MOZGBF1
FRIB Front End Construction and Commissioning

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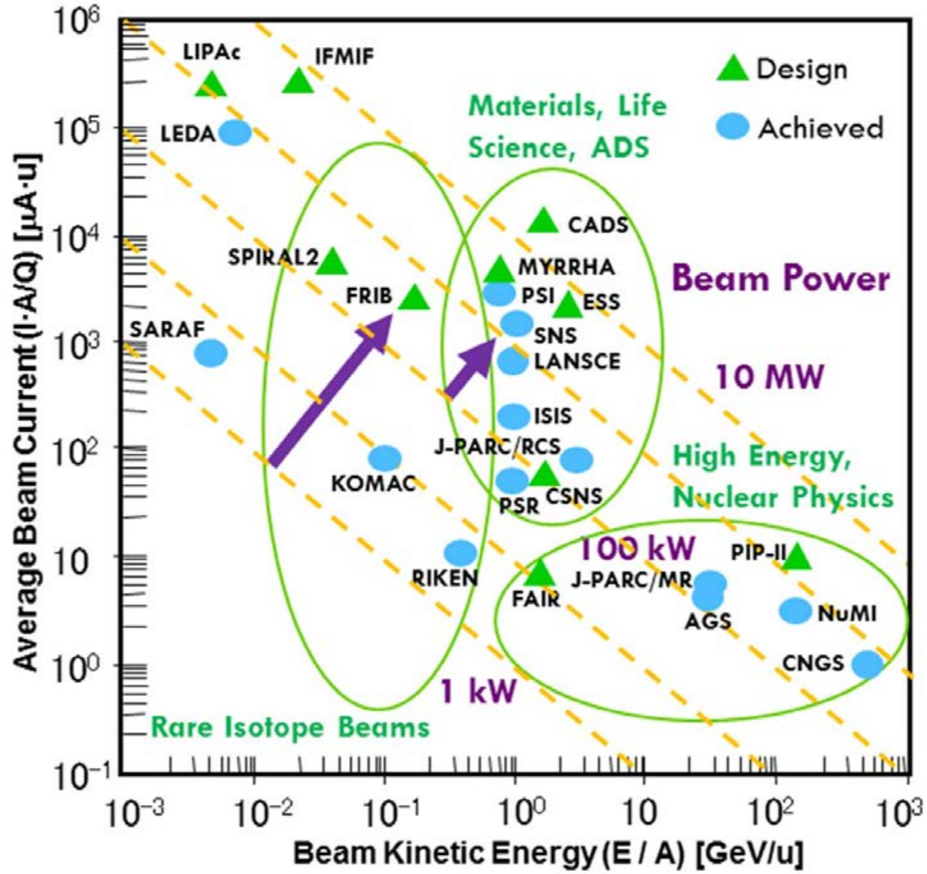
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support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

Outline

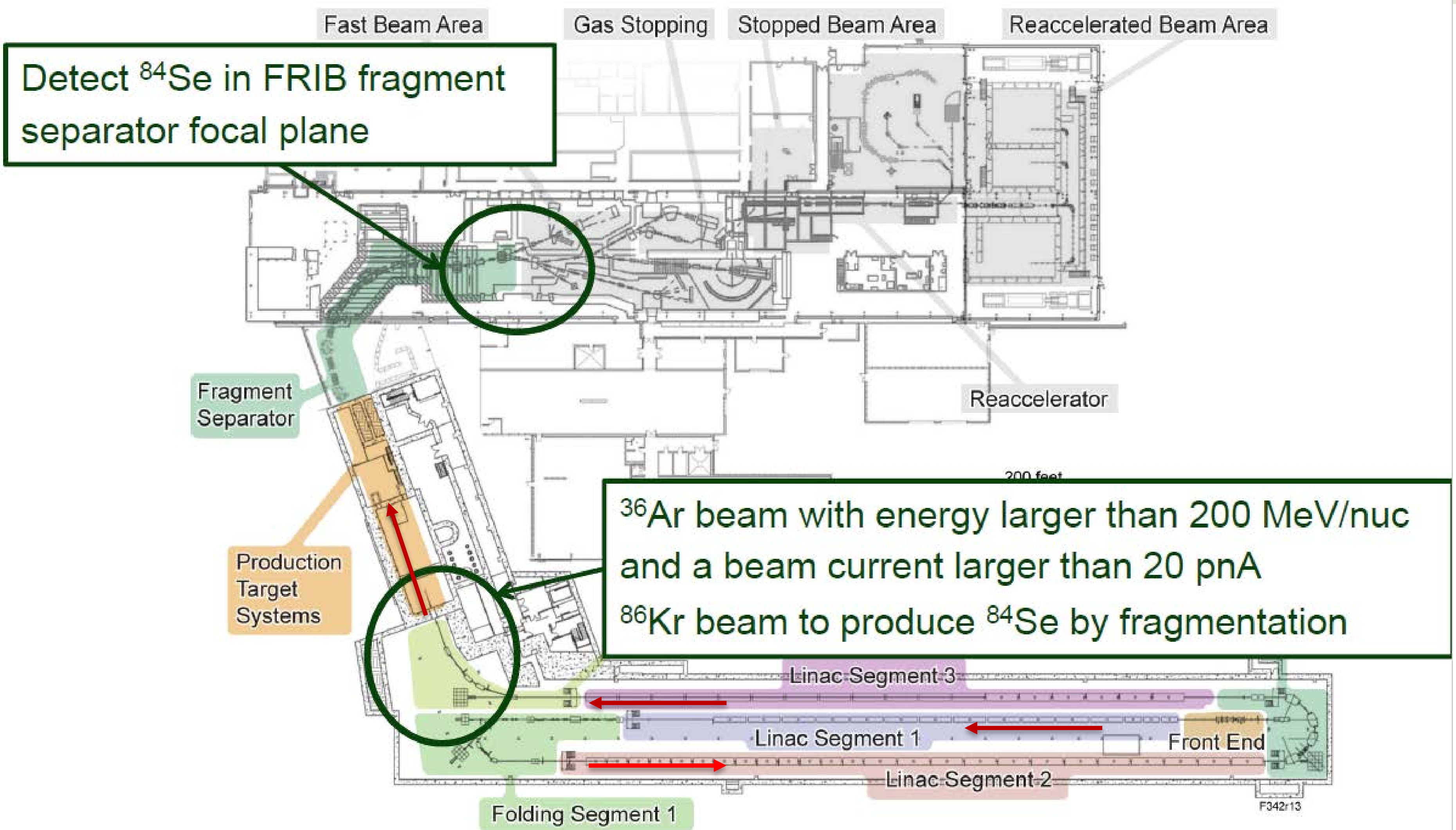
- Introduction
- Technical system highlights
- Authorization of integrated testing and commissioning
- Commissioning results
- Front End schedule
- Path forward with SRF linac commissioning and transition to Operations
- Summary

