



**FRIB**

**MOXZO03**

# **FRIB 28 GHz ECR Ion Source Development and Status**

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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
- Ion sources for FRIB
- High power superconducting ion source status
- Challenges and development
- Summary

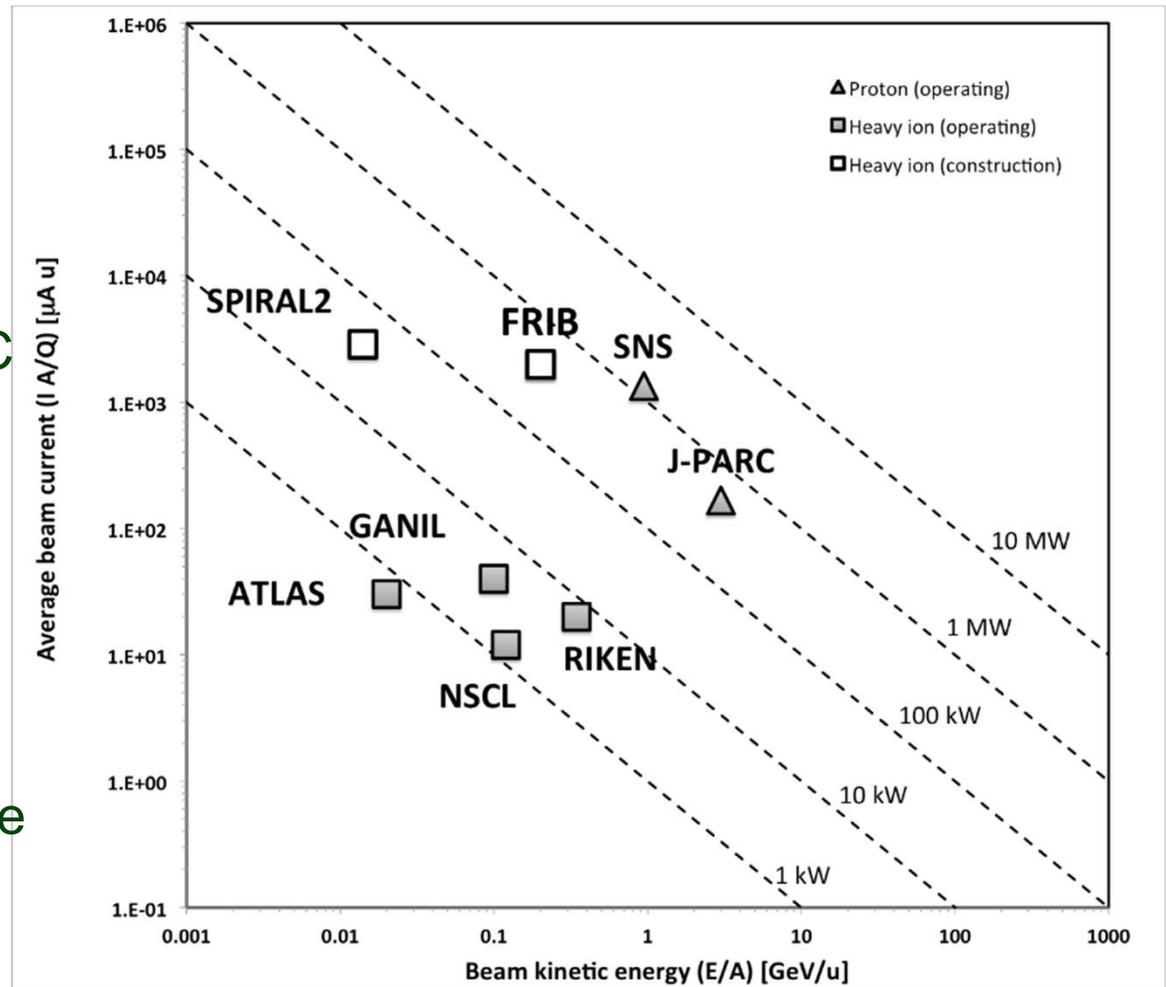


**Facility for Rare Isotope Beams**  
U.S. Department of Energy Office of Science  
Michigan State University

# FRIB at Accelerator Power Frontier

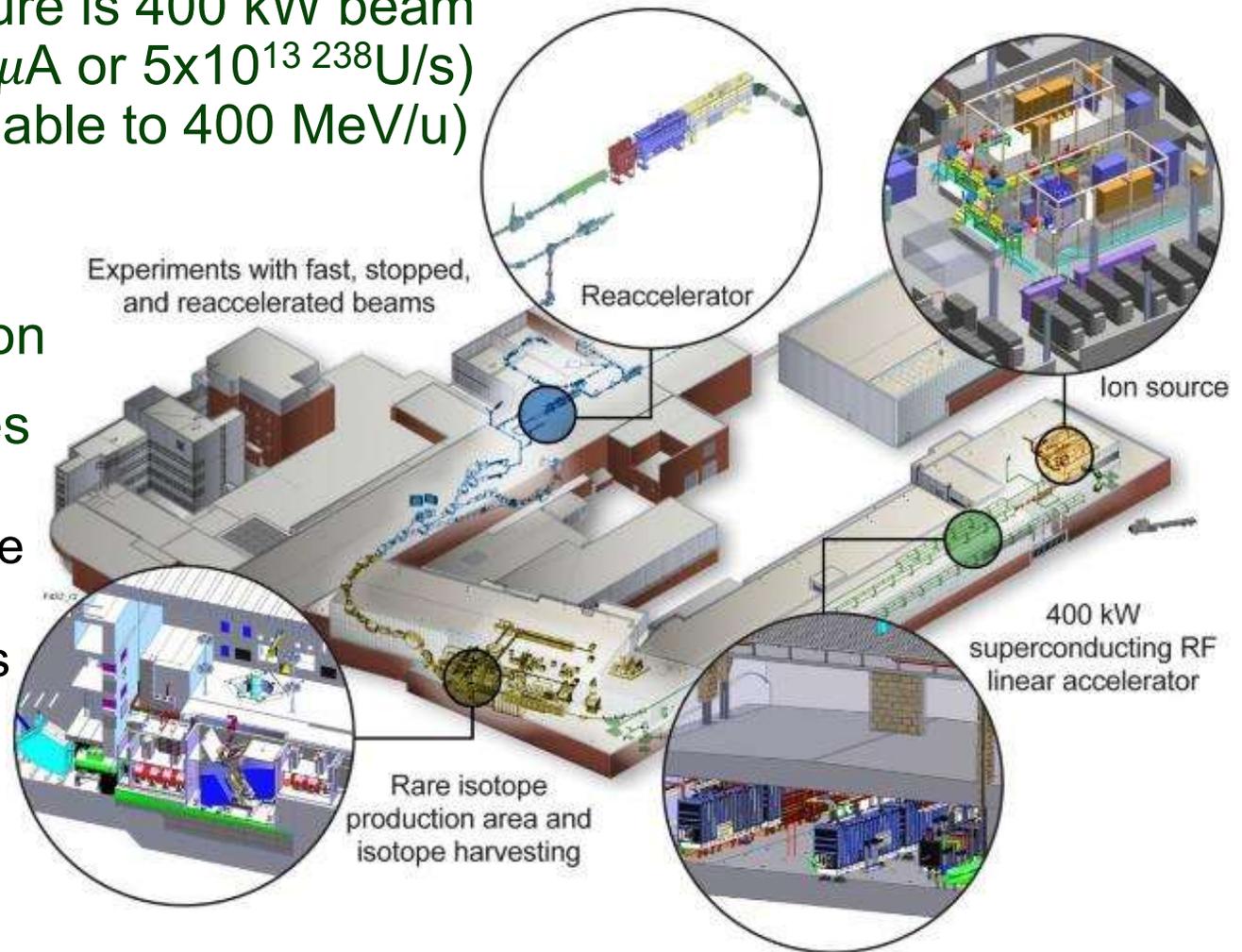
## among Three Major Frontiers: Energy, Power, Brightness

