FRIB Linac Beam Commissioning

Peter Ostroumov

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Outline

- Brief description of the FRIB Linac
  - Beam commissioning stages
- High Level Applications (HLA)
- Accelerator tuning
- Beam diagnostics
- Beam parameters
- Toward project completion: demonstration of isotope production
- Summary

- Accelerator Science and Engineering Traineeship (ASET) Program at MSU

DOE Traineeship in Accelerator Science & Engineering

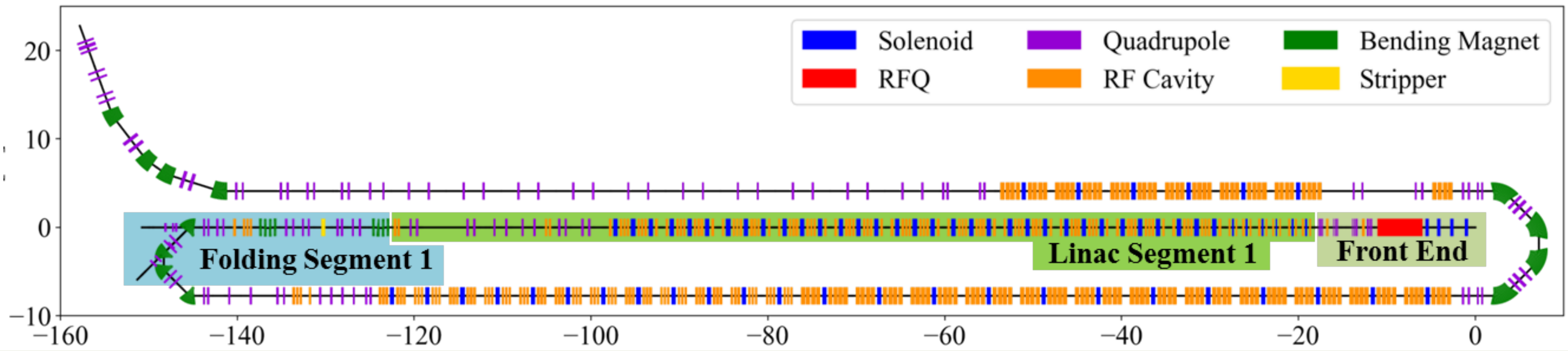
- Accelerator Science & Engineering Traineeship (ASET) at MSU
- Nation's sole grant in the FY 2017 DOE HEP Traineeship FOA in the four critical areas of workforce need
  - (1) Physics of large accelerators and systems engineering
    - » Beam physics at the systems level
    - » Knowledge of technologies of large accelerators
    - » Engineering expertise in high reliability design and failure analysis
    - » Knowledge of the fundamentals of project management, science communication, entrepreneurial skills, technology transfer
  - (2) Superconducting radiofrequency accelerator physics and engineering
  - (3) Radiofrequency power system engineering
  - (4) Cryogenic systems engineering (especially liquid helium systems)
- ASET budget covers about 17% of total amount of students' support required for PhD completion
- https://www.frib.msu.edu/science/ase/index.html

ASET

- After successful completion of courses at MSU (2 years) the students should be placed at DOE Lab for thesis research
- ASET Degree Certificate is established in Physics and Astronomy Department at MSU
- The ASET program will produce five to seven MSU graduates per year in the critical areas of workforce need.
  - 6 students (4 PhD and 2 MS) are graduating this year
- Currently we have 24 grad students enrolled in ASET
  - Training takes places in all 4 critical areas of workforce need
  - 6 students were admitted for AY2021
- The Accelerator Traineeship Advisory Panel (ATAP) is a national advisory committee established nearly three years ago to help guide MSU's ASET program and its outcomes
  - A. Chao (Chair), M. Harrison and S. Nagaitsev

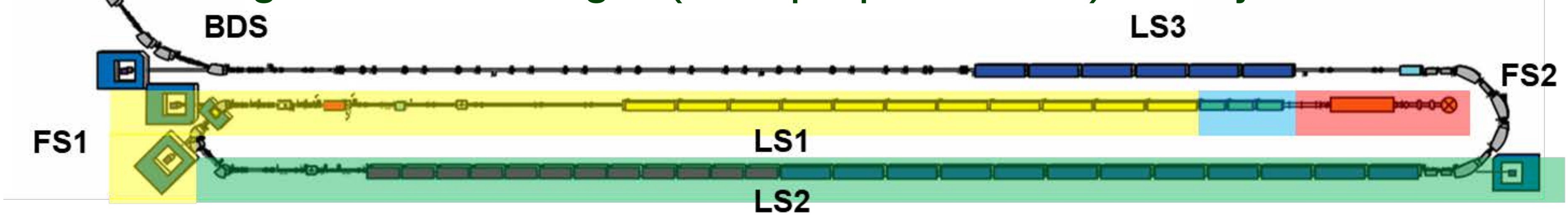
FRIB Linac

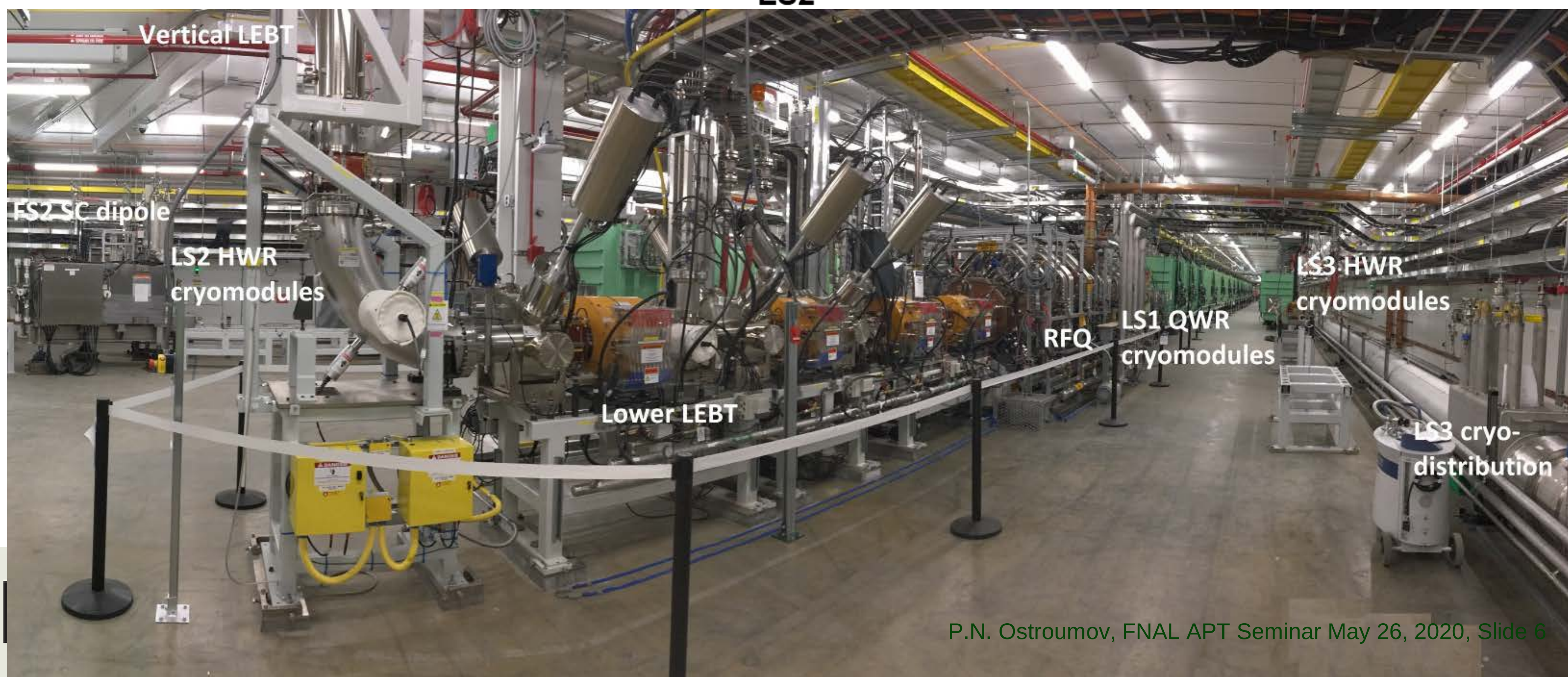
- The linac consists of 316 accelerating and 8 bunching SC resonators
- Beam energy: 200 MeV/u uranium, 600 MeV protons
- Total available voltage: 855 MV, effectively lower due to TTF
- Focusing with solenoids in SC sections and quadrupoles in warm sections
- 80 m space is foreseen to upgrade beam energy to 400 MeV/u, protons ~1 GeV
- Complexity: ECR source; all stable ions from O to U; Liquid Li stripper; multi-charge beam acceleration; 1-mm diameter beam on the target; cooling of target and beam dump; SRF and 2K/4K cryogenics; uncontrolled losses $<10^{-4}$



Linac Commissioning Stages

- Beam commissioning: Front End; First 3 cryomodules; Linac Segment 1, Linac Segment 2, Linac Segment 3 and Fragmentation Target (Isotope production) – Project KPP





High Level Applications

Global Launcher for FRIB Physics Apps

FRIB High-level Physics Controls Applications

Double-clicking to Launch App

	Name		Description	Version
1	Achromat Tuning		All-in-one solution for achromat bending section tuning	0.2
2	Allison Scanner App		Operating allison-scanner device and processing the acquired data	3.3
3	Cavity Scan App		The phase scan application for cavities	0
4	Cavity View		Display field levels for LS1 cavities	0
5	Correlation Visualizer		Visualize the parameter correlation, general-purposed parameter scan analysis	6.1
6	Device Viewer		Visualize/capture device readings from EPICS controls network	2.2
7	Energy Gain Calculator		Calculate the icon energy gain within a cavity	0
8	ISAAC		Generic single/multi-pv scan, envelope/trajectory reconstruction	0
9	Lattice Viewer		Show/investigate the lattices/elements information	1.3
10	MHB-Tuner		Plots the RFQ longitudinal acceptance and beam phase-space	0
11	Online Model		Simulate accelerator behaviors by online-modeling	0.3
12	PM Viewer		Inspect/Operate a list of wire-scanner devices	0.2
13	Physics Calculator		Cheatsheet for accelertor physics calculations	1.1
14	Quad Scan App		Calculate transverse emittance based on single quad scan approach	1.5
15	Settings Manager		Manage the physics settings of the accelerator	2.1
16	Synoptic View & Control		Another novel way to visualize and control the accelertor facility	0
17	Trajectory Correction		Steering trajectory with optics response matrix	3.5
18	Trajectory Viewer		Visualize/Manipulate beam central trajectory	3.2
19	Unicorn App		Manage/visualize the scaling laws between engineering and phyiscs units	1.4
20	Virtual Accelerator Launcher		Launch FRIB virtual accelerators	2.2
21	Wire Scanner App		Operating wire-scanner device and processing the acquired data	2.9

FRIB Physics Applications (v3.3)

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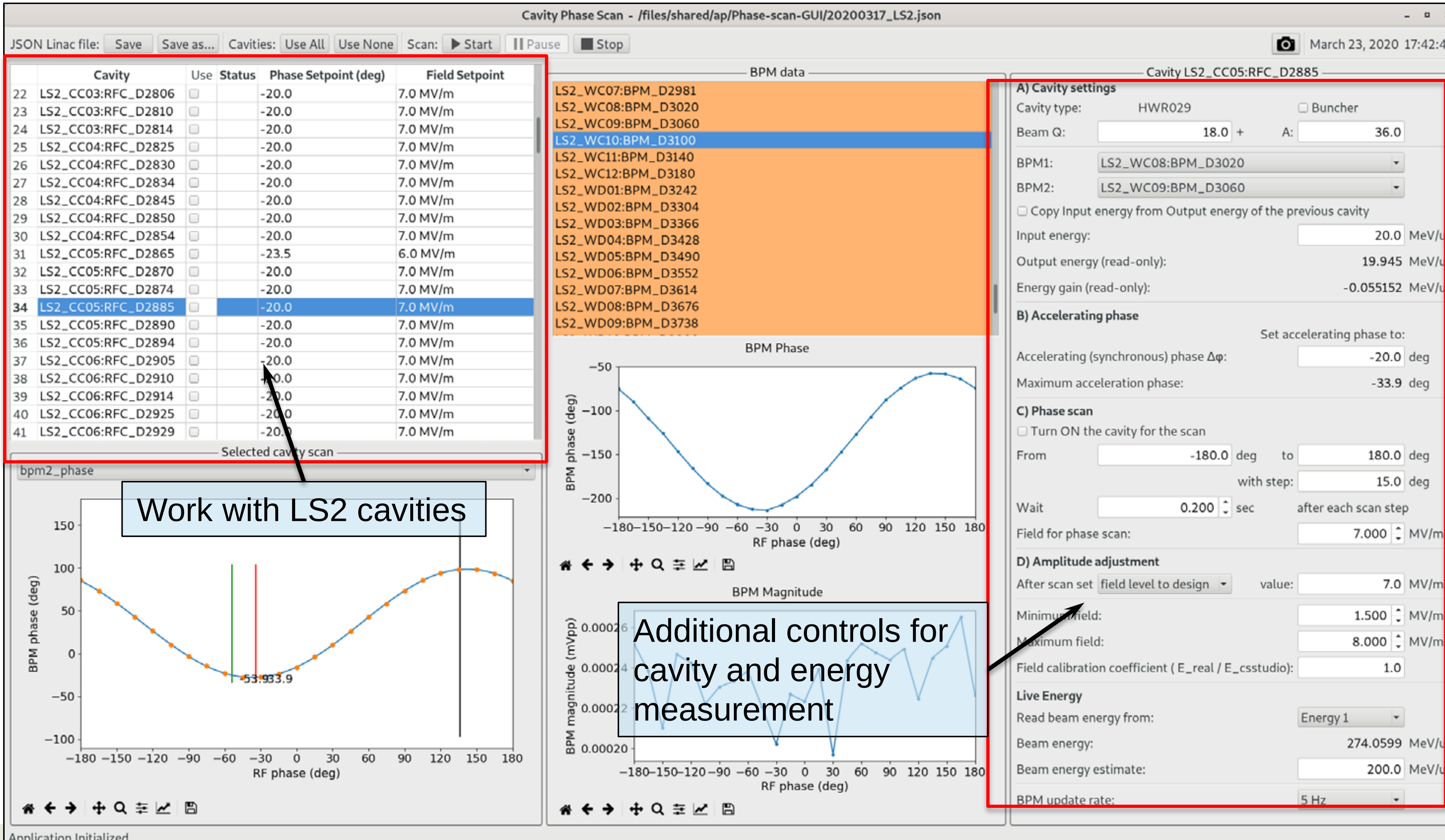
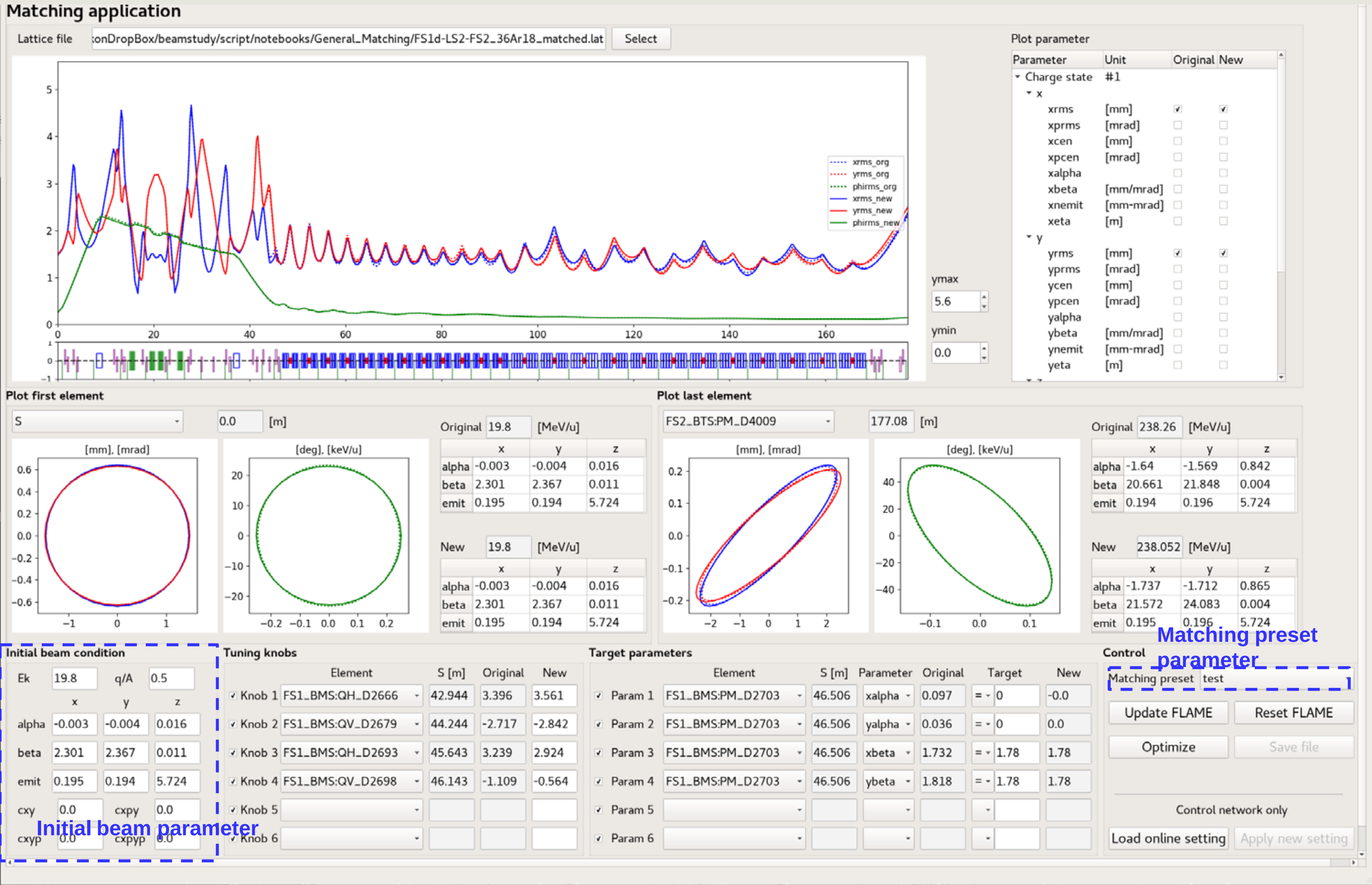
Phase Scan App

