OPERATION MODE AND MACHINE STATE CONTROL FOR FRIB DRIVER LINAC OPERATION *

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Abstract

FRIB (Facility for Rare Isotope Beams) is a heavy ion linac facility to accelerate all stable ions to the energy of 200 MeV/u with the beam power of 400 kW, which is under construction at Michigan State University in USA. It is one of major challenges in FRIB to clearly define operation modes and machine state and to develop a controls system to realize safe and high beam availability operation with various operation modes required from physics experiments. To this end, it is indispensable to have clear definition of operation modes and machine states with appropriate management of transition of those. RPS (Run Permit System) is one of major application software to play a pivotal role to meet the requirement, which helps operators to follow adequate procedures depending on operation mode and machine state. In this paper, we overview main features of RPS for FRIB together with operation modes and machine states to define operation procedures.

INTRODUCTION

The 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 (Continuous Wave) mode and accelerates all stable ions to kinetic energies above 200 MeV/u with the beam power on target up to 400 kW. It aims to realize the world highest beam power as a heavy ion linac facility and it is one of major challenges to develop a controls system to support its safe operation with high beam availability. Figure 1 shows a schematic layout of FRIB driver linac.

As a heavy ion accelerator facility, various operation modes are expected with different ion species, beam energy, and so on to meet requirements from physics experiments. At the same time, as a high power accelerator, mitigation of hazards and risks of component damage are major challenges. To meet this requirement, we define operation modes and machine states with their transition procedures, which is basis for establishing safe operation. We also designed Run Permit System (RPS) to help operators to follow the established procedures mitigating risks of operational errors. In this paper, we present operation modes and machine states transitions together with main design features of RPS.

MACHINE MODES AND BEAM MODES

In nominal operation, the primary beam is delivered to the target and the secondary beam generated at the target is delivered to an experimental beam line. However, the beams can be delivered to other destinations such as linac beam dumps during beam tuning. We introduce two basic modes of operation, namely, Machine Modes and Beam Modes, to define basic operation envelope. Machine Modes define the area with beam as summarized in Table 1. In each Machine Mode, critical devices define the area with beam. Beam Modes define beam time structure and the maximum peak intensity or beam power. An extracted list of major Beam Modes is shown in Table 2. In nominal operation, CW beam is accelerated. However, we use different beam time structure, such as 50 μs pulse with 1 Hz repetition rate, for tuning purposes. Machine Modes and Beam Modes define a basic set of operation parameters which are sufficient to ensure that the operation is within safe envelope. However, more detailed information is required to adequately configure Machine Protection System (MPS) to protect machine such as information on which of four beam dumps in linac tunnel is in use in Machine Mode M2. It should be noted that Personnel Protection System (PPS) controls Machine Mode as it is closely related to access control.

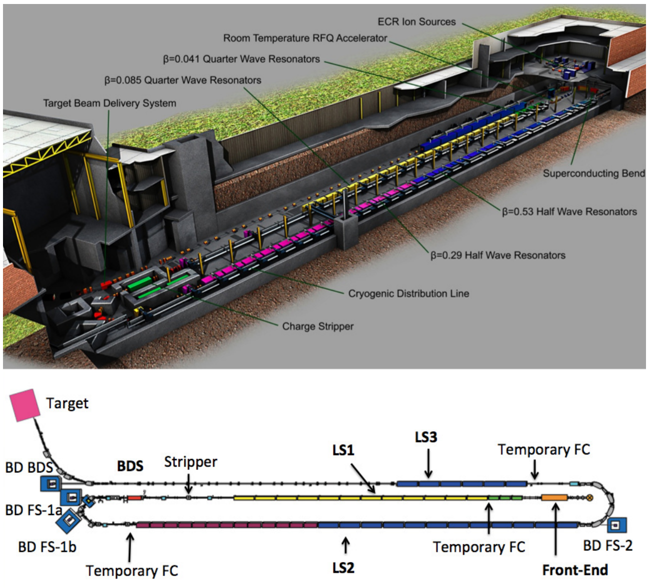

Figure 1: Layout of FRIB driver linac. Top: Cut view of FRIB driver linac building. Bottom: Schematic layout for the FRIB driver linac (top view).

