rf chopper for prebunched radioactive ion beams

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An rf chopper system is being designed for the ReAccelerator (ReA) linac at the Facility for Rare Isotope Beams at Michigan State University. The 80.5 MHz ReA radio-frequency quadrupole accelerates prebunched 16.1 MHz beams, producing four satellite bunches for every main bunch. The chopper system includes an rf deflector that kicks every bunch vertically to spatially separate main and satellite bunches. A constant magnetic field superimposed with the chopper electric field biases the beam trajectory to ensure the high-intensity bunches do not experience a net deflection and are injected straight to the ReA6 cryomodule or sent for experiments. The kicked bunches are low in intensity and will be sent to a beam dump, resulting in a clean 16.1 MHz beam structure, which allows for a reliable time-of-flight separation of the isotopes.

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I. INTRODUCTION

The Michigan State University (MSU) ReAccelerator (ReA) is a superconducting linear accelerator that "reaccelerates" stopped rare isotopes produced in the FRIB high-power target or in a batch mode ion source [1]. ReA was commissioned as ReA3 in 2015 and includes two general purpose user stations and a beamline dedicated to astrophysics experiments. The ReA6 cryomodule was added in 2021 to provide higher beam energies and another two user stations as shown in Fig. 1 [2]. The chopper system proposed and described in this paper will produce a beam with a clean 16.1 MHz bunch structure, which will allow ReA users to perform time-of-flight measurements. For example, time-of-flight is necessary for the Isochronous Spectrometer with Large Acceptances [3], a novel type of recoil mass spectrometer that is being developed for ReA beams.

ReA includes an electron beam ion trap that strips the stopped rare isotopes from the charge state of 1+ to a charge state acceptable for ReA3 [4]. The linac can accelerate ions with an A/Q ratio between 2 and 5. The stripped high-charge-state beams are prebunched by an 80.5 or a 16.1 MHz multiharmonic buncher and injected into an 80.5 MHz radio-frequency quadrupole (RFQ) [5,6]. The 16.1 MHz bunch structure is very beneficial for the time-of-flight separation and detection of reaccelerated isotopes, though, after the RFQ, there are four low-intensity, "satellite," bunches for every one intense, "main," bunch. The bunch structure before and after the chopper can be seen in Fig. 2.

II. DESIGN

Separator systems for cw beams typically solely rely on an rf electric field to split the beam [7]. Our proposed chopper system uses a combination of an rf electric field and a static magnetic field to deflect the satellite bunches while keeping the main bunches on axis in a similar way as we earlier proposed for an FRIB MEBT chopper system [8,9]. We explored the possibility of using only an rf electric field and phasing the cavity so the main bunches experience zero net deflection, similar to the CEBAF rf separator system [10]. In this case, the chopper system would require double the voltage and 4 times the rf power to produce the same deflection compared to our design where the magnetic and electric fields contribute equally to the deflection of the bunches. Therefore, our approach is considered more efficient.

Two potential locations were considered for the chopper system. The first location, between the RFQ and the first ReA3 cryomodule (see Fig. 1), has a lower beam energy (0.5 MeV/nucleon), but was not chosen because there is very limited space 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/nucleon. 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 m downstream of the chopper.

A. rf design

The rf chopper design is based on a quarter-wave resonator cavity (QWR) with deflecting plates that kick