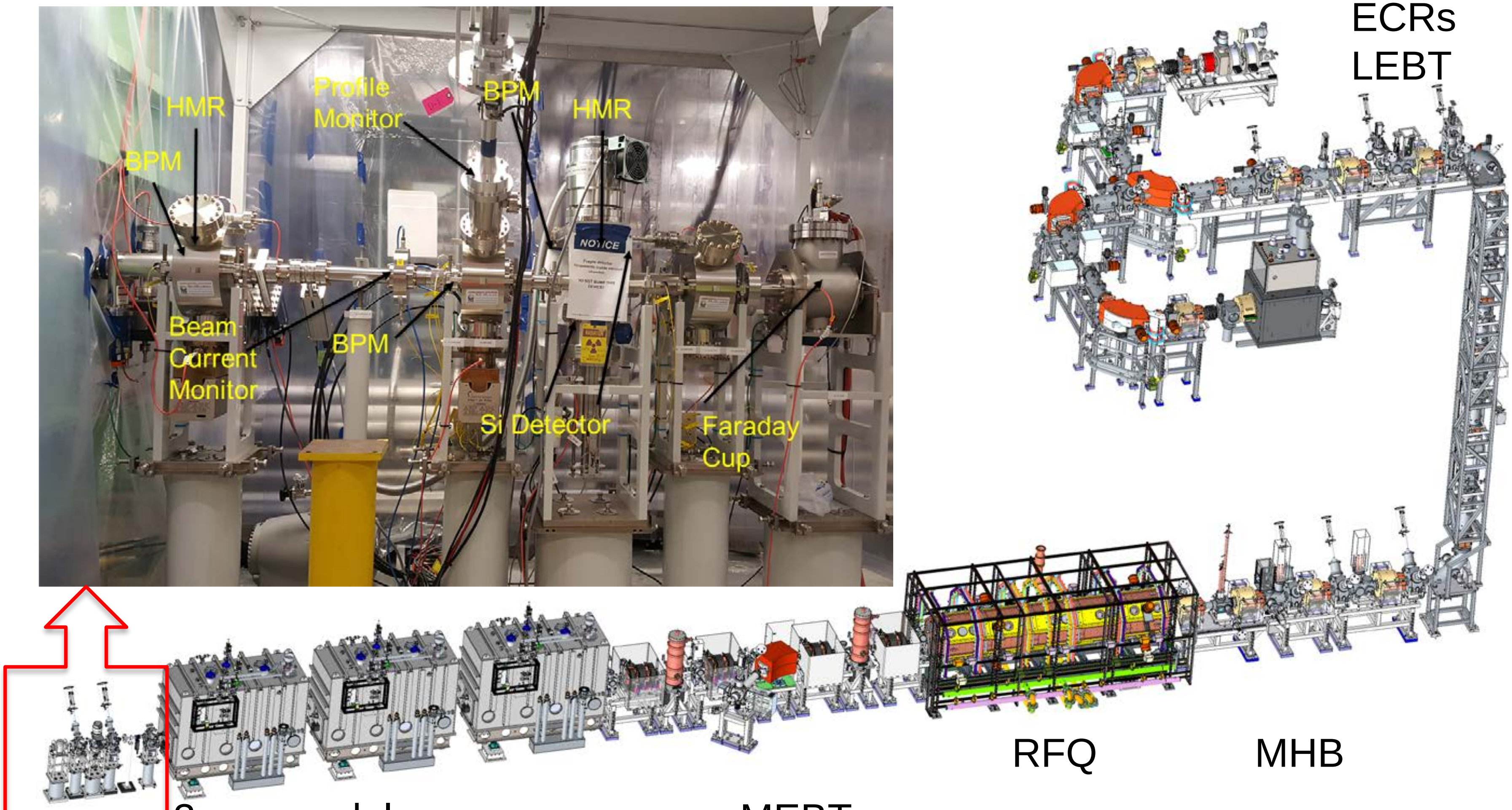


On-Line Beam Simulation and Matching



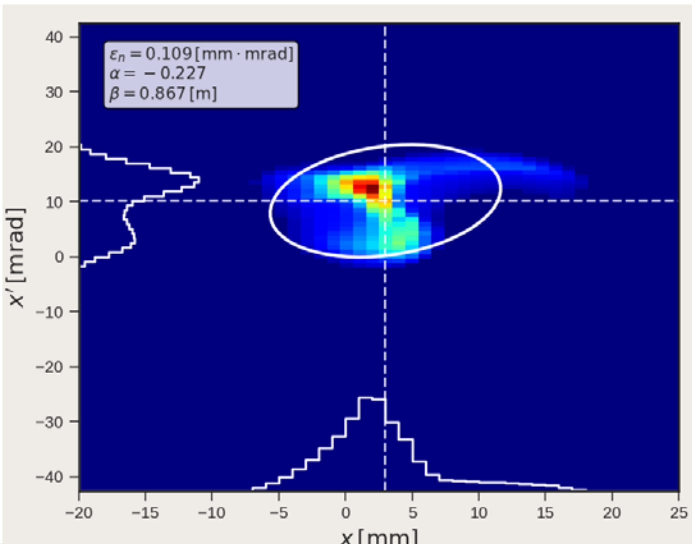
Beam Commissioning of First Three Cryomodules

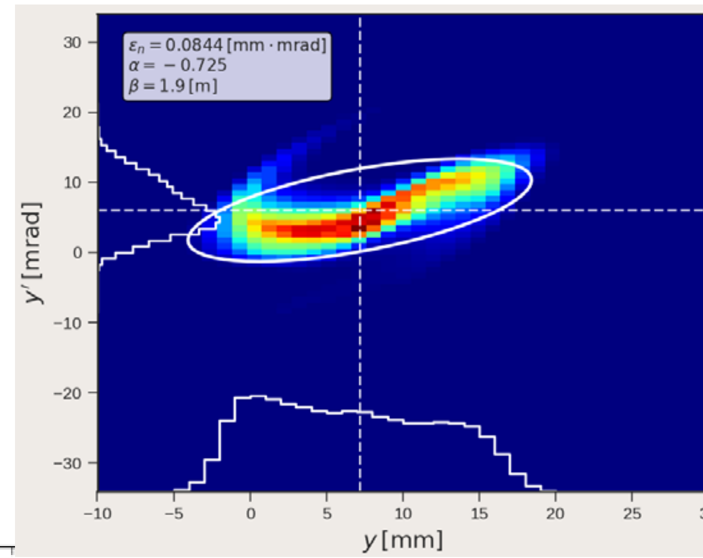
Commissioning beam diagnostics station

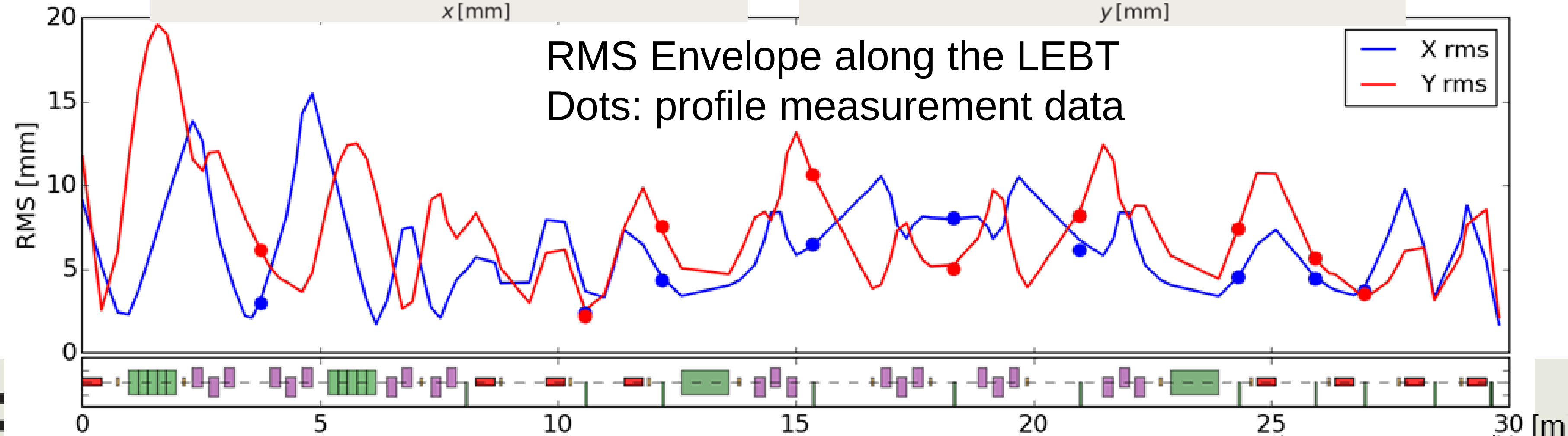


Argon Beam in LEBT

- ECR normalized rms emittances for 280 μA (50% of the FRIB design intensity) $^{40}Ar^{9+}$ beam by Allison scanner

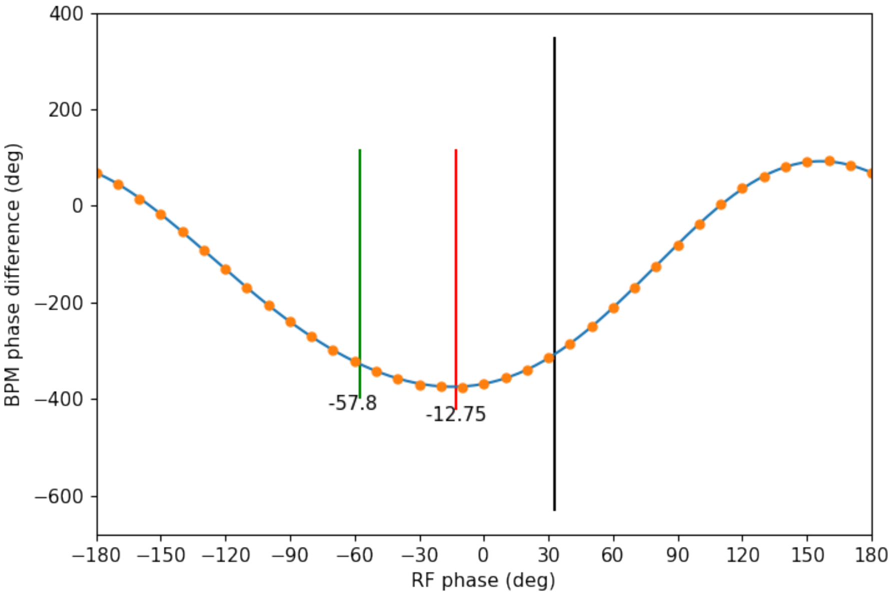


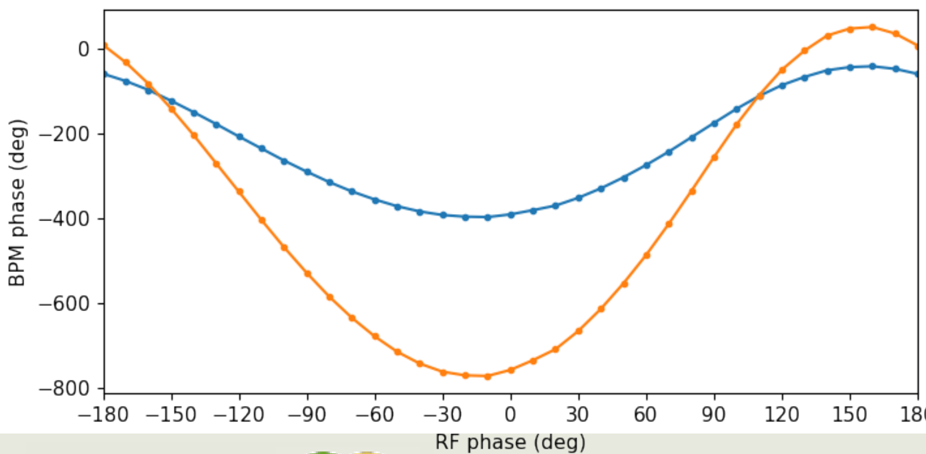


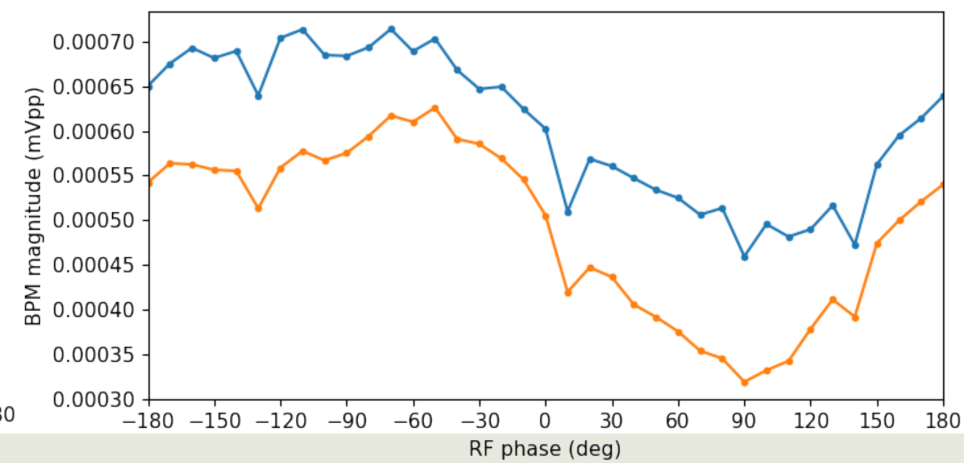


Phase Scan

- Phase scan procedure was applied at 1.1 MV/m to avoid beam steering
- For phase scan of SC cavities we use very low average beam current
  - Peak current ~100 nA
  - Duty Cycle ~0.025% (5Hz, 50 μs)
  - Attenuation in the LEBT
  - Average beam power: <2 W



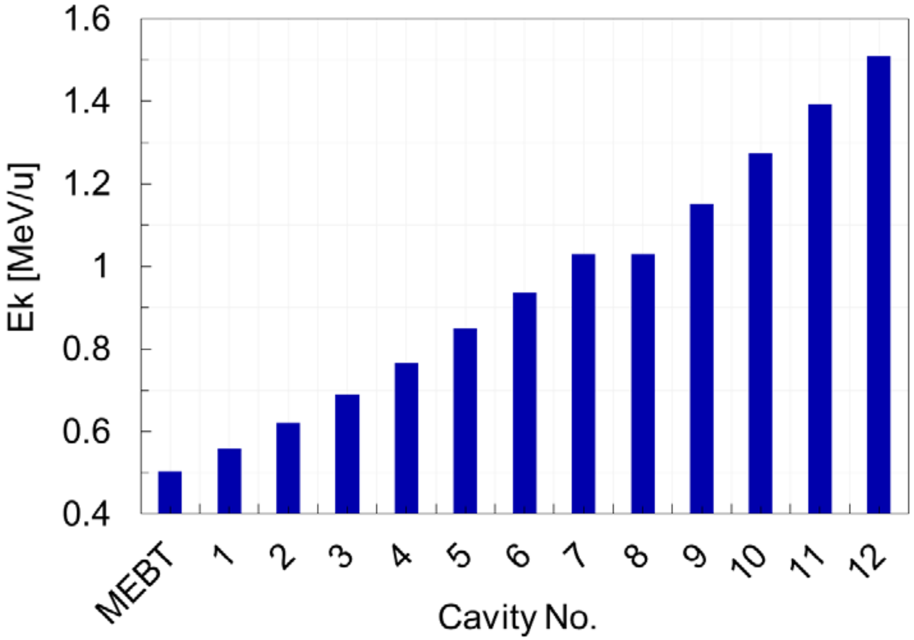




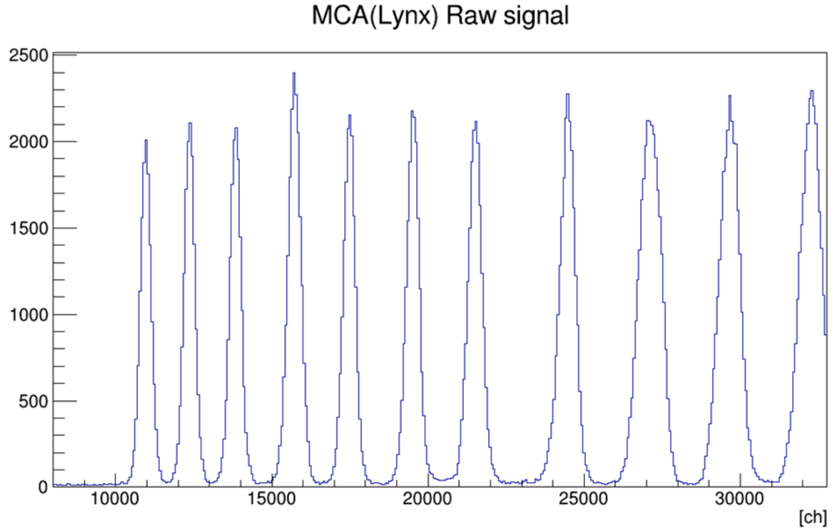
Beam Energy Measurements

- Precise beam energy measurements with BPMs and Silicon Detector (SiD)
- Design energy gain profile per nucleon is the same for all ion species in the first 3 cryomodules
  - SiD energy measurements were done for Ar beam

