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FRIB

FRIB ECR Ion Sources Operation and Future Development

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U.S. DEPARTMENT OF ENERGY | Office of Science

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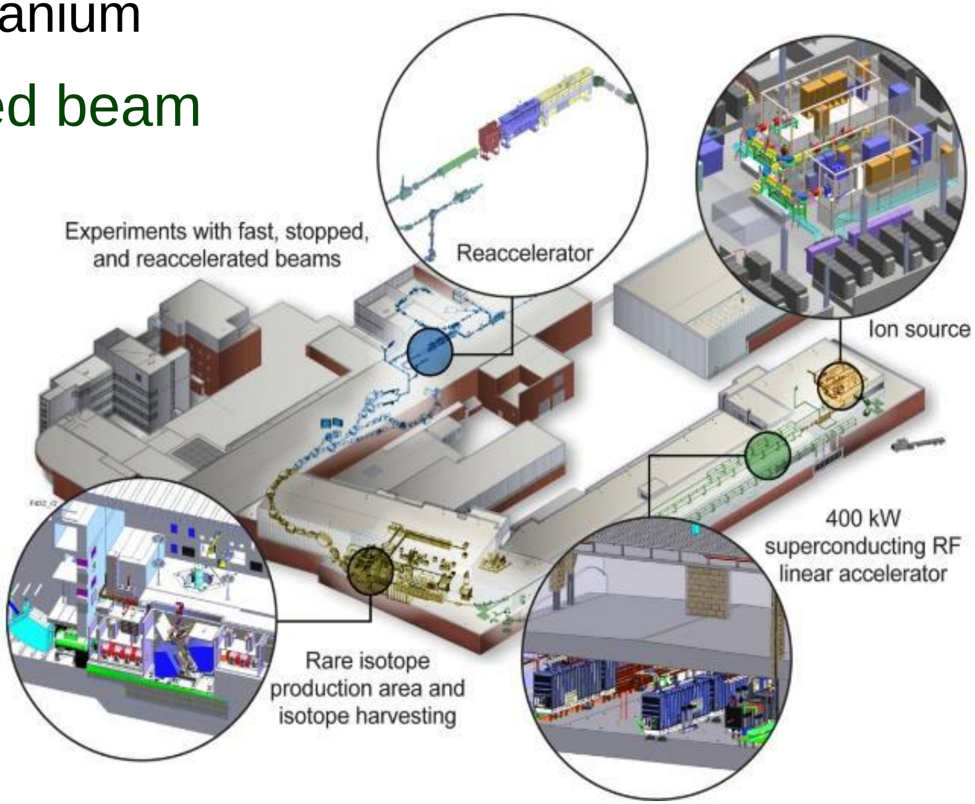
Outline

- FRIB Introduction
- Ion source operations status
- Key technologies development
  - Microchannel cooling plasma chamber
  - High-temperature oven
  - 28 GHz microwave system
- Second 28 GHz ion source development
- Summary

FRIB- Facility for Rare Isotope Beam

World-leading Next Generation Rare Isotope Beam Facility

- Rare Isotope production via in-flight technique with primary Beams up to 400kW, 200MeV/u (400 MeV/u upgrade)
  - Primary beam from Oxygen to Uranium
- Fast, stopped and re-accelerated beam
- FRIB linac includes:
  - 2 ECR ion sources, 1 RFQ
  - 46 superconducting cryomodules (3 linac segments)
    - »324 SRF cavities (β=0.041, to 0.53)
  - 208 cold, 350 warm magnets
  - Liquid helium for 2 K, 4 K operations
  - Liquid lithium charge stripping
  - Rotating target for isotope production



Timeline of the Facility for Rare Isotope Beams (FRIB)

Key Milestones:	Date
DOE and MSU sign cooperative agreement	2009
CD2-3a Start of civil construction and procurement. **LBNL CDR for SC-ECR Start**	2013
Start of technical construction	2014
First beam from 14 GHz ECR ion source Start of beam commissioning	2016
Front End Commissioning (ARR1). **Delivery of SC-ECR Cold mass to FRIB**	2017
Linac Segment 1 (β=0.041) (ARR2)	2018
Linac Segment 1 (β=0.085) (ARR3)	2019
FS1, Linac Segment 2 (β=0.53) (ARR4), 200MeV/u Demonstrated	03/ 2020
FS2, Linac Segment 3 (β=0.53) (ARR5)	04/ 2021
BDS, target hall pre-separator (ARR6)	10/ 2021
Project technical completion. **SC-ECR first plasma at 18 GHz (ARR7)**	01/ 2022
CD-4 Project Completion	04/ 2022
Start of user experiment at 1kW beam power	05/ 2022
First beam from SC-ECR	10/2022
SC-ECR Integrated into Operations	01/2023

FRIB Has Been Delivering Beam To Scientific Users Since May 2022

- Hours delivered for user operations
  - FY 2022: 3677 Hours with 93% beam availability
  - FY 2023: 4252 Hours with 91% beam availability
    - » 998 Hours for Single Event Effect (FSEE for Industrial users)
    - » 1 Week commitment per month (testing area at the end of LS1)

- Planned power ramp up in 6 years
  - May 2022: 1 kW
  - November 2022:3 kW
  - February 2023: 5 kW
  - **October 2023: 10 kW**
    - » Successful test in July 2023 with 48Ca/36Ar
  - Aim at reaching 400 kW around 2028

Epoch	1	2	3	4	5	6
Beam Power (kW)	**10**	**20**	**50**	**100**	**200**	**400**
14 GHz ARTEMIS Light ion beams (gas)	■	■	■	■	■	■
14 GHz ARTEMIS Heavy ion beams	■	■				
28 GHz SC-ECR light to Heavy ion beams	■	■	■	■	■	■
Dual charge state heavy ions					■	■
Rotatable target ,1 Slice	■	■	■			
Rotatable target ,Multi Slice			■	■	■	■
Beam Dump 6º slant (S-shape)	■	■				
Rotatable beam dump, 1mm wall			■	■	■	
Rotatable beam dump, 0.5 mm wall						■

More than 210 Rare Isotope Beams Have Been Delivered to FRIB Experiments

Experiments since December 2022:

