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MACHINE AND PERSONNEL PROTECTION FOR HIGH POWER HADRON LINACS

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Abstract

Machine and personnel safety are increasingly important for high power hadron linacs as involved beam power increases. Design requirements and characteristic features of machine protection system and personnel protection system are reviewed for operating and proposed high power hadron linacs, such as J-PARC, SNS, FRIB, ESS, and IFMIF.

INTRODUCTION

Demand for high power hadron linacs has been increasing for various applications in recent years, which include driver for spallation neutron source, irradiation of material for fusion reactor development, and physics experiments utilizing intense secondary beams. A number of high power hadron linacs are currently under operating, construction, or planning around the world to meet this demand. Prospect for future application for an accelerator driven subcritical reactor or transmutation of nuclear waste has further motivated the pursuit of higher beam power.

Seeking higher beam power, the personnel and machine safety become increasing important as a risk of catastrophic failure has also been increased. PPS (Personnel Protection System) and MPS (Machine Protection System) are key systems to protect personnel and machine safety for accelerators. In this paper, we review design requirements and characteristic features for PPS and MPS for operating and proposed high power hadron linacs. Among a number of high power hadron linacs, we take the following five projects in this paper, namely, FRIB (Facility for Rare Isotope Beams), J-PARC (Japan Proton Accelerator Research Complex), SNS (Spallation Neutron Source), ESS (European Spallation Source), and IFMIF (International Fusion Material Irradiation Facility). For IFMIF, the linac for IFMIF/EVEDA (Engineering Validation and Engineering Design Activities) is also discussed. As summarized in Table 1, the average beam power level we discuss in this paper ranges from a few hundred kW to a several MW.

PERSONNEL PROTECTION SYSTEM

Challenges in PPS specific to high power hadron linacs are mostly related to radiation hazard mitigation. As the involved beam power is high, it can cause radiation hazard both with prompt and induced radiation.

Prompt Radiation During Normal Operation

For prompt radiation during normal operation, it is usual to control the radiation level at accessible area by shielding assuming certain amount of chronic beam loss. For example, shielding for the linac tunnel of FRIB is designed to keep the expected radiation dose rate at accessible area below 1 μSV/h assuming uniform beam loss of 1 W/m for the beam line. The goal of 1 μSv/h is deduced from the internal yearly dose limit (or ALARA goal) for radiation workers in FRIB and assumption for possible occupying hours per year. As shielding design involves radiation transport calculation, some margin is added in FRIB for its ambiguity. The beam loss assumption of 1 W/m comes from the empirical hands-on maintenance limit for proton accelerators, and we assume that we won't operate for long term with tolerating the beam loss exceeding this level. Radiation monitors connected to PPS are placed in accessible areas to monitor the radiation level, and they inhibit the beam if the radiation dose rate exceeds the assumed level. The linac itself could be operated with higher beam loss than 1 W/m, but the radiation monitor system guarantees that the radiation dose rate from chronic beam loss does not exceed the expected level. Although the dose rate limit for accessible area and assumed beam loss may be different for each facility, they share the basic strategy in their shielding design. As the dose limit is defined as an average over a period of time usually longer than one hour, fast response is not required for radiation monitor in this context.

Prompt Radiation at an Abnormal Event

However, the situation can be very different at a fault event where the dose rate can be higher by orders of magnitudes than that in normal operation. We here consider two kinds of faults. One is the worst case beam loss event where full power beam is lost at a single point. The other is beam delivery to unintended area.

Single point beam loss For the former, detailed fault analysis with radiation transport calculation is indispensable to design appropriate protection. In the case of FRIB, the most vulnerable locations to this hazard in the linac building is in the front-end area due to its unique linac layout (See Fig. 1). In FRIB, ion sources are located at the surface level and the beam is led to linac tunnel through a vertical drop. Then, the accelerated beam comes back to the vicinity of the vertical drop due to its folded layout. The dose rate around the vertical drop can be very high if we have a full power single point beam loss of the accelerated beam in the vicinity of the vertical drop. Radiation transport calculation shows that the dose rate could reach a few tens of mSv/h at the surface of the shielding block (See Fig. 2) [1]. Systematic analysis reveals that we have significant radiation dose rate only in the vicinity of four large openings in the linac building, which enables us to focus on protection around those limited areas. Our tentative internal goal for integrated dose at a single abnormal

