# The Latest Progress of 45 GHz FECR


**L. Sun**

**H. W. Zhao, W. Wu, W. Lu, J. B. Li, X. Y. Wang, B. M. Wu, X. J. Ou, E. M. Mei, S. J. Zheng, L. B. Li, X. Z. Zhang, L. Zhu, C. J. Xin, Y. Q. Chen**

**and the other FECR team members**

***Institute of Modern Physics, CAS, 730000, Lanzhou, China***

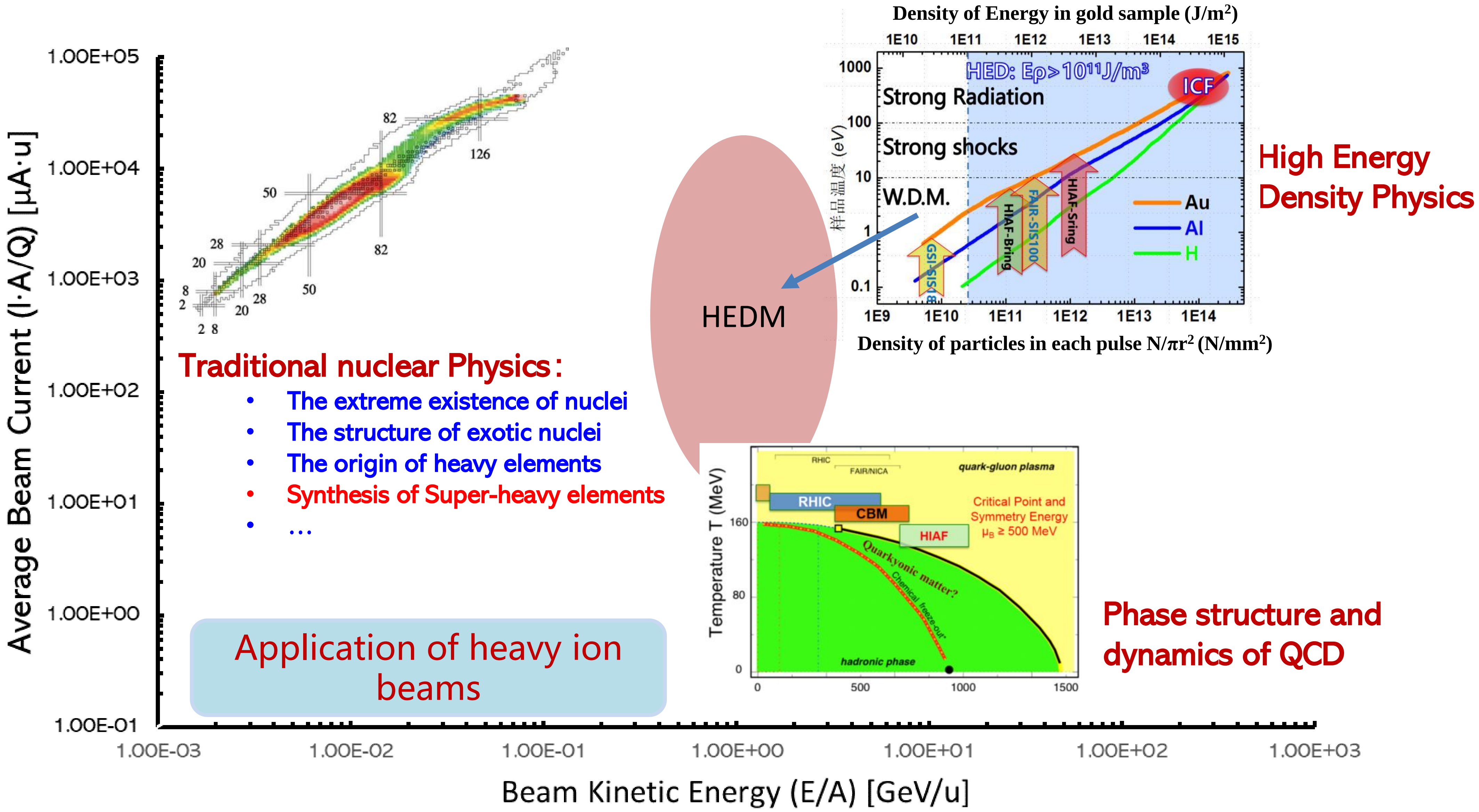


*ICIS'23, Sept. 17~22, 2023, TRIUMF, Canada*

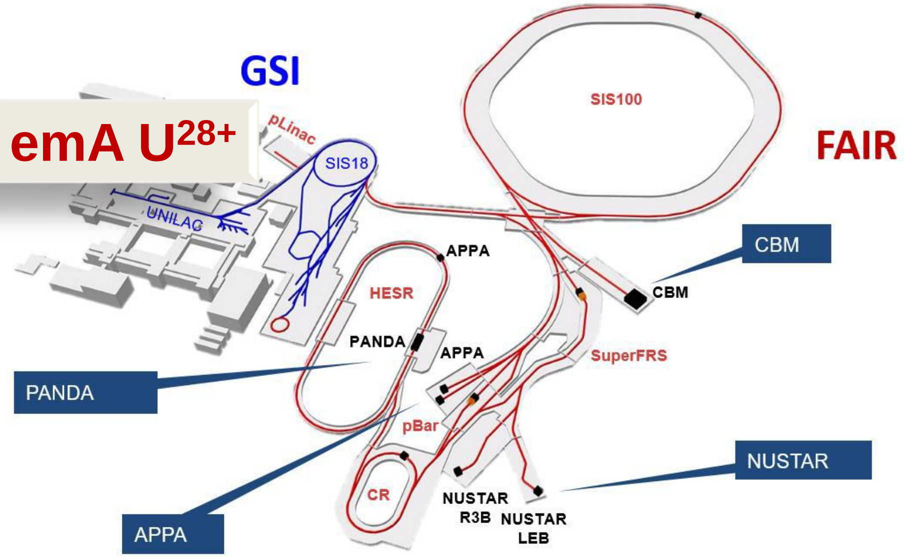
# Outline

- Global needs on HCI beams production
- Progresses with the $3^{rd}$ G ECRISs and the challenges
- Status of FECR development
- Summary

# Global needs on HCI beams

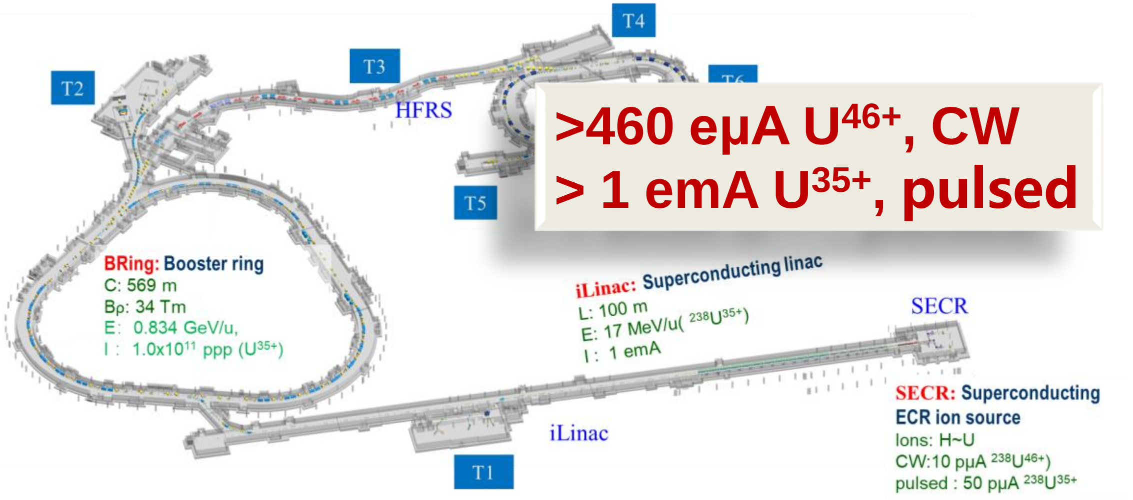


# Global needs on HCI beams



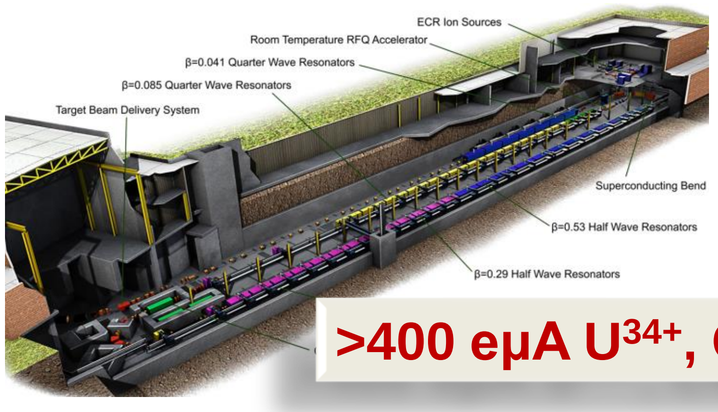

15 emA $U^{28+}$

GSI FAIR (under construction)



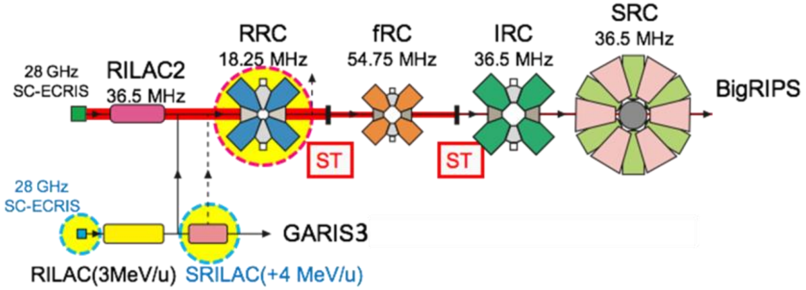

>460 eμA $U^{46+}$, CW
> 1 emA $U^{35+}$, pulsed

IMP HIAF (under construction)



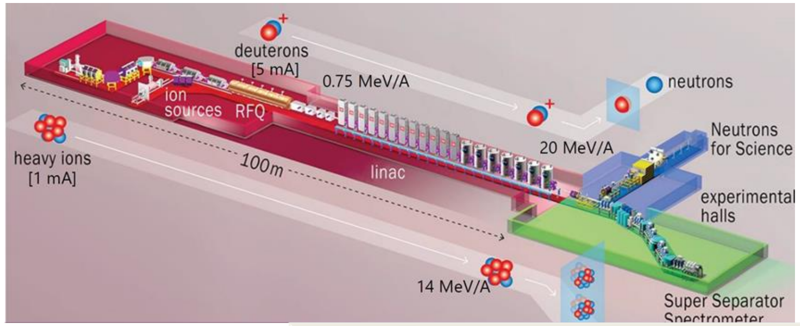

>400 eμA $U^{34+}$, CW

MSU FRIB (in operation)




>500 eμA $U^{35+}$, CW

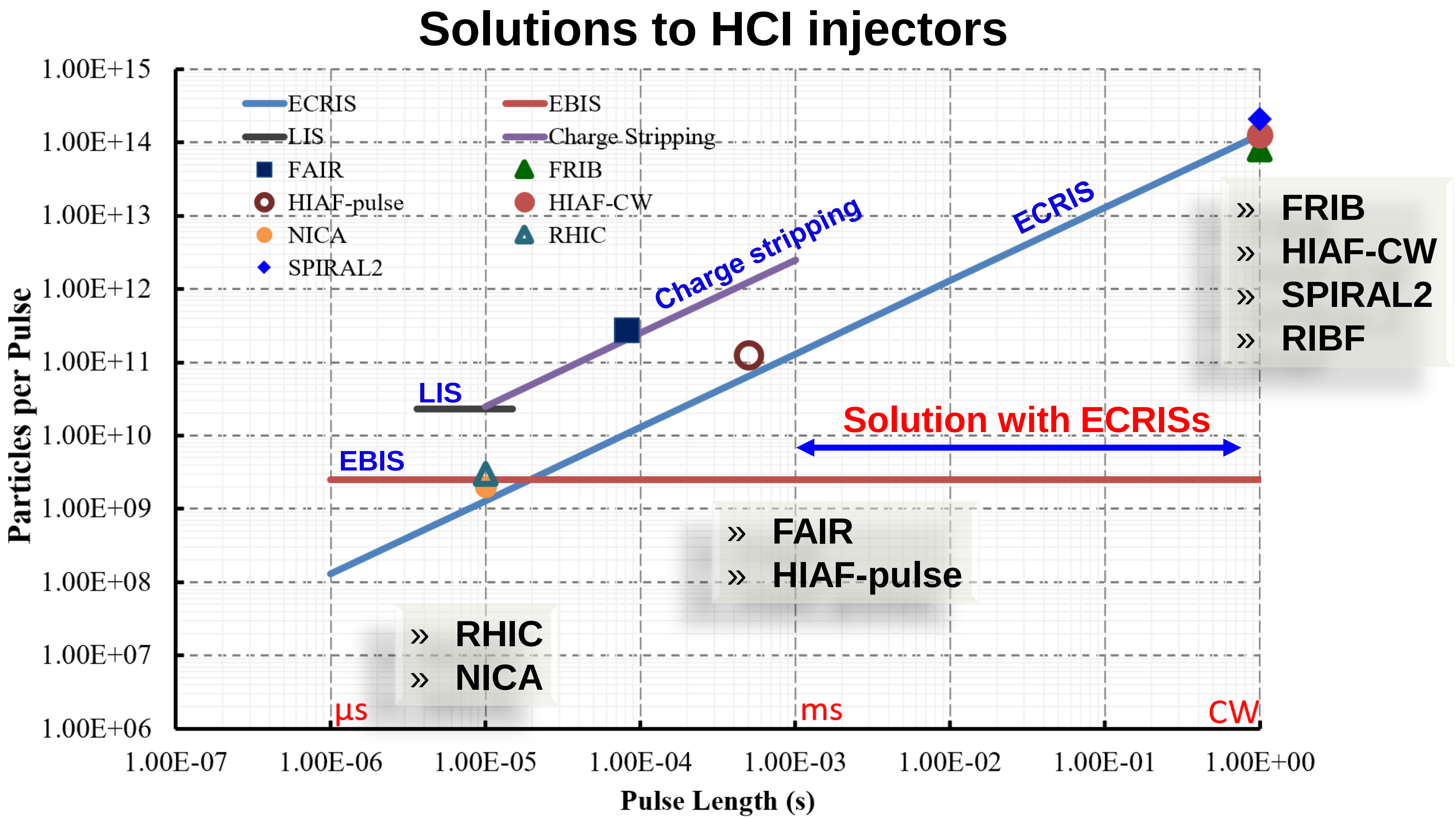
RIKEN RIBF (in operation)



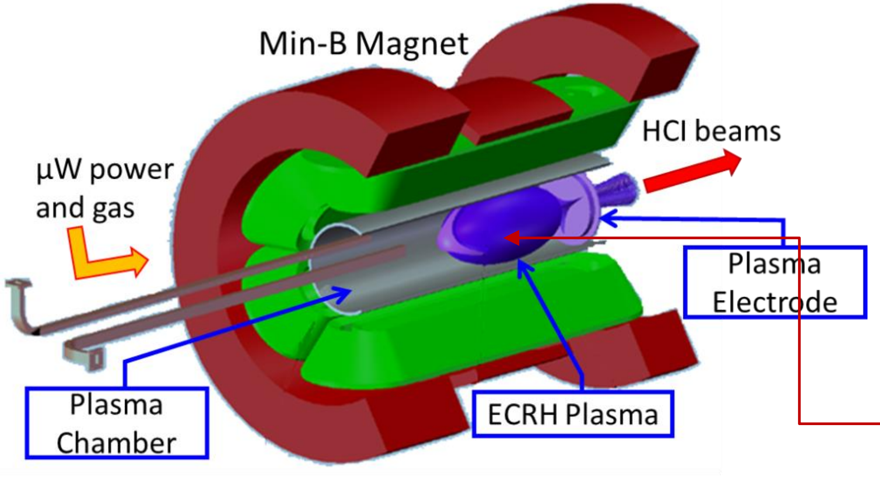

> 1 emA $Ar^{12+}$, CW

GANIL SPIRAL 2 (in operation)

