OPTIMIZING CAVITY CHOICE FOR FRIB ENERGY UPGRADE PLAN*

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Abstract

Isotope production yield rate is directly proportional to beam power, especially for heavy ions. Higher beam kinetic energy on target drives more isotope yield. FRIB has an energy upgrade plan up to ≥ 400 MeV/u for Uranium and already prepared a vacant space in the design stage and cryogenic capacity that accommodates for the energy upgrade plan [1]. This upgrade requires an optimized linac design and challenging technology for cavity performance improvement. In this paper, we will approach this issue concerning; maximizing final energy, optimum beta, cavity operating frequency, cryogenic power, fabrication and cost in order to develop a cavity that is suitable for the energy upgrade plan.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a heavy ion linac under construction at Michigan State University. FRIB is a unique linac in such a way that it accelerates multi-species ions. FRIB baseline design will accelerate ions to energies ≥ 200 MeV/u. It will accelerate all stable ion beams from Proton to Uranium. FRIB has an energy upgrade plan [1] and prepares a vacant space of approximately 74 meters in the design stage and cryogenic capacity to accommodate the plan. Cavity class choice is important for the energy upgrade due to the dependence of transit time factor curve width (velocity acceptance) on number of gaps. For multi-species linac such as FRIB, less gaps increase velocity acceptance as shown in Figure 1 where Transit Time Factor (TTF) versus beta geometry is plotted for varies number of gaps for elliptical cavity. For instance, in FRIB elliptical cavities with high number of acceleration gaps will be inefficient for Protons due to the Proton's beta will fall in the transit time factor curve tail.

Transit time factor model equations are below [2].

$$T = \left(\frac{\beta}{\beta g}\right)^2 sin\left(\frac{\pi N}{2\beta/\beta g}\right)\frac{(-1)^{(N+2)/2}}{N((\beta/\beta g)^2-1)} \qquad (1),$$

for odd number of gaps

$$T = \left(\frac{\beta}{\beta g}\right)^2 cos\left(\frac{\pi N}{2\beta/\beta g}\right)\frac{(-1)^{(N-1)/2}}{N((\beta/\beta g)^2-1)} \qquad (2),$$

for even number of gaps

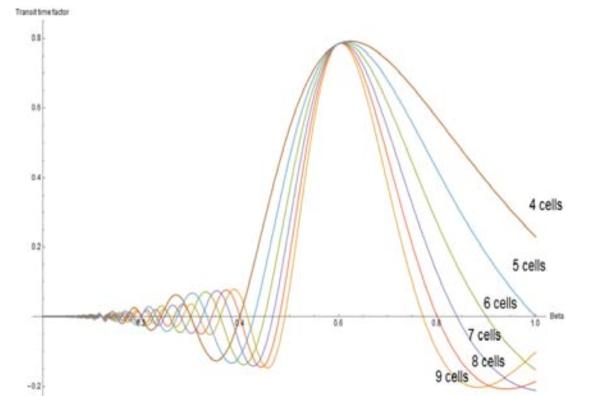

Figure 1: Transit Time Factor (TTF) vs. beta with varying number of cells (gaps) for elliptical cavities.

POSSIBLE CAVITY CLASSES

FRIB energy upgrade linac design has to choose an optimized cavity class: cavity frequency, number of cells for the cavity, and beta geometry for multi-species in order to maximize the benefits for FRIB upgrade. Table 1 compares potential cavity classes where the crucial cavity parameters are quantitatively presented. One can note that the higher operating frequency can allow the higher accelerating gradient. In contrast, compared to elliptical cavities the FRIB beta=0.53 Half Wave Resonator (HWR) has higher transit time factor at beta optimum. Whereas, elliptical cavity has higher acceleration efficiency (R/Q). The cavity aperture is kept the same as the FRIB HWR aperture (40 mm). For elliptical cavity classes, a small aperture lowers cell to cell coupling. FRIB beam current is very low (several mA). This parameter won't play an important role in the energy upgrade plan. An overview of potential cavity classes for FRIB energy upgrade are discussed in next page to see their advantages and disadvantages.

- *FRIB beta = 0.53 Half Wave Resonator (HWR)*

No R&D is needed in this case. FRIB already uses the 0.53 HWR. Eight 0.53 HWR cryomodules will be utilized for the upgrade.

- *Spoke cavity*

Spoke cavity has benefits for low frequency and heavy beam loaded cavities, however these benefits are not so important for FRIB energy upgrade because of the low current machine. Due to the complexity of the cavity shape, cavity production cost is a concern.