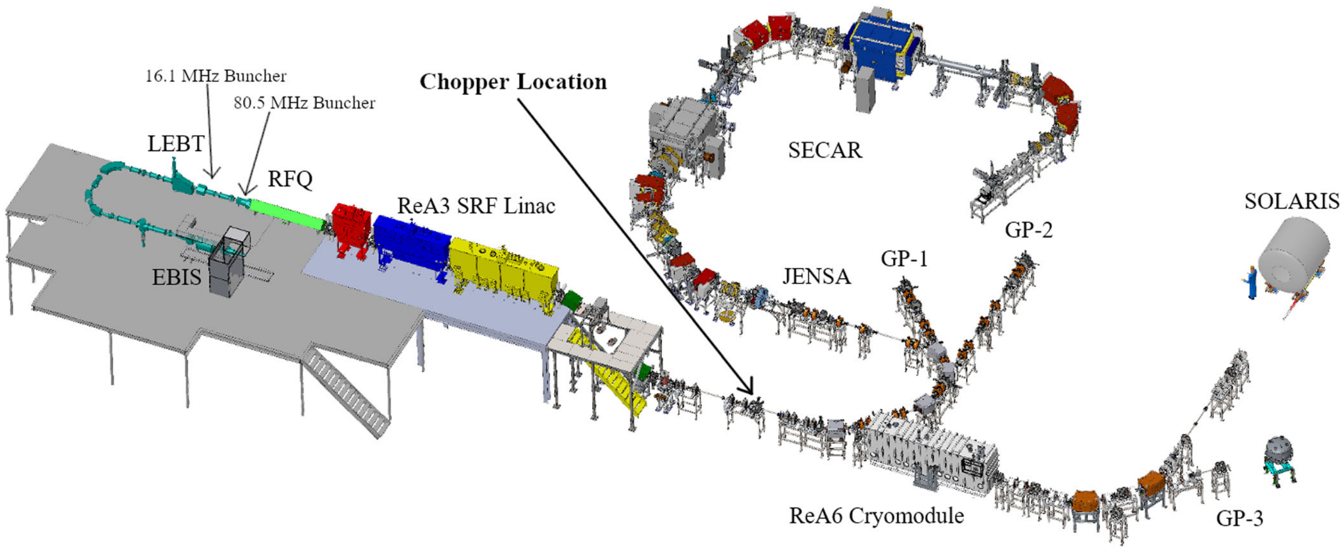

FIG. 1. ReA layout.

the beam bunches in a vertical direction. Other types of cavities used for deflectors include a half-wave resonator and an H-type deflector [11]. QWR was chosen because it is the most compact of the deflector options. At MSU, we are also familiar with the QWR mechanical design, as it is used as the design for the FRIB MEBT bunchers [12] and the ReA buncher [1].

The chopper design is shown in Fig. 3. 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, see the bunches' pattern in Fig. 4. Indeed, the cavity resonates at the beat frequency of the actual bunch frequency and the desired 16.1 MHz bunch repetition rate. At 64.4 MHz, the QWR is a 1.1 m high cavity with a straight rigid inner conductor, whereas a 16.1 MHz resonator would require a coil inductor [13] and a completely different mechanical design.

The optimum length of the plates is 168 mm, which corresponds to $L = 0.9\ \beta\lambda/2$. This length was chosen to optimize rf power consumption by the cavity and is a trade-off between the gap capacitance and the deflection strength, as the largest deflection occurs when the length of the plates is equal to $\beta\lambda/2$. The vertical component of the electric field along the beam axis is shown in Fig. 5, and the electric field distribution inside the cavity is shown in Fig. 6.

To ensure that all particles of the satellite bunches are intercepted by an aperture of 1 cm in radius located 1.4 m downstream of the chopper, the minimum required deflection of the satellite bunches is 14 mrad. The distance was chosen based on available space in the beamline. To reach the required kick, the amplitude of bunch deflection provided by the rf electric field must correspond to 21 mrad (see Figs. 4 and 7). These equations from Bongardt [14] were used to calculate the electric field amplitude required to produce this deflection:

$$x'_c(L) = x'_c(0) + f(L), \tag{1}$$

with

$$f(L) = \frac{-QeE}{Am\gamma\omega v_c}\left[\cos\left(\frac{\omega L}{v_c} + \phi\right) - \cos(\phi)\right], \tag{2}$$