- FRIB will provide more beam power by two-to-three orders of magnitude over existing heavy-ion facilities
- Past experience for proton machines, PSI, SNS, J-PARC (now ESS), indicates steep learning curve
- Successful early operation is key to achieving desired power ramp-up profile
- Beam losses will limit power ramp-up, mitigation takes time and experience



# FRIB: CW Heavy Ion Linac + Reaccelerator with Fast, Stopped and Reaccelerated Rare Isotope Beams

- Driver Linac key feature is 400 kW beam power for all ions ( $8\text{p}\mu\text{A}$  or  $5 \times 10^{13} \text{ }^{238}\text{U/s}$ )  $> 200 \text{ MeV/u}$  (upgradable to  $400 \text{ MeV/u}$ )
- High-power target of rotating graphite for rare isotope production
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - Beams of all elements and short half-lives
  - Fast, stopped, and reaccelerated beams



# Facility for Rare Isotope Beams Projected for Early Completion in 2022

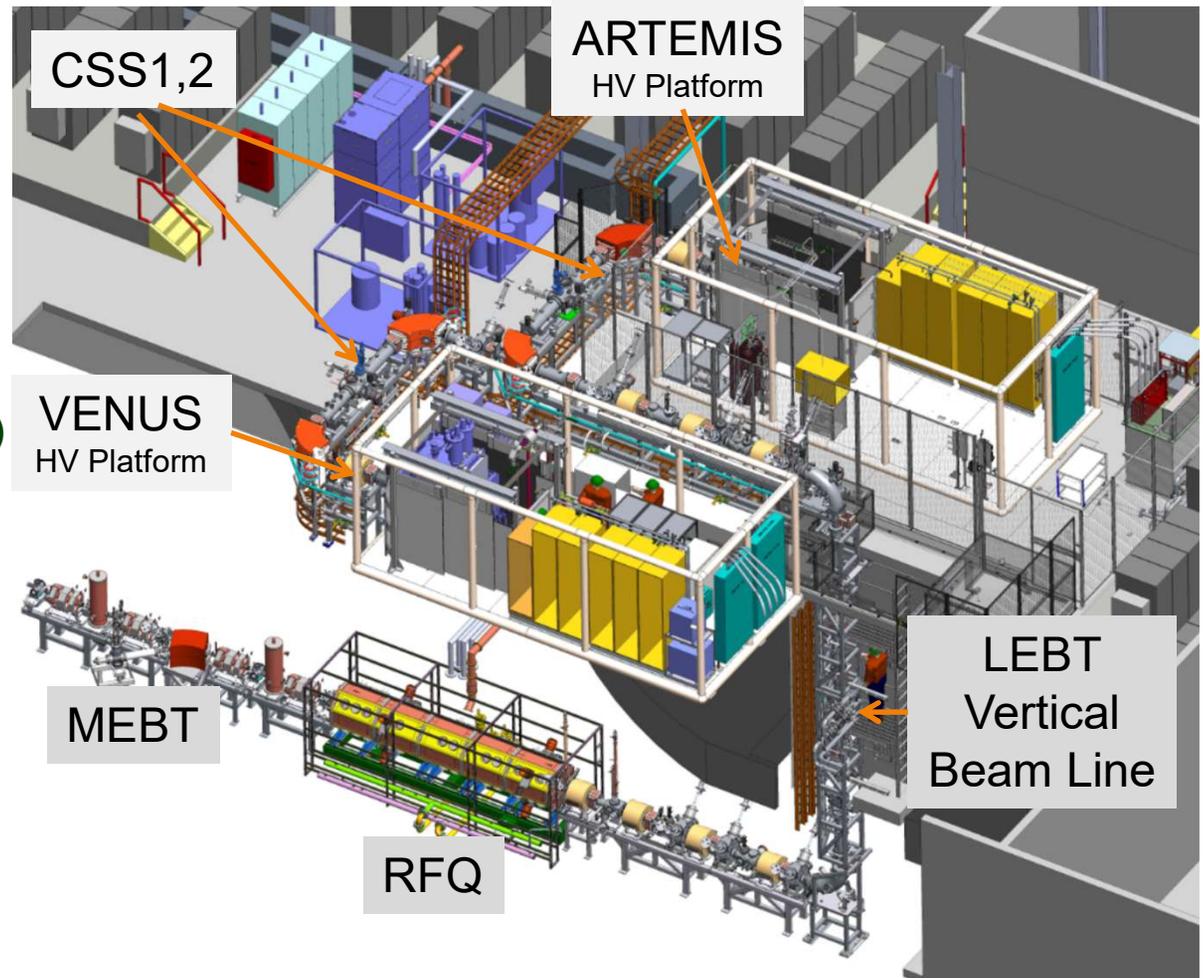
- FRIB Project constructs a \$730 million national user facility funded by the U.S. Department of Energy Office of Science (DOE-SC), Michigan State University, and the State of Michigan
- Technical construction started (CD-3) in August 2014. Planned project construction completion date is June 2022
- FRIB will be a DOE-SC scientific user facility for rare isotope research supporting the mission of the Office of Nuclear Physics in DOE-SC



**Facility for Rare Isotope Beams**  
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# Front End Systems and Operations System Overview

- Two ECR sources on High Voltage (HV) platforms
  - ARTEMIS –existing 14 GHz room temperature source
    - » Used Throughout commissioning and early operations
  - High performance source – 28 GHz based on VENUS (LBNL)
    - » Installation on going
- Low energy beam transport (LEBT)
  - $E = 12 \text{ keV/u}$
  - Chopper
  - Collimation system
  - Vertical transport line
  - Buncher and velocity equalizer
- Radio Frequency Quadrupole (RFQ)
  - $E = 500 \text{ keV/u}$
- Medium energy beam transport (MEBT)
  - Two bunchers, quadrupoles



# Ion Sources Performance Requirements

## ■ Commissioning

- 36-Ar, 86-Kr, 129-Xe Beam
- 25 to 50 euA with  $M/Q > 7$
- $\text{Ar}^{8+}$  to  $\text{Ar}^{11+}$  -  $\text{Kr}^{14+}$  to  $\text{Kr}^{17+}$  Depend on RFQ conditioning
  - $\text{Ar}^{9+}$  and  $\text{Kr}^{17+}$  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  $^{238}\text{U}^{33+}$  through MEBT with HV platform operated 71kV and RFQ at 100kW

## ■ FRIB Operations

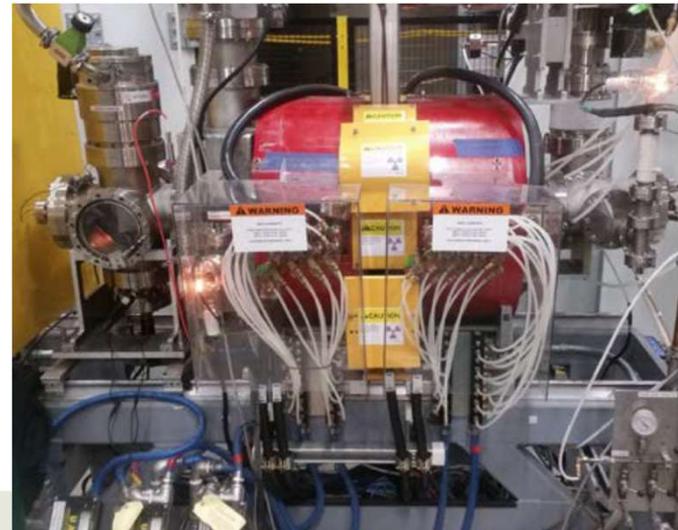
- Produce ion beams for injection into FRIB linac for a large base of stable elements ranging from oxygen to Uranium
  - » All beam required for first PAC developed with ARTEMIS except for Uranium
- Source UPP: 400 to 450euA for all elements from ion source to reach 400kW on Target (UPP) (Single Charge State) with  $M/Q > 7$
- Able to sustain intensity for several weeks (NSCL based operation)
- Beam energy 12keV/u