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

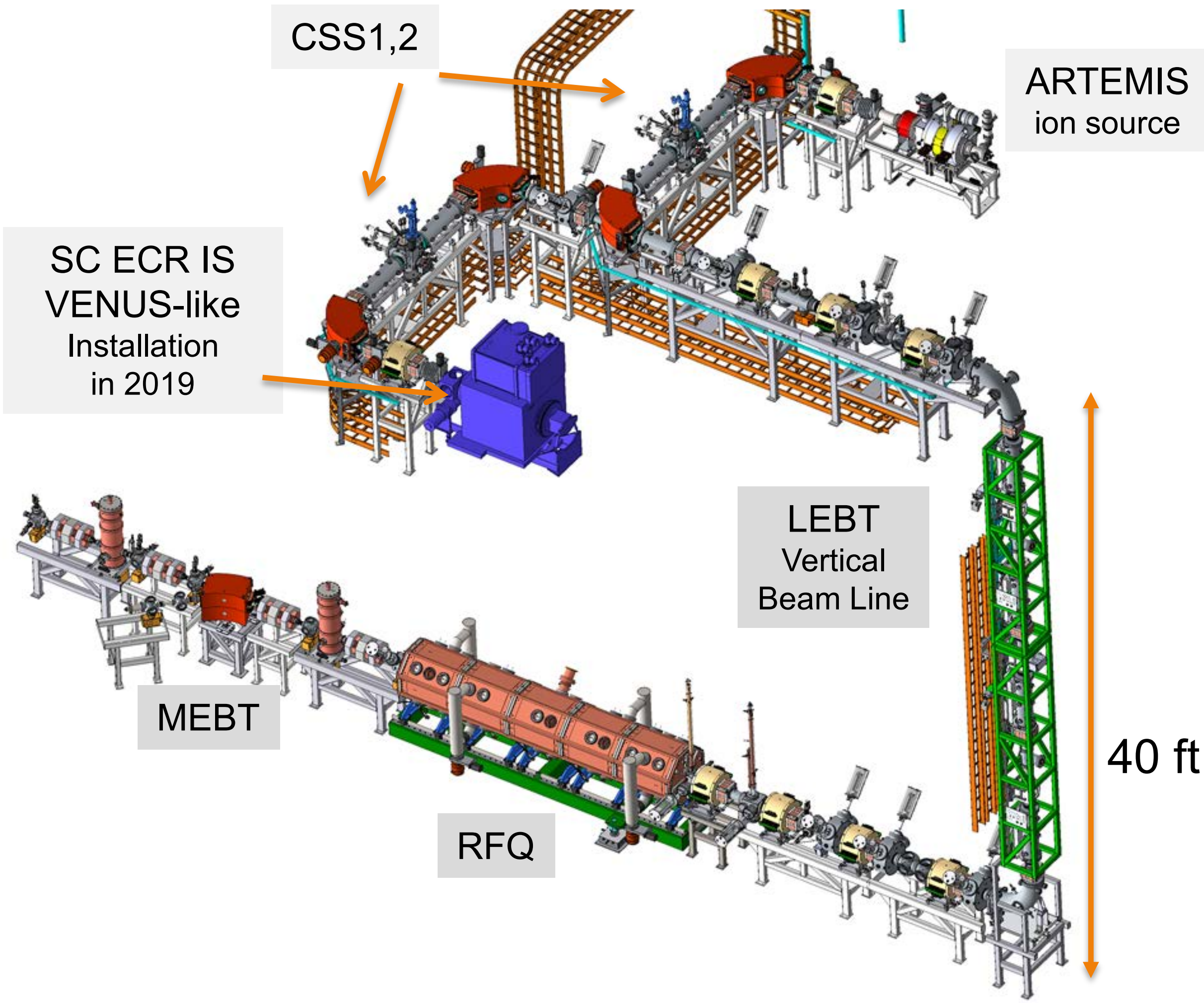


Commissioning Performance Requirements Defined by Key Performance Parameters (KPP) for CD-4



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.



Front End Performance Goals and Key Performance Parameters

Parameter	KPP/Commissioning	Operations
Ion species	Ar, ^{86}Kr	O - U
Beam intensity (eμA, typical)	5 - 25	350
Beam energy LEBT/MEBT (keV/u)	12 / 500	12 / 500
Beam power LEBT/MEBT, 25 euA (W)	1 / 50	50 / 1500

KPP beams are Ar and ^{86}Kr

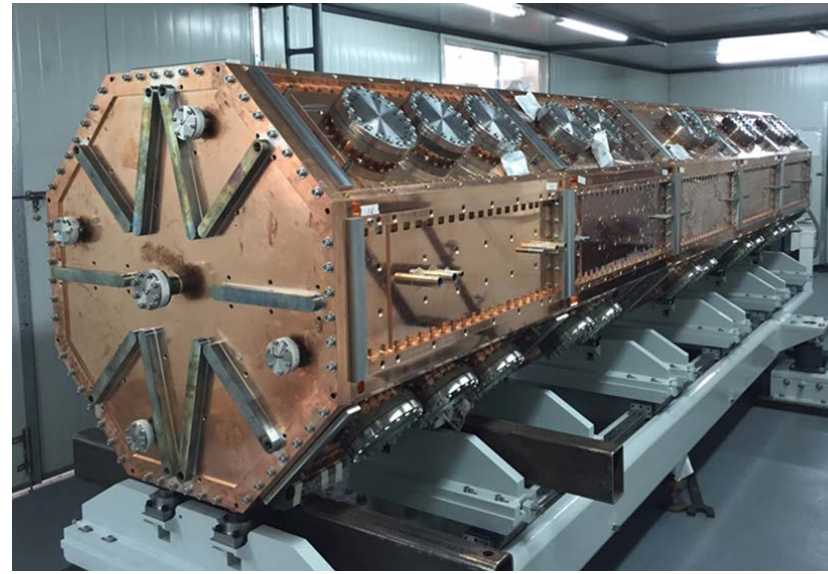
High priority beams for first two years of Operations defined:

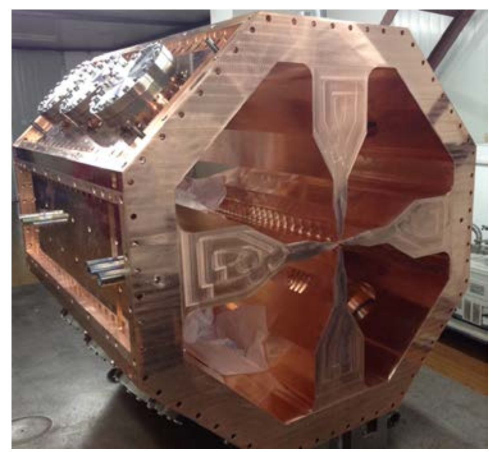
FY22 - ^{238}U, ^{48}Ca, ^{78}Kr, ^{124}Xe, ^{18}O, ^{86}Kr, ^{16}O, ^{36}Ar, ^{82}Se – 24 weeks
FY23 – (in addition to FY22) ^{92}MO, ^{58}Ni, ^{22}Ne, ^{64}Ni

RFQ Construction Completed in June 2016

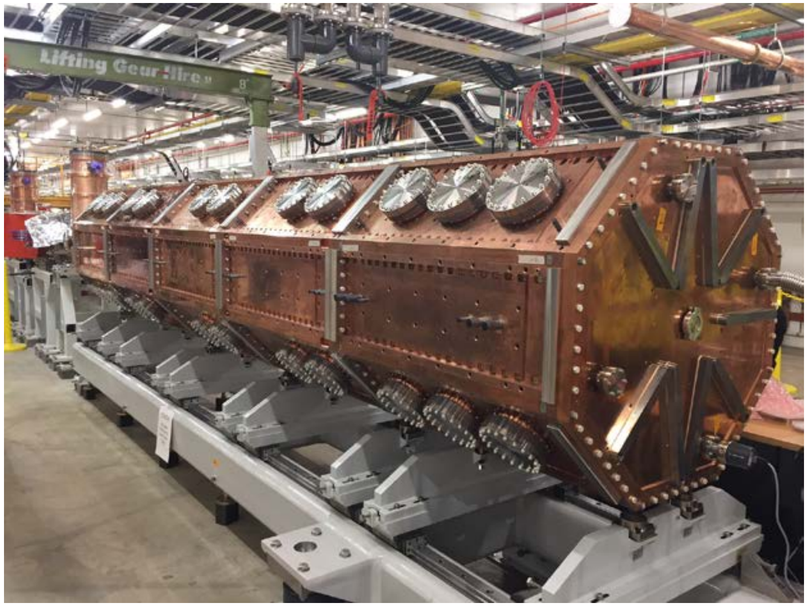
Parameter	Value
Frequency (MHz)	80.5
Injection/extraction energy (keV/u)	12 / 500
Q/A	1/3 – 1/7
Transmission efficiency (typ.)	> 80%
CW RF Power (kW), Uranium	100
Length (m)	5