Beam energy vs cavity number, TOF measurements

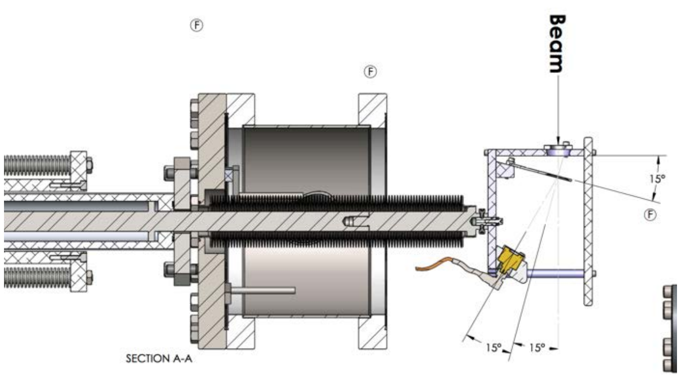


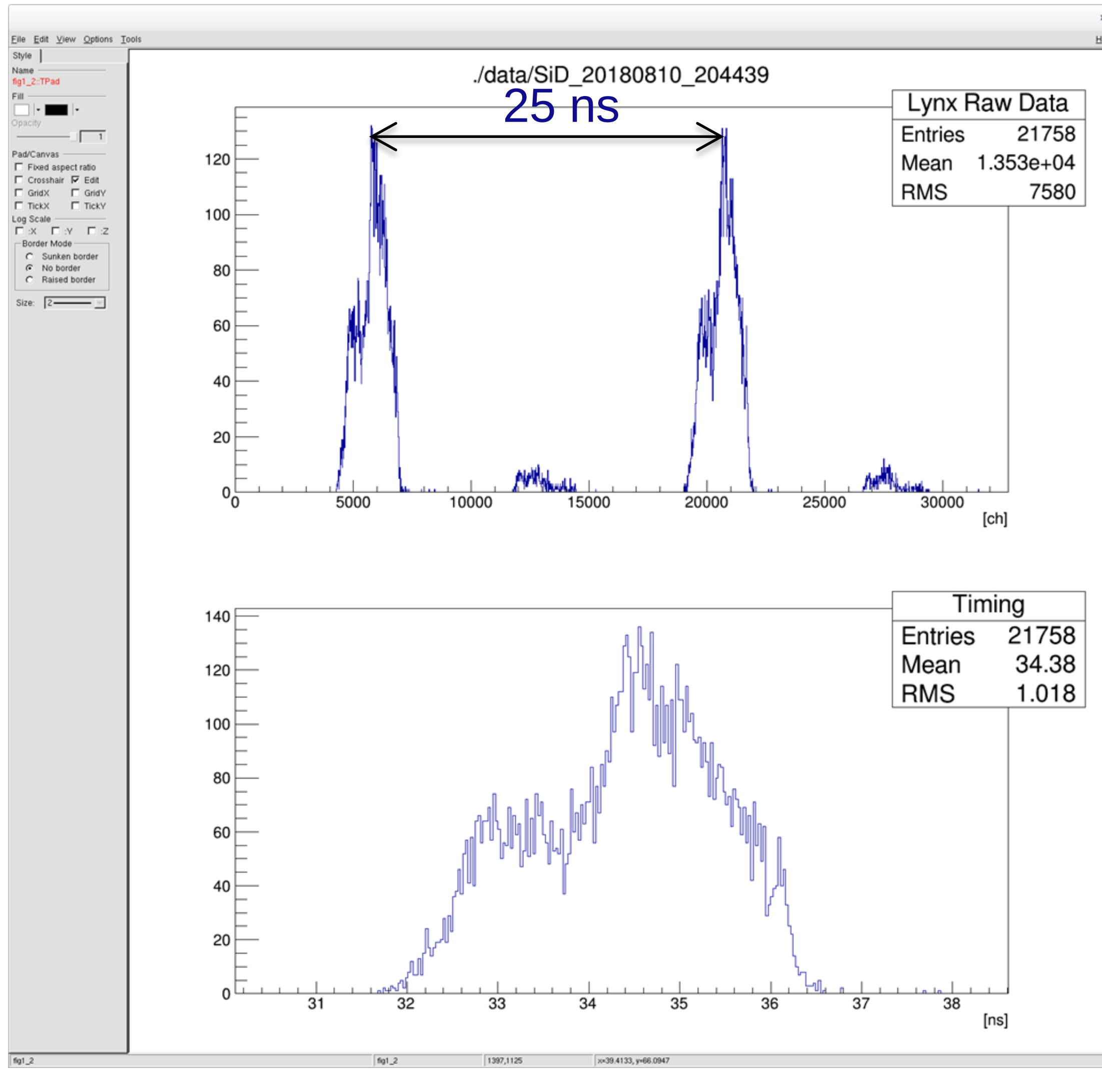
Silicon Detector measurements after turning each cavity on



Bunch Shape Measurements with SiD

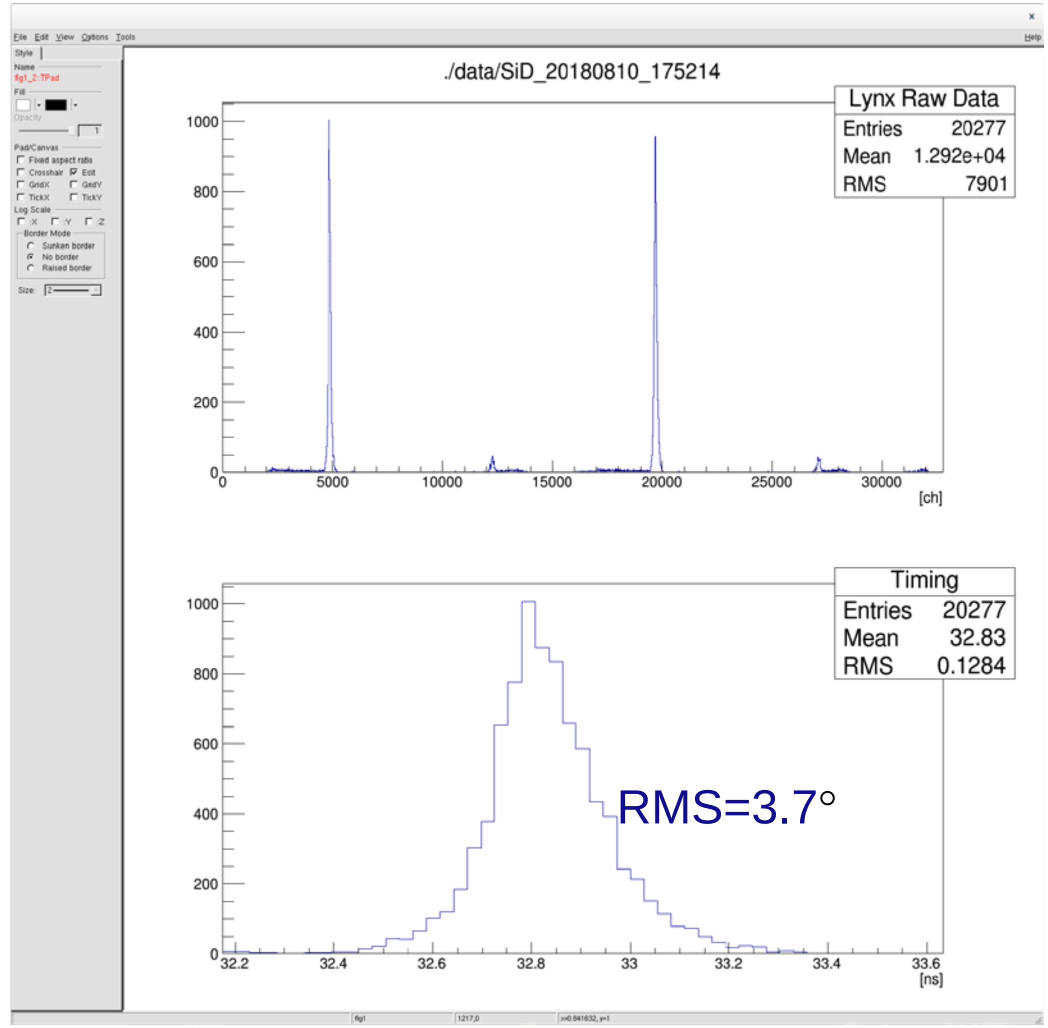
- 504 keV/u beam with one rebuncher
- Beam drifts for 15 meters
- 40.25 MHz bunch structure formed by Multi-Harmonic Buncher
- RFQ: 80.5 MHz





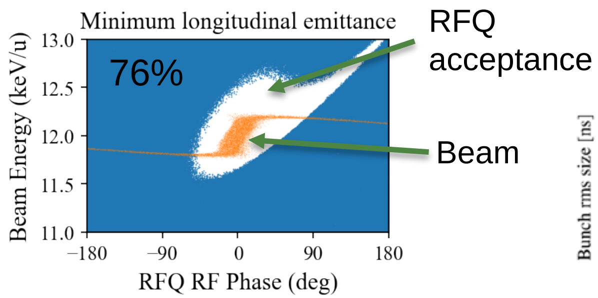
Bunch Shape of 1.4 MeV/u Ar Beam Measured with Silicon Detector

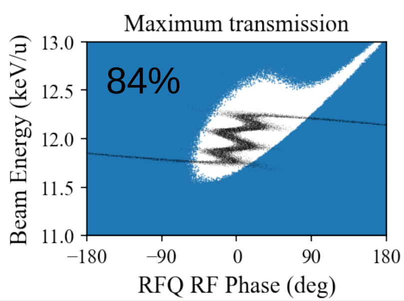
- SiD provided very good time resolution, ~100 psec
- Bunch shape of 1.4 MeV/u Ar beam, time focus to the SiD is provided by cavity #12
- SiD does not show any beam halo in the longitudinal phase space as expected

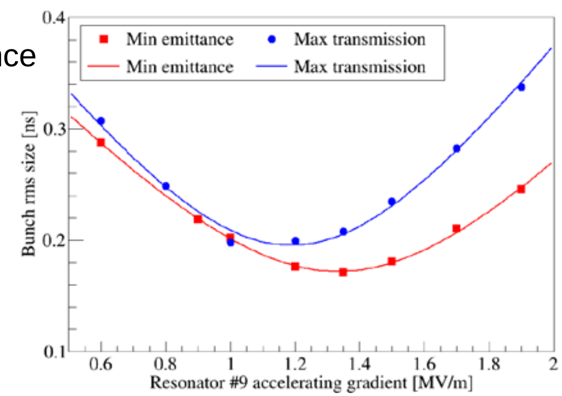


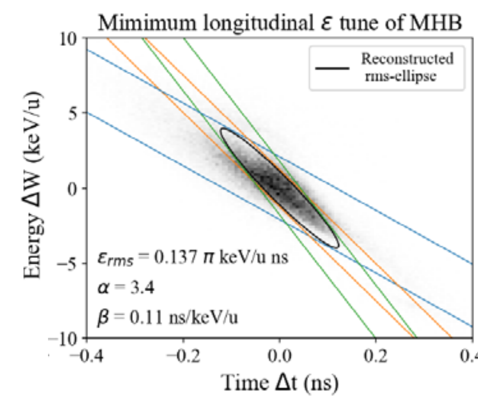
Longitudinal RMS Emittance for Two MHB Settings

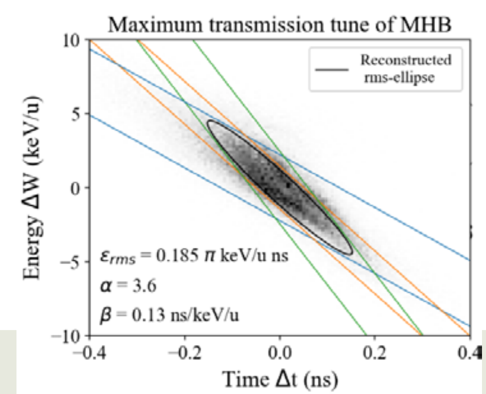
- The longitudinal emittance was measured by scanning RF amplitude of one of SC resonators at bunching phase
  - ^{40}Ar beam accelerated to 1.0 MeV by the first seven resonators
  - Bunch length was measured by silicon detector in the D-station
- Measure the longitudinal emittance with two multi harmonic buncher settings
  - Minimum longitudinal emittance
  - Maximum beam transmission





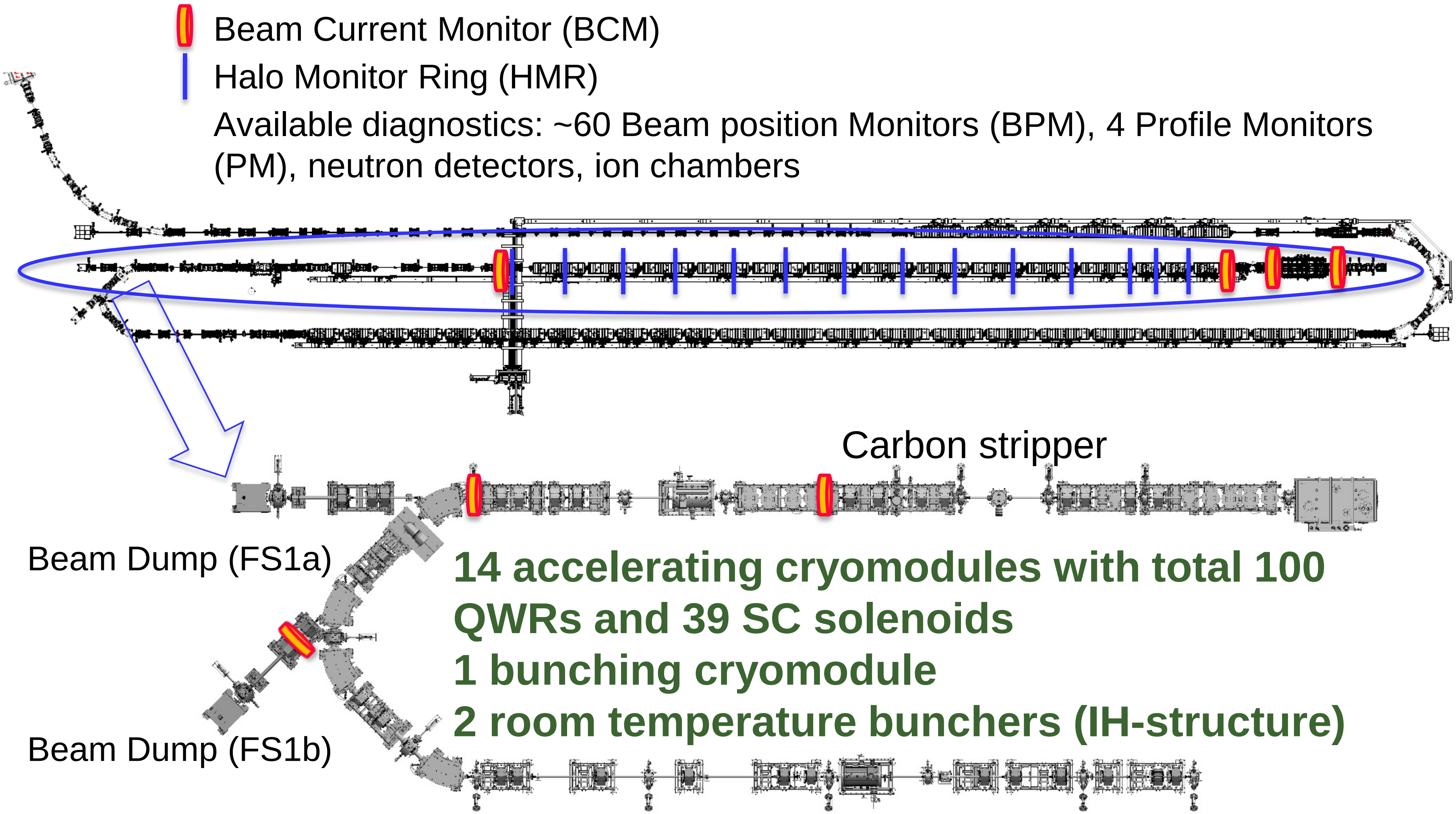






[πkeV/u nsec]	Meas.	Sim.
Min. emit.	0.14	0.12
Max. trans.	0.19	0.14

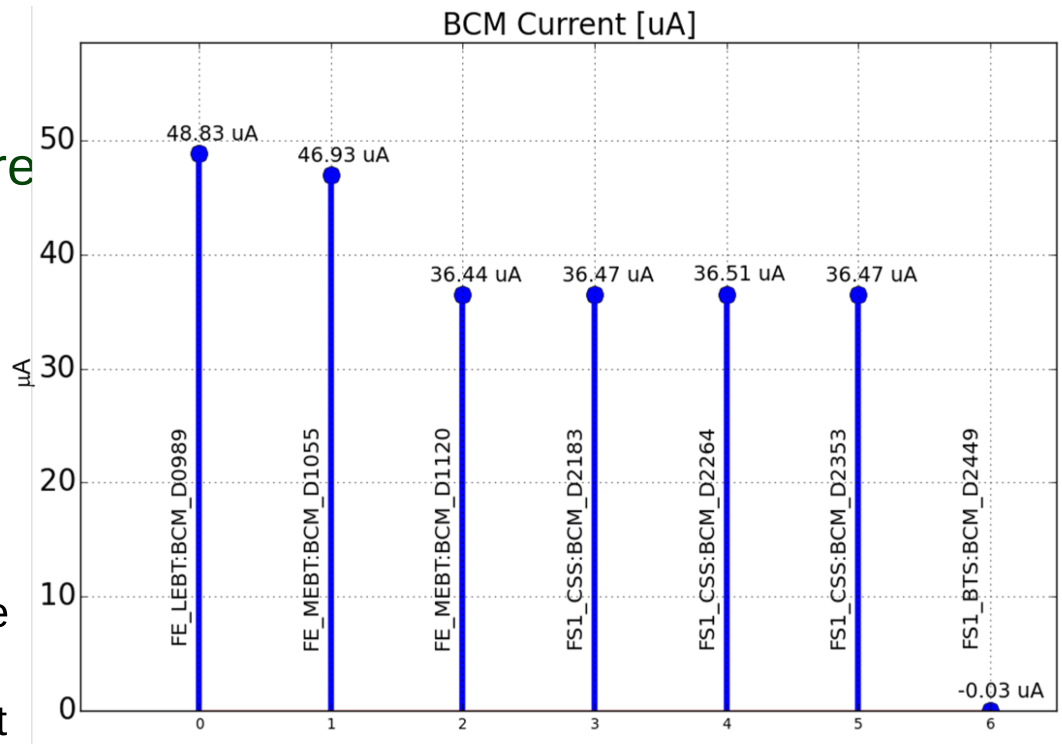
Beam Diagnostics in Linac Segment 1



14 accelerating cryomodules with total 100 QWRs and 39 SC solenoids
1 bunching cryomodule
2 room temperature bunchers (IH-structure)

