Development and status of the FRIB 28 GHz SC ECRIS

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On Behalf of FRIB ECR Ion Source Team

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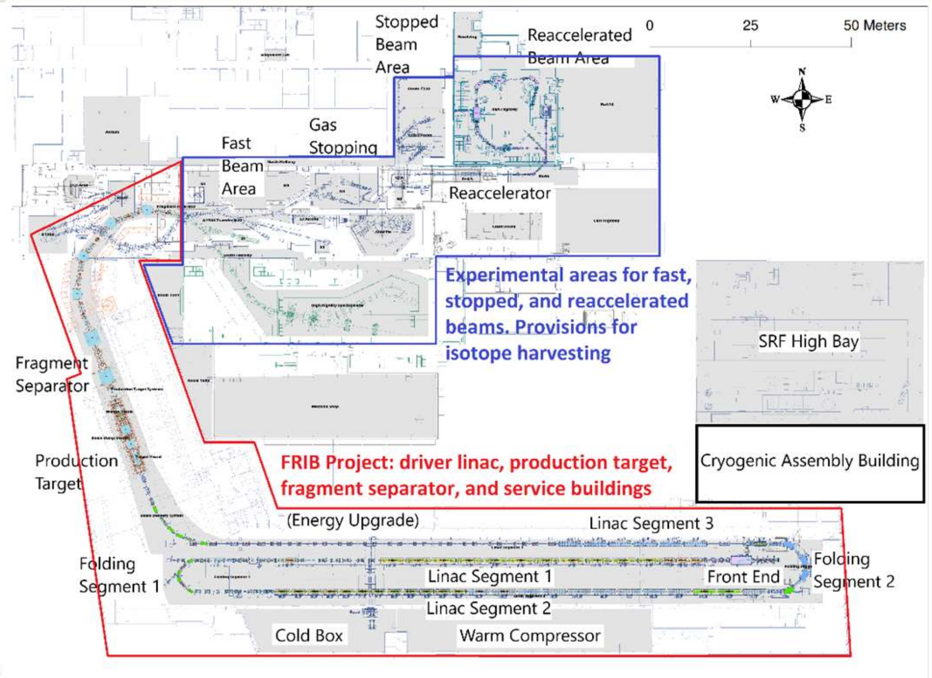
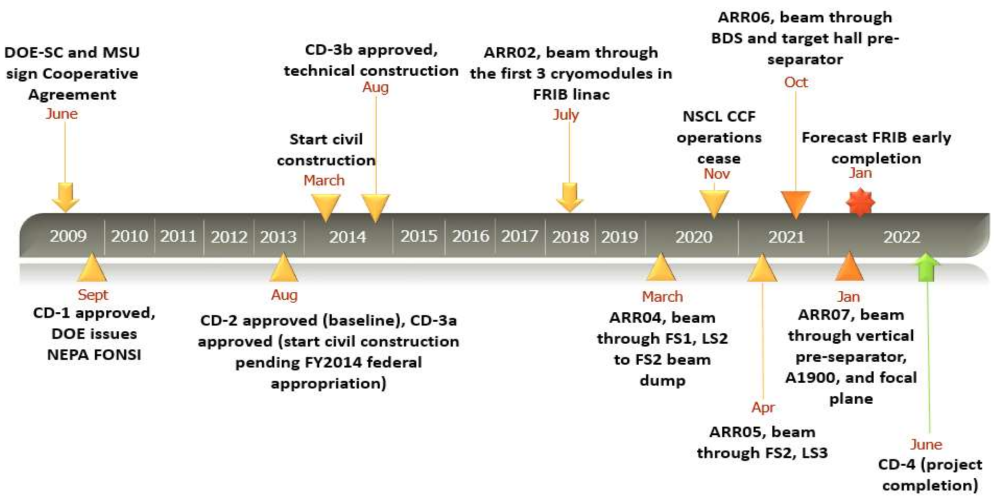
Outline

- FRIB Introduction
- FRIB SC ECR ion source
- Magnet assembly and first cooldown
- Conventional parts assembly status
- Path Forward
- Summary

Facility for Rare Isotope Beams
A DOE Office of Science User Facility

- Funded by DOE–SC with contributions and cost share from Michigan State University
- FRIB project scope includes accelerator, target system, pre-separator, fragment separator
- Accelerate ion species up to ^{238}U with energies of ≥ 200 MeV/u and beam power up to 400 kW for rare isotope production





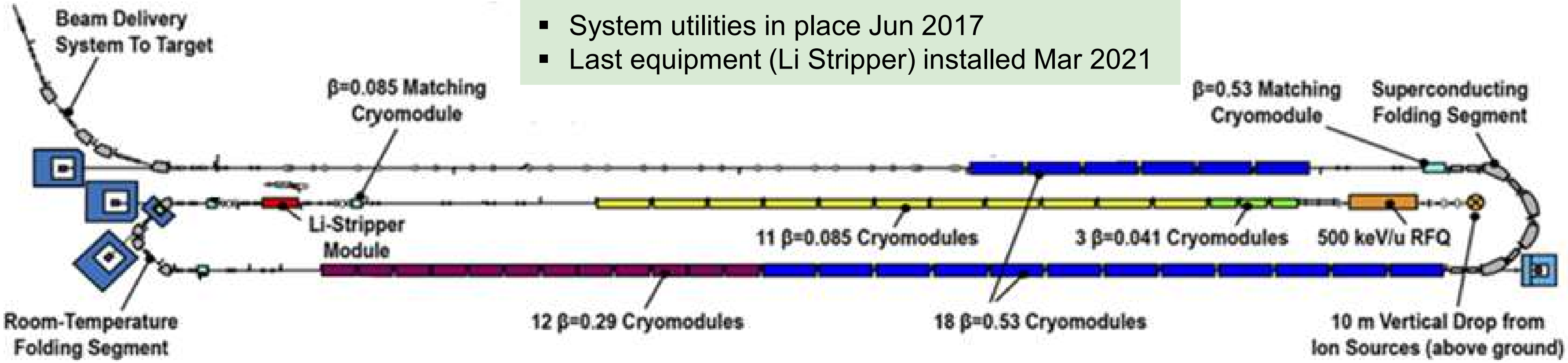
ARR – Accelerator Readiness Review

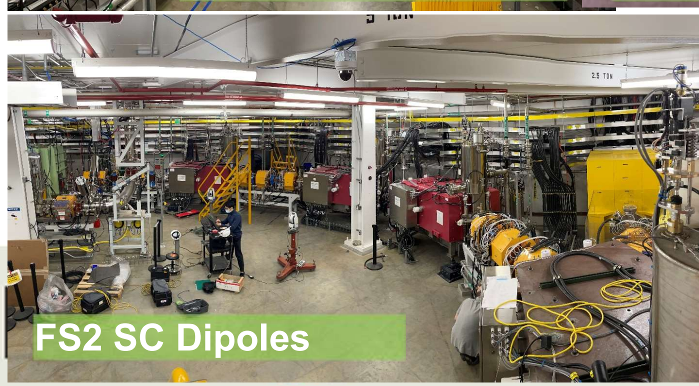
- Fast, stopped, and reaccelerated beam capabilities
- First user experiments expected in 2022

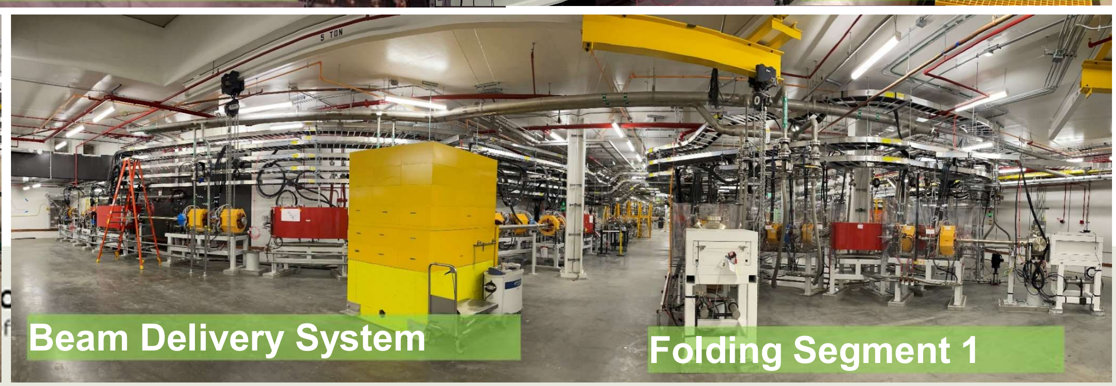
FRIB Driver Linac Technical Construction Completed

46 Cryomodules, 4 SC Dipoles, 242 RT Magnets, 7 RT Bunchers, 1 RFQ

- System utilities in place Jun 2017
- Last equipment (Li Stripper) installed Mar 2021







SRF Production Completed: May 2020

- 4 cavity types, 6 cryomodule types: designed, developed, fabricated, and tested at MSU with industrial suppliers.
- A dedicated full SRF processing and cryogenic testing facility was built 2014 to support in-house SRF production.
- Total of 6 years of production to deliver all cryomodules for FRIB linac.
  - Jan 2015: received first production cavity (β = 0.53 HWR) from vendor
  - Production completed May 2020 after Covid-19 pandemic shutdown.
  - Peak production rate was 3 cold masses and 1.5 cryomodules per month.
- Last cryomodule installed in tunnel July 2020. Last segment (LS3) cooled down Nov 2020, energized Feb 2021.