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



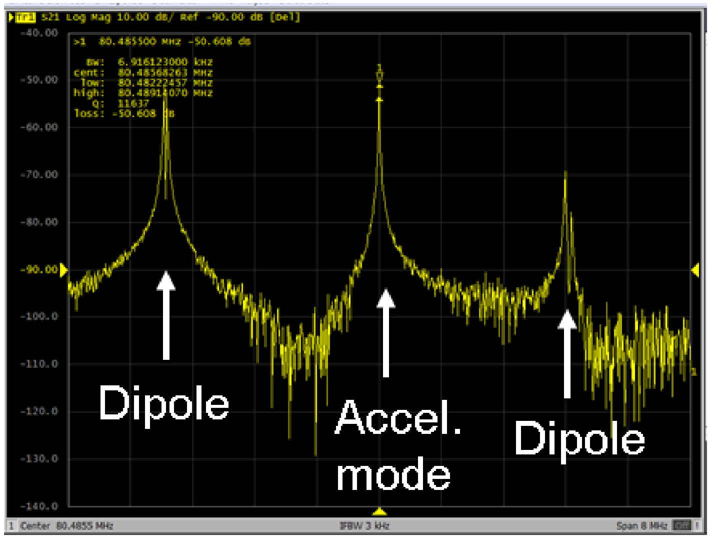


RFQ Delivered and Installed in FRIB Tunnel in Oct-Nov, 2016



RFQ Tuned with Low Power in November 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



- RFQ tuned with low power in November 2016. The slug tuners were cut at FRIB to match the required frequency and the voltage profile (in all four quadrants). The frequency correction for the effect of vacuum was implemented

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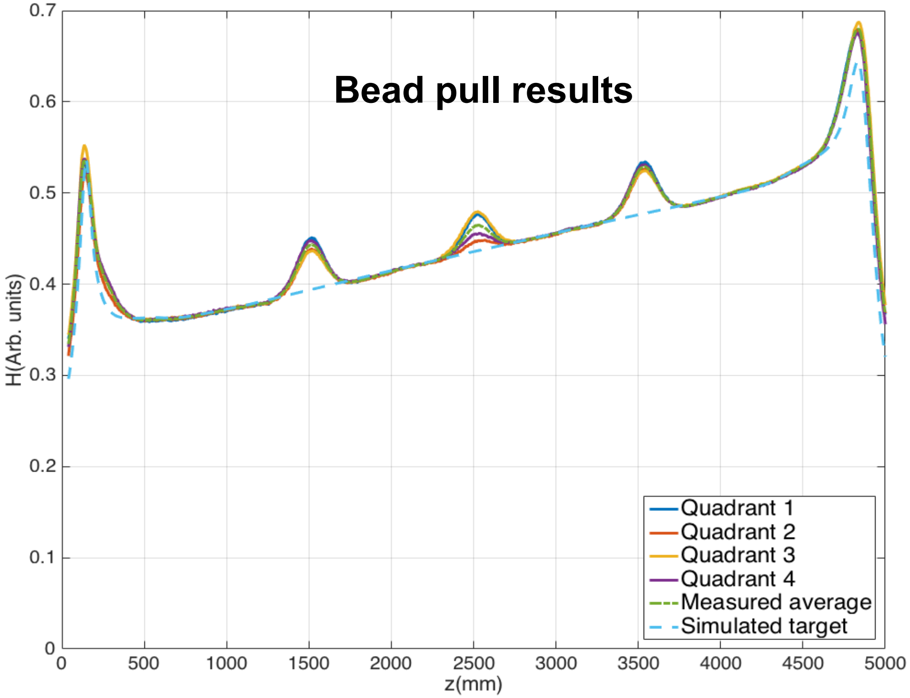
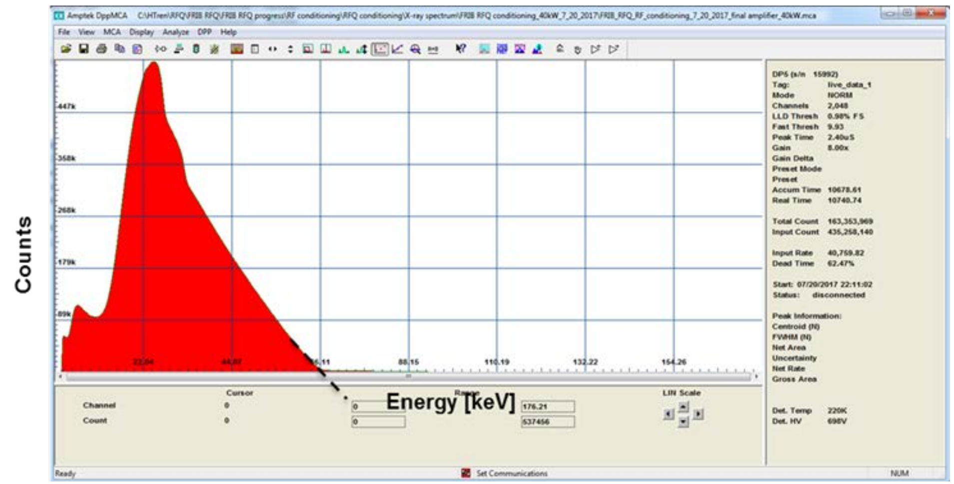


RFQ Integrated Test Completed in 08/2017
RFQ Performs as Expected

- RFQ has been conditioned to 60 kW, sufficient to accelerate KPP beams
  - RF power was limited to allow RFQ operations with personnel present in the tunnel
- Thermal behavior is as predicted
- Vane voltage calibrated by measuring X-ray spectra
- Vacuum
  - No RF power: ~1e-8 Torr
  - Operational: ~2-3e-8 Torr
- RFQ Behaves As Expected

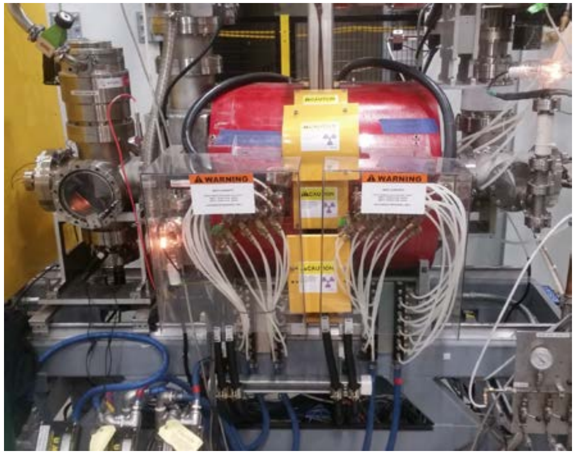
	CST Simulations	ANSYS simulations	Measurement
	[kHz/degC]	[kHz/degC]	[kHz/degC]
(dF/dT)_V	-8.73	-9.5	-8.2
(dF/dT)_W	6.92	7.0	7.0
(dF/dT)_V&W	-1.85	-2.5	-1.39



