High intensity highly charged ion beams production and operation at IMP

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

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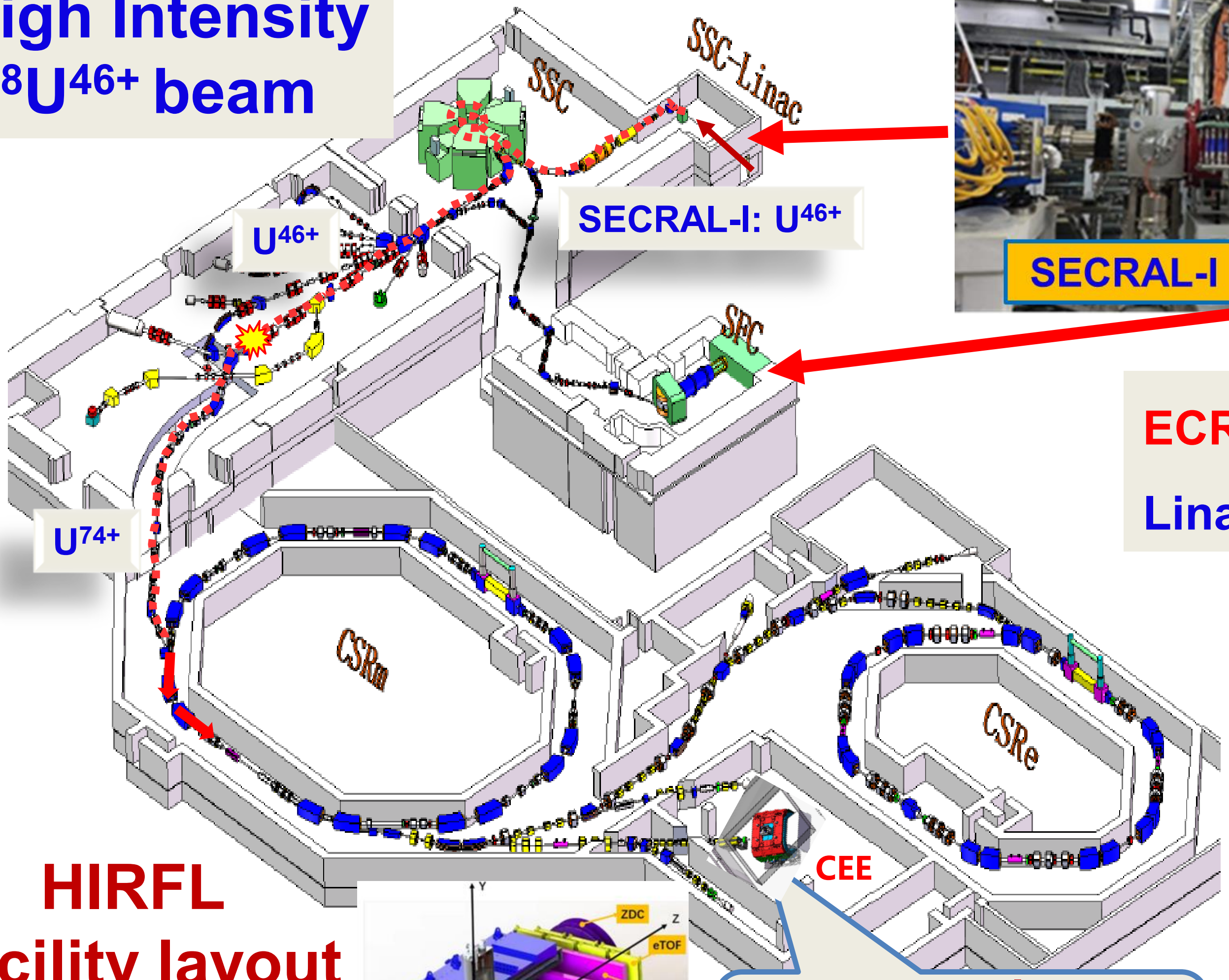
ECRIS'24, Sept. 15~19, 2024, GSI, Darmstadt, Germany

Outline

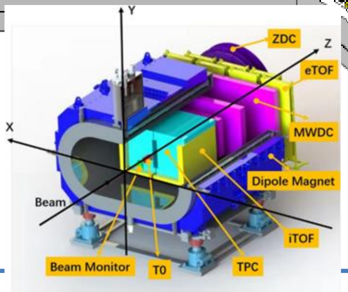
- **Introduction: High intensity HCI beam needs at IMP**
- **High intensity HCI solutions**
  - **Operation status**
  - **New technical approaches**
  - **FECR ion source development**
- **Summary**

Introduction: HIRFL and physics request high intensity HCI

High Intensity $^{238}U^{46+}$ beam



HIRFL facility layout



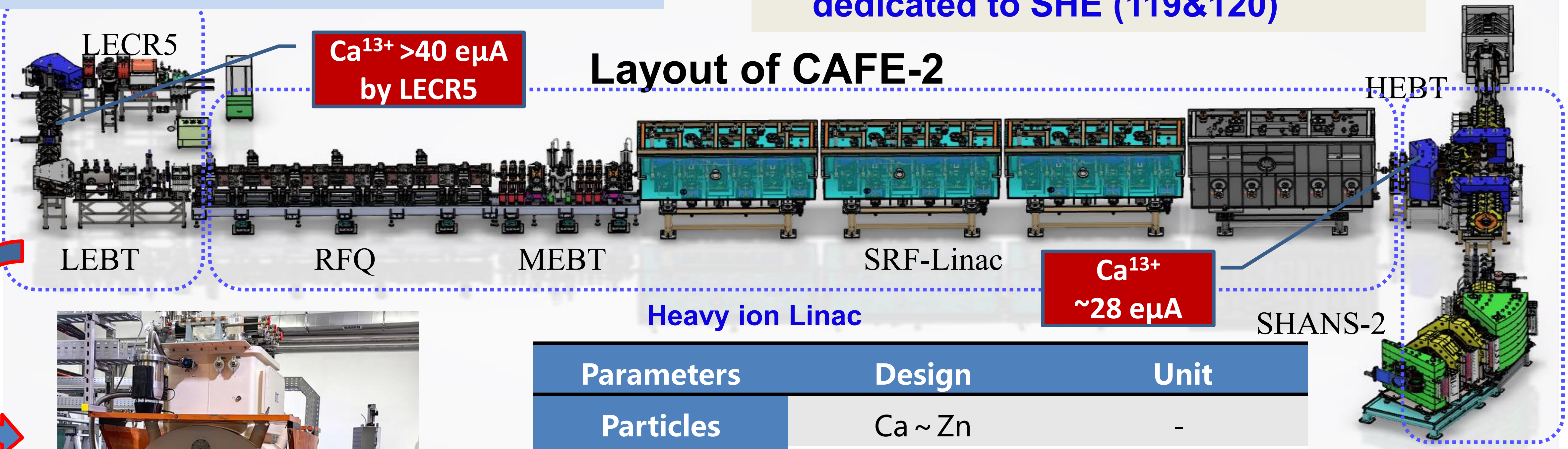
CSR External target Experiment CEE

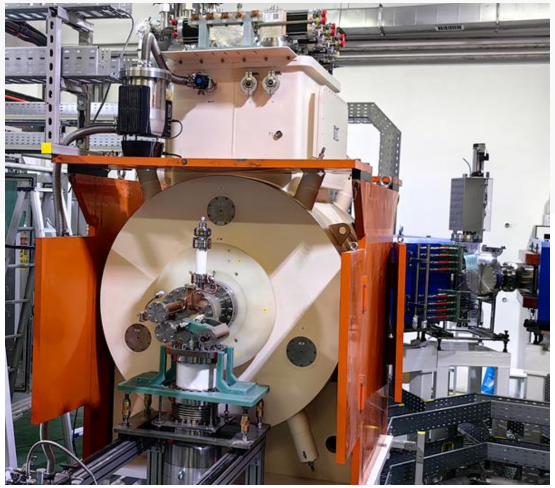
ECR (50~100 eμA U^{46+})→SSC-Linac→SSC→Striper→U^{74+}→CSRm→≥500 MeV/u U^{74+}

Physics	Needed Ion Beam Energy (MeV/u)
Equation of state of nuclear matter at low temperature and high density Quarkonium symmetry energy	Xe: 10^5pps E = 400 - 600 C: 10^5pps E = 400 - 600
Baryon number fluctuations QCD critical point	$^{238}U^{7x+}$: 10^4 pps E = 500—700 C: 10^5 pps E = 500

Introduction：SHE Facility-CAFe 2

- **Upgraded the ADS SC proton linac Demo-machine**
- **High Intensity SC HC HI linac for Medium Mass Metallic Ion Beams dedicated to SHE (119&120)**





