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A cooler-buncher for the $N = 126$ factory at Argonne National Laboratory

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ABSTRACT

The $N = 126$ factory currently under construction at Argonne National Laboratory's ATLAS facility will make use of multi-nucleon transfer reactions to produce nuclei around the $N = 126$ shell closure that are of interest for the study of the rapid neutron capture process and are not available in sufficient quantities using common particle-fragmentation, target-fragmentation, or fission production techniques. As part of this facility, a radio frequency quadrupole (RFQ) buncher will cool and accumulate the beam, converting a high-emittance, continuous beam into a low-emittance bunched beam suitable for trapping. Here, the construction of the RFQ cooler-buncher, based on the design used at the National Superconducting Cyclotron Laboratory's BECOLA and EBIT cooler-bunchers, will be discussed. This design features injection optics optimized to maximize acceptance, separated cooling and bunching regions, and a simplified RFQ electrode construction.

1. Introduction

The $N = 126$ Factory is a facility under development at the Argonne Tandem Linear Accelerator System (ATLAS) at Argonne National Laboratory, intended to produce nuclei around the $N = 126$ shell closure. The properties of these nuclei, particularly their masses, are critically important for understanding the rapid neutron capture or r process [1,2]. Measurements of these masses, however, are currently impossible based on the available production techniques for rare isotope beams. In the case of target- or projectile-fragmentation, the necessary targets are unavailable, and relevant beams will have to wait for next-generation facilities like FRIB. Fusion, the other common production technique for heavy nuclei, is also unable to produce these isotopes. In all these cases, the production cross sections of the isotopes of interest in the $N = 126$ region are too low to allow for mass measurements [3]. An alternate production method, multi-nucleon transfer (MNT) reactions, makes use of the transfer of multiple nucleons between heavy beams and heavy targets in deep inelastic collisions near the Coulomb barrier [4,5]. The $N = 126$ factory will make use of MNTs between heavy beams and heavy targets to produce ions; for example, a 9 MeV/u, 5 pμA beam of ^{136}Xe impinging upon a target of ^{198}Pt is expected to produce isotopes near $N = 126$ with individual rates in excess of 10^4 particles per second at the target.

The wide-angle-distributed MNT reaction products will need to be converted into isotopically-separated bunches that can be delivered to an experimental station. They will be collected using a large-volume helium-filled radiofrequency (RF) gas catcher [6], built following the linear RF gas catcher [7] design developed at Argonne and currently in use at CARIBU [8]. A dipole mass separator magnet with mass resolving power $R \sim 10^3$ will be used to separate ions by mass number for matching the limited acceptance of the downstream devices. The continuous ion beam will then be injected into a beam cooler and buncher, which is a buffer-gas-filled linear radiofrequency quadrupole (RFQ) trap designed to convert a high-emittance continuous source into low-energy, low-emittance ion bunches [9]. Collisions with the buffer gas reduce the transverse emittance and energy spread, providing a damping force and "cooling" the ions, while the RFQ electrodes are segmented and a potential gradient is applied such that a weak electric field drags the ions axially to the end of the cooler-buncher [10]. Here, a potential well is created accumulating or "bunching" ions; these bunches are then released downstream by switching the trap potential. Cooler-bunchers are used in many facilities in this role, including at CARIBU [8], ISOLTRAP [9,11], JYFLTRAP [12], LEBIT [10], SHIPTRAP [13], TITAN [14], and TRIGA-SPEC [15,16]. Finally, the Notre Dame Multi-Reflection Time-of-Flight Mass Spectrometer (ND MR-TOF) [17] will provide high mass separation ($R \sim 10^5$), suppressing isobaric contaminants. MR-TOFs are a common choice for isobaric separation at many rare isotope beam facilities [18–22], including at CARIBU [23].