14 GHz ECR Ion Source ARTEMIS Used To Commission FRIB

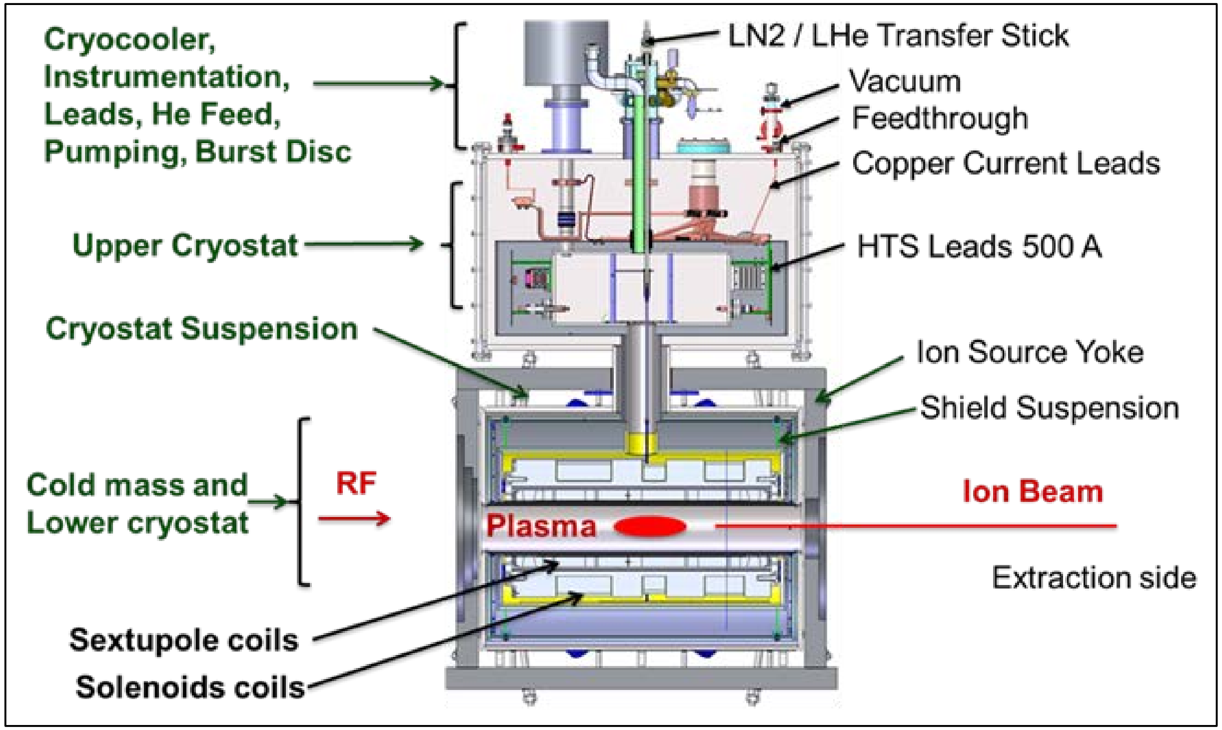
- ARTEMIS based on AECR-U design (LBNL) – 2 copies built at NSCL (1999, 2005)
  - Low risk- extensive experience at NSCL with ARTEMIS operation and maintenance
- Performance meets intensity requirement for commissioning and 1st year of operation
  - Demonstrated 40Ar10+ current is ~150 eμA
  - Demonstrated 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



SC ECR Ion Source is Under Development Completion Expected in 2019

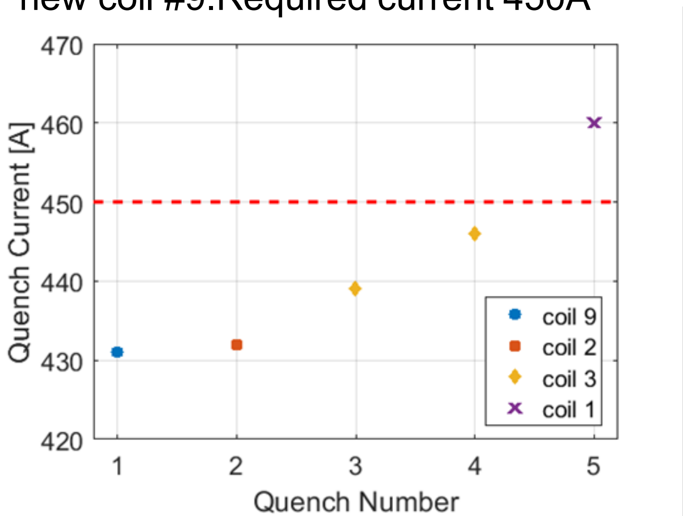
- FRIB develops 28 GHz SC ECR Ion Source in collaboration with Berkeley
  - Magnet developed by Berkeley
  - Cryostat and conventional components developed by MSU
- Parameters are similar to those of VENUS ECR but mechanical design was modified based on experience with LARP magnets
  - Key – bladder design is used to preload the structure



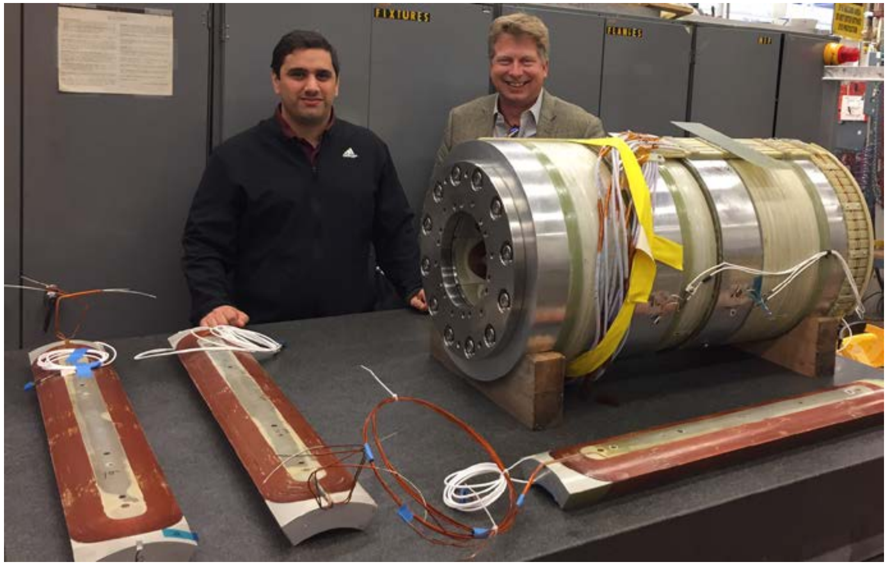
SC ECR Magnet Completed at Berkeley Met Performance Requirements

Charge 1

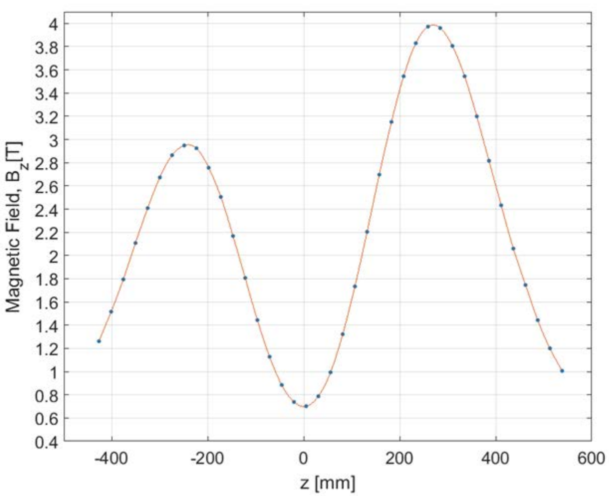
Quenches of sextupole magnet with new coil #9.Required current 450A



