Beam Diagnostics for FRIB Comissioning

Steve Lidia, Facility for Rare Isotope Beams

2022 IBIC International Beam Instrumentation Conference

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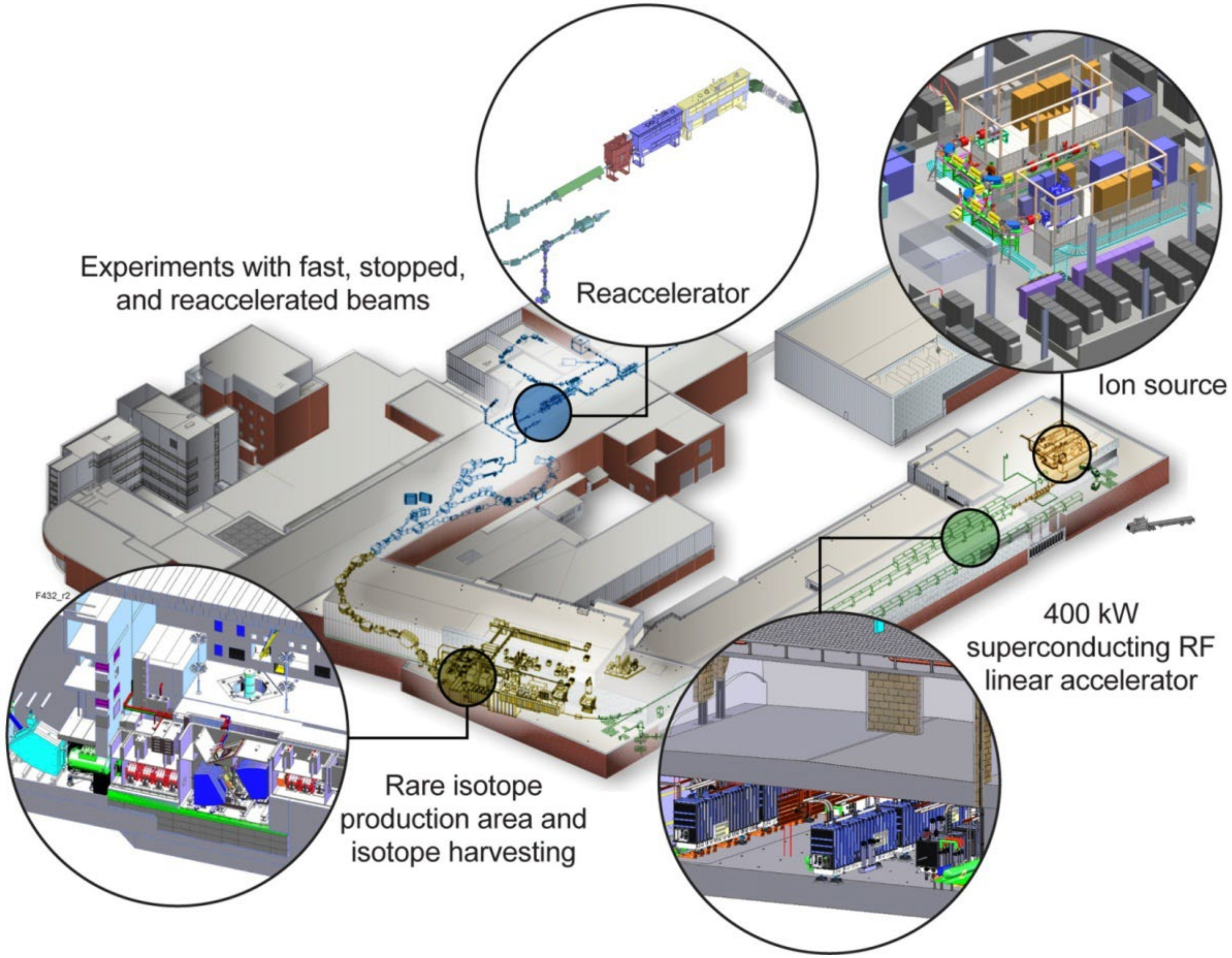
Outline

- Facility and Instrumentation Challenges
- Diagnostic Systems for Linac Commissioning
- Target Imaging Systems
- Fragment Separator Systems
- Detector Development
- 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-live
  - 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 (β = 0.03 – 0.60)
  - Multiple-charge-state beam dynamics
    - A/Q ranges 3 – 7
  - Ensuring low beam losses (< ~1 W/m)
  - Robust, Fast Machine Protection Systems (35 μs)
  - Safe operation of liquid lithium charge stripper
  - 400 kW heavy ion beam target and pre-separator systems
  - High-rate Fragment Separator
- Operational flexibility requires 10^5-10^8 dynamic range in beam intensity; CW and pulsed modes
  - Challenging conditions for beam diagnostics and MPS
- Frequent retuning for various ion species
  - Each run extends 1-2 weeks
  - New radiation effects beamline operations interleaved with nuclear physics program

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

Acceleration Goals Have Been Achieved

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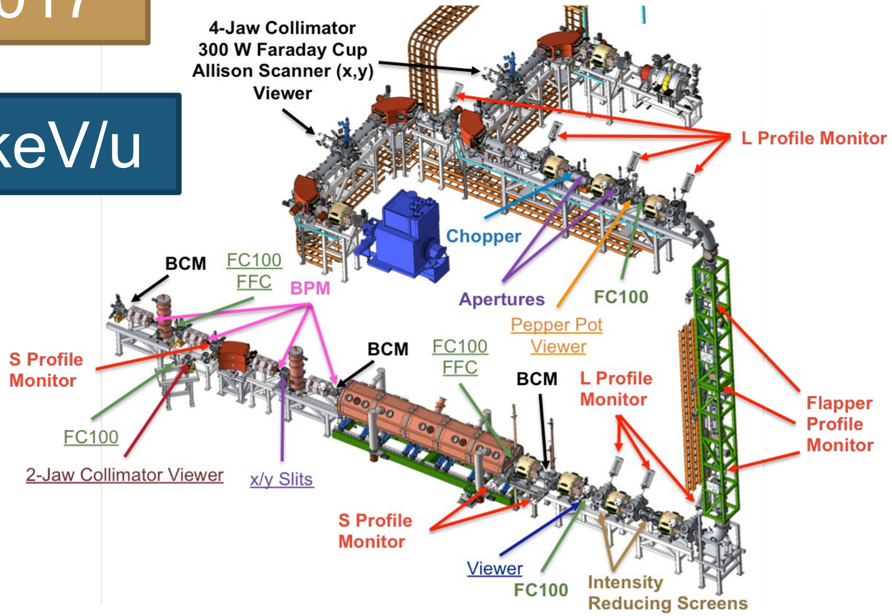
2017

500 keV/u



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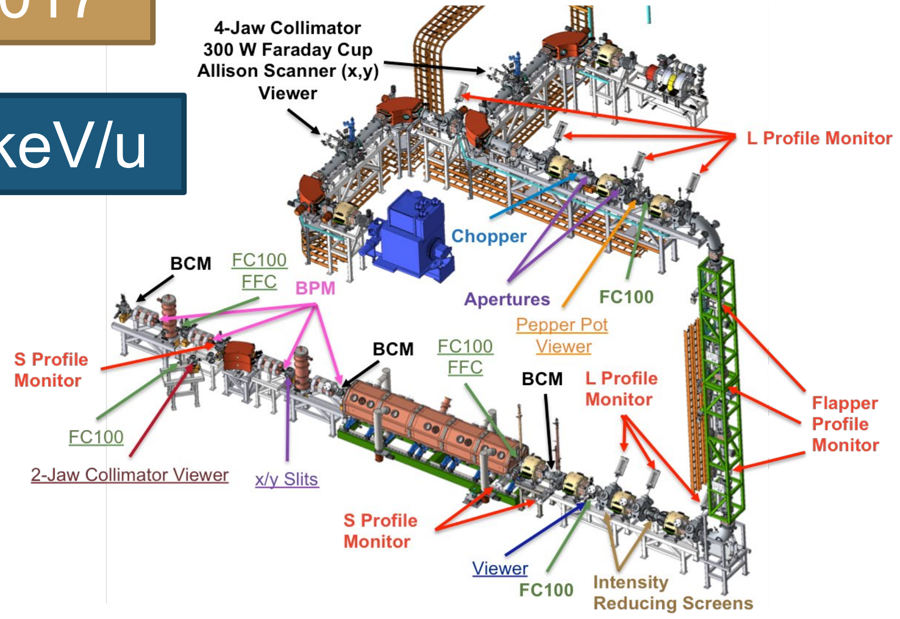
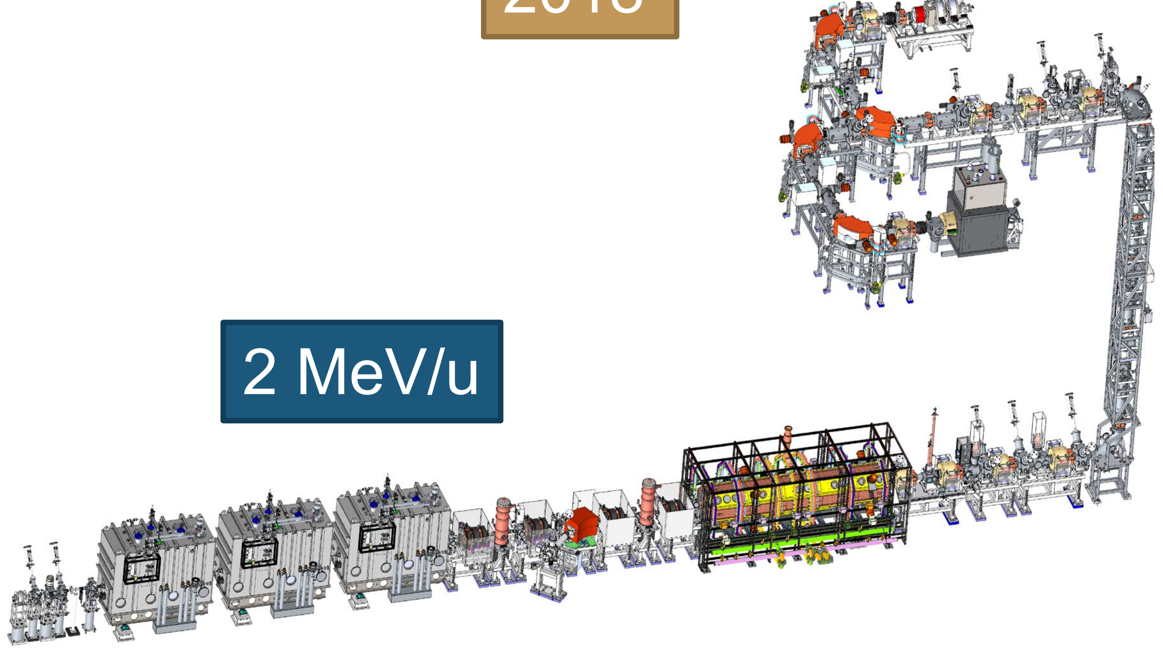


2018

2 MeV/u



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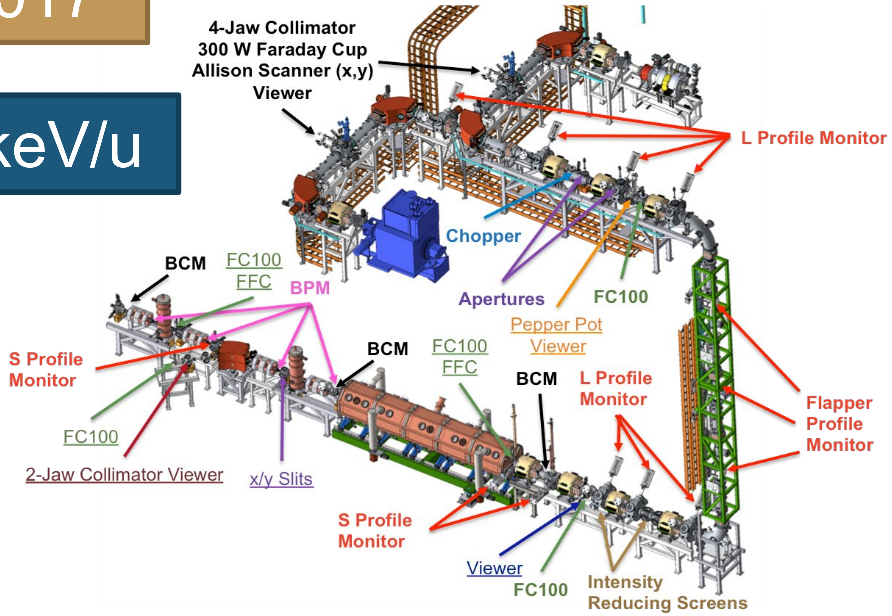
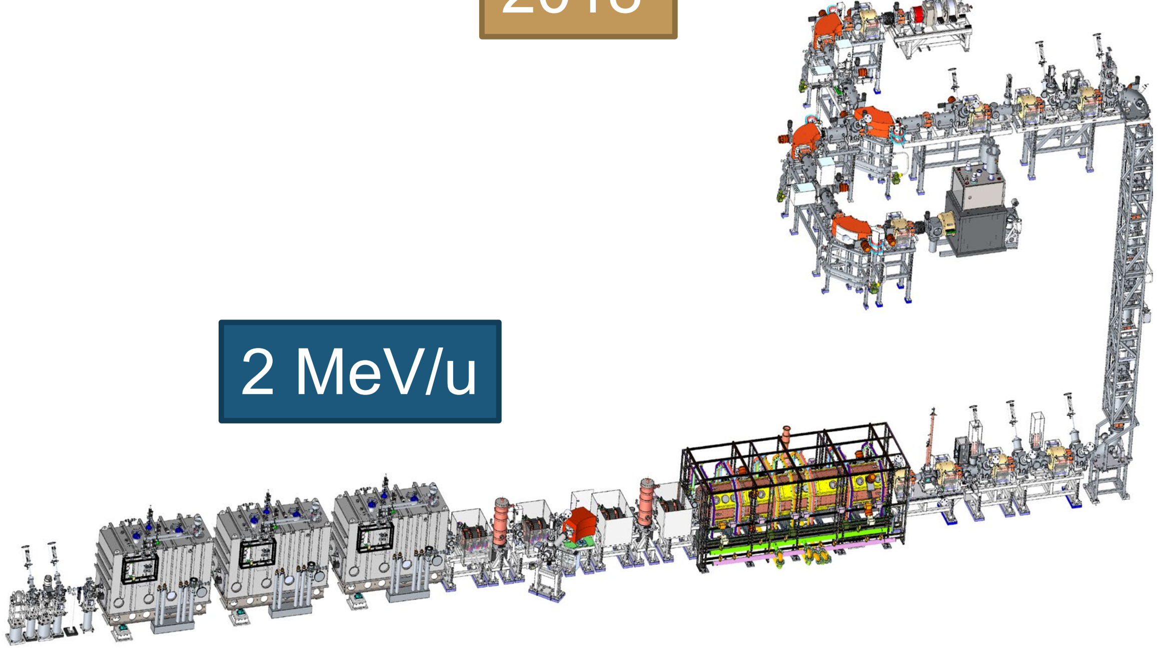