Quarter Wave Cryomodule				
β	Type	Component Counts (baseline + spares)		
		Cryomodules	Cavities	Solenoids
0.041	accelerating	3 + 1	12 + 4	6 + 2
0.085	accelerating	11 + 1	88 + 8	33 + 3
	matching	1 + 1	4 + 4	-
Half Wave Cryomodule				
0.29	accelerating	12	72	12
0.53	accelerating	18	144	18
	matching	1	4	-
TOTALS		46 + 3	324 + 16	69 + 5

FRIB Linac Commissioning

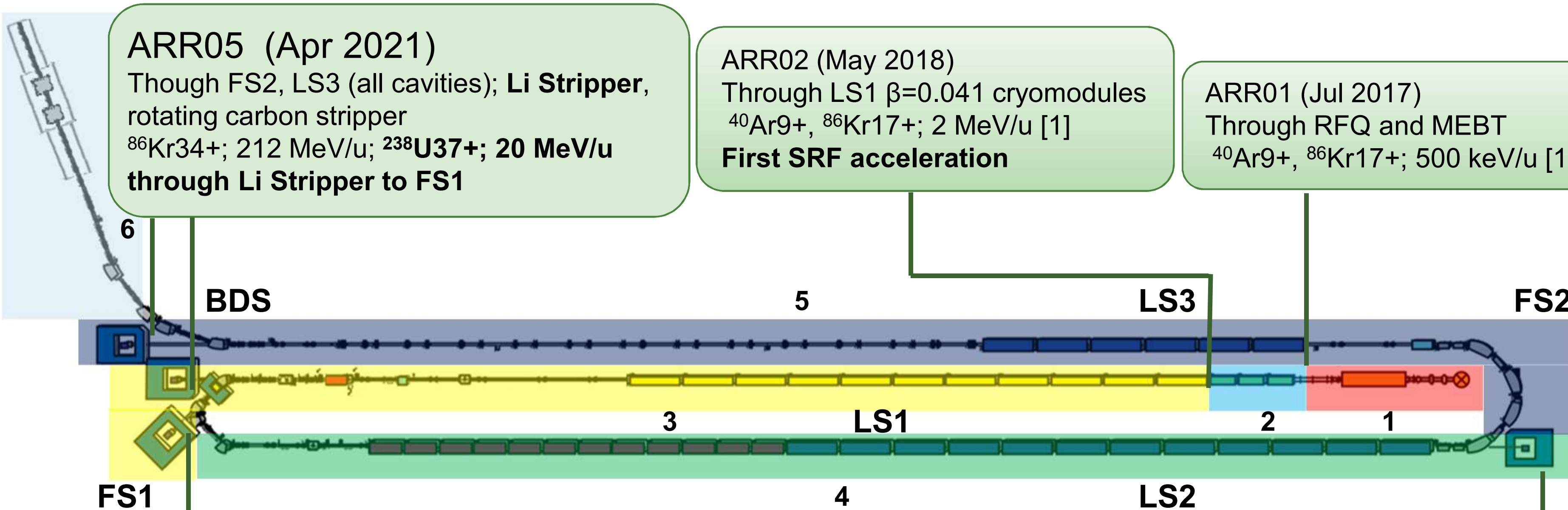
Phased Beam Commissioning in Parallel with Installation

- We planned 7 beam commissioning stages with an Accelerator Readiness Review (ARR01-07) preceding each stage. ARR01-05: through Linac. ARR06-07: through target and secondary beam line.

ARR05 (Apr 2021)
Though FS2, LS3 (all cavities); **Li Stripper**, rotating carbon stripper
^{86}Kr34+; 212 MeV/u; **^{238}U37+; 20 MeV/u through Li Stripper to FS1**

ARR02 (May 2018)
Through LS1 β=0.041 cryomodules
^{40}Ar9+, ^{86}Kr17+; 2 MeV/u [1]
First SRF acceleration

ARR01 (Jul 2017)
Through RFQ and MEBT
^{40}Ar9+, ^{86}Kr17+; 500 keV/u [1]



ARR03 (Feb 2019)
Through LS1 and FS1 (all QWRs)
^{40}Ar9+, ^{20}Ne6+, ^{86}Kr17+, ^{129}Xe26+; 20.3 MeV/u [2]

ARR04 (Mar 2020)
Through LS2 (all QWRs, 168 HWRs)
^{36}Ar18+; 204.4 MeV/u **KPP Reached**
^{129}Xe49+, 50+, 51+; 180 MeV: **multi-charge-state Acceleration** [3]

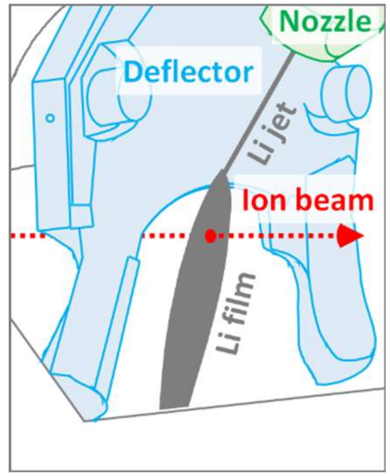
Stripping efficiency into 49+,50+, 51+: 76.5%

[1] LINAC2018-WE2A01
[2] SRF2019-MOFAA3
[3] *Phys. Rev. Lett.* **126**, 114801

KPP – Key performance parameters

Lithium Stripper Commissioned with Beam:
World's First Beam Stripping with Lithium

- Lithium stripper is one of the key elements for FRIB high power beam
- Design allows physical coexistence of lithium stripper and carbon stripper for enhanced availability
- Commissioned April 2021 with beam in FRIB tunnel
  - ^{124}Xe26+ at 17 MeV and ^{238}U37+ at 20 MeV through LS1 and Li stripper to FS1 beam dumps.
  - High power beam tested successfully: ^{36}Ar10+ at 400 W, duty cycle = 5.4%



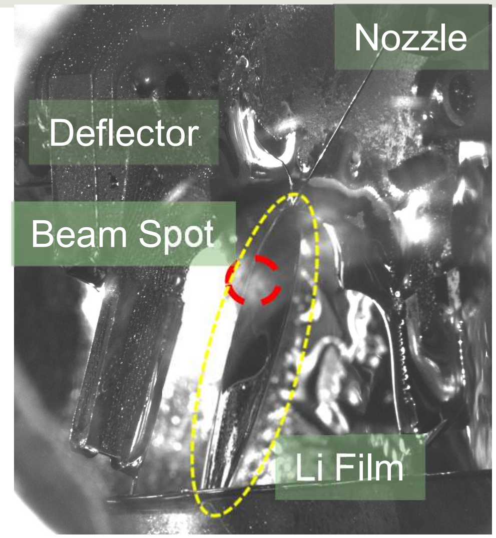
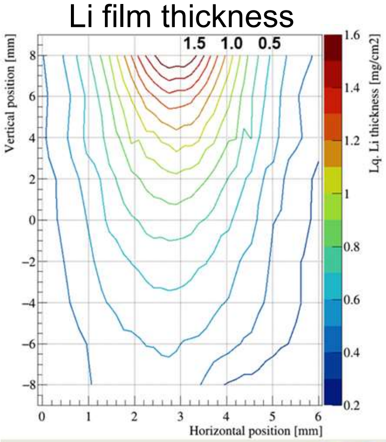
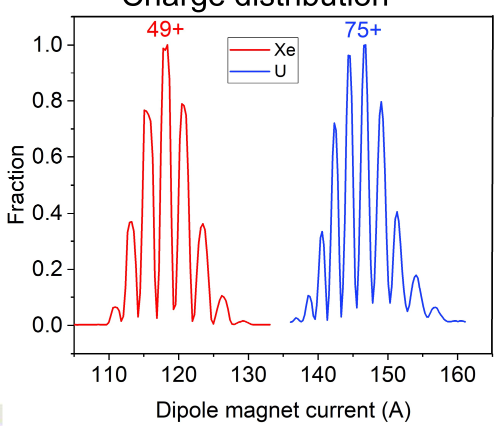