# Global needs on HCI beams



# Progresses with the 3rd G ECRISs and the challenges




**Plasma Magnet Microwave**

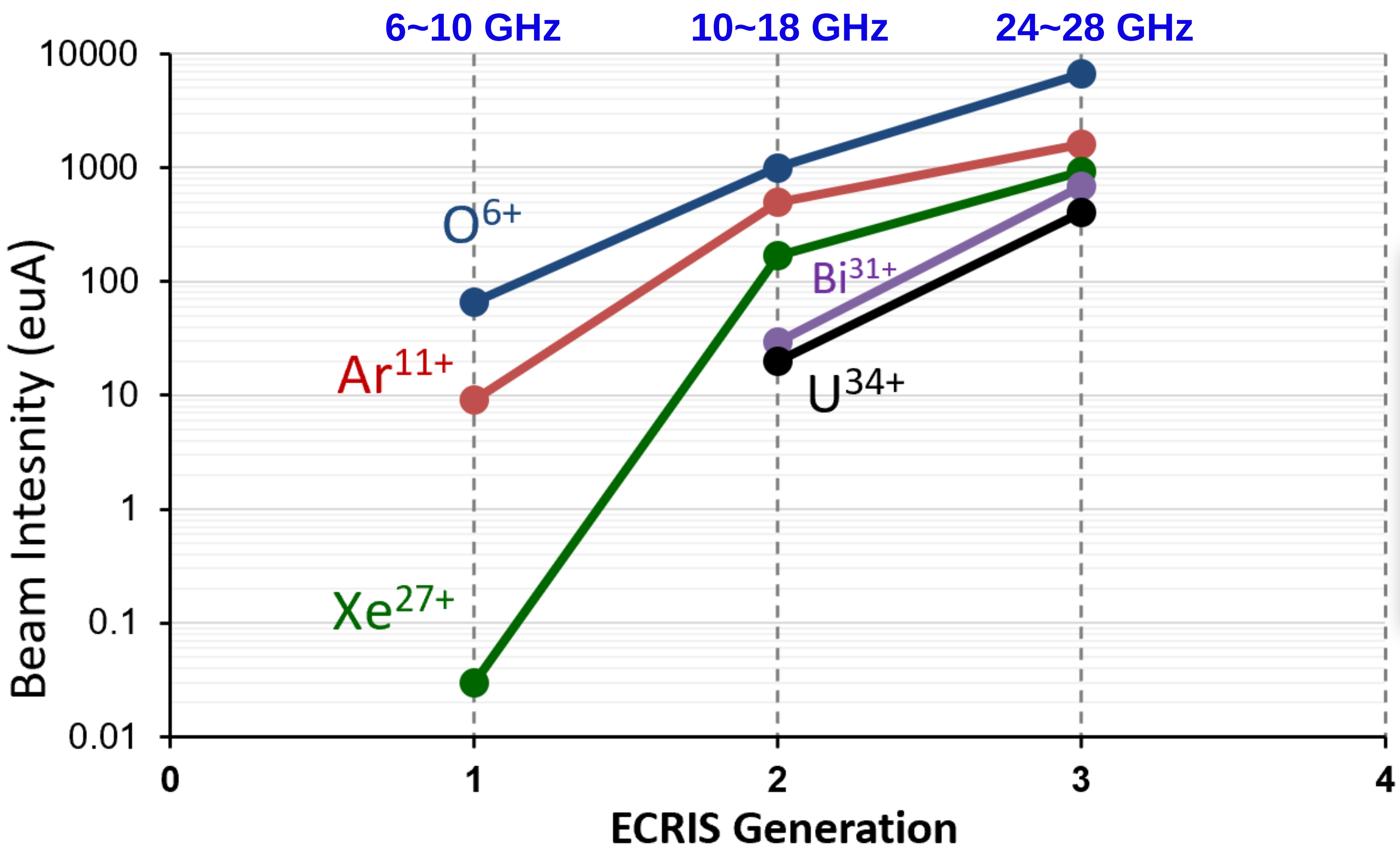
**Electron Cyclotron Resonance**
**Ion Source**

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

**BH²**

- $I_i^q = \frac{1}{2} \frac{n_i^q \, q \, e V_{ex}}{\tau_i^q}$ — $n_i^q$ ion density for species i charge q; $\tau_i^q$ Confinement time for species i charge q; $\sum_{i,q} n_i^q q_i = n_e$ (Plasma neutrality) → **Bigger Volume**
- RF dispersion equation at resonance : $(n_e T_e) \approx (\frac{m_e \varepsilon_0 \omega_{rf}^2}{e^2}) m_e c^2$ — $I^q \propto \omega^2_{ECR}$ → **Higher Frequency**
- Plasma Stability condition : $\beta = \frac{n_e k_b T_e}{(\frac{B^2}{2\mu_0})} < 1$ — As $n_e \nearrow$ $B \nearrow$ → **Higher B Field**

# Progresses with the 3rd G ECRISs and the challenges



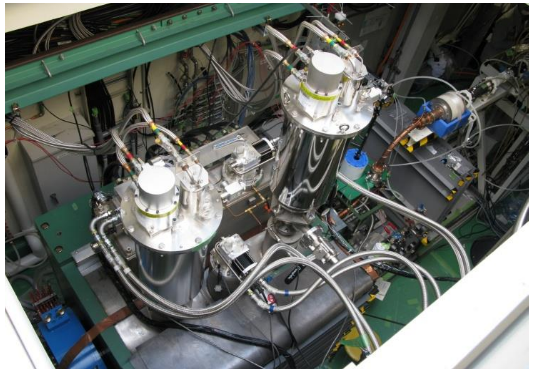

**G1** (1970~1980) **G2** (1980~1990) **G3** (2000~now)

**State of the art ECRIS:**

- $\omega_{ECR}$: 18~28 GHz
- RF power: 3~10 kW
- Chamber volume: 3~10 L

# Progresses with the 3rd G ECRISs and the challenges

VENUS@LBNL: 28+18 GHz



SCECRISs@RIKEN: 28+18 GHz

**More to come:**

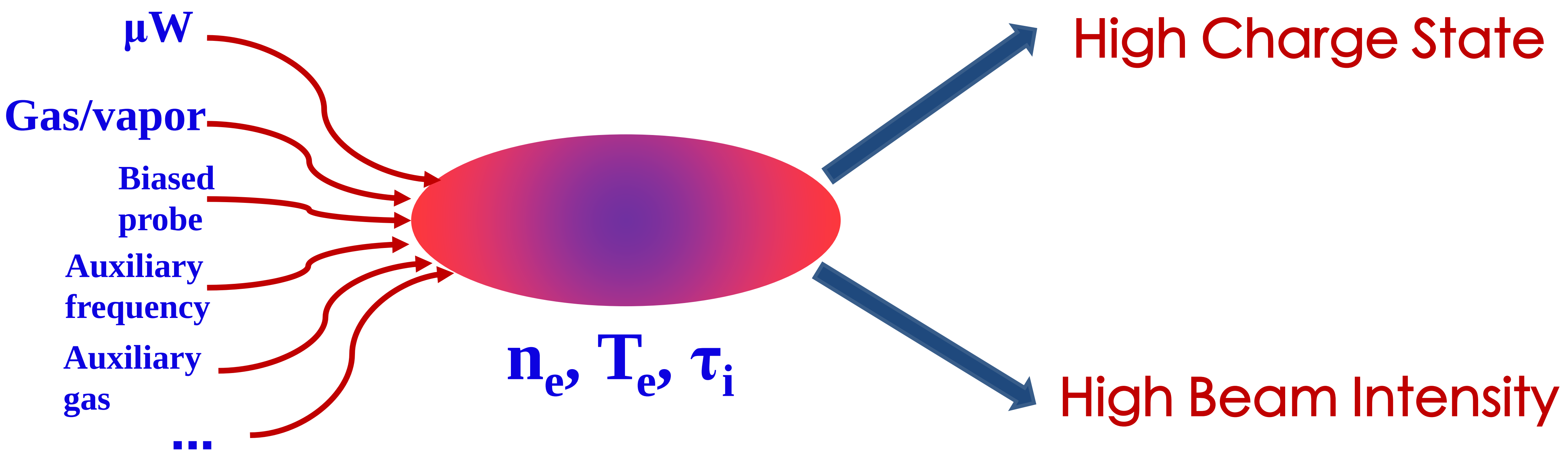
- 28 GHz SECRAL-III@IMP
- 28 GHz ASTERICS@GANIL
- 28 GHz SC-ECRIS@JINR
- ….

SuSI@MSU: 24+18 GHz

FRIB-SCECRIS: 28+18 GHz

SECRAL-I, SECRAL-II@IMP: 28/24+18 GHz

# Progresses with the 3rd G ECRISs and the challenges

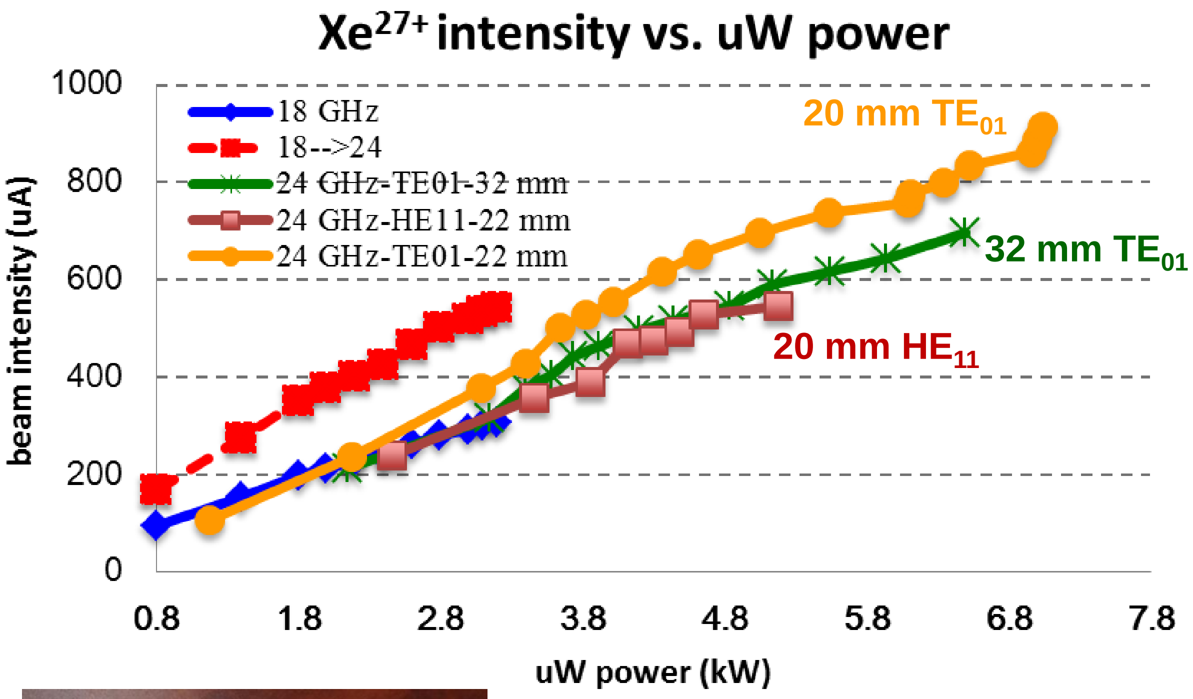



**Challenges**

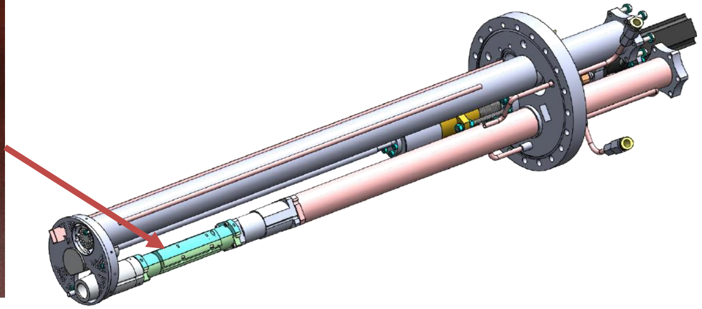
- ◆ High frequency high power coupling to ECR plasma
- ◆ Efficient cooling to hot dense plasma
- ◆ Refractory metallic ion beam production

# Progresses with the 3rd G ECRISs and the challenges

***Efficient microwave coupling***

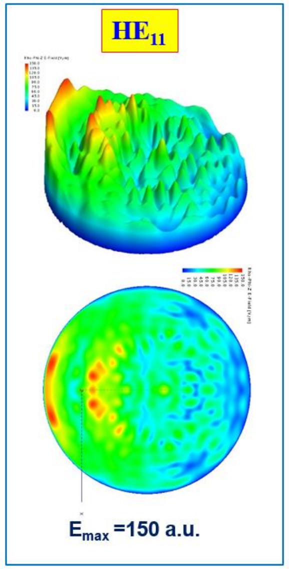


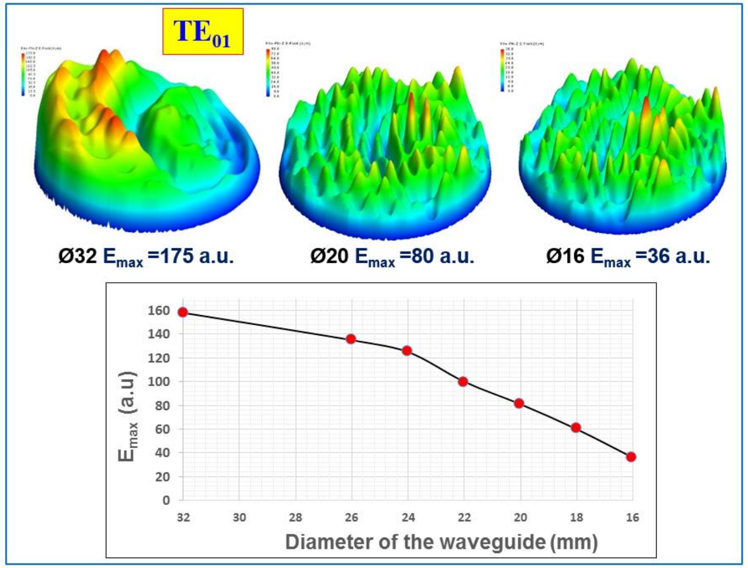




## Efficient microwave coupling via WG opening tuning:

- Ø20 mm$TE_{01}$ show obvious advantage in HCI production at high power level
- No sign of saturation even at high power level

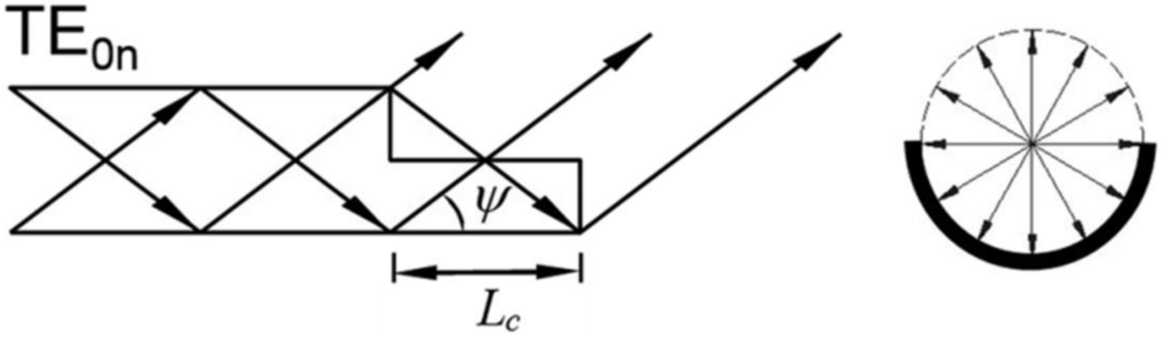


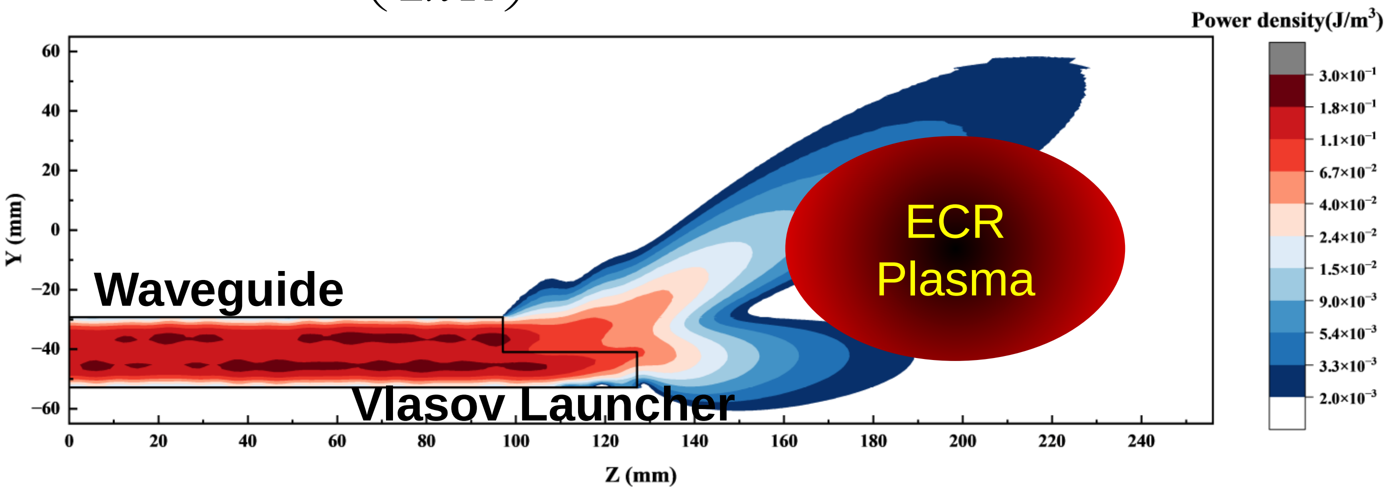

L. Sun, et al., Review of Scientific Instruments **87**, 02A707 (2016);

## *Efficient microwave coupling*

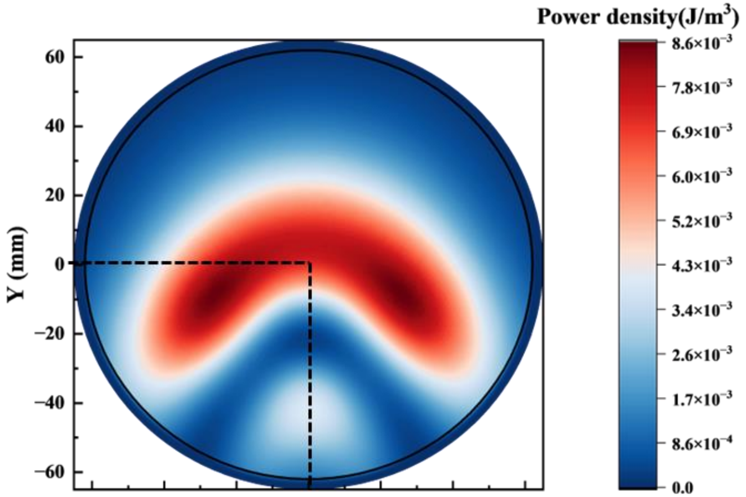
### More flexible tuner for μW coupling: Vlasov Launcher




$$\psi = \sin^{-1}\left(\frac{\mu_{0n}\lambda}{2\pi R}\right) \qquad L_c \geq 2R\cot\psi = 28.14\text{mm}$$

