Instrumentation Design and Challenges at FRIB

Steve Lidia, Facility for Rare Isotope Beams

Working Group F: Instrumentation and Beam Material Interactions

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MICHIGAN STATE UNIVERSITY

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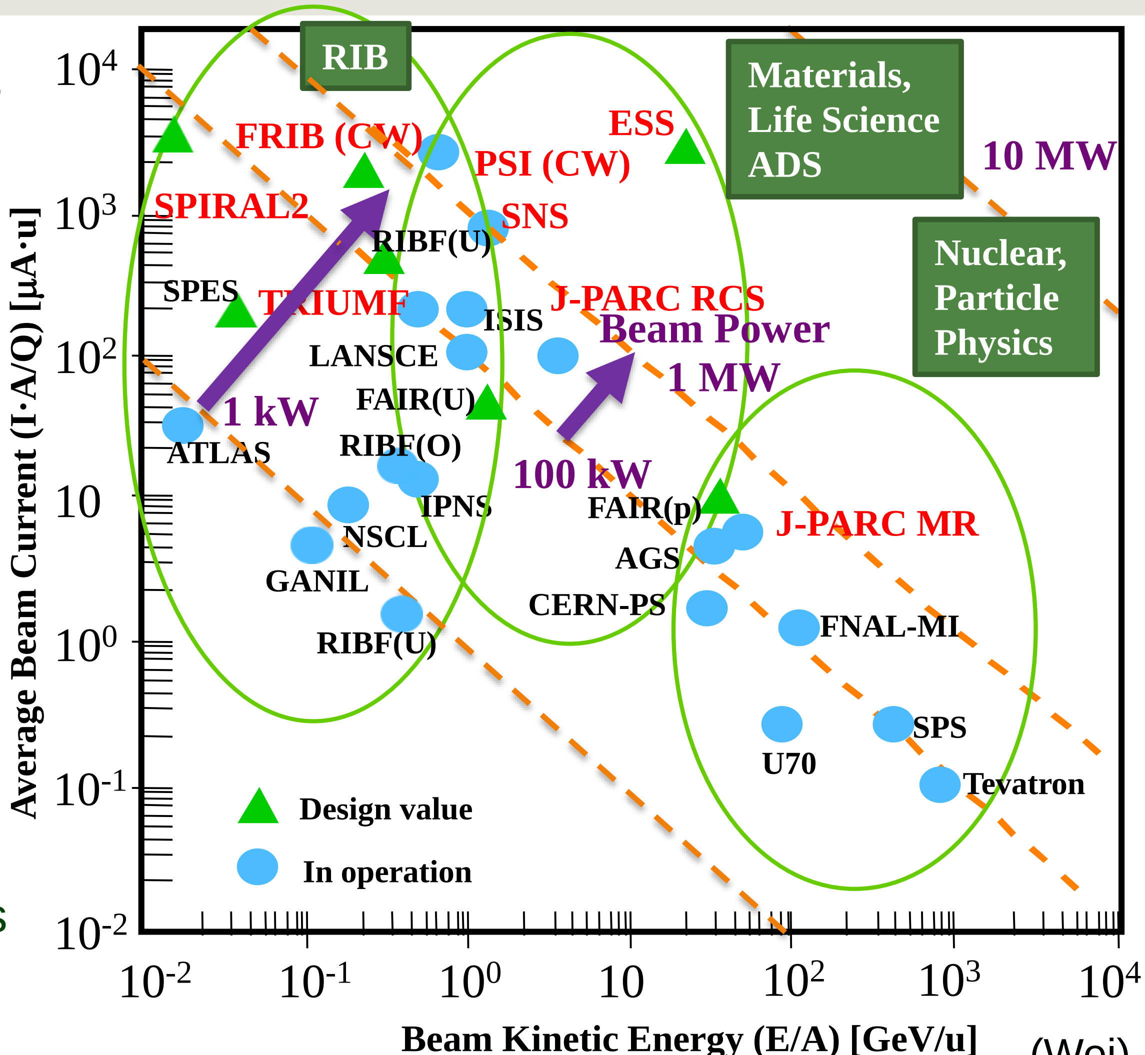
Overview

- FRIB facility and beam requirements
- Beam diagnostic instrumentation overview
- Challenges to beam instrumentation
- Summary

FRIB Among High-intensity Accelerators

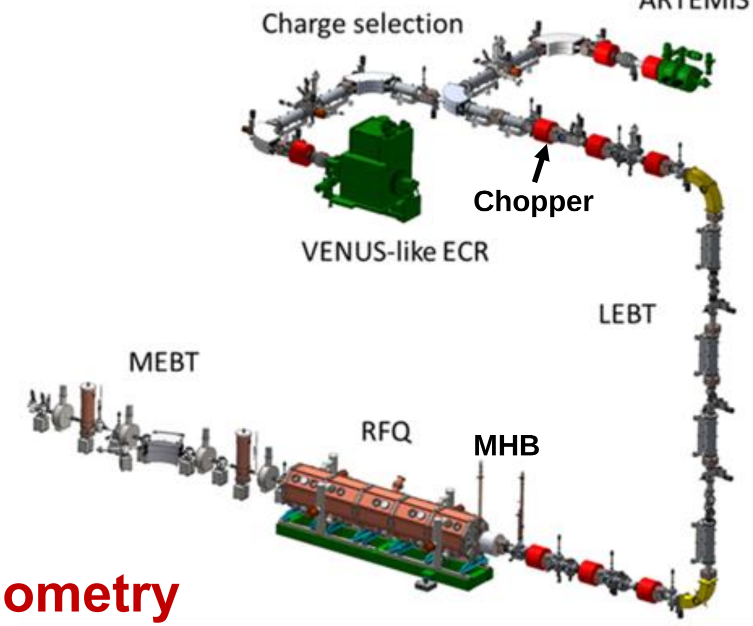
- During the past decade, proton accelerators raised beam power to ~ 1 MW
  - SNS (USA): 1 MW pulsed; SRF linac/accumulator
  - J-PARC (Japan): 0.3 MW pulsed; warm linac/RCS
  - PSI (Switzerland): 1.4 MW CW; cyclotron
- FRIB is in the same energy and power category (400 kW)
  - From proton to ^{238}U
  - Using SRF linac from 0.5 MeV/u to > 200 MeV/u
- Operational flexibility requires 10^5-10^8 dynamic range in beam intensity; CW and pulsed modes
  - Challenging conditions for beam diagnostics and MPS



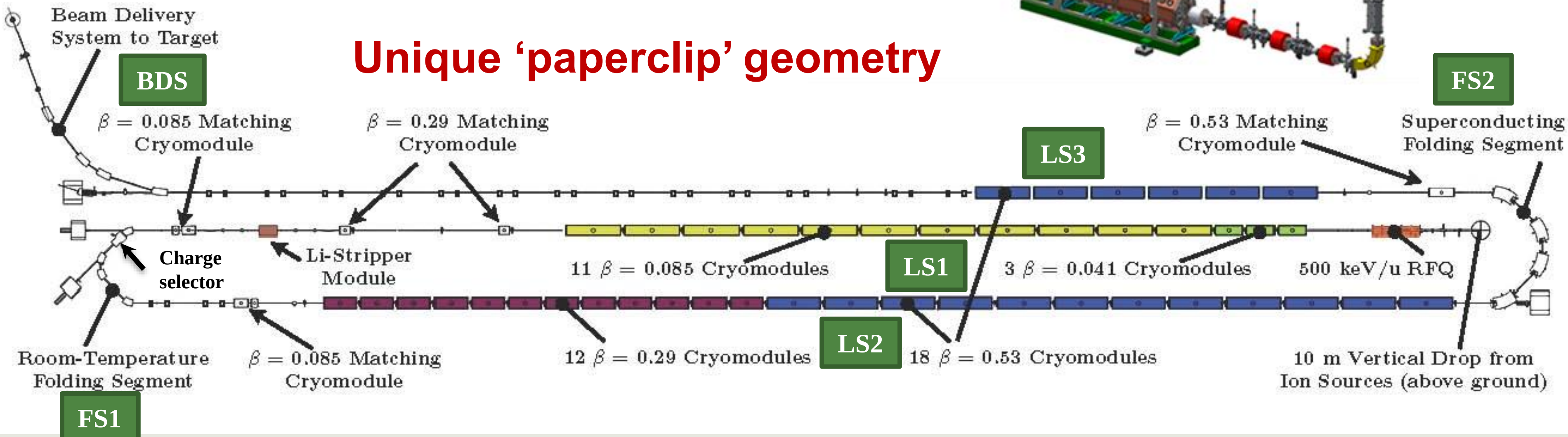
(Wei)

FRIB Facility Overview

- All ion species, multiple charge states
- Two sources and injectors
- Folded linac geometry
- Energy >200 MeV/u
- Current >500 eμA
- Power > 400 kW
- Graphite target, fragment separator

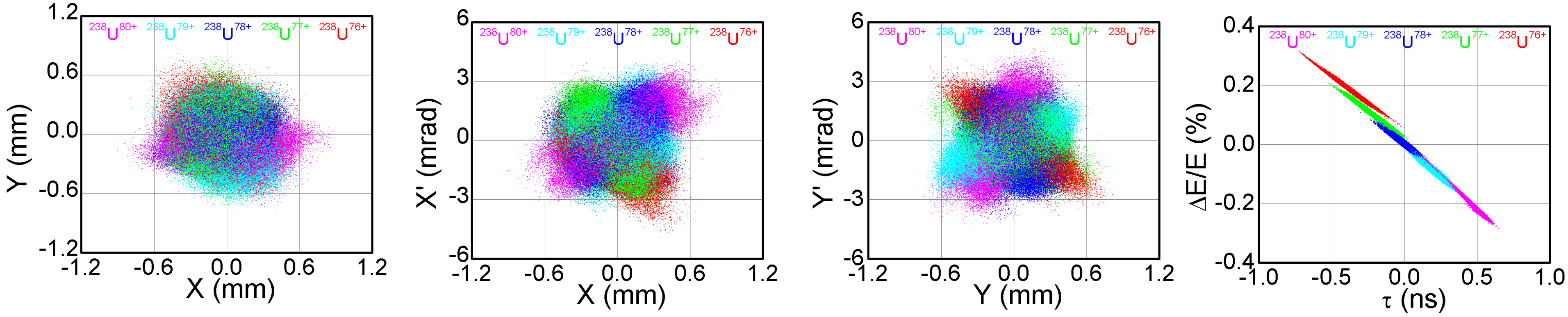


Unique 'paperclip' geometry



Design Meets Beam-on-target Requirements With Five-charge-state Uranium

Parameter	Value	Required	Achieved	Meet
Beam spot size	1 mm	≥ 90%	95.6%	✓
Angular spread	±5 mrad	≥ 90%	100%	✓
Bunch Length	3 ns	≥ 95%	100%	✓
Energy spread	± 0.5%	≥ 95%	100%	✓



FRIB Instrumentation Overview

- **Instrumentation package has been devised to**
  - Facilitate initial commissioning and tuning
  - Monitor beam transport and acceleration
  - Provide sensors for machine protection during operations

