First Acceleration at FRIB

Eduard Pozdeyev

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.

Acknowledgements [1]

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- We thank our colleagues at MSU: B. Barnes, S. Beher, E. Berryman, R. Bliton, C. Compton, J. Crisp, T. Embury, A. Facco, I. Grender, M. Holcomb, A. Hussain, G. Kiupel, G. Morgan, S. Nash, I Nesterenko, J. Priller, L. Popielarski, X. Rao, R. Shane, M. Scherer, S. Rodriguez, T. Russo, A. Taylor, A. Villari, R. Webber, O. Yair, J. Yurkon and many others.
- We also thank A. Aleksandrov, J. Bisognano, H. Edwards, J. Galambos, S. Henderson, G. Hoffstaetter, N. Holtkamp, B. Laxdal,, S. Ozaki, R. Pardo, S. Peggs, J. Qiang, D. Raparia, T. Roser, J. Stovall, L. Young, and many other our colleagues for their valuable advice, discussions, and collaborations.
- This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661. 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.

Acknowledgements [2]

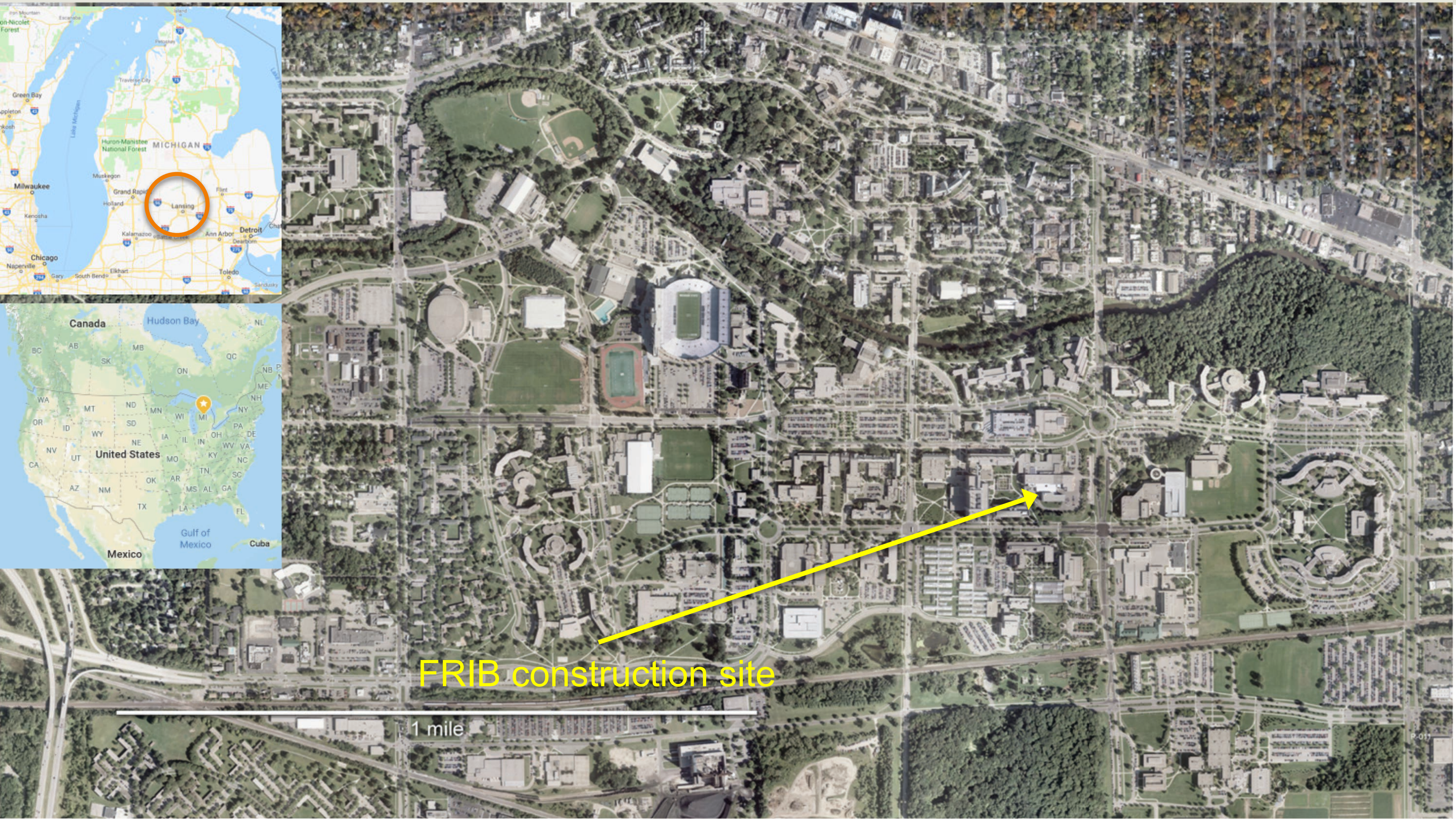
- We thank colleagues, collaborators, and partners from other laboratories for their direct contributions to the project and useful discussions
- ANL
- Berkeley
- BNL
- Femilab
- INFN, Legnaro
- LANL
- SNS
- Thomas Jefferson National Laboratory
- TRIUMF
- Tsinghua University

Outline

- Introduction
- Commissioning of Front End systems
- Commissioning of the first three cryomodules ($\beta = 0.041$)
- Path forward with SRF linac commissioning
- Summary

FRIB Construction Site Located on MSU Campus

Enrollment 50540, Staff 12100; Campus 40 km^2; Endowment $3B; Established 1855

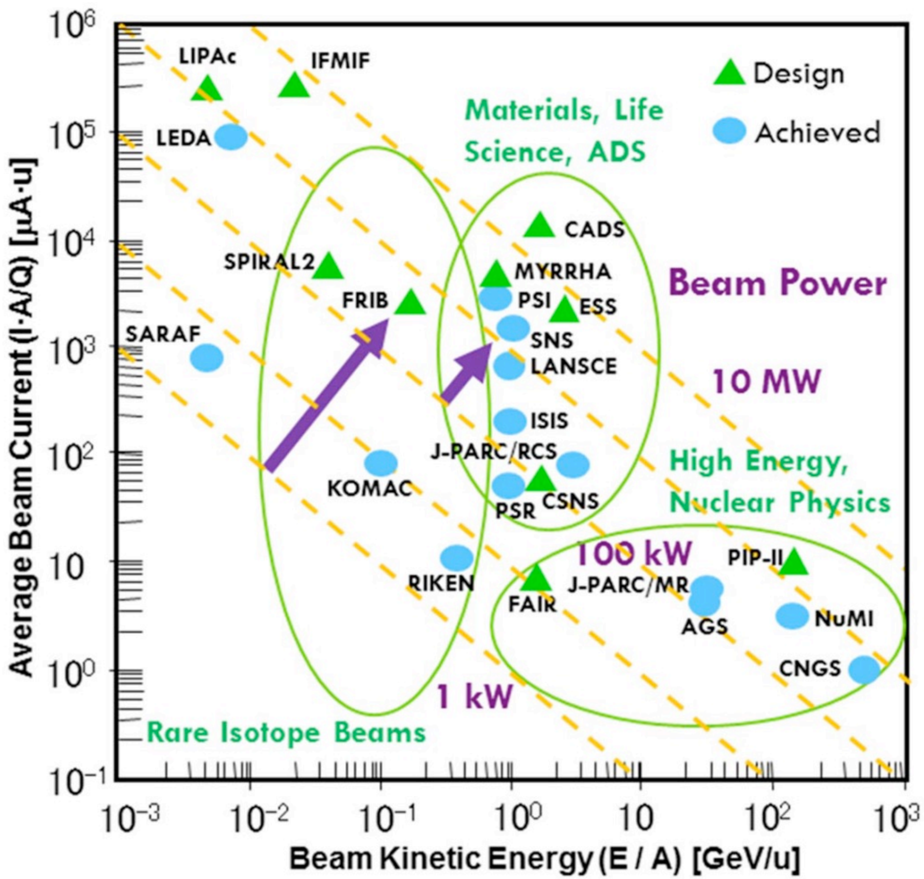


Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

FIRB Site Layout

Facility for Rare Isotope Beams at MSU Premier DOE-SC National User Facility

- Ions up to uranium, E>200 MeV/u, beam power on target 400 kW, Superconducting linac
- Rare isotope beams by fragmentation, gas stopping, reacceleration
- FRIB pushes the beam power on target by two orders of magnitude comparatively to existing medium and heavy ion facilities
- FRIB scientific focus aligned with National Science Priorities
  - Properties of nuclei
  - Astrophysical processes
  - Test of fundamental symmetries
  - Societal application and benefits

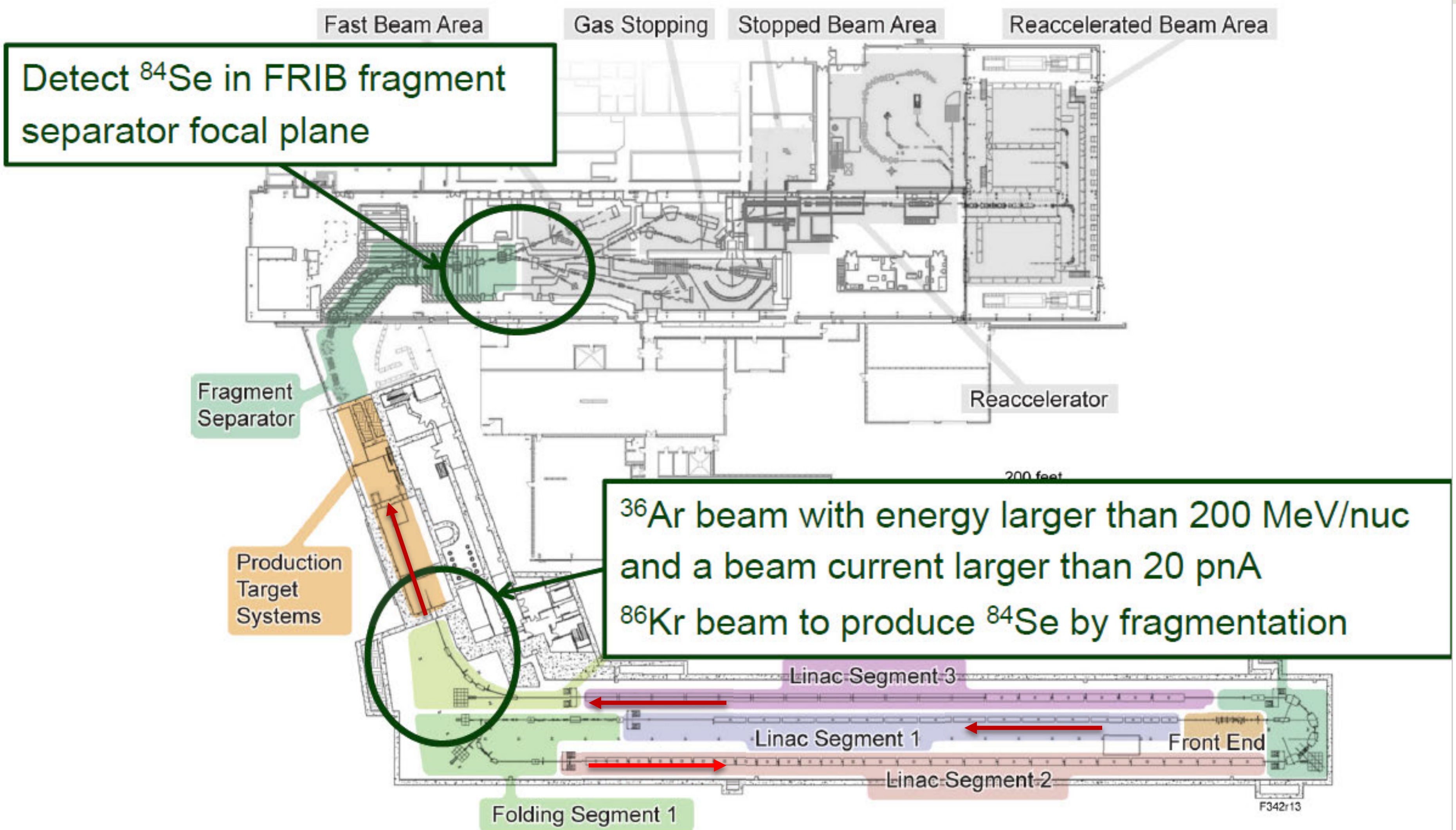


Time Line
FE Construction and Commissioning

- 12/2008 – MSU selected as site for FRIB
- 09/2010 – CD1 approved
- 04/2012 – CD2/CD3A – approval of CF construction and long term procurements
- 11/2015 – Ion Source platforms moved to FRIB site – First technical equipment moved in the building
- 09/2016 – Artemis ECR Ion Source commissioned, 14 months ahead of baseline schedule
- 9/2017 – Beam accelerated through the RFQ, 10 months ahead of schedule
- 2/2018 – Front End commissioning completed
- 07/2018 – First three 0.041 cryomodules commissioned
- Now – LINAC 2018

