Machine and Personnel Protection for High Power Hadron Linacs

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Acknowledgement

This talk will be a review from perspective of commissioning/operation

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- ESS
  - Annika Nordt (MPS), Stuart Birch (PPS)
- FRIB
  - Sheng Peng (MPS), Larry Hoff (PPS), Paul Wright (PPS), Steve Lidia (MPS sensor), Reg Ronningen (Radiation Transport Analysis), Mikhail Kostin (Radiation Transport Analysis)
- IFMIF, IFMIF/EVEDA
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  - Nobuhiro Kikuzawa (MPS), Fumio Hiroki (PPS), Hironao Sakaki (MPS)
- SNS
  - Douglas Curry (MPS), Kelly Mahoney (PPS) , Willem Blokland (MPS Sensor)

Outline

- Review of high power hadron linacs covered in this talk
  - FRIB, J-PARC, SNS, ESS, IFMIF, IFMIF/EVEDA
- Challenges and design approaches in PPS
  - Fault analysis
  - Beam inhibit device design
  - Confinement of radiated air
  - Design verification with beam
- Challenges and design approaches in MPS
  - Beam loss detection methods
  - MPS architecture
  - MPS risk analysis
- Design comparison tables for PPS and MPS
- Summary

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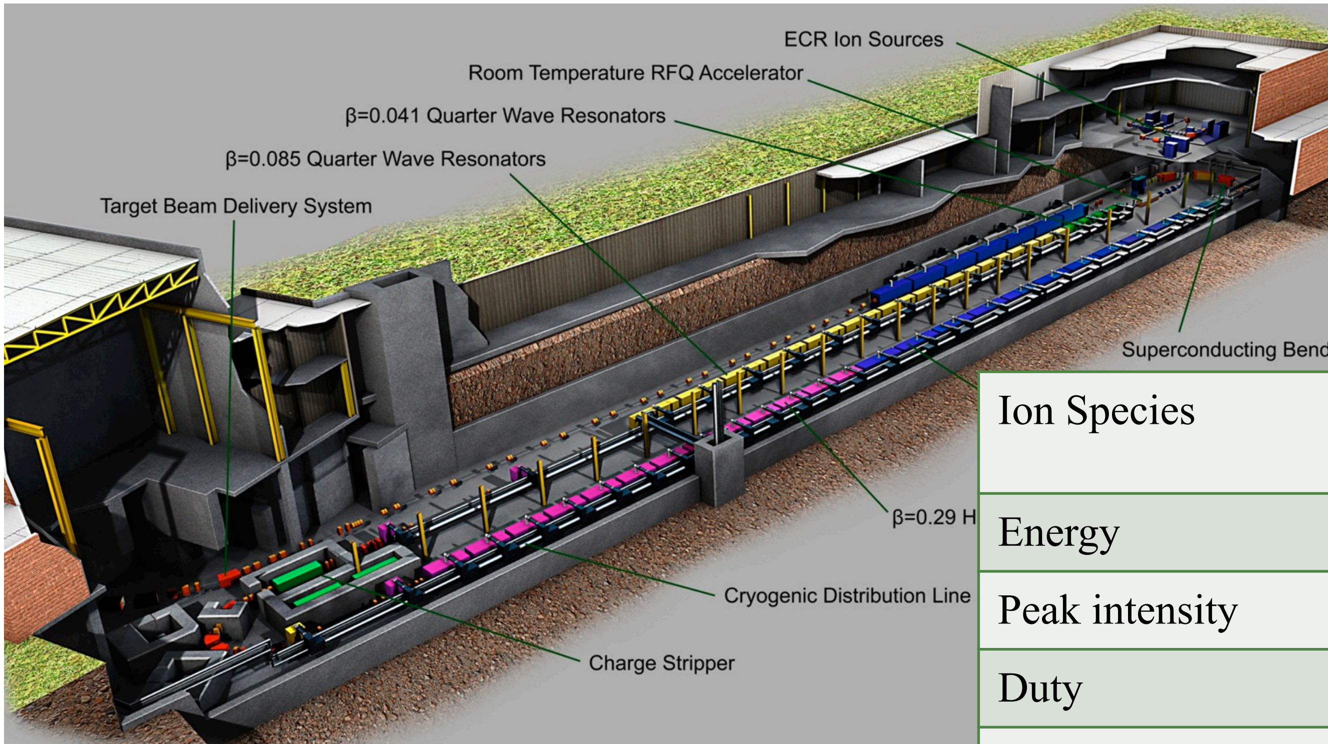
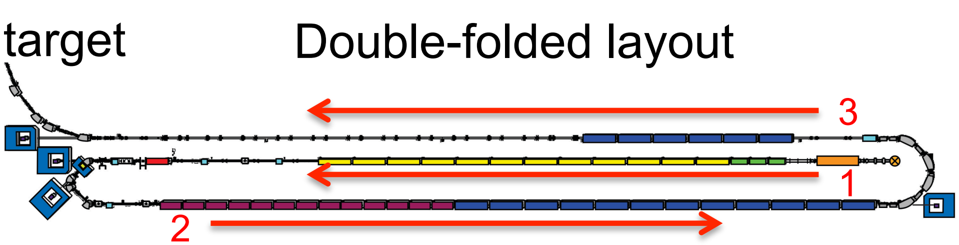
FRIB Driver Linac





Ion Species	All stable ions up to uranium
Energy	200 MeV/u
Peak intensity	0.7 emA
Duty	100% (CW)
Average beam power	400 kW
Cavity type	SC QWR, SC HWR
Frequency	80.5/322 MHz
Status	Under construction

J-PARC Linac

Ion Species	H^-
Energy	400 MeV
Peak intensity	50 mA*
Duty	1.25 %**
Average beam power	133 kW***
Cavity type	RT DTL, RT CCL
Frequency	324/972 MHz
Status	Under operation

* W/o including chopping duty factor
** Macro pulse duty factor
*** Including chopping duty factor

SNS Linac

Ion Species	H^-
Energy	1 GeV
Peak intensity	38 mA*
Duty	6 %**
Average beam power	1.4 MW***
Cavity type	RT DTL, RT CCL, SC Elliptic
Frequency	402.5/805 MHz
Status	Under operation

* W/o including chopping duty factor
** Macro pulse duty factor
*** Including chopping duty factor

ESS

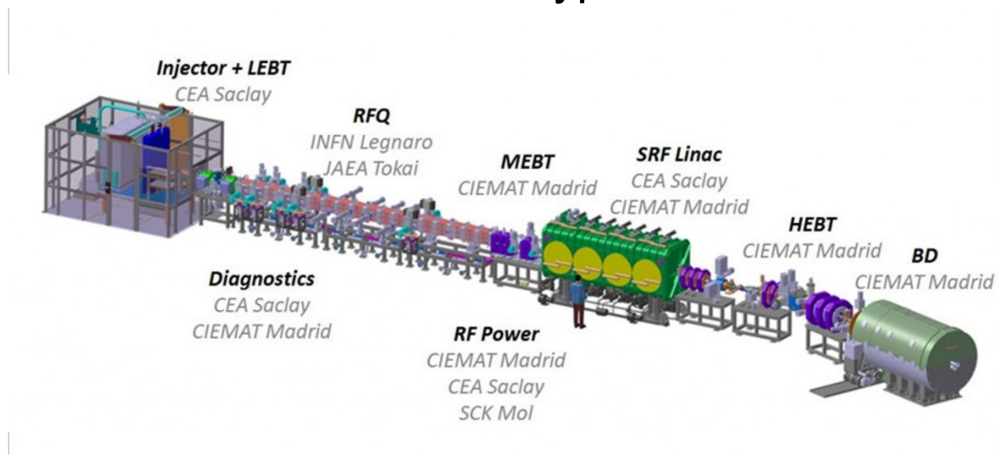
Ion Species	H^+
Energy	2 GeV
Peak intensity	62.5 mA
Duty	4 %
Average beam power	5 MW
Cavity type	RT DTL, SC Spoke, SC Elliptic
Frequency	352/704 MHz
Status	Under construction