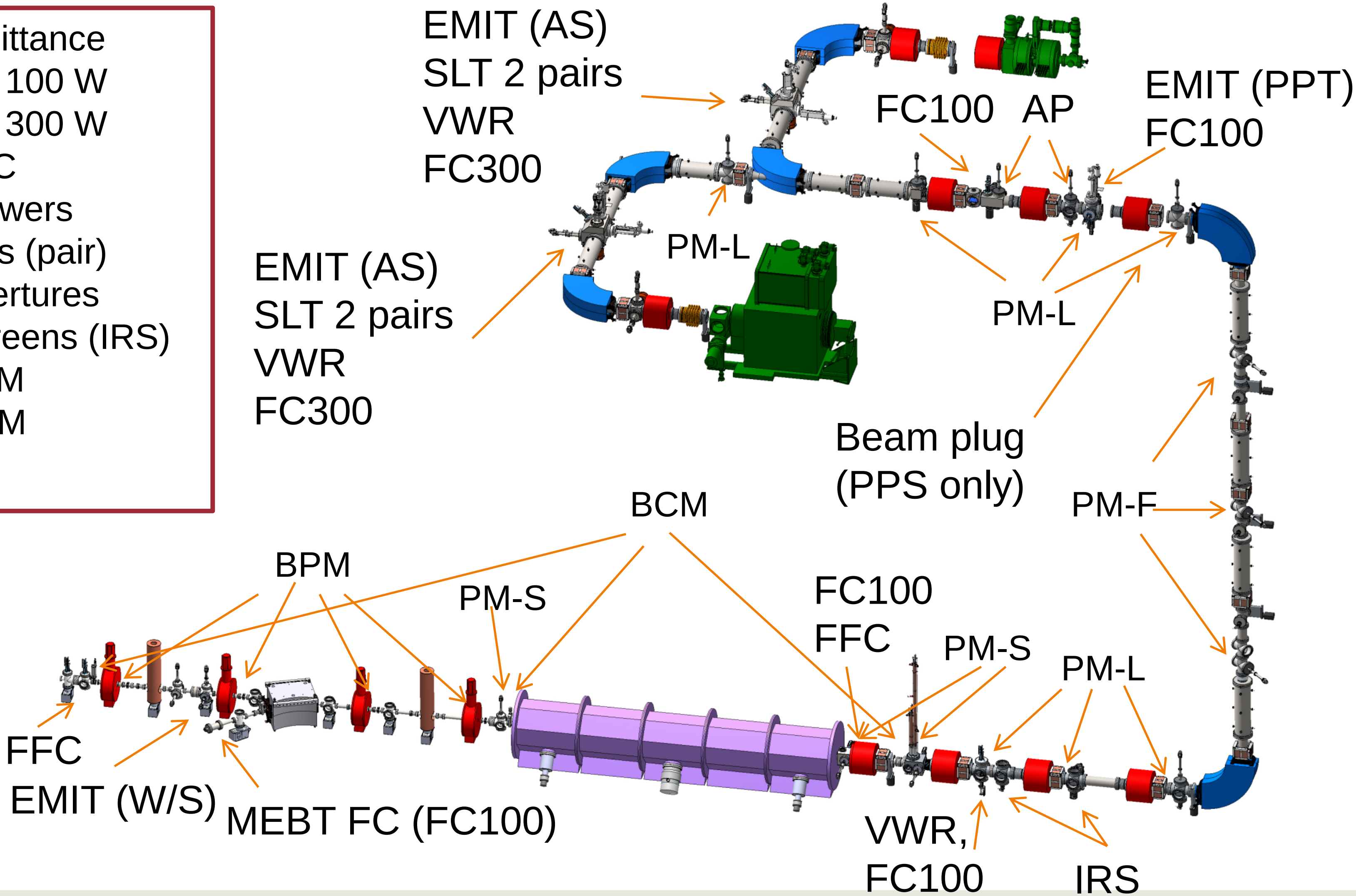
- **Diagnostic systems will continuously monitor**
  - Beam position and orbit deviations
  - Beam current and transmission at several points
  - Beam loss induced radiation fields

- **On-demand diagnostics will measure**
  - Beam phase space densities in the Front-End
  - Bunch duration at key injection points
  - 1-D beam profiles and 2-D transverse (x-y) or hybrid (x-z) distributions

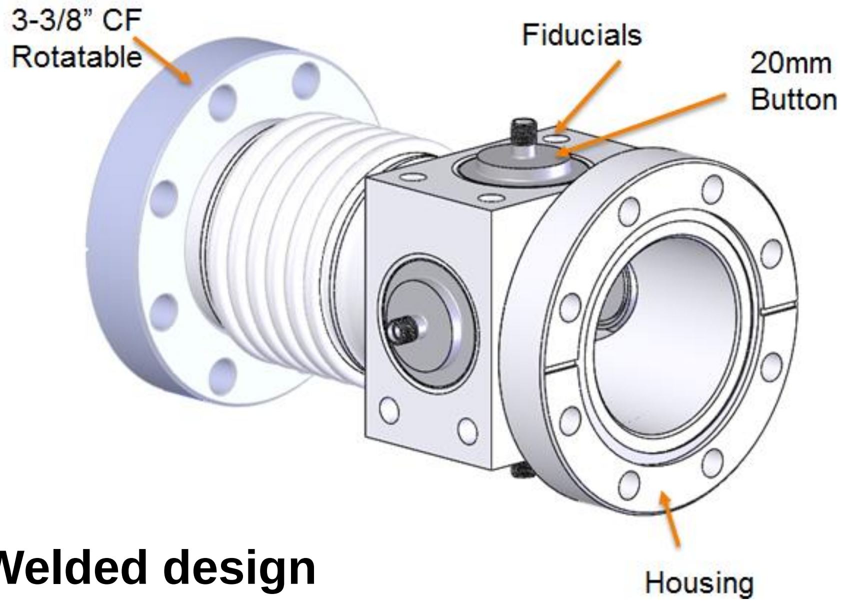
- **Time of flight measurements using a BPM network**

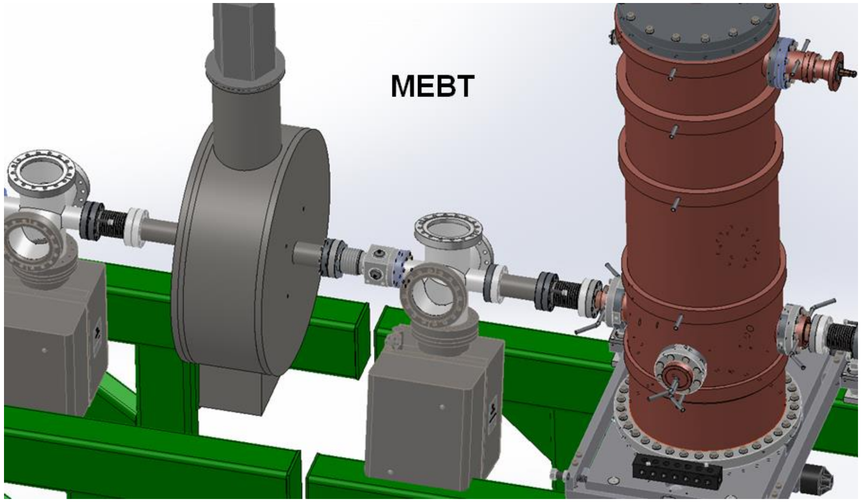
Front End Instrumentation

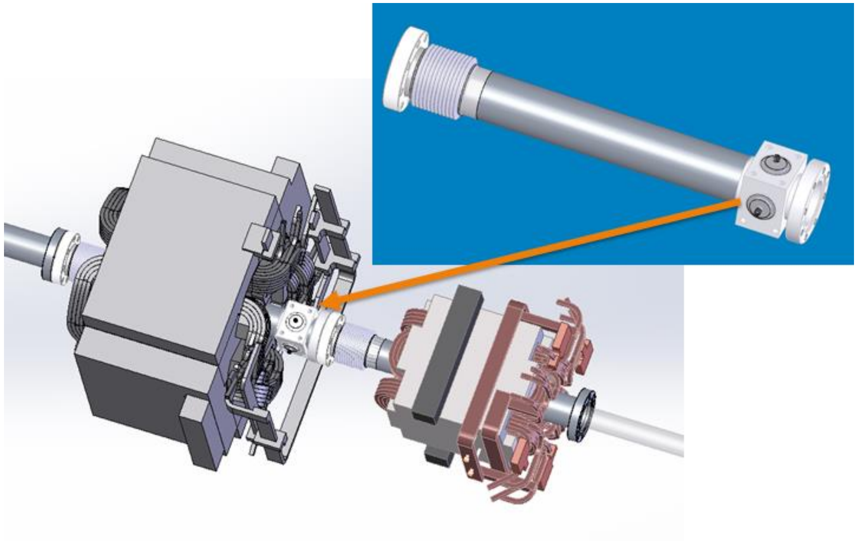
- 4x Emittance
- 5x FC 100 W
- 2x FC 300 W
- 2x FFC
- 3x Viewers
- 4x Slits (pair)
- 2x Apertures
- 2x Screens (IRS)
- 4x BPM
- 3x BCM
- 13x PM



Beam Position Monitors



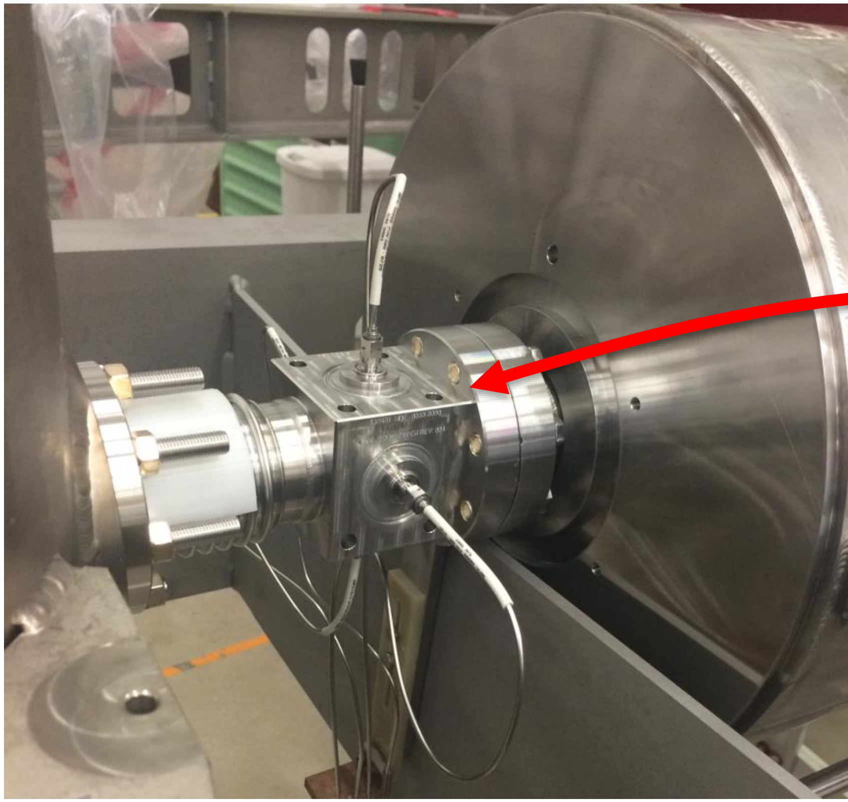


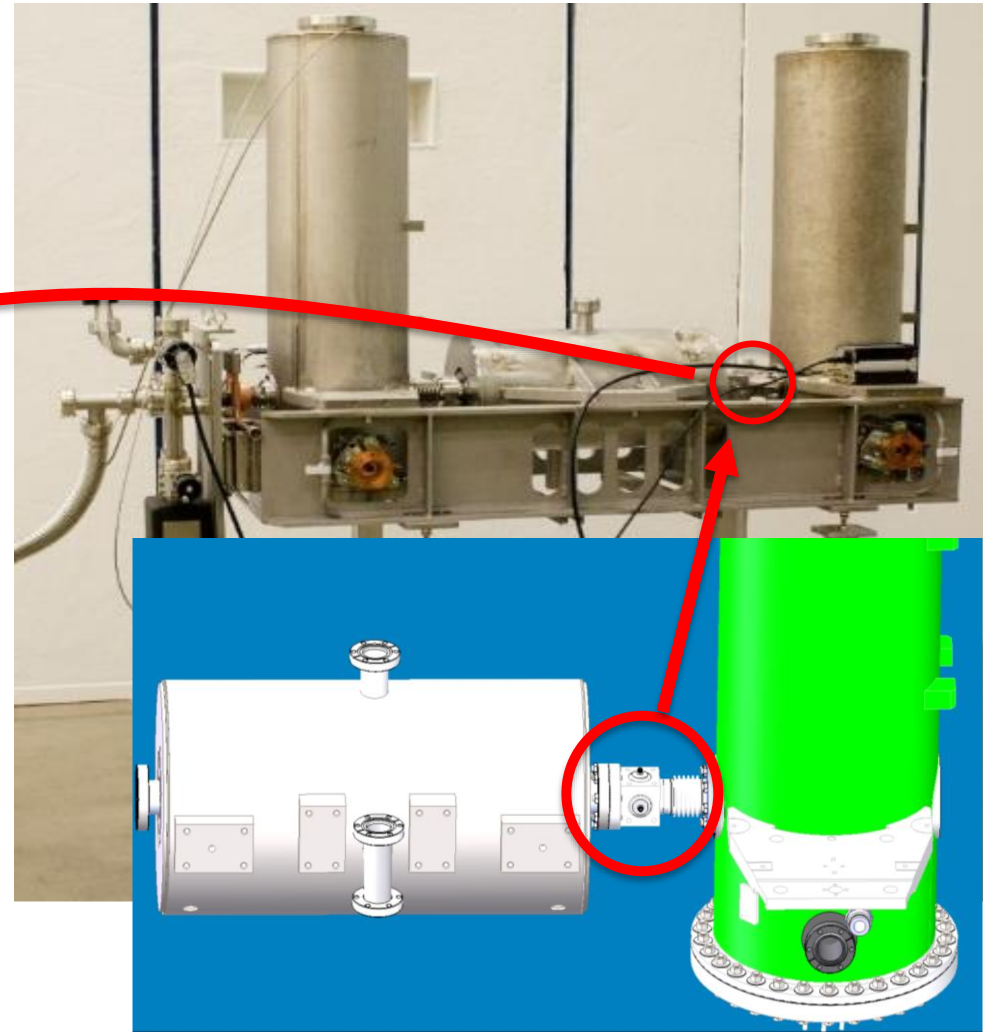


Welded design
41.3, 47.5, 98.4 mm apertures

Electronics:
Direct digital conversion, undersampling (~100 MSPS)
Platforms still under consideration: Libera-H, μTCA.4 (eg. Struck, FGPDB), VME

