



Commissioning of Beam Instrumentation at FRIB

Steve Lidia, Facility for Rare Isotope Beams



MICHIGAN STATE
UNIVERSITY

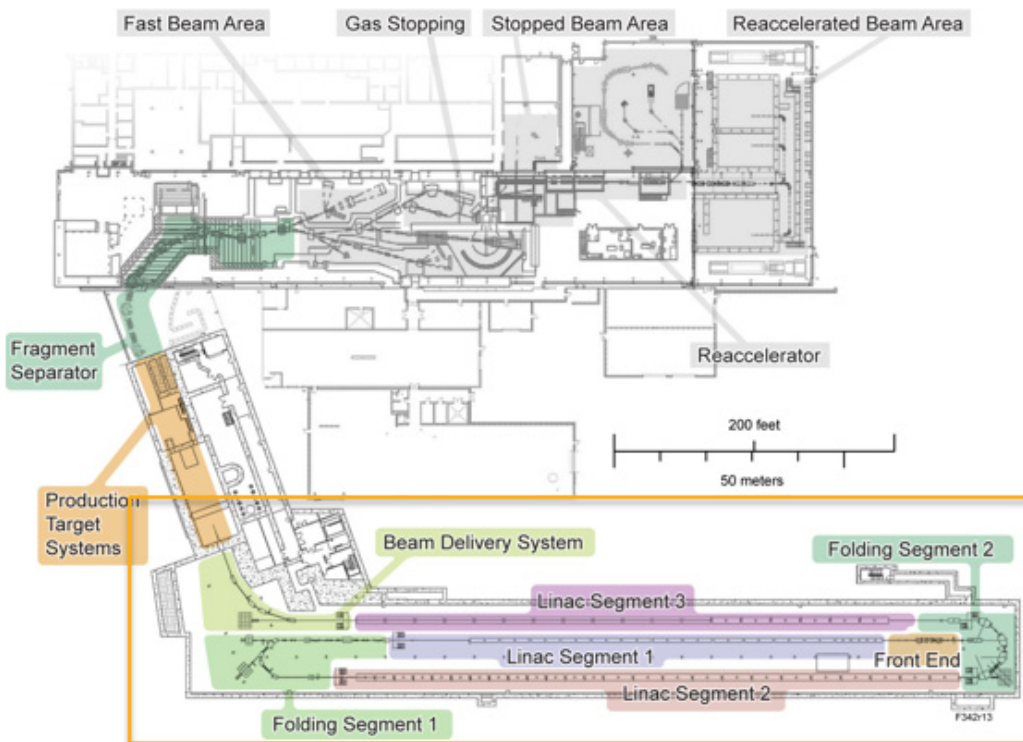


U.S. DEPARTMENT OF
ENERGY

Office of
Science

FRIB Scope and Facility Deliverables

- Deliver FRIB accelerator as part of a DOE-SC national user facility with high reliability & availability
- Accelerate ion species up to ^{238}U with energies of no less than 200 MeV/u
- Provide primary beam power up to 400 kW
- Satisfy beam-on-target requirements

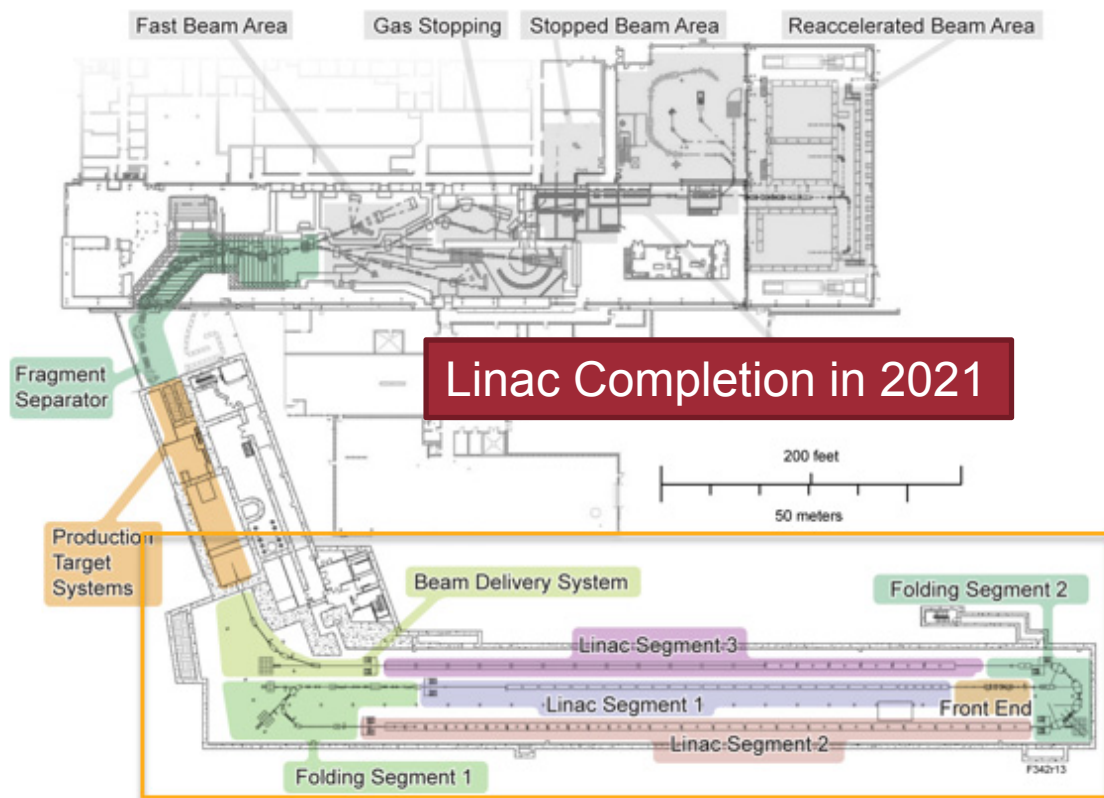


- Option for energy upgrade to >400 MeV/u
- Maintain Isotope Separation On-Line (ISOL) option
- Upgradable to multi-user simultaneous operation of light / heavy ions with addition of a light-ion injector

Challenges to Diagnostics and Instrumentation

- Handling intense, low energy ion beams
 - Multiple charge state beam dynamics
 - Ensuring low beam losses
 - Robust Machine Protection and diagnostics
 - Safe operation of liquid lithium charge stripper
 - 400 kW heavy ion beam target and pre-separator systems
- Frequent retuning for various ion species
 - Each run extends 1-2 weeks

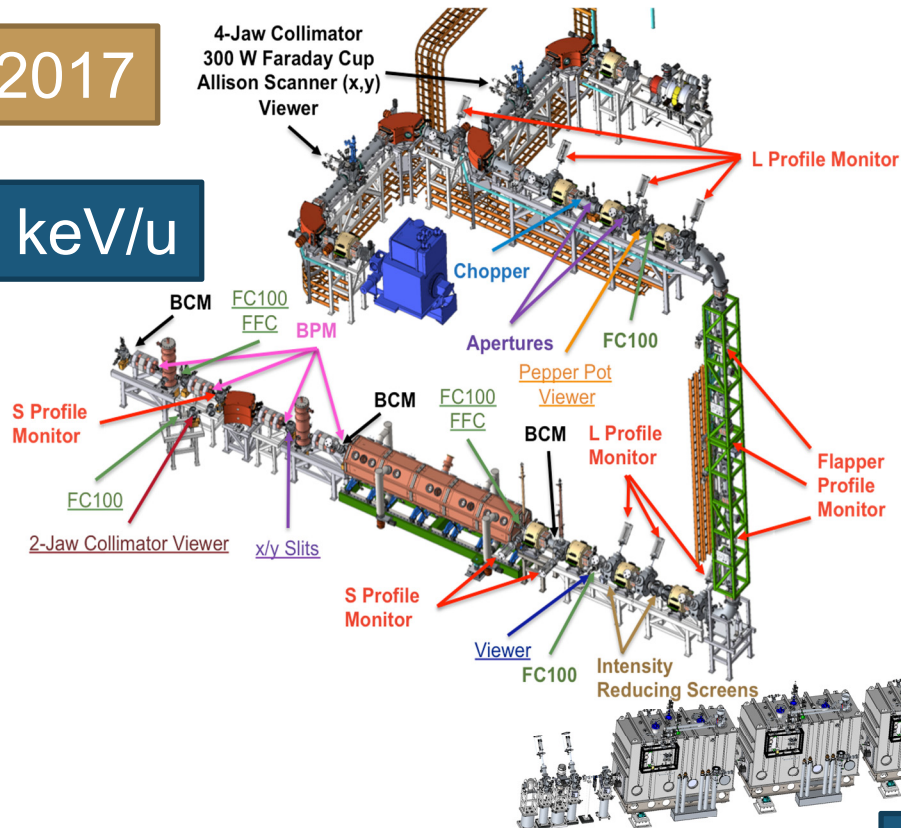
Primary Beam	No. benchmark beams	No. rare isotope beams
^{238}U	23	1446
^{48}Ca	4	104
^{78}Kr	7	98
^{124}Xe	4	64
^{18}O	1	21
$^{86}\text{Kr}^*$	2	27
^{16}O	1	38
$^{36}\text{Ar}^*$	1	28
^{82}Se	2	155
^{92}Mo	8	98
^{58}Ni	4	130
^{22}Ne	2	10
^{64}Ni	1	49



Commissioning Phases Completed

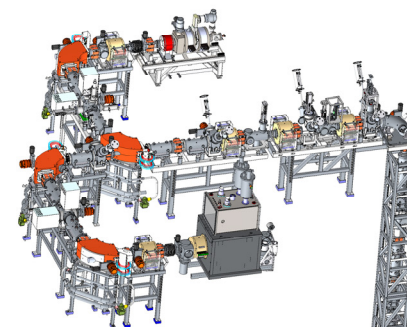
2017

500 keV/u



2018

2 MeV/u



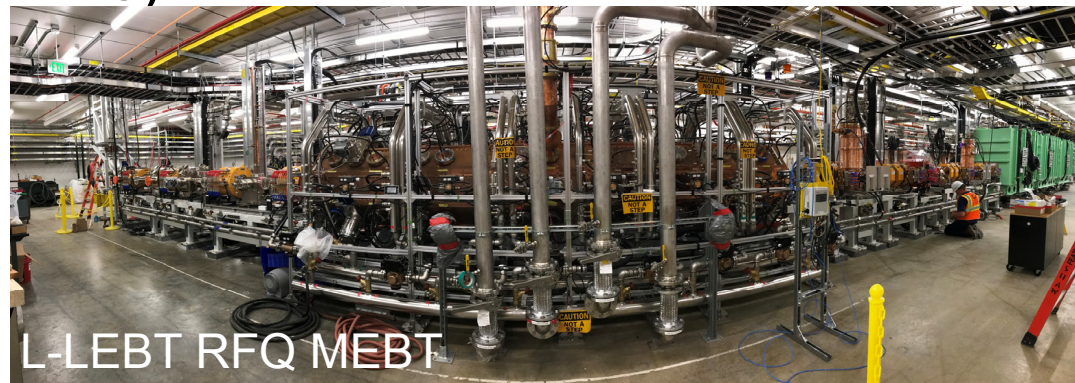
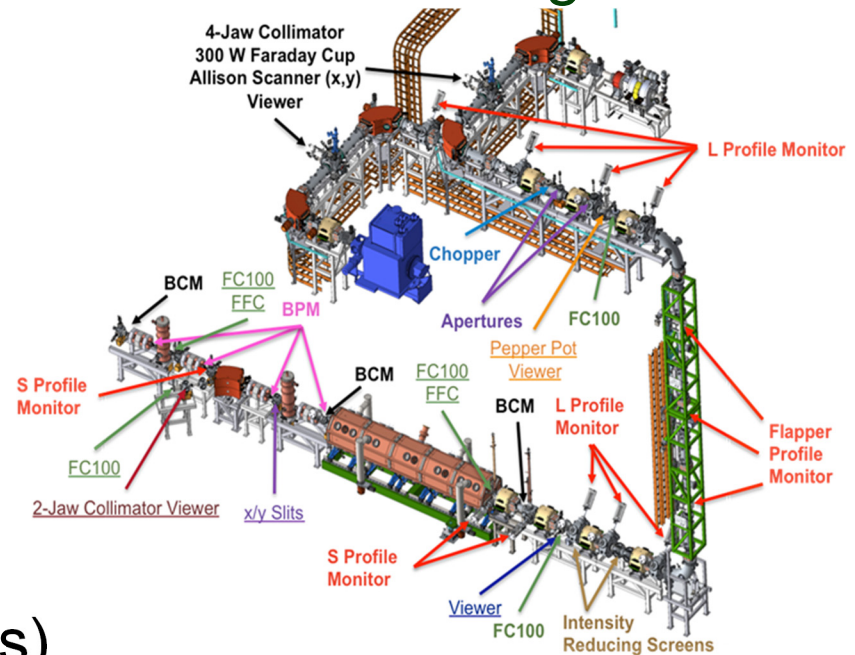
2019

20 MeV/u

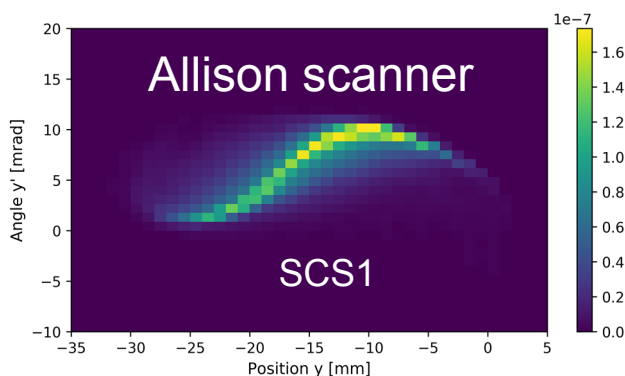


Front End Instrumentation

- Array of diagnostics devices were available for beam tuning and finding set points of optical devices and accelerating cavities
 - 4-Jaw Charge selection slits
 - Allison emittance scanner
 - Pepper Pot
 - Image viewers
 - Wire Profile Monitors
 - Faraday cups
 - Electrostatic Chopper
 - Intensity Attenuators
 - Beam Position Monitors (BPMs)
 - Beam current monitors (BCM) (transformers)
 - Fast Faraday Cups