2018

2 MeV/u

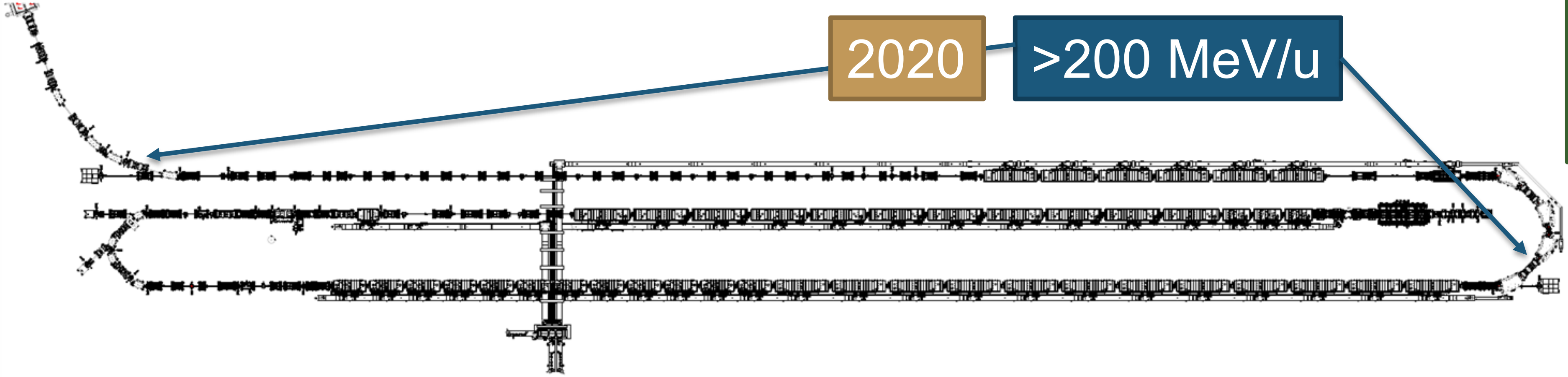


2019

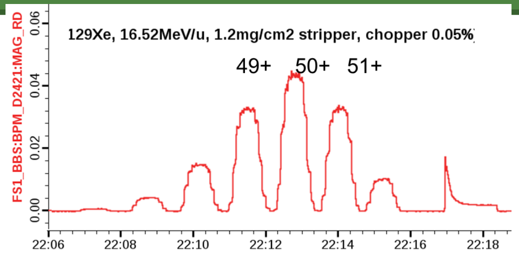
20 MeV/u

Commissioning Phases Completed

Commissioning Phases Completed



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



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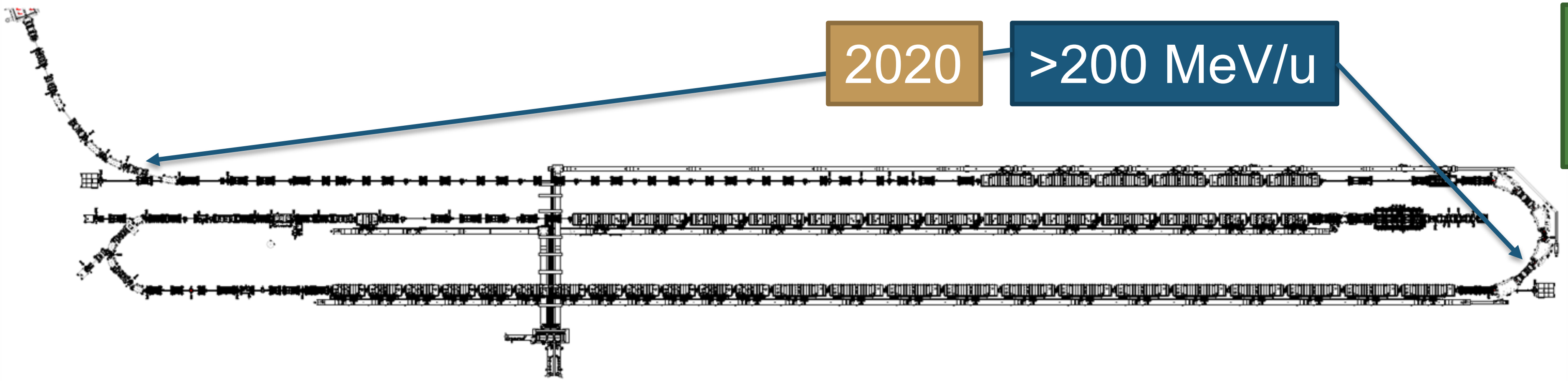

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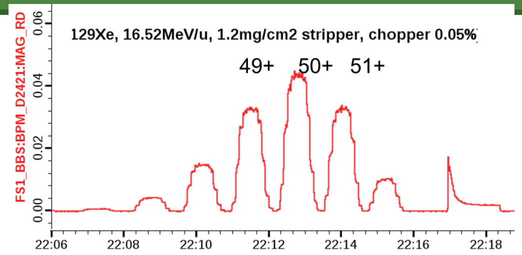
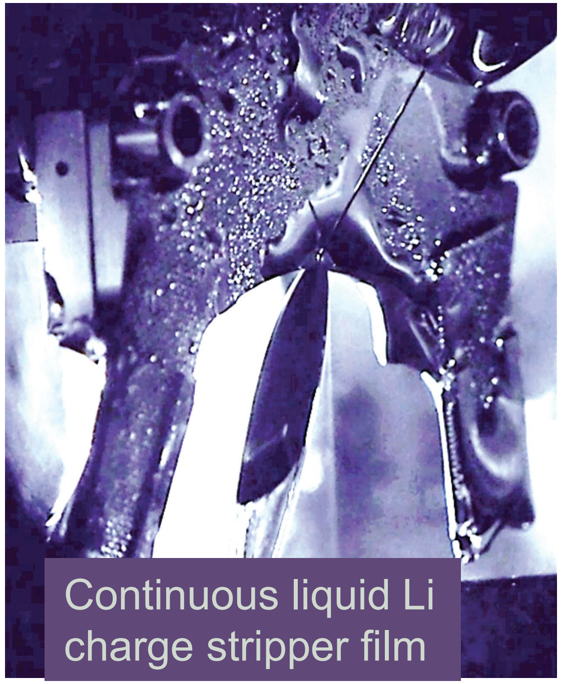


2021

Liquid Li charge stripper

HP ECR first plasma

Beam on target and first rare isotope production

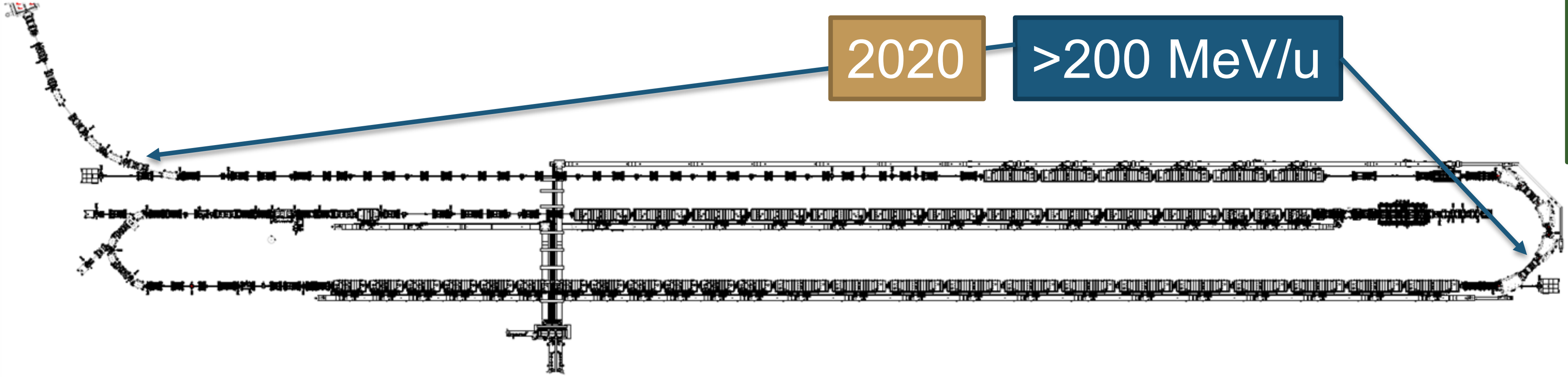


Continuous liquid Li charge stripper film

Commissioning Phases Completed

2020

>200 MeV/u



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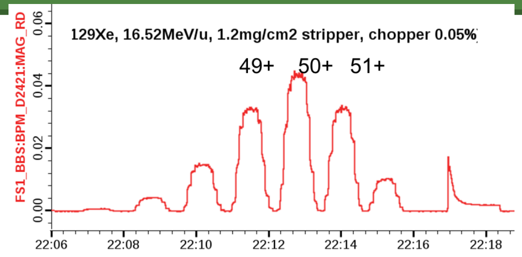

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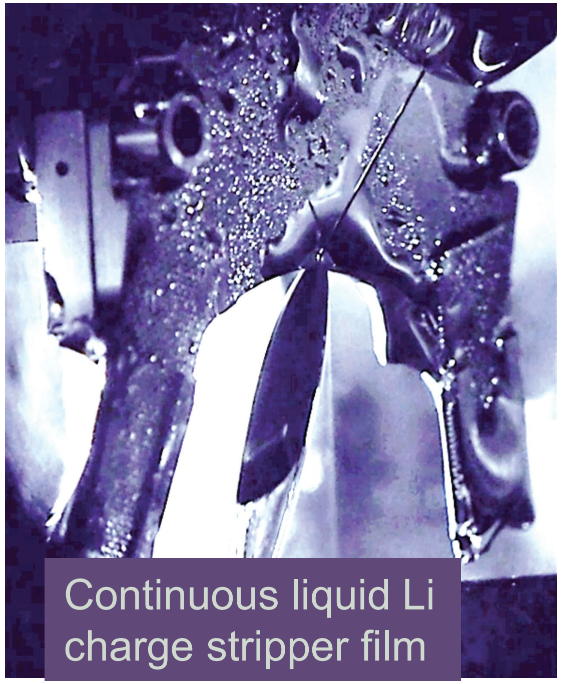
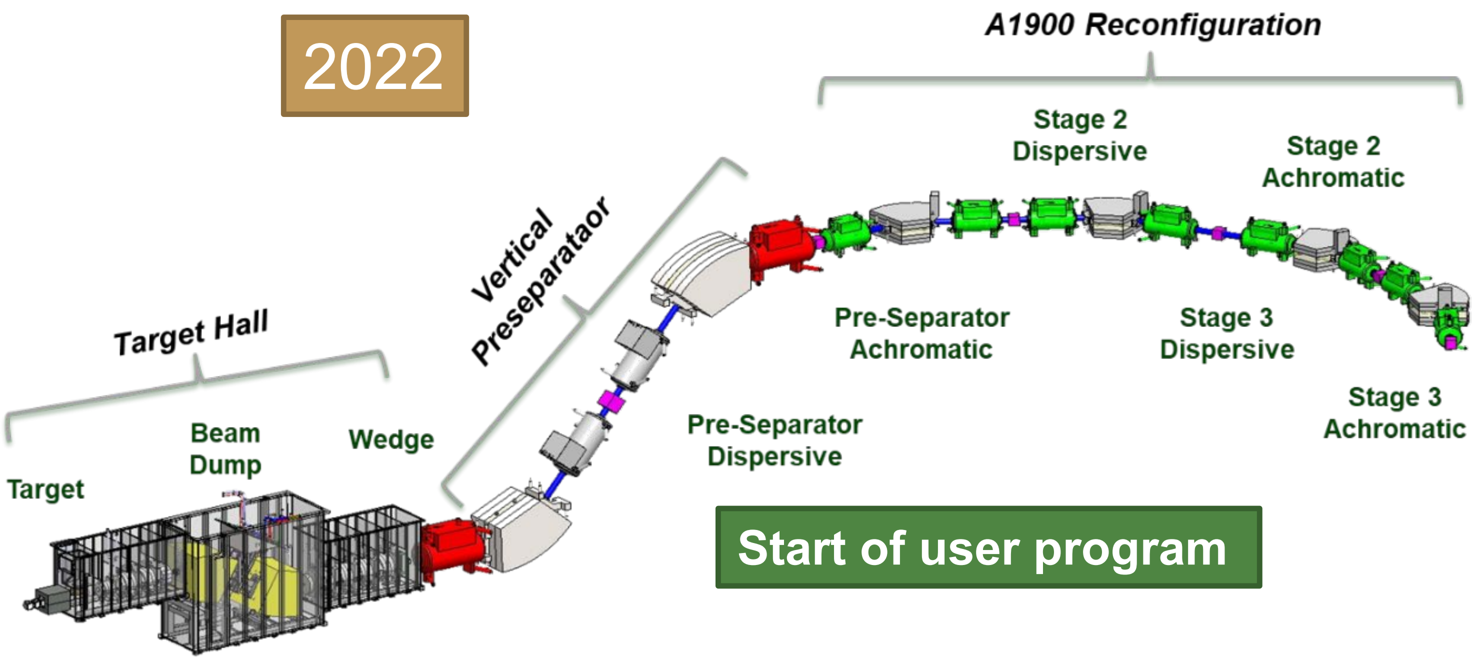