First cold BPM has been installed

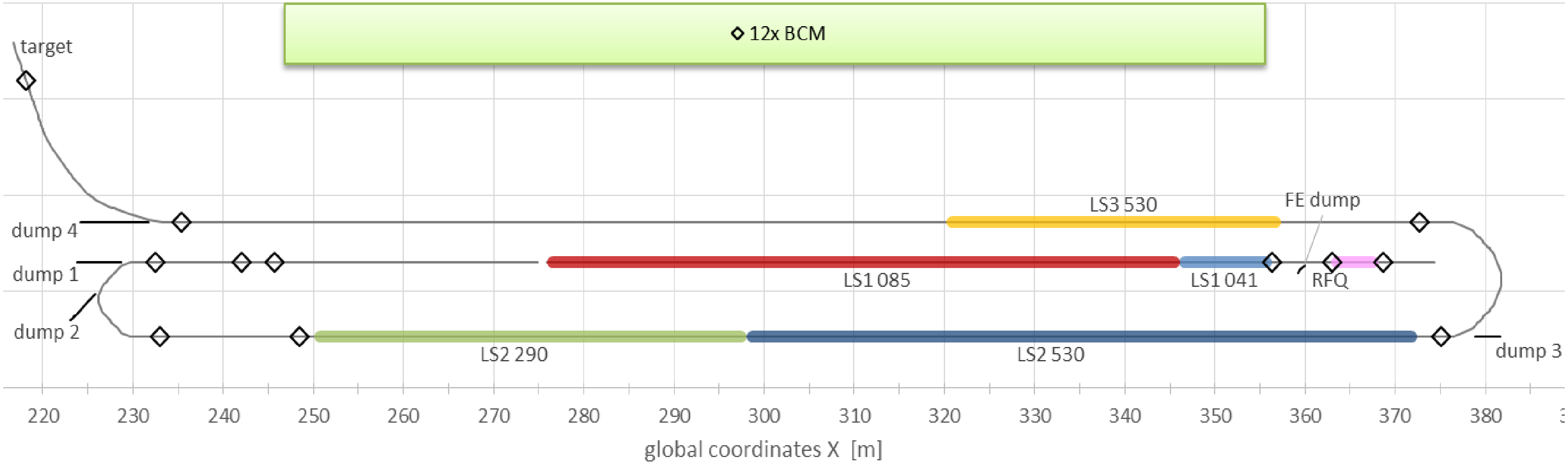




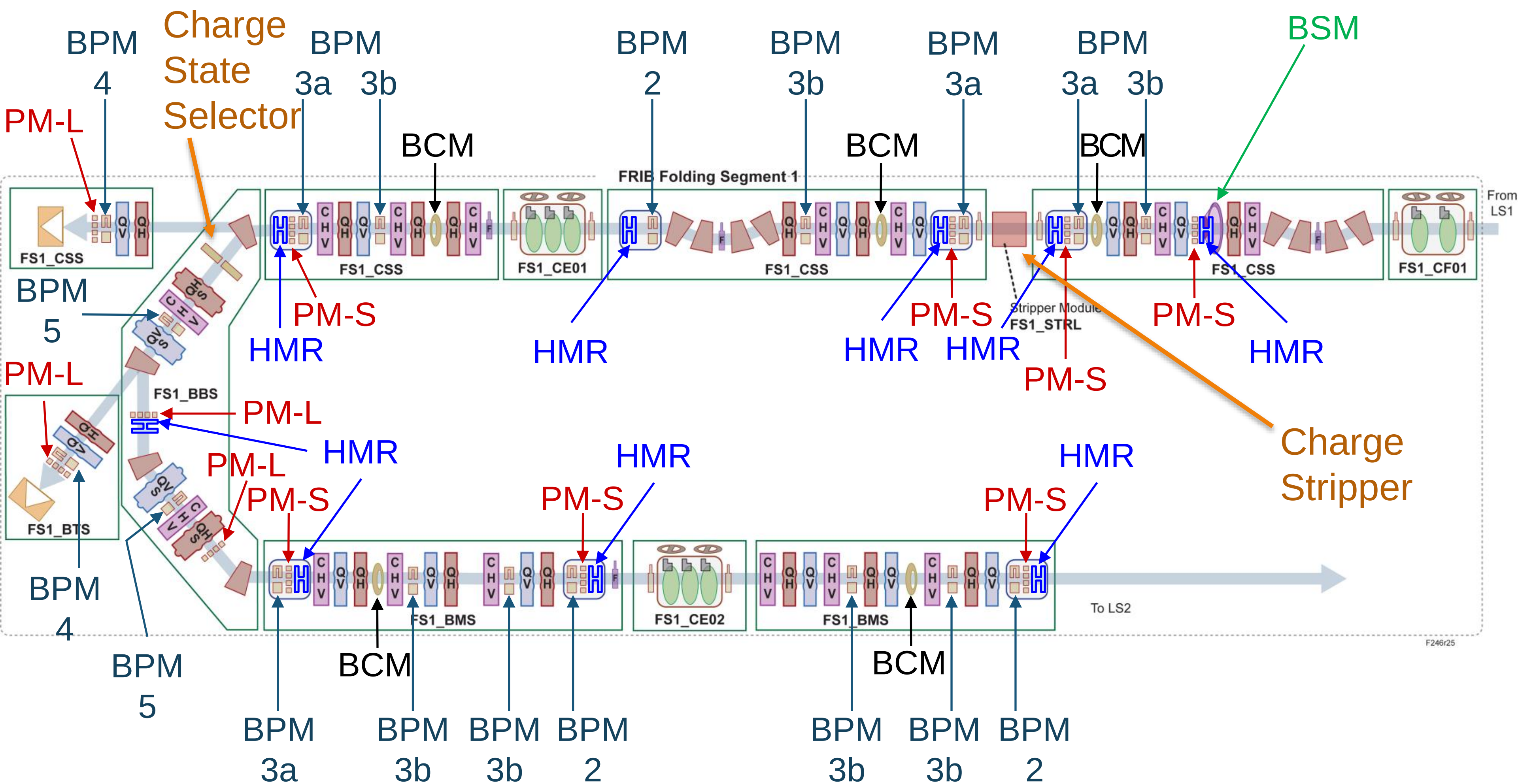
SiO2 cables (Times-Microwave) routed through 300K intercept.

Beam Current Monitors

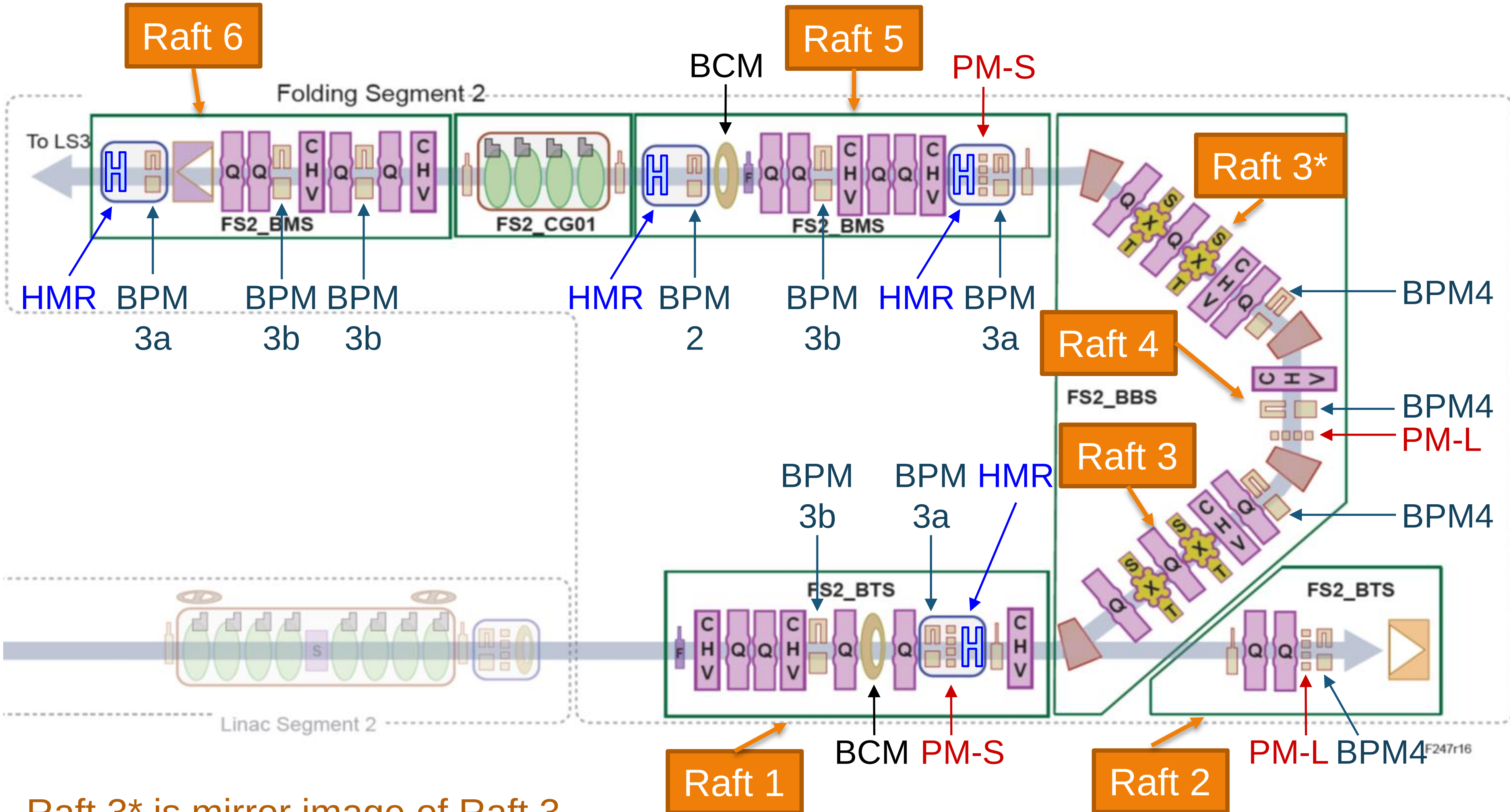
- Bergoz ACCT (300 kHz BW)
- Located at entrance and exit of RFQ to measure RFQ transmission efficiency and accelerated beam current
- Located in FS1, FS2 and BDS – span Linac Segments
- Provide Differential Beam Current Monitor (DBCM) functionality
- BCM system is supported by BPM beam intensity measurements



Folding Section 1 Instrumentation



Folding Section 2 Instrumentation



Raft 3* is mirror image of Raft 3.

