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RF CHOPPER FOR PREBUNCHED RADIOACTIVE ION BEAMS

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Abstract

An RF chopper system is being designed for the Re-Accelerator (ReA) linac at the Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU). The chopper system is designed to clean out satellite bunches and produce a 16.1 MHz bunch structure, which allows for time-of-flight separation of the isotopes. The chopper system's location in the beamline is between the ReA3 and ReA6 cryomodules. In ReA, the beam can be prebunched at the frequency of 16.1 MHz and accelerated in a 80.5 MHz RFQ, producing four satellite bunches for every one high-intensity bunch. The chopper system includes an RF deflector operating at 64.4 MHz, which is the beat frequency of 80.5 MHz and 16.1 MHz. The deflector deflects every bunch to spatially separate high-intensity and satellite bunches. The beam trajectory is biased by a constant magnetic field to ensure the high-intensity bunches do not experience any total deflection. The kicked bunches are low in intensity and will be sent to a beam dump, resulting in a clean 16.1 MHz beam structure injected into the ReA6 cryomodule.

INTRODUCTION

The Re-Accelerator [1] is a superconducting linear accelerator that "re-accelerates" rare isotopes produced in experiments done with the FRIB linear accelerator. ReA was commissioned in 2015 and includes three general purpose beamlines and a beamline dedicated to astrophysics experiments. The ReA6 cryomodule was added in 2021 to provide higher beam energies. ReA can accelerate ions with an A/Q ratio between 2 and 5. The chopper system will produce a beam with a clean 16.1 MHz bunch structure, which will allow ReA users to perform time-of-flight measurements. The ReA beamline includes a radio-frequency quadrupole

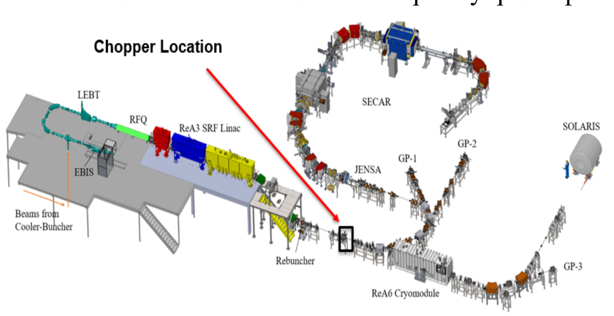

Figure 1: ReA layout.

(RFQ), which generates an 80.5 MHz bunch repetition rate. Upstream from the RFQ is a multi-harmonic buncher (MHB) which produces high-intensity bunches at a frequency of 16.1 MHz. This means that, after the RFQ, there are four low-intensity ("satellite") bunches for every one intense ("main") bunch. This chopper system uses a combination of an RF electric field with a frequency of 64.4 MHz and a static magnetic field to deflect the satellite bunches while keeping the main bunches on axis. Two potential locations were considered for the chopper system. The first location, between the RFQ and the first ReA3 cryomodule, has a lower beam energy (0.5 MeV/u), but was not chosen because there is limited space (only about 70 cm) for the chopper system. The second location, shown in Fig. 1, is between the ReA3 cryomodules and the ReA6 cryomodule. The beam energy at this location is around 3 MeV/u. This location was chosen because there is plenty of space for both the chopper and a beam dump for the deflected satellite bunches. The beam dump will be located about 1.4 meters downstream of the chopper.

DESIGN

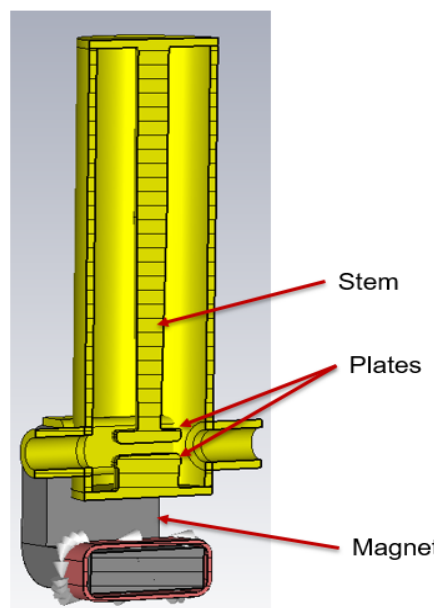

Figure 2: Cross-section view of the final RF chopper cavity model designed in CST Studio (dimensions shown in Table 1).

