BEAM PHYSICS CHALLENGE IN FRIB DRIVER LINAC*

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Abstract

The Facility for Rare Isotope Beams (FRIB) driver linac at MSU provides CW beams of all the stable ions (from protons to uranium) with a beam power of 400 kW and a minimum beam energy of 200 MeV/u in order to produce a wide variety of rare isotopes for nuclear physics study. The low beam emittances, both transverse and longitudinal, are key performance requirements, together with beam stability. These are required for efficiently separating one isotope from another, the reason for choosing this linac configuration. Multi-charge states (five charge states for the uranium case) are accelerated for maximizing the beam current, while keeping the low emittances. The efficient acceleration of high beam currents from 0.5 MeV/u through the superconducting linac is, needless to say, one of the biggest challenges. The beam power is more than 200 times higher than existing similar SC heavy ion linac. In particular, the SC cavities are difficult to protect from heavy ion beam damage, which can be more than 30 times larger locally than a proton beam with the same beam power. Other challenges peculiar to the FRIB linac will be presented, together with possible solutions.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) driver linac at Michigan State University [1] is the first heavy ion accelerator aiming to join the beam power front as shown in Fig. 1 with a beam power of 400 kW and a beam energy over 200 MeV/u. The Chart like Fig. 1 was first used at J-PARC [2] to show "Proton Beam Power Front" throughout the wide range of the beam energy, where both SNS and J-PARC 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 a certain radioactivity level a few hours after stopping the beam operation, that is, the hands on maintenance is possible afterwards. Therefore, one of the technological 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 one from the proton accelerators to the heavy ion ones. It should be noted that the PSI cyclotron 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 former, the beam loss at extraction limits the beam power, while that at injection is the main issue for the latter. This is the reason for the different beam power front. The heavy ion beam power front may have different technical implication.

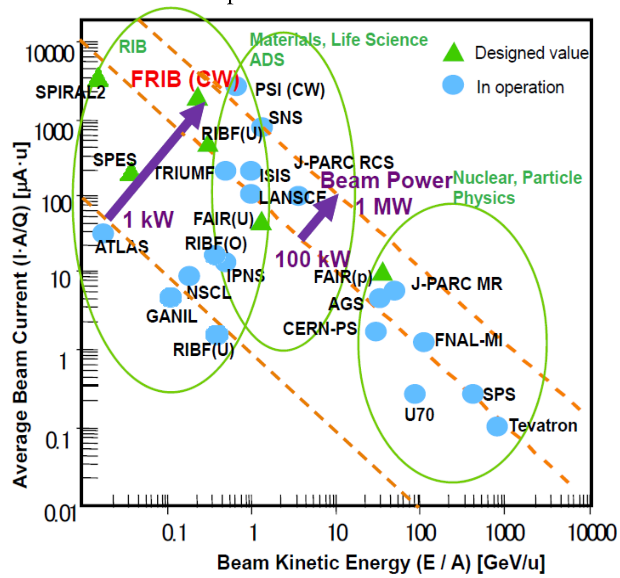

Figure 1: Average hadron beam power versus beam energy.

This article presents what we learned from design study and development for the FRIB driver linac, and what will be outcome from its completion for the future prospects of the world wide accelerator physics and technology.

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 output 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 [3]. 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. And of course, high availability and reproducibility are important for efficient experiments.

Table 1 numerically summarizes the required beam quality. These parameters are only feasible with a linac. This is the reason why we chose the relatively expensive linac scheme. Another requirement is to make a full use of

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the existing experimental facility at National Superconducting Cyclotron Laboratory (NSCL) as well as Re-Accelerators ReA3 and ReA6. In other words, only the driver linac, the target and the fragment separator are to be constructed. For that purpose, the linac was compactly folded twice, requiring special beam optics efforts [4].

Table 1: Beam Emittance Specifications at Target

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

RATIONALE FOR FRIB SC LINAC PARAMETERS

In contrast to spallation neutron source based experiments, and long baseline neutrino experiments, nuclear physics experiments mostly require CW-like beams for detector dead time issues rather than a μs pulsed beams. In general, if the required pulse length is beyond an order of 1 ms, superconducting (SC) linacs are advantageous over room-temperature (RT) ones, regarding their operational costs, 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. Here, 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, FRIB linac still needs frequent focusing to some extent in order to keep the beam sizes within tolerable level. Also, the alignment should be within 0.5 mm in order to thread the beam through the beam bore radii of the SC cavities without any orbit correction.