E21001: ^{42}Si, ^{43,44}P

E21010: ^{19}Ne, ^{20}Na, ^{21,23}Mg, ^{22,24}Al, ^{23,25}Si, ^{26}P, ^{27}S

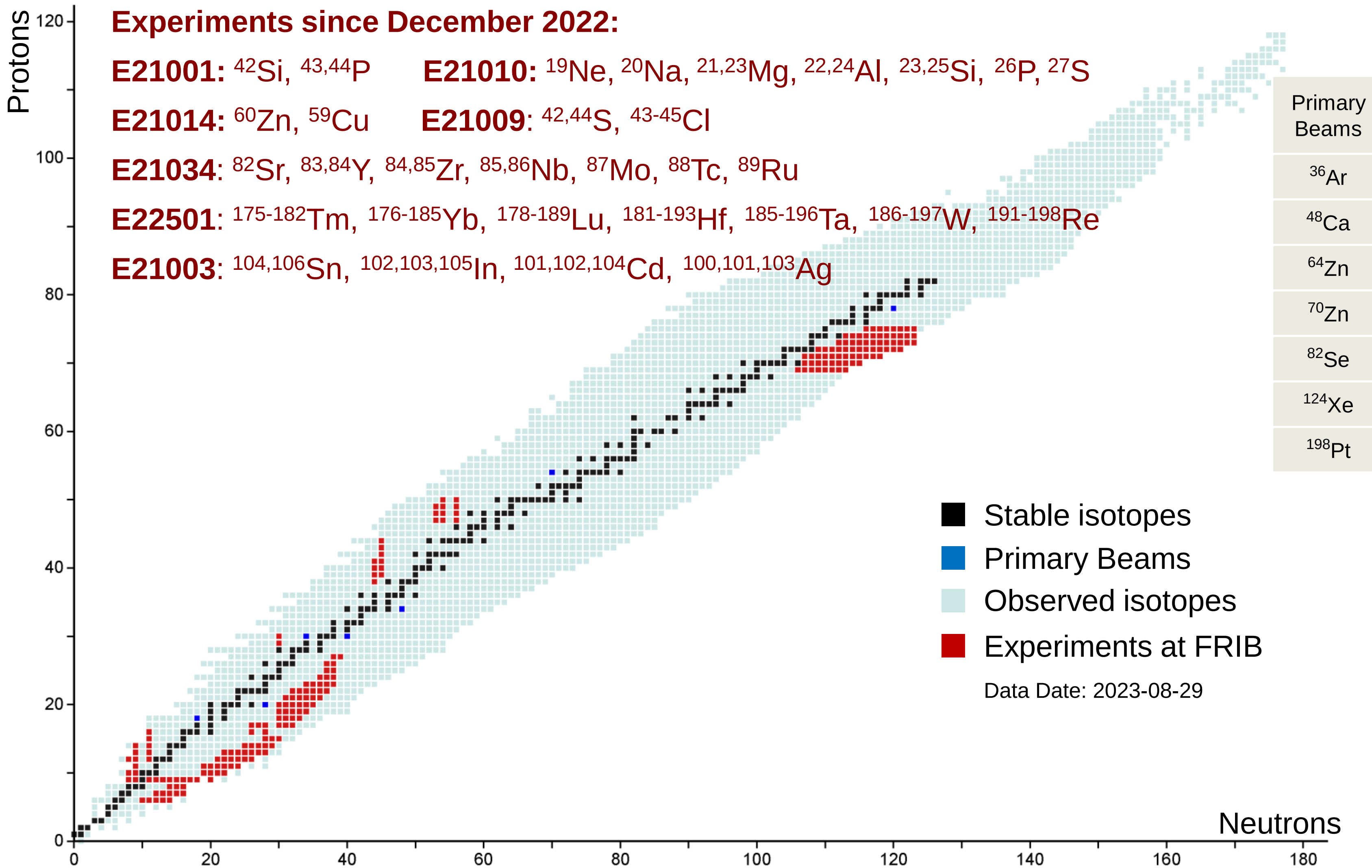
E21014: ^{60}Zn, ^{59}Cu

E21009: ^{42,44}S, $^{43-45}$Cl

E21034: ^{82}Sr, ^{83,84}Y, ^{84,85}Zr, ^{85,86}Nb, ^{87}Mo, ^{88}Tc, ^{89}Ru

E22501: $^{175-182}$Tm, $^{176-185}$Yb, $^{178-189}$Lu, $^{181-193}$Hf, $^{185-196}$Ta, $^{186-197}$W, $^{191-198}$Re

