COMMISSIONING PLAN FOR THE FRIB DRIVER LINAC *

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Abstract

Facility for Rare Isotope Beams is a high-power heavy ion accelerator facility now under construction at Michigan State University. An overall commissioning plan for its driver linac is established with emphasis on safety, which is presented in this paper together with hazard mitigation and machine protection assumed during commissioning.

INTRODUCTION

Facility for Rare Isotope Beams (FRIB) is a high-power heavy ion accelerator facility now under construction at Michigan State University under a cooperative agreement with the US DOE [1]. Its driver linac operates in CW mode and accelerates all stable ions to energies above 200 MeV/u with the beam power on target up to 400 kW. The linac has a folded layout as shown in Fig. 1, which consists of a front-end, three Linac Segments (LSs) connected with two Folding Segments (FSs), and Beam Delivery System (BDS) to deliver the accelerated beam to target. The linac is located in a tunnel underground with the exception of two ECR ion sources and a part of LEBT (Low Energy Beam Transport) located on the ground level (not shown in Fig. 1). The beam is delivered to the linac tunnel through a vertical beam drop. LSs consist of two types of superconducting QWRs (Quarter Wave Resonators) with geometrical β of 0.041 and 0.085, and two types of superconducting HWRs (Half Wave Resonators) with geometrical β of 0.29 and 0.53. LS1, LS2, and LS3, respectively, have 14, 24, and 6 cryomodules. The total number of superconducting cavities is 330 including rebuncher cavities in FSs. A charge stripper is located after LS1. The linac has four tuning Beam Dumps (BDs), BD FS-1a, BD FS-1b, BD FS-2, and BD BDS, as shown in Fig. 1.

FRIB driver linac is substantially larger both in scale and beam power than existing facilities of a similar kind, which poses significant challenges in realizing safe commissioning. The unique layout of the linac adds additional difficulties. We present overall commissioning plan for the FRIB driver linac in this paper with emphasis on hazard mitigation and machine protection. Detailed tuning algorithms for specific operation parameters will be discussed elsewhere. The commissioning plan presented in this paper builds on a preliminary plan [2] by incorporating hazard mitigation and machine protection details.

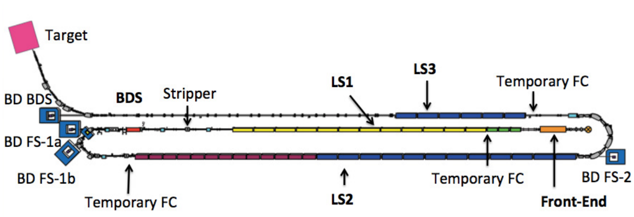

Figure 1: Schematic layout for FRIB driver linac.

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GOALS FOR COMMISSIONING AND COMMISSIONING BEAMS

Although we will accelerate various ions up to uranium with the FRIB linac, ^{36}Ar and ^{86}Kr are chosen for commissioning beams. One key commissioning goal is to accelerate an Ar beam with energy exceeding 200 MeV/u. A second key goal is to detect ^{84}Se at fragment separator for secondary beams at the FRIB experimental system. To achieve the second goal, the driver linac is expected to accelerate a CW ^{86}Kr beam as a primary beam. We adopt single-charge-state beams for commissioning, although multi-charge-state beams are planned to increase the beam power in later stages. Assumed charge states for the commissioning beams are listed in Table 1.

While the FRIB linac is a CW linac, most of the tuning during the commissioning will be performed with a pulsed beam. Considering the risk of single point beam loss during the initial phase of beam commissioning, the peak current, pulse width, and repetition rate for the beam are chosen to be 50 eμA after stripping, 50 μs, and less than 1 Hz, respectively. The pulse structure is generated with a LEBT electrostatic chopper. The peak current corresponds to several % of the full intensity, which is chosen to give sufficient resolution/accuracy for beam diagnostics. The corresponding average beam power is approximately 1 W for Ar beam, which poses no radiation hazard even if it is totally lost at a single point. We refer to this pulse beam as "medium intensity short pulse beam" hereafter. The peak power for the medium intensity short pulse beam is about 20 kW in the case of Ar beam.

We need to accelerate a CW beam to achieve the second key goal for the commissioning. We plan to have a "low intensity long pulse beam" as an intermediate step from the medium intensity short pulse beam to low current CW beam. The peak current, pulse width, and repetition rate for the low intensity long pulse beam are 350 enA after stripping, 5 ms, and less than 1 Hz respectively. The corresponding average beam power is approximately 1 W for Kr beam. In the final stage of the beam commissioning for driver linac, we plan to deliver a CW Kr beam with the peak intensity of 350 enA to target for the beam commissioning

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Table 1: Charge states for commissioning beams

	^{36}Ar	^{86}Kr
Before stripper	10+	17+
After stripper	18+	35+

for experimental systems.

