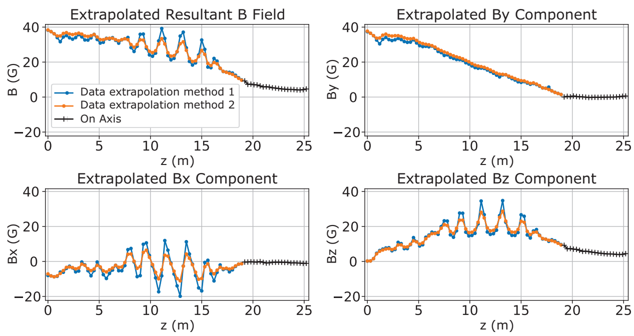

Figure 4: Measured stray magnetic field: the horizontal scale represents the distance from vertical beamline (z=0) along the horizontal section.

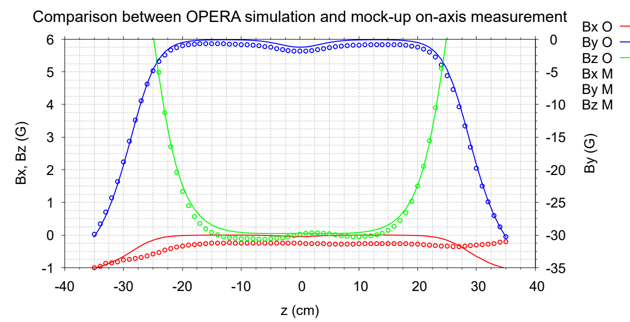

Figure 6: OPERA® simulation (O) compared to μ-metal mock-up on-axis measurement (M): z=0 corresponds to the center of the mock-up and hence the diagnostic port openings, z=±20 correspond to the HV feedthrough openings, z=±27 correspond to the edges of the mock-up.

The measurements are represented in Fig. 4 (right); spikes in the data are attributed to soft steel elements in the existing beamline.

The vertical is the strongest component of the magnetic field, and it reaches a peak of about 35 G close to the vertical injection line. The horizontal component is on average less than 5 G, while the longitudinal one, with a peak of about 20 G, does not affect the beam transverse dynamics. The transverse components (vertical and horizontal) must be compensated as per requirements to avoid beam losses along the beamline. The compensated residual field should be, on average, below 1 G.

A passive compensation system (versus an active one) has been developed consisting of a 2 mm thick μ-metal shielding liner fitted inside the vacuum chamber as represented in Fig. 5 (in blue). Dedicated openings are implemented for the HV feedthroughs (1.33″ CF) and diagnostic devices (8″ CF). Optical elements (quadrupoles and steerers) are located inside the liner. Liners of adjacent vacuum chambers are magnetically (and mechanically) connected to form a single shielding unit for the whole length of the beamline.

The shielding design has been simulated in OPERA®, and two μ-metal mock-ups have been fabricated, and measured in the cyclotron stray field along the existing horizontal beamline about 1 m eastward close to the vertical section.

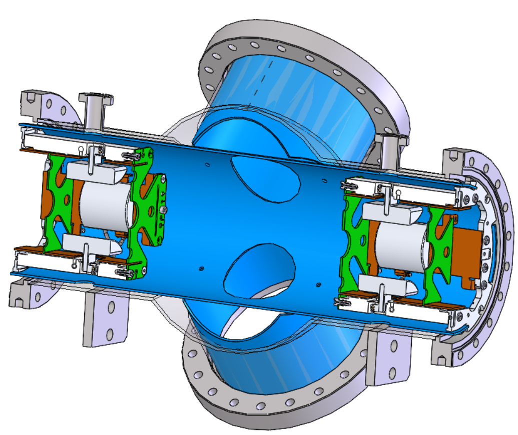

Figure 5: Model of the μ-metal shielding liner (blue) inside the vacuum chamber. Quadrupole skimmers (green) and ceramic protection plates (brown) are biased to 300 V.

OPERA® simulations and the mock-up on-axis measurements are in agreement, as represented in Fig. 6, showing an average field suppression to < 1 G, with a peak at the diagnostic port location (z=0 cm), as expected.

DIAGNOSTIC

The new diagnostics is mostly going to be an upgraded version of the ARIEL RIB transport system [4]. The upgrade is for higher power beam, up to 300 W. Such diagnostics includes: Faraday cup, wire profile monitor, selection slits and Allison emittance scanners. In addition ACCT non-intercepting current monitor are going to be installed.

The selection slits are an essential feature because they select the beam current from 0 to 1 mA. This allows for the source to run always at the same settings, hence producing the same beam output in the terms of intensity (space charge) and beam dynamic parameters. On the other hand, this requires the slits to be able to sink a full mA. Controlling the beam current with slits also allows to benefit from the reduced emittance when reduced current is required.

MACHINE PROTECTION SYSTEM

As in the current installation, the main component of the machine protection system is the current read-back of the optical element (quadrupole, steerers and benders) skimmers, which are the front and back protection plates with round beam aperture, see Fig. 5 (in green).

The skimmers are biased at 300 V; this provides an absolute current readback of the 300 keV H^- beam lost on the skimmers. The readback from all the skimmers, combined with the ACCT readings, allows for beam loss detection.

SUMMARY

The new injection beamline is in an advanced stage of detailed design. Critical components have been developed. Assembly is expected in the second half of 2023, while installation is planned for the 2024 winter shutdown.

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