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Table 1: Main Parameter Comparison

	J-PARC	SNS	ESS	IFMIF/EVEDA	IFMIF	FRIB
Ion	H^-	H^-	H^+	D^+	D^+	All stable ions
Pulse/CW	Pulse	Pulse	Pulse	CW	CW	CW
Energy	400 MeV	1 GeV	2 GeV	9 MeV	40 MeV	200 MeV/u
Average power	133 kW	1.4 MW	5 MW	1.125 MW	5 MW x2	400 kW
Technology	RT	SC	SC	SC	SC	SC

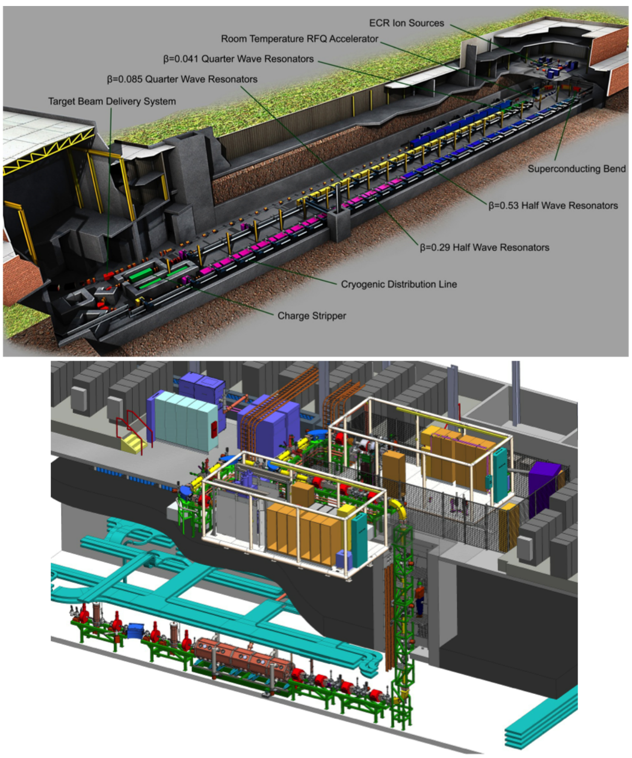

Figure 1: Top: FRIB layout with ion source on the surface level and rest of linac in the linac tunnel. Linac has a folded layout. Beam from ion source is led to linac tunnel through a vertical drop. Bottom: Close up around the vertical drop.

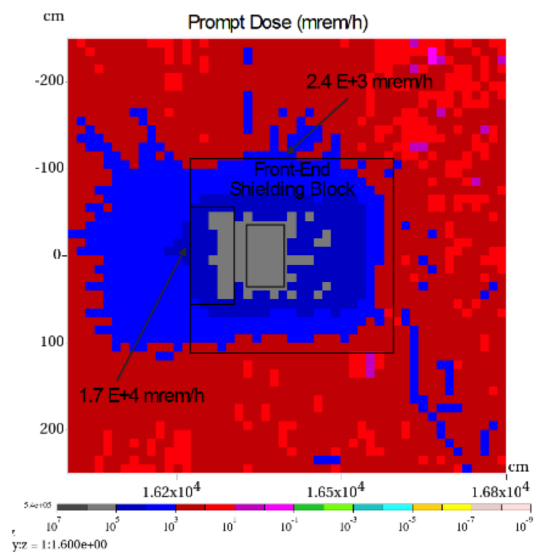

Figure 2: Preliminary radiation transport calculation around the vertical drop for the worst case beam fault in tunnel (with courtesy of M. Kostin).

event at accessible areas for radiation workers is 50 μSv, which is rather stringent as our linac is in the middle of university campus. For the area accessible for general public, there is a regulation that integrated dose for any of one hour should be lower than 20 μSv. Strategy for protection against the worst case beam loss is established based on those systematic radiation transport analyses. In designing radiation control system, we should not rely on MPS to inhibit the beam. Then, expected integrated dose until PPS inhibits the beam should be within the above mentioned goal or limit. As the response time of 10 seconds is assumed for radiation monitors to inhibit the beam, physical barrier is planned to be installed around the high dose rate area so that the integrated dose for 10 seconds is kept lower than 50 μSv. We should note that the area around the vertical drop is a radiation control area and no attendance of general public is assumed.