E21003: ^{104,106}Sn, ^{102,103,105}In, ^{101,102,104}Cd, ^{100,101,103}Ag

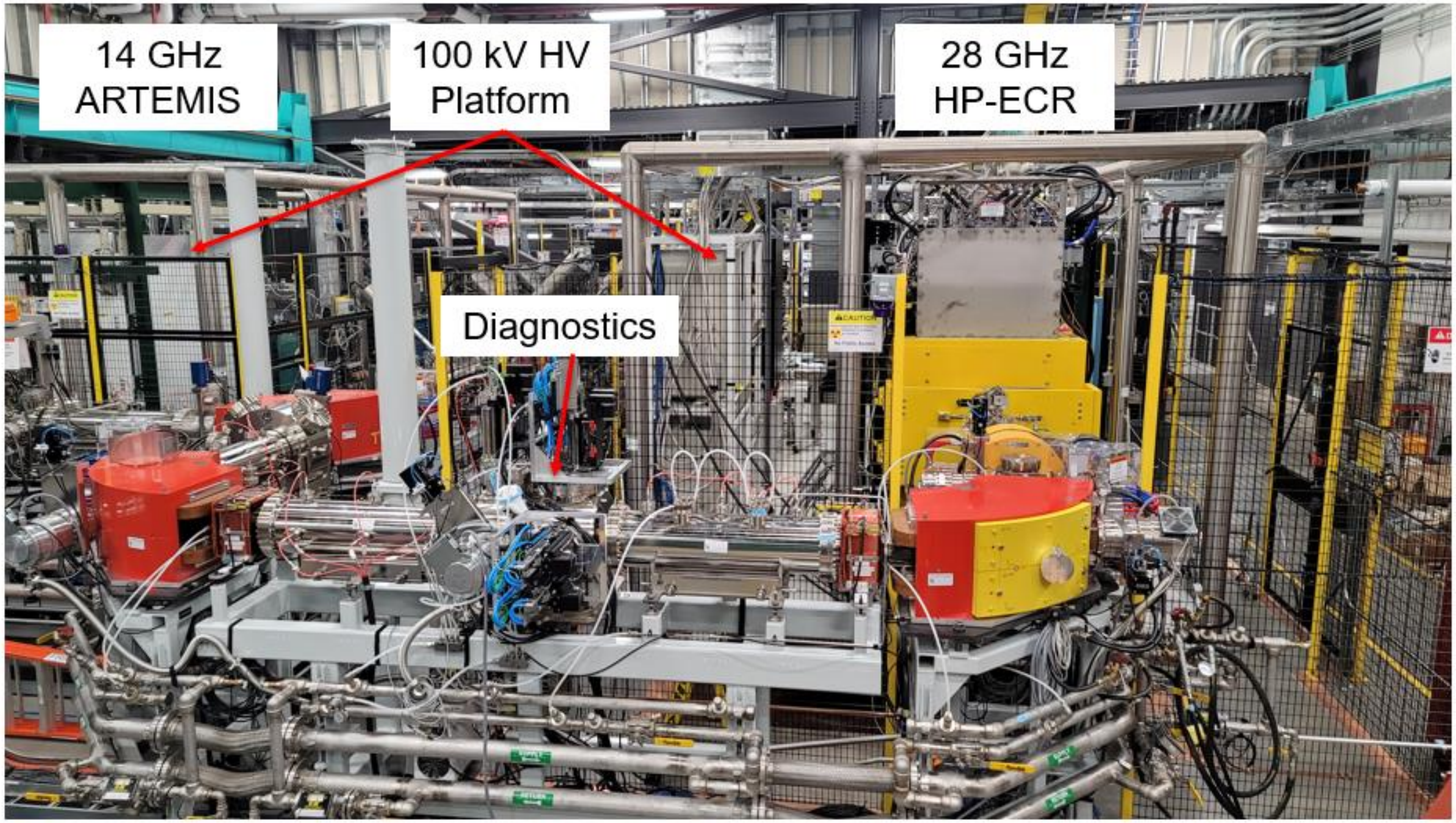


FRIB Requirements for Ion Sources

- Beam energy requirement from ECR is 12 keV/u
  - Ion source floating on 100 kV HV platform
- Charge state
  - Q/A from 1/3-1/7. For Uranium Q=33+, 34+
- Intensity :
  - ~2 euA from ion source /kW of beam on Target
    - With 10kW on target , ion source needs to provide ~20 euA
  - ~400 euA for a wide range of elements for 400 kW on target
    - Two charge states transport and acceleration from ion source
- Transverse emittance requirement
  - 0.1 $\pi.mm$.mrad RMS normalized

Front End Ion Sources on HV Platform
Dual-source Operations, More Time for Users

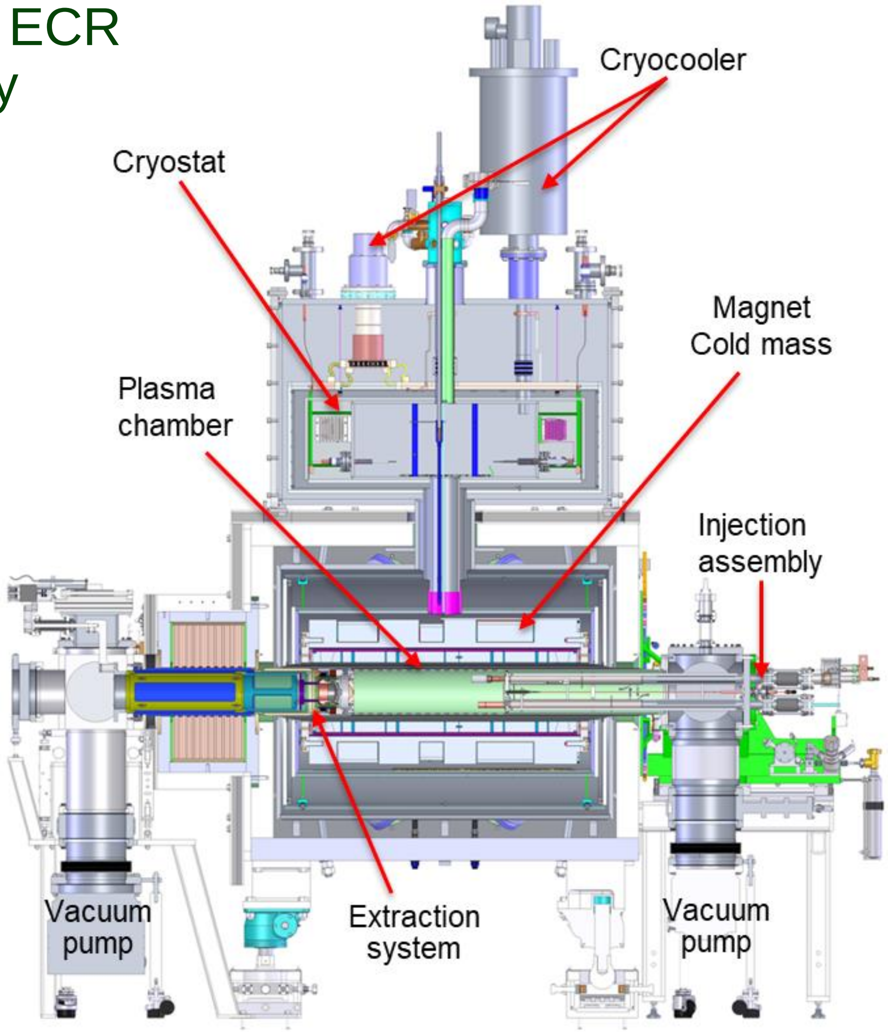
- Ion Species
  - Already developed: 36Ar, 48Ca, 70Zn, 82Se, 124Xe, 198 Pt
  - Next to be developed: 28Si, 58Ni, **238U** (for 10 kW beam operation)
  - Cocktail development for industrial users (Ar, Kr, Xe, Bi, Tm, etc.)