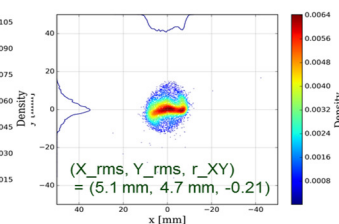
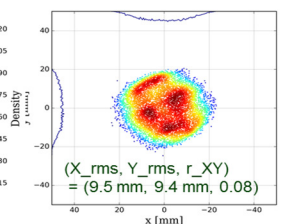
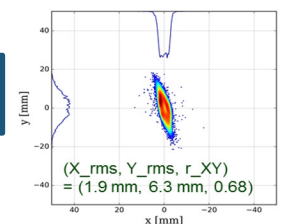
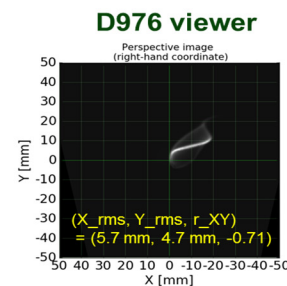
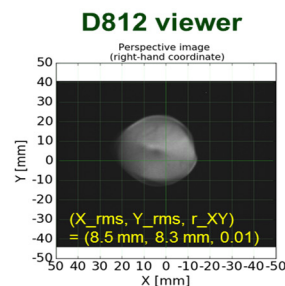
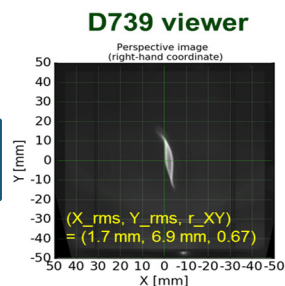


Diagnostics Support Tuning Through Front End



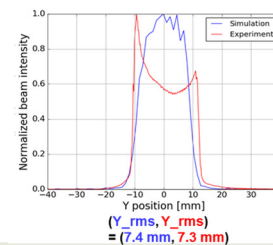
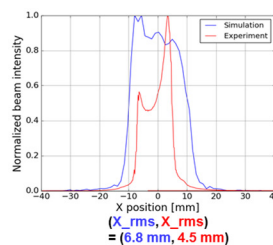
Measured

Simulated

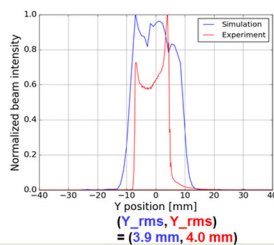
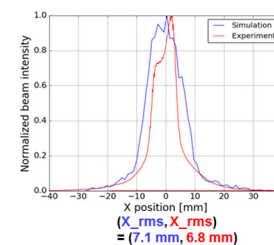


Wire Profile Monitor Measurements

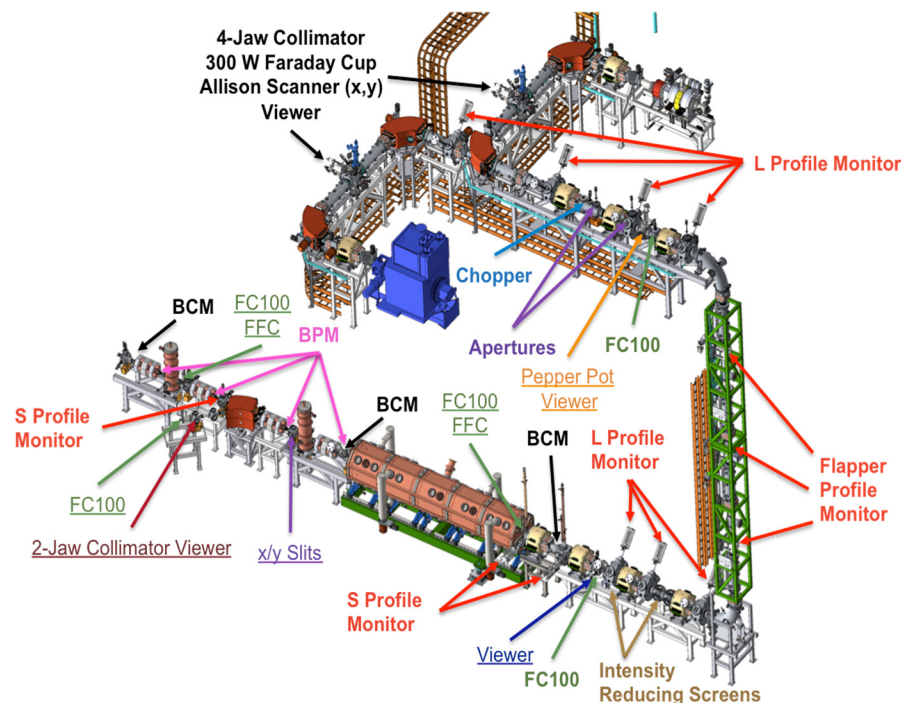
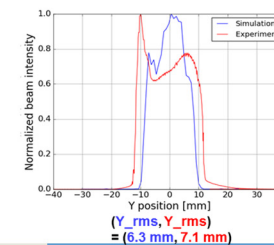
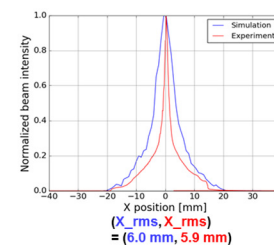
PM_D0856



PM_D0885

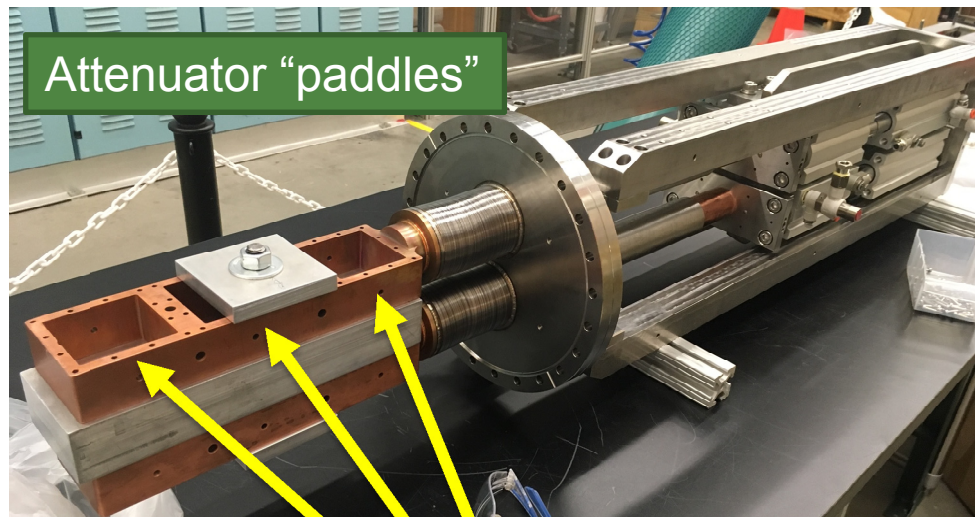


PM_D0912



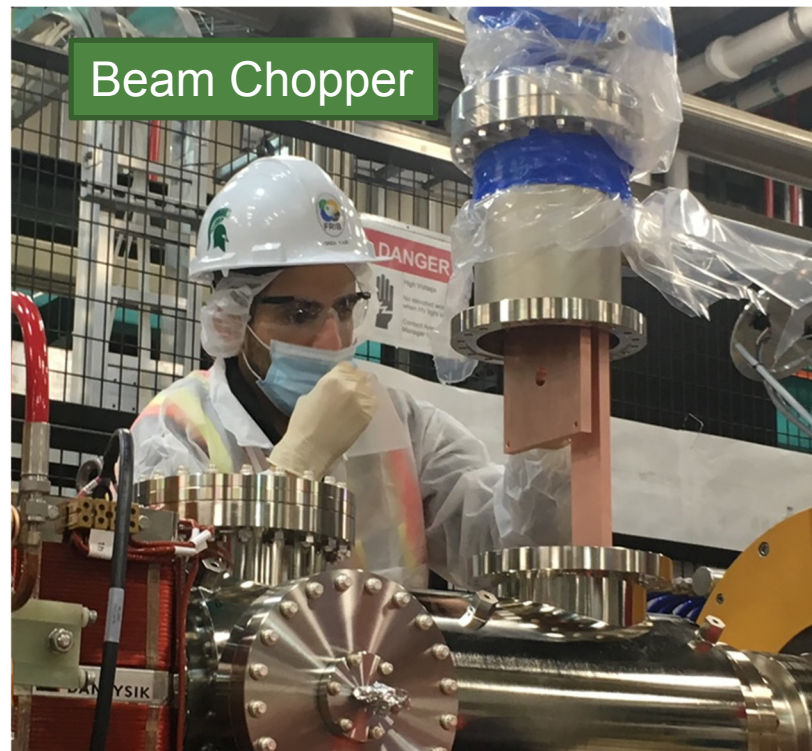
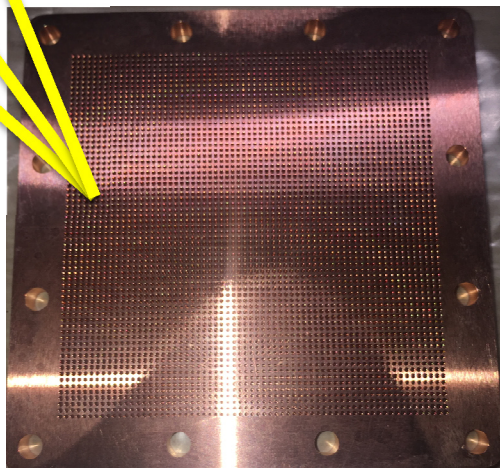
Instrumentation for Intensity Control

- Electrostatic beam chopper
- Beam attenuator system (10X – >100000X)



Hole plates

Optics designed to preserve phase space envelope

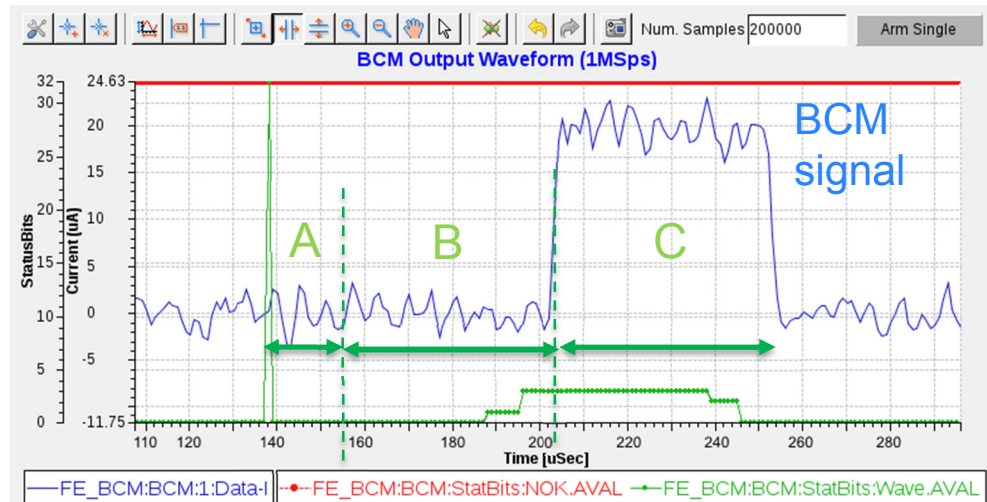
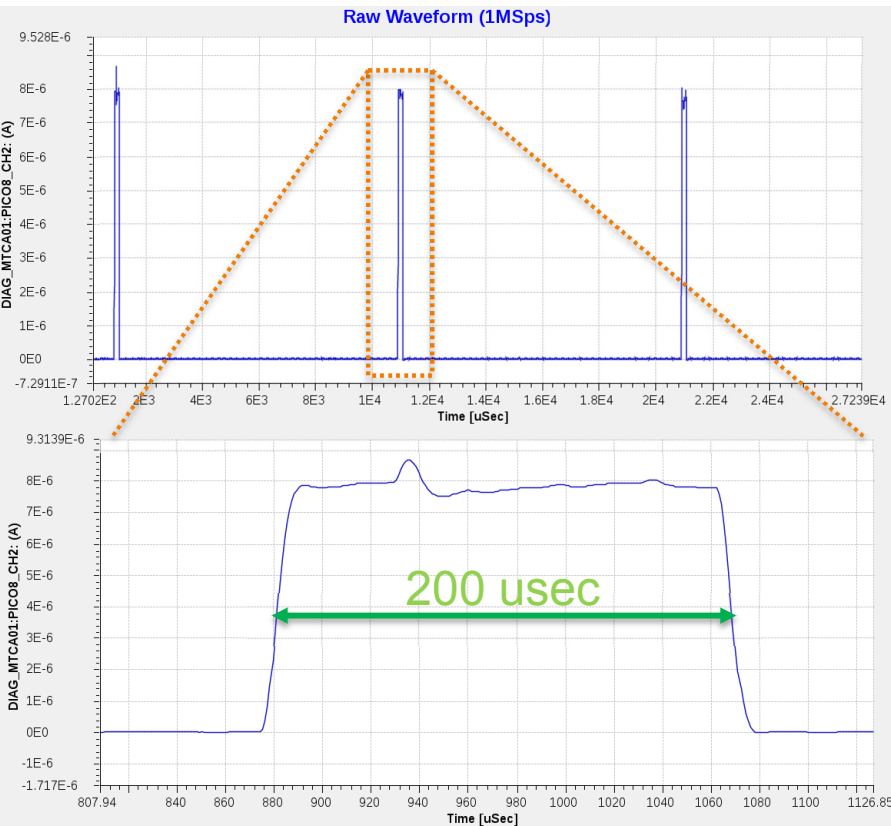


1 μ s – 10 msb pulse duration
1,5,10,20,50,100 Hz repetition rate
3500 kV +/- per plate

Chopper Operation Validated with Beam Diagnostics

- Faraday Cup with chopper
 - 2.0% duty cycle
 - 200 usec beam active
 - 8uA beam current

- Beam Current Monitor with chopper
 - 0.5% duty cycle
 - 50 usec beam active
 - 19uA beam current