Continuous liquid Li charge stripper film

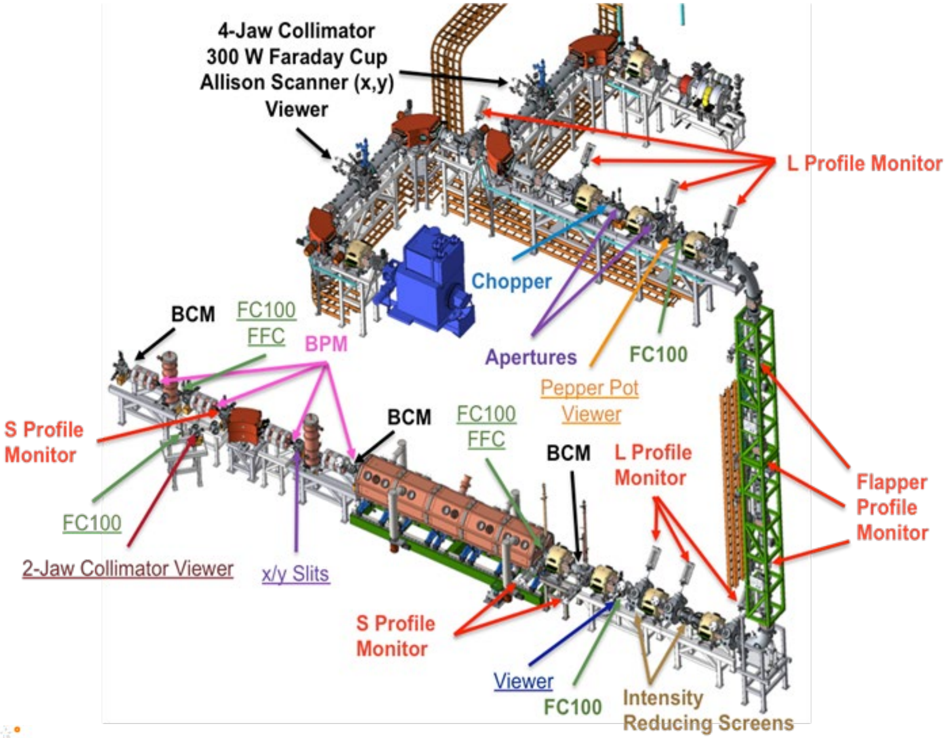
2022



Start of user program

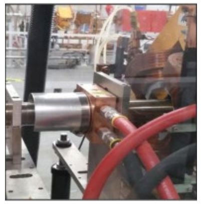
Diagnostics System Completed: Linac

- Diagnostics systems for linac are installed and tested with beam

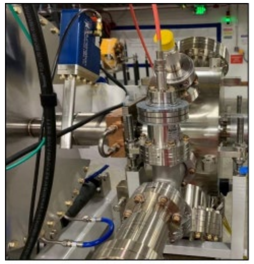


Profile monitor in Linac Segment (LS3)

Beam loss monitor in LS2

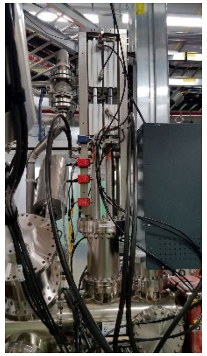


Collimator aperture in Folding Segment (FS1)

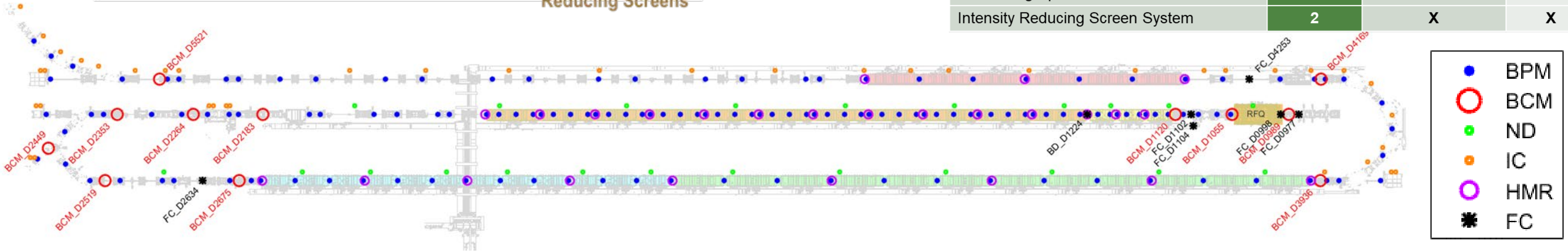


Beam position monitor in LS1

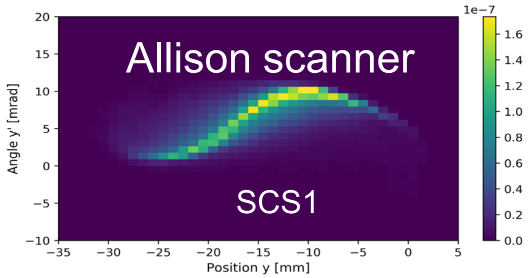
Accelerator Systems - Diagnostics	TOTAL	Electronics and Controls On line	Beam Measured	Meets Requirements
Total systems	**548**	X	X	X
Beam Position Monitor	150	X	X	X
Beam Current Monitor (ACCT)	13	X	X	X
Beam Loss Monitor – Halo Monitor Ring	20	X	X	X
Beam Loss Monitor - Ion Chamber	47	X	X	X
Beam Loss Monitor - Neutron Detector	24	X	X	X
Beam Loss Monitor – Fast Thermometry	240	X	X	X
Profile Monitor (Lg., Sm., Flapper)	24	X	X	X
Silicon Detector	1	X	X	X
Bunch Shape Monitor	1	X	X	X
Allison Emittance Scanner (2 axis)	2	X	X	X
Pepper pot emittance meter	1	X	X	X
Faraday Cup	10	X	X	X
Fast Faraday Cup	2	X	X	X
Viewer Plate and Camera	5	X	X	X
Selecting Slits System - 300 W	5	X	X	X
Collimating Apertures - 100 W	2	X	X	X
Intensity Reducing Screen System	2	X	X	X



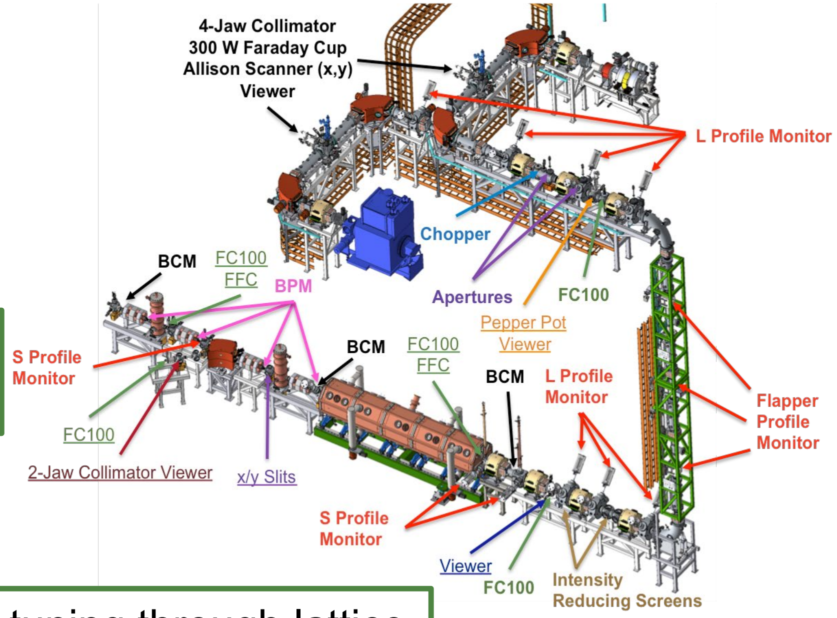
Intensity reducing screen in front-end

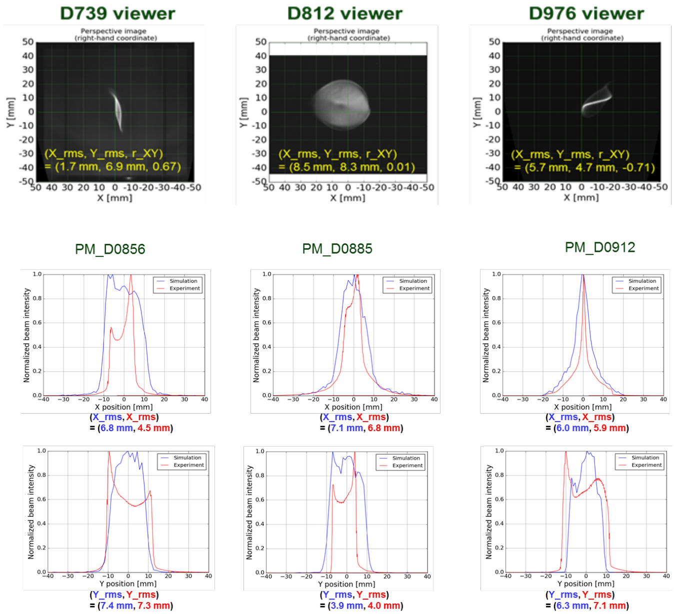


Diagnostics for Front End and Linac Matching

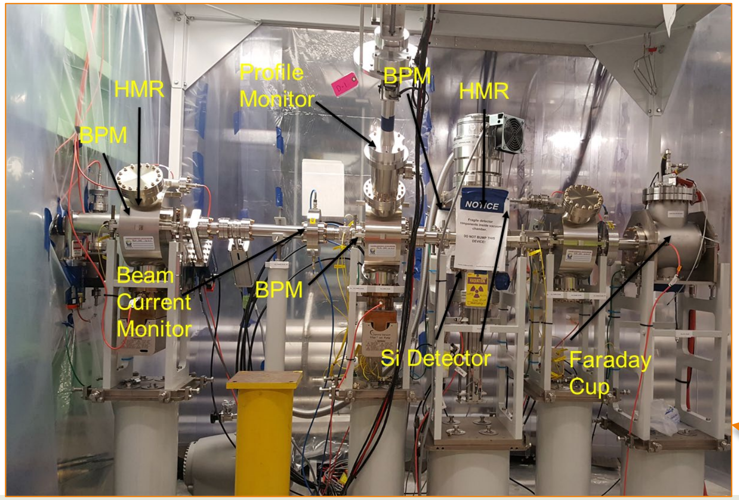


Beam generation, low energy transport and injection to linac

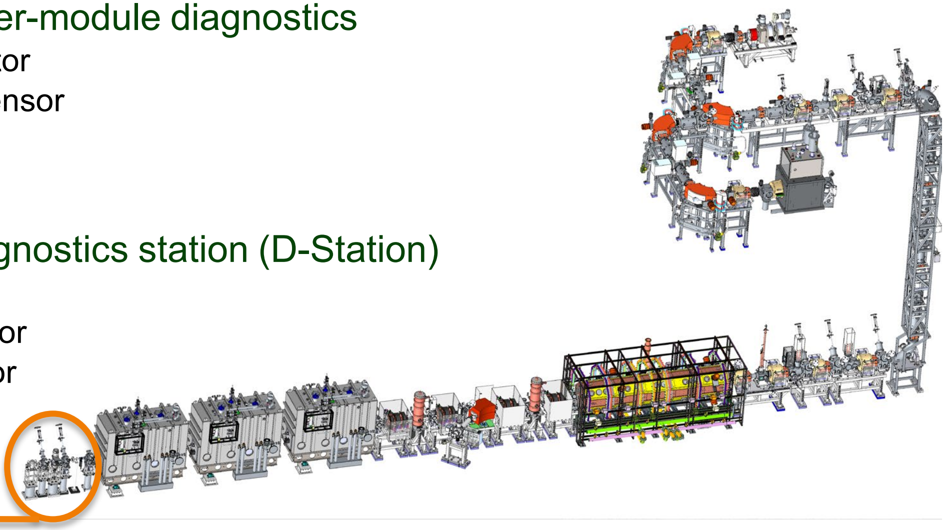




Early test of beam acceleration, tuning through lattice transition, linac diagnostics, machine protection



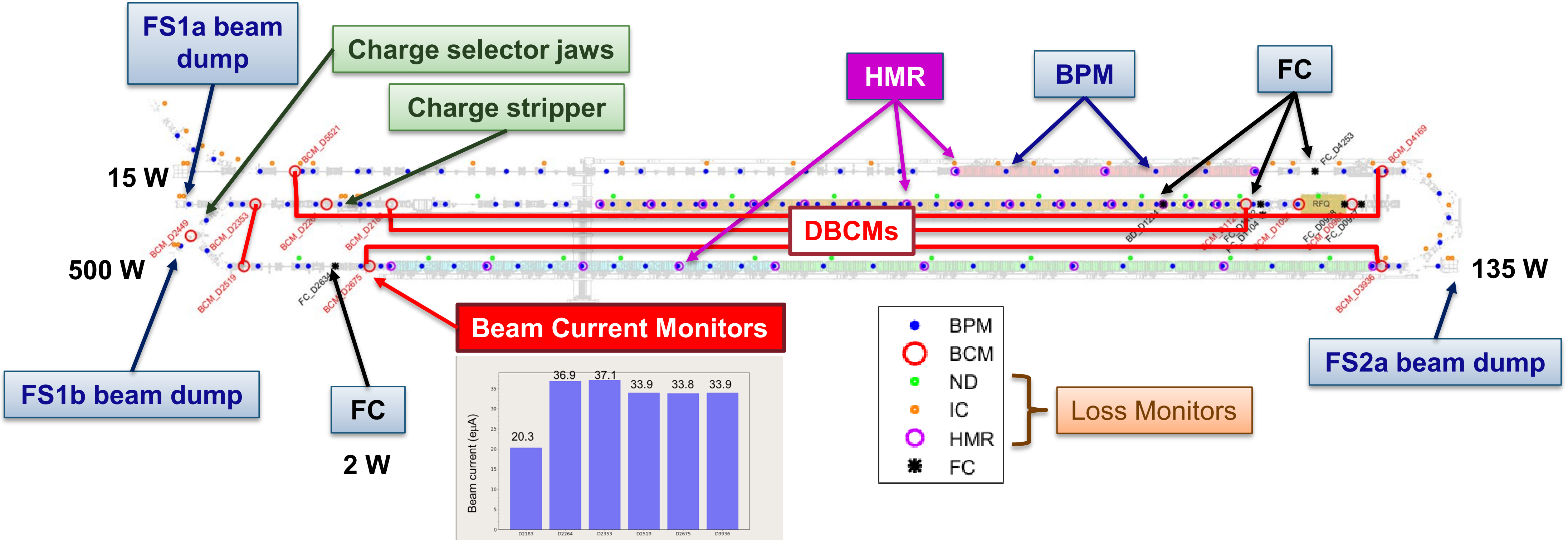
- Cryomodule and inter-module diagnostics
  - Beam Position Monitor
  - Fast thermometry sensor
  - Halo monitor ring
  - Neutron monitors
- Commissioning Diagnostics station (D-Station)
  - Profile monitor
  - Beam position monitor
  - Beam current monitor
  - Halo Monitor ring
  - Faraday cup
  - Si Detector