- Spring 2019 – Plan to commission Linac Segment 1 (E=20 MeV/u)
- 2020 – Plan to commission the rest of the accelerator
- 2022 – CD4: Project completion

Commissioning Performance Requirements Defined by Key Performance Parameters (KPP) for CD-4



Detect ^{84}Se in FRIB fragment separator focal plane

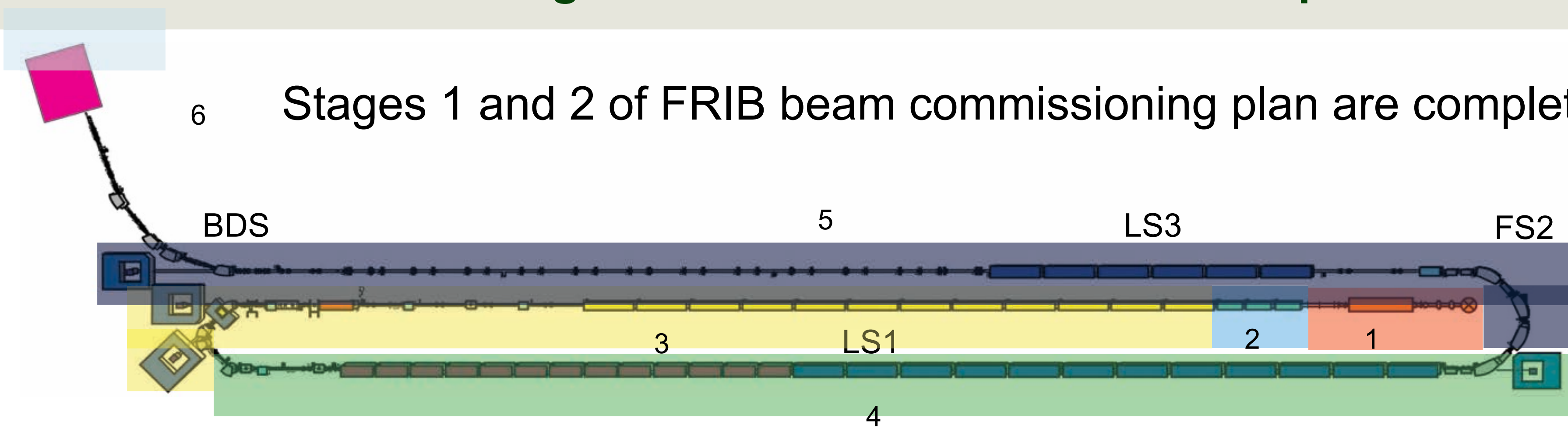
^{36}Ar beam with energy larger than 200 MeV/nuc and a beam current larger than 20 pnA

^{86}Kr beam to produce ^{84}Se by fragmentation

Phased Beam Commissioning towards CD-4

Commissioning of Front End and 0.041 CM Complete

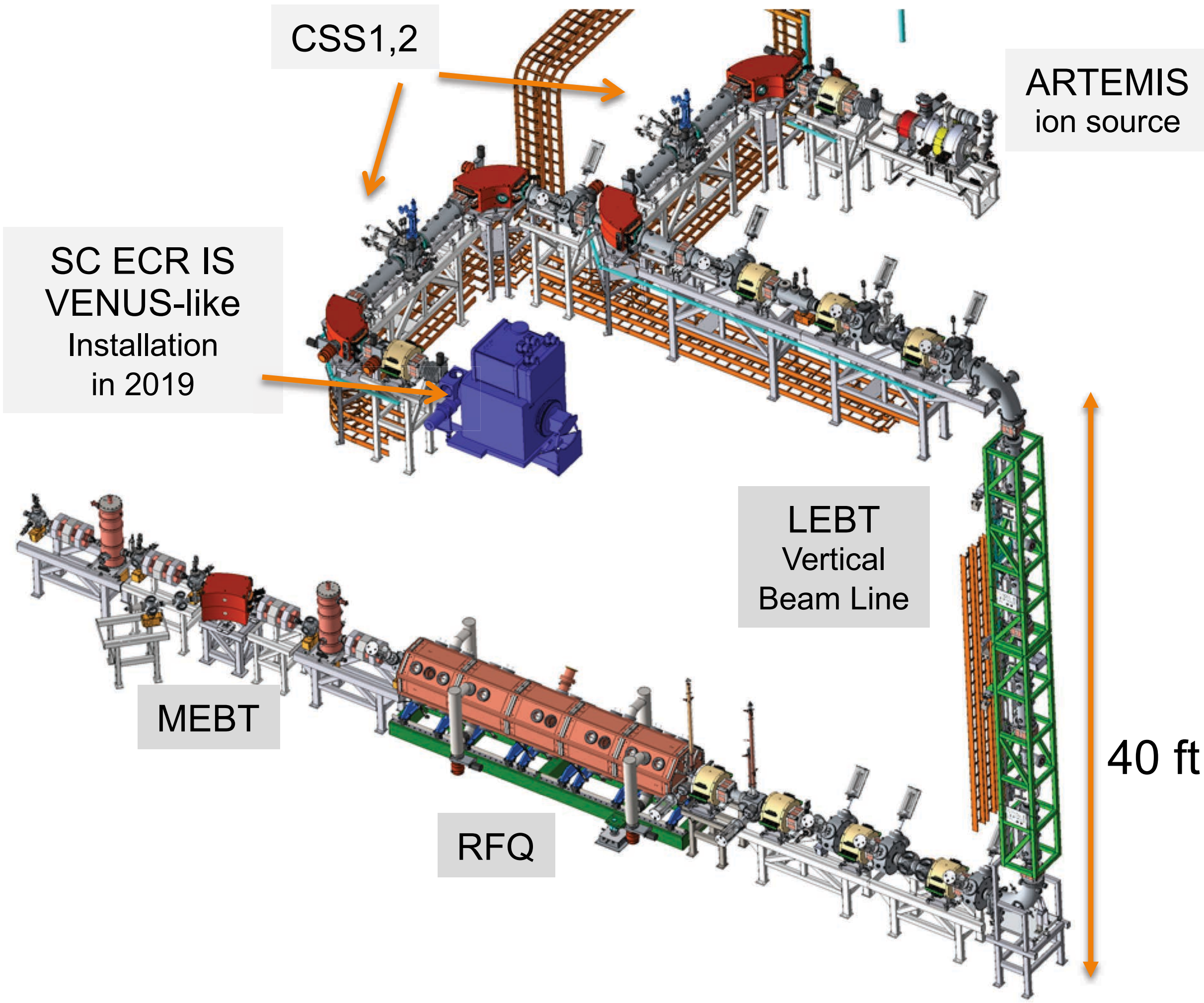
Stages 1 and 2 of FRIB beam commissioning plan are complete



ARR	Area with beam	Date
1	**Ion Source, Low Energy Beam Transport, RFQ, Medium Energy Beam Transport**	**Commissioned, 09/2017**
2	**Linac Segment (LS) 1 (β=0.041 cryomodules)**	**Commissioned, 07/2018**
3	Remainder of LS1 and first 45 degree dipole of FS 1	02/2019
4	Remainder of FS1, LS2	04/2020
5	FS2, LS3	09/2020
6	Beam Delivery System, Target, Pre-Separator in Target Hall	TBD
Final	Prior post-start items, Pre-Separator outside Target Hall, reconfigured A1900, entire facility	Before 06/2022

Front End Systems and Their Parameters

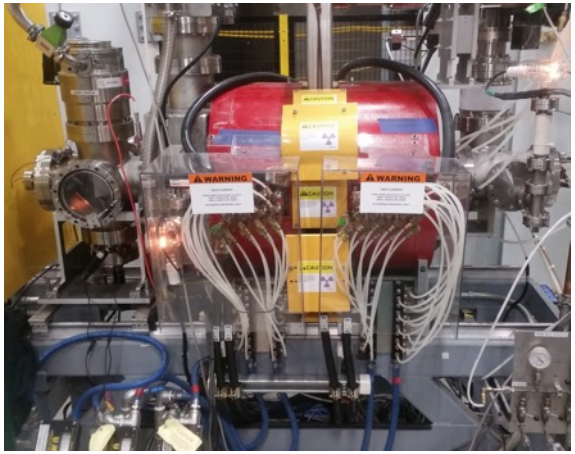
- Two ECR sources on High Voltage (HV) platforms
  - ARTEMIS – 14 GHz ECR ion source
  - 28 GHz superconducting source based on VENUS (LBNL). Installation in 2019
- LEBT (E = 12 keV/u)
  - Beam energy – 12 keV/u
  - Chopper
  - Electrostatic quads
  - Solenoids
- RFQ (E = 500 keV/u)
- MEBT (E = 500 keV/u)
  - Two RF bunchers,
  - Simple quadrupole magnets
  - Instrumenation
- Subsystems enabling front end hardware: RF, PS, Vacuum, etc.



14 GHz ECR Ion Source ARTEMIS Used To Commission FRIB

- ARTEMIS based on AECR-U design (LBNL)
- Low risk, extensive experience at NSCL with ARTEMIS operation and maintenance
- Performance meets intensity requirement for commissioning and two first years of operation
  - Demonstrated 40Ar10+ current is ~150 eμA
  - Demonstrated 86Kr17+ current is ~35 eμA

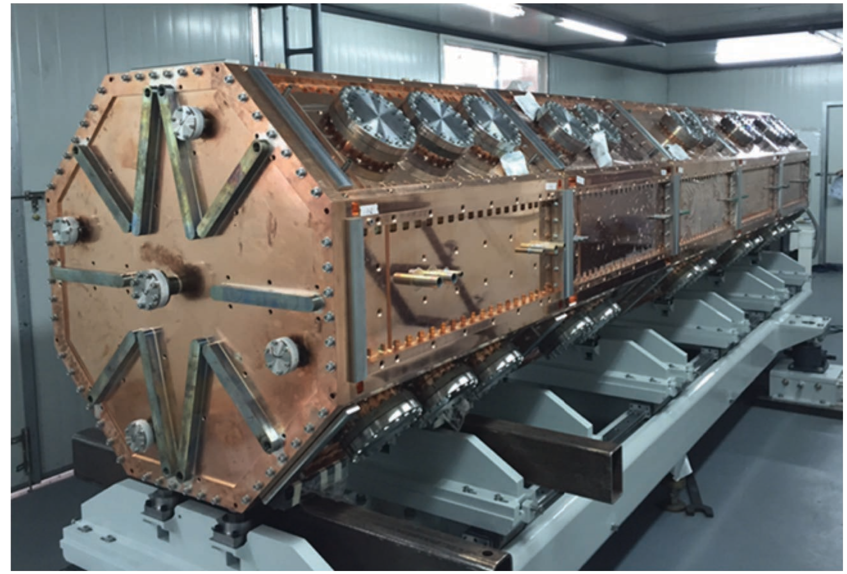
ECR Subsystem	Parameters
Primary RF system	14.5 GHz, 2 kW
Plasma chamber	75 mm Dia. Aluminum
Solenoid coils (x2)	2T (Injection)-0.9T (Extraction)
Solenoid Magnet	Room temperature
Sextupole Magnet (NdFeB)	0.8T (plasma chamber)
Extraction voltage	Up to 25 kV