New source: SECRAL-III, 28GHz

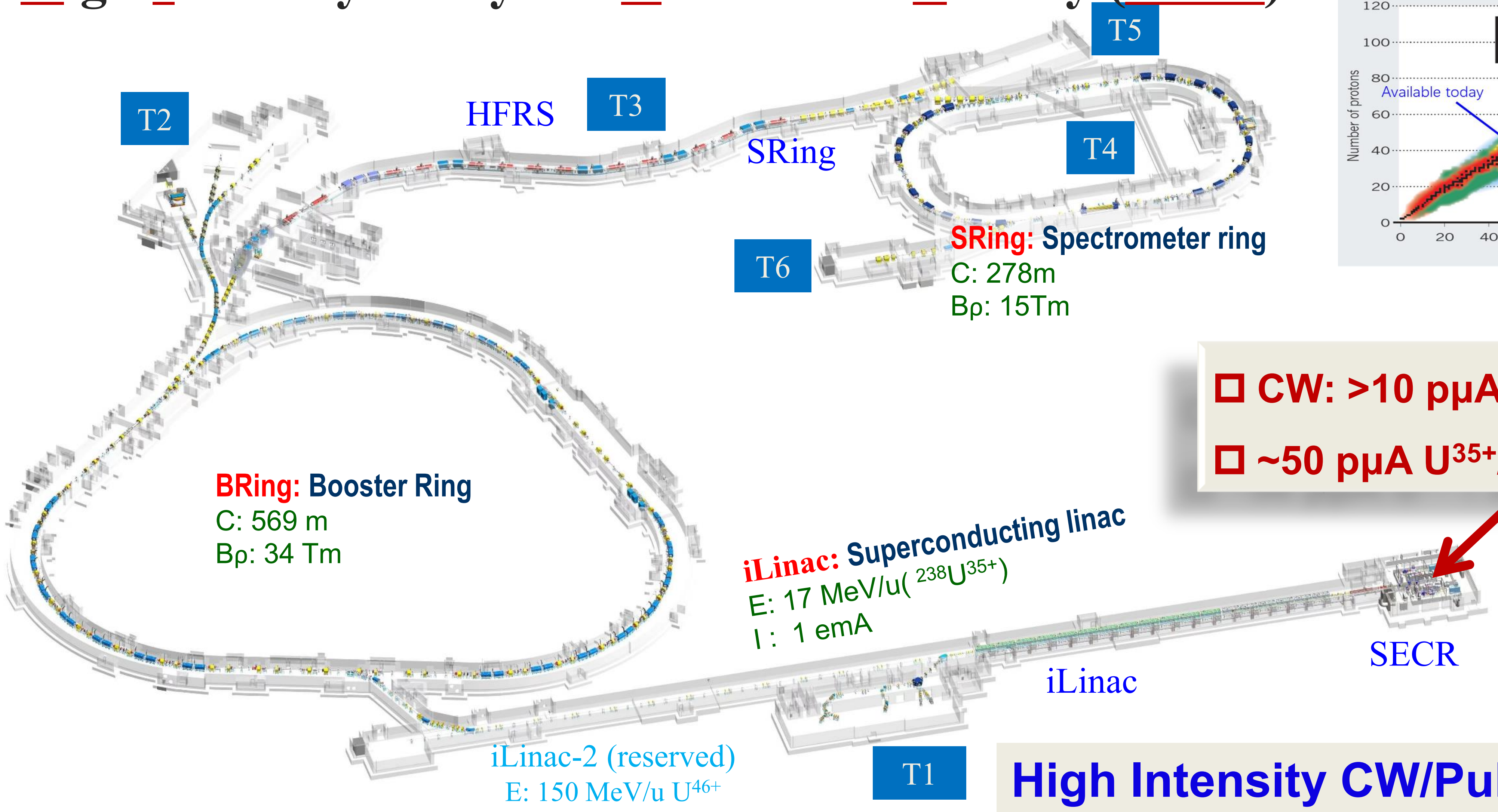
Parameters	Design	Unit
Particles	Ca～Zn	-
M/Q	～1/3	-
Energy	～6	MeV/u
Intensity	3-5/10~20	pμA
Operation Mode	CW	-

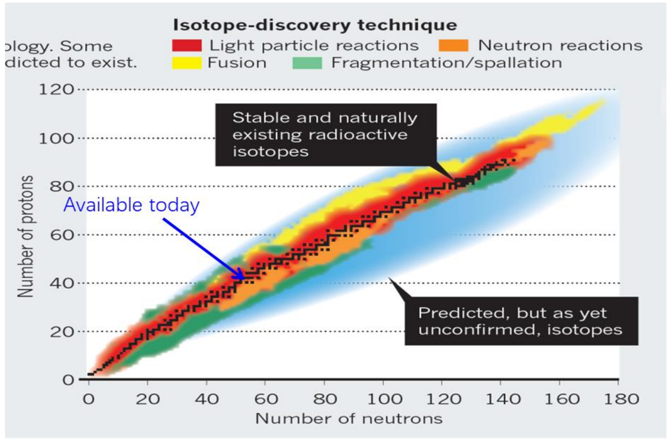
See Lu's talk MOC3 this afternoon

& Nuclear Inst. and Methods in Physics Research, A 1062 (2024) 169207

Introduction: HIAF

High Intensity heavy-ion Accelerator Facility (HIAF)





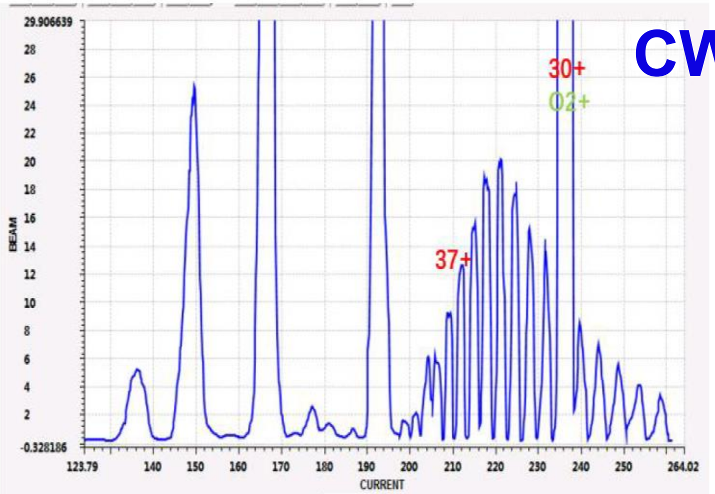
- ☐ CW: >10 pμA U^{46+}
- ☐ ~50 pμA U^{35+}/ ≤3 Hz@0.5~2 ms

High Intensity CW/Pulsed Ion Beams

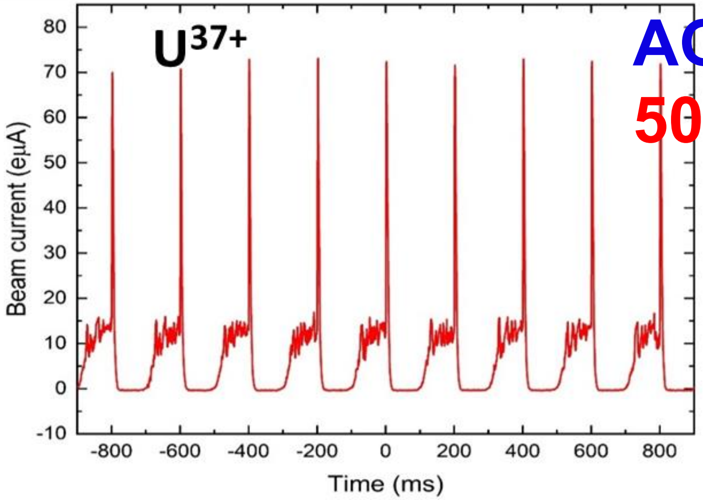
Solutions : HIRFL Uranium Beam Operation

LECR4: 18 GHz ECR ion source with evaporative cooling of the axial coils.
Used to be delivering U^{37+} beam for SSC-linac.

