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DESIGN OF A MULTI-HARMONIC BUNCHER FOR TRIUMF 500 MeV CYCLOTRON

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Abstract

The TRIUMF 500 MeV cyclotron injection system consists of a 40 m long beamline to transport the 300 keV H^- ion beams into the cyclotron. Part of the original beamline, the vertical injection section, was replaced in 2011, while the remaining horizontal injection section is currently being redesigned for replacement. As part of the horizontal injection beamline upgrade, the present buncher system will be replaced with a new one. The current buncher configuration consists of two double gap bunchers: the first buncher operates at the cyclotron RF frequency (23.06 MHz) while the second operates at the second harmonic frequency (46.12 MHz). The proposed new buncher is based on a two-electrode multi-harmonic system, which will be operated by up to three harmonics. The beam dynamics studies have been performed, including the space-charge effects using the particle-in-cell code WARP. Simulation results of longitudinal beam dynamics are presented for transporting beam intensity up to 1 mA.

INTRODUCTION

The demand for the total extracted beam from the TRIUMF 500 MeV cyclotron is increasing with the addition of the new rare isotope beam facility ARIEL [1]. In order to meet the increased total output from the cyclotron, the injection intensity and beam brightness also needed to be improved. The injection beam upgrade program has started in order to meet the increased total output by improving the injection intensity of high-brightness beams. The vertical injection beamline was upgraded in 2011 as the initial phase [2]. The second phase of the upgrade program consists of upgrading the horizontal injection beamline [3] and adding a new ion source injection terminal (I2) [4]. The new buncher is part of the ongoing upgrade of the horizontal injection beamline. The basic parameters through the injection beamline is presented in Table 1.

Currently, two double gap bunchers are being used in the injection beamline [5]. The first buncher is located 21 m downstream from the injection point in the horizontal injection beamline, while the second buncher is located 4.54 m downstream from the first buncher. The first buncher operates at the cyclotron RF frequency of 23.06 MHz, while the second buncher operates at the second harmonic of 46.12 MHz. Using the current buncher system, the total extracted current from the cyclotron is approximately 0.28 mA, with an injection current of 0.4 mA. As part of the upgrade of the horizontal injection beamline, the current buncher system will be replaced with a new multi-harmonic buncher.

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Table 1: Basic Beam Specifications

Parameter	Value
Beam species	H^-
Beam energy	300 keV
Maximum beam intensity	1 mA
Maximum emittance ($4\epsilon_{RMS}$) at 300 keV	12.0 µm
Beam duty cycle	0.1% – 99%
Bunching frequency	23.06 MHz

MULTI-HARMONIC BUNCHER

The concept of a multi-harmonic buncher has been widely used elsewhere in an ion bunching system by combining the fundamental RF wave with its various higher harmonics to obtain a nearly sawtooth-like waveform [6–8]. In our case, a two-electrode three-gap multi-harmonic buncher system has been designed with a 1.27 cm cm aperture radius and a 0.5 cm gap between the electrodes. The layout of the buncher system is shown in Fig. 1. The center distance between the first and second RF gap is 16.765 cm and 8.383 cm for the second and third RF gap, respectively. The first (23.06 MHz) and third harmonics (69.18 MHz) are applied to the first electrode, while the second electrode is applied with the second harmonics (46.12 MHz). The electrostatic modeling of the buncher has been done with the code COMSOL [9]. Figure 2 shows the calculated electrostatic field along the

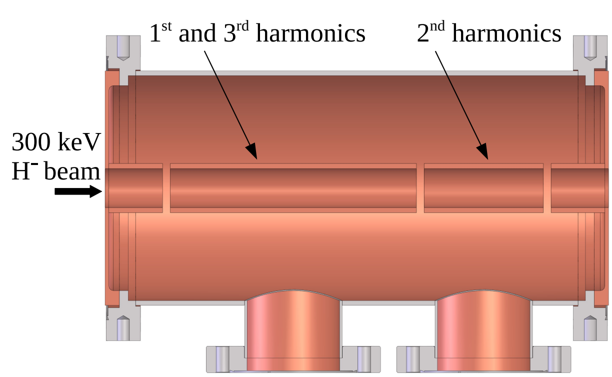

Figure 1: A cross section view of the new multi-harmonic buncher. Note that the RF resonators are not included in this figure.