High-Power ECR Ion Source

- FRIB develops 28 GHz superconductor ECR ion source in collaboration with Berkeley
  - Cold mass - LBNL
  - Cryostat - FRIB
  - Conventional components - FRIB

Parameters	HP ECR
RF Frequency (GHz)	28 + 18
RF Frequency (kW)	10 + 2
Axial Field Peaks (T)	4.0 (Inj.), 3.0 (Ext.)
Mirror Length (mm)	500
Resonance zone Length (mm)	170
B_{min} (T)	0.4~0.8
B_r at Plasma Chamber Wall (T)	2.0
SC-material	NbTi
Chamber ID (mm)	143.5
Max. Cooling Capacity@4.2 K (W)	10
Max. extraction voltage (kV)	30

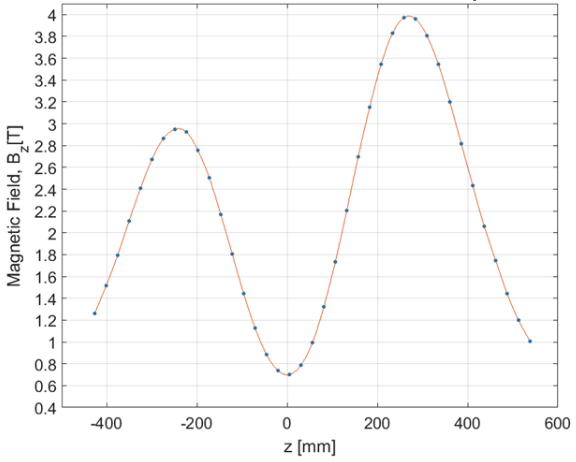


FRIB ECR Cold Mass Magnet Based on VENUS
Designed and Fabricated by ATAP (LBNL)

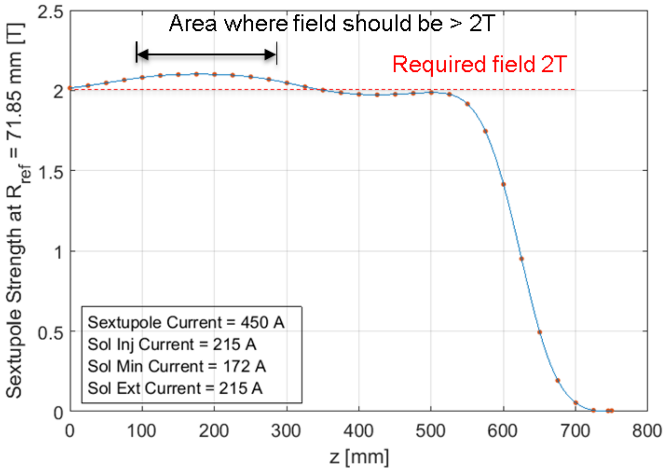
- Met Performance Requirements
  - 28 GHz resonance zone 170 mm long
  - Sextupole field at plasma chamber wall (R=71.85 mm): 2.03 T
  - Solenoid field 3 T at extraction and 4 T at injection
  - Adjustment of B_{min} demonstrated without quenching
  - Field cycling from 0 to the nominal value demonstrated without quenching

FRIB SC ECR magnet at Berkeley in November 2017

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

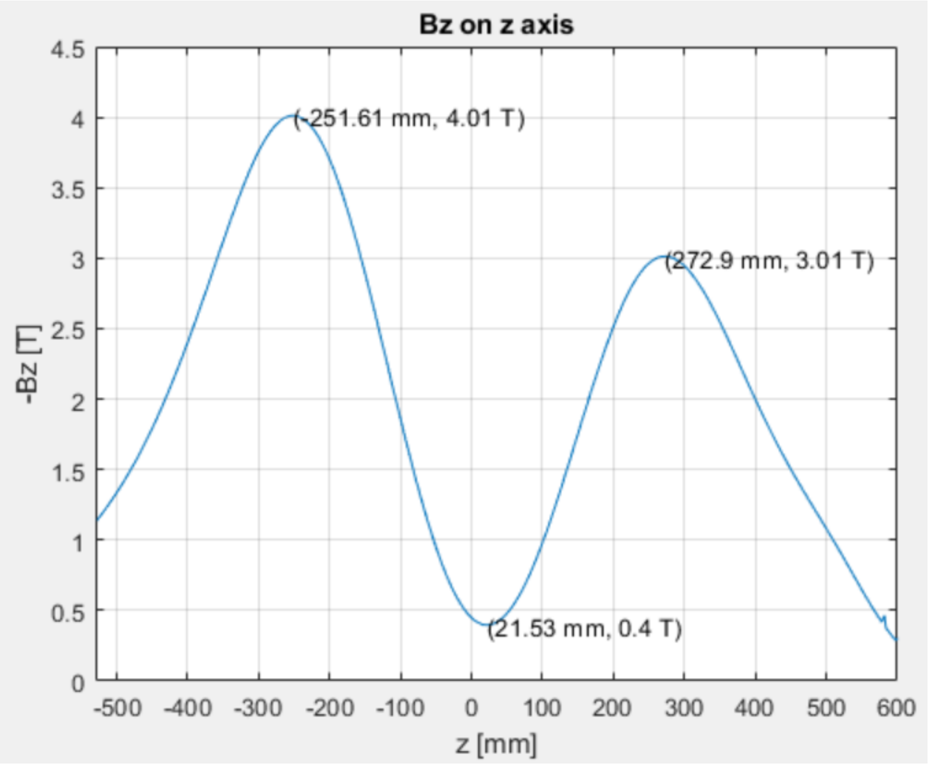


Sextupole field. Probe cannot reach beyond z<0.