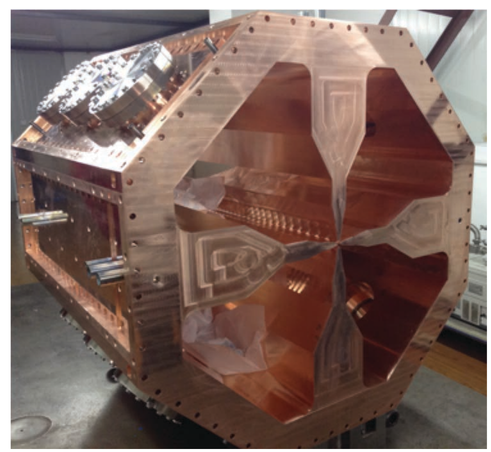


RFQ Construction Completed in June 2016

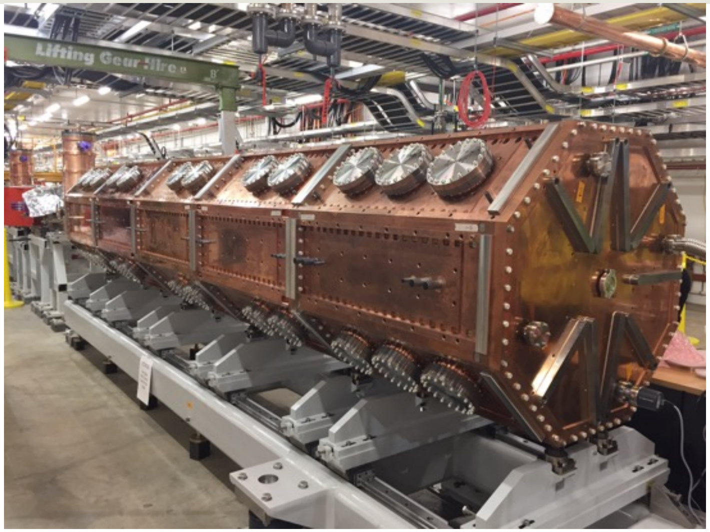
Parameter	Value
Frequency (MHz)	80.5
Injection/extraction energy (keV/u)	12 / 500
Q/A	1/3 – 1/7
Transmission efficiency (typ.)	> 80%
CW RF Power (kW), Uranium	100
Length (m)	5

- Engineering design developed at MSU
  - In consultations with L. Young and J. Stovall
  - Details of thermal design developed by Tsinghua University (Q. Xing)
- RFQ Procured through an industrial vendor
- RFQ amplifier is 150 kW, tube-based
  - Developed at MSU
- Frequency controlled by cooling water

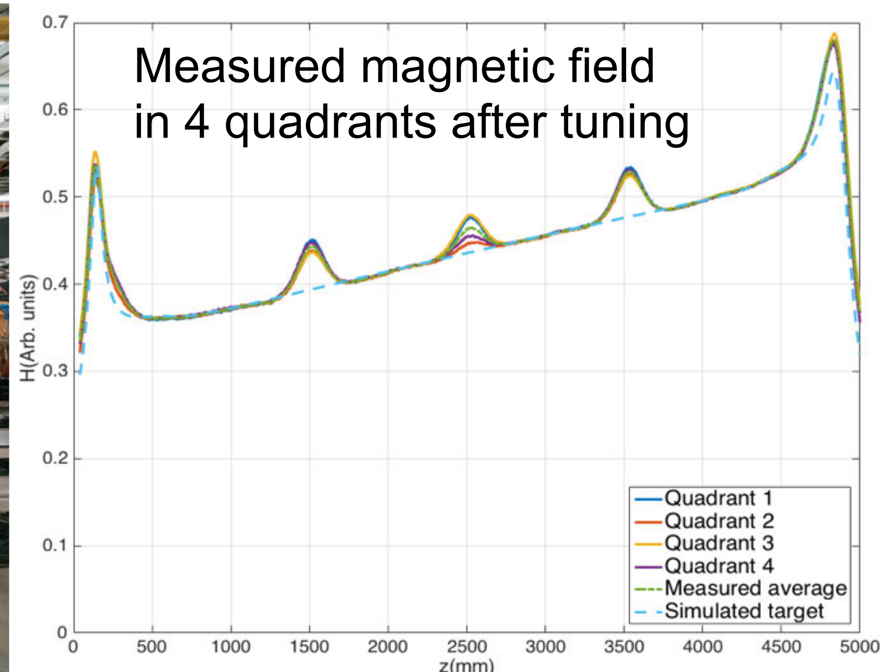




RFQ Installed and Tuned in FRIB Tunnel in Oct-Nov, 2016

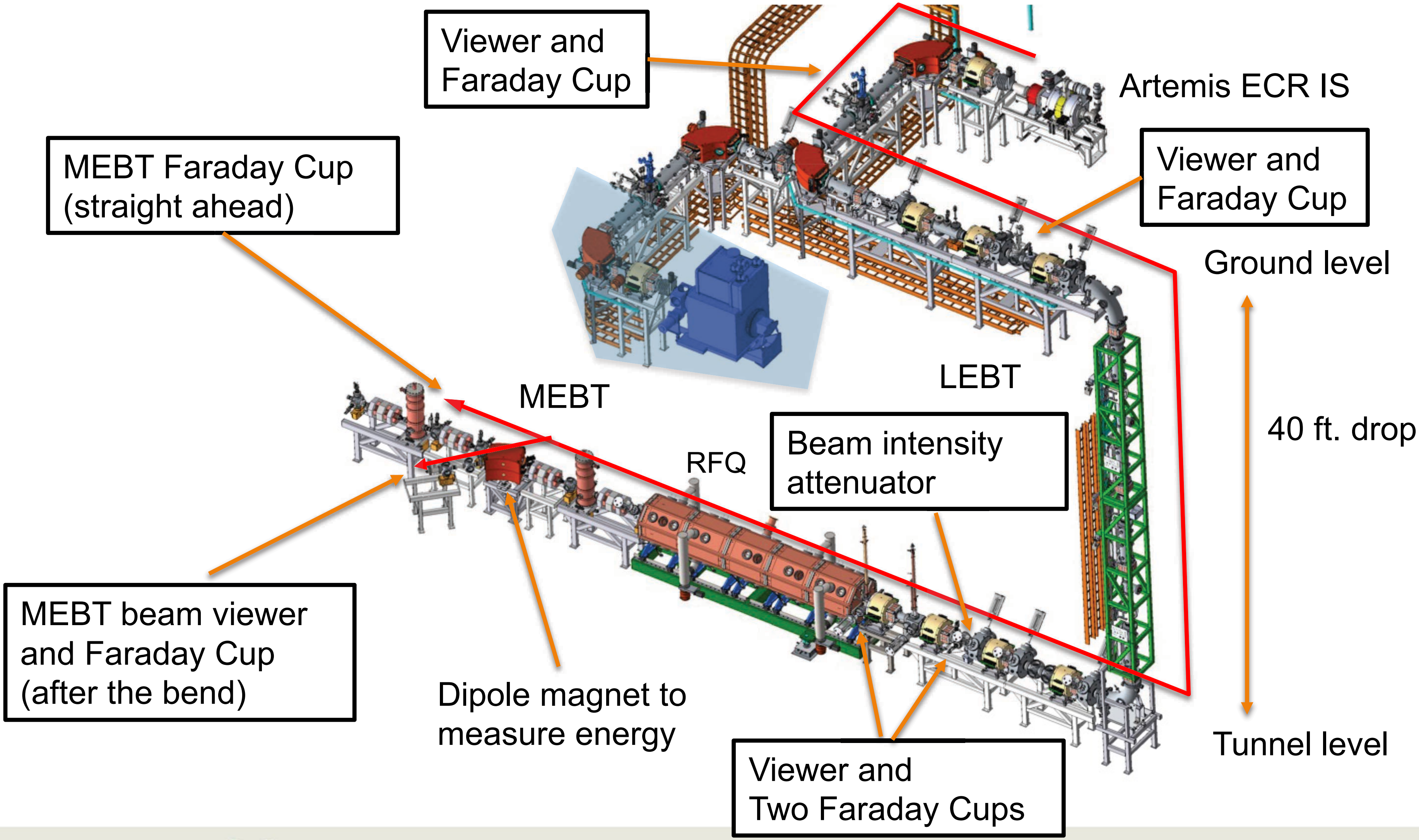


Parameter	Measured value
Q	14700
F_{accel} (MHz)	80.503 (under vacuum)
F_{dipole}(MHz)	77.797 / 82.888
F_{dipole_rod}(MHz)	83.207 / 76.325
Coupling β	1.2

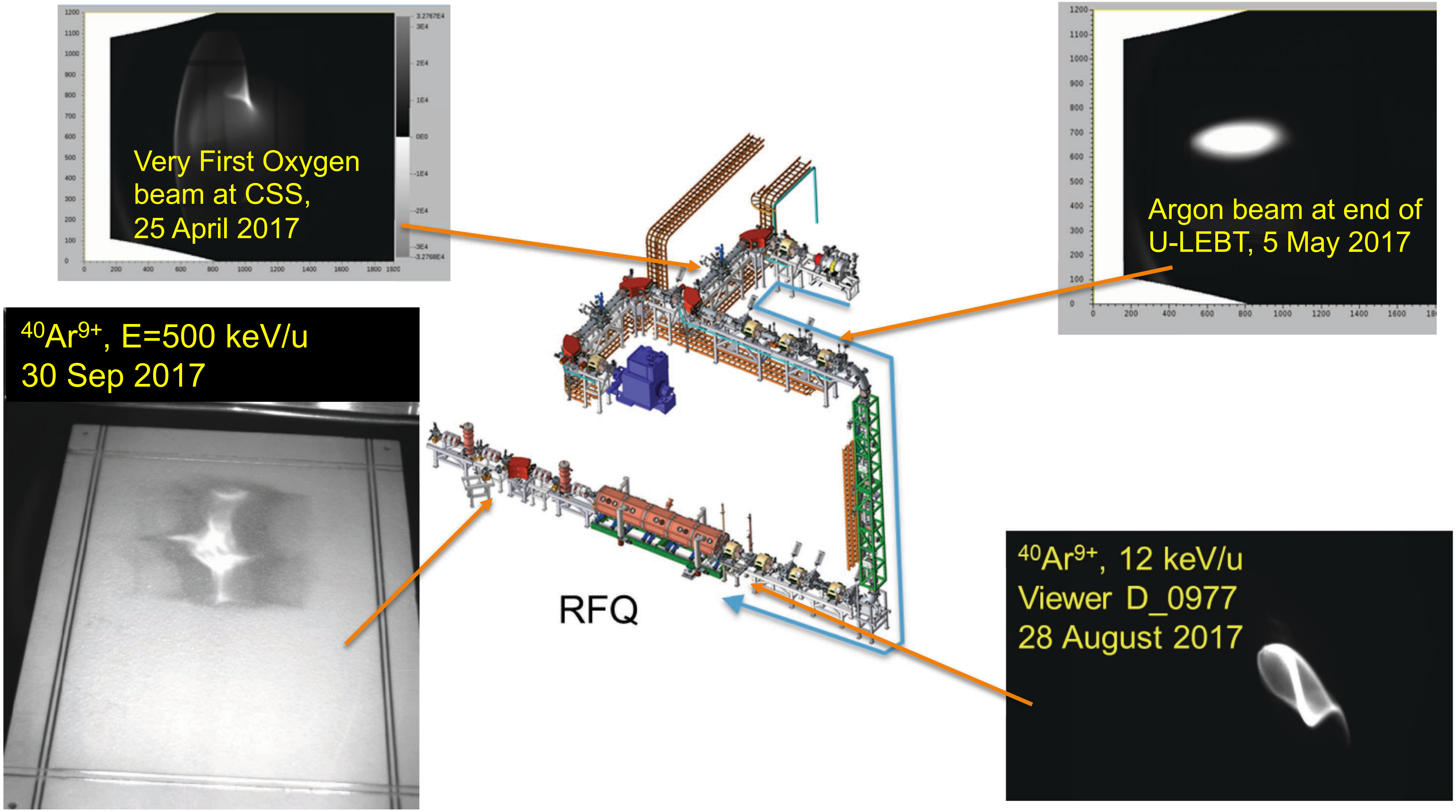


Front End Beam Line Construction Complete 7/2017

Simple Set Of Diagnostics Used for Commissioning Other Systems Were Brought Online Later