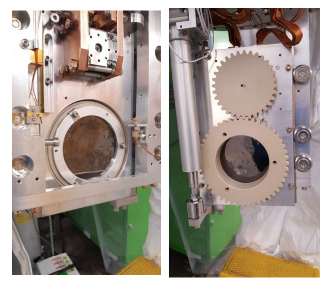
Image through viewport

Li film thickness

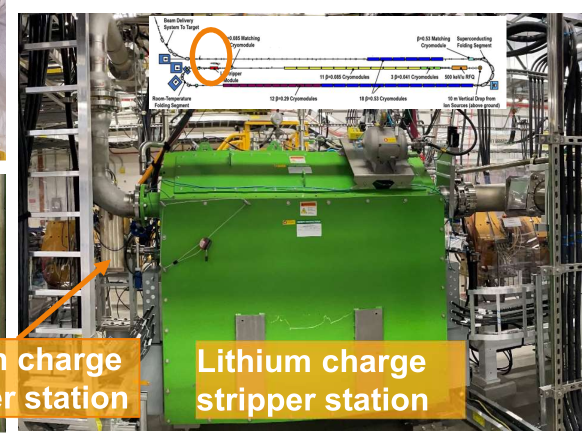


Charge distribution





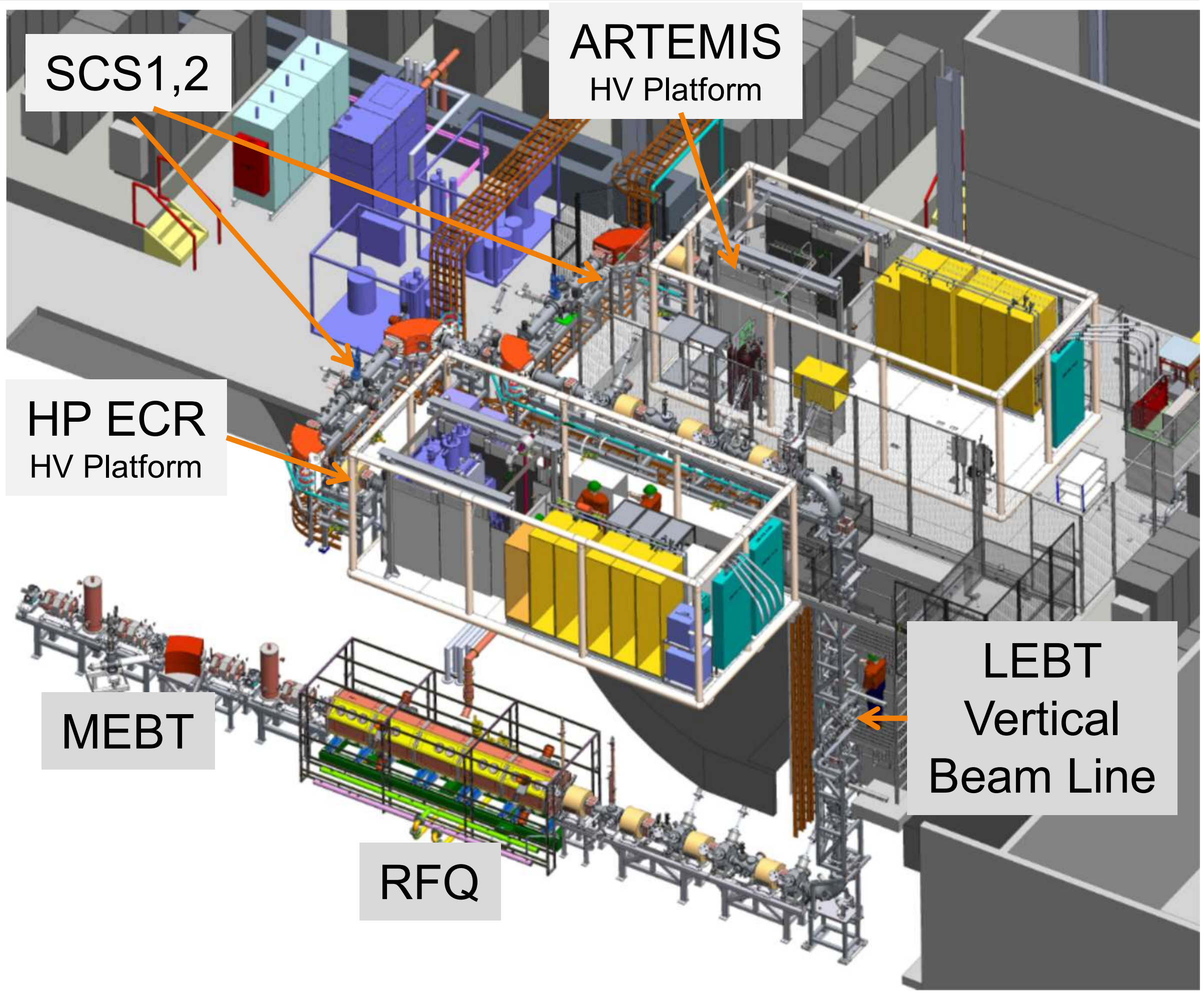
Rotating carbon foil stripper installed and tested under vacuum at 20 rpm with beam



Beam current

FRIB Front End Overview

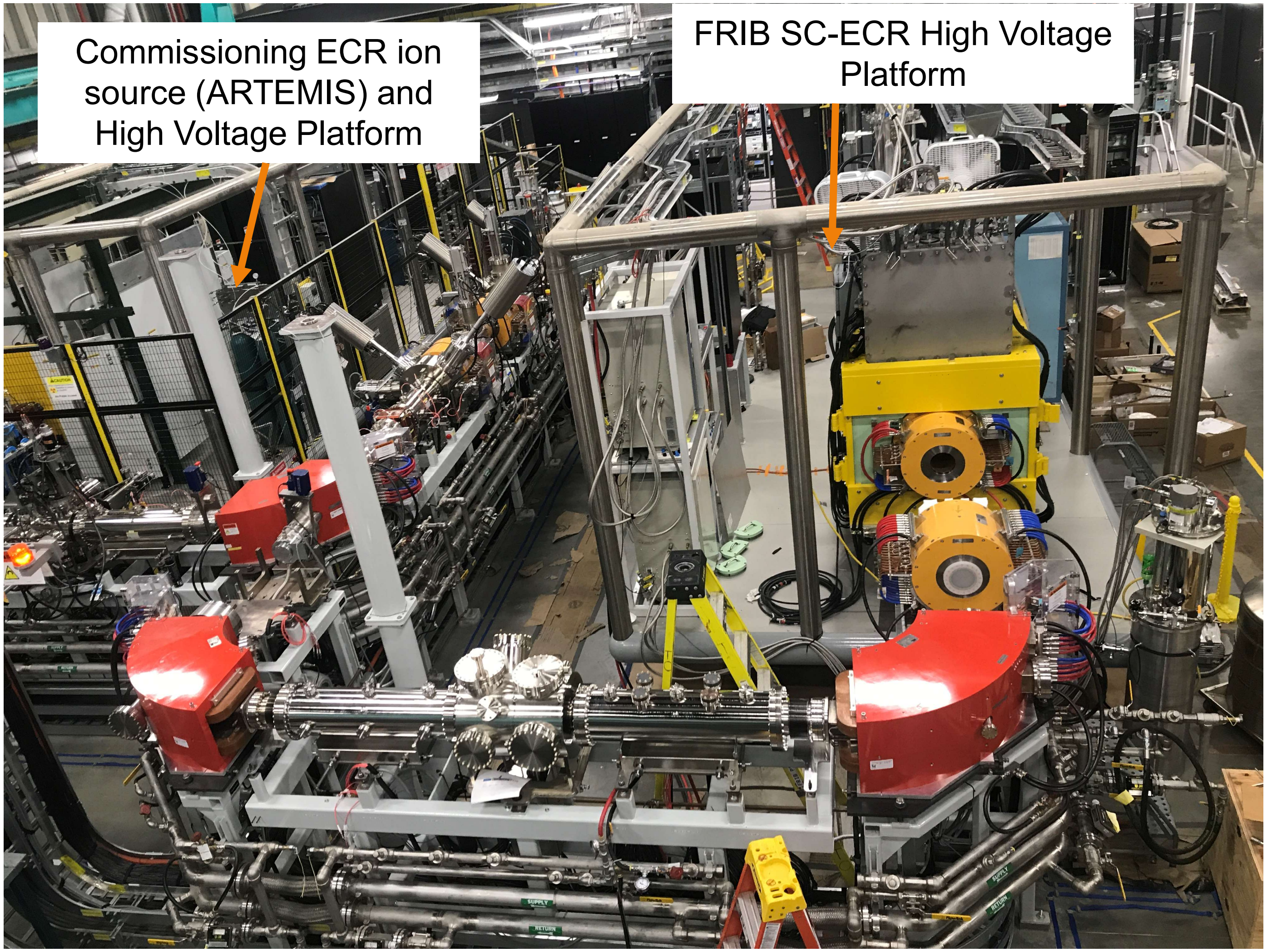
- Two ECR sources on High Voltage (HV) platforms
  - ARTEMIS –existing 14 GHz room temperature source
    - » Used Throughout commissioning and early operations
  - SC ECR ion source – 28 GHz based on VENUS (LBNL)
    - » Expect to start commissioning early next year (2022) @ 18 GHz
- Low energy beam transport (LEBT)
  - E = 12 keV/u
  - Chopper
  - Collimation system
  - Vertical transport line
  - Buncher and velocity equalizer
- Radio Frequency Quadrupole (RFQ)
  - E = 500 keV/u
- Medium energy beam transport (MEBT)
  - Two bunchers, quadrupoles