Four Ion Species Accelerated to 20.3 MeV/u

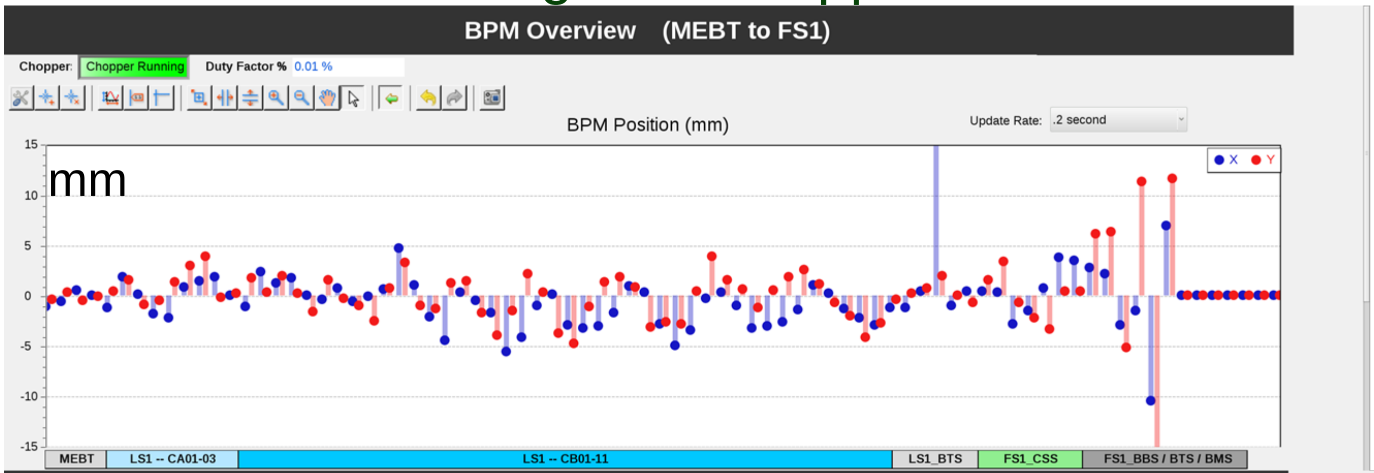
- Beam energy is verified both by Time-Of-Flight (TOF) measurements and 45° bending magnet field
- Detailed tuning was performed for $^{40}Ar^{9+}$
  - $^{86}Kr^{17+}$, $^{20}Ne^{6+}$, $^{129}Xe^{26+}$ beams were accelerated by scaling of all electromagnetic fields
  - 100% transmission
- Typical measurements of the beam transmission is shown here
  - Signals are average over several minutes
- Beam current monitors:
  - D0989 – before the RFQ
  - D1055 – right after the RFQ
  - D1120 – right before the first cryomodule
  - D2182 - right after the last cryomodule
  - D2264, D2353 – after the stripper
  - D2449 – after the 45° bending magnet



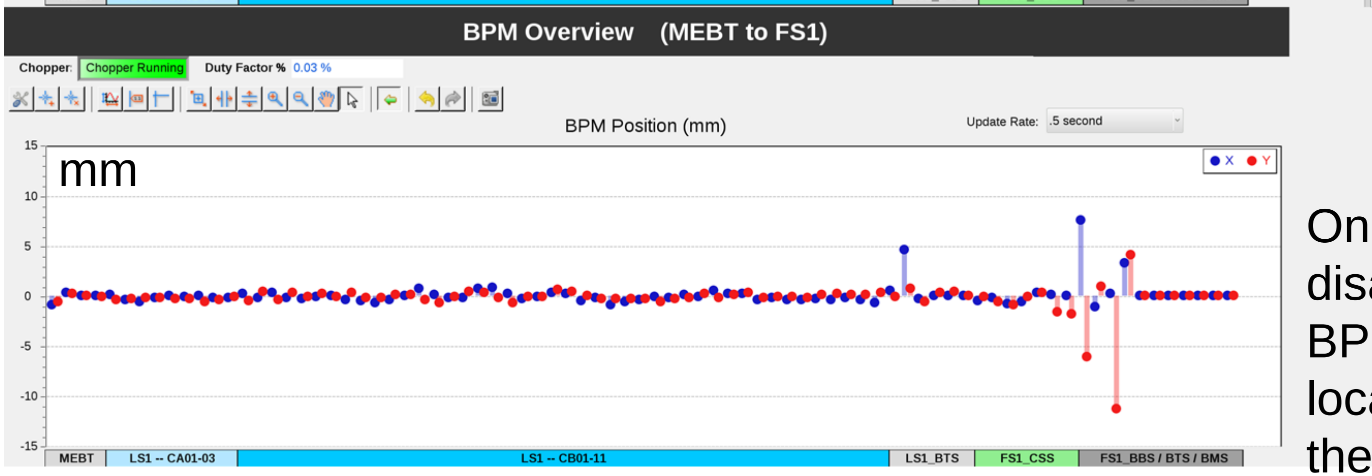
Central Trajectory Correction in LS1 Consisting of 100 SC QWRs and 39 Solenoids

- Beam centroid was tuned to be within ±0.5 mm using on-line Optics Response Matrix - based High Level Application

Before



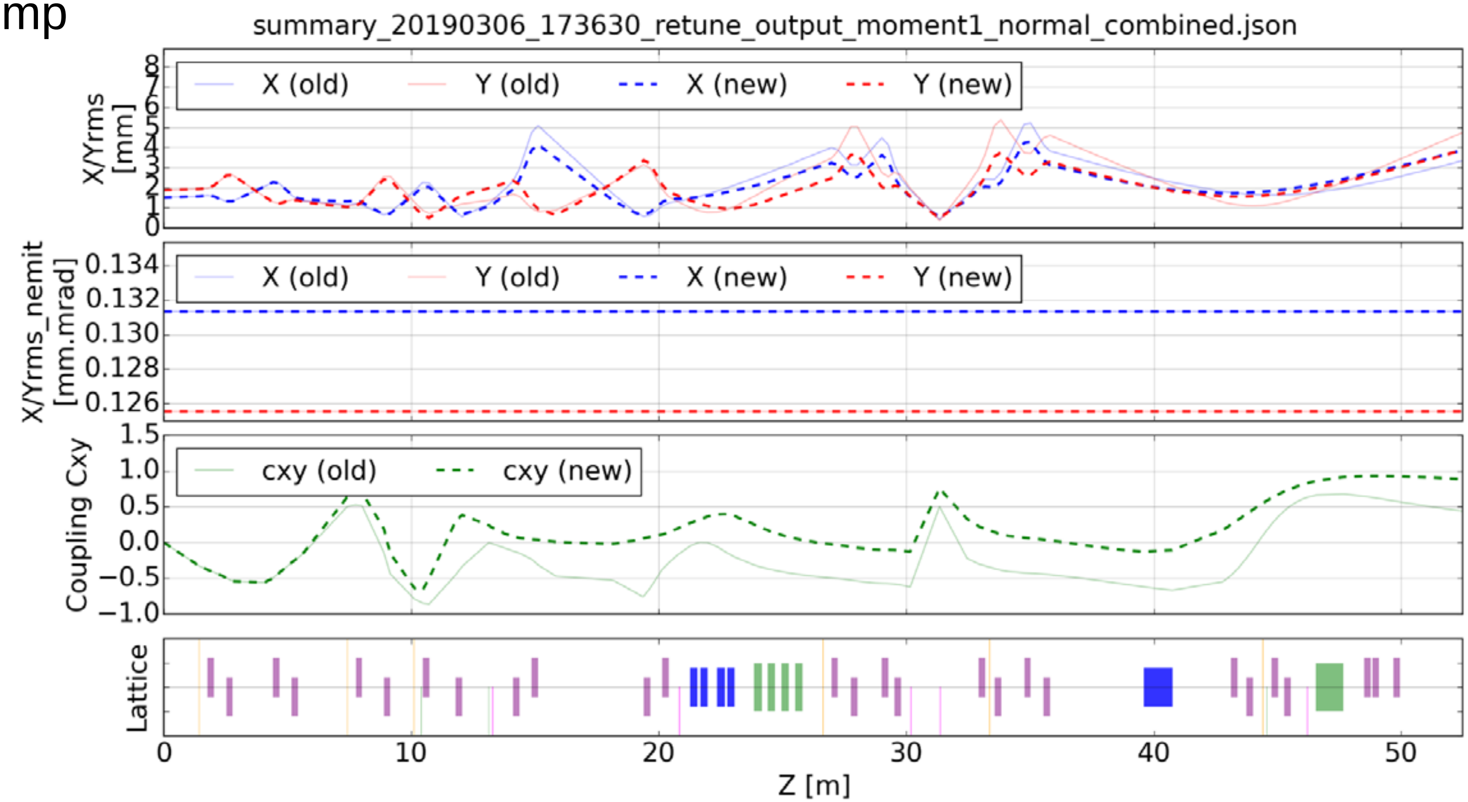
After



One BPM was disabled, 4 BPMs are located after the bend

Transverse Beam Dynamics Is Consistent with the Design

- Envelope tuning in warm section is based on Profile Monitor (PM) measurements
  - "old" - design; "new" – retuned to minimize beam envelope and match to beam dump

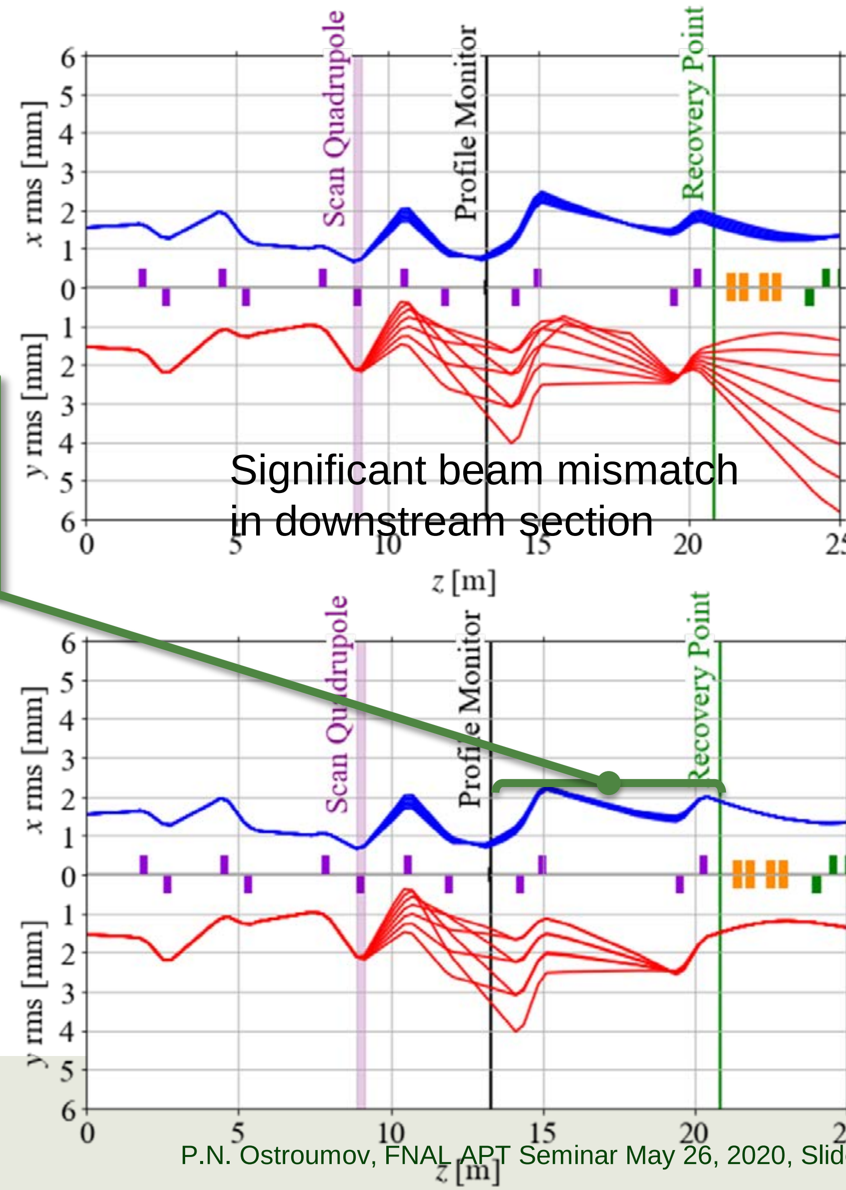


Location	MEBT, W=0.5 MeV/u		LS1, W=20.3 MeV/u	
RMS norm emittance (π μm rad)	ε_x	ε_y	ε_x	ε_y
I_{peak}=33 μA	0.14	0.10	0.15	0.12
I_{peak}=133 μA	0.13	0.11	0.12	0.14

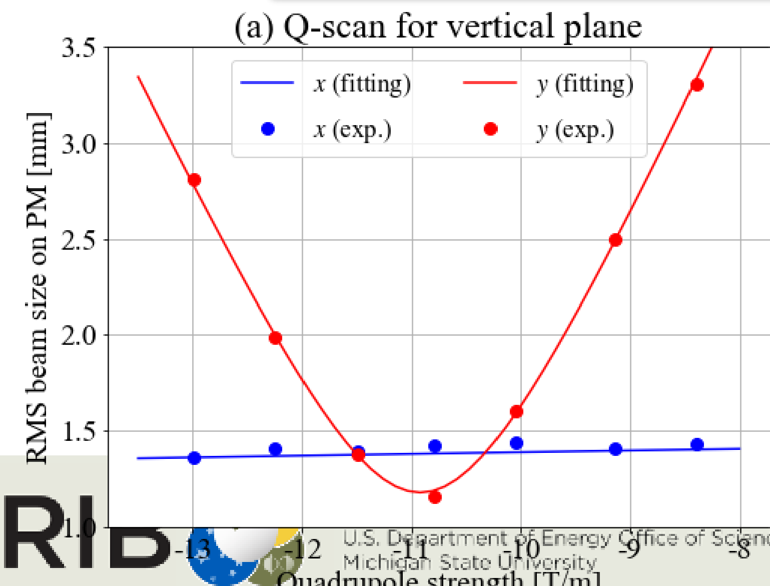
Transverse RMS Emittance with Low Beam Losses

- Quadrupole scan and profile measurements to restore transverse RMS emittance
- Avoid beam losses downstream of the profile monitor

Recover original Twiss parameter by using these 4 quads



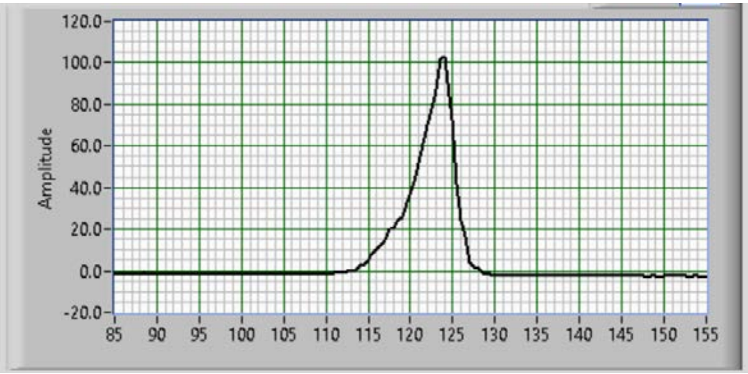
Significant beam mismatch in downstream section



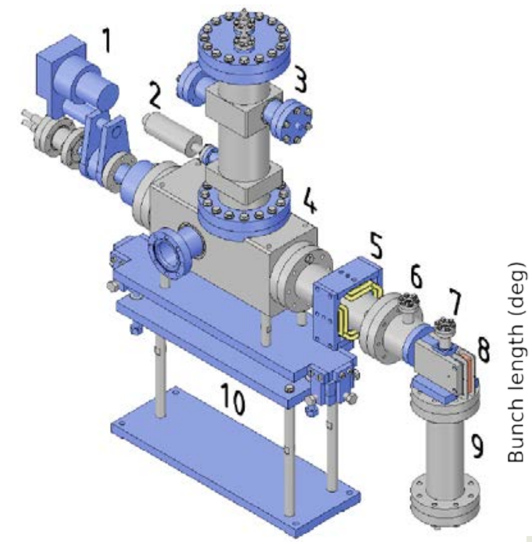
Bunch Shape and Longitudinal Emittance Measurements

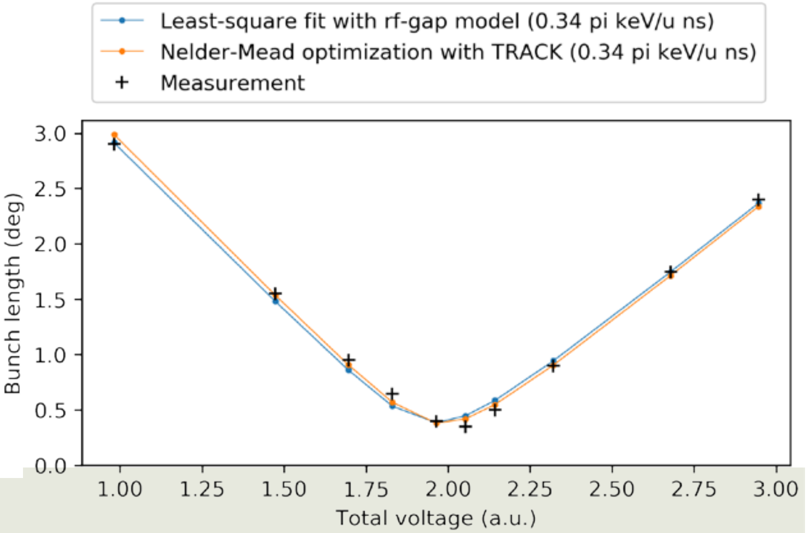
- Bunch Shape Monitor (BSM)
  - Very small bunch length can be created at the location of the stripper
- Bunch shapes were measured for different setting of the buncher
  - Longitudinal emittance was evaluated from this data

Typical bunch shape, rms bunch size is ~1°



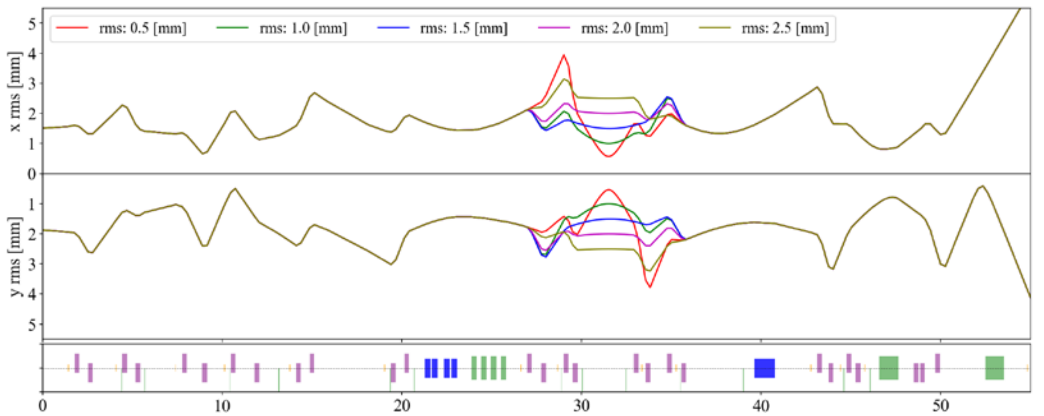
RMS bunch size as a function of the buncher voltage

