FRIB

Commissioning Results from FRIB

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Facility for Rare Isotope Beams, Michigan State University

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MICHIGAN STATE UNIVERSITY

U.S. DEPARTMENT OF ENERGY | Office of Science

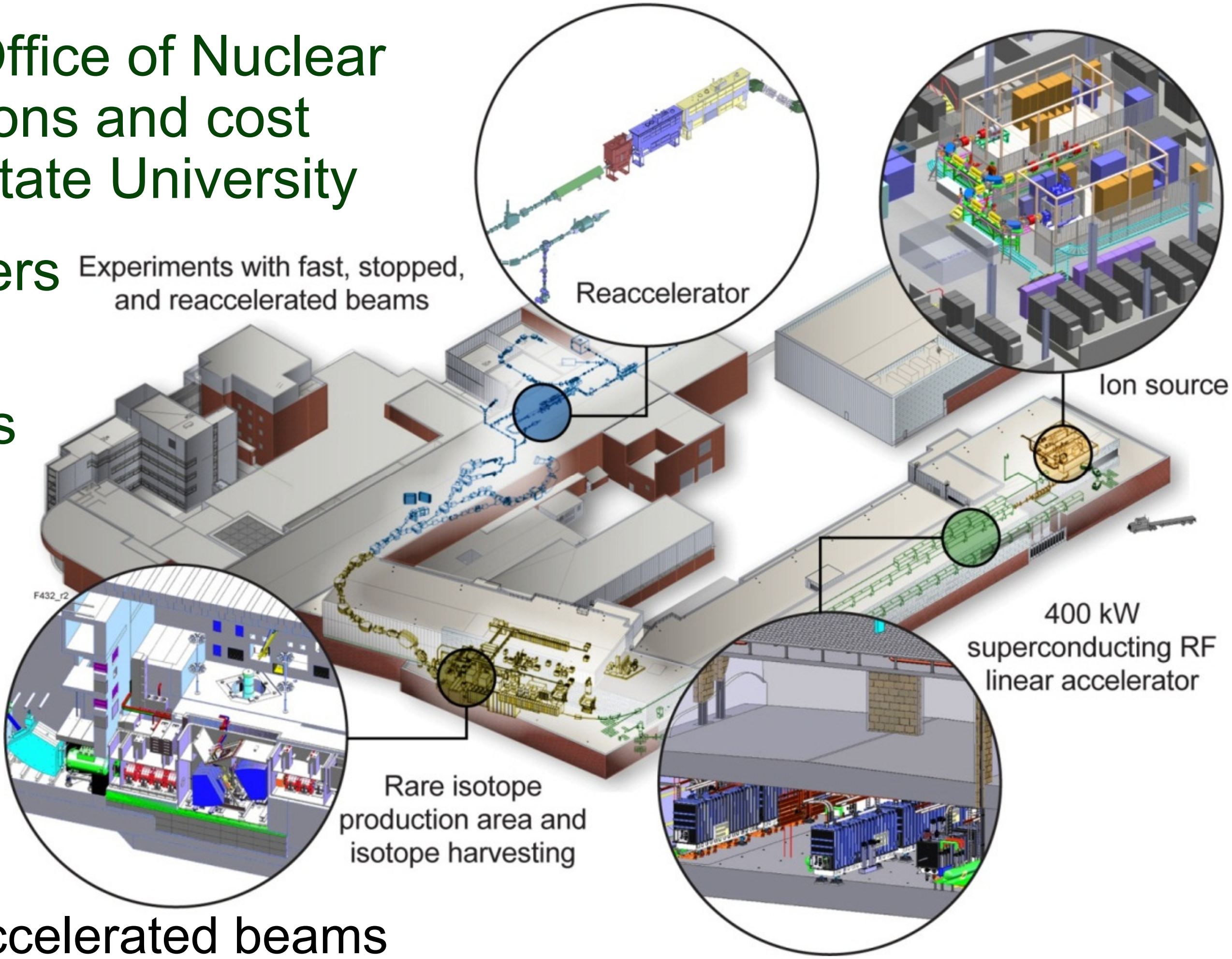
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support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

Outline

- Introduction
- Front-End commissioning
  - Front-End beam commissioning completed
  - Front-End in operation
- FRIB linac commissioning
  - Beam commissioning through β=0.041 cryomudules completed
    - Beam measurement results
  - Preparing for commissioning of β=0.085 cryomodules & transport lines
- Summary

Facility for Rare Isotope Beams (FRIB) A Future DOE-SC National User Facility

- 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



FRIB Project Timeline
$730.0M ($635.5M DOE + $94.5 MSU)

- Dec. 2008: DOE selected MSU to establish FRIB
- June 2009: DOE and MSU signed corresponding Cooperative Agreement
- Sept. 2010: CD-1 approved (Alternative Selection and Cost Range)
- Aug. 2013: CD-2/3A granted (Performance Baseline and Start of Civil Construction)
- Aug. 2014: CD-3B approved (Start of Technical Construction)
- Sept. 2016: Existing Artemis ECR ion source recommissioned
- Sept. 2017: LEBT commissioned with beam
- Oct. 2017: RFQ accelerated beam
- Feb. 2018: Front-End commissioning completed
- July 2018: Beam commissioning of first three cryomodules

- Feb. 2019: Beam commissioning of entire Segment 1 and transport line
- …
- Jan. 2021: Early Project Completion Goal
- June 2022: CD-4 approval (accomplish Key Performance Parameters)

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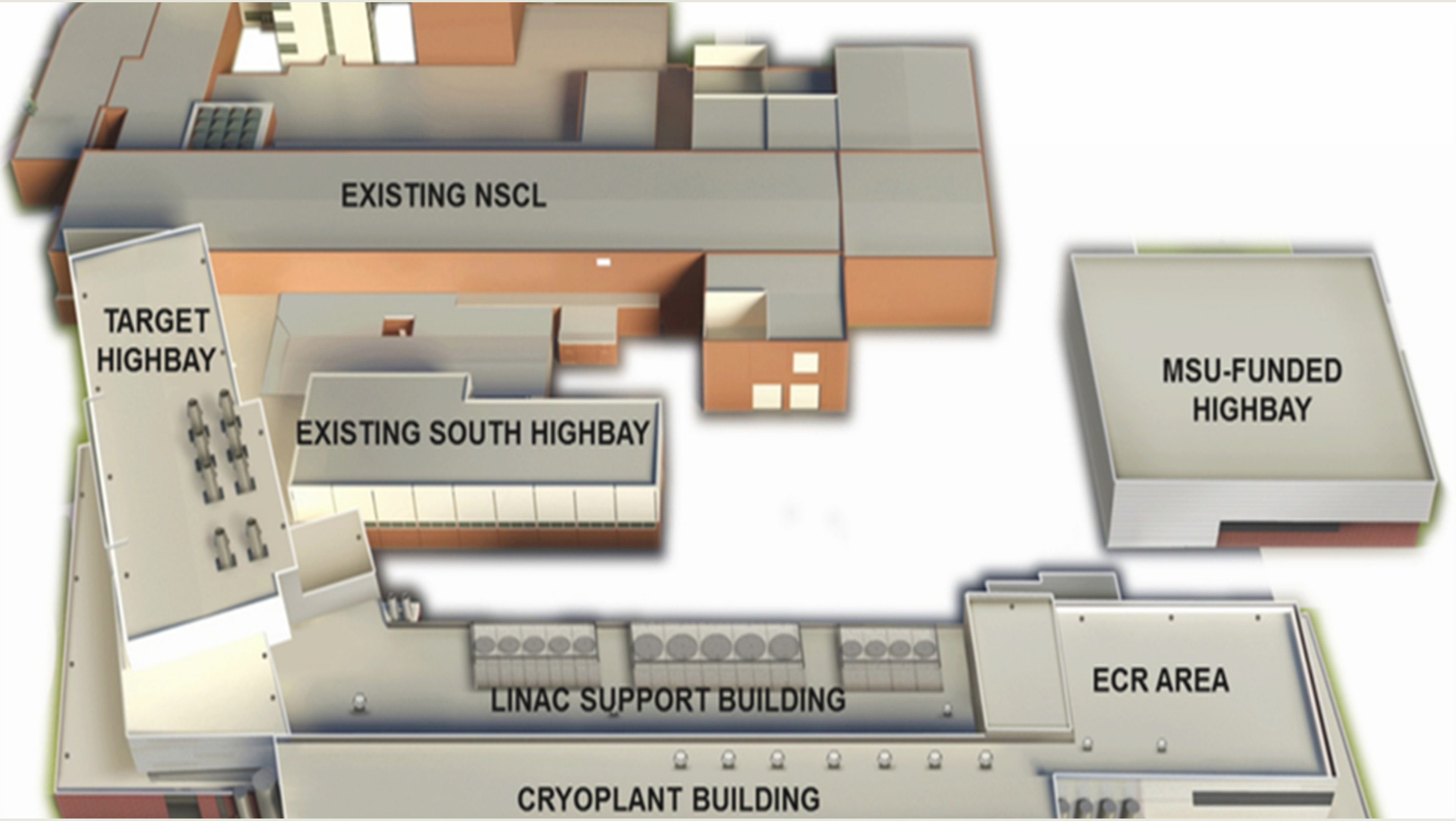
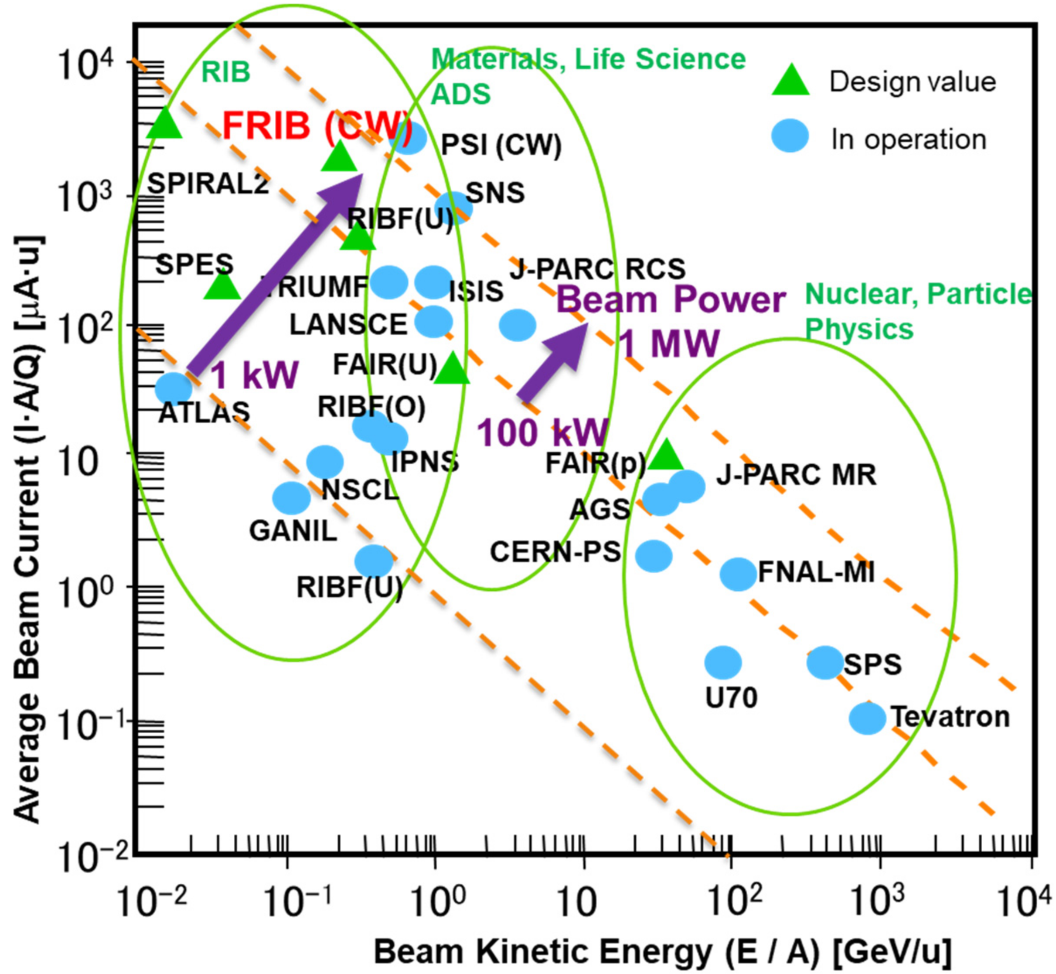
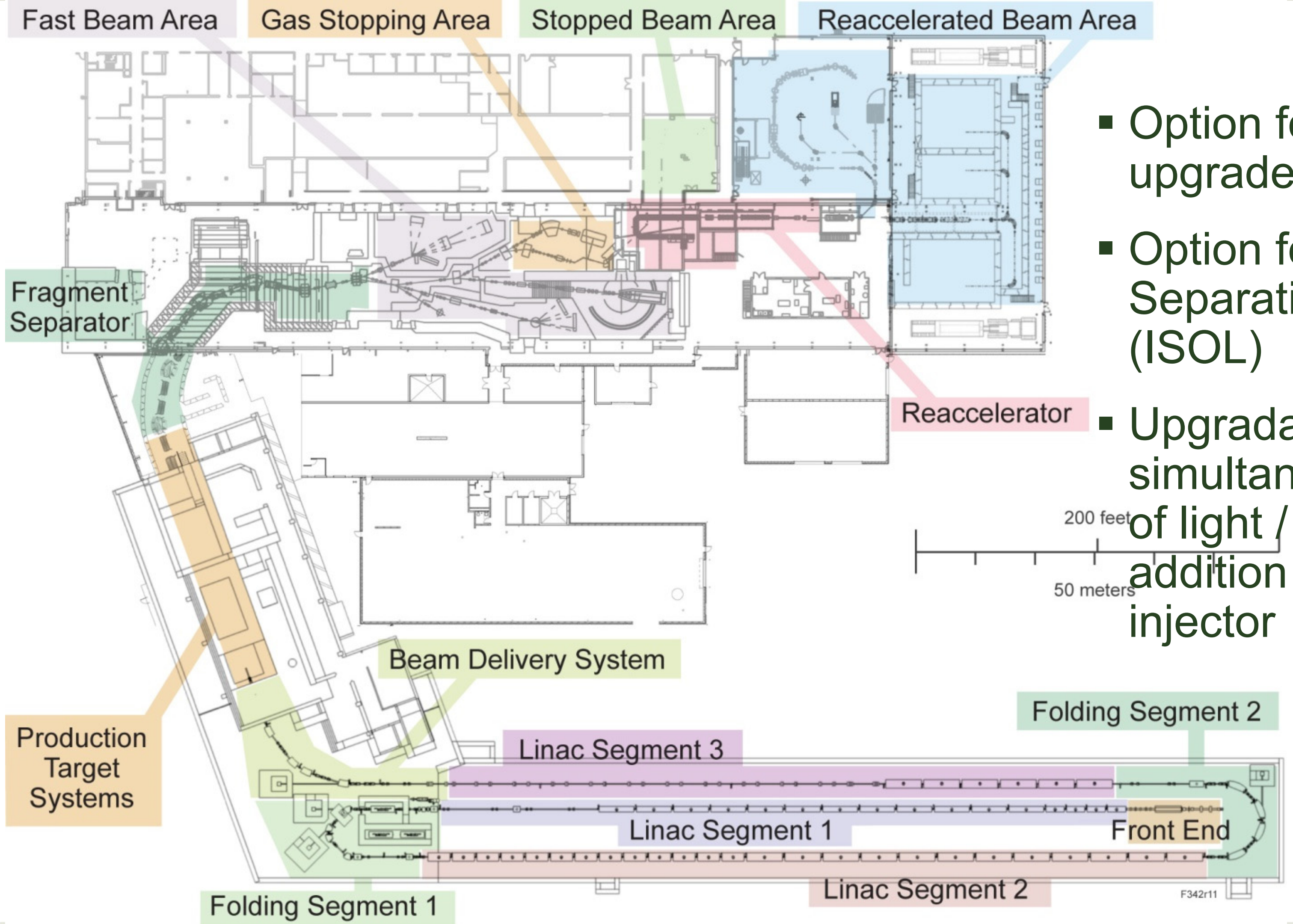