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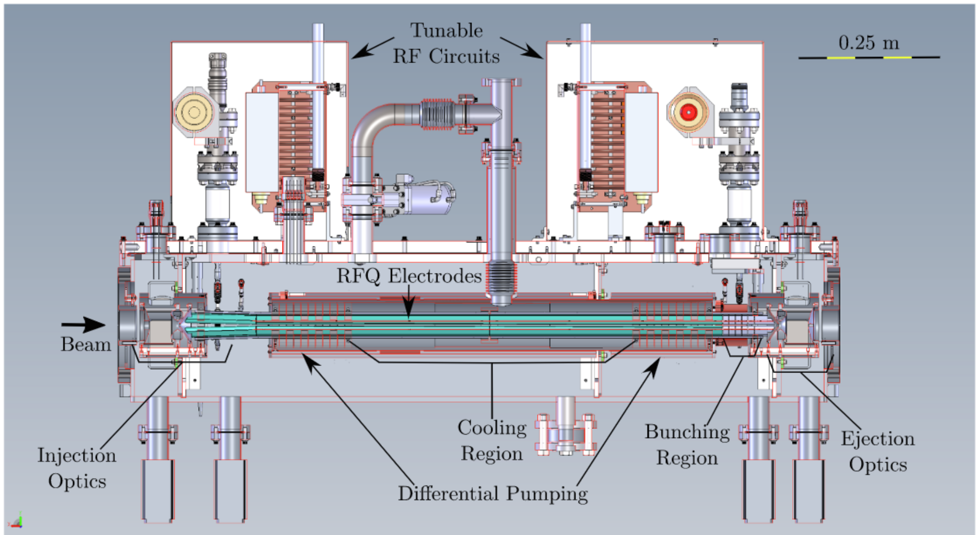

Fig. 1. Cross-section view of the cooler-buncher design. This view shows the RFQ electrode structure (teal), the PEEK disks that form the differential pumping barriers (off-white), and the injection and ejection electrodes. Also highlighted are the separate cooling and bunching regions.

An overview of the $N = 126$ facility can be found in Ref. [24], with a detailed discussion of the ND MR-TOF in Ref. [25].

2. Cooler-buncher design

The design selected for the $N = 126$ factory cooler-buncher is the same as the RFQ currently in use at the NSCL to provide bunched beams for the ReA post-accelerator Electron Beam Ion Trap (EBIT) [26], which in turn was based on the design used for the cooler-buncher at the Beam Cooler and Laser Spectroscopy (BECOLA) facility at the NSCL [27,28]. A cross-section of this design can be seen in Fig. 1, and an overview of the three primary novel features of this design follows.

2.1. Maximizing injection acceptance

As a device designed to operate using rare isotope beams, it is important to maximize the capture and transmission efficiency of the cooler-buncher. Minimizing losses on injection into the cooler-buncher can be done by ensuring that the emittance of the incident beam fits within the acceptance of the cooler-buncher. Since the upstream optics for the $N = 126$ factory were not determined when the cooler-buncher design was determined, maximizing the injection acceptance is particularly important. The injection optics of a device determine its characteristics. In this design, these ion optical elements consist of an immersion lens that decelerates the injected beam, a hyperboloid ring electrode, and a cone electrode [28]. The hyperboloid ring electrode creates a cylindrically symmetric quadrupole field, which both decelerates and focuses the beam into the RFQ region; the cone electrode is along an equipotential of the field of the hyperboloid ring, and reduces the penetration of the RF field from the RFQ electrodes into the deceleration region [29]. The first segment of the RFQ electrodes were also designed to maximize acceptance. Here, the RFQ electrodes are flared away from the beam axis to a 16 mm radius similar to that of the hyperboloid ring electrode and tapering back to the 7 mm radius of the other RFQ electrodes over several centimeters [27]. This allows the beam to expand slightly after passing through the hyperboloid ring electrode without colliding with the RFQ electrodes, while allowing the majority of the RFQ to have a smaller radius, which produces a steeper trapping pseudopotential and thus better radial confinement for the same RF amplitudes and frequencies. A cross-section view of this design and of the assembled injection optics can be seen in Fig. 2.

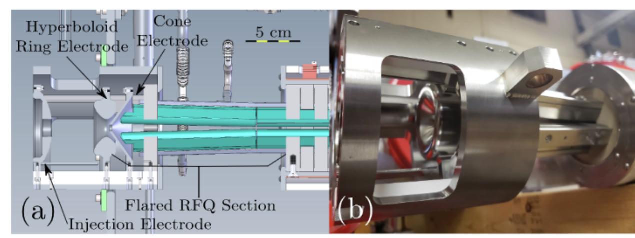

Fig. 2. (a) Cross-section view of the injection optics design, showing the injection electrode, hyperboloid ring electrode, cone electrode, and flared RFQ section. (b) Photograph of assembled injection optics.