RF Deflection

The RF chopper design is based on a quarter-wave resonant cavity (QWR) with deflecting plates that kick the beam bunches in a vertical direction. The cavity cross-section is shown in Fig. 2 The resonant frequency of the cavity is 64.4 MHz, which in combination with the bunch frequency of 80.5 MHz (driven by the RFQ frequency) produces a 16.1 MHz deflection waveform. Indeed, the cavity resonates at the beat frequency of the actual bunch frequency and the desired 16.1 MHz bunch repetition rate. At this frequency, the QWR is a 1.1 meter-high cavity, whereas the 16.1 MHz

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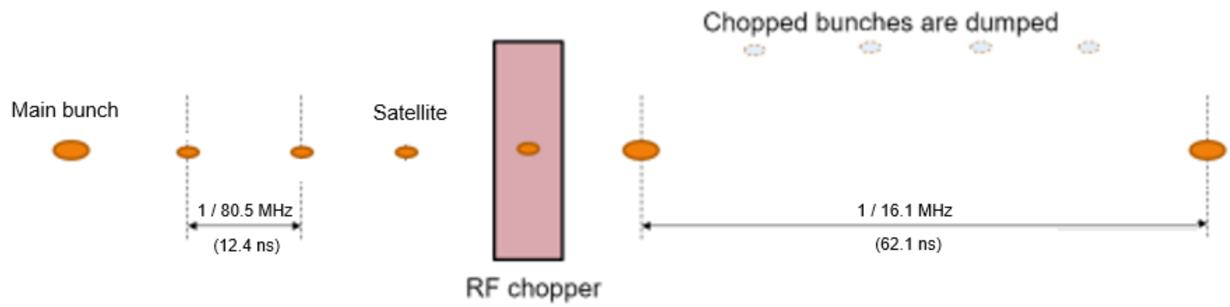

Figure 3: Bunch structure before and after the RF chopper system.

Table 1: Important Design Parameters of the RF Chopper System

Parameter	**Value**
Cavity Height	1130 mm
Cavity Diameter	340 mm
Plate Length	168 mm
Gap Between Plates	30 mm
Power	10 kW
Electric Field in Gap	4.6 MV/m
Voltage in Gap	137 kV
Peak Electric Field	7.9 MV/m
Magnetic Field in Gap	68 mT

resonator would require a coil inductor [2]. The peak electric field inside the cavity is limited by electric breakdown. The peak electric field in the chopper system is 7.9 MV/m, which is 80% of the Kilpatrick limit [3] at 64.4 MHz (9.7 MV/m). The length of the plates was set to 168 mm, which corresponds to 0.9 * $\beta\lambda/2$. This length is a trade-off between the deflection strength and the gap capacitance and was chosen to optimize RF power consumption by the cavity. After multiple simulations, we determined that the minimum required kick angle of about 18 mrad can be achieved at 10 kW of power to the cavity. The bunch structure of the beam can be seen in Fig.3, while Fig. 4 shows the kick waveform at 10 kW.

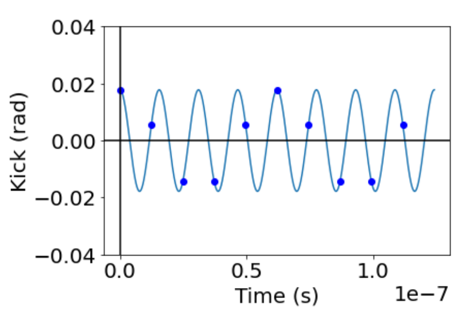

Figure 4: Average bunch deflection in the chopper due to the RF electric field overlaid onto a 64.4 MHz waveform.

Magnetic Bias

In order to keep the main bunches on axis, a static magnetic bias is needed to cancel out the deflection the main bunches feel from the RF electric field inside the cavity. The magnetic bias comes from a iron-dominated, C-shaped dipole, which is designed to produce a magnetic field of 68 mT inside the cavity. The magnet is located on the cavity so the bunches can experience both the electric and magnetic deflections in the same space. If we used one magnet upstream and one magnet downstream of the cavity then the bunches would enter the cavity already deflected off the beam axis, which requires a larger gap and higher voltage. One magnet after the cavity would not work either because it cannot cancel out both offset and angle of the beam trajectory. The dipole requires about 1 kW of power and it uses water-cooled hollow copper conductors for the coil. Figure 5 shows the effect of the magnetic field on the deflection of the bunches. The intense bunches are on the peak of the waveform and biased to zero kick in Fig. 5, compared to the pure RF deflection case where they experience a deflection of around 18 mrad.

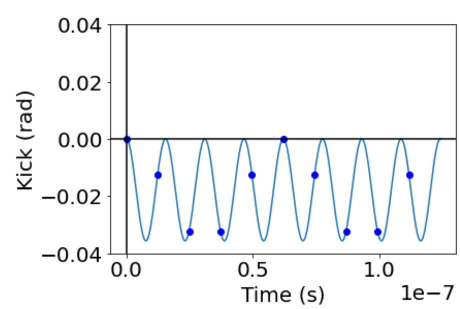

Figure 5: Average bunch deflection in the chopper due to the RF electric field combined with the static magnetic field provided by the chopper dipole overlaid onto a 64.4 MHz waveform.

Beam Dumping

The satellite bunches are dumped on the beampipe and on a circular aperture 1.4 meters downstream from the chopper. The aperture has a diameter of 1.0 cm, which allows all the particles in the main bunches to pass through and intercept the satellites before they reach the ReA6 cryomodule as shown in Fig. 6.

