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UNIQUE ACCELERATOR INTEGRATION FEATURES OF THE HEAVY ION CW DRIVER LINAC AT FRIB*

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Abstract

The FRIB driver linac is a front runner for the future high power hadron linacs, making full use of CW, superconducting acceleration from very low β. accelerator driven nuclear waste transmutation system (ADS), international fusion material irradiation facility (IFMIF), Project-X type proton accelerators for high energy physics and others may utilize the technologies developed for the design, construction, commissioning and power ramp up of the FRIB linac. Although each technology has been already well developed individually (except for charge stripper), their integration is another challenge. In addition, extremely high Bragg peak of uranium beams (several thousand times as high as that of proton beams) gives rise to one of the biggest challenges in many aspects. This report summarizes these challenges and mitigations, emphasizing the commonly overlooked features.

INTRODUCTION

The continuous wave (CW) heavy ion linac with a beam energy over 200 MeV/u and a beam power of 400 kW for Facility for Rare Isotope Beams (FRIB) [1] is a driver to produce various isotope species for nuclear physics study. The linac is to accelerate all the stable ions from proton to uranium by making full use of superconducting (SC) RF acceleration technology from a very low beam energy of 0.5 MeV/u. The linac is to use 330 SC cavities with four different types; β = 0.041 quarter wave resonator (QWR), β = 0.085 QWR, β = 0.29 half wave resonator (HWR) and β = 0.53. Most of the SC cavities are housed together with focusing SC solenoid magnets in 44 acceleration cryomodules (CMs), while the remaining 14 SC cavities in 5 rebuncher (matching) CMs (Recently, the rebuncher CMs and cavities therein were further optimized [2]). Needless to say, manufacturing of a great number of SC cavities and CMs of different kinds is one of the biggest challenges in this project. Also, it should be emphasized that the FRIB CMs equipped with the focusing SC solenoids and beam position monitors (BPMs) are much more complicated than those of SNS linacs and many electron SC linacs without the solenoids and BPMs inside. Furthermore, each of the FRIB CMs is equipped with many fundamental mode input couplers (FPCs) and each solenoid is with two SC corrector steering dipoles. The development of these FRIB SC technologies is detailed in Ref. [3, 4].

This driver is the first heavy ion linac to join the beam power front of an order of 1 MW as mentioned in Ref. [5], in which beam physics challenge in the FRIB driver linac is detailed. This article is a continuation of Ref. [5] in a sense that accelerator physics integration features of the FRIB driver linac is discussed.

MPS AND BEAM DUMPS

In order to contrast heavy ion beams against proton ones, take uranium beams as the most extreme example. One of the striking difference of the uranium beams from proton ones is their extremely high Bragg peak, that is, energy loss density dE/dx in materials. The uranium one is typically by several thousand times [5] as high as the proton one, depending upon their energy. The range is by several ten times smaller [5]. As a result heavy ion beam loss damage is significantly larger than proton one by this factor, while the radiation arising from the uranium beam loss is by several ten times lower than that of the proton one. The latter implies that the uranium beam loss is very hard to detect, in particular, at an energy below 100 MeV/u. It is one of the biggest challenges how to protect accelerator components from the beam impinge damage. For this reason, Machine Protection System (MPS) [6, 7] implements a redundant, multi-layer scheme, responding to fast events and slow losses.

The extremely high beam loss energy density gives rise to many technical challenges in the FRIB, like liquid lithium charge stripper [8], the target [9], the charge selector and others. In order to show the difficulty arising from high beam damage, take the beam dump design here as an example.

The linac beam dump is used for beam commissioning and beam tuning. For this purpose, we are going to use a beam pulse length of 50 μs and a repetition rate lower than 1 Hz in most cases in order to minimize the beam dump cost. However, after the commissioning and/or tuning, we have to increase the beam duty to CW. The difference between the 50 μs beam and the CW beam is the beam loading. Since the stored energy of SC cavities is very large, no beam loading can be observed with the 50 μs beam. In order to ramp up the beam to CW, we need to confirm the beam loading well compensated with low level RF control system. Since the filling time of the FRIB SC cavities is typically of 5 ms, we need the beam with a pulse length several times as long as this filling time, like 20 ms, in order to confirm the beam loading

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compensation. In other words, we need the beam dump which can stand the 20 ms long uranium beam, but this is very difficult or expensive to fabricate.

It is here noted that we do not need the uranium beam to confirm the beam loading, since the beam loading is not different between uranium and oxygen, for example. Figure 1 shows the 20-ms, 400 kW oxygen beam effect (one pulse) with enlarged beam size on the beam dump made of tungsten successfully designed.

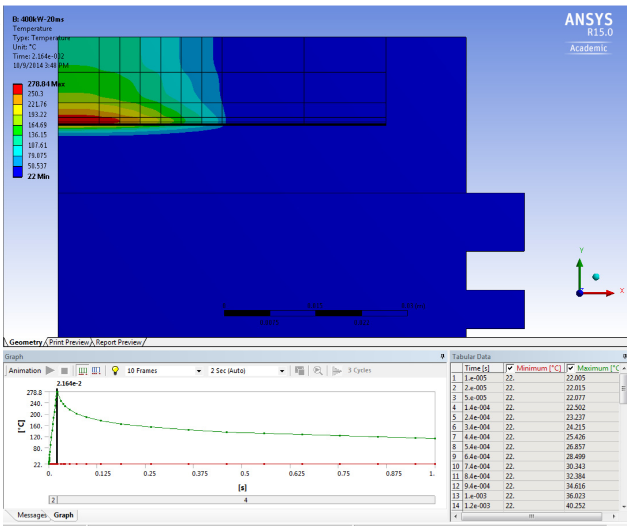

Figure 1: Temperature distribution in the beam dump for 400 kW, 20 ms oxygen beams. The highest temperature is 278 °C, while the melting point is 3370 °C. The maximum stress is 473 MPa, while the yield stress is 750 MPa at 22 °C.