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Table 1: Potential Cavities for FRIB Energy Upgrade Plan

Parameter	0.53HWR[3] FRIB	Double Spoke[4] ESS	Ellipti-cal	Elliptical	Elliptical	Elliptical
Frequency [MHz]	322	352	644	805	966	1288
β	0.53	0.5(?)	0.70	0.70	0.70	0.70
E_{acc} [MV/m]	10	8	16.5	17	17.5	18
Energy Gain/cavity [MV]	5	5.76	21.54	17	15.75	13.14
TTF at β optimum	0.904		0.72	0.72	0.72	0.72
Q_0	7.6x10^{9}		1.5x10^{10}	2.0x10^{10}	2.5x10^{10}	3.0x10^{10}
R/Q [Ω]	229.5	425	1480			1036
G [Ω]	107.4	131	250			270
Aperture diameter [mm]	40	50	40	40	40	40
High field Q-slope	Yes	Yes	No	No	No	No
Shape complexity	No	Yes	No	No	No	No
Final energy for 238U, q = 78, and E_i = 262 MeV/u	400		447	440	434	422

- *Elliptical Cavity*

Elliptical cavity is much simple compared to other HWR or spoke cavity. The technology is well established. It would be a higher potential for FRIB energy upgrade. Important parameters for such as operating frequency, number of cells in cavity, and beta geometry (beta optimum) will be the main focus.

Choice of Operating Frequency

Too large frequency jump in linac is not desired. It produces emittance growth and causes mismatch in beams. The longitudinal acceptance is an important parameter for frequency choice. The energy acceptance is estimated using the following formula [5].

$$w_{max} = \frac{\Delta W_{max}}{mc^2} = \sqrt{(\phi_s cos\phi_s - sin\phi_s)\frac{2qE_0T\beta_s^3\gamma_s^3\lambda}{\pi mc^2}} \quad (3),$$

where w_{max} is the maximum energy half width, mc^2 rest mass, ϕ_s is synchronous phase, q is the ion charge state, E_0 is the cavity potential, T is the transit time factor, β_s is the ion velocity, and λ is the wavelength. Acceptance for potential cavity frequency choices is summarized in Table 2 for Uranium 238 and the charge state 78. The initial energy is presumed to be a 262 MeV/u similar to the baseline FRIB upgrade plan [6].

The frequency jump in a linac requires a matching section to preserve beam quality. This can be done via starting with a lower accelerating gradient than the baseline and gradually increasing the gradient, which would reduce the final energy. To determine the energy reduction, beam dynamics simulations are required via codes such as IMPACT or TRACK. Usually choosing higher number of cells in a cavity is advantageous for the cost point of view. It reduces linac components and minimizes fabrication time. In FRIB, the beam current is low (~ mA), i.e. higher Order Modes (HOM) are not a concern that means increasing number of cells won't affect cavity performance by HOM trapping. The practical limitation is the cavity length for efficient handling and processing.

Choice of Beta Geometry (Beta Optimum)

As seen in Figure 2a, for the light ions case such as Argon 36, beta =0.70 is the optimum. Whereas, for the heavy ions case such as Uranium 238, beta =0.68 is the optimum as shown in Figure 2b. To further optimize one beta geometry for both light and heavy ions, let's consider a quantitative comparison between final energy difference (Δw) with beta geometry 0.70 and 0.68 for both light and heavy ions with 644 MHz. Panofsky's famous equation was used to calculate the final energy for ions [8]. Figure 2a and Figure 2b show the result with 644 MHz.

$$\Delta w = qE_0 lT cos\varphi \quad (4),$$

q is a charge, E_0 is the electric field, l is the cavity length, T is transit time factor, ϕ is the cavity phase.

- Light ion case such as Argon 36 with q =18, we obtain ΔE = Final energy at β_g 0.70 - Final energy at β_g 0.68 = 658 – 631 MeV/u = 27 MeV/u see Figure. 2a.
- Heavy ion case such as Uranium 238 with q =78, we obtain ΔE = Final energy at β_g 0.68 - Final energy at β_g 0.70 = 454 – 447 MeV/u = 7 MeV/u see Figure. 2b.

Table 2: Longitudinal Acceptance for Varies Operating Frequencies is Calculated

Cavity type	f	N gaps	V_c	w_{max}	$\Delta\Phi$	Acceptance $\pi*\Delta\Phi*\Delta w_{max}$
	MHz		MV	MeV	ns	π-ns-MeV/u
HWR	322	2	4.93	25.45	0.22	5.65
Elliptical	644	8	21.51	28.80	0.11	3.20
Elliptical	805	8	17.73	23.39	0.088	2.06
Elliptical	966	8	15.21	19.77	0.073	1.45
Elliptical	1288	8	11.73	15.04	0.06	0.83
Elliptical	1288	11	16.13	13.91	0.06	0.77

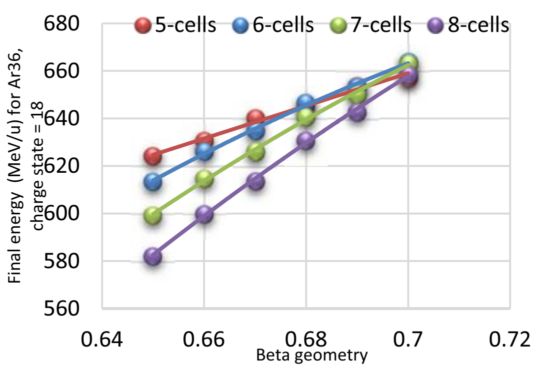

Figure 2a: Final energy gain for 36Ar, q =18, and E_i = 401 MeV/u versus beta geometry utilizing FRIB energy upgrade 644 MHz linac. The purple represents the final energy for 8 cells cavity, the green for 7 cells cavity, the blue for 6 cells cavity, and the red for 5 cells cavity.