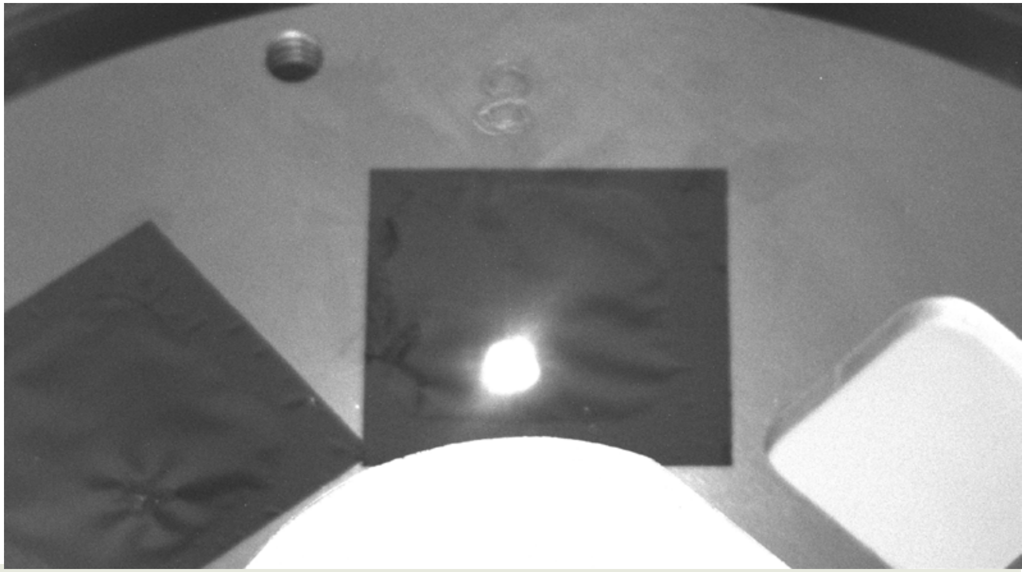




Heavy Ion Stripping

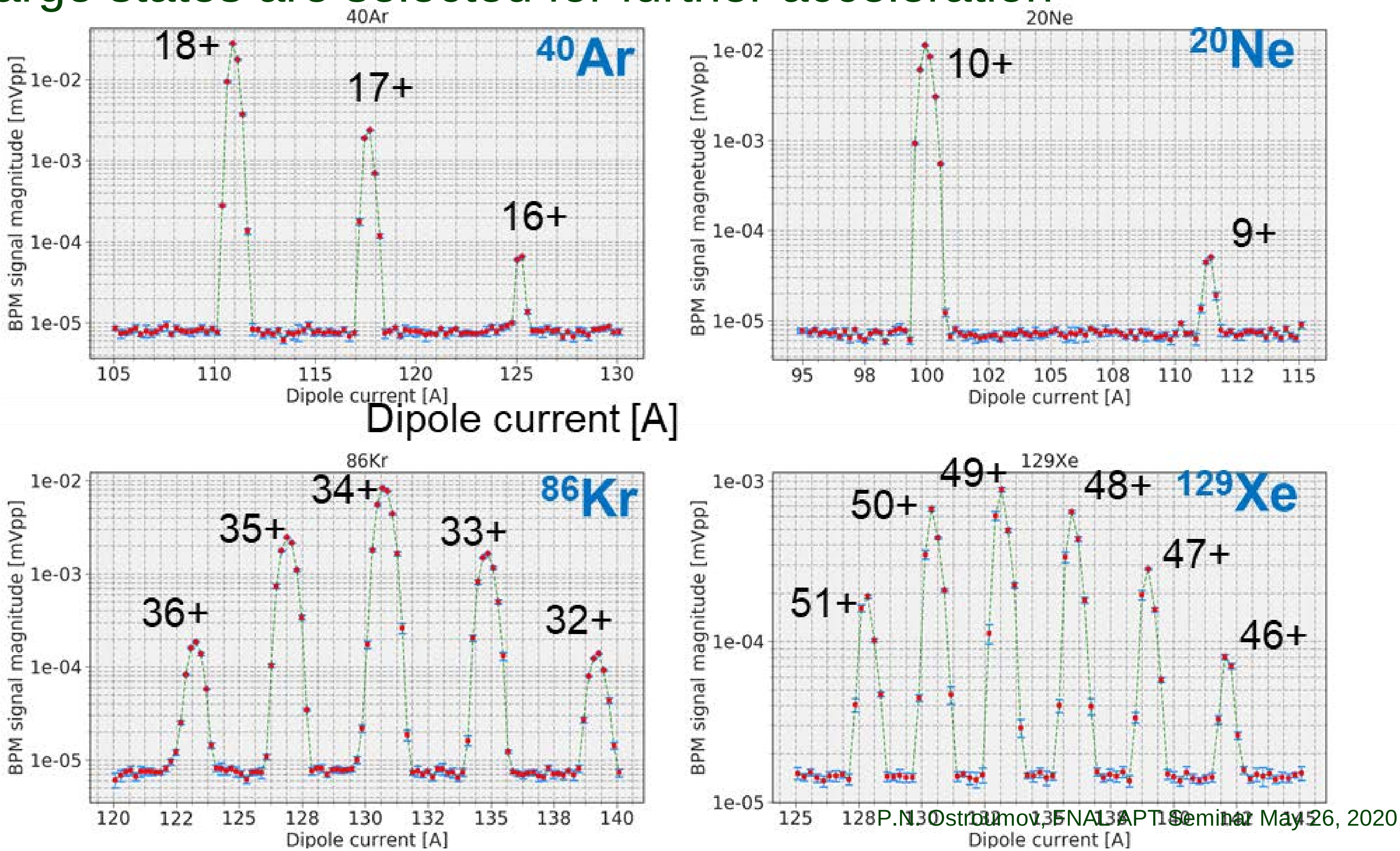
- 0.36 pμA 20.3 MeV/u CW Argon Beam Image on Carbon Stripper
- Beam image size can be easily varied by matching quadrupoles
- To reduce emittance growth due to scattering beam size should be small
- High density beam can quickly destroy carbon foil
- Recommended rms beam size:
  - Carbon stripper: 1.5 mm
  - Lithium stripper: 0.5 mm





Charge State Distributions after the Stripper Measured for Four Ion Beam Species

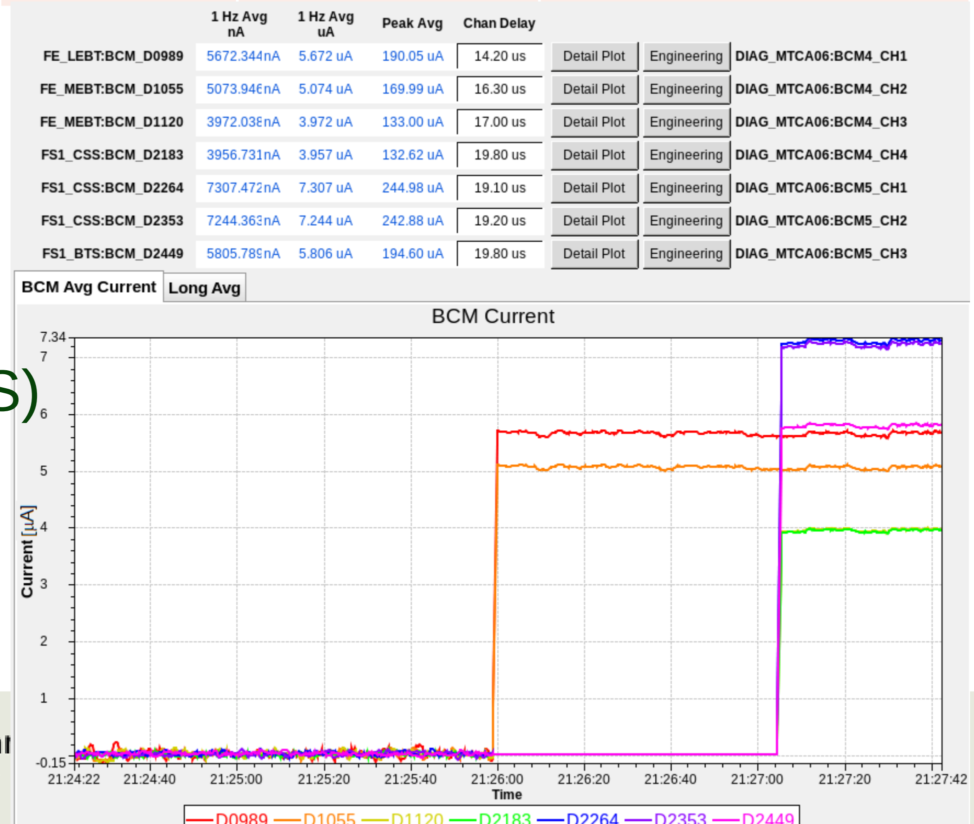
- 0.8 mg/cm^2 carbon foil was inserted on the beamline
- BPM signal after 4-mm slit vs 45° dipole current
- Charge states are selected for further acceleration



High Power Equivalent Beams

	Ion	I_{peak} in LS1 (μA)	Pulse length (μs)	Rep. rate (Hz)	Duty Factor (%)	Average beam power (W)
1	Ar	34.3	1000	100	10	309
2	Ar	3.2	9995	100	CW	290
3	Ar	156	300	100	3	415
4	Ar	133	6000	5	3	360

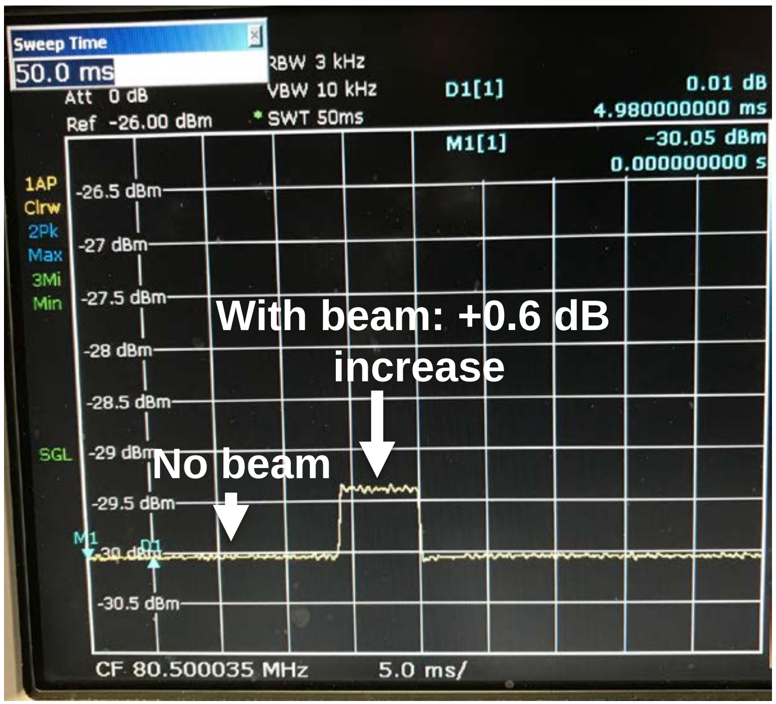
- The average power is limited by the beam dump
- Differential signals from BCMs were used as sensors for the machine protection system (MPS)
- Transmission is 100%
- Signals from the Halo Monitor Rings read background noise.



Beam Loading Compensation

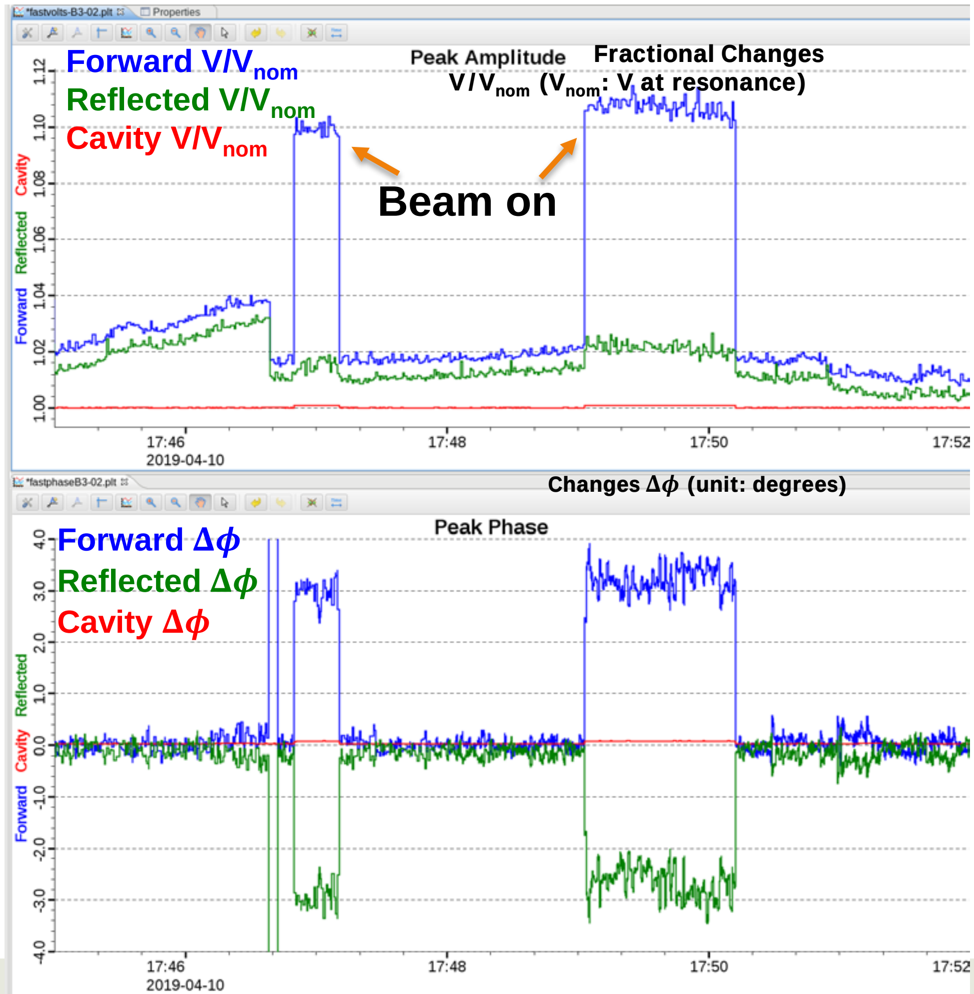
- 6 ms, 5 Hz beam pulse structure

Forward RF power, $P_{forward}$



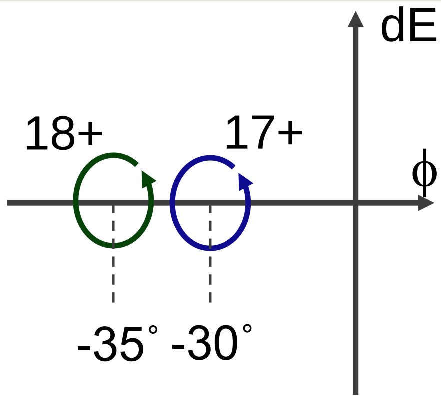
Peak detection over 7 minutes

(Each data point: a peak value in 1 sec period)



^{86}Kr Two Charge States Acceleration

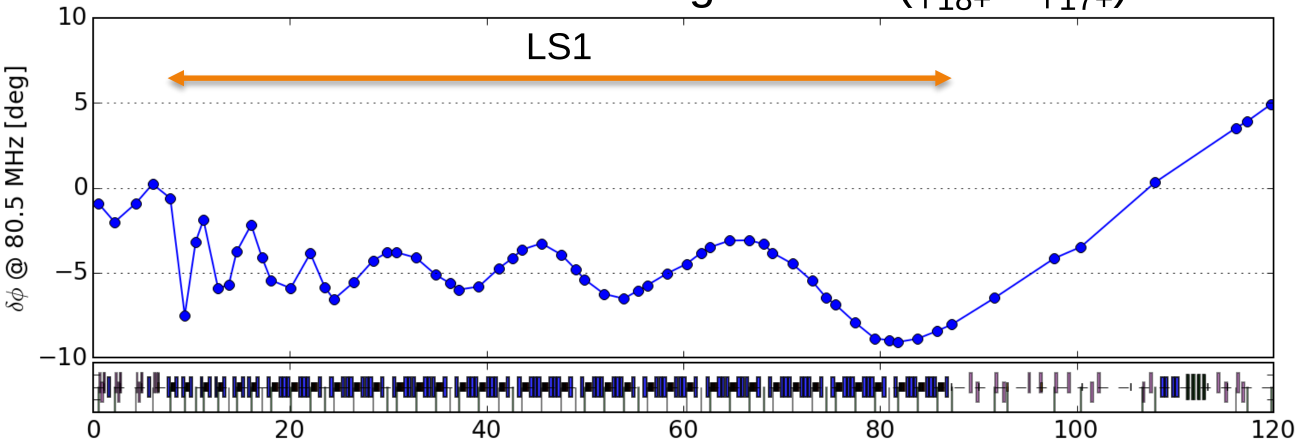
- Velocity equalizer upstream of the RFQ is not available yet
- 18+ is ~5 degree earlier than 17+ for entire LS1
  - Charge states oscillate around their synchronous phase
- Energy difference after the LS1 is very small
  - Beam centroid on the charge selector is close enough for selection



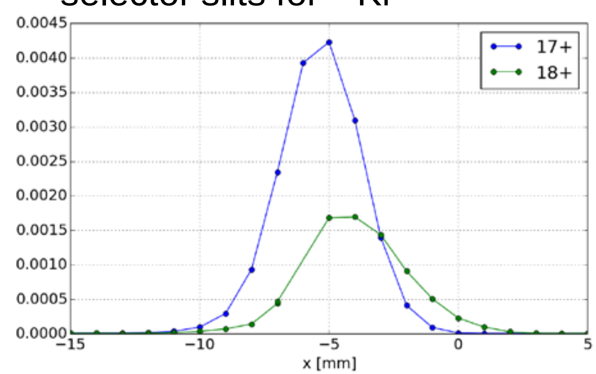
$$q_{18+}\cos(\phi_{18+}) = q_{17+}\cos(\phi_{17+})$$

[MeV/u]	17+	18+
LS1 end	20.30	20.26

Phase difference of two charge states (ϕ_{18+} - ϕ_{17+})