IFMIF, IFMIF/EVEDA

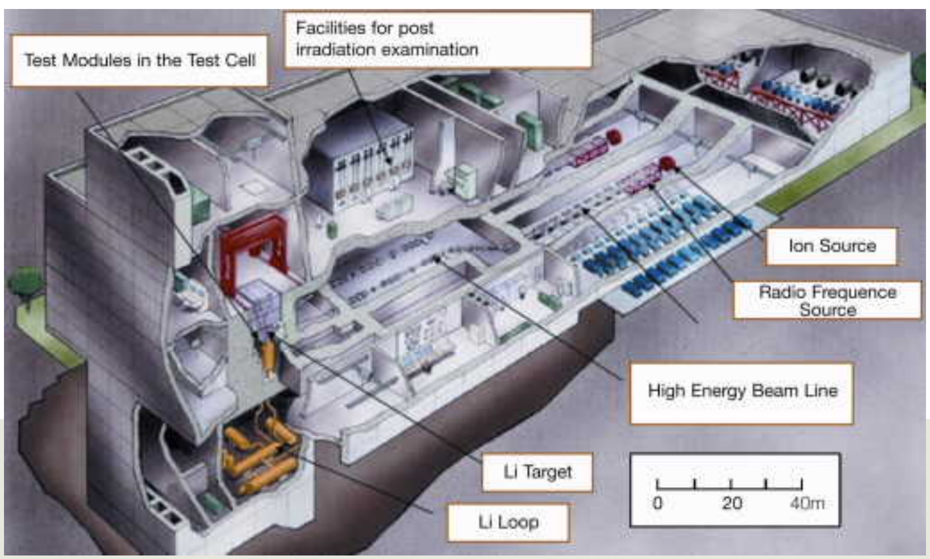
Ion Species	D^+
Energy	9 MeV
Peak intensity	125 mA
Duty	CW
Average beam power	1.125 MW
Cavity type	RT RFQ, SC HWR
Frequency	175 MHz
Status	Under commissioning

IFMIF/EVEDA

Linear IFMIF Prototype Accelerator



IFMIF



Ion Species	D^+
Energy	40 MeV
Peak intensity	125 mA x 2
Duty	CW
Average beam power	5 MW x 2
Cavity type	RT RFQ, SC HWR
Frequency	175 MHz
Status	Under design

Design Parameter Comparison

	J-PARC	SNS	ESS	IFMIF/ EVEDA	IFMIF	FRIB
Ion	H-		H+	D+		All stable ions
Pulse/CW	Pulse			CW		
Energy	400 MeV	1 GeV	2 GeV	9 MeV	40 MeV	200 MeV/u
Average beam power	133 kW	1.4 MW	5 MW	1.125 MW	5 MW x 2	400 kW
Peak beam power*	10.6 MW	23.3 MW	125 MW	-	-	-
Technology	RT	SC				

* Defined here as average power divided by macro pulse duty factor

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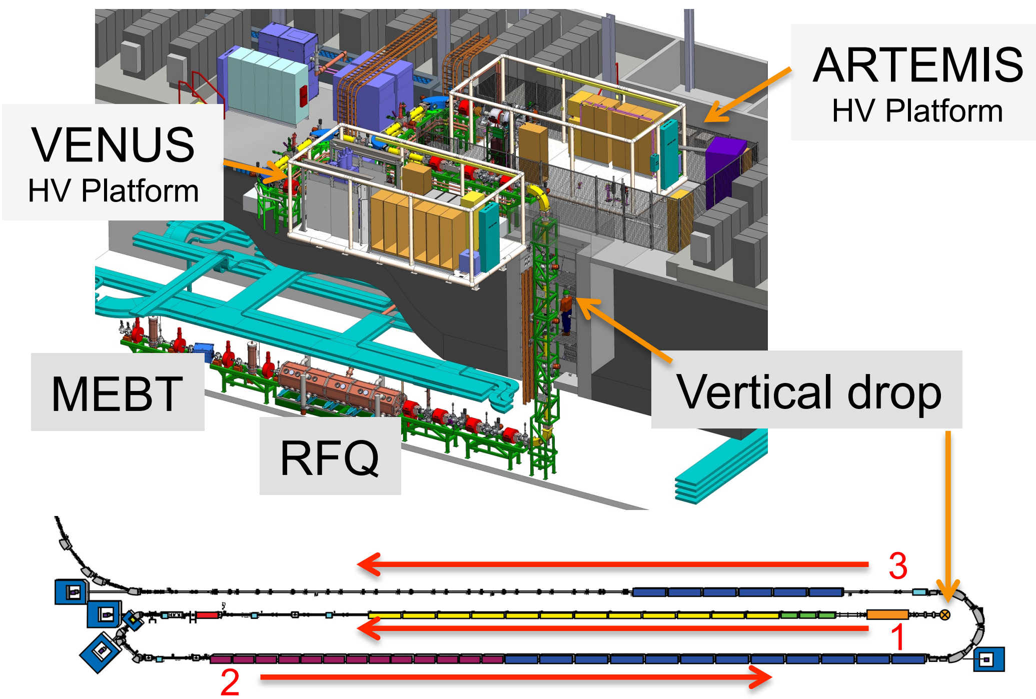
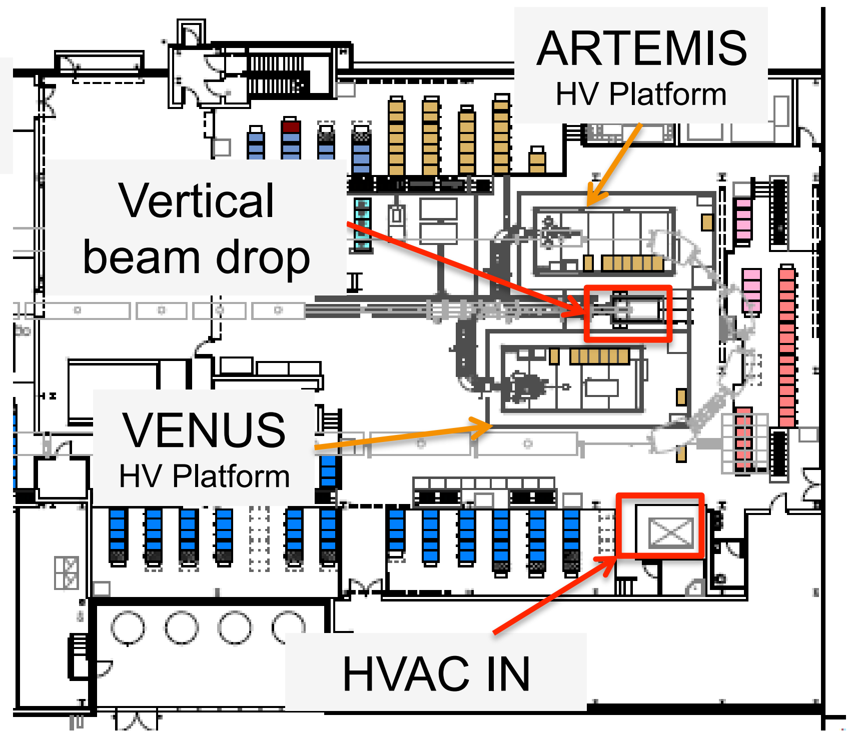
PPS Challenges in High Power Hadron Linacs: Radiation Hazards Mitigation

- Protection against prompt radiation
  - Can be divided into two categories
    - » During normal operation
    - » At abnormal event
  - We here focus on abnormal events as it can involve significantly higher radiation dose rate
  - We discuss abnormal events with the following two types
    - » The worst case beam fault, or a single point full power beam loss
    - » Beam delivery to unintended area
- Protection against induced radiation
  - Most protections are by administrative control and not subject to PPS
    - » Scheduled cooling time before entering into tunnel
    - » Careful planning for work at high radiation dose rate area
  - We here discuss confinement of radiated air for which PPS plays a role in some facilities
- Verification of design with beam
  - Design verification is increasingly important as beam power increases