W. Lu, WEOMMH02@ECRIS'14



CW operation

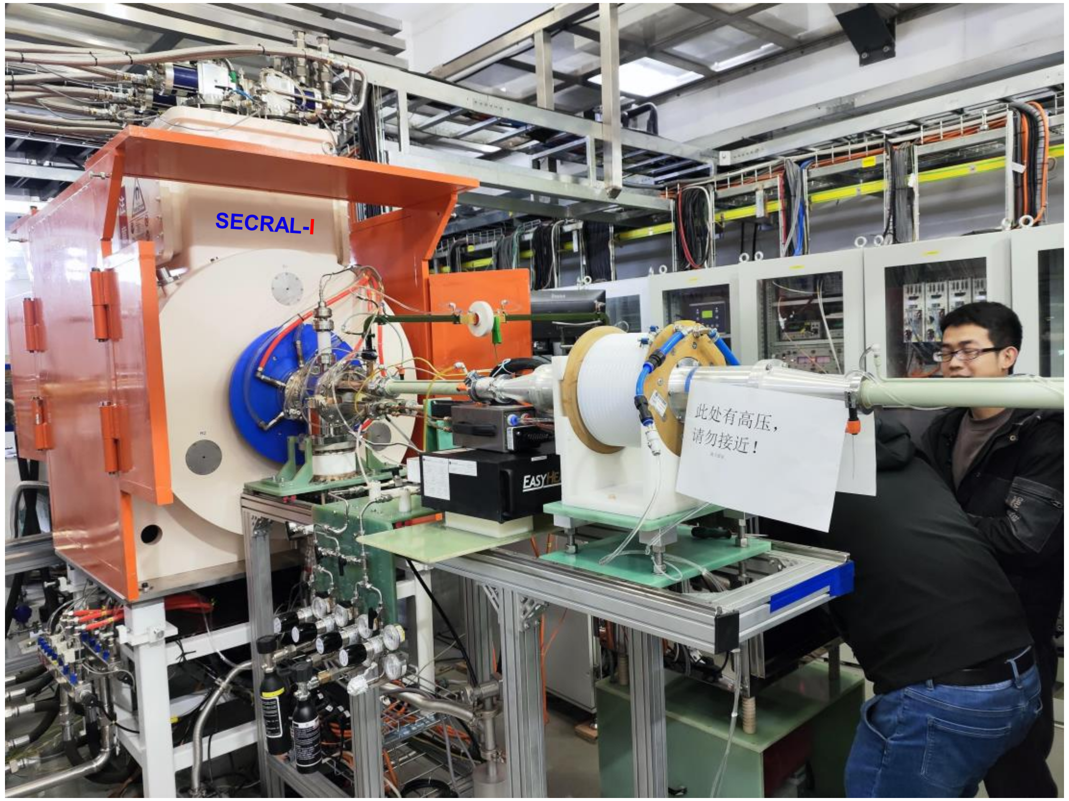


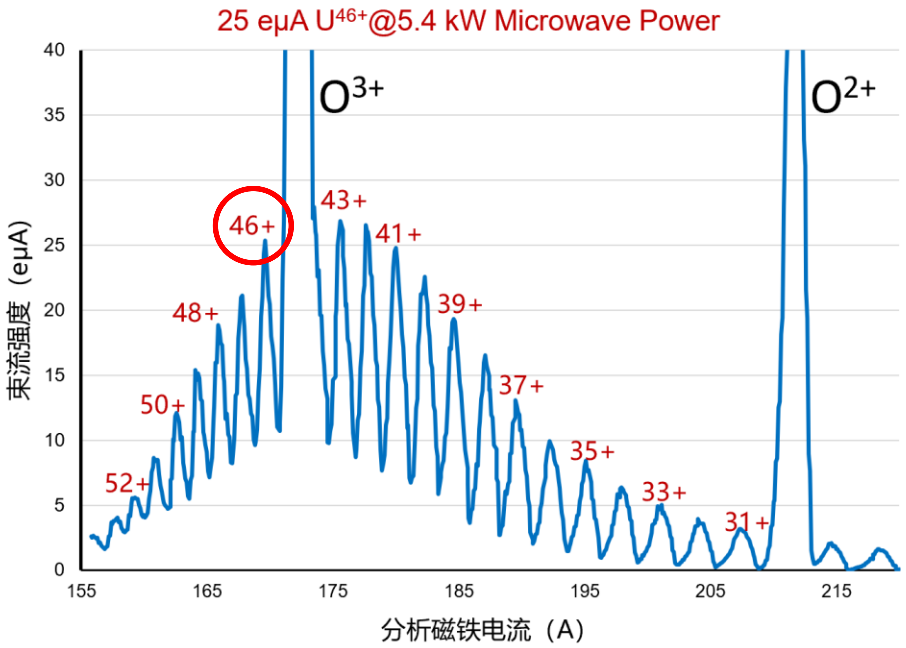
AG operation

50~70 eμA U^{37+}

4.6 eμA 10.67 MeV/ u U^{37+} extracted from SSC, but not sufficient for 500 MeV/u with CSRm

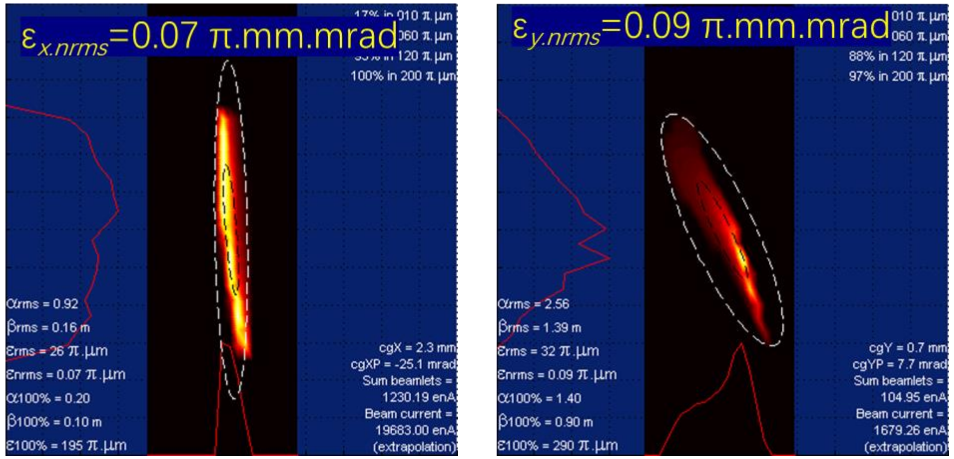
Solutions : HIRFL Uranium Beam Operation





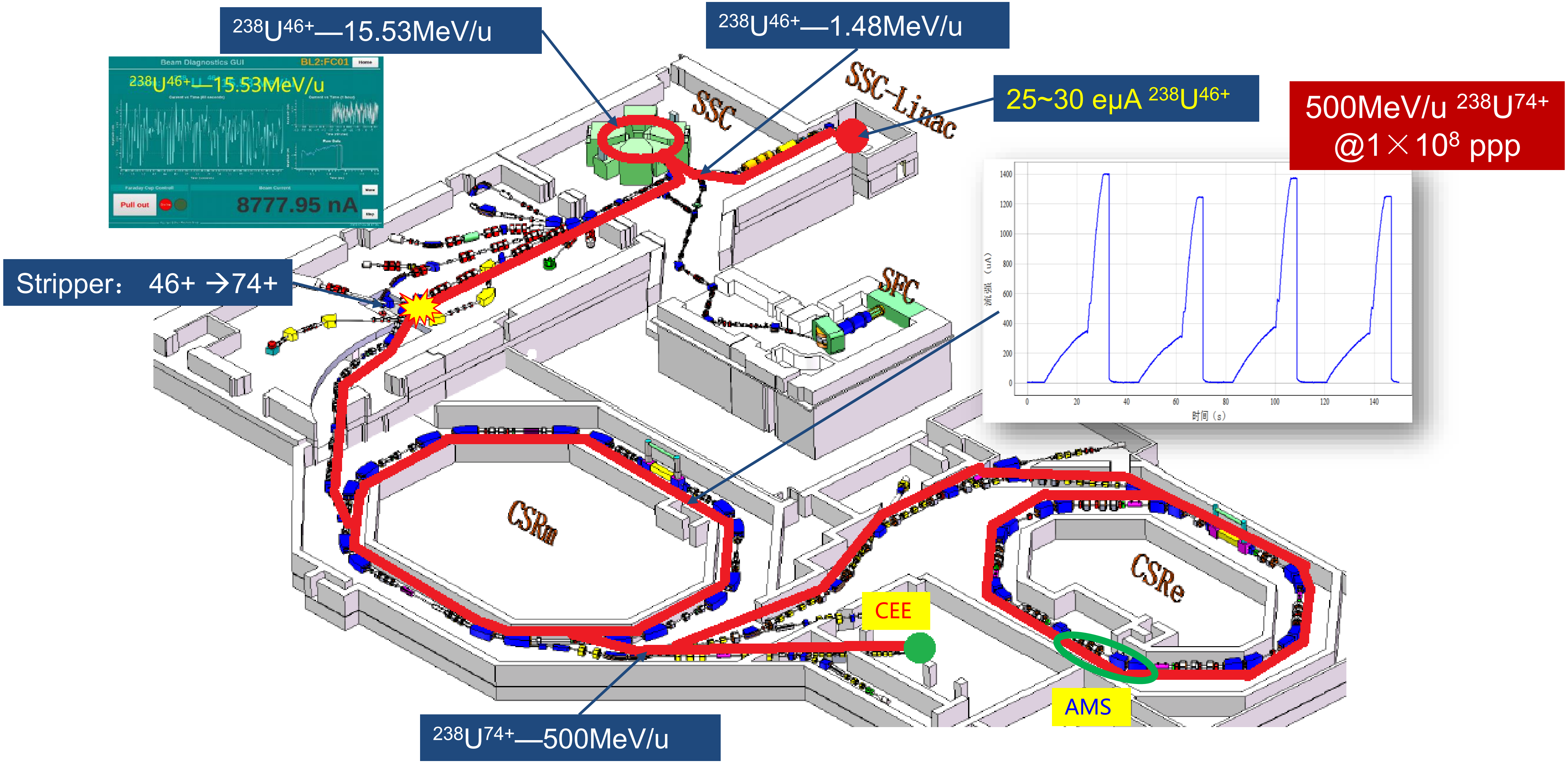
SECRAL-I: 28 GHz ECR ion source

- Upgraded from 24 GHz SECRAL
- Ø 120 mm ID plasma chamber
- 10 kW max. μW power
- Al plasma chamber with micro-channel cooling