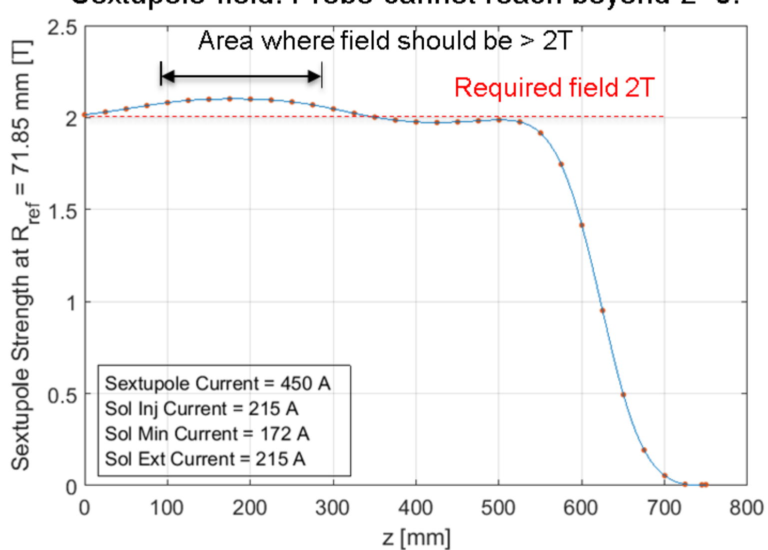
SC FRIB ECR magnet before shipping in Dec 2017



Measured solenoid magnetic field. Required fields 3 T at extraction and 4T at injection

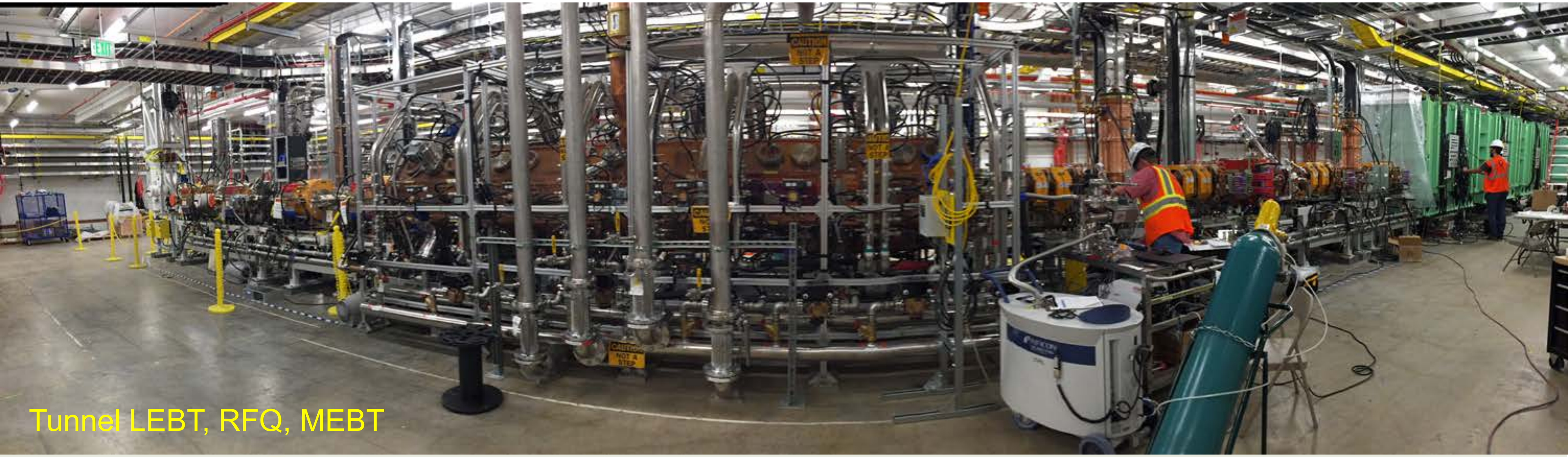


Sextupole field. Probe cannot reach beyond z<0.



Beam Line Construction Complete in 7/2017

- Run one source while the second source is maintain: two ion sources on ground level
- Transport two-charge-states simultaneously
- Collimate beam halo
- Beam chopping to control average intensity and provide a beam gap for diagnostics calibration

