CONCEPTUAL DESIGN OF A RING FOR PULSE STRUCTURE MANIPULATION OF HEAVY ION BEAMS AT THE MSU NSCL*

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Abstract

The Reaccelerator (ReA) Facility at the National Superconducting Cyclotron Laboratory (NSCL) located at Michigan State University (MSU) offers the low-energy nuclear science community unique capabilities to explore wider ranges of nuclear reactions and the structure of exotic nuclei. Future sensitive time-of-flight experiments on ReA will require the widening of pulse separation for improved temporal resolution in single bunch detection while minimizing loss of rare isotopes and cleaning of beam decay products that might pollute measurements. In this proceedings, we present a preliminary design of a heavy ion ring that will address the task of bunch compression, bunch separation enhancement, satellite bunches elimination, cleaning of decay products, beam loss mitigation, and improvement of beam transmission.

INTRODUCTION

The Coupled Cyclotron Facility (CCF) at the NSCL [1–3] utilizes two superconducting cyclotrons to accelerate primary ion beams up to 160 MeV/u at 1 kW beam power on a production target for rare isotope beam (RIB) production for use in nuclear physics experiments. Secondary RIBs from the target are delivered to one of three main experimental areas. In the fast-beam experimental area, the shortest-lived RIBs are delivered with energies >150 MeV/u to experiments. In the stopped-beam experimental area, delivered RIBs are thermalized (~eVs) in either gas cells or a cyclotron gas stopper before transport to the trap and laser spectroscopy area. Lastly, in the ReA experimental area shown in Fig. 1, thermalized RIBs are captured and rapidly ionized in an Electron Beam Ion Trap (EBIT) charge breeder [**?**, 4]. The 12 keV/u [6] RIBs emerging from the EBIT then undergo separation in a Q/A achromatic spectrometer (operational range of $0.2 \leq Q/A \leq 0.5$), are bunched in a mutli-harmonic buncher (MHB), injected into a radio-frequency quadrupole (RFQ) for pre-acceleration to 600 keV/u, and finally injected into the superconducting linear accelerator (LINAC) for final acceleration up to 6 MeV/u. Upgrade plans exist to accelerate RIBs up to 12 MeV/u by adding more superconducting cyromodules.

The ReA RFQ and LINAC are designed to operate at 80.5 MHz. This allows ReA to serve as a testbed for Facility for the Rare Isotope Beam (FRIB) RFQ and superconducting RF (SRF) technology. The EBIT charge breeder produces high-charge state RIBs for ReA. Typical extracted beam properties of the EBIT are given in Table 1. The time structure of the bunch emerging from the EBIT depends strongly on the extraction scheme implemented [7]. To achieve optimal beam transmission through the RFQ, a MHB using three harmonics is utilized in the beam transport line [8]. For time-of-flight (TOF) measurements, the existence of satellite bunches at integer multiples of 12.4 ns from the primary pulse formed in the bunching process creates uncertainties in the measurements. Due to the short bunch pulse separation, the satellite bunches create ambiguity in the pulse time spread at the location of the detector as well as in the bunch detection. Figure 2 shows the bunched beam just before injection into the RFQ with non-linear tails overlapping the neighboring buckets of the RFQ. This results in the satellite bunches that were measured at the exit of the LINAC after acceleration. We present a conceptual design of a flexible buncher ring for heavy ions to address bunching challenges in ReA. The limited acceptance of the ring will also "clean" the RIBs of decay products that can confound measurements of interest of very short-lived isotopes.

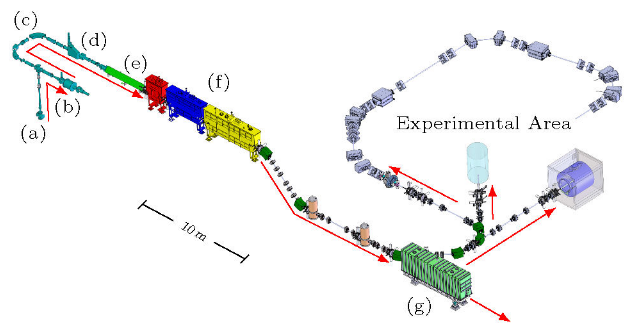

Figure 1: Diagram of the ReA facility where (a) thermalized RIBs are injected into (b) the EBIT charge breeder, undergo (c) A/Q separation after extraction, (d) matched and bunched with a MHB, (e) accelerated by a RFQ, and (f) finally injected into the SRF LINAC. Further acceleration (g) in a second LINAC section is possible.

