FECR: A 28~45 GHz Next Generation Ion Source and Its First Results

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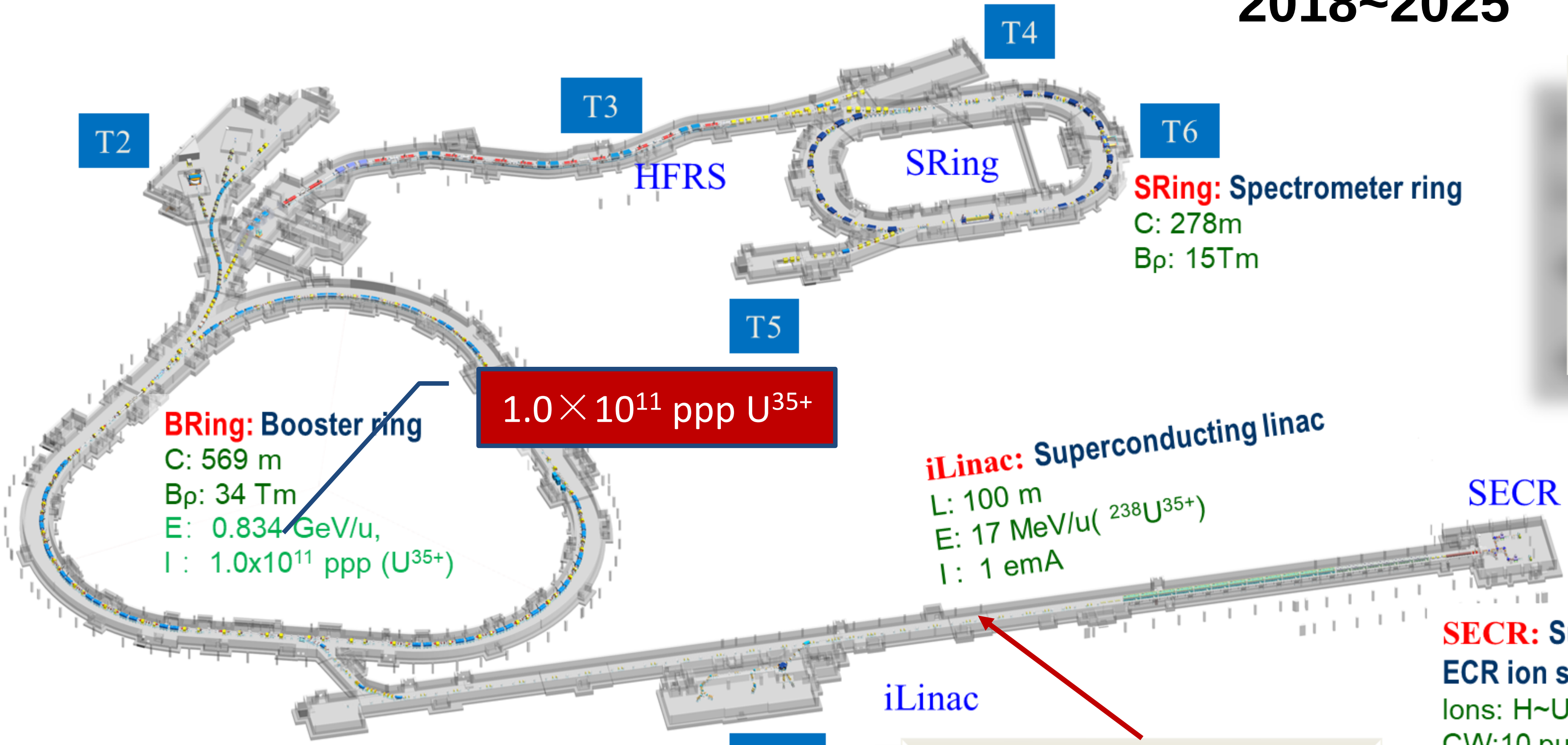
Outline

- Introduction
- FECR development
- First plasma with FECR and perspectives
- Summary

Introduction: HIAF Needs

HIAF: High Intensity heavy-ion Accelerator Facility

2018~2025



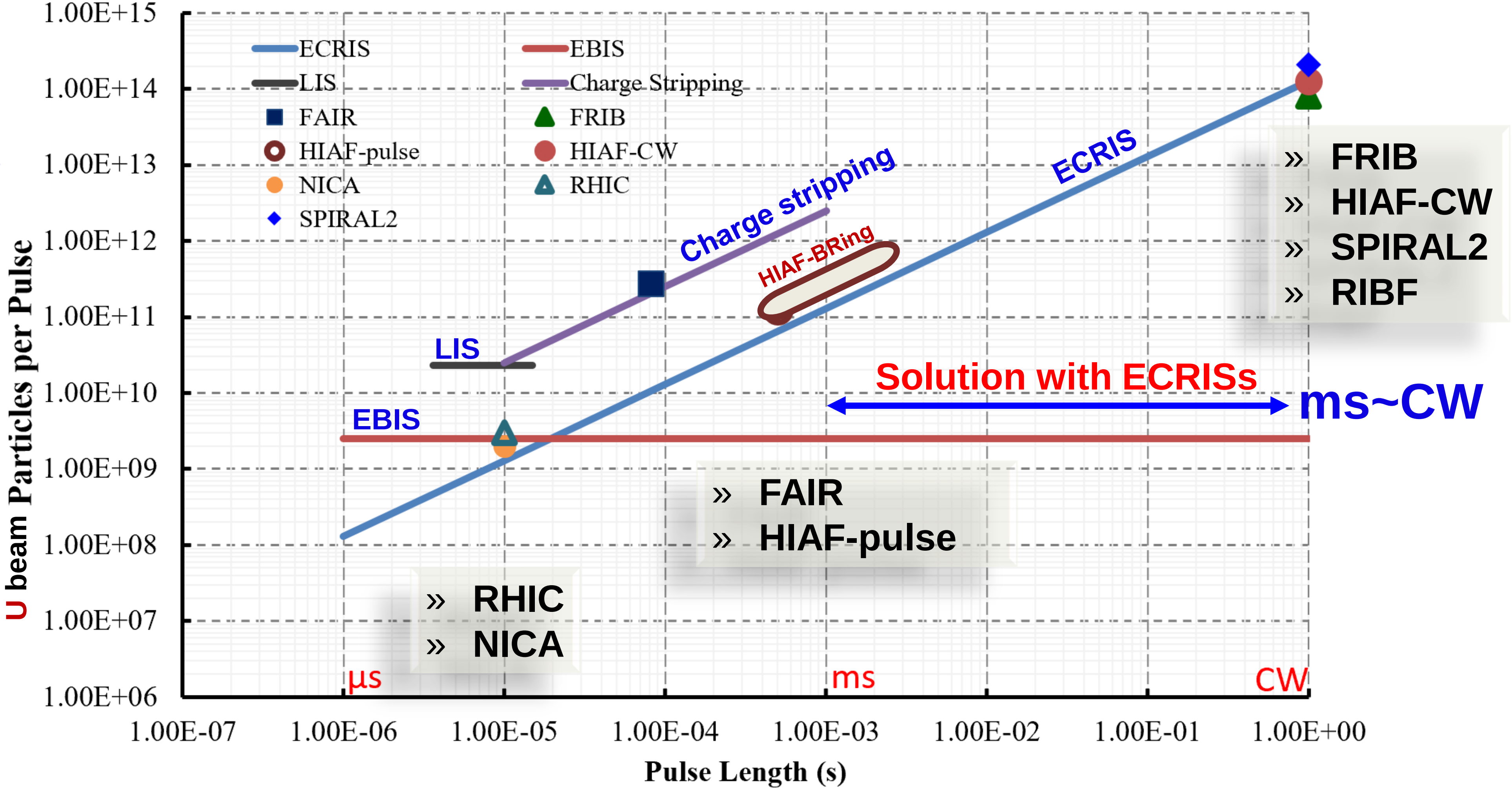
>460 eμA U^{46+}, CW
> 1 emA U^{35+}, pulsed

Highly charged ion beams:
- ◆ **High Intensity**
- ◆ **High Quality**

Introduction: HIAF Needs

HCI Sources:
- ECRIS
- EBIS
- LIS
- MEVVA + Stripping

Solutions to HCI injectors

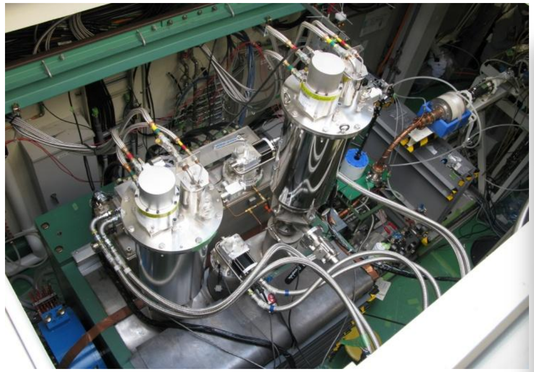


L. Sun, doi:10.18429/JACoW-IPAC2018-FRXGBF3

Introduction: Status of SC-ECRISs

VENUS@LBNL
28+18 GHz

SECRAL-II@IMP
28/24+18 GHz

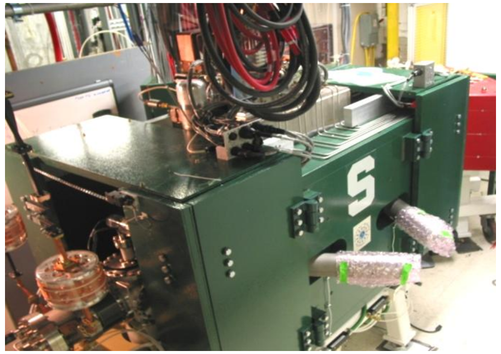


SCECRIS@RIKEN
28+18 GHz

About 10 in operation

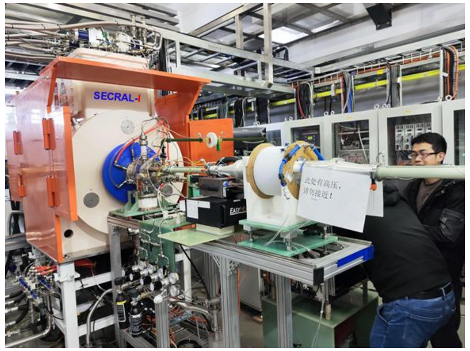
More to come:

- **28 GHz SECRAL-IV@IMP**
- **28 GHz ASTERICS@GANIL**
- **28 GHz SC-ECRIS@JINR**
- **….**



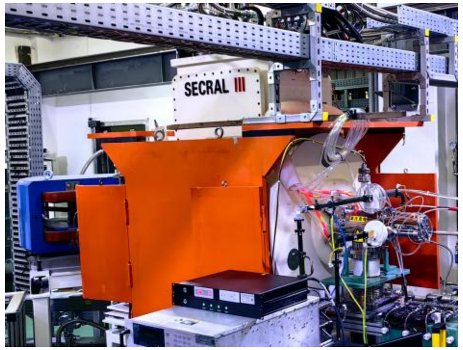
SuSI@MSU
24+18 GHz

SCECRIS@RIKEN
28+18 GHz



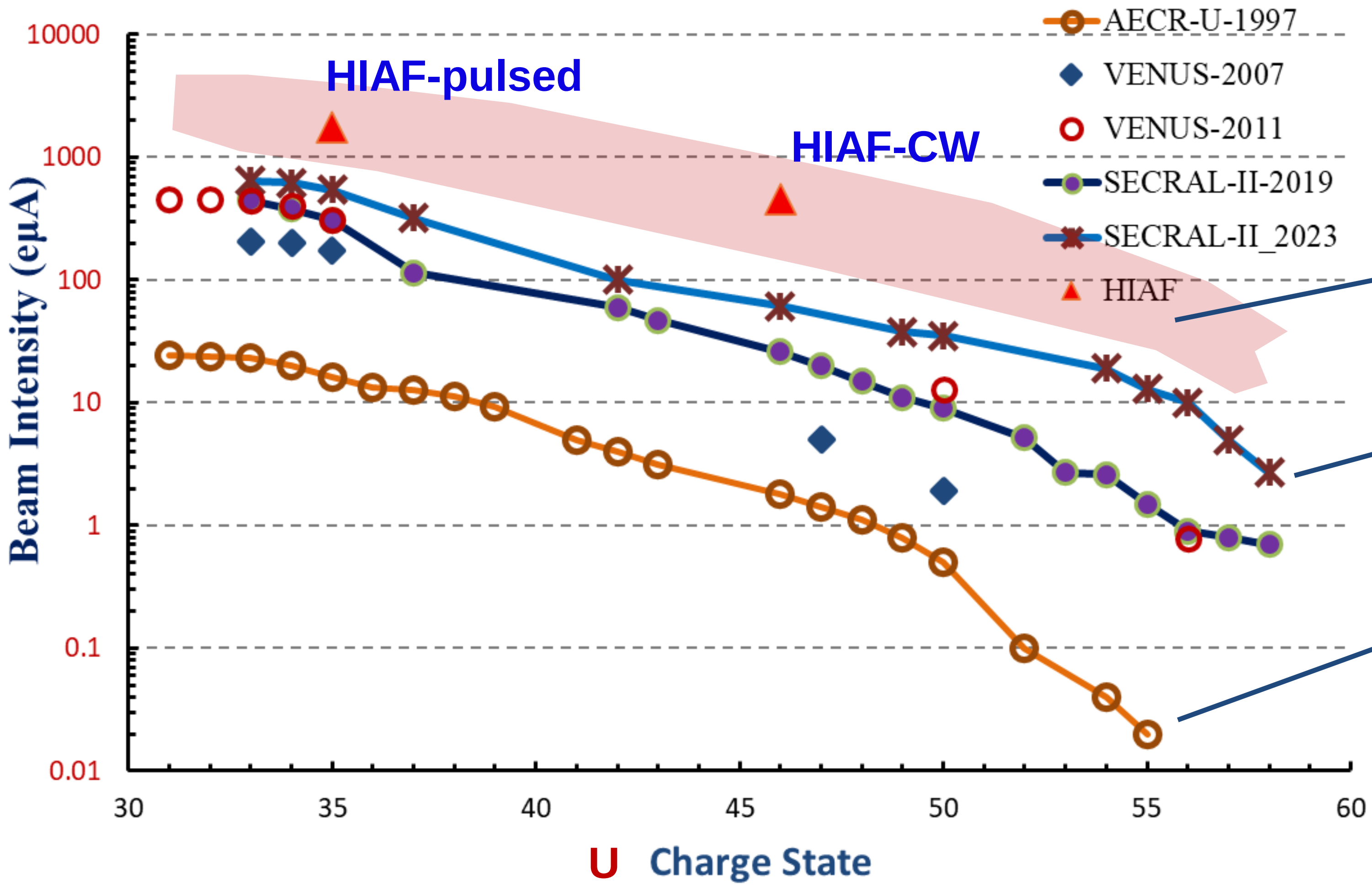
SECRAL-I@IMP
28/24+18 GHz

HPECR@FRIB
28+18 GHz



SECRAL-III@IMP
28/24+18 GHz

Introduction: Status of SC-ECRISs



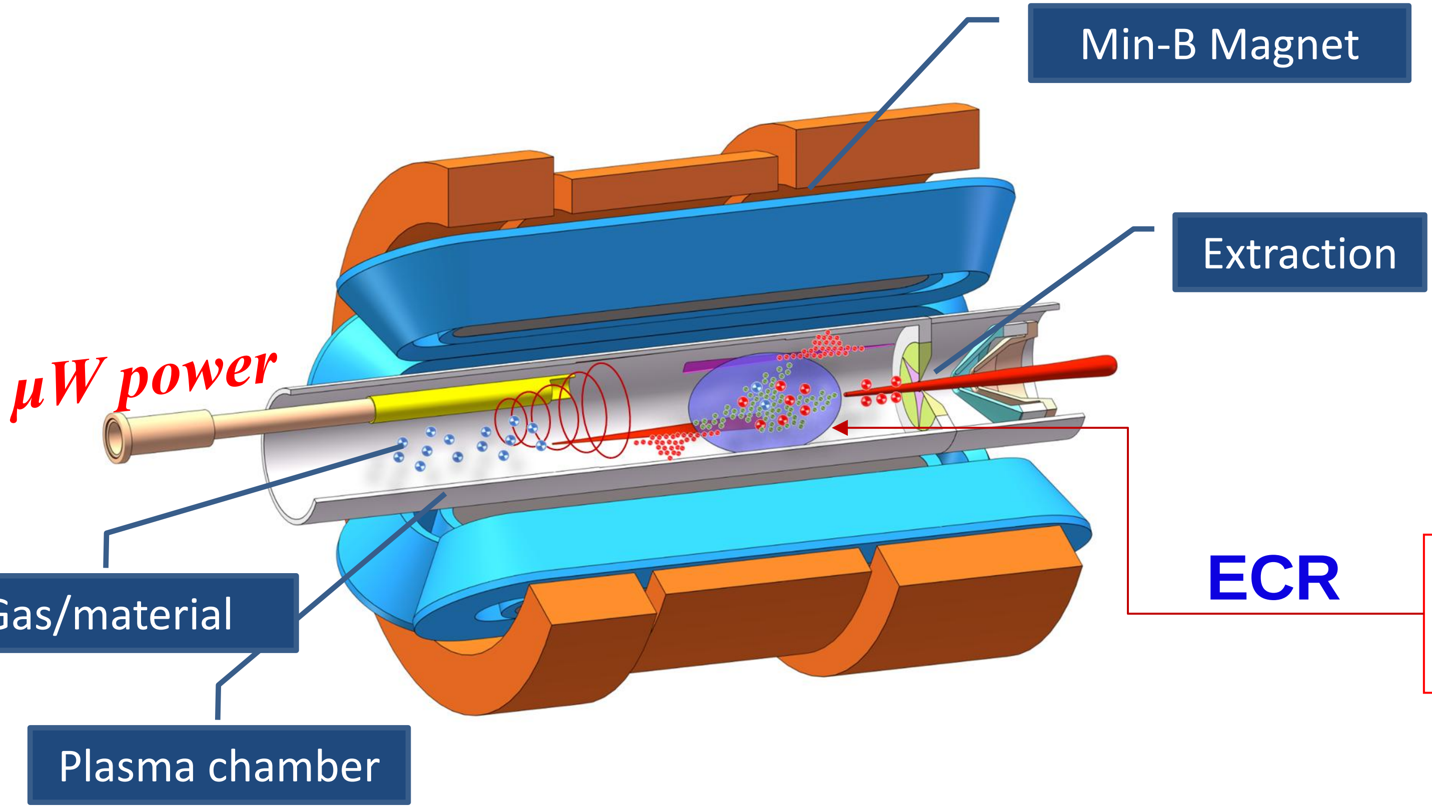
Uranium ion beam production

4th G ECRIS

3rd G ECRIS

2nd G ECRIS

Introduction: Status of SC-ECRISs



$$< q > \sim log\omega^3$$

$$I_q \sim \omega^2 \cdot V \cdot M^{-1}$$

ECR

$$\omega = \omega_{ce} = \frac{e \cdot B_{ecr}}{m_e}$$

Higher charge state + higher I_q =

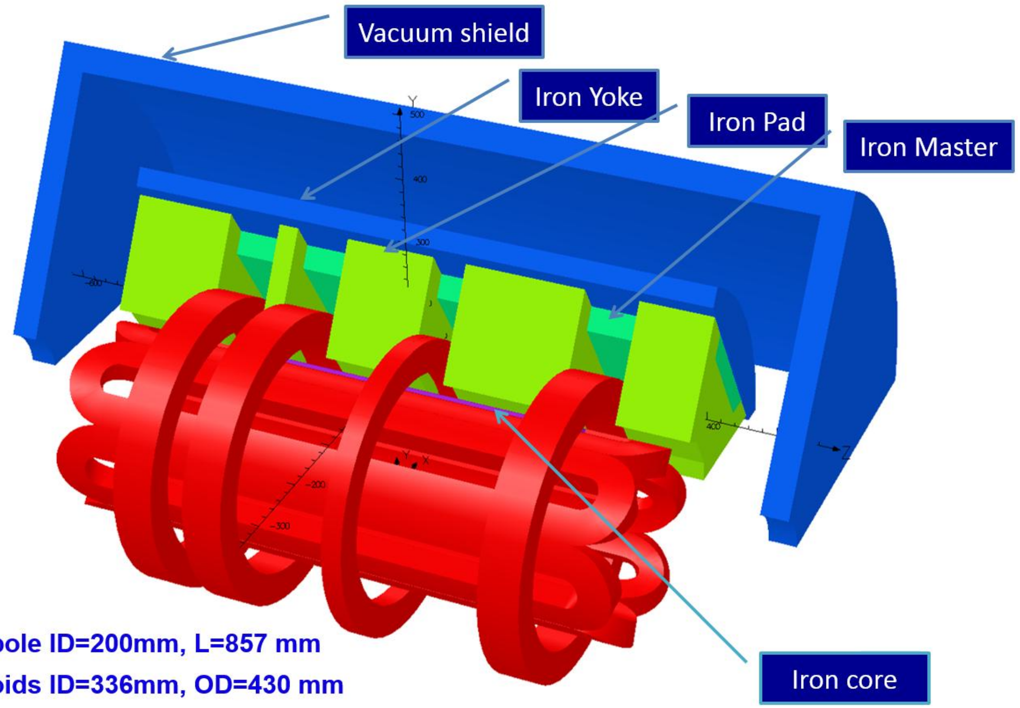
Higher ω + Higher B + Bigger plasma volume (V)

Introduction: FECR

Specs.	Unit	3^{rd} G ECRIS	4^{th} G ECRIS	FECR
frequency	GHz	24-28	40~56	45
Operational RF Power	kW	4~10	10~40	20
B_{ECR}	T	0.86~1.0	1.4~2.0	1.6
B_{rad}	T	1.8~2.2	2.8~4.0	≥3.2
B_{inj}	T	3.4~4.0	5.6~8.0	≥6.4
B_{min}	T	0.5~0.7	/	0.5~1.1
B_{ext}	T	1.8~2.2	3.0~4.5	≥3.4
B_{max} in conductor	T	~7.0	>10.0	11.8
Plasma Chamber ID	mm	100~150	>100	≥140
Mirror Length	mm	420~500	≥500	500
Cooling Capacity@4.2 K	W	0~6.0	>10.0	≥10.0