Example of Fault Study for PPS Design: FRIB Front-End Area

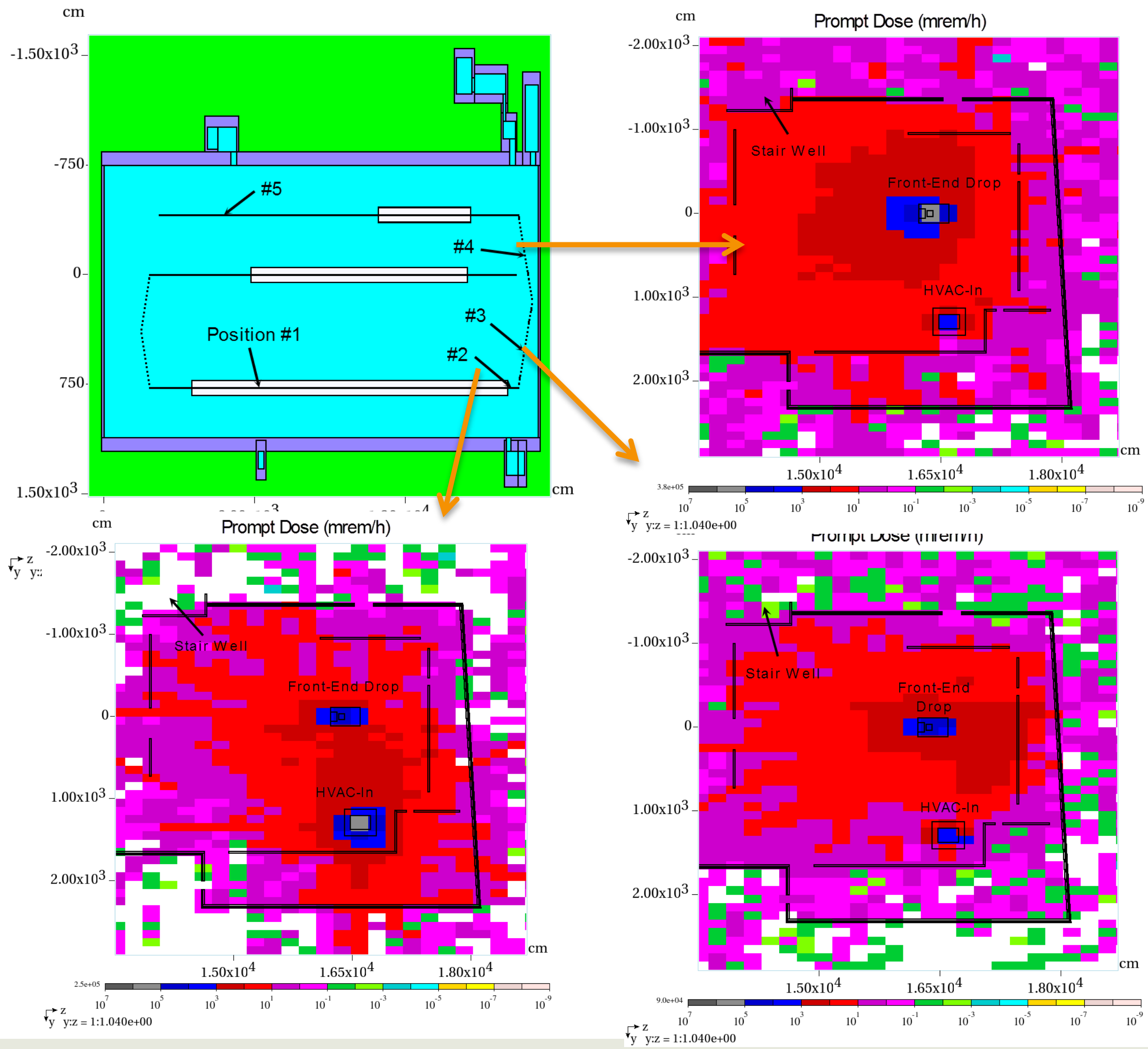
- Front-end area is the most vulnerable in linac building to beam fault with large openings and double folded linac layout
- Accelerated beam can be lost in the vicinity of the vertical drop in linac tunnel





Full Power Beam Loss Analysis Example
Worst Case Analysis to Support PPS Design

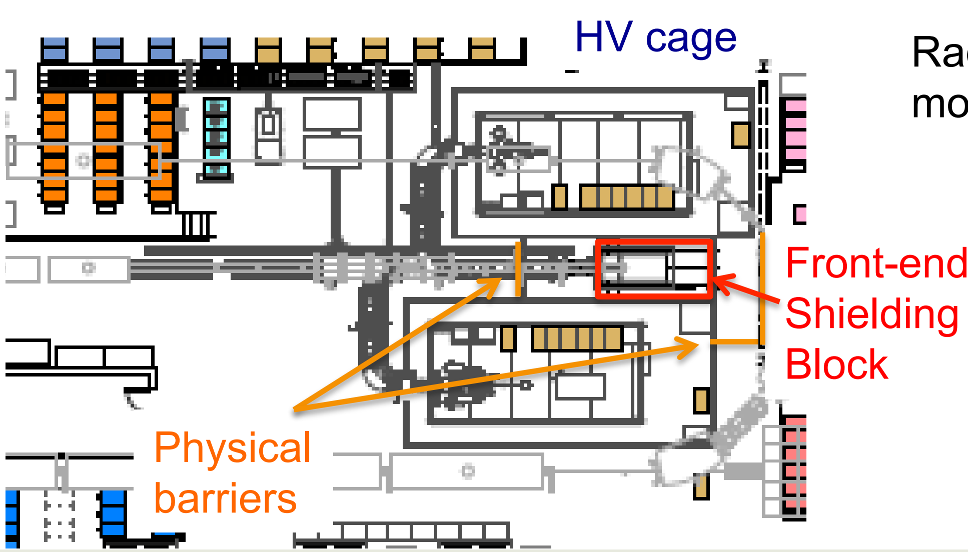
- Preliminary radiation transport calculation has been conducted assuming full power beam loss at various locations in linac tunnel
- The highest radiation dose rate at accessible area (front-end area at surface level) is estimated by systematic radiation transport calculation

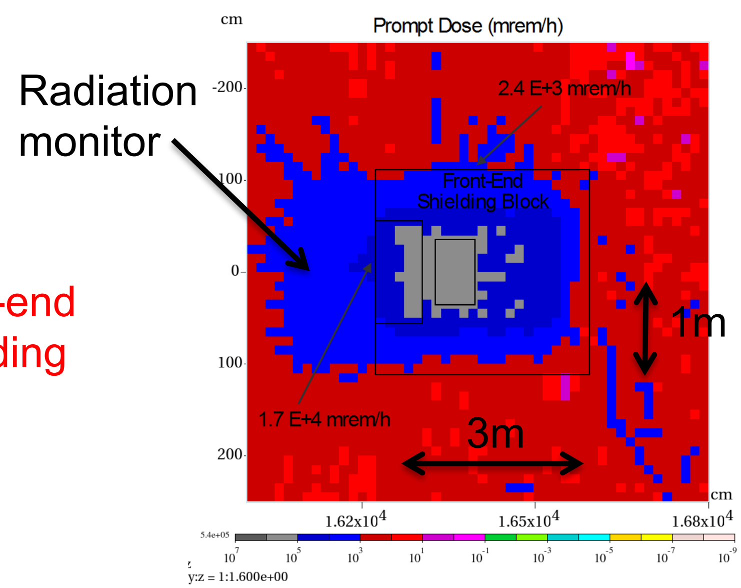


(M. Kostin)

Radiation Hazard Mitigation Strategy at FRIB

- Strategy to mitigate the radiation hazard established based on the radiation transport calculation
  - Install radiation monitors at locations where highest dose rates are expected
  - Connect radiation monitors to PPS to terminate the beam in 10 seconds
  - Install physical barriers to keep the integrated dose at accessible area at the worst case beam fault below 50 μSv (tentative internal goal)
- Systematic beam fault analysis is indispensable for PPS design

