Beam Instrumentation for the Facility for Rare Isotope Beams

Steve Lidia, Facility for Rare Isotope Beams

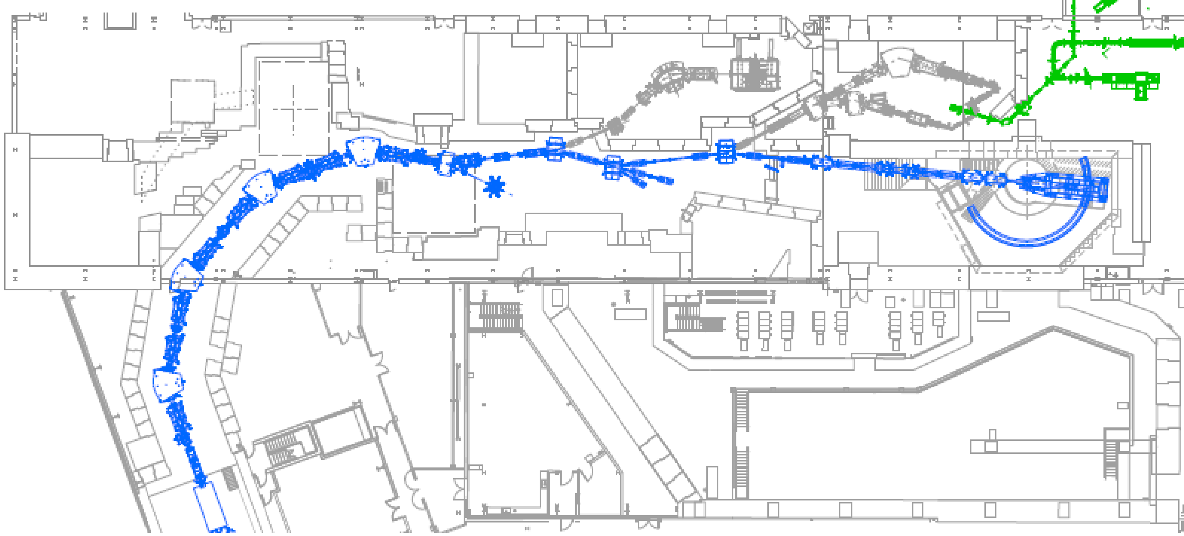
FNAL Accelerator Physics and Technology Seminar

12 November 2020

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

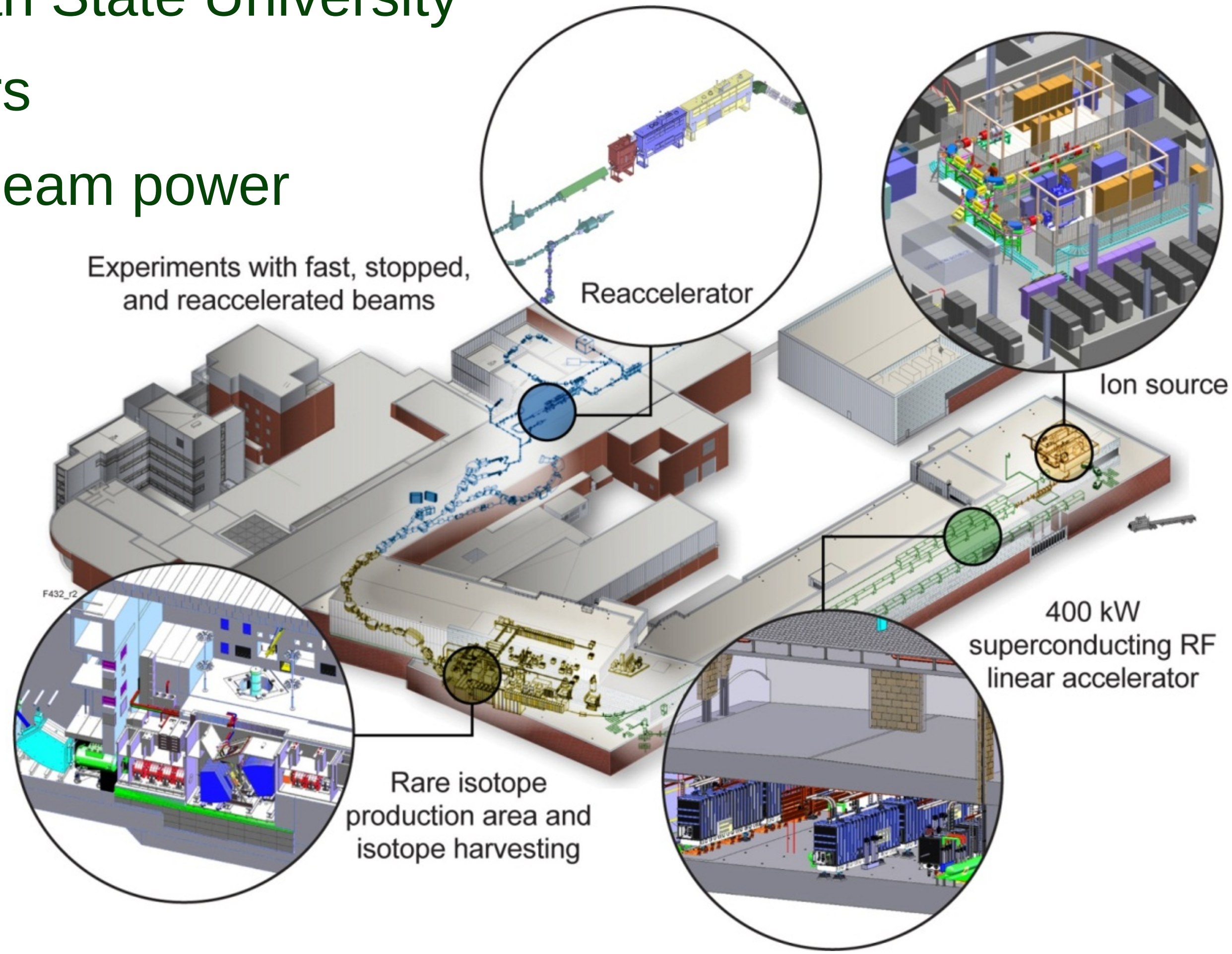
Outline

- Facility and Instrumentation Challenges
- Diagnostic Systems for Linac Commissioning
- Timing and Machine Protection Systems
- Target Imaging Systems
- Fragment Separator Systems
- Fast Beam Containment
- Summary and Look Ahead



Facility for Rare Isotope Beams*

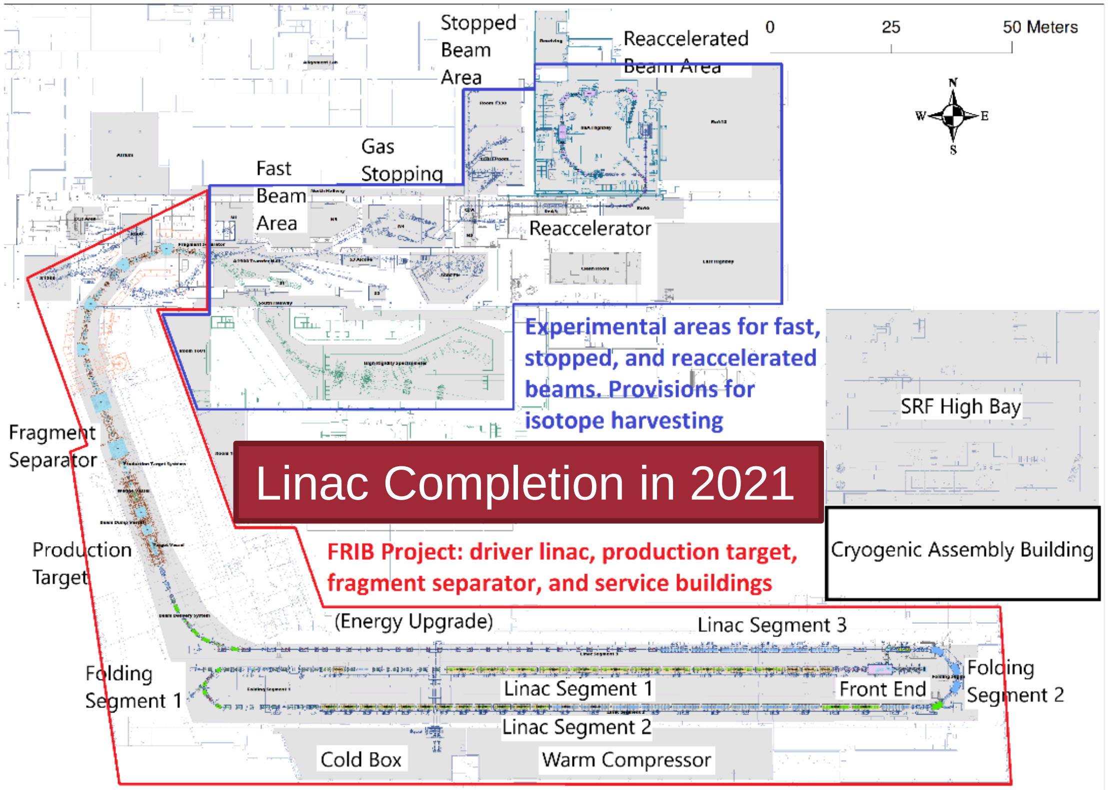
- Funded by DOE–SC Office of Nuclear Physics with contributions and cost share from Michigan State University
- Serving over 1,300 users
- Key feature is 400 kW beam power for all ions (e.g. 5×10^{13} ^{238}U/s)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - All elements and short half-lives
  - Fast, stopped, and reaccelerated beams



***U.S. DOE designated FRIB as a National User Facility on 29 September, 2020**

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



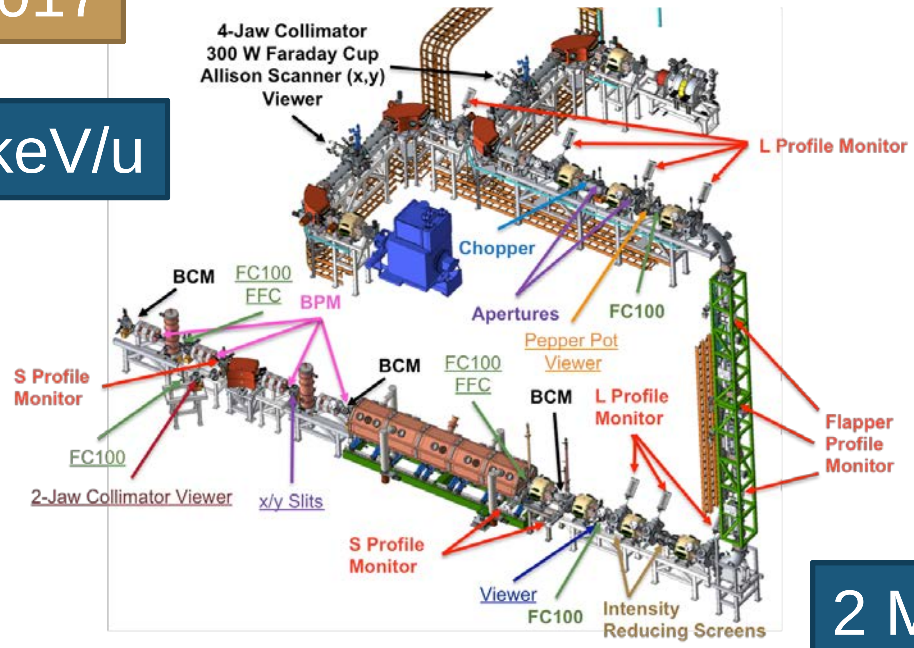
- Frequent retuning for various ion species
  - Each run extends 1-2 weeks

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}Kr *	2	27
^{16}O	1	38
^{36}Ar *	1	28
^{82}Se	2	155
^{92}Mo	8	98
^{58}Ni	4	130
^{22}Ne	2	10
^{64}Ni	1	49

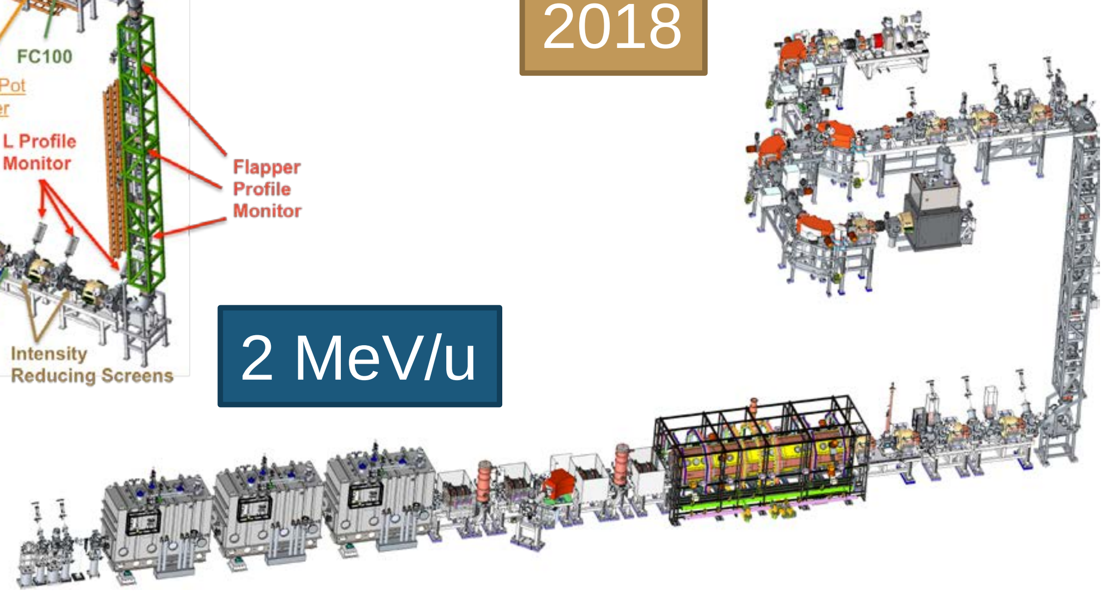
Commissioning Phases Completed

2017

500 keV/u



2018



2 MeV/u

2019

20 MeV/u

Commissioning Phases Completed

2020

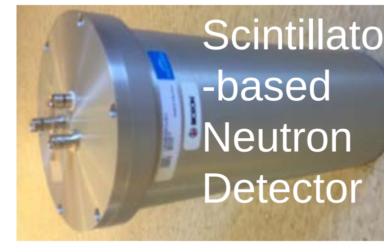
>200 MeV/u

Simultaneous multi-charge state acceleration, $^{49,50,51}Xe$ >185 MeV/u

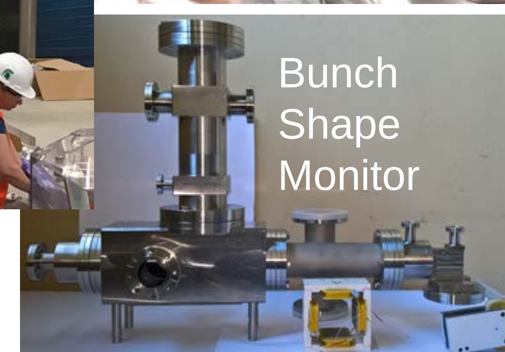
1 KPP left to demonstrate.

FRIB Linac Diagnostic Systems

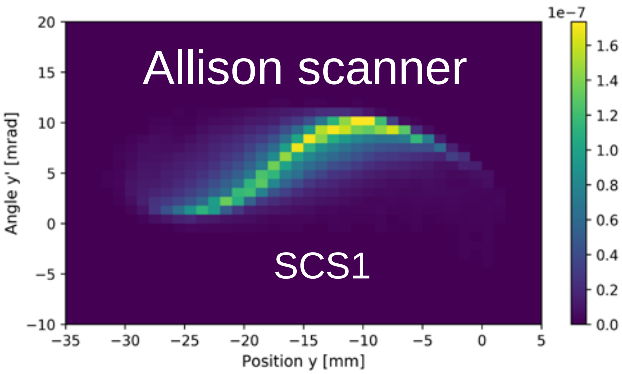
Accelerator Systems - Diagnostics	TOTAL
Beam Position Monitor	150
Beam Current Monitor (ACCT)	13
BLM - Halo Monitor Ring	30
BLM - Ion Chamber	47
BLM - Neutron Detector	24
BLM – Fast Thermometry System	240
Profile Monitor (Lg., Sm. Flapper)	41
Bunch Shape Monitor	1
Allison Emittance Scanner (2 axis)	2
Pepper pot emittance meter	1
Faraday Cup	7
Fast Faraday Cup	2
Viewer Plate	5
Selecting Slits System - 300 W	5
Collimating Apertures - 100 W	2
Intensity Reducing Screen System	2