BEAM DYNAMICS

CST Studio

The 3D model of the chopper was constructed in CST [4]. The initial particle distribution was exported from the

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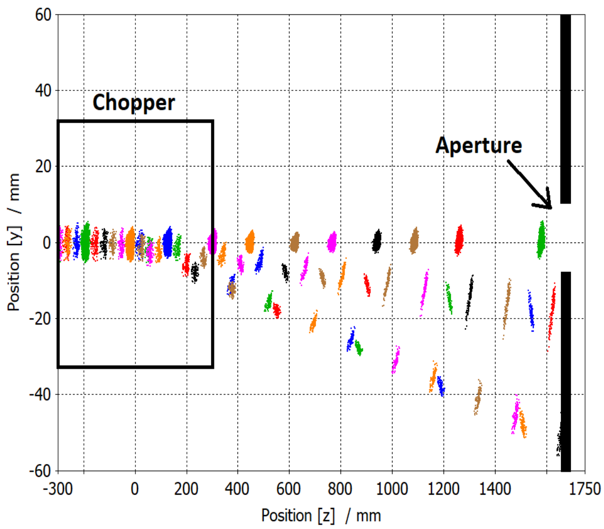

Figure 6: CST Studio simulation of the trajectory of bunches through the chopper, drift space, and the aperture.

TRACK model of the ReA beamline and imported into the CST PIC solver. The electric field inside the cavity was scaled to a level corresponding to 10 kW of input RF power and the magnetic field was adjusted to provide zero deflection for the main bunches. A snapshot of the bunches produced in CST can be seen in Fig. 6.

TRACK

In addition to our CST simulations, we also used TRACK [5] to simulate the motion of the beam. However, TRACK cannot simulate an RF electric field and a static magnetic field in the same element. To simulate the chopper system, we imported the 3D RF electric field map of the chopper from CST and then used two zero-length dipole corrector elements on each side of the cavity to simulate the magnetic bias produced in the chopper. The results from these simulations are shown in Fig. 7. It can be seen in the y-y' plot after the chopper in Fig. 7 that the average kick of each bunch is the same as in the design waveform in Fig. 5. Thanks to great time resolution of the bunches, the purity of the main bunches is 100%.

CONCLUSION

The ReA chopper system was designed in CST studio and the design was validated by simulations in both TRACK and CST Studio. The chopper uses a combination of an RF electric field and a static magnetic field to deflect low-intensity bunches in the negative y direction, while keeping the intense 16.1 MHz bunches on the beam axis. The electric field requires a moderate RF power of 10 kW and the dipole magnet requires around 1 kW of power. The chopper will provide deflections of 15 mrad and 35 mrad to the satellite bunches ensuring 100% purity of the main intense bunches. These deflected bunches will be cleaned out by a circular

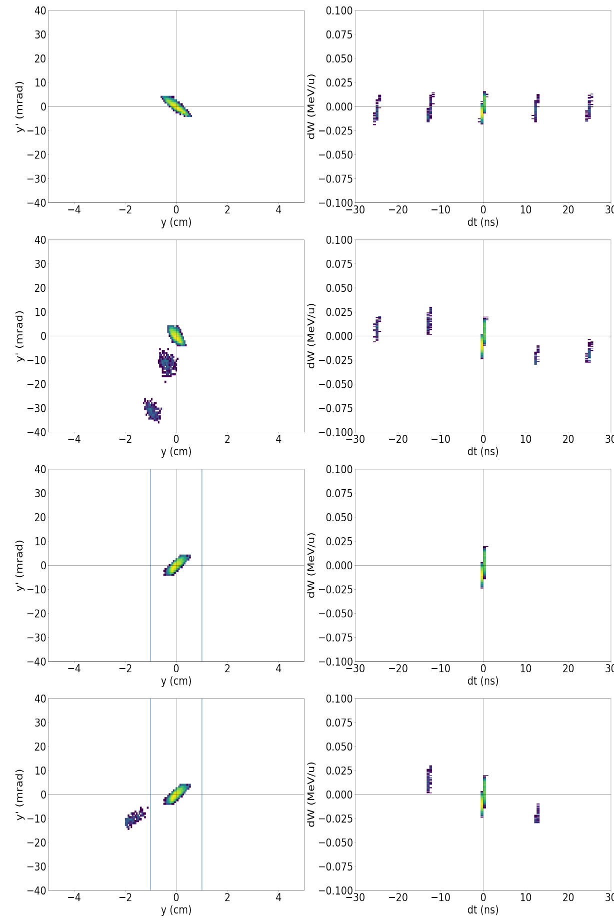

Figure 7: Y-Y' (left) and longitudinal (right) beam snapshots simulated by TRACK: before the chopper, after the chopper, before the beam dump, and after the beam dump (vertical lines represent aperture size).

aperture with an opening radius of 1 cm placed 1.4 meters downstream of the chopper system.

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