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axis of the buncher with an applied potential of 1 V. The particle-in-cell code WARP3D [10] was used in an earlier work to simulate the longitudinal beam dynamics for the existing buncher system in the injection beamline [11]. In this work, the WARP3D code has also been chosen to study the performance of the multi-harmonic buncher.

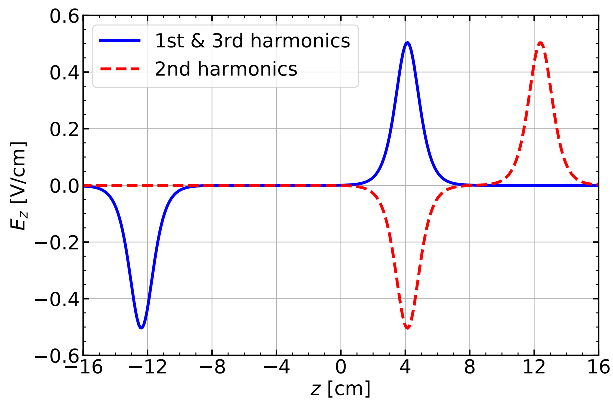

Figure 2: Calculated electrostatic field (E_z) along the axis of the buncher with an applied potential of 1 V.

Beamdynamics Simulations

The calculated electrostatic field along the axis of the multi-harmonic buncher is shown in Fig. 2 and the calculated field map is imported into the particle tracking code WARP3D. The buncher is used to create a more focused beam of ions by modulating the beam with the first three harmonics of 23.06 MHz. The buncher is installed at a distance of 20 m from the injection point, which is one meter closer than the existing buncher system. In order to keep the simulation model simple, 20 lattice periods have been assumed between the multi-harmonic buncher and the injection point at the cyclotron. The length of one lattice period is 1 m with a phase-advance of 45°, and each lattice consists of two electrostatic quadrupoles. Space-charge effects from the neighboring bunchers are included in the simulations by using periodic boundary conditions along the beam direction.

The TRIUMF cyclotron's longitudinal acceptance is determined by the spiral inflector's dispersion, the RF dee voltage, and space charge [12]. To simplify comparisons, the buncher performance is evaluated using a rectangular window in phase space, with 50° phase acceptance and 1 % in $\Delta p/p$. The multi-harmonic buncher is compared to the existing buncher using simulations with an initial beam intensity of 0.650 mA. The results of the simulations show that the performance of the multi-harmonic buncher is comparable to the existing buncher, with approximately 56 % of the particles within the desired phase acceptance and momentum spread. Figure 3 (left) shows the calculated longitudinal phase-space for the existing buncher, and Fig. 3 (right) shows the calculated longitudinal phase-space for the new multi-harmonic buncher at the injection point.

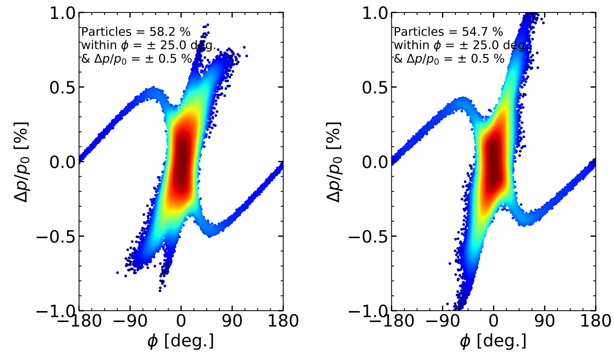

Figure 3: Calculated longitudinal phase-space of the 300 keV H^- beam at the cyclotron injection for the existing two double gap buncher(left) and for the multi-harmonic buncher configuration (right) with an initial beam intensity of 0.650 mA and $\varepsilon_{4\mathrm{rms}}$ = 8 µm .