Instrumentation Challenges

- Measuring and Tuning High Power Beams
- Accurate Low-β Beam Position Monitoring
- Monitoring Multiple-charge-state Beams
- Measurements Over High Dynamic Range
- Ensuring Machine Protection

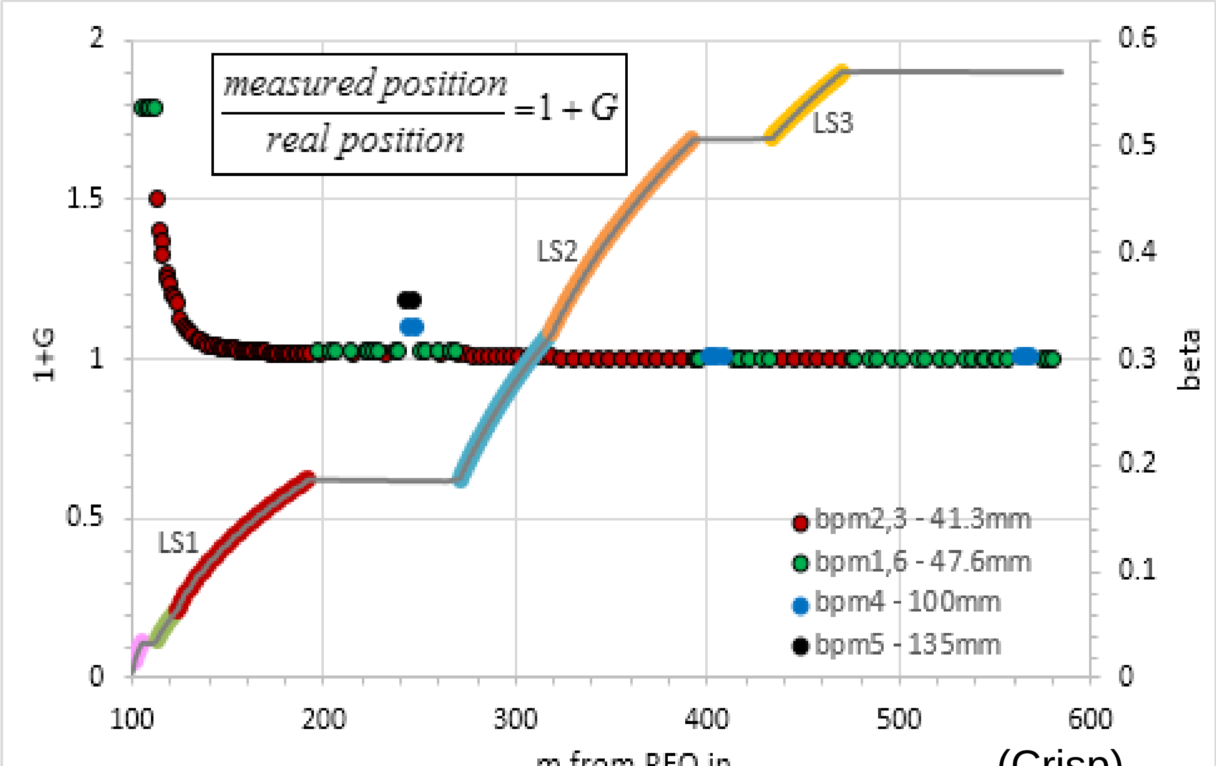
Beam Instrumentation for Intense, High Brightness Hadron Beams

- Standard diagnostics packages for constant beam monitoring
  - Button-style BPMs
  - ACCT-type current monitors
    - » Requires 'notch' in beam current to reset zero-current baseline - 50 μs @ ~100 Hz
  - Loss monitors to measure secondary radiation fields
- Interceptive diagnostics limit acceptable beam power
  - Transverse wire profile monitors
  - Feschenko-type bunch shape monitor
  - 50 μs 'tuning' mode
  - Front-end diagnostics must accept full beam power (300 W)
- SCRF linac performance concerns limit types of instrumentation
  - Standard prohibition against intercepting diagnostics
  - Cryomodule diagnostics limited to BPMs, halo monitor rings between modules
  - Non-intercepting profile monitors will be developed as an upgrade

Low-β beams induce position measurement errors

Low-β effects:

- EM field lines spread out
- Longer, slower image currents
- Reduced high-frequency content
- Nonlinear velocity and position dependence to button response



(Crisp)

Shafer (1994) analyzed the dependence to lowest order.

$$\Delta x \cong \frac{1}{1+G}\frac{D}{\pi}\frac{A-B}{A+B}$$

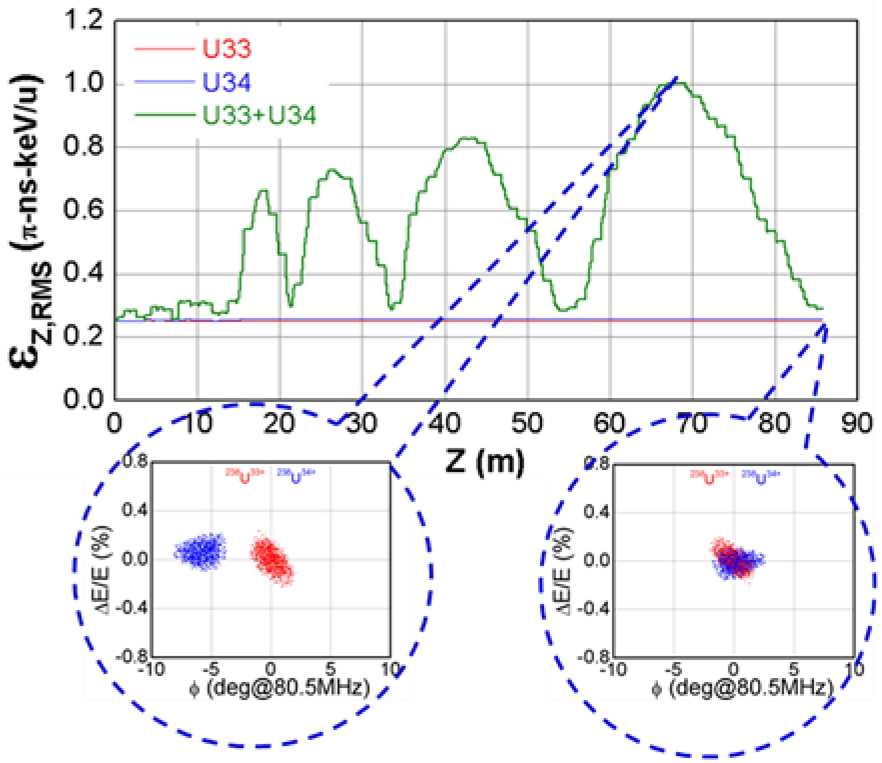
$$1+G = 1+\ 0.0347\left(\frac{\omega}{\beta c}\frac{D}{\gamma}\right)^2 - 0.00181\left(\frac{\omega}{\beta c}\frac{D}{\gamma}\right)^3$$

BPM response to purely geometric nonlinearities must be included as well.

Multi-charge-state Beam Present Measurement and Tuning Challenges

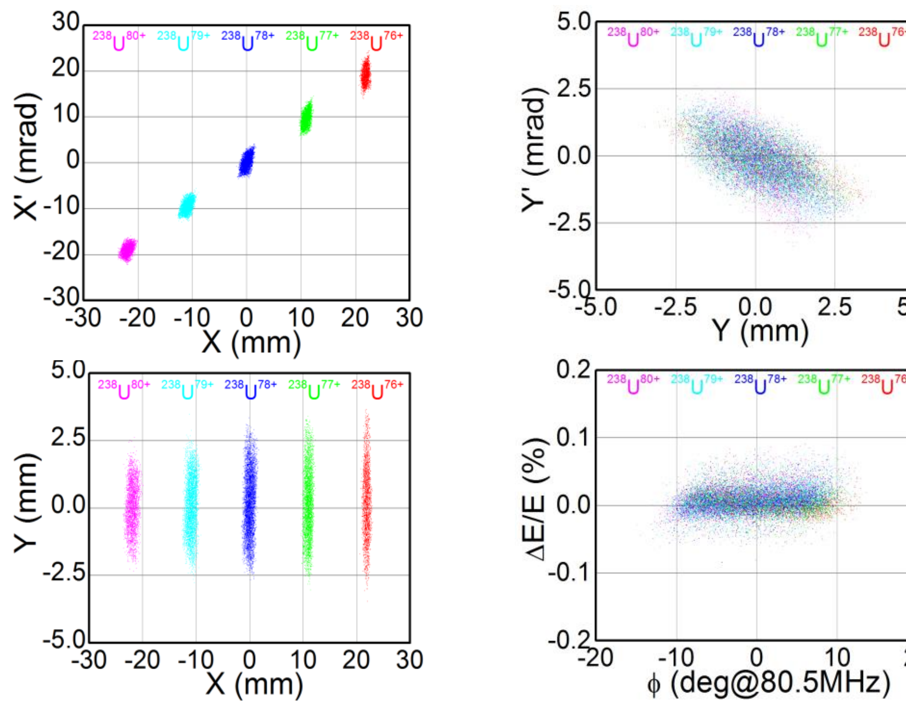
Two-charge state beam in LS1

Longitudinal emittance oscillations of beamlet ensemble and phase matching at LS1 exit requires satellite monitoring