Beam delivery to unintended area Accelerator facility is often divided into several PPS areas to allow workers to enter into an area while continuing beam operation in some other areas. For example, we may conduct beam tuning using a tuning dump while workers are performing maintenance work at target. The area with beam should be clearly defined by PPS to prevent beam from being delivered to unintended area. The risk of beam delivery to unintended area is mitigated by BIDs (Beam Inhibit Devices) for PPS. Requirements for BID are defined as follows by a safety guideline in US [2].

- At least two dissimilar BIDs are recommended.
- BID should be fail safe.
- If a beam shutter or a beam plug are used as a BID, it should maintain its function at least until PPS shut off the beam

Again, beam shut off by MPS should not be assumed in the design of PPS. Although a beam plug is a conventional BID to define the boundary of area with beam, it is becoming difficult to adopt it for high power accelerator. An example is the BIDs for RTBT (Ring to Target Beam Transport)

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at SNS connecting the extraction of the storage ring to target [3]. There is a tuning dump called extraction dump in this beam line and one dipole magnet determines the beam destination between the extraction dump and target. It may be an intuitive mitigation method to install a beam plug in the beam line to target. However, it is difficult to assume a beam plug which will survive 1 MW beam power for PPS beam inhibit time of several seconds. Then, AC contactor and DC contactor are equipped to the dipole magnet power supply as two independent BIDs instead of a beam plug. The AC contactor shuts off AC power for the dipole power supply, and DC contactor both disconnects and shorts the output of the power supply. This example illustrates that it is becoming difficult to adopt some conventional BIDs for high power accelerators due to increase of involved beam power. Although the above example is not for the linac part, similar configuration is planned for beam transport line between linac and target in FRIB.

Induced Radiation

Induced radiation also poses radiation hazards in high power hadron linacs. However, protection against induced radiation is often through administrative controls and not subject to PPS. We here touch upon confinement of activated air produced during operation for which PPS plays a role in some facilities (See Table. 2). A way to minimize the leak of activated air is negative pressure control between linac tunnel and accessible area. On the other hand, it is also preferable not to exhaust air from linac tunnel during operation to minimize the release of activated air to the environment. It can be realized by assuming re-circulation of air in linac tunnel during beam operation. However, the negative pressure control and re-circulation are often incompatible. J-PARC linac offers an interesting solution for this incompatibility by having a sub-tunnel between linac tunnel and klystron gallery (accessible area) and exhaust from sub-tunnel to realize negative pressure control while keeping re-circulation in linac tunnel [4]. This tunnel design ensures minimum leakage and release of activated air.

Design Validation with Beam

Design of radiation safety system is based on radiation transport calculation. As the radiation transport calculation has some ambiguity, it would be preferable to assume controlled beam loss experiment to validate the design while the policy for design validation varies for each facility. There seems to be a room for further efforts to establish a standard methodology in this area. In SNS, a controlled beam loss experiment is part of validating all new or significantly modified shielding configurations [3]. To the extent possible, the experiment verifies source term calculations, shielding effectiveness, and radiation monitor placement and performance assuming linear extrapolation from low power measurement to high power conditions.

MACHINE PROTECTION SYSTEM

Challenges in MPS specific to high power hadron linacs are centered around protection against beam losses. As the involved beam power is high, fast response time is required to avoid component damage at the worst case beam loss.

Detection of Beam Loss

To protect against beam losses, it is necessary to establish rigorous detection method for beam losses. Usual BLMs (Beam Loss Monitors) detect radiation from beam loss. However, they have difficulty in detecting a beam loss in low energy part of proton linacs as it produces little radiation. This difficulty is shared with heavy ion linacs for a wider energy range. Various detection methods have been adopted for high power hadron linacs to overcome this difficulty. We here show only two examples leaving comprehensive coverage of this topic to other papers.