ARTEMIS ECR Source Supporting Linac Operations and the SC-ECR Source Under Construction

Beams developed on Artemis

Beams	Developed?	Date
^{40}Ar	Yes	2017-10
^{86}Kr	Yes	2017-10
^{20}Ne	Yes	2019-03
^{129}Xe	Yes	2019-03
^{238}U	Yes	2020-09
^{82}Se	Yes	2020-12
^{40}Ca	Yes	2020-12
^{124}Xe	Yes	2021-01
^{82}Pb	Yes	2021-02



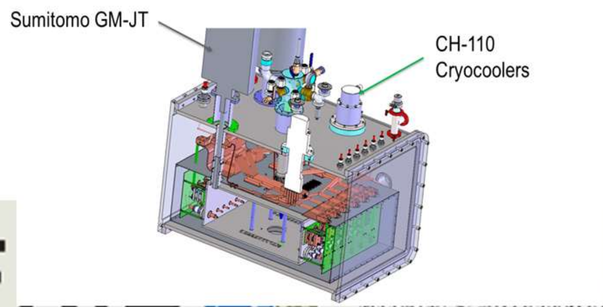
Ion Sources Performance Requirements

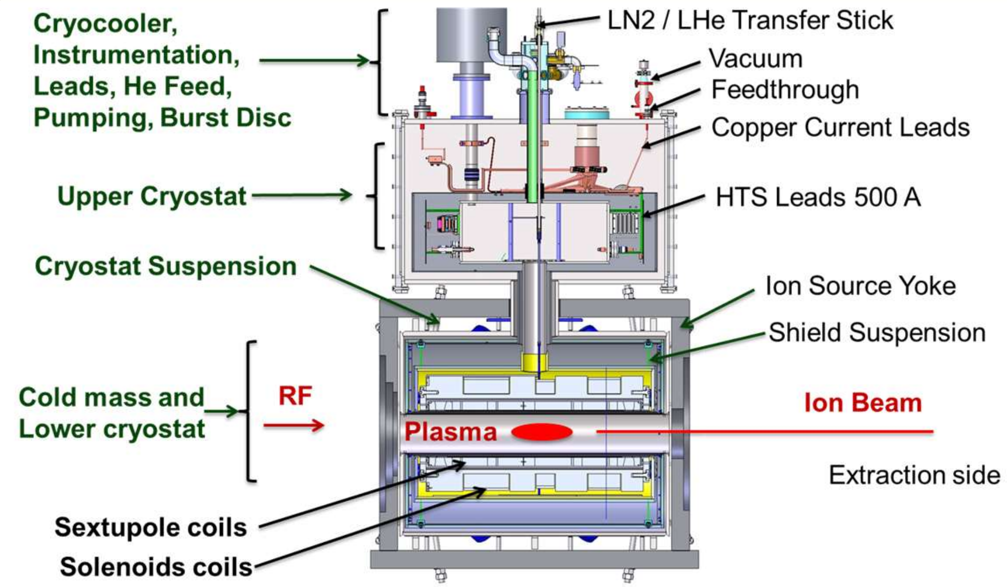
- Commissioning
  - 36-Ar, 86-Kr, 129-Xe Beam
  - 25 to 50 euA with M/Q > 7
  - Ar^{8+} to Ar^{11+} - Kr^{14+} to Kr^{17+}
    - Ar^{9+} and Kr^{17+} used most of the time
    - Over 200euA of Ar 9+ demonstrated and used in LEBT
  - Beam energy 12keV/u
    - » Demonstrated acceleration of M/Q=7.2 with $^{238}U^{33+}$ through MEBT with HV platform operated 71kV and RFQ at 100kW CW
- FRIB Operations
  - Produce ion beams for injection into FRIB linac for a large base of stable elements ranging from oxygen to Uranium
    - » All beam required for first PAC developed with ARTEMIS except for Uranium
  - Source UPP: 400 to 450euA for all elements from ion source to reach 400kW on Target (UPP) (Single Charge State) with M/Q > 7
  - Able to sustain intensity for several weeks (NSCL based operation)
  - Beam energy 12keV/u

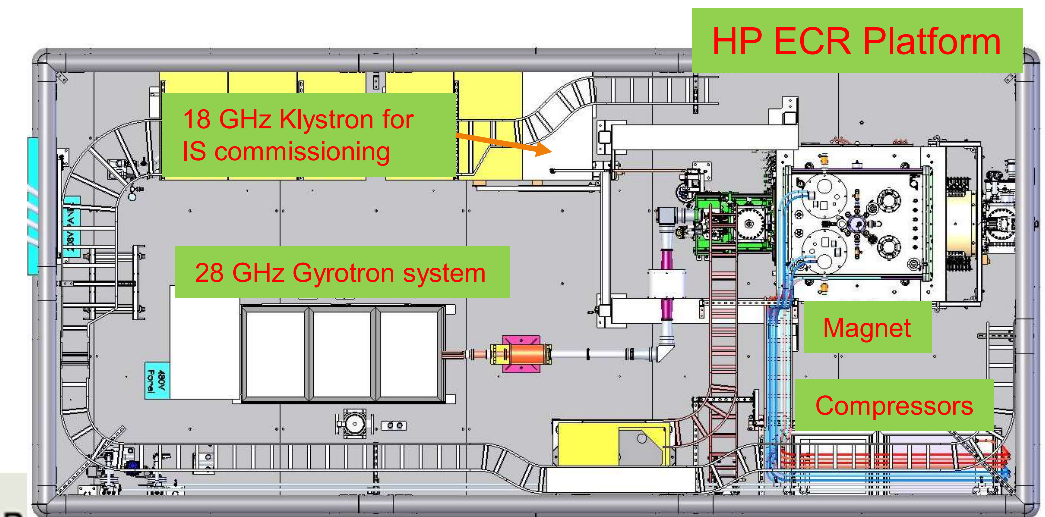
UPP - Ultimate Performance Parameters

SC ECR System Overview

- 28 GHz SC ECR ion source is based on VENUS design
  - Cold mass - LBNL
  - Cryostat – FRIB
  - Conventional components - FRIB
- 18 GHz Klystron for commissioning
  - Tested with dummy load
- 28 GHz Gyrotron for high intensity beams
  - Procurement in progress
- Two GM-JT cryocoolers with total capacity 10 W @ 4K to re-condense helium in the cryostat
- Two shield cryocoolers to cool the heat shield

