INVESTIGATION OF THE POSSIBILITY OF HIGH EFFICIENCY L-BAND SRF CAVITY FOR MEDIUM-BETA HEAVY ION MULTI-CHARGE-STATE BEAMS

S. Shanab†, K. Saito, and Y. Yamazaki, Michigan State University, East Lansing, USA

Abstract

The possibility of L-band SRF elliptical cavity in order to accelerate heavy ion multi-charge-state beams is being investigated for accelerating energy higher than 200 MeV/u. A first simple analytic study was performed and the result showed that the longitudinal acceptance of 1288 MHz is sufficient for heavy-ion multi-charge-state (5 charge states) medium-beta linac. The cryogenic heat load is calculated for this linac with taken into consideration cavity doping technology. In this paper, a summary of the beam dynamics and cryogenic heat load calculations for 1288 MHz linac for heavy-ion multi-charge-state (5 charge states) medium-beta beams.

INTRODUCTION

High Superconducting Radio Frequency (SRF) structures are attractive for a variety of reasons. They make the accelerator very compact since the cross-section of the cavity is proportional to the inverse of the frequency squared, i.e. the higher frequency RF the smaller cavity becomes. Although, the SRF cavity surface resistance is proportional to frequency squared, it can be minimized via doping technology. That reduces cavity cryogenics' heat load significantly. In addition, cavity-doping technology has shown the trend that its reduction in cavity surface resistance is more pronounced in higher frequency cavities [1, 2]. That reduces cavity cryogenics' RF heat load significantly at L-Band frequency.

HEAVY ION LINAC CRITERIA

Longitudinal acceptance must be sufficient. Continues-Wave (CW) operation, high Q_0 is desired. Low current linac (Uranium < 1mA), i.e. HOMs are not a serious concern. Multi-species and multi-charge state acceleration i.e. accelerates protons to uranium. Velocity acceptance must be sufficient; number of cavity-cells must be optimized. Optimized energy upgrade to boost U-238 from 200 MeV/u to 400 MeV/u.

1288 MHz LINAC PARAMETERS

The proposed 1288 MHz (L-band) linac layout consists of eleven cryomodules; each includes nine 6-cell 1288 MHz SRF cavities and 22 room temperature magnetic quadrupoles for beam focusing. Table 1 summarizes the 1288 MHz linac parameters. The conceptual cryomodule layout is shown in Fig. 1.

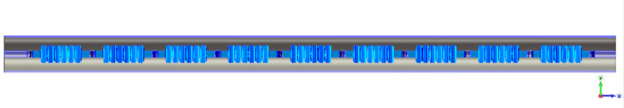

Figure 1: 1288 MHz conceptual cryomodule layout.

Table 1: Summarizes the 1288 MHz Linac Parameters

Parameter	Unit	Value
Number of Cryomodules		11
Number of Cavities		99
Number of Cells per Cavity		6
Number of Cavities per Cryomodule		9
Number of Quadrupoles		22
Operating Frequency	[MHz]	1288
Beta Geometry β_g		0.61
Cryomodule Length	[cm]	633.0
Bellow Length	[cm]	7.1
Linac Total Length	[cm]	7933.0
Number of Cryomodules		11
Number of Cavities		99

SUMMARY OF 1288 MHz CAVITY PARAMETERS

The number of cells of the cavity was chosen to be six, such that it accelerates a multi-charge-state uranium-238 beam from an initial energy of 200 MeV/u to ≥ 400 MeV/u and maintain a sufficient velocity acceptance for lighter ions and protons. The larger cell number than six also investigated but it does not meet the upgrade requirement. The length of the accelerating cell is $\beta_g \lambda/2$ and the total length (flange-to-flange) of the cavity is 58.59 cm including beam pipes at both ends with $\beta_g = 0.61$ and a bore radius of 3.0 cm. The choice of the cavity bore radius to be 3.0 cm is advantageous due to the smaller cavity radius the uniform accelerating fields the ions will experience, i.e. smaller transverse kicks when ions pass through cavities, which minimizes the beam centroid oscillations in the space-phase plane. Specially, there were not beam correctors utilized in the 1288 MHz linac structure. In addition, a smaller radius cavity lowers the E_{pk}/E_{acc} that is due to the fact that smaller radius adds more electric volume in the high electric field region of the cavity, i.e. cavity ends. The same thing is for H_{pk}/E_{acc} ratio.

---

*This work was supported in part by the U.S. National Science Foundation, under Grant PHY-1102511 and by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661.

Table 2: Summary of 1288 MHz Cavity Parameters

Parameter	Unit	Value
Cavity length	[cm]	58.59
Number of Cells per Cavity		6
Eacc	[MV/m]	25
Cavity Voltage	[MV]	10.6
H_{pk}	[G]	948.1
Beta Geometry, β_g		0.61
E_{pk}	[MV/m]	76.0
E_{pk} /E_{acc}		3.0
H_{pk} /E_{acc}	[mT/MV/m]	3.8
Cell-to-Cell Coupling	[%]	1.34
Geometry Factor, G	[Ohm]	217
R/Q	[Ohm]	262.6

1288 MHz LINAC BEAM DYAMNICS

20649 ions were tracked along the linac. The Root Mean Squared (RMS) longitudinal beam emittance of the beam was tracked along the linac with and without errors calculated via TRACK code [3]. It showed that the longitudinal acceptance is sufficient for multi-charge state (five charge states) heavy-ion medium-beta beams. Figure 2 shows the longitudinal emittance evolution along the linac without errors, while Fig. 3 shows the longitudinal emittance evolution along the linac with errors for 200 error trials. Since the beam is multi-charge state then each charge state will have its own centroid and bunch. As those bunches are accelerated they will oscillate around the synchronous ion in the phase-space thus the RMS longitudinal emittance is adequate to describe the motion of a multi-charge-state beam. The 200 seed error trials can be seen as an envelope that shows the maximum charge states centroid oscillations when the linac errors were implemented. The maximum growth in longitudinal emittance was observed in the error trial 82 shown in red in Fig. 3. In this error trial, the maximum value of RMS longitudinal emittance is approximately 44.3 π-ns-KeV/u at the linac end without any beam losses, i.e. the 100% beam was transported to the linac end.