Profile Monitors

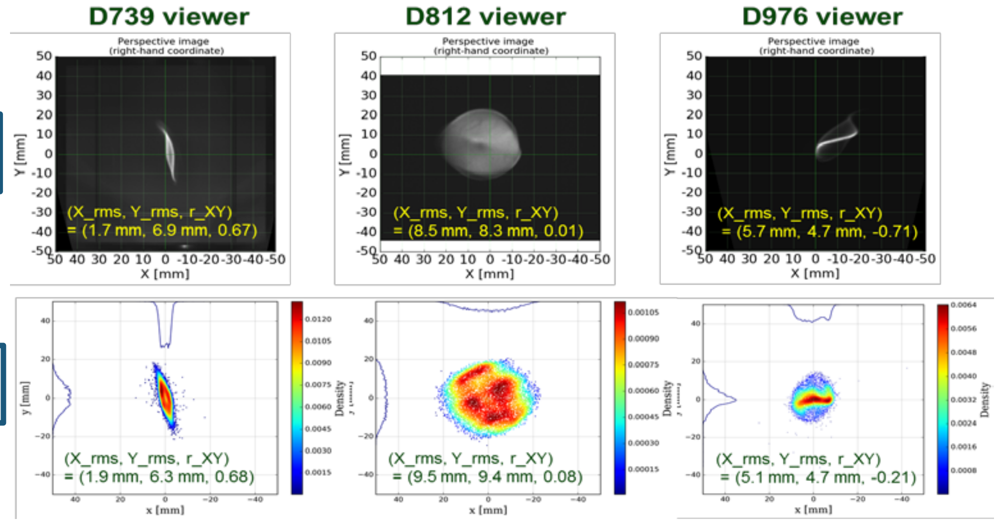


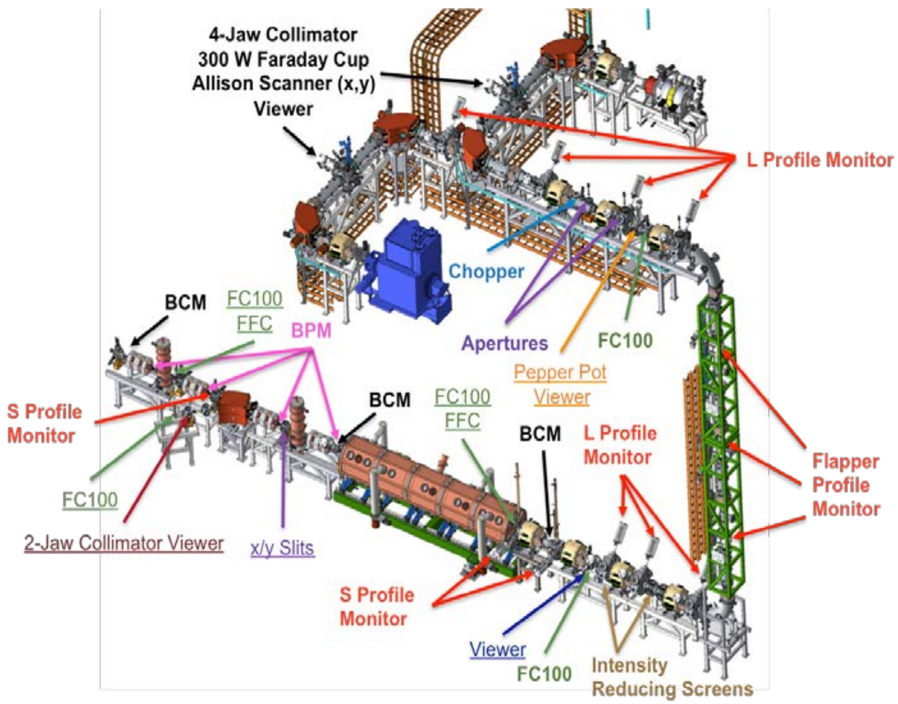
Diagnostics Support Tuning Through Front End



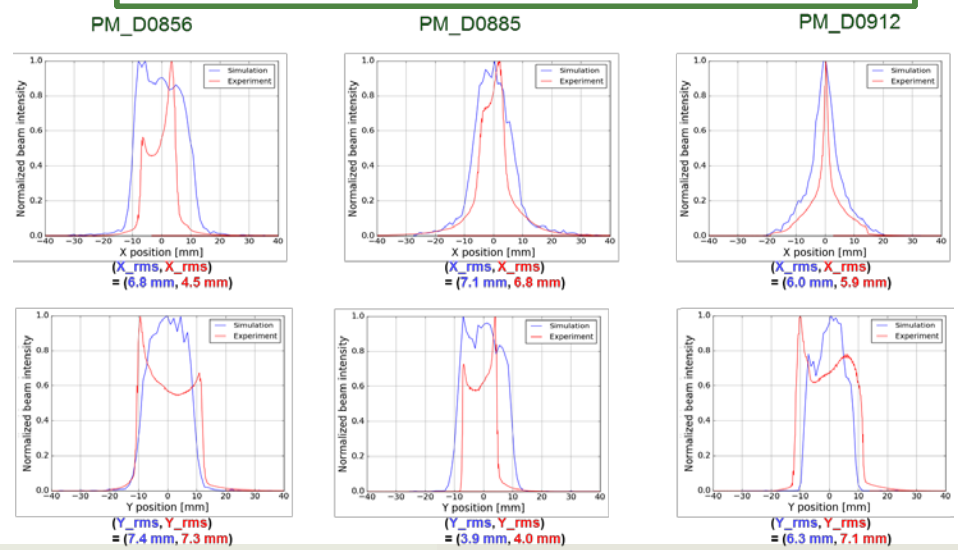
Measured

Simulated



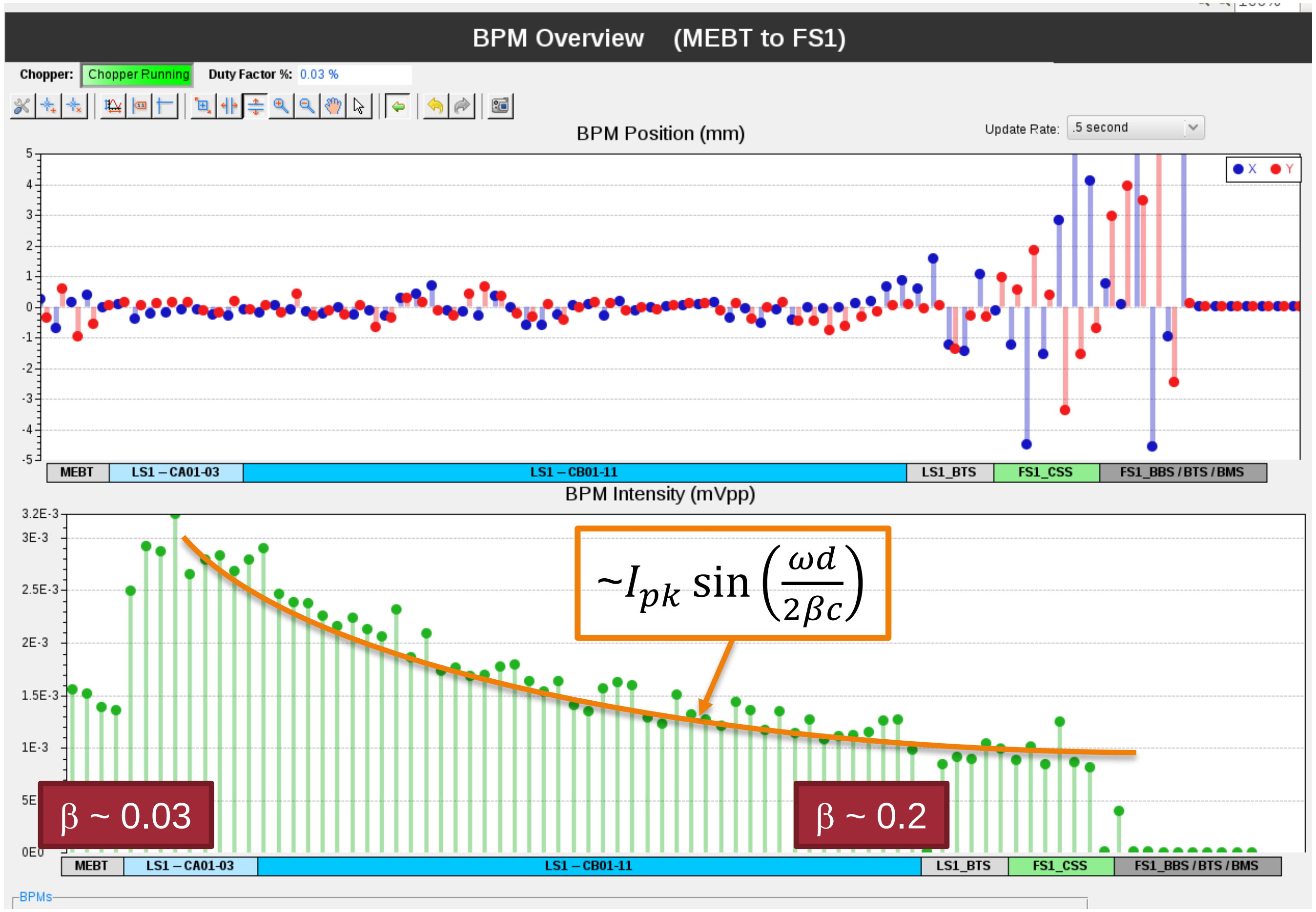


Wire Profile Monitor Measurements



Beam Position Monitors In Full Use

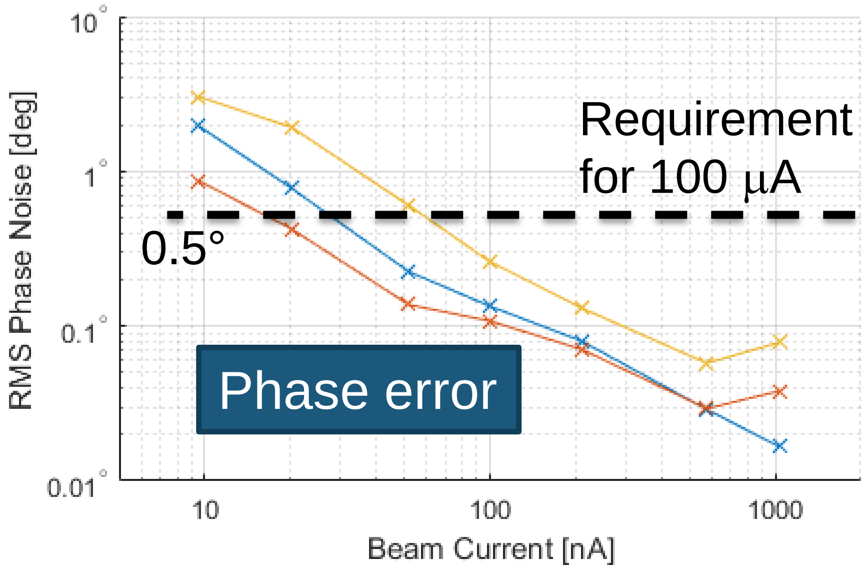
- BPMs installed and providing data
  - Position
  - RF phase and TOF measurements
- Used for steering correction with automated schemes
- RF cavity phase scans and beam energy measurements
- Analyzing multiple RF harmonics to limit cross talk effects
- Intensity used to cross-calibrate other measurements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

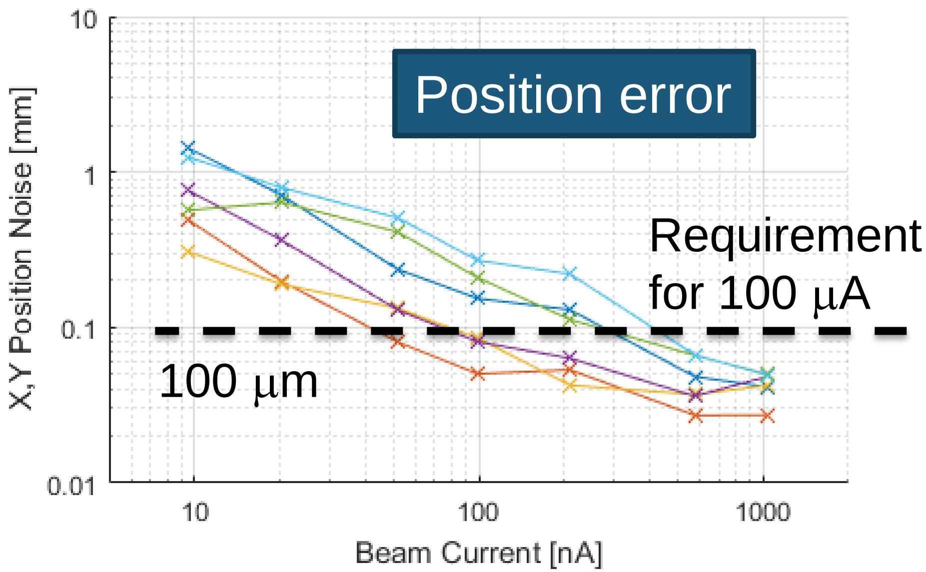


Warm and cryogenic button-type BPMs

BPM Position and Phase Error Meet Requirements

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





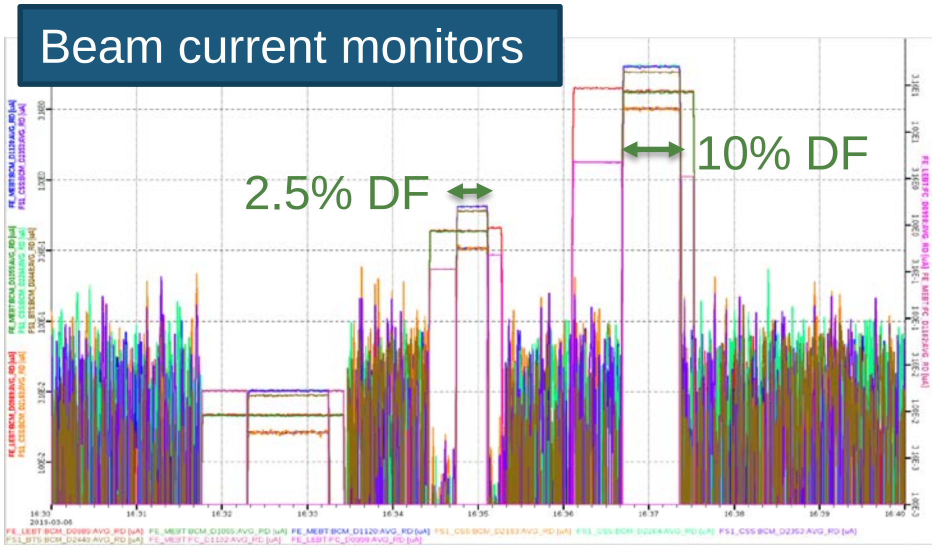
- Phase noise: 3 MEBT BPMs, 1-sec avg
  - Phase noise (rms) @ 1 μA: 0.04 deg
  - Phase noise (rms) @ 100 nA: 0.13 deg
- Position noise: 3 MEBT BPMs, X/Y, 1-sec avg
  - Position noise (rms) @ 1 μA : 0.040 mm
  - Position noise (rms) @ 100 nA: 0.140 mm

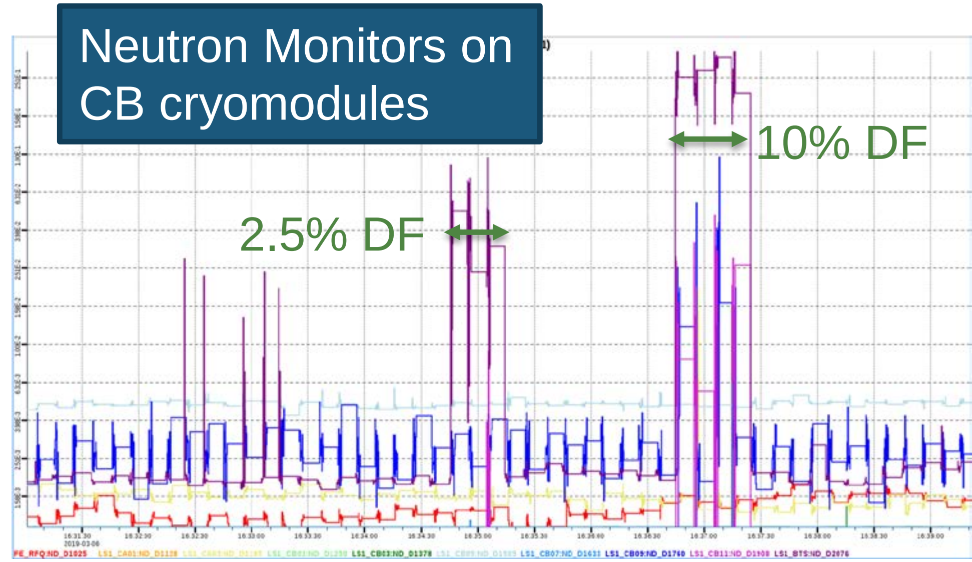
Narrowband measurements at 161 MHz

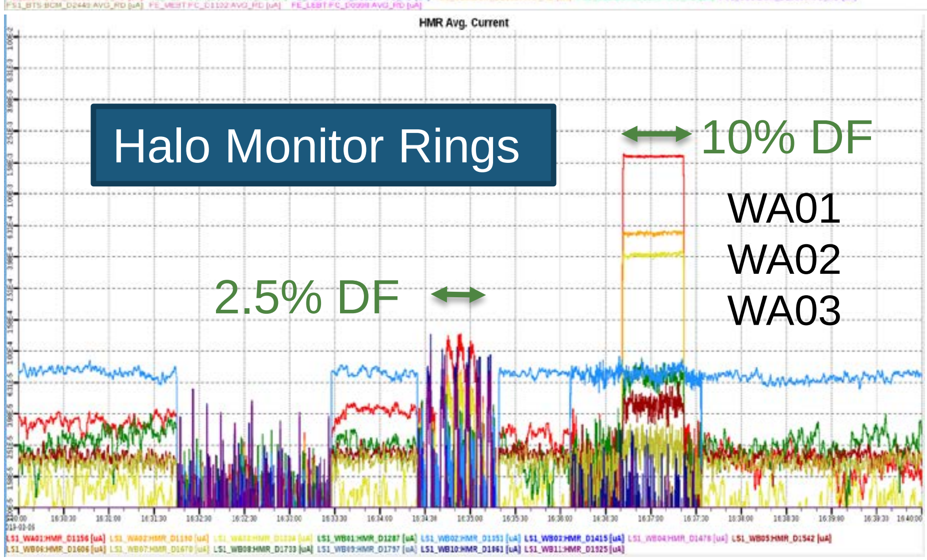
Loss Monitors Providing Correlated Signals