2.2. Separated cooling and bunching sections

It is common to operate a cooler-buncher with the same pressure in both the cooling and bunching regions [8,9,11–16,30]. Higher pressure buffer gas results in shorter cooling times, but higher pressure in the bunching region results in collision-induced “reheating” or increased emittance on ejection. However, many “next-generation” designs make use of differential pumping between the cooling and bunching regions [10,28]. This allows the cooling region to have a high enough pressure that the cooling time is short enough for experiments with short-lived isotopes to be conducted, while simultaneously operating the buncher region at a low enough pressure to reduce the reheating of the ions upon ejection [27]. Here, the 49 cm long cooling region, with an intended operating pressure of $\sim 10^{-1}$ torr, is separated from the 10 cm long bunching region, with an intended operating pressure of $\sim 10^{-3}$ torr, by a 14 cm long differential pumping barrier. A similar differential pumping barrier separates the cooling region from the injection region, also intended to be operated at $\sim 10^{-3}$ torr.

2.3. Simplified RFQ rod construction

The longitudinal static potential of a cooler-buncher usually takes the form of a shallow drag field through the cooling section, pushing ions axially, followed by a sharper, deeper potential well in the bunching section that can be pulsed to eject bunches. A common approach to generating the drag potential is to segment the RFQ rods perpendicular to their long axis and capacitively couple separate DC static potentials to each segment, or to connect each segment to the next with resistors, and thus create the necessary potential gradient [8,9,11–13,15,16,31,32]. While these approaches achieve the desired

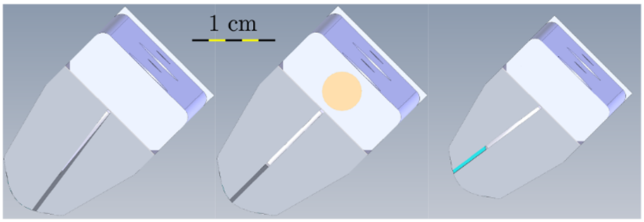

Fig. 3. Cross-sections of the RFQ electrode taken perpendicular to the beamline moving from downstream (left) to upstream (right), illustrating the diagonal segmentation creating the wedge-shaped DC electrodes (gray) and the RF backbone electrode (white) to which they capacitively couple.

results, they rely on many internal components and a large number of either external or internal electrical connections, which increases the number of possible failure points and complicates any maintenance. To reduce the number of electrodes, this design, as illustrated in Fig. 3, segments the RFQ electrode diagonally along their long axis, creating two wedges to which different potentials can be applied, creating a uniform drag field changing ~ 30 V across 82 cm with a significant reduction in electrical connections [27].

When the RFQ electrodes are segmented, it is necessary to ensure that each RF rod is driven with the same frequency with alternating rods at opposite phases, independent of the DC potential applied to an individual segment. Commonly, this is achieved through a network of capacitors or transformers isolating the DC potential applied to each segment from the RF amplifier. In the design for this cooler-buncher, however, an approach that reduces the complexity of the system has been adopted. A common RF "backbone" electrode runs the length of the 103 cm RFQ electrode, and the various RFQ segments couple capacitively to this electrode; the DC offset voltages of tens of volts is applied through leads passing through the RF backbone but separated by ceramic insulators [27]. Applied RF frequencies and amplitudes are anticipated to be 4–5 MHz and hundreds of volts for the mass range. Fig. 3 illustrates the wedge design of the DC electrodes and the RF backbone electrode through a series of cross-sections.

2.4. Assembly and commissioning

Assembly of the Cooler-Buncher following the design in Fig. 1 was completed, and electrical connections for the static and RF potentials were then made. The RF signal is applied through a feedthrough flange connected to the RF backbones with hollow y-shaped arms. The RF is applied to the flange with a tunable resonant LC circuit. The DC signals pass through the hollow RF connectors. These systems have been successfully tested, and further commissioning using stable ions and rare isotope beam from CARIBU is planned for 2019.

3. Conclusion

In summary, a cooler-buncher for the $N = 126$ factory at the ATLAS facility of Argonne National Laboratory has been assembled and the electrical systems tested. Further commissioning using stable and rare-isotope beam from CARIBU is planned for 2019, with the completion of the assembly of the $N = 126$ factory and the beginning of its commissioning planned for the end of 2019, with a measurement campaign to begin in 2020.

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