# 14 GHz ECR Ion Source ARTEMIS Used to Commission FRIB

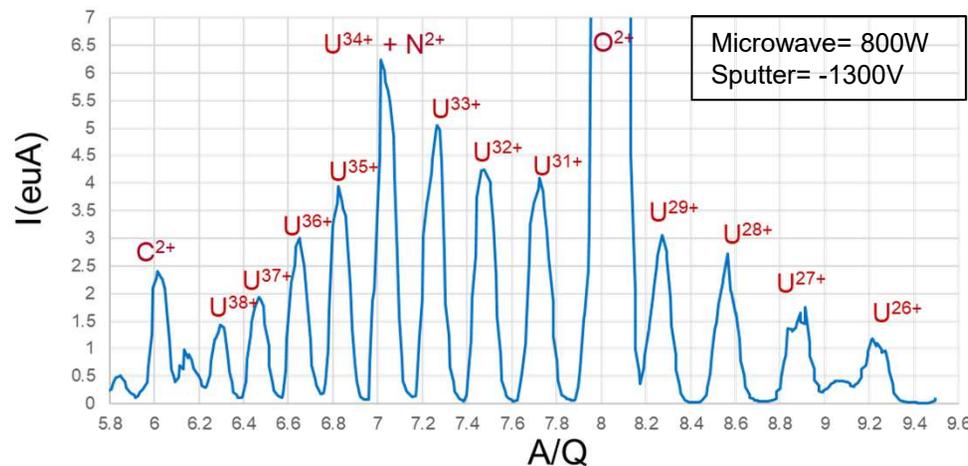
- ARTEMIS based on AECR-U design (LBNL) – 2 copies built at NSCL (1999, 2005)
  - Low risk – extensive experience at NSCL with ARTEMIS operation and maintenance
- Performance meets intensity requirement for commissioning and 1<sup>st</sup> year of operation
  - Demonstrated  $40\text{Ar}9+$  current is  $\sim 200 \text{ e}\mu\text{A}$
  - Demonstrated  $86\text{Kr}17+$  current is  $\sim 35 \text{ e}\mu\text{A}$

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	0.8T (plasma chamber)
Extraction voltage	Up to 25 kV



# Uranium Beam Developed with ARTEMIS and Accelerated through RFQ

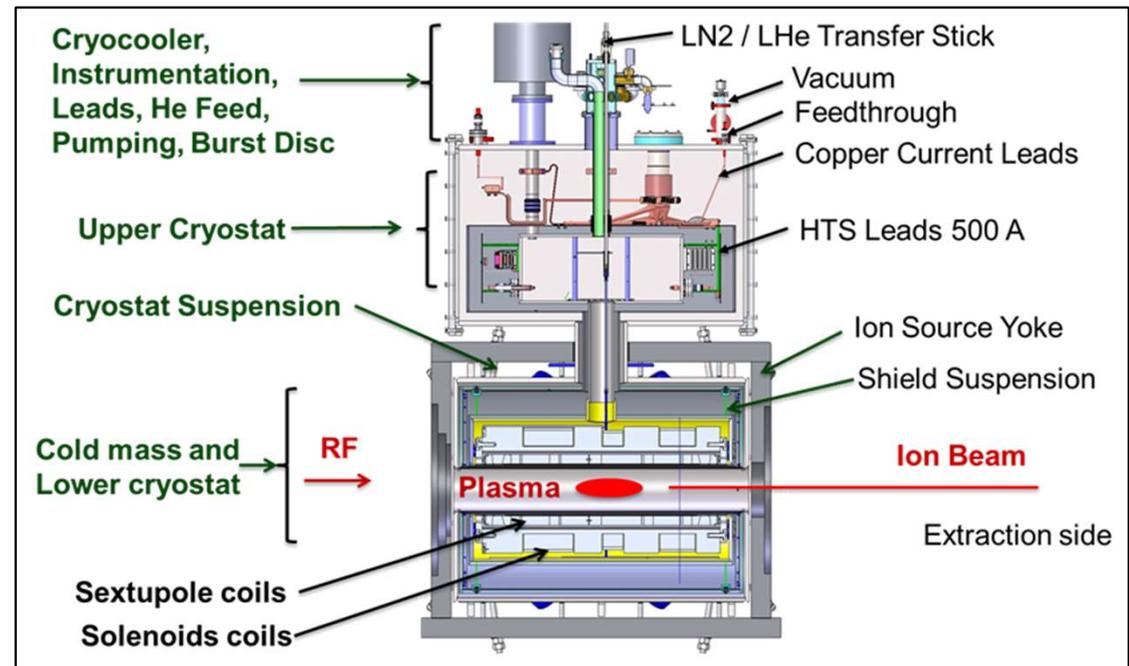
- Uranium beam was developed using sputtering in September 2020
  - Depleted Uranium sample installed on axis at ion source injection
  - Negative voltage applied to sample
  - HV platform operated at 71 kV for a total acceleration of 86 kV



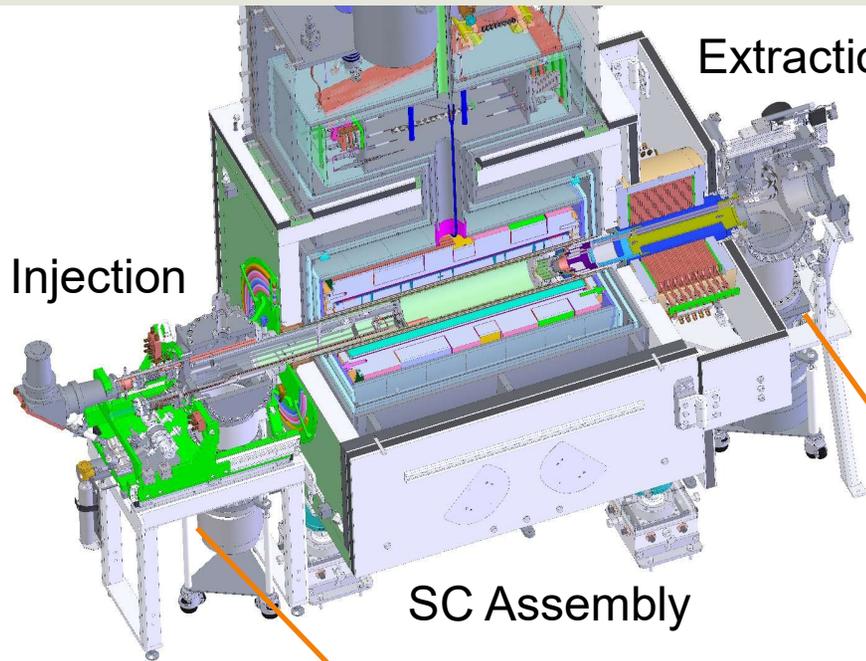
- $^{238}U^{33+}$  beam successfully accelerated through Front End
  - RFQ operated at full design power of 100 kW in CW mode
  - Measured output beam energy was 505 keV/u
  - Accelerated beam transmission through RFQ is ~80%, in good agreement with the design value