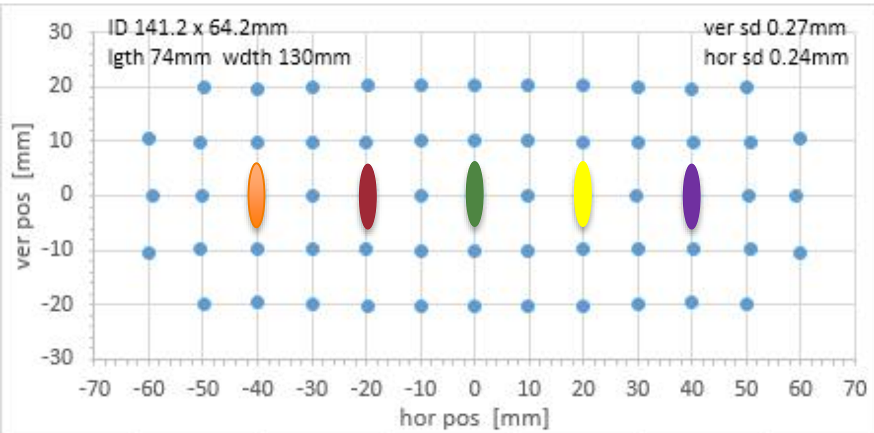


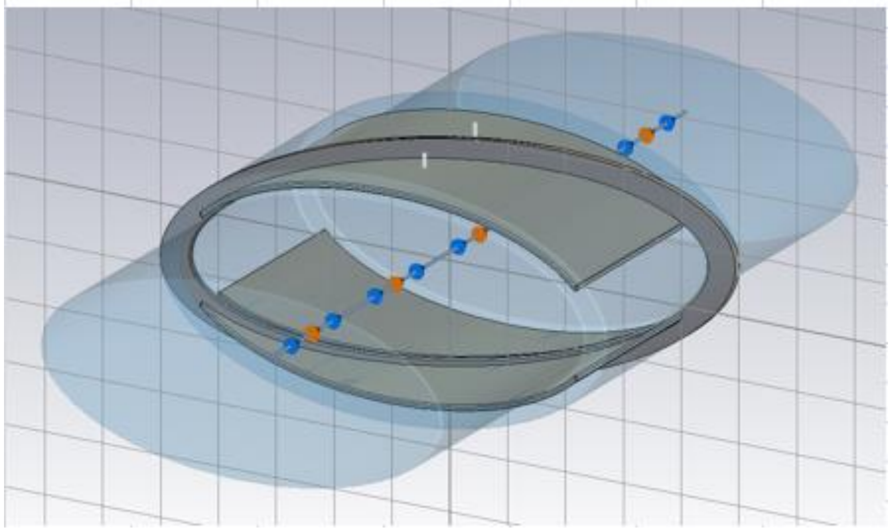
Five-charge state beam in FS1

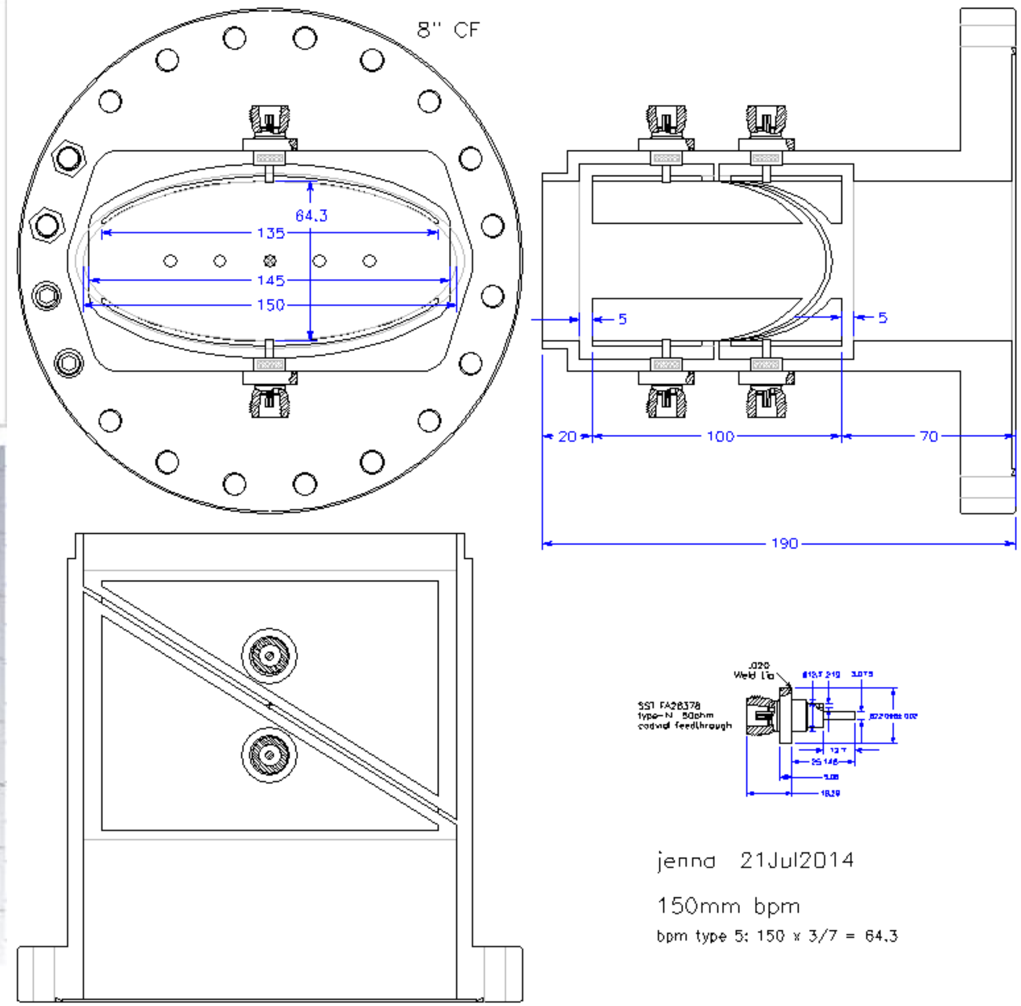
Large horizontal dispersion relative to beamlet size and varying beamlet charge complicate BPM analysis



Large aperture, elliptical BPM in high dispersion section of FS1







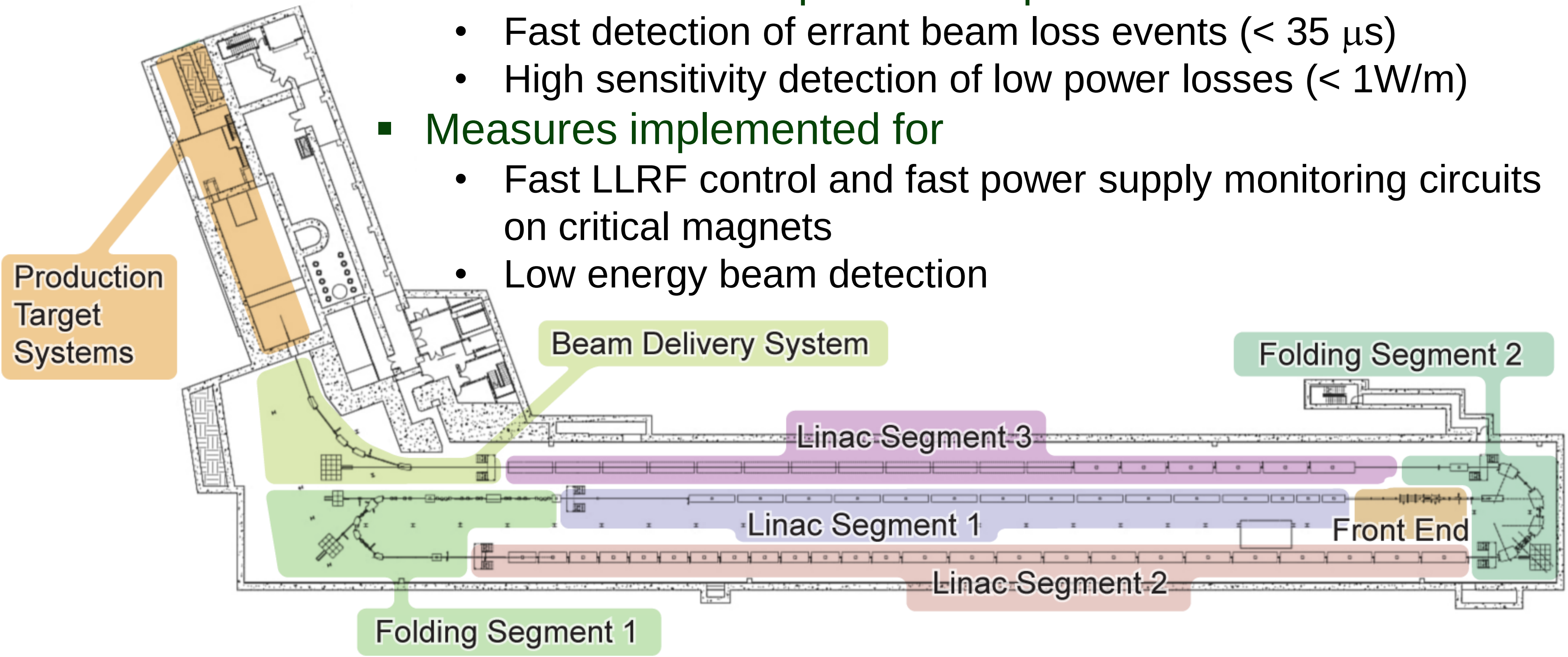
Large Dynamic Range of Intensity Demands Flexibility in Diagnostic Systems

- Beam modes vary in ion species, CW vs. pulsed operation, dynamic pulse duration and duty cycle
- Continuously acquired diagnostics (BCMs, BPMs, BLMs)
  - Designed to have simplified analog front end (gain, band-pass filtering)
  - Flexibility in digital processing - various operating modes encoded in firmware
- Average beam intensity ranges over 10^5 (10^8 upgrade) dynamic range
  - <u>Primary beam diagnostics requirements</u>
    - » Specifies beam detection from ~1 mA peak current to ~1 μA,
    - » Bandwidth sufficient to provide sensitivity over duty cycle (CW to 50 μs duration at 1 Hz)
  - <u>Ultra-low average power modes</u>
    - » Tune beam transport at low power, then decrease further.
    - » Necessary diagnostics may be reconfigured on a mode-by-mode basis to function with resonant or higher gain and ultra-low bandwidth detection schemes
    - » "The detector is the diagnostic"- Utilize nuclear detection schemes to assist tuning to optimize beam transmission and delivery

$$\boxed{\frac{signal}{noise} \propto \sqrt{\frac{impedance}{bandwidth}}}$$

FRIB Challenges Conventional MPS Approaches

- Different beam energy linac segments ‘stacked’ in close proximity
- Large X-ray background and radiation cross-talk
- Low energy heavy ion beams deposit energy on vacuum surfaces
  - Reliable machine operation requires
    - Fast detection of errant beam loss events (< 35 μs)
    - High sensitivity detection of low power losses (< 1W/m)
  - Measures implemented for
    - Fast LLRF control and fast power supply monitoring circuits on critical magnets
    - Low energy beam detection



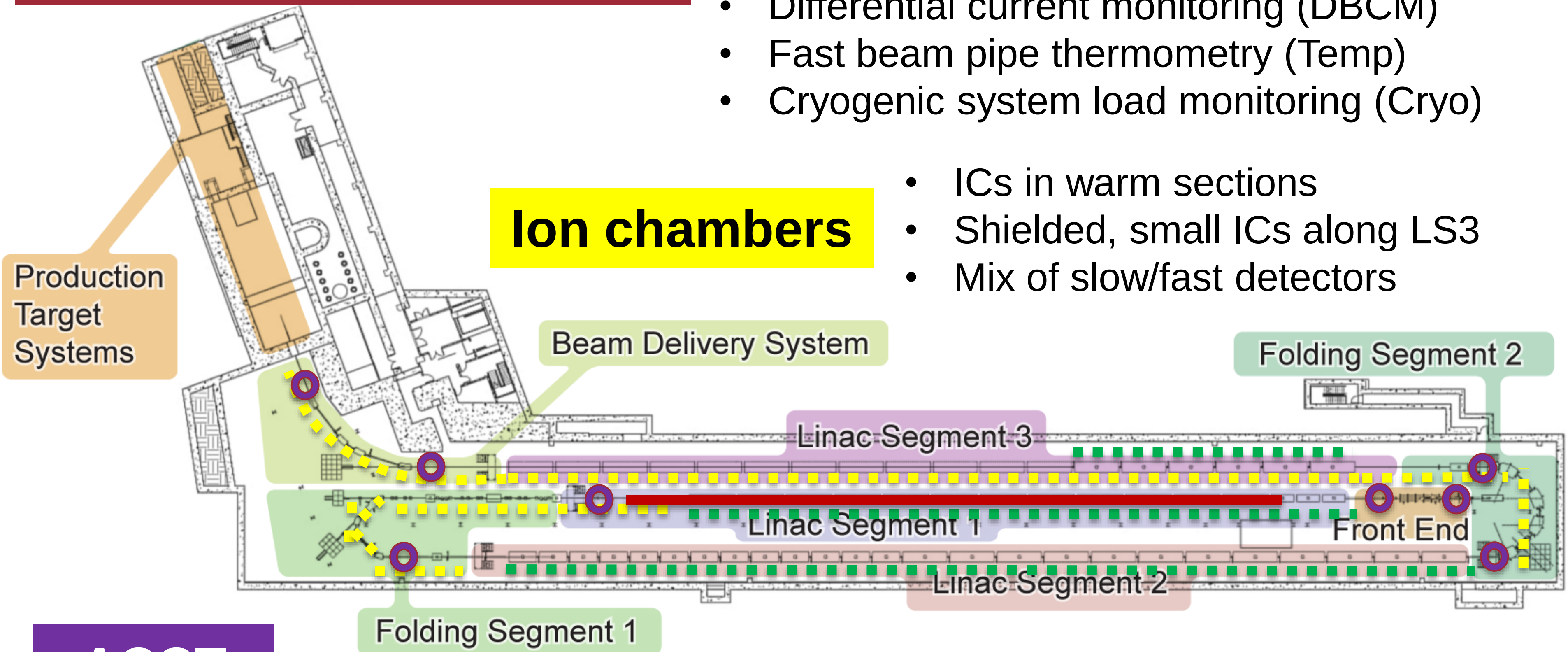
Beam Loss Detection is Based on Multi-Layer, Multi-Time Scale Network