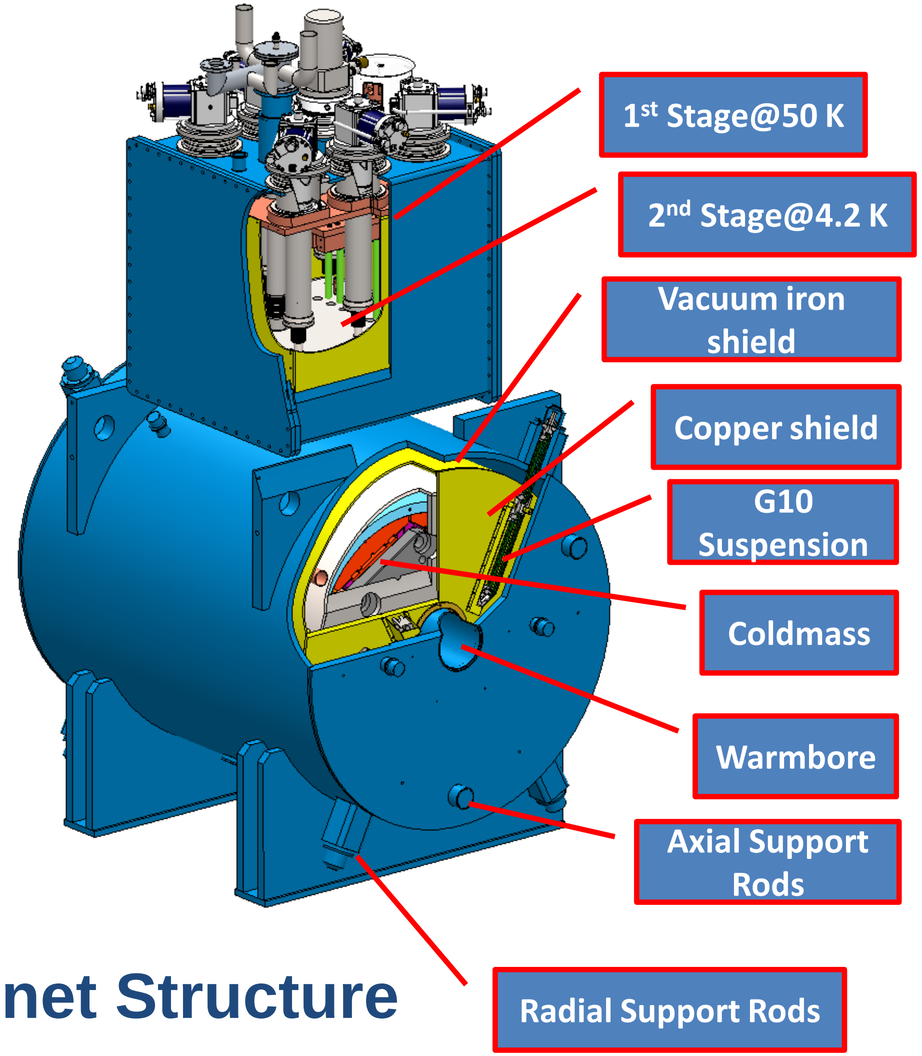
(1993—2003--) (2007-- ??)

Introduction: FECR



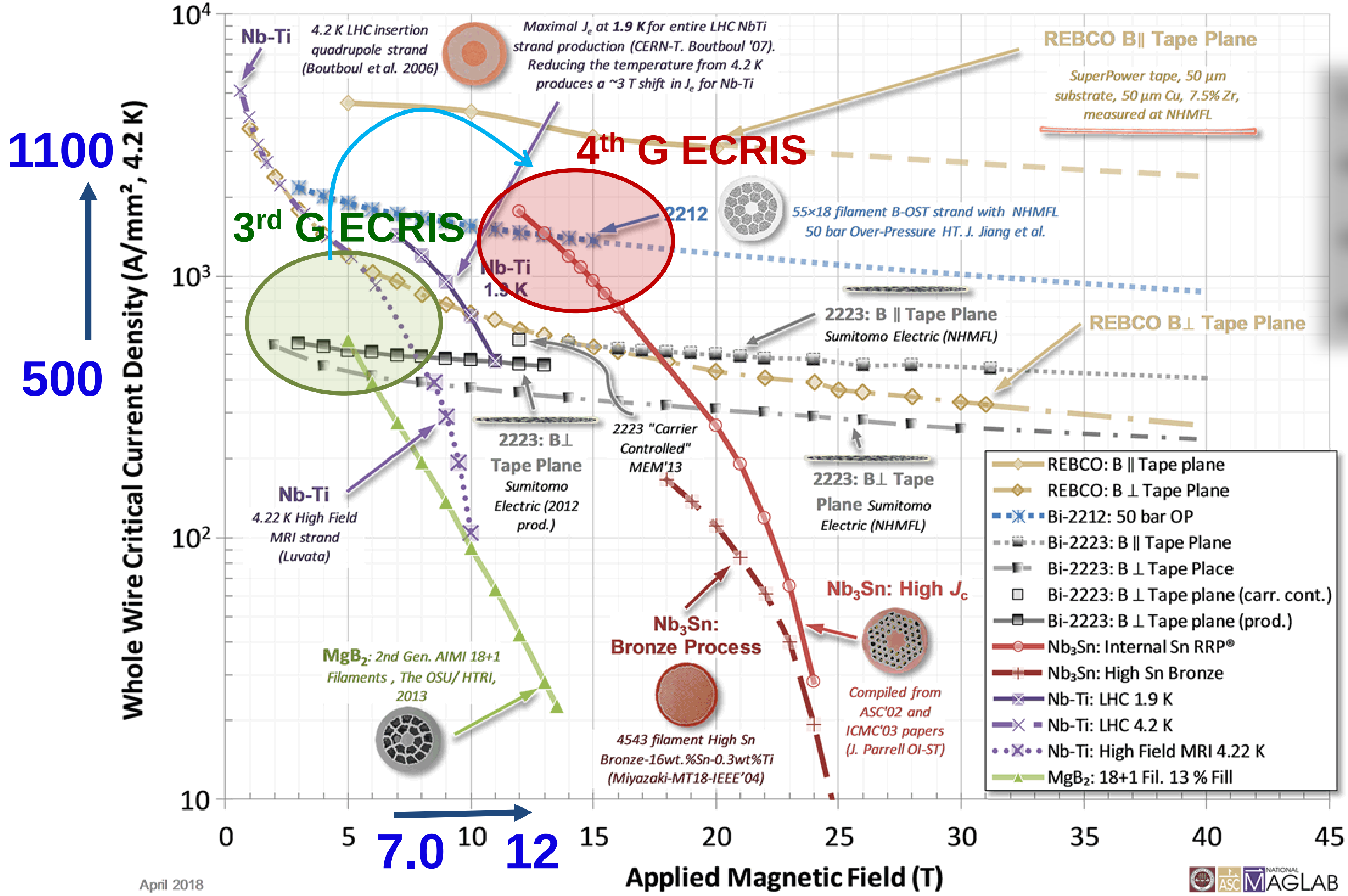
Coldmass Structure

Peak field: 11.8 T, Stored energy: 1.6 MJ



Magnet Structure

Introduction: FECR

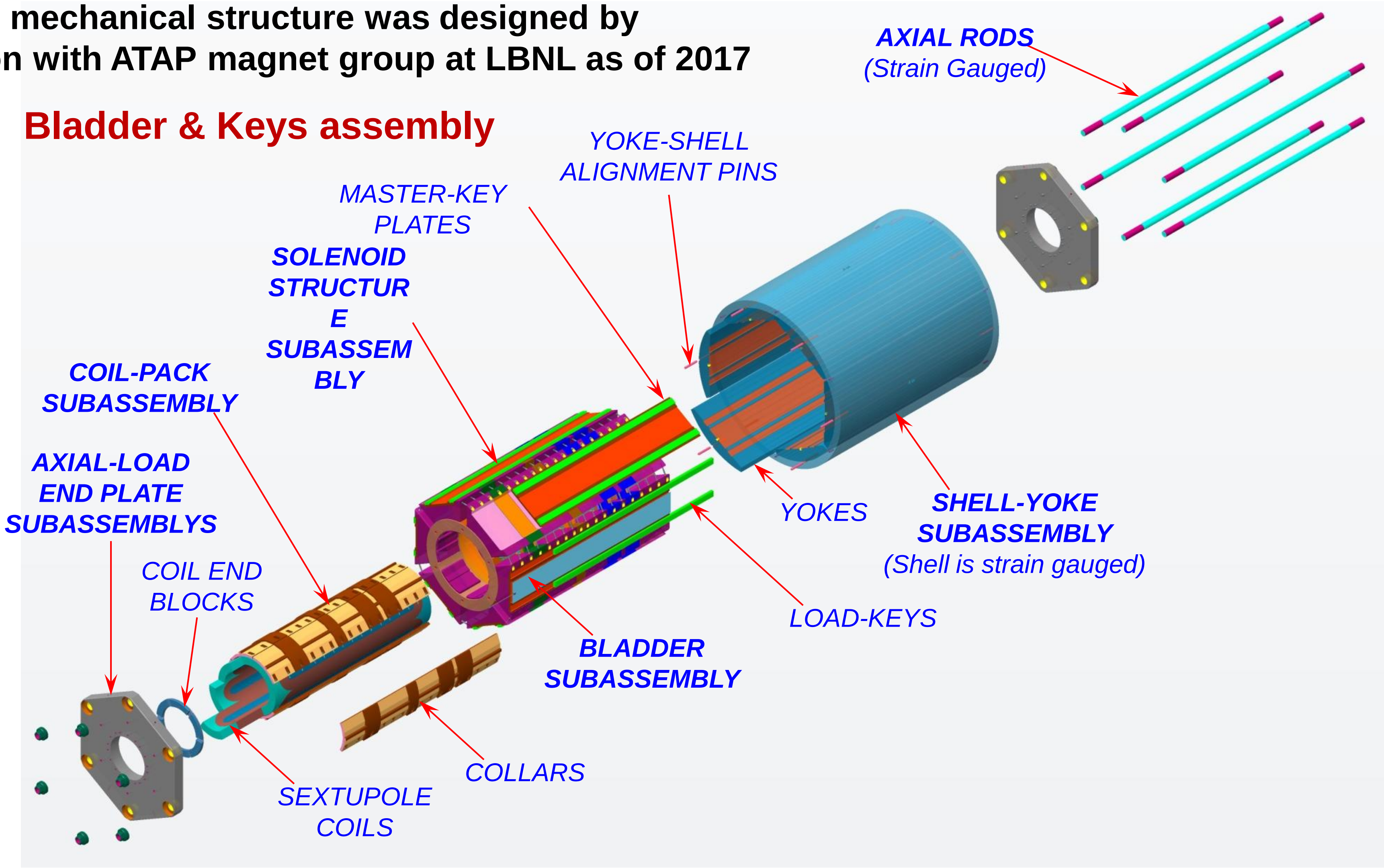


Nb_3Sn vs. NbTi:

- Fragile
- Treatment sensitive
- Stress sensitive

Courtesy of MagLab

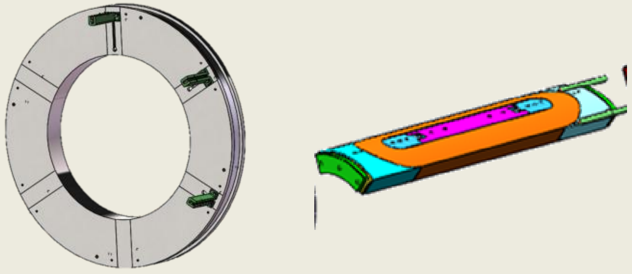
The magnet mechanical structure was designed by collaboration with ATAP magnet group at LBNL as of 2017



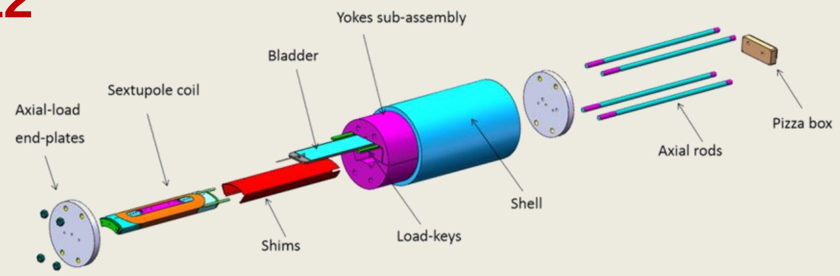
This Nb_3Sn magnet is being built by a Chinese company without collaboration with ATAP/LBNL. DOE did not approve such collaboration.