Horizontal profile at the charge selector slits for $^{86}Kr^{35+}$



[mm]	17+	18+
Center	-5.34	-3.93
RMS	1.68	2.18

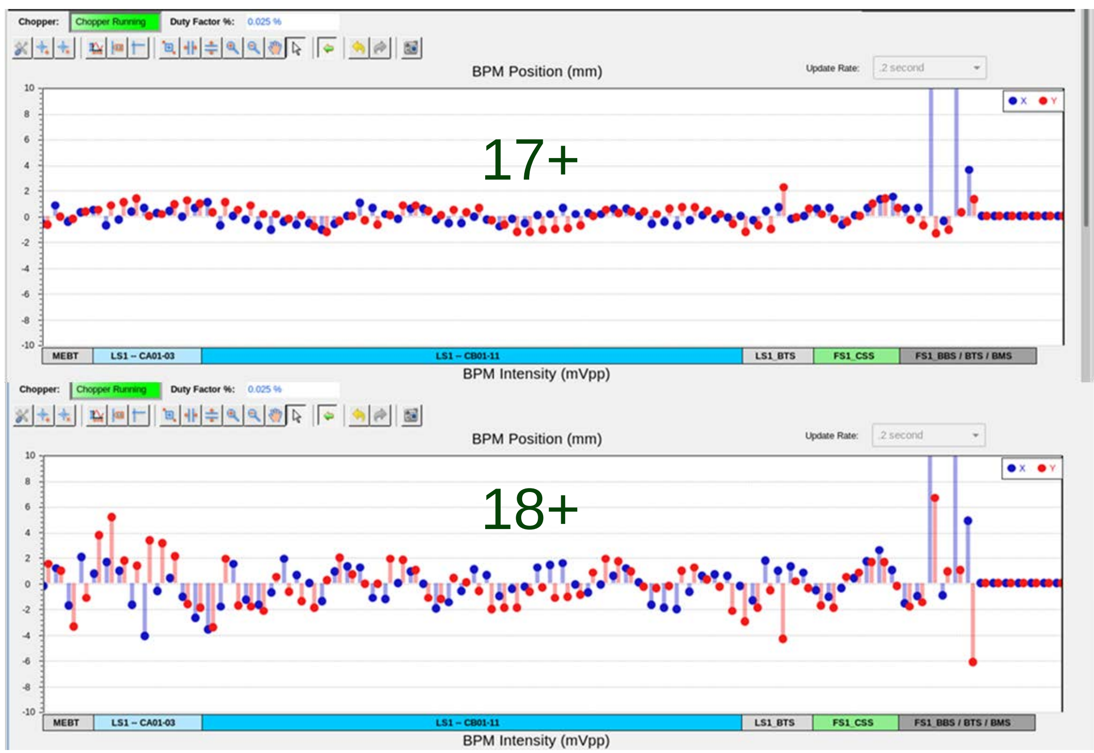
^{86}Kr Two Charge States Acceleration

Capability of LS1 for Dual Charge State Beam Acceleration Demonstrated

- Everything is tuned for $^{86}Kr^{17+}$
  - Beam trajectory aligned within $\pm$1 mm
  - Transverse matching was conducted at the FS1 entrance

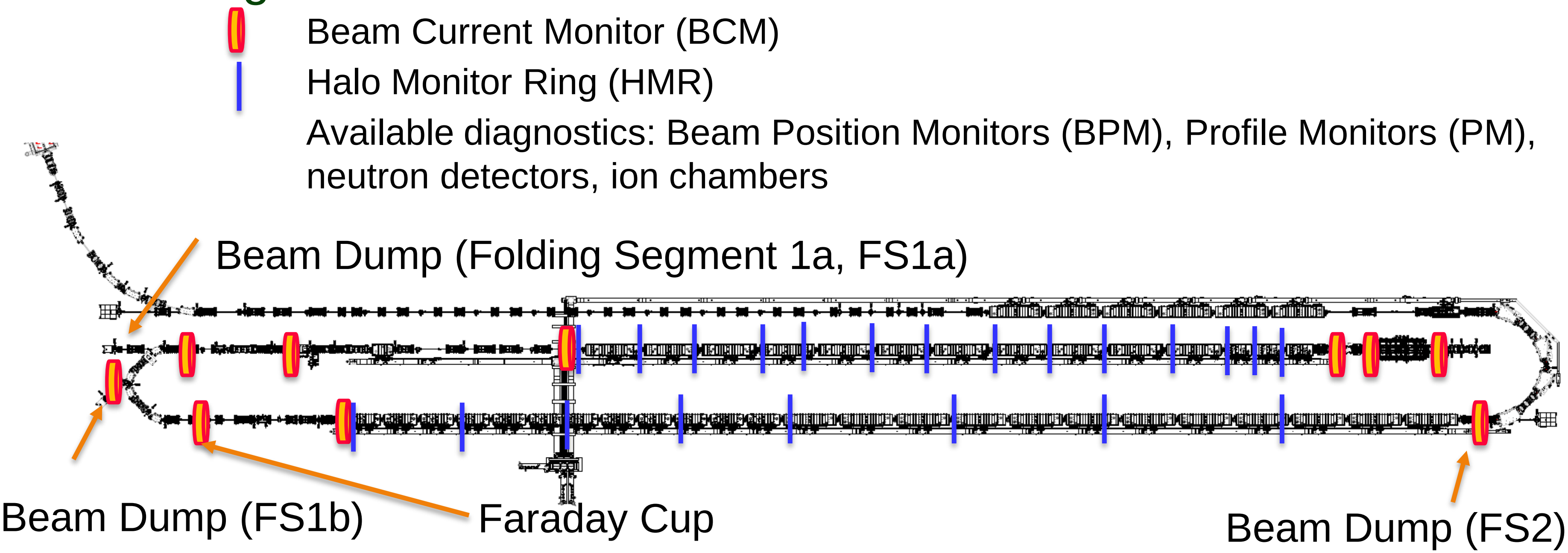
$$\frac{2(q_1 - q_2)}{q_1 + q_2} = 5.7\%$$

- ECR and LEBT are tuned to $^{86}Kr^{18+}$ because the velocity equalizer at the RFQ entrance is absent at present
  - Extraction voltage is set for 18+ to be 12 keV/u
  - Scale LEBT optical elements by 17/18
- 100% transmission in LS1
- For uranium $\frac{2(q_1 - q_2)}{q_1 + q_2} = 3.0\%$



Beam Acceleration in LS2

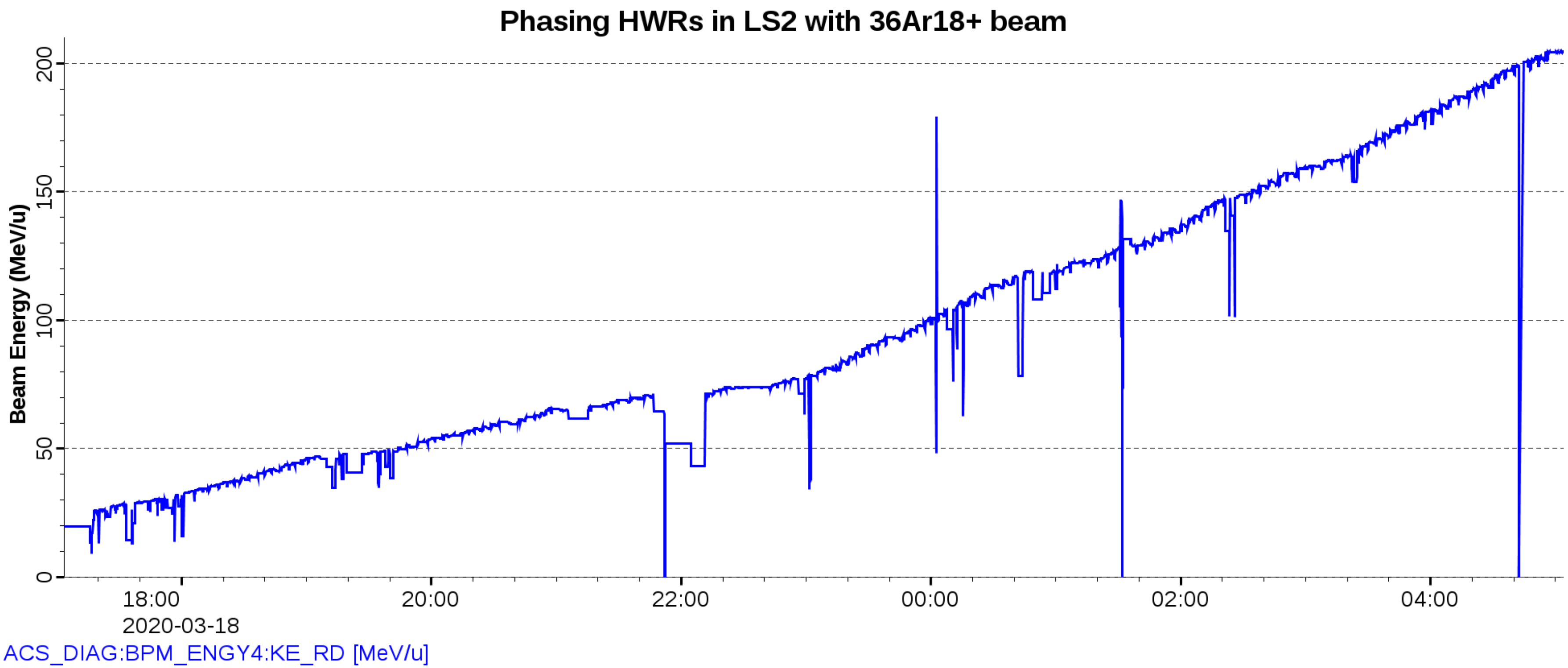
- Linac configuration for ARR04



- 9 Beam Inhibit Modes (beam destinations)
- Number of SC cavities used to achieve the KPP: 204 MeV/u of ^{36}Ar
  - 103 out of 104 in LS1
  - 148 in LS2, 4 cavities were not available and 16 cavities were not energized

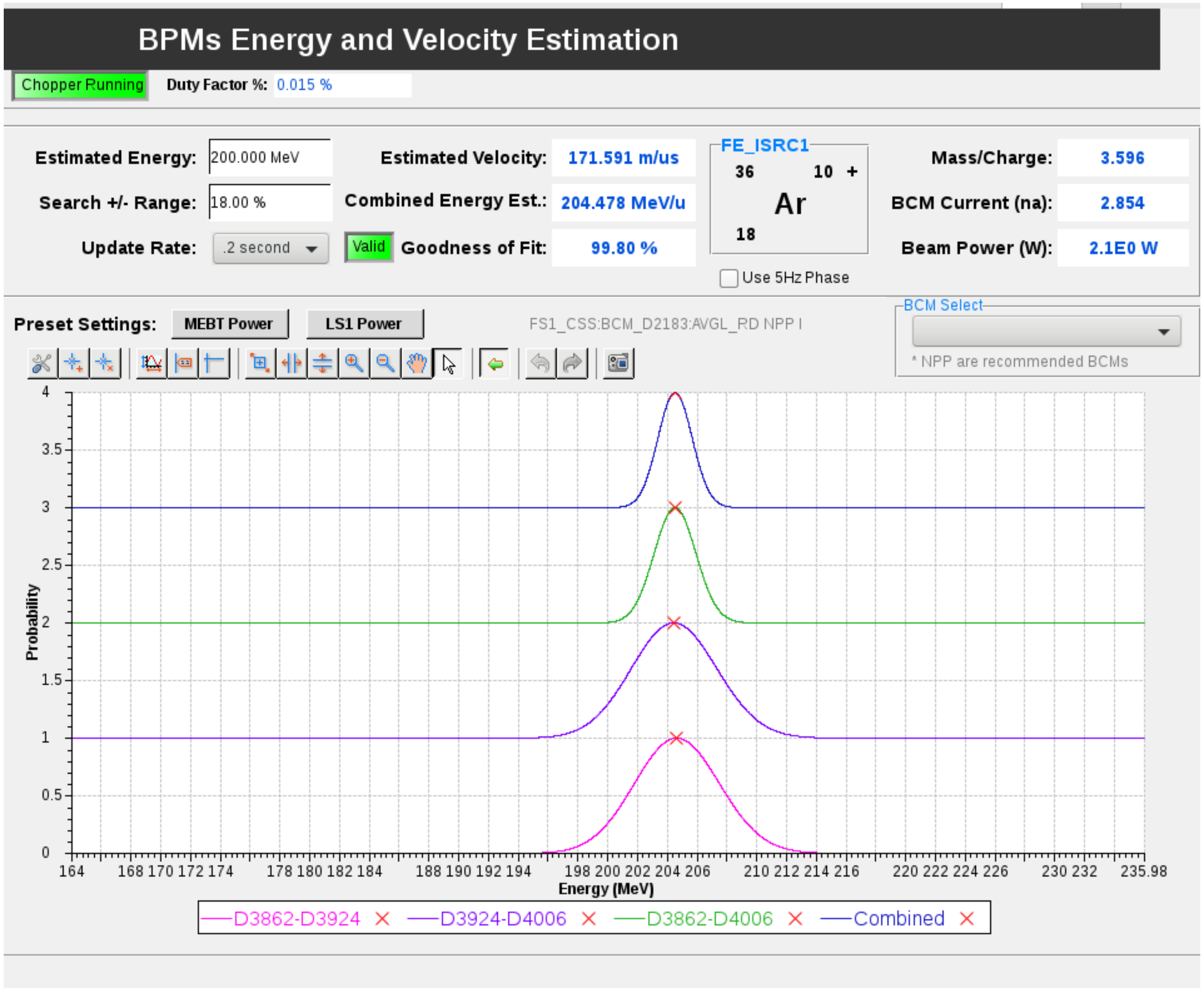
Tuning of HWRs for Acceleration from 20 MeV/u to 204.4 MeV/u Took about 12 Hours

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



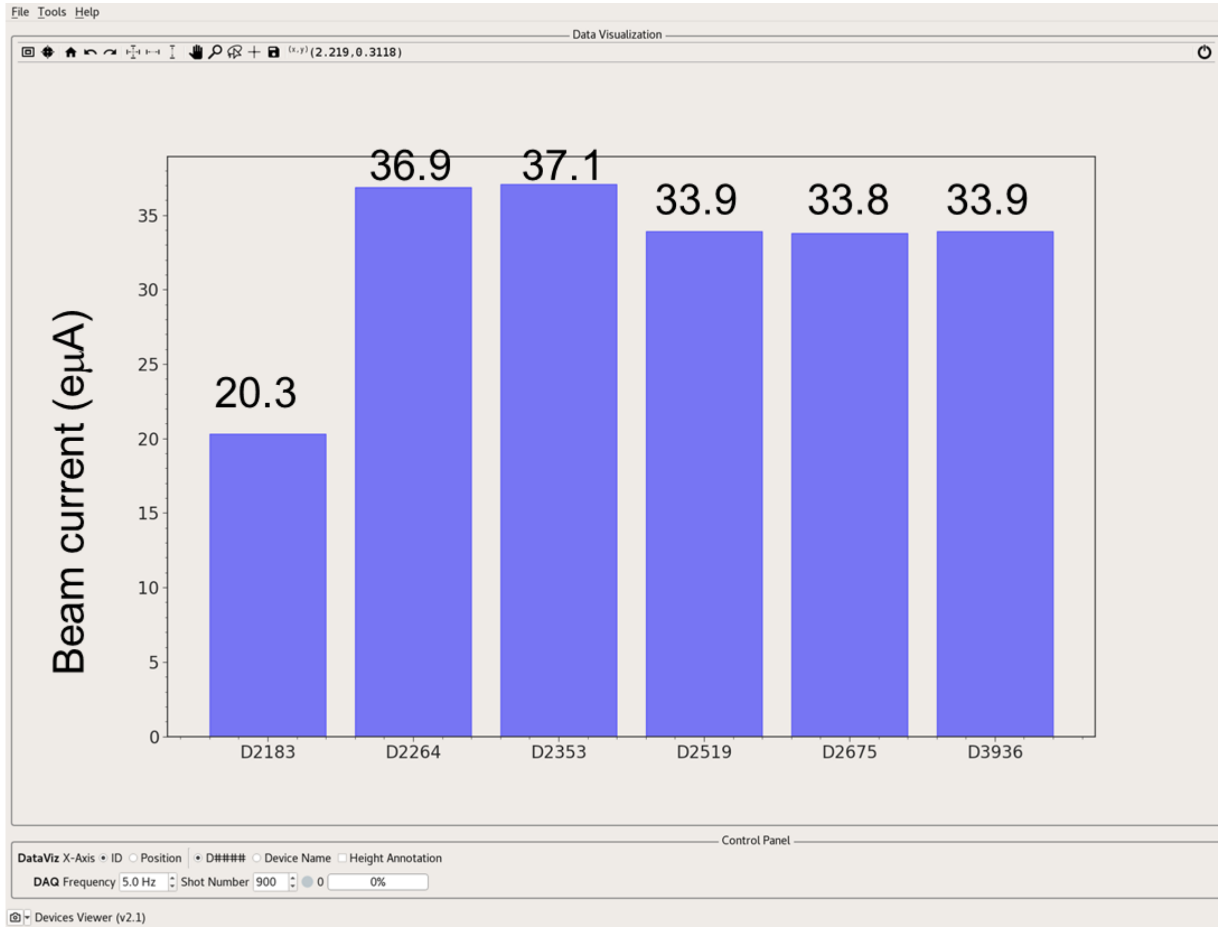
Final Beam Energy

- Beam energy measurements were performed using 3 pairs of BPMs



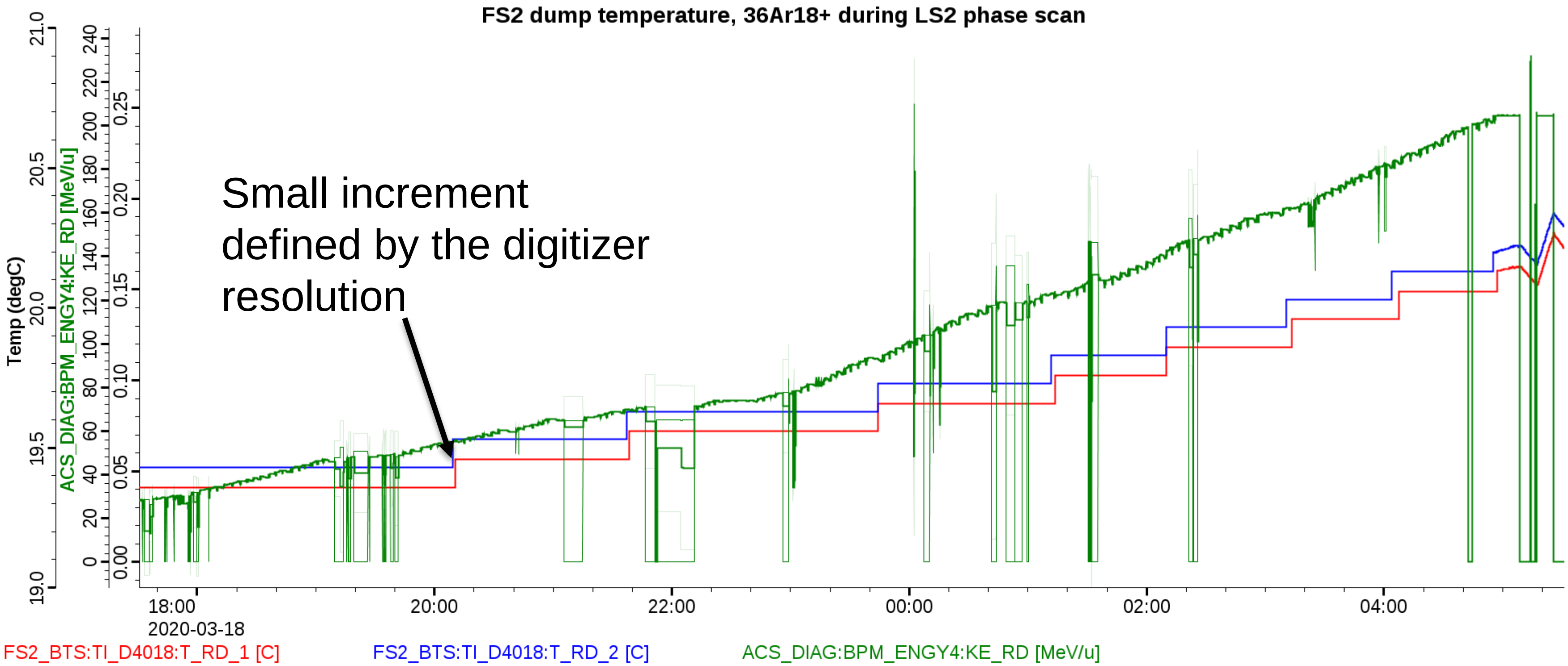
Transmission from MEBT to FS2 Beam Dump

- 100% through the LS1 SC section
- 100% through the LS2 SC section
- 91.6% through 180°-bend
  - 8.4% losses Intercepted with Charge Selection Slits after 45° bend in 17+ charge state
- Accuracy of beam current measurements is 1%