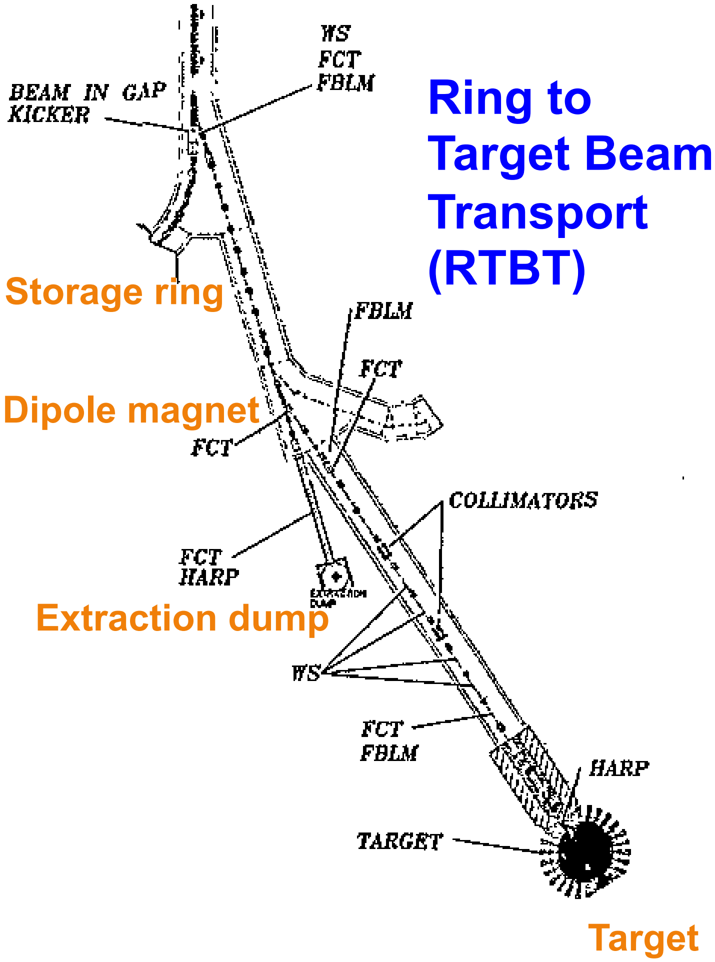




Prevention of Unintended Beam Delivery: Beam Inhibit Device

- Another abnormal event which can cause significantly high dose rate is beam delivery to unintended area
- We often allow beam operation in a part of facility with workers entering other access controlled areas
  - Example: Linac beam tuning while target area maintenance
- Beam delivery to unintended area is prevented with beam inhibit device (BID)
- Requirements for BID are defined by a safety guideline in US (ANSI/HPS N43.1-2011)
  - At least two dissimilar BIDs 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 (without relying on MPS)
- Radiation monitors used for PPS usually require several seconds to shut off the beam, which determines endurance time for some BIDs

Beam Inhibit Device Example in SNS: Beam Transport Line between Ring to Target



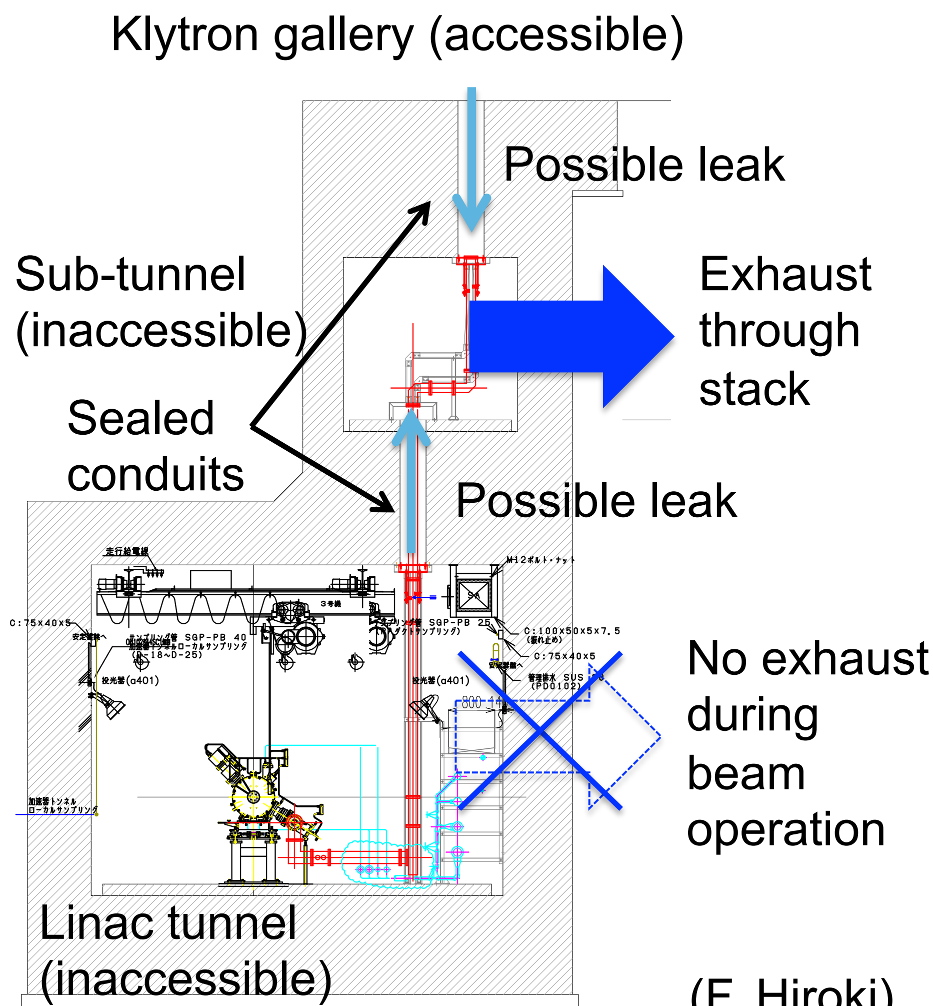
- One dipole magnet determines the beam destination between the extraction dump and target at RTBT in SNS
- Difficult to assume beam plug which will survive 1 MW beam power for several seconds (until radiation monitor inhibit beam)
- BIDs other than beam plug are adopted to prevent beam from entering target
  - AC contactor to shut off AC power for the dipole magnet power supply
  - DC contactor to both disconnect and short the output of dipole magnet power supply
- Similar configuration is planned for beam transport line between linac and target in FRIB

(K. Mahoney)

Some standard BIDs no longer practical for high power hadron linac

Example of Induced Radiation Hazard Mitigation: Radiated Air Confinement in J-PARC Linac

- Conduits between linac tunnel and accessible area are usually sealed to prevent leakage of radiated air
  - Difficult to eliminate a small leak
  - Negative pressure control necessary
- Not preferable to exhaust radiated air in linac tunnel while operation
  - Recirculation in linac tunnel
- Incompatiblity between negative pressure control and recirculation solved by tunnel design in J-PARC
  - Exhaust from sub-tunnel between accessible area and linac tunnel for negative pressure control
  - Recirculation in linac tunnel



(F. Hiroki)

Design Verification with Beam in SNS

- Design verification of radiation hazard mitigation is increasingly important for high power hadron linacs
- Although shielding and radiation monitor system are designed based on radiation transport calculation, it has some ambiguity
- It may be reasonable to verify the design with beam although policy is different for each facility
- We need further effort to establish standard methodology

> - A controlled beam loss experiment is part of validating all new or significantly modified shielding configurations at SNS
> - To the extent possible, the experiment verifies
>   - Source term calculations
>   - Shielding effectiveness
>   - Radiation monitor placement and performance
> - Assumed linear extrapolation from low power measurement to high power conditions
>
> (K. Mahoney)

