BEAM PHYSICS AND TECHNICAL CHALLENGES OF FRIB DRIVER LINAC*

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Abstract

The FRIB driver linac accelerates all the stable ion beams including uranium over 200 MeV/u with a CW beam power of 400 kW in order to produce isotopes as rare as possible. Except for 0.5 MeV/u RFQ, the linac is making use of superconducting (SC) RF technology. The beam power, which is an order of 2.5 as high as those of existing SC heavy ion linac, gives rise to many technical challenges as well as beam physics related ones. In particular, the uranium beam loss power density is approximately 30 times as high as the proton one with the same beam energy per nucleon and the same beam power. For this reason, the machine protection system needs a special care. Another example of the technical challenges is to install beam focusing solenoid as close as possible to SC cavities in order to keep the beam focusing as frequent as possible both longitudinally and transversely. This paper reviews all these challenges with development results of their mitigation as well as construction status.

INTRODUCTION

Facility for Rare Isotope Beams (FRIB) [1] is now under construction at Michigan State University for innovative study of nuclear physics and applications, being under cooperative agreement with the United States Department of Energy. In order to discover and study isotopes as rare as possible, the FRIB driver linac is to accelerate all the stable ions (including uranium) up to a beam power of 400 kW (5×10^{13} ^{238}U/s), which is chosen as the present technical limit for the fragmentation target. The beam energy is at lowest 200 MeV/nucleon (MeV/u) for uranium with higher energies for lighter ions. Civil construction started in March, 2014, followed by technical construction in October, 2014, to be completed in June, 2022 (Critical Decision 4), but the project is managing to early completion in fiscal year 2021. This early completion is driven by the strong demand from nuclear physicists all over the world, exemplified by the FRIB Users Organization [2] with 1,354 members from 50 countries (as of September, 2015).

The civil construction is 10 weeks ahead of the baseline schedule with 16 months ahead for Front End (FE). Making full use of this ahead schedule, the ion source on-site commissioning will start towards the end of 2016. The commissioning of the upstream section will be conducted in parallel with installation and integrated testing of the downstream sections. The technical construction is mostly on track for the early completion.

FRIB driver linac is the first heavy ion (HI) accelerator aiming to join the beam power front as shown in Fig. 1. The Chart like Fig. 1 was used at J-PARC to show “Proton Beam Power Front” [3] throughout the wide range of the beam energy, where both SNS [4] and J-PARC [5] were challenging to push the front from an order of 100 kW to 1 MW. The Proton Beam Power Front is nothing but the technology front to control the beam loss rate within the radioactivity level allowing hands on maintenance. Therefore, one of the technical challenges of the SNS and J-PARC was to suppress the beam loss rate by an order of magnitude from the existing accelerators.

Figure 1 was extended [6, 7] from the proton accelerators to the heavy ion ones. It should be noted that the PSI cyclotron [8] had already marked the beam power of 1 MW, when the SNS and J-PARC started their construction. The beam loss control issue at cyclotrons is different from that at synchrotrons. For the cyclotron, the beam loss at extraction limits the beam power, while that at injection is the main issue for the J-PARC rapid-cycling synchrotron, the SNS accumulator ring and other proton synchrotrons shown in Fig. 1. This is the reason for the different beam power front of the PSI cyclotron from the others. The HI beam power front may have different technical implication as well. In addition, the HI beam power increase in the FRIB driver linac is more than two orders of magnitude compared with similar superconducting HI linac like ATLAS.

This article summarizes the beam physics challenges and associated technical ones, which are specific for the HI superconducting (SC) linac together with the present status of the linac construction. Good trade-offs between

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these two challenges are a key to the success in cutting-edge accelerator projects.

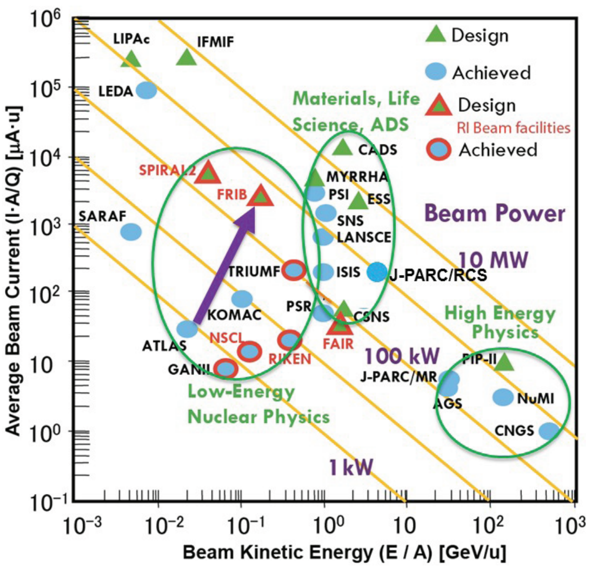

Figure 1: Average hadron beam power vs beam energy.