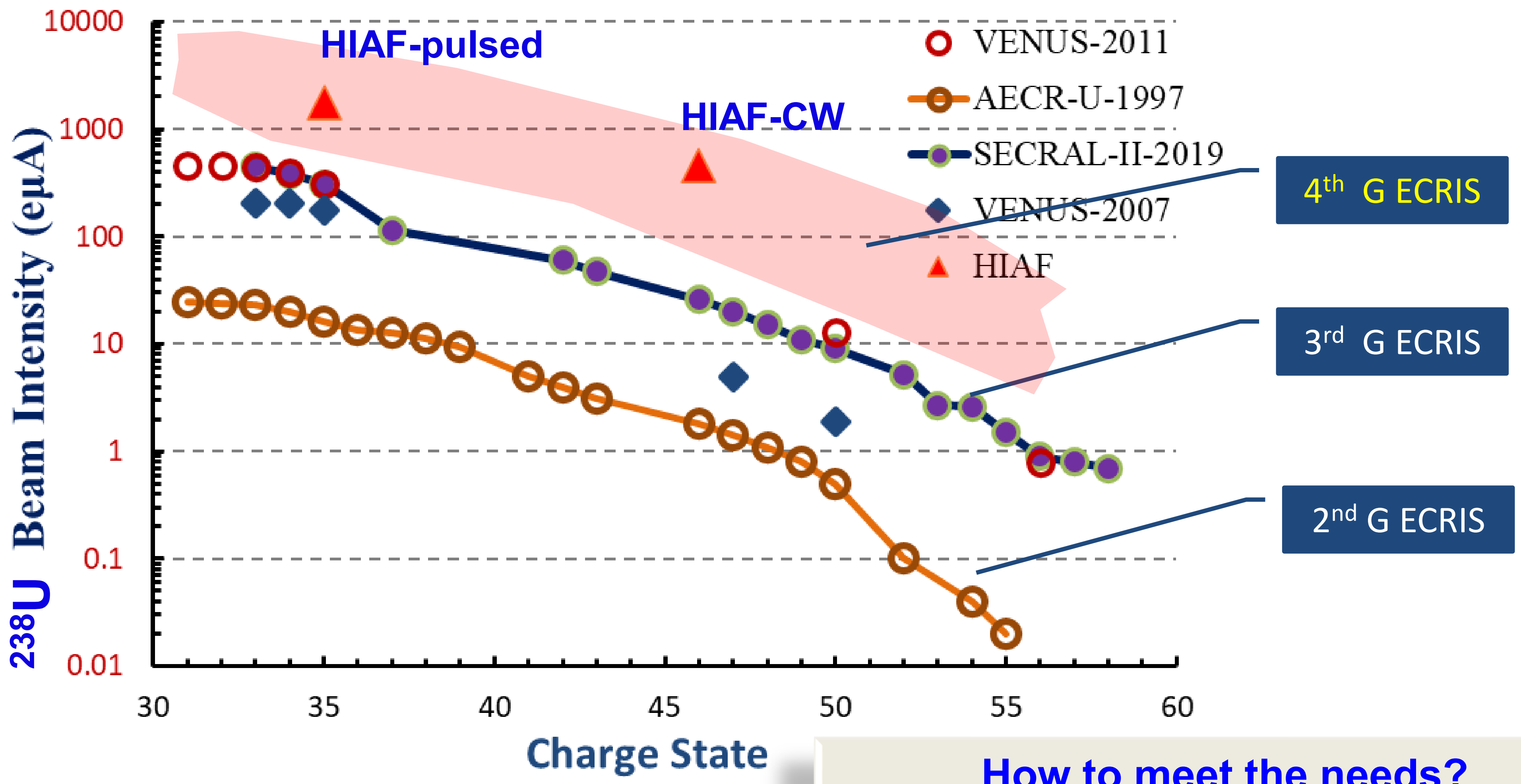


Lower emittance for higher charge state

Solutions : HIRFL Uranium Beam Operation



Solutions : Intense ion beam needs for HIAF

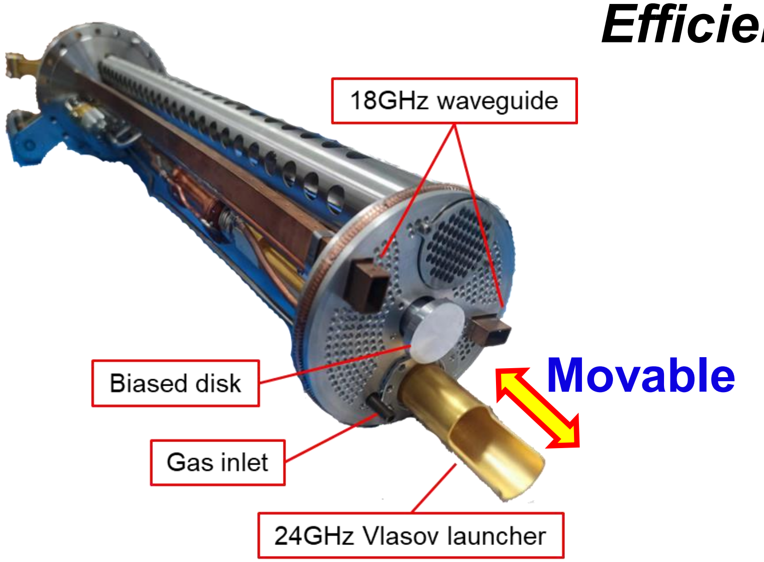


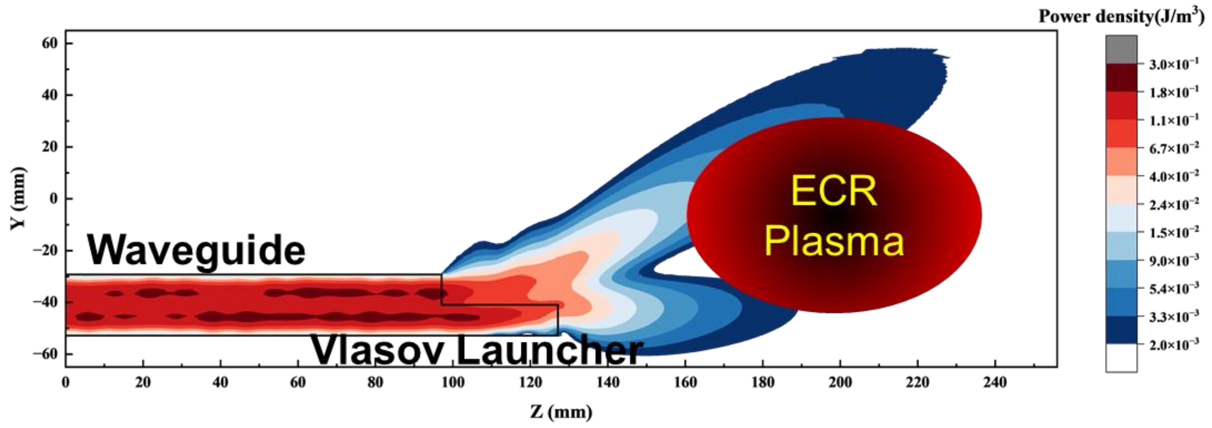
HIAF needs both intense CW and pulsed HCI beams

How to meet the needs?

- ☐ **New techniques for CW and pulsed beam**
- ☐ **Next generation ECRIS**

Efficient microwave launching:Vlasov Launcher



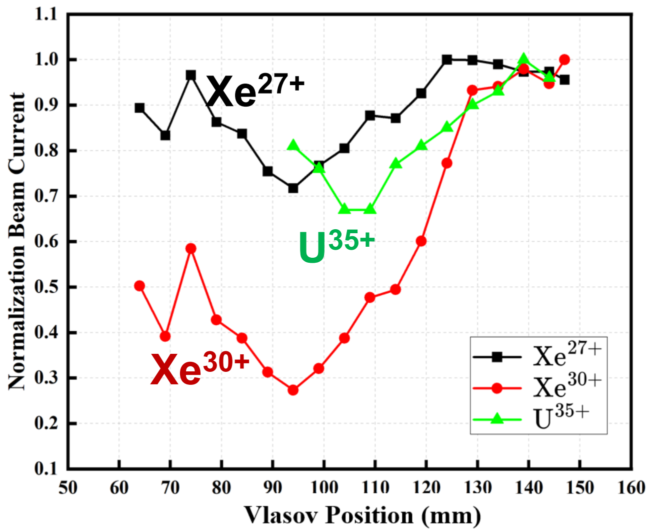


J.W.Guo, et al., Rev. Sci. Instrum. ***91****, 013322 (2020)*

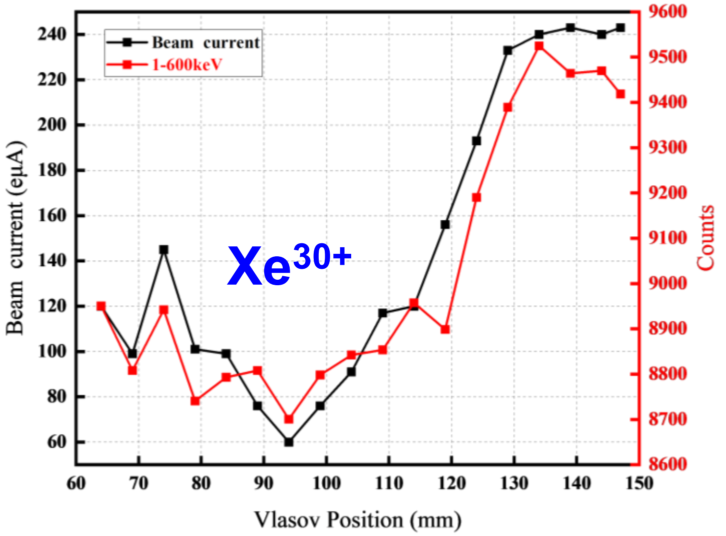
- Vlasov launcher vs. oversized WG: more efficient in plasma heating
- μW power distribution might be a key to efficient HCI production
- Recorded beam intensities production：