In-vacuum/Cryo monitors

- Halo monitoring rings (HMR)
- Differential current monitoring (DBCM)
- Fast beam pipe thermometry (Temp)
- Cryogenic system load monitoring (Cryo)

Ion chambers

- ICs in warm sections
- Shielded, small ICs along LS3
- Mix of slow/fast detectors



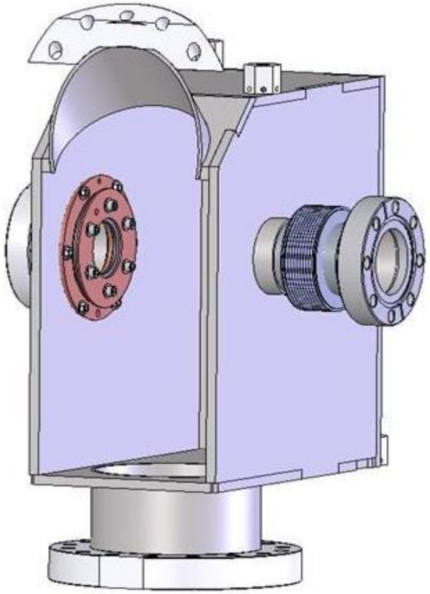
ACCT Network

Scintillator/MCPs

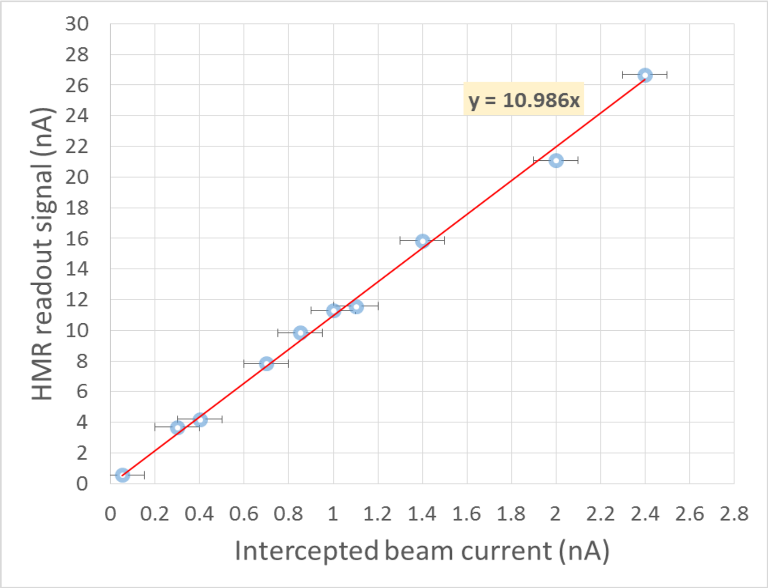
- Neutron detection
- LS2/3, LS1 (tuning primarily)
- Mix of slow/fast detectors

Halo Monitor Ring (HMR)

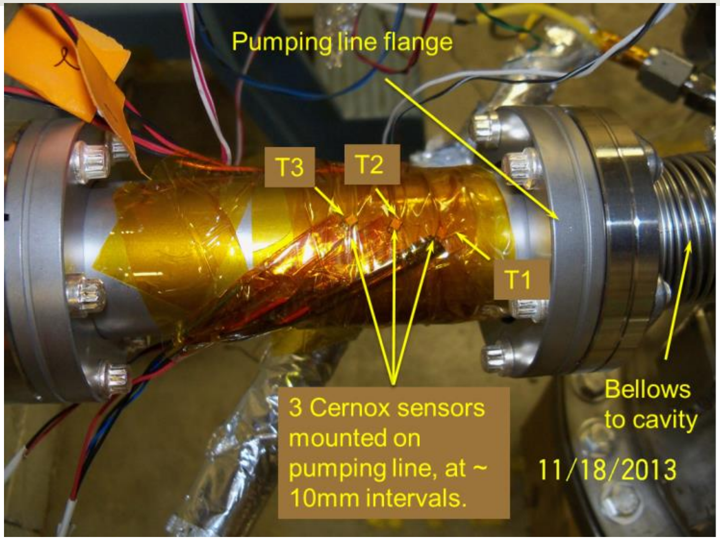
- The halo ring monitor is a niobium ring designed to intercept ions in the halo of the beam that are likely to be lost farther downstream
- It has high sensitivity (~0.1nA) for integrated small signal and fast response time (~10 µs) for large signal
- Optimize aperture based on fault mode studies. Monitor signal for large beam excursions. Install in warm sections between cryomodules

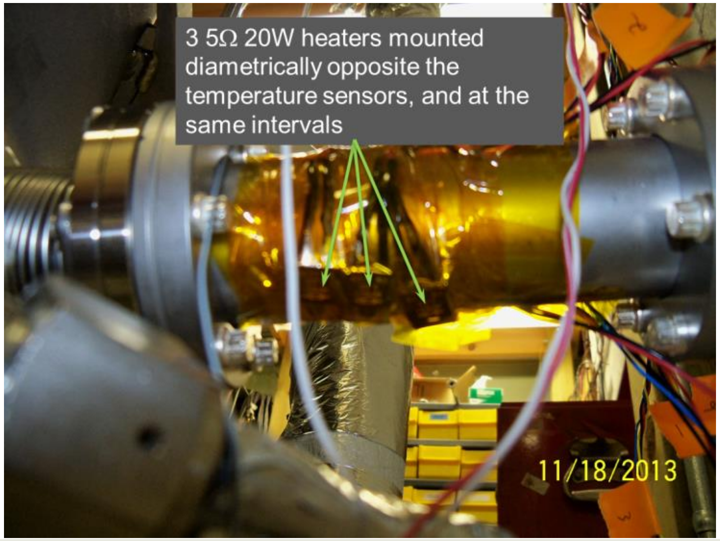


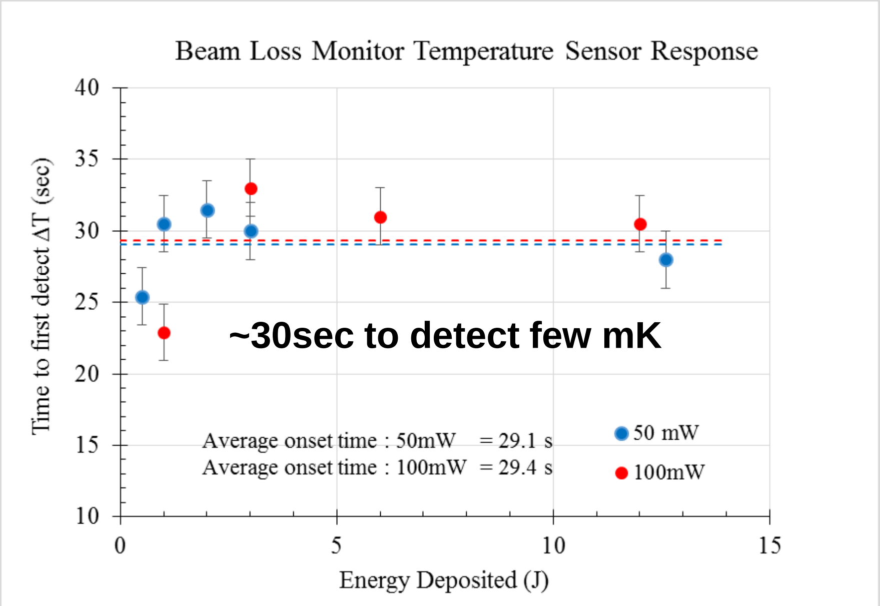
HMR measurement at NSCL with $^{18}O^{3+}$ at 11 MeV/u



Fast Thermometry at Aperture Limits in SCL







Faster detection requires

- ~mK resolution/stability
- More sophisticated DAQ (eg. Fermilab FTS – 1-10kHz timing, mK resolution)

WEPMN105 Proceedings of PAC07, Albuquerque, New Mexico, USA

FAST THERMOMETRY FOR SUPERCONDUCTING RF CAVITY TESTING*

Darryl Orris#, Leo Bellantoni, Ruben H. Carcagno, Helen Edwards, Elvin Robert Harms, Timergali N. Khabiboulline, Sergey Kotelnikov, Andrzej Makulski, Roger Nehring, Yuriy Pischalnikov
Fermilab, Batavia, Illinois, USA

Proposed Beam Loss Detection Methods

		LS1	FS1	LS2 low energy	LS2 high energy	FS2	LS3	BDS
Fast Loss	Primary	DBCM	DBCM	DBCM	DBCM	DBCM	DBCM	DBCM
< 35 μs	Secondary	HMR	HMR	HMR	BLM	BLM	BLM	BLM
	Tertiary				HMR	HMR	HMR	
Slow loss	Primary	HMR/Temp	HMR	HMR/Temp	BLM	BLM	BLM	BLM
> 100 ms	Secondary	HMR/Temp		HMR/Temp	HMR/Temp	HMR	HMR/Temp	
	Tertiary	Cryo		Cryo	HMR/Temp		HMR/Temp	
					Cryo		Cryo	

Candidates for additional MPS detection schemes

- Beam orbit MPS with BPMs - To detect faults with small fractional fast beam loss
- DBCM with BPMs or capacitive rings – Increase network density and reduce response time

Summary

- FRIB is a new design for an intense, heavy ion facility
  - All ion species
  - Multiple charge states
  - Low energy superconducting linacs
  - Folded geometry
- Presents new challenges to beam instrumentation
  - Very high dynamic range in average intensity
  - Low-β position detection
  - Fast detection and spatial resolution of beam losses
- The FRIB instrumentation diagnostic suite
  - Designed to provide sensitivity over a large dynamic range to meet the required operational flexibility
  - Provides a network of complementary devices to detect errant beam and slow losses
  - Meets requirements for commissioning and reliable operation

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Nathan Bultman
Thomas Russo

Primary Beam-on-Target Parameters
(Requirements from Experiment Systems Division)

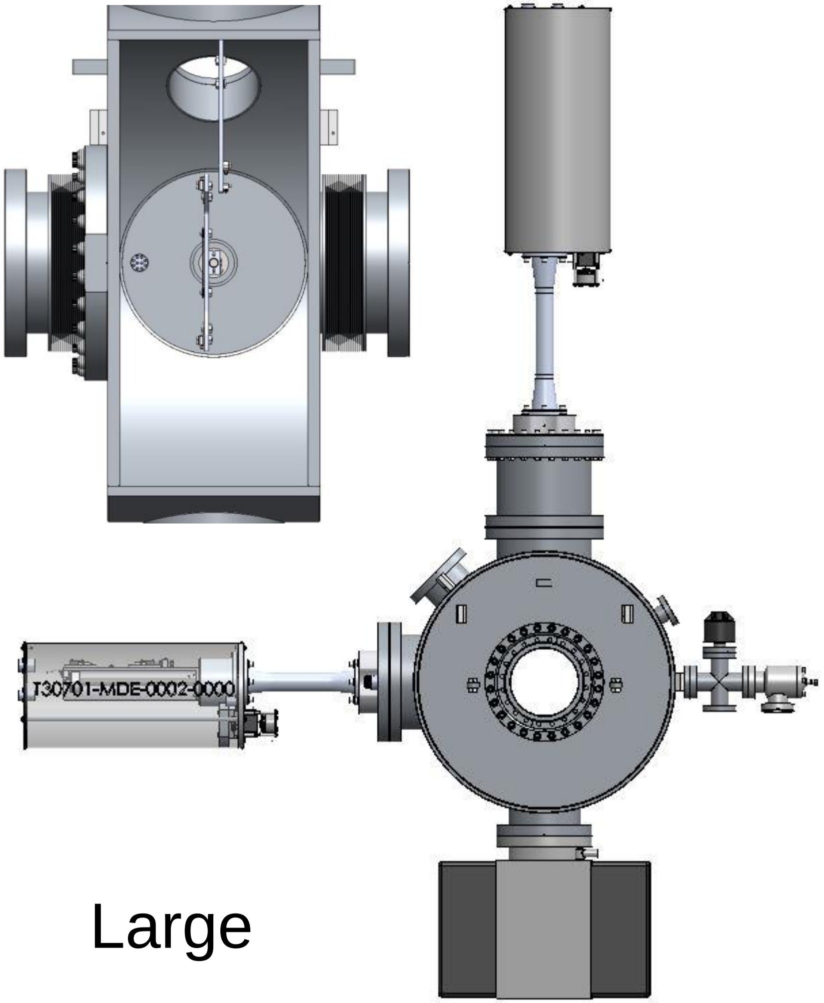
- All stable ions, energy ≥ 200 MeV/u, beam power ≤ 400 kW
- Additional parameters established to meet experimental systems requirements