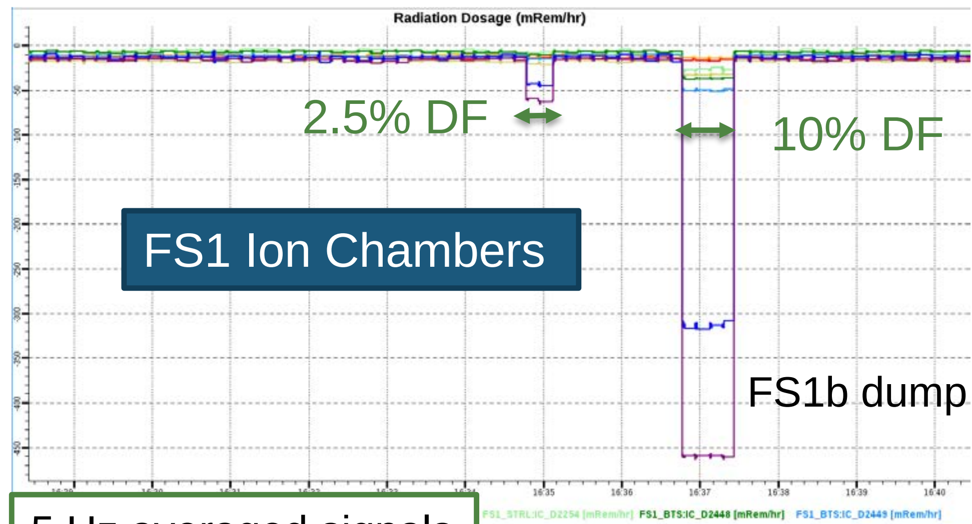
- High power tests

Verified high power transmission losses sensitivity < 2 10^{-4}









5 Hz averaged signals

All Chassis Electronics are in Operations

20 MTCA.4 chassis for the entire linac

CAENels 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 μsec to detect >10% beam loss**
- 150 μsec to detect 10% beam loss
- Detect chronic small losses of 1 W/m or less

15 μs requirement →
- Fast sampling data acquisition, >= 1 MSPS
- Analog signal response, DC to 35 kHz

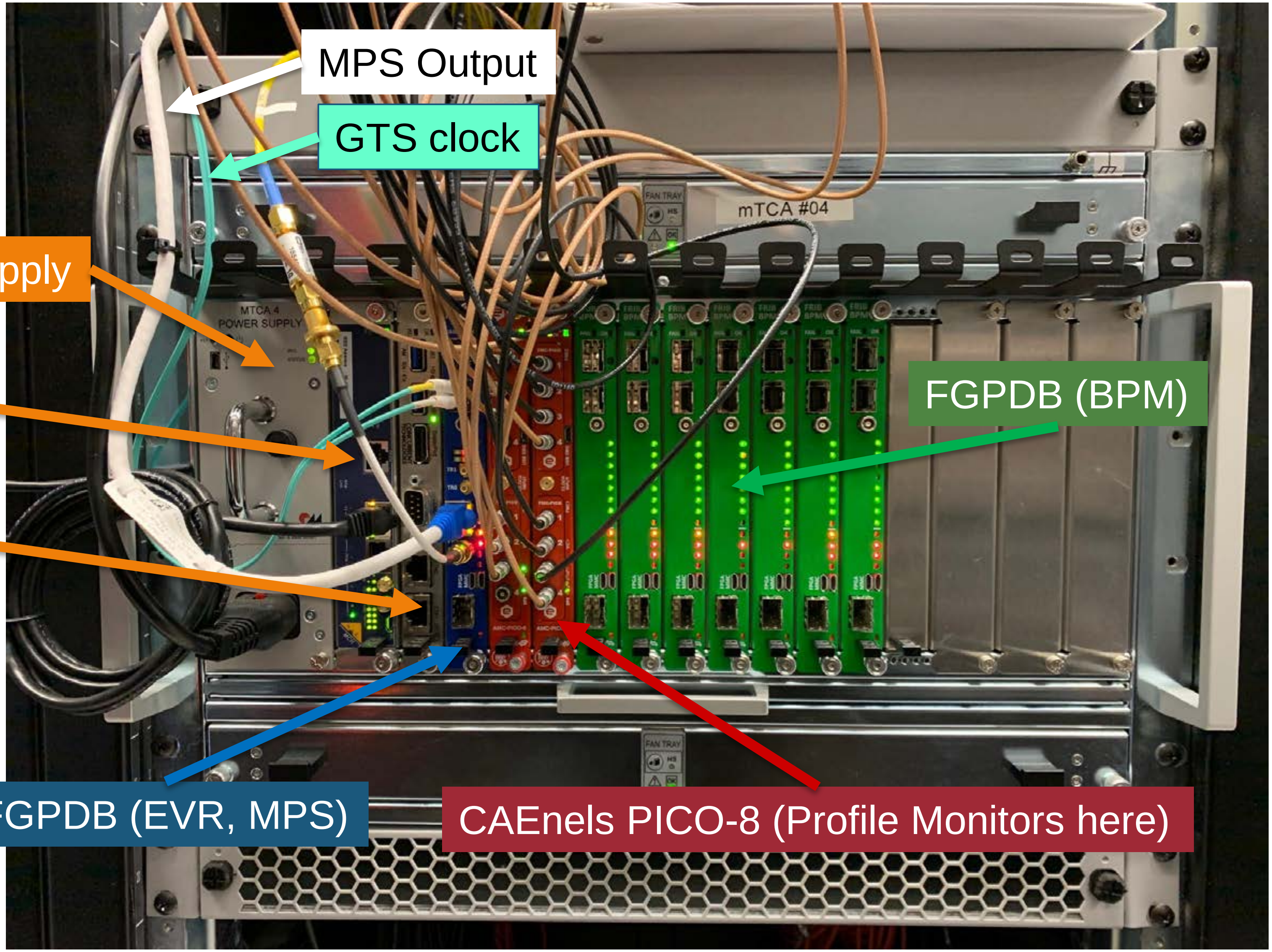
FRIB Digital Board
General purpose
150x Beam Position (BPM)
20x Event Receiver
20x Machine Protect System (MPS)
>300x LLRF

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

75% of devices covered by these three MicroTCA cards

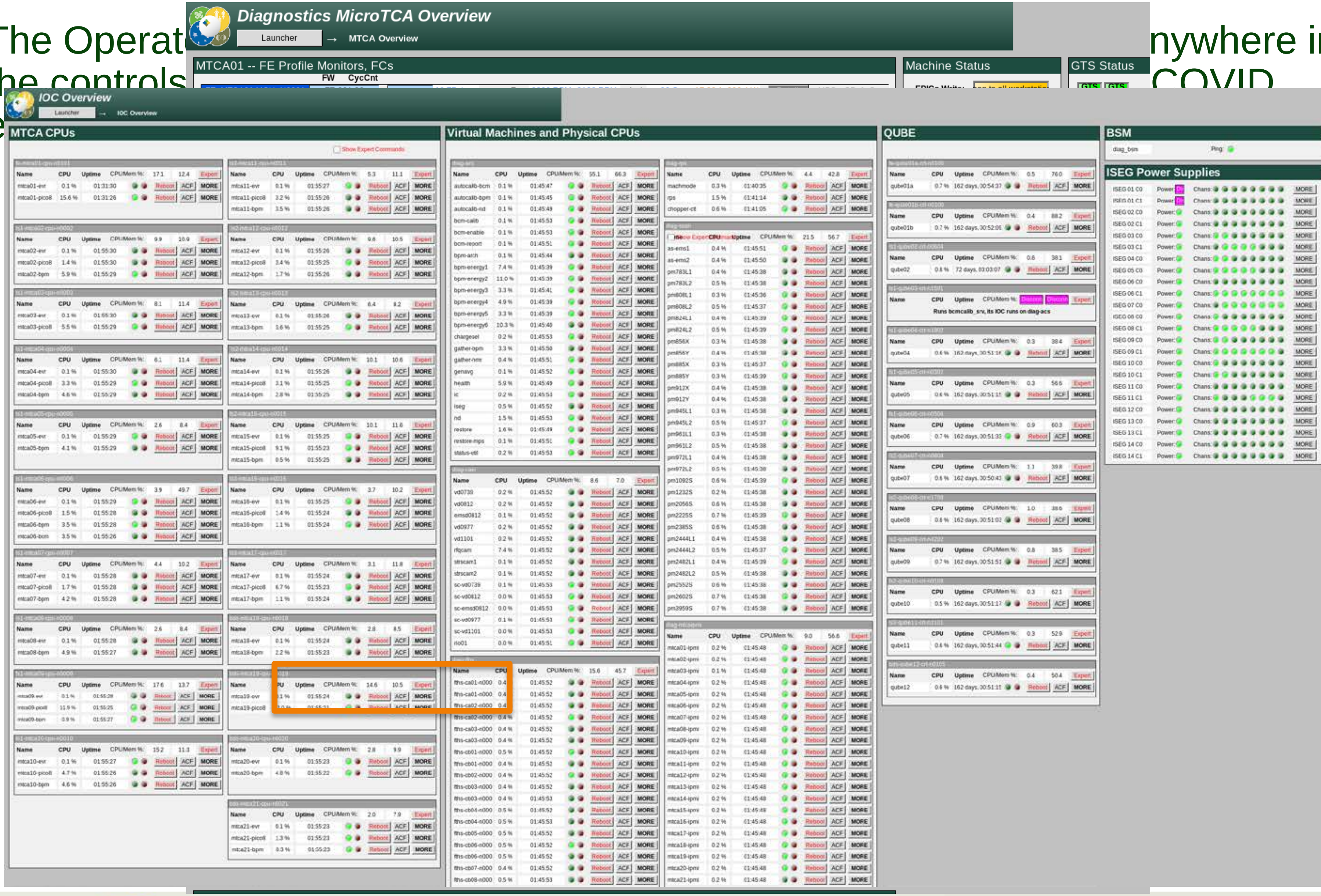
All utilize field programmable gate array (FPGA) for real-time signal processing and machine protection (MPS)

MTCA Chassis Installation



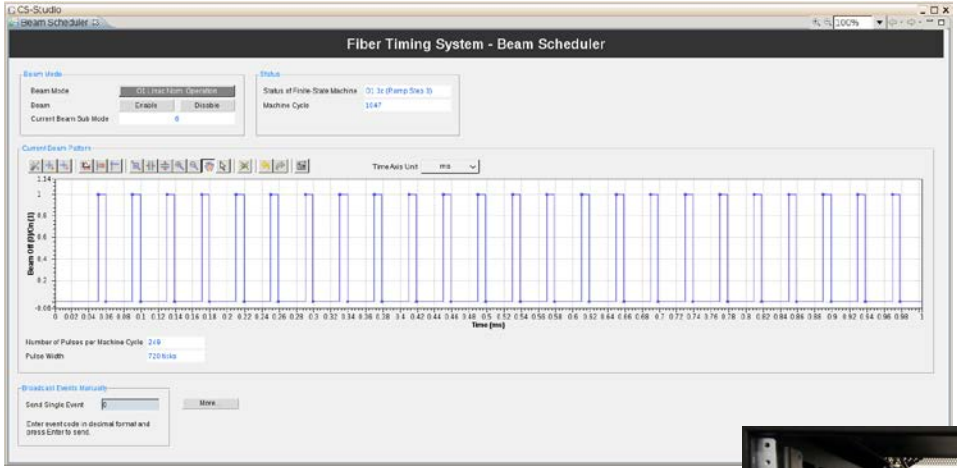
Controls Integration with EPICS

- The Operat… nywhere in the controls… COVID e…

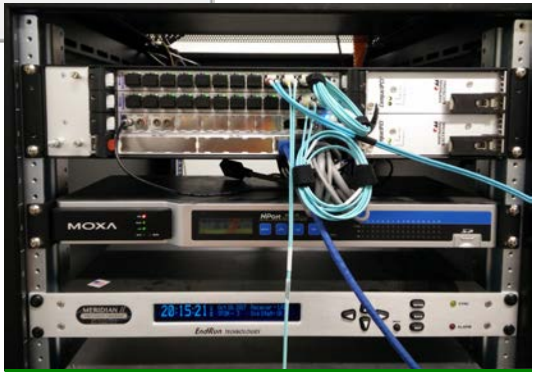


Global Timing System

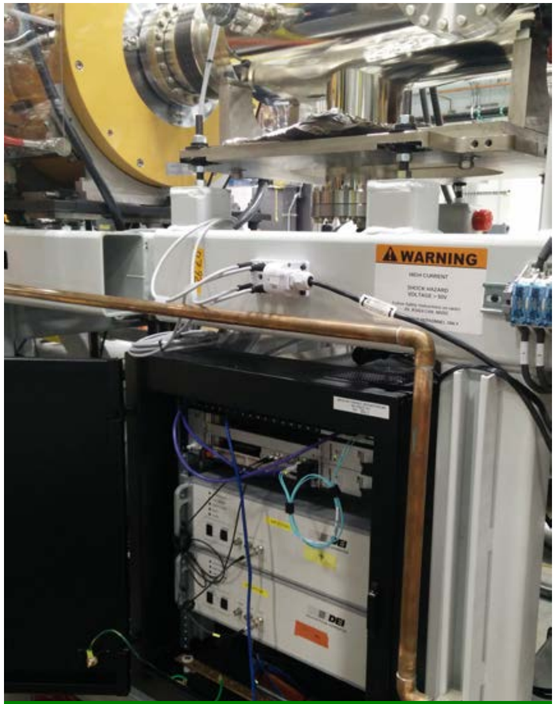
- All beam timing modes have been verified in production
- Time is synchronized to GPS time for long-term stability
- Timing distributed over fiber between cPCI EVG and cPCI or MTCA EVR



GPS Antenna



Timing Master

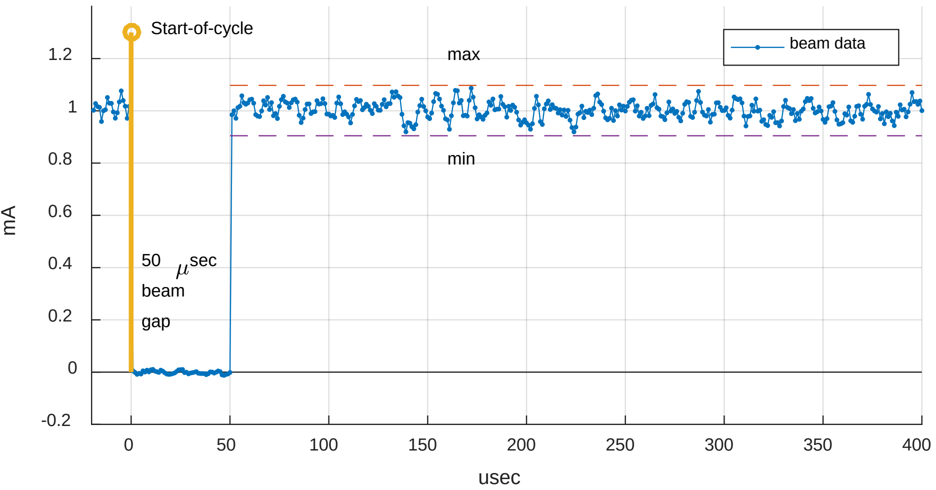


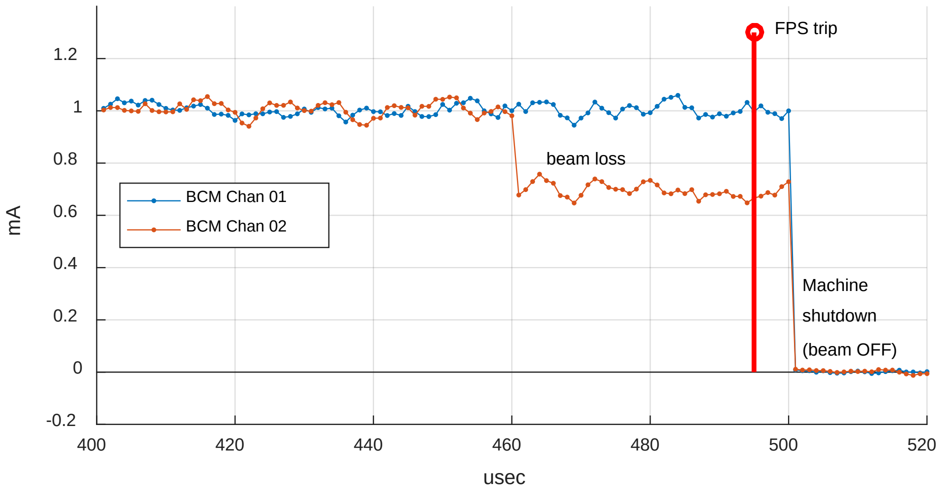
Event Receiver for Chopper

Beam Data Reporting
Common to all Fast Acquisition Devices

- Per-cycle measurements
  - Summarize data from each 10 ms cycle
  - Each cycle starts with 50 us beam gap
    - » Opportunity for background subtraction
  - Statistics calculated on per-cycle data

- Ring Buffer (Post-mortem buffer)
  - > 1 sec history (per channel), @ 1MS
  - Always running (freeze when MPS trips)
  - Acquired upon MPS trip interrupt