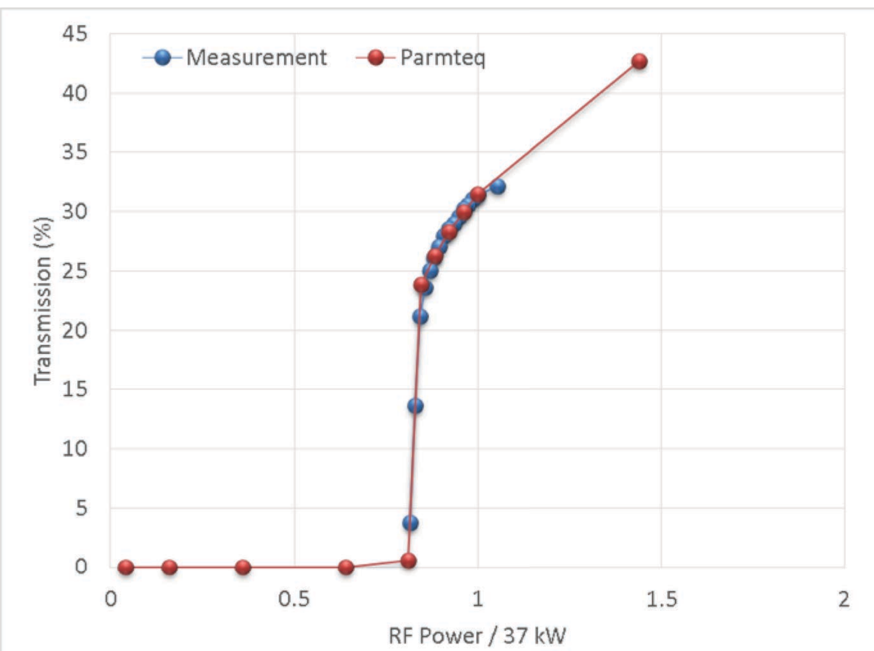


Front End Commissioned with Ar and Kr in 2017
Transmission Efficiency is 100% of Design



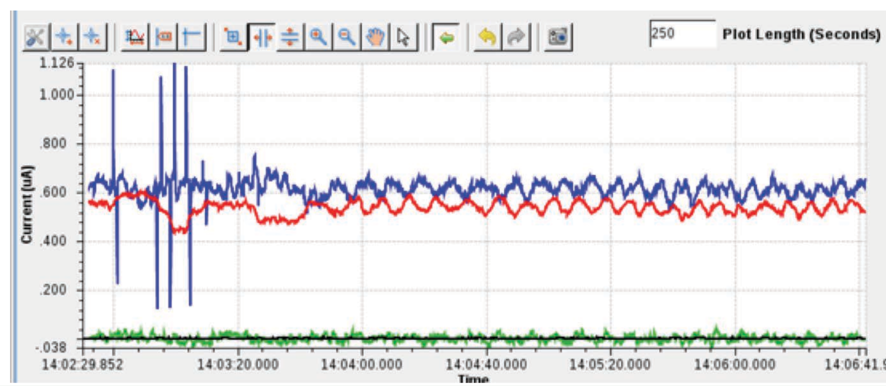
RFQ Commissioning Results
Without Multi-Harmonic Buncher

- RFQ does not have an internal buncher and accelerates DC beam with a lower efficiency. PARMTEQ predicts 31.5% of DC beam will be accelerated without MHB.
- Total transmission, including non-accelerated beam, reaches 100%.
  - Transmission of non-accelerated beam can be used to optimize beam matching



Measured and simulated accelerated current transmission though the RFQ as a function of the cavity RF power. The power is normalized on 37 kW.

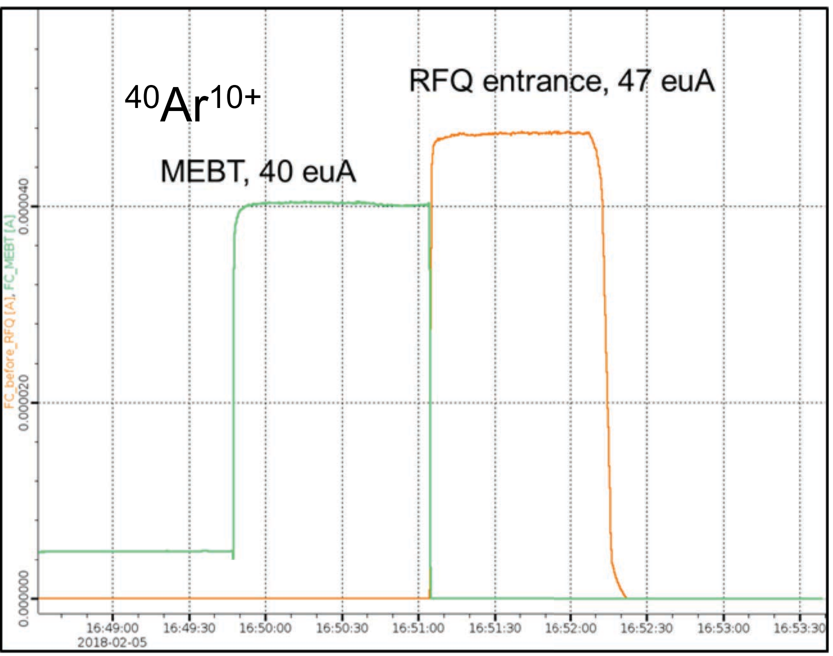
Total transmission, including non-accelerated beam, as measured by two ACCTs, one before and one after the RFQ.

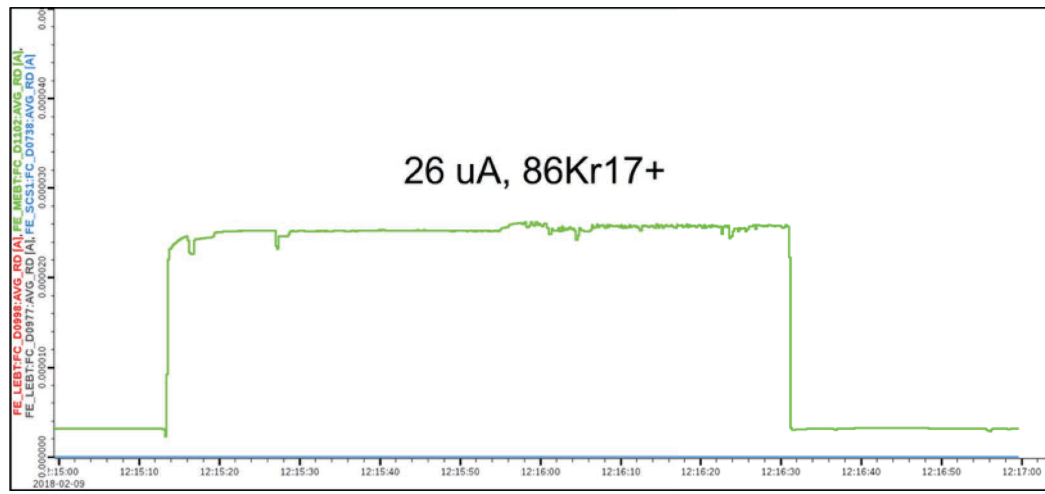


RFQ Commissioning Results

With Multi-Harmonic Buncher

- 40euA of $^{40}Ar^{10+}$ and 26euA of $^{86}Kr^{17+}$ were accelerated with MHB operational
- Achieved acceleration efficiency up to 86% vs. simulated 83%
  - Acceleration efficiency similar for Ar and Kr beams



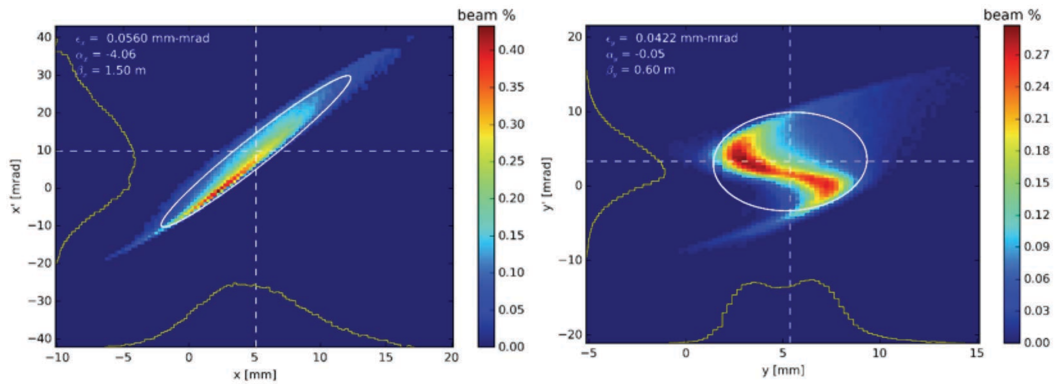


Measured Beam Parameters Are as Expected and Satisfy Requirements

- Beam emittance after ECR IS was measured using Alisson scanners, confirmed with a moving pinhole and a viewer setup (r.m.s. values):
  - ε_x : 0.056 mm.mrad
  - ε_y : 0.05 mm.mrad
  - (design value 0.1 mm.mrad at the entrance of RFQ)

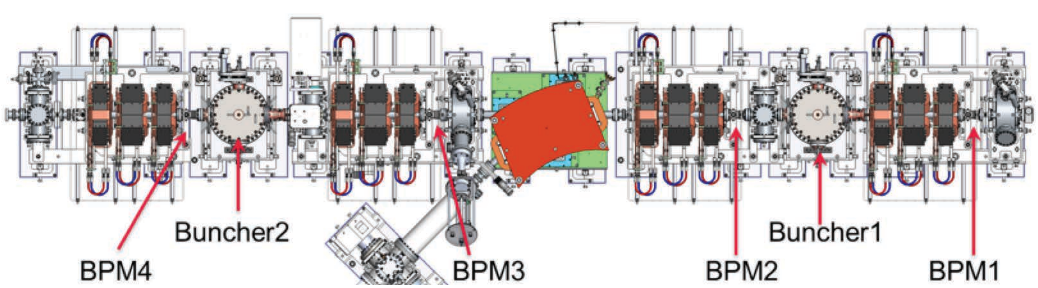
Alisson scanner measurements in LEBT
20 eμA $^{40}Ar^{9+}$

X-X' plane *Y-Y'* plane

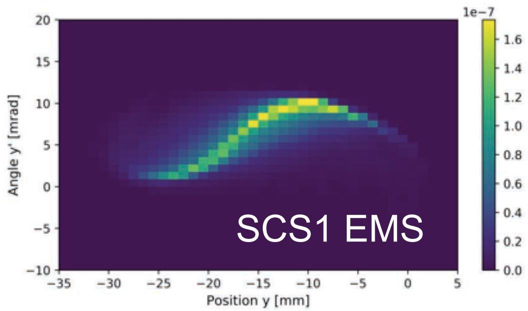


- Beam energy after RFQ measured in MEBT using a 45 deg. magnet and BPMs
  - 500 keV/u