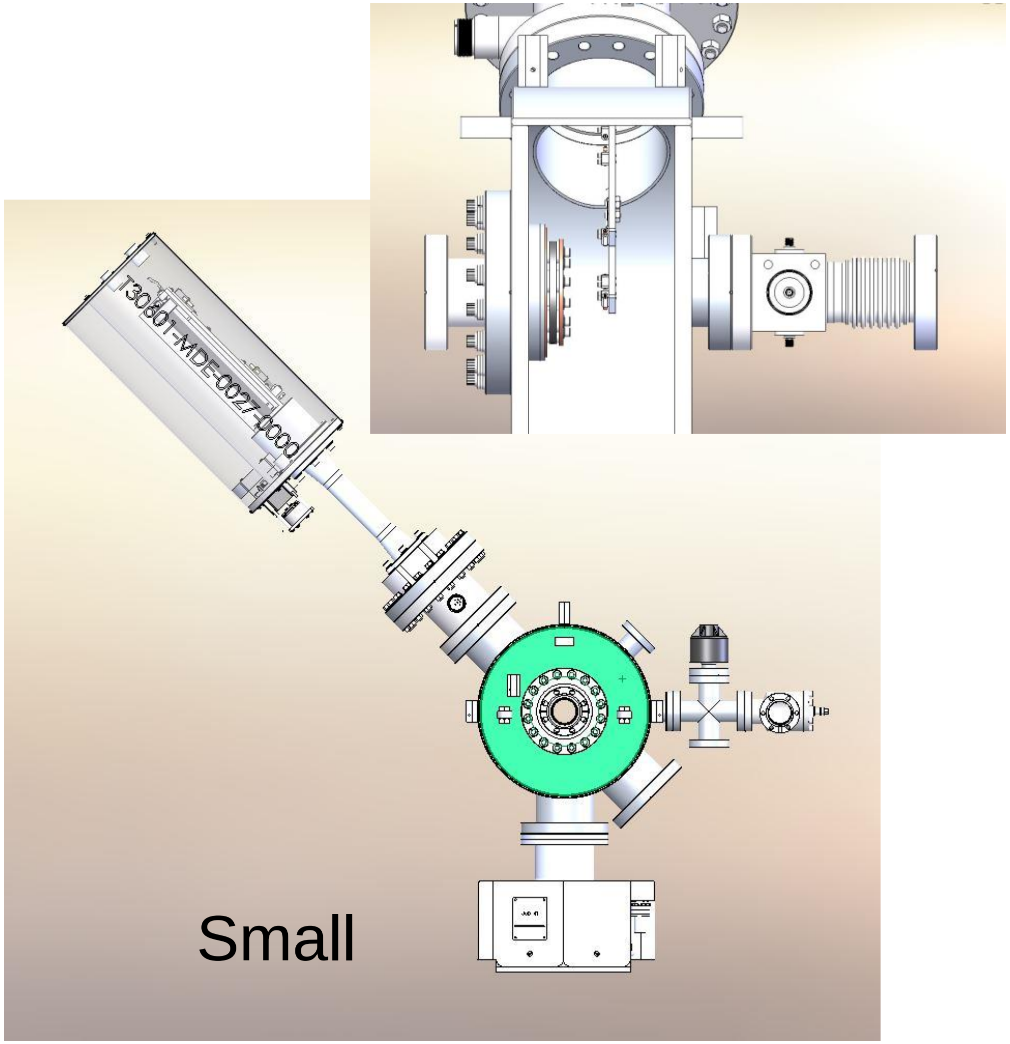
	Parameter	Description	Baseline	Basis/Comments
1	Beam spot size (diameter)	Contains 90 % of beam, incl. fluctuations	1 mm	Necessary for beam purity - scientific reach
2	Beam trajectory on target reproducibility	Position and angle w.r.t. fragment separator magnet axis	≤ ± 0.1 mm, ≤ ± 3 mrad	Position necessary for beam purity - scientific reach Angle necessary to prevent primary beam hitting dipole Upgrade option: ≤ ± 0.1 mm, ≤ ± 2 mrad
3	Beam angular spread	Horizontal and vertical, contains ≥ 90% of beam, incl. fluctuations	≤ ± 5 mrad	Prevent primary beam hitting dipole – facility efficiency- operational cost
4	Beam power control dynamic	Without time structure change (not chopping)	10^{-5} – 1	Characterization of rare isotope beams for experiments; physics experiments requirements Upgrade option: 10^{-8} – 1
5	Beam energy reproducibility		≤ ± 0.5 %	Facility efficiency - operational cost
6	Beam energy spread	Contains 95 % of beam, incl. fluctuations	≤ ± 0.5 %	Selection of rare isotope between magnetically separated primary beam charge states so as to not truncate scientific reach Upgrade option: ≤ ± 0.2 %
7	Bunch length	Contains 95 % of beam	3 ns	Particle identification (TOF measurement) Upgrade option: 95 % in ≤ 1.5 ns and 99.9 % in ≤ 3 ns → necessary for RF separation of rare isotopes (spacing a few ns) – important for very proton-rich isotopes – scientific reach
8	Bunch repetition rate		80.5 MHz or 40.25 MHz	Particle identification (TOF measurement) Upgrade option: 80.5, 40.25, or 20.125 MHz → necessary for RF separation of rare isotopes (spacing a few ns) – important for very proton-rich isotopes – scientific reach

Beam Modes Supported

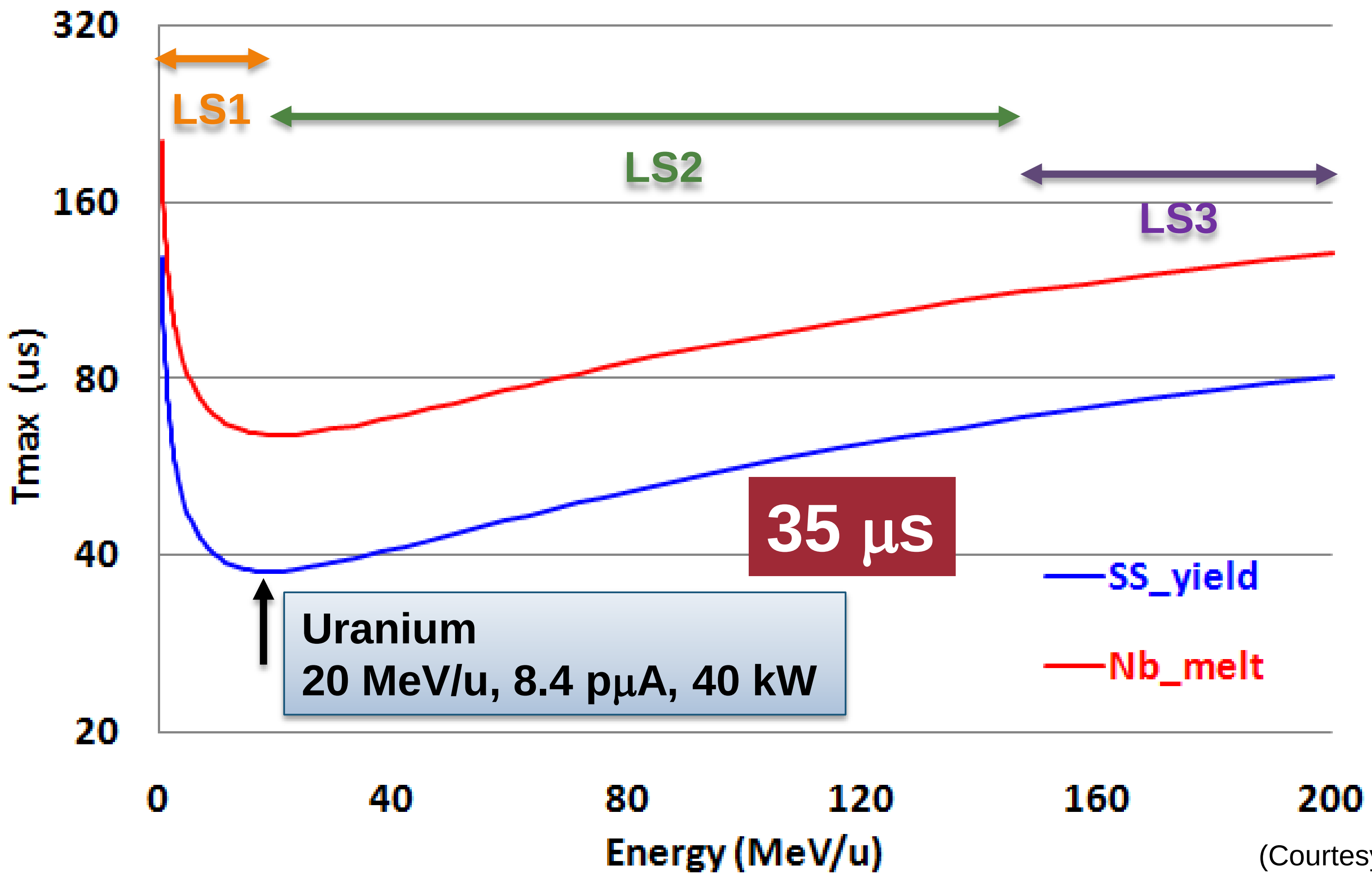
- **Short pulse** (<5 – 50 ms), low duty cycle (< ~1 Hz), varying intensity (50 to 650 mA)
- **Moderate pulse length** (~0.01 s to s), low duty cycle (< ~1 Hz to 5% duty factor), nominal intensity (3 – 10 pmA)
- **Approximately CW** (50 ms gap @ 100 Hz), low to nominal intensity (<10 to 400 kW)
- **Dynamic ramp to high power** (variable intensity, pulse duration, and repetition rate) to slowly increase the target temperature (~10 minutes)
- **Other modes**
  - Front End commissioning (2-650 eμA)
  - Fragment Separator and Secondary beamline commissioning (0.0001-30 pnA)

Diagnostic boxes come in two sizes





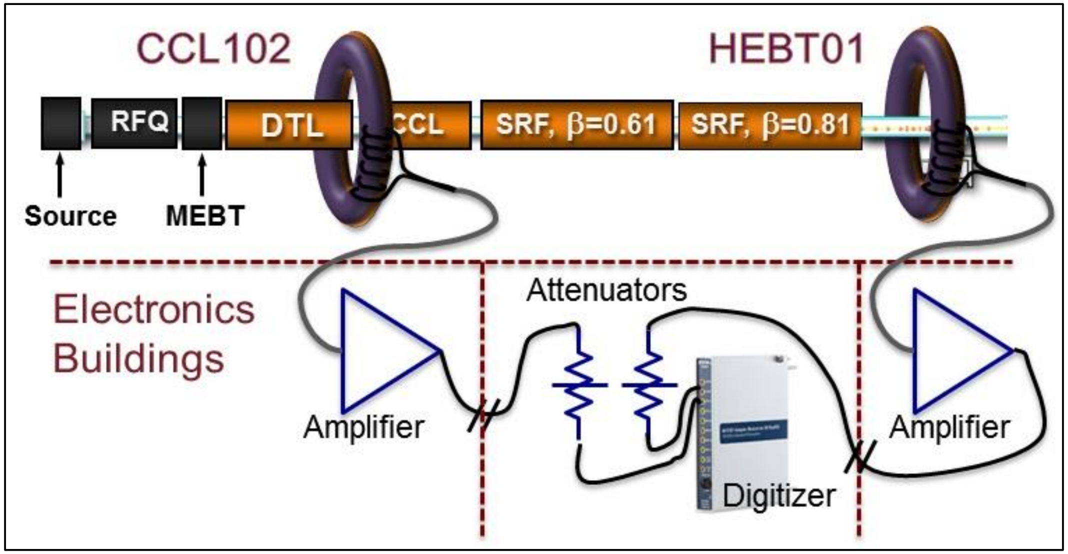
Maximum FPS Response Time Determined by Minimum Damage Threshold