SCHEDULE AND STAGING STRATEGY

We plan to start beam commissioning of FRIB driver linac in December 2017 and to start providing beam for experimental system commissioning in the middle of 2020. In parallel, we plan to conduct the installation and integrated testing of accelerator components from March 2017 to December 2019. This overlapped schedule is adopted to achieve early completion of the project. To accommodate the schedule overlap, we have developed an eight-stage commissioning agenda, which is summarized in Table 2 Commissioning is started at the front end and extended downstream in a staged manner. The area with beam is clearly defined for each commissioning stage by tuning beam dumps and Faraday cups. The installation sequence is designed to be consistent with the commissioning sequence. The interlaced nature of installation and commissioning is illustrated in Fig. 2.

The first stage is beam commissioning of ECR ion sources and LEBT on the ground level. In this stage, beam injection into linac tunnel is prevented with a beam plug located at LEBT. Vertical bends in the beam drop are disabled as a redundant safety measure. Beam commissioning in this area only may be conducted with workers occupying the linac tunnel.

The second stage is commissioning of the RFQ and MEBT (Medium Energy Beam Transport) in the linac tunnel. As seen in Fig. 2, we conduct in-situ cooling test of LS1 cryomodules and installation of LS2 cryomodules in parallel. We have similar parallel activities through stage 6, and mitigation of involved hazard is discussed in the next section. The whole linac tunnel is a single PPS (Personnel Protection System) area, and the beam commissioning in this and later stages is conducted with workers evacuated from the tunnel by sweeping procedures.

The first three cryomodules in LS1 (with $\beta = 0.041$ QWRs) are commissioned with beam in the next stage. These three stages are particularly important to confirm the integrity of accelerator systems. The staged commissioning enables us to validate these key components early, which reduces the risk of project delay.

We first deliver the beam to a far downstream beam dump in stage 4 after tuning of remaining cryomodules in LS1 (with $\beta = 0.085$ QWRs). Stage 5 is dedicated to tuning of stripper and charge selector, which are other key components of the FRIB driver linac.

After commissioning the HWR cryomodules in LS2 (with $\beta = 0.29$ and $\beta = 0.53$) in stage 6, final tuning is conducted in stage 7 before delivering beams to target.

Table 2: Commissioning stages

Stage	Area to be commissioned	Beam destination
1	Ion source, LEBT	LEBT FCs
2	RFQ, MEBT	MEBT FCs
3	LS1 ($\beta = 0.041$)	Temp. FC
4	LS1 ($\beta = 0.085$)	BD FS-1a
5	FS1	BD FS-1b, Temp. FC
6	LS2, FS2	BD FS-2, Temp. FC
7	LS3	BD BDS
8	BDS	Target

This includes demonstration of low current CW beam acceleration. We also plan experimental verification of radiation shielding in this stage. The tuning in stage 8 would be seamlessly connected to commissioning of secondary beam lines in experimental systems.

HAZARD MITIGATION

The interlaced nature of commissioning and installation increases the exposure to hazards. The hazards are mitigated by time sharing between commissioning and installation. Two scenarios are under consideration for the time sharing. One is to have installation in day time and commissioning at night, and the other is to have installation in week days and commissioning in extended weekends. We assume no installation work during beam commissioning in both cases. Access to linac tunnel is controlled with PPS from the beginning of commissioning, and beam is not allowed when workers occupy the tunnel. High power RF is also inhibited by PPS while tunnel is occupied. Exempted are normal conducting cavities at front-end including the RFQ. The front-end cavities are allowed to operate with high power RF with tunnel occupancy under strict radiation control with X-ray monitors located inside the linac tunnel.

Staged commissioning also necessitates installation work in parallel with cryogenic operation in upstream sections. This poses a risk of Oxygen Deficiency Hazard (ODH). ODH mitigation system is a part of PPS, which consists of ODH monitors, alert system, and ventilation system. The ODH mitigation system operates for the entire

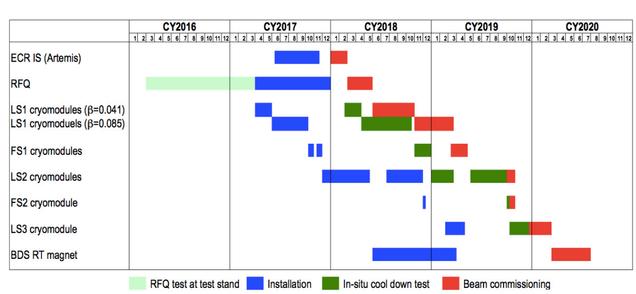

Figure 2: Schedule for installation, integrated testing, and beam commissioning for FRIB driver linac.