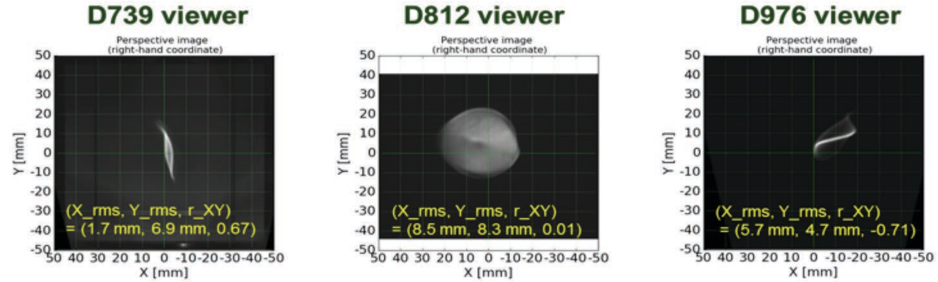
MEBT with BPMs and



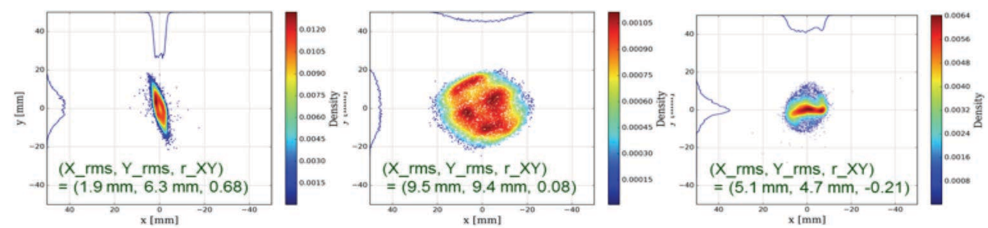
Beam Transport in Close Agreement with Simulations

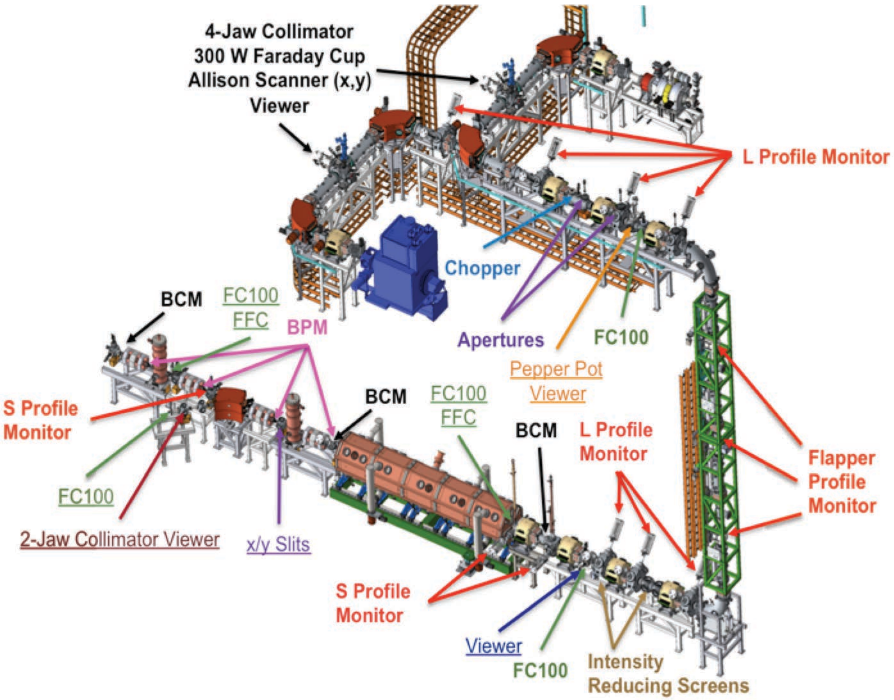


Measured

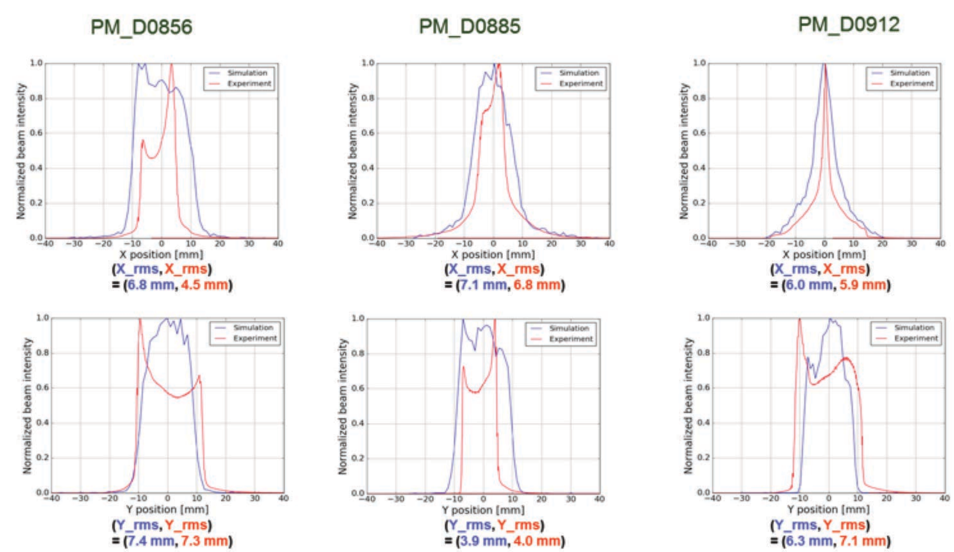


Simulated



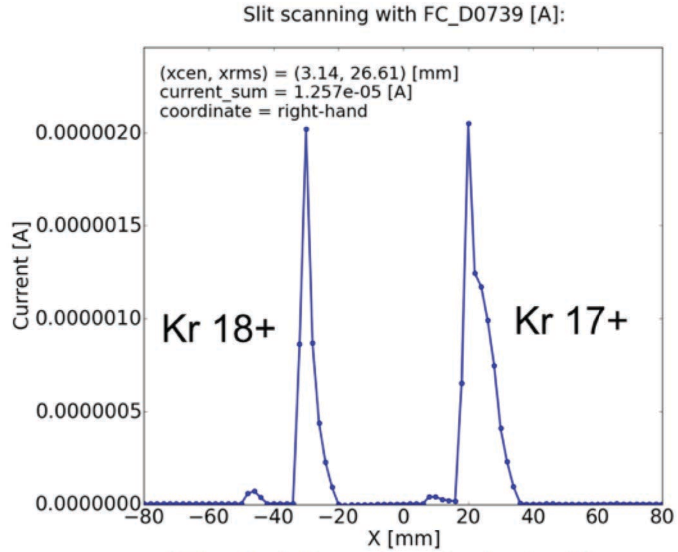


Wire Profile Monitor Measurements



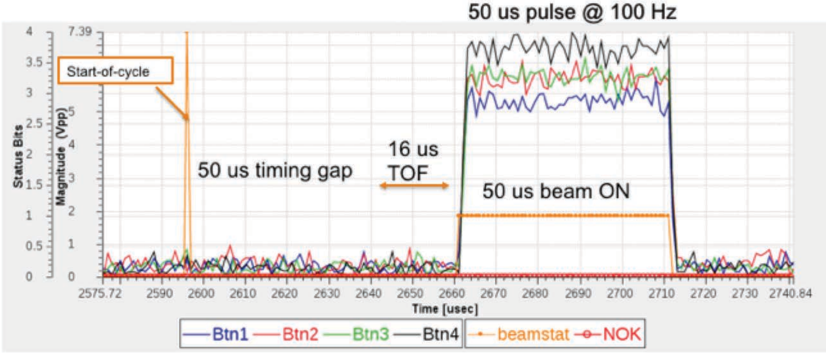
FE Operated for Eight Months Provided Valuable Experience

- FE has been operated for 8 months, showing stable performance of main hardware systems
- Accelerator Physics improves understanding of beam parameters and transport, develops and tests high level software and algorithms.
- Front End is used to commission diagnostics, instrumentation, and machine protection system (MPS)/run permit system (RPS)
- Opportunity to test and improve operational procedures



17+ & 18+ selected at slit

Chopper/GTS system test

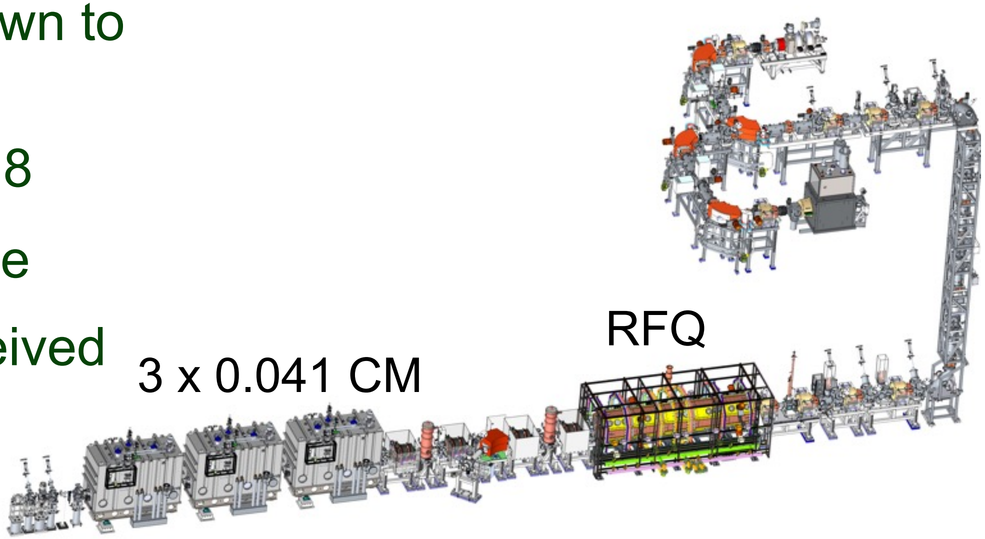


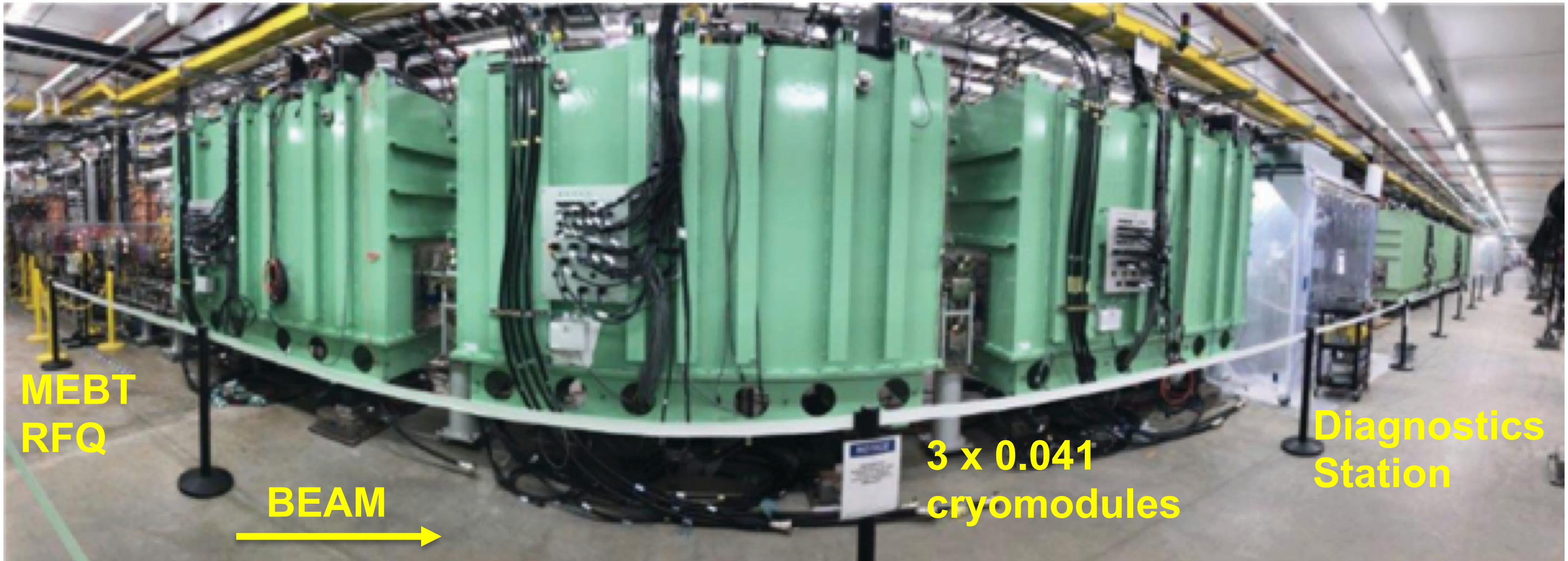
FE Commissioning Complete
Commissioning Goals Met

