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ELECTROMAGNETIC DESIGN OF A COMPACT RF CHOPPER FOR HEAVY-ION BEAM SEPARATION AT FRIB*

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Abstract

Rare isotope beams are produced at FRIB via fragmentation of a primary heavy ion beam in a thin target. The isotope beam of interest is contaminated with other fragments, which must be filtered out to ensure the delivery of rare isotopes with desired rates and purities. One of the stages of fragment separation uses an RF deflecting cavity to provide time-of-flight separation. However, to avoid neighboring bunches overlapping with each other and with the contaminants, it is necessary to increase the inter-bunch distance by a factor of four, corresponding to a 20.125 MHz rate. To solve this problem, we have developed an RF chopper system for the 500 keV/u primary heavy-ion beams. The system consists of a deflecting quarter wave resonator (QWR) cavity operating at 60.375 MHz, two dipole steering magnets, and a beam dump. In this paper, we present and discuss the optimization of the electromagnetic design of the QWR cavity and magnets, as well as some aspects related to beam dynamics and conceptual engineering design.

INTRODUCTION

Radioactive beams play a key role in studies of nuclear structure, nuclear physics, and nuclear astrophysics [1, 2]. Among the different facilities around the world that perform experiments with rare-isotope beams, the Facility for Rare Isotope Beams (FRIB) will be a cutting-edge research facility to enable breakthrough discoveries in nuclear science [3-5].

At FRIB, isotope production is performed via projectile fragmentation. A high-power superconducting linear accelerator will be used to create rare isotopes by accelerating primary ion beams up to 200 MeV/u to strike a target [6, 7]. However, many isotope species including the desired rare isotopes are produced in this process. The secondary fragments must be removed to deliver rare isotopes with high rates and high purities [8].

An important component of FRIB is a next-generation three-stage magnetic projectile fragment separator, designed to handle the very intense primary and secondary beams [9]. For further beam purification on the proton-rich side, it is necessary to have an additional method for purifying the beam. This will be realized through time-of-flight separation [10] using an RF fragment separator (RFFS) [11], proposed at FRIB and designed by RadiaBeam and capable of producing a 4-MV transverse kick.

However, to avoid neighboring bunches mixing due to widening in the time difference before entering the separator cavity, it is necessary to increase the inter-bunch distance. For this purpose, an RF chopper (RFC) system is being designed for the FRIB facility at Michigan State University (MSU) in a collaboration between RadiaBeam and FRIB Accelerator Physics department.

The chopper system will be located in the Medium-Energy Beam Transport (MEBT) line of the FRIB superconducting RF (SRF) linac. It is designed to generate a clean 20.125-MHz bunch structure of the primary heavy ion beam accelerated in the FRIB linac to allow for the time-of-flight separation of the produced rare isotope beams [11]. The baseline 40.25-MHz bunch repetition rate at FRIB is generated by a multi-harmonic buncher (MHB) upstream of an 80.5-MHz radio frequency quadrupole (RFQ) section [12].

The RFQ produces accelerated high and low-intensity bunches alternating at the frequency of 80.5 MHz (see Fig. 1). The high-intensity bunches contain 97% of the beam intensity, and low-intensity ones, also called satellite bunches, contain another 3%. The high-intensity bunch rate is 40.25 MHz as they are formed by the 40.25 MHz MHB. The chopper system must kick every other high-intensity bunch to produce the 20.125 MHz separation between neighboring rare isotope bunches, as well as to clean the beam out of the satellite bunches. The kicked bunches will be sent to a beam dump.

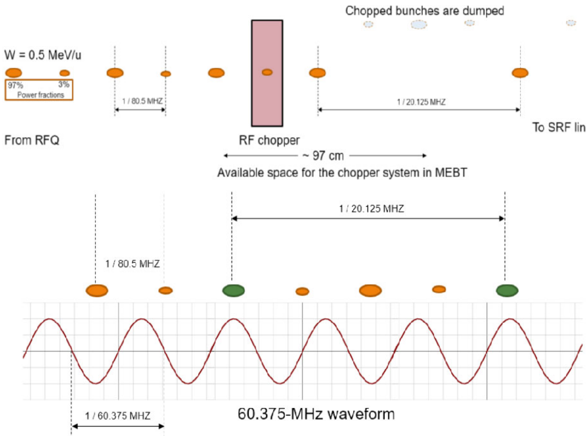

Figure 1: Bunch structure before and after the RFC system (top) and waveform of the 60.375-MHz deflecting field overlapped with the bunch structure of the incoming beam (bottom).

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ELECTROMAGNETIC DESIGN

The basis of the RFC system design is a quarter-wave resonant cavity (QWR) with deflecting plates on its electrical end providing a transverse kick to the beam bunches. The design includes an external magnetic field that doubles the kick strength of the chopper while passing the bunches of interest straight to the SRF linac.

The cavity frequency must be an odd harmonic of 20.125 MHz. We selected the frequency of 60.375 MHz, i.e. the 3rd harmonic of the beam structure, as the QWR cavity height at this frequency is about 1.5 meters, which is close to the 1-meter-high FRIB MEBT buncher cavities operating at 80.5 MHz.