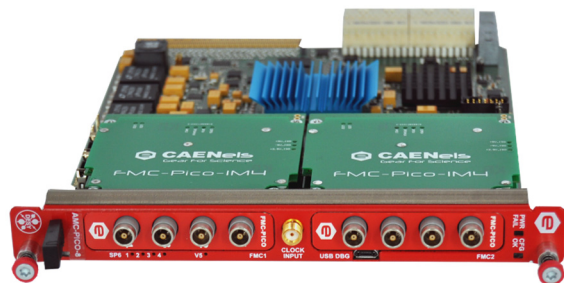


- A. ToF delay (Chopper to BCM), ~15 usec
- B. Beam “gap”, 50 usec
- C. Beam active, 50 usec

Independent Chopper Monitor system validates chopper operation and informs MPS for critical variations

All Chassis Electronics are in Operations

20 MTCA.4 chassis for the entire linac



CAENeIs AMC-PICO-8

8 chan @ 1MS (35kHz BW)

65x Halo Ring Monitors

42x Ion Chambers

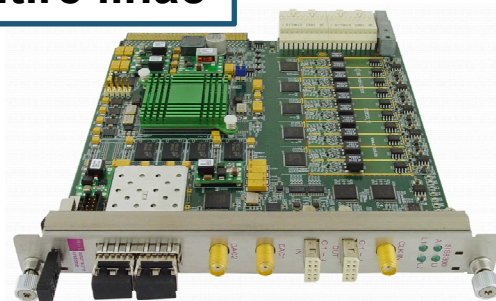
24x Neutron Detectors

8x Faraday Cups

2x Allison Scanner

41x Profile Monitors

*Not required for MPS,
but shared Data Acquisition
(DAQ) system*



Struck SIS8300-L2

10 chan @ 125MS

12x Beam Current Monitor
(Differential BCM)

Machine Protection System requirements

Detect and respond to beam loss events

15 μ sec to detect >10% beam loss

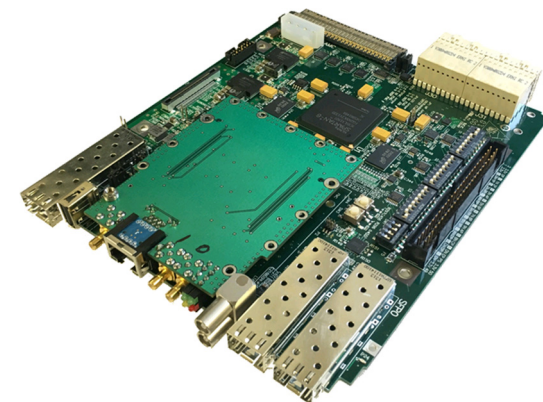
150 μ sec to detect 10% beam loss

Detect chronic small losses of 1 W/m or less

15 μ s requirement $\rightarrow$

Fast sampling data acquisition, ≥ 1 MSPS

Analog signal response, DC to 35 kHz



FRIB Digital Board

General purpose

150x Beam Position
(BPM)

20x Event Receiver

20x Machine Protect
System (MPS)

>300x LLRF

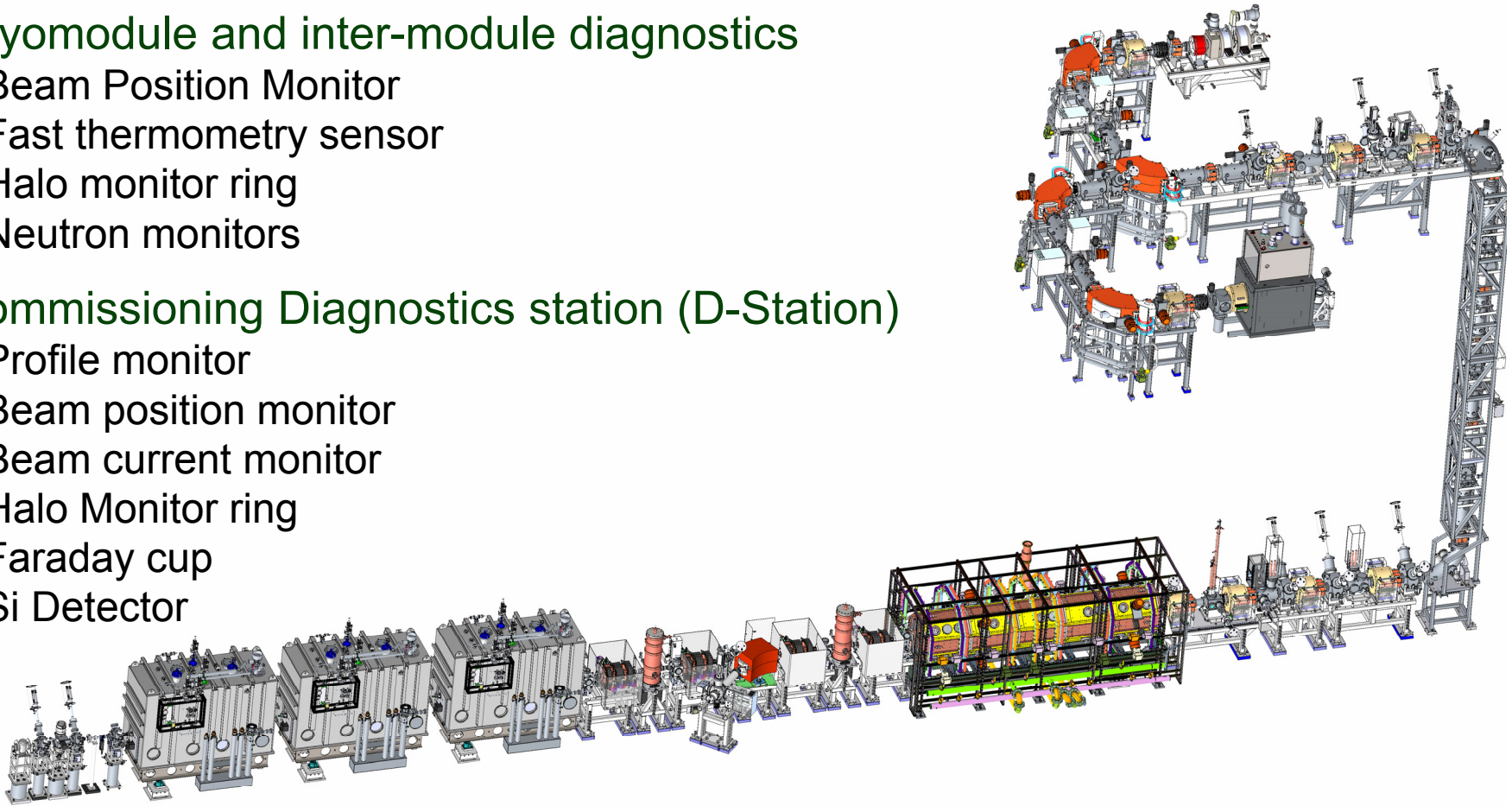
*Developed at FRIB, used by
Diagnostics, Low Level Radio
Frequency (LLRF), and
Controls*

75% of devices covered by these three MicroTCA cards

All utilize field programmable gate array (FPGA) for real-time signal processing and machine protection (MPS)

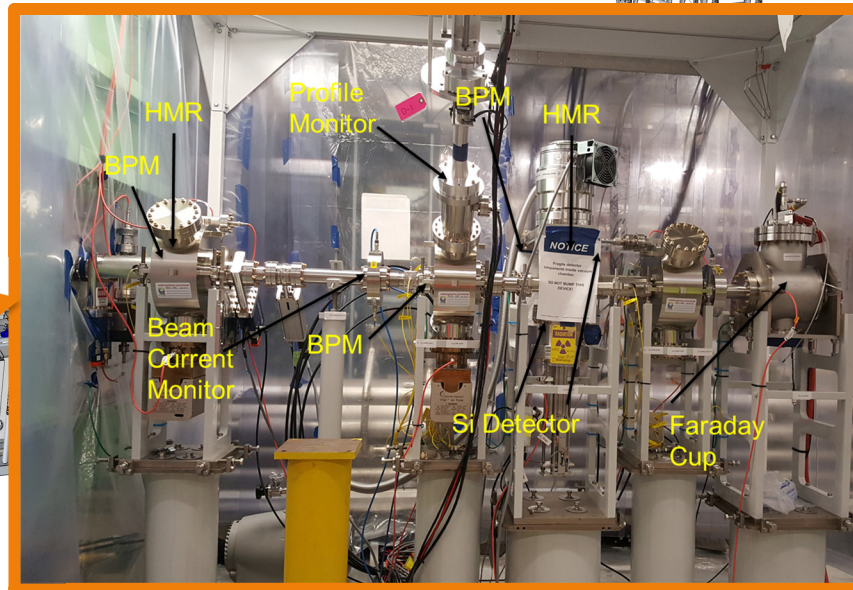
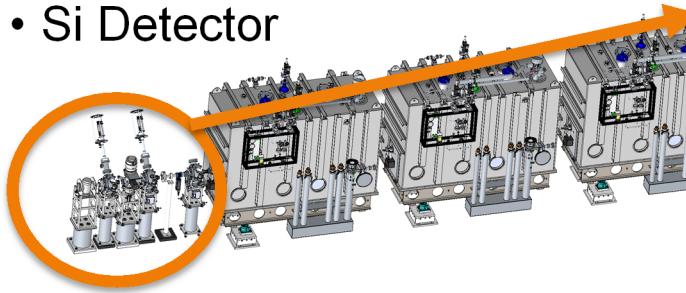
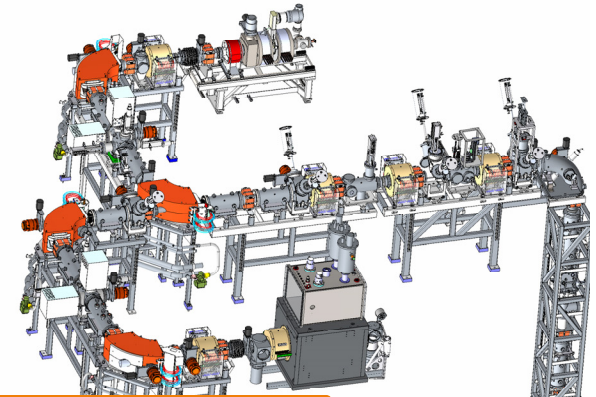
Linac Systems Early Commissioning

- Early test of beam acceleration, tuning through lattice transition, diagnostics, MPS
- Cryomodule and inter-module diagnostics
 - Beam Position Monitor
 - Fast thermometry sensor
 - Halo monitor ring
 - Neutron monitors
- Commissioning Diagnostics station (D-Station)
 - Profile monitor
 - Beam position monitor
 - Beam current monitor
 - Halo Monitor ring
 - Faraday cup
 - Si Detector



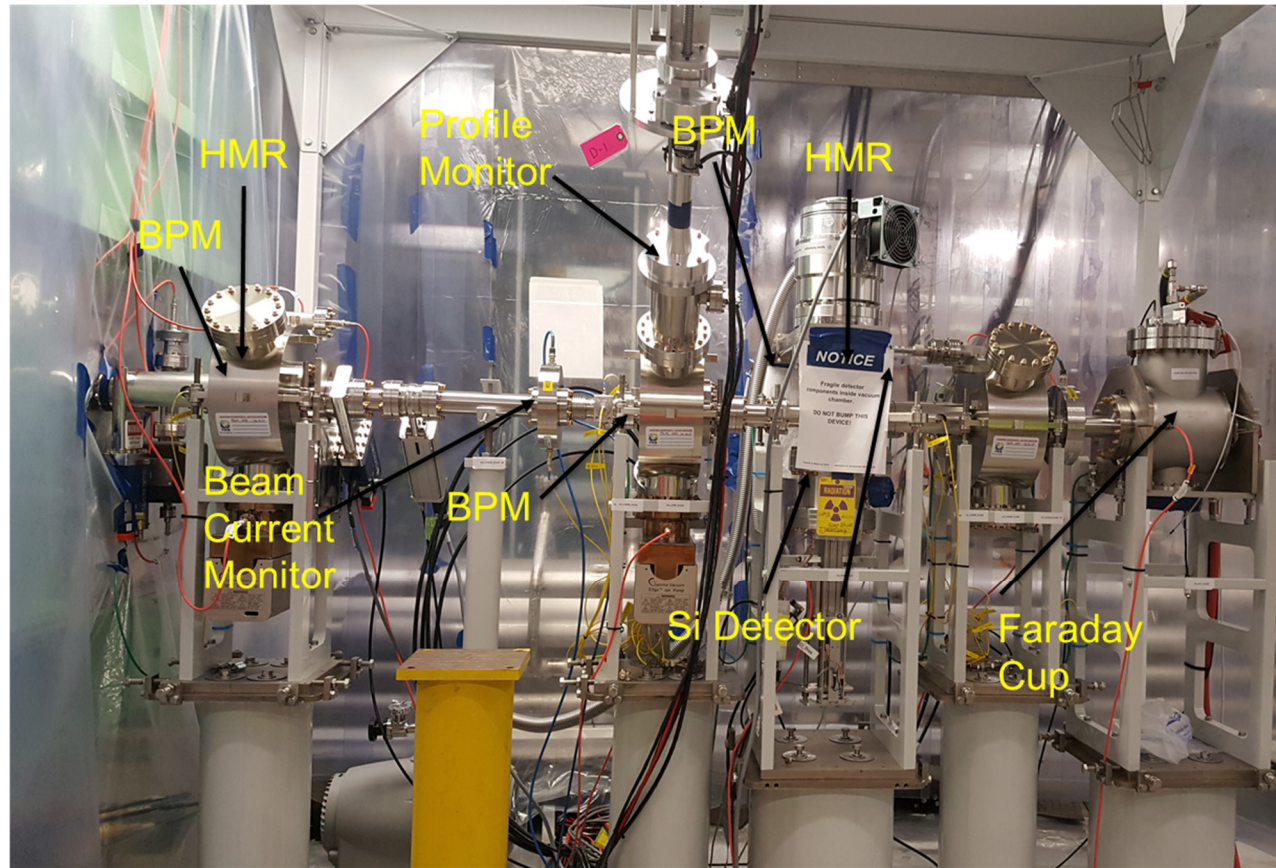
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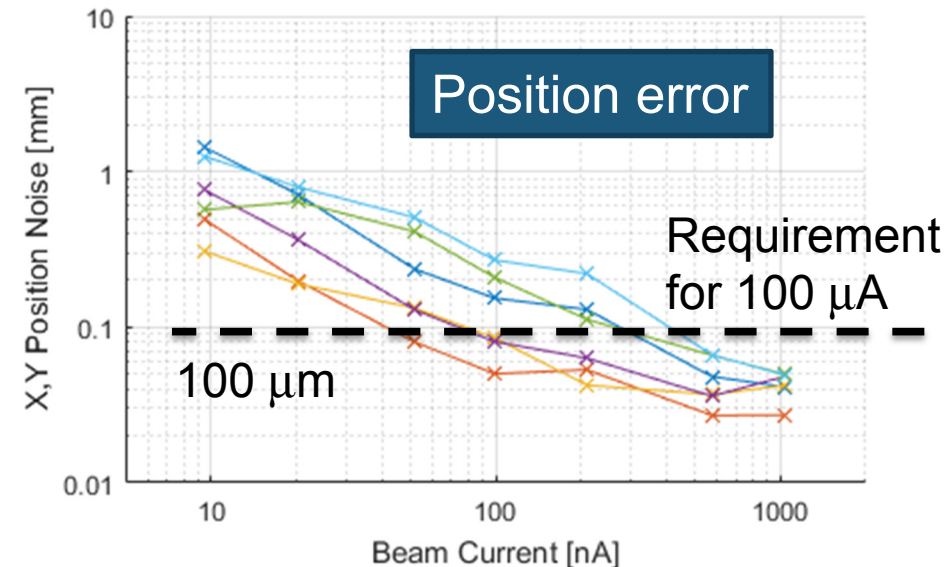
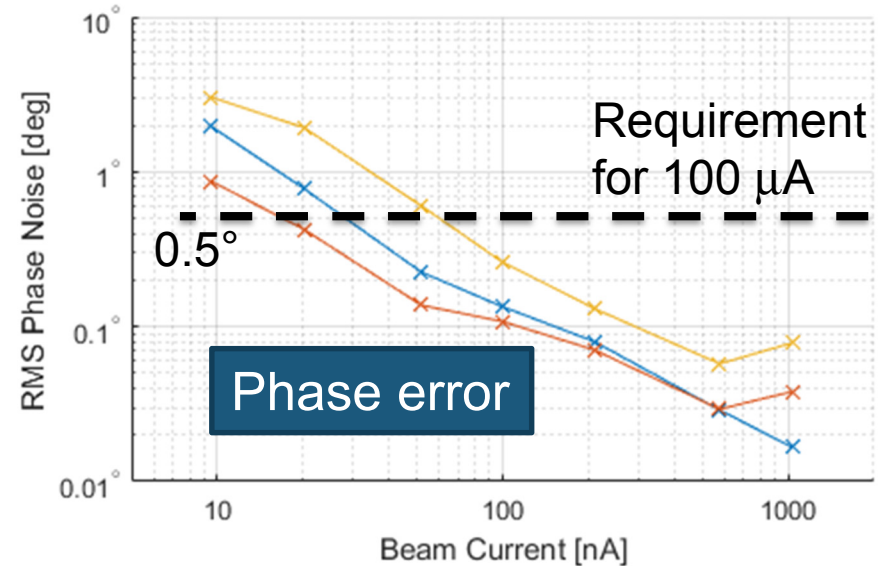
Beam Measurements with D-station