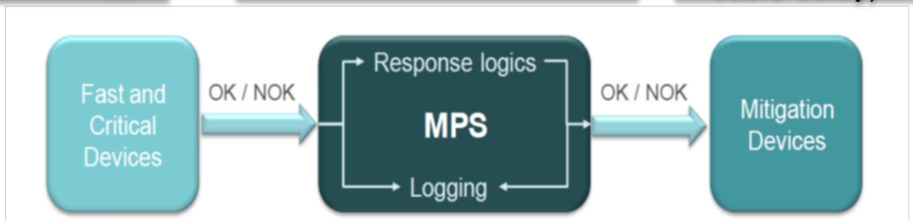
Per-Cycle Record (10 ms)
• Total Charge (TC)
• Average Beam
• Typical Beam
• Min / Max
• Time ON
• Timestamp

x100 per second

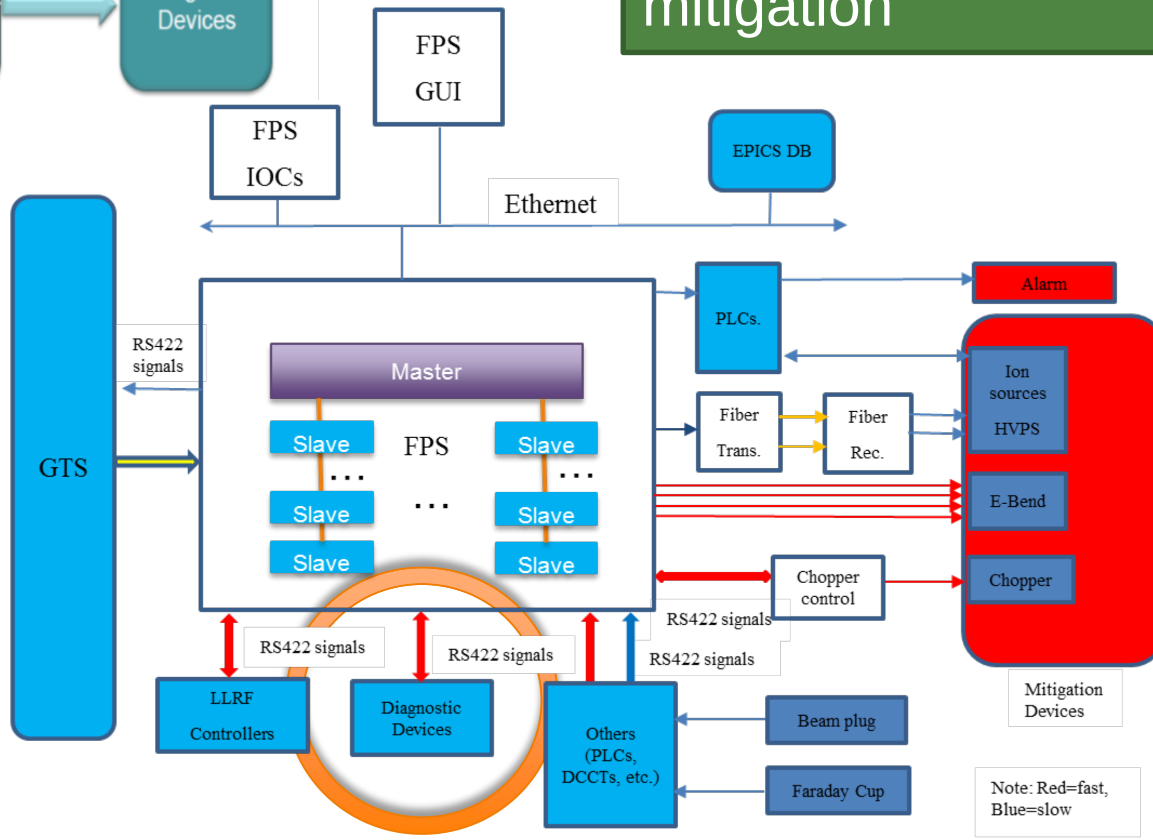
Machine Protection System in Operations

10 µs	10µs	5 µs	10 µs
Sensing and indicating error condition to FPS (include cable delay)	FPS Response Time From Input OK/NON to output to mitigation device	Mitigation Action (include cable delay)	Beam mitigation time

35 µs time budget includes sensing, signal trans-mission, logic, and mitigation

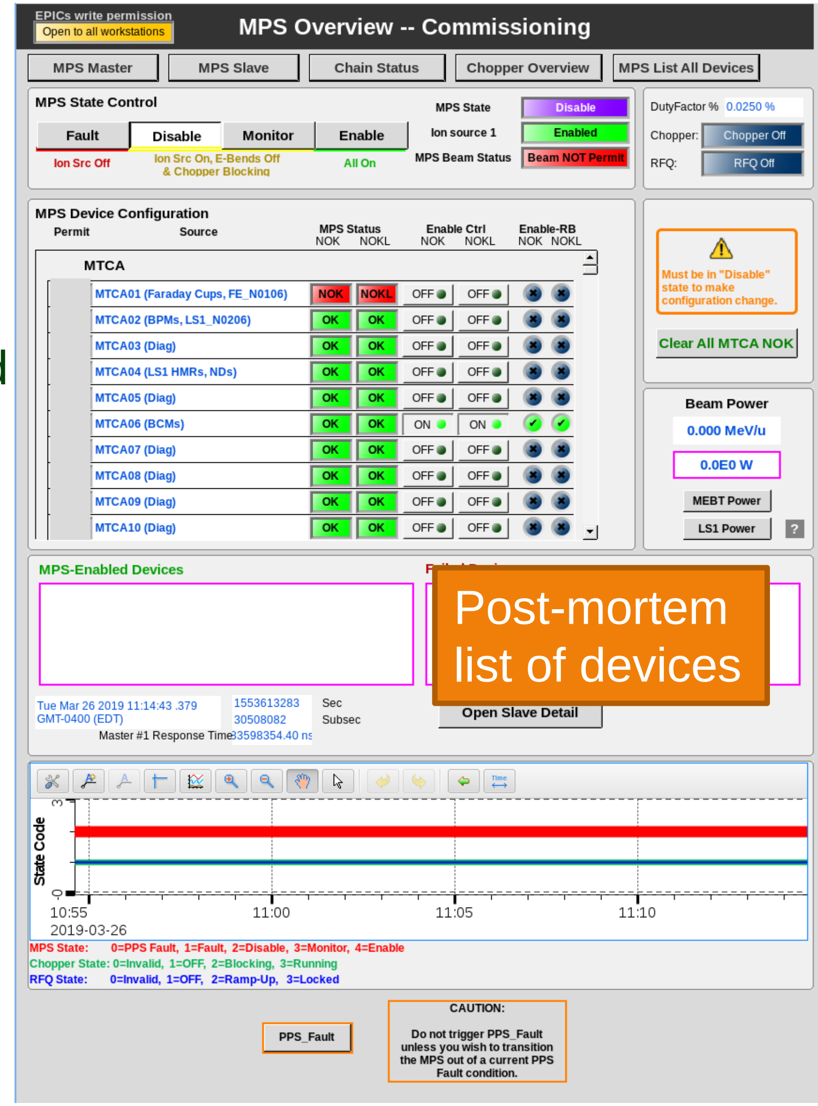


- Diagnostics interface to MPS is implemented at the board and chassis level
- Thresholds are compared at various sensitivity/time-averaged stages
- Special purpose FMC cards are used with FGPDBs to send & receive to MPS network



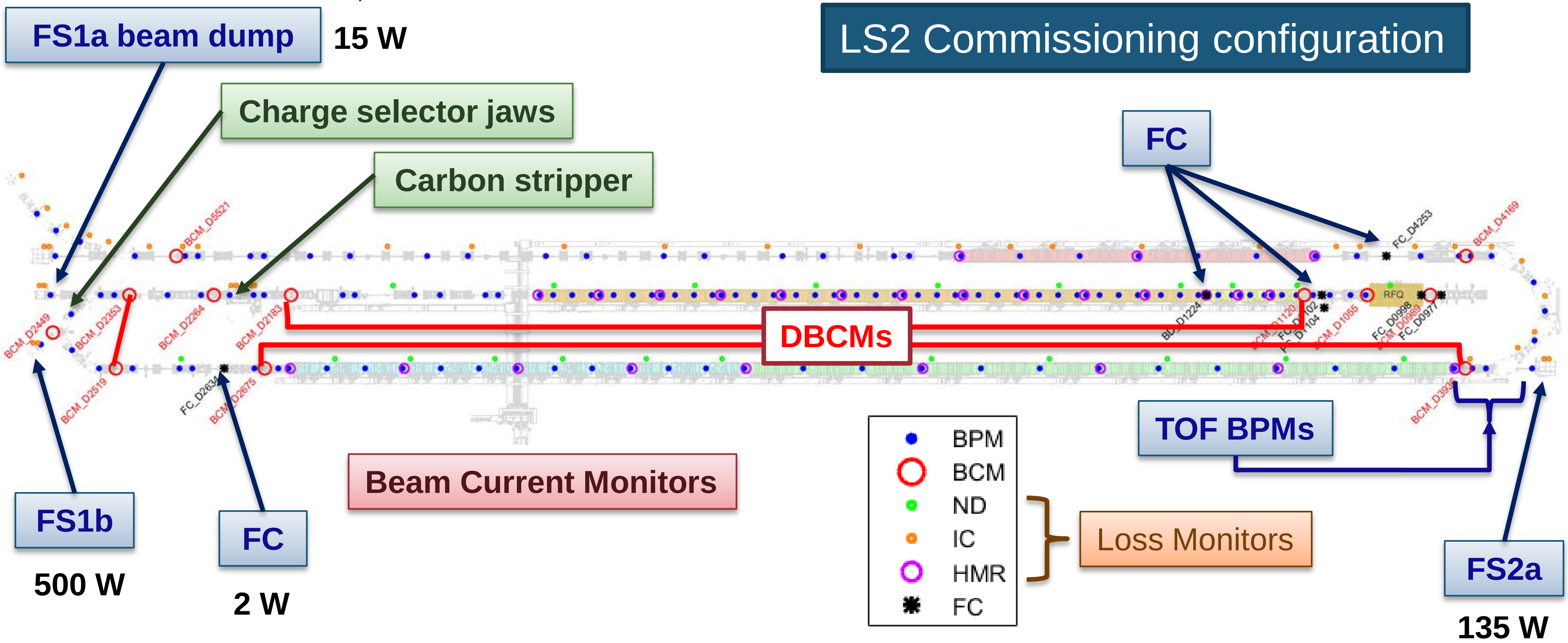
Machine Protection and Global Timing Controls

- Operators interact through Chopper and MPS controls
- Lower Level Interface for Run Permit System
- Expert-level control during Commissioning
- EPICS PVs exposed and available to Run Permit System
- Operator facing controls are constantly improved from control room experience



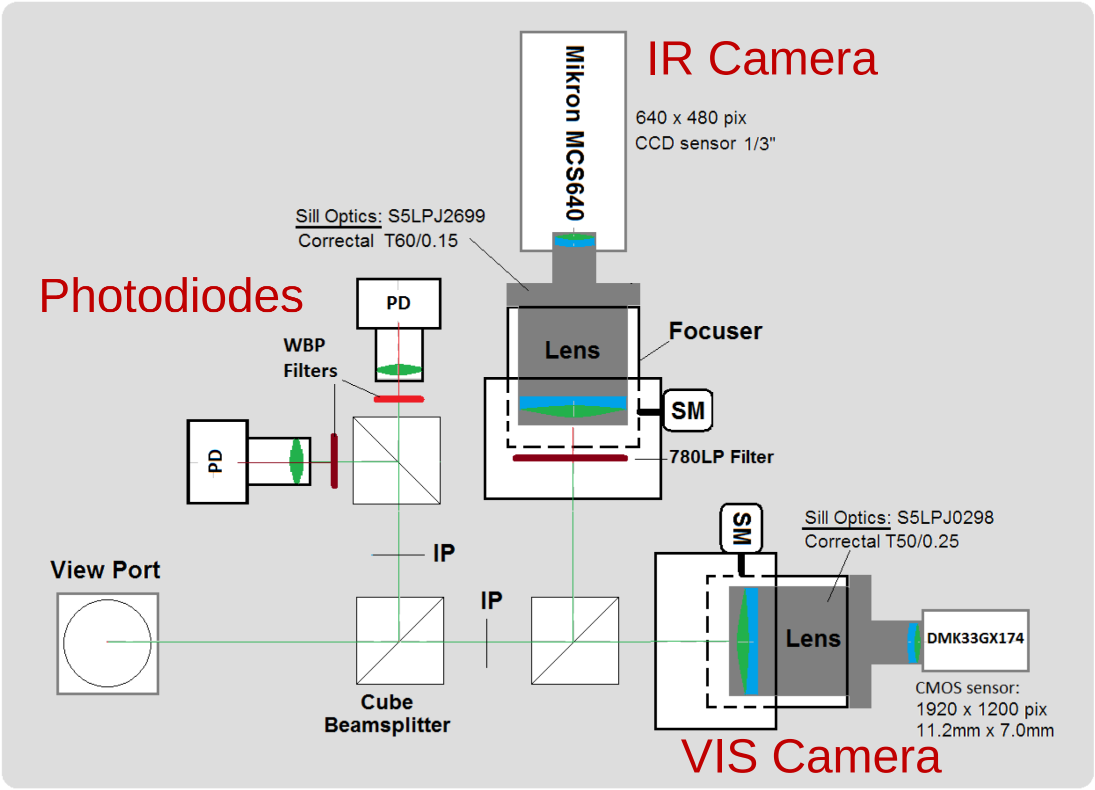
High Energy Beam Monitoring
Verifying OSE/MPS Limits

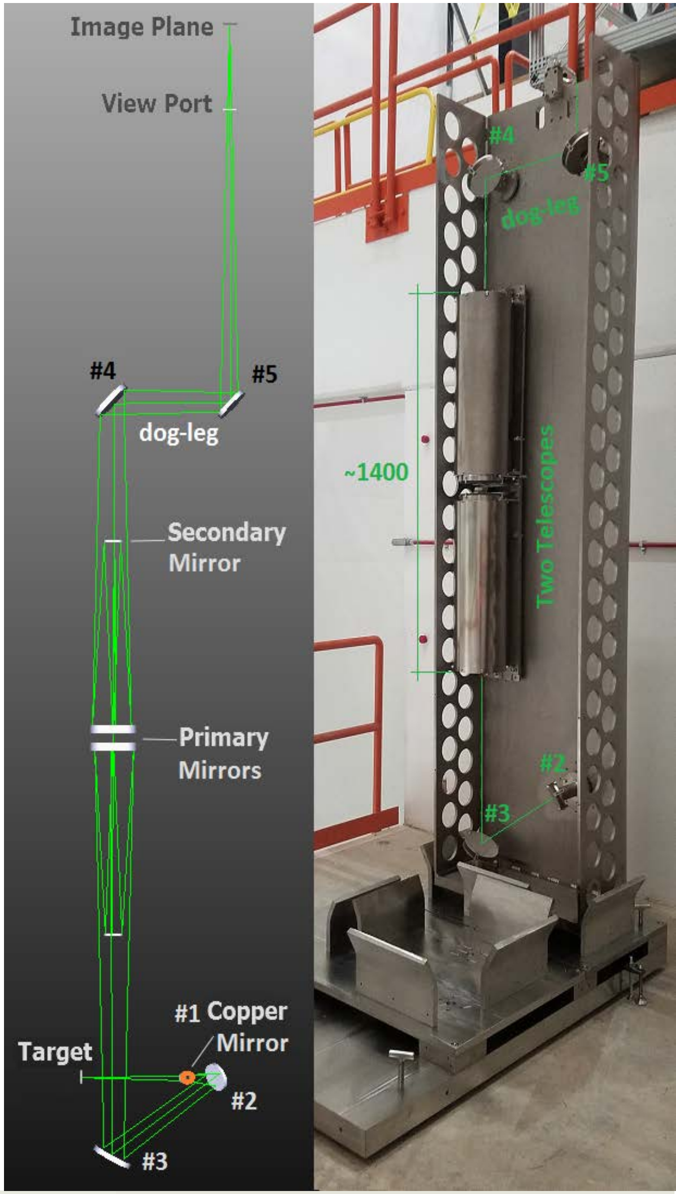
- Average power delivered to beam dumps
  - **Intensity** monitored with Beam Current Monitors (BCMs) D3936
  - **Energy** measured via Time of Flight with Beam Position Monitors (BPMs)
    - » LS1: D1923, D1967, D2130 LS2: D3924, D3958
  - **Losses** monitored with Differential Beam Current Monitoring
    - » LS1: D1120/D2183, LS2: D2519/D3936



High Power Target Thermal Imaging System

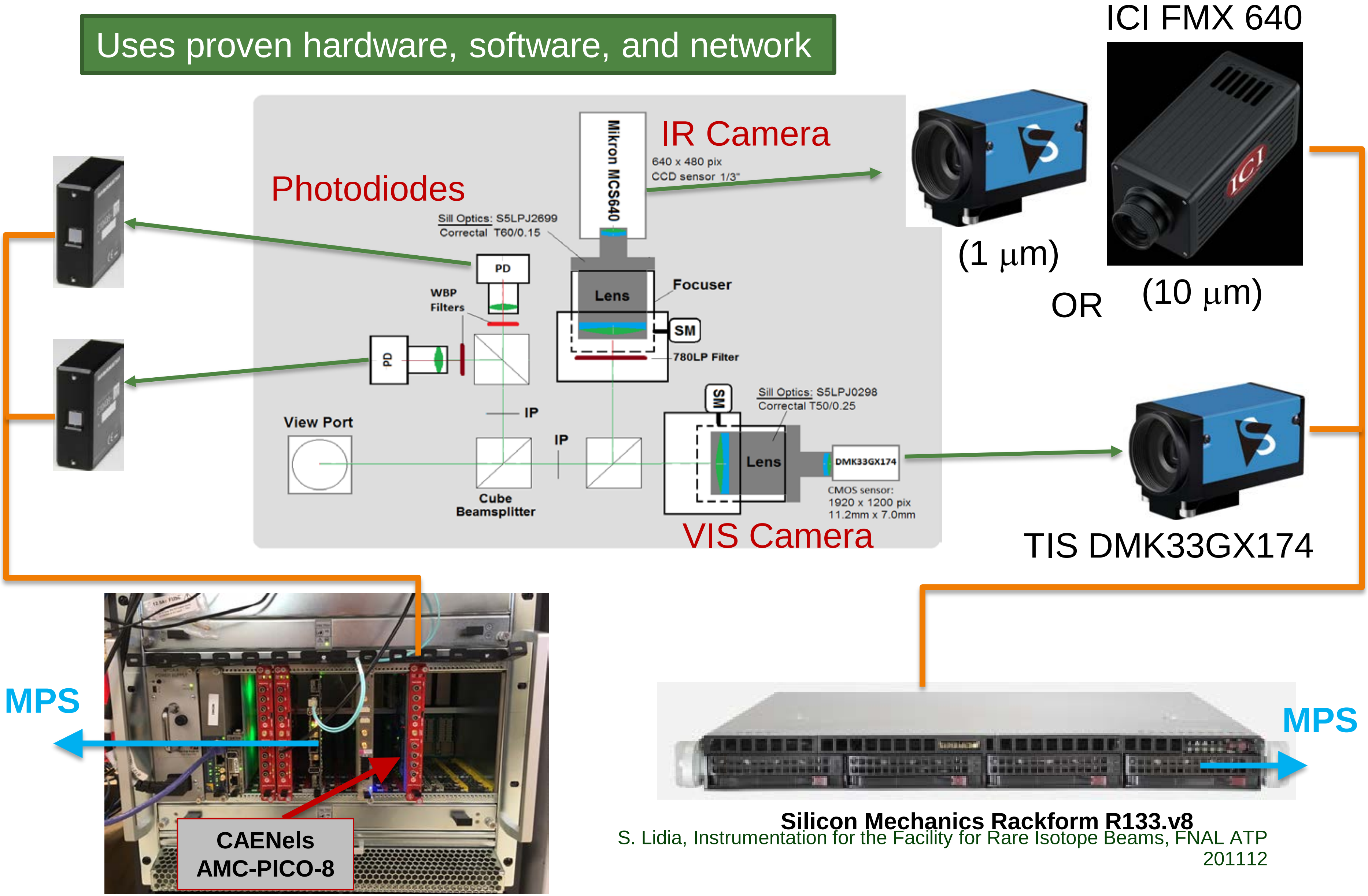
- Monitoring beam on target and dump
  - Variations in position, distribution, intensity
  - Target temperature
- Interface to Fast Machine Protection System
  - Intensity and temperature changes monitored with fast detectors