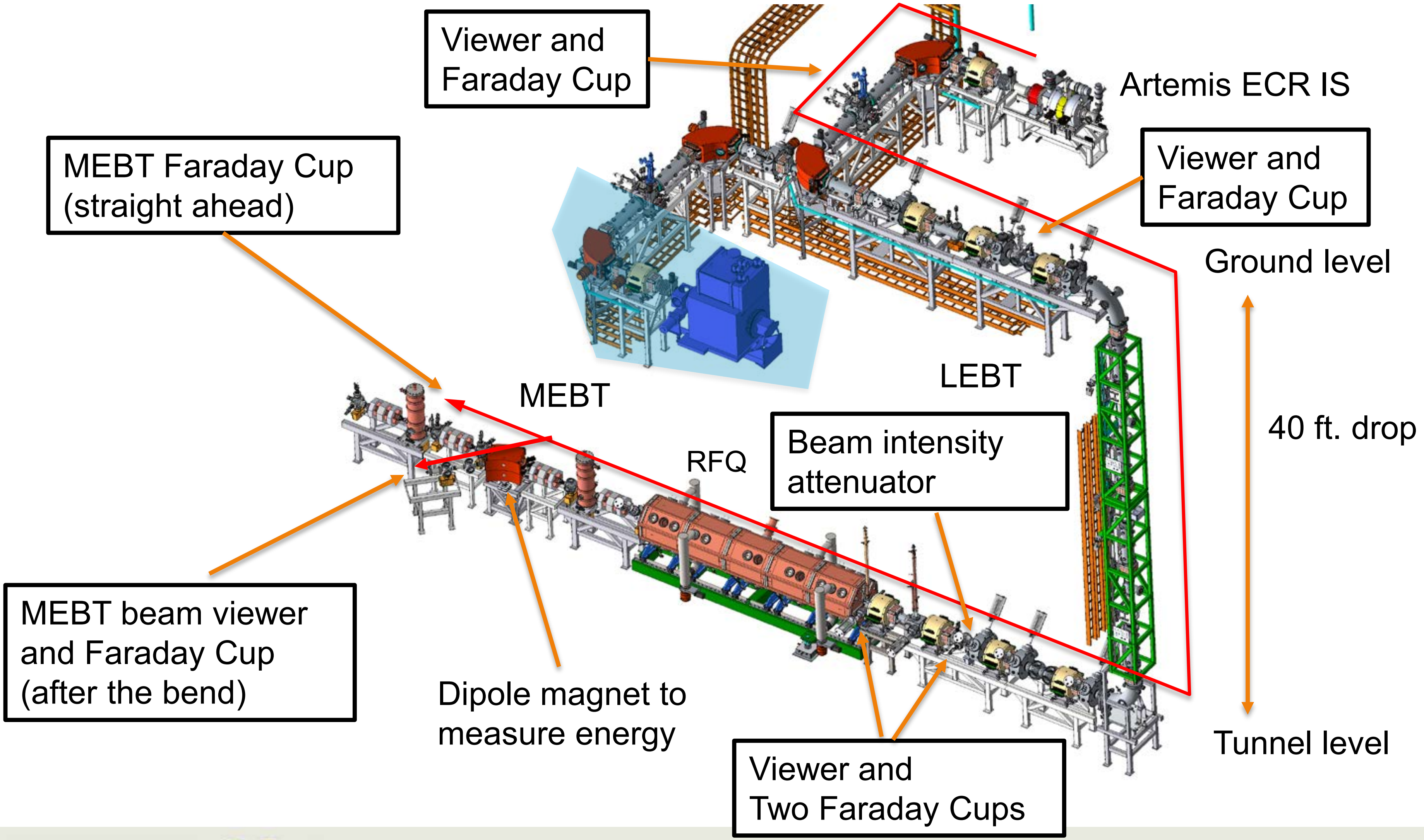


Accelerator Startup Authorization Process

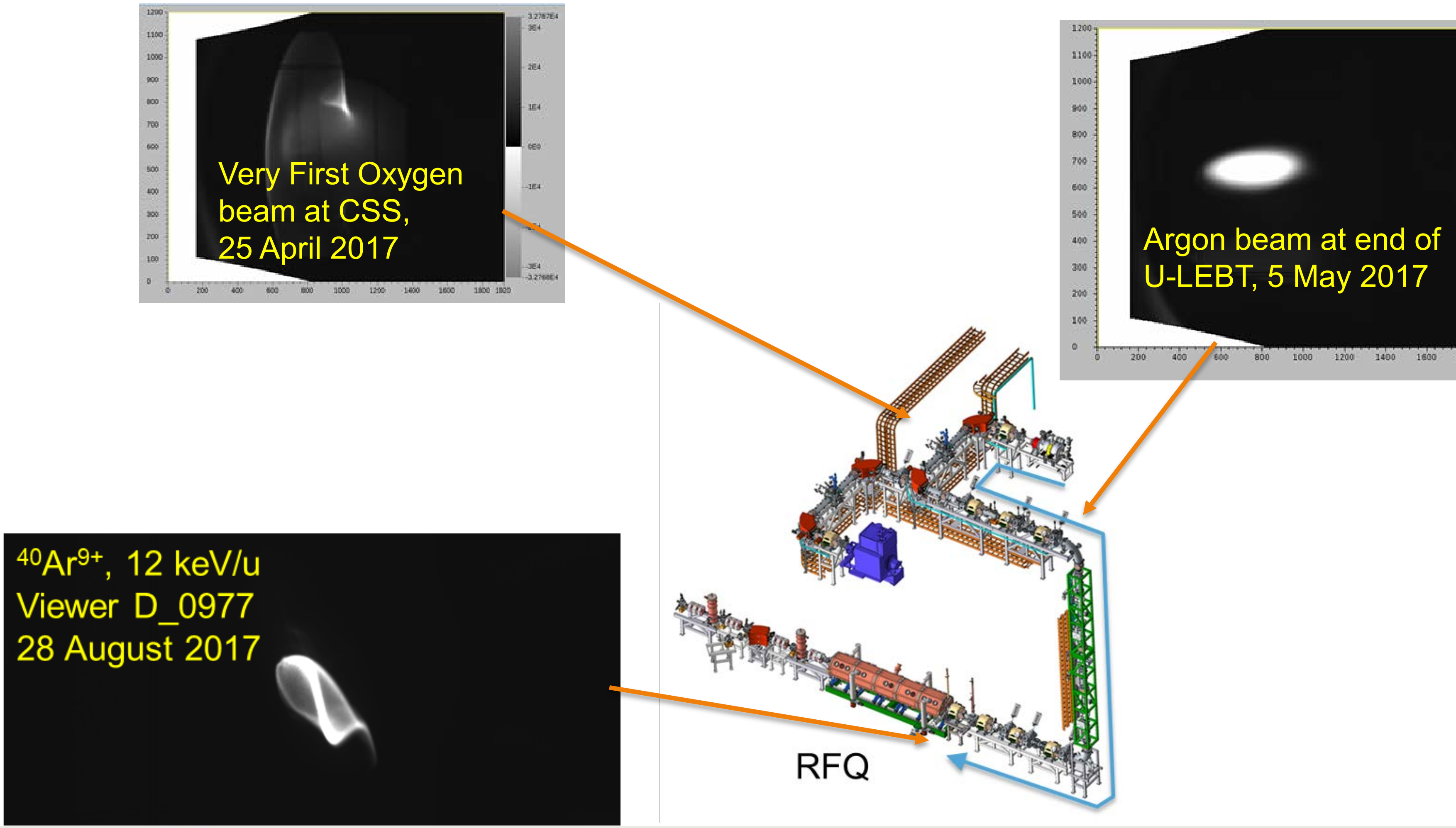
- Device Readiness Review assesses hardware readiness, authorizes start of integrated testing of reviewed scope (typically internal reviewers)
  - Division Director’s request for integrated power up / test for operations
  - FRIB Laboratory’s approval upon recommendation from the chief engineer
- Accelerator Readiness Review assess readiness of accelerator for beam commissioning
  - System and documentation readiness, people readiness, hardware readiness
  - FRIB Laboratory Director’s request for area beam commissioning
  - MSU President’s approval upon recommendation from ESH Director

Review	Date	Scope	Comment
DRR01-1	21 Sept 2016	Artemis ion source	Approved 12 keV/u beam
DRR01-2	30 Mar 2017	LEBT ground level	Approved 12 keV/u beam
DRR01-3	5 June 2017	RFQ, LEBT, MEBT	Approved 12 keV/u beam, no beam through RFQ
ARR01	22 July 2017	Complete Front End	Approved beam through RFQ and MEBT

Beam Accelerated to the End of MEBT Relied on Simple Suite of Instrumentation

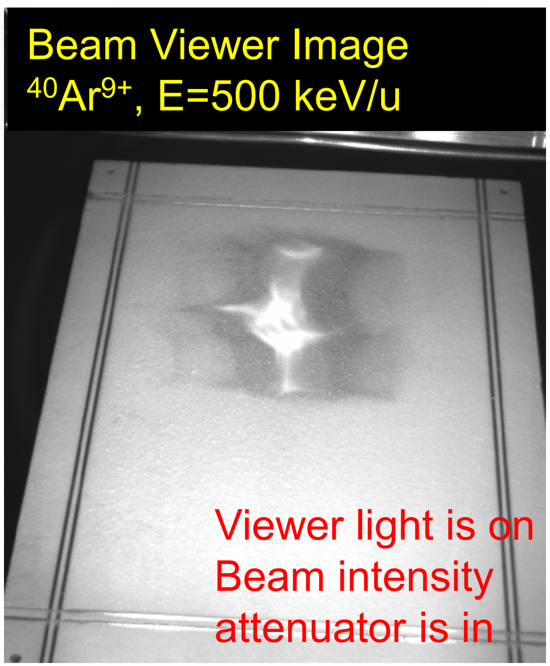


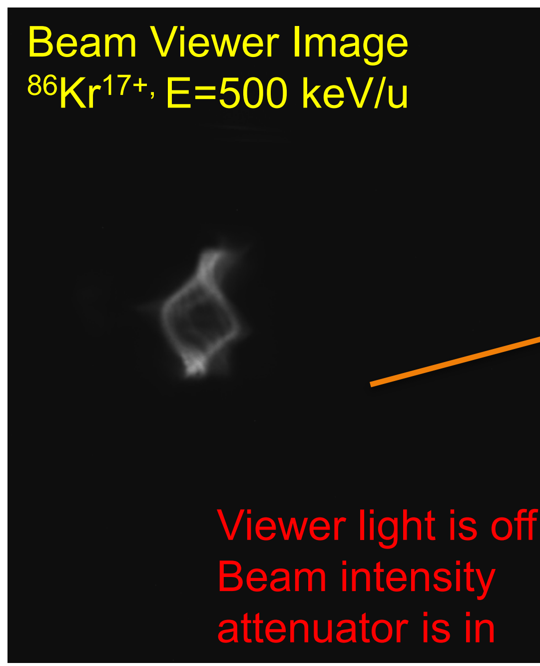
LEBT Beam Line Commissioned in Summer 2017 Transmission Efficiency is Nearly 100%