Goals for front-end commissioning	Status
Detect ^{36}Ar beam with the peak current of larger than 25 eμA at Faraday Cup before the vertical drop	Complete ~150 eμA of $^{40}Ar^{9+}$
Detect ^{86}Kr beam with the peak current of larger than 25 eμA at Faraday Cup before the vertical drop	Complete 38 eμA of $^{86}Kr^{17+}$
Confirm that chopper can produce pulsed beam with the pulse width of 50 μs and repetition rate of 1 Hz.	Complete
Accelerate ^{36}Ar beam to 0.5 MeV/u with the peak current of larger than 25 eμA at Faraday Cup in MEBT	Complete 40 eμA of $^{40}Ar^{9+}$ CW
Accelerate ^{86}Kr beam to 0.5 MeV/u with the peak current of larger than 25 eμA at Faraday Cup in MEBT	Complete 26 eμA of $^{86}Kr^{17+}$ CW

Three 0.041 Cryomodules and D-Station Installation Completed in 2018

- Cryomodules successfully cooled down to 4K in May 2018
- ARR02 was held on May 30–31, 2018
- Cavity conditioning completed in June
- Approval to start commissioning received on July 10th, 2018

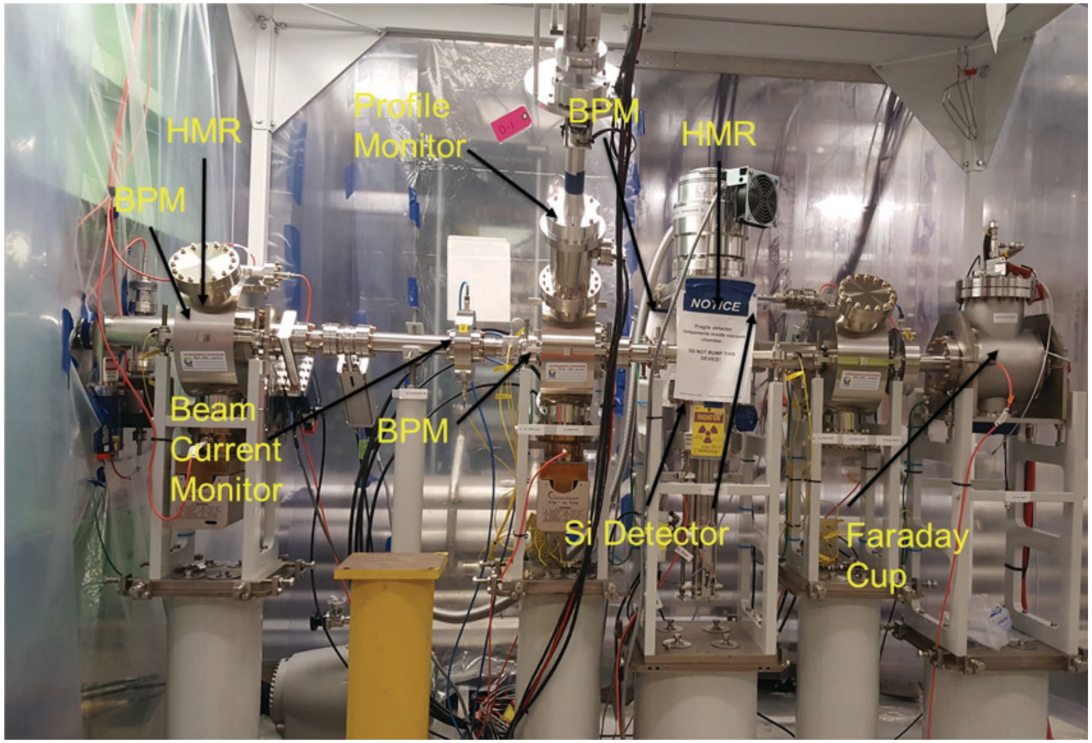


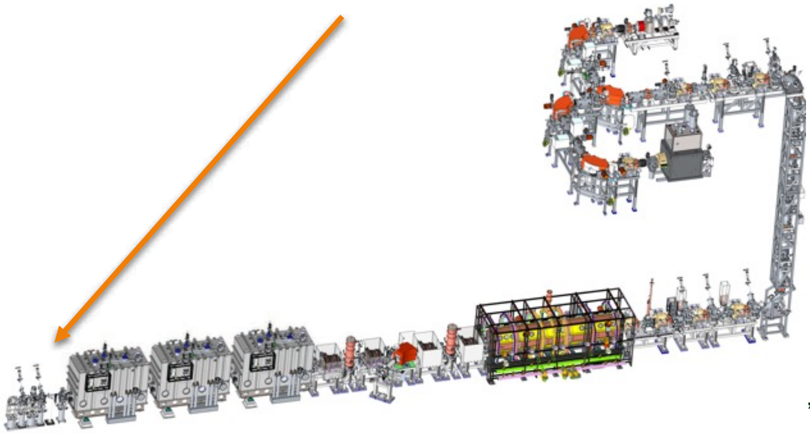


Beam Measurements with D-station

- Diagnostics station was temporarily installed to characterize beam after 0.041 CMs
  - First 0.085 cryomodule was temporarily set aside

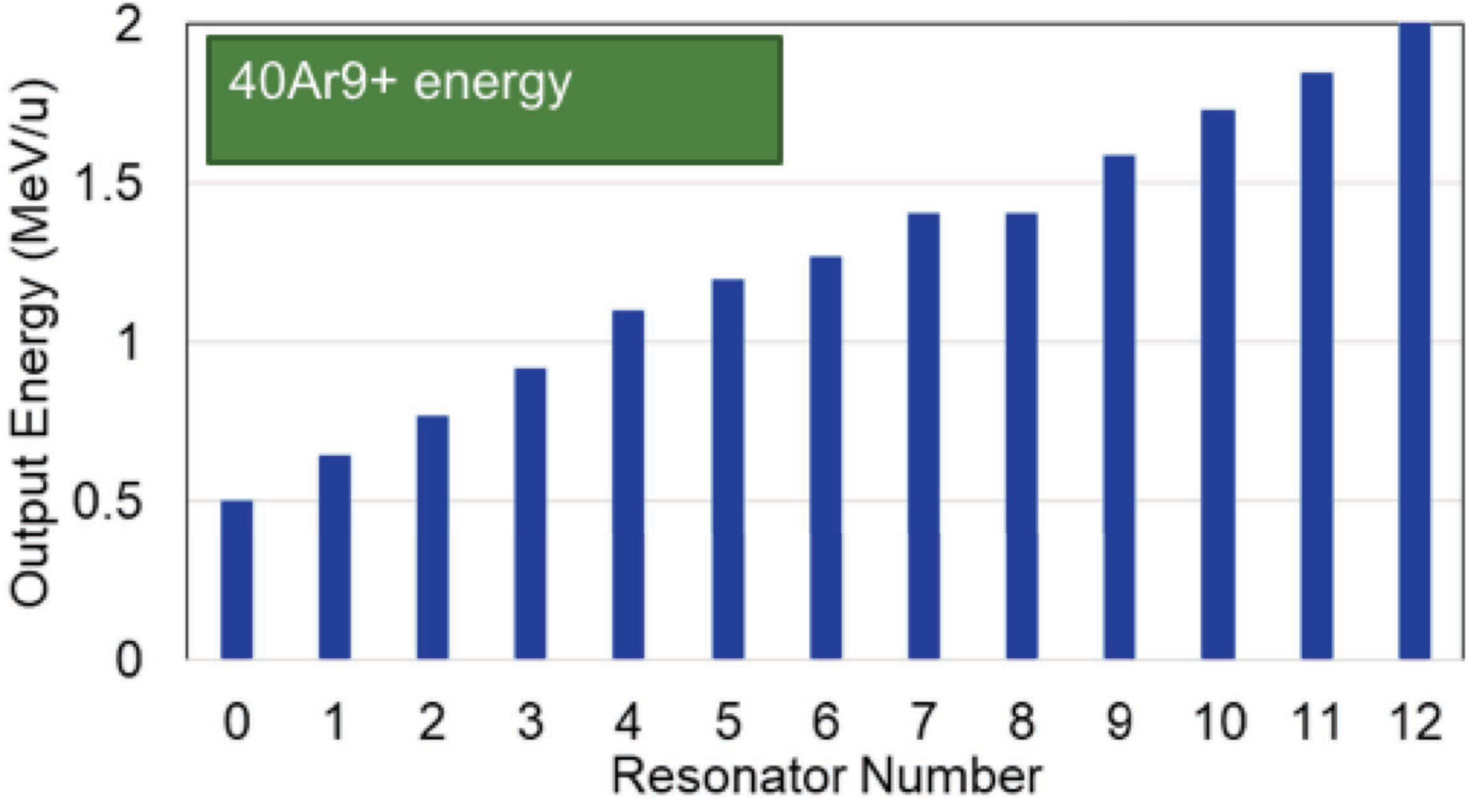
- Diagnostics to measure
  - Beam position and bunch phase
  - Transverse profile, rms emittance reconstruction
  - Absolute energy, energy spread, contaminant ions and their relative intensity
  - Beam halo signal
  - Absolute beam current (pulsed) and differential signal
  - Bunch longitudinal profile,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





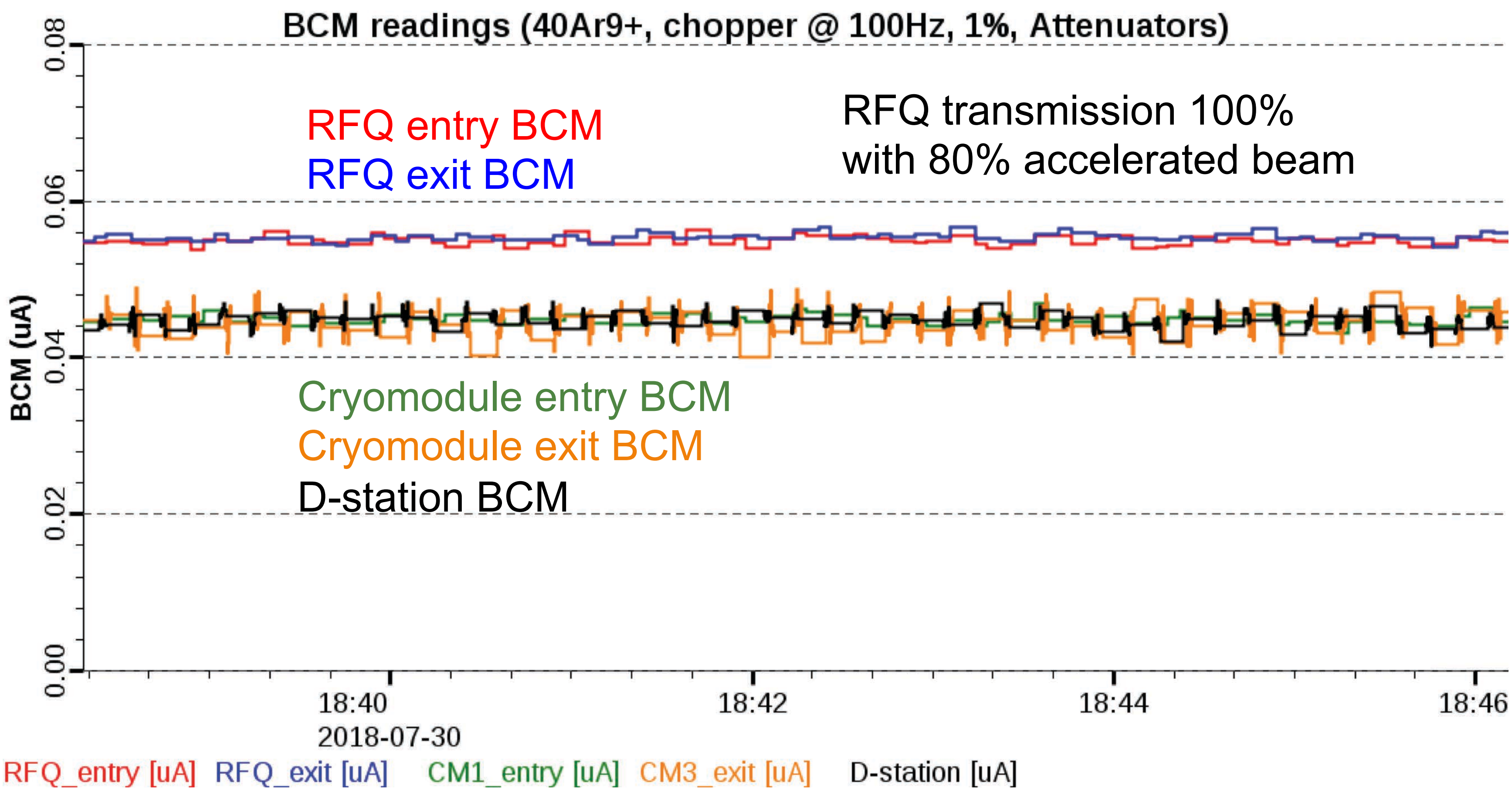
$^{40}Ar^{+9}$ CW Beam Accelerated to 2.3 MeV/u All 12 Cavities Run at ~ 5.1 MV/m