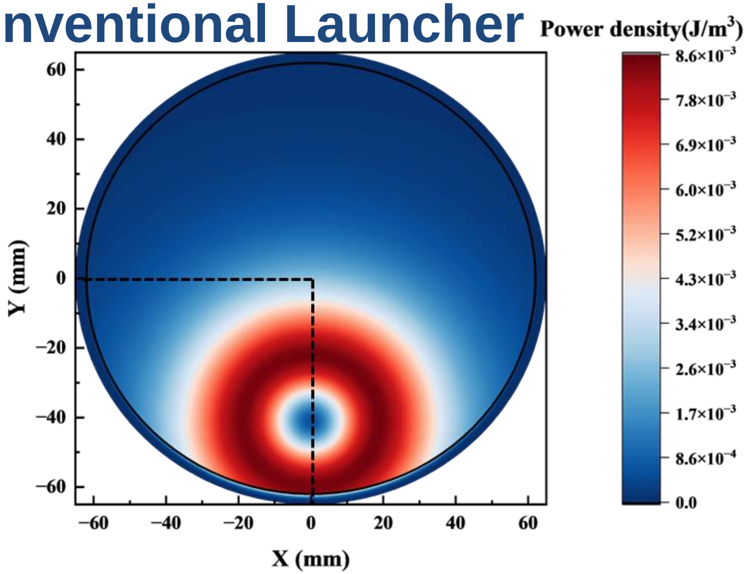



J.W.Guo, et al., Rev. Sci. Instrum. **91**, 013322 (2020)



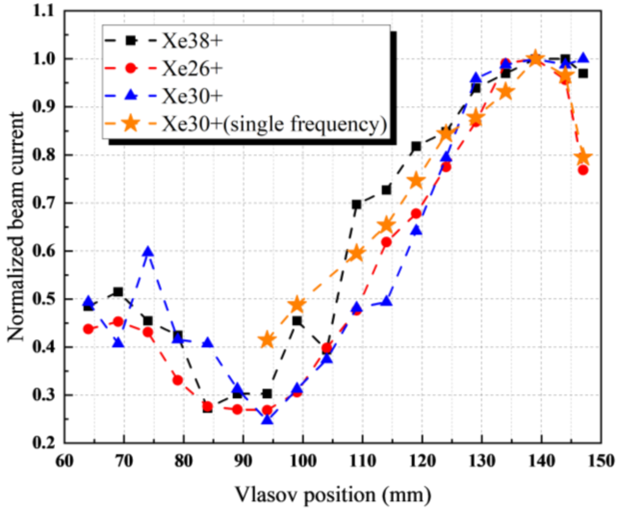

**Power density on 1st ECR surface**

### Conventional Launcher

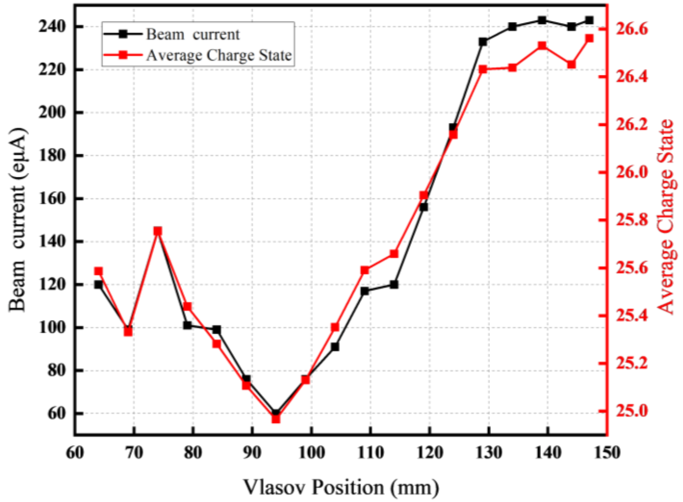


# Progresses with the 3rd G ECRISs and the challenges

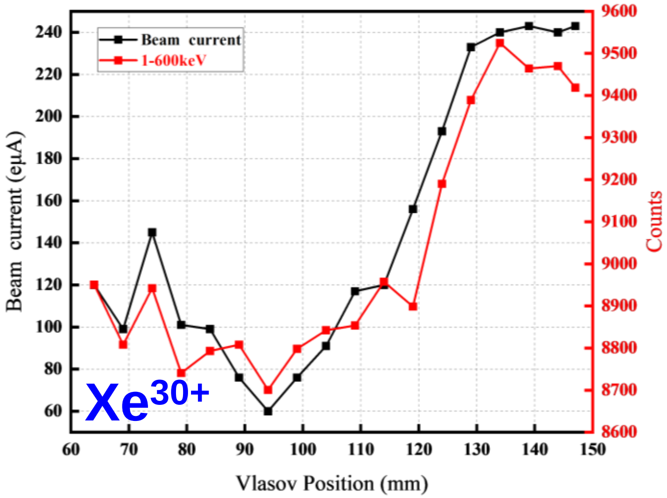
***Efficient microwave coupling***



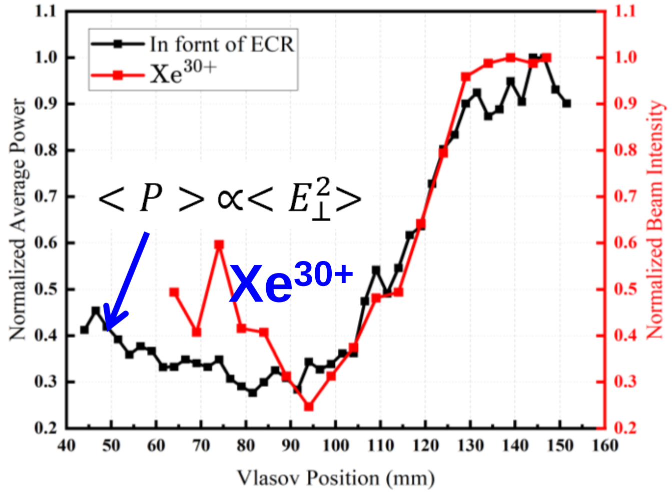

Beam intensity $I_q$ response to Vlasov launcher position




Average charge state<Q> response to Vlasov launcher position




$I_q$ and Bremsstrahlung counts responses to Vlasov launcher position




$I_q$ and calculated average μW radiation <P> response consistency

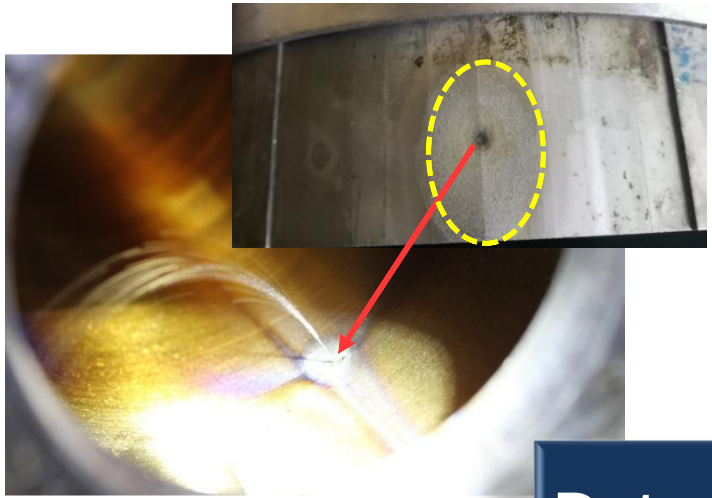
- Vlasov launcher is an efficient tuner to microwave plasma coupling
- μW radiation <P> distribution might be a key to efficient HCI production
- Recorded beam intensities production：

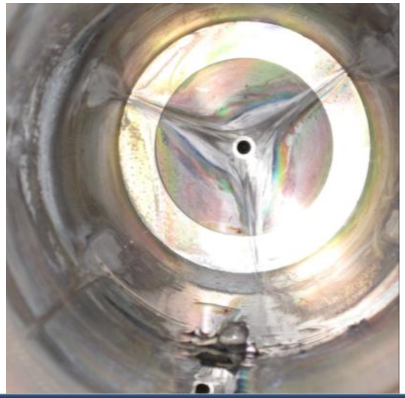
  **18 eμA $Xe^{42+}$、47 eμA $Xe^{38+}$、146 eμA $Xe^{34+}$、374 eμA $Xe^{30+}$**

*Xinyu Wang@Poster session on Monday*

# Progresses with the 3rd G ECRISs and the challenges

***Efficient Chamber Cooling***

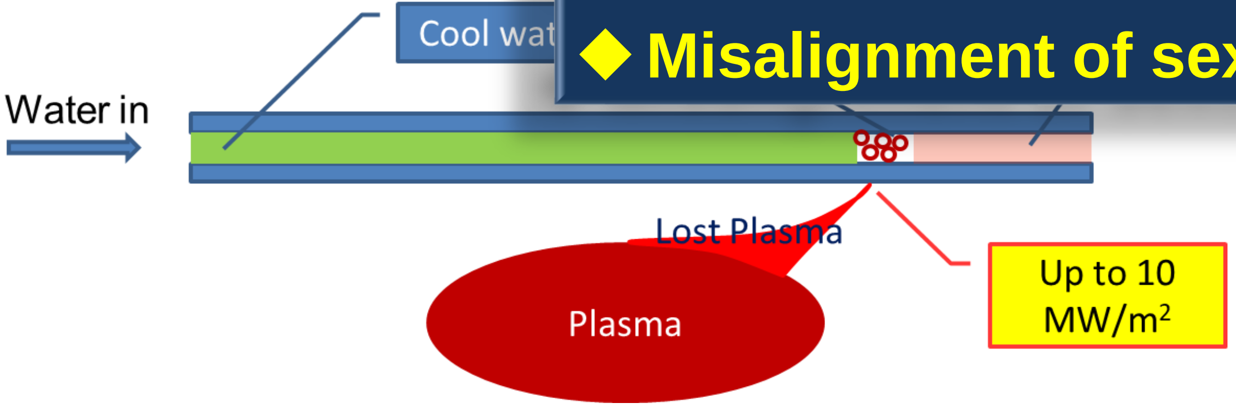




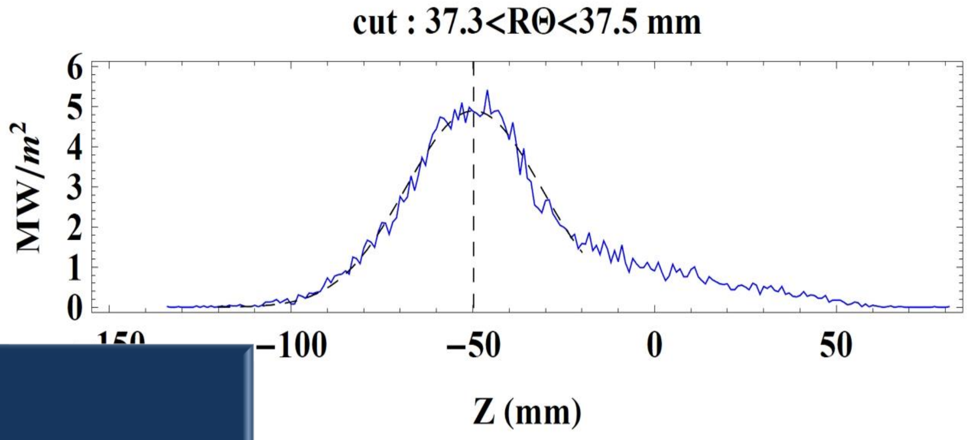
**Chamber burnt with SECRA**
**Typically：>7 kW**

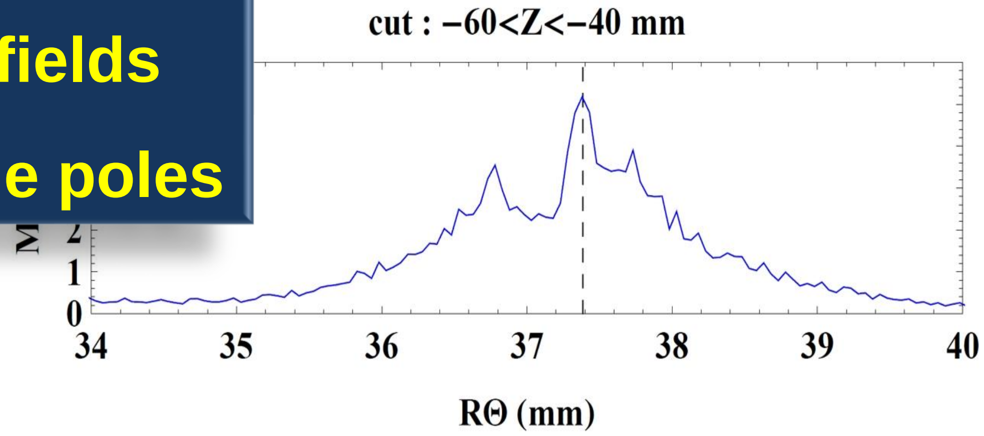
**Deteriorate the situation:**

- **Differences in sextupole fields**
- **Misalignment of sextupole poles**




**LCW pressure of 6 kg/cm²，water BP =150~160℃**



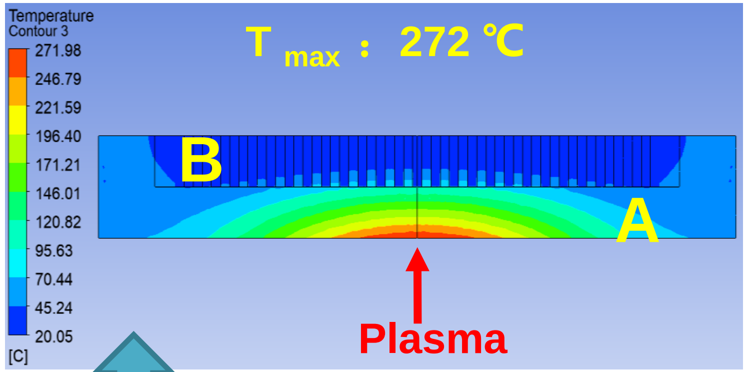

**1 kW μW~1.25 MW/m² heat sink**

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

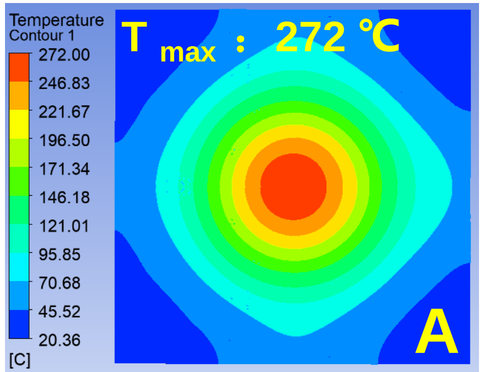
## Efficient Chamber Cooling

# Maximum permissible operating power exceeds 10 kW

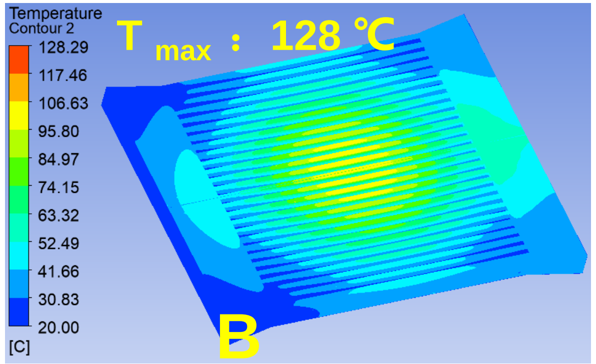
Chamber ID:125 mm, Microchannel:0.4 mm *20, Channel height:1.5 mm, Channel flow rate: 4 L/min