# High Power SC ECR is Under Development Completion Expected in 2021

- 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



# FRIB HP ECR Source Top Assembly



Extraction

## ■ Injection Assembly

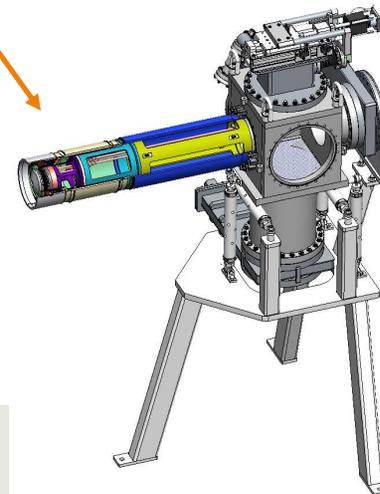
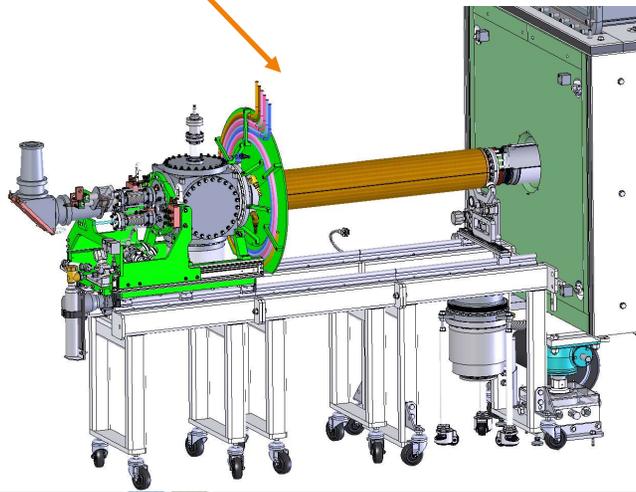
- Gas system, Ovens, Bias disk, RF waveguides

## ■ SC Assembly

- Upper cryostat, Lower cryostat, Cold mass

## ■ Extraction Section

- Plasma chamber, Electrode, puller, HV break



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Beams  
cience

Ren, ECRIS 2020, Slide 11

# 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

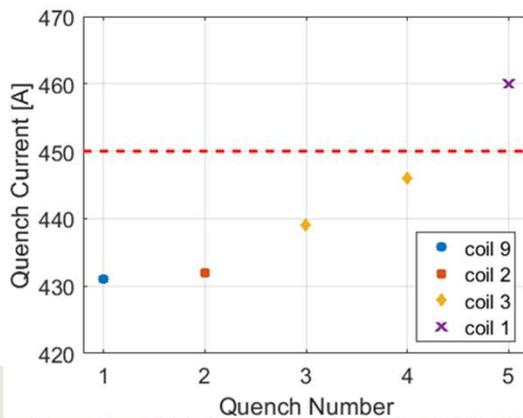
■ Sextupole training reduced from 16 to 5 quenches with new sextupole coil

- Five new quenches likely were caused by the redistribution of stresses caused by the disassembly and reloading of the magnet support structure

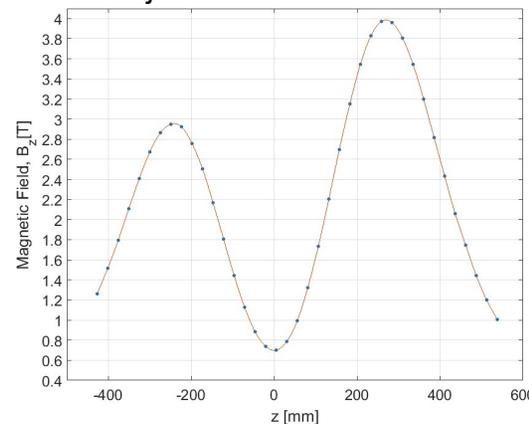
FRIB SC ECR magnet before shipping in Dec 2017



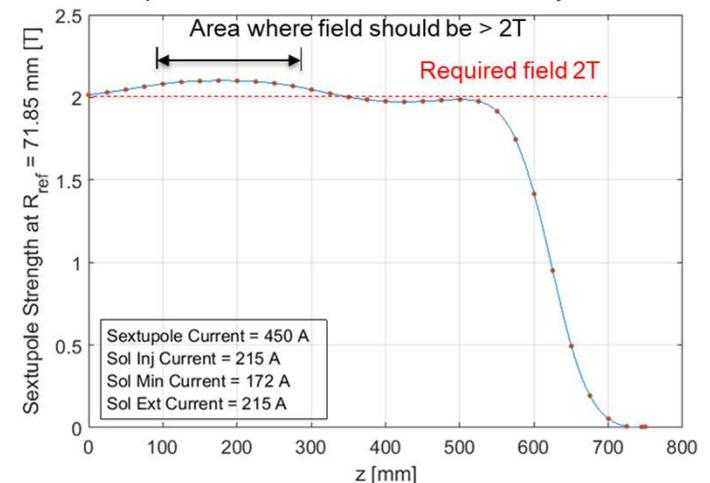
Quenches of sextupole magnet with new coil #9. Required current 450A.



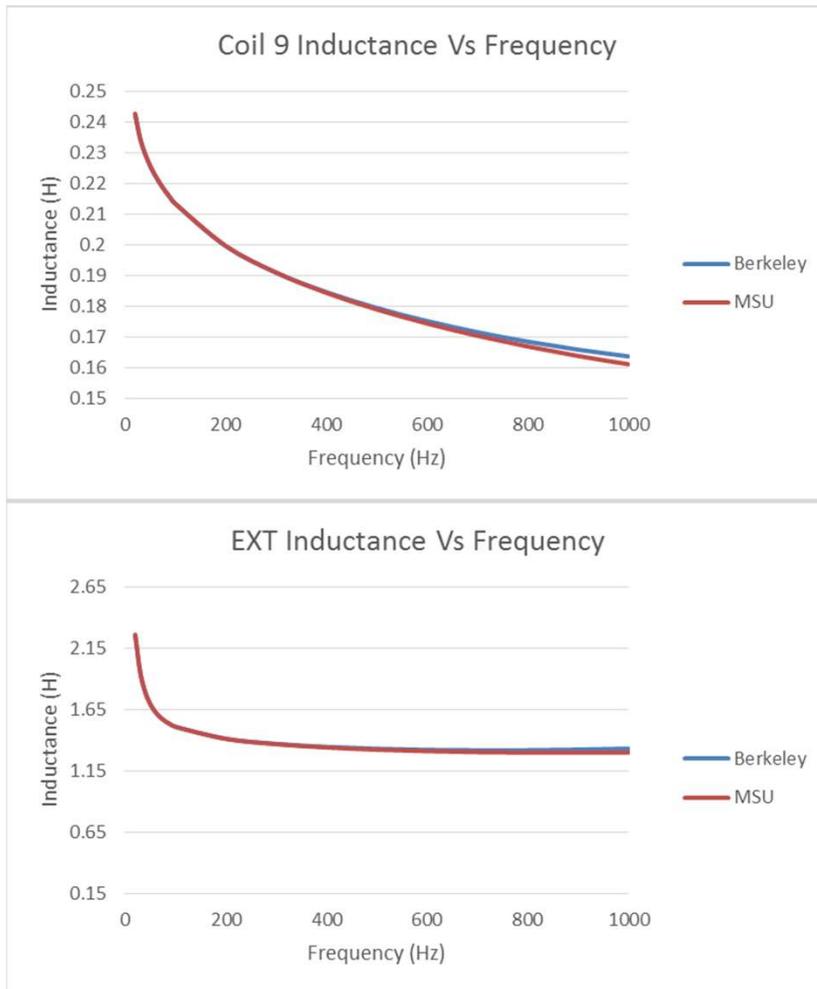
Measured solenoid magnetic field. Required fields 3T at extraction and 4T at injection.