- Beam position and bunch phase
- Transverse profile, rms emittance reconstruction
- Absolute energy, energy spread, time spread, contaminant ions and relative intensity
- Beam halo monitor signal
- Absolute beam current (pulsed) and differential signal
- Longitudinal profile, longitudinal rms emittance reconstruction



BPM Position and Phase Error Meet Requirements

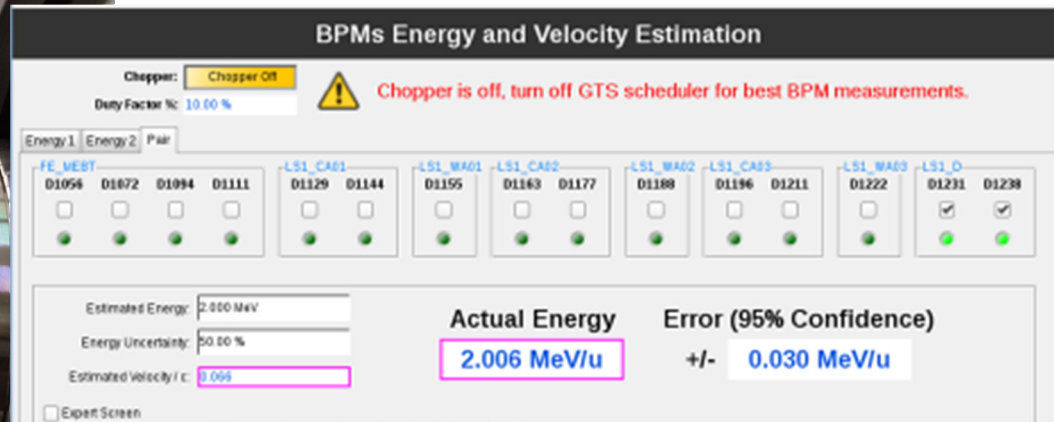
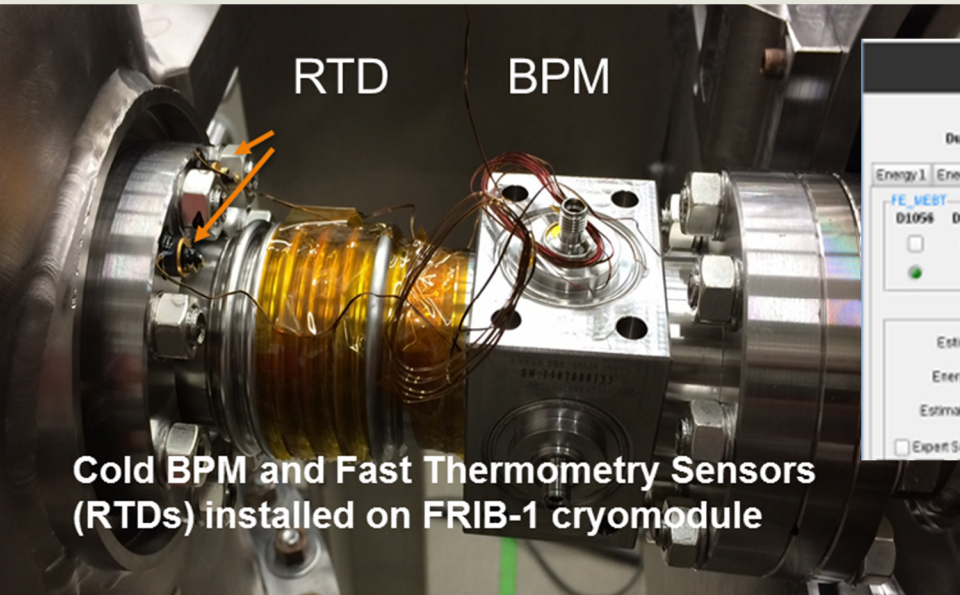
- **Sensitivity and resolution**
 - Meet requirements at <1% of nominal current (100 μ A)
- **Noise floor**
 - Narrow bandwidth analog filters (300-400 MHz)
 - Downsampling 119 MHz $\rightarrow$ 100 Hz
 - Permits measurements with beam intensities as low as 100 nA



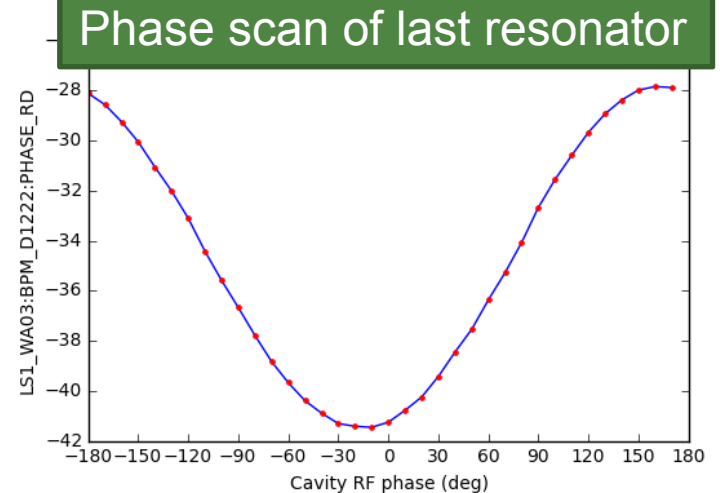
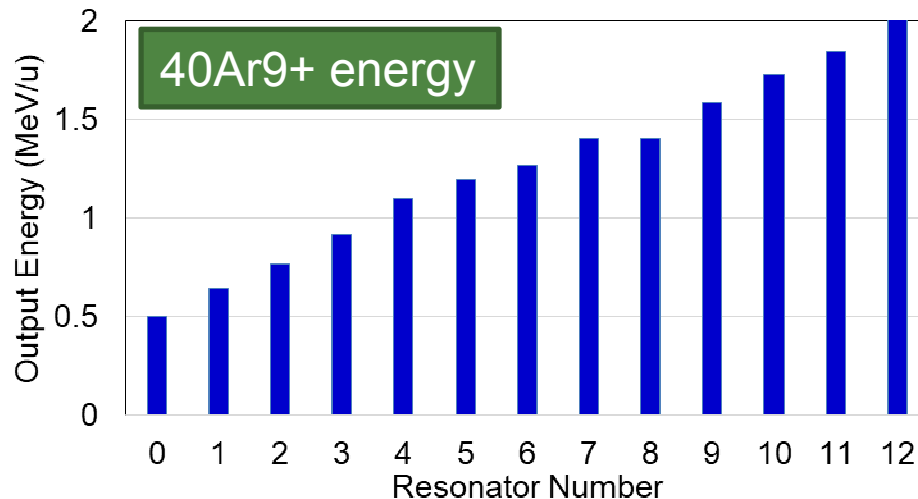
- **Phase noise: 3 MEBT BPMs, 1-sec avg**
 - Phase noise (rms) @ 1 μ A: 0.04 deg
 - Phase noise (rms) @ 100 nA: 0.13 deg
- **Position noise: 3 MEBT BPMs, X/Y, 1-sec avg**
 - Position noise (rms) @ 1 μ A: 0.040 mm
 - Position noise (rms) @ 100 nA: 0.140 mm

Narrowband measurements at 161 MHz

BPMs Used for On-Line, Time-Of-Flight Energy Monitor



On-line Energy Analysis



Diagnostic 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 μ s	Secondary	HMR ✓		HMR	BLM	BLM	BLM	BLM
	Tertiary				HMR		HMR	
Slow loss	Primary	HMR/Temp ✓		HMR/Temp	BLM	BLM	BLM	BLM
> 100 ms	Secondary	HMR/Temp		HMR/Temp	HMR/Temp		HMR/Temp	
	Tertiary				HMR/Temp		HMR/Temp	
DBCM: Differential Beam Current Monitor BLM: Beam Loss Monitor (neutron, gamma)					HMR: Halo Monitor Ring Temp: Fast Thermometry			

Candidates for additional MPS detection schemes

- Beam trajectory 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

Machine Protection System in Operations

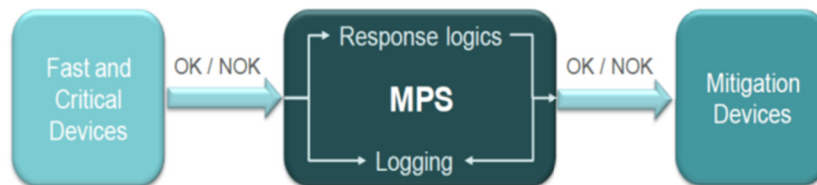
10 μ s
Sensing and indicating
error condition to FPS
(include cable delay)

10 μ s
FPS Response Time
From Input OK/NON to
output to mitigation device

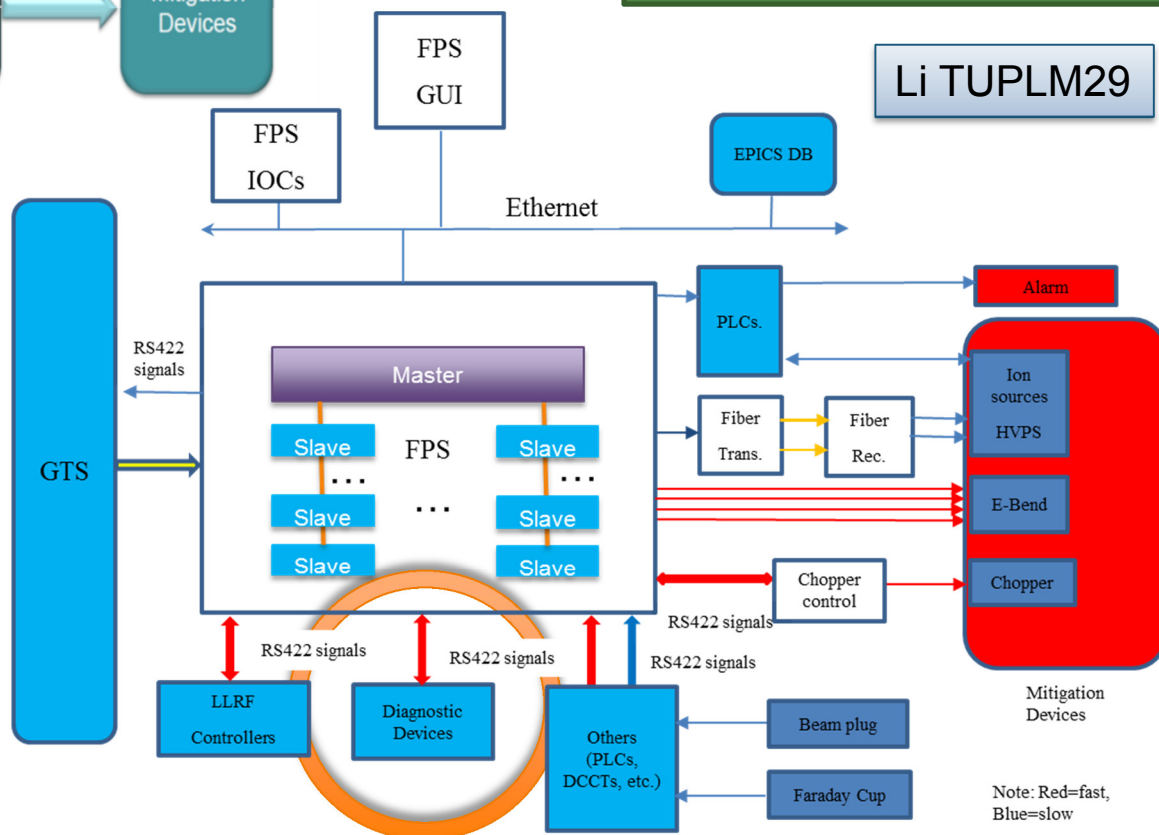
5 μ s
Mitigation
Action (include
cable delay)