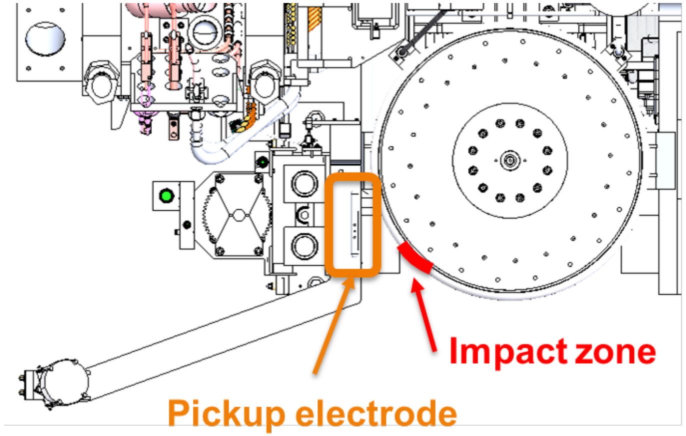
Interfaces for Thermal Imaging and Optical Pyrometry

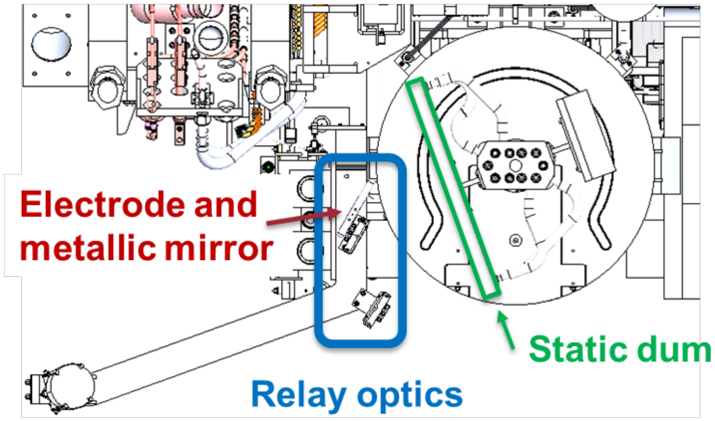
Uses proven hardware, software, and network



Beam Dump Monitoring

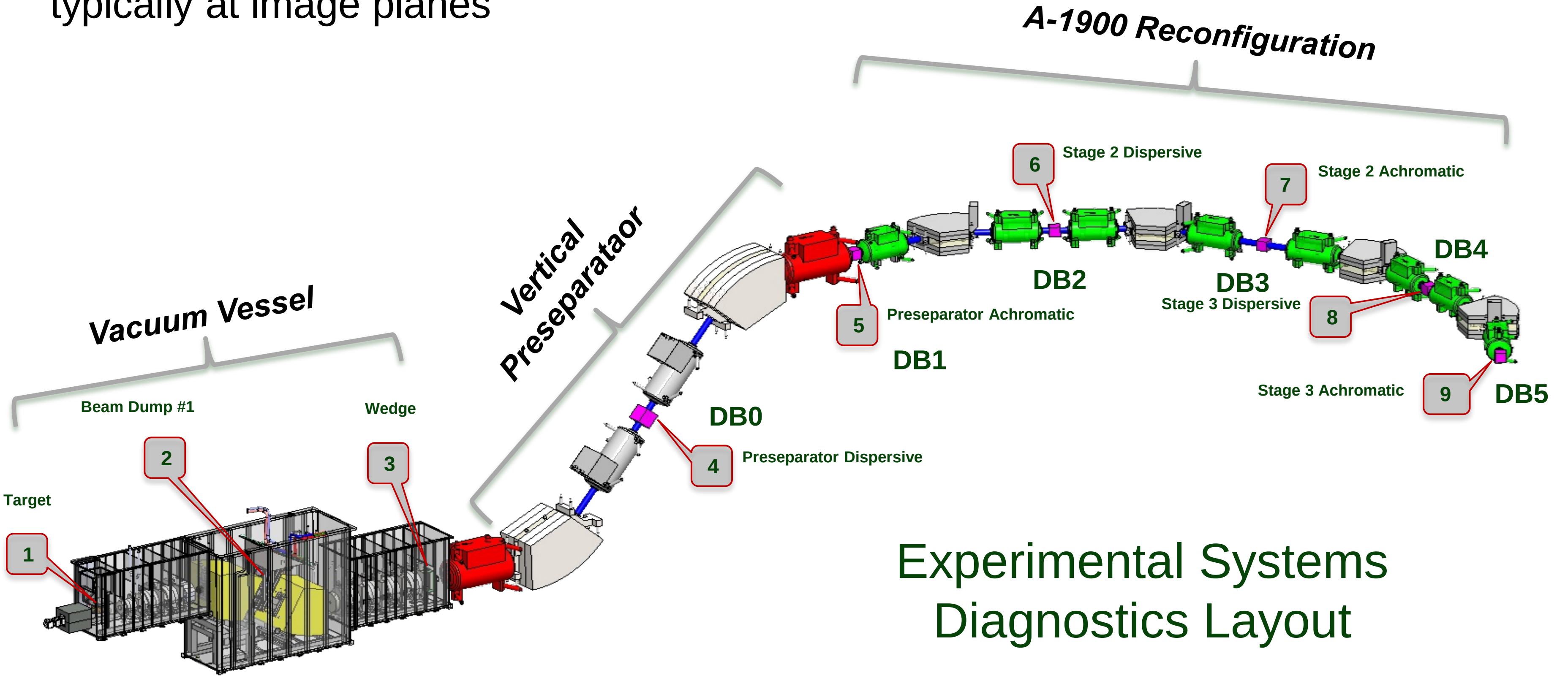
- Thermal imaging system is similar to that in the Target area
  - Monitors image from 10 μm radiation
  - Camera server is tied to MPS
- We have designed a secondary electron emission monitor to provide defense-in-depth
  - Electron signal provides OK/NOK feedback to Machine Protection System
    - » DAQ for current signal is CAENels PICO-8 picoammeter board
    - » Standard FRIB MTCA.4 system for reporting to MPS
  - Pickup electrode geometry and position fit to constraints of beam dump geometry and maintains thermal imaging optical aperture
  - System has passed 90% review and is in procurement.





Fragment Separator Diagnostics – Overview

- Verify primary beam position on target and beam dump
  - Thermal imaging in locations #1 and #2
- Rare-isotope beam diagnostics to tune and characterize beam to experiments
  - Tracking detectors, time-of-flight detectors, particle-ID detectors, viewer plates, etc.
  - Concentrated in strategic locations (#3 – 9), typically at image planes



Fragment Separator and A1900 Diagnostics

	Wedge	DB0 Presep Dispersive	DB1 Presep Achromat	DB2 Stage 2 Dispersive	DB3 Stage 2 Achromat	DB4 Stage 3 Dispersive	DB5 Stage 3 Achromat	DB6	DB7
Viewer	1	1	1	1	1	1	1	1	1
PPAC Profile Monitor			2		2	1	2		
Selection Slits	1 (V)		1 (V)		2 (H)	1 (H)	2 (H, V)		
Wedge	1			1	1	1			
Energy Loss Detector	PIN		1 (PIN)				1 (PIN)		
Total Energy	PIN						2 (PIN, Scint)		
Timing Detector			1 (Scint)		1 (Scint)		1 (Scint)		
Faraday Cup							1		
High resolution photon detector							1 (HPGe)		

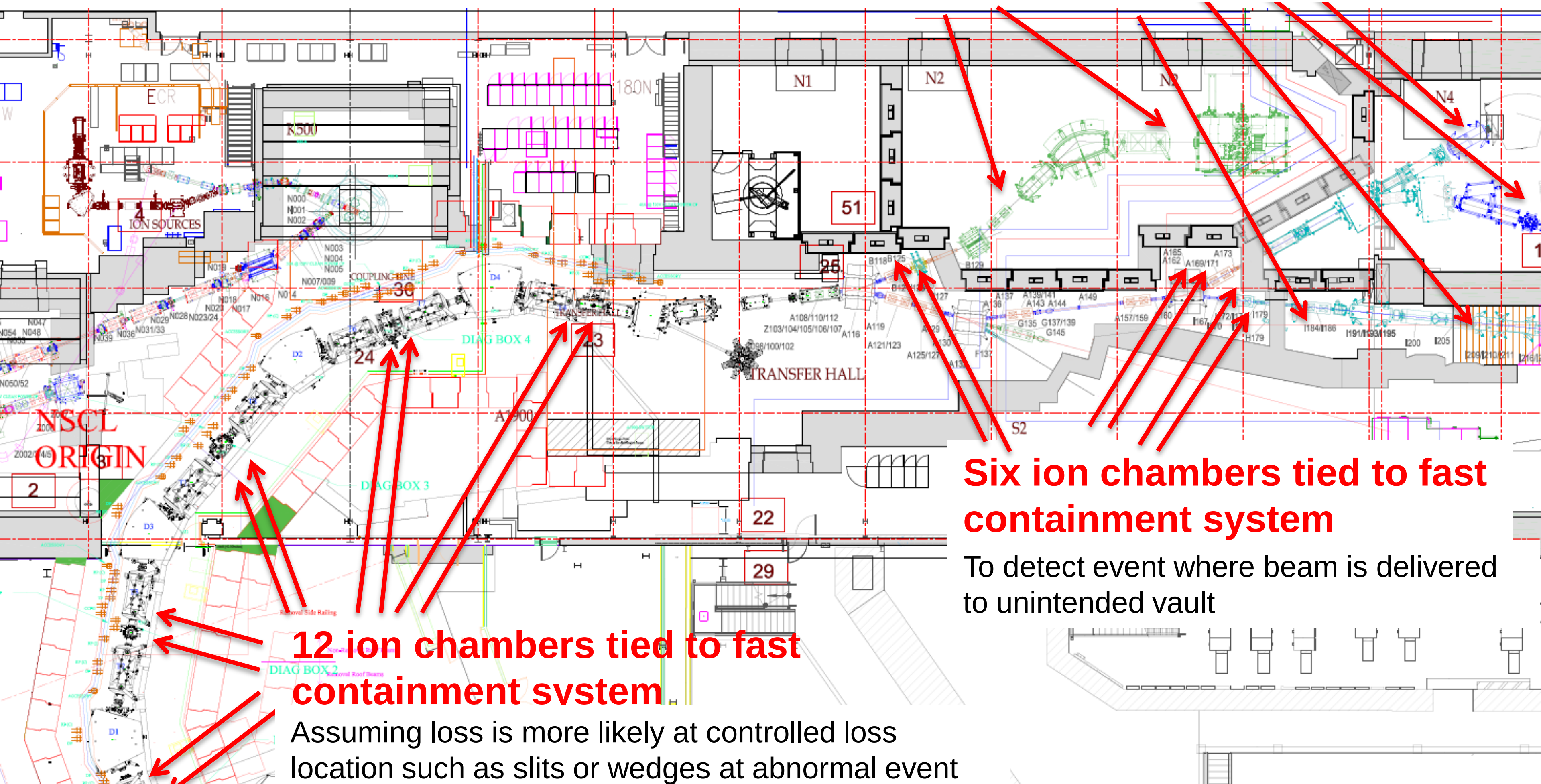
Existing component
Design complete
Future

Location on Fast Radiation Monitors
Fragment Separator, Transfer Hall, Vaults

- Scope for fast beam containment system is extended to transfer hall and experimental vaults

Six ion chambers tied to fast containment system

To detect unintended increase of beam power



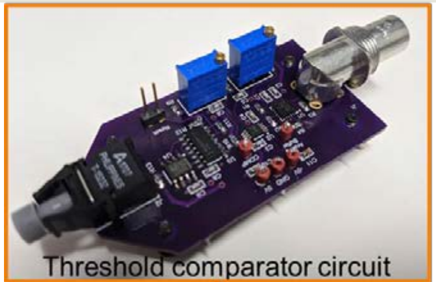
Six ion chambers tied to fast containment system

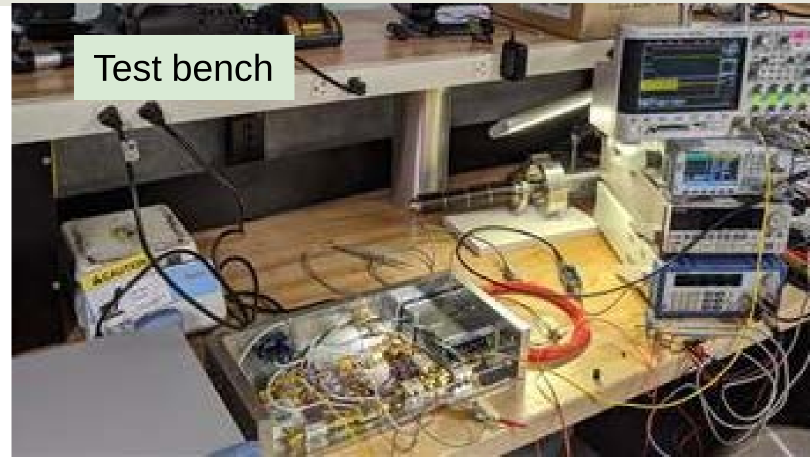
To detect event where beam is delivered to unintended vault

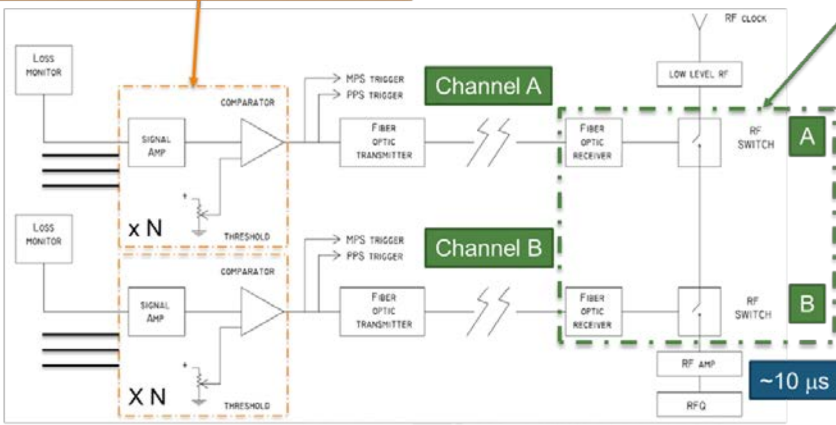
12 ion chambers tied to fast containment system

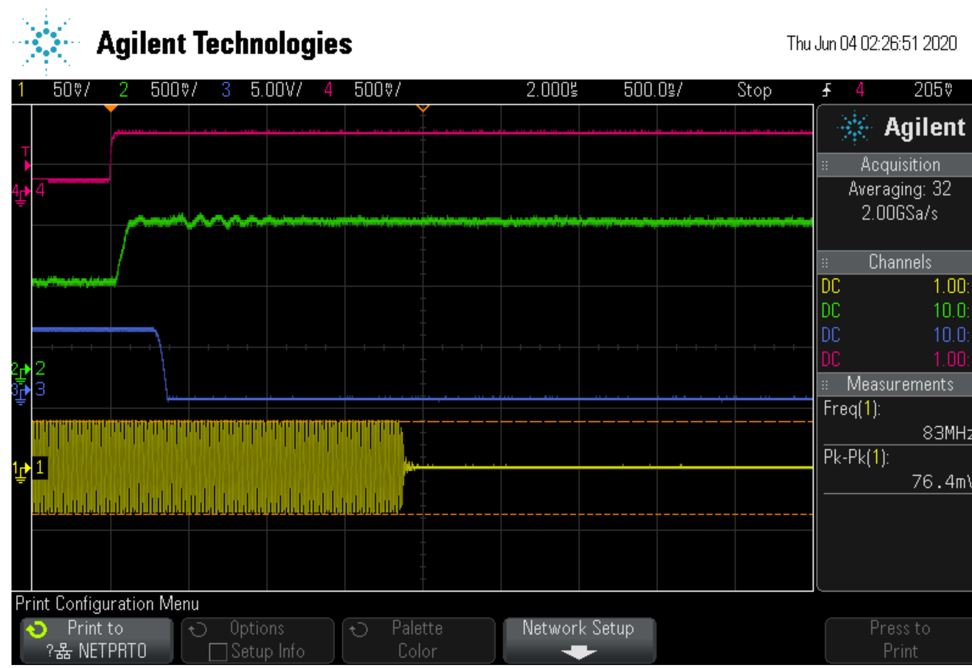
Assuming loss is more likely at controlled loss location such as slits or wedges at abnormal event

Fast PPS System Tests in Progress (6/4/2020)









In the attached scope plat arranged from top to bottom you can see:

1 – Output of the pulse generator

2 – Analog buffer response of the detector board

3 – TX pulldown

4 – RF Output

From the pulse input to the cutoff of RF is consistently less than 2 us.

The Pulse input is moving from 1uA to 50uA (25uA trip threshold), but with a 156pA/rad/hr ion chamber sensitivity represent a quite large 6.5k rad/hr to 320k rad/hr jump.