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Table 1: FRIB Machine Modes

Machine Model	Description	Primary beam destination
M0	Maintenance (no beam)	None
M1	Ion source tuning	Front end at surface level
M2	linac tuning	Linac tunnel
M3	Secondary beam development	Target
M4	User operation	Target

Table 2: Major FRIB Beam Modes

Beam Mode	Description	Beam time structure	Beam intensity/power
O0	Maintenance (no beam)	NA	0W
O1	Nominal operation	CW	$<$ 400 kW
O2	CW low power operation	CW	$<$ 10 kW
O3	Nominal linac tuning	50 μs, $<$ 1 Hz	50 eμA nominal
O4	Short pulse linac tuning	5 μs, $<$ 1 Hz	200 eμA nominal

BEAM SUB-MODES

Beam Modes define basic operation envelope in terms of beam intensity/power and beam time structure. We assume reconfiguration of MPS with operator intervention in changing Beam Mode as involved beam power can be very different. We introduce Beam Sub-modes to define more detailed beam time structure. For example, a Beam Mode is defined for 50 μs pulse width with 1 Hz repetition rate for tuning. Inside the Beam Mode, we are allowed to operated with smaller repetition rate as long as it is predefined. For example, it allows us to have single shot operation before starting continuos 1 Hz operation without changing Beam Mode. Temporary beam off is also defined as a Beam Sub-mode inside a Beam Mode. Beam Sub-modes are controlled by Global Timing System (GTS), which is closely related to machine status discussed in the next section. Introduction of Beam Sub-modes enables us to have automatic transition of beam time structure in a predefined envelope.

One of special requirements for the timing system for FRIB is to realize dynamic ramping of beam duty factor in resuming high-power beam operation. This is required to control heat shock to the target during transition. The pulse width and repetition rate are required to be increased continuously during ramping following a predefined pattern, and it should be seamlessly transit to nominal high power CW operation. This transition is realized with seamless and automatic changing of Beam Sub-modes by GTS within constraint set by MPS.

MACHINE STATES

We introduced six machine states, namely, STOP, STANDBY, RUN (ramping), RUN, FAULT, and PPS FAULT. FAULT and PPS FAULT are the states with MPS and PPS are fault respectively. RUN is the state where beam is delivered to the designated beam destination. RUN (ramping) is a transient state in starting beam operation as discussed in the previous section. Beam is turned off for both STOP and STANDBY with no beam Beam Sub-mode. The difference between STOP and STANDBY is that MPS is active with STAND-BY but inactive with STOP. STOP state enables us to reconfigure MPS, which is necessary in chaining operation modes. With STANDBY state, accelerator is ready to start beam operation by changing Beam Sub-mode.

Figure 2 shows schematic diagrams for Machine State transition. Top figure shows Machine State transition with Beam Mode for high power CW operation where dynamic ramping is involved to control heat shock. Bottom fig-

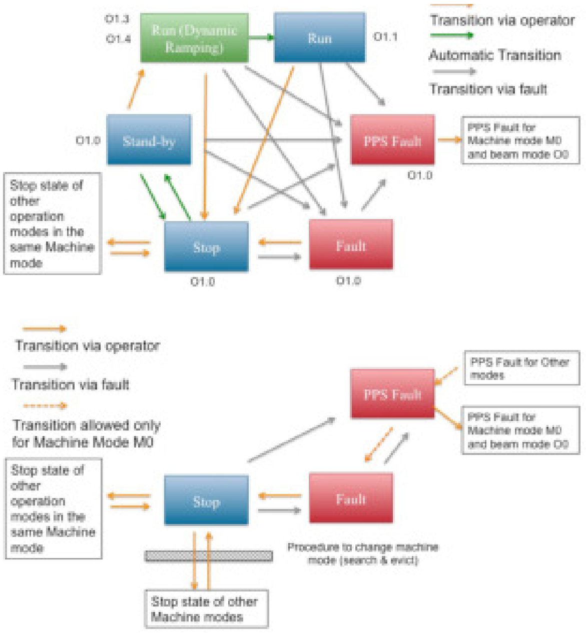

Figure 2: Machine State transition diagrams. Top: High power CW operation Beam Mode, O1. Bottom: No beam Beam Mode, O0.