10 μ s
Beam
mitigation
time

Time budget includes
sensing, signal trans-
mission, logic, and
mitigation

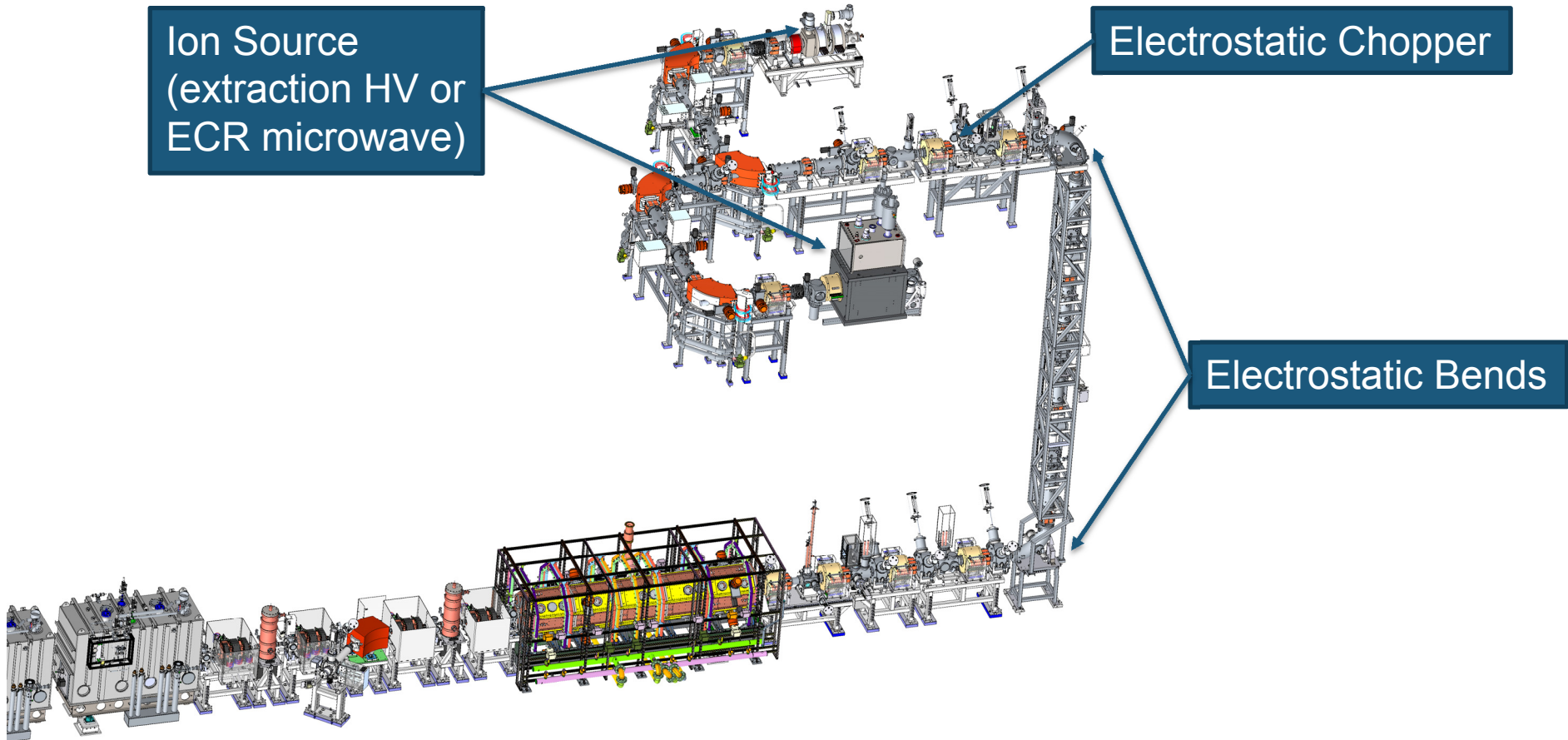


- Diagnostics interface to MPS is implemented at the board and chassis level
- Thresholds are compared at various sensitivity/time-averaged stages
- Special purpose FMC cards are used with FGPDBs to send & receive to MPS network



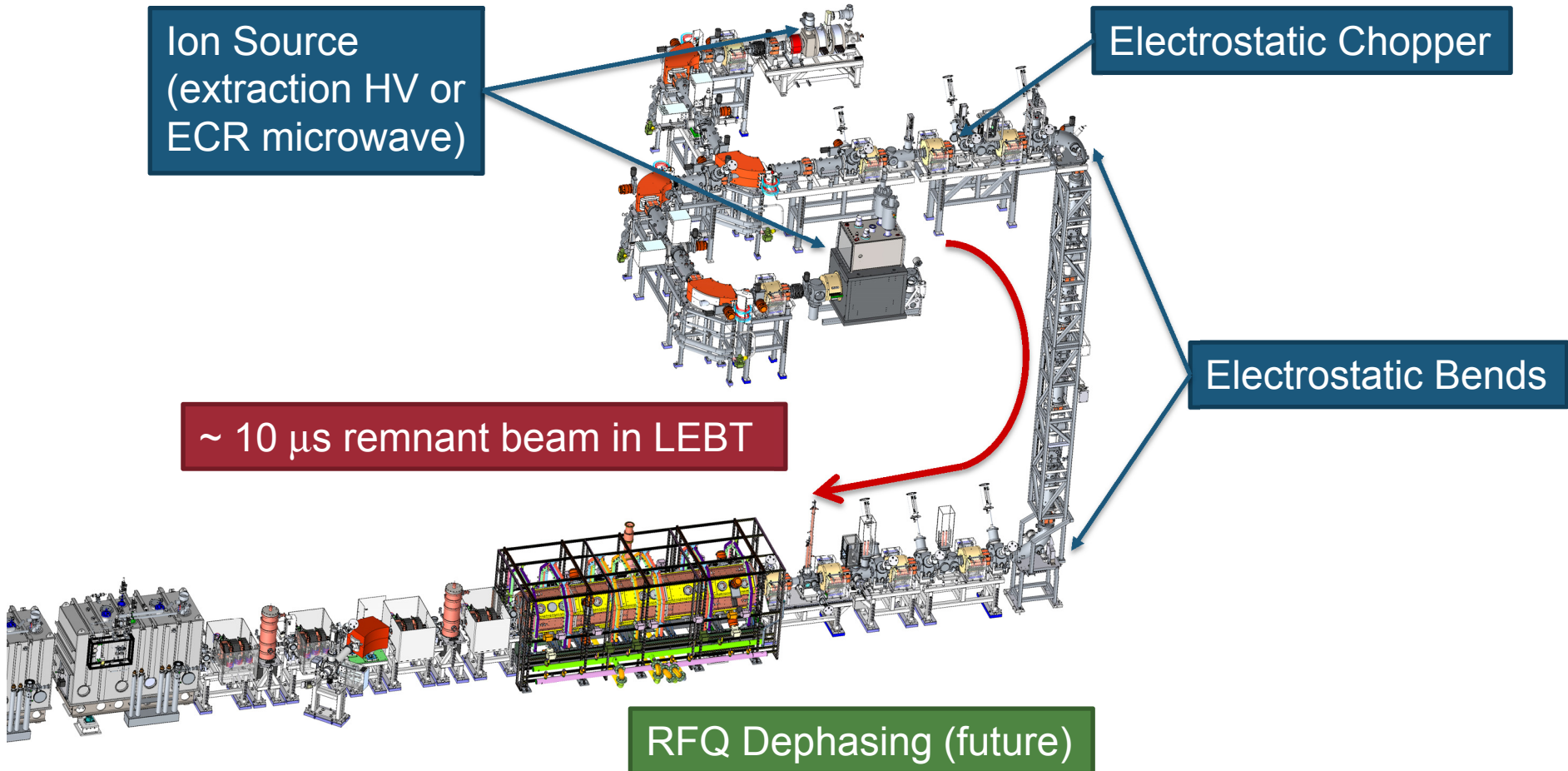
Beam Mitigation Systems

- Beam mitigation time budget incorporates
Sensing/decision + Network transmission + Mitigation action + Remnant beam



Beam Mitigation Systems

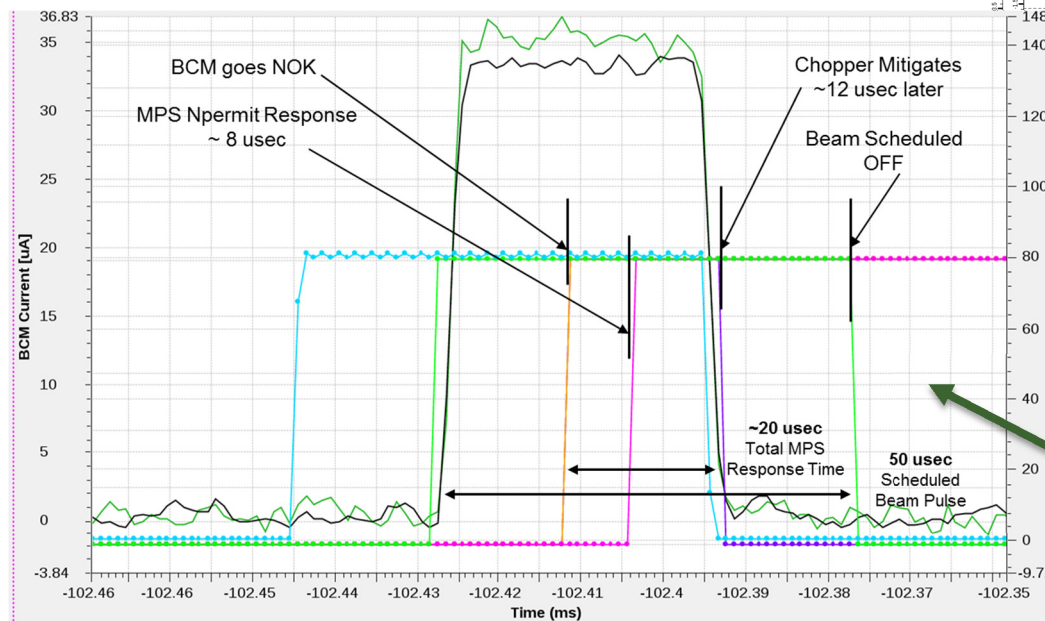
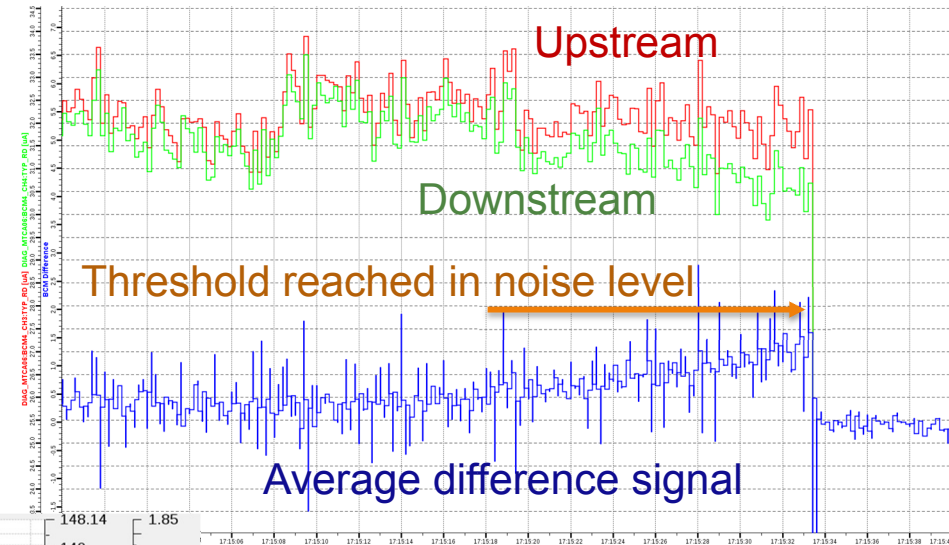
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Sensing/decision + Network transmission + Mitigation action + Remnant beam



Differential Current Monitoring Is Established

Satisfies Linac Fast Protection System Requirement

- Observed current monitors upstream and downstream of cryomodules
 - Losses induced by detuning optics
- 2 different averaging timescales used
 - 15 μs – fast losses
 - 150 μs – more averaging to reduce noise influence
 - Difference analyzed in firmware
 - Beam mitigated within 35 μs