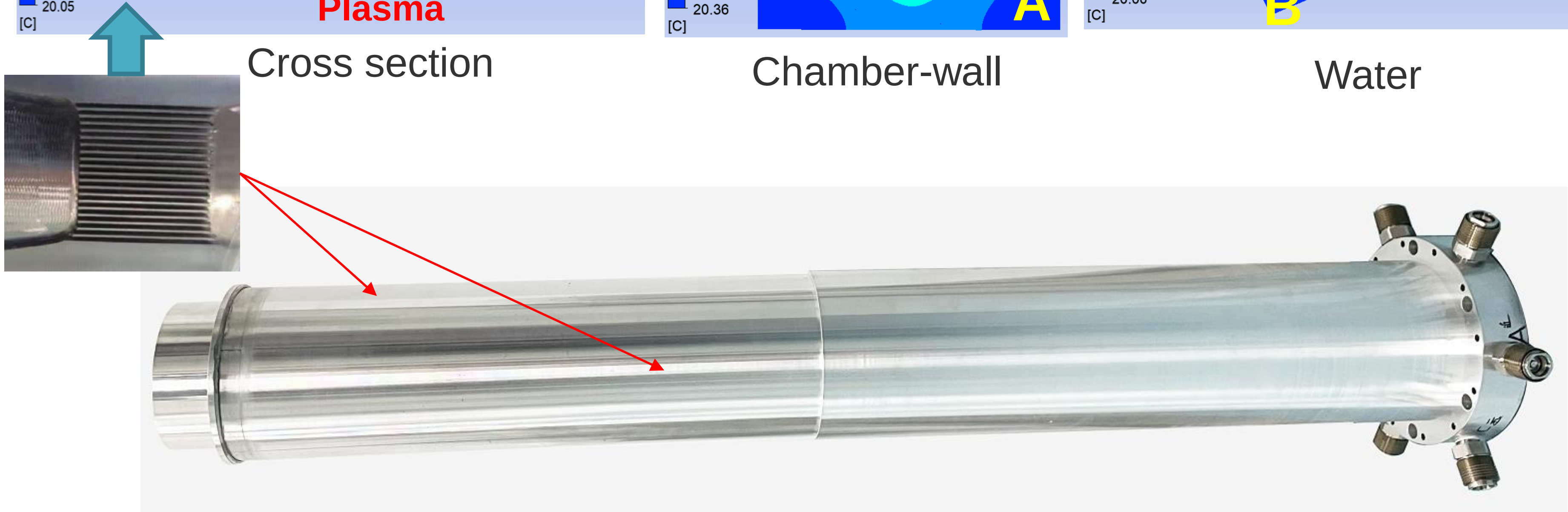

Cross section




Chamber-wall

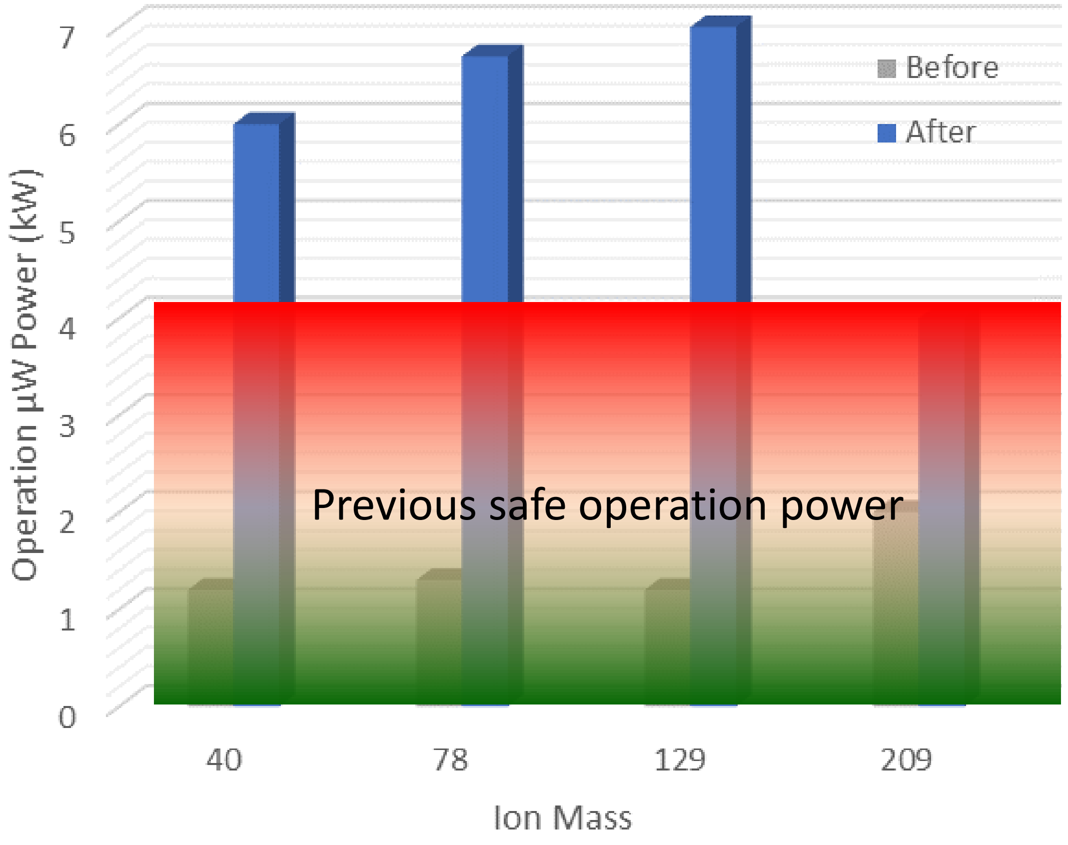



Water

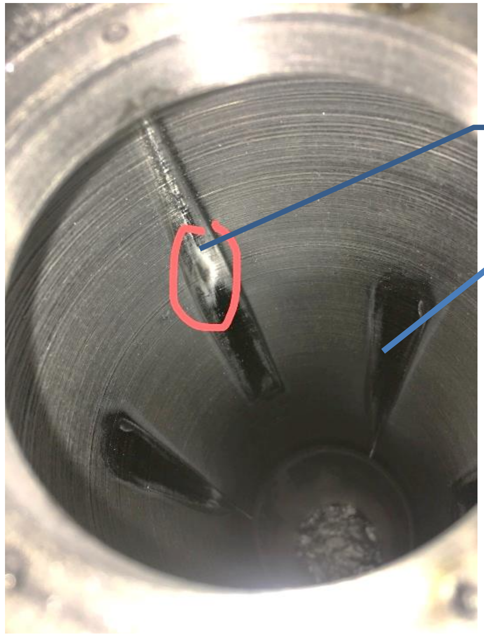


# Progresses with the 3rd G ECRISs and the challenges

***Efficient Chamber Cooling***

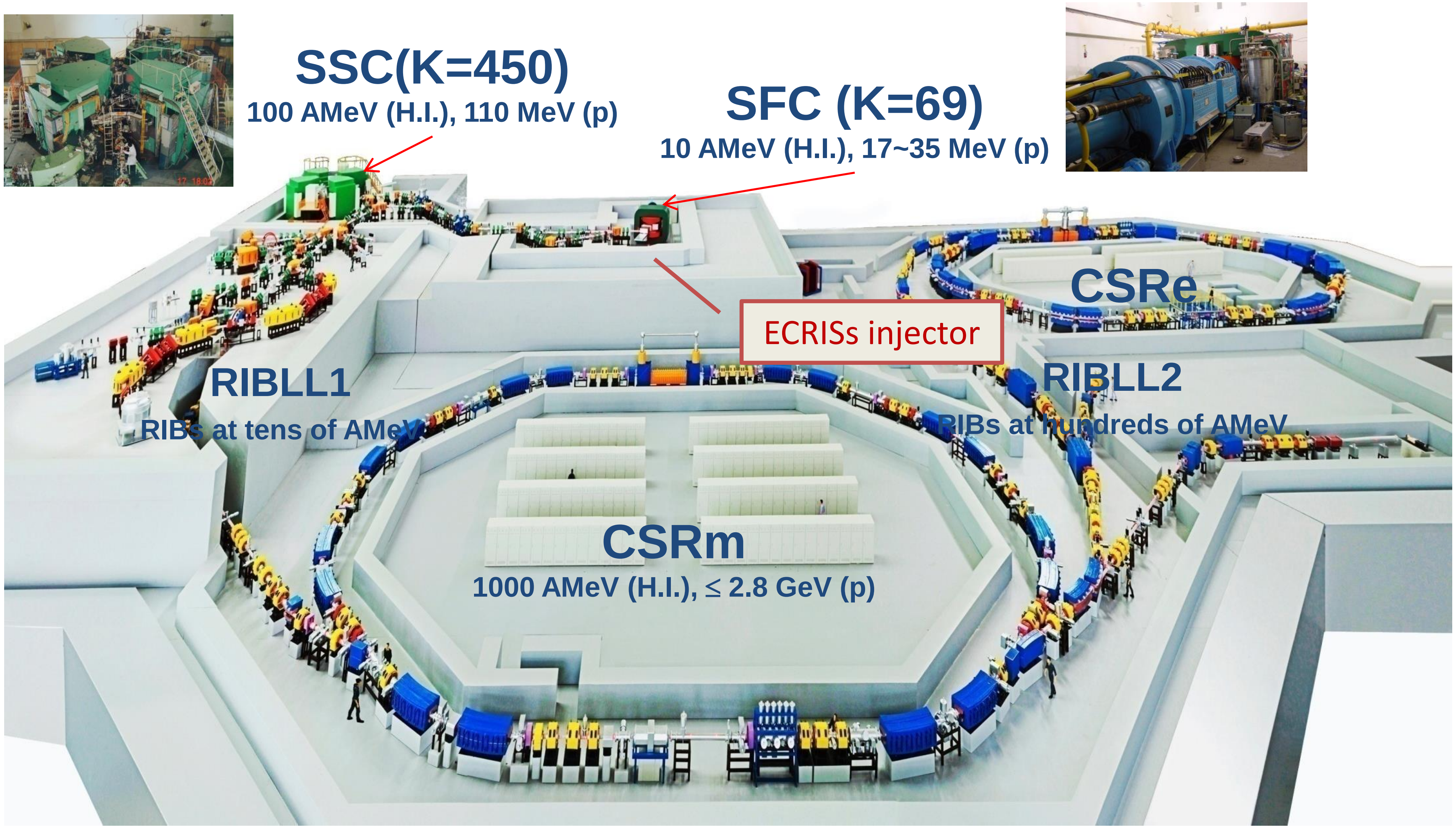



- **Routine safe operation power obviously increased with new chamber structure**
- **Reliable long-term operation at 5~10 kW level applicable**



Server etching marks after continuous high power Ar beam operation

# Progresses with the 3rd G ECRISs and the challenges




**HIRFL Operation scheme: ECR + Cyclotron + Synchrotron**

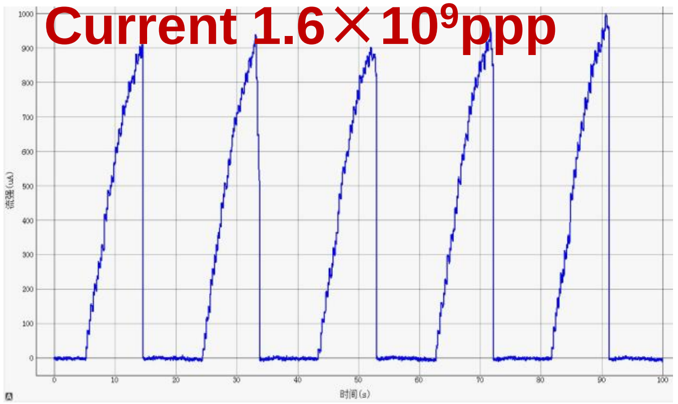
# Progresses with the 3rd G ECRISs and the challenges

## HIRFL performance enhancement

### $^{36}Ar^{15+}$

**SECRAL-II: ~350 eμA （~4 times historical operation current）**

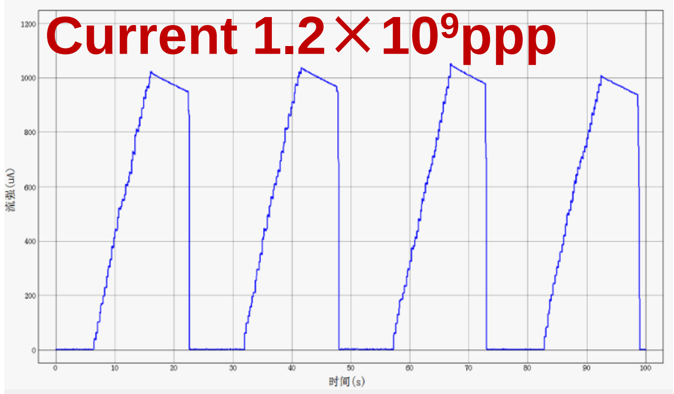
- High current：SFC--8.5 AMeV/15 eμA
- $CSR_m$ Beam Current Increase by a factor of 5




### $^{78}Kr^{26+}$

**SECRAL-II: ~280 eμA (not available before)**

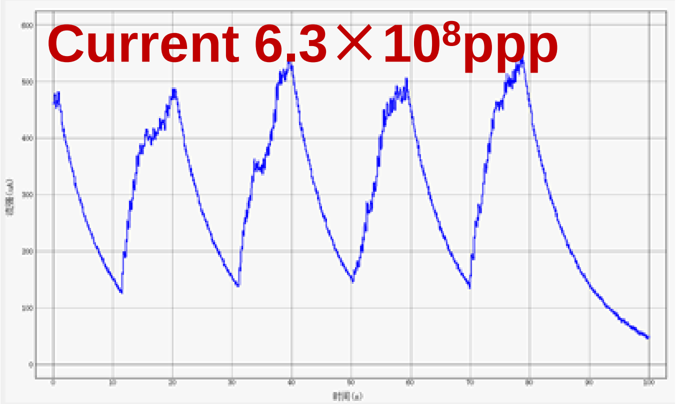
- High current：SFC--6 AMeV/12 eμA
- $CSR_m$ Beam Current Increase by a factor of 10




### $^{129}Xe^{32+}$

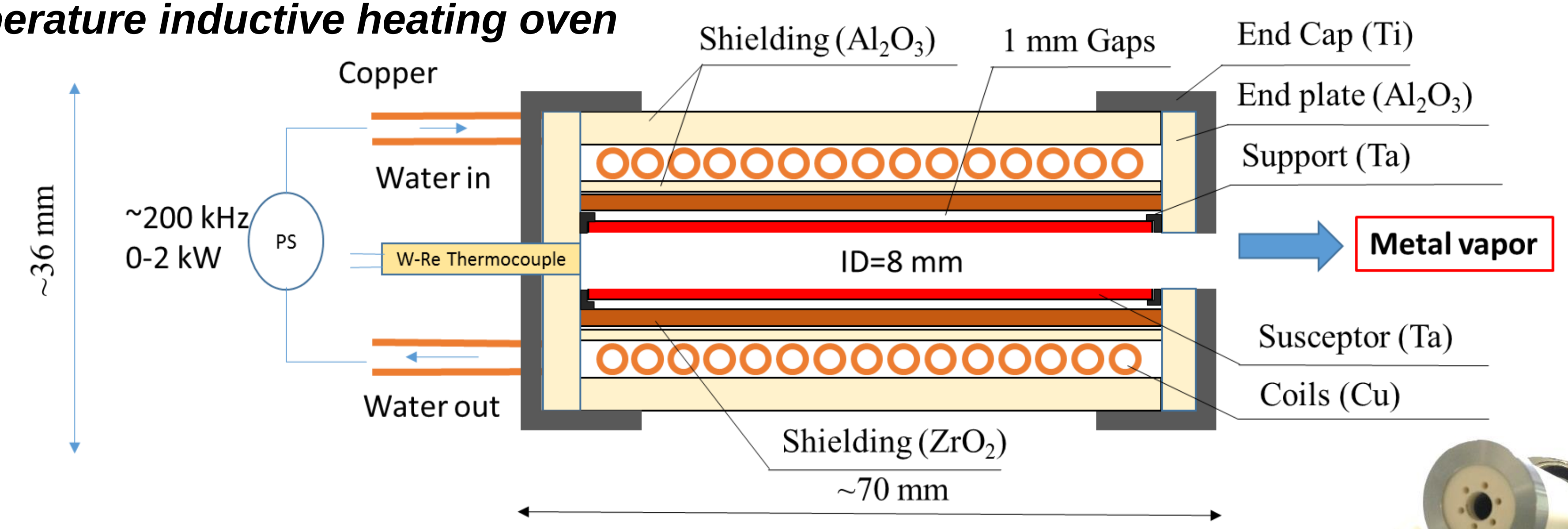
**SECRAL-II: ~200 eμA (not available before)**

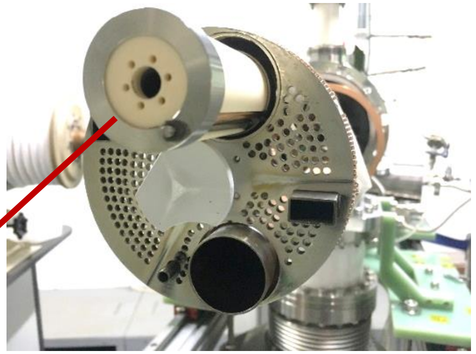
- High current：SFC—3.9 AMeV/8 eμA
- $CSR_m$ Beam Current Increase by a factor of 5



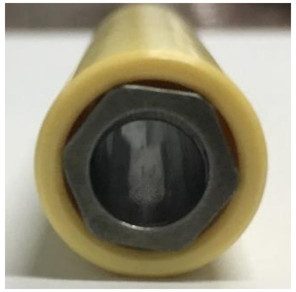
# Progresses with the 3rd G ECRISs and the challenges

***High temperature inductive heating oven***



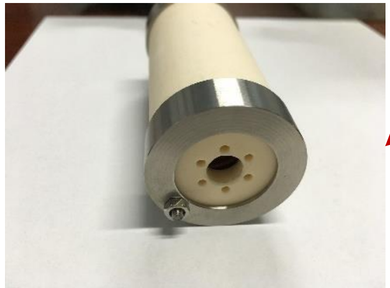



1 mm of Susceptor (Ta)



