Beam Loss Detection for MPS at FRIB

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Outline

- Beam loss induced damage
- Layered requirement for beam loss detection
- Diagnostic devices for beam loss detection
  - Radiation detectors
  - Differential beam current monitor (DBCM)
  - Differential beam position monitor (DBPM)
  - Halo monitor ring (HMR)
- Differential current monitoring for MPS
- Early-operation / commissioning planning of loss detection
- Beam loss monitoring system for commissioning
Fast Beam Loss Induces Thermal Damage
Deposited Energy Matters!

The worst case (uranium beam ~20 MeV/u): may damage a SS bellow in less than 40 µs
Errant Beam Loss Induces SRF Degradation
Example: Errant beam mitigation at SNS*

- Errant beam: off-energy beam generated and transported to the downstream
- Errant beam hits cavity surface, desorbs gas/particulates, increases possibilities of arcing/discharge and leads to degradation
  - e.g. two coupler windows leaks in 6c and 20d presumably from 2009
  - Historically most degradation has been recovered by thermal cycling of cryomodules
- MPS detects errant condition from SNS RF system or BLM and trigger MPS in 15µs
- <10% of BLM trips were due to ion source/LEBT
  - Most ion sources induces BLM trips during the first week of new source installation
- >90% of BLM trips were due to warm LINAC RF faults
- Adequate BLM and shorter beam stop time is wanted to reduce the degradation
The ratios of dose rates from heavy-ion beams to the dose rate from the proton beam are very nearly the same as the ratios of the produced neutrons.

Scale the residual dose rate for heavy ions relative to the 1 W/m, 1GeV proton beam loss. In the case of slow losses, FRIB ions produce low activations.

### Table: Prompt Neutron Fluxes from 1 W/m loss relative to that from proton beam [%]

<table>
<thead>
<tr>
<th>Ion (Specific Energy in MeV/u)</th>
<th>Residual Dose Rate [mrem/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (1000)</td>
<td>98.9</td>
</tr>
<tr>
<td>$^{238}$U (200)</td>
<td>1.5</td>
</tr>
<tr>
<td>$^{18}$O (300)</td>
<td>12.1</td>
</tr>
</tbody>
</table>

* R. Ronningen “Studies of limits on uncontrolled heavy-ion beam losses for allowing hands-on maintenance”
The present slow loss detection criterion has been set to 1 W/m, corresponding to $10^{-5} \sim 10^{-6}$ fractional power loss per meter.

- An average 1 W/m beam loss adds ~250 W heat load to the cryoplant, which is 10% of the total 2 K design load.
- The design margin for cryoplant heat load is limited, ~100%.

Will the SRF cavity experience long-term degradation from the low-level chronic beam loss?

The current slow loss threshold will not trigger FPS trips. It is an optional detection criteria for commissioning/tuning.
The criterion for fast beam loss MPS is to mitigate the beam energy deposition for each event.

Adopt a lost beam energy limit, based on damage thresholds –

\[ 20 \text{ kW} \times 35 \mu\text{s} = 1.4 \text{ J} \]

Example design detection/mitigation schema for Fast MPS (FPS)

<table>
<thead>
<tr>
<th>Threshold of full current</th>
<th>Beam detection time (µs)</th>
<th>Beam mitigation time (µs)</th>
<th>Maximum beam energy loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100%</td>
<td>15</td>
<td>20 kW x 100% x 35 µs = 1.4 J</td>
</tr>
<tr>
<td>2</td>
<td>10%</td>
<td>330</td>
<td>20 kW x 10% x 350 µs = 1.4 J</td>
</tr>
<tr>
<td>2</td>
<td>1%</td>
<td>3480</td>
<td>20 kW x 1% x 3500 µs = 1.4 J</td>
</tr>
</tbody>
</table>

Beam current from ion source fluctuates on order ~10% over tens of ms. Monitoring at fluctuation thresholds below ~10% will require feed-forward from the injector current monitoring system.
Traditional Radiation Detectors include Ion Chamber and Neutron Detector. However, they are not sufficient for FRIB superconducting linac segments because

- Cavity X-ray background can be several rad/hr
- Radiation cross talk from LS3 overshadows LS1 and LS2

Radiation detectors are still useful at high power deposition areas and for tuning purpose.

Gamma intensity from LS3 decreases to 7.5% for a line loss and 0.6% for a point loss, it is still larger than LS1 loss signal.