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linac tunnel and cryoplant from the beginning of integrated testing of cryomodules.

Another risk involved in the beam commissioning is accidental acceleration of a CW beam. The ion source and RF cavities are operated in CW mode even during pulsed beam operation and are therefore capable of delivering a CW beam. We extensively require medium intensity short pulse beams during commissioning. The LEBT chopper is responsible for creating this pulsed beam structure. Failure of the chopper could lead to unintended acceleration of a 20 kW beam, which is beyond the beam power capacity of beam dumps. As shielding around beam dumps is based on the design capacity of the dumps, the excessive beam could result in unacceptable radiation levels at neighboring, potentially occupied areas. Our strategy to mitigate the hazard is to have two independent layers of protection. The first layer is stringent beam power limitation implemented as MPS (Machine Protection System), which is discussed in the next section. The second layer is certified PPS, which turns off the beam by detecting abnormal increase of radiation level with radiation monitors placed at potentially occupied area. The most vulnerable location for this kind of hazard is near the vertical beam drop at front-end. We plan to have a physical barrier to prevent workers from approaching potentially high dose area around the beam drop and to control radiation dose at the worst case beam loss event sufficiently below the regulation limit with radiation monitors. PPS inhibits beam by disabling vertical bends and high voltage of ion sources. It also inserts a LEBT beam plug for redundancy. The location of the physical barrier is carefully determined based on radiation transport calculation.

Access control system, radiation control system, and ODH mitigation system are three main building blocks of PPS. All of the systems will be fully functional from the beginning of commissioning to ensure the personnel safety during the commissioning. Small part of PPS could be evolved as the commissioning stage progresses. This includes adjustment of sweeping procedures to address transient layout of the linac. PPS is carefully designed to capture the transient configurations, and its readiness will be reviewed for each commissioning stage.

MACHINE PROTECTION

MPS for FRIB linac consists of FPS (Fast Protection System) and RPS (Run Permit System). FPS is designed to shut off beams in 35 μs based on the analysis of damage due to impinging beams of full intensity [3]. However, this response time is not required during beam commissioning as beam intensity is significantly limited. We assume all MPS inputs detecting hardware failure function from the beginning of beam commissioning. However, we assume commissioning of MPS itself for those inputs utilizing beam signals, such as differential beam current monitoring and beam loss monitors. We refer to this kind of MPS as "beam loss MPS" hereafter.

We only assume differential current monitoring for beam loss MPS during commissioning. Other beam loss MPS inputs, such as beam loss monitors, are assumed to be commissioned in the course of commissioning as a preparation for later stages. We adopt pulsed beams for beam commissioning except for the last two stages as discussed above. The commissioning beam is designed so that the energy deposition of a full pulse is below the damage tolerance [3]. As the loss of one full pulse does not cause damage to accelerator components, the minimum requirement for beam loss MPS in early stages of beam commissioning is to terminate the next pulse when it detects significant beam loss. We plan to start beam commissioning with single shot operation, and to proceed to continuous operation with 1 Hz repetition after demonstrating beam loss MPS function to terminate the next pulse. We assume CW operation at the last stage of commissioning. We demonstrate MPS beam termination in the middle of beam pulse before proceeding to CW operation, which is an important step in the commissioning in the last stages.

As for MPS to terminate the beam with accidental CW operation, we plan to implement a comparator for electrode voltage of LEBT chopper and its command signal to monitor proper functioning of chopper power supply. In addition, the command signal is generated as logical AND of two independent signals to mitigate the risk of command signal failure.

SUMMARY

An overall commissioning plan is established for FRIB driver linac with emphasis on both personnel and machine safety. The commissioning is to be conducted in parallel with installation and integrated testing downstream. This is enabled by adopting staged commissioning where commissioning is started from upstream portion of the linac and the area with beam is extended downstream in a staged manner. The involved hazard is to be mitigated by hazard segregation with time sharing and PPS which is carefully designed to capture transient configurations.

Another significant risk in the commissioning is accidental acceleration of CW beam. Commissioning beam is designed to preclude any radiation hazard by limiting the beam duty factor. Protection from acceleration of CW beam, which could result from chopper failure, is provided by PPS radiation monitors and by certain components of the MPS. MPS is designed to protect accelerator components with interlocked signals to hardware failure and beam loss monitoring with DBCM. Staged deployment strategy for beam loss MPS is identified to protect accelerator components during commissioning.

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