18 eμA Xe^{42+}、56 eμA Xe^{38+}、
146 eμA Xe^{34+}、374 eμA Xe^{30+}

X. Wang, PHYS. REV. ACCEL. BEAMS ***27****, 083401 (2024)*

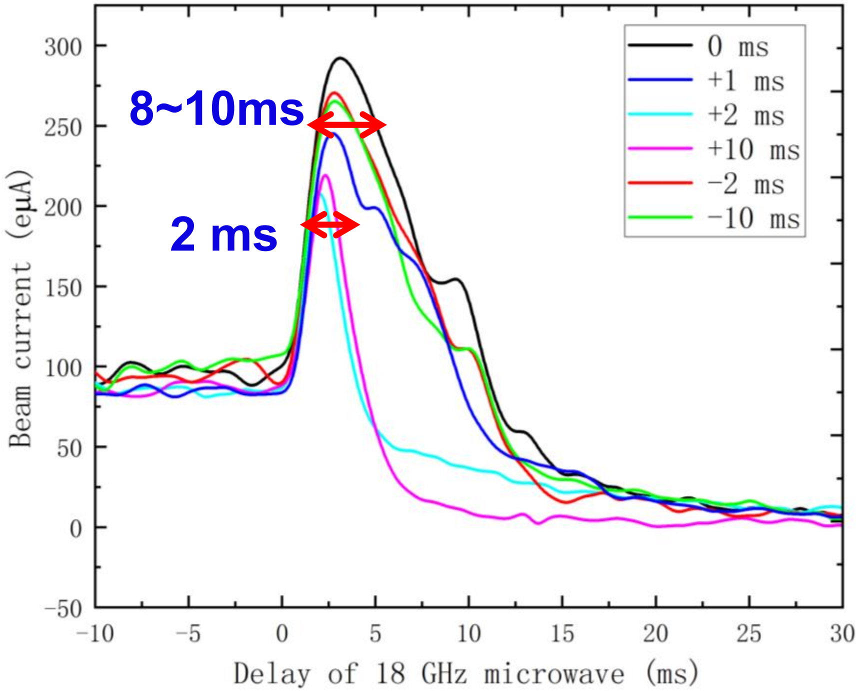


Beam intensity I_q response to Vlasov launcher position



I_q and Bremsstrahlung counts responses to Vlasov launcher position

Solutions 2: New Techniques— Optimizing Afterglow



Optimize AG to get the peaks with higher intensity and longer pulses. 24-28 GHz SC ECRIS?

ion/current (eμA)	SECRAL-II 28+18 GHz (CW~10 kW)	SECRAL-II 24+18 GHz (AG 8-9 kW)	AG peak incease factor
Xe^{30+}	365	503	1.37
Xe^{34+}	135	266	1.97
Xe^{38+}	56	169	3.02
Xe^{42+}	16	50	3.12

Double frequency heating:

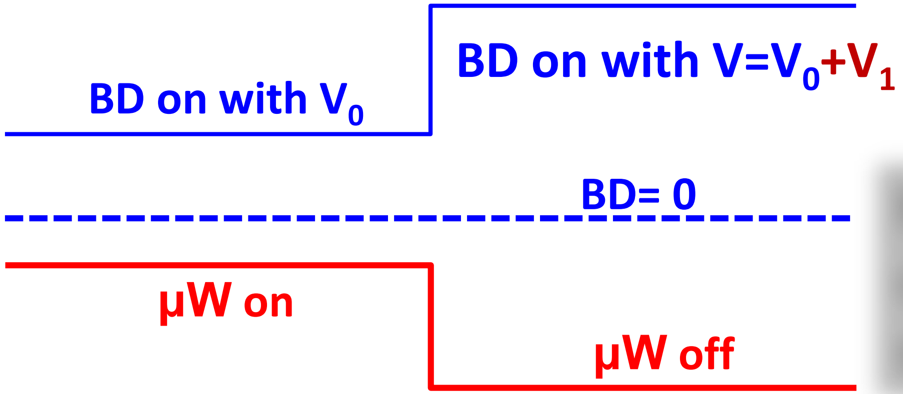
- **Higher AG peak beam intensities**
- **Manipulate AG beam pulse length**

Longer AG pulses with 3rd generation ECRIS :

- **Higher B field** $n_\alpha = n_{\alpha 0} e^{-t/\tau} = n_{\alpha 0} e^{-D_\alpha t/C}$
- **Bigger plasma volume** $D_{\mathrm{Bohm}} = \frac{kT_e}{16eB}$

L. X. Li, PHYS. REV. ACCEL. BEAMS ***25****, 063402 (2022)*

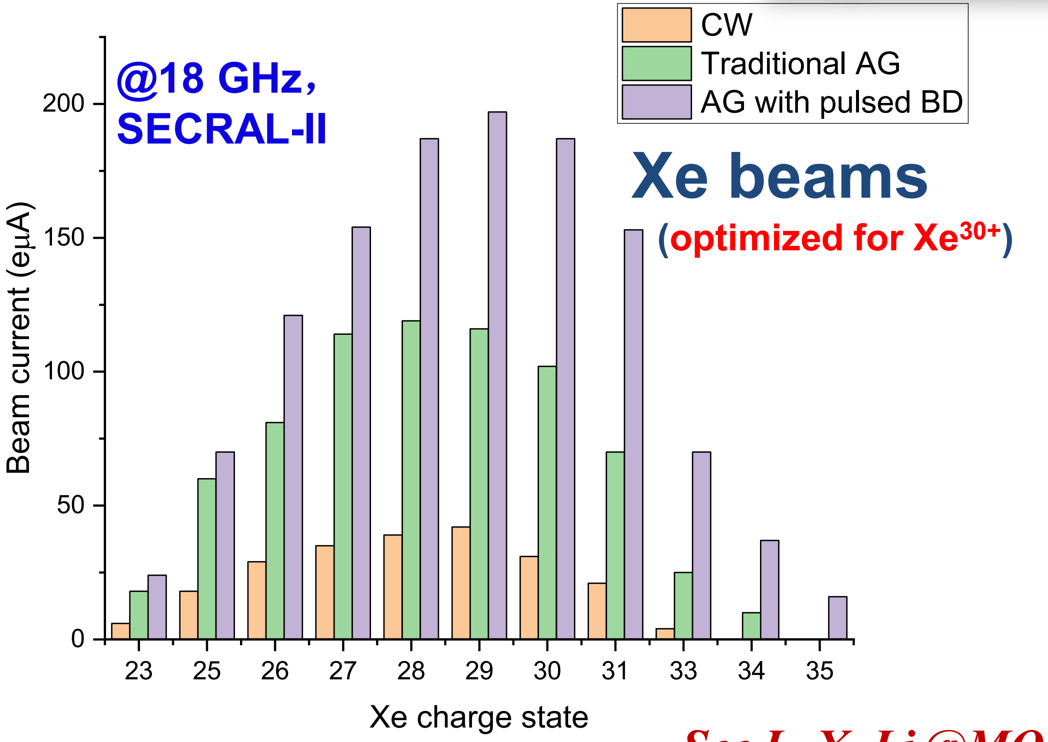
Solutions 3: New Techniques— New pulsed biased-disk

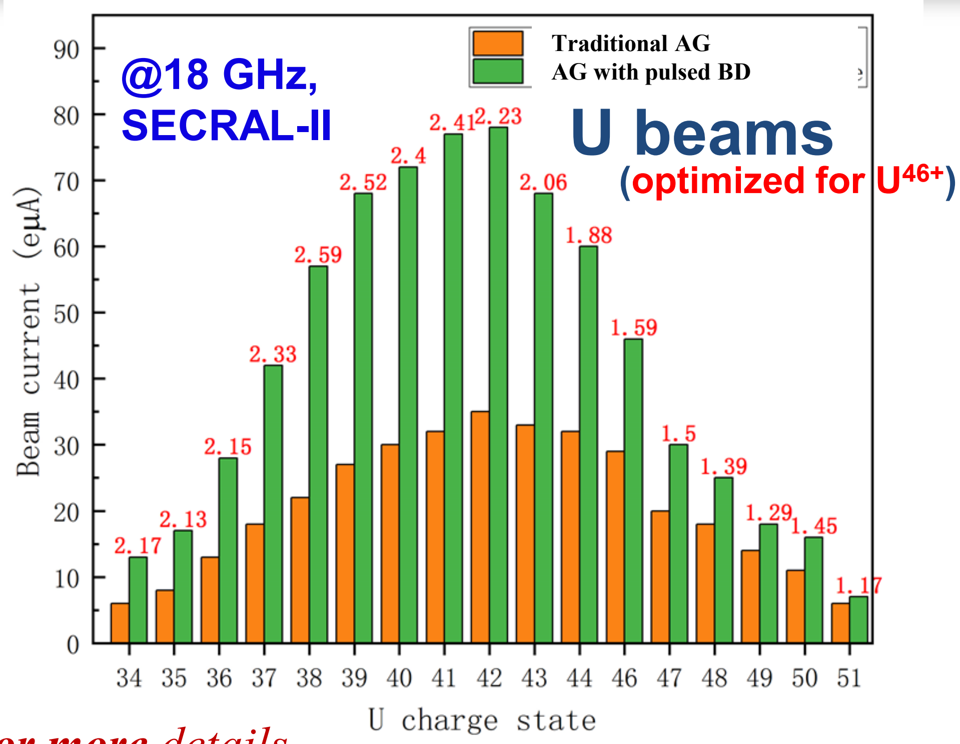


- Previous or traditional work: only V pulsed
- **This work**: V_0+ V1, V_0 DC voltage, V_1 pulsed