Neutron radiation is more penetrating than gamma and therefore its cross talk effect is even worse.
Design Example of DBCM (Bergoz BCM)

- **Example: LS1 differential currents**
  - Current difference measurements are performed in <10 µs with a current resolution better than 4 µA (~1% of full beam current)

### Design Example of DBCM (Bergoz BCM)

<table>
<thead>
<tr>
<th>Beamline Segment</th>
<th>Time of flight (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEBT</td>
<td>1.3</td>
</tr>
<tr>
<td>RFQ</td>
<td>0.7</td>
</tr>
<tr>
<td>MEBT</td>
<td>0.7</td>
</tr>
<tr>
<td>LS1</td>
<td>2.4</td>
</tr>
<tr>
<td>FS1</td>
<td>1.4</td>
</tr>
<tr>
<td>LS2</td>
<td>1.2</td>
</tr>
<tr>
<td>FS2</td>
<td>0.3</td>
</tr>
<tr>
<td>LS3 and BDS</td>
<td>0.9</td>
</tr>
</tbody>
</table>

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**Example: LS1 differential currents**

- Current difference measurements are performed in <10 µs with a current resolution better than 4 µA (~1% of full beam current)

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Experiment was set up at ReA3 with Fermilab BPM receivers
- Measures second harmonic 161 MHz
- 81 dB gain pre-amp; 1.32 dB cable loss
- Effective BW ~37kHz (∝~4.3µs)

For 37 kHz, the calculated intensity RMS resolution (std) is 126 nA

From experiment, the RMS intensity resolution (std) for single BPM is measured as 67-106 nA for 204800 samples, assuming beam is at the center. The differential intensity resolution is ~140 nA

FRIB BPM intensity resolution is comparable with ReA3 BPM, and it features fast evaluation (~15µs)

However, the BPM resolution is very sensitive to beam position and beam velocity. Calibration is necessary
Halo Monitor Ring (HMR)

- The halo ring monitor 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 (~0.1 nA) for integrated small signal and fast response time (~10 µs) for large signal.

- Drawback: Its aperture is hard to determine by simulation. Have to use large aperture and may skip 1st phase commissioning to avoid possible limitation.

HMR measurement at NSCL with $^{18}$O$^{3+}$ at 11 MeV/u
There are two hot spots of potential beam loss inside the cryomodule, the drift space before and after solenoid.

We consider a localized slow loss on beam pipe, 0.05 W on a 1cm$^2$ spot, the resulted rising time at the hot spot is $\sim$2 seconds / 0.1 K. After 10 second, the temperature is 5 K.
Differential current monitoring is mainly for large beam losses.

Current from ion source fluctuates at 10% in a time scale of tens of ms, hence the differential current monitoring is less effective for small losses.

BPM and BCM differential current measurement should be cross-calibrated.
MPS trips trigger beam abort within 35 µs
- Ion sources
  » Removal of extraction HV ceases beam production
- LEBT E-bends
  » Removal of HV prevents low energy beam to further acceleration downstream.

After abort up to 10 µs of beam remains in pipe
- CW operation continuously generates beam
- Downstream BID may be required to further limit unplanned beam energy deposition
For initial *pulsed* beam (50 eµA, 50 µs, <1 Hz)
- Total lost beam energy deposition is below damage threshold
- May not require FPS in this mode

For initial, *low power CW* beam (<340 enA K^{17+}, 344 W full power)
- Requires beam mitigation in ~50 ms
- Conductive thermal flux may alleviate the energy deposition limit

Fast beam loss monitoring could be performed by differential beam current measurements
- Demonstrate FPS beam mitigation at fastest time scales

Slow loss beam monitoring will be calibrated and commissioned
- Demonstrate detection limits, response time, crosstalk
Operations Approach

- Fast protection systems will be commissioned at necessary response times
- Slow loss MPS can serve any mode once it has been established
- Beam loss thresholds and faults will require study for various operating modes and ion species
- Low power CW operation (mode O2) may require dedicated Faraday cups in warm sections to calibrate beam current monitors
- Dynamic Ramping is a mode of special interest
  - Quickly evolving pulse length and duty cycle over time scale of seconds
  - Data acquisition may require reconfiguration from gated to continuous mode
Beam Loss Monitoring Network for Commissioning

- Slow response time
- Commissioning segment by segment
- 2 K/4 K header heater PS current
- Novel techniques?
  - Si/CVD diamond detectors
  - LHe ionization detectors

Production
Target
Systems

Beam Delivery System

Folding Segment 1

Linac Segment 3

Linac Segment 1

Linac Segment 2

Front End

Folding Segment 2

Ion chambers

Beam Pipe Temperature Sensor

Halo Monitoring Rings

Neutron detectors

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