FRIB Among High-Intensity Ion Accelerators

- Proton accelerators raised beam power >1 MW
  - SNS: >1 MW pulsed; SRF linac/accumulator
  - J-PARC: 0.3 MW pulsed; warm linac/RCS
  - PSI: 1.4 MW CW; cyclotron
- FRIB is in the same energy and power category (400 kW)
  - From proton to ^{238}U
  - SRF linac above 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



FRIB Technical Components

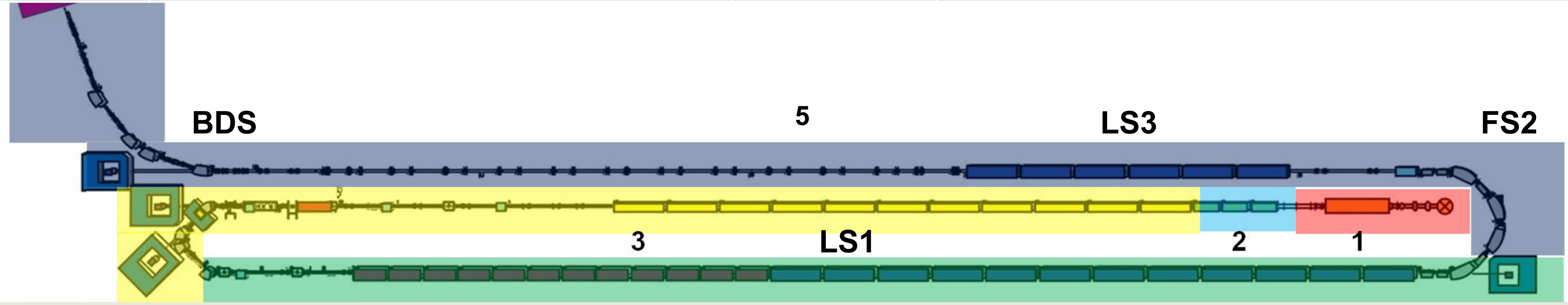


- Option for energy upgrade to >400 MeV/u
- Option for Isotope Separation On-Line (ISOL)
- Upgradable to multi-user simultaneous operation of light / heavy ions with addition of a light-ion injector

FRIB Accelerator Commissioning Plan

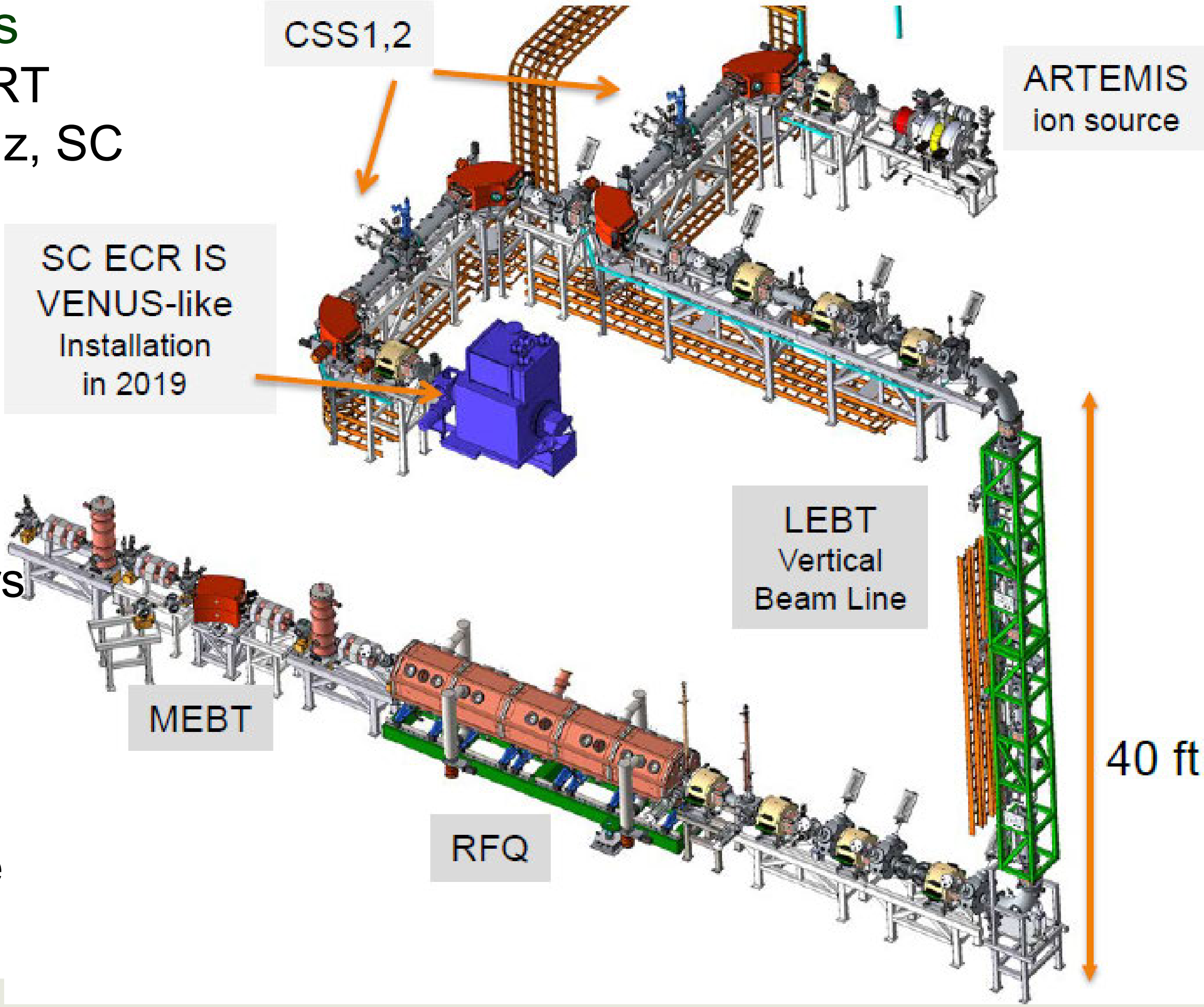
- FRIB beam commissioning is organized into 5 stages
  - Each stage is accomplished with an Accelerator Readiness Review followed by commissioning activities to demonstrate Key Performance Parameters
  - Stage 1 and 2 completed

Stage	Area with beam	ARR	KPP, Ar and Kr beam energy & current
1	**Front End**	**08/2017**	**0.5 MeV/u, >25 euA**
2	**3 β=0.041 cryomodules in Linac Segment (LS) 1**	**05/2018**	**≥1.46 MeV/u**
3	Rest of LS1 and part of Folding Segment (FS) 1	02/2019	≥16 MeV/u
4	Rest of FS1, LS2	04/2020	≥200 MeV/u for Ar Linac KPP
5	FS2, LS3, Beam Delivery System, Target, and Fragment Separator	TBD	≥200 MeV/u, ≥20 pnA



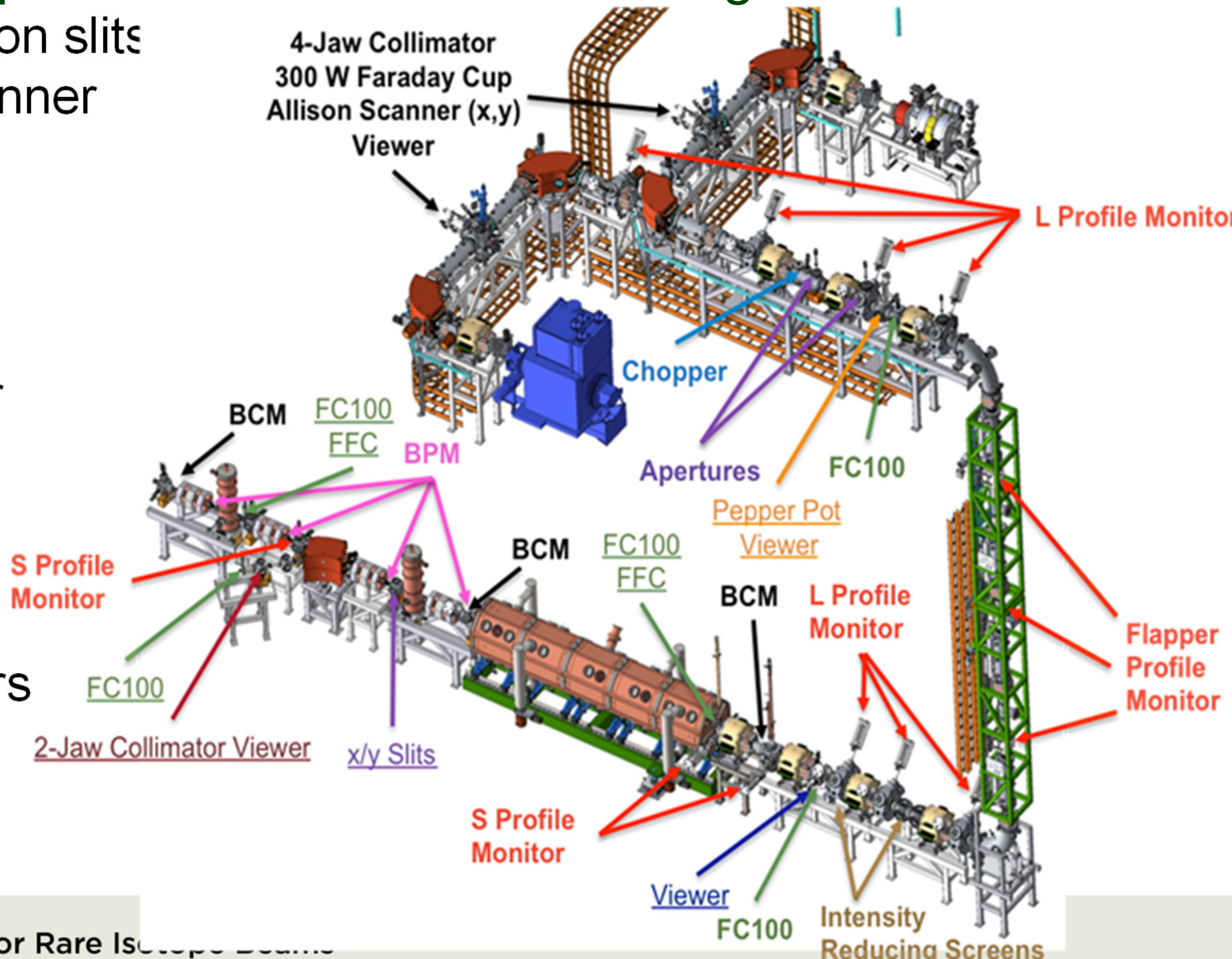
Front-End Layout and Its Major Systems

- Two ECR ion sources
  - ARTEMIS –14 GHz, RT
  - VENUS type – 28 GHz, SC
- LEBT (12keV/u)
  - Electrostatic quads
  - Solenoids
  - Chopper
  - MHB
  - Emittance meters
  - Wire scanners/viewers
  - Faraday cups
- RFQ (next slide)
- MEBT
  - Triplets, 45deg-dipole
  - Rebunchers
  - BPMs



Front End Beam Instrumentation

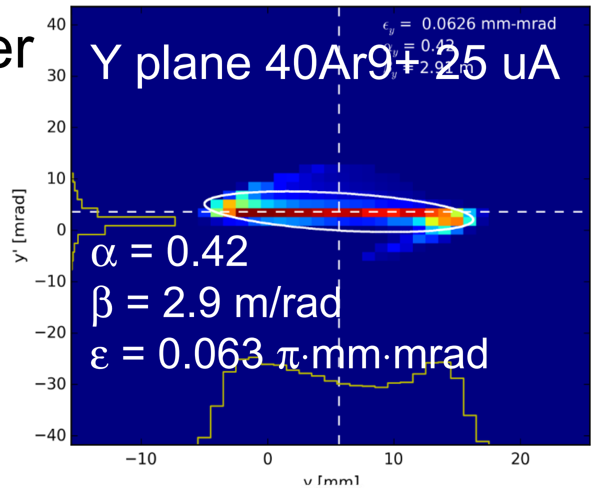
- Array of diagnostics devices were available for beam tuning and finding setpoints of optical devices and accelerating cavities
  - 4-Jaw Charge selection slits
  - Allison emittance scanner
  - Pepper Pot
  - Image viewers
  - Wire Profile Monitors
  - Faraday cups
  - Electrostatic Chopper
  - Intensity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