Other development activities

- Development of next generation FPGA processing
  - MOU with LNLS (Brazillian Light Source) t develop hardware and firmware based on Open Hardware Artix-7 FPGA
  - https://creotech.pl/wp-content/uploads/2015/08/CTI-AFC_datasheet.pdf

- Development of beam contamination monitor
  - Looking at (h,c)BN as intrinsic semiconductor (5.2-6.4 eV bandgap). Radiation hard, similar to Diamond as a detector.
  - 20 MeV/u monitoring point. 500 keV/u considered but poses difficulties
  - ^{10}B (~20% natural abundance) has high cross section for thermal neutron capture. Can be used for compact neutron monitor

Advanced Detector Development

- Led by Marco Cortesi, NSCL/FRIB Detector Lab
  - S800, HRS
- Optical PPACs and E-Loss detectors (MHz particle rates)
- Gas Electron Multiplier and novel Gas/Solid State Grid arrays for high speed particle tracking
  - Micro-pattern Gas Detector (MPGD)
  - Thick Gaseous Electron Multiplier (THGEM)
- Fast electronic systems for detector readout (AT-TPC)
  - RD51 Collaboration

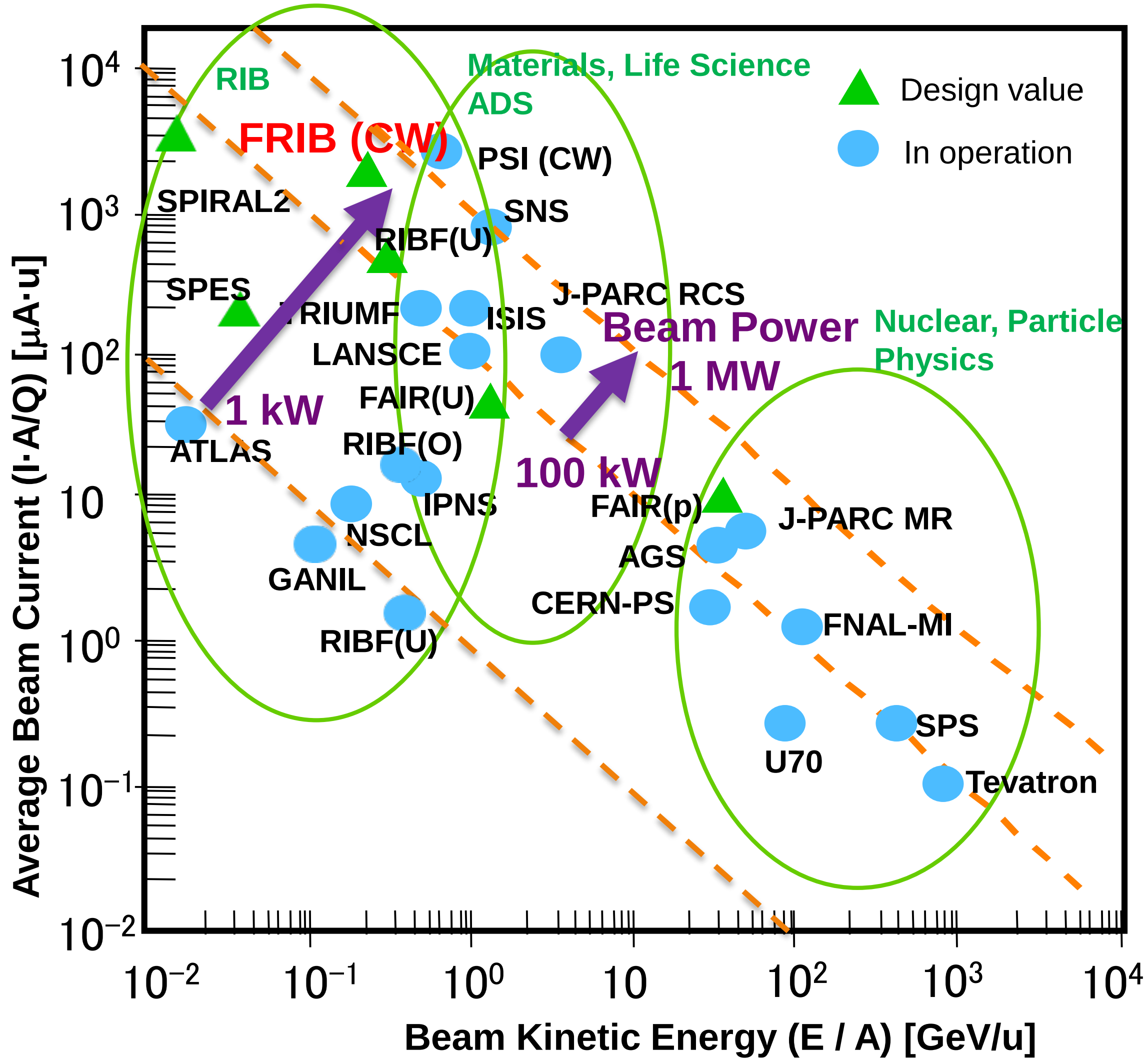
Acknowledgements

H. Ao, B. Barnes, J. Brandon, N. Bultman, F. Casagrande, S. Cogan, J. Crisp, K. Davidson, E. Daykin, P. Gibson, I. Grender, L. Hodges, S.-H. Kim, W. Hartung, M. Hausmann, L. Hodges, K. Holland, M. Ikegami, M. Konrad, T. Larter, Z. Li, I. Malloch, G. Machicoane, H. Maniar, P. Manwiller, T. Maruta, B. Martin, D. Maxwell, D. Morris, P. Morrison, C. Morton, D. Omitto, P. Ostroumov, A. Plastun, J. Popielarski, L. Popielarski, E. Pozdeyev, H. Ren, P. Rodriguez, T. Russo, K. Saito, S. Stanley, A. Stolz, R. Webber, J. Wei, T. Xu, Y. Yamazaki, T. Yashimoto, T. Zhang, Q. Zhao, S. Zhao

THANK YOU

FRIB Among High-Intensity Accelerators

- During the past decade, proton accelerators raised beam power to ~ >1.7 MW
  - SNS (USA): >1.7 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



All Types of Hardware IOCs Are Deployed

µTCA.4

Delta Tau MC

DNA PPC5

BPM - EVR

DMK 33GX174

AI 207

Picoammeter

Iseg EHS 8620n

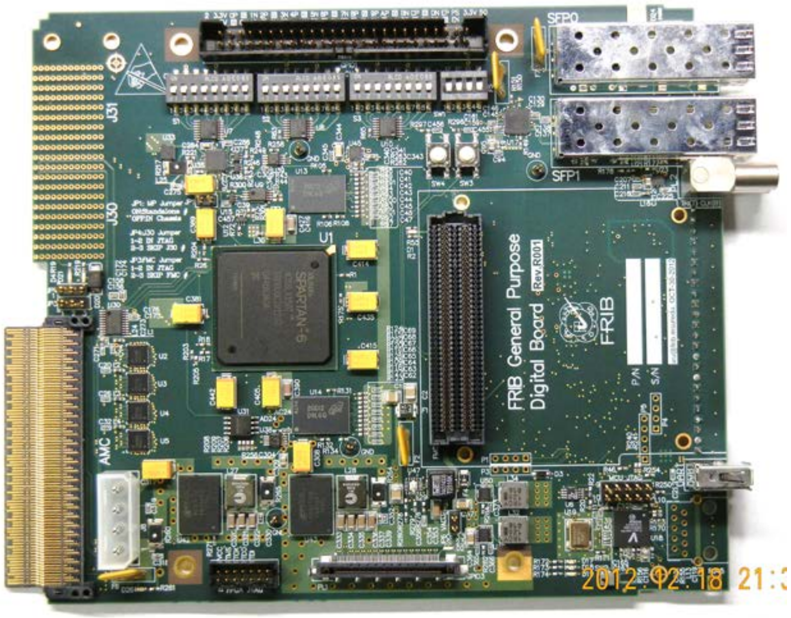
AO 308-020

BCM

Cryocon 18c

AO 308-350

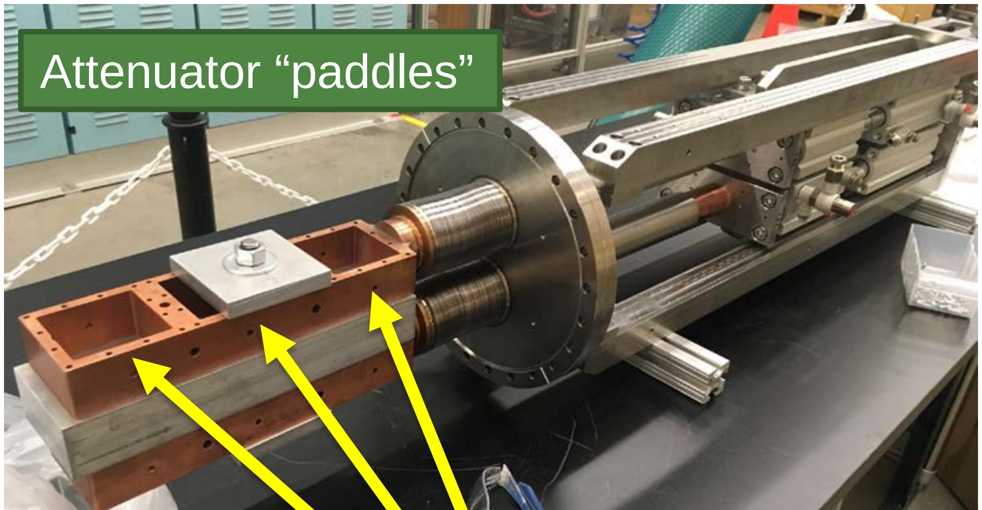
FRIB General Purpose Digital Board (FGPDB)



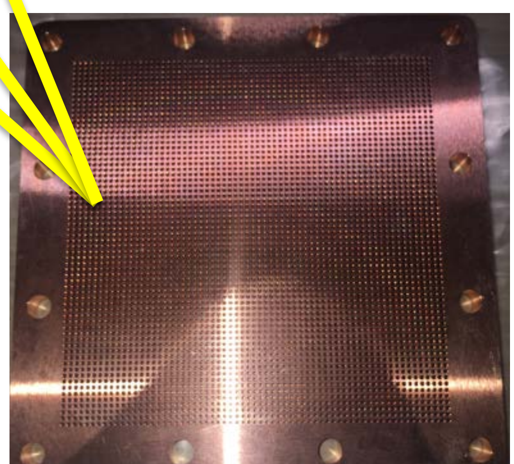
- FRIB
  - In-house design, for FRIB
- General purpose
  - Multiple groups utilizing common board
  - MTCA.4 or “pizza box” compatibility
- Digital board
  - Digital signal processing with Field Programmable Gate Array (FPGA)
  - Optical fiber transceivers
  - Many I/O for high-speed data
- Prototype boards working in existing systems:
  - LLRF control box, FPS slave node box, EVR/FPS receiver for diagnostics
  - Latest FGPDB Rev 4 for diagnostics, fits single-slot in MTCA.4 chassis
- Inexpensive: < $1K per finished board in production quantities
- Looking towards Open Hardware for upgrade (MOU with LNLS)

Instrumentation for Intensity Control

- Electrostatic beam chopper
- Beam attenuator system (10X – >10^6X)



Hole plates



Optics designed to preserve phase space envelope

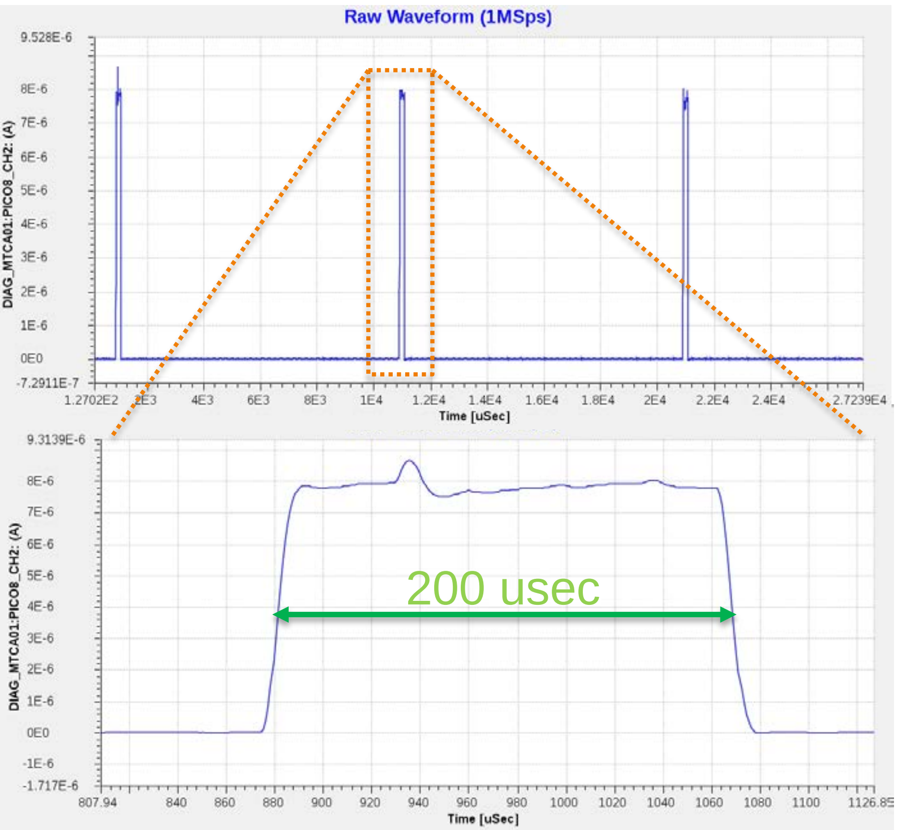
1 μs – 10 msb pulse duration
1,5,10,20,50,100 Hz repetition rate
3500 kV +/- per plate