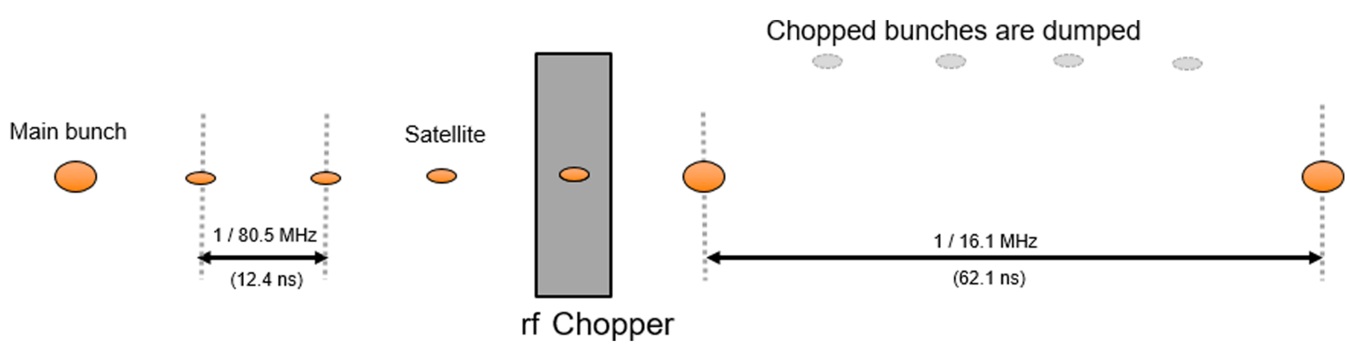

FIG. 2. Bunch structure before and after the rf chopper system.

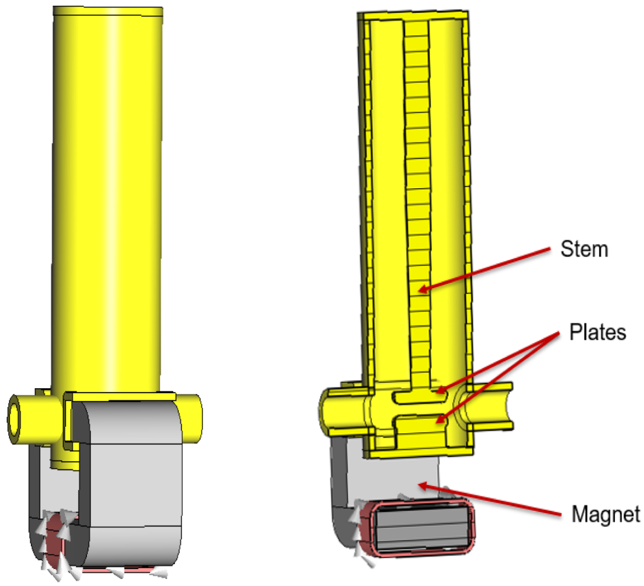

FIG. 3. Full and cross-section views of the rf chopper cavity model designed in CST Studio (dimensions shown in Table I).

$x'_c(L)$ is the vertical angle of the beam trajectory after passing through the deflector plates, and $x'_c(0)$ is the initial vertical angle of the beam, which is 0 in our case because all bunches are on the beam axis prior to the chopper. In Eq. (2), Q is the charge state of the ions in the beam, e is the elementary charge, A is the mass number of the ions in the beam, m is the atomic unit mass, γ is the Lorentz factor of the beam, v_c is the beam velocity, $\omega = 2\pi f$ where f is the cavity frequency, ϕ is the cavity phase with $\phi = 0$ producing the largest deflection, and E is the effective electric field strength. In our calculations and simulations, we used a beam with a charge-to-mass ratio of 1/4 and an energy of 3.0 MeV/nucleon. ReA3 can accelerate beams with a charge-to-mass ratio of 1/5, but to a slightly lower energy [15], giving them about the same rigidity as our design beam.

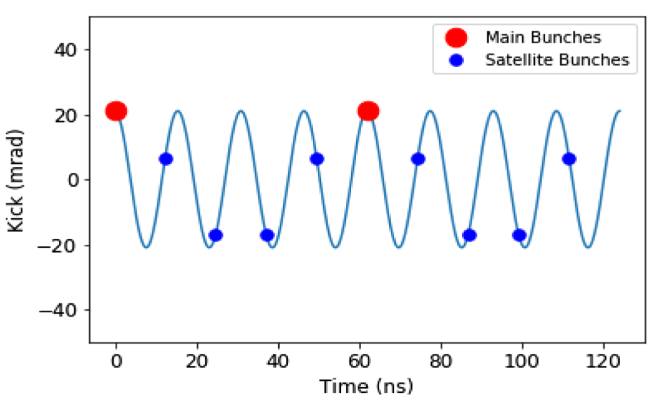

FIG. 4. Average bunch deflection in the chopper due to the rf electric field overlaid onto a 64.4 MHz waveform with no magnetic bias.