Diagnostics for SC RF Linac Commissioning

- **Beam intensity (and differential loss)** – Beam Current Monitors, Faraday Cups (low power), BPMs
- **Beam offsets** – BPMs (dense network)
- **RF tuning (beam energy and phase)** - BPMs and narrowband receiver
- **Beam profile and lattice tune** – Profile Monitors, Halo Monitor Rings and Beam Loss Monitors
- **Transverse Beam emittance** – Profile Monitors
- **Longitudinal phase space distribution** – Bunch Shape Monitor, BPM waveforms
- **Beam losses** – Neutron Detectors, Ionization Chambers, Halo Monitor Rings, Differential BCM

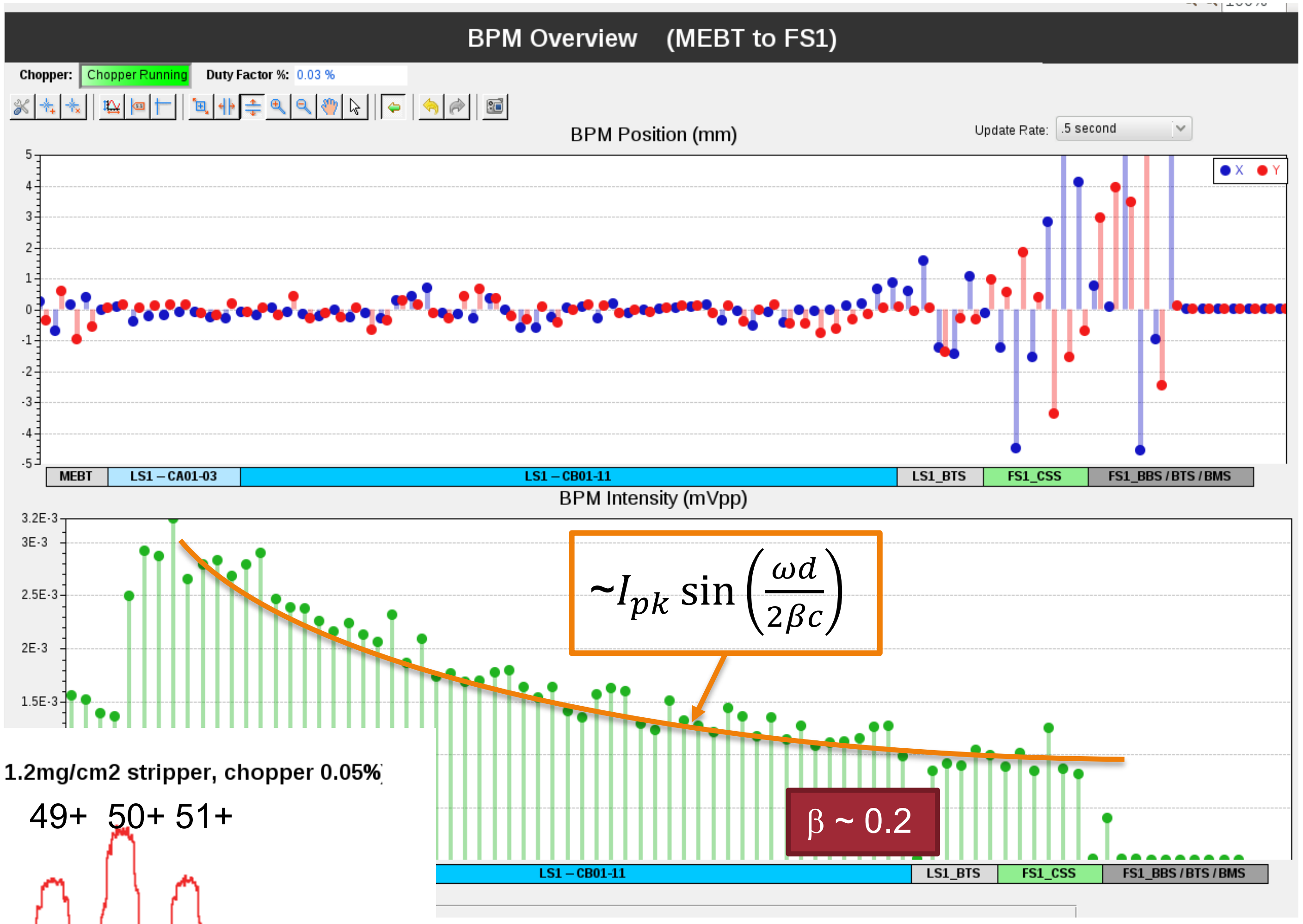
*Interceptive diagnostics

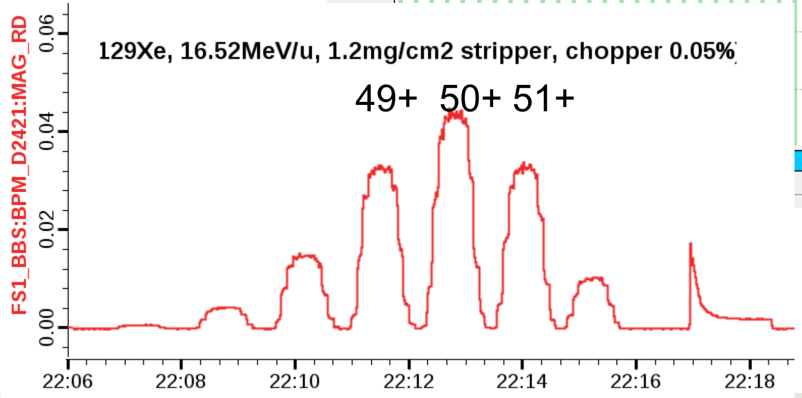


Beam current monitor readings

Beam Position Monitors In Full Use

- 150 20-mm Button-type
  - (40, 50, 75, 100)mm diameter
- 2 High-aspect ratio, Shoebox-type
- 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
  Charge State Distribution)

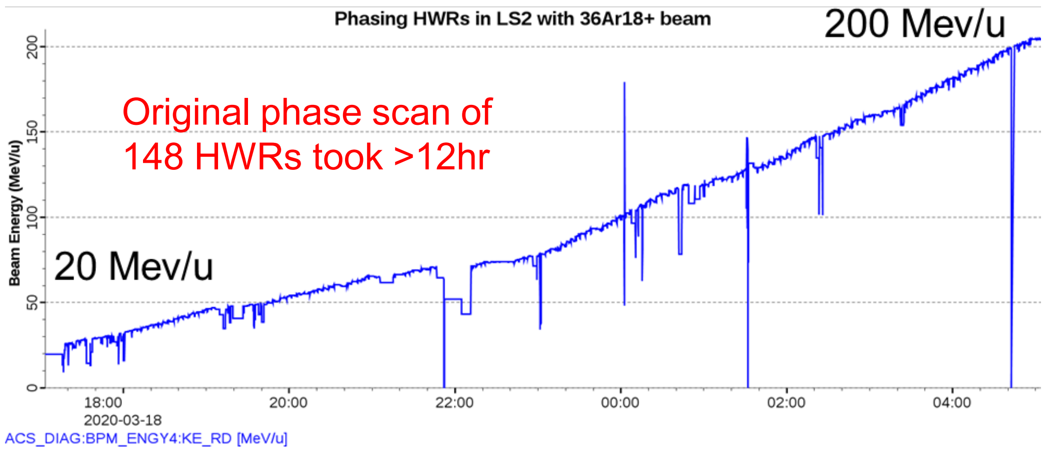




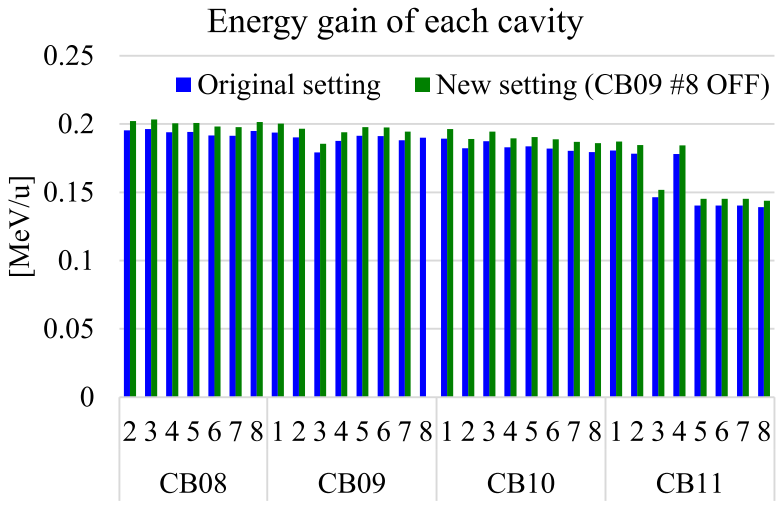
Warm and cryogenic button-type BPMs

Automatic Tuning Algorithms Deployed

- Cavity Retuning
  - Few minutes to calculate field and phase of all LS1 cavities
  - BPM phases are consistent within +/-1 degree between tuning model and measurement
  - Successfully developed 4 ion species with 10 different energies
    - » Calculated energy after LS1 (15-40 MeV/u) is consistent with measured energy to within +/-10 keV/u
  - Intensive beam studies have been conducted for LS2 and LS3 sections

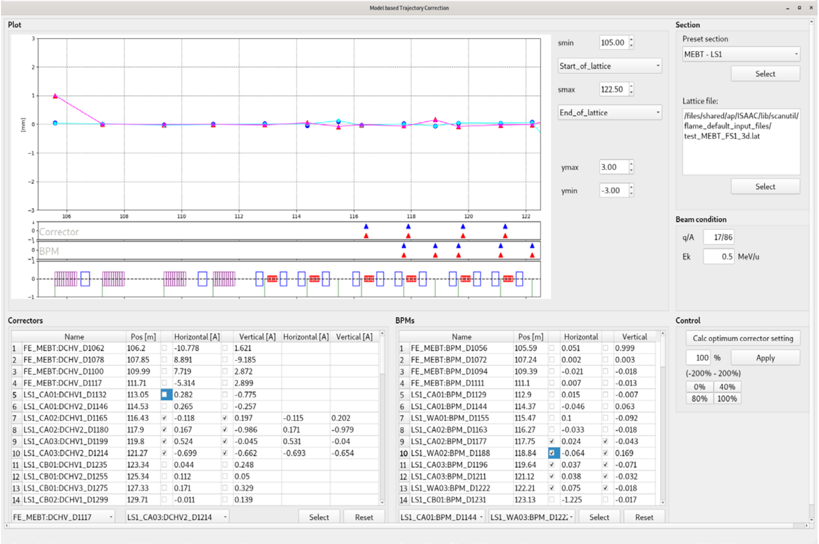


- Cavity failure retune and rebalance
  - Routine can correct within 10 minutes – can be improved to ~1 min
  - Energy difference <10 keV/u



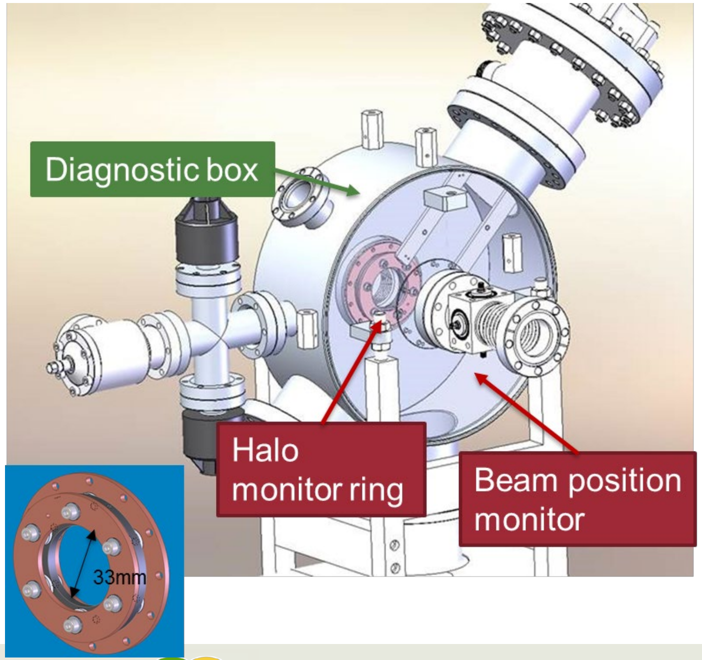
Energy before 20.314 MeV/u
Energy after 20.307 MeV/u