REQUIREMENTS FOR FRIB DRIVER LINAC

It is needless to say that any particle accelerator for scientific study should be designed so as to maximize the scientific and technical outputs economically and efficiently. The FRIB is aiming for a large number of prominent scientific research results, studying rare isotopes, in particular, to be produced by nuclear fragmentation process. For that purpose, it is important to produce not only a large number of rare isotopes, but also to efficiently and precisely separate one isotope from another. Isotopes produced by the nuclear fragmentation process are separated by means of time of flight technique as well as a series of magnet systems referred to as a fragment separator [9]. Then, not only the high beam power, but also the low beam emittances are crucial both longitudinally and transversely. It is thus oversimplification to judge the accelerator performance only by its beam power. Table 1 summarizes the required beam quality. These parameters are only feasible with a linac, and this is the reason for the FRIB choice of the linac scheme.

In contrast to spallation neutron source based experiments, and long baseline neutrino experiments, nuclear physics experiments mostly require high-duty or Continuous Wave (CW) or direct current beams for detector dead time issues rather than a µs pulsed beams. Another difference is that a wide variety of nuclear species are required for projectiles, depending upon users' interests, and a quick change of accelerated particles needs a high degree of tunability. It should be noted that this tunability is one of the important items to keep high availability and reproducibility, which are important for efficient, precise experiments.

Table 1: Beam Emittance Specifications at Target

Beam Parameter	Requirement
90 % Beam Diameter	$\leq$ 1 mm
90 % Full Angular Spread	$\leq$ 5 mrad × 2
95 % Full Energy Spread	$\leq$ 0.5 % × 2
95 % Full Bunch Length	$\leq$ 3 ns
Full Position Reproducibility	$\leq$ 0.1 mm × 2
Full Angle Reproducibility	$\leq$ 3 mrad × 2
Full Energy Reproducibility	$\leq$ 0.5 % × 2

Another, but the project-specific requirement is to make a full use of the existing experimental facility at National Superconducting Cyclotron Laboratory (NSCL) as well as Re-Accelerator ReA3. In other words, only the driver linac, the target and the fragment separator are to be constructed. For that purpose, the linac has to be housed in a tunnel annexed to the existing NSCL building, and the linac is compactly folded twice, requiring special beam optics efforts [10].

RATIONALE FOR FRIB SC LINAC DESIGN PARAMETERS AND THEIR OPTIMIZATION

In general, if the required pulse length is beyond an order of 1 ms, SC linacs are advantageous over room-temperature (RT) ones, regarding the required wall plug power, since the filling time of the SC linac is of that order. An issue here is what the transition energy should be from the RT to the SC acceleration or what the lowest possible energy is for the SC acceleration. It is noted that the space charge force is negligibly small except for the low energy beam transport because of the low peak beam current of the CW operation (0.8 mA even for fully stripped uranium ions). Even with negligible space charge force, the FRIB linac still needs frequent focusing to some extent in order to keep the beam sizes within tolerable level. In order to ensure the frequent focusing both longitudinal and transverse, focusing solenoids are housed in cryomodules (CMs), being placed as close as possible to longitudinally focusing, that is, accelerating cavities.

For the bore radii, a special note may be necessary in order to remove any possible wrong preconception regarding the shunt impedances of SC cavities. The shunt impedances should be still optimized even for the SC cavities, in particular, if they are for the low β structures, since the lowered shunt impedance to widen the bore radii increases the heat load on the cryogenics, which is the major source of the power consumption for SC linacs. For this reason, we have to keep the cavity bore radii within the reasonable size, which is one of the major trade-off issue with the beam loss. The large bore radii for the elliptical SC cavities to be used for high β acceleration are to keep sufficient coupling among cavities, and their immunity against the beam emittance growth and/or beam halo formation is just a by-product.