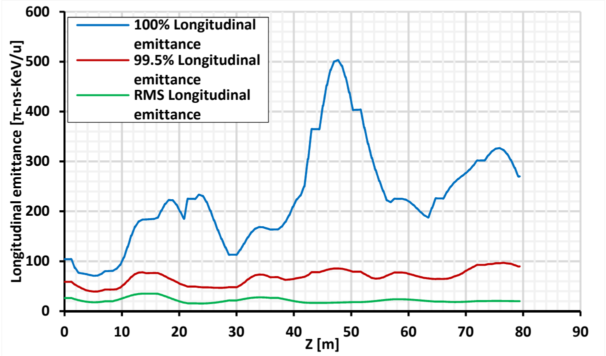

Figure 2: The longitudinal emittance evolution along the linac. Blue is 100% longitudinal emittance, the red is 99.5% longitudinal emittance and the green is RMS longitudinal emittance for uranium-238 with multi-charge-states.

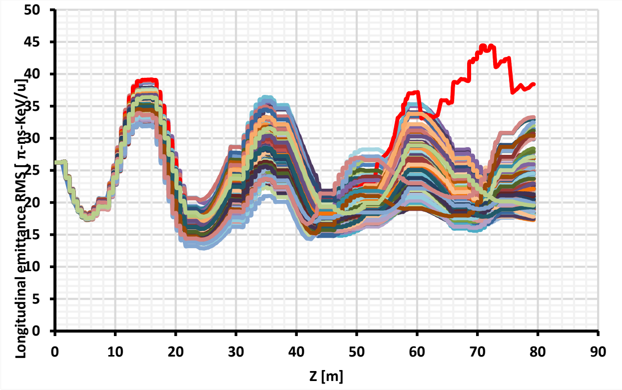

Figure 3: The RMS longitudinal emittance was tracked along the linac for 200 seeds error trial.

1288 MHz LINAC CRYOGENICS

The RF dynamic load (P_{loss}) is calculated from the following equation:

$$P_{\text{loss}}\,[W] = \frac{L_{\text{eff}}^2}{(R/Q)}\,\frac{E_{acc}^2}{Q_o} \tag{1}$$

Here, for our design, with (R/Q)=262.6 Ω, $L_{eff} \equiv \frac{\beta_g N \lambda}{2}$, β_g=0.61, λ= 0.233 m, N=6, the result is L_{eff} = 0.426 m

when input these numbers into Eq. (1), the RF dynamic loss/cavity at E_{acc}= 25 MV/m is:

$$P_{\text{loss}} = \frac{4.32\times10^{11}}{Q_0} \tag{2}$$

If Q_o= 4x10^{10}, P_{loss} = 10.8 W/cavity. The total with the nitrogen doping technology, the cavity cryogenic heat load can be lowered significantly. The linac dynamic heat load for the 1288 MHz linac is calculated for varies cavity intrinsic quality factors, Q_0. As expected and shown in Fig. 4, higher cavity quality factor reduces the dynamics heat of the linac.

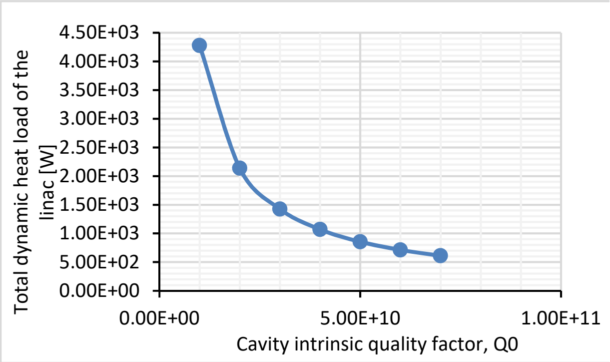

Figure 4: 1288 MHz linac's heat load calculations for different cavity quality factors.

CONCLUSION

Our simple study showed that the longitudinal acceptance of the proposed high (L-band) frequency linac for medium-beta heavy ions multi-charge-state beams is sufficient for keeping the beam loss within the order limit allowing the hands-on maintenance and it preserves the beam quality (no beam loss of 20000 implies lower beam loss power than an order of several 10 W). Nitrogen doping technology has shown that it is more beneficial for higher frequencies cavities. That is because BCS surface resistance, R_{BCS} is higher than the residual surface resistance, R_{res} in higher frequencies.

REFERENCES

[1] M. Martinello *et al.*, “Advancement in the Understanding of the Field and Frequency Dependent Microwave Surface Resistance of Niobium”, in *Proc. SRF'17*, Lanzhou, China, Jul. 2017, pp. 364-367. `doi:10.18429/JACoW-SRF2017-TUYAA02`

[2] M. Martinello *et al.*, “Anti-Q-slope enhancement in high-frequency niobium cavities”, in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2707-2709. `doi:10.18429/JACoW-IPAC2018-WEPML013`

[3] P.N. Ostroumov, V.N. Aseev, and B. Mustapha, “TRACK – a Code for Beam Dynamics Simulation in Accelerators and Transport Lines with 3D Electric and Magnetic Fields”, `https://www.phy.anl.gov/altas/TRACK/Trackv37/Manuals/tv37_man_index.html`