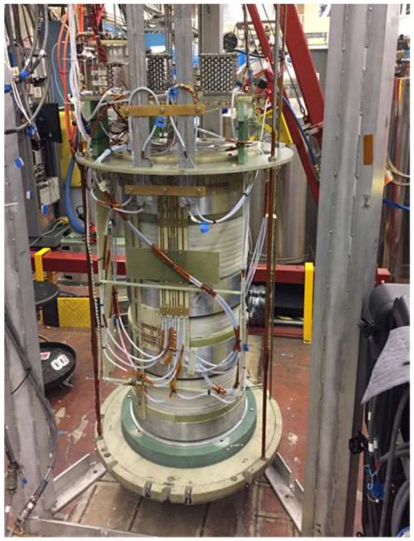




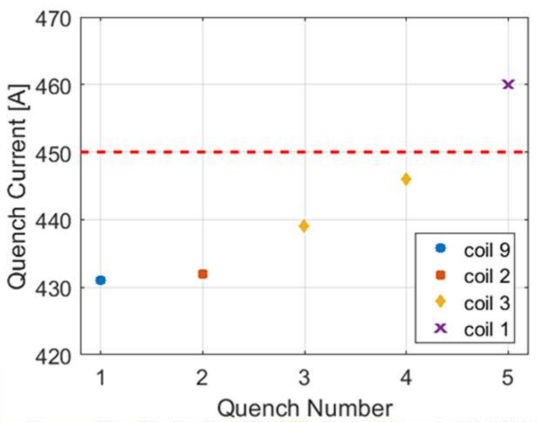


SC ECR Magnet Completed at Berkeley Met Performance Requirements

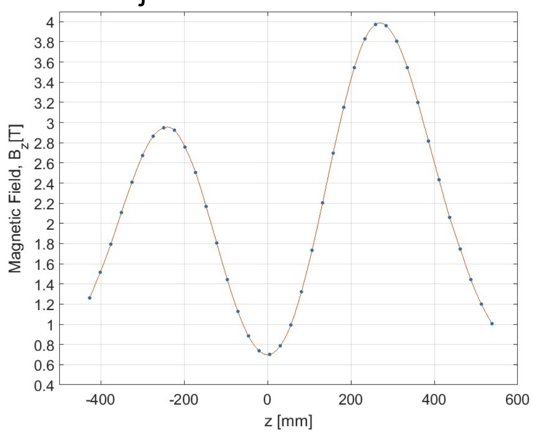
- Superconducting magnet was designed through ATAP division at LBNL
  - Magnetic field meets requirements.
  - Adjustment of B_{min} demonstrated without quenching
  - Field cycling from 0 to the nominal value demonstrated without quenching
- Sextupole training reduced from 16 to 5 quenches with new sextupole coil (October 2017)
  - Five new quenches likely were caused by the redistribution of stresses caused by the disassembly and reloading of the magnet support structure

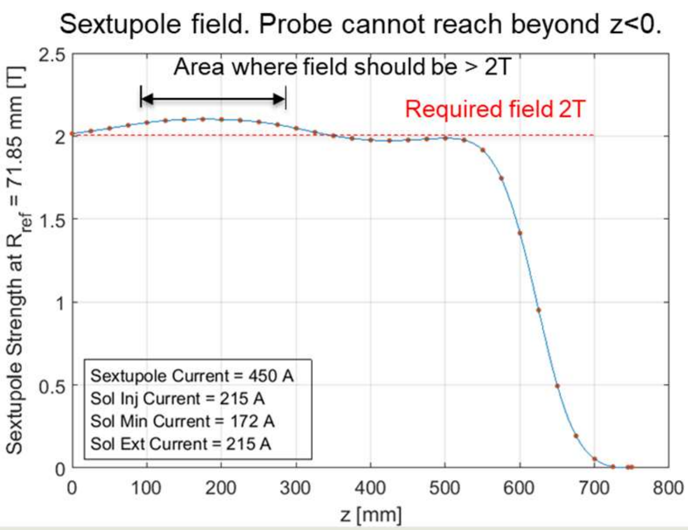


Quenches of sextupole magnet with new coil #9. Required current 450A.



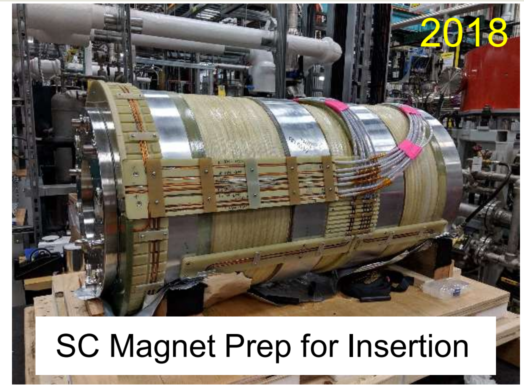
Measured solenoid magnetic field. Required fields 3T at extraction and 4T at injection.

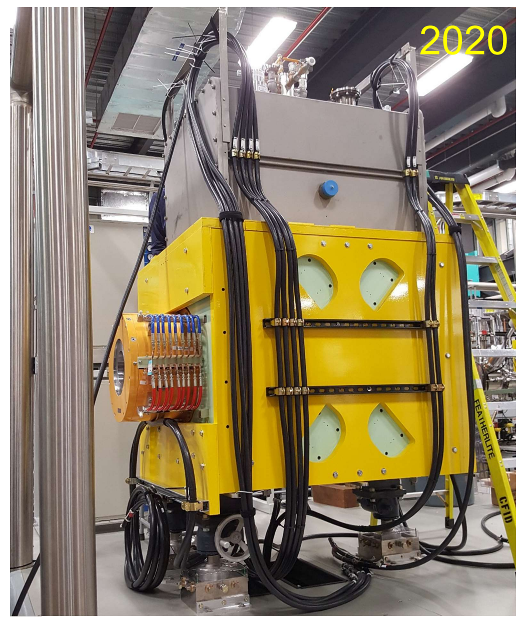




Magnet and Cryostat Assembled at FRIB
Conventional Components Assembly In Progress

- Cryostat with the cold mass assembled in-house
- HV Platform utilities, rack equipment and cabling installed
- Conventional components assembly offline in progress (room temperature components such as plasma chamber, gas distribution system, etc.)

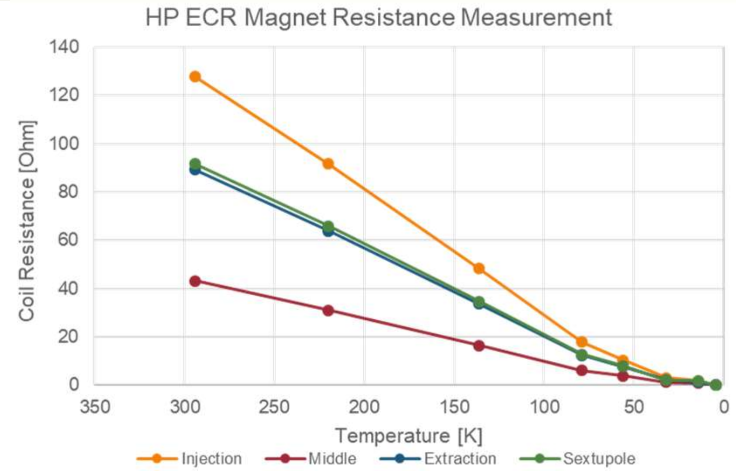


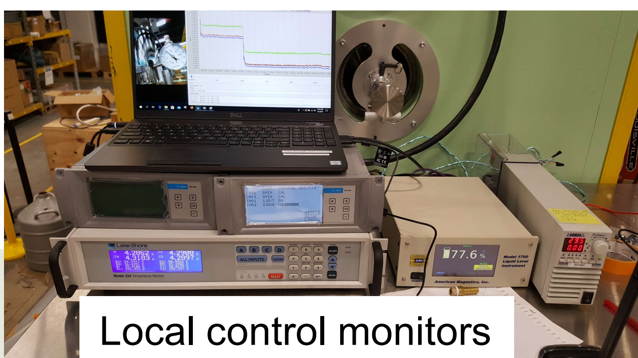


Magnet Assembled on Platform

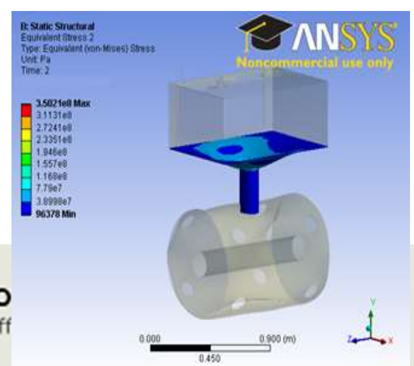
SC ECR Magnet Cooled Down to 4 K

- HP ECR magnet was cooled to 4K with local control in December, 2020
- Measured heat leak 1.2 W, close to design value.
- One GM-JT cryocooler (cooling capacity ~5 Watt) is sufficient for cooldown.
- Resistance measured during the cooldown process.