On the basis of various optimization and integration efforts, the transition from the RT Radio-Frequency Quad-

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rupole (RFQ) to the lowest β SC acceleration by 80.5 MHz, Quarter Wave Resonator (QWR) cavities has been chosen at 0.5 MeV/u (β = 0.033) with a bore diameter of 36 mm (we have increased the bore diameter twice, that is, very originally 30 mm, then 34 mm). The optimization and integration include the extensive study of shielding the SC cavities from the focusing magnetic fields [12] in order to place the focusing solenoids as close as possible to the SRF cavities. Here, we have chosen the maximum possible magnetic field of 8 T (NbTi wires) at the beam axis with a tuning contingency of 10 % and a temperature one of 0.5 K beyond the operational temperature of 4.5 K. These contingencies were considered necessary in order to ensure the sufficient reliability for the cryomass components. In particular, failure of any focusing solenoid would disable the beam operation in contrast to cavity cases, in which other cavities can compensate. Further worse, the replacement of a solenoid is nothing but that of CM, giving rise to a quite long beam shut down. It is noted that the solenoid magnet is a unique solution in order to ensure the frequent focusing for the low β acceleration, since the quadrupole magnets can be only used as a lengthy triplet for sufficiently focusing both horizontally and vertically.

The focusing solenoid magnets are equipped with corrector dipole coils both horizontal and vertical. The cold beam position monitors (BPMs) are as well attached to the focusing solenoids in order to ensure the accurate relative positioning between the BPMs and the solenoids, which shall enable the reliable beam based alignments by the beam commissioning, tuning, and studies. In this way sufficient tunability is ensured as requested for the nuclear physics experiment. It is emphasized that the reliable assembling of the cavities, BPMs and solenoids in compact space is one of the mechanical challenges. The beam dynamics simulation study, including the error study, has been conducted for the trade-off between this mechanical challenge and the lattice periodicity.

The periodicity, even if it is approximate, is still crucial for keeping immunity against any errors, and any change should be as adiabatic as possible. Also, the parametric resonance should be avoided, if the beam has to experience the resonance for several periods. Further attempt to improve the reliability by decreasing the solenoid magnetic field is difficult for this reason.

On the basis of these optimization effort the main parameters of the FRIB linac are established as Table 2. Here, it is interesting to note that the digital Low Level (LL) RF Control technology and the solid state power electronics technology, recently developed, are replacing the classical accelerating scheme based upon a multi-cell, long accelerating structure powered with a MW RF power source by a single cell SC accelerating structure (strictly speaking, this two gap structure is equivalent to a two-cell structure very strongly coupled) powered by a few kW solid state RF power amplifier.

Table 2: FRIB Driver Linac SC Cavities

	QWR1	QWR2	HWR1	HWR2
β_0	0.041	0.085	0.29	0.53
Frequency (MHz)	80.5	80.5	322	322
Aperture (mmϕ)	36	36	40	40
Output Energy (MeV/u)	1.4	16.6	55	>200
Number of cavities	12	88+12	76	144+4
Number of solenoids	6	33	12	18
Number of CMs	3	11+3	12	18+1

HWR stands for Half-Wave Resonator. The number after + is for the matching CMs. The energy is for uranium.

LINAC FOLDING WITH MULTI CHARGE STATE ACCELERATION

The FRIB linac design work needs another effort in order to manage two compactly folded arcs, which has to simultaneously transport the multi-charge states, being analogous to the large momentum spread beam. The folding section should be achromatic and isochronous to the second order by making chromaticity correction with sextupoles, keeping sufficient acceptance for the multi-charge states beam transport. Since the ion species should be quickly varied from experiment to experiment, the efficient beam tuning is also crucial. All these conflicting requirements could be met by keeping the horizontally wide acceptance with pole piece shape optimization for both the separate function quadrupoles and sextupoles [13].

Accurate RF phase control of σ = 0.5° with a cutoff of 3σ to meet the beam requirements at the target [10] is locally ensured by the digital LLRF technology, recently developed. The global phase control tolerance need not be stringent for the following two reasons, eliminating the expensive thermostatic chambers for the reference line. First, the linac being twice folded is not so spatially spread out as a common linac. Second, the gradual variation of the reference phase from one end to the other in the tunnel can be adiabatically followed by the low β beams, exerting the synchrotron oscillation several times [14].

HIGH BRAGG PEAK CHALLENGE

One of the biggest challenges inherent to high beam power heavy ion accelerators arises from the extremely high Bragg Peak of the heavy ions, that is, the high stopping power (beam loss power density). If we use Livingston-Bethe formula [15], the ratio of the ion stopping power (beam loss power density) to the proton one with the same velocity is given by

$$\frac{[d\,(E/A)/dx]_{ion}}{[d\,(E/A)/dx]_{proton}} = \frac{Z^2}{A}, \tag{1}$$

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where Z and A are the charge (atomic) number and mass number of the ion, respectively. The range ratio obtained by integrating the Livingston-Bethe formula is just the inverse of Eq. (1). Here, the same velocity means that we are using the ion beam energy per nucleon. If we take the uranium case (Z = 92, A = 238) as an example, the beam loss power density ratio, that is, the heat shock ratio is 36. This extremely high stopping power gives rise to big challenges at the Machine Protection System (MPS), the beam dumps, the charge stripper, the charge selector and the target [9].