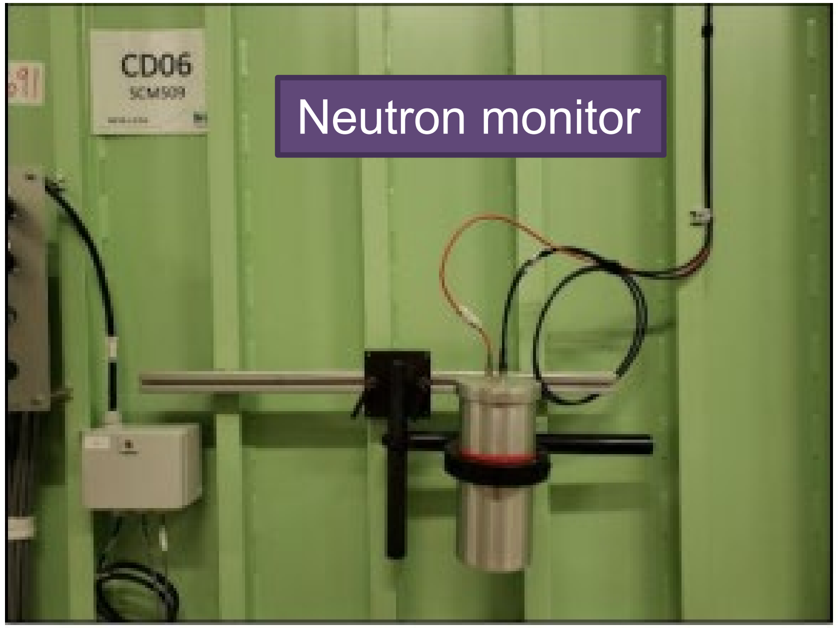
- Trajectory correction
  - Based on BPM measurements
  - Uses Orbit Response Matrix (ORM)

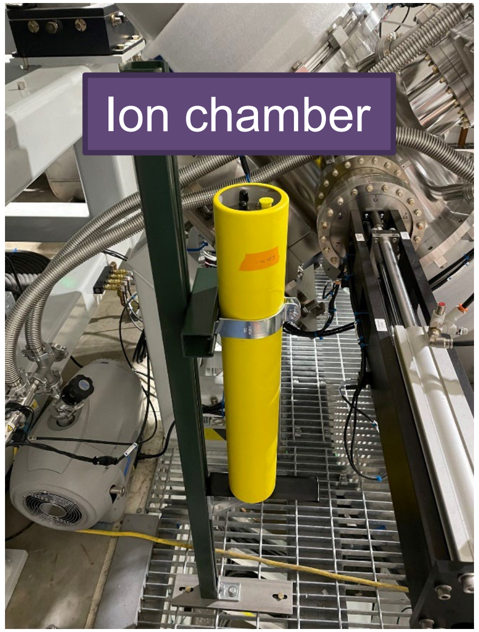


Several Types of Beam Loss Monitors are Used

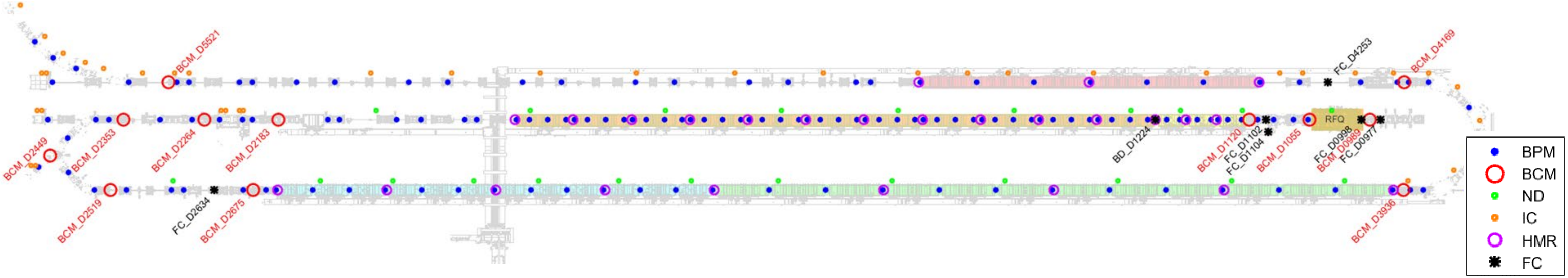
- Ion chambers – 1.5 L, parallel-plate design. Pressurized to 8 or 15 atm with N2 or Ar.
- Neutron monitors – scintillator/PMT design
- Halo Monitor rings – installed between cryomodules, instrumented as Faraday cups
- Differential Beam Current Monitors (DBCMs) – multiple pairs of BCMs provide fast (15 μs) and slow (millisecond to second) detection







Beam Loss Monitors – Background at 1kW Beam



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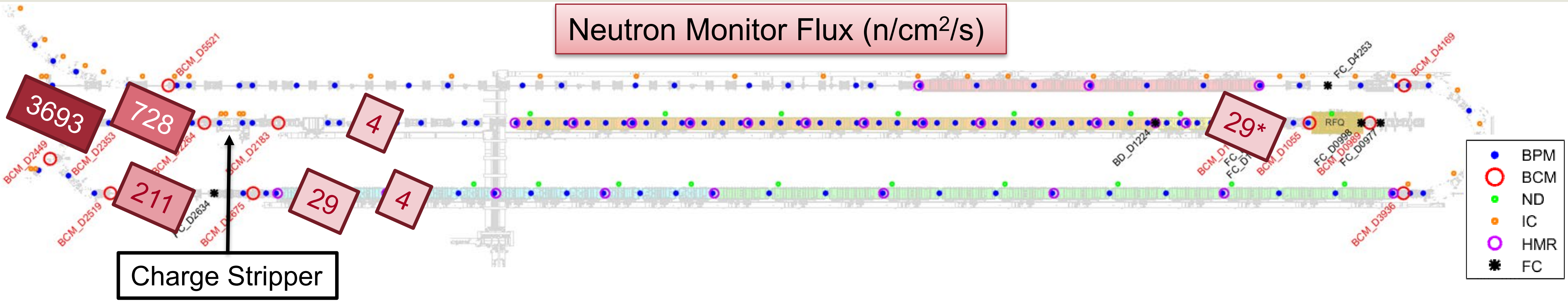

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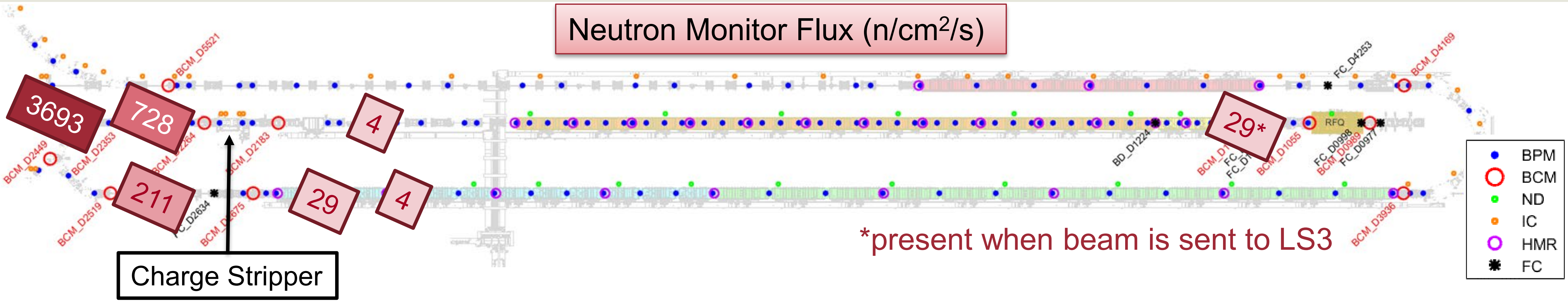

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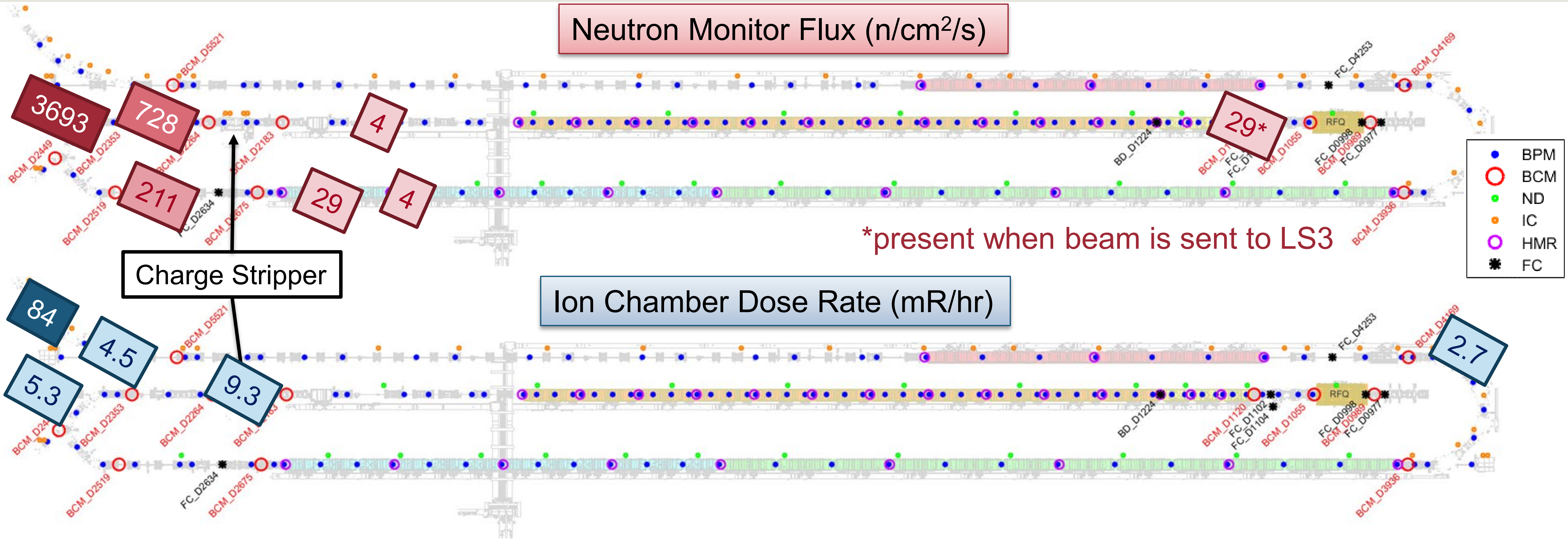

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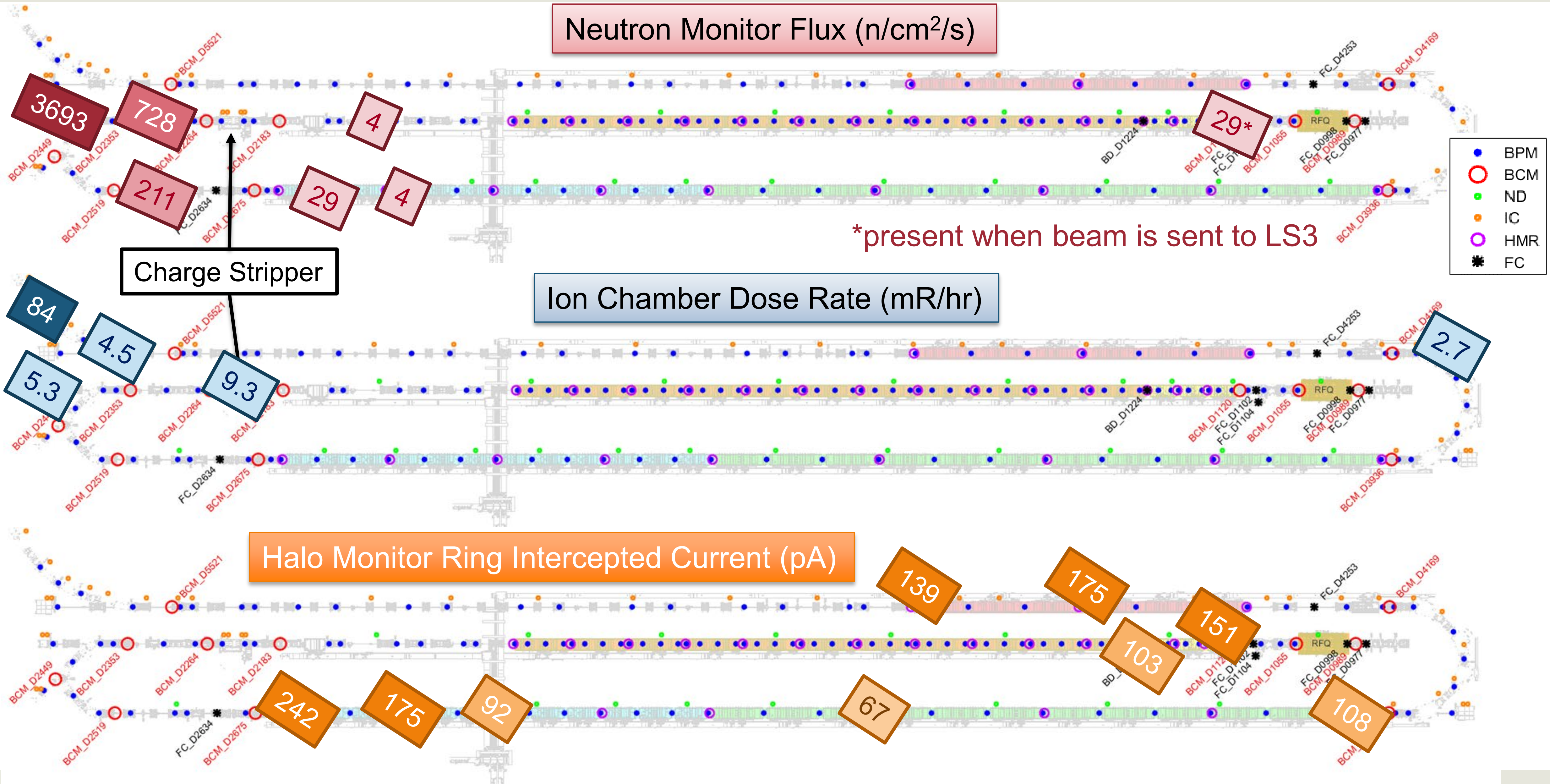