Introduction: FECR

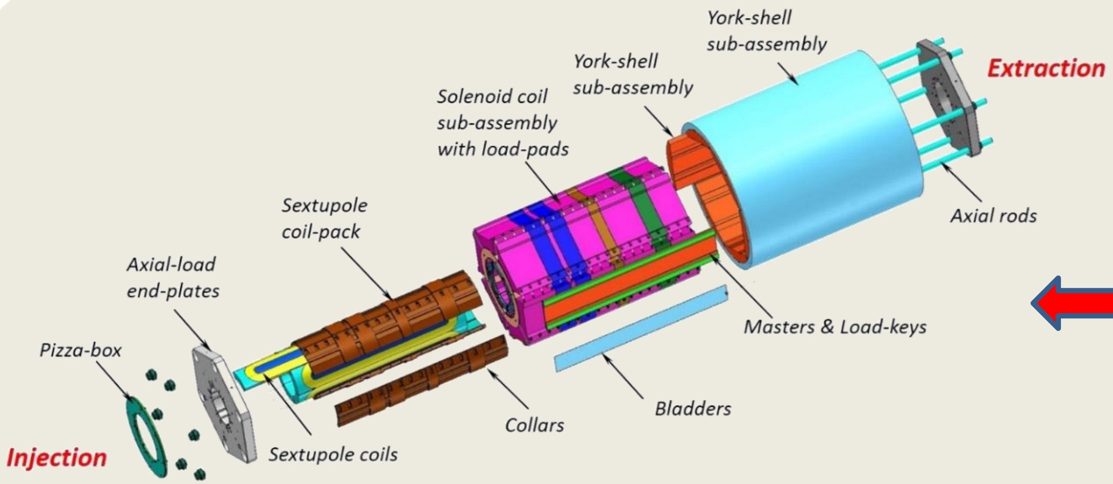
2015.07~2018.12



1.Prototyping coils

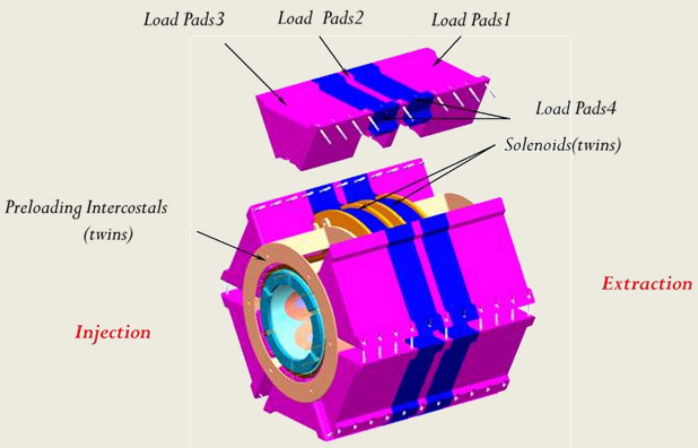


2.Key components and tech.



4. FECR coldmass full assembly

（2021.10-2023.09）

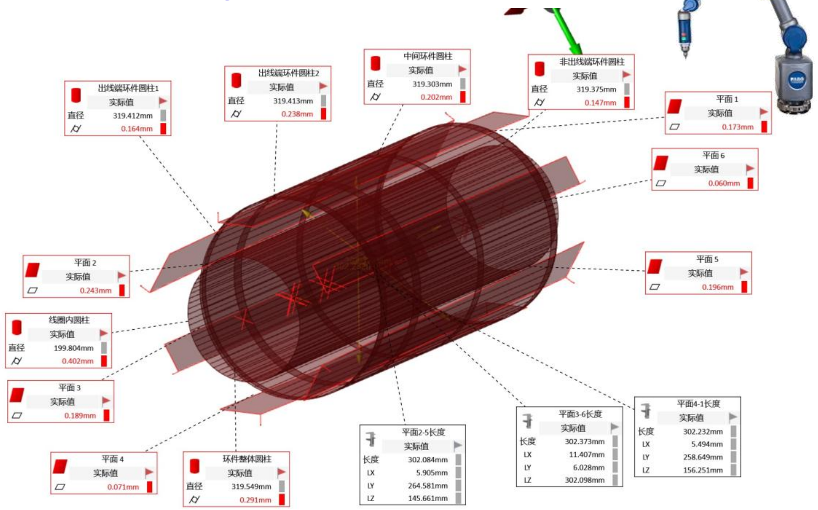


3. ½-length prototype

（2017.11-2021.12）

Introduction: FECR

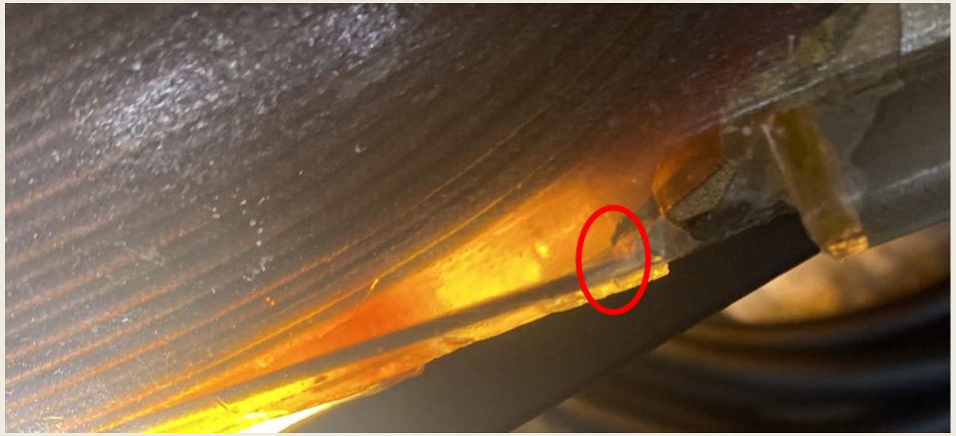
With Quantum Max FaroArm



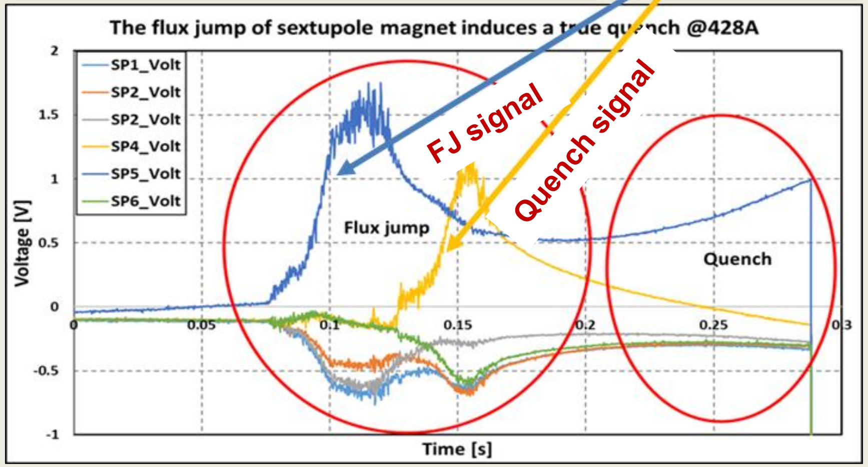
Completed FECR coldmass

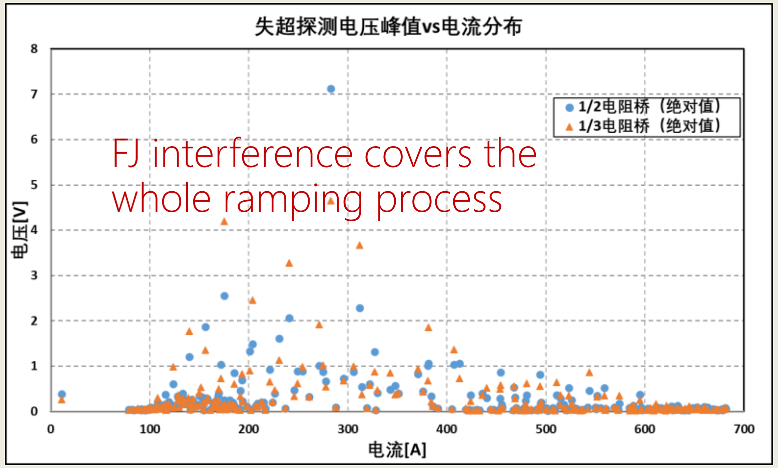
Introduction: FECR

- **Stress on Wire**: Improper handling and failing to protect the coil leads

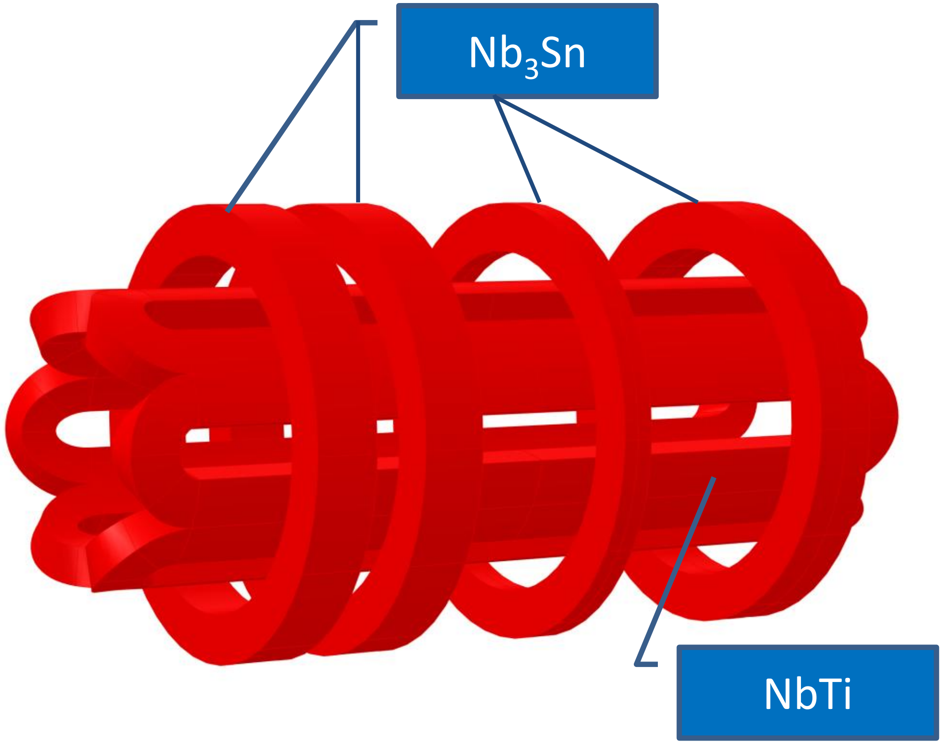


- **Intense Flux Jump (FJ) Interference**: challenging in fast quench detection





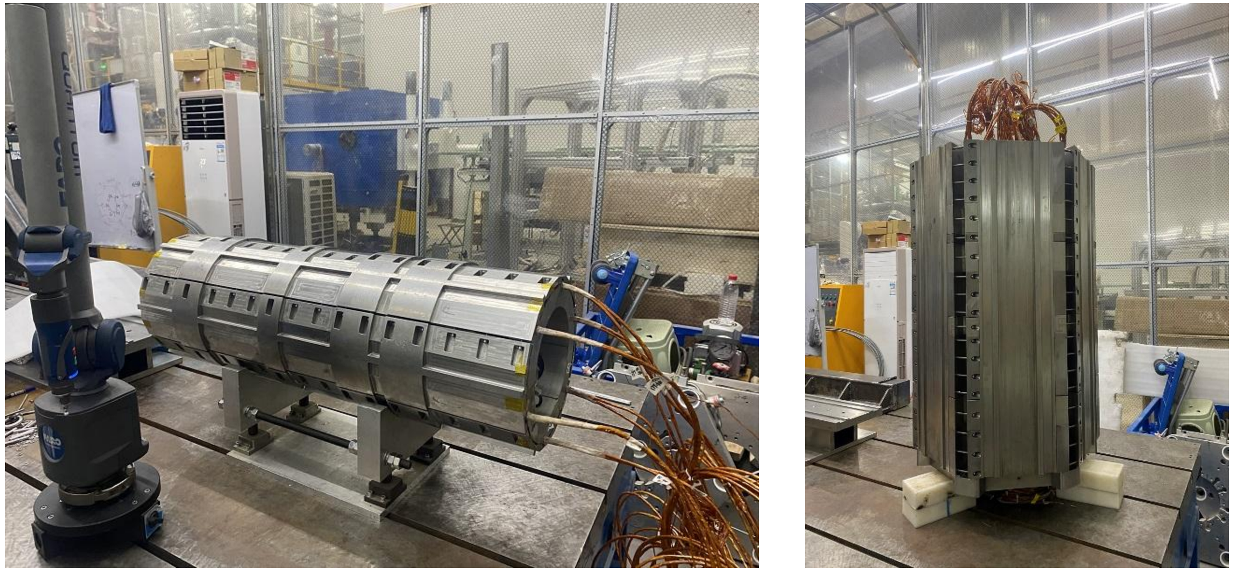
Introduction: Hybrid FECR



Hybrid coils:

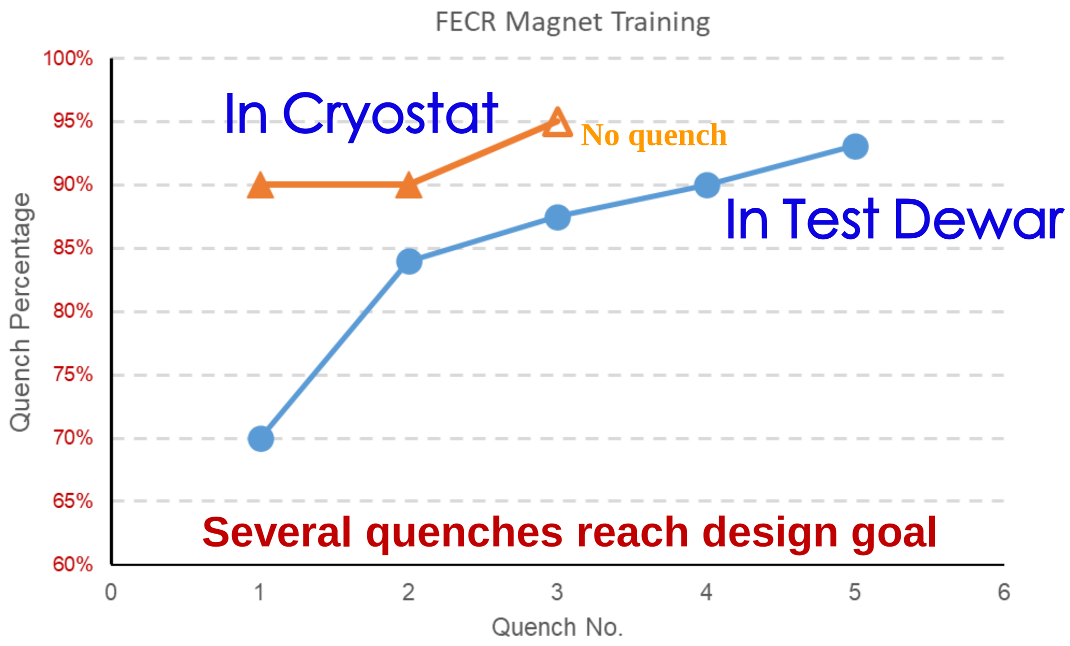
- NbTi sextupole + Nb_3Sn solenoids
- Intense FJ mitigation
- Assembly test
- Operation safe

NbTi sextupole coils



Sub-assembly of the cold mass

Introduction: FECR

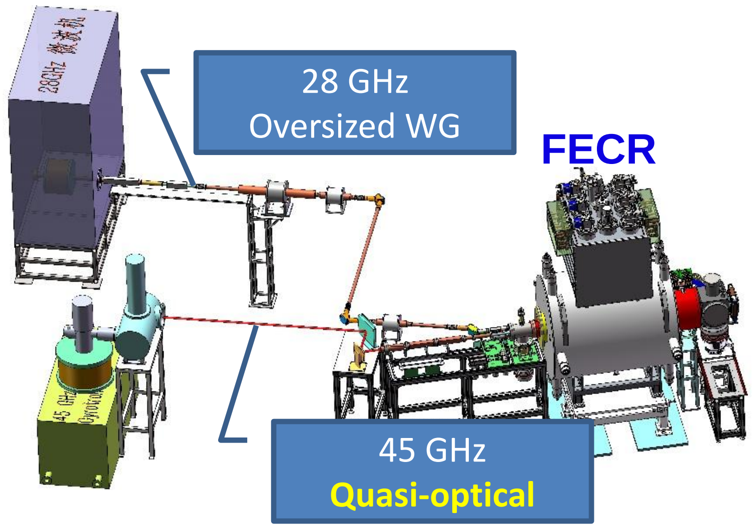


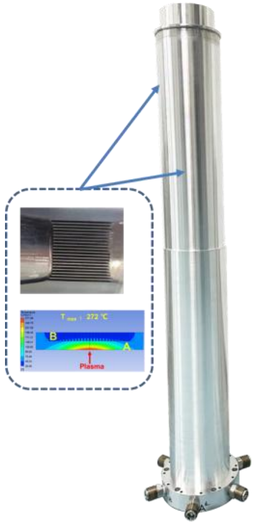
FECR with Nb_3Sn+NbTi coils:

- Nb_3Sn Coils development
- High precision assembly
- Successful operation against Flux Jumps
- Quench protection strategy

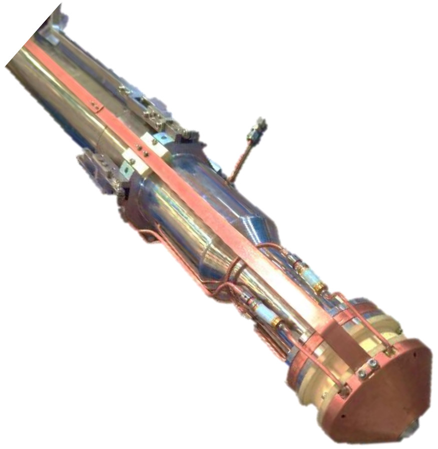
FECR 1st Plasma and Perspectives

Parameters	Designed	FECR
Microwave (GHz)	45 + 28	45 + 28
µW Power (kW)	20+10	20 + 5
Dynamic cooling capacity@4.2 K (W)	>10	~4.5
Mirror peak fields (T)	Axial: 6.4/3.4 B_r= 3.2 T	Axial: 4.5/2.6 B_r= 2.7 T
Operation voltage	30 kV	25 kV

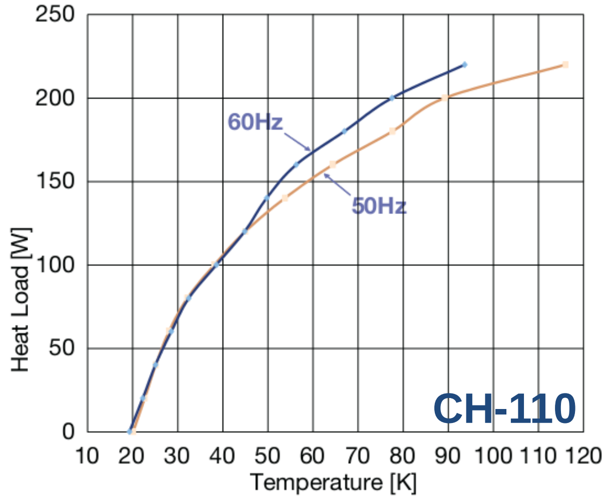



Micro-channel plasma chamber

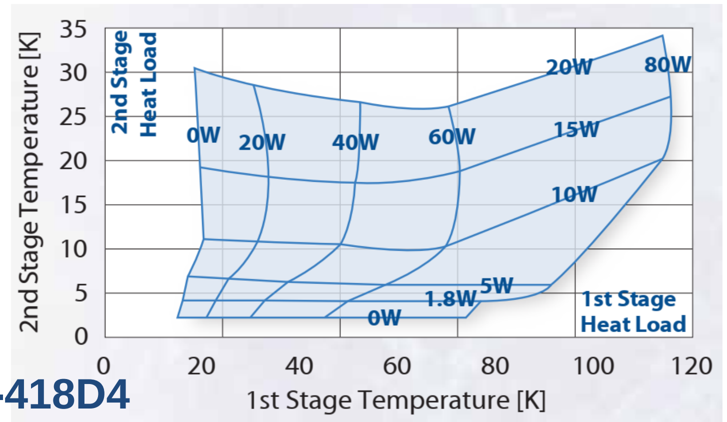

Conventional Injection setup

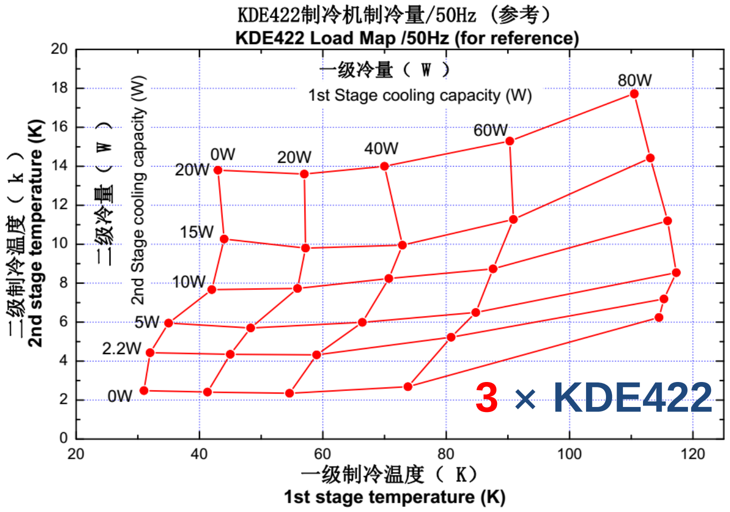

Movable Extraction electrodes

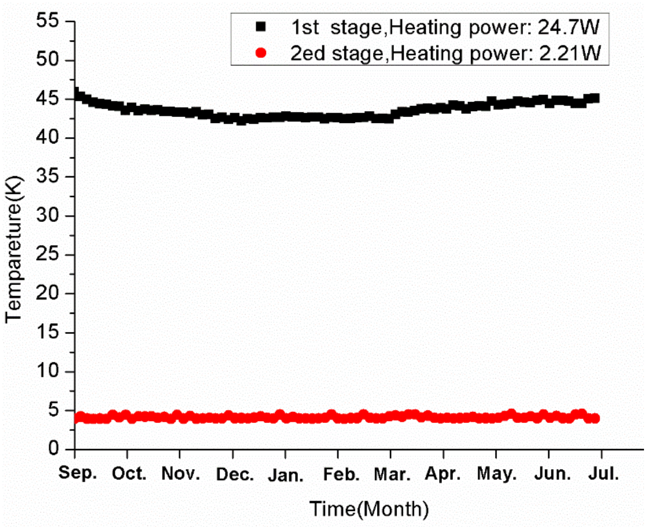
FECR 1st Plasma and Perspectives: Cryogenics