2 mm of $ZrO_2$

$Al_2O_3$ End plate



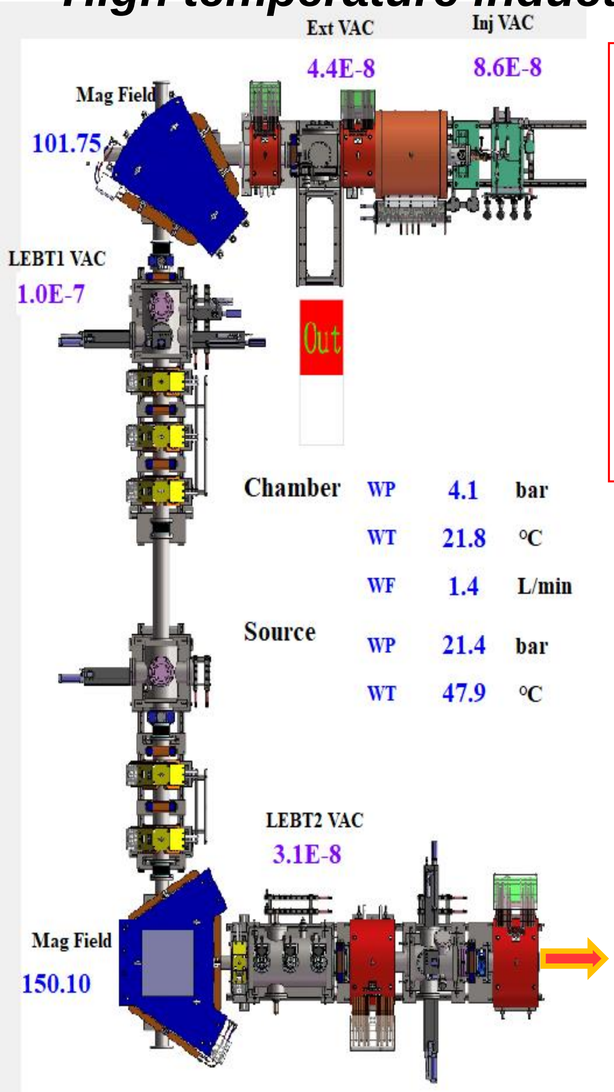
Inductive oven-2019

**Inductive heating oven**

- **Durable for weeks operation**
- **Reliable at ~2000℃**

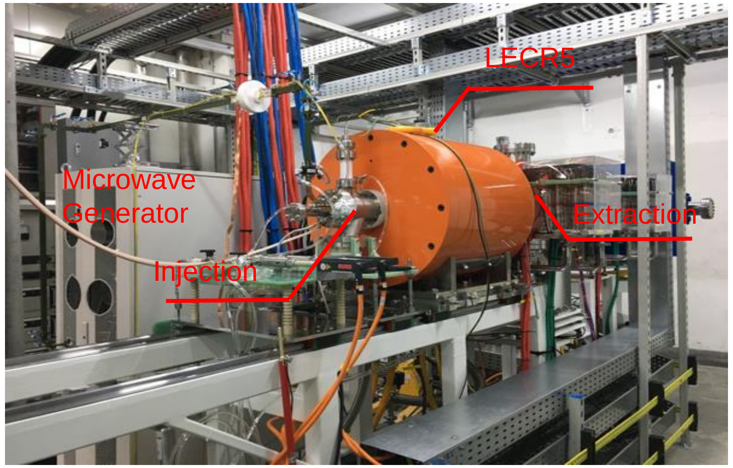
# Progresses with the 3rd G ECRISs and the challenges

***High temperature inductive heating oven***




SHE facility injector at IMP

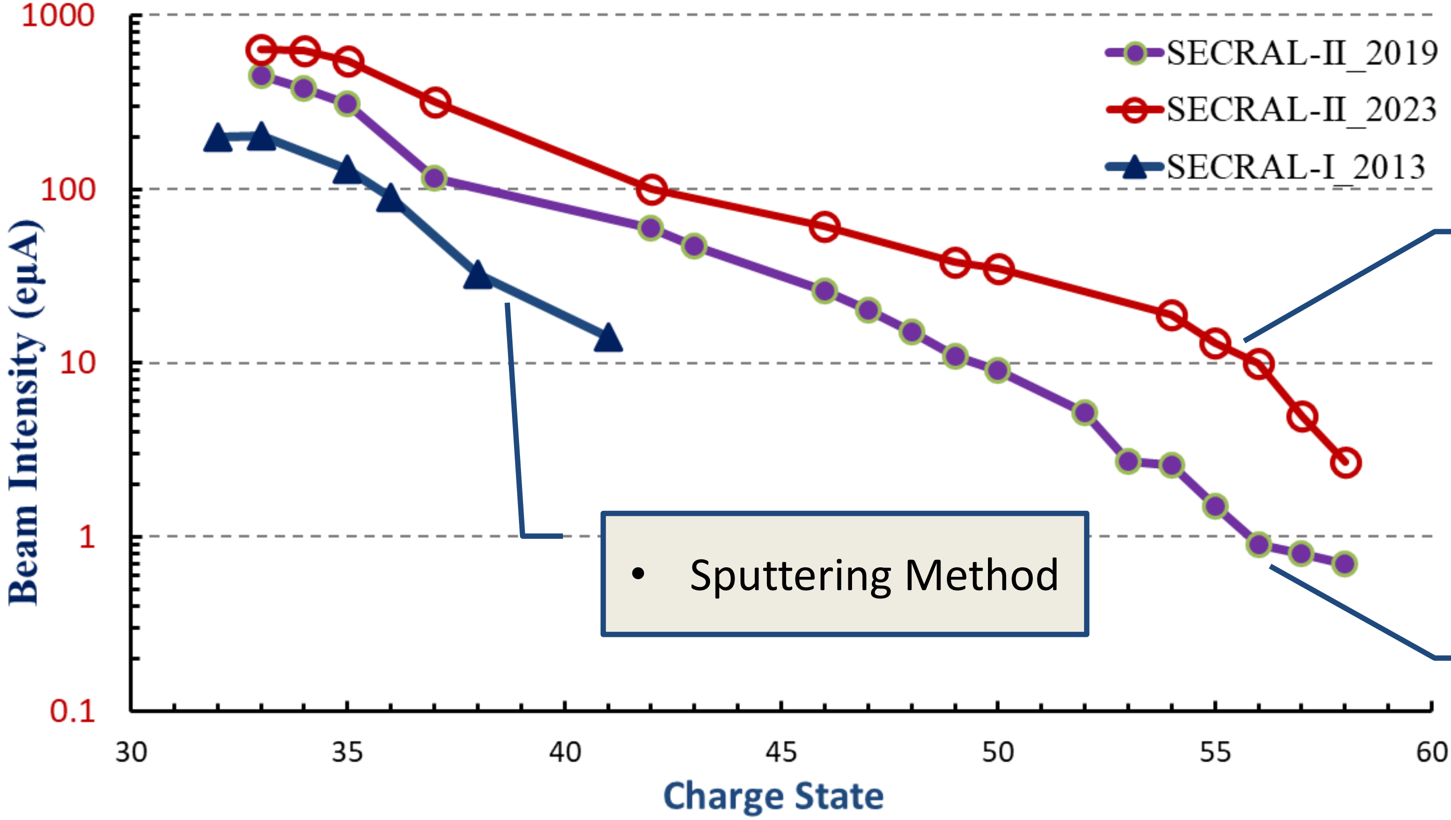
- Metallic ions delivered from LECR5 (2021-2023)：
  $^{40}Ca^{13+}$, $^{55}Mn^{17+}$, $^{54}Cr^{17+}$, $^{48}Ca^{14+}$；
- RF Power: 18+14.5 GHz/ 1.5- 2.0 kW
- IS extraction voltage: 30.8- 34.2 kV
- Technical features:
  **Inductive heating oven, CaO+Al**




RT ECR ion source - LECR5

| Ion species | M/Q | Method | Supporting Gas | IS Ext. Voltage [kV] | FC01 （IS） [euA] | FC03 （RFQ） [euA] | RFQ entrance RMS emittance （π.mm.mard） | Transmission efficiency [FC03/FC01] | Delivering time [Hrs] |
|---|---|---|---|---|---|---|---|---|---|
| $^{40}Ca^{13+}$ | 3.08 | **$^{40}$CaO+ Al** | $^{16}O_2$ | 30.8 | 40-60 | 35-50 | Ɛx=0.12, Ɛy=0.05 | 85~90% | 1500 |
| $^{55}Mn^{17+}$ | 3.24 | **$^{55}$Mn** | $^{14}N_2$ | 32.4 | 40-60 | 35-50 | Ɛx=0.08, Ɛy=0.06 | 85~90% | 428 |
| $^{54}Cr^{17+}$ | 3.18 | **$^{54}$Cr** | $^{14}N_2$ | 31.8 | 40-60 | 35-50 | Ɛx=0.08, Ɛy=0.06 | 85~90% | 1183 |
| $^{48}Ca^{14+}$ | 3.43 | **$^{48}$CaO+ Al** | $^{16}O_2$ | 34.3 | 10-40 | 10-35 | Ɛx=0.09, Ɛy=0.08 | 85~90% | ~600 |

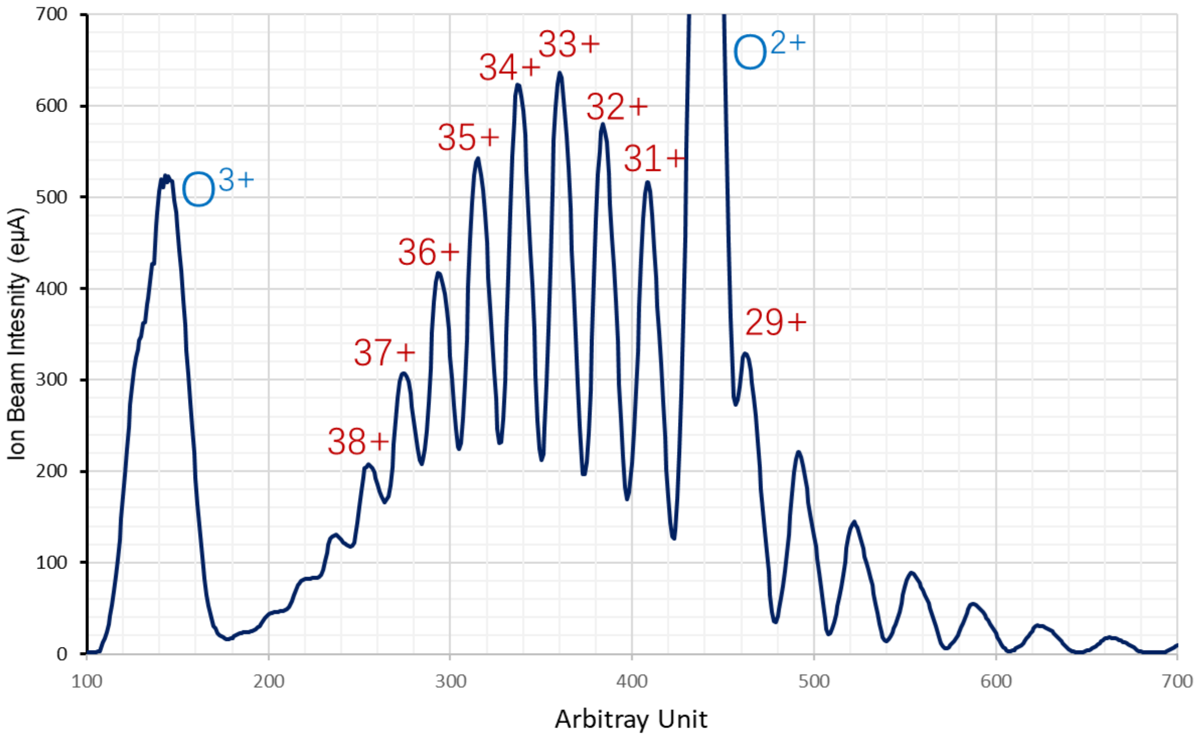
## Technologies advancement with intense U beam production

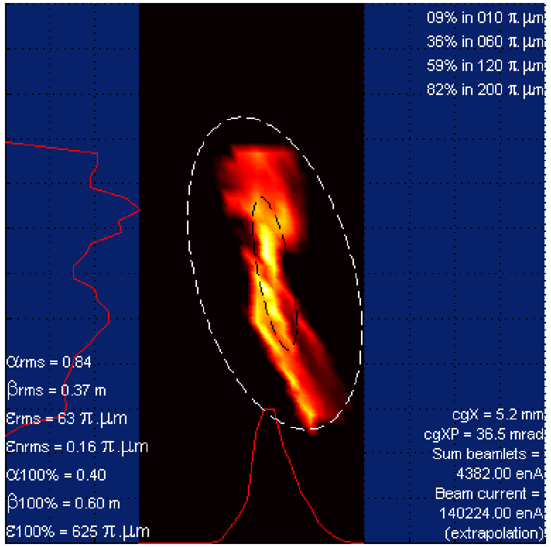



- Inductive heating oven
- New plasma chamber

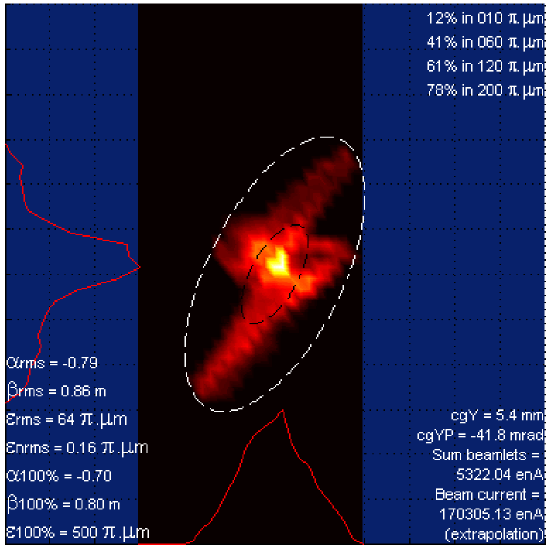
- Inductive heating oven

# Progresses with the 3rd G ECRISs and the challenges



X-$\varepsilon_{n.rms}$: 0.16 π.mm.mrad



Y-$\varepsilon_{n.rms}$: 0.16 π.mm.mrad

- **Material: $UO_2+O_2$**
- **Frequency: 24+18 GHz**
- **RF power: ~7.9 kW**
- **Total drain: ~13.2 emA**

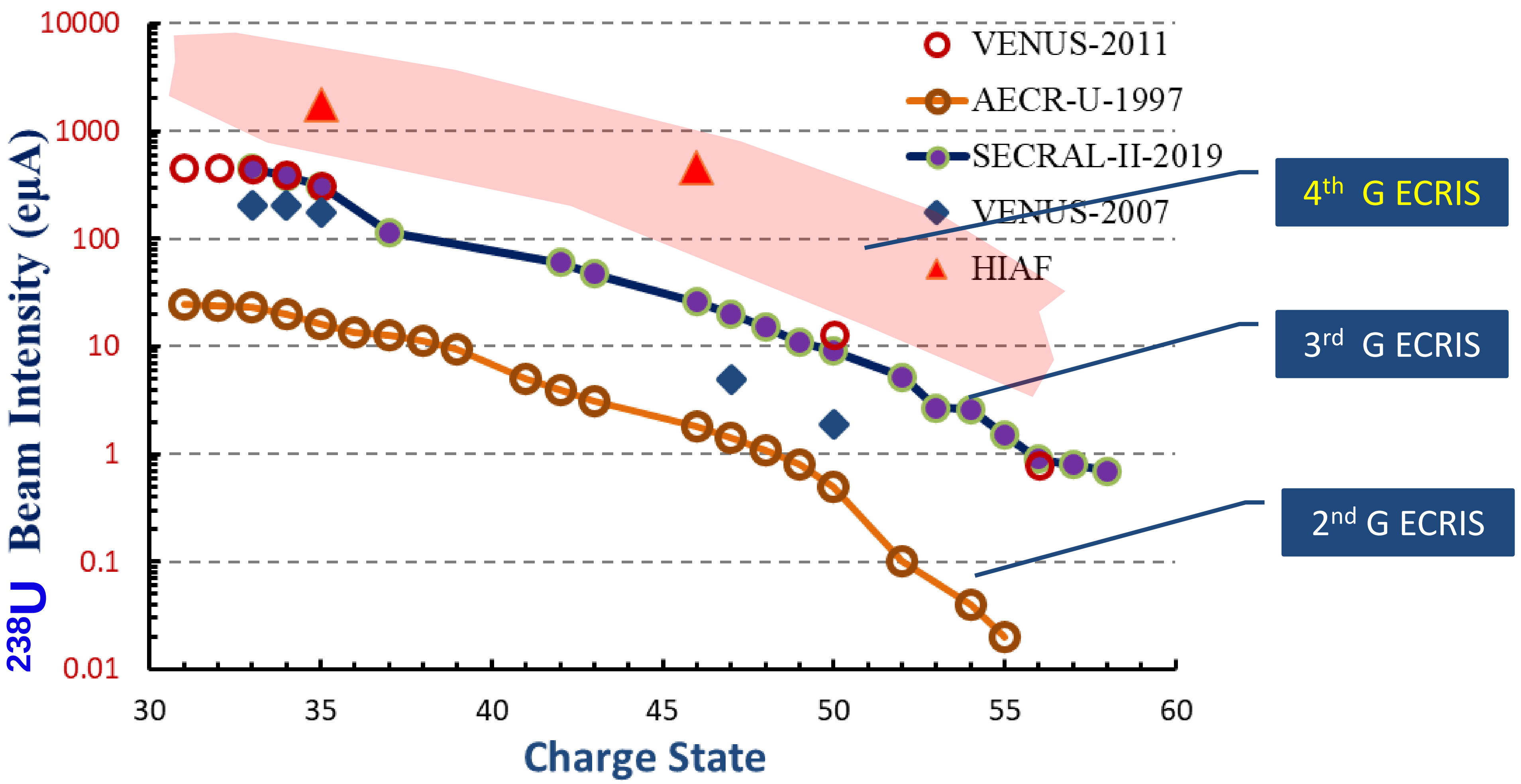
**Production of 547 eμA $U^{35+}$**

# Progresses with the 3rd G ECRISs and the challenges

| U Charge State | SECRAL-2023 (eμA) | Records as of 2022 (eμA) | Contributors as of 2022 |
|---|---|---|---|
| 33 | 640 | 450 | SECRAL-II/IMP[1] |
| 34 | 620 | 400 | VENUS/LBNL[2] |
| 35 | 547 | 310 | VENUS/LBNL， SECRAL-II/IMP |
| 42 | 100 | 62.6 | SCECRIS/RIKEN[3] |
| 46 | 61 | 36.2 | SCECRIS/RIKEN |
| 50 | 38 | 20.1 | SCECRIS/RIKEN |
| 54 | 19 | 10.4 | SCECRIS/RIKEN |
| 56 | 9.5 | 0.9 | SECRAL-II/IMP |
| 58 | 2.7 | 0.7 | SECRAL-II/IMP |