(Courtesy, Y. Zhang)

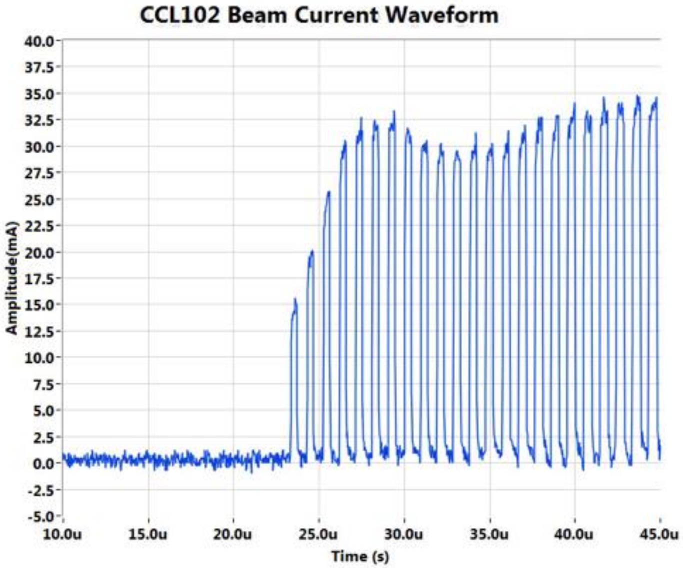
The worst case (uranium beam ~20MeV/u): may damage a SS bellow in less than 40 μs

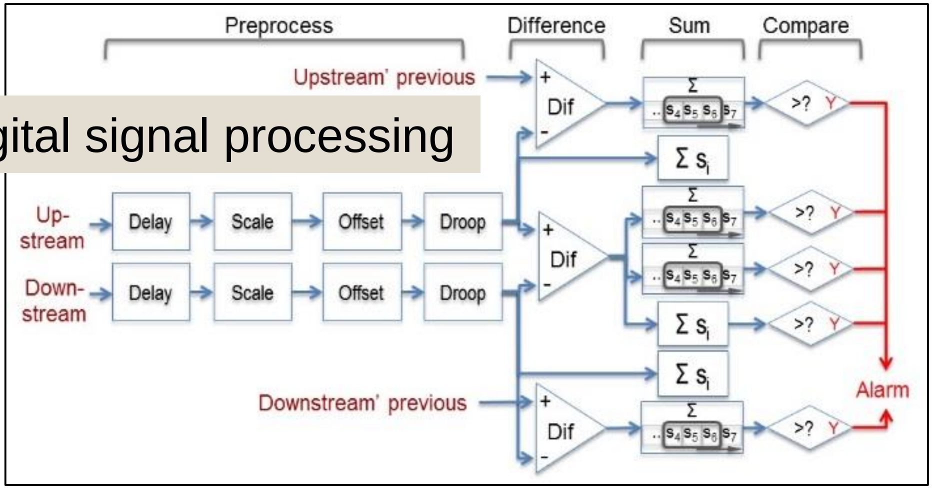
SNS Differential Beam Current Monitoring



Demonstration of fast MPS network to detect errant beams

- Wideband CTs:
  - 1 GHz with 1 ms droop time constant
  - Nearest one before and after SCL
  - Long cable lengths (500-1200ft)





Digital signal processing

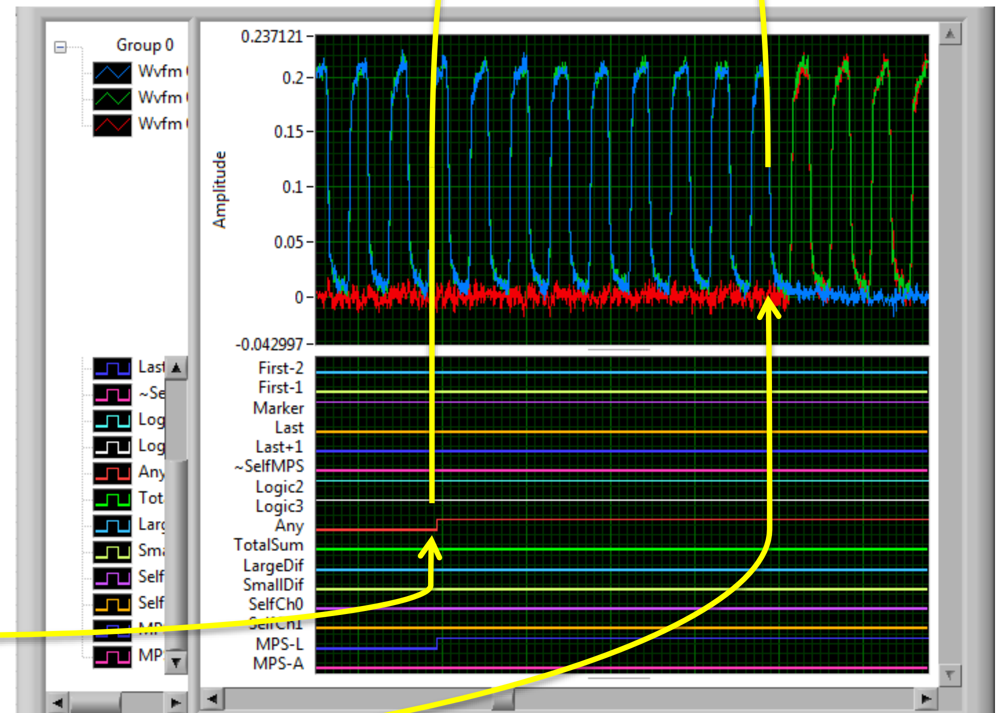
Abort test demonstrates improved response time

- Temporary change to the Machine Protect System
- DBCM will automatically abort in middle of the beam pulse
- Using slow and long cables

→ ~8.5µs abort time

→ 2-3x improvement

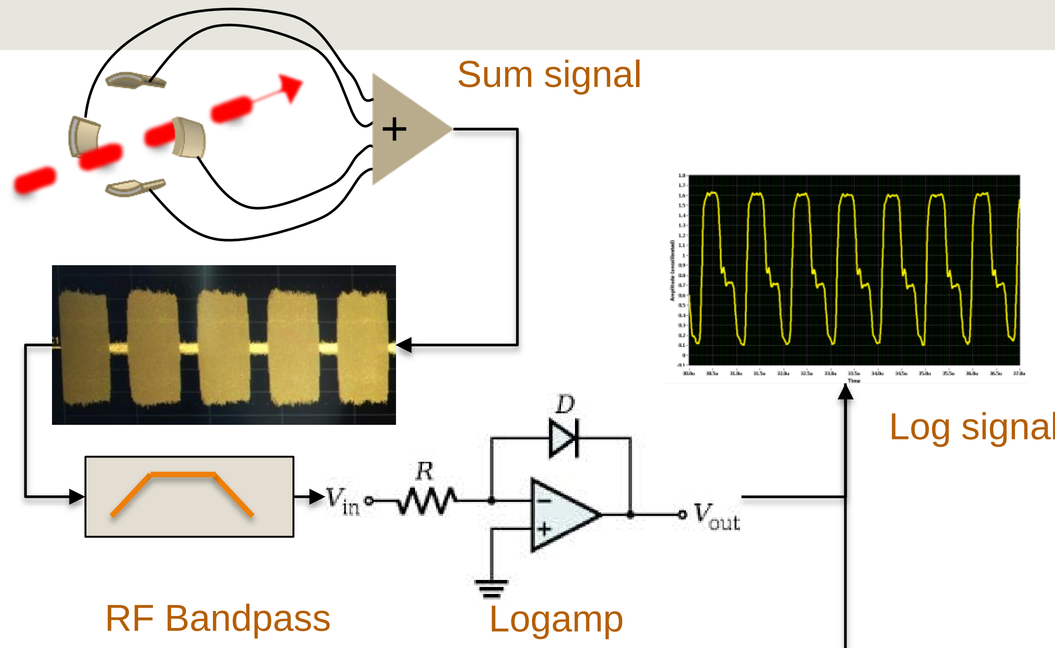
→~6µs best possible once optimized for cable length, pickup locations, and abort mechanism

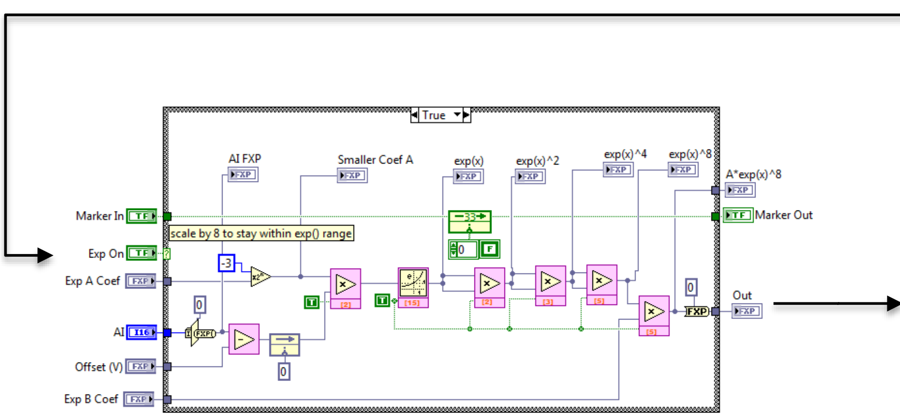


Current and previous beam pulse

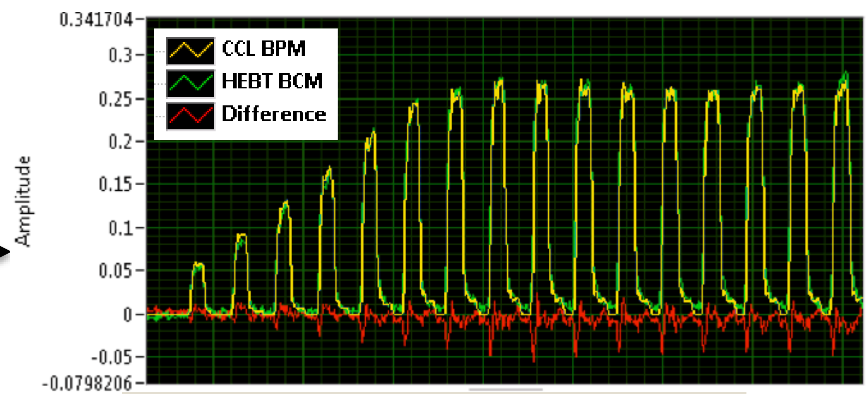
Current measurements using BPMs (SNS)

- Beam Position Monitor:
  - ✓Use sum from all four plates
  - ✓Use demo log-amp board with band-pass filter in front
  - ✓Add correction in FPGA with exponential function
  - ✓Use existing BCM as reference for calibration





FPGA code to correct log signal



Final signals. Calibration done using downstream BCM

Phased MPS System Deployment

Start up Phase	Beam power on target (kW)	Risk	MPS Systems	Mitigation
Commissioning (to CD4)	0.1 - 0.3	• Unintentional CW (~20 kW) delivery • 100% beam loss	• Fast Trip Monitors[1] • Beam Power Limiter[2] • DBCM • (Establish HMR, BLM)	Terminate beam before next pulse (or within 50 ms)
1	10	• Component damage from errant beam (~1% beam loss allowed) • Cavity degradation from slow losses	• As above • Fast DBCM, HMR, BLM • Slow HMR, BLM • (Establish Temp, Cryo)	Terminate beam within 0.5 ms
2	>10	• Component damage from errant beam • Cavity degradation from slow losses	• As above • Fast DBCM, HMR, BLM • Slow loss HMR, BLM, Temp, Cryo	Terminate beam within 35 µs

[1]Fast trip monitors are LLRF detectors, DCCTs, Quench detectors, Chopper bias monitor, etc.
[2]Beam power limiter to be deployed at Stage 2 and thereafter.