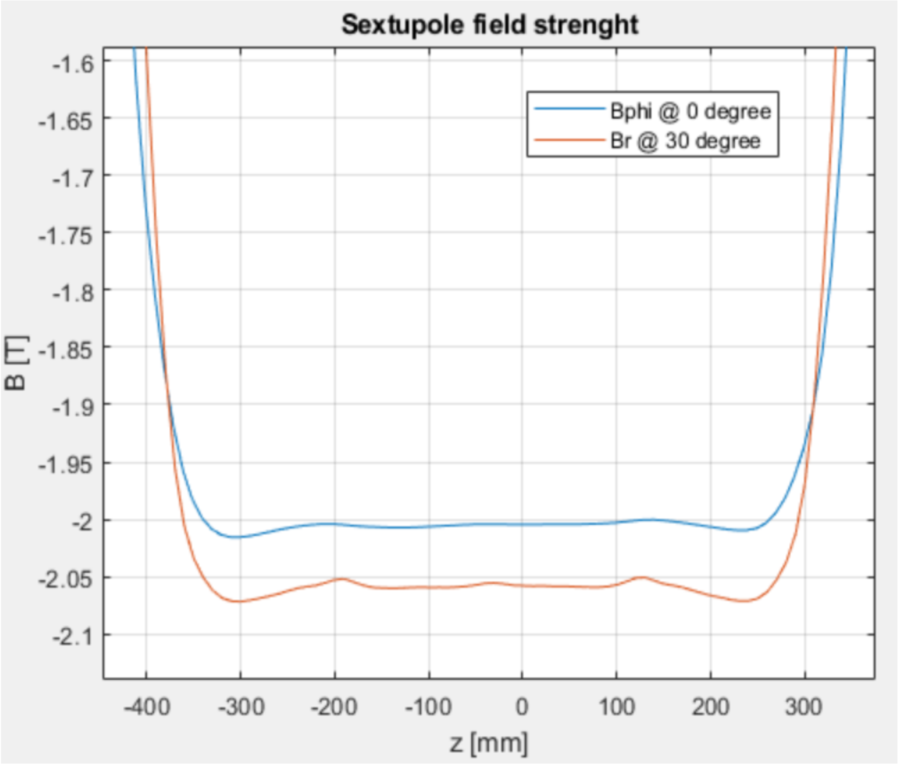


Magnet Ramped to Full Design Field after Integration into the Cryostat

- Only one quench happened during first energization in cryostat
- The magnetic field has met the requirements of 28 GHz



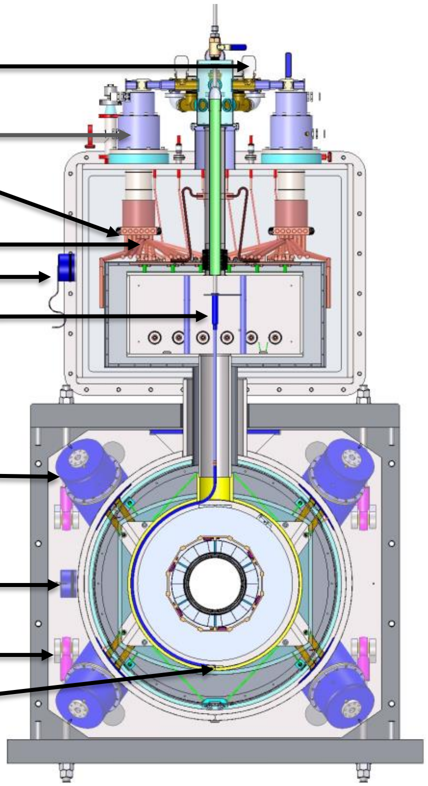
Solenoid Current: 217 A, 224A, 218A

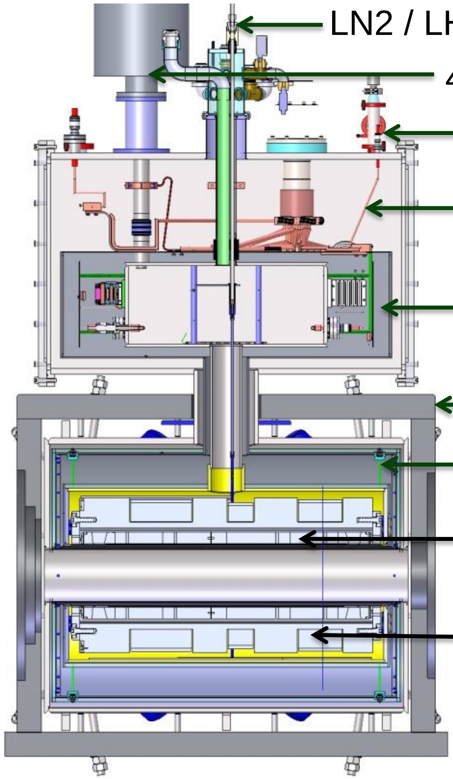


Sextupole Current: 445 A

FRIB HP ECR Cryostat

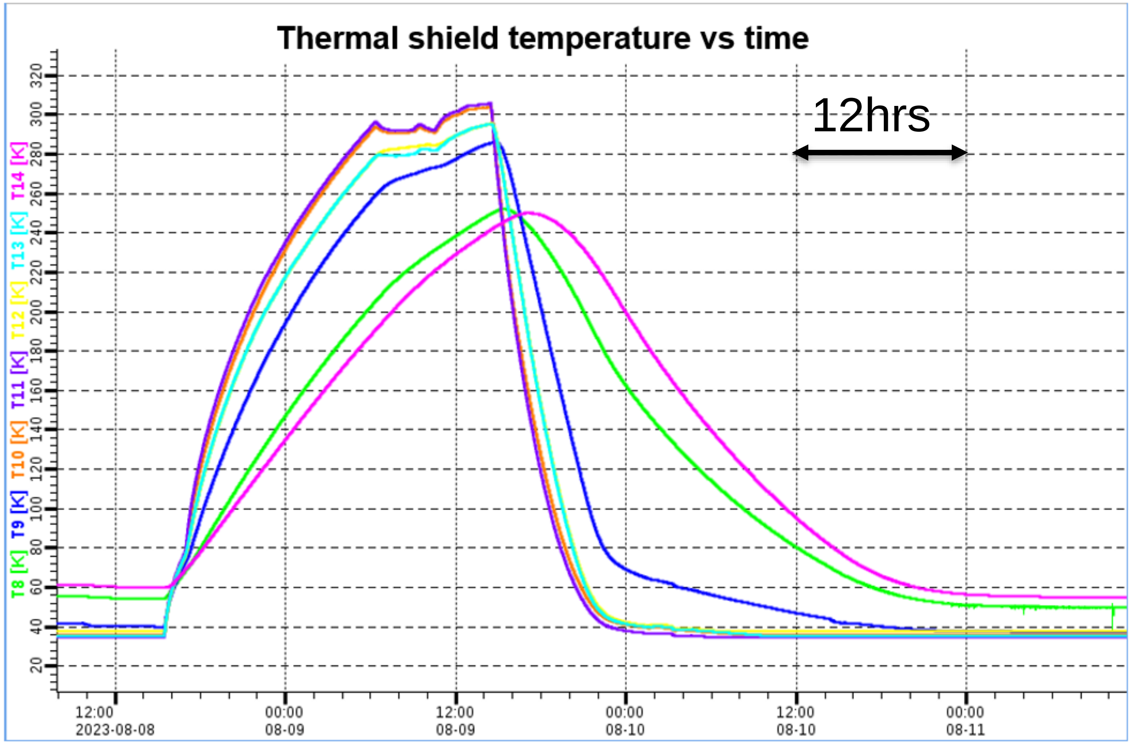
- Design departed from VENUS for several aspects
  - Two GM-JT, 5 Wx2=10 W @ 4.2 K, only 1 unit is required for operation below 5 kW
  - Heat Shield cooled with CH-110,150 Wx2=300 W@50 K