New pulsed BD scheme contributes evenly to all charge states and increases AG peak intensity significantly

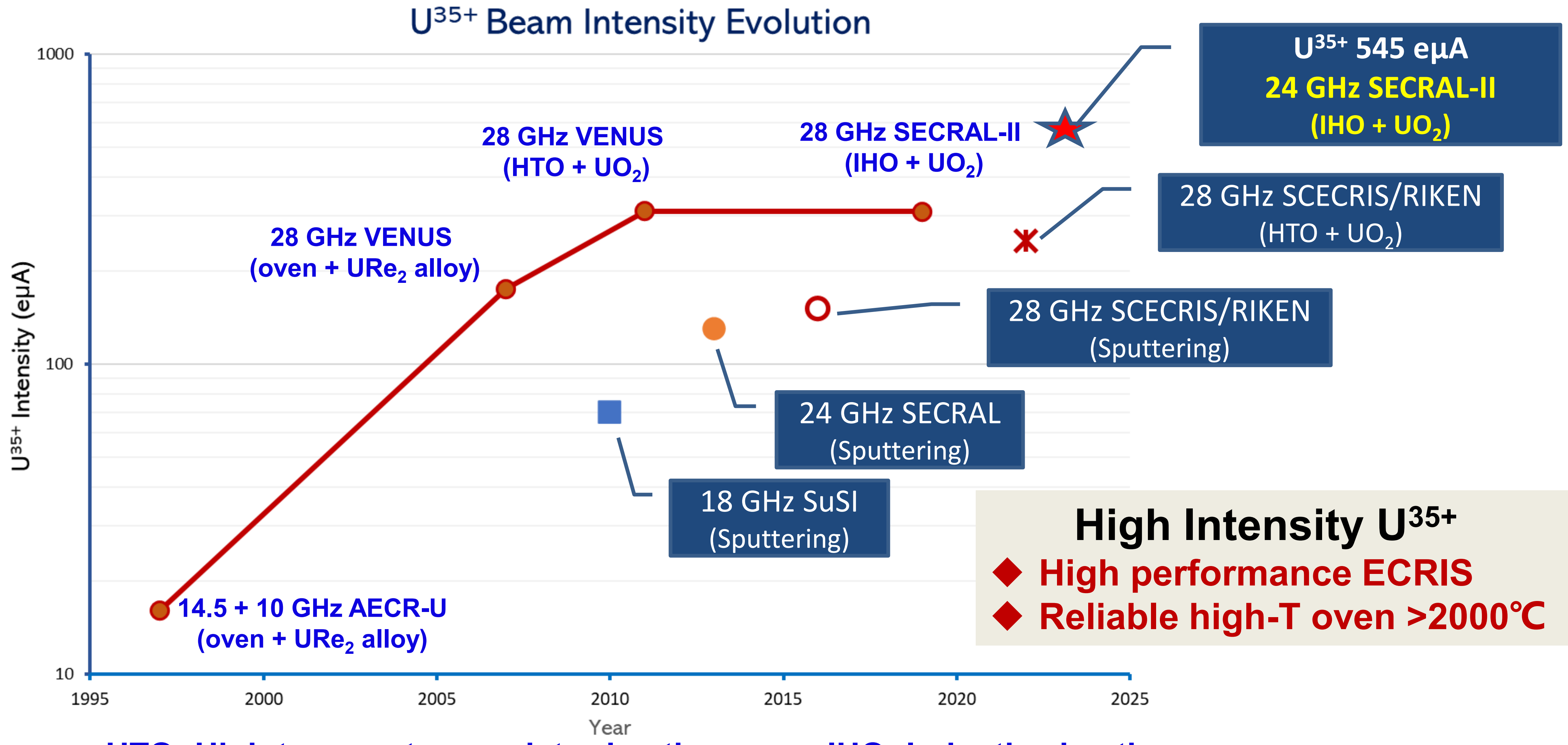
How to explain?





See L. X. Li @MOP02 for more details

Solutions 4: High Intensity Uranium Beam Production

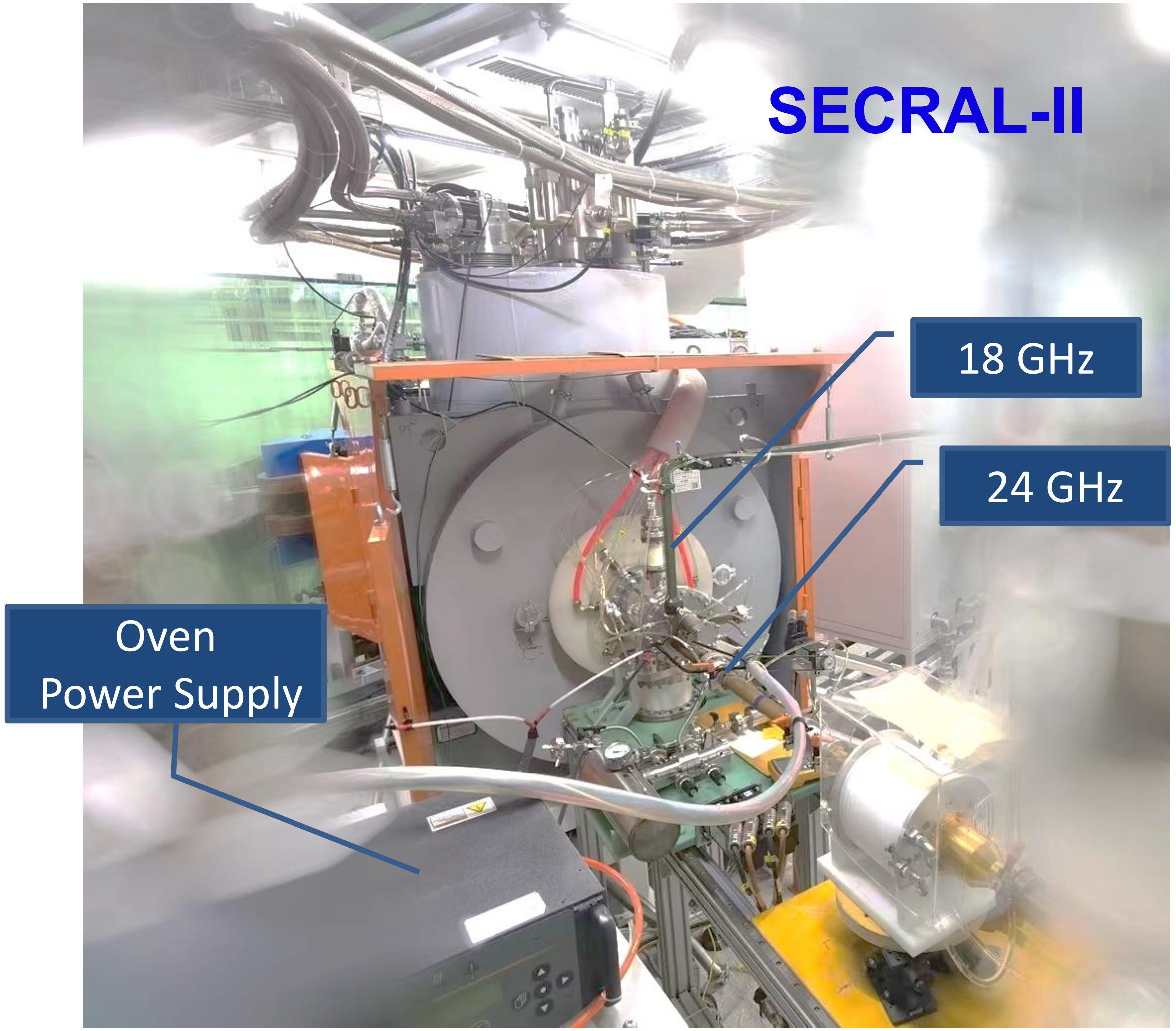


High Intensity U^{35+}

- **High performance ECRIS**
- **Reliable high-T oven >2000℃**

HTO: High temperature resistor heating oven, IHO: Inductive heating oven

Solutions 4: Record Intensities of Uranium Beams



Features:

- High performance SECRAL-II ion source
- High power: 7 kW@24 GHz + 2 kW@18 GHz
- Reliable IHO oven: >2000℃

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	**545**	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