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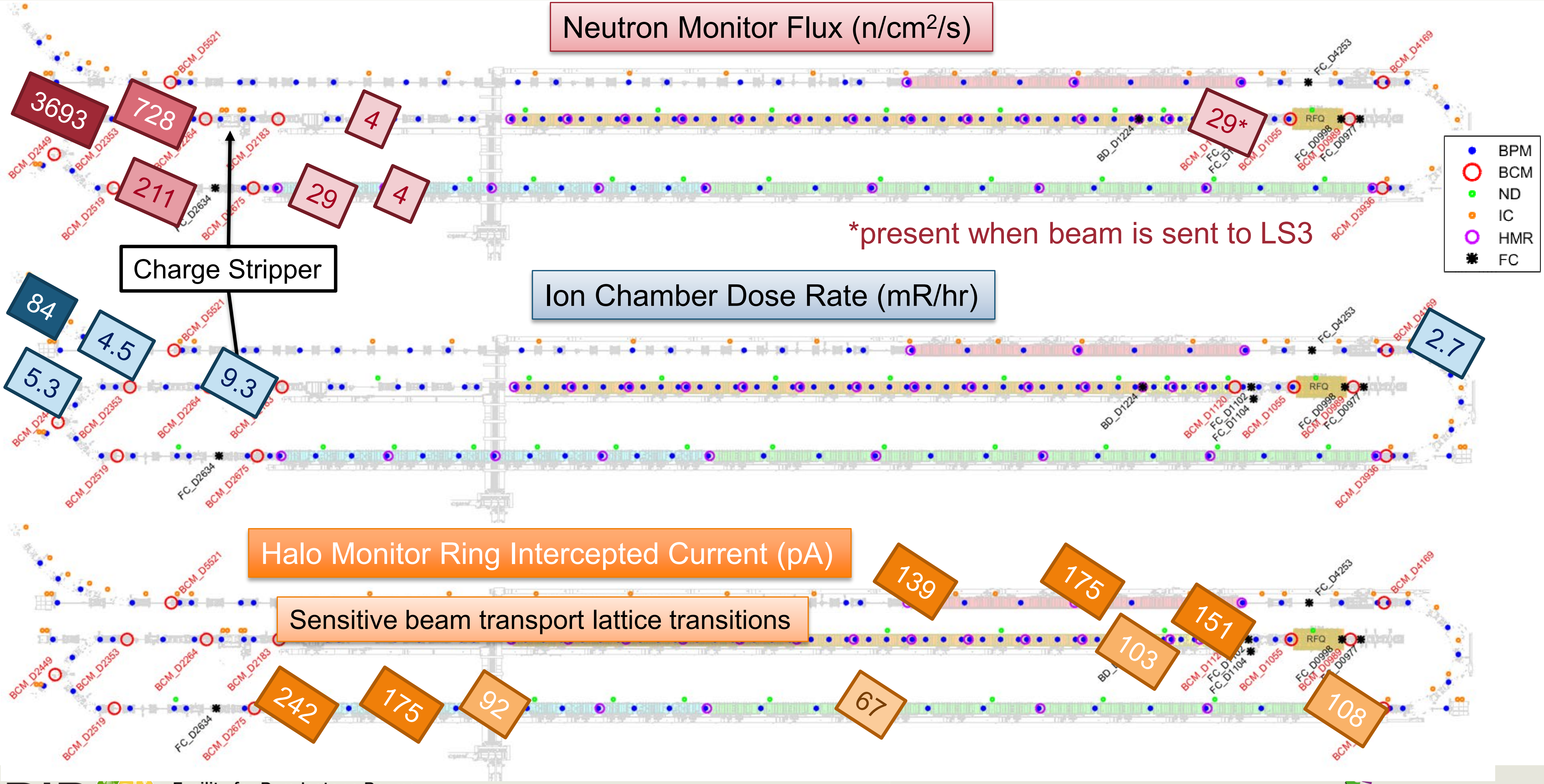
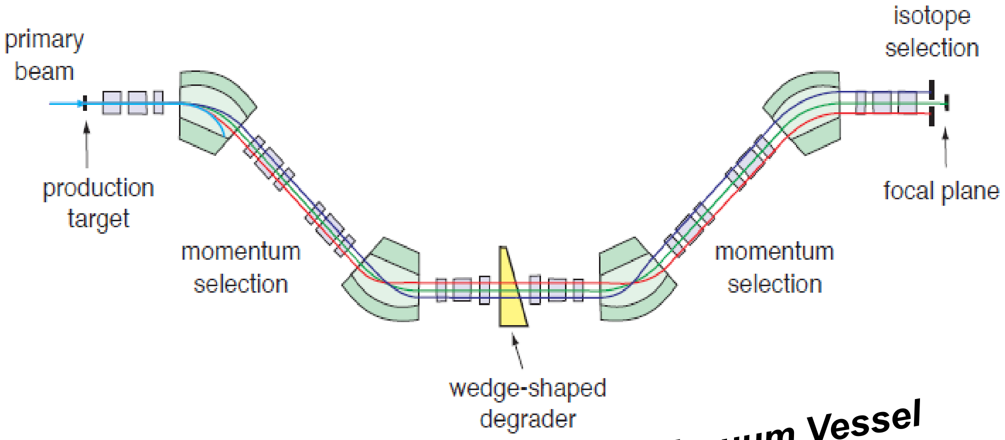
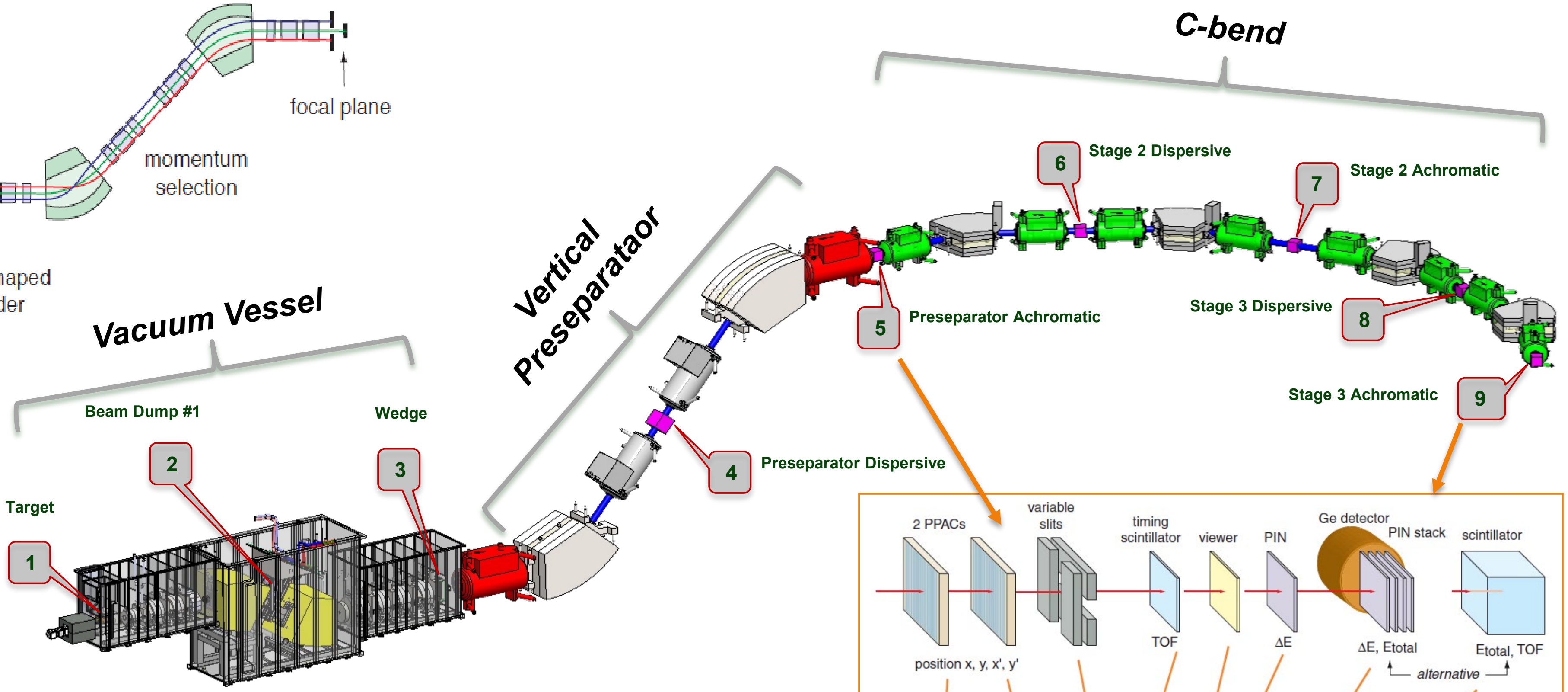
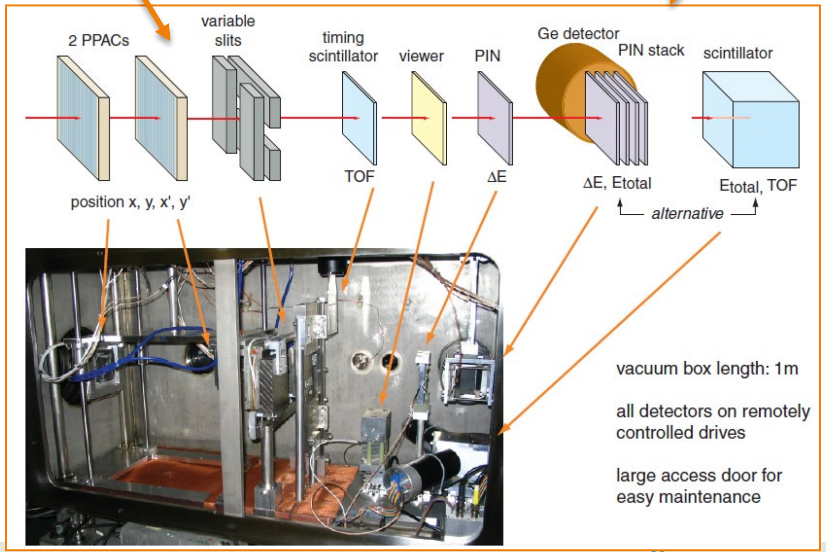


Target and Advanced Rare-Isotope Separator (ARIS)