1. *W. Lu et al., Rev. Sci. Instrum.* ***90****, 113318 (2019)*
2. *J. Benitez, et al., ECRIS2012, THXO02-talk*
3. *T. Nakagawa, Cyclotron'22, invited talk*

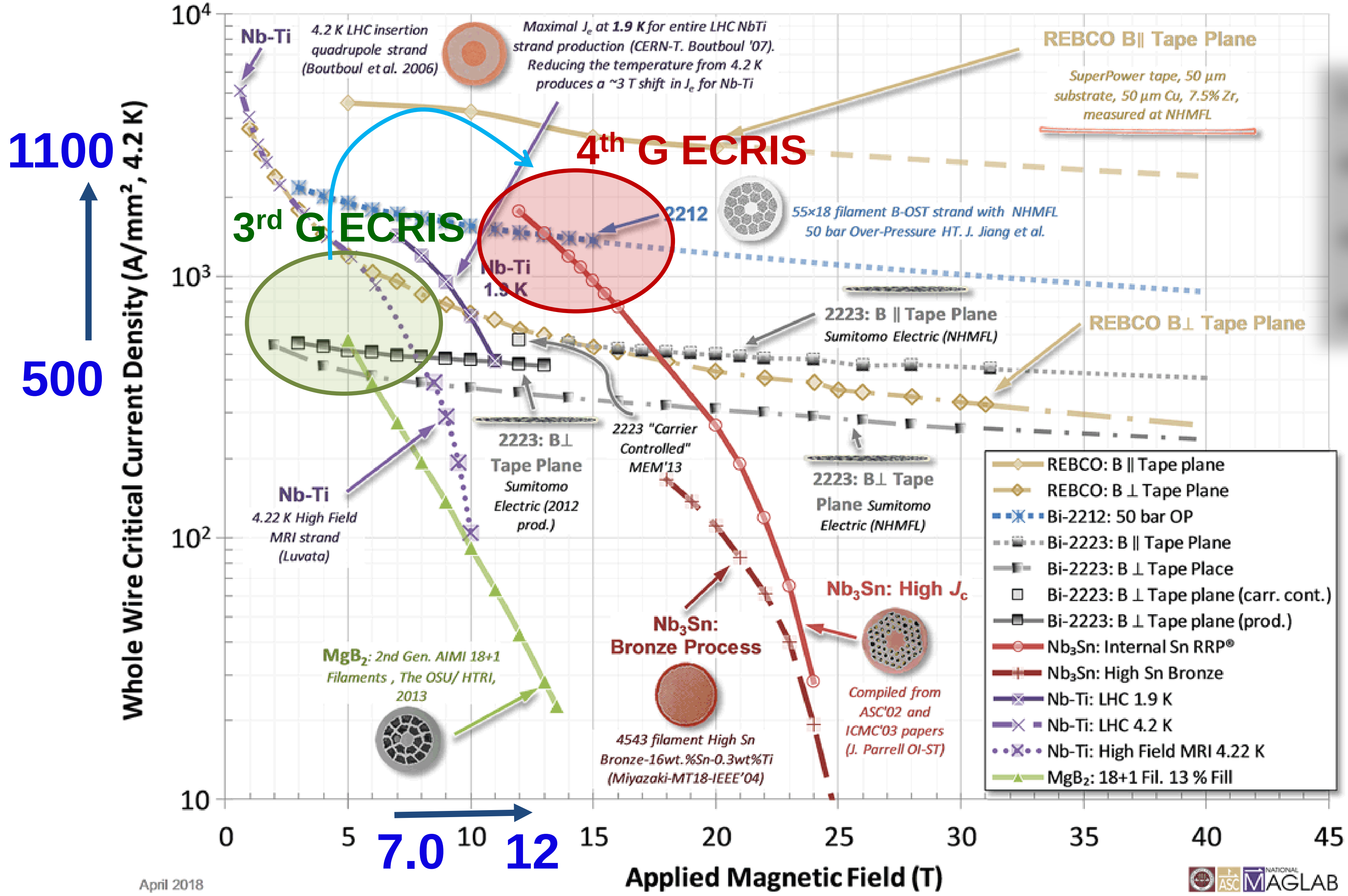
# Progresses with the 3rd G ECRISs and the challenges



# Status of FECR development

| Specs. | Unit | 3rd G ECRIS | 4th 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 |

# Status of FECR development

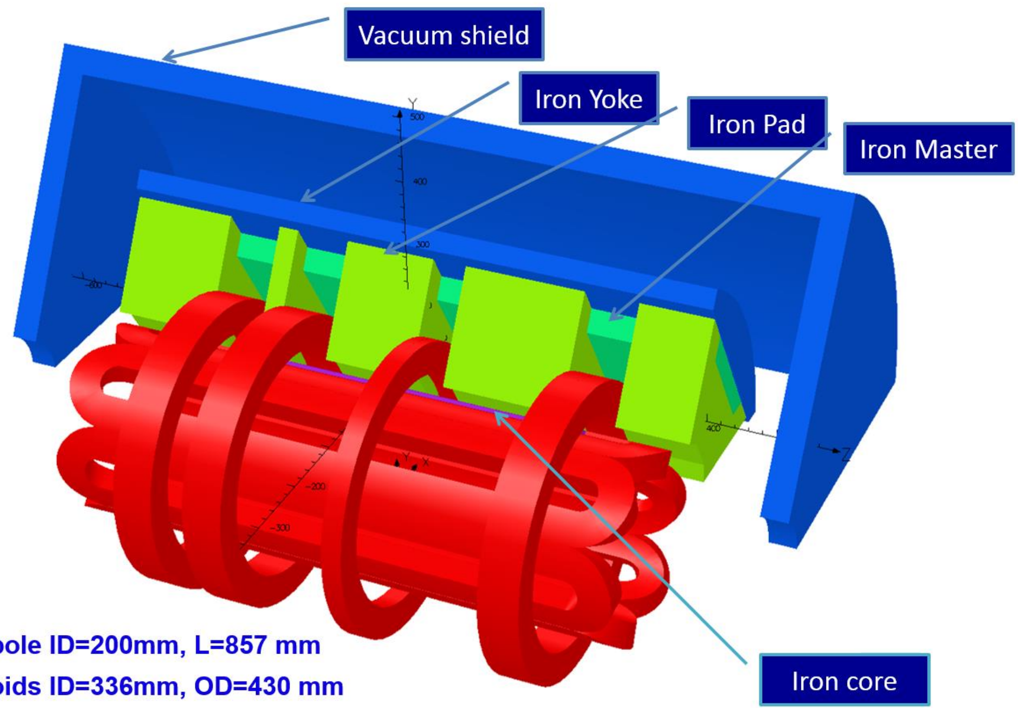



## $Nb_3Sn$ vs. NbTi:

- Fragile
- Treatment sensitive
- Stress sensitive

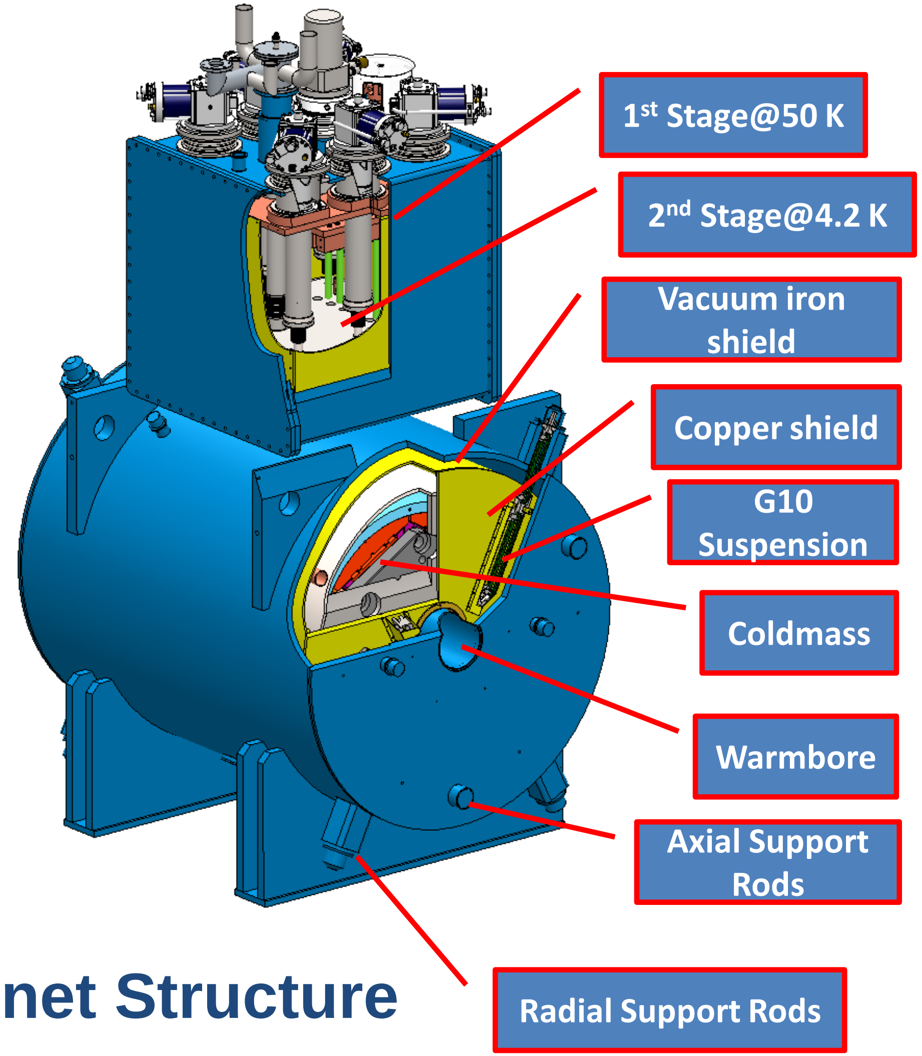
Courtesy of MagLab

# Status of FECR development




**Sextupole ID=200mm, L=857 mm**
**Solenoids ID=336mm, OD=430 mm**

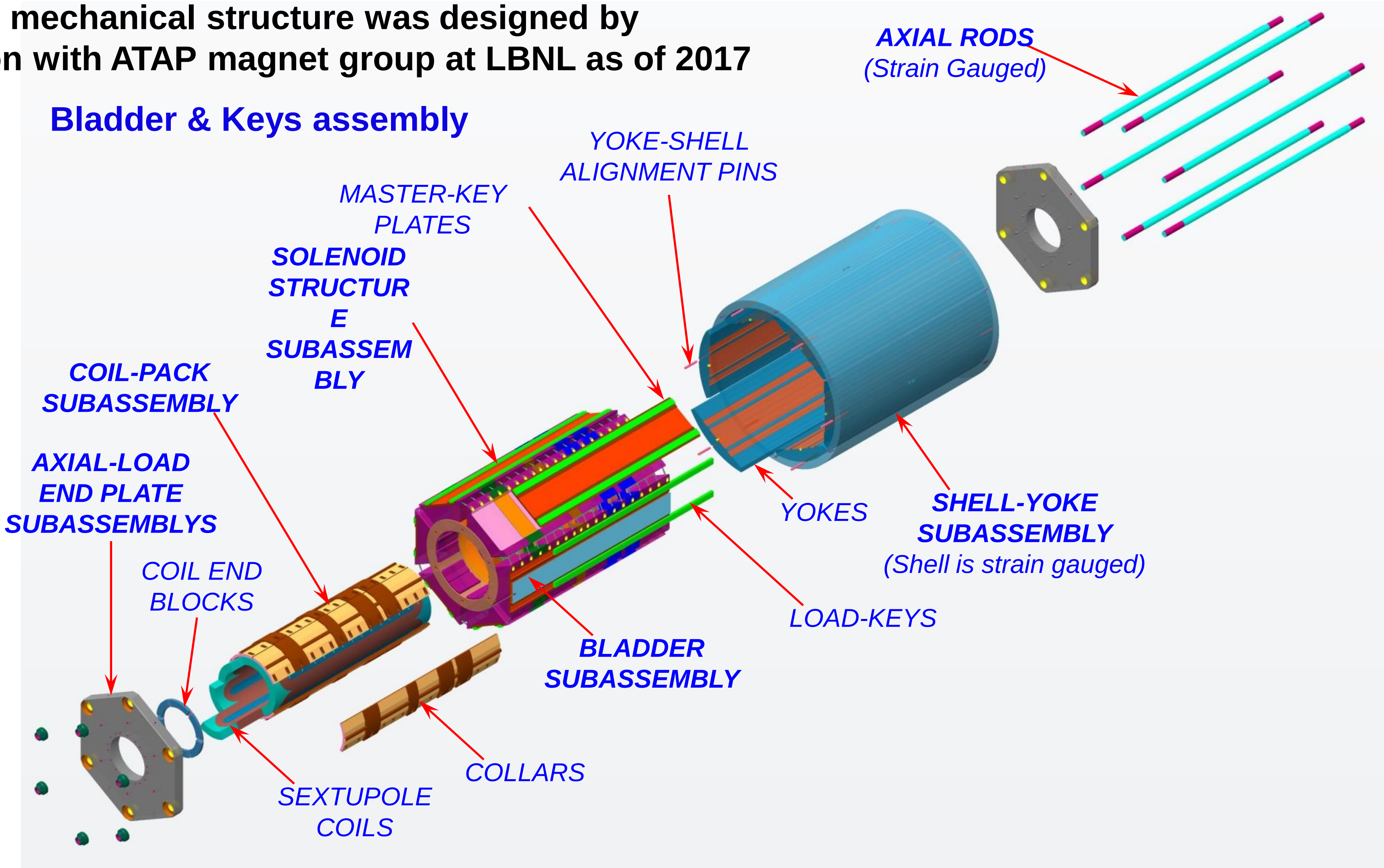
## Coldmass Structure




## Magnet Structure

# Status of FECR development

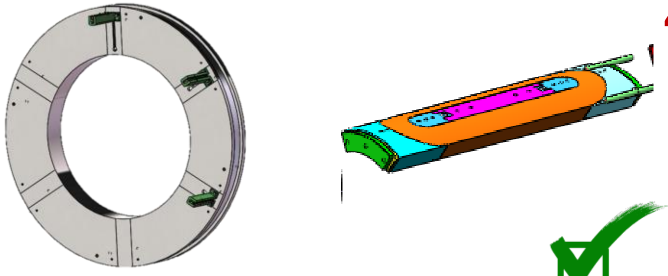
**The magnet mechanical structure was designed by collaboration with ATAP magnet group at LBNL as of 2017**



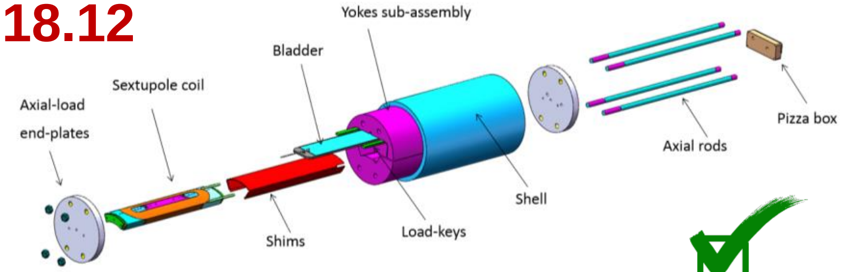

**This $Nb_3Sn$ magnet is being built by a Chinese company without collaboration with ATAP/LBNL. DOE did not approve such collaboration.**