Table 1: Properties of RIBs extracted from the ReA EBIT.

EBIT Parameters	Values
Extraction Kinetic Energy W_s	12 keV/u
Total Bunch Length σ_z	100 ns - 10s μs
Energy Spread $\Delta W/W_s$	< 0.5%
RMS Transverse Emittance ϵ_x, ϵ_y	< 10 mm·mrad

* Research supported by Michigan State University, MSU NSCL, ReA Project, and NSF Award PHY-1415462.
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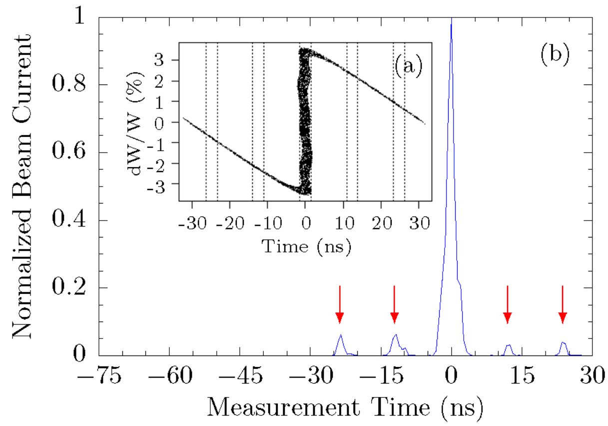

Figure 2: (a) Simulation of the longitudinal phase-space at the entrance of the RFQ. Dotted lines indicate neighboring buckets. (b) Measured normalized beam current. Red arrows highlight satellite bunches after final acceleration.

LATTICE DESIGN

A conceptual ReA buncher ring lattice is designed with four 90° sector dipole magnets– each with an effective length of 0.5 m and bending radius of 0.318 m. Edge angles entering and exiting the dipoles are chosen to be 30° to provide vertical focusing. Eight quadrupole magnets, 20 cm in length, provide horizontal focusing where the quadrupole coefficient is defined as $k_1 = (1/B\rho)(\partial B_y/\partial x)$. Two 1 m long straight sections on opposing sides of the ring have vanishing horizontal dispersion function and betatron function derivative at the centers. An insertion/extraction section will be placed in one straight section and a RF acceleration structure placed in the other. The momentum compaction factor [9], given as

$$\alpha_c \equiv \frac{\mathrm{d}C/C_o}{\mathrm{d}(B\rho)/(B\rho)_o} = \frac{1}{C_o}\oint\left(\frac{D(z)}{\rho}\,\mathrm{d}z\right), \qquad (1)$$

with $D(z)$ and ρ denoting the horizontal dispersion function and local bend radius, is $\alpha_c = 0.091$ for the ring. Figure 3 shows relevant lattice functions for the buncher ring design as calculated by MAD-X [10] and the MAD-X Polymorphic Tracking Code (PTC) library [11]. Corresponding lattice properties are summarized in Table 2. The resulting 8 m circumference storage ring is two-fold symmetric, and is compact to conserve space on the ReA platform.

LONGITUDINAL CONSIDERATIONS

The Hamiltonian for synchrotron motion of a heavy ion of charge state Q and mass number A in phase space coordinates $(\phi, \Delta W/\omega_o)$ can be expressed as

$$H = \frac{eV_p}{2\pi}\left(\frac{Q}{A}\right)\left[\cos(\phi_s+\Delta\phi)+\Delta\phi\sin\phi_s\right] + \frac{1}{2}\frac{h\eta\omega_o^2}{\beta^2 W_s}\left(\frac{\gamma-1}{\gamma}\right)\left(\frac{\Delta W}{\omega_o}\right)^2. \qquad (2)$$