Local control monitors

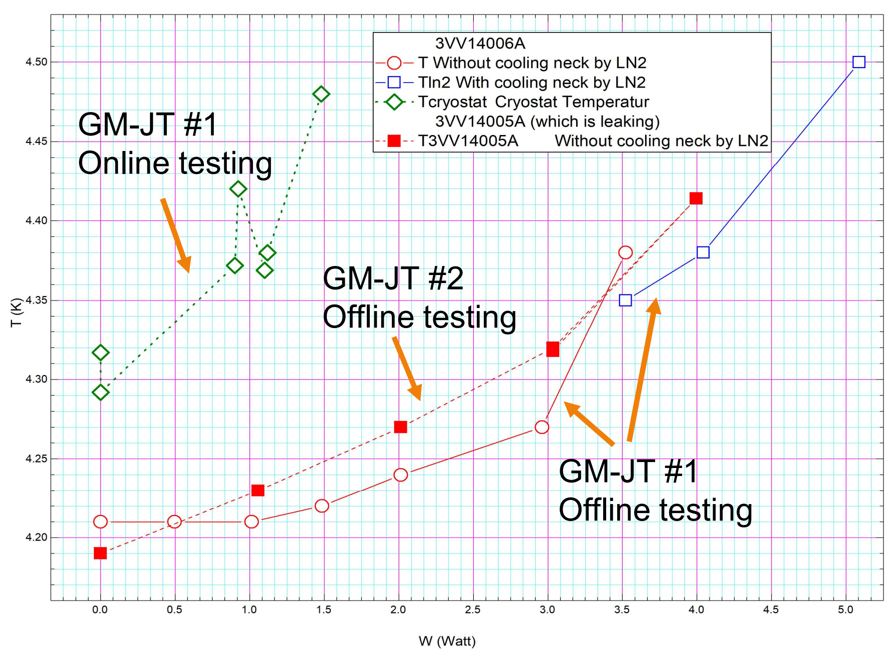


Thermal Analysis Results

Heat Load Source	Heat Load mW
Radiation Heat Load	110
HTS	206
Helium Tube	41
Suspension System	152
Instrumentations	10
Relief Tube - Radiation	61
Relief Tube - Conduction	131
GM-JT Cryocooler	310 X 2
Total	**1333 mW**

Both GM-JT cryocoolers tested successfully

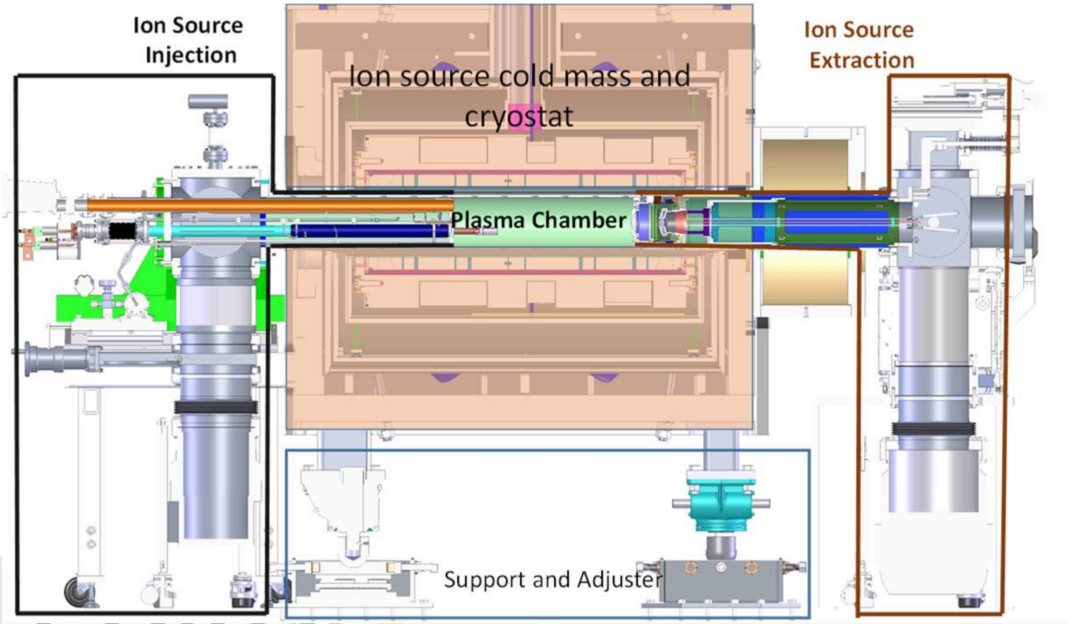
- Maximum Cryo-cooling capacity 10W @ 4 K
  - Dynamic heat load on the cryogenic system produced by x-rays generated by ECR plasma can reach several Watts.
  - Available RF power is 10 kW.

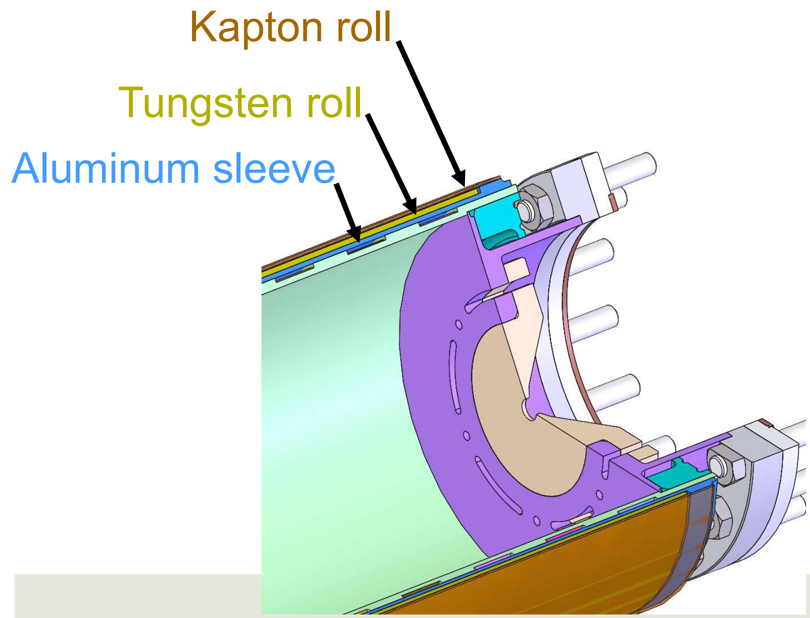


- Both GM-JT cryocoolers were successfully tested offline.
- Only one installed to the magnet
- The cyrocooler has been reliably operating for ~9 months

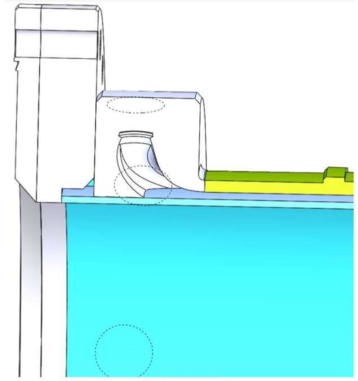
X-ray Damage to Components and Mitigation in Design

- Plasma chamber housing the ECR Plasma is floating at high voltage potential while warm bore of cryostat is grounded: Insulator in between
  - Insulator can be damaged by X-Rays (Material choice PEEK, Kapton, Mylar)
  - Since PEEK is a costly option, Kapton was chosen as a baseline material
- 2mm Tungsten shield to protect the insulator
  - Cylindrical tube outside of plasma chamber tube
- 20 mil Kapton can be able to hold over 100 kV