# Status of FECR development

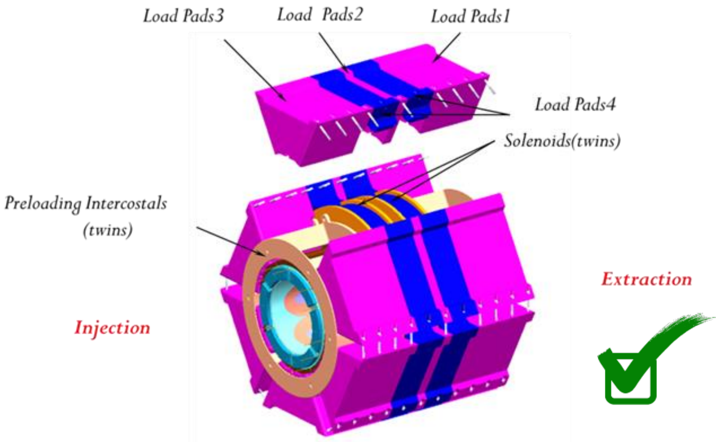
2015.07~2018.12



**1.Prototyping coils**

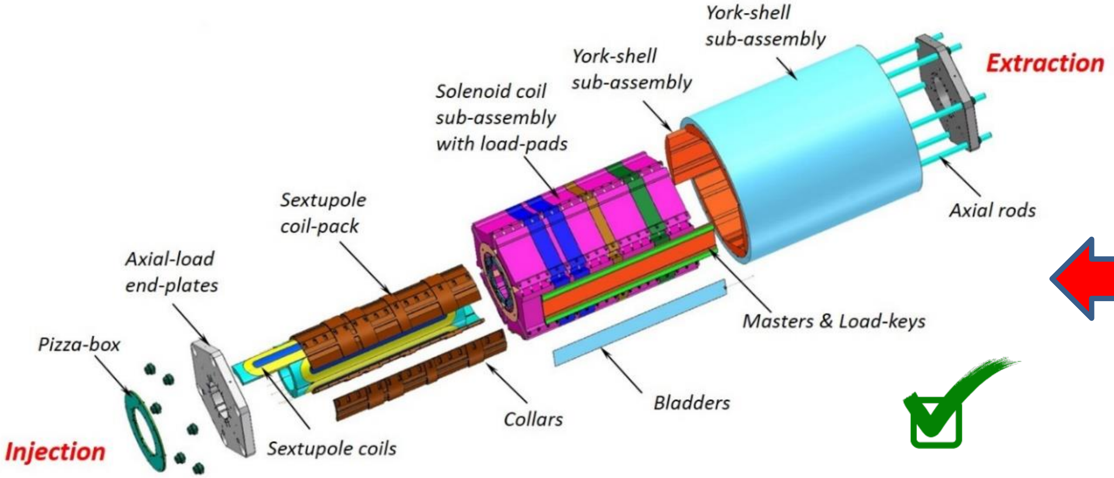



**2.Key components and tech.**




**3. ½-length prototype**

（2017.11-2021.12）

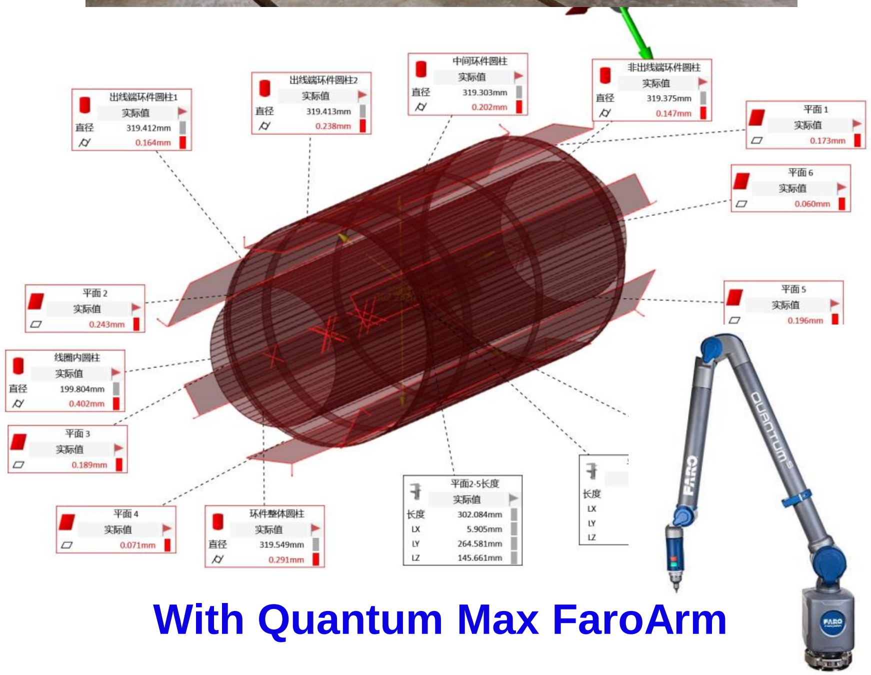



**4. FECR coldmass full assembly**

（2021.10-Now）

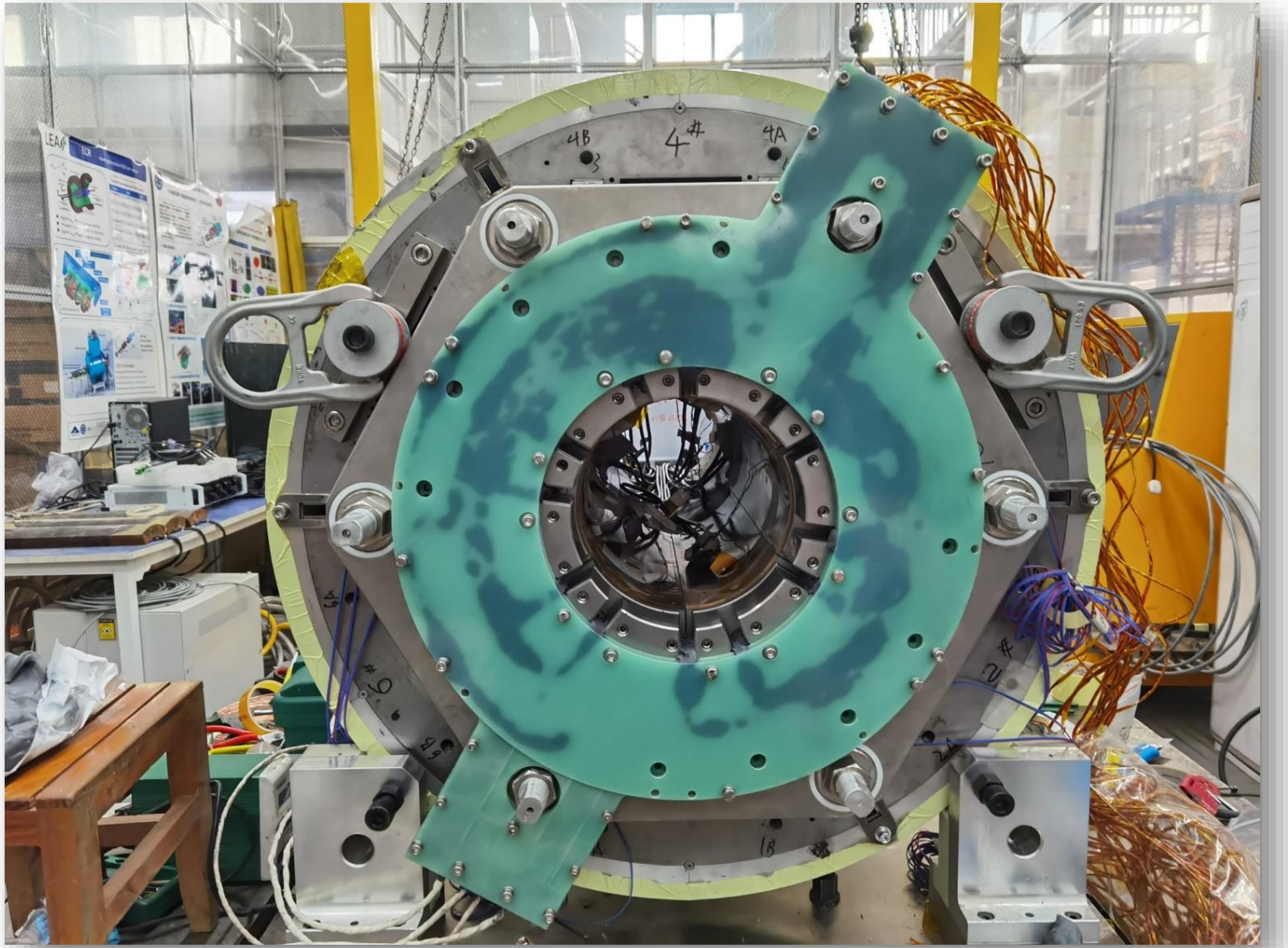
# Status of FECR development


8 sextupole coils for full assembly




With Quantum Max FaroArm

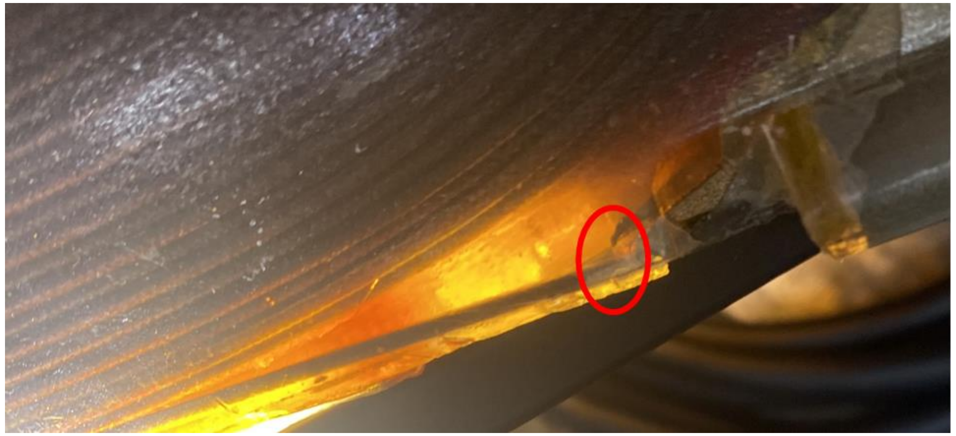
# Status of FECR development

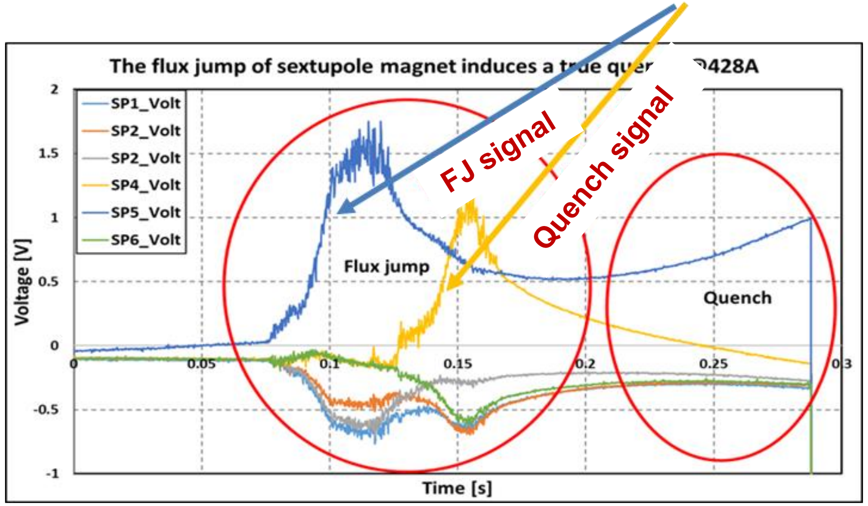
**Completed FECR coldmass**

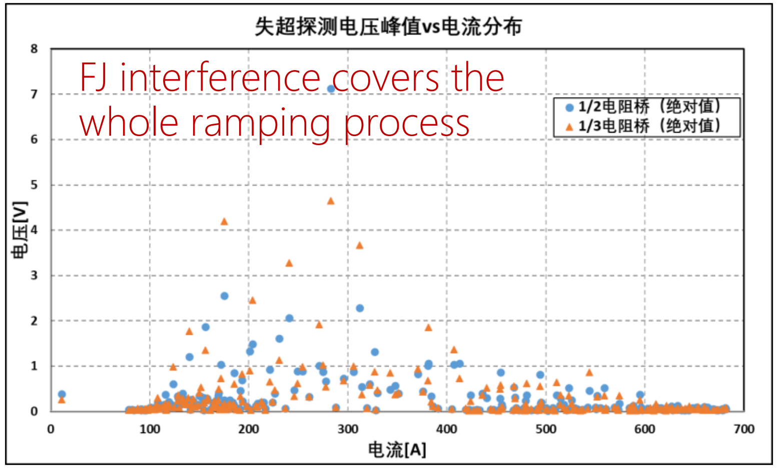
# Status of FECR development

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

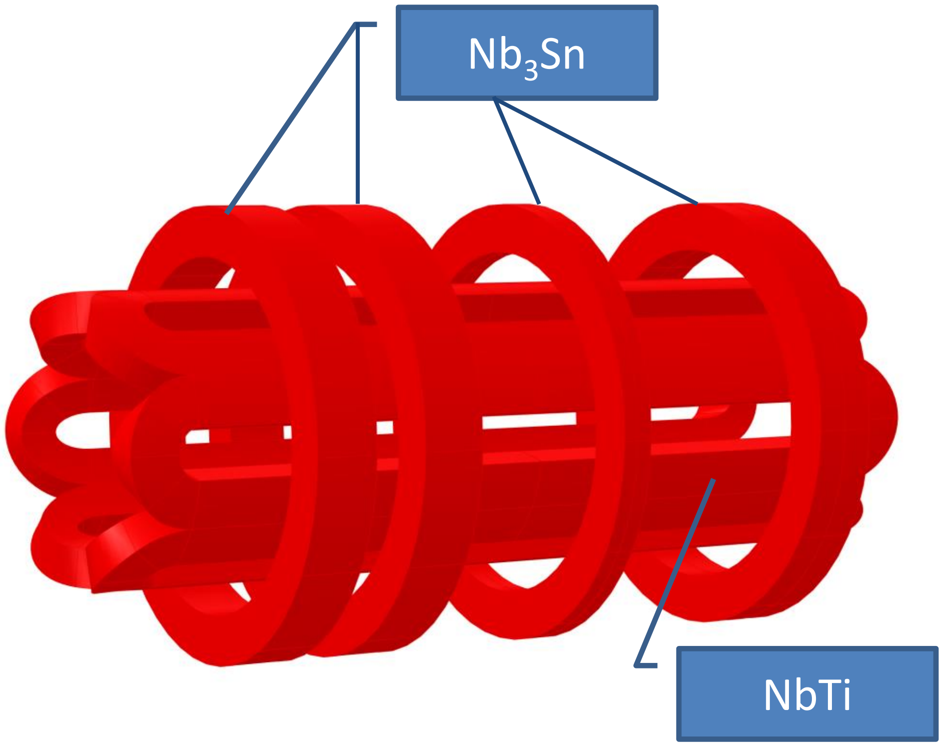


- **Intense Flux Jump (FJ) Interference**: challenging in fast quench detection (during ½-prototype test)