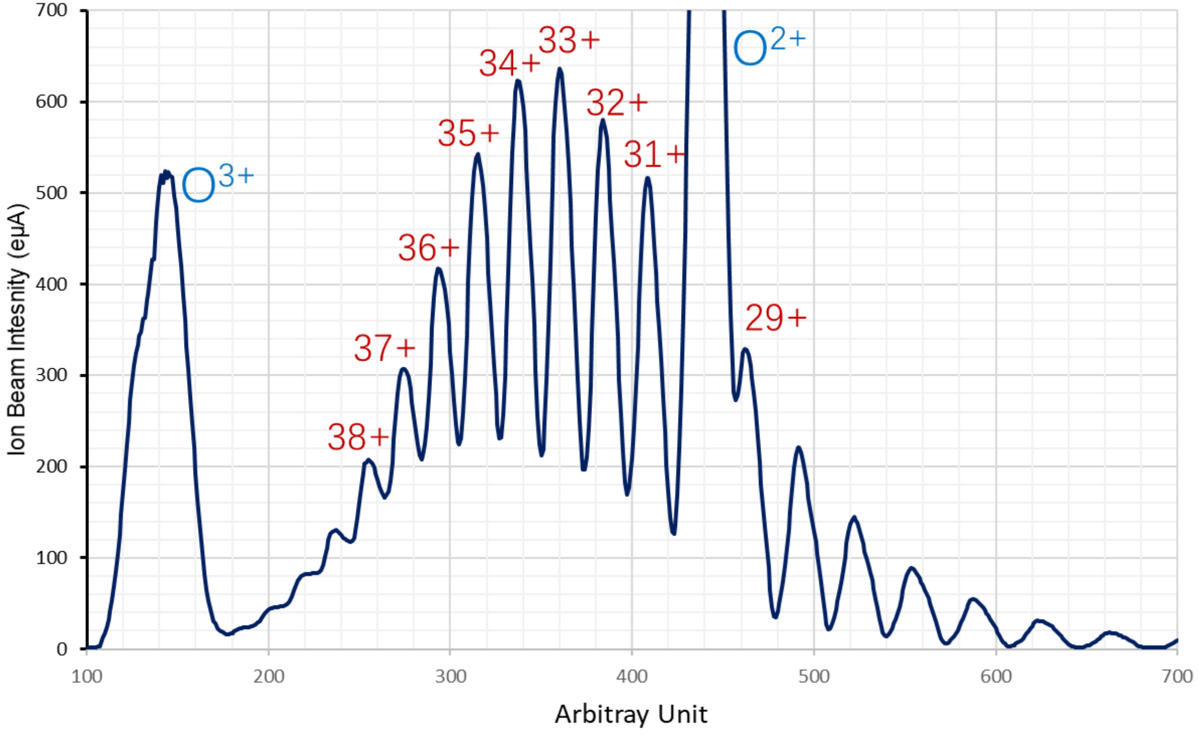
1. *W. Lu et al., Rev. Sci. Instrum. **90**, 113318 (2019)*
2. *J. Benitez, et al., ECRIS2012, THXO02-talk*
3. *T. Nakagawa, Cyclotron'22, invited talk*

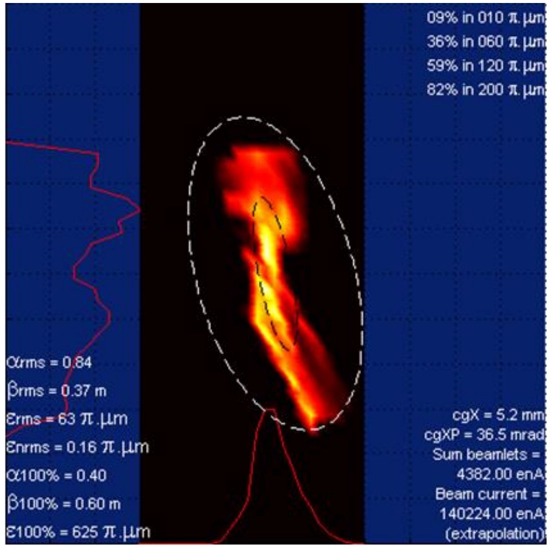
See Lu's talk MOC3 this afternoon

Solutions 4: High Intensity Uranium Beams

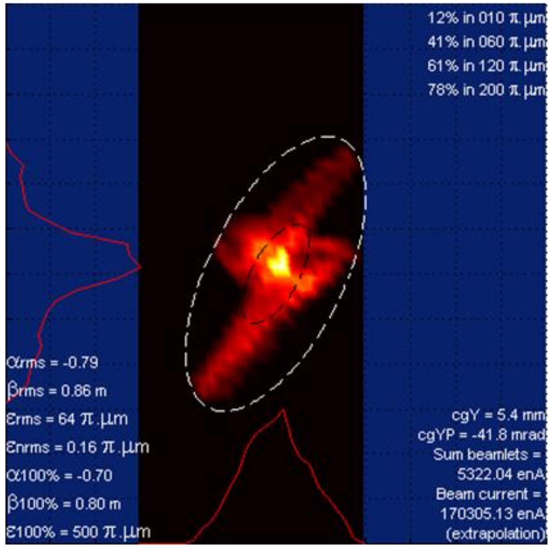
Production of 545 eμA $^{238}U^{35+}$ by SECRAL II

- Material: UO_2+O_2,IHO
- Frequency: 24+18 GHz
- μW power: ~7.9 kW
- Total drain: ~13.2 emA





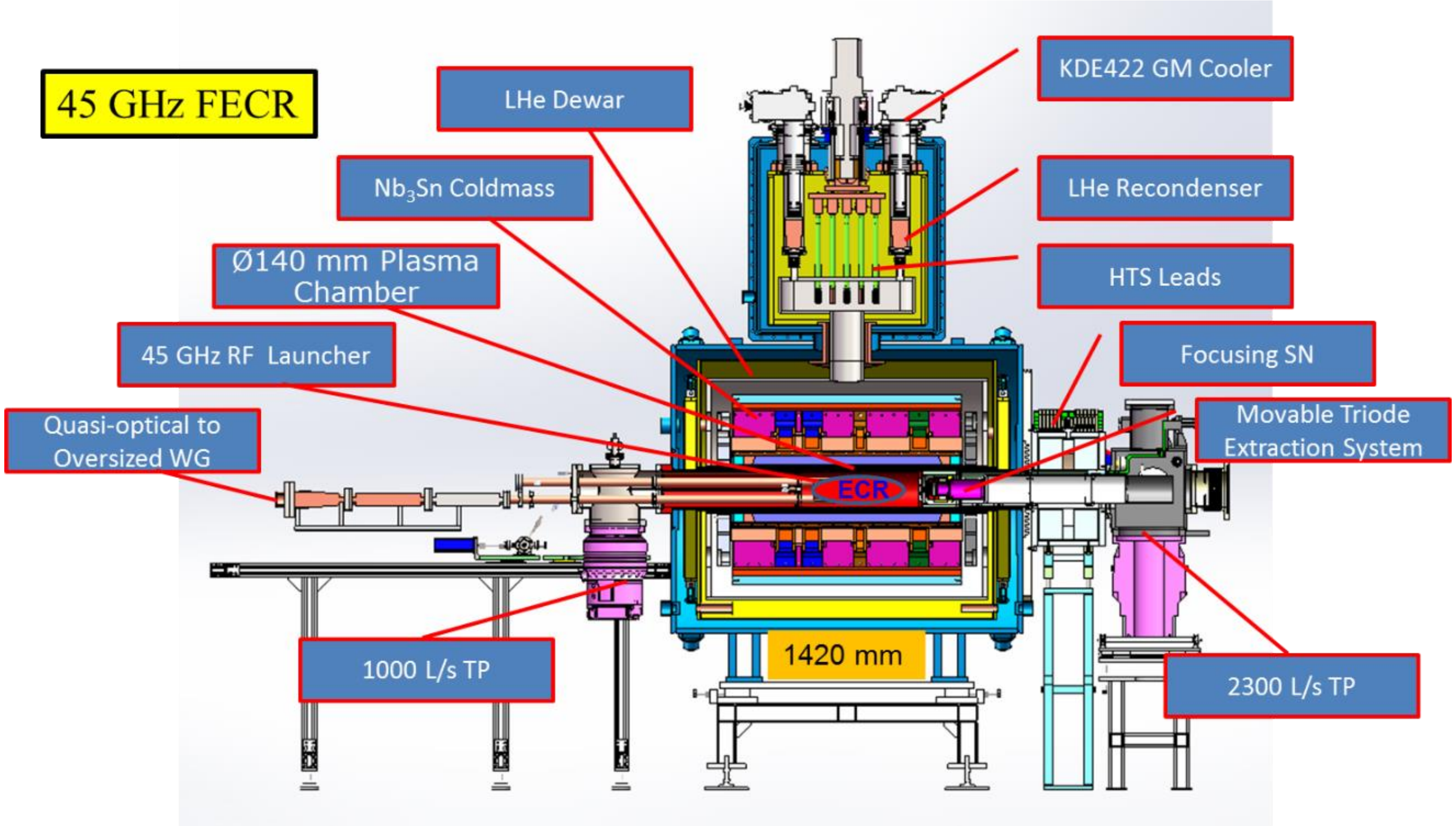
X-$\varepsilon_{n.rms}$: 0.16 π.mm.mrad



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

Solutions 5: Next Generation ECRIS

FECR (First 4th generation ECR ion source)



Specs. of FECR

Specs.	Unit	Value
Frequency	GHz	45
RF Power	kW	20
Chamber ID	mm	≥Ø140
Mirror Fields	T	≥6.4/3.2
B_{rad}	T	≥3.2
Mirror Length	mm	~500
B_{max} in conductor	T	~11.8
Magnet coils	/	Nb_3Sn
Nb_3Sn	J_c>1500 A/mm^2@12T	
Cooling Capacity@4.2 K	W	>10.0