Differential beam current monitoring Differential beam current monitoring, or DBCM, is adopted in SNS to establish a fast protection system against faults involving significant fractional beam loss [5]. This method assumes two current monitors to capture a beam loss in between by monitoring difference between their beam current readings. This method is applicable to low energy part as it is not based on radiation detection. BPMs (Beam Position Monitors) can also be used to detect beam current for this system as it only requires relative measurements. It is successfully adopted in SNS to capture a significant beam loss to realize beam inhibit time of less than 14 μs foreseeing to realize 6 to 8.5 μs by improving its monitor and mitigation path [6].

Halo monitor ring Although DBCM provides a rigorous detection for a significant beam loss, it is not sensitive to a small fractional beam loss. It is a significant challenge in heavy ion linac to measure a chronic small fractional beam loss in low energy part as it produces little radiation but might cause severe damage at the component surface over a long period of time. In FRIB, HMR (halo monitor ring) is planned to be adopted to detect a chronic beam loss [7]. HMR is a ring aperture which limits the transverse acceptance to capture the particles which are likely to be lost downstream. High sensitivity of HMR has been demonstrated at CCF (Coupled Cyclotron Facility) in MSU to reach 0.1 nA level, and fast response of around 10 μs is also demonstrated for a large signal.

MPS Architecture

The required beam shut off time for high power hadron linacs typically ranges from a few to a few tens of μs (See Table. 3), which requires a specially designed architecture for MPS. We here take MPS architecture of J-PARC linac as an example for the one fully optimized to realize fast response [8]. It has a MPS unit for each rack row connected with the neighboring units with parallel metal wires (See Fig. 3). Beam shut off signal sent from a component to a MPS unit is passed to the neighboring unit by activating

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Table 2: PPS Comparison

	J-PARC	SNS	ESS	IFMIF/EVEDA	IFMIF	FRIB
Integrated dose at an abnormal event	None	< 5.5mSv	Not yet determined	None	None	$< 50\mu$Sv (tentative)
Response time for radiation monitor	< 10s	< 2s	Not yet determined	Several seconds	Several seconds	< 10s
Negative pressure control	Yes, not connected to PPS	No	Yes, not connected to PPS	Yes, connected to PPS	Yes, connected to PPS	Yes, connected to PPS
Integrated beam power control	PPS	MPS	Admin. control	Admin. control	Not yet determined	Admin. control
Controlled beam loss experiment	None	Yes	Yes	None	None	Yes

Table 3: MPS Comparison

	J-PARC	SNS	ESS	IFMIF/EVEDA	IFMIF	FRIB
Beam loss detection method	Gas proportional counter	Ion chamber, DBCM	DBCM, BLMs, halo monitors	Ion chamber, diamond detector	To be determined based on EVEDA	DBCM, ion chamber, HMR
Beam inhibit device	RF for RFQ, ion source timing, beam stopper	Pre-chopper, RF for RFQ, Ion source	RF for ion source, LEBT chopper, MEBT chopper, RF fro RFQ	Ion source	To be determined based on EVEDA	Electoric bends, ion source
Beam inhibit time	$< 10\mu$s	$< 20\mu$s	$< 5\mu$s for warm part, 10-30μs for cold part	$< 40\mu$s Target 30μs	$< 33\mu$s	$< 35\mu$s

one of the metal wires. Each wire corresponds to an area and category of the event. This signal is relayed to MPS logic controller situated at the upstream end to shut off the beam. The beam inhibit method is also optimized to realize fast response. It shuts off RF for RFQ, which is the fastest beam inhibit method in J-PARC, and then shift the timing of extraction voltage of ion source away from RF timing and close a beam shutter before RFQ for redundancy. Figure 4 shows demonstration of response time of this system, which shows the beam inhibit time of around 7.5 μs for the input at 118 m downstream of the ion source. With this topology, the response time for the signal from downstream is longer. However, it is reasonable as the beam loss at upstream part is often more demanding for responding time. The demonstration in Fig. 4 shows that the responding time for this system is around or less than 10 μs for the entire linac. The basic idea of this system is to inhibit the beam as quick as possible by sending the minimum signal with "hard wire", and then collect the information regarding the MPS event through EPICS taking time. Similar architecture is adopted for IFMIF/EVEDA although the beam mitigation method is different [9].