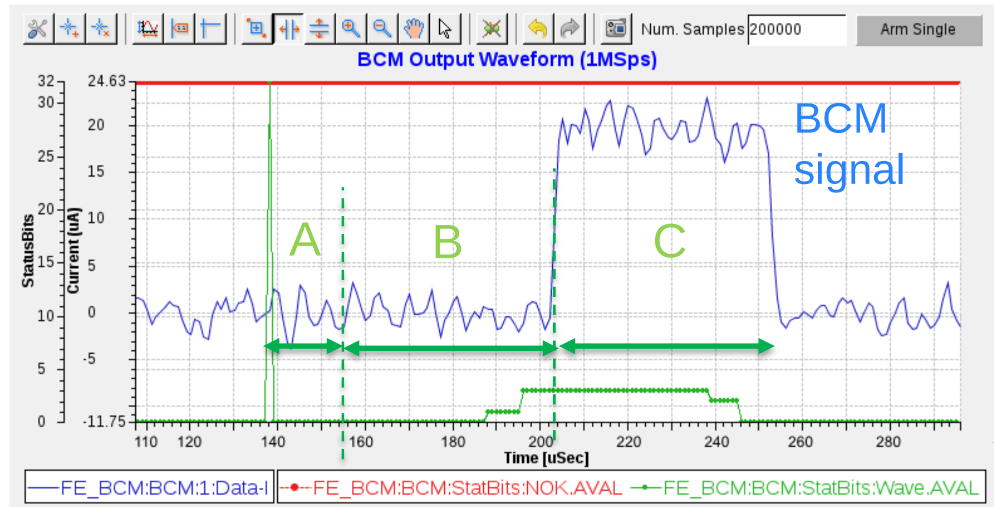
Chopper Operation Validated with Beam

High Level of Care System Validated to Provide Operational Safety Envelope

- 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

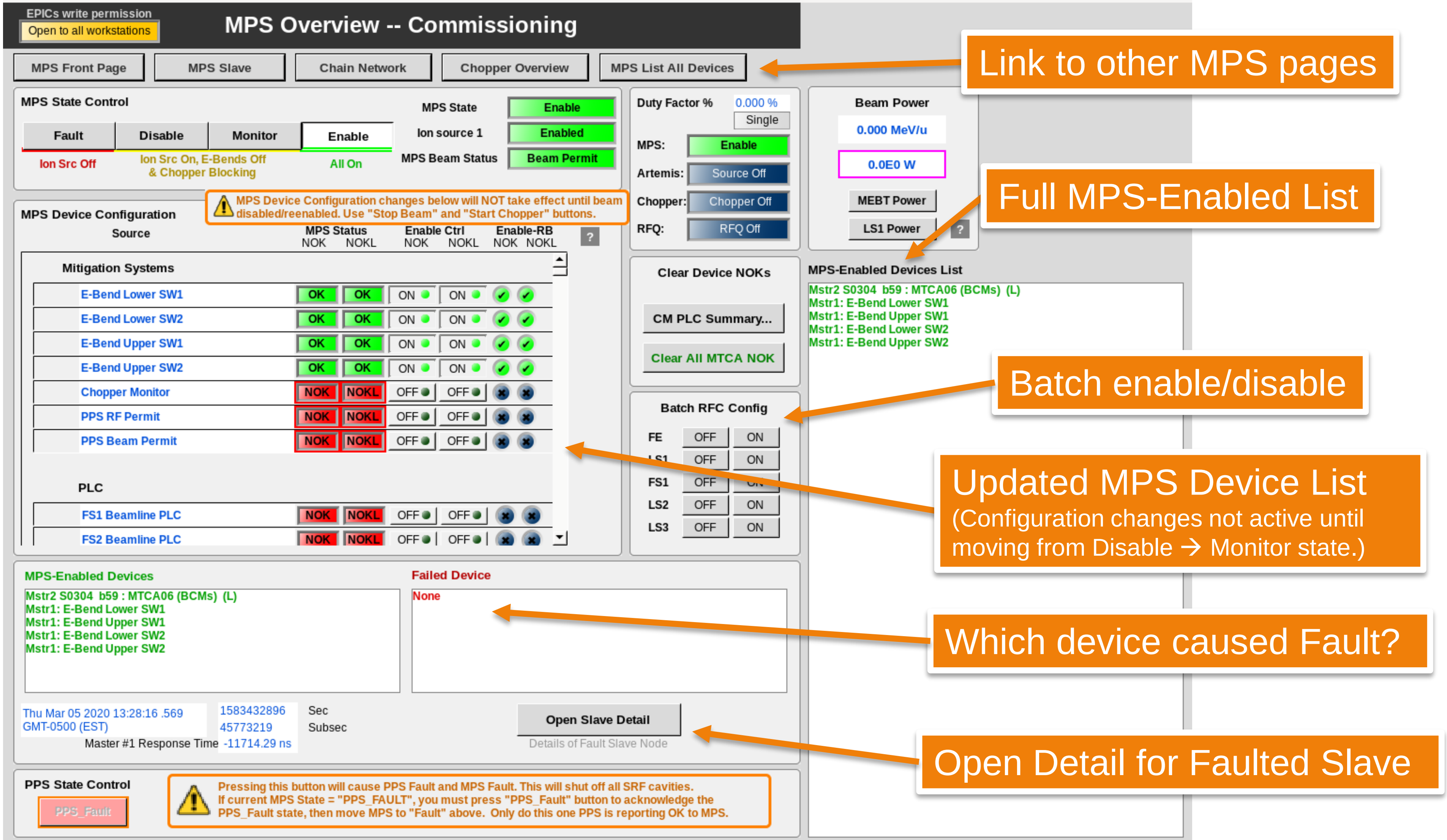




A. ToF delay (Chopper to BCM), ~15 usec
B. Beam "gap", 50 usec
C. Beam active, 50 usec

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

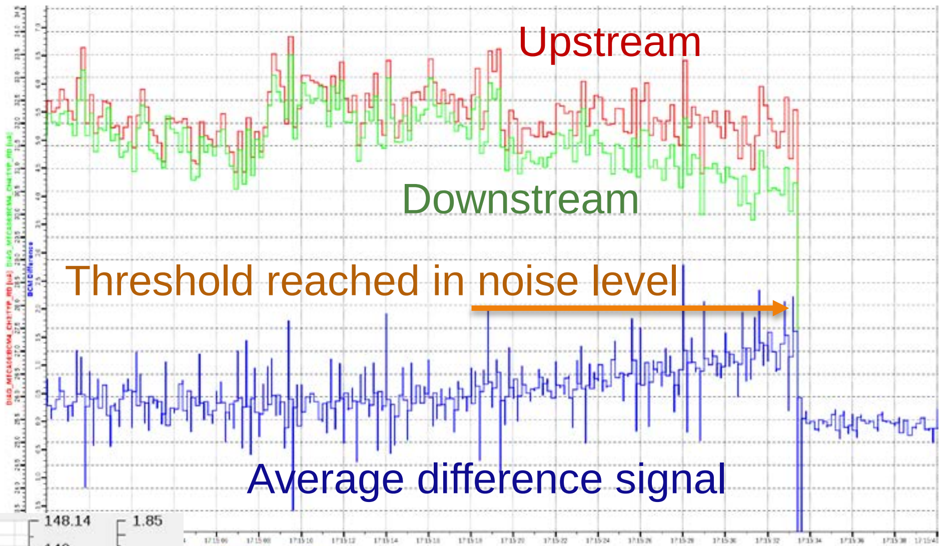
MPS Commissioning Overview Screen

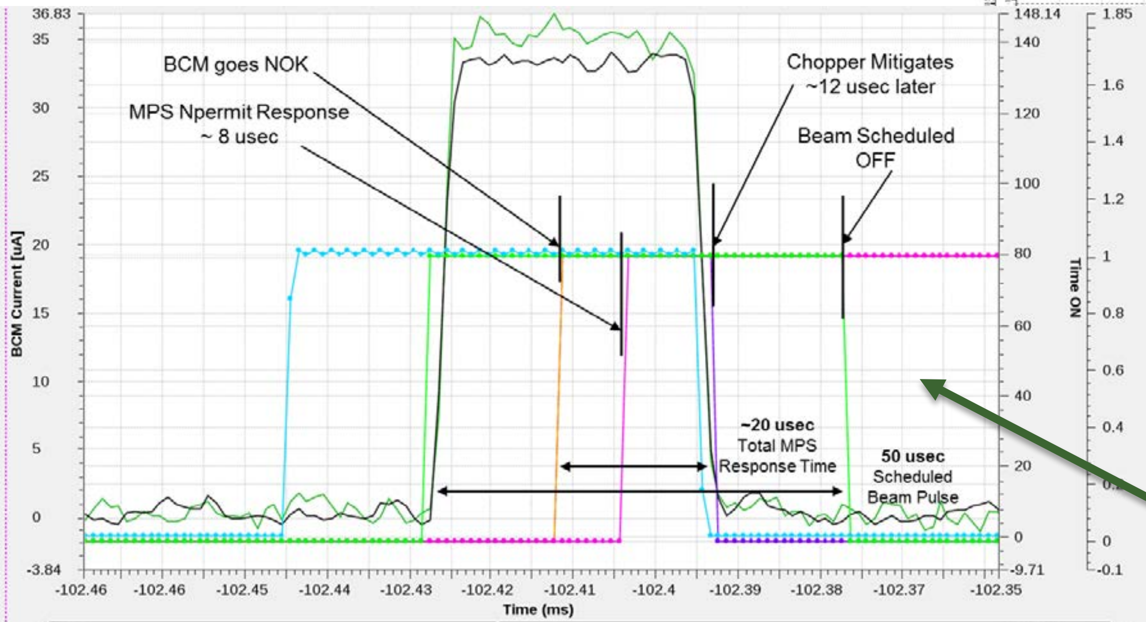


Differential Current Monitoring Is Established

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



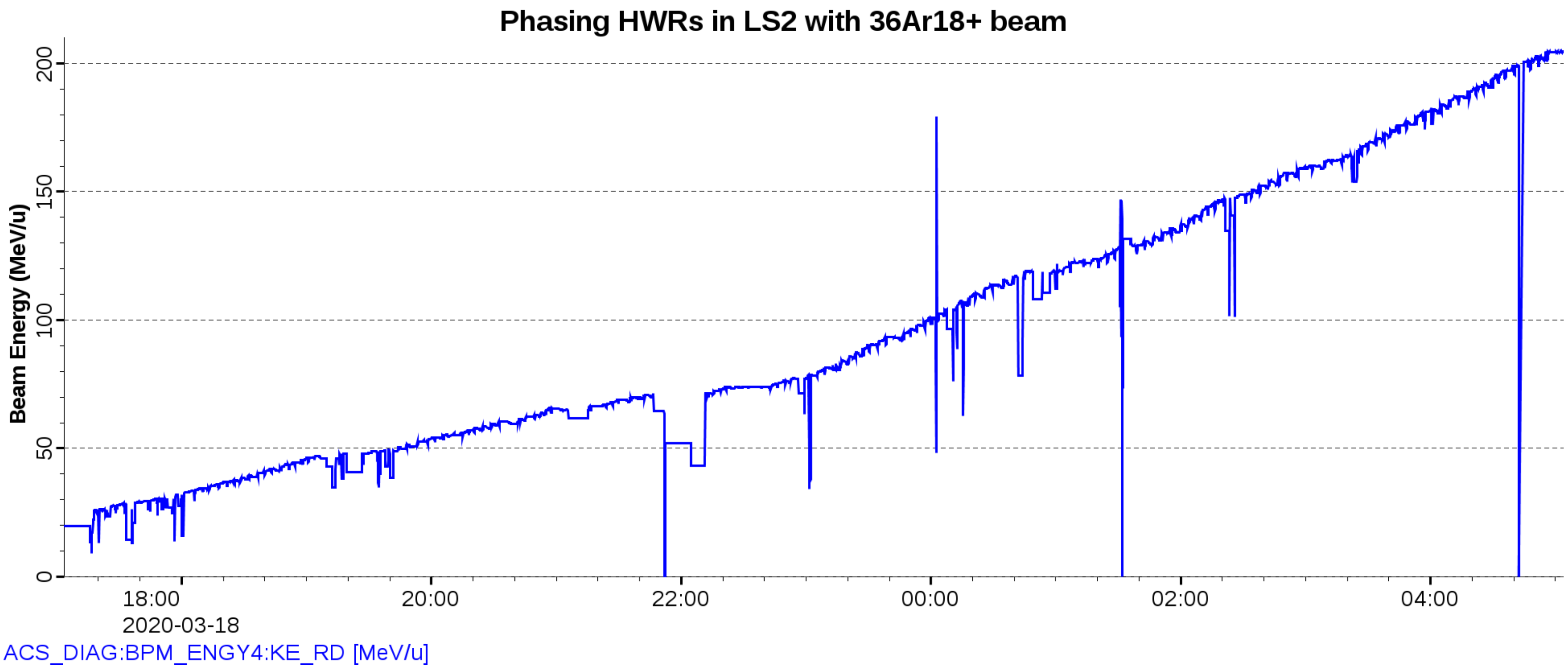


- **1.5 MeV/u case**
  - MPS trip setpoint at **ΔI ~ 1.5 μA**
  - ~4.5% difference
- **2.3 MeV/u case**
  - Threshold level reduced
  - MPS trips when **ΔI ~ 1.0 μA**
  - ~2.8% difference

Postmortem buffer demonstrates time sequence of MPS mitigation

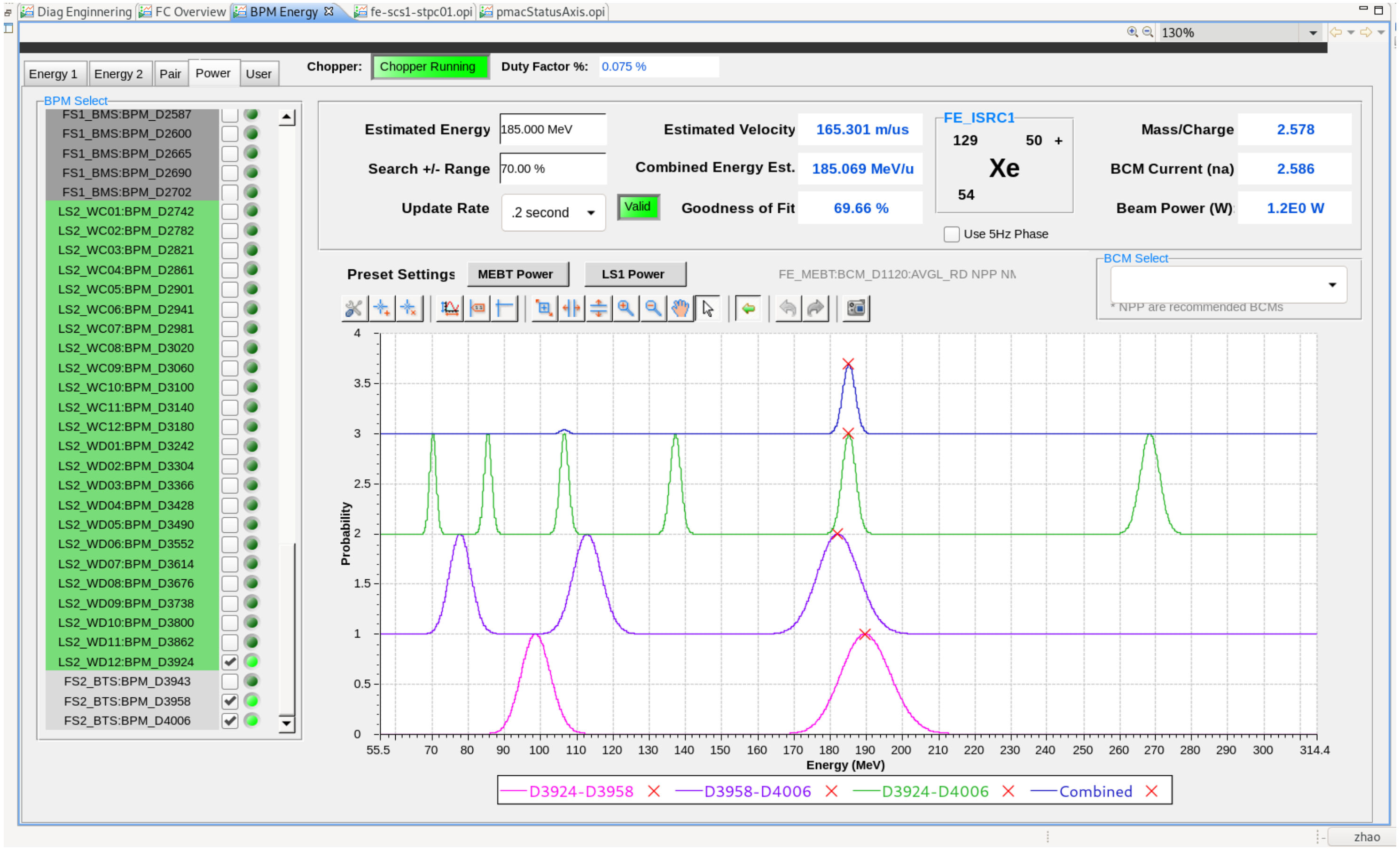
Tuning of HWRs for Acceleration from 20 MeV/u to 204.4 MeV/u Took about 12 Hours

- Phase scan of 148 HWRs took 12h18'
  - Beam availability during this time was 91.9%
- Machine Protection System was activated



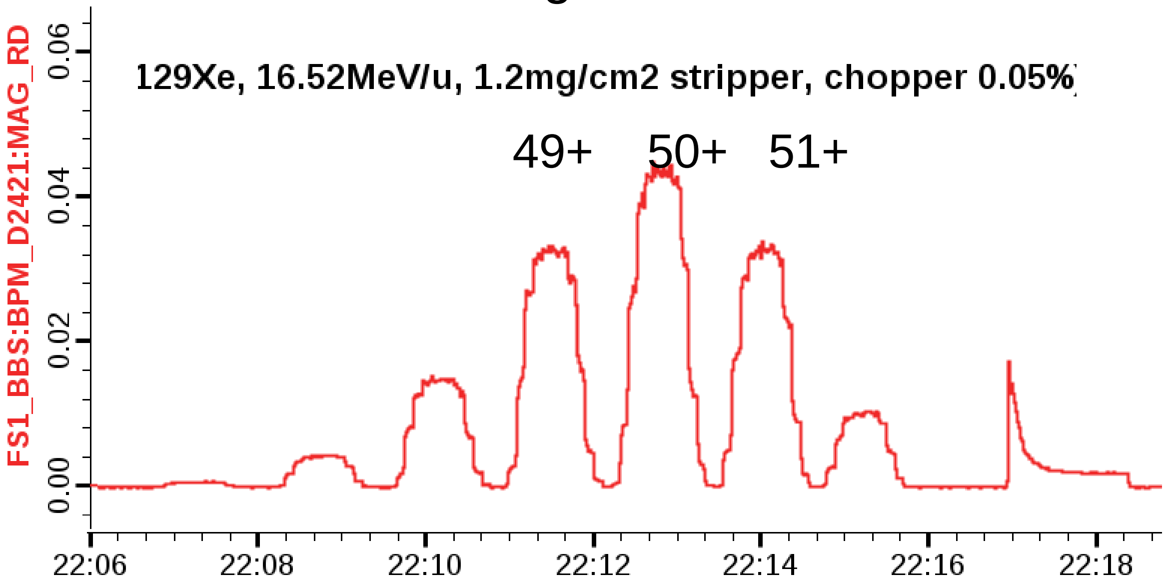
185 MeV/u vs. Design 180 MeV/u in LS2

- Beam energy after acceleration with 39 cryomodules comprising total 272 superconducting cavities



Stripping at 17 MeV/u

- LS1 setting was developed for adiabatic acceleration of $^{129}Xe^{27+}$ beam up to 17.06 MeV/u
  - Energy after 1.2 mg/cm^2 carbon foil is 16.52 MeV/u
  - In future, this setting of the LS1 will be used for acceleration of all FRIB ion species including $^{238}U^{33+}$ after scaling with q/A
- Charge state distribution
  - 30.5% in 50+, 76.0% in 3 charge states

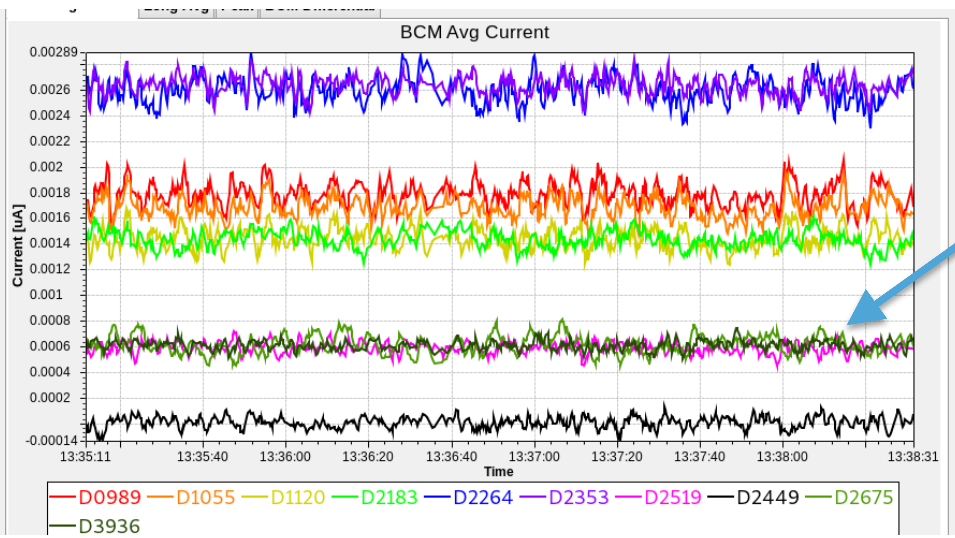


Factor of 2.5 Increase of Beam Intensity with Three Charge States Acceleration

- Simultaneous Acceleration of 3 charge states of ^{129}Xe up to 185 MeV/u
- Transmission is 100%