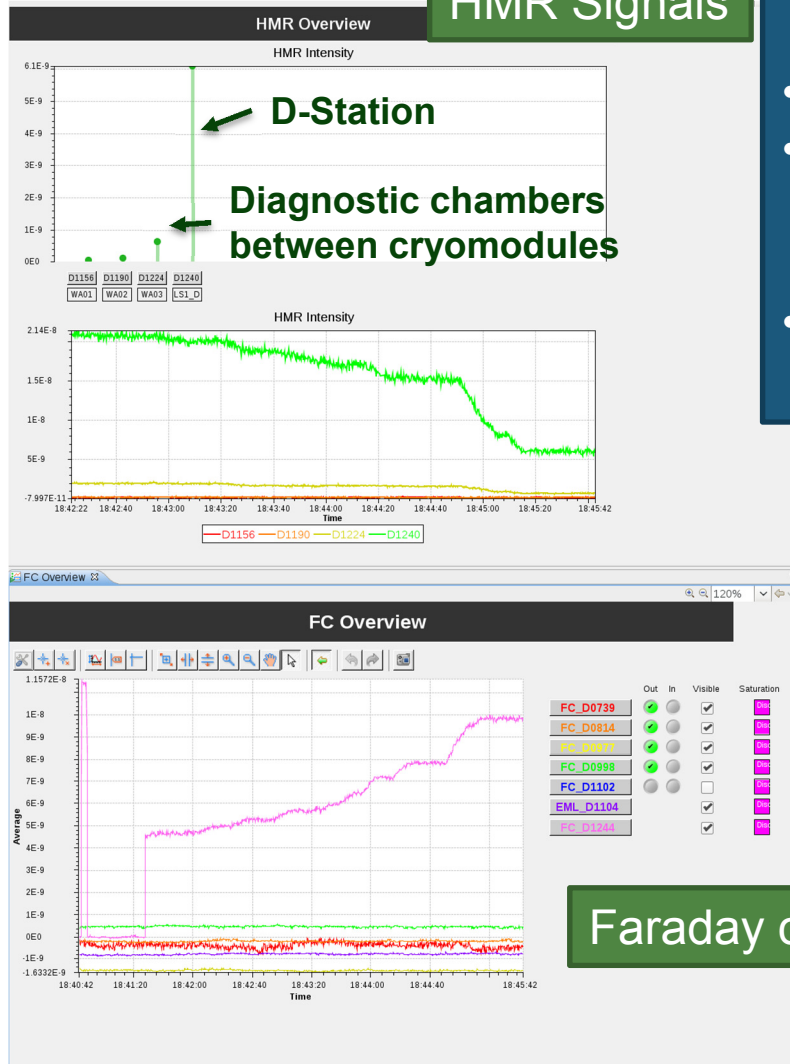


- 1.5 MeV/u case**
 - MPS trip setpoint at $\Delta I \sim 1.5 \mu\text{A}$
 - ~4.5% difference
- 2.3 MeV/u case**
 - Threshold level reduced
 - MPS trips when $\Delta I \sim 1.0 \mu\text{A}$
 - ~2.8% difference

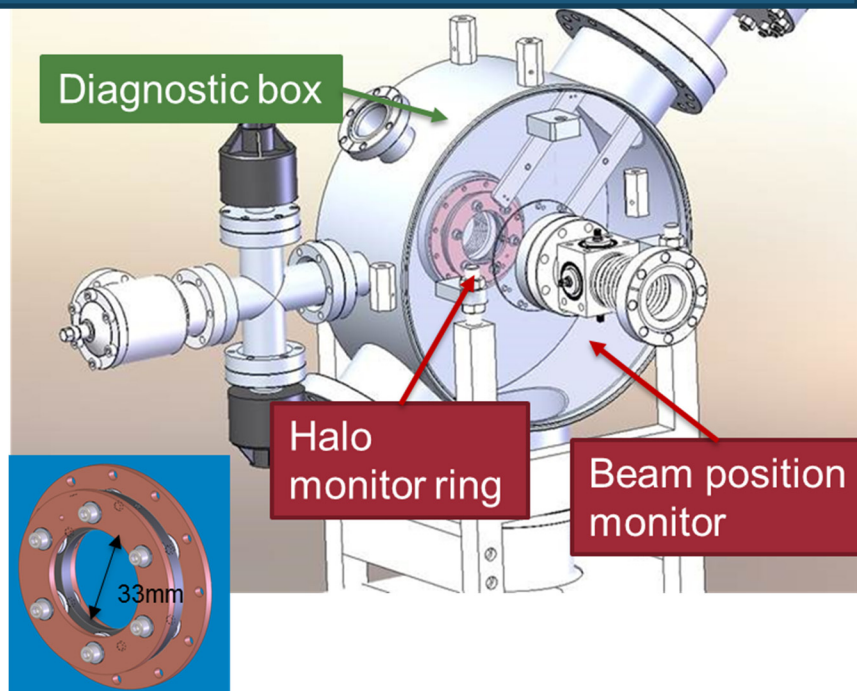
Postmortem buffer demonstrates time sequence of MPS mitigation

Halo Monitor Ring Signals Aid Tuning

HMR Signals

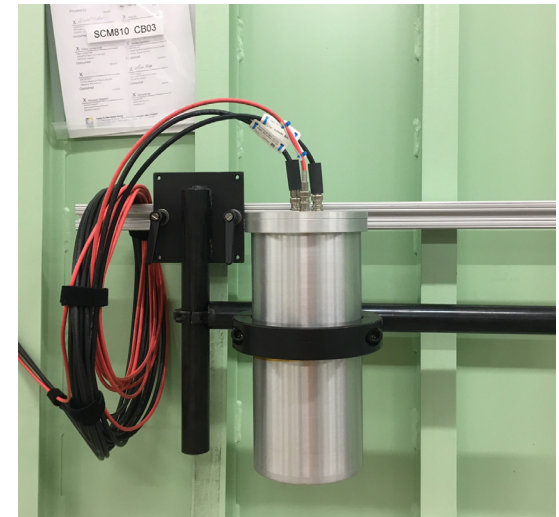
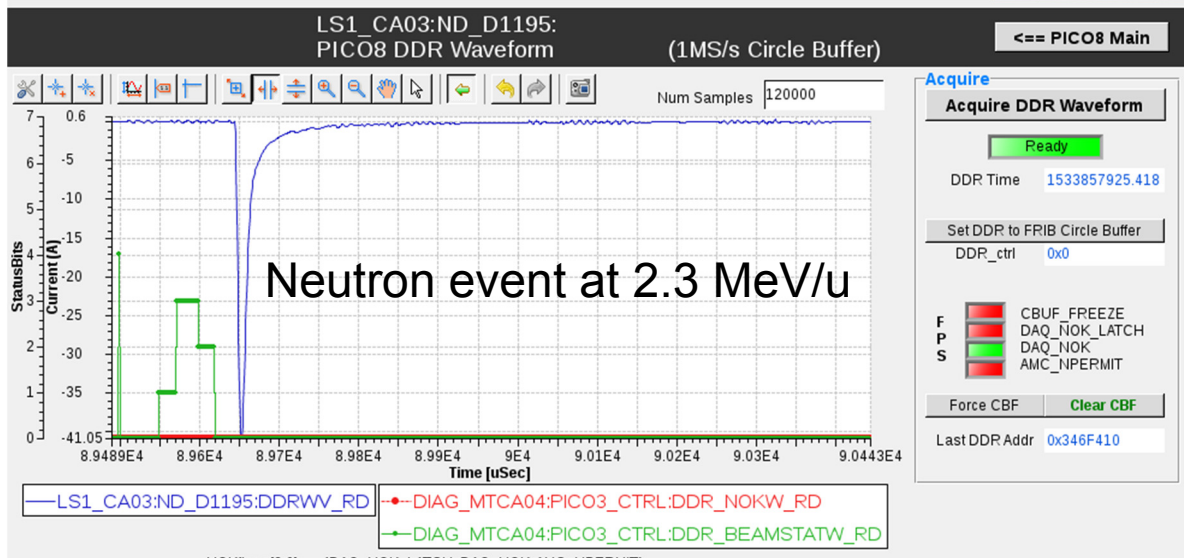


- Very sensitive to low losses, noisy at $\sim 1 \mu\text{s}$ time scale
- Added averaging can detect nA-scale losses
- Intercepted beam signals on Halo Monitor Rings (HMR) anti-correlate with Faraday cup measurements.
- Useful signal for optimizing transmission through cryomodules and lattice transitions



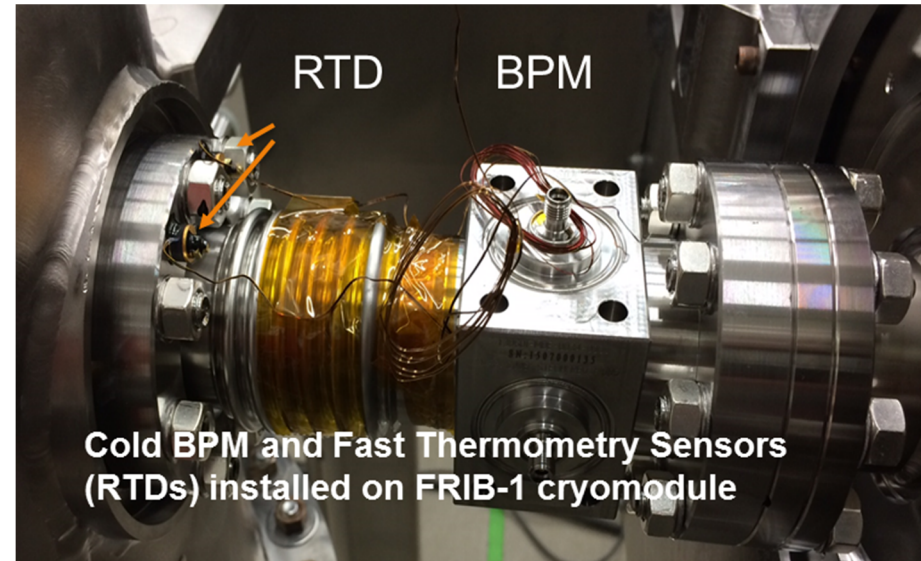
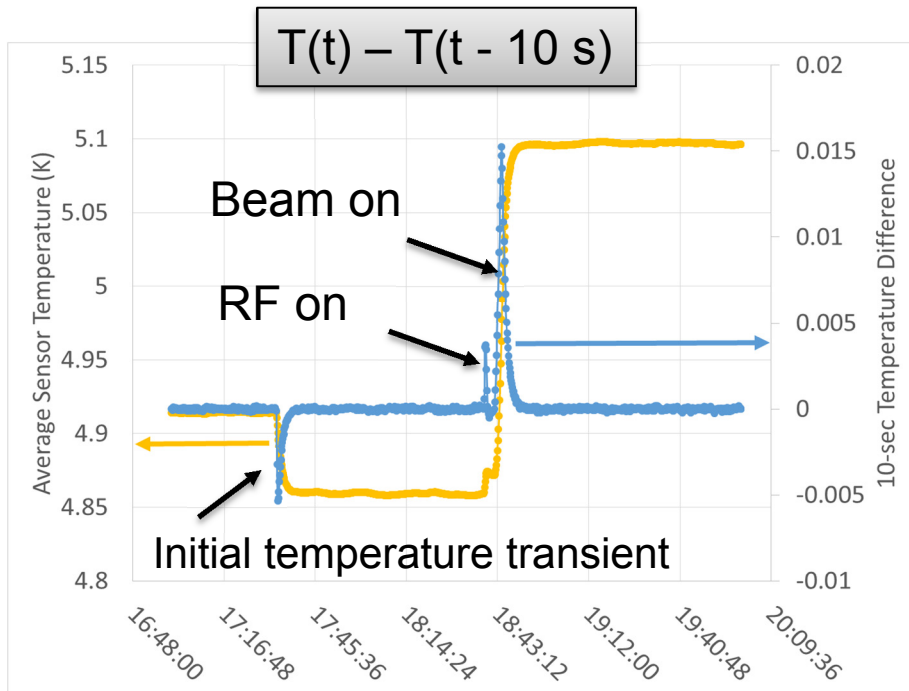
Neutron Monitors Are Commissioned

- Personnel Protection System (PPS) and Diagnostics monitors used to validate onset of neutron production with beam energy
 - Neutron signal strength larger and shows decay behavior (asymmetry)
 - Current mode sensitive to single event



'Fast' Thermometry Sensors Commissioned

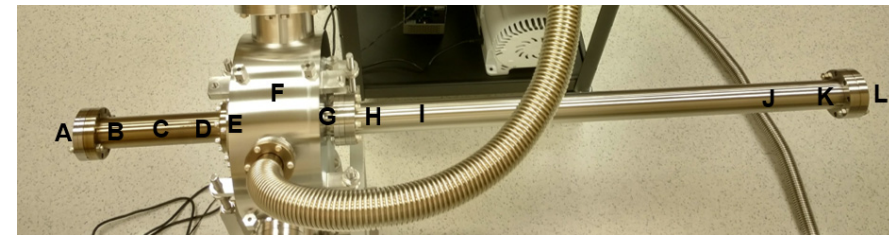
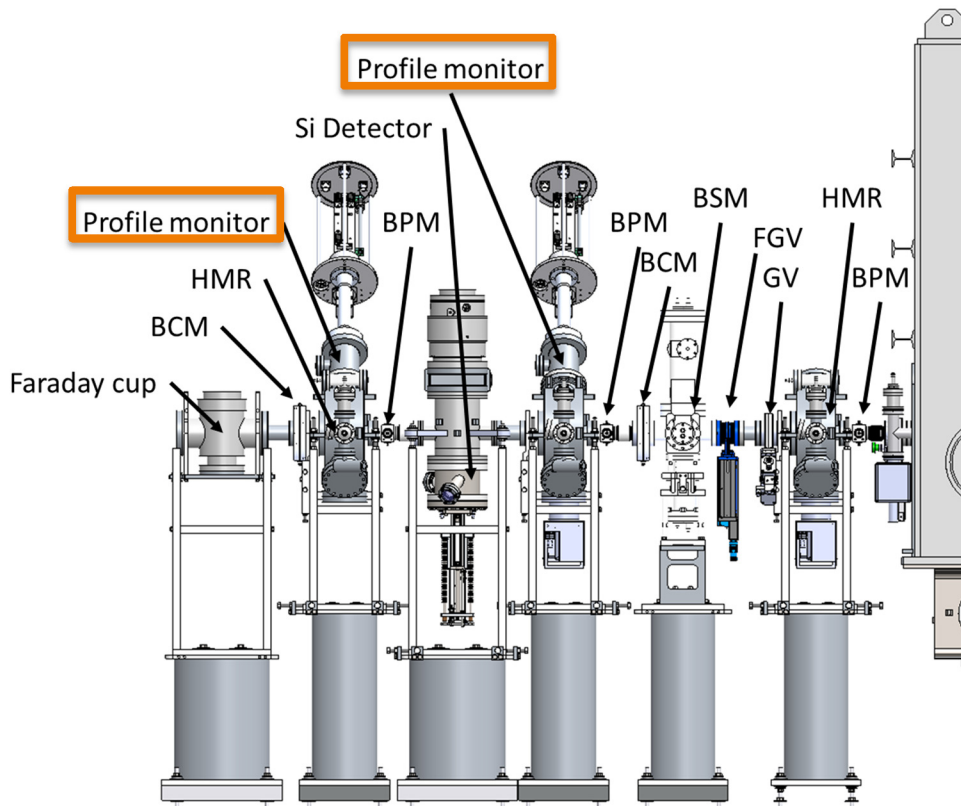
- Sensitive to beam losses in cryomodule cold mass
- Monitored during beam tuning with sequential cavity energization
 - Responsive to introduction of cavity RF power
 - Responsive to localized beam losses on 10s seconds time scale
- Response to measured losses still required for final calibration