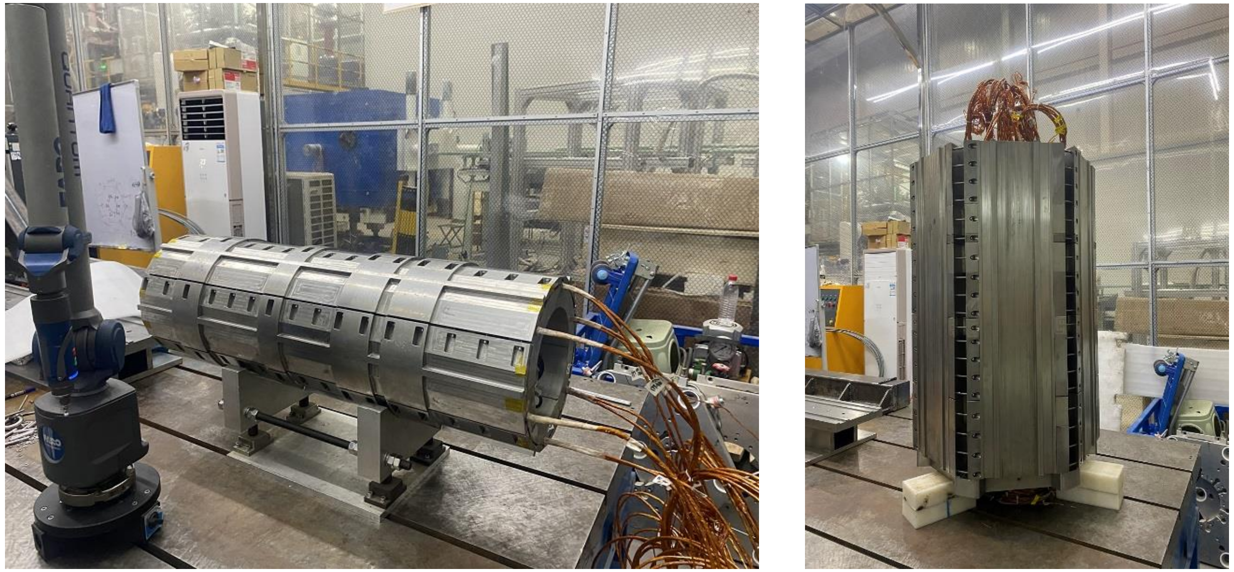


# Status of FECR development




NbTi sextupole coils



Sub-assembly of the cold mass

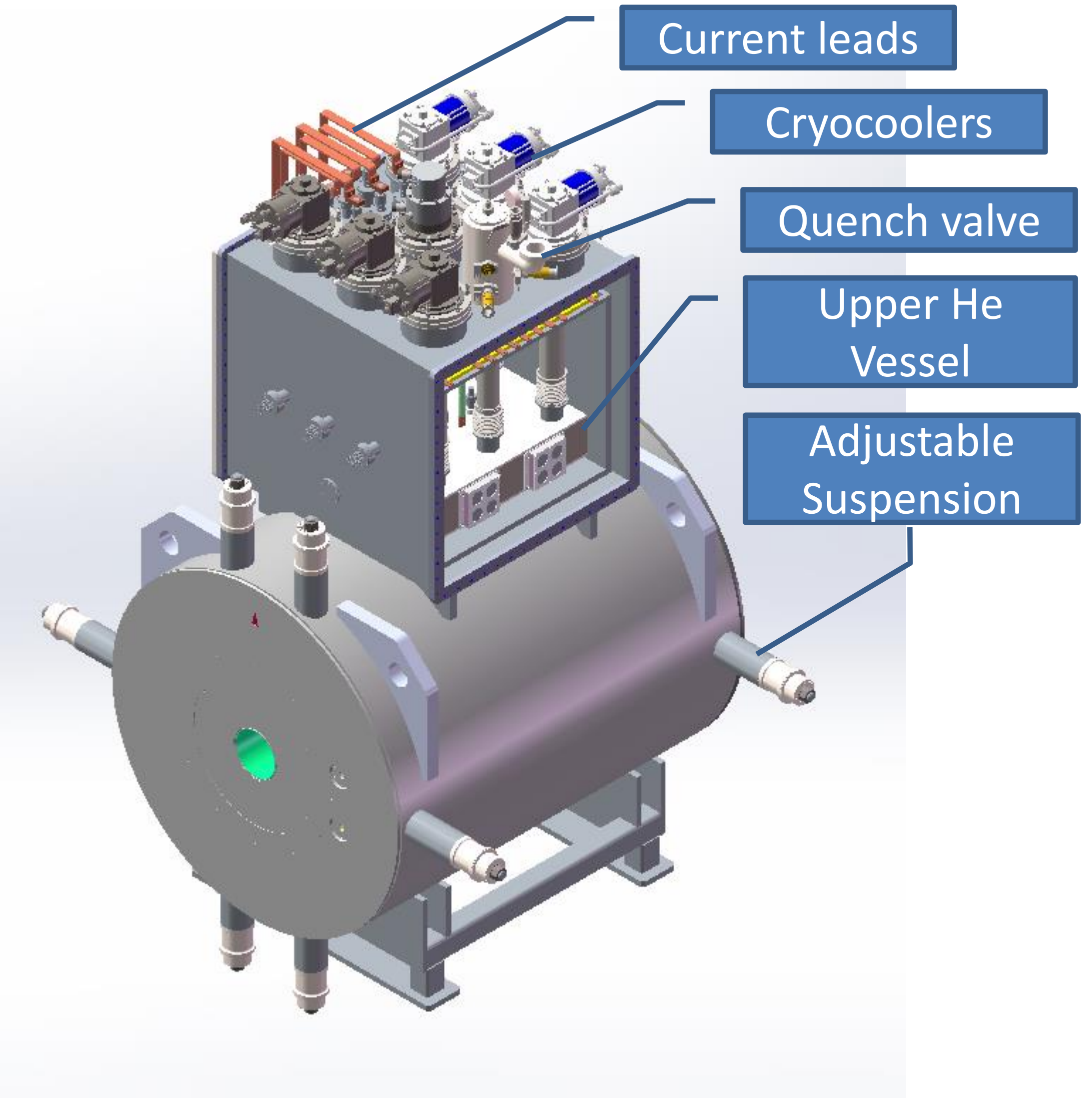
**Hybrid coils:**

- NbTi sextupole + $Nb_3Sn$ solenoids
- Intense FJ mitigation
- Assembly test
- Operation safe
- $Nb_3Sn$ Sextupole with cable in progress

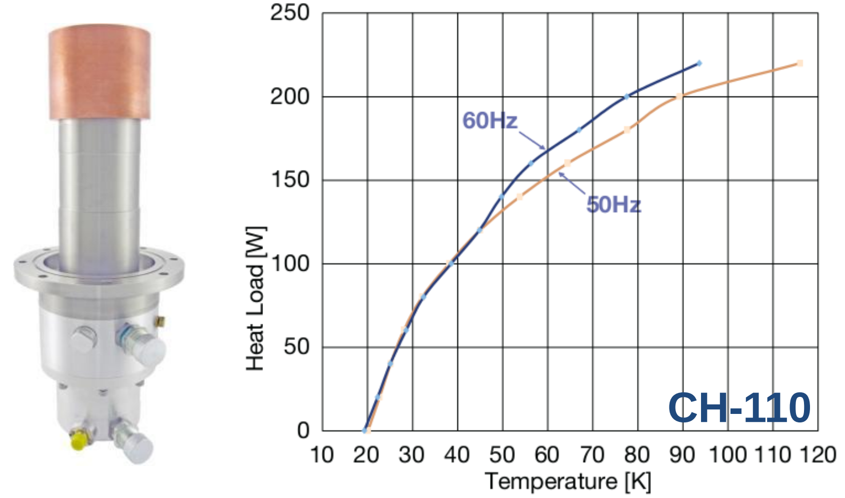
# Status of FECR development

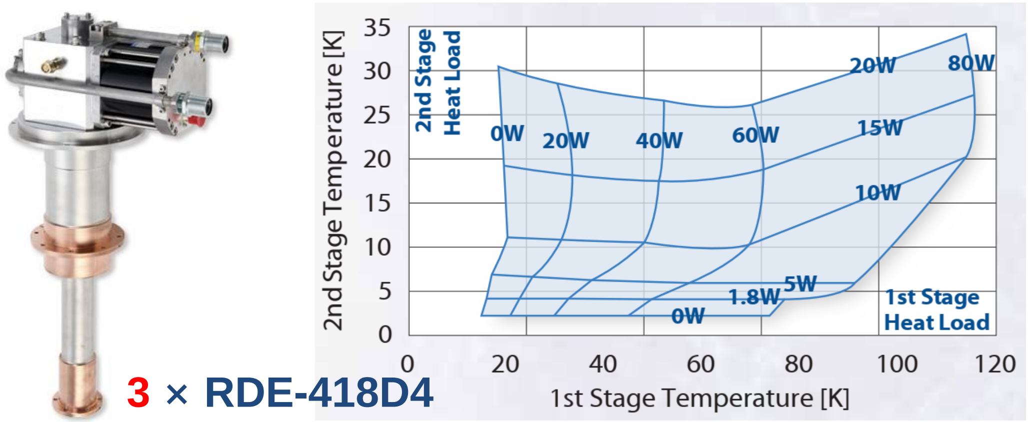
## Key parameters of FECR Cryogenic System

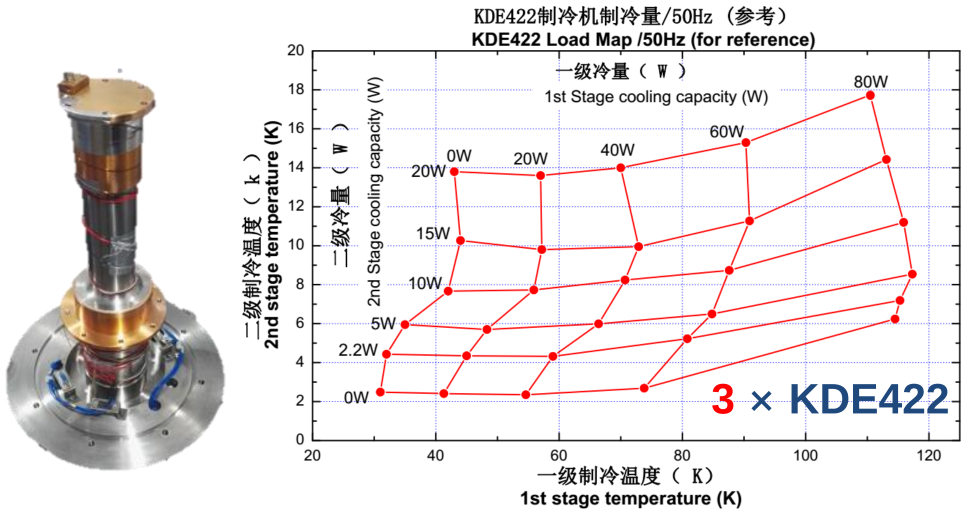
| Parameters | Value | Note |
|---|---|---|
| Operation Temp. (K) | 4.3 K | |
| Magnet Cooling | LHe bathing and "0" boiling-off | |
| Stored Energy (MJ) | ~1.6 | 100% currents |
| Required heat load (W) | ≥ 12 | ~2 W static at 100% currents |
| Warm Bore (mm) | Ø162 | |
| LHe Volume (L) | ~330 | |
| Cryocoolers | 6 two-stage + 1 single stage coolers | Cold service enabled |
| Dimension (mm) | L1456×Ø1200×H2690 | |
| Total weight (ton) | ~6.1 | |

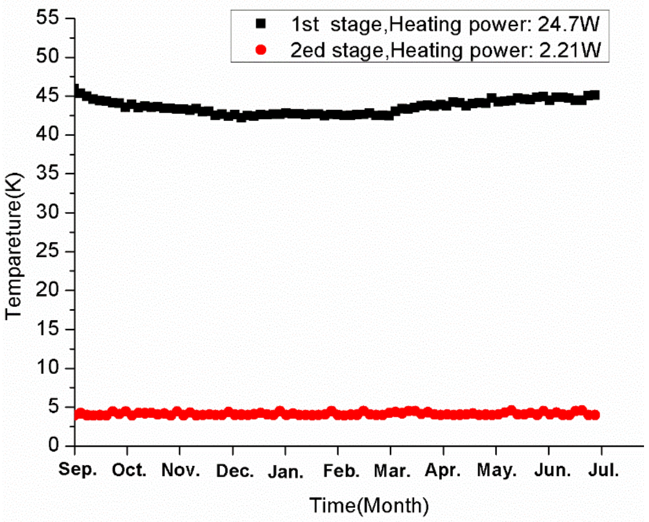


# Status of FECR development




## High power GM Cooler:

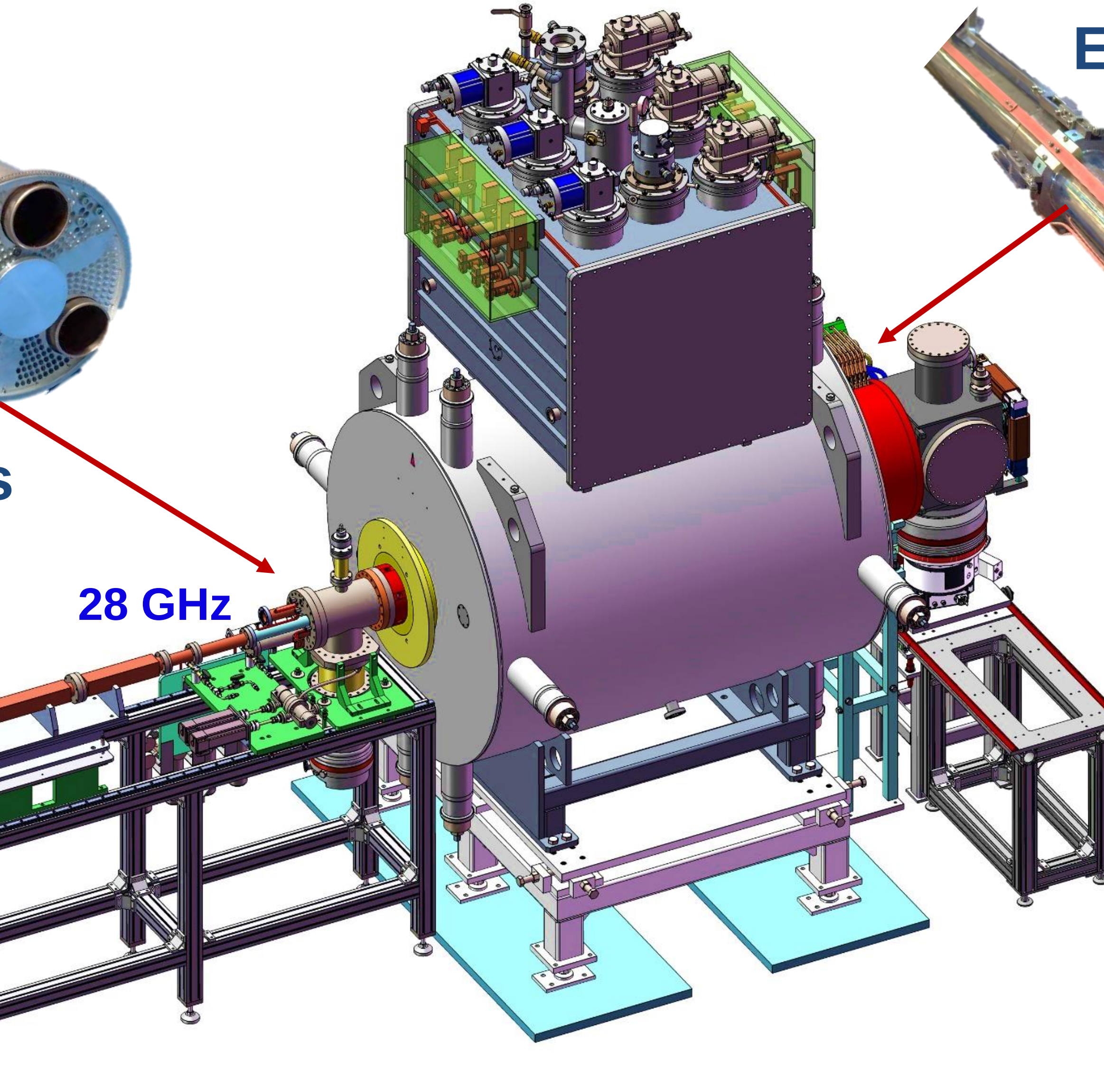
- 10 months continuous stability and reliability checking-test
- 3×KDE422 coolers ~6.6 W@4.2 K cooling capacity

# Status of FECR development

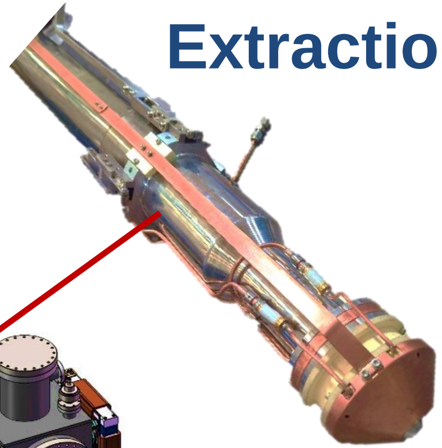

| Key Parameters | FECR Chamber | SECRAL-II Chamber |
|---|---|---|
| Max. Microwave Power | 25 kW | 12 kW |
| Max. Localized Power Density | 20 MW/m$^2$ | 10 MW/m$^2$ |
| Chamber ID | Ø140 mm | Ø125 mm |
| Chamber OD | Ø156 mm | Ø136 mm |
| Length | 1225 mm | 887 mm |
| Microchannel region | 15×15.6×1.5 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 |

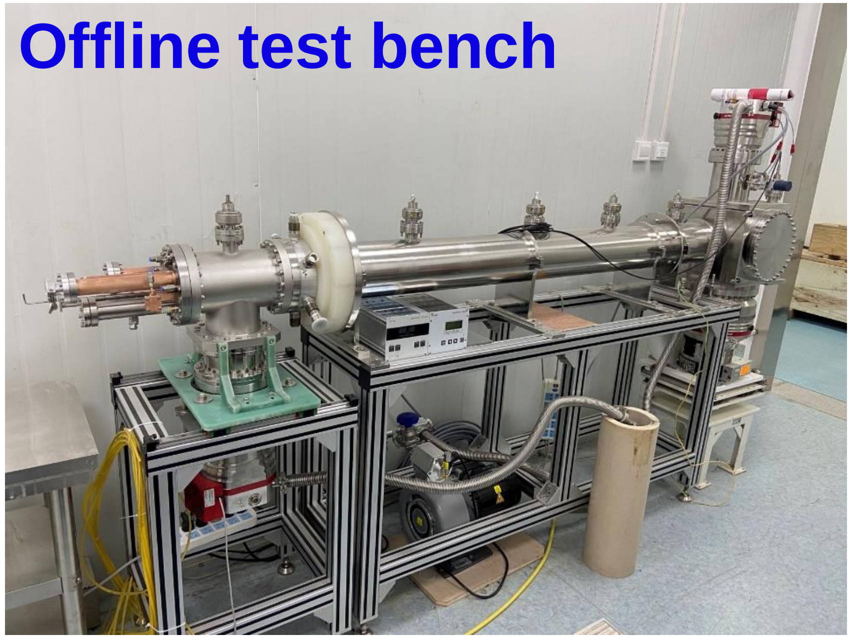
# Status of FECR development

Injection parts




Extraction parts





# Summary

- Technical advancement makes intense HCI beams production feasible and durable
- New records on highly charged ion beams production
  - ✓ 620 eμA $U^{34+}$, 547 eμA $U^{35+}$, …
  - ✓ 18 eμA $Xe^{42+}$、47 eμA $Xe^{38+}$、146 eμA $Xe^{34+}$、374 eμA $Xe^{30+}$
- FECR development still having challenges in terms of $Nb_3Sn$ magnet

# 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!!**