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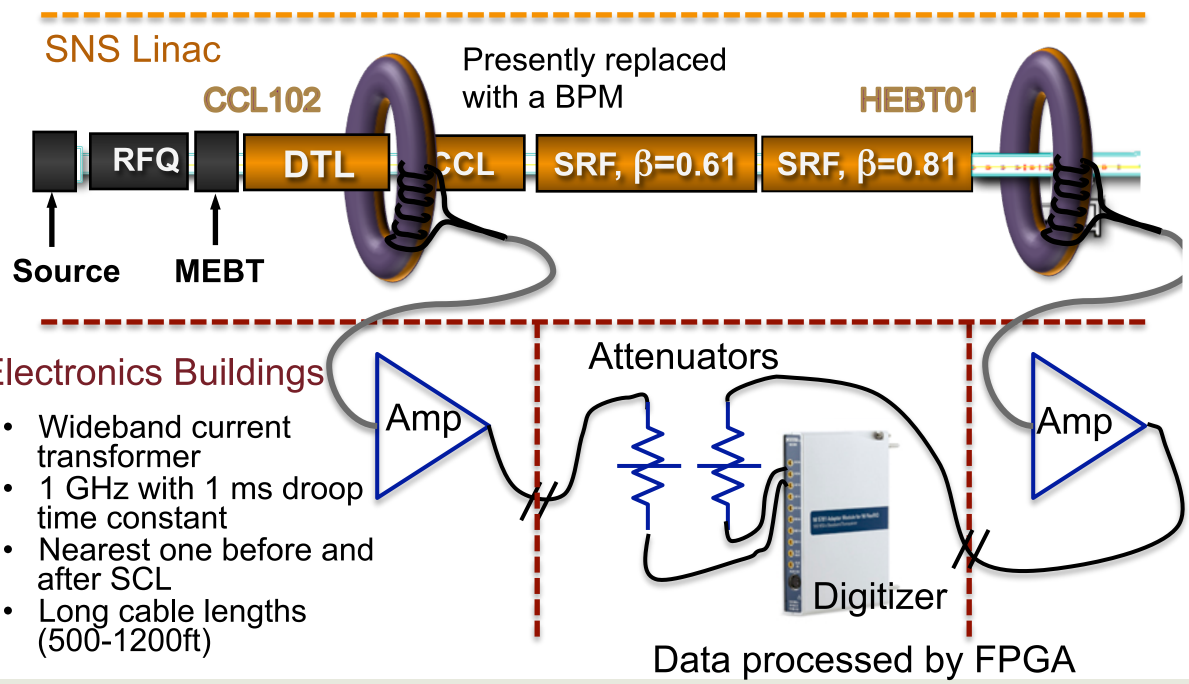
MPS Challenges in High Power Hadron Linacs: Protection against High Power Beam Loss

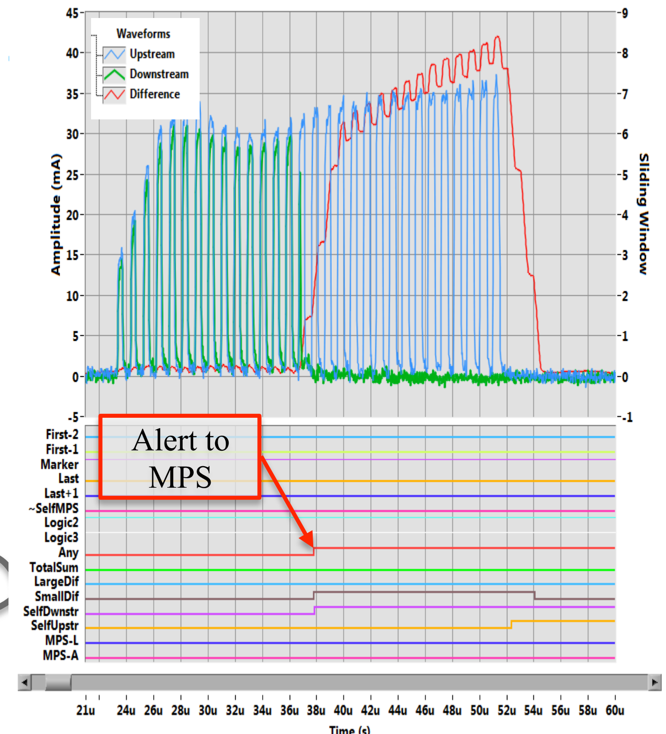
- Fast response time
  - As the involved beam power is very high, fast response time is required for MPS to shut off the beam to prevent component damage.
    - » Required response time ranges from a few to a few tens of microseconds
    - » Requirement for the response time is often tighter in low energy part
  - Appropriate architecture is necessary to realize required response time
- Detection of beam loss in low energy part
  - Beam loss monitors (BLMs) usually detect radiation from beam loss
  - It is difficult to use usual BLMs for low energy part of proton linac as beam loss produces little radiation
  - This difficulty is shared with heavy ion linacs for wider energy range
- Capturing of MPS fault modes
  - In addition to beam-loss-detection-based MPS, it is also important to capture and mitigate the cause of beam loss
  - Capturing of MPS fault modes are increasingly important as high power beam has potential to cause catastrophic MPS faults

Differential Beam Current Monitoring (DBCM): Attempt to Realize Fast Beam Inhibit in SNS

- DBCM detects beam loss between two current monitors by comparing current readings from two monitors
- It is applicable to low energy part
- Implemented at SNS for faster beam inhibit



DBCM initial result

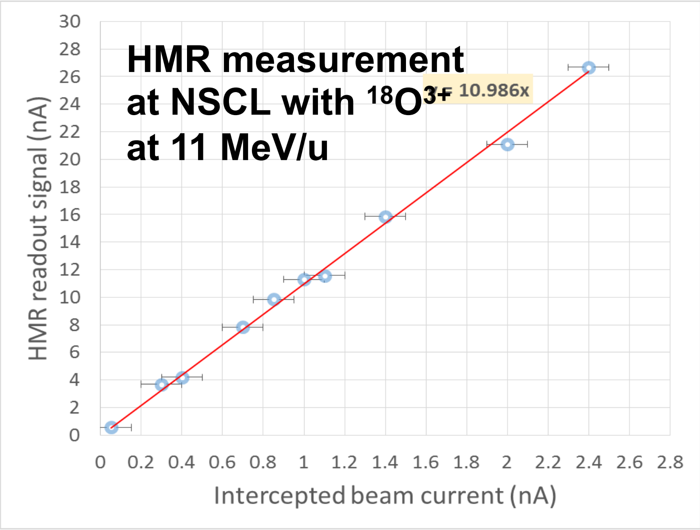


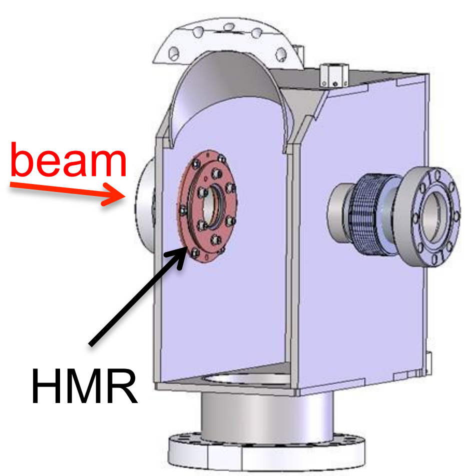
Beam inhibit < 14 μs
Under improvement aiming at 6-8.5 μs beam inhibit time

(W. Blokland)

Halo Monitor Ring (HMR): Planned in FRIB for Chronic Beam Loss Detection

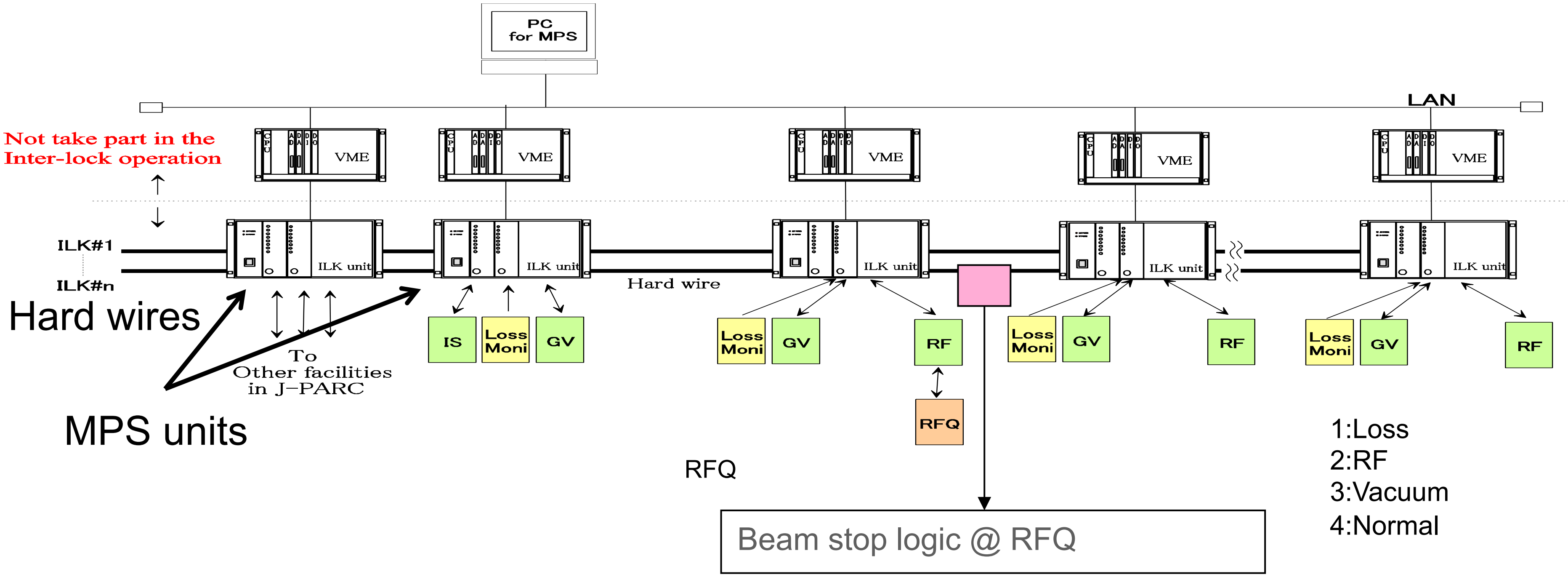
- A disadvantage of DBCM is insensitivity to small fractional beam loss
- In high power hadron linac, small fractional beam loss could cause component damage over a long period of time if it is chronic
- We plan to adopt HMR in FRIB to detect low-energy heavy ion beam loss
- HMR is a niobium ring designed to intercept ions in the halo of the beam that are likely to be lost farther downstream
- It has high sensitivity (~0.1nA) for integrated small signal and fast response time (~10 μs) for large signal