Testing SRF Vacuum Preservation with Actuated Diagnostics

- Particle counts of actuated profile monitors were taken.
- Excessive counts observed due to ceramic components and non-SRF cleaning protocols
- PEEK components were fabricated to replace ceramics (MACOR).
- Particle transport tests were conducted to evaluate risk to cryomodules

Particle counting in clean room



Location	Particle Counts (0.3μm)	Location	Particle Counts (0.3μm)
A	1.83, 0.17	G	0.0, 0.0
B	0.17, 0.33, 1.67	H	0.0, 0.0
C	0.33, 7.33, 0.17, 0.67	I	0.0, 5.67, 0.17
D	0.0, 0.33	J	0.0, 0.0
E	0.0, 0.0	K	0.17, 0.0
F	7.33, 4.5, 19.33, 1.17, 3.5	L	5.83, 0.5

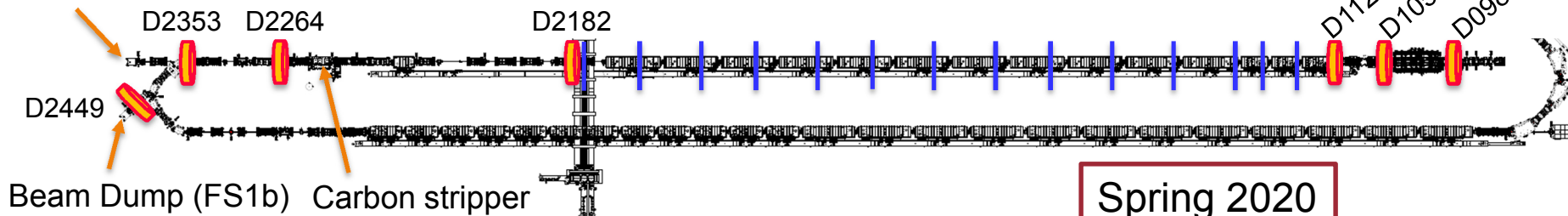
MACOR components replaced with PEEK.
 Slow pump down (<1 Torr/s)
 Profile monitor actuator cycled 100x.

Full Scale Linac Operations in 2019

- LS1 Commissioned in 2019
- Achieved full energy (>17 MeV/u) and peak beam power
- Achieved full CW operation of SRF heavy ion linac
- Established charge stripping and multiple charge state transport in arcs
- Operational experience with full scale linac
- Deployment of high level applications for tuning, optimization
- Validated multi-master MPS

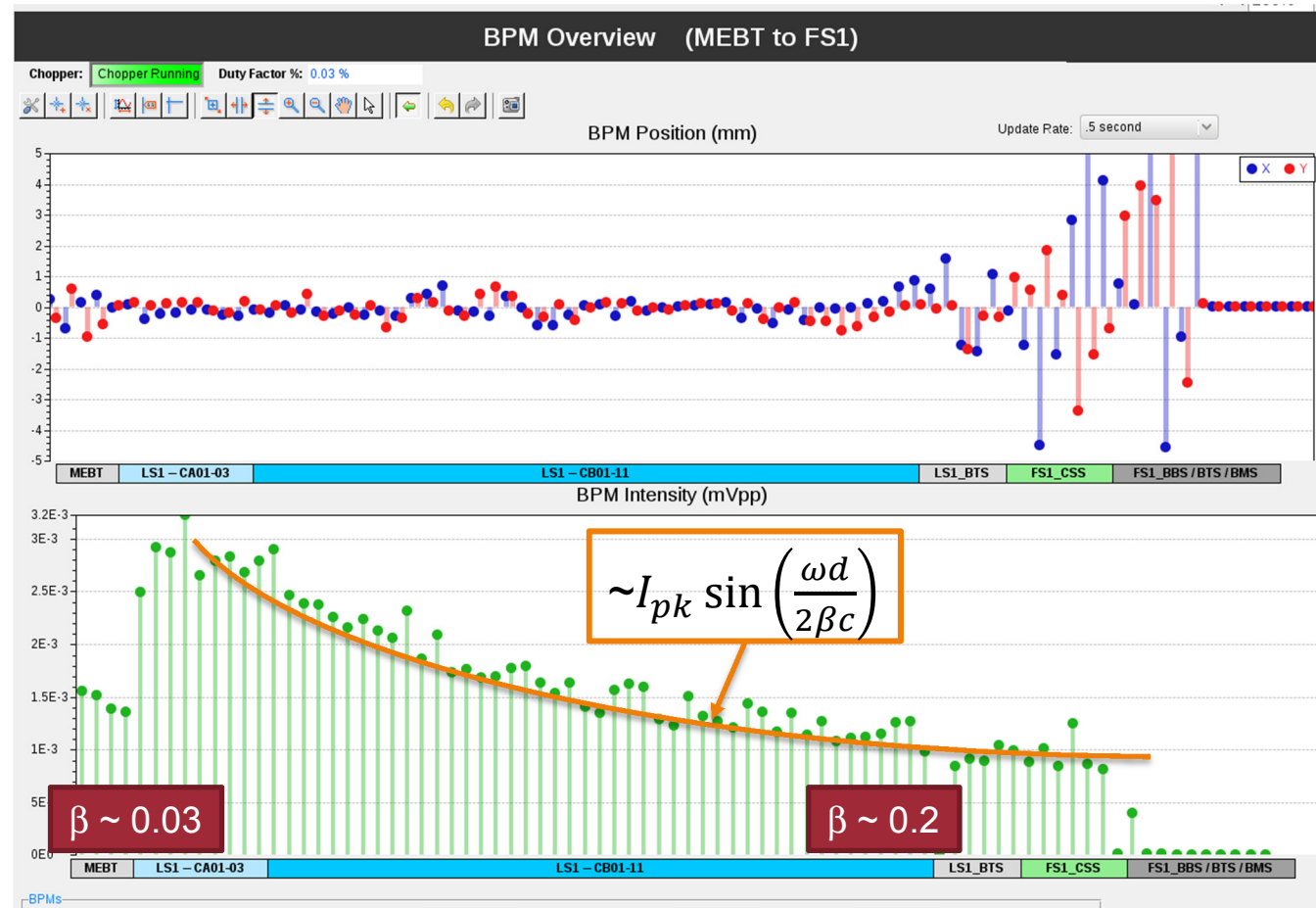


Beam Dump (FS1a)



Beam Position Monitors In Full Use

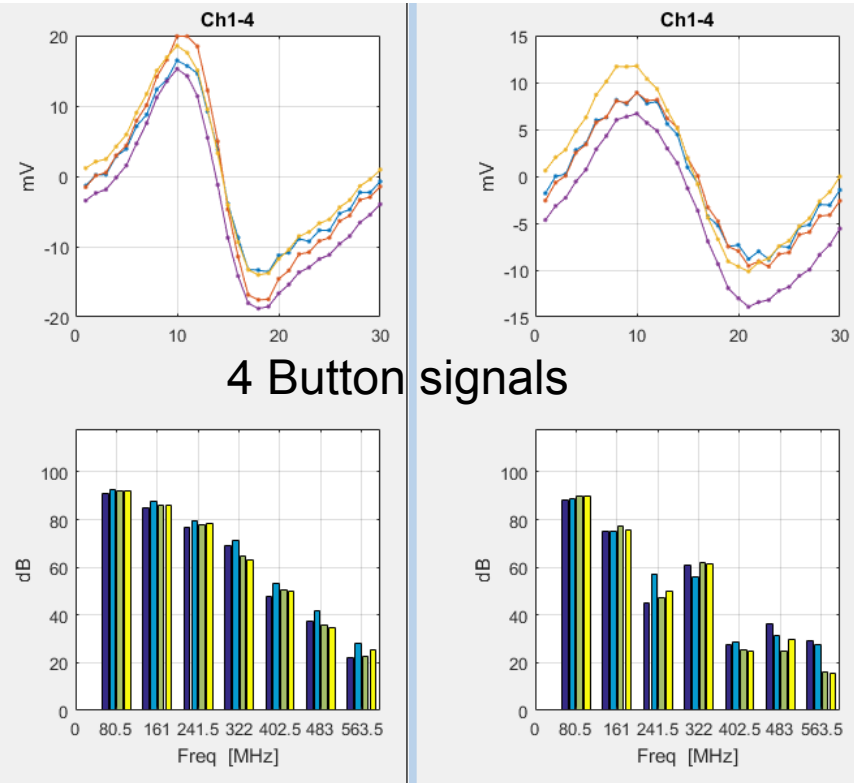
- BPMs installed and providing data
 - Position
 - RF phase and TOF measurements
- Used for steering correction with automated schemes
- RF cavity phase scans and beam energy measurements
- Analyzing on RF multiple harmonics to limit cross talk effects
- Intensity used to cross-calibrate other measurements (eg. Charge State Distribution)



Warm and cryogenic button-type BPMs

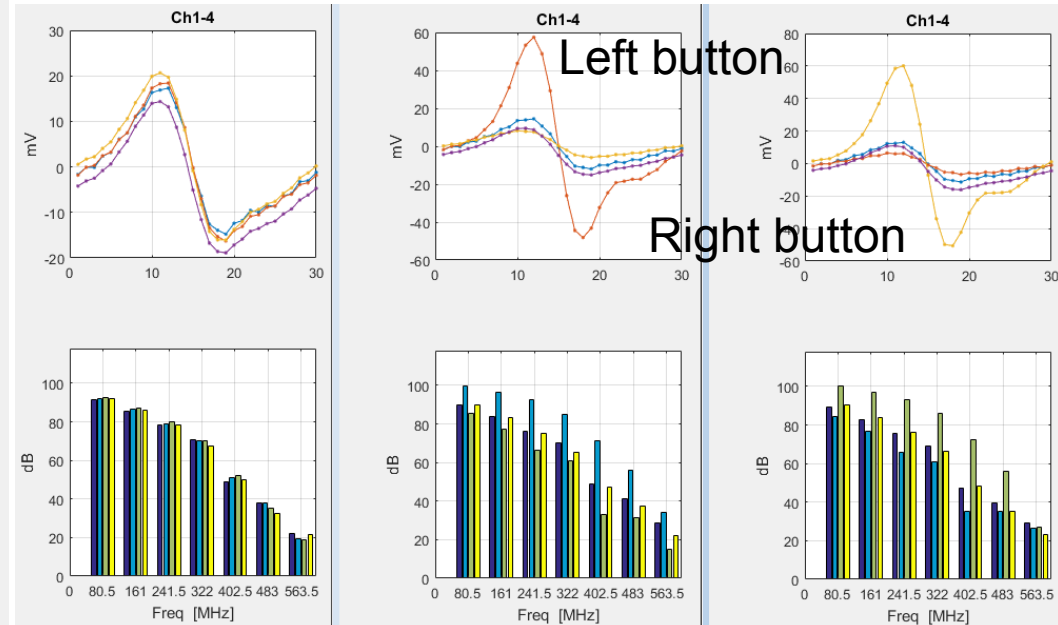
Initial Bunch Shape Measurements From Time Interleaved Sampling Algorithm

Adjusting Rebunching Cavity Phase



Bunched vs. Debunched.

Adjusting D1078 corrector magnet to scan beam across BPM aperture



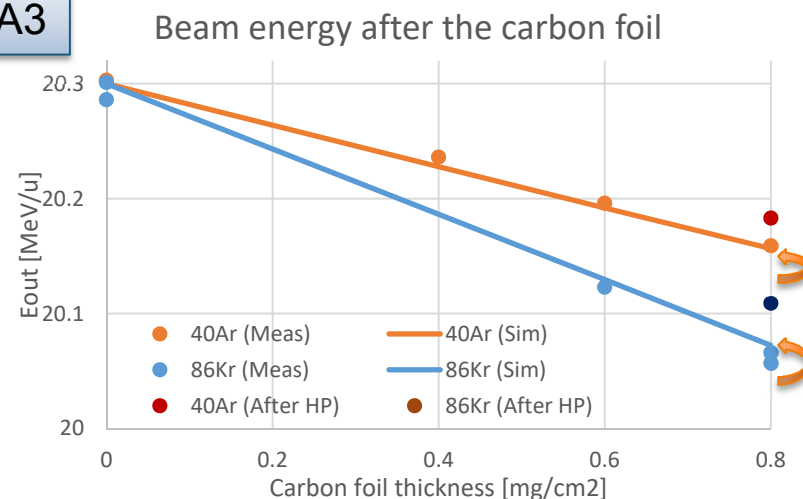
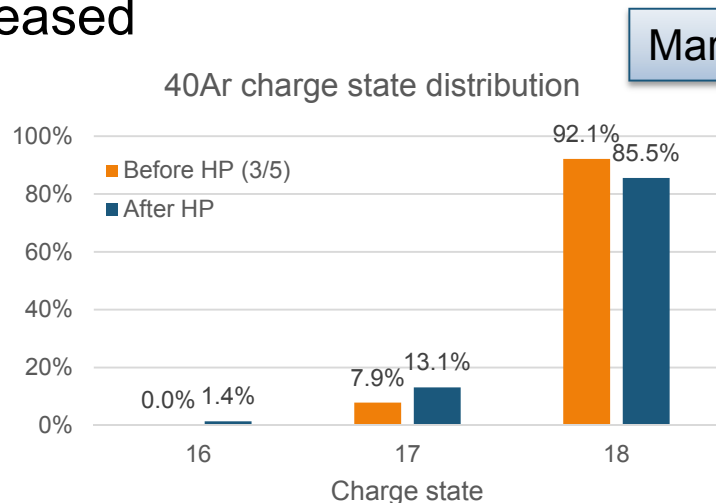
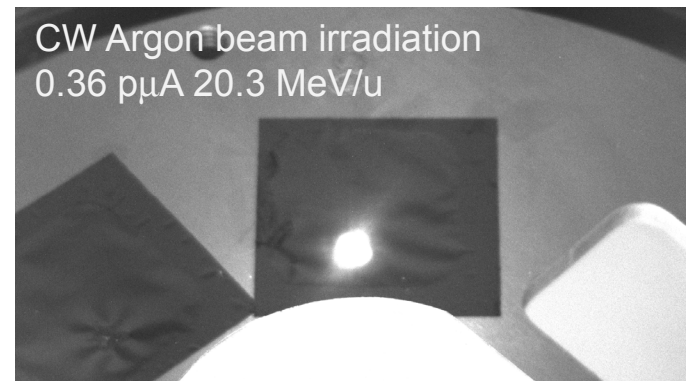
Center, Left, Right.