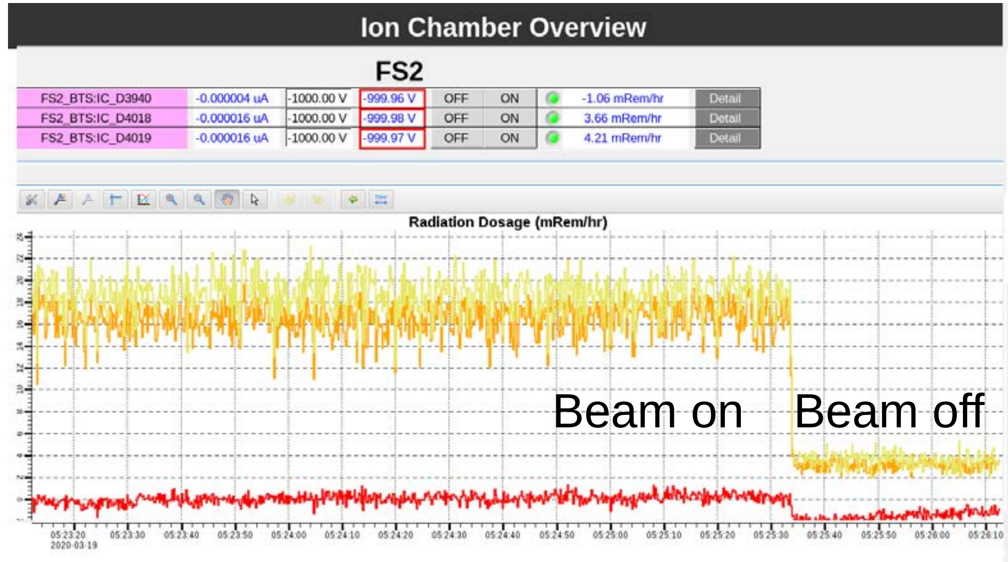
Temperature of the FS2 Beam Dump

- Two temperature probes from the beam dump during the process of energy increase
  - These signals are clearly correlated with the beam power as expected

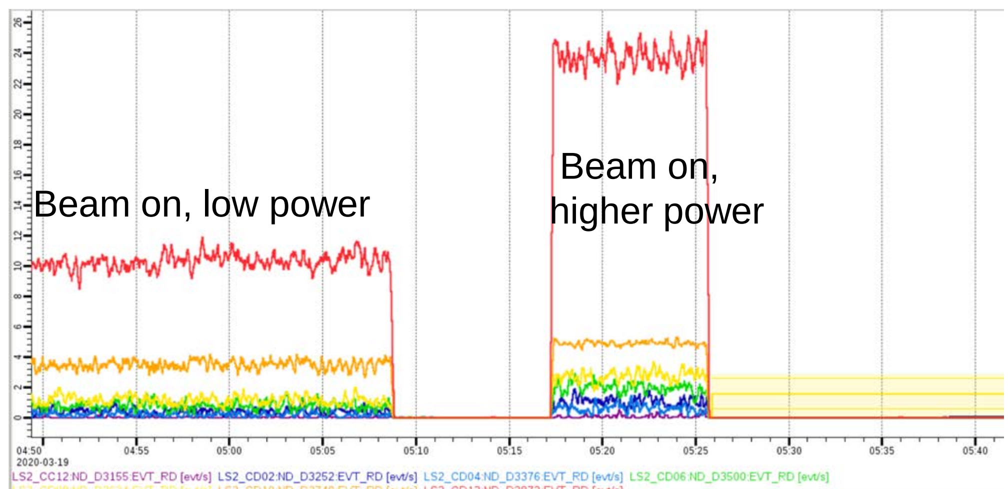


Neutron, γ Radiation from FS2 Beam Dump

- Ion chambers show radiation dosage near FS2 beam dump, FS2_BTS:BD_D4018

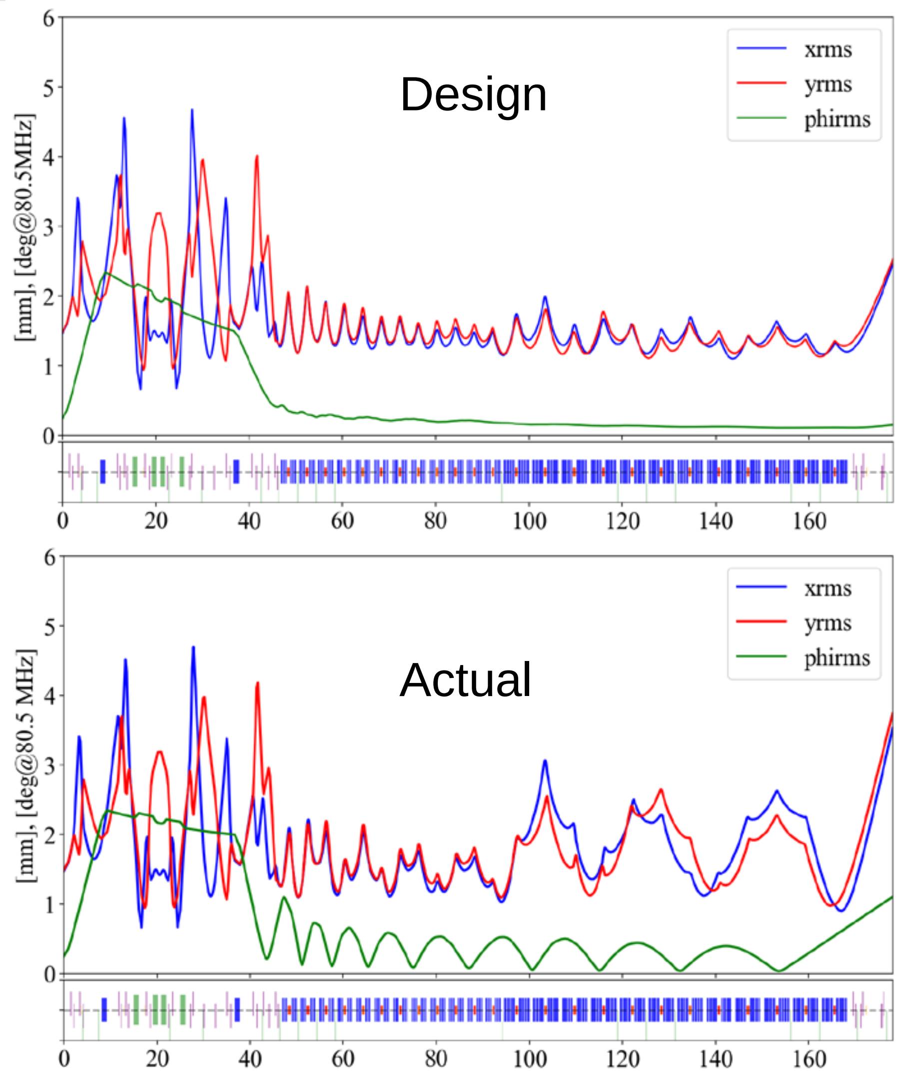


- Neutron detectors (events)



“Design” and “Actual” Setting of LS2

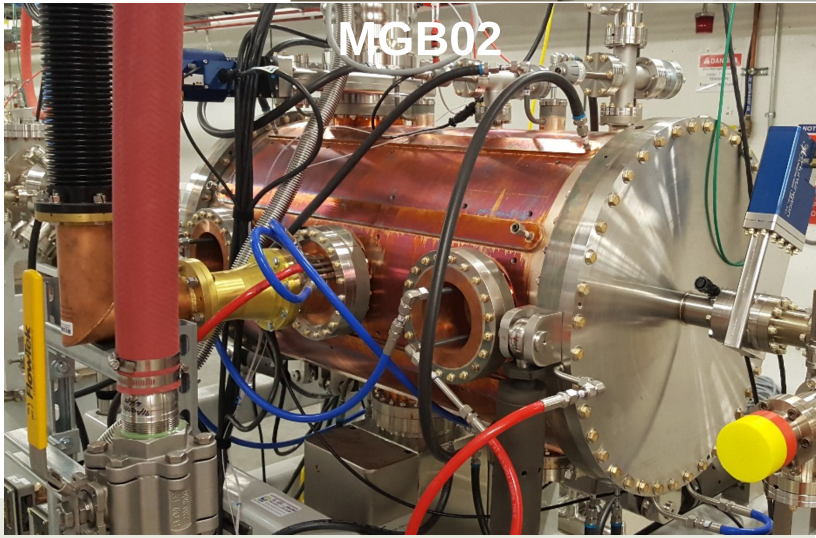
- The design setting for $^{36}Ar^{18+}$ beam was developed using FLAME code
- Four different settings of solenoids were developed to minimize beam losses while energy increased from 20 to 204 MeV/u by phase scan of each cavity
- Actual setting of solenoids was adjusted manually during the commissioning together with dipole magnets to minimize beam deviation in X- and Y-planes



Novel Room Temperature CW Bunchers for 20 MeV/u Ion Beam

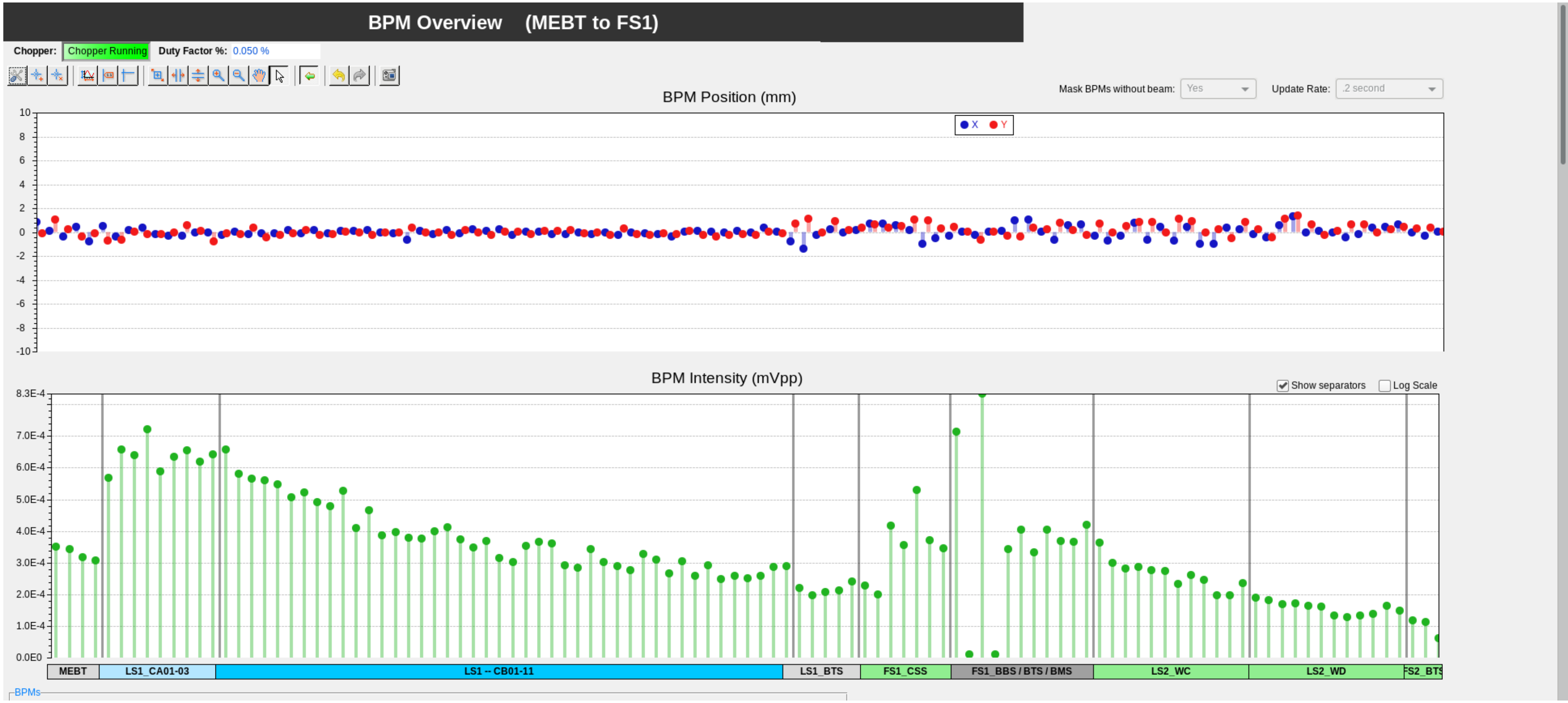
- Replaced bunching cryomodules
- RF parameters of both bunchers are excellent:
  - $Q_0 \approx 15600$ and equal to the CST simulations with OFE cooper
  - Frequency is 161 MHz
  - Only 9.1 kW is required to achieve the design voltage of 0.72 MV for the most heaviest uranium ions

- Both bunchers were tested up to 18 kW, CW RF, which is 2x higher than required nominal power
- The cavity voltage calibrated with beam 11 kW $\rightarrow$ 0.77 MV
- IH structure can be an efficient accelerating structure up to $\beta \approx 0.2$



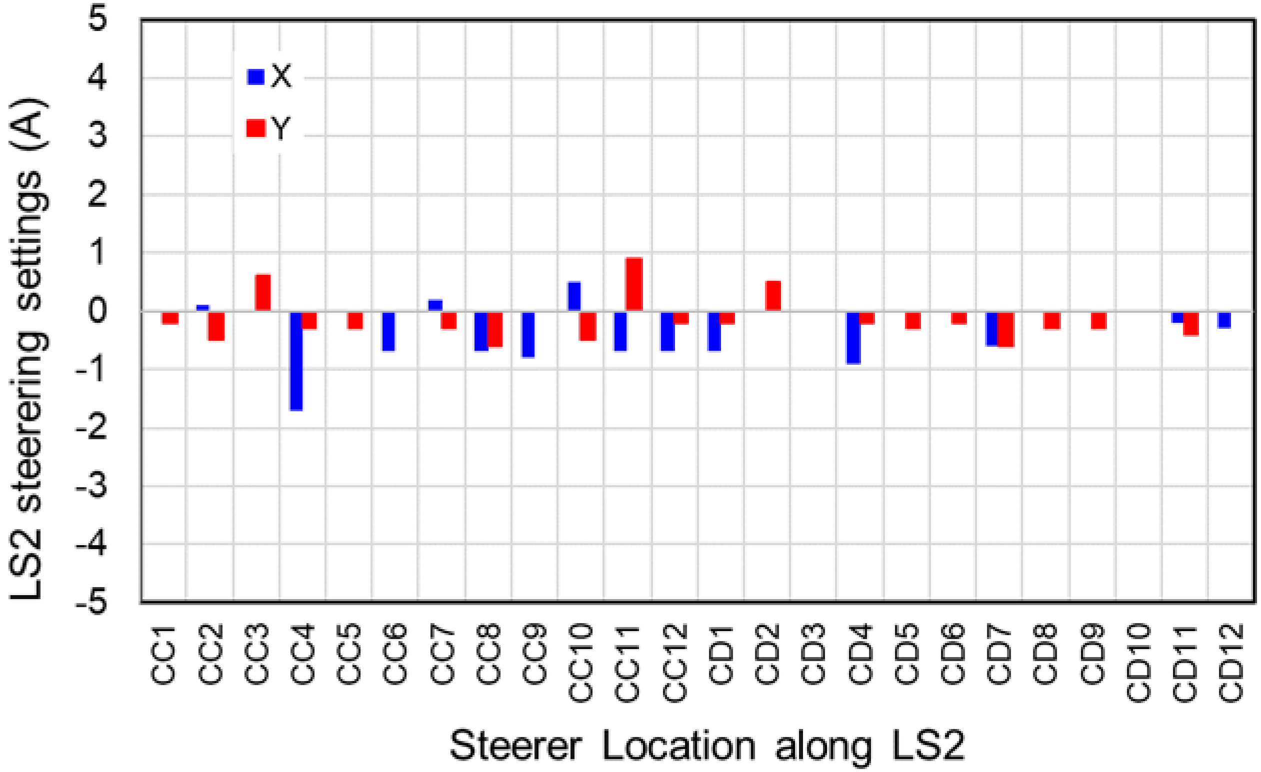
Beam Central Trajectory Correction

- The beam centroid position in LS1 was corrected using High Level Application (HLA) based on Orbit Response Matrix method
- The beam centroid position in FS1 and LS2 was corrected manually: beam centroid deviation is well below ±2 mm