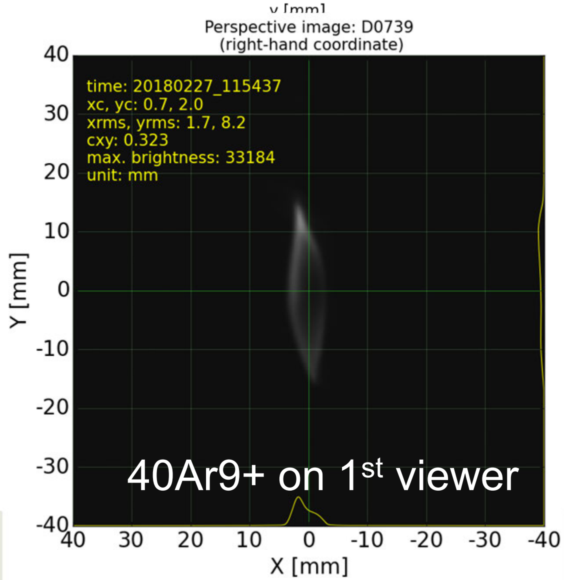
Beam Measurements in LEBT – Samples

- Each device provides multiple beam information

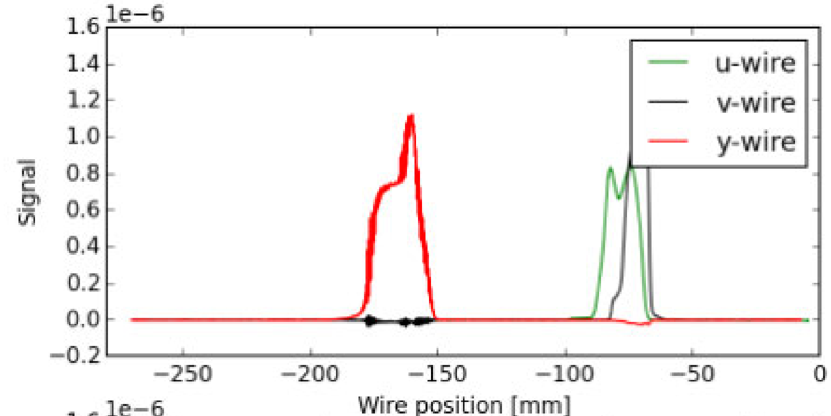
Allison scanner
Horizontal
Vertical

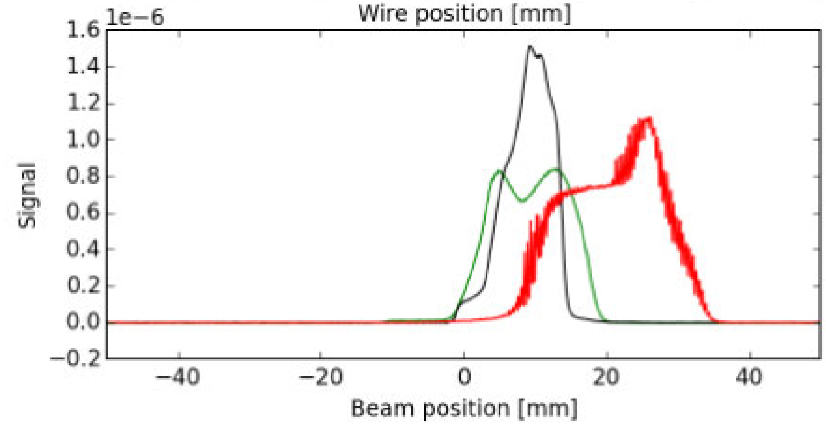


View plate



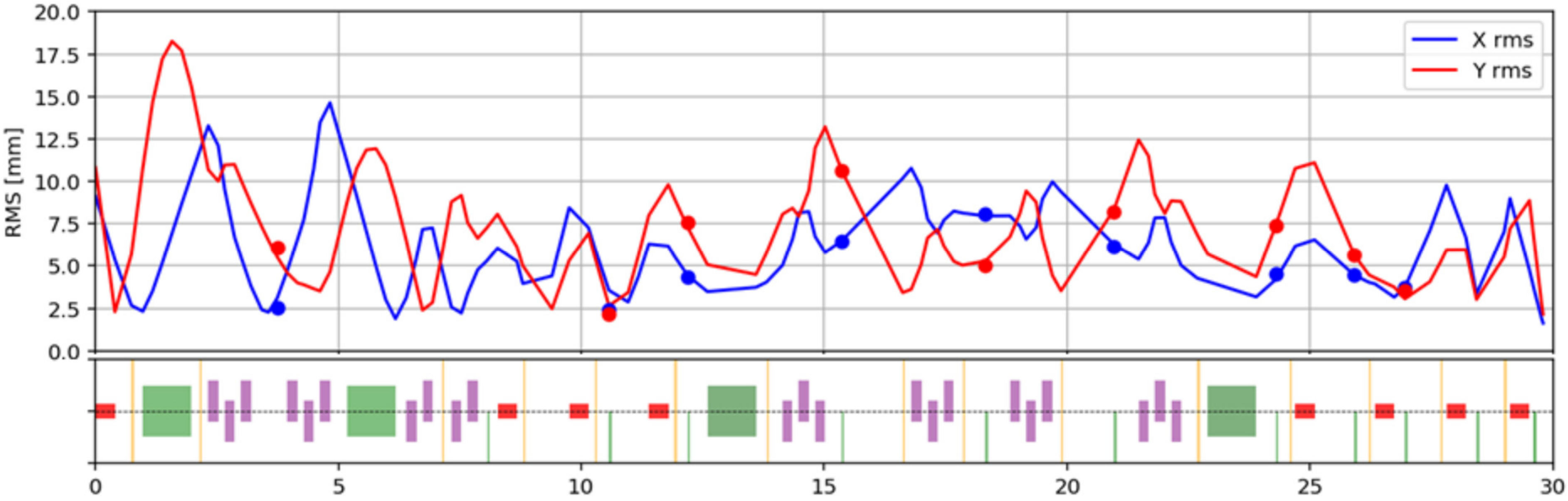
3-wire scanner
Horizontal, vertical, 45deg diagonal





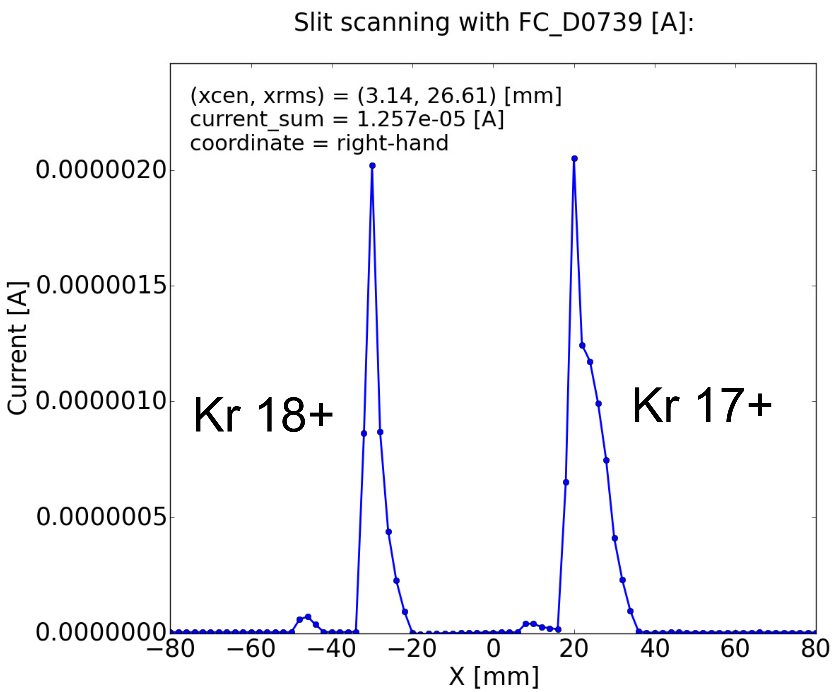
Beam Envelopes Reconstructed from Profile Measurements Along LEBT

- $^{40}Ar^{9+}$, 65 euA
- Beam parameters obtained by fitting to match measured rms beam sizes from all profile monitors
- Simulations agree with measurements



Kr^{17+} and Kr^{18+} Simultaneously Transported in LEBT and Accelerated in RFQ

- Both $^{86}Kr^{17+}$ (33uA) and $^{86}Kr^{18+}$ (27uA) transported to the entrance of the RFQ
  - Set electrostatic elements for 17+, scale magnetic elements for 17.5+
  - ~100% transmission achieved, beam profiles measured



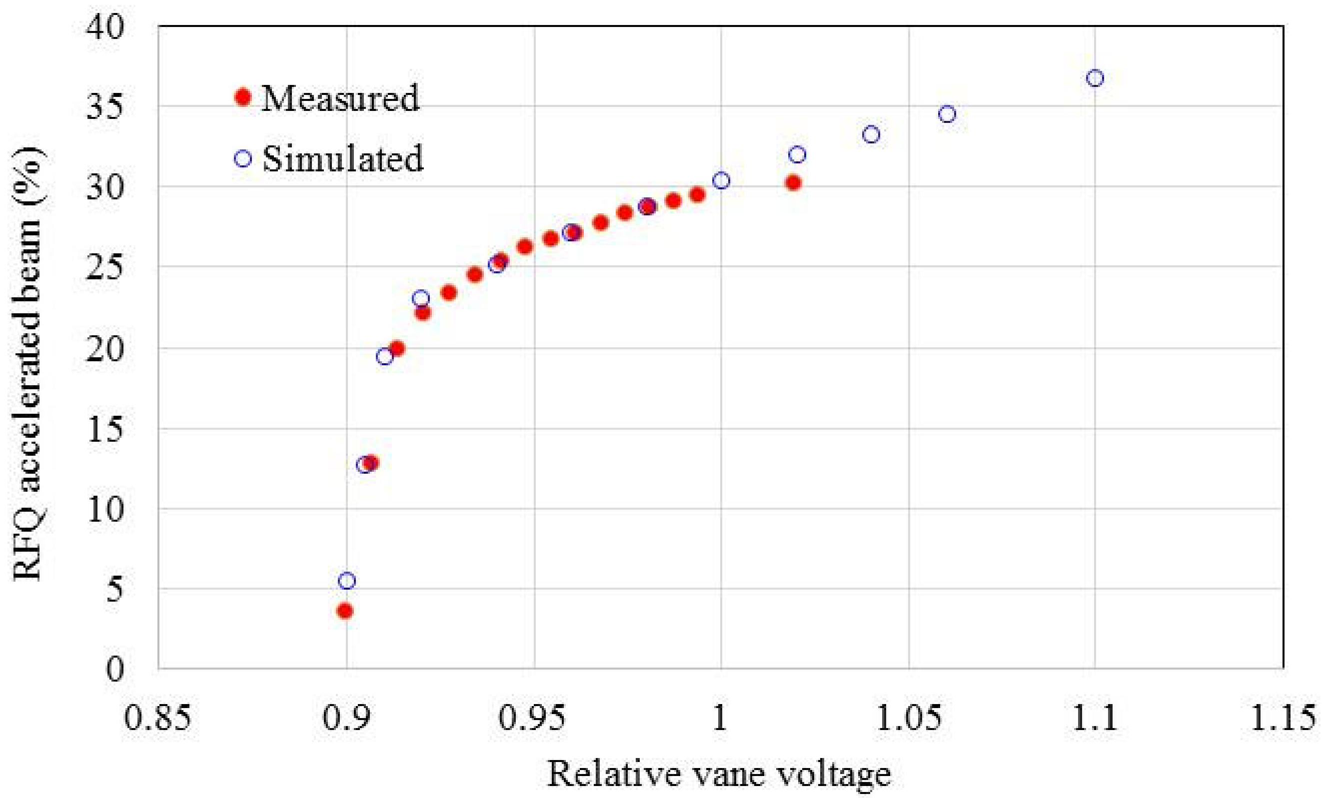
17+ & 18+ selected at slit

Optimized for 17.5+ with 100x attenuation

86Kr	RFQ FC0998 (uA)	MEBT FC1102 (uA)	Efficiency (%)
17+	0.2	0.056	28
18+	0.16	0.07	44
17+&18+	0.36	0.122	34

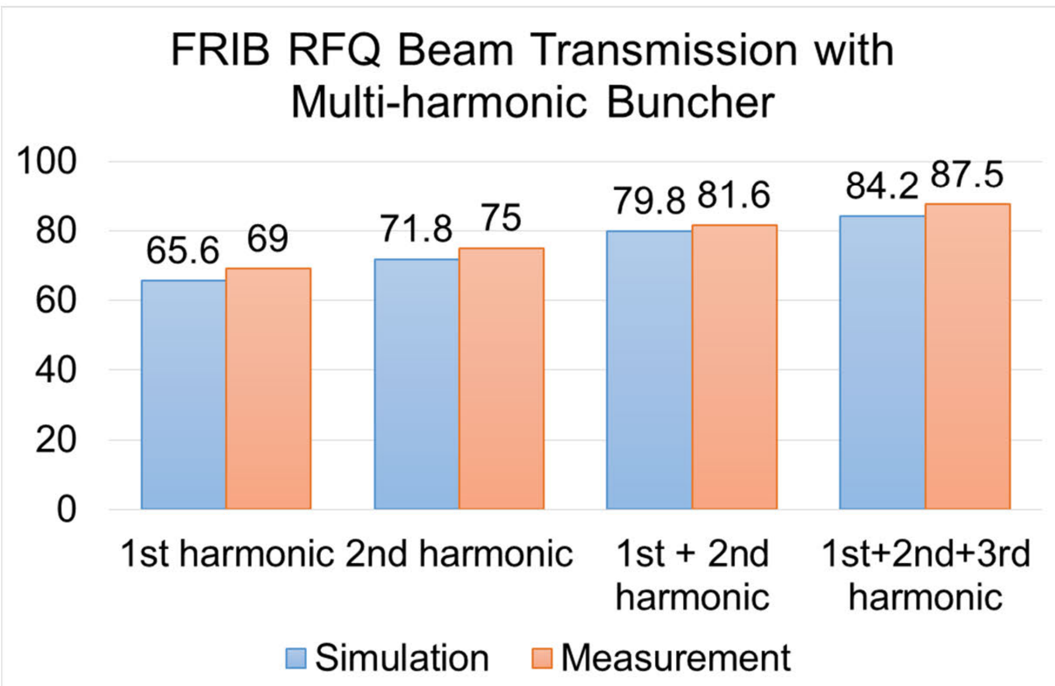
DC Beam Transmission through RFQ

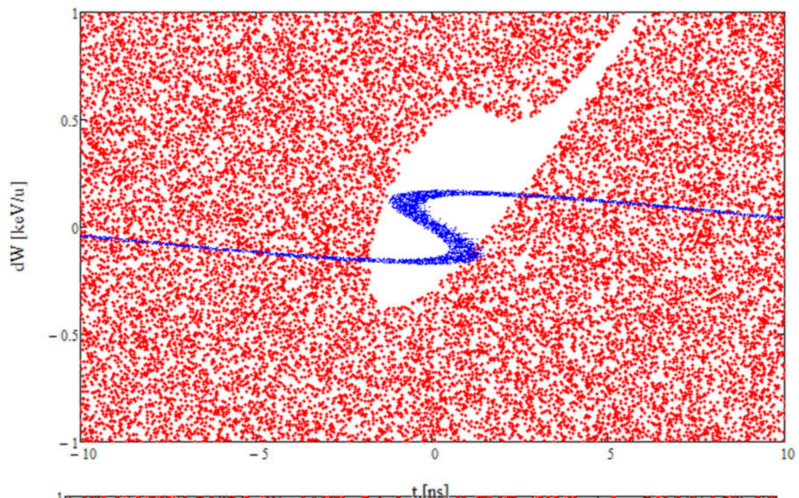
- DC beam (MHB off) Transmission (accelerated) through RFQ as function of vane voltage
  - Measurement agrees with simulation