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 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 the immunity against the beam loss there is just a by-product.

On the basis of various optimization and integration efforts, the transition from the RT RFQ to the lowest β SC acceleration by 80.5 MHz, Quarter Wave Resonator cavities has been chosen at 0.5 MeV/u (β = 0.033) with a bore diameter of 36 mm. The optimization and integration include the extensive study of shielding the SC cavities from the focusing magnetic fields [5] 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 margin of 10 % and a temperature margin of 0.5 K beyond the operational temperature of 4.5 K. These margins were considered necessary in order to ensure the sufficient reliability for the cryomass components. 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 cold beam position monitors (BPMs) are 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. It is emphasized that the reliable assembling of the cavities, BPMs and solenoids in compact space is one of the mechanical challenges. A special care has been taken of balanced difficulty distribution among all the above factors.

Finally, it is interesting to note that the digital Low Level 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 two-gap SC accelerating structure powered by a few kW solid state RF power amplifier.

LINAC FOLDING WITH MULTI CHARGE STATE ACCELERATION

The FRIB linac is compactly folded twice, yet we need to accelerate the multi-charge states, which are analogous to the large momentum spread beam. The folding section should thus be achromatic 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 [6].

Accurate RF phase control 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 spacially spread out as a common linac. Second, the gradual variation of the reference phase from one end to the other in the tunnel can

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be adiabatically followed by the low β beams, exerting the synchrotron oscillation several times [7].

HIGH BRAGG PEAK CHALLENGE

One of the biggest challenges inherent to high beam power heavy ion accelerators is the extremely high Bragg Peak of the heavy ions, that is, the high stopping power (beam loss power density). Although the FRIB driver linac shall accelerate all the stable ions, take the uranium case (Z = 92, A = 238) in order to let the difference from proton accelerators sharply stand out. The ratio of the uranium stopping power (beam loss power density) to the proton one and the range ratio are approximately given by

$$\frac{(-dE/dx)_U}{(-dE/dx)_H} = \frac{Z_U^2}{Z_H^2} = 92^2 = 8{,}500,$$

and

$$\frac{R_U}{R_H} = \frac{A_U Z_H^2}{A_H Z_U^2} = \frac{238}{92^2} = \frac{1}{36},$$

respectively. This extremely high stopping power gives rise to big issues at the charge stripper, the beam dumps, the machine protection system (MPS), the charge selector and the target [3]. First, the solid charge stripper cannot stand this stopping power. This is the reason why FRIB has been developing liquid Lithium charge stripper [8]. Second, the tungsten to be used for the beam dumps is locally heated up beyond its yield point by 2 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). We have to manage to tune the beams with this beam dump performance.

Third, the requirements for the MPS are much more stringent than the proton case. 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, being dependent upon the beam energy, the radioactivity arising from the beam loss is not the primary issue of the beam loss like the proton case at least up to a beam energy of 100 MeV/u. Instead, beam loss damage on the accelerator components, in particular, the SC cavities, can be a main issue. It is here noted that the beam loss is extremely difficult to detect by means of radiation based beam loss monitor (BLM) for the low energy beam (typically lower than 100 MeV/u), since the radiation from the beam loss is too small to detect.

As far as we have studied, the most dangerous are acute 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, no beam is lost at any cavity under normal operational condition. Here, the admittance A is defined by the beta function β(s) 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. In other words, 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 is possibly activated 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 this kind of events showed that the maximum possible power dissipation on a cavity is a little less than 1 kW with halo monitor/scraper ring. The simulation study is in progress in order to confirm that a power dissipation of 1 kW with a duration of 35 μs (MPS time constant to stop the beam) on a spot of 1 mm diameter never exceeds a yield point of niobium [9].

The charge selector is to choose the charge states to be accelerated after the charge stripper. Since the charge selector will use the similar technique to that for the target, it is under development together with the target [3].

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. 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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