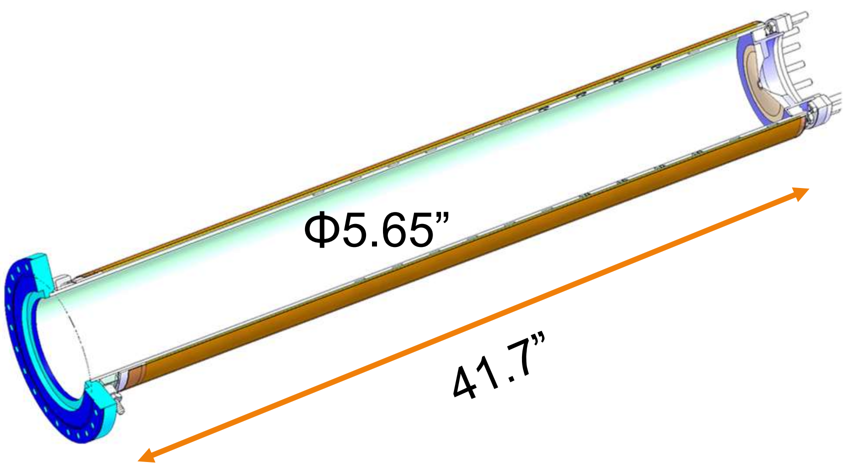




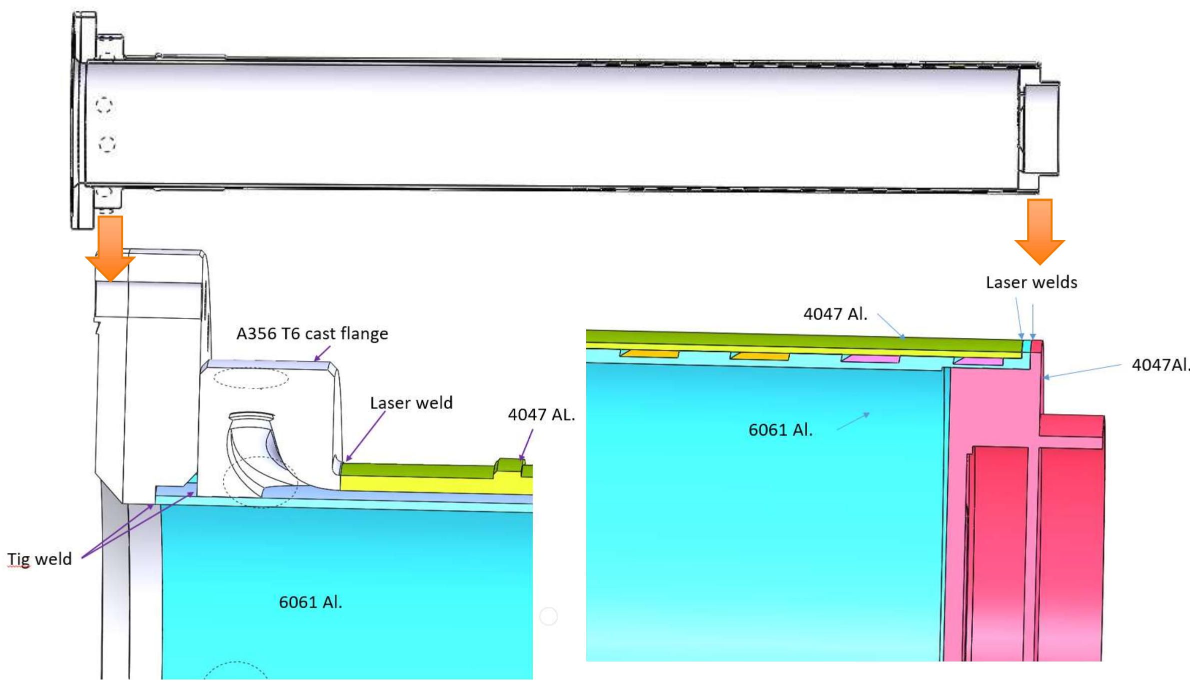
Plasma Chamber Welding and Pressure Test Completed



- Thermal analysis applied to improve water cooling design
- Radiused channel used to improve water flow at the injection end
- Spiral cooling channels can safely cool plasma tube with 9 kW operation
  - 15 GPM required for 9 kW operation (5 GPM per channel)
  - 60 psi drop within plasma tube
- Plasma tube is ready for water flow test, and assembly to the Magnet



Plasma Chamber Design Improvement Proposal for Discussion



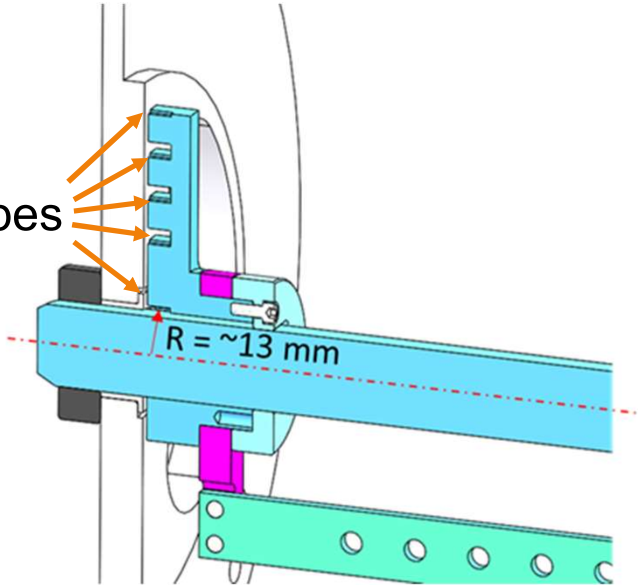
TIG welding

- Current plasma tube: 6061 Al.
  - Laser welding may cause crack with 6061 Al.
- Proposal: To allow Laser welding or E-beam welding (in vacuum)
  - Tube – 6061 Aluminum
  - Sleeve – 4047 Aluminum
  - Extraction flange – 4047 Aluminum
  - By using 6061 and 4047 no filler metal is required
- Advantage of Laser welding vs. TIG
  - Computer controlled process vs. hand welding. A much higher chance for success

TIG - Tungsten Inert Gas Welding

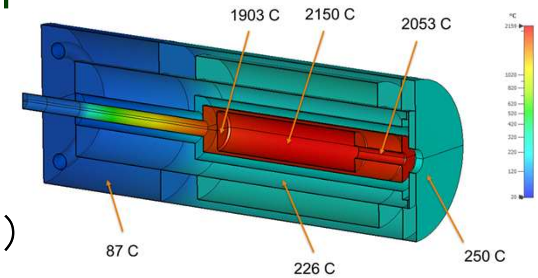
Mapper Design and Assembly Completed

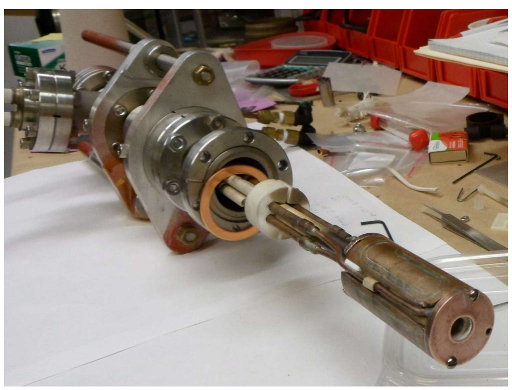
- Mapper has been developed based on mapper of SUSI at MSU
- Mapper assembled and installed to the magnet.



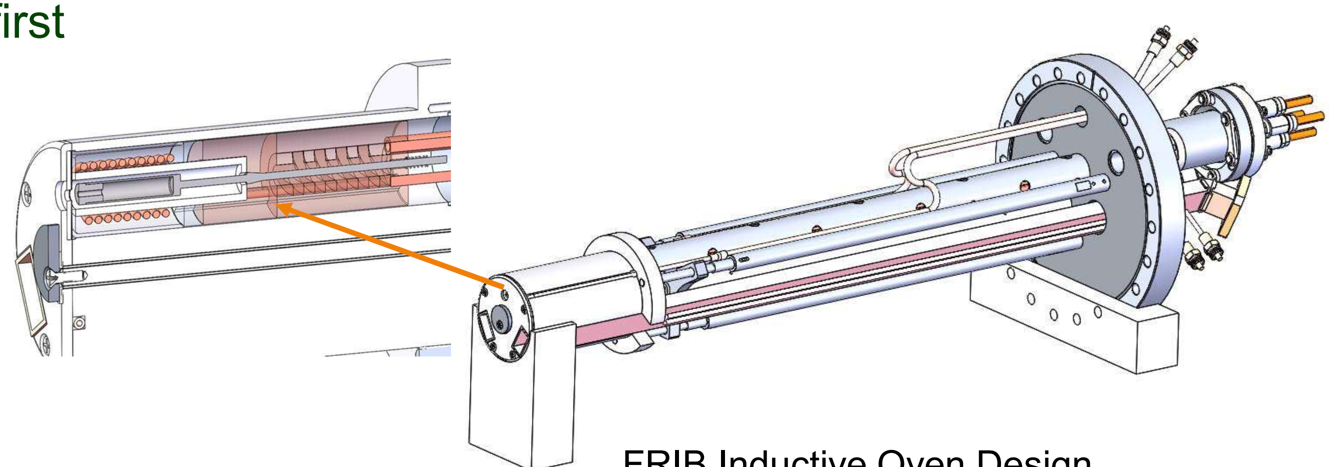
High Temperature Oven Design Completed

- High temperature oven options: Resistive Oven, Inductive Oven
  - Resistive Oven can destroyed under Lorentz forces
- Uranium Properties
  - Uranium melts at 1,132 ℃ (Very Reactive)
  - Uranium Oxide sublimate (1-10 mTorr vapor pressure around 2000℃)
- Adapt and improve inductive oven used at NSCL for FRIB ECRs
  - Inductive oven used at NSCL for Nickel and Germanium (1500 ℃)
  - IMP (China) with a similar design demonstrated temperature > 2000 ℃
- FRIB Inductive Oven design completed. Fabrication is in progress. It will be tested on the Artemis ion source first