COMPACT FOLDING

One of the unique features of the FRIB driver linac is that the linac is twice folded to be compact, thus enabling FRIB to reuse the existing experimental facility. The arcs achromatic to the second order have been successfully lattice designed together with interfaces as shown in Fig.2, which is 3 dimensional view of folding segment 2, which is the most congested area. After all the accelerator components with interfaces are successfully placed in 3D modelling, the field interference between closely located magnets is another concern. The biggest interference effect is found as seen in Fig. 4 for the combination of hexadecupole (sextupole) H1, correcting dipole C3 and quadrupole Q4. The effect is that 17 percent more current is required for the C3, being not harmful.

SHUNT IMPEDANCE AND BEAM FOCUSING

The RF power dissipation in SC cavities is negligible compared with the beam loading. Therefore, one might believe that the shunt impedance optimization were not necessary for the SC cavities. This is not true as SC cavity experts know well. The power dissipation negligibly small compared with the beam loading can be still a big load on cryogenics. For this reason, the shunt impedance and Q value of the SC cavities need to be optimized sometimes. In general, the shunt impedance decreases as the cavity beam aperture increases. The beam bore radii chosen for the FRIB linac are the results of trade-offs between the two conflicting requirements. In order to keep the beam size reasonably smaller than the cavity beam aperture, the strong, frequent transverse focusing is necessary to some extent. As a result, strong focusing SC solenoid magnets [10] are placed closely to SC cavities inside CMs. The FRIB SC cavities are locally shielded by permalloy sheets against the strong focusing magnetic field.

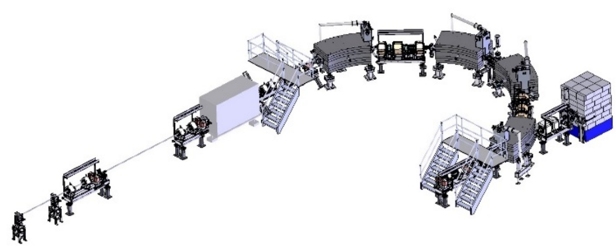

Figure 2: 3D View of FS2.

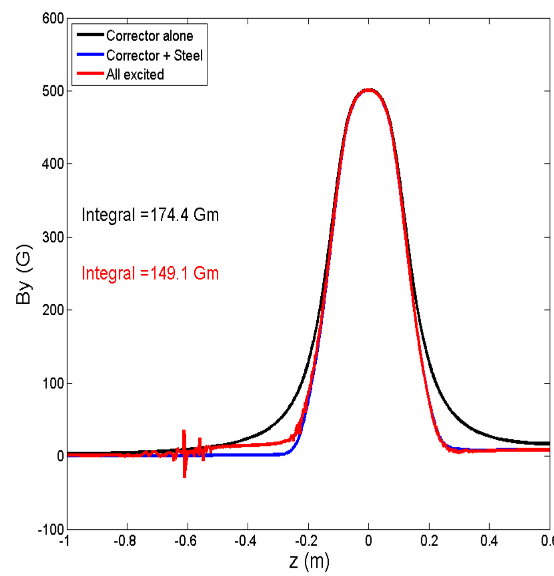

Figure 3: Magnetic field B_y on axis for three different models of the dipole corrector. The black curve shows the case where the dipole is just sitting by itself. The blue curve shows the field when the steel from the neighboring magnets (quadrupole and sextupole) are added. The red curve corresponds to the case where all the magnets are excited.

In general, the focusing solenoids inside CMs are difficult to align, since all the cryomass components are thermally contracted. The strong non-linear space charge force requires the small alignment tolerance of an order of

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50 μm for focusing quadrupole magnets inside drift tubes of proton drift tube linacs in order to keep low emittances and to suppress halo formation. Since the high FRIB beam power is ensured by its CW operation, its peak current is significantly lower than pulsed proton linac, the space charge force is negligible except for low beam energy transport. The alignment error influence can then be compensated by correcting dipoles. The correcting dipoles are attached to the solenoid, while a BPM is also attached to the solenoid on axis.

The transition energy from room temperature acceleration to SC acceleration should be carefully optimized for the future space charge dominated CW high intensity proton linac to be used for accelerator driven nuclear waste transmutation system (ADS), international fusion material irradiation facility (IFMIF), the project X type proton accelerators, and others. The alignment accuracy improved by FRIB linac construction will have a big impact on this transition energy choice.

SUMMARY

Unique integration features of the FRIB CW heavy ion driver linac are discussed. Some features are FRIB specific like folding, while some are common to future high intensity CW proton linacs. Experience and development results to be obtained through FRIB design, construction and operation will strongly influence the design optimization of these machines, determining the direction of high intensity hadron linacs.

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