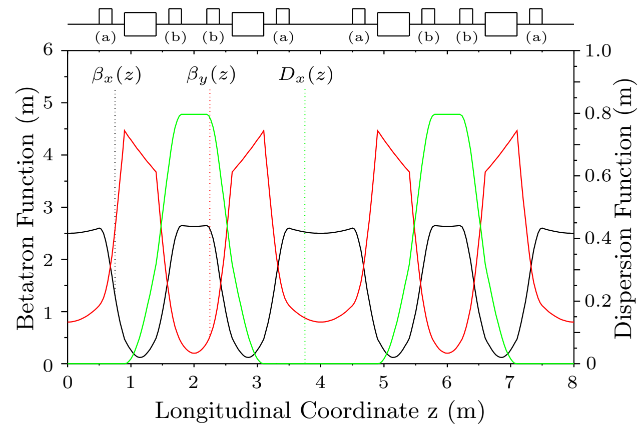

Figure 3: Horizontal and vertical betatron functions $\beta_{x,y}(z)$ and horizontal dispersion function $D_x(z)$ for the ReA buncher ring. (a) and (b) denote the quadrupole coefficients $k_1^{(a)}$ and $k_1^{(b)}$, respectively.

Table 2: Lattice parameters for the ReA buncher ring. Dipole edge angle definitions conform to MAD-X conventions.

Lattice Parameters	Values
Circumference C	8 m
Beam Kinetic Energy W_s	12 keV/u
Dipole Bending Radius ρ	0.318 m
Dipole Edge Angles ϵ_1, ϵ_2	30°
Quadrupole Coefficients $k_1^{(a)}$, $k_1^{(b)}$	11.007, 10.622 m^{-2}
β_x, β_y at Injection Point	2.5, 0.8 m
α_x, α_y at Injection Point	0, 0
Fractional Betatron Tunes ν_x, ν_y	0.11, 0.31
Momentum Compaction Factor α_c	0.091

Here, $\Delta\phi = \phi - \phi_s$ and $\Delta W = W - W_s$ are the deviations in RF phase and kinetic energy from a reference particle with synchronous phase ϕ_s and kinetic energy W_s, V_p is the peak RF voltage, h is the RF harmonic number, $\eta = \alpha_c - 1/\gamma^2$ is the phase slip factor, ω_o is the angular revolution frequency of a circulating reference particle, $\beta = v/c$, and $\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor. The RF phase ϕ is related to time t by $\phi = -h\omega_o t$. From Eq. (2), the turn-by-turn mapping equations are

$$\phi_{n+1} = \phi_n + \frac{2\pi h\eta}{\beta^2 W_s}\left(\frac{\gamma-1}{\gamma}\right)\Delta W_n,$$
$$\Delta W_{n+1} = \Delta W_n + eV_p\left(\frac{Q}{A}\right)\left[\sin\phi_{n+1} - \sin\phi_s\right], \qquad (3)$$

where n is the revolution number. These mapping equations are employed to study bunching effects of in ring. The longitudinal parameters used are summarized in Table 3.

The buncher ring extraction point is separated from the focus at the entrance of the RFQ by a ~2 m drift (similar separation relative to the current location of the MHB). The buncher ring must longitudinally focus beams at the end of the drift to improve transmission through the RFQ and

Table 3: RF parameters for the ReA buncher ring.

Radio Frequency Parameters	Values
Revolution Frequency f_o	190.2 kHz
Revolution Period T_o	5.3 μs
RF Harmonic Number h	5
RF Frequency f_{RF}	951.1 kHz
RF Phase Slip Factor η	-0.909
Peak Voltage V_p Range	0–2 kV

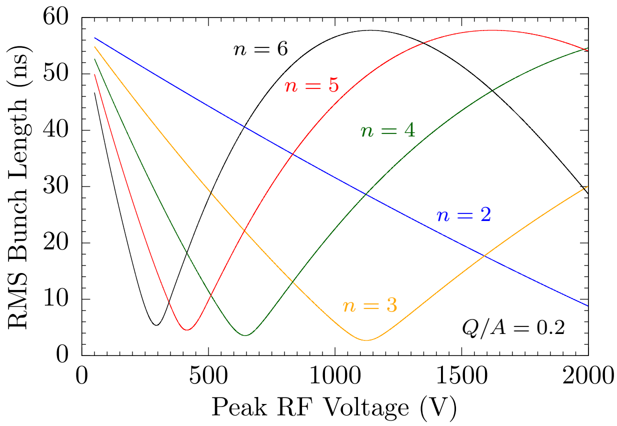

Figure 4: RMS bunch length at the entrance of the RFQ as a function of peak RF voltage for various values of extraction revolution number n for $Q/A = 0.2$.