Sextupole field. Probe cannot reach beyond  $z < 0$ .



# HP ECR Magnet Delivered to FRIB in January 2018



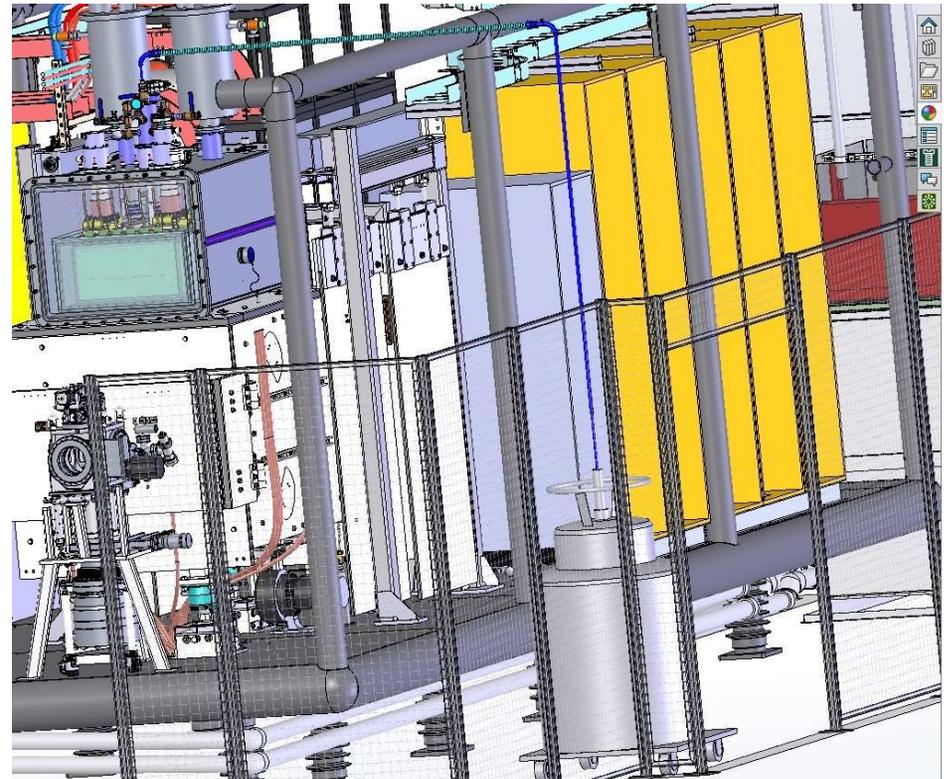
Magnet in FRIB ECR Building



Electrical Check upon delivery done in 2018

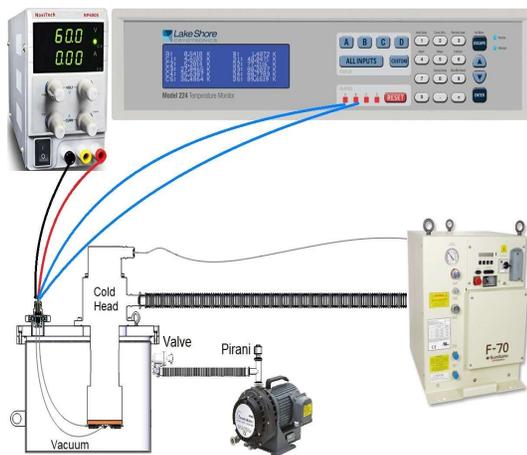
# Magnet Cooldown Plan

- Verification of electrical connections before cooldown
  - Pump down isolating vacuum
  - Preparation checklist
- Pre-cool with liquid Nitrogen
  - Pump down the cryostat
  - Fill cryostat with liquid Nitrogen
  - Blow out Nitrogen
- Helium transfer
  - Cool down cold mass to 4.2 K
  - Turn on cryocoolers
  - Turn on cryostat pressure regulation
  - Monitor temperature, pressure and helium level

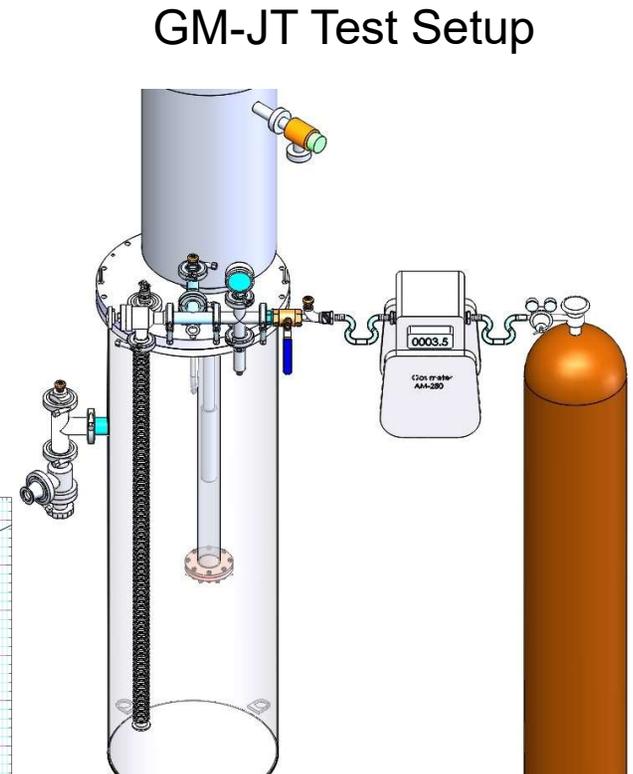
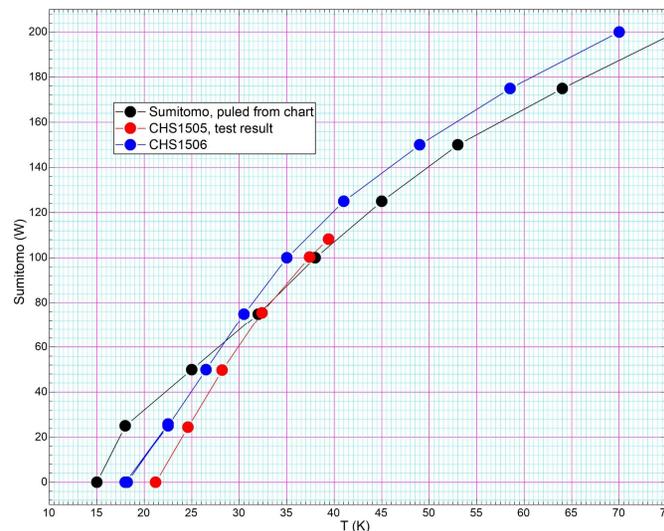


# Cryocooler Test In Progress

- Shield cryocoolers CH-110 test completed successfully
  - Both cryocoolers were brought to ~20 K
- GM-JT cryocooler test in progress
  - Reached 4.2 K but recondensation was not successful due to a thermal short in test setup
  - Test to be continued after modifications to eliminate thermal short