(Z. Liu)

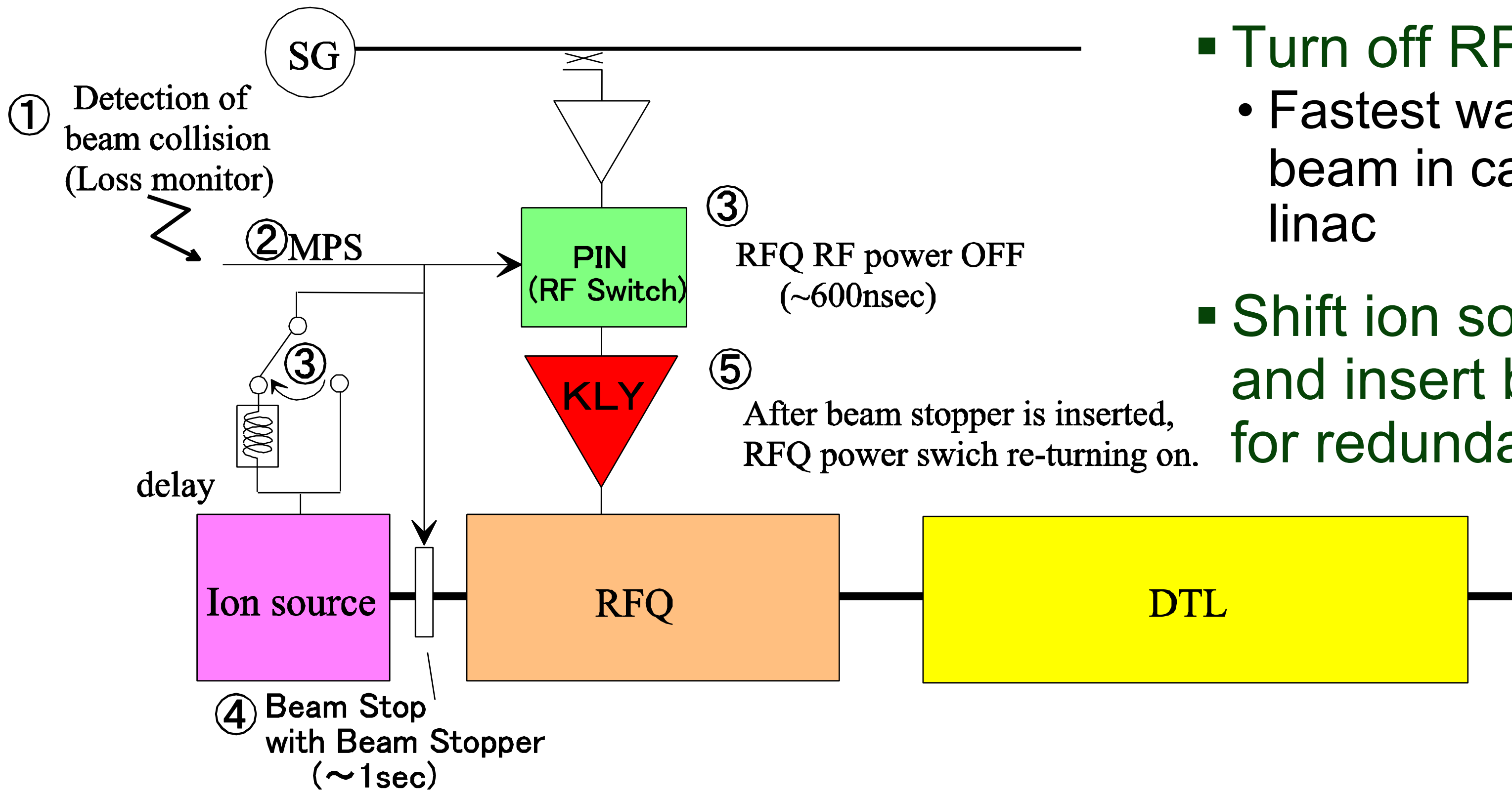
Example for MPS Design: MPS Architecture for J-PARC Linac



- MPS for J-PARC linac is fully optimized to realize fast response
  - An MPS unit for each rack row
  - Neighboring MPS units are connected with parallel “hard wires”
  - Only beam shut off signal is sent by “hard wires” to evoke beam inhibit procedure
  - Other information is collected through EPICS

(H. Sakaki)

Example for MPS Design: Beam Inhibit Procedure for J-PARC Linac

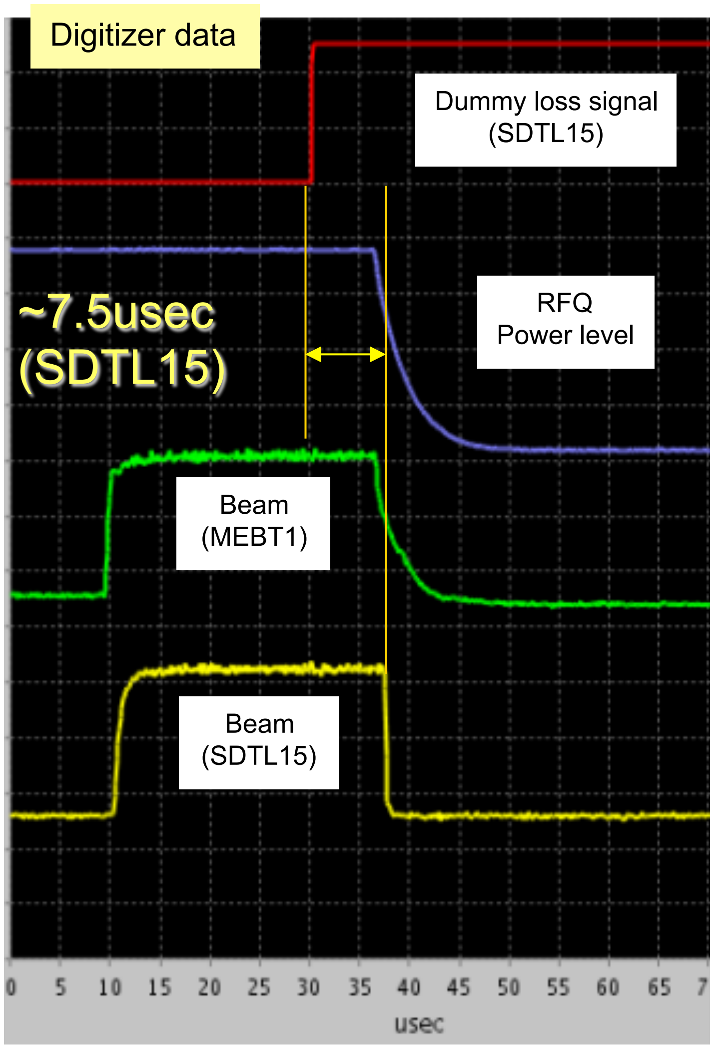


- Turn off RFQ RF
  - Fastest way to shut off beam in case of J-PARC linac
- Shift ion source timing and insert beam stopper for redundancy