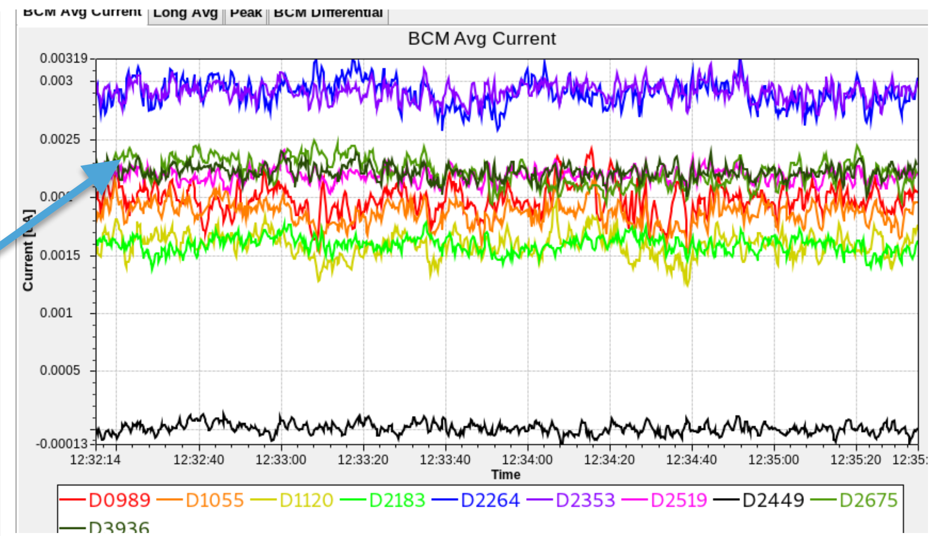
Charge state 50+

Stripping efficiency into 50+ = 30.5%

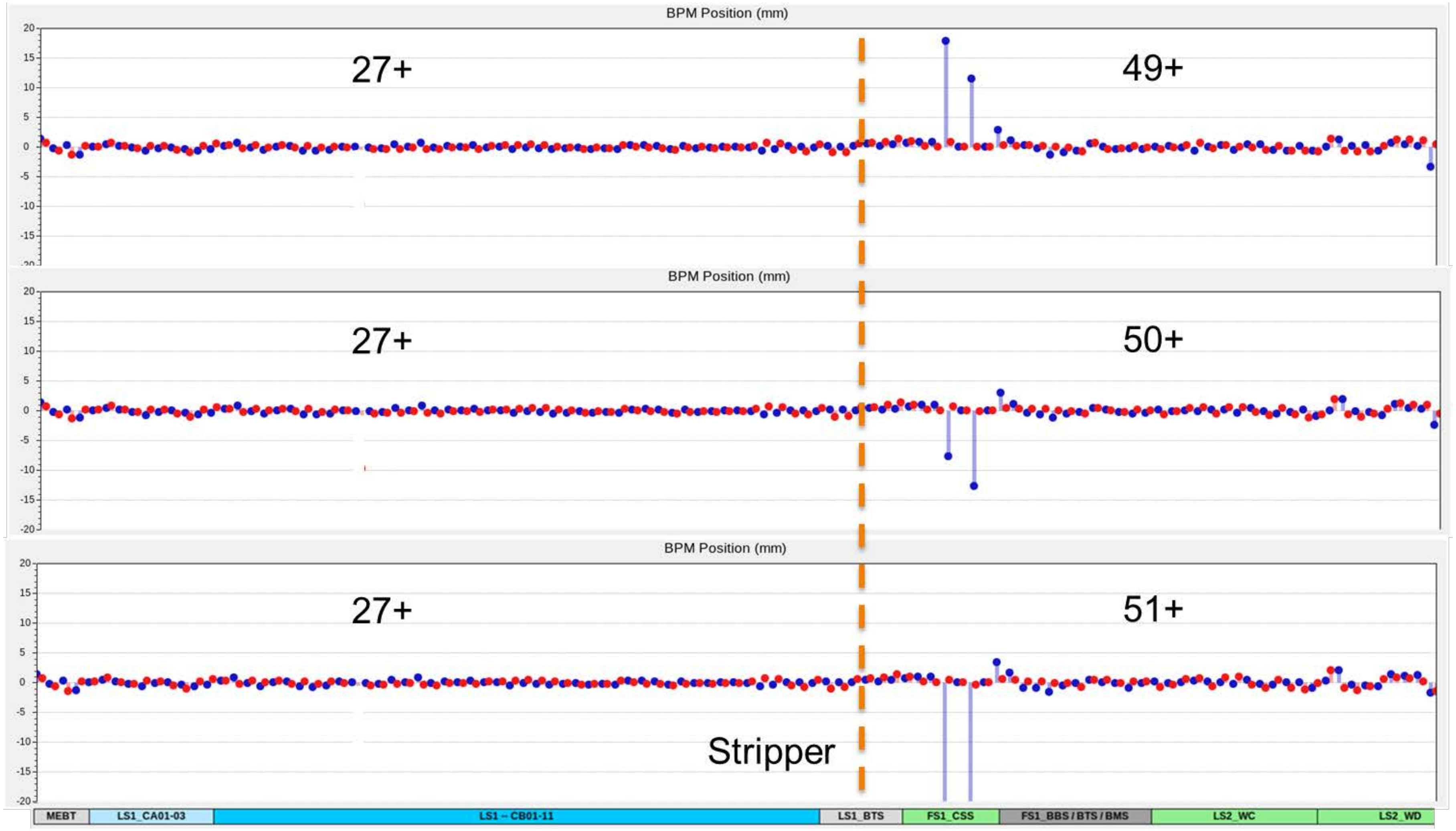


Charge state 49+,50+, 51+

Stripping efficiency into 49+,50+, 51+=76.5%



Beam Position in the Linac: 49+,50+,51+ in the Same Tune of Linac

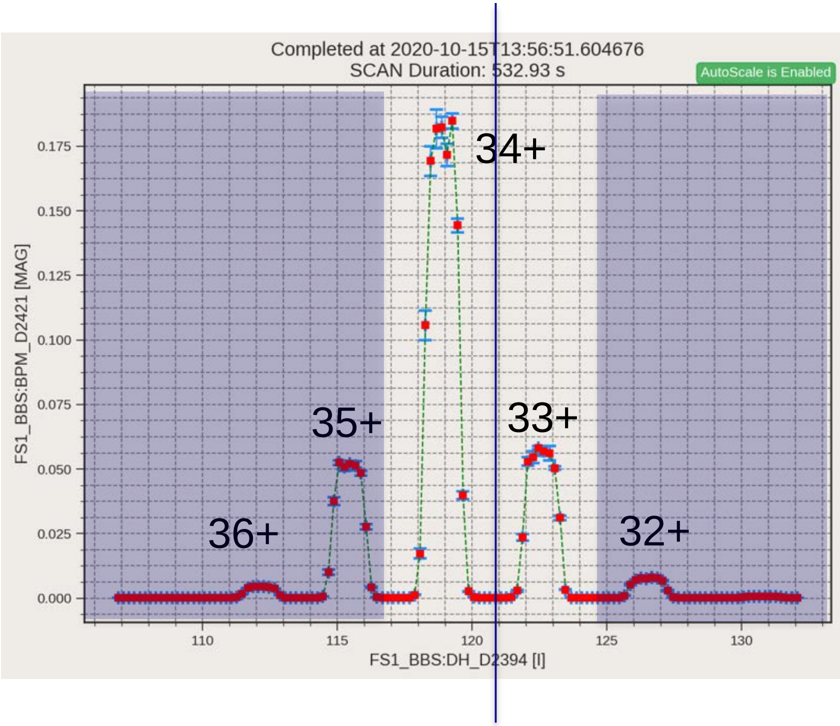


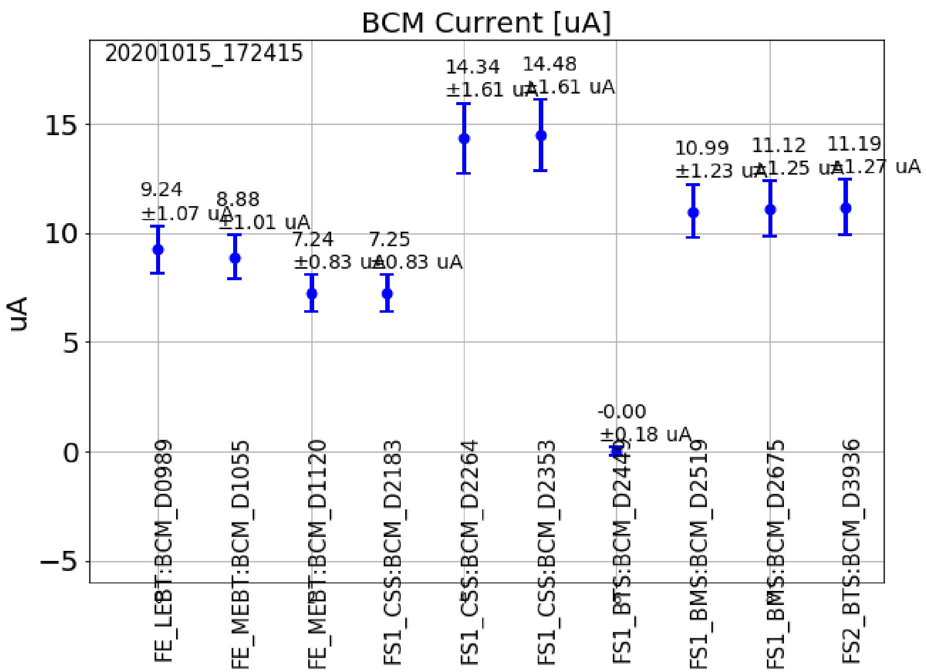
Simultaneous Acceleration of Two Charge States of $^{86}Kr^{34+, 35+}$ in LS2

- Allows us to dump only ~23% of 17 MeV/u Kr beam in the charge selector collimators in the FS1 and reduce the radiation in the tunnel

Xenon: 129/50=2.58
Krypton: 86/33.5=2.57

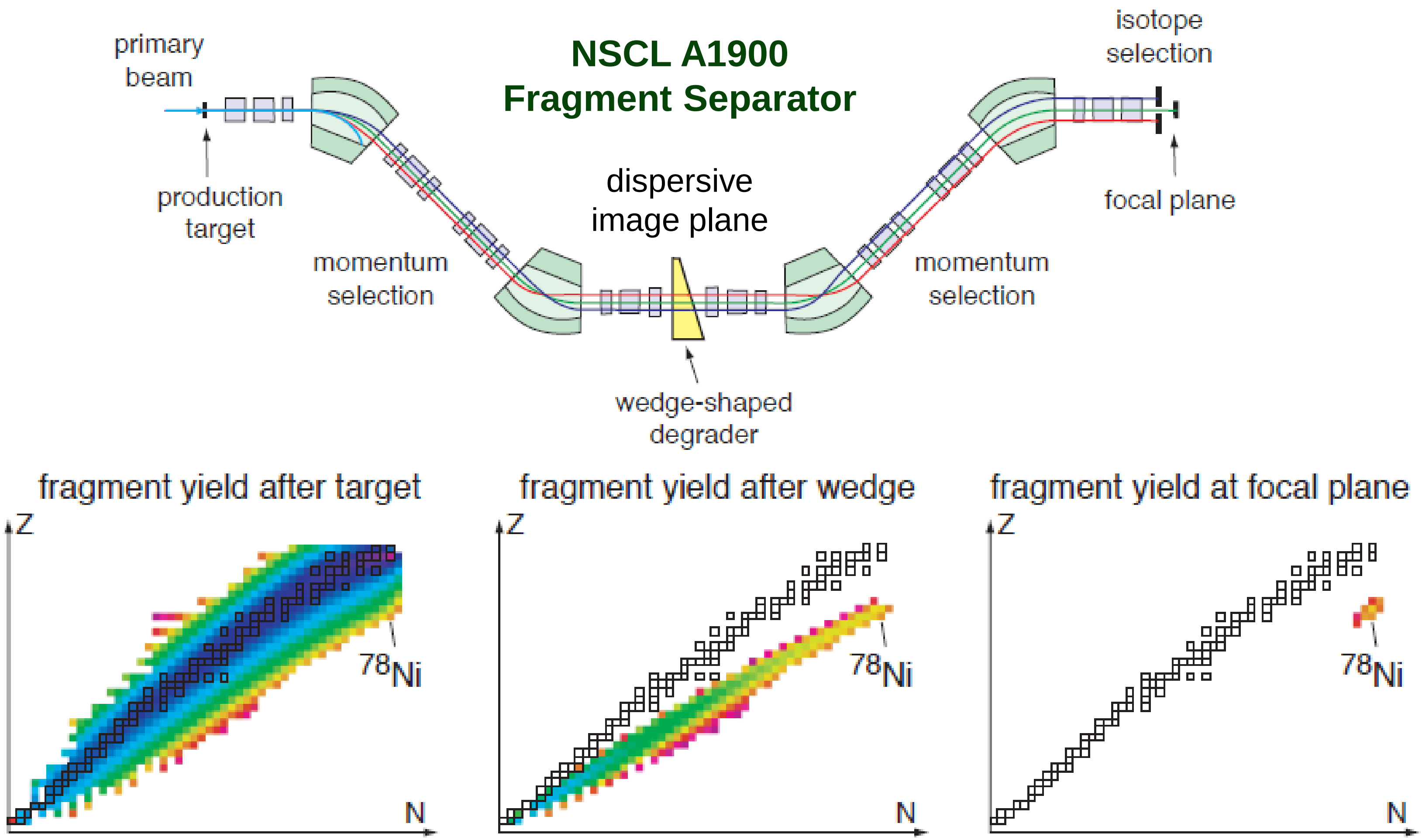
Transmission ~100%
77% is in charge states 33+ and 34+





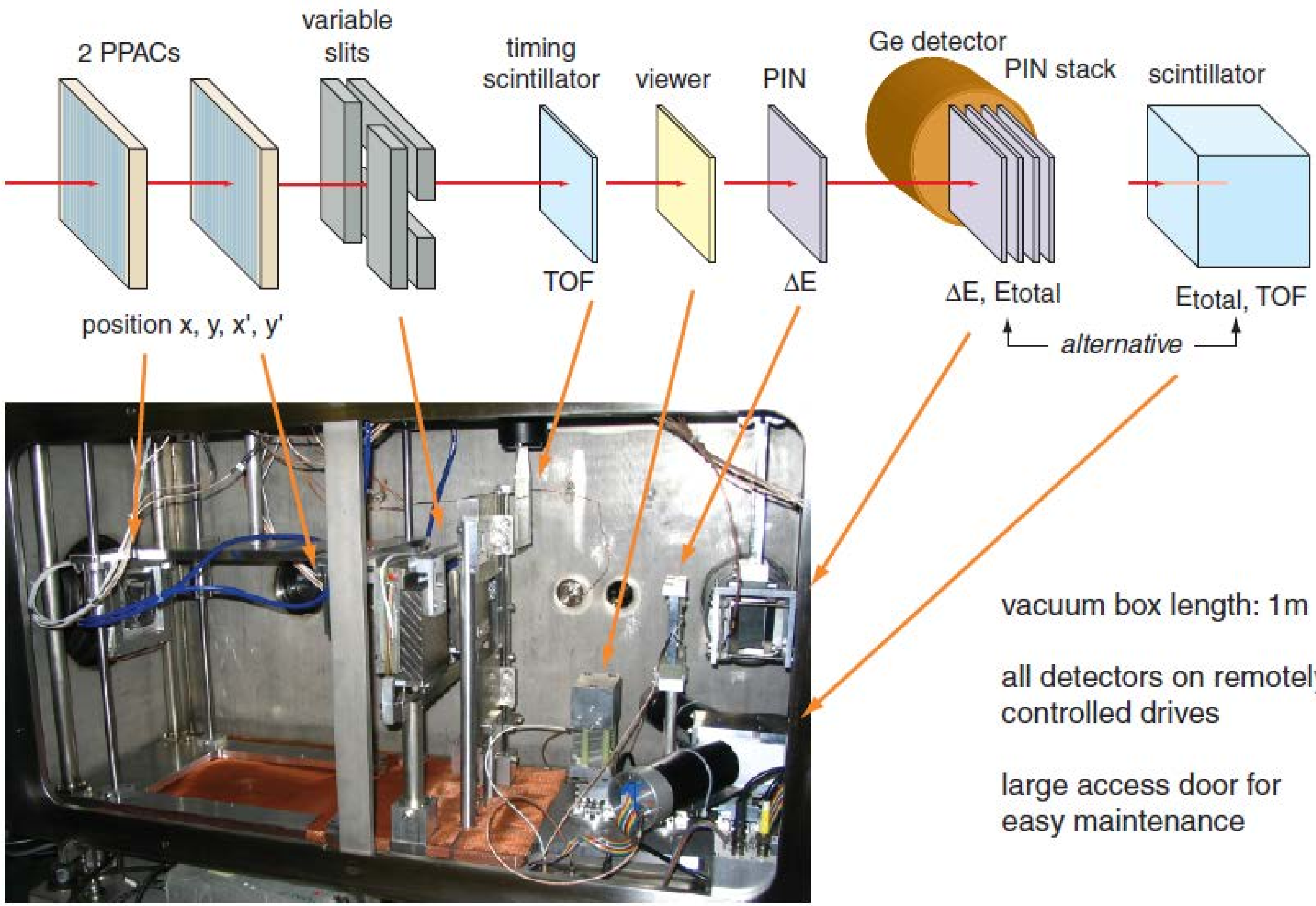
Fragment Separation Technique

Fragment separation using “momentum – energy loss – momentum” separation method



Detector Systems are integrated with vacuum chambers

- Existing NSCL A1900 Focal Plane Box (now DB5) will be reused



vacuum box length: 1m

all detectors on remotely controlled drives

large access door for easy maintenance

New PPAC Designs are Completed

- New vacuum enclosure reduces leakage
- Delay-line PPAC in high resolution (sigma ~ 0.25 mm) format
- 100x100, 200x100, 200x50 mm^2 active area formats
- Octafluoropropane (non-flammable) tested with excellent results