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MITIGATION OF LONGITUDINAL BEAM LOSSES IN THE FRIB LINAC

A. Gonzalez*, A.S. Plastun, P.N. Ostroumov
Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The linear accelerator at the Facility for Rare Isotope Beams (FRIB) at Michigan State University uses a thin liquid lithium film for charge stripping of high-intensity heavy ion beams. Energy straggling and energy loss of the beam in the inherently non-uniform lithium film affects the energy distribution in the beam. This can lead to non-linear "tails" in the longitudinal phase-space beam distribution after bunching at the two 161 MHz room-temperature Multi-Gap Bunchers (MGBs) between the stripper and the next accelerating segment. Some particles in these "tails" are lost in the downstream accelerator cryomodules. To mitigate these losses, we have designed a room-temperature IH-type buncher cavity with a resonant frequency of 322 MHz, the second harmonic of the MGBs. The new harmonic cavities will be installed next to each MGB, linearizing the waveform of the effective bunching voltage and eliminating the formation of non-linear "tails." The increase in the energy acceptance of the post-stripper part of the accelerator reached over 50% according to our simulations. We present the electromagnetic design of this cavity along with beam dynamics simulations that demonstrate how the losses are mitigated. The construction and installation of the cavity are being pursued as an accelerator improvement project.

INTRODUCTION

The FRIB linear accelerator is a state-of-the-art superconducting heavy ion linear accelerator. As shown in Fig. 1, the accelerator contains three linear accelerating segments and two 180 degree bending sections. For more efficient acceleration, a charge stripper is located after the first accelerating segment (LS1). Two options are available for charge stripping: a carbon foil for low intensity beams, and a thin liquid lithium film for high intensity beams [1]. Downstream of the stripper, we use two 161 MHz Multi-Gap Bunchers (MGBs) [2] to keep the beam longitudinally bunched before entering the second accelerating segment (LS2). Figure 2 shows a zoomed-in view of the layout between the stripper and the entrance to LS2.

When the lithium stripper is used, energy straggling, energy loss and non-uniformities in the film cause a large energy spread in the beam after the stripper. This means the longitudinal beam size is large when the beam arrives at the first MGB (MGB01). The large longitudinal beam size leads to non-linear "tails" in the longitudinal phase space distribution after the beam experiences the sinusoidal 161 MHz effective bunching voltage at MGB01. Particles in these "tails" are lost in the LS2 cryomodules. The lost fraction of the beam does not exceed 10^{-4}, which corresponds to a temperature increase of up to 0.3 K in the beam pipe in the LS2 cryomodules during 10 kW beam power on target operation [3]. As beam power ramps up to our ultimate goal of 400 kW [4], the temperature increase in the cryomodules will also ramp up, which may lead to degradation of SRF cavities due to field emission. Therefore, it is necessary to mitigate these losses.

Beam dynamics studies showed that the losses can be eliminated if the MGB effective voltage is linearized. To do this, we have designed a Second Harmonic Buncher (2HB) cavity to be installed downstream of each MGB as seen in Fig. 2. This new cavity will have a resonant frequency of 322 MHz, which is twice the resonant frequency of the MGBs. The effect of this second harmonic is shown in Fig. 3. The effective bunching voltage waveform of the combined harmonics, shown in orange, has a significantly longer linear region than the waveform of the 161 MHz MGB only.

BEAM DYNAMICS

We used the particle tracking code TRACK [5] to simulate the effect of the new cavities on the beam dynamics. First, we examined the effect of building only one 2HB and installing it downstream of MGB01 versus the effect of building two 2HBs and installing them downstream of each MGB. We simulated the longitudinal acceptance from the lithium stripper to the end of LS2 for three cases: no 2HBs added, one 2HB added downstream of MGB01, and two 2HBs added: one downstream of MGB01 and the other downstream of MGB02. The results can be seen in Fig. 4. From these plots, it is apparent that while installing one 2HB leads to a significant increase in energy acceptance, the highest energy acceptance is achieved when two 2HBs are installed.

The linearizing effect of the second harmonic can be directly seen in Fig. 5. To clearly demonstrate the effects of the new cavities, we created an artificial beam distribution with an exaggerated energy spread at the stripper and simulated it with TRACK from the stripper to the entrance of LS2, taking snapshots of the longitudinal distribution at the exit of 2HB1 and 2HB2. In the top plot, when 2HB1 is on, there are much fewer particles in the non-linear "tails" on the edges of the beam distribution compared to the case when 2HB1 is off. In the bottom plot, the distribution with the largest linear region is when both second harmonic bunchers are activated. In Fig. 6, it can be seen that when both 2HBs are activated, all particles in the simulation fit inside the longitudinal acceptance of LS2, whereas some particles are lost in the other cases. This further validates the decision to build and install two 2HBs.