The QWR cavity consists of a tank made of two cylinders connected by a conical transition as shown in Fig. 2. We reduced the on-axis length of the cavity to place two steering magnets closer to the RF deflector (RFD) gap, providing a longer drift space for the kicked bunches in order to separate them well in the direction of deflection.

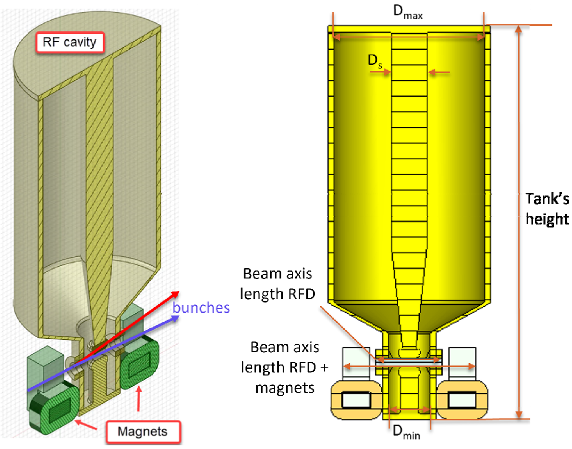
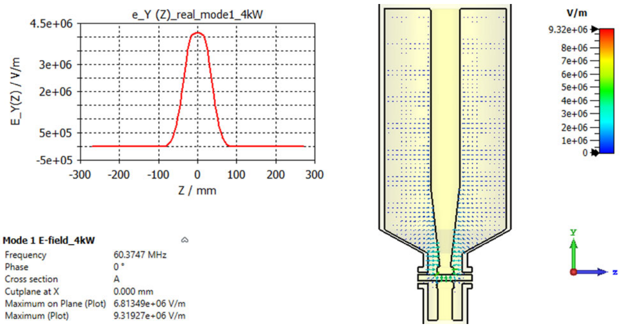


Figure 2: The proposed compact 60 MHz RF chopper cavity with integrated dipole magnets.

The electromagnetic design and optimization of the RF cavity were performed using CST Microwave Studio. The main parameter to achieve improvements in power consumption was the diameter of the tank (D_{max}). For higher quality factor and shunt impedance (i.e. efficiency) of the QWR cavity, D_{max} should be large, however, we limited it to 500 mm for practical considerations.

A small plate-to-plate gap also decreased the RF power consumption of the cavity, but we selected 27 mm which was about the limit to avoid interception of the kicked bunches by the electrode plates. The length of the electrode plates was optimized to be 70 mm to achieve the maximum transverse deflecting voltage.

The combined deflection must be at least 50 mrad to provide a reasonable bunch separation in the vertical plane at the beam dump location. Therefore the kick from the RFD was set to 25.4 mrad, which was achieved by using a 179-kV transverse voltage kick (the integral of the transverse electric field along the beam axis). We performed simulations to reduce the RFD power for a 25.4-mrad kick. The RFD beam axis length was reduced to 220 mm, which was the minimum length to avoid peak electric (E_{peak}) fields larger than the Kilpatrick limit at 60.375 MHz (E_k = 9.5 MV/m). The optimized design of the RF deflector was tuned for operation of the fundamental λ/4-mode at 60.375 MHz. The required RF power for the fundamental mode for 24.5-mrad kick corresponds to 4 kW. The electric field map of the fundamental mode is shown in Fig. 3.



Mode 1 E-field_4kW

Frequency	60.3747 MHz
Phase	0 °
Cross section	A
Cutplane at X	0.000 mm
Maximum on Plane (Plot)	6.81349e+06 V/m
Maximum (Plot)	9.31927e+06 V/m

Figure 3: The electric field profile and field map for the fundamental λ/4-mode at 4 kW input power is also shown.

Dipole Magnets

The two dipole magnets utilized in the system (Fig. 4) are very modest <650-Gs C-frame dipoles that can provide up to 15-mrad deflection each. As such, they only require 4.5 amps and 6.2 volts of power each and utilize air-cooled solid conductors. Natural convection is sufficient for thermal management of these dipoles which have current densities of <1.1 A/mm^2. Further optimization of the coil cross-section may be pursued to reduce the coil size while keeping the current density below the typical 1.5 A/mm^2.

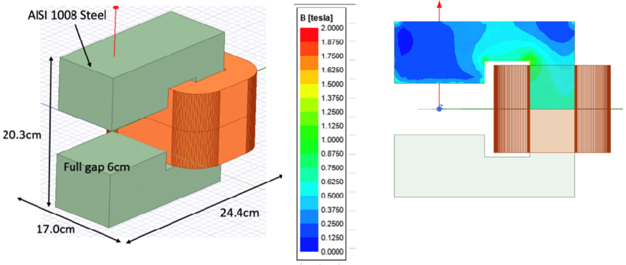


Figure 4: C-frame dipole dimensions (left) and field magnitude within the yoke (right).