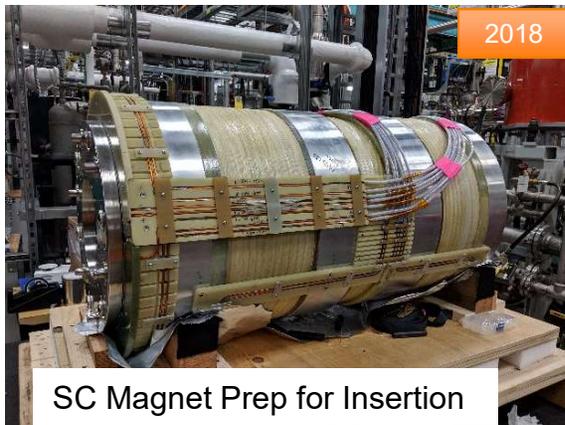


CH-110 Test Setup



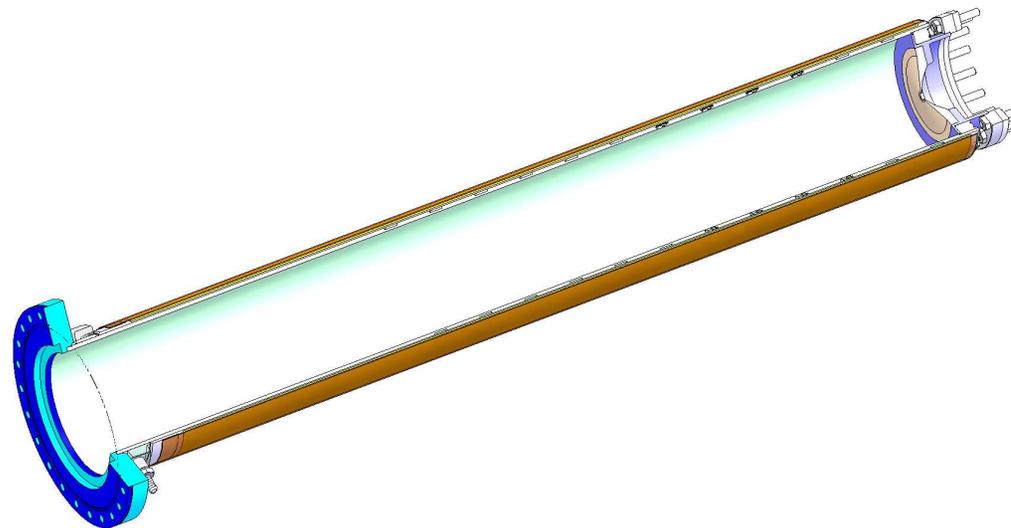
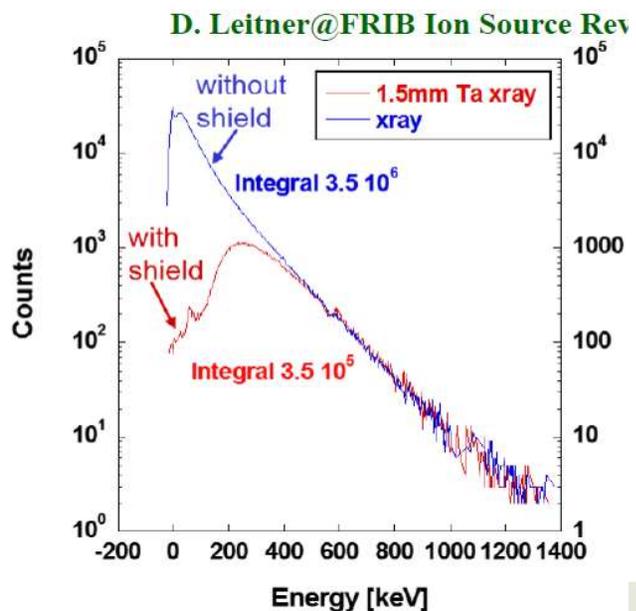
# HP ECR IS Proceeding towards Magnet Cooldown and Energization

- Cryostat coldmass and vacuum vessel assembly completed
- Integration of HV platform in process
  - Water system installed and pressure tested
  - Isolation transformer and HV platform tested to 100kV successfully
  - Power supplies installation and testing completed on HV platform
  - Room temperature solenoid attached to the IS yoke
  - Ion source shielding installed



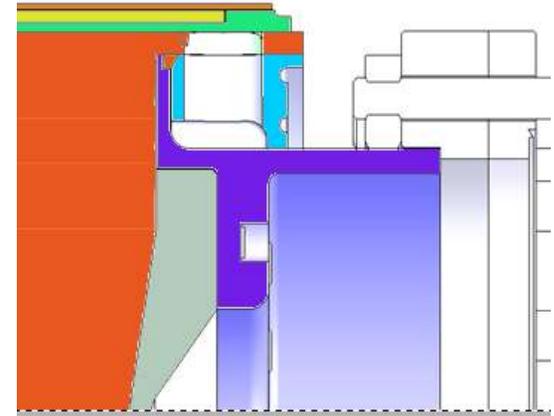
# X-ray Damage to Components and Mitigation in Design

- 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)
  - Since PEEK is a costly option, Kapton was chosen as a baseline material
- Flux of X-rays attenuated through 1.5 mm Tantalum (VENUS) / 2mm Tungsten (FRIB) shield
  - Cylindrical tube outside of plasma chamber tube

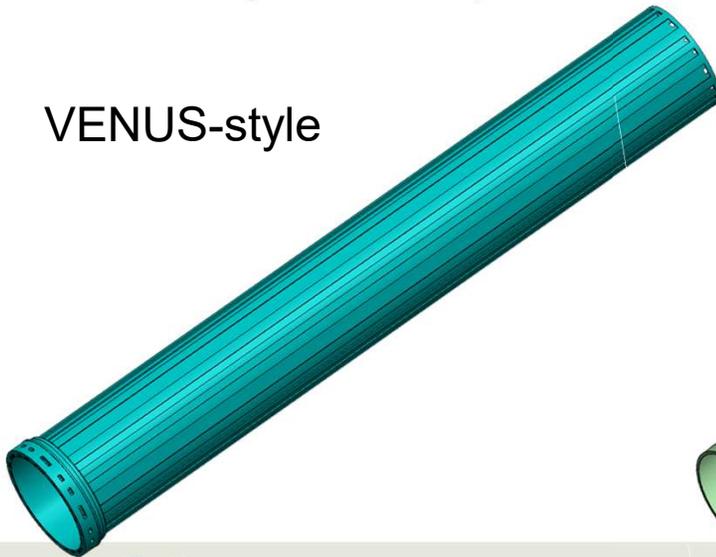


# Plasma Chamber Mechanical Design

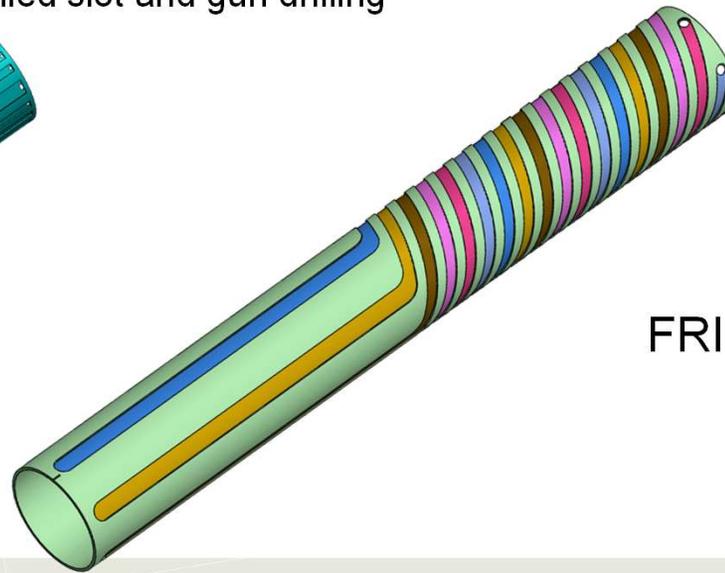
- Lessons learned from other SC ECR ion source
  - Cooling scheme has to be optimized for every components in the plasma chamber
- Plasma chamber consists of the following
  - Aluminum tube with a spiral cooling channel milled into it
  - Aluminum sleeve tube to act as a water jacket
- Opted for a spiral milled path versus straight water channels
  - Assumptions
    - » More turbulence due to spiral flow path
    - » Minimize the stratification of vapor bubbles
    - » Straight milled path on bottom could easily form a vapor layer
  - Less water channels (3 vs 6)
  - Ease of manufacturing versus the hybrid hole/milled slot and gun drilling option