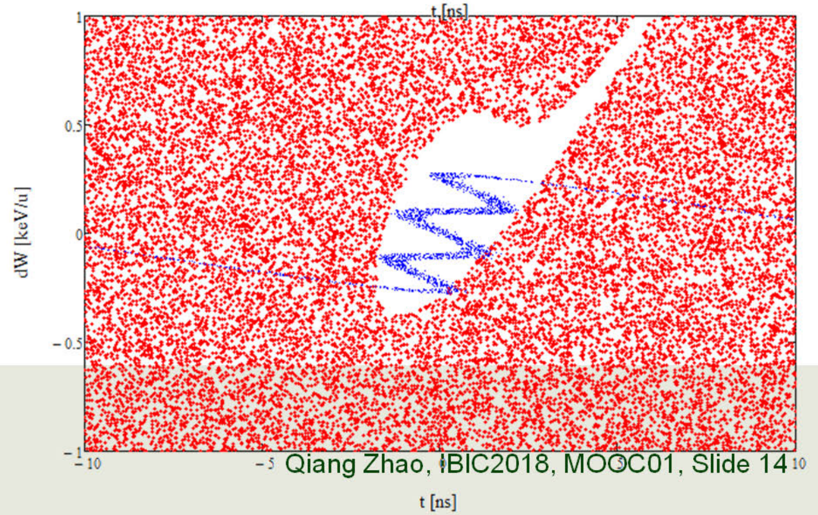


Beam Transmission in RFQ Increased with Multi-Harmonic Buncher in LEBT

- Bunching phase is found for each harmonic at some power level
- Combined level of RF power in all 3 harmonics optimized by iteration after phase setting for all harmonics

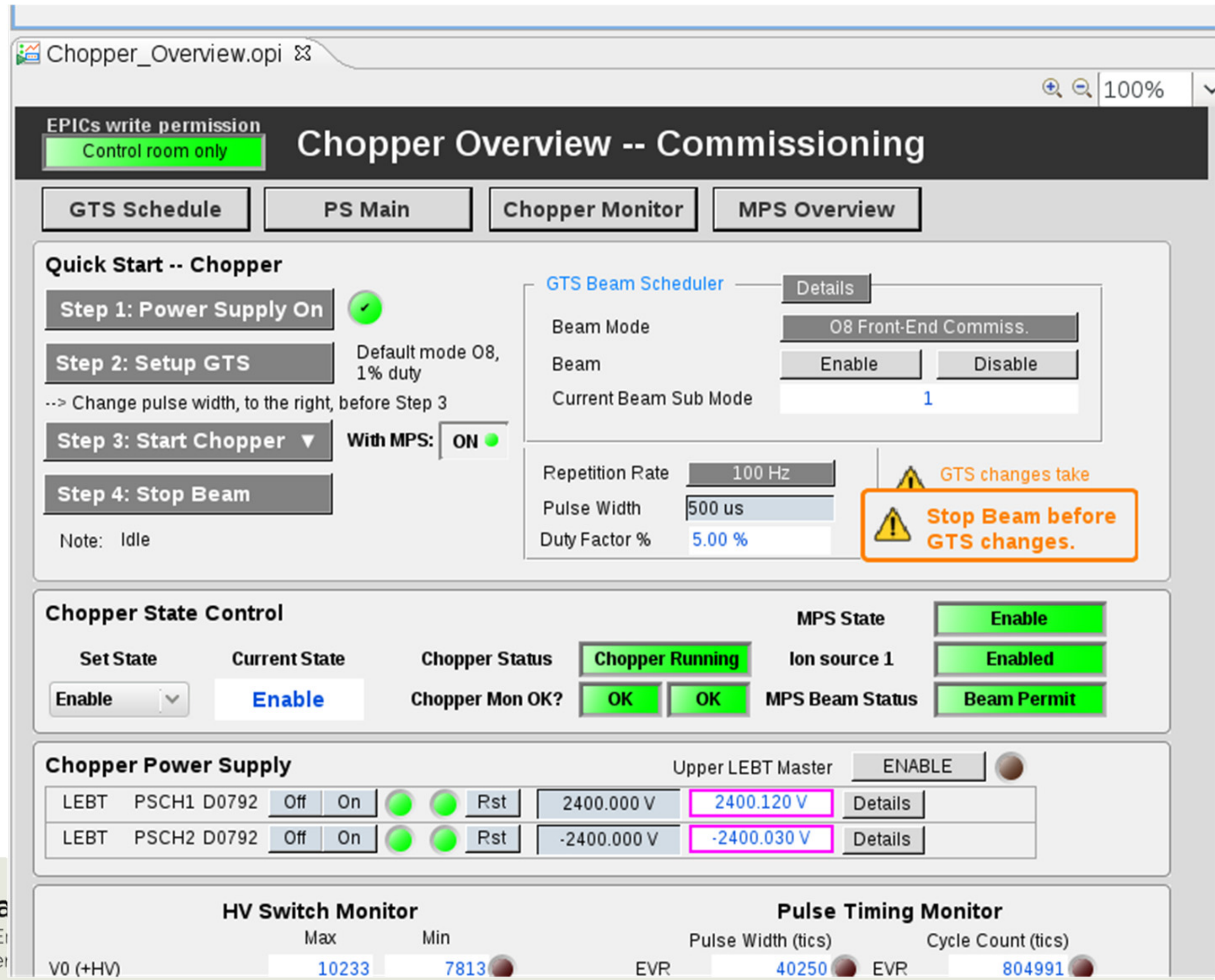






Chopper in LEBT is in Operation

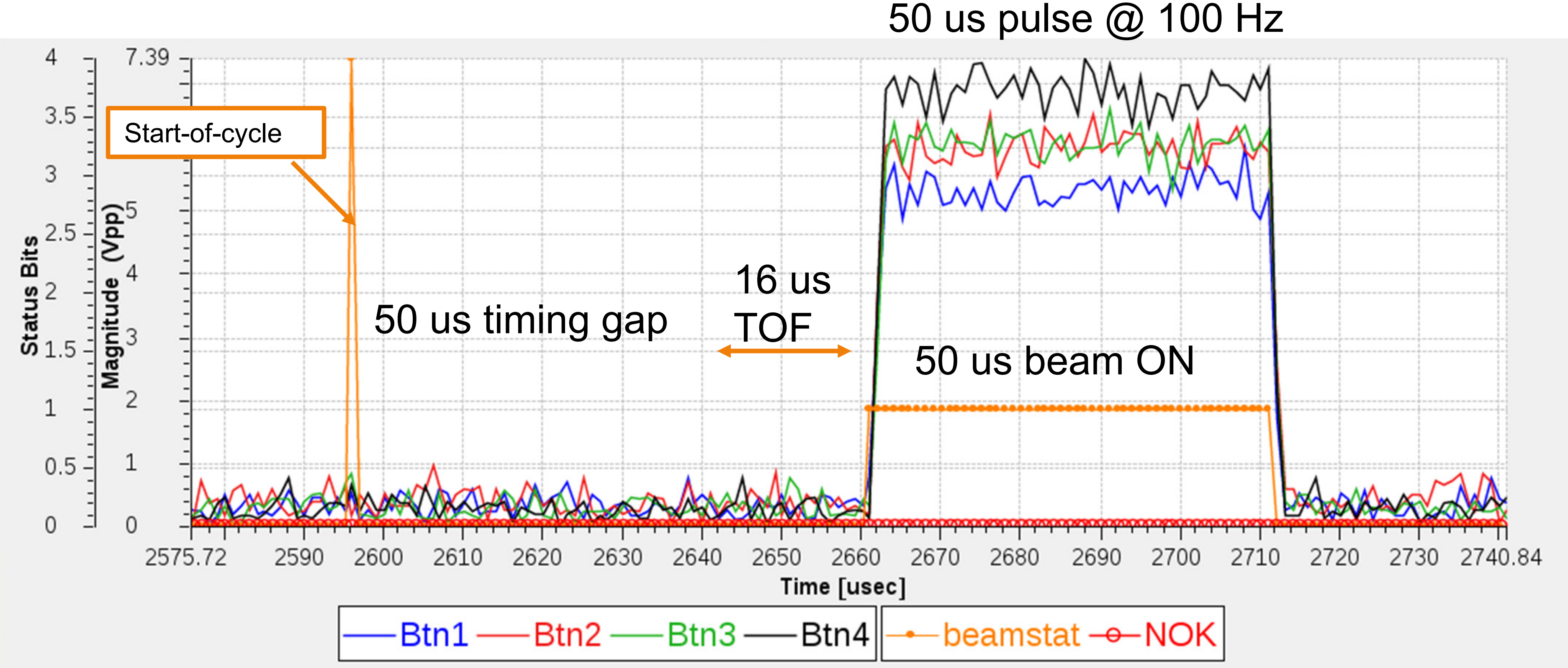
- Reduce average beam current
- Create beam notch
- Deflect/dump beam



BPMs after RFQ Validated with Chopped Beam

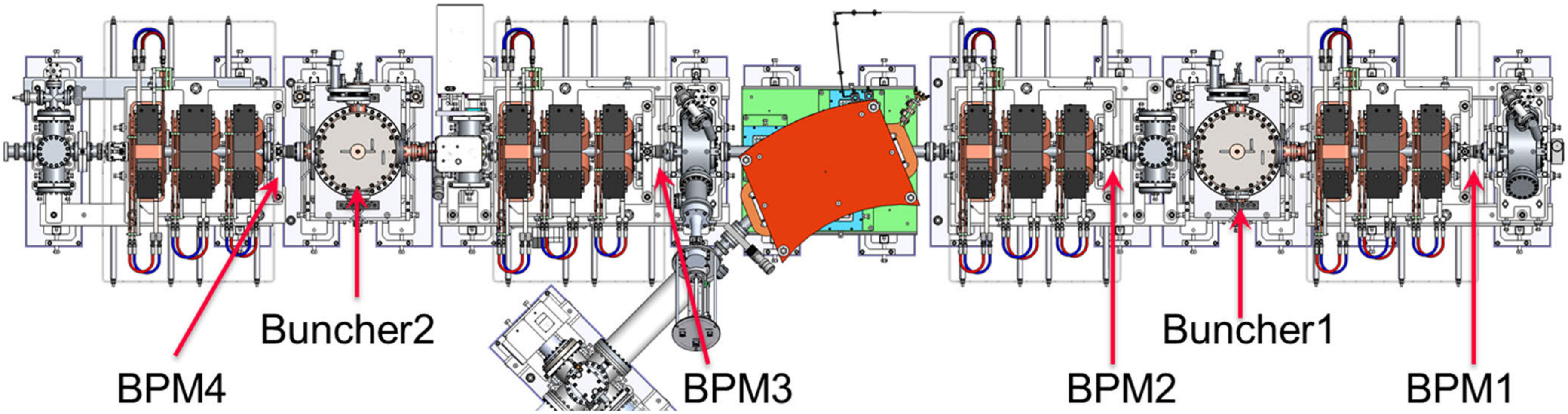
S. Cogan, TUPC07, First Results of FRIB Button BPMs

- Global timing systems and frequency feedback to the RFQ and warm RF systems were established
- RFQ can be run in either locked, closed-loop or self-excited loop modes
- In closed-loop the beam is modulated at 80.5 MHz
- Narrowband BPMs can detect 161 MHz



MEBT Beam Energy Measured using BPMs

- Beam arrival time in first 3 BPM were measured, respectively, with respect to the rf reference clock
  - Signal delays for each BPM were calibrated
- Set Buncher1 for maximum acceleration phase
  - Measured beam energy of 0.520 MeV/u
- Set Buncher1 for maximum deceleration phase
  - Measured beam energy of 0.492 MeV/u
- Obtained Buncher1 voltage of 61.6 kV, consistent with the measurements downstream of the bending magnet