In order to improve the bunching efficiency in the case of higher beam intensity, particularly above 0.5 mA, the buncher needs to be located closer to the injection point. As moving the position of the buncher along the beamline is impractical for various beam intensities, an additional first harmonic buncher (re-buncher) 13.5 m away from the multi-harmonic buncher has been included as a re-buncher in the simulation for beam intensities higher than 0.5 mA. The calculations show that adding a re-buncher 13.5 m away from the multi-harmonic buncher improves the bunching efficiency for beam intensities higher than 0.5 mA. As an example, Fig. 4 shows the calculated longitudinal phase-space with an initial beam intensity of 1 mA. The bunching efficiency of this system is about 67 % (within $\phi = \pm 25°$ and $\Delta p/p = \pm 0.5\%$) at a 1 mA injection line current, which could support up to 0.67 mA of extracted current from the cyclotron. Figure 5 shows the calculated transverse phase-space in the horizontal (x) and vertical (y) planes at the location of the injection point. Figure 6 shows the calculated

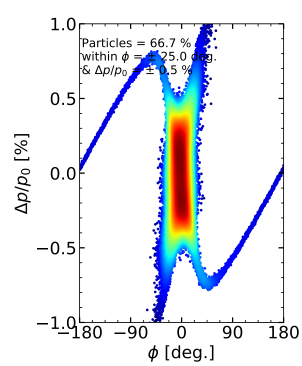

Figure 4: Calculated longitudinal phase-space of the 300 keV H^- beam at the cyclotron injection for the multi-harmonic buncher along with a re-buncher with an initial beam intensity of 1 mA and $\varepsilon_{4\mathrm{rms}}$ = 8 µm. About 67 % particles are within the phase acceptance of ±25° and momentum spread ($\Delta p/p$) of ±0.5%.

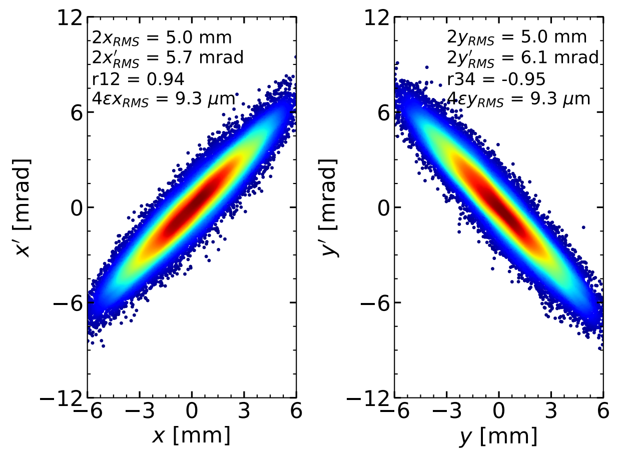

Figure 5: Calculated transverse phase-space of the 300 keV H^- beam at the cyclotron injection for the multi-harmonic buncher along with a re-buncher with an initial beam intensity of 1 mA and ε_{4rms} = 8 μm.

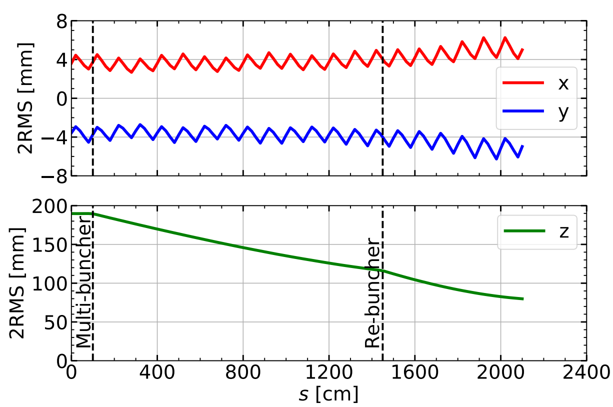

Figure 6: Calculated beam envelope (2RMS, positive for x, negative for y, longitudinal for z) for a 1 mA of 300 keV H^- beam transport through 21 periodical lattice along with the multi-harmonic buncher and a re-buncher with ε_{4rms} = 8 μm.

transverse (top) and longitudinal (bottom) beam envelope through these lattice periods, including the space-charge effects, with an initial beam intensity of 1 mA.

SUMMARY AND OUTLOOK

A new multi-harmonic buncher system has been designed that will be operated up to three harmonics. A particle-in-cell code was used to study the longitudinal beam dynamics for the new buncher system, including the space-charge effects. The new bunching system will be a combination of a multi-harmonic buncher and a first harmonic re-buncher for transporting beam injection beamline intensities higher than 0.500 mA. Simulation results of longitudinal beam dynamics are presented for transporting beam intensities up to 1 mA. In the near future, the new multi-harmonic buncher system will be installed and commissioned for use in the new horizontal injection beamline of the 500 MeV cyclotron at TRIUMF.

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