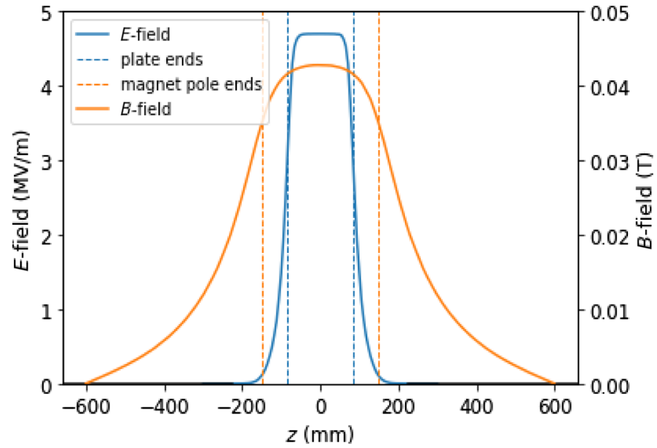

FIG. 5. Chopper electric and magnetic fields along beam axis.

By rearranging Eqs. (1) and (2), we can calculate the electric field amplitude to produce a minimum required kick of 21 mrad with

$$E = \frac{-x'_c(L)Am\gamma\omega v_c}{Qe}\left[\cos\left(\frac{\omega L}{v_c} + \phi\right) - \cos(\phi)\right]^{-1}. \quad (3)$$

From this calculation, we determined that the rf chopper requires an effective electric field strength of 4.7 MV/m. This field strength can be achieved with 10 kW of power. Figure 4 shows the kick waveform at this power level. The peak electric field inside an rf cavity is limited by electric breakdown. The Kilpatrick limit [16] at 64.4 MHz is 9.7 MV/m, and the peak electric field in the chopper system is 7.9 MV/m, which is 80% of this limit.

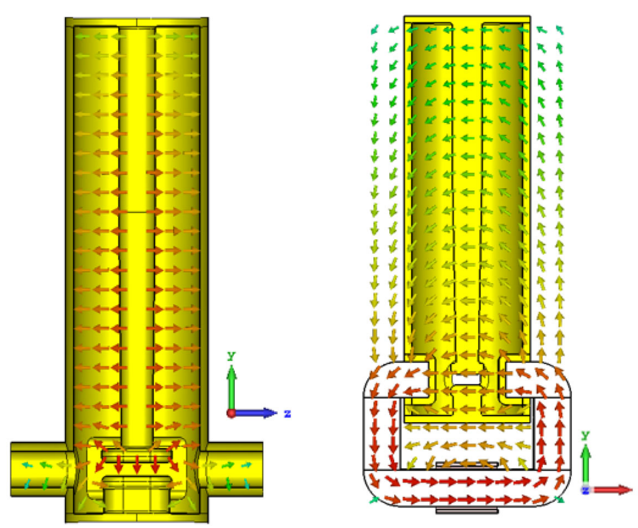

FIG. 6. Chopper electric (left) and magnetic (right) field distributions.

B. Magnetic bias

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 an iron-dominated, C-shaped dipole.

To calculate the necessary magnetic field integral, we first determine the rigidity of the beam at the chopper using Eq. (4):

$$(B\rho) = \frac{p}{Qe}, \tag{4}$$

where p is the momentum of the beam. Using a beam energy of 3 MeV/nucleon and a charge-to-mass ratio of 1/4, the rigidity is calculated to be 1.0 T m. To find the bending radius of the magnet, we use Eq. (5):

$$\rho = \frac{L_{\mathrm{eff}}}{\theta}, \tag{5}$$

where L_{eff} is the effective length of the magnet, and θ is the deflection angle provided by the magnet, which must be 21 mrad to cancel out the peak deflection provided by the rf electric field. After combining Eqs. (4) and (5), we can find the required magnetic field integral with Eq. (6):