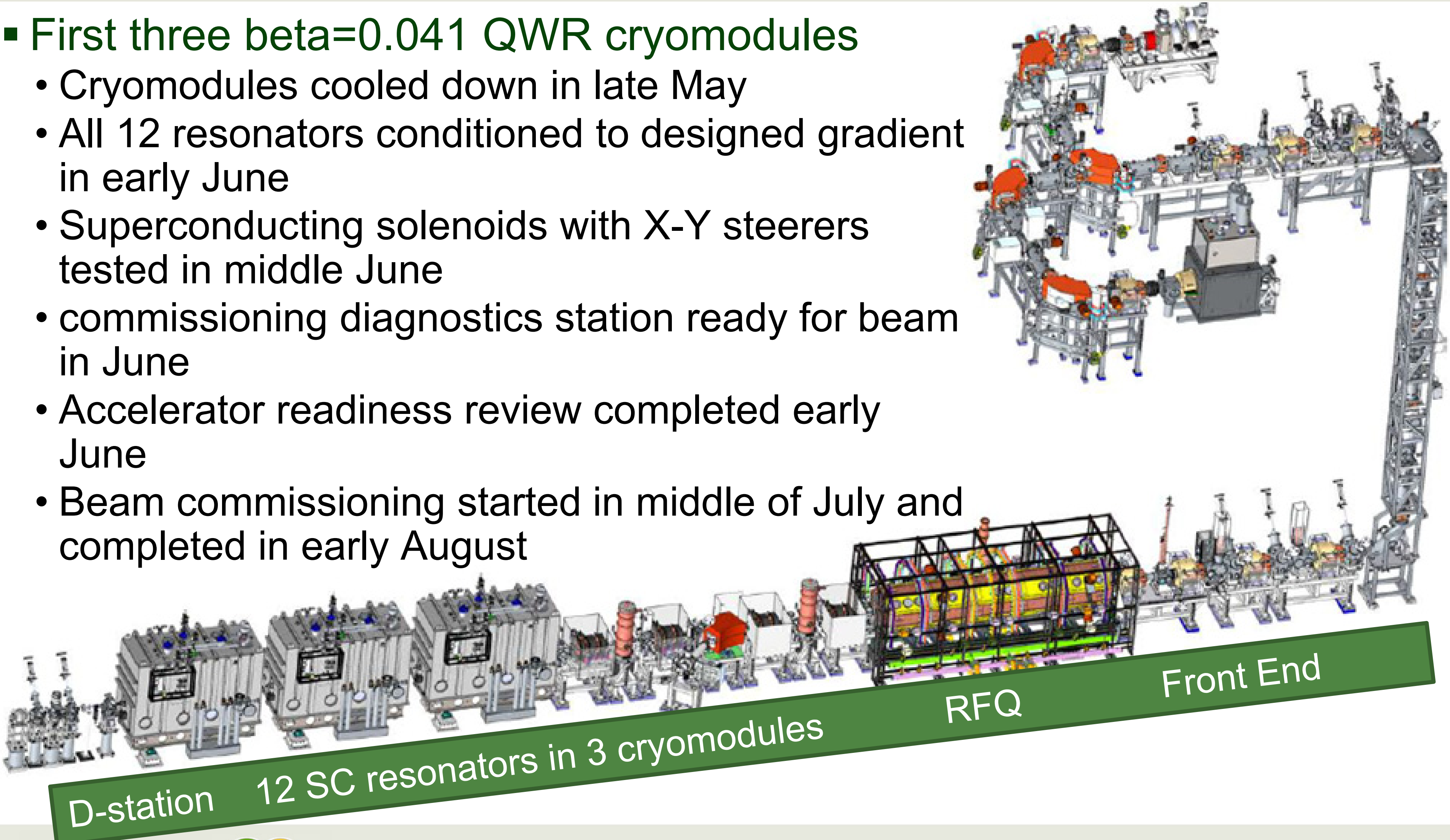
Front-End Commissioning (Stage 1) Completed

- Front-End has been in operation for about seven months
  - Major hardware systems are running reliably and stably
  - Beam test studies were performed to improve understanding of beam parameters, beam optics and transport, and to develop high level software
- Front-End is used to commission diagnostics, instrumentation, Machine Protection System and Run Permit System
- Front-End operation also provides opportunity to test and improve operational procedures

Objective Measures	Date
Beams from FRIB RT ion source	10/2016 ✓
Beams through end of upper LEBT	4/2017 ✓
Beams through end of LEBT	6/2017 ✓
Beams accelerated through RFQ	9/2017 ✓
Deliver all Key Performance Parameters	2/2018 ✓

Commissioning of the First 3 Cryomodules

- First three beta=0.041 QWR cryomodules
  - Cryomodules cooled down in late May
  - All 12 resonators conditioned to designed gradient in early June
  - Superconducting solenoids with X-Y steerers tested in middle June
  - commissioning diagnostics station ready for beam in June
  - Accelerator readiness review completed early June
  - Beam commissioning started in middle of July and completed in early August



First Three Cryomodules and the Commissioning Diagnostics Station Installed

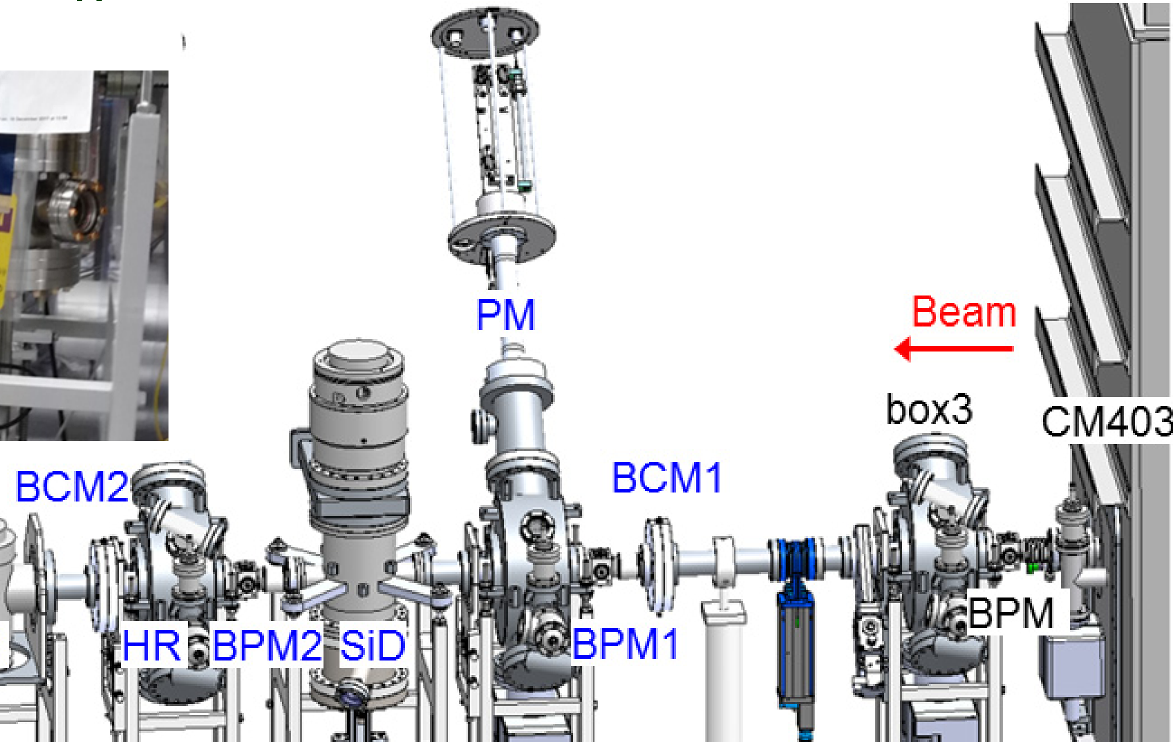
- All beam line elements installed in a portable clean room
  - Stringent SRF cleaning/assembly procedures followed

Beam Measurements with D-station

S. Lidia, OPA08, Design and Implementation of the FRIB 0.041 Cryomodule Diagnostics

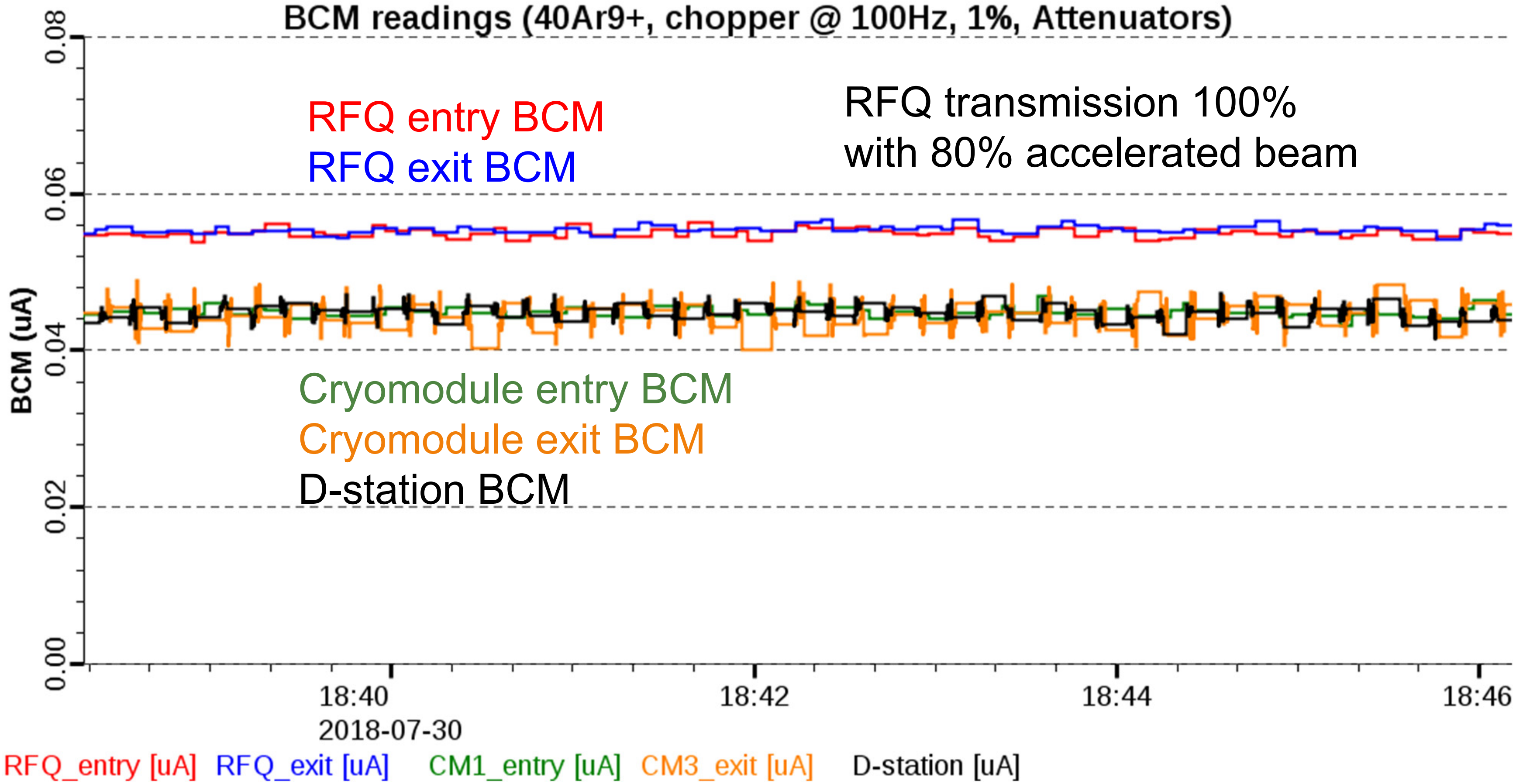
- Beam position and bunch phase
- Transverse profile, rms emittance reconstruction
- Absolute energy, energy spread, contaminant ions and their relative intensity
- Beam halo signal
- Absolute beam current (pulsed) and differential signal
- Bunch longitudinal profile, longitudinal rms emittance reconstruction

Installed Electronics



100% Beam Transmission through Cryomodules

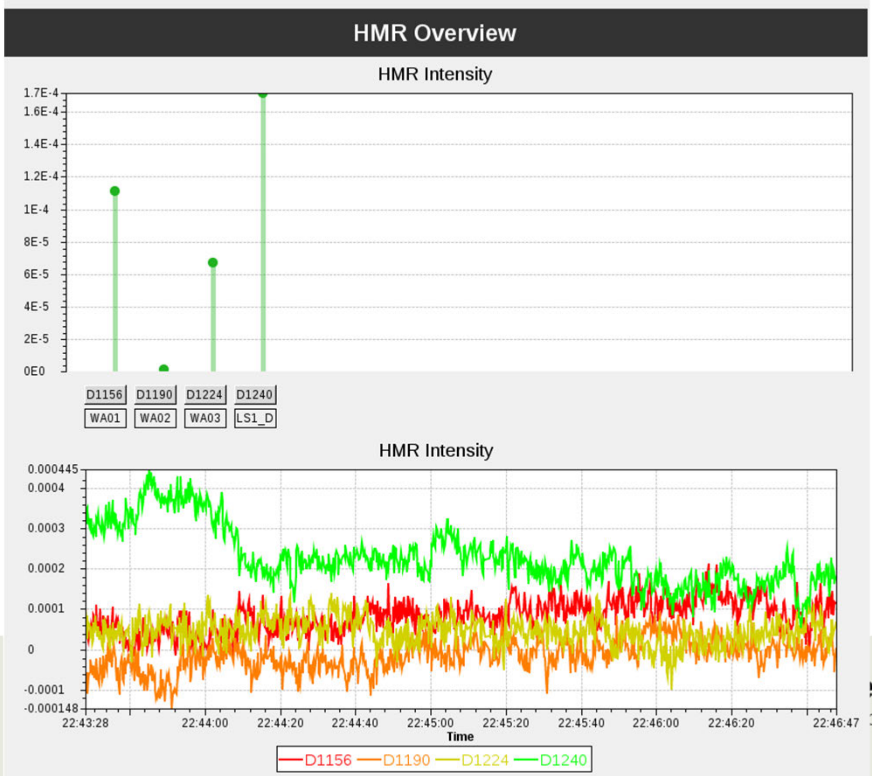
- 100% beam transmission from MEBT to D-station measured by BCMs
  - BCMs work well with chopper (100 Hz, 1% Duty Factor)