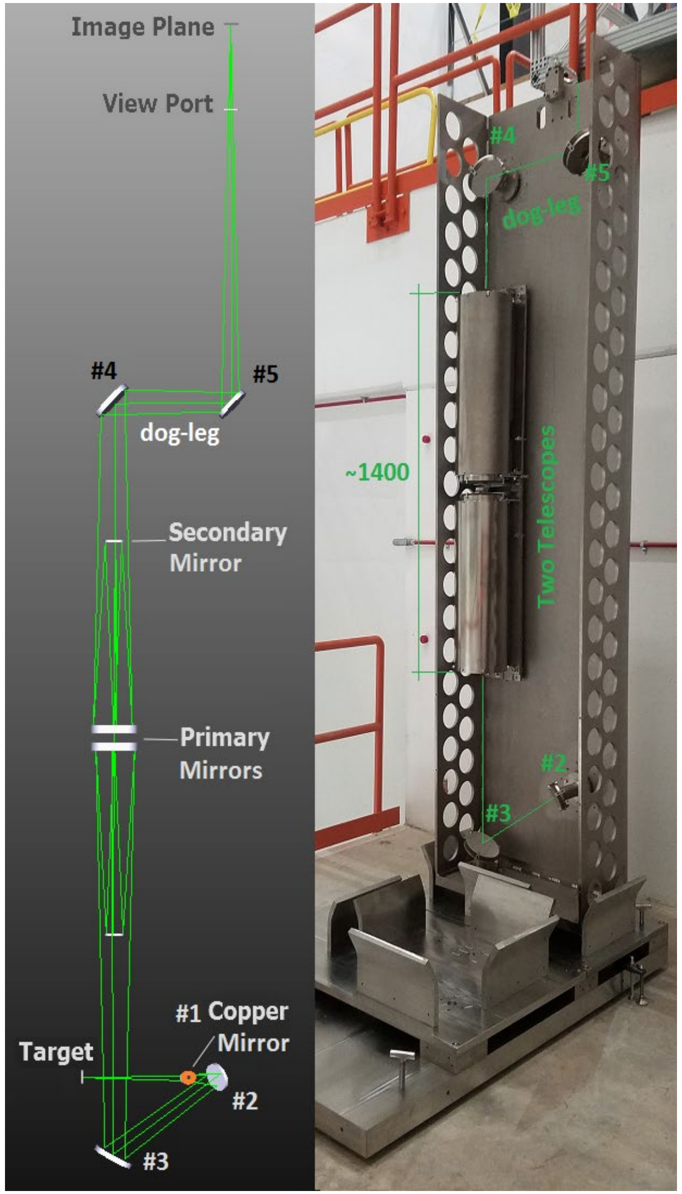


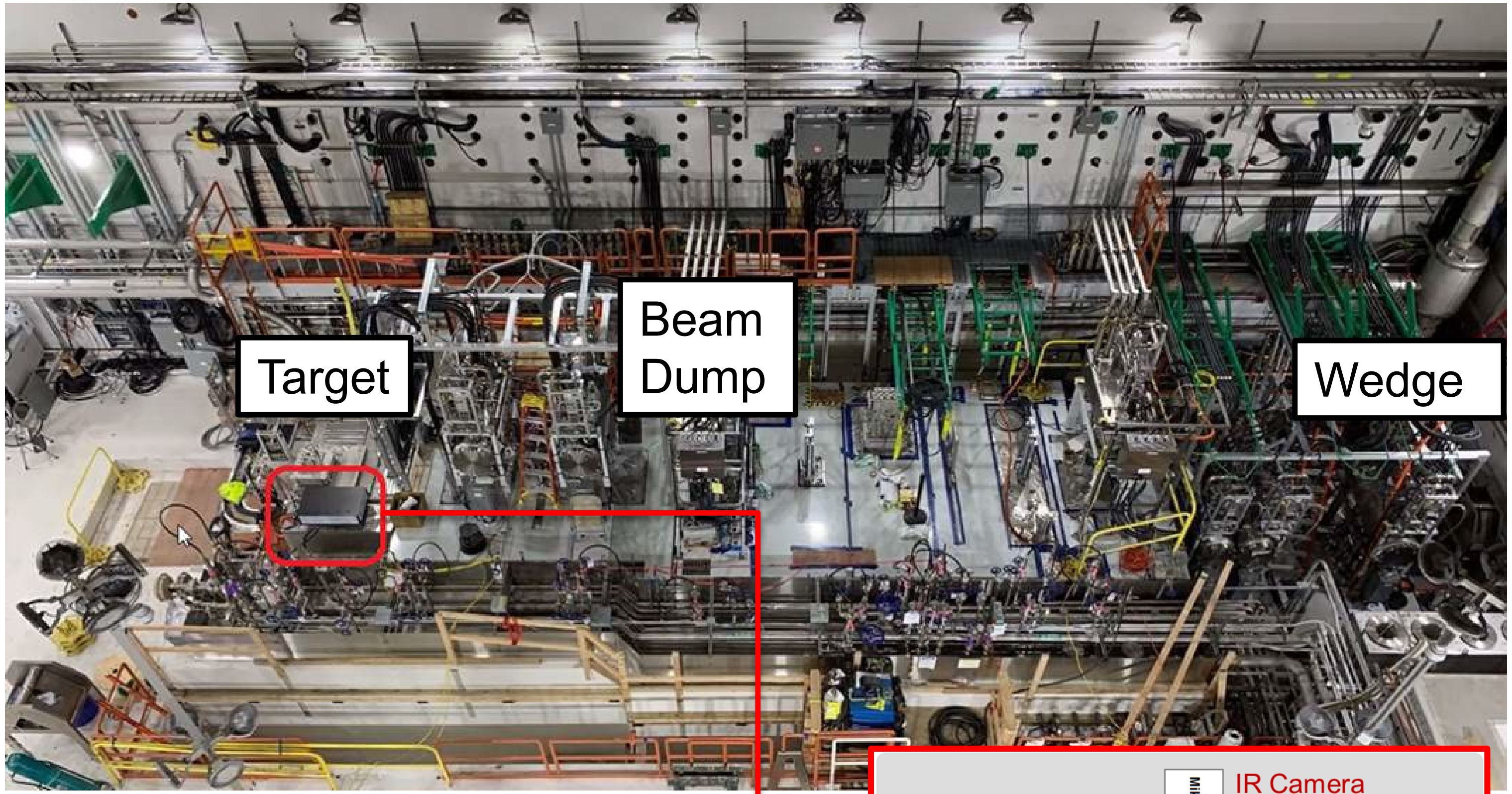


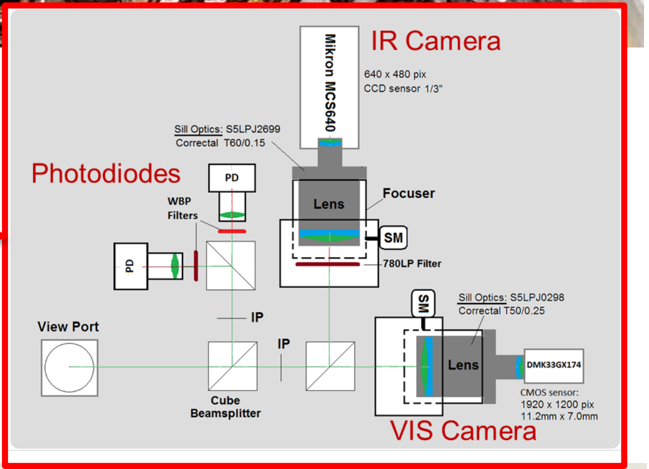
Management and tuning of 400 kW primary beam and high event rate (> 10^6/sec) secondary beam

- Thermal imaging of target, beam dump
- Discrimination and identification of rare isotope beams

Thermal Imaging System is Commissioned



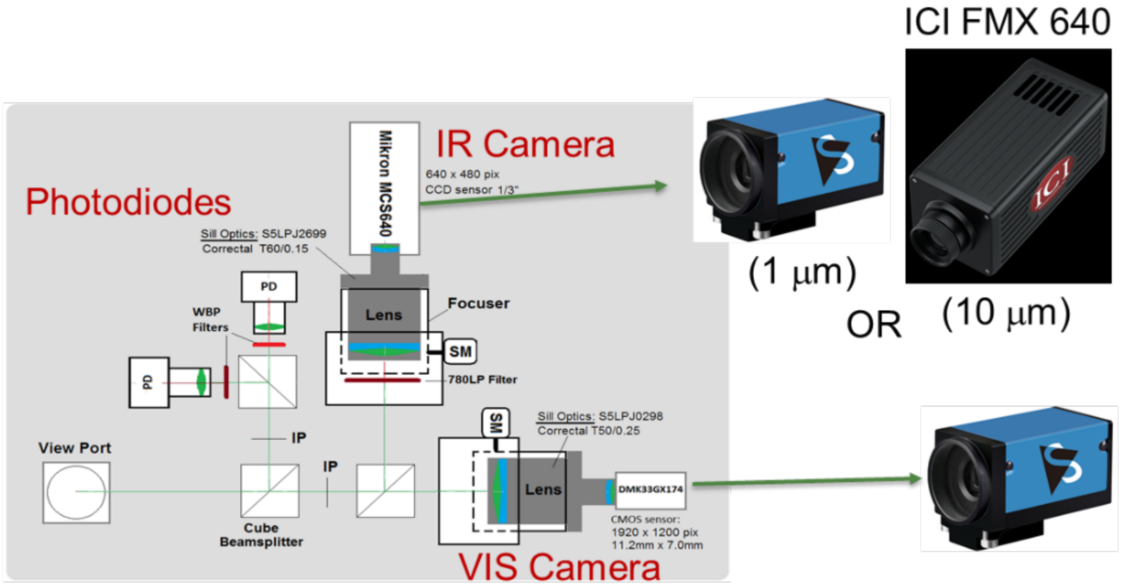


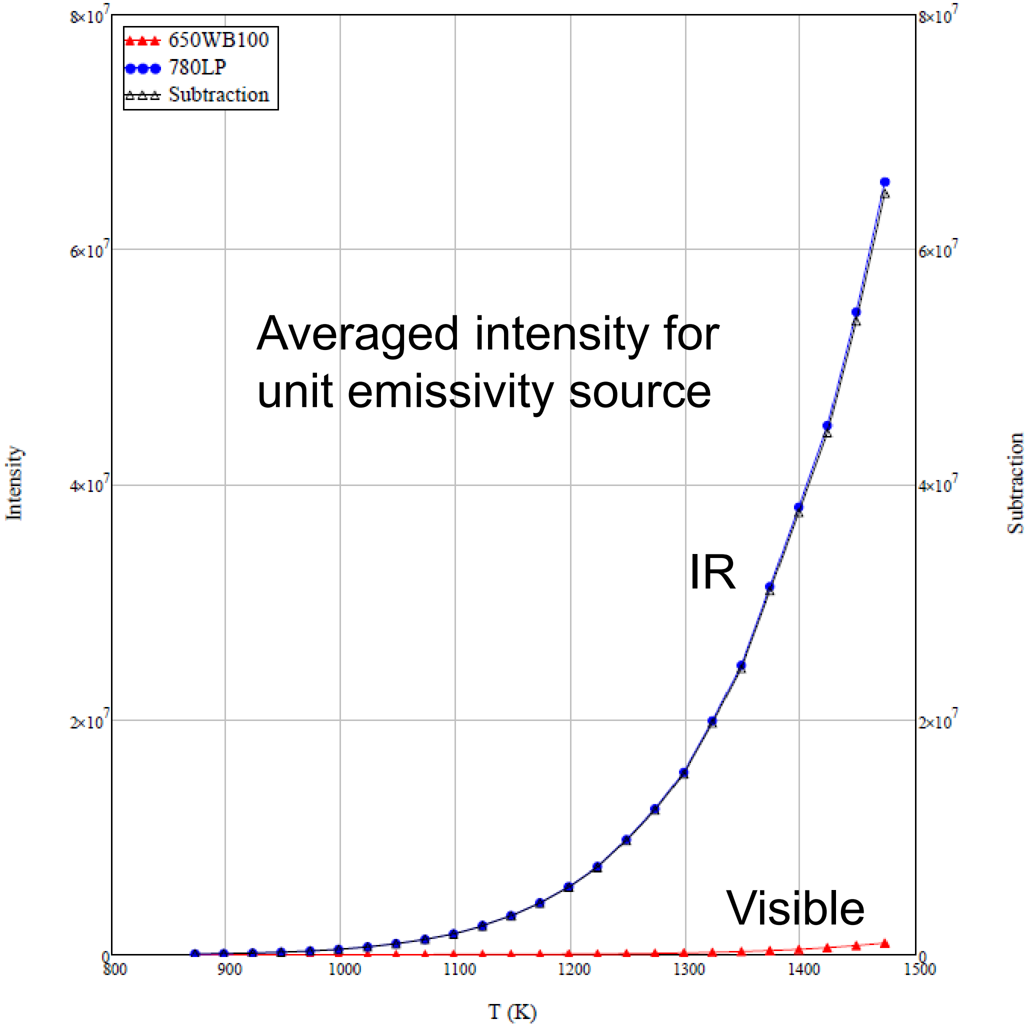


- Monitoring beam on target and dump
  - Variations in position, distribution, intensity
  - Target temperature (*to be completed*)
- Interface to Fast Machine Protection System
  - Intensity and temperature changes monitored with fast detectors (*to be completed*)

Target Thermal Imaging System Is Calibrated

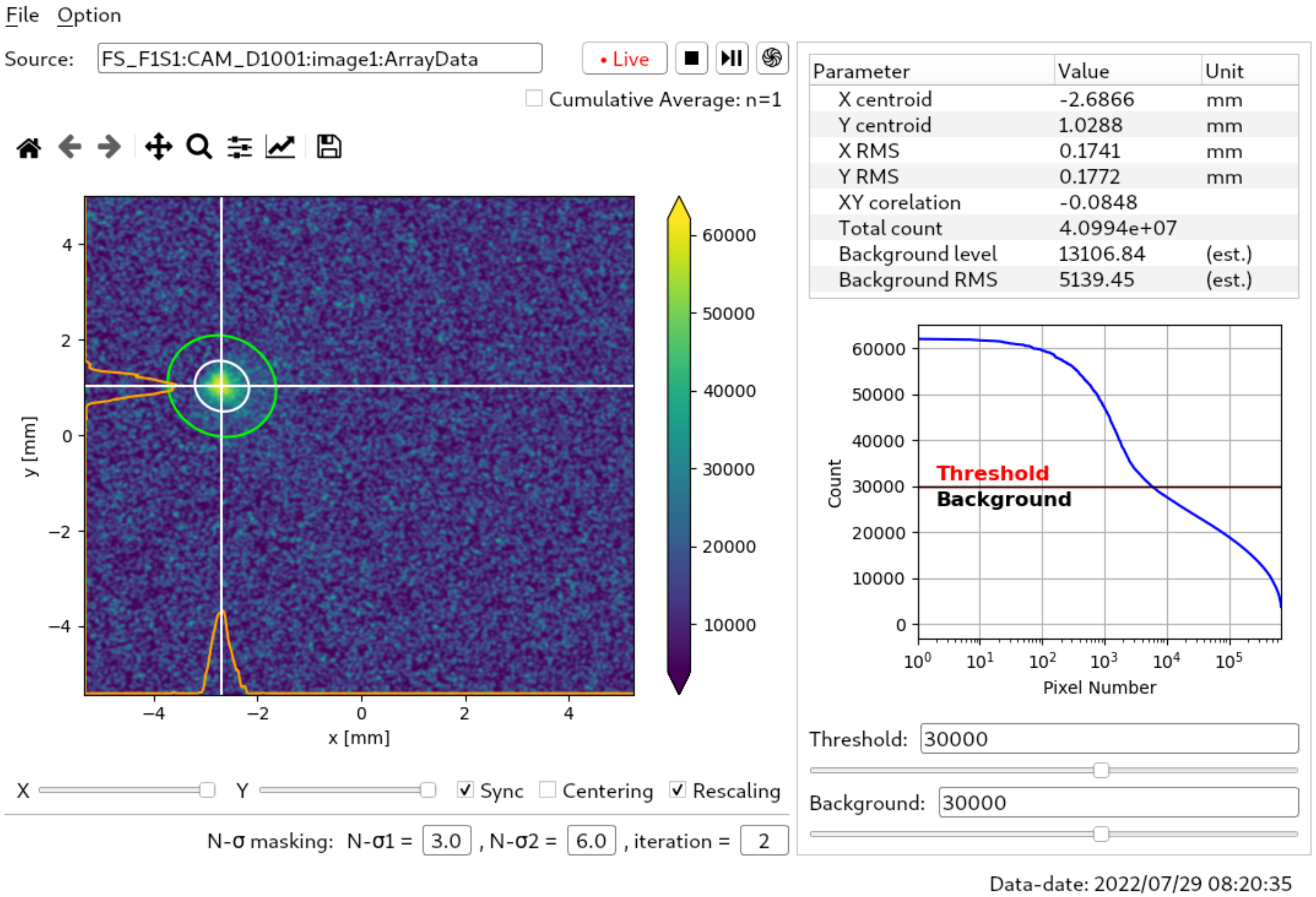
- The target system has been calibrated with an in situ blackbody source.
  - IR backlights through ‘hole’ in multi-position target
  - Identical cameras with visible or IR filters recorded image and calculate spatial/temporal average intensity
- IR signal is available for temperature measurement
  - Calibrate against target emissivity
  - Calibrate against beam power
- Will gain operational experience then commission photodiode detectors