NSCL ARTEMIS
Inductive Oven ~1500 ℃

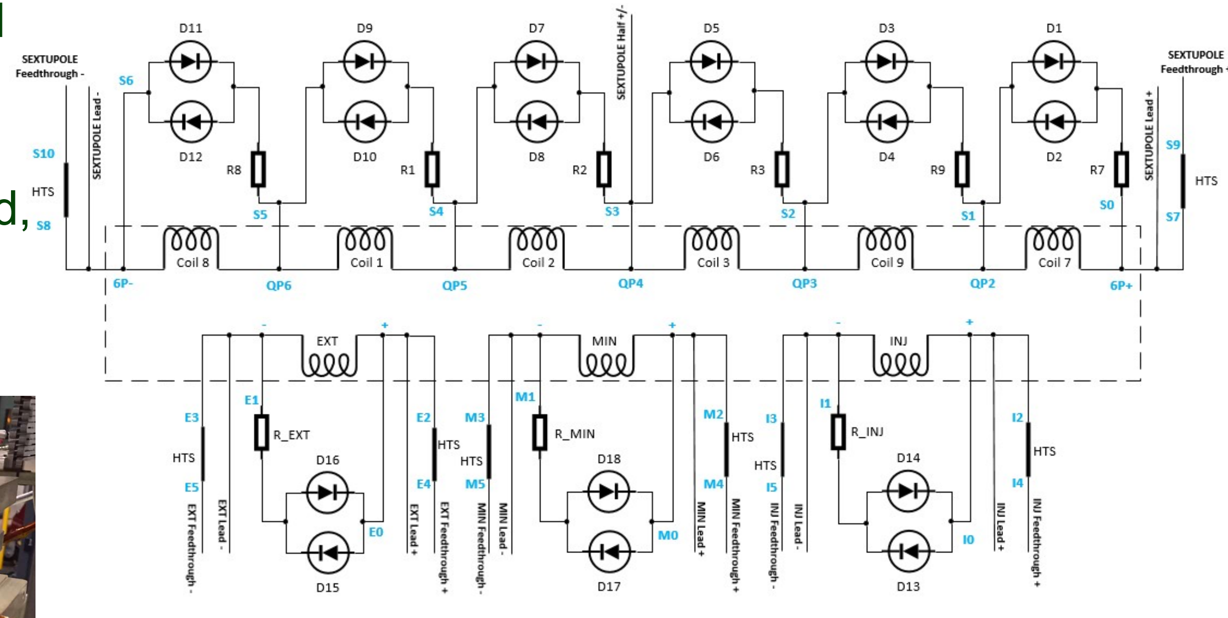


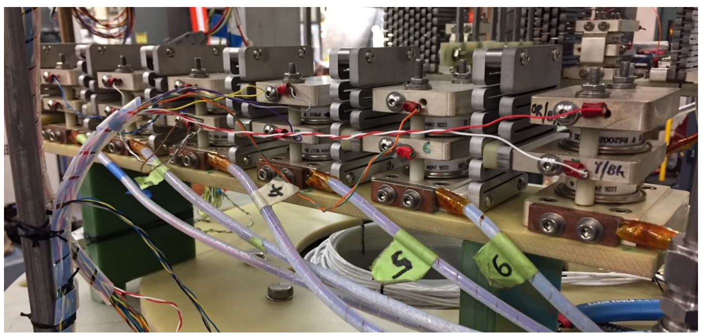
FRIB Inductive Oven Design

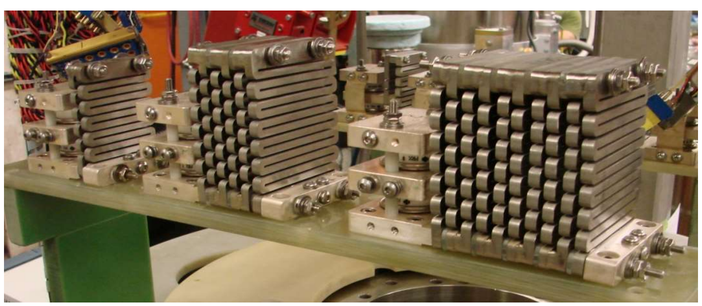
**W. Lu, L.T. Sun. et al, Rev. Sci. Instrum.90, 113318 (2019)*

Magnet Quench Protection and Interlocks

- Magnet is passively protected using internal diodes and energy extraction resistors
- Interlocks definition completed, and PLC programming and testing in progress







Coil ramp to zero:
- Helium level
- Helium pressure
- HTS voltage drop
- Coil voltage drop
- Water leak detection
- Vacuum vessel pressure
- Sensing stud
- PS water flow

Power supply disable:
- Helium level
- Helium pressure
- Coil voltage drop
- PS water flow

HP ECR Ion Source Proceeding towards Magnet and Energization and First Plasma

Objective measures	Date	
60% design review	Nov. 2017	✓
90% design review	May. 2018	✓
Cold mass delivered	Jan. 2018	✓
Cryostat assembled with magnet	Oct. 2019	✓
Shield cryo-cooler test complete	Mar. 2020	✓
Magnet power supplies installed	Aug. 2020	✓
Ion source shielding installed	Sep. 2020	✓
Magnet cooldown with local control	Dec. 2020	✓
Second GM-JT cryocooler test	Jan. 2021	✓
18 GHz Klystron test on HV platform	Jul. 2021	✓
Magnet energization and mapping	Oct. 2021	
First plasma with 18 GHz Klystron	Dec. 2021	
First beam to SCS2 beamline	May. 2022	
28 GHz Gyrotron installation & test	Dec. 2022	

- Plan to develop the second SC ECR, to ensure high availability of heavy beams

HP ECR magnet @4 K on the high voltage platform

Summary

- FRIB driver Linac system installation is complete: 46 cryomodules with 324 cavities.
- After 5 stages of commissioning, FRIB successfully commissioned beam through the entire SRF linac to the Beam Delivery System (BDS) dump and demonstrated 200 MeV/u (Key Performance Parameter of the project).
- SC ECR magnet assembled on HV platform. Magnet cooldown completed.
- Approaching to magnet energization and field measurement

We Cannot Build FRIB Alone and Are Leveraging Expertise Worldwide

- Argonne National Laboratory
  - Liquid lithium charge stripper; stopping of ions in gas; fragment separator design; beam dynamics; SRF
- Brookhaven National Laboratory
  - Radiation-resistant magnets; plasma charge stripper
- Fermilab
  - Diagnostics
- Jefferson Laboratory
  - Cryogenics; SRF
- Lawrence Berkeley National Laboratory
  - ECR ion source; beam dynamics
- Oak Ridge National Laboratory
  - Target facility; beam dump R&D; cryogenic controls
- Stanford National Accelerator Lab
  - Cryogenics
- Sandia
  - Production target
- Budker Inst. of Nuclear Physics (Russia)
  - Production target
- GANIL (France)
  - Production target
- GSI (Germany)
  - Production target
- INFN Legnaro (Italy)
  - SRF
- KEK (Japan)
  - SRF technology; SC solenoid magnets
- RIKEN (Japan)
  - Charge strippers
- Soreq (Israel)
  - Production target
- Tsinghua University & CAS (China)
  - RFQ
- TRIUMF (Canada)
  - SRF; beam dynamics

Co-authors

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