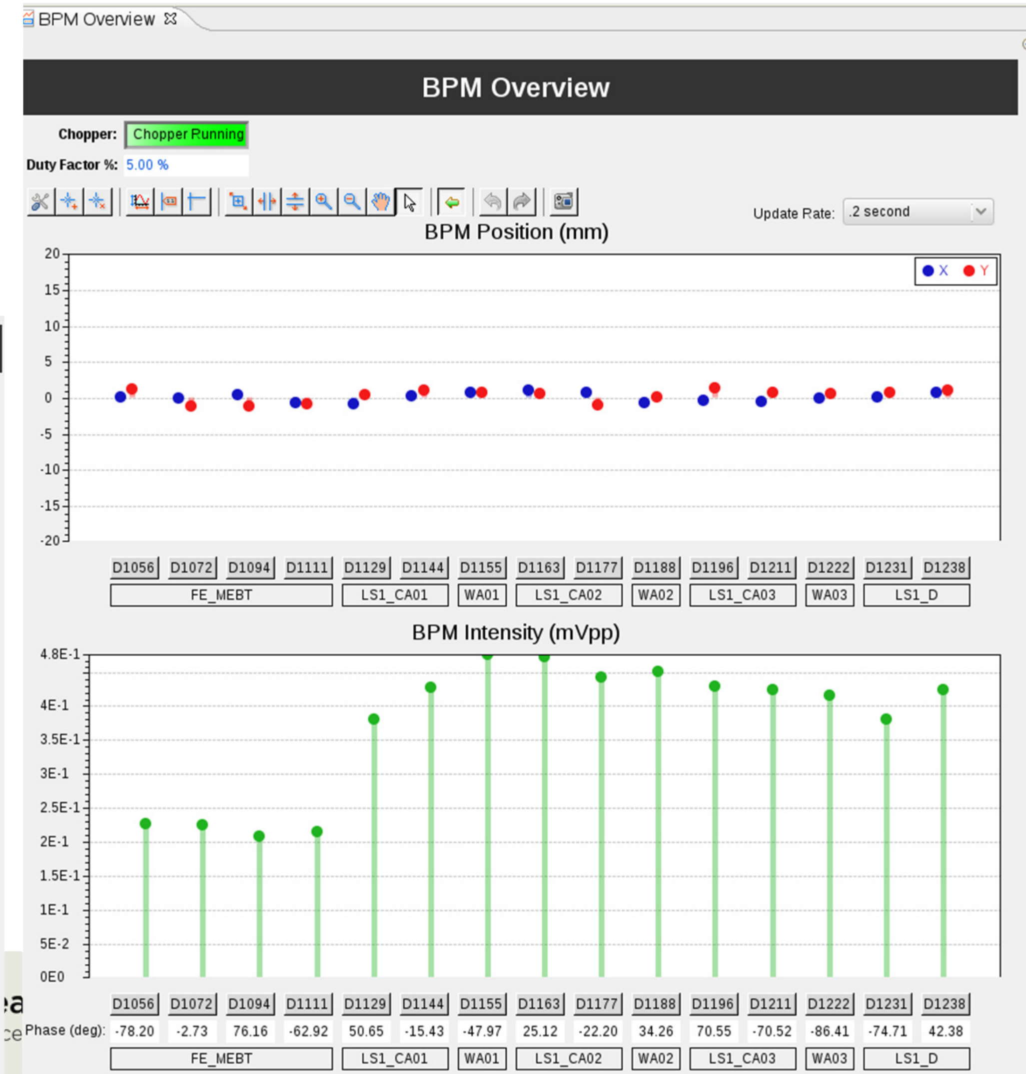


Pulsed Beam Transport Established Using BPMs

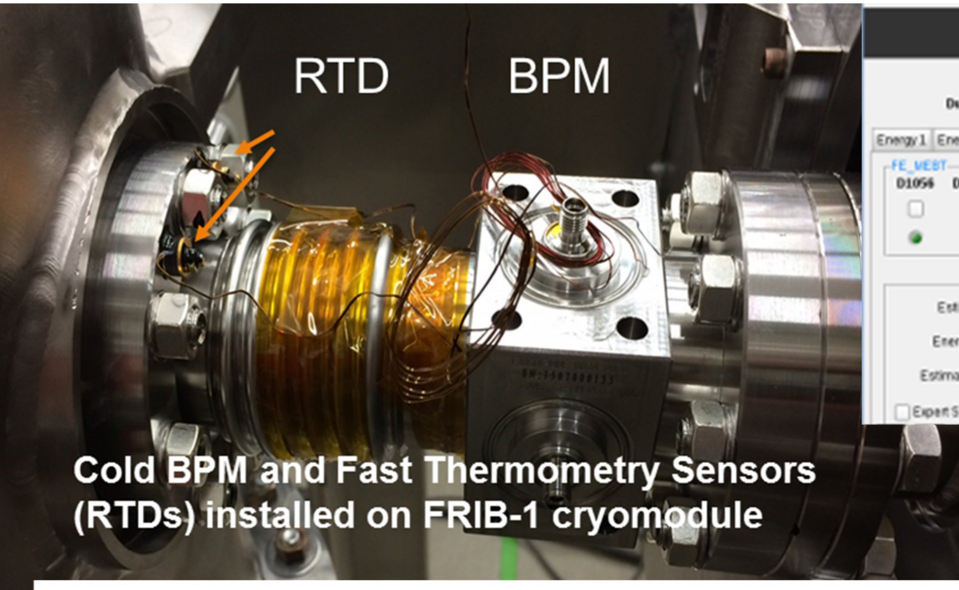
S. Cogan, TUPC07, First Results of FRIB Button BPMs

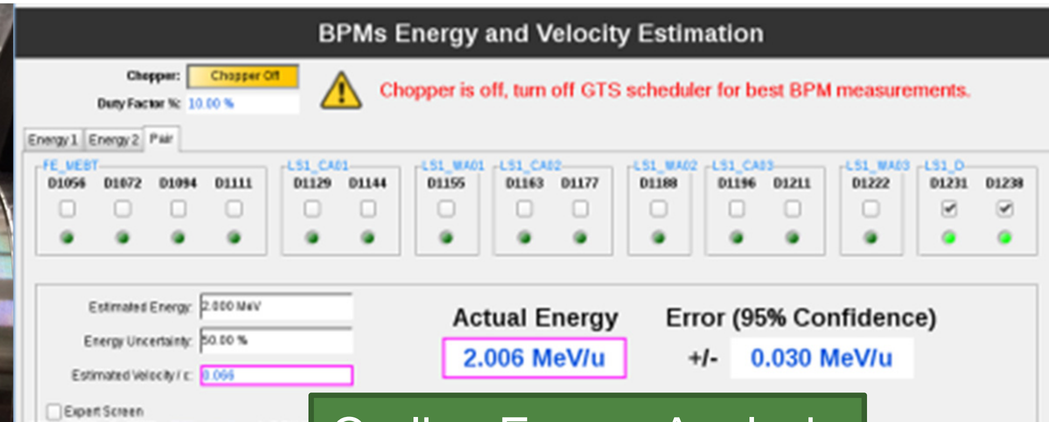
- Beam position within ±2 mm from MEBT through to the LS1
- No beam center correction is required; Beam halo monitors read only noise
  - Halo monitor signal indicative of tuning errors – orbit or envelope