Spectrum shifts towards high frequencies with closer beam approach to button

Spectrum features indicate low-beta distortions, encode bunch shape information

Carbon Foil Distortions in High Power Test

- The foil seems to be thinner after high power tests
 - ~20% lower energy loss
 - Charge state distribution shifts to lower states
- The beam was focused on the carbon to 0.5 mm, RMS, to minimize emittance growth
 - Heat density is too high
- Beam size was changed 1.0 mm or more to avoid further deterioration
 - No further deterioration was observed when the beam diameter was increased

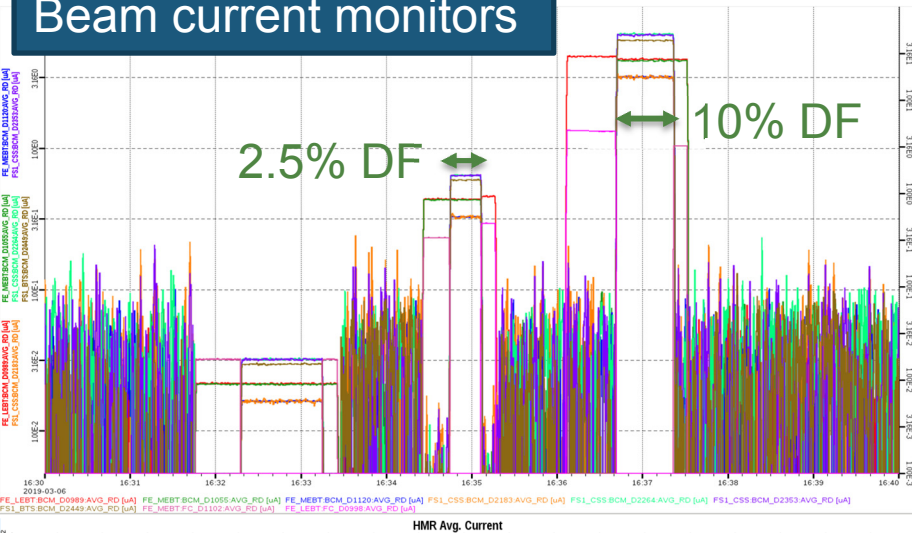


Loss Monitors Providing Correlated Signals

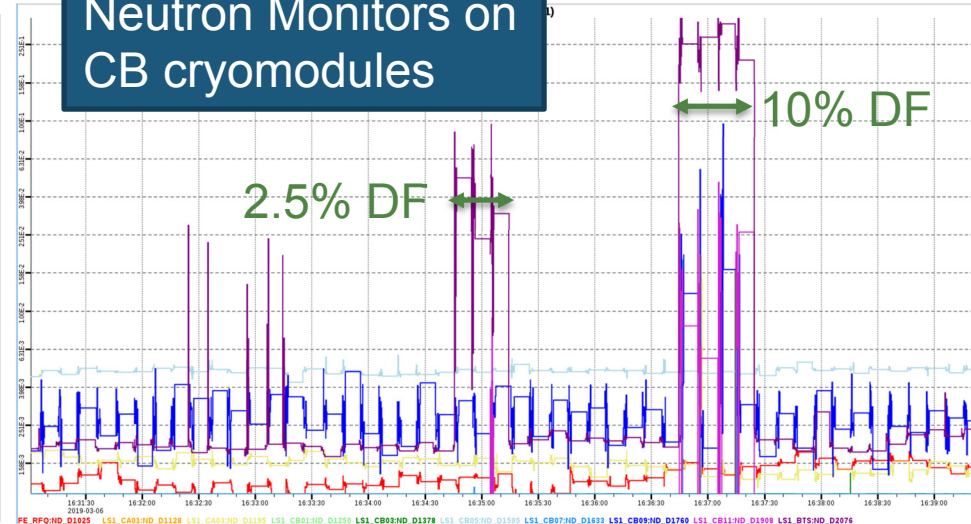
Shane THZBB4

High power tests

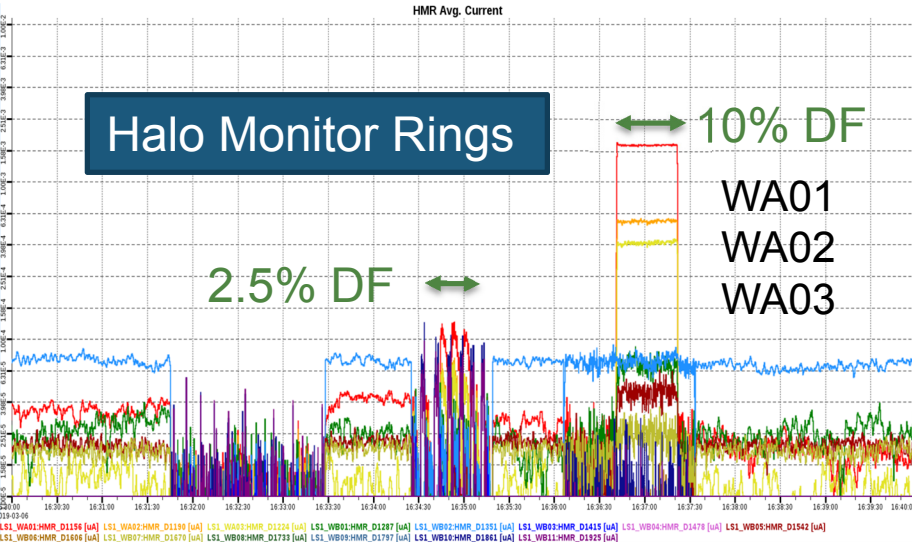
Beam current monitors



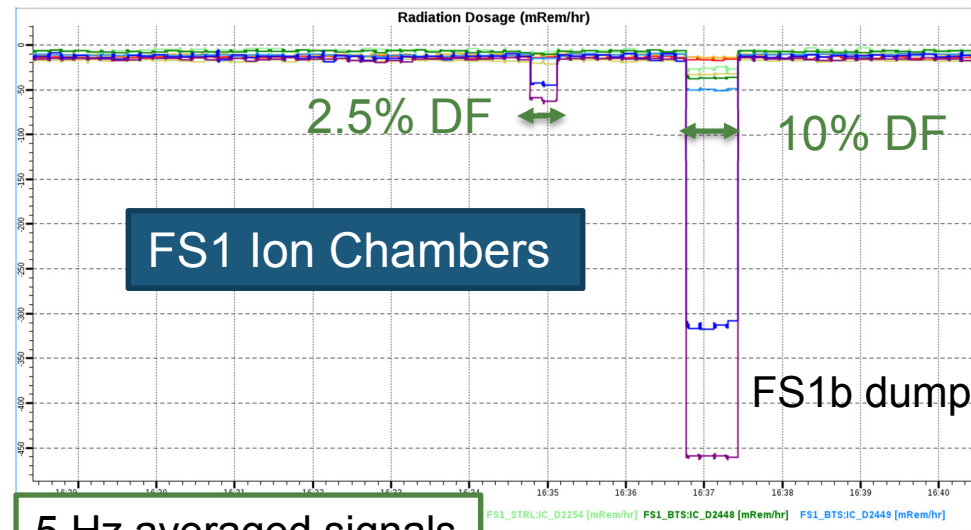
Neutron Monitors on CB cryomodules



Halo Monitor Rings



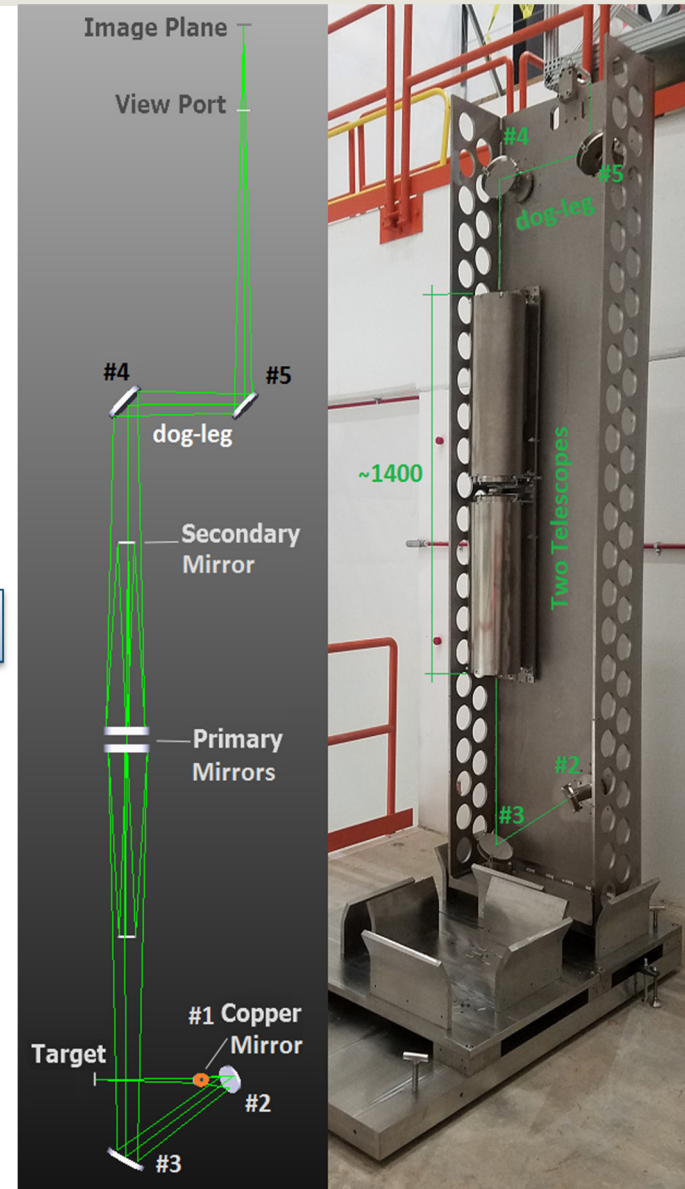
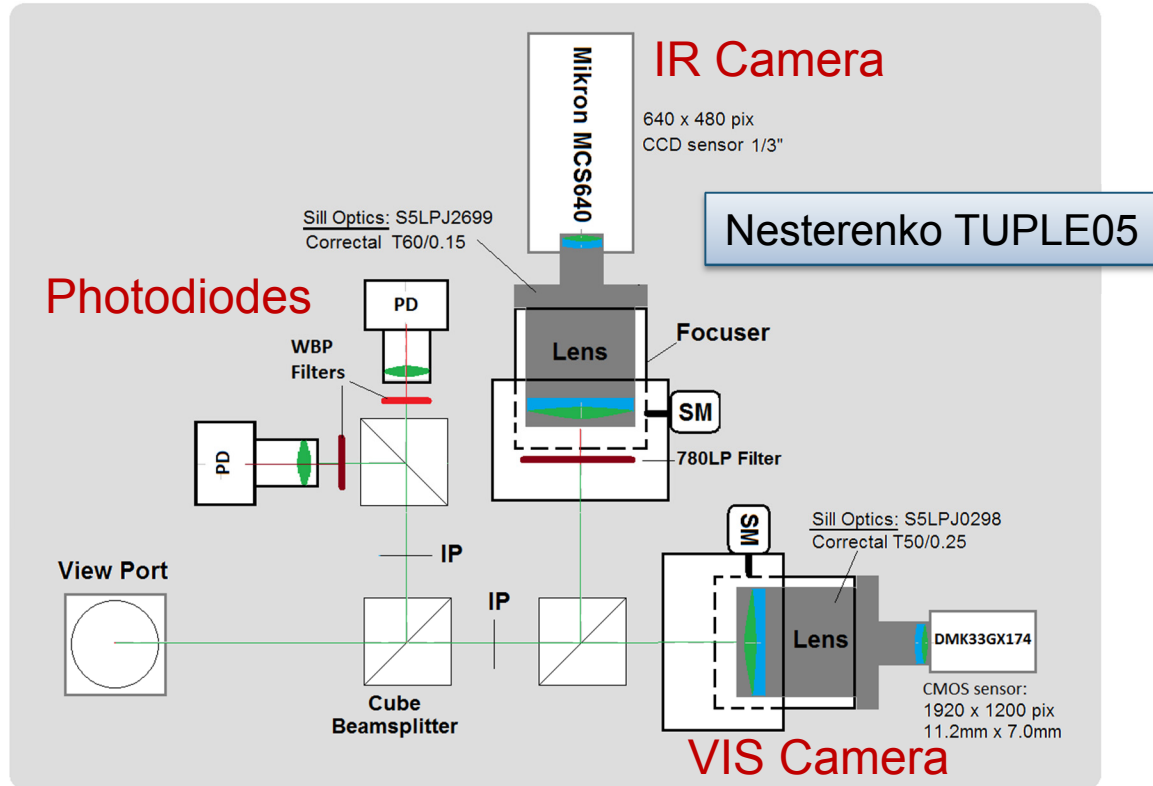
FS1 Ion Chambers



5 Hz averaged signals

High Power Target Thermal Imaging System

- Monitoring beam on target and dump
 - Variations in position, distribution, intensity
 - Target temperature
- Interface to Fast Machine Protection System
 - Intensity and temperature changes monitored with fast detectors



Looking Forward

- **Completing the accelerator, commissioning the target**
 - LS2 commissioning in 2020
 - Linac completion in 2021
- **Improving reliability, robustness, operability**
 - Software controls for Run Permit System
 - Control and remove noise in BCMs
 - Validate beam loss models and monitor sensitivity
- **Ramping to high power**
 - Develop understanding of loss distributions and mechanisms
 - Develop high dynamic range halo monitoring
- **New instrumentation to advance tuning and operations**
 - Collect beam harmonic amplitudes by AC coupling to Halo Rings
 - Augment the loss monitor network with additional sensors and
 - Develop beam contamination monitoring
 - Develop non-invasive transverse and longitudinal profile monitoring

Year after CD-4	Beam power on target (kW)
1	10
2	50
3	100
4	200
5	400

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