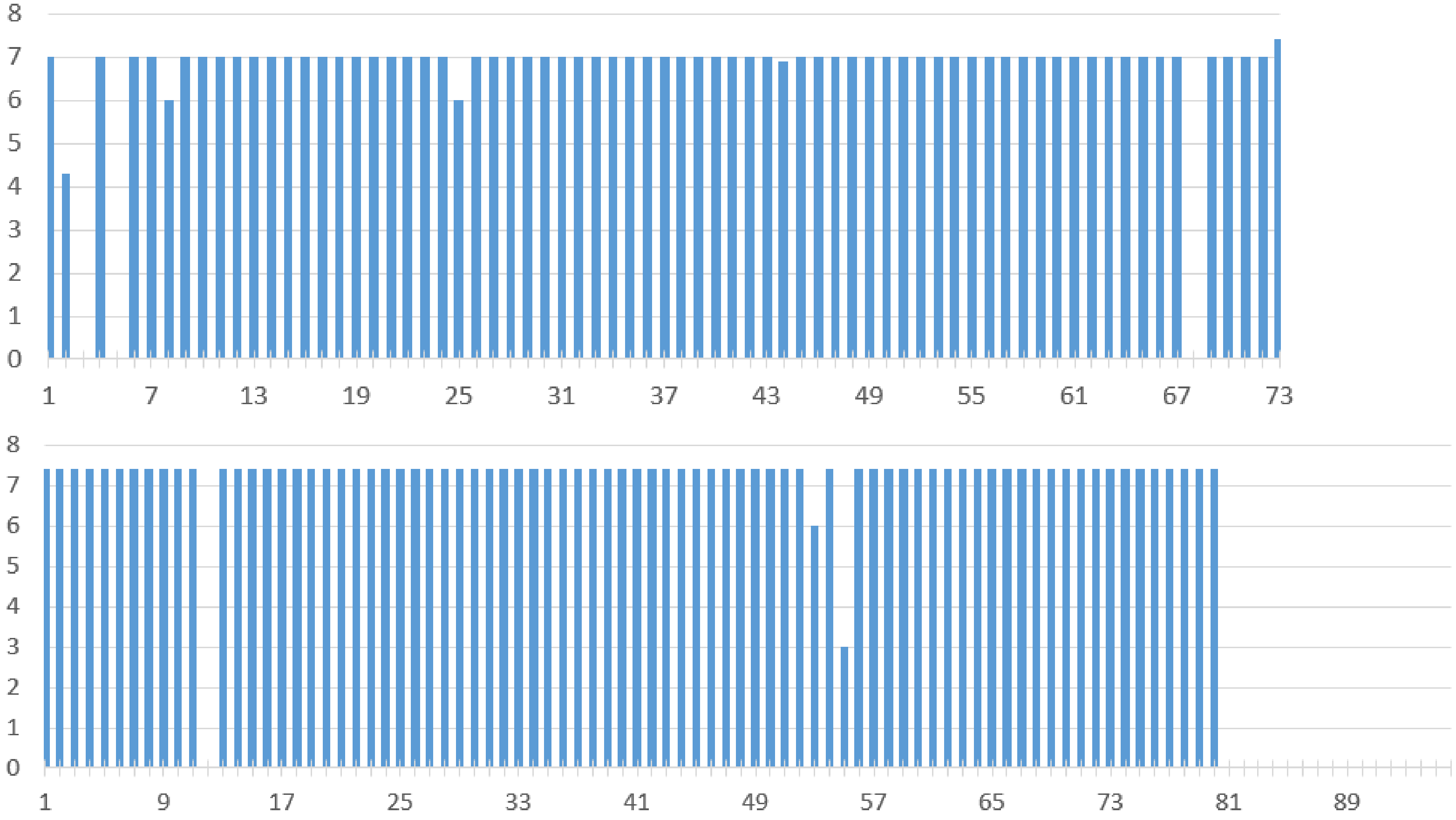
Beam Steering Correction in LS2

- Currents in SC dipole coils are less than 10% of the design value



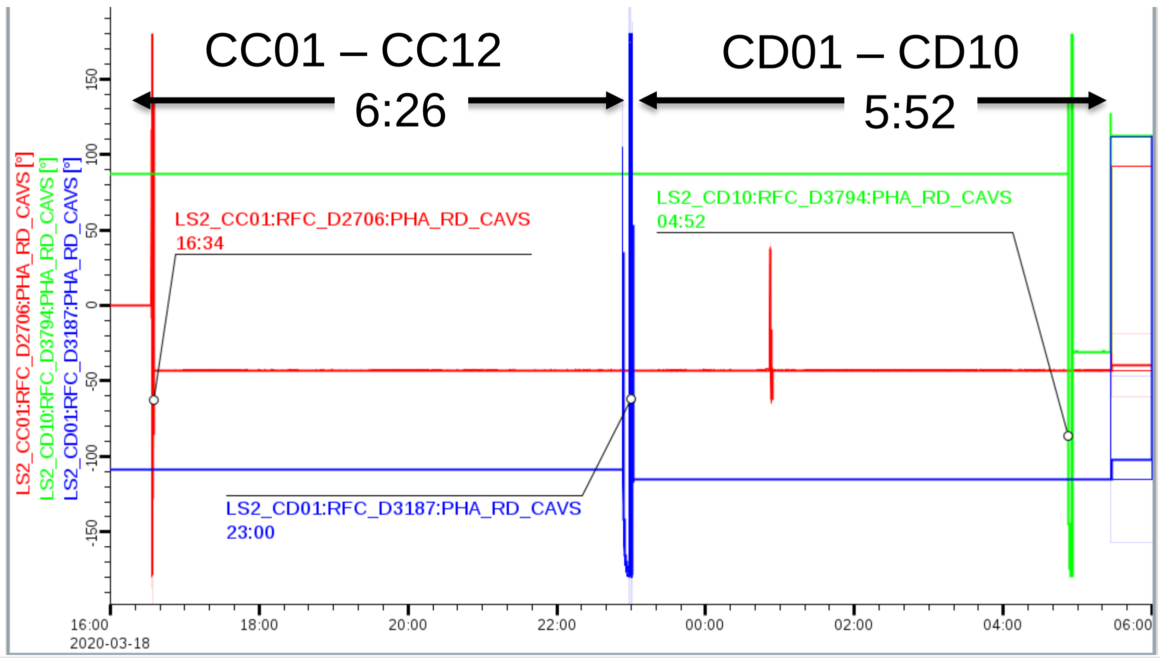
Phase Scan of LS2 Cavities

- 69 β_G=0.29 cavities at 7 MV/m and 79 β=0.53 cavities at 7.4 MV/m
- 16 β_G=0.53 cavities were not energized



Summary of Phase Scan

- Auto-start was not available for LS2 cavities
  - Manual field ramp rate for most cavities was 0.1 MV/m/sec
  - Some delay in several cavities
- Several cavities were skipped due to minor issues to save tuning time
- There were multiple trips of cavities both in LS1 and LS2
  - MPS was activated
  - Beam availability was 91.9%
- CC: 5.6 min/cavity
- CD: 4.5 min/cavity



Machine Protection System Helped to Achieve High Availability of Beam

- Several Levels of MPS were applied

Maximum power of accelerated beam (Watt)	Inhibit modes	MPS Level	MPS response time	Comments
2	5-8	Level 1	≤100 ms	Exact value of the response time as a function of the beam peak current
2	9	Level 2	≤100 ms	
20-500	7	Level 3	≤100 μs	
20-135	9	Level 4	From 35 μs to 20 ms	

	Sensors	Connection to MPS	Comments
Level 1	Beam line gate valves	Through PLC and RPS	
	Magnet/corrector PS	Through PLC and RPS	
	Cold cathode gauge	Through PLC	
	Chopper monitoring device	Directly to MPS node	
	Peak beam current in MEBT	Directly to MPS node	Measured with MEBT BCM
	LLRF controller of FE, LS1 (CH01, MGB01, 02 not included)	Directly to MPS node	Not required but can be activated
Level 2	Level 1 + LLRF of FE, LS1 (CH01, MGB01, 02 not included)	Directly to MPS node	

Other Observations

- Transitions between “beam inhibit mode” was very quick unlike during the ARR03
  - Total number of beam inhibit modes is 9; the first 4 at low energy and are not critical
  - Operators were well trained to switch beam inhibit modes
- Excellent performance of all types of BPMs
  - High sensitivity, high accuracy
- All Halo Monitor Rings did not show any signal above the noise level
- Only 2 neutron monitors located close to the FS2 beam dump showed events
- Radiation survey of the accelerator after completion of the beam commissioning was done in 72 h and did not show anything above the background including the shielded beam dumps

Path Forward with Beam Commissioning

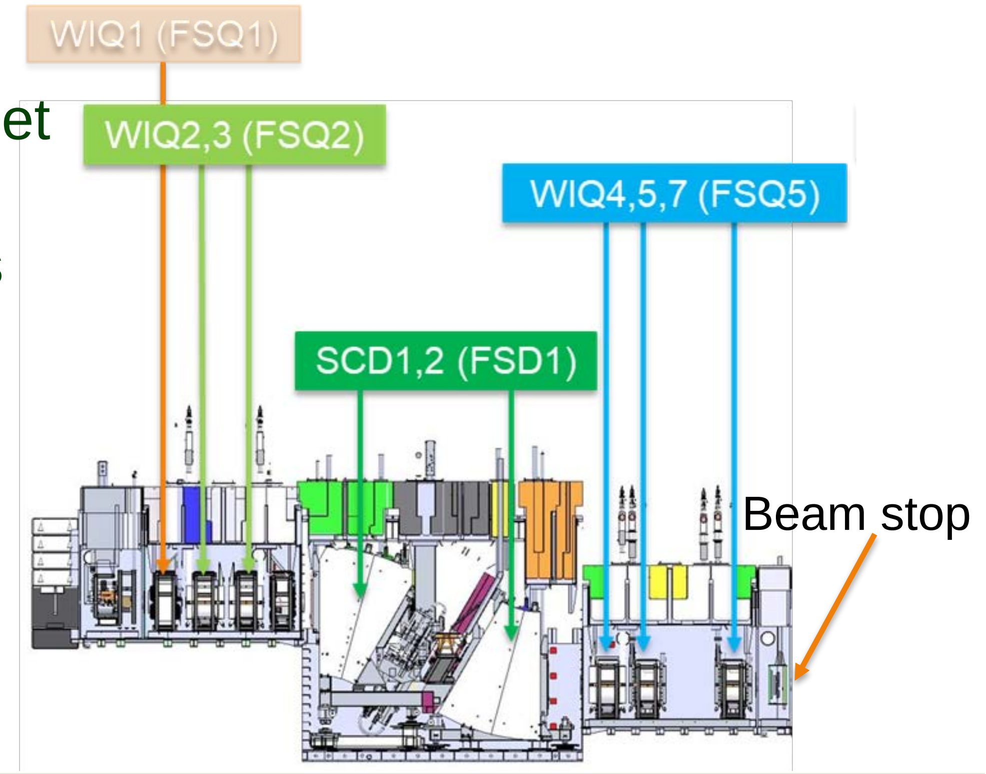
- 2-3 weeks of Linac operation is planned in August-September, 2020
- Li stripper test with beam in LS1
- ARR05 goal is to commission FS2 and LS3
- ARR06 goal is to demonstrate the project KPP: produce and detect ^{84}Se isotopes

Phase	Area with beam	ARR
Li stripper	**Re-commission with lithium charge stripper**	**11/2020***
ARR05	FS2, LS3, part of Beam Delivery System (BDS) to straight dump	04/2021*
ARR06	**BDS, target hall pre-separator, Project KPP**	**09/2021***
IRR01	**Vertical pre-separator (outside target hall), reconfigured A1900, commencement of user operations instrument readiness**	**12/2021***

* Subject to changes caused by COVID-19

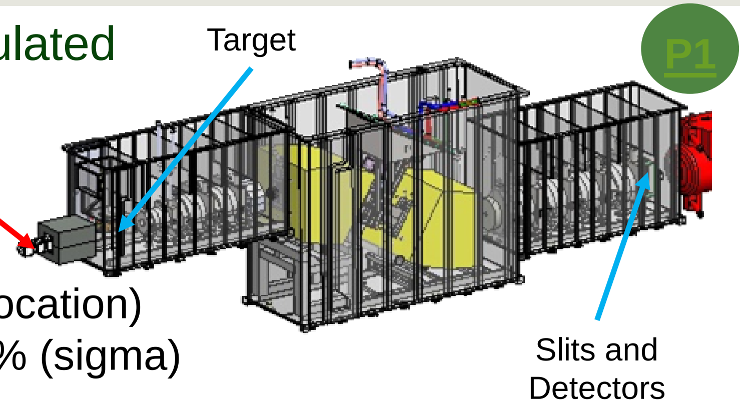
Beam Commissioning in Target Hall

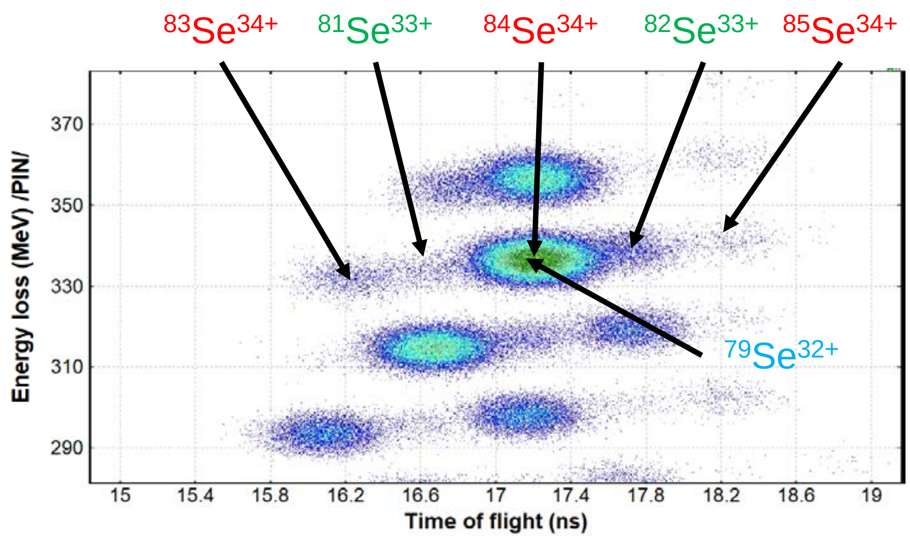
- Define Operational Safety Envelope
  - Beam intensity is sufficient to tune BDS and demonstrate Project KPP
  - Beam power control can be provided by credited attenuators at LEBT
- Install additional PIN diodes for Time-of-Flight (TOF) and ΔE measurements
- Provide 200 MeV/u of ^{86}Kr on target
- Use 2-mm slits at the wedge location and separate Se isotopes
- Most difficult task is to separate ^{84}Se from ^{83}Se at the same charge states
  - Requires good time-of-flight resolution

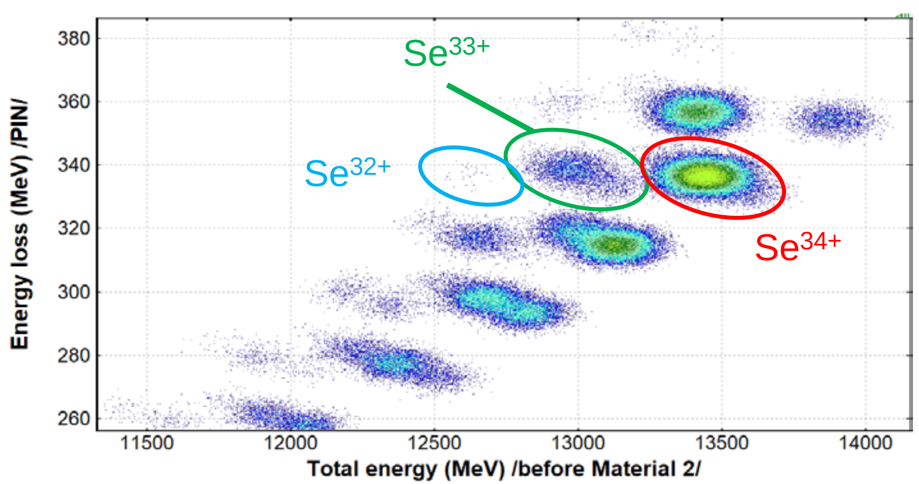


Identification of ^{84}Se in Target Hall

- Separation and identification of ^{84}Se in target hall simulated
  - 200 MeV/u ^{86}Kr beam, bunch length 0.1 ns (sigma)
  - 3 mm graphite target
  - Magnetic rigidity separation
    - » 2 mm slits ≈ 0.1 % momentum window
  - Detection in ΔE-E telescope (to be installed at the wedge location)
    - » Timing resolution 0.1 ns (sigma), Energy resolution 0.5 % (sigma)
    - » Resolution achieved with Silicon detectors
  - ^{84}Se^{34+} well be resolved in ΔE-TOF plot after suppressing charge states via total kinetic energy measurement
  - Beam intensity of 1 W yields about 380 ^{84}Se^{34+} per second (overall 1200 particles per second)







Summary

- FRIB Linac System KPP demonstrated
  - 1.88 pμA ^{36}Ar beam accelerated up to 204.4 MeV/u
  - Beam energy can be increased to ~240 MeV/u by energizing additional two available cryomodules in LS2
- Transmission is 100% with the measurement error of <1%, no issues with beam steering
- Performance of all types of BPMs was excellent
- All other accelerator components (diagnostics, controls, cryogenics, vacuum, SRF, Front End,…) operated as expected
- Two warm bunchers in FS1 were used for the beam matching in longitudinal phase space for the first time
- Work in progress to get ready for FRIB Project KPP in September-October 2021

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    - » Cryomodules, cavities – T. Xu
    - » Diagnostics - S. Lidia
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