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ure shows Machine State transition with ”no beam” Beam Mode where operator can change Machine Mode or recover from PPS FAULT state.

OPERATION MODES

The role of MPS is to protect components from beam-induced damage or excess activation to realize operation with high beam availability. Machine modes and Beam modes define the basic envelope for safe operation for FRIB. However, more detailed envelope for operation is required for elaborated management of MPS thresholds and masks which is essential for a high power accelerator. Operation Modes were introduced to define detailed operation envelope for this purpose. Operation Modes are defined as a combination of the following parameters, namely, Machine Mode, Beam Mode, beam destination, ion source, ion species, charge states before stripper, charge states after stripper, and beam energy. Approved Operation Modes and corresponding MPS thresholds and masks are stored and maintained in Global Database (GDB).

RUN PERMIT SYSTEM

Run Permit System (RPS) is a software-based system with interface to operators to serve the following three functions.

- Machine State management
- Operation Mode management except for Machine Mode
- MPS thresholds/masks management

As stated above, Machine Modes are managed by PPS. RPS obtains information on Machine Modes from PPS through EPICS. Operator sets parameters except for Machine Mode to define operation mode with RPS, and RPS accesses to GDB to confirm that the designated operation mode has prior approval. If it has approval, RPS also extracts the corresponding MPS thresholds/masks from GDB and set it to MPS. Then, RPS sets Beam Mode to GTS. Those changes are allowed only with STOP machine state, where you can disable MPS. Once all changes are completed and MPS is all OK, operator can change the Machine State to STANDBY where MPS is activated. Then, RPS sends a run permit signal to GTS to allows change of Beam Sub-mode to start beam operation.

RPS deals with two classes of thresholds, both of which are maintained in and extracted from GDB. One is MPS thresholds for parameters which MPS is continuously monitor to activate beam mitigations in case of deviations. The other is RPS thresholds for parameters which RPS confirms to be within the assumed range in permitting beam operation. For those parameters, RPS ensures that values outside the assumed range can not be set by operators.

RPS also allows Machine State transitions such as abort (from RUN to STOP) and fault clear (from FAULT to STOP, or PPS FAULT to FAULT). RPS itself does not have a function to mitigate the beam. RPS has controls to deactivate the MPS beam mitigations when Machine State transits from FAULT to STOP. RPS has no controls over PPS devices. RPS only monitors the status of PPS. Operator is required to clear PPS FAULT with an independent PPS system, and RPS detects changes in status of PPS to allow operator to proceed to the next procedure.

SUMMARY AND FUTURE PLAN

FRIB is a heavy ion linac facility aiming to realize the world highest beam power, and it is one of major challenges to develop a controls system to realize safe and high beam availability operation with supporting various operation modes physics experiments require. In the controls system, RPS plays a pivotal role in coordinating the functions of other critical systems such MPS and GTS.

One of the keys to achieve the beam availability goal is to ensure that a proper set of MPS thresholds and masks for an intended operation mode is used. As operation modes for FRIB are complex due to a nature of heavy ion accelerator, it requires us to carefully define operation modes to this end. It is also required to establish a system and procedures to clarify approved operation modes and corresponding MPS thresholds. Database, or GDB, with appropriate design plays an essential role in this part. In safe operation, operator is required to use MPS, GTS, and GDB in a complicatedly coherent way depending on the Machine State, and RPS helps operators to follows correct procedures to mitigate the risk of operational errors. To help clarify the procedures, it is also important to clearly define Machine States and their transitions.

In FRIB, we are starting the beam commissioning of front-end part. As a limited numbers of Operation Modes is involved in front-end commissioning, we plan to start implementing RPS with a smaller scale to support this. RPS will be required in a later part of front-end commissioning where we start beam acceleration with RFQ. We are stating to implement a RPS to support the RFQ commissioning. It gives us a chance to demonstrate basic function of RPS and to feedback from actual beam operation to a full scale implementation for linac segment commissioning scheduled in early 2018.

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[1] J. Wei, *et al.*, “FRIB accelerator status and challenges”, LINAC’12, Tel Aviv, August 2012, p. 417.