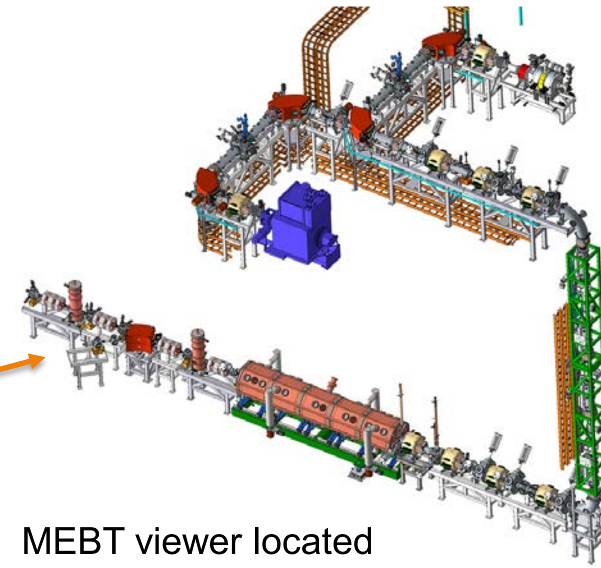


Beam Accelerated Through RFQ in 9/2017 Beam Energy Verified

- Transmission efficiency ~31%. The straight ahead Faraday Cup and the Faraday Cup after bend read same current – only accelerated current
- The viewer after the MEBT 45 deg. bend is used to measure beam energy, energy spread, and beam profile
- Measured energy was 500 keV/u, Energy spread ~1%



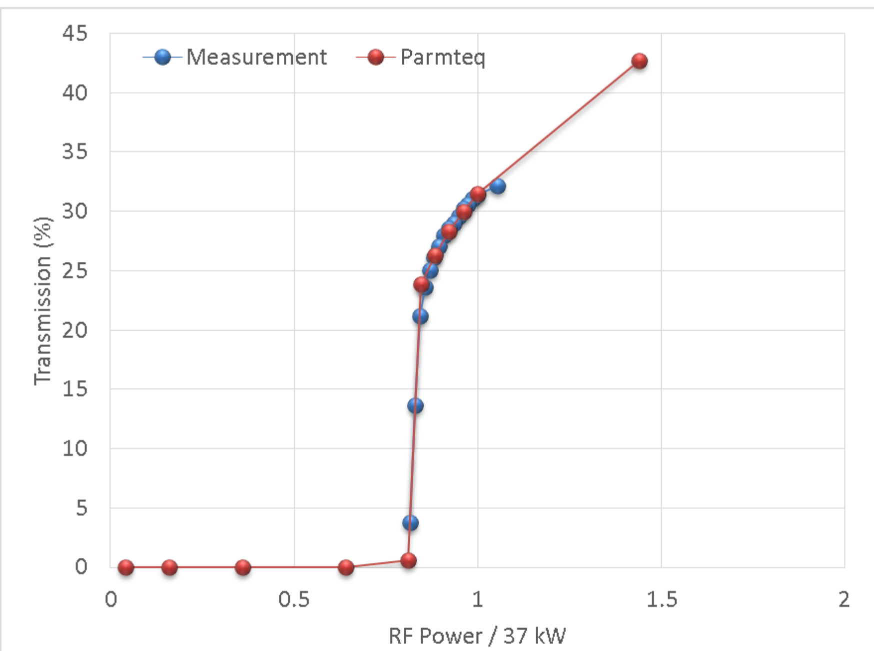




MEBT viewer located after the 45 deg. bend

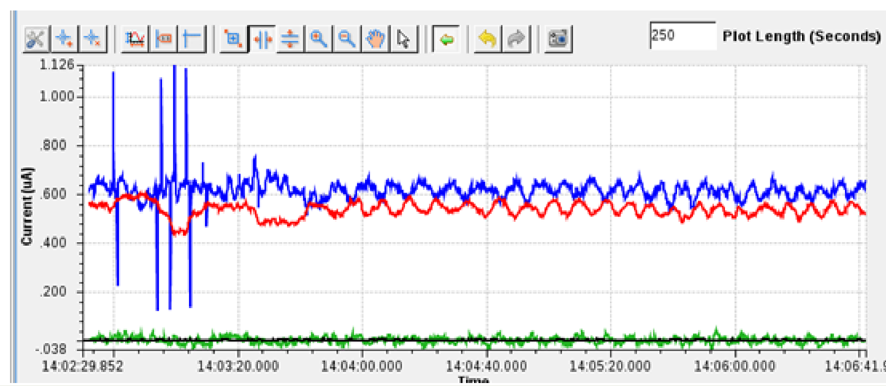
RFQ Commissioning Results Without Multi-Harmonic Buncher

- Multi Harmonic Buncher (MHB) was not operational, reducing the transmission efficiency. The RFQ does not have an internal buncher and is not designed to accelerate DC beam
- PARMTEQ predicts 31.5% of DC beam will be accelerated without MHB. Total transmission, including not accelerated beam, simulated by PARMTEQ, is ~90%



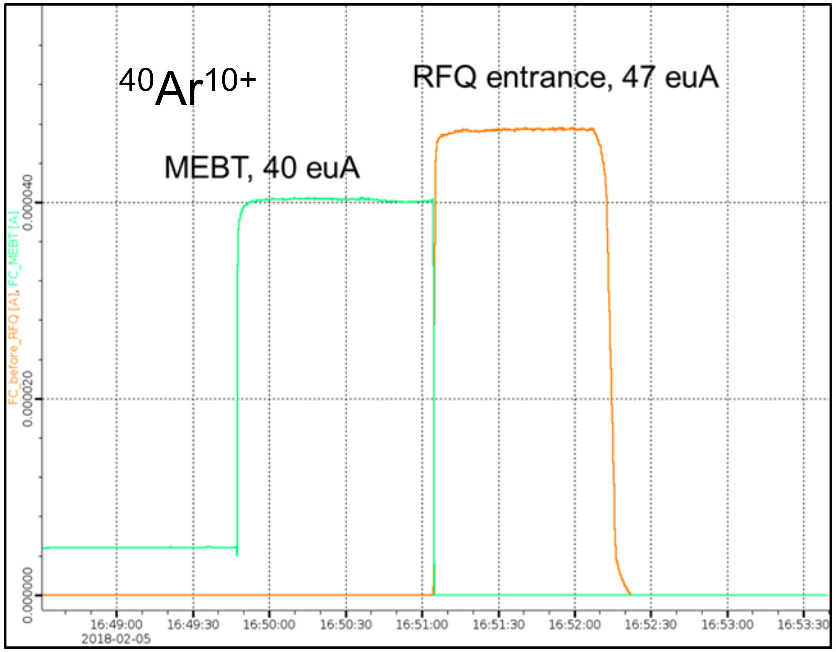
Measured and simulated accelerated current transmission though the RFQ as a function of the cavity RF power. The power is normalized on 37 kW.