3 × RDE-418D4







High power GM Cooler:

- 10 months continuous stability and reliability checking-test
- 3×KDE422 coolers ~6.6 W@4.2 K cooling capacity

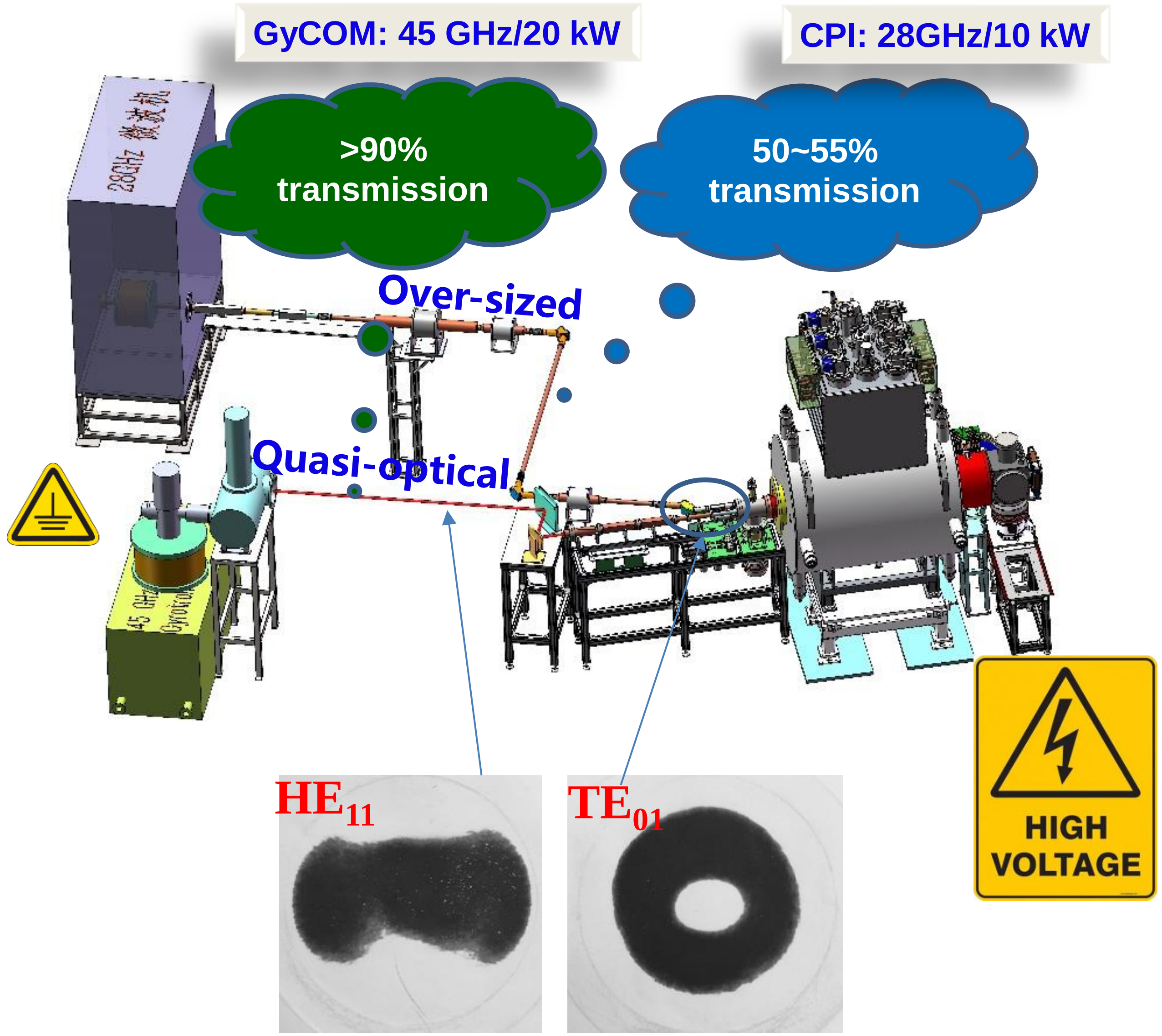
$P_{4.2\ K}$~6.6+5.4= 12.0 (W)

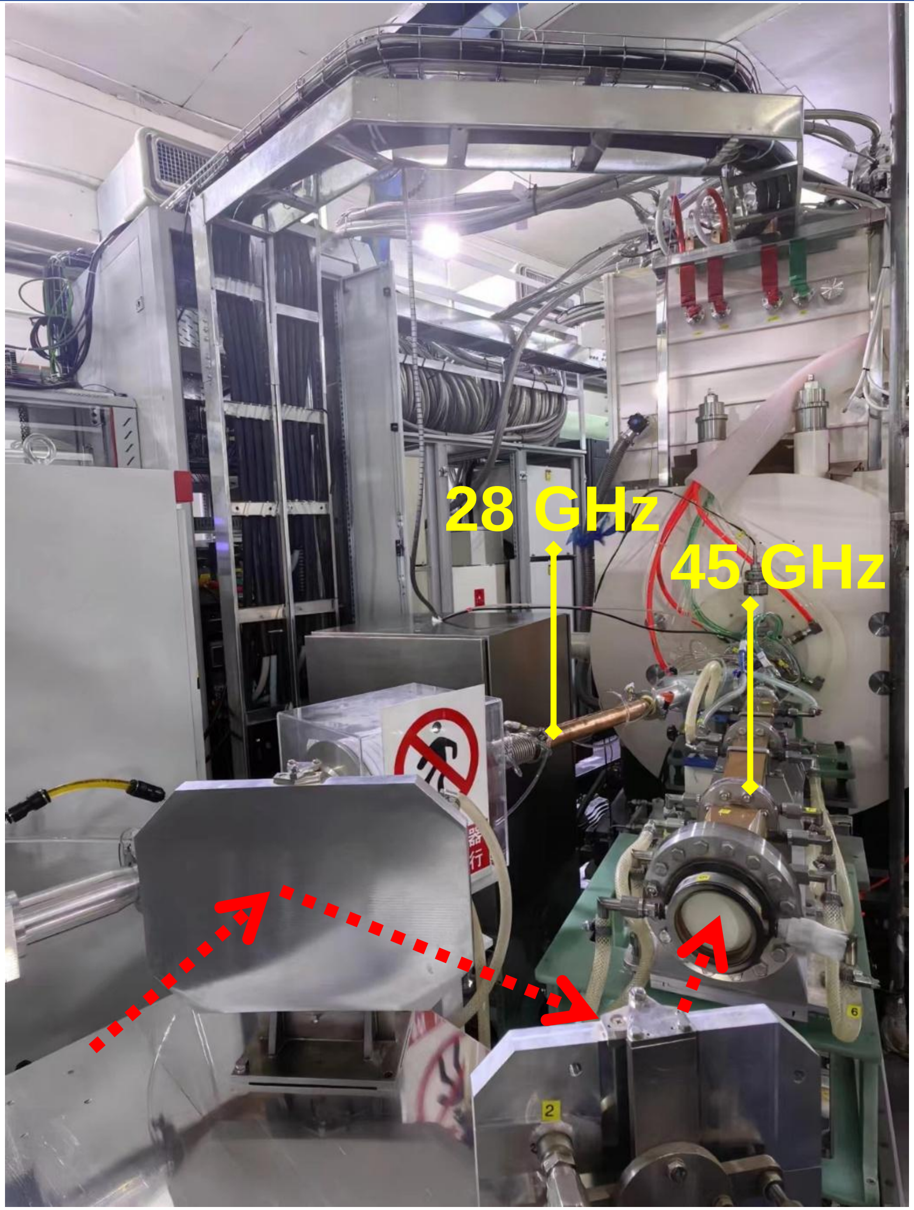
Test value: ~5.3 W

FECR 1st Plasma and Perspectives: HP Chamber

Key Parameters	FECR Chamber	SECRAL-II Chamber
Max. Microwave Power	25 kW	12 kW
Max. Localized Power Density	20 MW/m^2	10 MW/m^2
Chamber ID	Ø140 mm	Ø125 mm
Chamber OD	Ø156 mm	Ø136 mm
Length	1225 mm	887 mm
Microchannel region	15×15.6×1.5 mm^3	15×15.6×1.0 mm^3
Fins	0.4 mm×19	0.4 mm×19
Channel	0.4 mm×20	0.4 mm×20
Inside-wall thickness	1.5 mm	1.5 mm
Outside-wall thickness	1.5 mm	1.5 mm
Water pressure	10 bar	8.9 bar
Water flow per channel	＞ 15 L/m	＞ 4.0 L/m
Total water flow	＞ 50 L/m	＞ 13 L/m
Max. flow velocity (m/s)	10~20	10~20

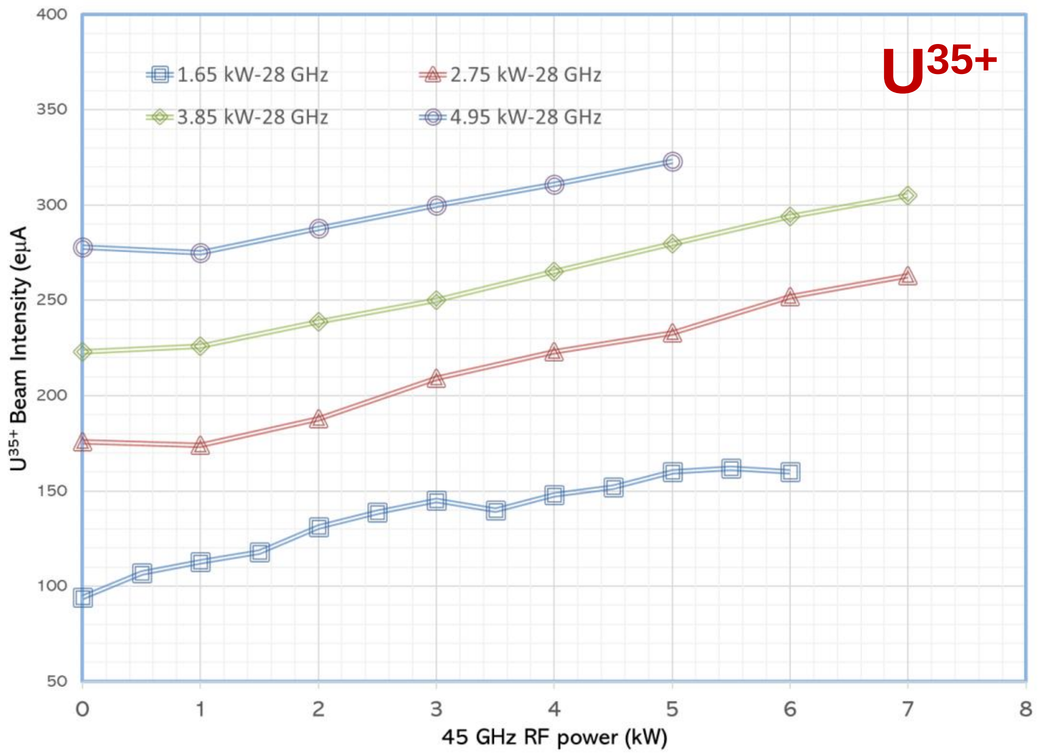
FECR 1st Plasma and Perspectives: μW System