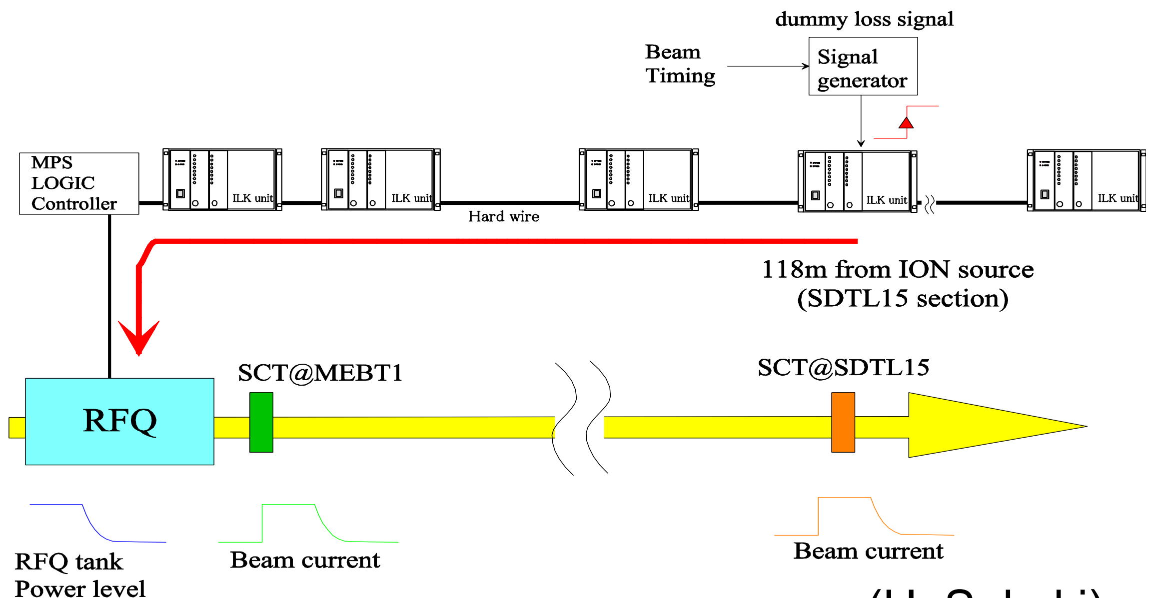
1. Cut off the input of low level RF to RFQ immediately. (for fast response)
2. Beam Stopper just before RFQ is inserted into the beam line. (block the beam)
3. Faraday Cup just before RFQ is inserted into the beam line. (redundancy for Beam Stopper)
4. RF power to RFQ inputs again as soon as possible. (stabilize the thermal state of RFQ)

(H. Sakaki)

Example for MPS Design: Beam Inhibit Time Demonstration at J-PARC



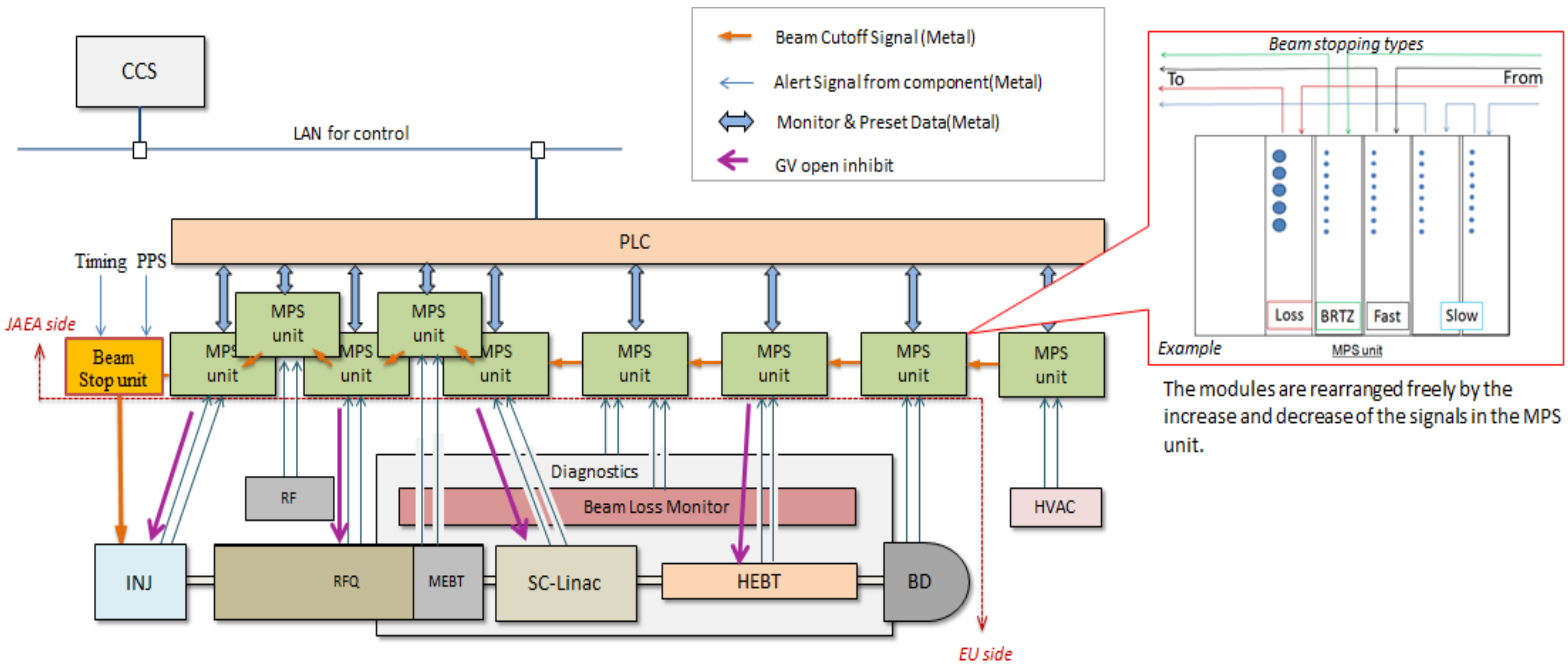
- Total beam inhibit time for MPS is around 7.5 μs in the case of dummy beam loss signal at SDTL15 (118 m downstream of ion source)
- It indicates beam inhibit time of < 10 μs for entire linac



(H. Sakaki)

MPS Architecture at Other Facility: Similar Approach at IFMIF/EVEDA

- Similar architecture with J-PARC is adopted for IFMIF/EVEDA
  - Aggregated beam inhibit signal sent by "hard wire"
  - Additional information to analyze MPS event collected through PLC
  - Different beam inhibit device (ion source) adopted

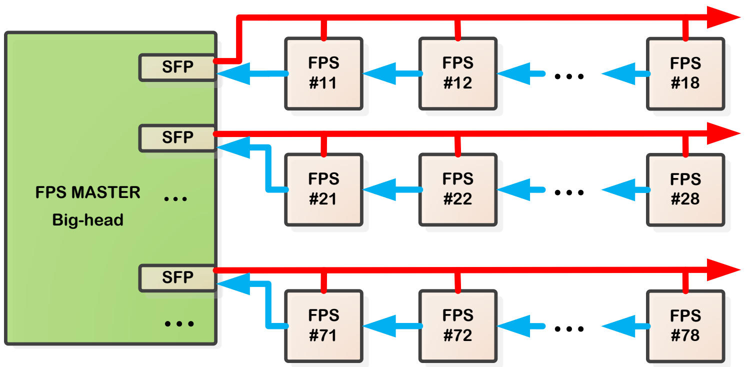


The modules are rearranged freely by the increase and decrease of the signals in the MPS unit.