MPS Challenges

A criterion of 1 W/m widely used for the allowable beam loss is based upon the radioactivity, still enabling hands-on maintenance for 1 GeV proton beam loss. Neutron yield and radioactivity produced by the proton beams are approximately proportional to the beam power at a beam energy between 500 MeV and 3 GeV, but they are getting less as the beam energy lowers, in particular, very small at an energy below 70 MeV. Furthermore, since the radioactivity to be generated by the uranium beam loss is by a factor of approximately several ten (by nearly the ratio of ranges) lower than the proton case, the radioactivity is not the primary issue of the HI beam loss, although it still needs due care. In other words, the beam loss criterion of 1 W/m is not applicable here.

This also implies that the beam loss is very hard to detect by means of commonly used radiation based Beam Loss Monitor (BLM). Further worse for the FRIB specific case, the low energy linac is located in parallel to the high energy linac. The beam loss radiation at the former can be drowned out by that at the latter. In addition, x rays from SC cavities make it also difficult to distinguish the beam loss radiation from the x rays. The difficulty in beam loss detection is a very serious issue, if one considers the relatively small beam bore radii of the SC cavities under the extremely high beam loss power density.

The most dangerous are acute (fast) beam losses at some of SC cavities, when an upstream cavity trips. Since the admittances at the SC cavities are designed larger than those at the stainless steel beam pipes inside the focusing SC solenoids, that is, the beta function $\beta(s)$ is the maximum at the focusing elements, no beam is lost at any cavity under normal operational condition, theoretically speaking. Here, the admittance A is defined in such a way that $(A\beta(s))^{1/2}$ is the bore radius. However, once a cavity trips, the beam energy is lowered, invalidating the above admittance definition, that is, the beta function. The beam is over-focused to hit the cavity surface. Any malfunctioning of other components than cavities takes some time to give rise to beam loss, since the components have some stored energy to decay. Thus, the MPS can be activated in time to stop the beam to be lost, after detecting the malfunctioning. On the other hand, the cavity trip can immediately exhaust its stored energy, leaving no time to stop the beam loss.

The extensive study of cavity trip events showed that the maximum possible power dissipation on a cavity is a little less than 5 kW. An FRIB MPS response time of 35 μs can then protect the FRIB cavities from acute beam loss damage, if scaled [16] from the SNS MPS response time of 20 μs. Here, the MPS is activated by LLRF control detecting the cavity trip and/or Halo Monitor Rings (HMRs) and/or differential current monitoring.

Actually, the FRIB MPS implements a redundant, multi-layer scheme, responding to these fast events and chronic (slow) beam losses [17]. Allowable chronic beam loss in the high power heavy ion SC linac may be limited by the allowable heat load on cryogenics. The average beam loss of 1 W/m throughout all the CMs amounts to 10 % of the cryogenics heat load. The present budget for the beam loss heat load is 25 W in total [1], being of an order of 0.1 W/m in average. The temperature sensor to be installed to the CM beam pipes can monitor this order of beam loss. Note that the heavy ion radiation damages on solid materials are much more than estimated by the stopping power ratios. The temperature sensors are crucial in order to protect the beam pipes from the long-term radiation damages.

Beam Dumps

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 LL 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 compensation. In other words, we need the beam dumps which can hopefully stand the 20 ms long uranium beam, but this is very difficult or expensive to fabricate. The tungsten to be used for the beam dumps is locally heated up beyond its yield point by 20 ms, 400 kW uranium beam bombardment, even if the beam size is widened to an envelope diameter of 10 cm (an rms diameter of 1 cm).

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. We successfully designed the beam dumps [13], which can stand the 20-ms, 400 kW oxygen beam (one pulse) with enlarged beam size as well as 50-μs uranium beams, and will use this beam for the beam loading compensation test.