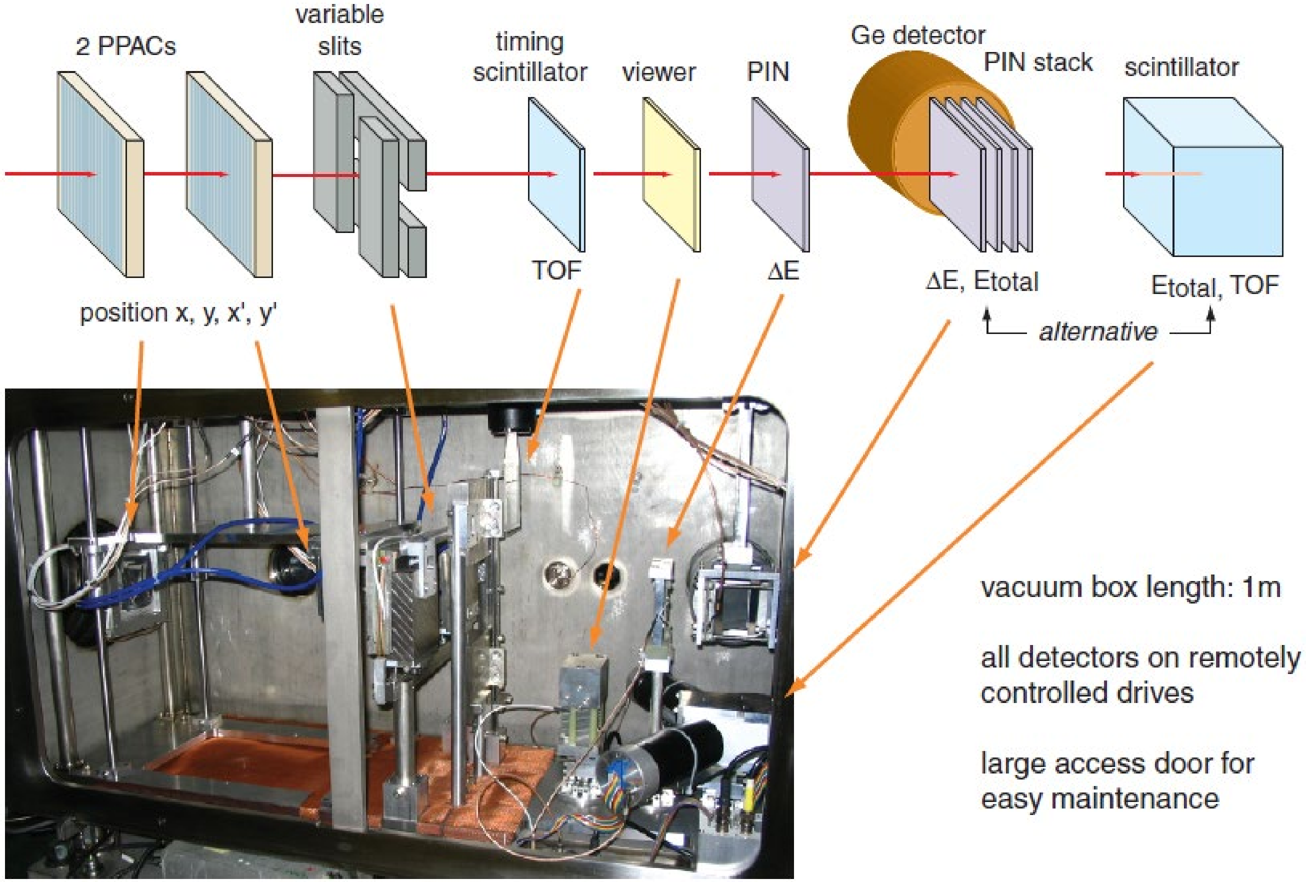
Initial Thermal Imaging Results

- Primary beam is ^{70}Zn, 173 MeV/u
- 922 W (CW) beam power on static target
- Image is acquired in near-IR (~1 μm)



Fragment Separator Diagnostics

- 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, typically at image planes



vacuum box length: 1m

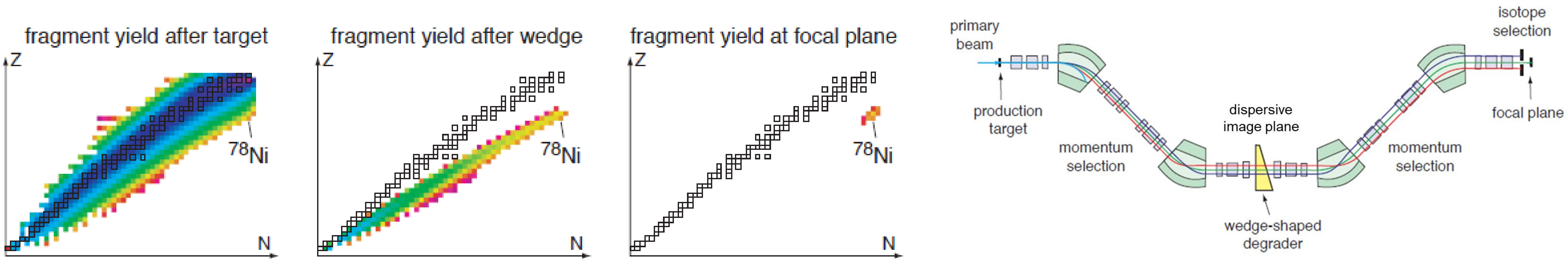
all detectors on remotely controlled drives

large access door for easy maintenance

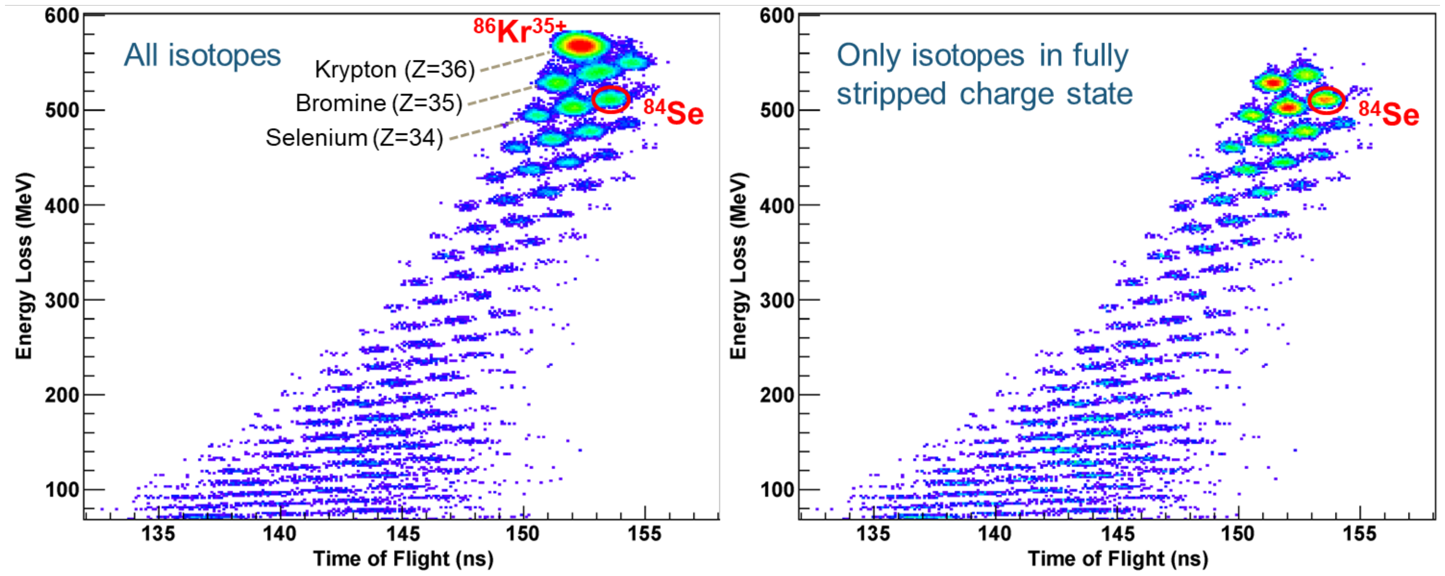
- Dual Parallel Plate Avalanche Counters (PPACs)
- TOF Scintillator + PMT
- Viewer+camera
- Resolving slits
- Wedge assembly

Particle Identification Enabled With Diagnostic Systems

Fragment separation using "momentum – energy loss – momentum" separation method

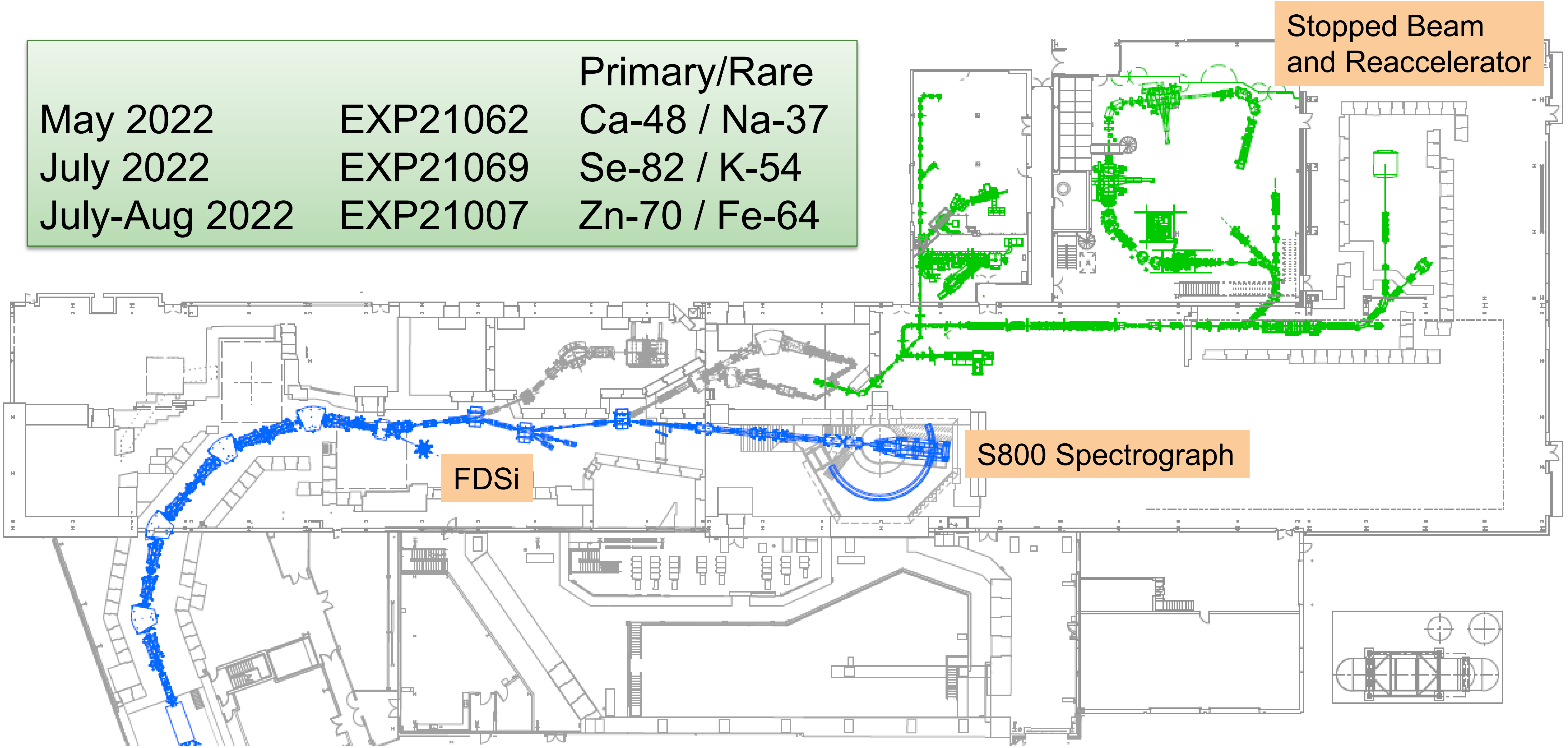


On December 11, 2021, rare isotopes were produced by fragmentation of a Krypton-86 beam on a 3 mm thick graphite target. Se-84 isotopes were detected and identified by measurement of energy loss, total energy, and time-of-flight with a stack of silicon detectors



Experimental Program has Begun

		Primary/Rare
May 2022	EXP21062	Ca-48 / Na-37
July 2022	EXP21069	Se-82 / K-54
July-Aug 2022	EXP21007	Zn-70 / Fe-64

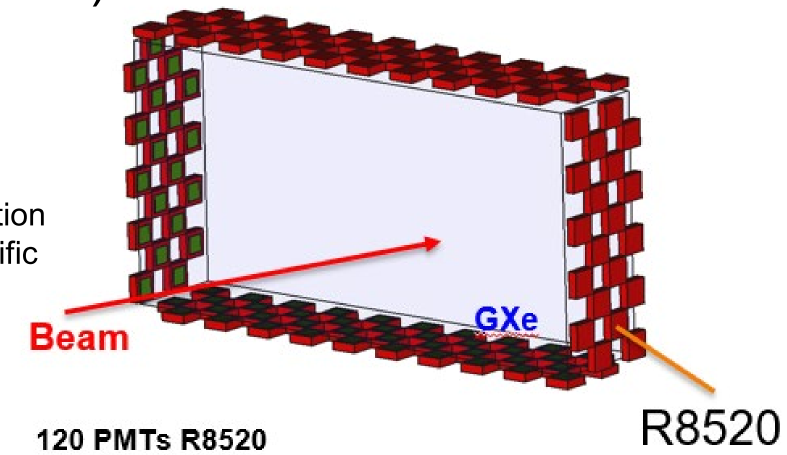


Instrumentation Upgrade Outlook

- Primary beams
  - Multiplex Faraday cup electronics
  - Develop new OpenHardware BCM AFC board to manage BCM network
  - BLM network improvements and predictive capabilities
  - Gas sheet profile monitor

- Secondary beams
  - Large format delay-line PPACs (200x200 mm^2)
  - Optical PPACs (MHz rates)
  - ELOSS: GXe detectors for high mass states (A>50)
    - » LXe in study (A>80)
  - Fast electronic systems for detector readout

M. Cortesi, et al.,"Design and construction of a novel Energy-Loss Optical Scintillation System (ELOSS) for Heavy-Ion Particle Identification", submitted to Review Scientific Instrumentation, September 2022.



Dimension 30mm x 30mm
Effec. Area 20.5mm x 20.5mm

Summary

- All linac diagnostics systems have been commissioned
- Target and fragment separator diagnostic systems are commissioned
- Machine power ramp-up is commencing
  - First experiments at 1 kW
  - Next stage is 3 kW, 5-6 kW, 10 kW in 2023
- Diagnostic and detector development continues to support high primary beam power and high particle rates

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