- First acceleration of argon beam in 0.041 SRF cavities
- Beam energy with 11 cavities is 2 MeV/u (cavities operated at 4.4 MV/m)
- Beam energy of Argon beam measured by BPMs
- Next day Kr beam was accelerated using same profile (voltage 5.1 MV/m)



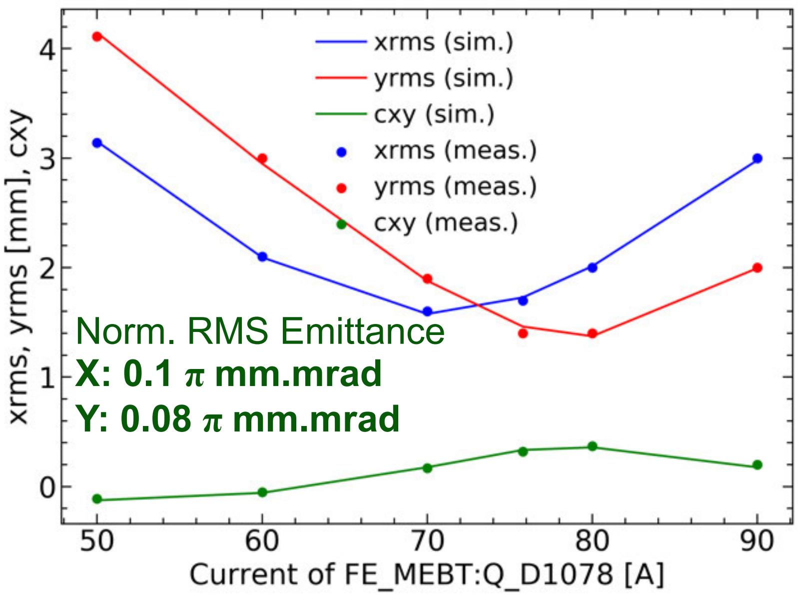
100% Beam Transmission through Cryomodules

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

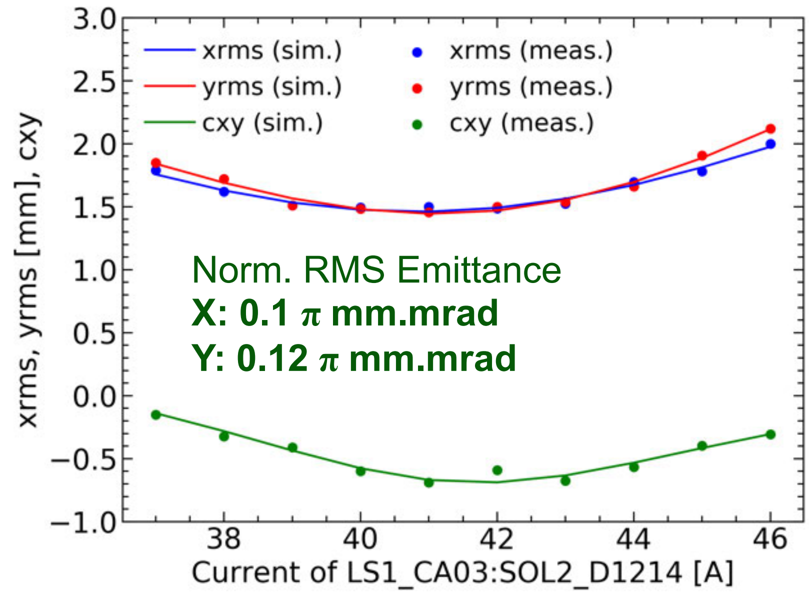


Beam Quality Maintained Between MEBT and Linac Solenoid Lattices

Quad scan in MEBT, 0.5 MeV/u

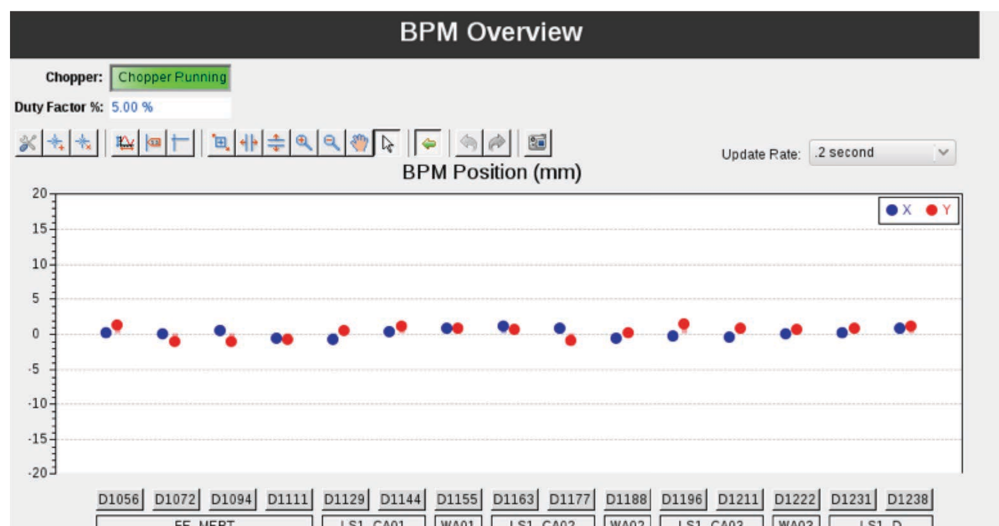


Solenoid scan in after



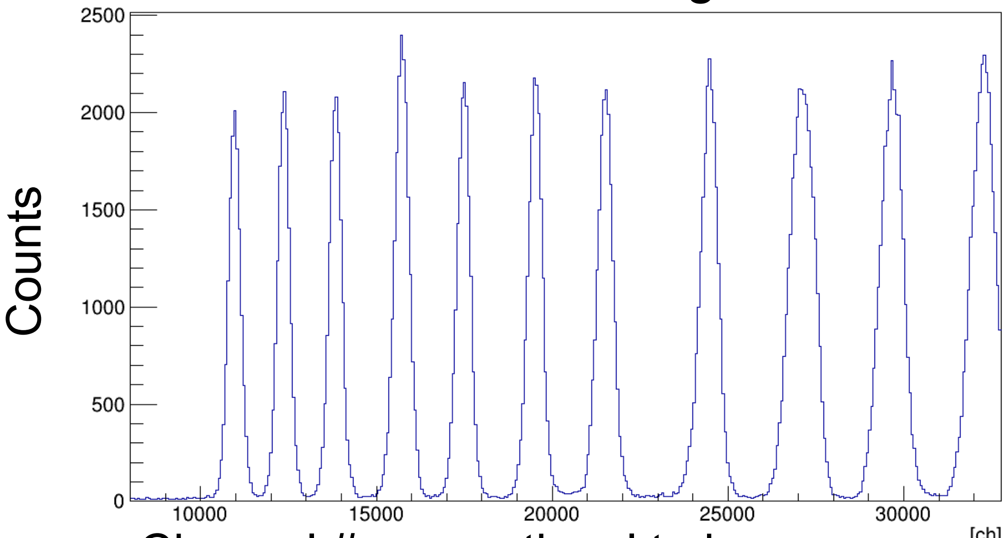
design value 0.1 mm.mrad

- Beam position is within ±2mm along the LS1
- Minimal beam center correction was required