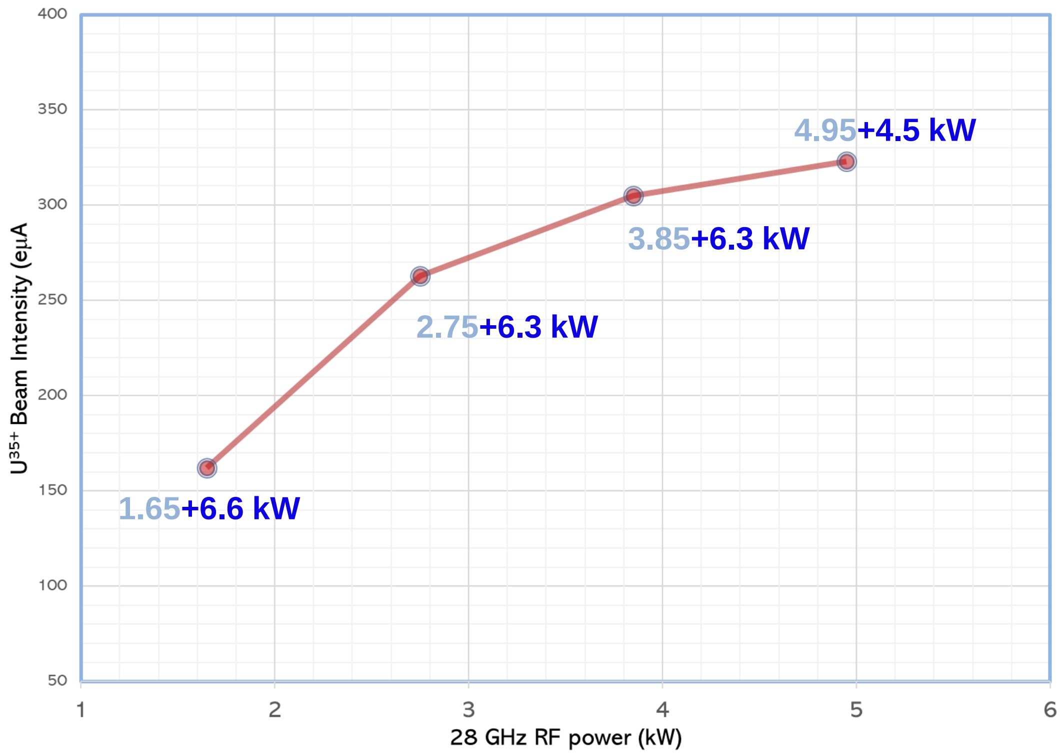




FECR 1st Plasma and Perspectives: U^{35+}

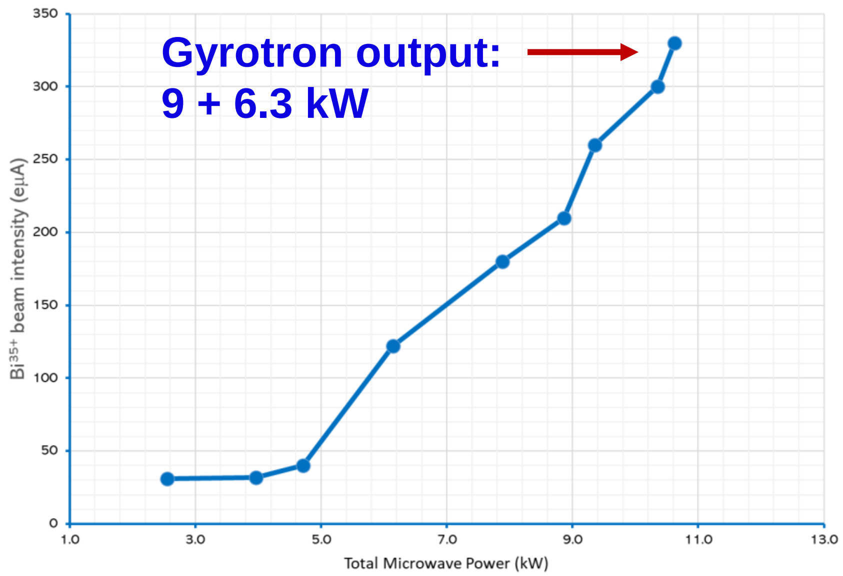
1st test with uranium beam

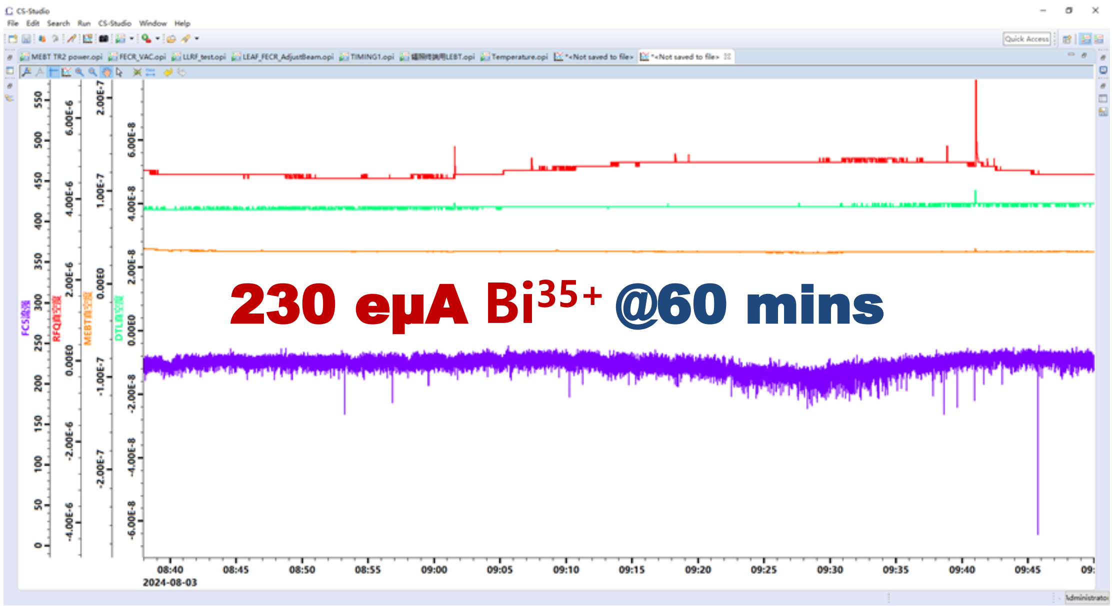


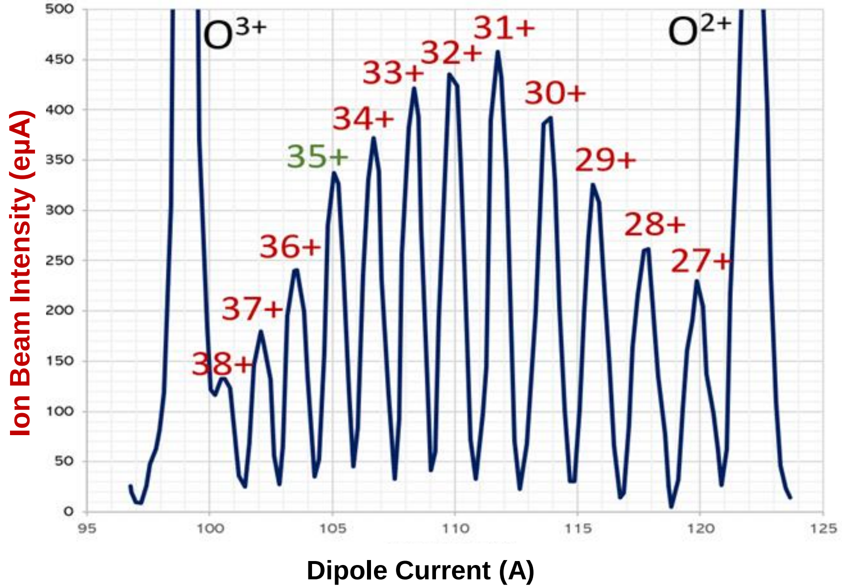


- Reasonable beam intensity produced
- Power efficiency not promising
- 45 GHz as a 2nd ECRH frequency