Liquid Lithium Charge Stripper

It is obvious from Eq. (1) that no solid charge stripper can stand the Uranium beam with a power of 400 kW. The radiation damage is much more than this scaling. The FRIB baseline is to use the liquid lithium jet film moving at a velocity of about 50 m/s in vacuum (a back-up is the helium gas stripper with plasma windows). The beam

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tests with the similar power depositions to the FRIB uranium beams were successfully conducted with the LEDA [18] ion source with a period of a few minutes [19]. An electromagnetic pump for circulating liquid lithium is required for longer period tests after this successful proof of principle beam test, and its manufacturing is another focus for the stripper development. The system will be tested at a temporary test location before that at the tunnel. The piping associated with the safety exhaust system is being designed for this test in order to keep the secondary containment vessel filled with argon gas during operation and to fill the main vacuum chamber with the argon gas in the vacuum leak event from the rest of the beam line into the stripper chamber.

SRF TECHNICAL CHALLENGES AND PROJECT STATUS

Needless to say, the mass production of FRIB CMs is most challenging. The low-β cavities are much more complicated in structure than high- β, elliptical cavities, and FRIB is to use two types of cavities of QWR and HWR, each with two different β values (see Table 2). In addition, the accelerating CMs are equipped with solenoid magnets and cold BPMs with many leads extracted outside. The number of CM types amounts to six; four accelerating CM types and two matching CM types. Here, the number of the matching CM types is reduced from three to two, recently, and that of the CMs themselves from five to four in order to save the design and production efforts [20].

SRF Cavities

The manufacturing of the four types of Superconducting (SC) cavities were developed in house [21] with more than several year effort together with collaborative supports from other research institutes. The manufacturing technologies transferred to industry for mass production.

The cavity surface treatments have been established [11, 22] by means of Buffered Chemical Polishing (BCP) followed by degassing in a 600 °C furnace (hydrogen removal for Q disease remedy) and High Pressure Rinsing (HPR) by ultra clean water. The BCP process is comprised of about 150-μm bulk etching and cavity-tuning differential etching. About 30-μm light etching follows the degassing. The robotic HPR system, recently implemented, significantly improved the process efficiency. The surface treatments of all cavities will be conducted in house.

A few kW RF power to be fed to each cavity sounds easy compared with MW klystron systems. However, this power level is just located in the multipactoring (MP) region of the 50-Ω coaxial wave guide. Fundamental mode power couplers (FPCs) for the HWR cavities were designed MP free by adjusting the ratio of outer radius to inner one [24]. The ceramics window region design is based upon the design improved for the KEKB 1-MW, CW FPCs [25]. The significantly short conditioning time has been very recently verified by powering tests of the MP free FPCs.

CM Production Status

The FRIB CM design and development started from ReA3 β = 0.085 CM [26] and β = 0.53 Technology Demonstration CM (TDCM). The former CM equipped with the same number of cavities, solenoids and BPMs as those of the FRIB CM is now in operation at 4.2 K for the reacceleration at NSCL. The latter CM equipped with two HWR cavities and one solenoid was successfully tested at their operating temperatures of 2 K and 4.5 K, respectively. Afterwards, the design has significantly evolved from the "top-down" assembling used for ReA3 and TDCM to a new "bottom-up" style in order to simplify the support system and the mechanical performance during cool down [27]. The concept was validated by cooling Engineering Test CM (ETCM) to liquid nitrogen temperature. Then, a full volume CM with two β = 0.085 cavities and one solenoid was fully tested at design performances.

At present, the first production β = 0.085 CM with a full set of eight cavities and three solenoids is under powering test with phase and amplitude locked at design temperatures of 2.1 K and 4.5 K, respectively, after the successful 4.5 K test. The second β = 0.085 CM assembling is on track, and the first β = 0.54 production CM is under assembly. The CM assembly is thus progressing to the production phase. Two in-house teams are assembling QWR CM and HWR CM, respectively.

FE Installation and Commissioning Preparation

One of the present FRIB focuses is the front end (FE) [28] installation for its early commissioning. The CW RFQ is another technical challenge. Following three segments among five in total, the segment 4 was recently assembled and brazed, nearing the RFQ completion. Manufacturing and assembling of the medium energy beam transport bunchers were completed and were tuned to the operational frequency. The 10 FE RT solenoid magnets, 4 charge selection dipoles and a bending dipole have been manufactured, being ready for commissioning.

CONCLUSION

The FRIB driver linac is a front runner for the future high beam power hadron accelerators, making a full use of SRF technology. The technologies developed for the FRIB will contribute a lot to the future prospect of this exciting field. Experience and development results obtained and 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. In particular, we are placing strong focusing solenoids closely to SRF cavities with a high alignment accuracy. More accuracy shall be required for the higher beam power hadron linac with a strong space charge force. The FRIB is on the way for these ultimate machines.

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