$$B_0 \cdot L_{\mathrm{eff}} = \theta(B\rho). \tag{6}$$

This gives us a required magnetic field integral of 0.021 T m. We used CST Studio [17] to design and simulate our magnet, varying current, and the number of turns in the coil until we obtained the required magnetic field integral. From our simulations, we found that B_0, the field strength in the center of the magnet, is 41.7 mT. We can then calculate the effective length of the magnet using Eq. (7):

$$L_{\mathrm{eff}} = \frac{\int B\,dl}{B_0}. \tag{7}$$

This equation gives an effective length of 50.3 cm, compared to the geometrical length of 30 cm, which was chosen to fit on the diameter of the cavity.

The magnet is not very different from steering magnets used in accelerators [18]. It was designed to assume a coil current density of 10 A/mm^2, which is common for water-cooled magnets. It uses 5 mm by 5 mm hollow copper wire with a hole diameter of 3 mm. It requires 65 turns with 195 A of current, which corresponds to a power of about 900 W. The magnetic field distribution inside the cavity and magnet is shown in Fig. 6.

The magnet is located in 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 a higher voltage to achieve the required field strength. One magnet after the cavity would not work either because it cannot cancel out both the offset and angle of the beam trajectory.

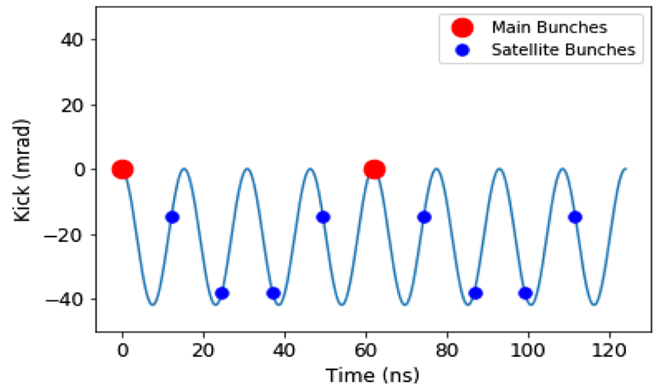

FIG. 7. Average bunch deflection in the chopper due to the rf electric field combined with the static magnetic field provided by the chopper dipole overlaid onto a 64.4 MHz waveform.

Figure 7 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, compared to the pure rf deflection case where they experience a deflection of 21 mrad. The trajectory angles of the satellite bunches are 14 and 37 mrad and meet the required minimum deflection to be cleanly intercepted by the beam dump aperture.

C. Beam dump

The satellite bunches are dumped on the beampipe and on a circular aperture of 1.4 m downstream from the chopper. This distance was chosen because it is in between magnets on the beamline and also provides sufficient drift space for the satellite bunches to be deflected away from the main bunch. The aperture has a diameter of 2.0 cm, which allows all the particles in the main bunches to pass

TABLE I. Important design parameters of the rf chopper system.

Parameter	Value	Unit
Cavity height	1130	mm
Cavity diameter	340	mm
Plate length	168	mm
Gap between plates	30	mm
Electric field in gap	4.6	MV/m
Voltage in gap	137	kV
Peak electric field	7.9	MV/m
rf power	10	kW
Magnet pole tip length	300	mm
Magnet gap length	184	mm
Magnetic field integral	0.021	T m
Peak magnetic field on axis	0.042	T
Magnet power	900	W

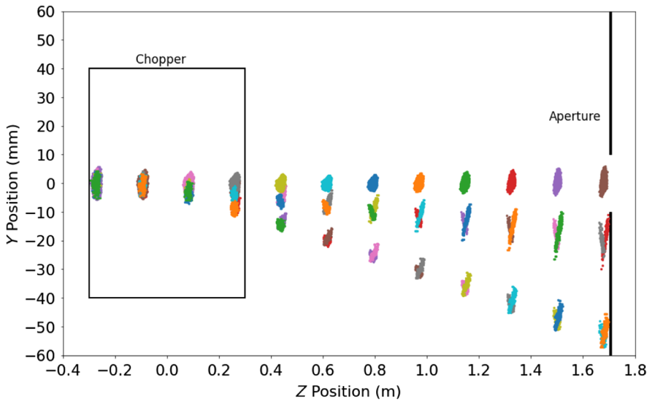

FIG. 8. Snapshots of the simulated beam motion through the chopper, drift space, and the aperture. The time between each snapshot is one-half of an 80.5 MHz rf period (6.2 ns).

through and intercept the satellites before they reach the ReA6 cryomodule as shown in Fig. 8.