FECR 1st Plasma and Perspectives: Bi^{35+}







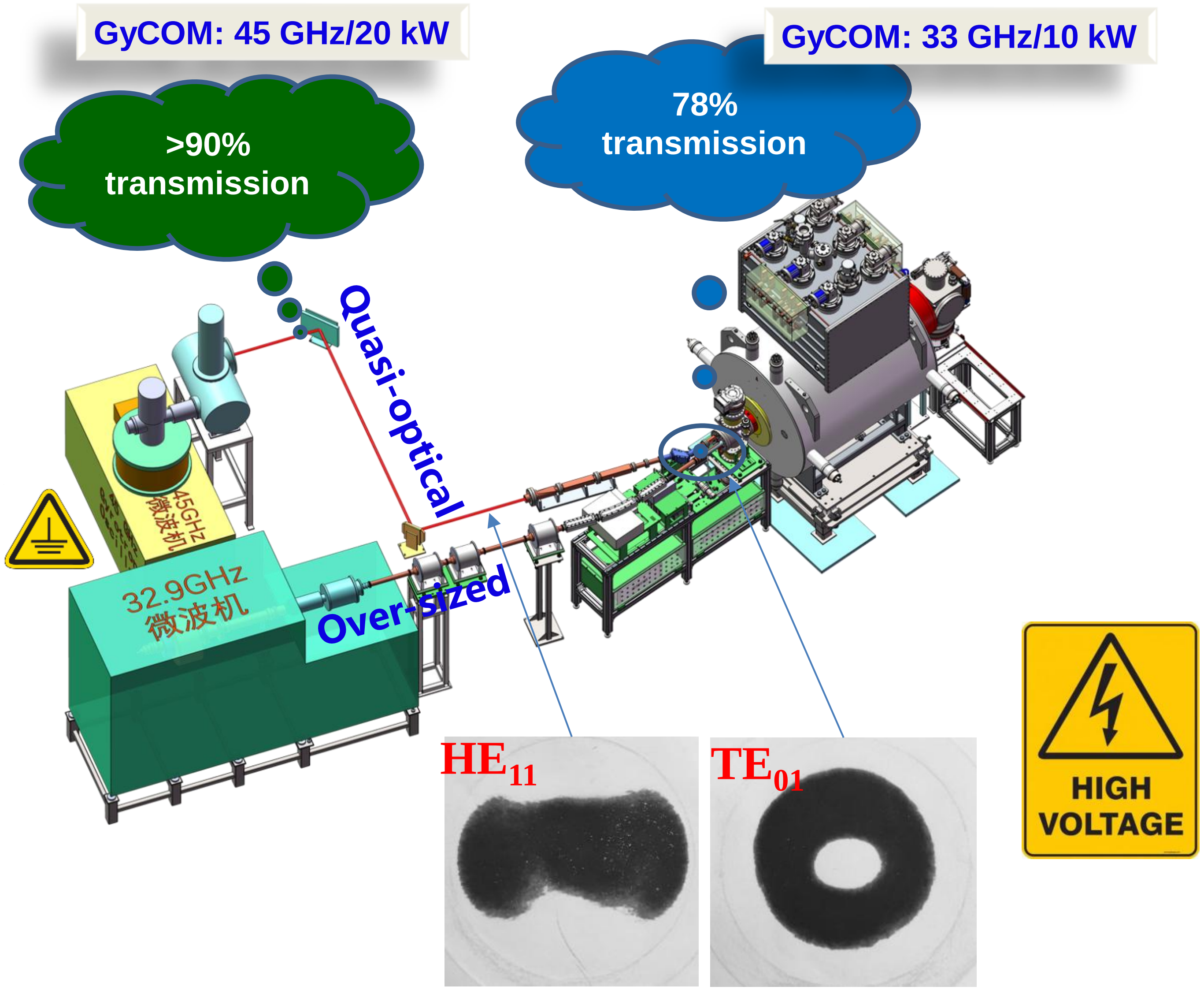
Intense beam produciton

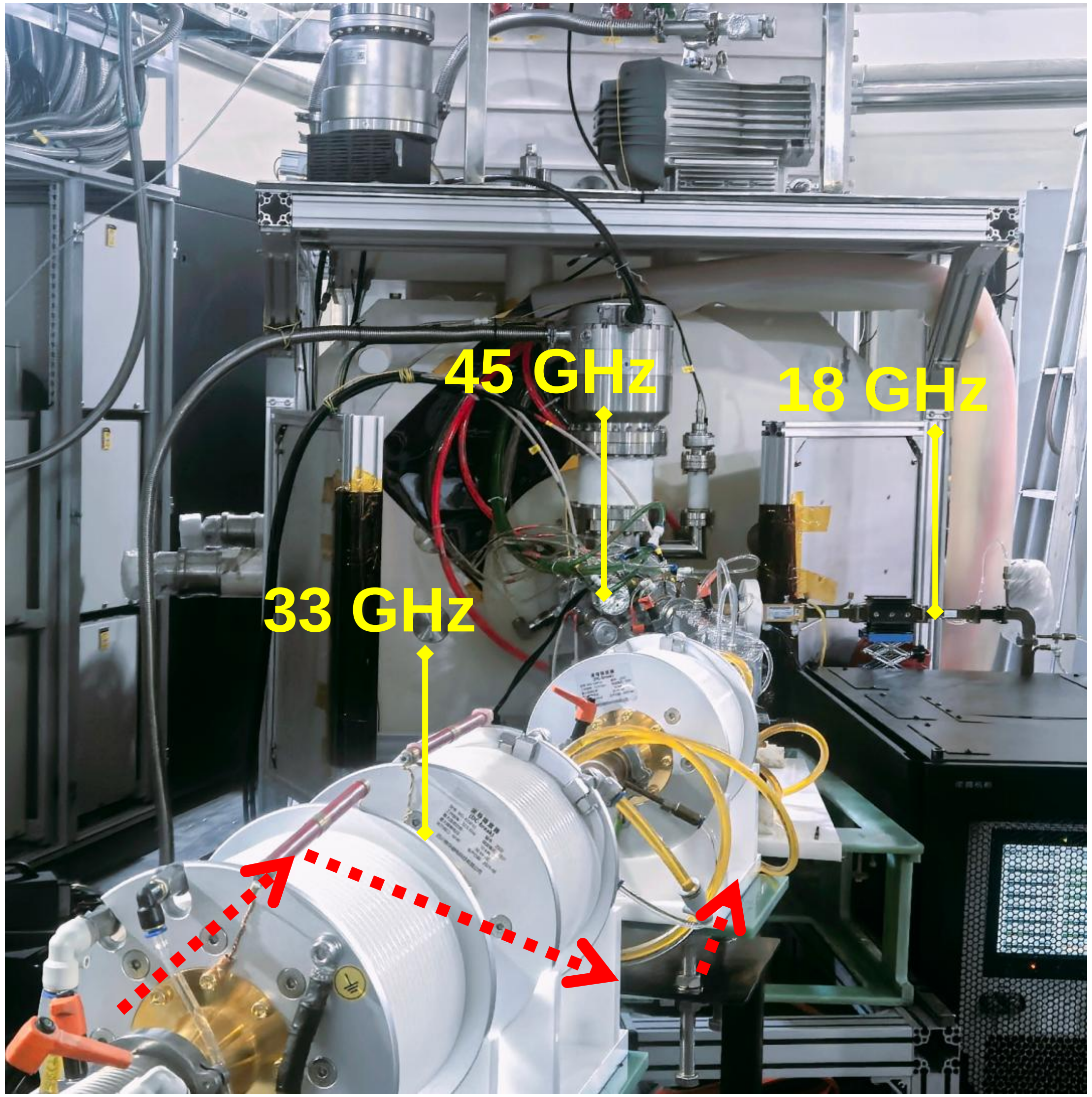
- 350 eμA Bi^{35+} production
- 230 eμA Bi^{35+} acceleration

High power operation

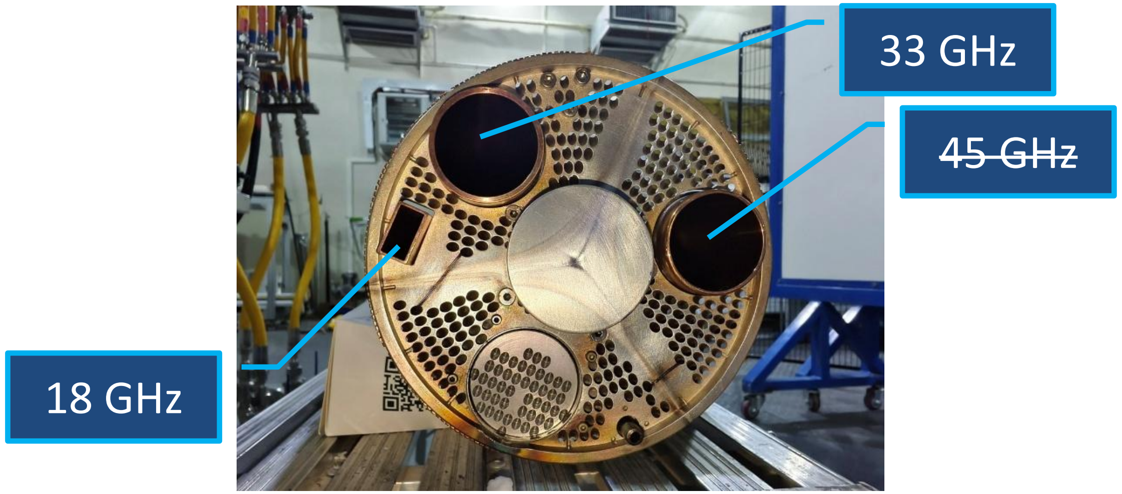
- Highest effective operation ~11 kW for hours

FECR 1st Plasma and Perspectives: 33 GHz

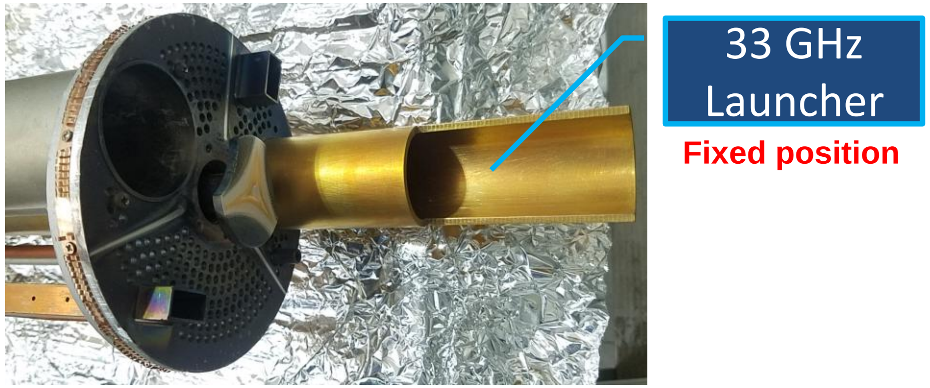




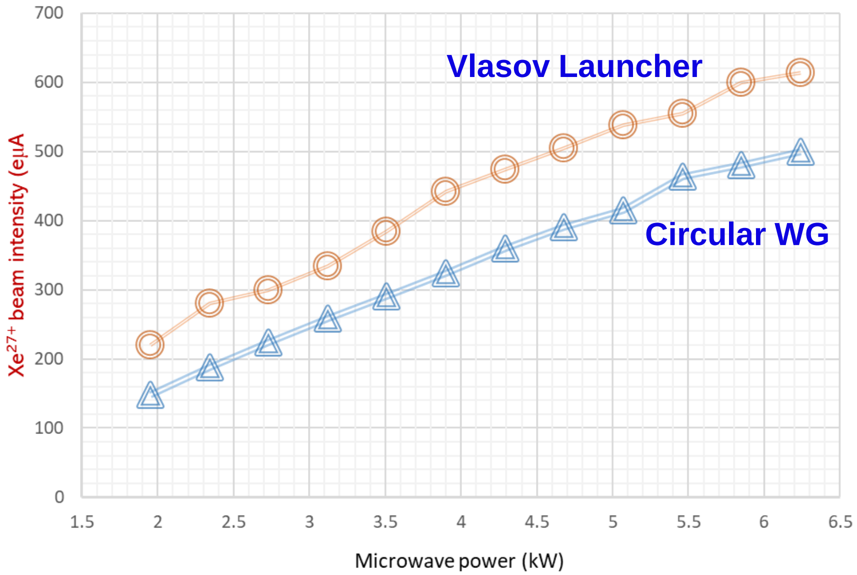
FECR 1st Plasma and Perspectives: 33 GHz



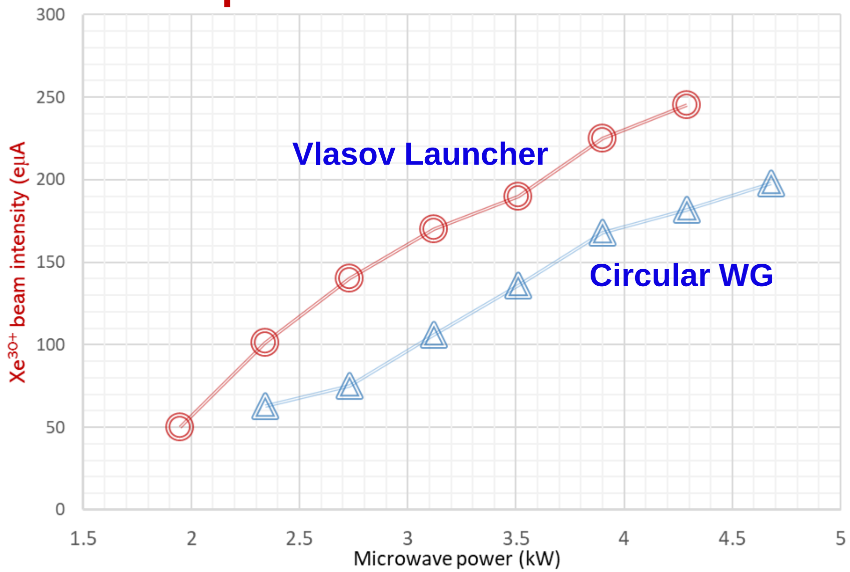
FECR Injection Baffle



SECRAL-II with Vlasov (borrowed picture)



Optimum fields still not found



FECR 1st Plasma and Perspectives: Status

Nb$_3$Sn coils tested to its operation currents

- **Nb$_3$Sn sextupole OK**
- **Structure reliability OK**
- **Assembly process safety OK**

Summary

- Prototype of the 4th generation ECRIS has been made with FECR, and typical challenges have been tackled
- First plasma with FECR has been obtained
- More work needs to be done to understand the ECR plasma at higher frequencies
- The high field FECR or HFECR is on the way, and likely be ready for 45 GHz operation in 2026
  - Quench protection
  - Microwave heating efficiency

Acknowledgement

Xi'an Superconducting Magnet Technology Inc.
- Coil fabrication
- Cold mass fabrication and assembly

Bruker OST LLC.
- Nb_3Sn Wire

Western Superconducting Tech Co., Ltd.
- Nb_3Sn Wire
- Wire braiding

Lanzhou Kejin Taiji New Technology Co., Ltd.
- Mirror structure
- Mechanical mapping

Lawrence Berkeley National Laboratory
- Coldmass structure design

Shanghai Chenguang Medical Technologies Co., Ltd.
- Cryogenic system fabrication and integration

GyCOM Co., Ltd.
- Gyrotron microwave generator and microwave transmission solutions

And all those have given us fruitful suggestions!!