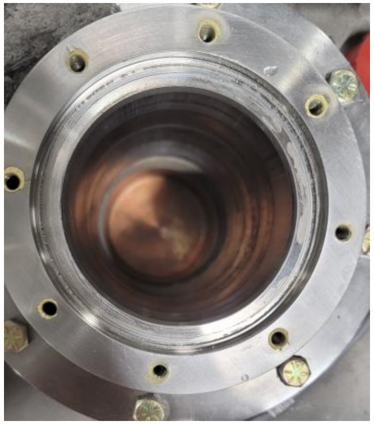




On-site GM Cryocoolers Maintenance Completed

- Require to warm shield to room temperature
- Cold mass stayed at 4.2K but overall used 250l Liquid helium
- Warm Up/Cool down time ~15/20 hours



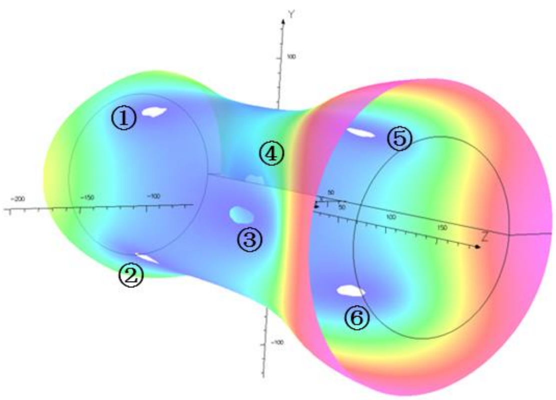


GM-JT Cryocooler Maintenance Completed

- Maintenance performed in house
  - Ten years of spare parts have been ordered with Sumitomo
- Remove a GM-JT cryocooler from the cryostat under cold condition
- GM-JT cryocooler maintenance yearly
  - Replacement of displacer in expander (~10,000H)
  - Flushing of JT circuit
  - Evacuation of isolation vacuum
- ~ 6 W of extra capacity @4.3 K

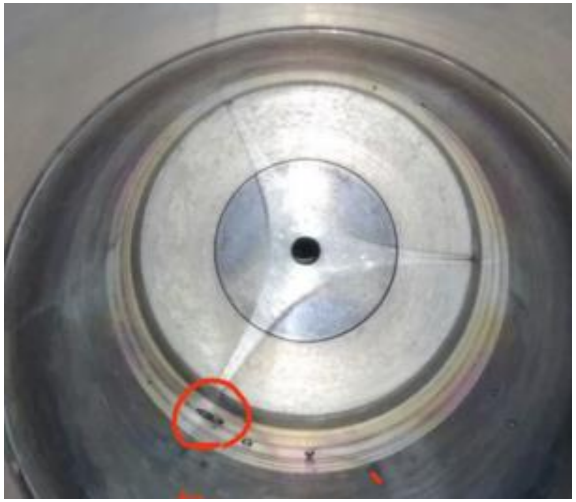
Challenges for 28 GHz High Power Operation - Plasma Chamber Cooling

- Many laboratories had the experience of damaged plasma chambers by localized overheating at high power operating conditions
- Challenges : 6 overheated spots where the magnetic field is weakest
  - Very high heat power density ~1 kW/cm^2 *
  - Chamber radial thickness is limited to a few mm for sufficient magnetic field



Intrinsic 6 spots of weakest magnetic fields in ECR ion source

Chamber burnt with VENUS at LBNL



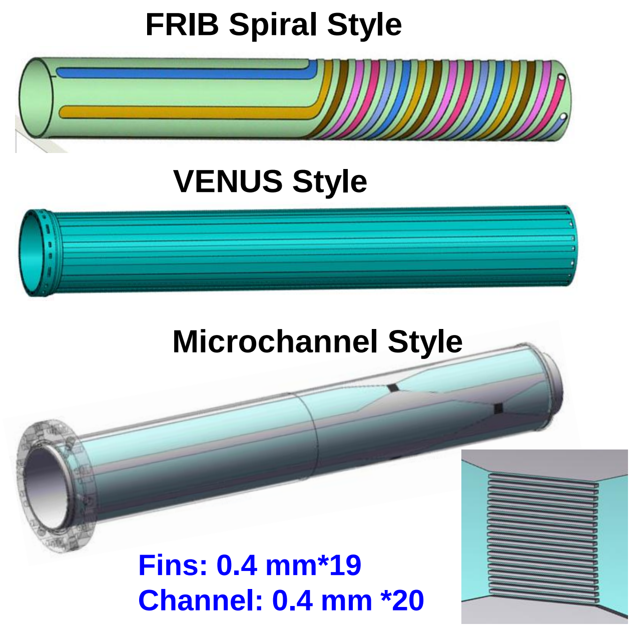
Chamber burnt with SECRAL-II at IMP

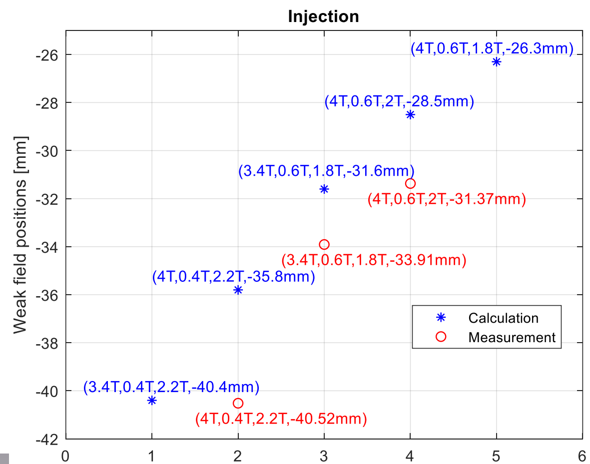
* T. Thuillier, et al., Rev. Sci. Instrum. 87, 02A736 (2016)