* gonzalea@frib.msu.edu

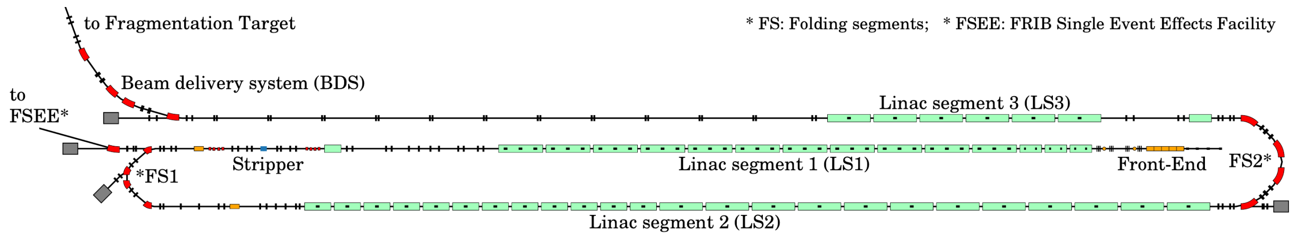

Figure 1: FRIB accelerator layout.

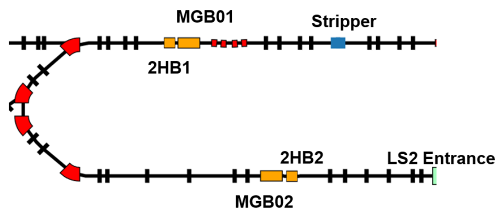

Figure 2: Folding Section 1 (FS1) layout.

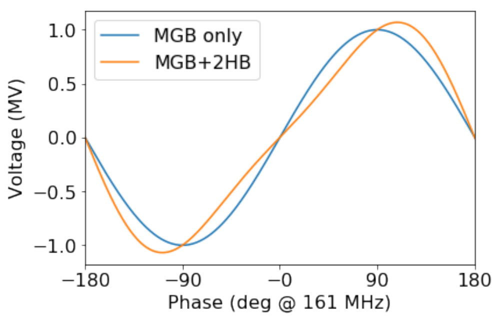

Figure 3: Effective bunching voltage waveforms.

Table 1: Cavity Parameters

Parameter	Value
Q factor	13000
Effective voltage (uranium beam)	260 kV
RF power (uranium beam)	4.6 kW
Peak surface E-field	0.46 Kilpatrick

CAVITY DESIGN

The design effective voltage of the 2HB cavity was determined from TRACK simulations of a $^{238}U^{78+}$ beam because it is the heaviest beam we use. We used beam energies of 16.5 and 20.0 MeV/u for our studies because those cover the range of realistic beam energies between the stripper and the LS2 entrance for all beam species. For each beam energy, we adjusted the voltages of MGB01 and 2HB1 to minimize the rms energy spread of the beam after 2HB1. Then we adjusted the voltages of MGB02 and 2HB2 to longitudinally focus the beam at the entrance of LS2. We added a margin of 10% higher than the highest voltage calculated to get a design effective voltage of 260 kV.

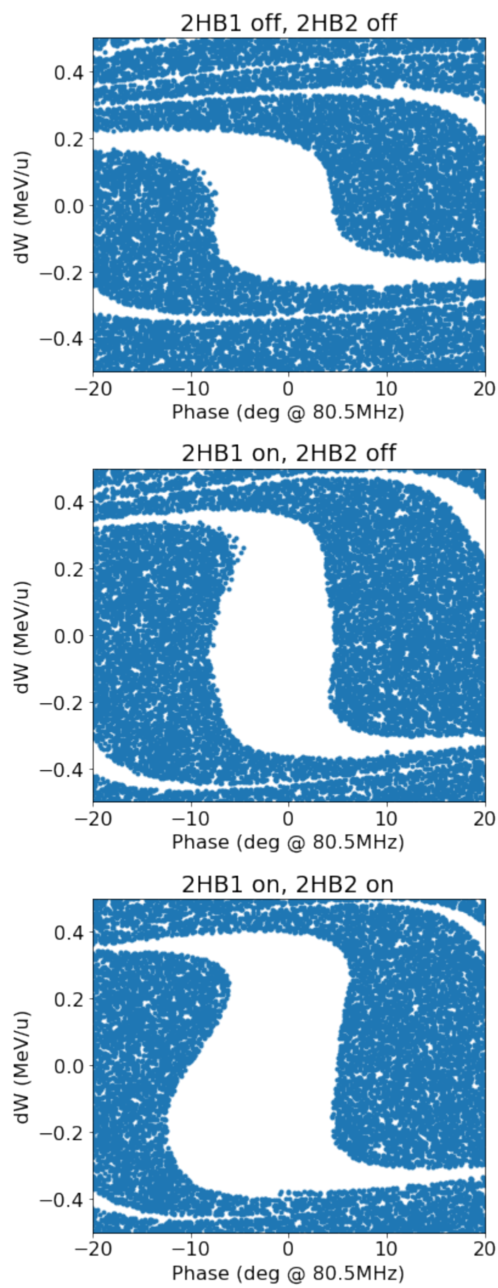

Figure 4: Longitudinal acceptance from stripper to end of LS2.