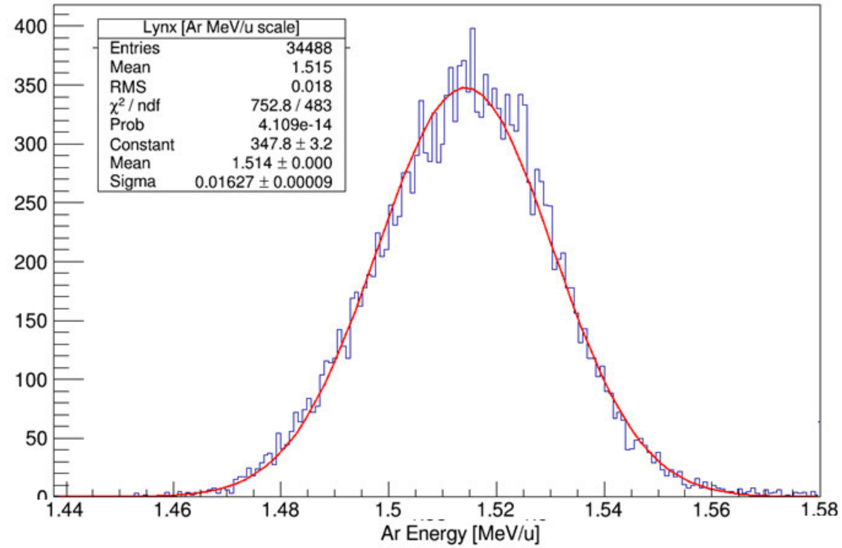
Beam Measurements with Silicon Detector

Absolute energies

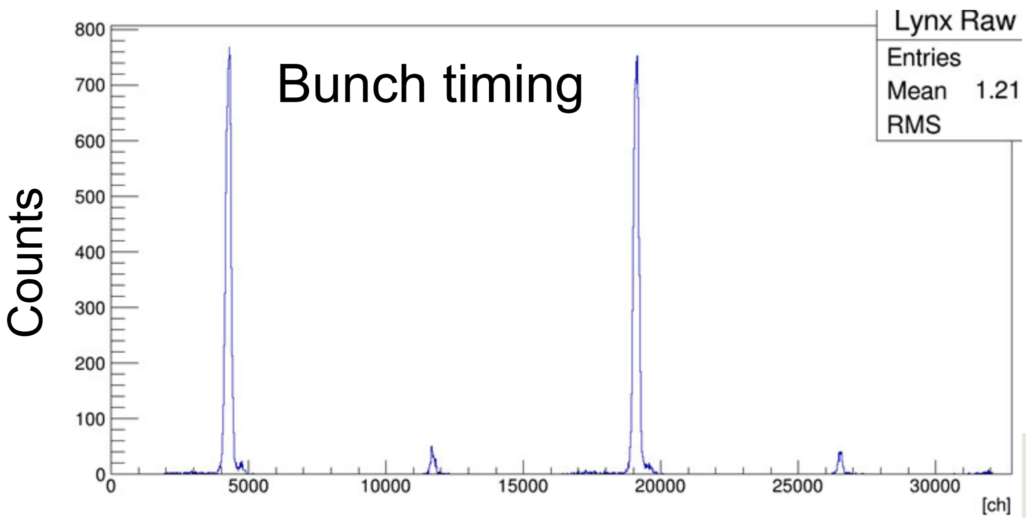


Channel #, proportional to beam energy

Energy spectrum

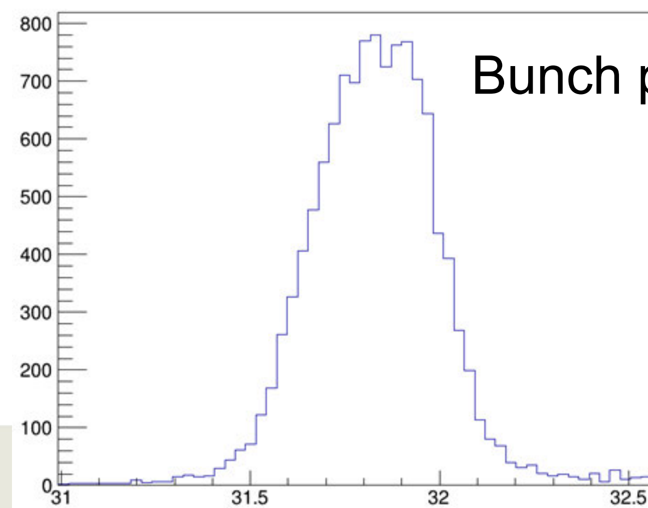


Bunch timing



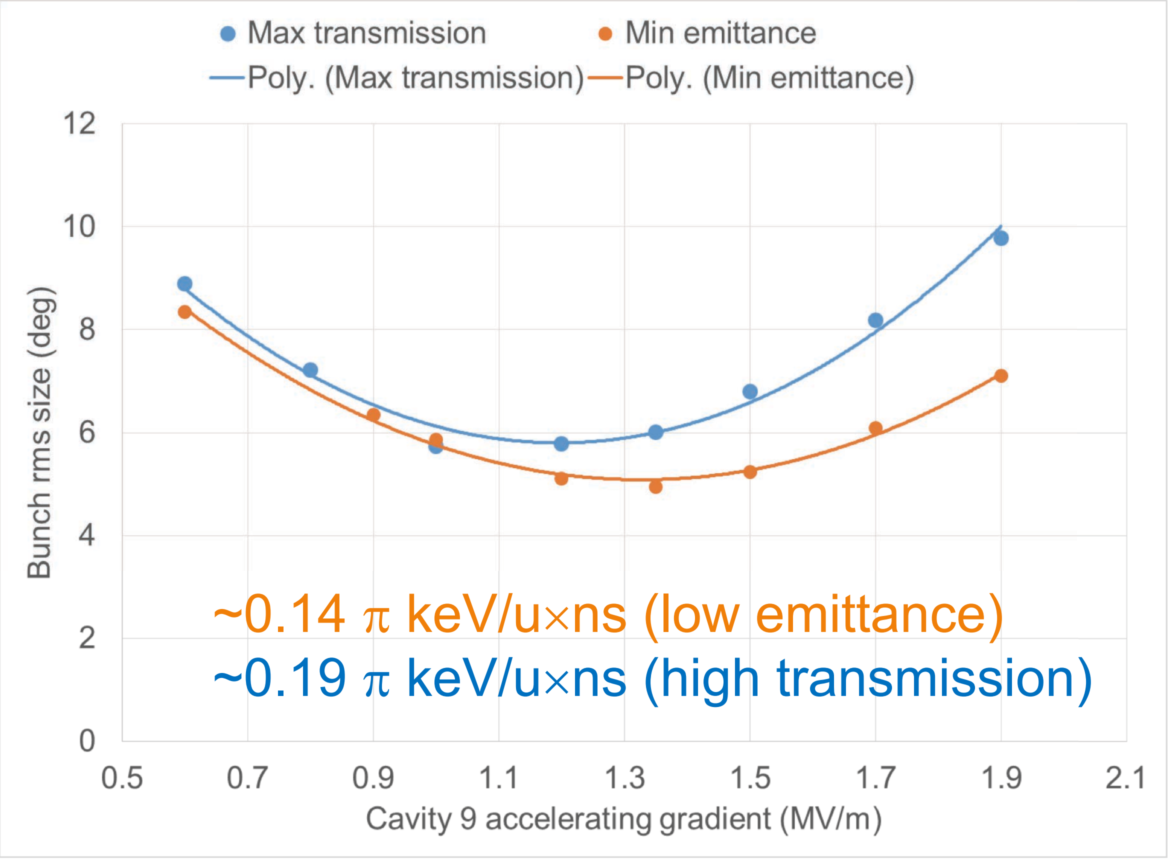
Channel #, proportional to bunch phase

Bunch profile



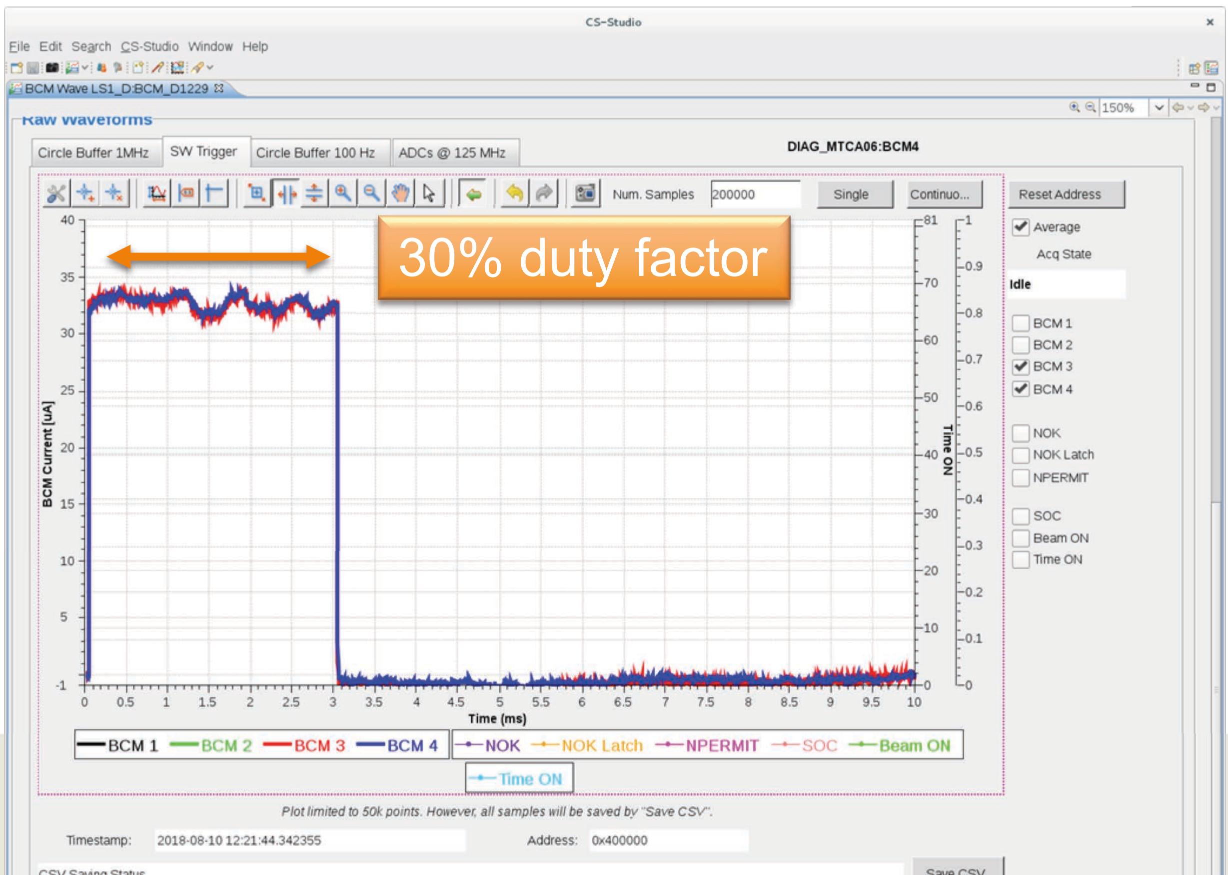
Longitudinal Emittance at D-Station Matches Simulations

- Longitudinal rms emittance is consistent with simulations
  - 0.14 π keV/u×ns (low emittance)
  - 0.19 π keV/u×ns (high transmission)
  - (Design value is 0.15 π keV/u×ns)
- MHB in LEBT can be set differently
  - Highest transmission
  - Lower transmission but smaller longitudinal emittance



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



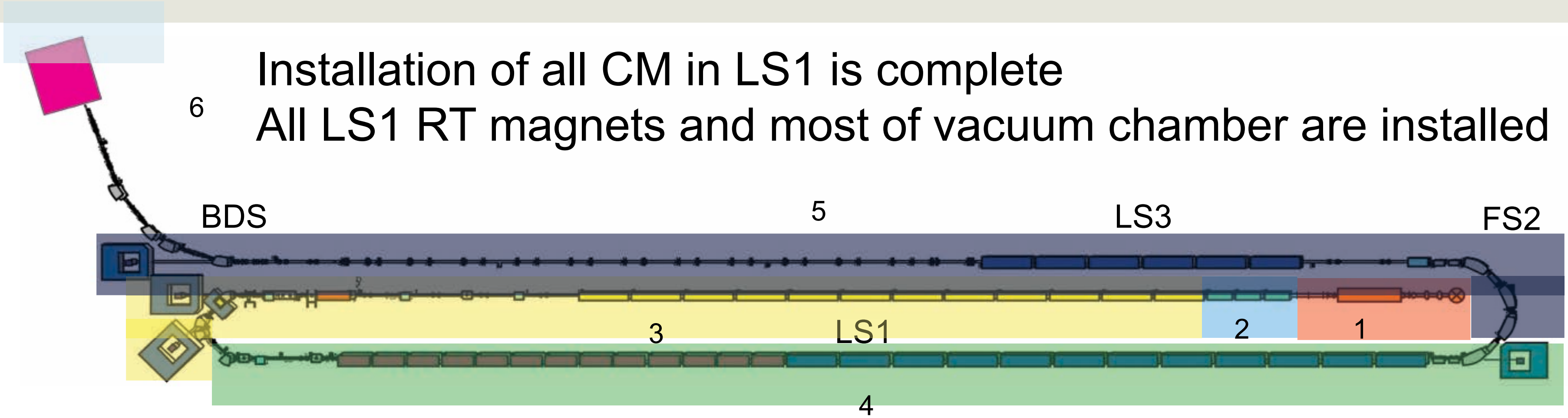
If further accelerated to linac exit, it would be ~38 kW on target with energy of 250 MeV/u as designed

First 3-Cryomodule Commissioning Complete Commissioning 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	✓
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. Measurements match simulated values.	✓
Verify Fast Machine Protection interlocks	Beam mitigated within 35 usec using Differential Beam Current Monitor	✓

Next Step is Commissioning of Complete LS1 FE + 0.041 CM + 0.085 CM

Installation of all CM in LS1 is complete
All LS1 RT magnets and most of vacuum chamber are installed



ARR	Area with beam	Date
1	**Ion Source, Low Energy Beam Transport, RFQ, Medium Energy Beam Transport**	**Commissioned, 09/2017**
2	**Linac Segment (LS) 1 (β=0.041 cryomodules)**	**Commissioned, 07/2018**
3	Remainder of LS1 and first 45 degree dipole of FS 1	02/2019
4	Remainder of FS1, LS2	04/2020
5	FS2, LS3	09/2020
6	Beam Delivery System, Target, Pre-Separator in Target Hall	TBD
Final	Prior post-start items, Pre-Separator outside Target Hall, reconfigured A1900, entire facility	Before 06/2022

Summary

- FRIB Front-End and First Three-Cryomodules have been successfully commissioned with $^{40}Ar^{9+}$ and $^{86}Kr^{17+}$
- Beam energy of 2.3 MeV/u reliably demonstrated, exceeds required 1.5 MeV/u
- Beam properties are consistent with simulations, satisfy requirements
- All accelerator components operate reliably and as expected
- Diagnostics and MPS/RPS verified
- Commissioning of the rest of LS1 linac systems on track for successful completion
  - All LS1 cryomodules installed and are being cooled down
  - Superconducting resonators to be conditioned this Fall
  - All magnets and most diagnostics installed
- FRIB commissioning proceeds according to the established plan and schedule

Thank you!

Peter took the picture, lead 0.041 CM commissioning