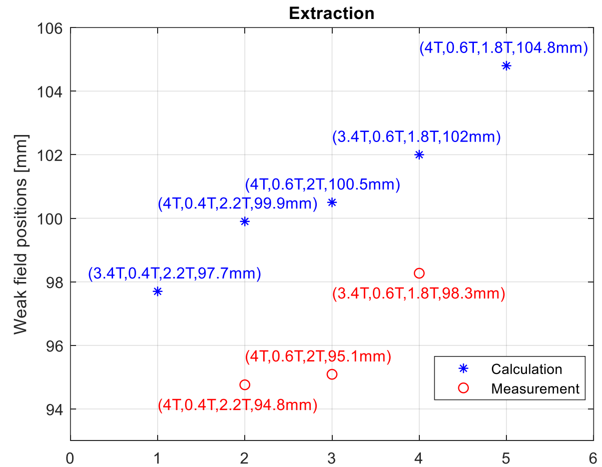
J. W. Guo's talk @ECRIS 2020

New Plasma Chamber Is Under Development Based on Microchannel Cooling Solution

- Existing FRIB chamber operate ~ 4 kW is reasonable, higher power is risky
  - Designed water flow for 10 kW is 5 GPM, but measured is 1.5 GPM
- The microchannel plasma chamber was validated to be durable and reliable at high power operation (~10 kW) by IMP(China)*
- FRIB new microchannel chamber design is in progress





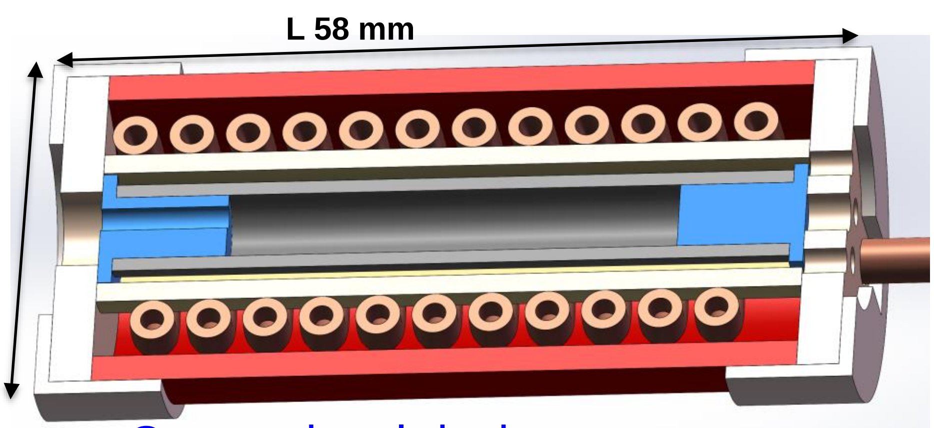


Microchannel area configuration
(L 20* W 15.6 * H 1.5 mm)

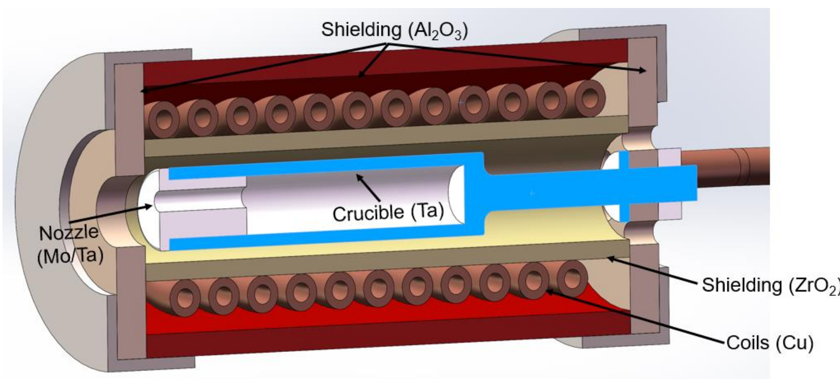
Liangting Sun's talk @ICIS 2021

High-temperature Oven for Uranium Production
Two Designs of Inductive Ovens Were Built

- Challenge: maintain operate at 1800~2100 ℃ for several weeks
  - Material compatibility under high temperature
  - Thermal optimization
    - » Maximum temperature, temperature uniformity of crucible, nozzle temperature
- 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 improved design demonstrated temperature > 2000 ℃ *
- Two designs of high temperature ovens were built and tested



Φ27 mm Conventional design

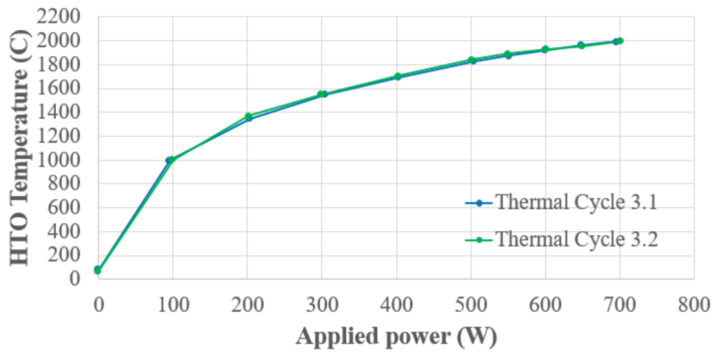


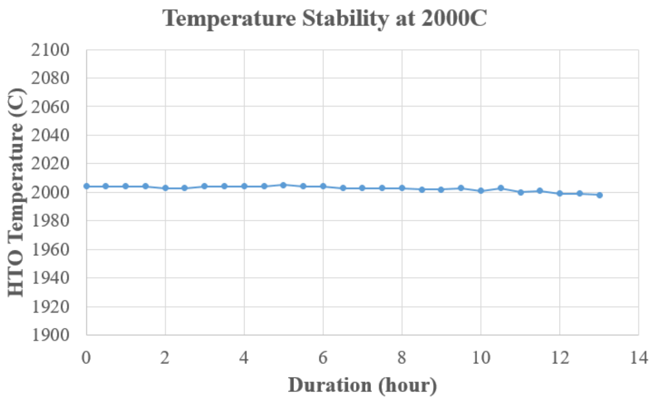
Integrated crucible design

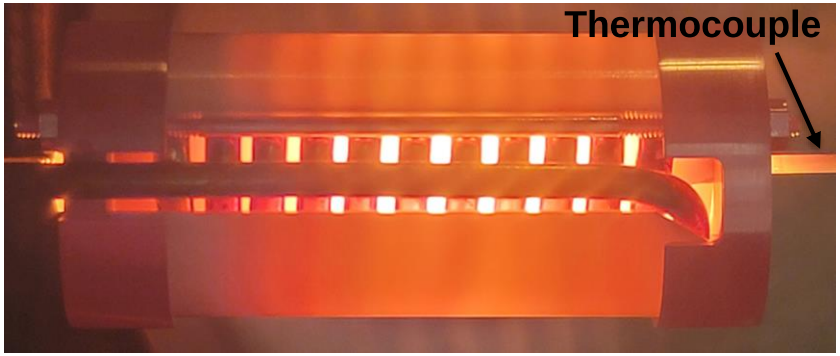
*W. Lu, L.T. Sun. et al, Rev. Sci. Instrum.90, 113318 (2019)