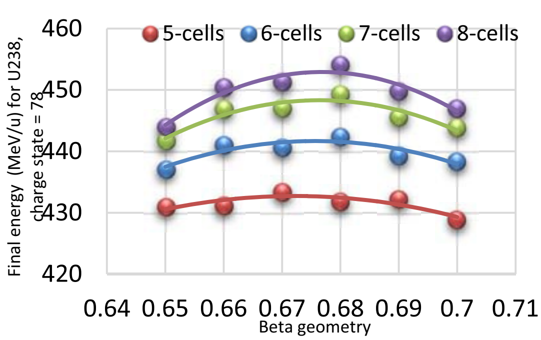

Figure 2b: Final energy 238U, q =78, and E_i = 262 MeV/u versus beta geometry utilizing FRIB energy upgrade 644 MHz linac. The purple represents the final energy for 8 cells cavity, the green for 7 cells cavity, the blue for 6 cells cavity, and the red for 5 cells cavity.

The energy gain is almost same for heavy ion acceleration in both betas, but 27 MeV/u is higher at β_g = 0.70 for light ion acceleration. We can see that beta geometry = 0.70 will be a good choice for both light and heavy ions from final energy gain point of view.

Combination of Betas Option

To investigate whether or not the energy gain increases significantly if two beta geometries were utilized in FRIB upgrade linac. The transit time factor for a combination of betas 0.65 and 0.71 for 238U, q = 78 is plotted versus beta (particle velocity) in Figure 3. In this configuration we obtain the energy gain of a 463 MeV/u at 644 MHz. In the single beta case of 0.68, the energy gain is a 454 MeV/u. The difference is very small. Thus the benefit of the two beta configuration is not attractive.

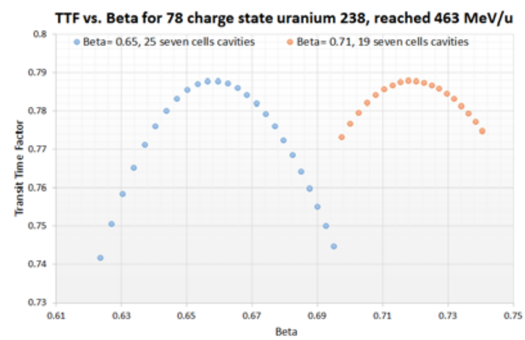

Figure 3: Transit time factor versus beta for 238U, q =78 reached 463 MeV/u at 644 MHz.

One might ask other combinations could provide higher final energy gains? A few different two beta geometry combinations were tried, however the final energy didn't exceed the combination of betas = 0.65 and 0.71 for 238U, q = 78 and initial presumed energy = 262 MeV/u. We conclude that the two betas combination scheme wouldn't be efficient for FRIB upgrade due to the insignificant final energy gain difference compared with one beta scheme. Moreover, two betas scheme requires more work than one beta scheme. Therefore, one beta geometry scheme is given the preference.

Cryomodule Options

Due to the limitation in FRIB tunnel entrance which limits the cryomodule length so that it doesn't exceed the hatch length, which is 6.7 meters. Anything needed to be loaded into the tunnel can't exceed 6.7 meters [9]. Economic cryogenic options such as maximizing number of cavities in the cryomodule and choosing either room temperature or superconducting quadruples for beam focusing will be investigated.

PATH FORWARD

End to end simulation via IMPACT code or TRACK code for FRIB energy upgrade section is required, which is on-going but does not get yet any conclusive result in this time. We will compare simulation results in terms of acceptance, operating frequencies, and final energy calculations and maximize benefits for FRIB upgrade. Frequency

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transition is crucial if the transition isn't done carefully, it will lead to an emittance growth and cause mismatch in beams. For FRIB baseline, the longitudinal acceptance at the segment 2 is about 0.140 π-ns-MeV/u and the beam emittance with errors (including 99.99% of 1.6 million tracked particles) of multi-charge-state Uranium is about 0.080 π-ns-MeV/u [10]. That means analytically acceptance for all candidate frequencies is sufficient from Table 2 so far. However, in a real linac, due to the particle velocity increases and the phase space motion, the separatrix becomes more complicated. As a result of that, the stable bucket becomes a golf-club shape which reduces the acceptance by an amount. The quantitative estimation needs more detailed calculations by beam dynamic simulations.

CONCLUSION

Beta geometry = 0.70 is preferable for both light and heavy ions in FRIB energy upgrade. From final energy gain point of view, 644 MHz will be a good choice for FRIB upgrade. However, the final energy difference between 644 MHz and 1288 MHz is not significant. 1288 MHz choice will be more economical and the technology is mature. The possibility of 1288 MHz will be investigated in more details by the beam dynamics simulation.

In any case, exploiting cutting edge technologies such as Nitrogen doping to improve Q_0 and solving high field Q-slope in BCP would be beneficial for FRIB energy upgrade.

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