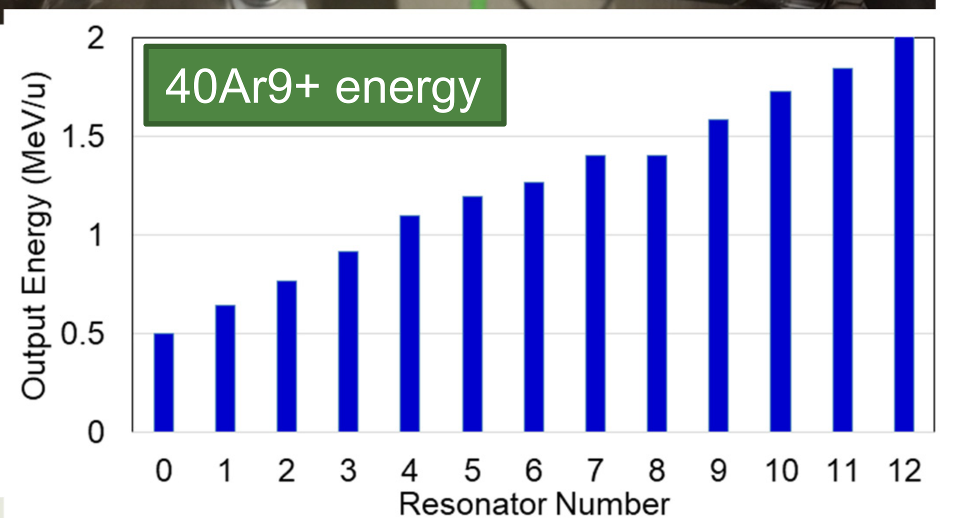


BPMs Used for On-Line, Time-Of-Flight Energy Measurement

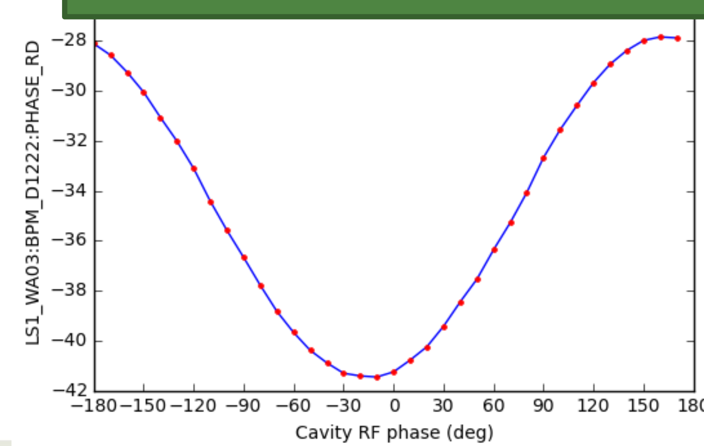




On-line Energy Analysis

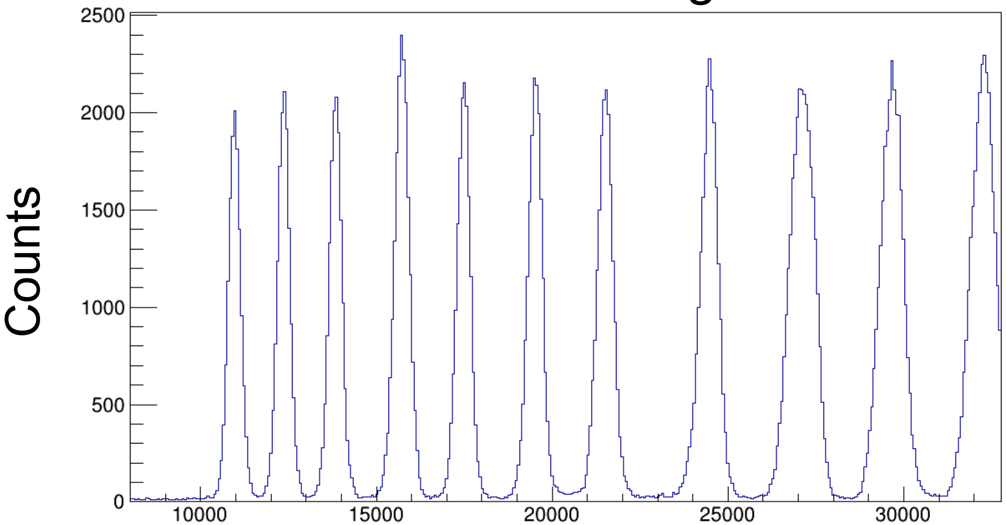


Phase scan of last resonator



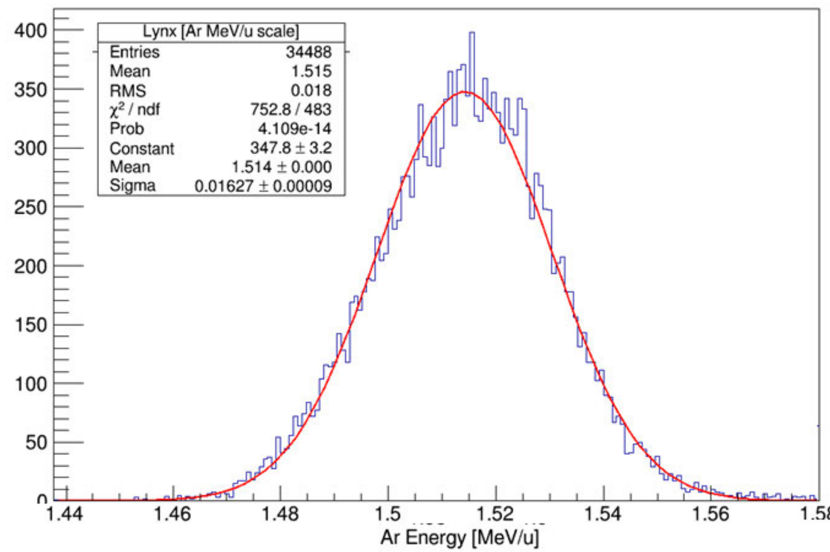
Beam Measurements with Silicon Detector

Absolute energies

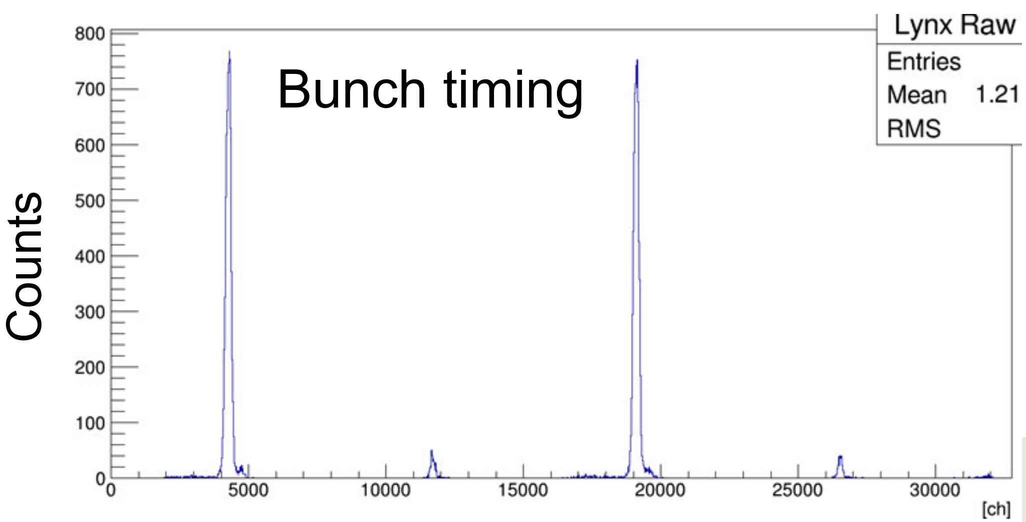


Channel #, proportional to beam energy

Energy spectrum

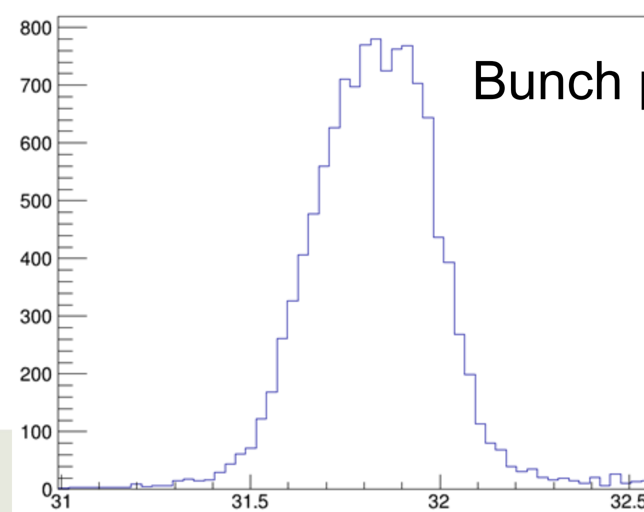


Bunch timing



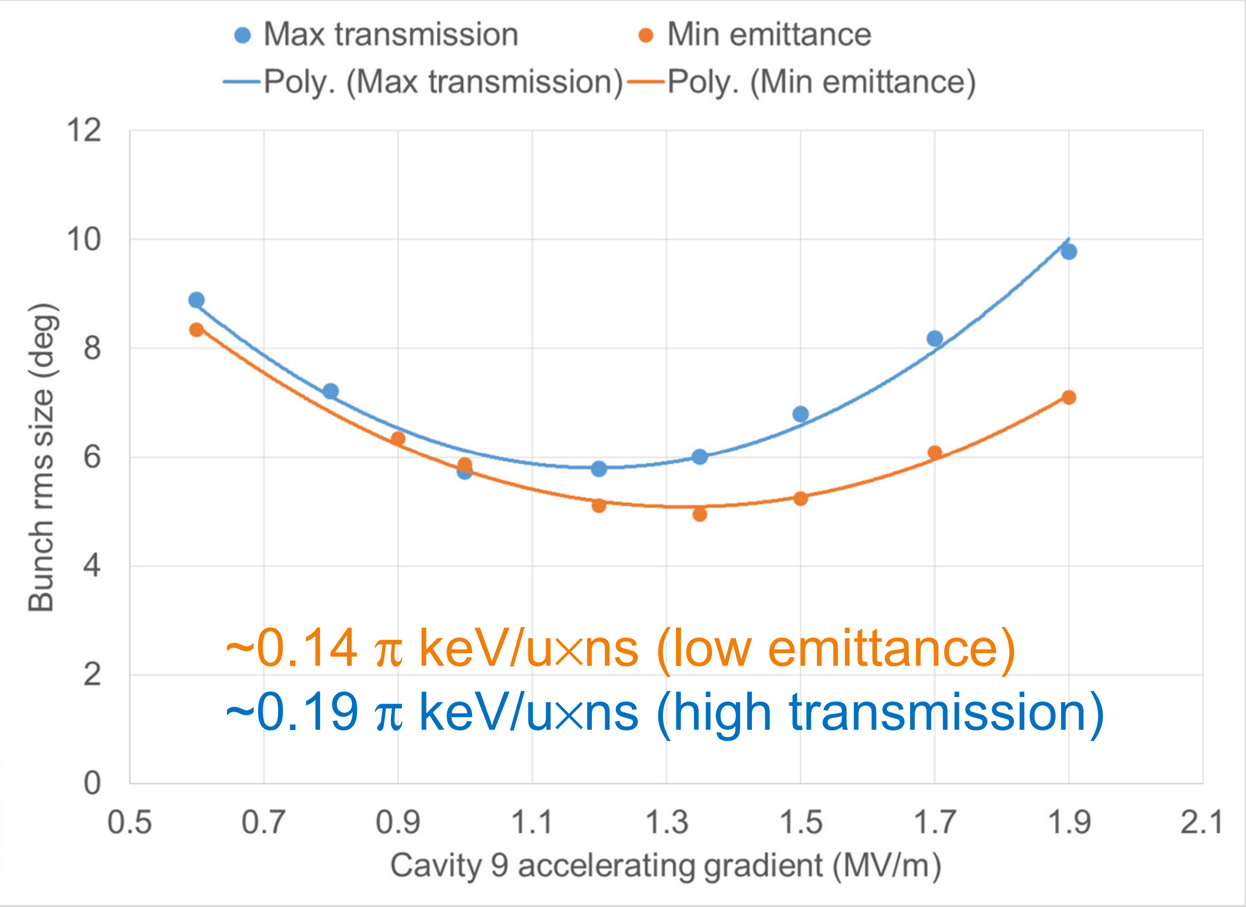
Channel #, proportional to bunch phase

Bunch profile



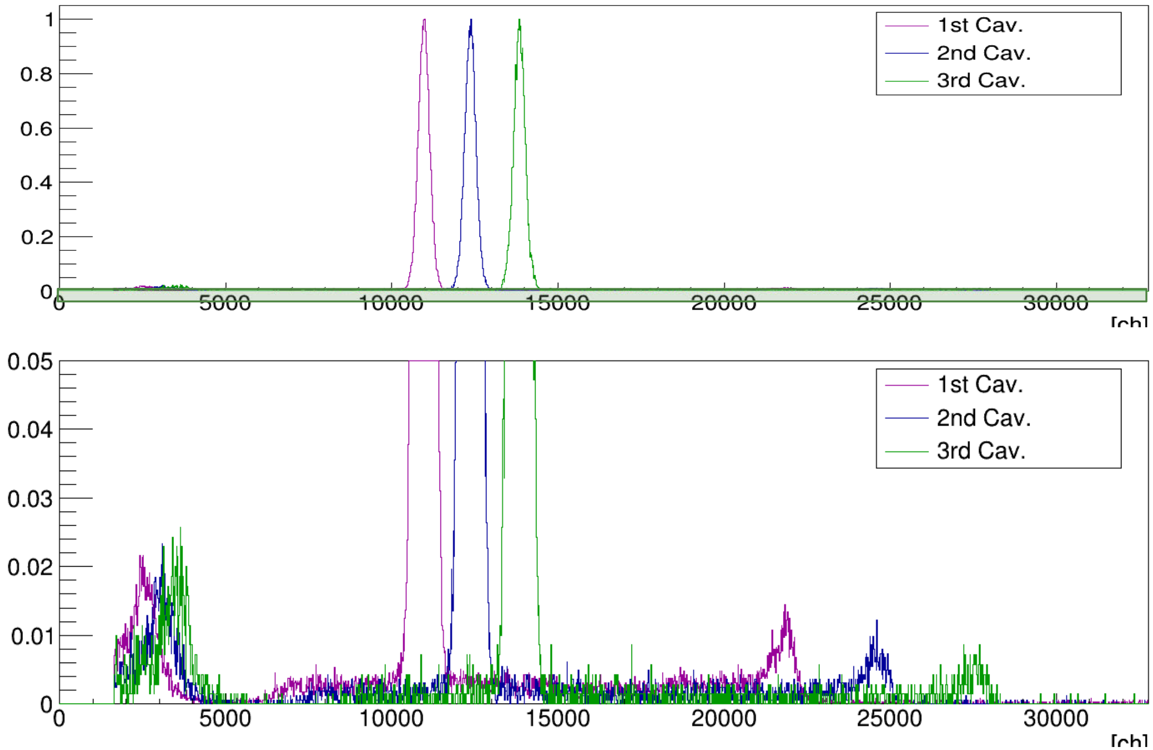
Longitudinal Emittance Measured at D-Station

- Longitudinal rms emittance is consistent with simulations
  - 0.14 π keV/u×ns (low emittance)
  - 0.19 π keV/u×ns (high transmission)
- MHB in LEBT can be set differently
  - Highest transmission
  - Lower transmission but smaller longitudinal emittance

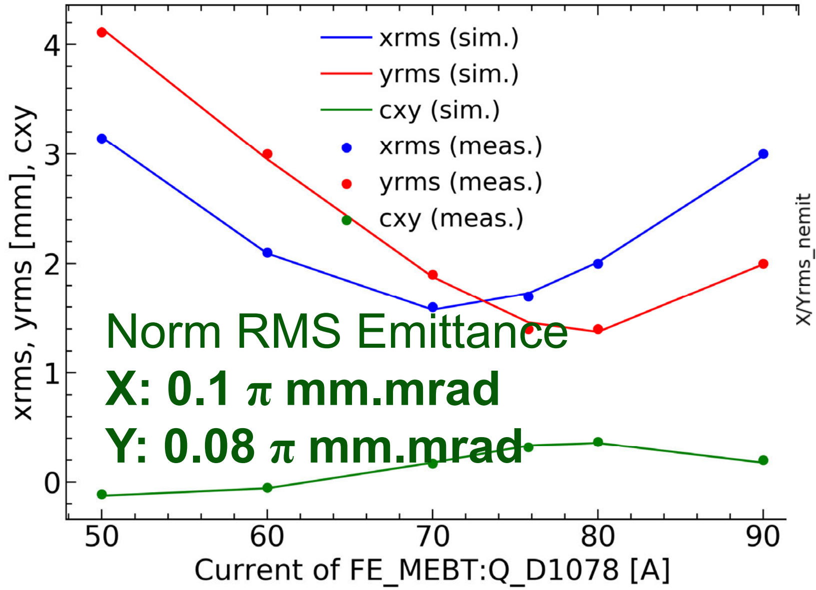


Beam Contaminants Observed with SiD

- Two beam contaminants are observed by the silicon detector during cavity tuning
  - The contaminants are also accelerated as beam ions
  - A few percent fraction of beam ions



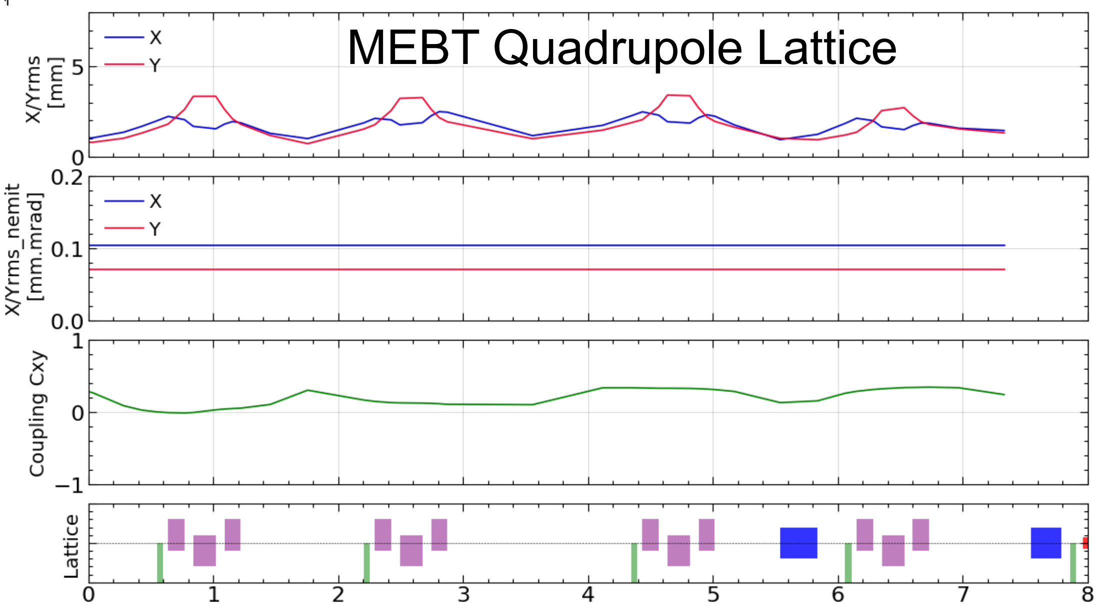
Beam Quality Maintained from MEBT to D-Station