HT Ovens Offline Testing Completed
Planned Uranium Beam Development in October

- Both designs reached 2000 degrees and ran stably for a week
- Planned beam development
  - SiO ~1000 ℃, Nickel~1500 ℃, UO_2 ~1900 ℃

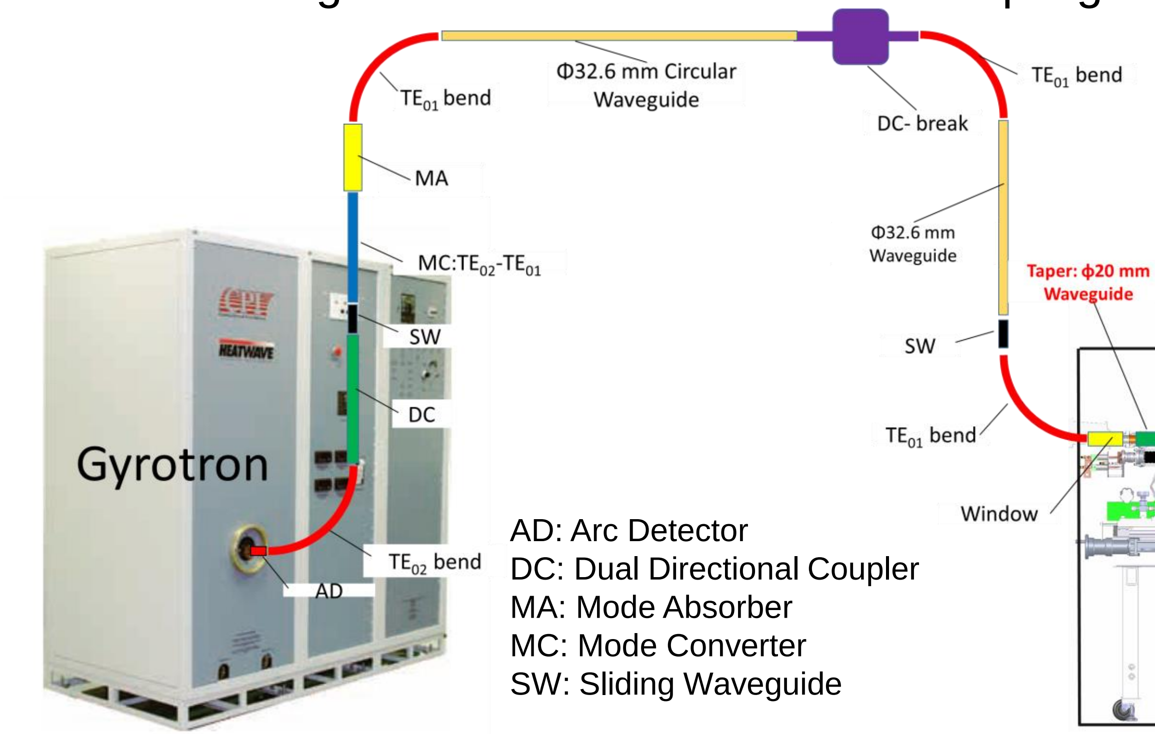


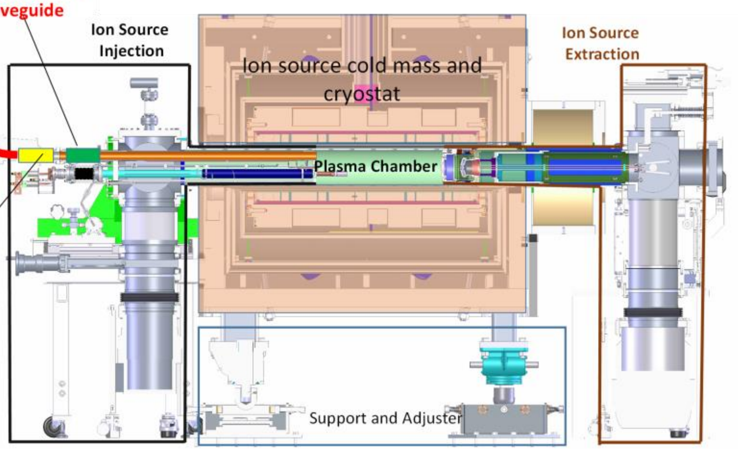




28 GHz10 kW Microwave System in Progress

- Gyrotron transmitter delivered in March 2023, dummy load test is ongoing
- Transmission line design completed and procurement in progress
  - The overall transmission efficiency is about 90%
  - 4 bends, DC-break, Mechanical compensator etc.
  - Φ20 mm waveguide is used for microwave coupling





Second FRIB 28 GHz SC Ion Source Development

- Why need second HP ion source?
  - Single-point failure mitigation, long lead time for replacement
  - Maintain high availability during ion change and source maintenance
- New enhanced features **See Mariusz Juchno's talk on Thursday, Sept. 21**
  - NbTi solenoids+ Nb_3Sn sextupole
  - 12 W cooling capacity @ 4.2 K by 6 of 2 W GM cryocooler (RDE-418D4)
  - Improvements and upgrades are based on lessons learned
- Development status and plan

Magnet conceptual design completed (LBNL)	2022 - 2023
Prototype coil development (LBNL)	2023 - 2024
Magnet manufacturing and assembly (LBNL)	2024 - 2026
Cryostat and conventional components	2024 - 2026
Ion source integrated assembly	2027- 2028
First beam to beamline	2028

Summary

- FRIB has been operating since May 2022, delivering beams with the desired reliability and availability.
- The primary beam power has been steadily raised from 1 to 10 kW.
- 28 GHz High power ion source successfully energized to full field and integrated to FRIB operations at 18 GHz since January 2023
- 28 GHz commissioning planned for December
- High temperature oven developed and 10 kW Uranium beam test is planned for early November
- Second 28 GHz source is being developed in collaboration with LBNL

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Tengming Shen, Diego Arbelaez, Ye Yang, Ray Hafalia, Mariusz Juchno, Paolo Ferracin, Soren Prestemon

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