VENUS-style



FRIB-style



# Plasma Chamber Analysis Summary

- Plasma chamber incorporated changes from thermal analysis
  - Tighter spiral pattern ( $64^\circ \rightarrow 68^\circ$ )
  - Wider width of channel ( $1/2'' \rightarrow 5/8''$ )
  - Depth of channel ( $.065'' \rightarrow .078''$ )
- All of these changes led to the design being able to handle 9 kW operation where:
  - Maximum stress of 235 MPa where limit is  $2 \times \sigma_y$  (258 MPa)
  - Maximum temperature is  $187^\circ\text{C}$
- Requires ~5 gallons per minute (GPM) per channel (15 GPM total) to safely cool 9 kW
  - 9-10 m/s flow velocity
  - 60 psi drop within plasma tube
- These water cooling requirements are however difficult to achieve with an Aluminum tube

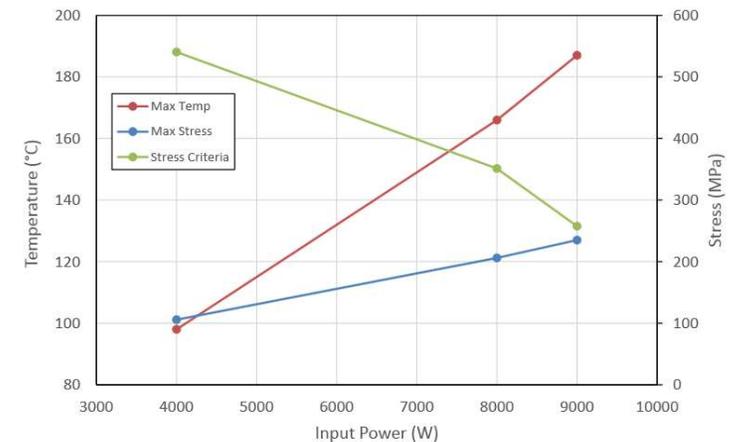
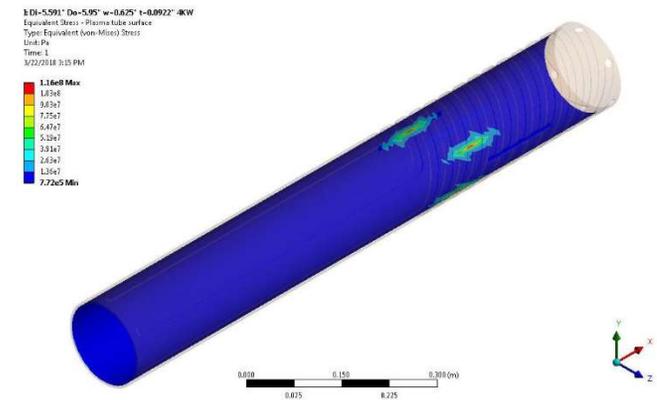


Figure 34: Maximal temperature and stress at different input powers

# Oven Design for High intensity Uranium beam

## Uranium Properties

- Uranium melts at 1,132 C (Very Reactive)
- Uranium Oxide sublimate (1-10 mTorr vapor pressure around 2000C)

## For 450euA U<sup>33+</sup> produced at LBNL with VENUS

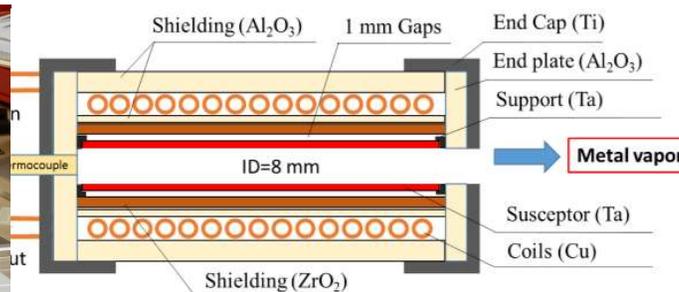
- Resistive Oven was destroyed under Lorentz forces
- Need to reach Higher temperature to get more vapor

## Adapt and improve inductive oven used at NSCL for FRIB HP ECR

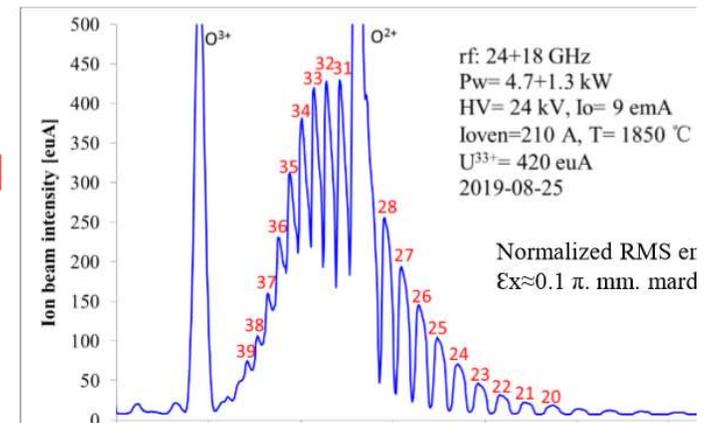
- Inductive oven used at NSCL for Nickel and Germanium (1500 °C)
- IMP (China) with a similar design demonstrated temperature > 2000 °C)