LINAC. Figure 4 shows the RMS bunch length at the entrance of the RFQ as a function of RF voltage for a number of bunching revolution values n. The peak RF voltage V_p can be adjusted to obtain bunch separations that are an integer multiple of the 5.3 μs revolution period. Figure 5 shows that the maximum energy spread of bunches emerging from the ring are within the RFQ energy acceptance of 12 keV/u ±5%. The value of $Q/A = 0.2$ in Fig. 4 and Fig. 5 constitute the lower performance limit. Buncher performance only improves with increasing Q/A due to lower peak voltage requirements. Figure 6 shows an example of the longitudinal particle distribution of a bunch after $n = 2$ revolutions. In this case, the peak RF voltage was optimized at 967.9 V to deliver RIB bunches with RMS longitudinal pulse duration of ~2 ns and an energy spread of 1.9% every 10.6 μs to the experimental areas with no beam loss. A high degree of linearity in the bunching process is observed thereby suppressing unwanted satellite bunches before injection into the RFQ and LINAC for acceleration.

FUTURE WORK

Studies are underway to design an injection and extraction beam transport line for the ReA ring and to explore more advanced modes of operation such as heavy ion beam accumulation as well as to study the cleaning of decay products due to the limited ring acceptance. Possible topics of future exploration include: use of higher-order codes such as COSY

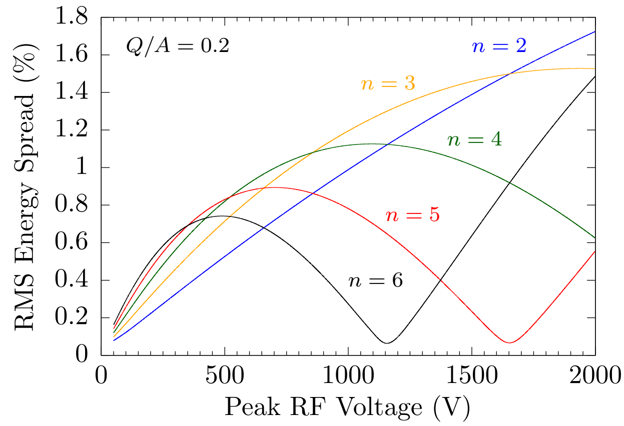

Figure 5: RMS energy spread at the entrance of the RFQ as a function of peak RF voltage for various values of extraction revolution number n for $Q/A = 0.2$.

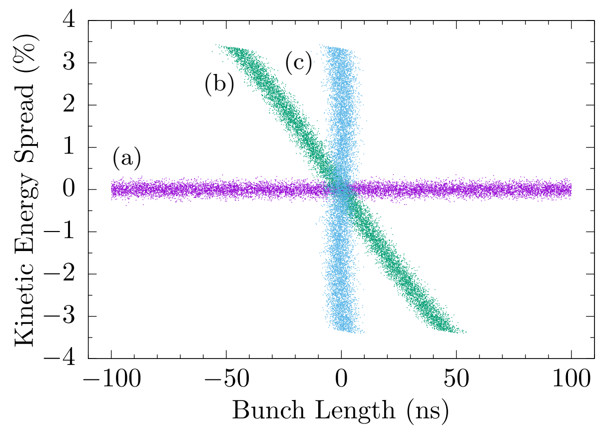

Figure 6: Longitudinal phase-space of a particle bunch with $Q/A = 0.5$: (a) initially extracted from the EBIT with a bunch length of 200 ns and energy spread of 0.3%, (b) at the extraction point after 2 revolutions in buncher operating at peak voltage of $V = 967.9$ V, and (c) at the entrance of the RFQ, 2 m from the buncher ring extraction.

Infinity [12] and WARP [13] to verify the performance of the ring to a higher degree of detail, design of a low frequency broadband RF acceleration system to accommodate a wider range of bunch lengths from the EBIT, use of electron beam cooling for enhanced mass resolution during separation, and nuclear isomeric separation by exploiting isomeric transition radiation of stored RIBs.

ACKNOWLEDGMENTS

We would like to thank Dan Alt, Daniela Leitner, Brad Sherrill, Antonio Villari, Sam Nash, John Brandon, Alain Lapierre, Daniel Bazin, and Wolfgang Mittig for their support and insightful discussions.

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