We started the cavity design process by using CST Studio [6] to design six different types of room temperature 322 MHz cavities, including Half-Wave Resonator, Quarter-Wave Resonator and Spoke. Ultimately, we chose a 4-gap Interdigital H-type (IH) cavity [7] because of the low RF power

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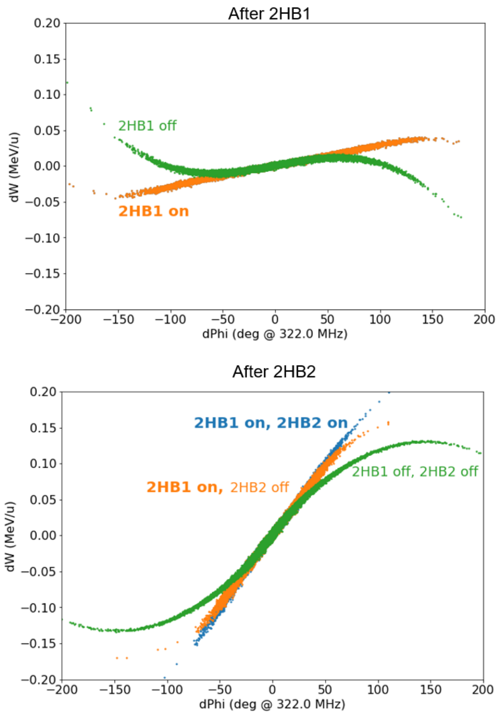

Figure 5: Longitudinal beam distribution with exaggerated energy spread after 2HB1 (top) and 2HB2 (bottom).

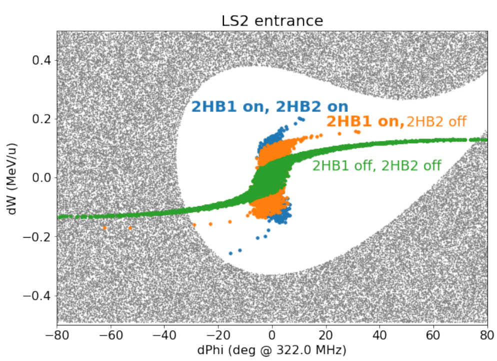

Figure 6: Longitudinal beam distribution with exaggerated energy spread at LS2 entrance and LS2 longitudinal acceptance.

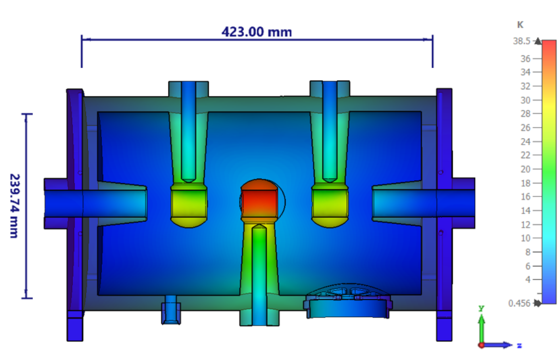

Figure 7: Cross-section view of the cavity with dimensions and temperature change at design voltage.

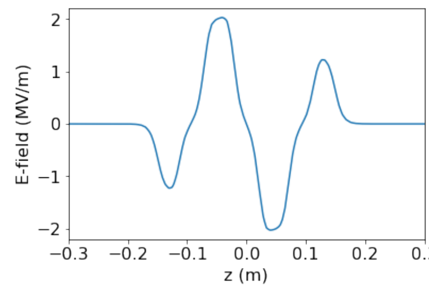

Figure 8: Longitudinal electric field distribution on the z-axis of the cavity.

consumption and the fact that we have experience building IH-type cavities, as the MGBs are 7-gap IH-type cavities [2]. During the design process, we performed electromagnetic, thermal, and mechanical simulations to optimize RF power consumption, temperature change, and mechanical stress. The cavity will be entirely made of copper. There are three identical stems and drift tubes brazed to the tank and a conical drift tube brazed to each end of the cavity. Figure 7 shows the inside of the cavity and relevant dimensions along with the temperature change when the cavity is at design voltage of 260 kV. Electromagnetic parameters of the cavity are listed in Table 1 and the longitudinal electric field along the beam axis is shown in Fig. 8. There are two tuners on the side wall of the cavity, one fixed and one motorized, and one coupler on the other side.

CONCLUSION

A 322 MHz IH-type room-temperature bunching cavity was designed for the FRIB linac. Our simulations show this new cavity will mitigate beam losses caused by energy straggling and non-uniformities in the liquid lithium charge stripper. The design of the cavity is feasible and similar to the FRIB Multi-Gap Buncher design. The construction and installation of this cavity has been designated as high priority in the FRIB Accelerator Improvement Plan.

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