NSCL ARTEMIS  
Inductive Oven-1500 °C



IMP inductive oven >2000 °C



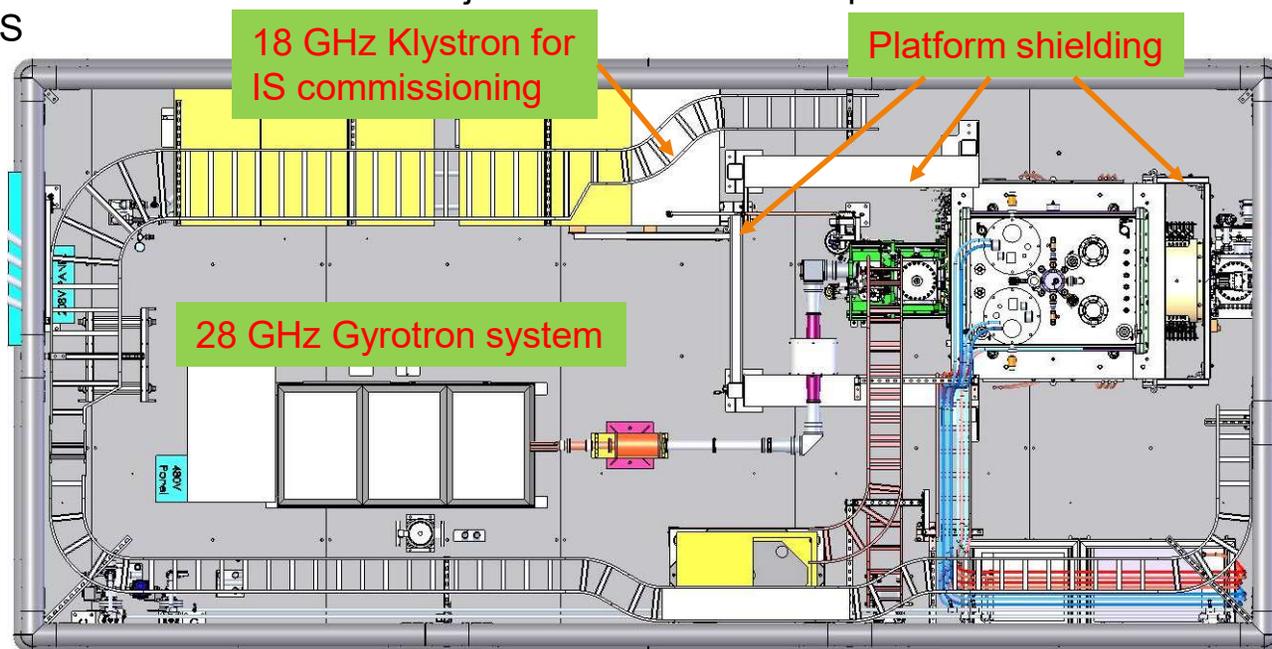
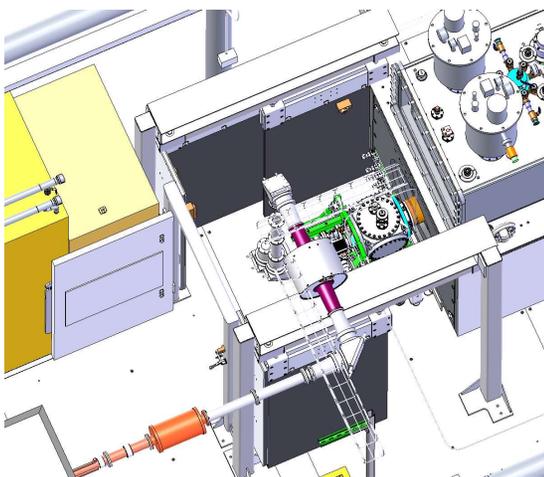
IMP uranium performance (28GHz)

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

# HV Platform Assembly and Shielding Design

- Radiation shielding includes:
  - Shielding components mounted directly on ion sources (installed)
  - Shielding Components at ion source injection (designed but not procured)
  - Shielding Components along Beamline (Not Designed)
- Ion Source
  - Most sides includes 2-3" of yoke steel, ¼" steel cladding, 1-1/4" thick lead, and ½" more of steel cladding
- Platform
  - Injection curtains are ½" thick lead and ¼" steel while the injection door has a lead piece 1-1/2" thick
  - Design very similar to ARTEMIS

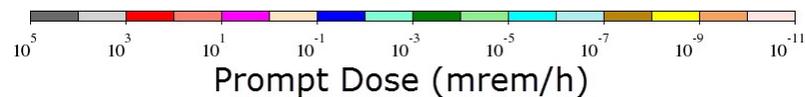
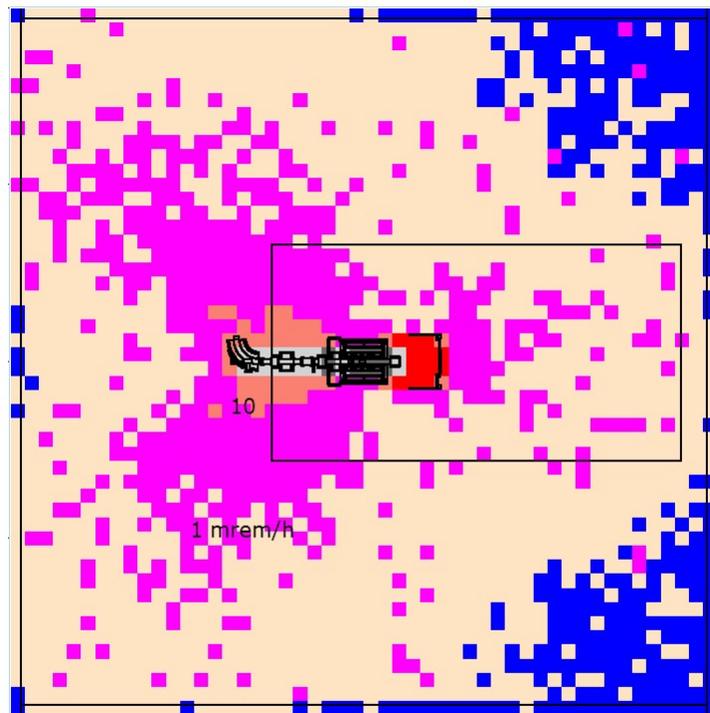
Injection Radiation Shielding



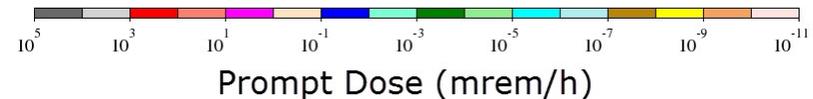
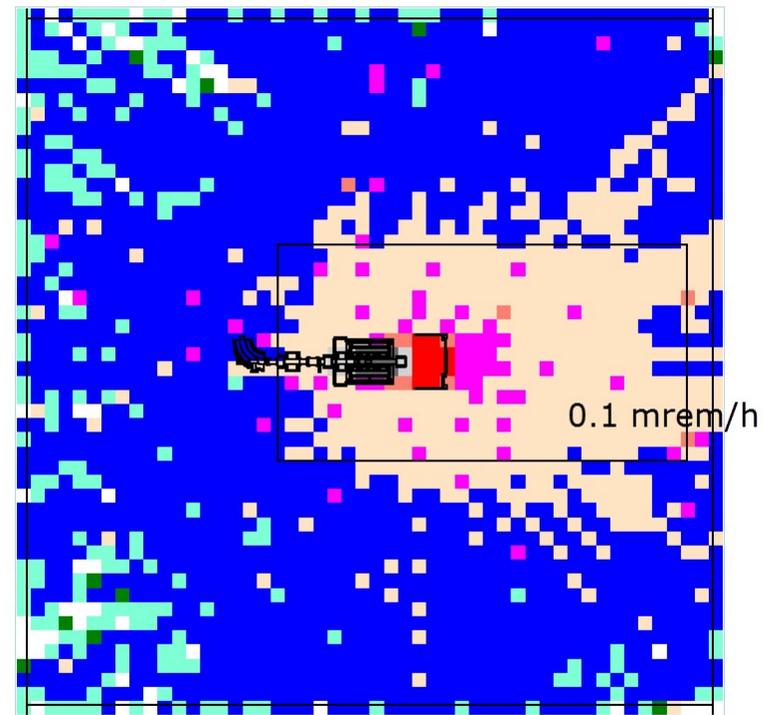
# Dose contribution from Beamline

- Contribution to dose from extraction optics is significant (dominant)
  - Need to add protection around bending magnet or around beamline (Not designed)

Unshielded and Unblocked Like



Blocked Line



# Path Forward and Schedule

- Nov-2020: Start magnet cooldown
- Dec-2020: Energize magnet and complete field mapping
- Jun-2021: Produce the first gas plasma with 18 GHz Klystron
- Dec-2021: Finish installation of the ion source and beamline. Ready for beam test



# Summary

- $^{238}\text{U}^{33+}$  beam developed with 14 GHz ECR ARTEMIS and accelerated through RFQ
- Design of the FRIB High power ECR followed closely the design of VENUS
  - Cold mass designed, built and tested at LBNL meet specifications
- Cryostat assembly complete with magnet on the HV platform
- Assembly on the platform is in progress towards magnet cooldown and energization by end of 2020