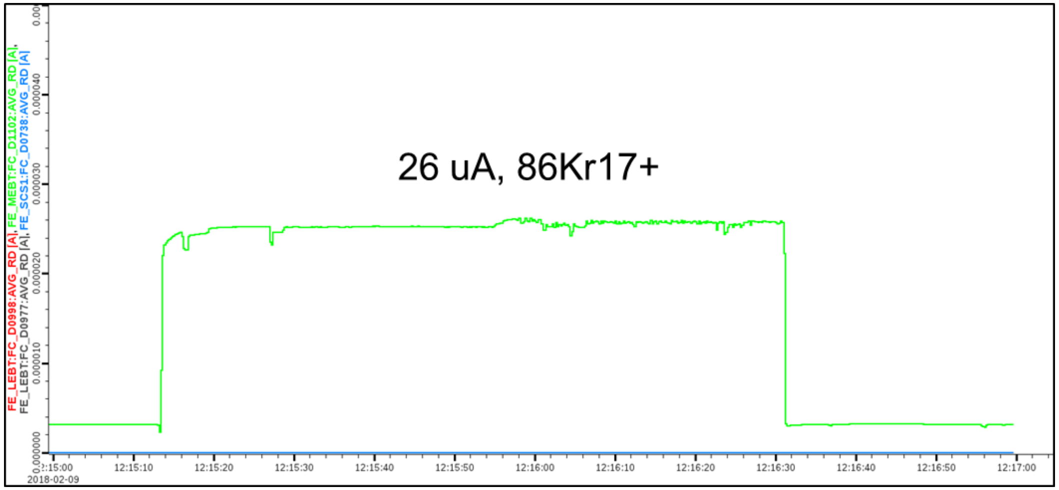
Total transmission, including non-accelerated beam, as measured by two ACCTs, one before and one after the RFQ.



RFQ Commissioning Results With Multi-Harmonic Buncher

- 40euA of $^{40}Ar^{10+}$ and 26euA of $^{86}Kr^{17+}$ were accelerated with MHB operational
- Transmission efficiency 80% - 86% vs. simulated 83% achieved
- Beam energy verified using the MEBT dipole magnet, E=500 keV/u





All Front End RF Systems Met Requirements

- All RF systems easily met amplitude and phase stability requirements with a margin of factor of 3 to 20

		MHB F1		MHB F2		MHB F3		RFQ		MEBT #1		MEBT #2	
		Amp. (Vp)	Phase (deg)	Amp. (Vp)	Phase (deg)	Amp. (Vp)	Phase (deg)	Amp. (Vp)	Phase (deg)	Amp. (Vp)	Phase (deg)	Amp. (Vp)	Phase (deg)
Forward Power (W)		~ 70		~ 20		~ 20		~ 40000		~ 1500		~ 1500	
Peak Error (%, deg)	Meas.	0.29	0.23	0.47	0.33	0.51	0.35	0.18	0.21	0.47	0.26	0.23	0.22
	Spec.	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
RMS Error (%, deg)	Meas.	0.07	0.04	0.12	0.07	0.13	0.08	0.02	0.04	0.06	0.05	0.03	0.05
	Spec.	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

FE Commissioning Goals Achieved
FE Commissioning Complete

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	✓

FE Has Been Operated for Four Months Serves as Testbed, Provides Valuable Experience

- FE has been operated for four months, showing stable performance of main hardware systems
- RFQ has been operated for a number of shifts over the last four month with a power of 40 kW (Ar) and 50 kW (Kr), demonstrating uninterrupted (no-spark) operations over a shift (~7 hours)
- Accelerator Physics works on improving understanding of beam parameters and transport, developing and testing high level software and algorithms.
- Front End is used to commission diagnostics, instrumentation, and machine protection system (MPS)/run permit system (RPS) in a combined and focused effort by Beam Instrument & Measurement and Accelerator Physics
- Opportunity to test and improve operational procedures

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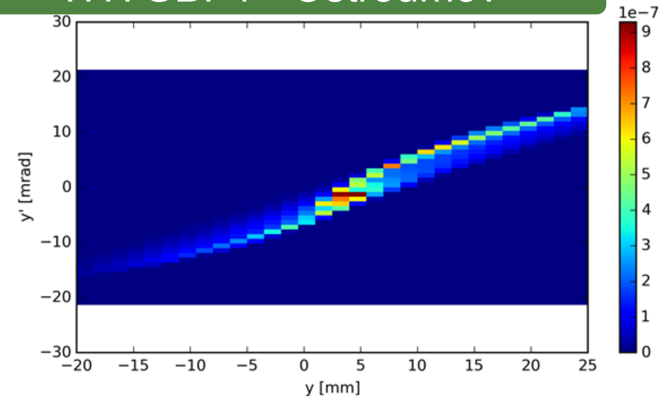

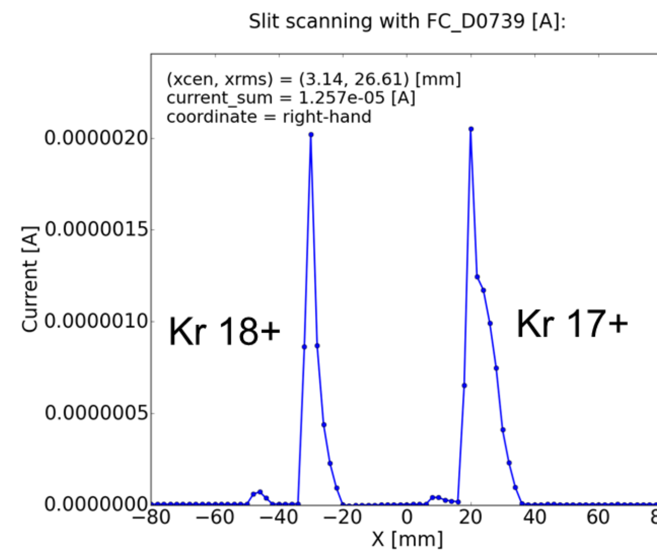

17+ & 18+ selected at slit

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
- 03/2013 – Order to build RFQ placed with a supplier
- 02/2014 – Order to build SC ECR Ion source Magnet placed with Berkeley
- 11/2015 – Ion Source platforms moved to FRIB site after RFE date
- 09/2016 – Aretmis ECR Ion Source commissioned, 14 months ahead of baseline schedule
- 09/2017 – The LEBT commissioned with BEAM
- 10/2017 – Beam accelerated through the RFQ, 10 months ahead of schedule
- 02/2018 – Operation of all FE systems demonstrated. Accelerated efficiency as expected. KPP parameters demonstrated. Front End commissioning completed
- Now – IPAC 2018

Path Forward
Commissioning of 0.041 Cryomodules

- Three 0.041 QWR cryomodules and a temporary Diagnostics station have been installed
- Cryogenics plans cooldown in May
- ARR02 is planed on May 30–31
- FRIB Accelerator Operations Department was formed 5 months ago to transition from the construction stage to operations and to support linac commissioning

Summary

- FRIB Front End has been successfully commissioned
- Commissioning goals achieved, KPP parameters demonstrated
- Front End has been operated for four months, providing valuable experience and serving as a testbed for equipment and operational procedures

Acknowledgements

- The presentation was given on behalf of the FRIB project. Many FRIB employees contributed to the successful construction and commissioning of the FRIB Front End
- We thank colleagues, collaborators, and partners from other laboratories for their direct contributions to the project and useful discussions
  - Berkeley
  - Tsinghua University
  - ANL
  - SNS
  - Femilab
  - LANL
  - BNL
  - TRIUMF
  - INFN