On the other hand, MPS for FRIB and SNS have very different topologies allowing more flexible configuration. It is also possible to send more information to MPS master than just a beam shut off signal, which allows more flexible logic control. However, there exists a trade off between flexibility and response time. In SNS, it is planned to implement a faster beam inhibit path for DBCM bypassing most part of the existing MPS. It would provide a hint for MPS for future high power hadron linacs where MPS consists of multilayers with flexible layers and a simple hardwire-based layer on top of it to realize the fastest response retaining reasonable flexibility.

MPS Risk Analysis

Efforts in capturing MPS fault modes in advance are becoming important to mitigate the risk of catastrophic MPS faults as the involved beam power is increased. In ESS, they capture MPS fault modes to analyze there risks utilizing "Protection Integrity Levels" rating which is similar to SIL (Safety Integrity Level) [10]. It enables them to

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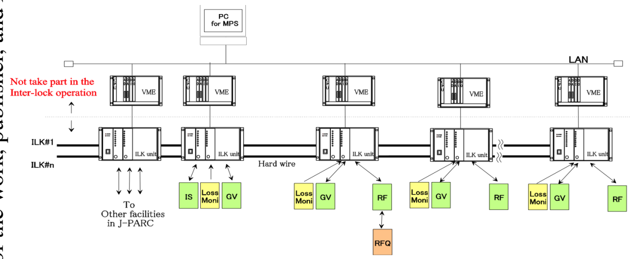

Figure 3: MPS Architecture for J-PARC linac (with courtesy of H. Sakaki).

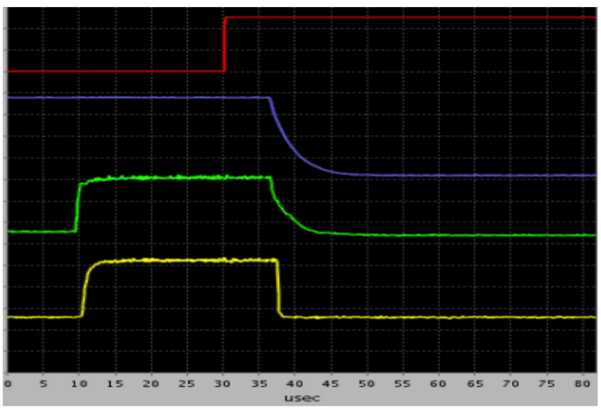

Figure 4: Demonstration of response time of J-PARC MPS (with courtesy of H. Sakaki). Red: waveform of dummy beam loss signal input 118 m downstream from ion source, violet: RFQ RF power level, green: beam current after RFQ, and yellow: beam current 118 m downstream. The beam inhibit time of around 7.5 μs is demonstrated.

efficiently mitigate MPS risks with serious consequences. Comprehensive risk analysis allows us to seek mitigations other than MPS such as change in component design and layout. This approach is similar to PPS design, and it may be natural to proceed in this direction as the potential consequences of involved events are becoming more serious.

SUMMARY

Table 2 shows a comparison of some aspects of PPS design for high power hadron linacs. As the involved beam power increases, hazard mitigation for the worst case beam loss becomes increasingly important. It is not practical to protect against the worst case failure only with passive protections such as shielding. Accordingly, demand for active system with radiation monitors connected to PPS is increasing. Nonetheless, there has been little improvement in the response time of PPS radiation monitors in recent years. In some cases, standard mitigations, such as a beam plug, are no longer practical with the presently assumed beam power and PPS beam shut off time. Development of a faster radiation monitor would greatly benefit PPS design for future high power hadron linacs providing a design breakthrough.

Table 3 shows a comparison of MPS designs for high power hadron linacs. The most significant challenge in MPS for a high power hadron linac would be realization of fast response time. Faster response time is required for MPS to shut off beam to prevent component damage from beam loss in increasing beam power. Meanwhile, flexible operation would also be important to meet needs of users or to achieve high beam availability. There is a trade off between fast response and flexibility in designing MPS architecture. A possible solution would be a combination of simple hard wire layer and slower but more flexible layers in MPS. In increasing the beam power, the importance of MPS risk analysis is also increasing to avoid a catastrophic failure. Systematic risk analysis would be essential for the design of MPS for future high power hadron linacs to realize smart and efficient MPS design.

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