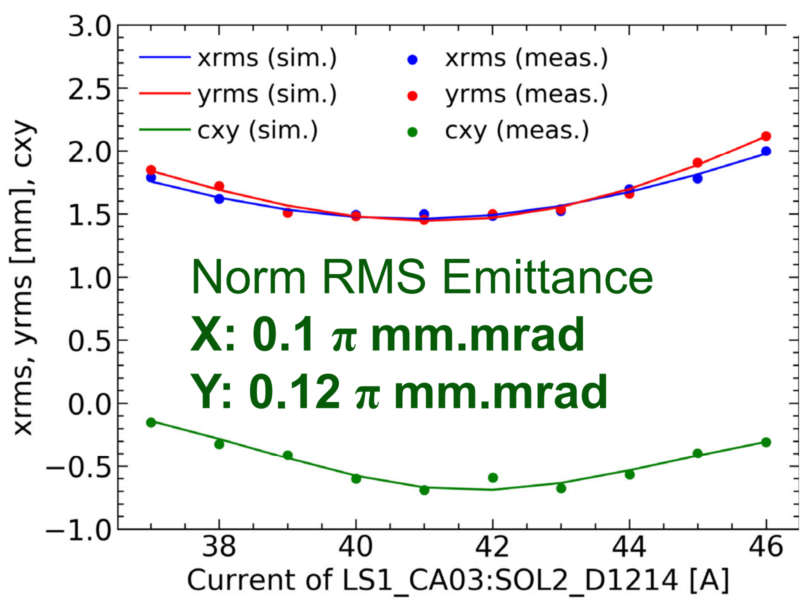


Norm RMS Emittance

X: 0.1 π mm.mrad

Y: 0.08 π mm.mrad

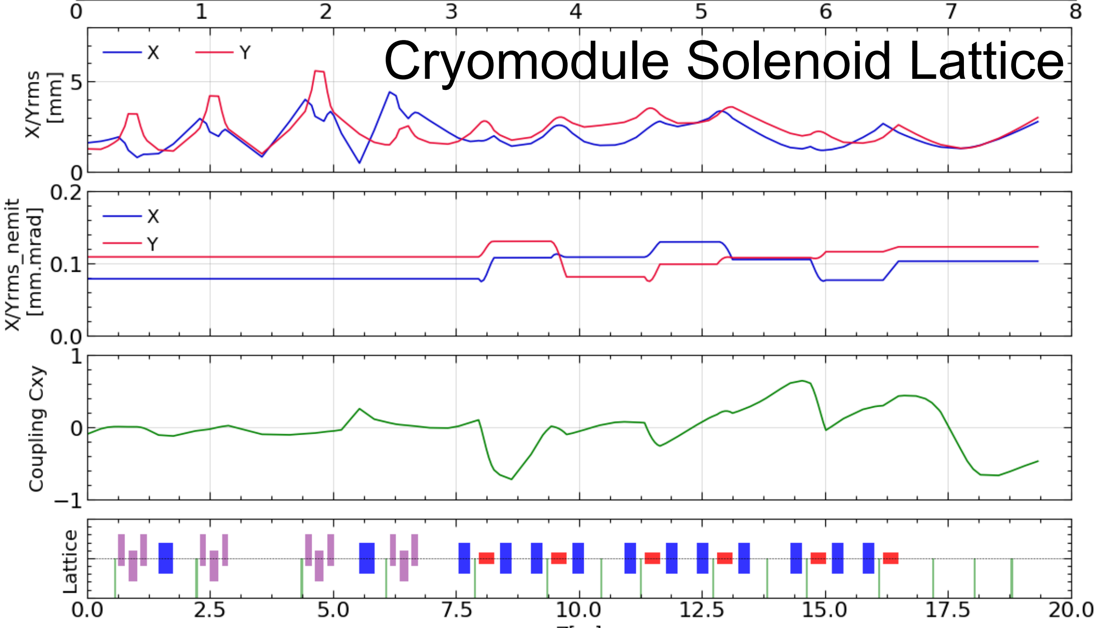




Norm RMS Emittance

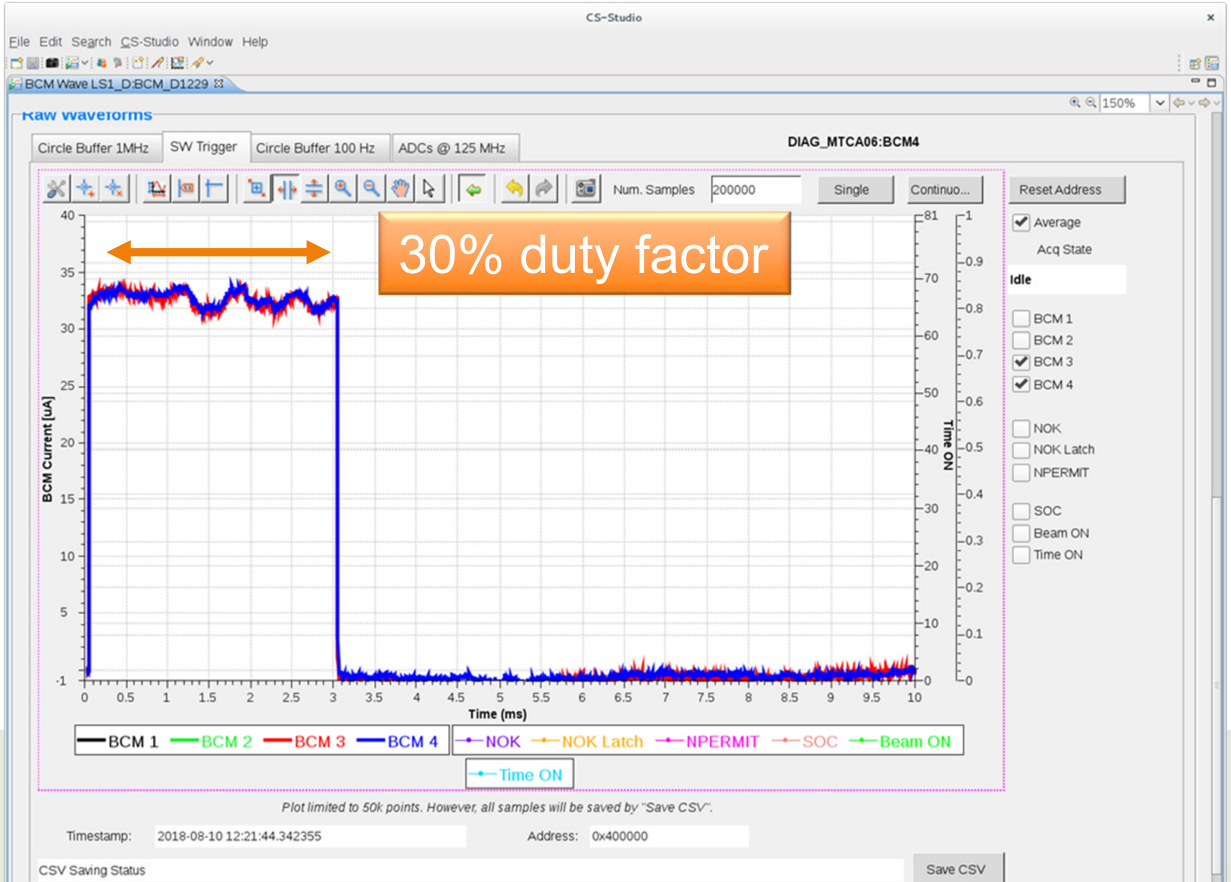
X: 0.1 π mm.mrad

Y: 0.12 π mm.mrad



Accelerated 230 W Beam to 1.5 MeV/u

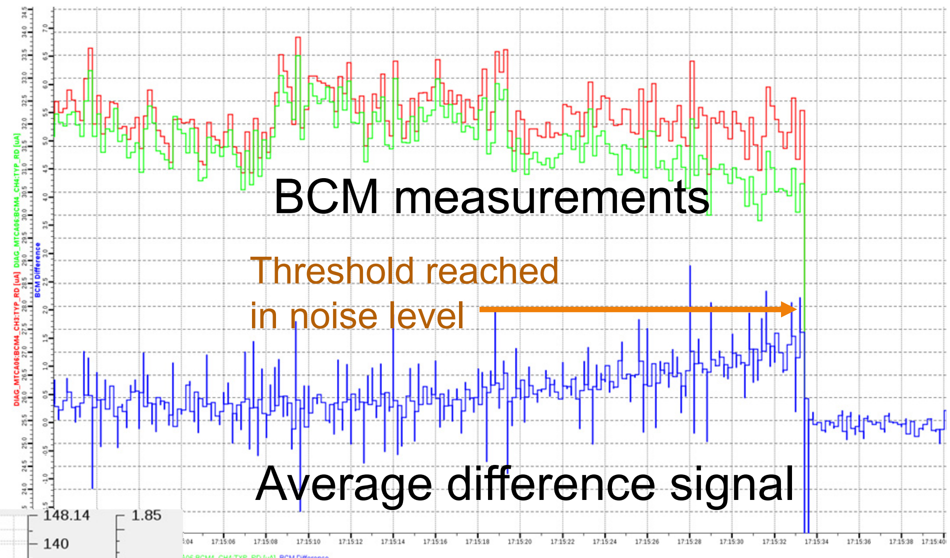
- 33 uA Ar^{9+} accelerated to 1.5 MeV/u with 30% duty factor
- 3 msec pulse at 100 Hz repetition rate
- Further increase of duty factor was limited by outgassing from Faraday cup

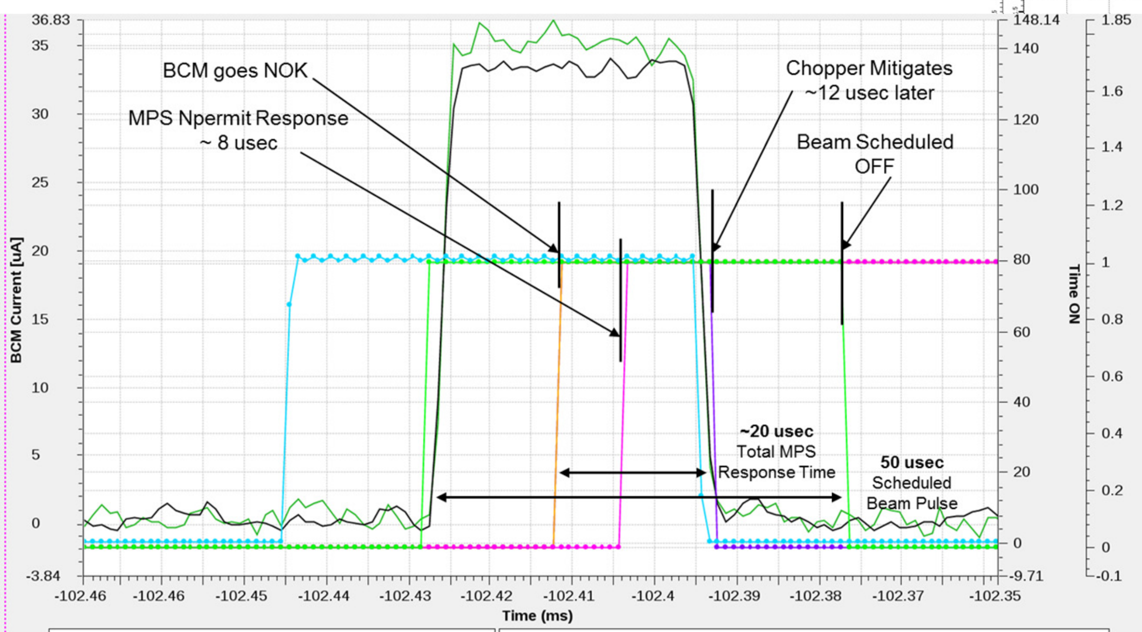


If further accelerated to linac exit, it would be ~38 kW on target with energy of 250 MeV/u as designed

Fast Differential Current Monitoring Established

- Observed current monitors upstream and downstream of cryomodules
- 2 different averaging timescales
  - 15 us – fast losses
  - 150 us – more averaging to reduce noise influence
  - Beam mitigated within 35 us, e.g.
    - » BCM → MPS: 8 us
    - » MPS → Chopper 12 us



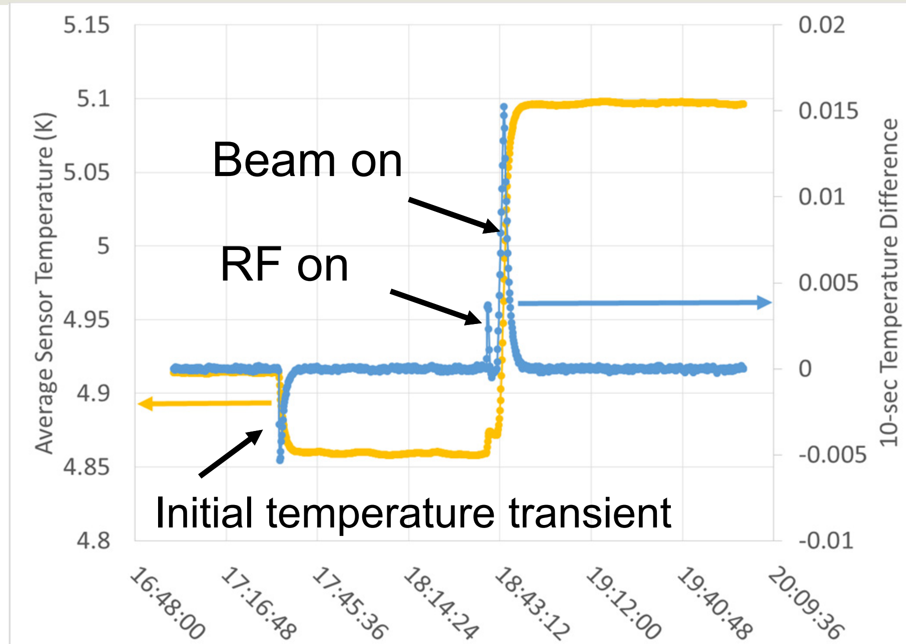


- 1.5 MeV/u case
- MPS trip setpoint at **ΔI ~ 1.5 uA**
- ~4.5% difference

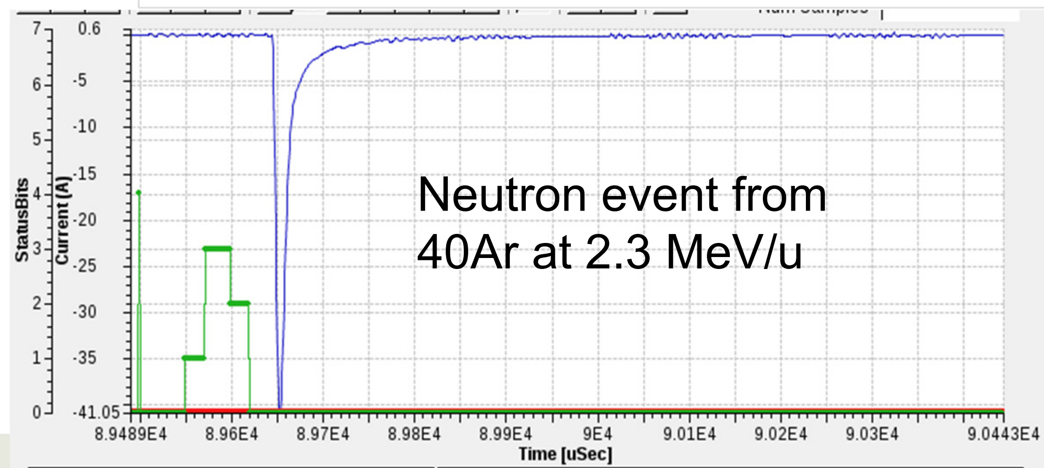
Postmortem buffer demonstrates time sequence of MPS mitigation

Chronic Beam Loss Monitors Commissioned

- Halo Monitor Rings
  - Very sensitive to low losses, but somewhat noisy at ~1 us time scale
  - Added averaging can detect nA-scale losses
- Fast Thermometry Monitoring
  - Exercised during beam tuning with sequential cavity energization
  - Responsive to localized beam losses on 10s seconds time scale
  - Sensitive to beam losses in cryomodule cold mass



- Neutron monitors
  - Personnel Protection and Diagnostics monitors used to validate onset of neutron production with beam energy
  - Both monitors have sensitivity to gammas; respond to cavity emission
  - Neutron signal strength larger and detector signal shows decay behavior (asymmetry)



First 3-Cryomodule Commissioning (Stage 2) Goals Met

Goal	Demonstration	Goal Met
Accelerate 40Ar beam up to 1.46 MeV/u and detect with Faraday Cup or BCM	>30 uA $^{40}Ar^{9+}$ accelerated to 2.3 MeV/u. 30% duty factor demonstrated	✓
Accelerate 86Kr beam with three β=0.041 cryomodules and detect with Faraday Cup or BCM	$^{86}Kr^{17+}$ accelerated to 2.0 MeV/u with scaled lattice and cavity settings	✓
Demonstrate RF phase and amplitude tuning of the second buncher in Medium Energy Beam Transport (MEBT)	Beam is longitudinally matched for acceleration with 100% transmission. Bunching and debunching recorded with BPM intensity signals.	✓
Evaluate accelerated beam properties including transverse and longitudinal RMS emittances of 40Ar and 86Kr beams with available diagnostic devices in D-Station.	Transverse and longitudinal emittances measured with profile monitor and silicon detector	✓
Verify Fast Machine Protection interlocks	Beam mitigated within 35 usec using Differential Beam Current Monitor	✓

Summary

- Commissioning of FRIB Front-End (Stage 1) and First Three-Cryomodule (Stage 2) have been successfully completed with both $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$
  - Beam properties were measured, consistent with simulations
  - Diagnostics and MPS/RPS verified
- All accelerator components (Ion source, RFQ, RF, diagnostics, controls, vacuum, cryoplant, cryomodule, and machine protection systems) are operated as expected
- Commissioning of Stage 3 linac systems on track for successful completion
  - All cryomodules installed being cooled down
  - Superconducting resonators to be conditioned
  - All magnets and most diagnostics installed
- FRIB project is on track

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Halo Monitor Rings

- Halo Rings and Current Monitors are complementary for beam tuning
  - Intercepted beam signals on HMRs anti-correlate with Faraday cup
  - Useful tool for optimizing transmission through cryomodules