III. BEAM DYNAMICS

A. CST Studio

The 3D model of the chopper was constructed in CST Studio for the realistic simulation of beam motion in superimposed rf and magnetic fields. The initial particle distribution was exported from our beam dynamics model for the TRACK code [19] 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. 8.

B. TRACK

In the ReA linac, TRACK [19] is the main code we use to simulate beam dynamics from the ion source to the user stations. Currently, 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. 9. It can be seen in the y-y' plot after the chopper that the average kick of each bunch is the same as in the design waveform in Fig. 7, which results in a clean 16.1 MHz beam structure.

The satellite bunches are deflected downward because in this case, the longitudinal component of the electric field bunches the beam. If the electric field were reversed, deflecting the bunches upward, there would be a debunching effect on the beam. The longitudinal phase space plot after the chopper shows the effect of this longitudinal component of the electric field, which is located between the deflecting plates and the edges of the cavity. The average energy of the main bunch is unaffected, while the satellite bunches are decelerated or accelerated.

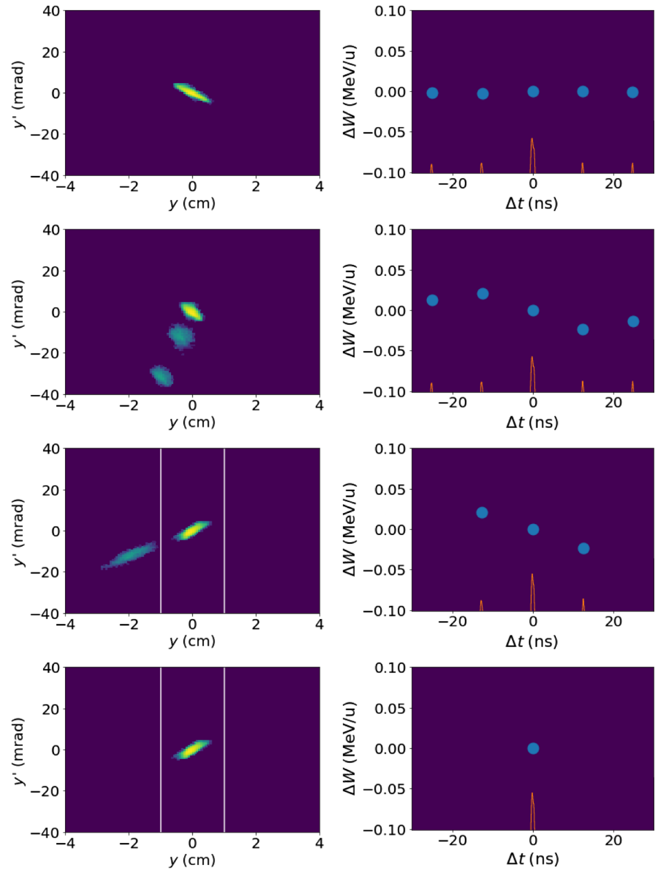

FIG. 9. Y-Y' beam snapshots (left) and longitudinal bunch centroid positions (right) simulated by TRACK: before the chopper, after the chopper, before the beam dump, and after the beam dump (vertical lines represent the beam dump aperture size).

IV. CONCLUSION

The ReA chopper system for reaccelerated rare isotope beams was designed, 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 vertically deflect low-intensity satellite bunches while keeping the main 16.1 MHz bunches on the beam axis. The rf design is feasible from the peak field and power consumption points of view. The design of the cavity is similar to the FRIB MEBT and ReA bunchers, which makes its mechanical design and construction straightforward. This work demonstrates the application of beat frequency cavities to a problem requiring much lower frequencies.

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