(K. Nishiyama, H. Takahashi, H. Sakaki)

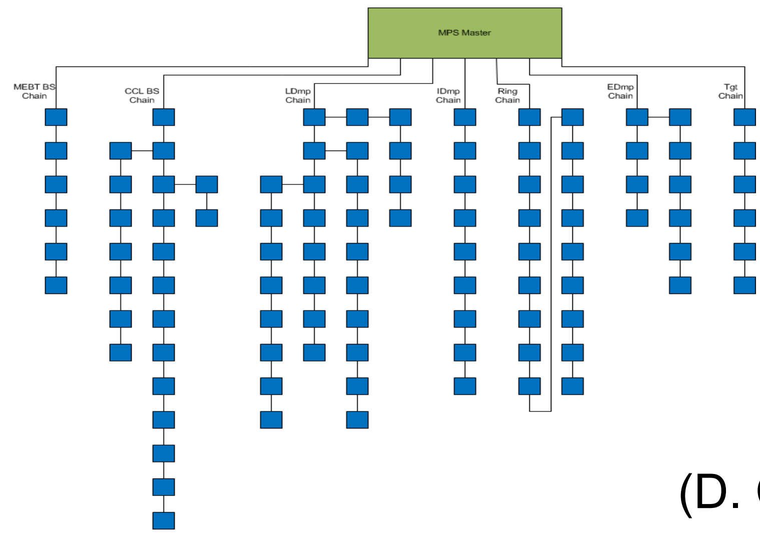
MPS Architecture at Other Facility: Very Different Approach at SNS and FRIB

MPS topology at FRIB



(S. Peng)

MPS topology at SNS



(D. Curry)

- MPS at SNS and FRIB have more flexible topology with serial connections
- More information can be sent to the MPS master
  - More flexible mask handling
  - Longer latency (10-20 μs)

Trade off: response time vs. flexibility

- SNS has an additional layer for DBCM to realize faster response time to make up the drawback, which gives us a hint for future direction

Effort to Capture MPS Risks in ESS

- To capture MPS risks is increasingly important in high power hadron linacs as the involved beam power increases with the risk of catastrophic damage
- In ESS, developing a complete catalog of MPS events to help design smart MPS
  - Identify risk/hazard of MPS related systems and rate it in risk matrix
  - Identify mitigation methods for all identified events
- This is similar approach to PPS design

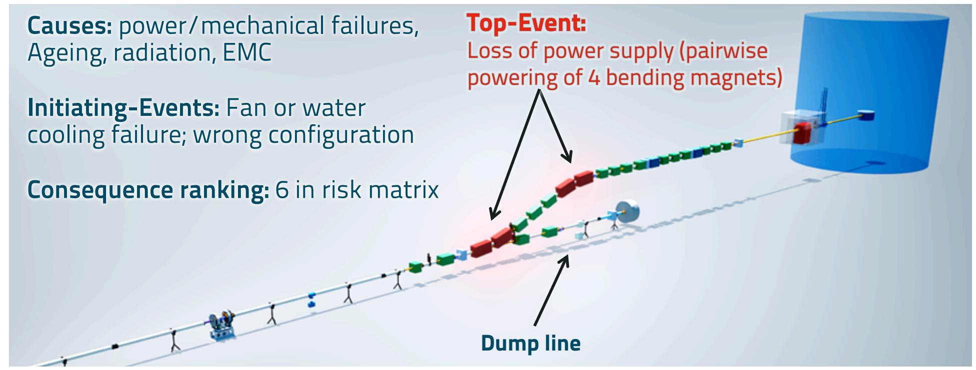
Probability	Consequence Ranking			
Frequent: At least once a year	3	4	5	6
Probable: Once between 1 and 10y	2	3	4	5
Rare: Once between 10 and 100y	1	2	3	4
Exceptional: Not in 100y	1	1	2	3
Severity	**Insignificant**	**Moderate**	**Major**	**Catastrophic**
Production Losses/year	<1 day	<1 week	<2 month	≤1 year
Property Losses	<150 KEUR	<1 MEUR	<8 MEUR	≤50 MEUR

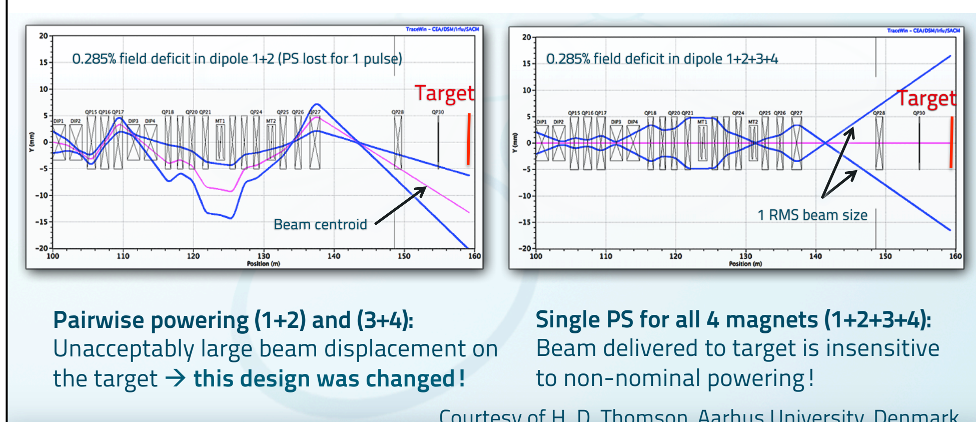
(A. Nordt)

Example for Mitigation of MPS Risks in ESS

- It illustrates their effort to mitigate the risk not only by MPS design but also by more comprehensive review of linac design
- Systematic risk analysis allows us comprehensive approach in MPS risk mitigation

MPS risk mitigation example in ESS beam transport line (old design)





- Failure of bending magnets in beam transport line between linac and target can cause catastrophic damage
- Risk of catastrophic failure can be mitigated by choice of powering scheme for bending magnets
  - Mitigating the risk of hitting of component with focused beam

(A. Nordt)

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PPS Design Comparison

	J-PARC	SNS	ESS	IFMIF/EVEDA	IFMIF	FRIB
Integrated dose at an abnormal event	None	<5.5 mSv	Not yet determined	None	None	<50 μSv (tentative)
Response time for radiation monitor	<10 sec	<2 sec	Not yet determined	Several seconds	Several seconds	<10 sec
Negative pressure control (linac tunnel)	Yes, Not connected to PPS	No, air recirculated during operation	Yes, Not connected to PPS	Yes, Connected to PPS through HVAC	Yes, Connected to PPS	Yes, Connected to PPS
Integrated beam power control for target or beam dump	PPS control	MPS control	Admin. control	Admin, control	Not yet determined	Admin. control
Cooling time before tunnel entry	4 hours, Air activation	Typ. 1 hour, Air activation	Not yet determined	Not determined yet	Not yet determined	4 hours Air activation
Controlled beam loss experiment	None	Yes for all shielding configuration changes	Yes, Details not yet determined	None	None	Yes, Details not yet determined

MPS Design Comparison

	J-PARC	SNS	ESS	IFMIF/EVEDA	IFMIF	FRIB
Detection method for beam loss	Gas proportional counter	Ion chamber, DBCM	DBCM, BLMs, halo monitors	Ion chamber, diamond detector	To be determined based on EVEDA experience	DBCM, ion chamber, halo monitor ring
Beam inhibit devise	RF for RFQ, ion source timing, beam stopper	Pre-chopper, RF for RFQ, Ion source	RF for ion source, LEBT chopper, MEBT chopper, RF for RFQ	Ion source	To be determined based on EVEDA experience	Electric bends, ion source
Beam inhibit time	< 10 μs	< 20 μs	< 5 μs for warm part, 10-30 μs for cold part	< 40 μs Target 30 μs	< 33 μs	< 35 μs
Design emphasis	Responding speed, reliability	Responding speed, reliability	Responding speed, reliability, flexibility, failure tracing	Responding speed, reliability	Responding speed, reliability	Responding speed, reliability, flexible mask

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Summary

- PPS
  - Hazard mitigation for the worst case beam fault becomes increasingly important to support PPS design
  - Standard mitigations are no longer practical in some cases as long as assuming beam inhibit with standard radiation monitor
    - » We may need to develop faster radiation monitor to deal with future high power
    - » Faster radiation monitor could provide a breakthrough in PPS design
- MPS
  - Trade off between fast response and flexibility
    - » Possible solution would be a combination of simple fast layer and less fast but flexible layer
    - » SNS implementation of DBCM may provide a hint for future model
  - Importance of MPS risk analysis increasing
    - » Consequence of MPS fault could be catastrophic
    - » Comprehensive mitigation approach is becoming essential for smart MPS design