The design of the FRIB RF chopper system was developed and validated by CST Particle Studio and TRACK beam dynamics simulations. The feasibility of the fundamental mode of operation was demonstrated. The 99.5% transverse emittance growth is less than 2%. Longitudinal emittance growth is up to 20% but can be reduced to 5-6% if the bunch length is reduced. The required kick of about 50 mrad provides a reasonable bunch separation in the vertical plane. A kick in the negative y-direction is

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preferable as the beam is bunched by the longitudinal component of the fringe field of the RF deflector cavity. A summary of the parameters of the optimized FRIB RF chopper system is shown in Table 1.

Table 1: Parameters of the FRIB RF chopper System

Parameter	**Value**
Deflection angle	50 mrad
Operating RF frequency	60.375 MHz
Q factor	14551
Beam energy	0.5 MeV/u
Charge-to-mass ratio	up to 1/7
Aperture diameter	4.75 cm
RF voltage	108 kV
RF power	4 kW
E_{peak}/E_k	1
Magnetic field	10,800 Gs*cm

BEAM DUMP DESIGN

The estimated intensities of the beams in the chopper dump and on the FRIB production can be as high as 1 kW. The design of the beam dump was performed to handle this power (mostly released on the surface due to low energy) and to minimize the outgassing from its surface. Figure 5 presents the beam envelopes along the FRIB MEBT with RF chopper system. A long water-cooled beam dump was considered for beam interception. Its aperture of 15 mm starts right after the second dipole magnet to intercept the beam gradually over a length of about 350 mm. After that, we assumed a water-cooled plate placed 10 mm away from the beam axis to intercept the low-intense satellite bunches. The beam dump design in shown in Fig. 6.

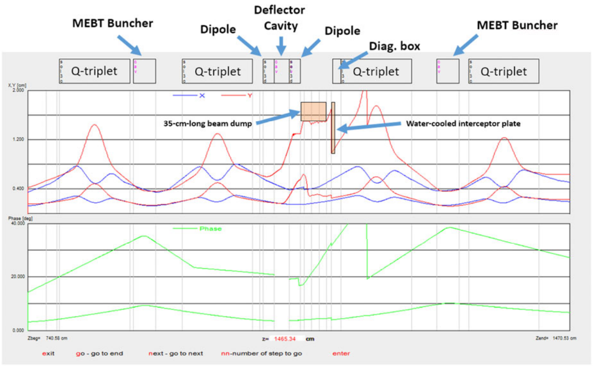

Figure 5: Beam envelopes along the FRIB MEBT with RF chopper system.

CONCEPTUAL ENGINEERING DESIGN

The conceptual engineering design of the full RF chopper system has been completed. This design incorporated all engineering requirements provided by FRIB personnel with a model of the system shown in Fig. 6. The RF chopper cavity is brazed into 3 parts. The assemblies are the main body, stem assembly, and lower cavity. They are flanged together with o-ring seals for vacuum hermeticity and utilize silver plated canted coil rf springs for electrical contact. The interior of the cavity will be made entirely of OFE C10100 copper and will maintain an ultimate vacuum level of ~$1x10^{-8}$ Torr. This is accomplished through the use of a 380 l/s turbo pump attached to the lower cavity that will pump through properly sized apertures to prevent RF power leakage. All water-cooled components have no water to vacuum braze or weld joints and conform to FRIB requirements.

To minimize the mechanical deformations, stresses, and frequency shift of the operating mode, a 50 l/min water flow rate at the stem cooling channel is required. The thermomechanical simulations show that the mechanical deformation due to heating causes a reduction of the gap between the electrode plates of ~250 microns and leads to a -44-kHz frequency shift. We consider that this frequency shift is manageable, although we will examine more robust cooling approaches in future efforts.

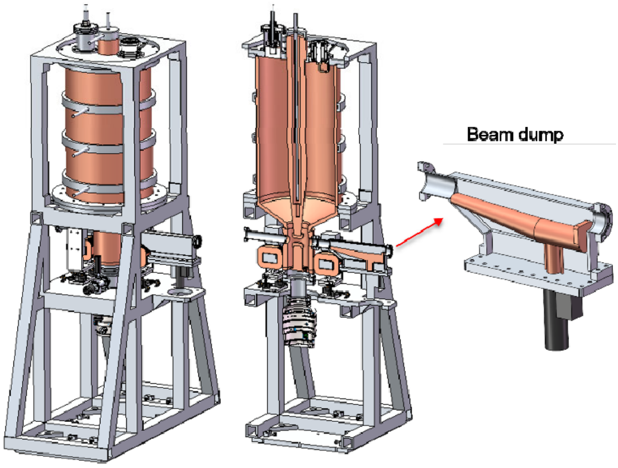

Figure 6: Conceptual engineering design of the RF chopper system.

CONCLUSIONS

We performed the electromagnetic design of the FRIB RF chopper system which includes a QWR cavity, dipole magnets, and a beam dump. The system will operate at 60.375 MHz and it has been optimized to provide a 50-mrad kick with 4 kW of RF power. The design was verified with 3D beam dynamics simulations. Additionally, we have performed the conceptual engineering design of all components, including beam dumps, with a high level of readiness for the prototype fabrication.

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