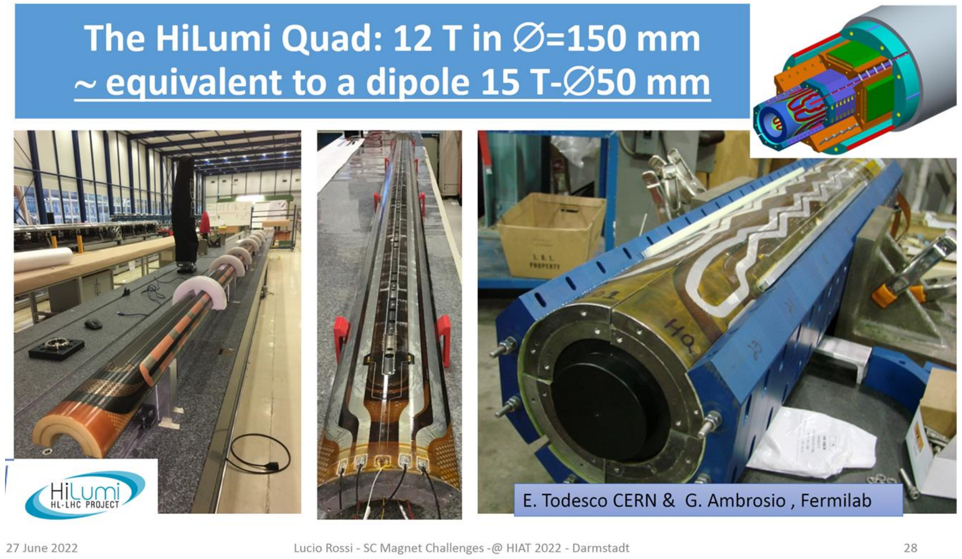
H. W. Zhao et al., Review of Scientific Instruments **89**, 052301 (2018)

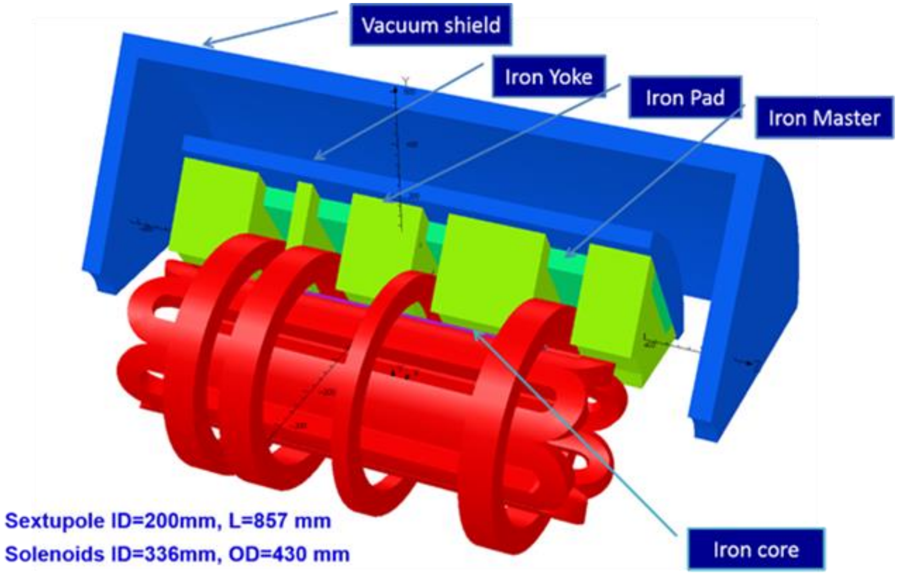
FECR : Technical Challenges

Specs.	Unit	FECR	Challenges
frequency	GHz	45	◆ High frequency high power microwave coupling ◆ High power chamber cooling
Operational RF Power	kW	20	
B_{ECR}	T	1.6	◆ Reliable high field Nb_3Sn magnet with min-B Field Configuration
B_{rad}	T	≥3.2	
B_{inj}	T	≥6.4	
B_{min}	T	0.5~1.1	
B_{ext}	T	≥3.4	
Plasma Chamber ID	mm	≥140	
Mirror Length	mm	500	
Cooling Capacity@4.2 K	W	≥10.0	◆ Radiation degradation and dynamic heat load
U^{35+}	mA	>1.0	◆ Intense solid material beam production
Pulsed Beam Frequency	Hz	0.5~3	◆ High afterglow yield and pulse duration
Afterglow pulse width	ms	>2.0	

Liangting Sun, ICFA-Newsletter **73**, p34.

FECR : The biggest Technical Challenge



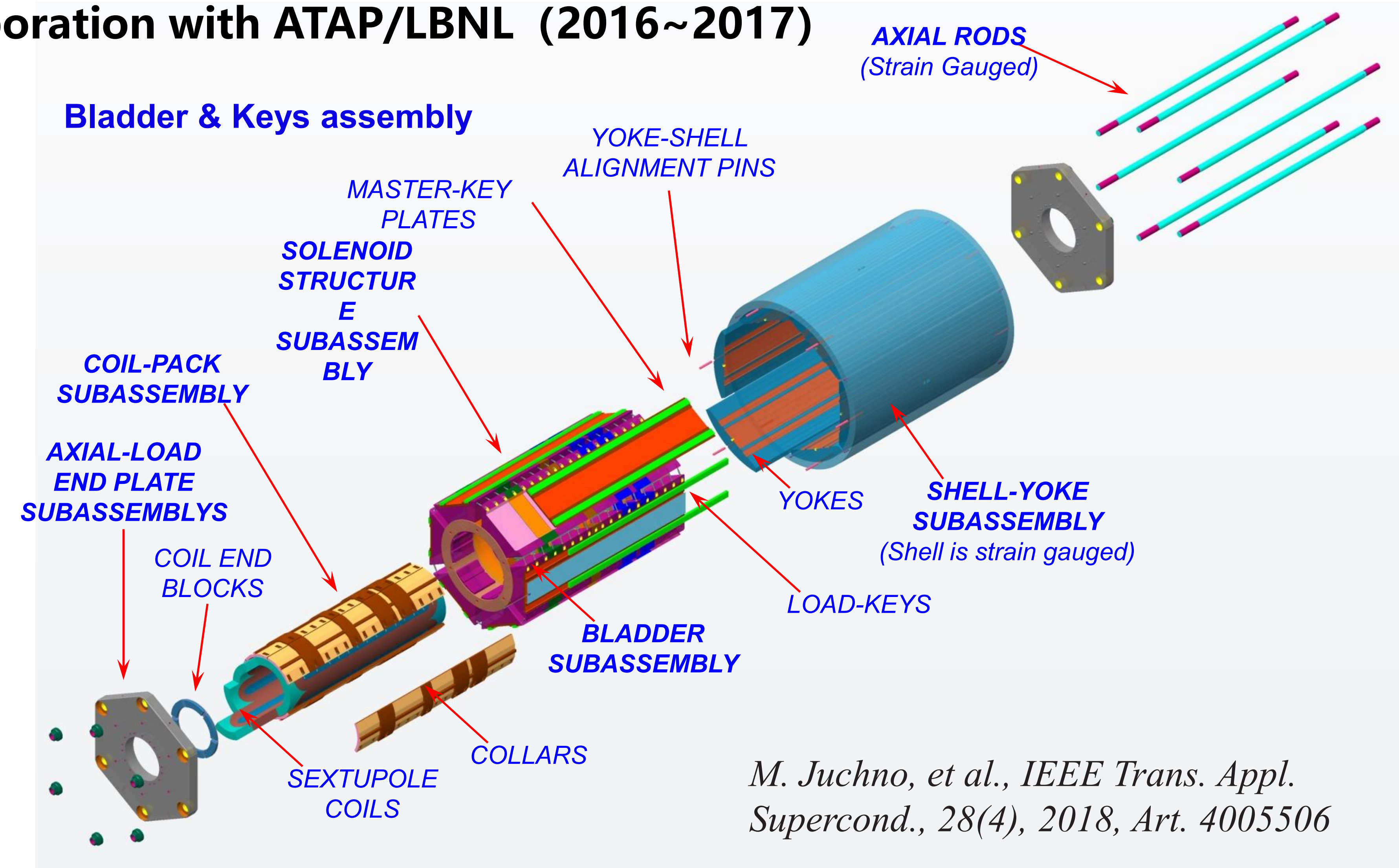


Typical Features of FECR Nb_3Sn magnet coldmass

- **B_{max} in sextupole coils 11.3 T (ID Ø200 mm)**; HL-LHC Quad: 12 T, ID Ø150 mm.
- **B_{max} in solenoids 11.8 T (ID Ø336 mm).**
- **Stored energy 1.6 MJ (Ø160 mm), Stored energy density: 1.9 MJ/m, 60 MJ/m^3**
- HL-LHC MQFXA(1.9 k, 12 T, Ø150 mm) Stored energy density: 1.2 MJ/m,
- FCC Dipole(4.2 k, 16 T, Ø50 mm) Stored energy density: 2.5 MJ/m, 180MJ/m^3.

FECR : Nb_3Sn Magnet Cold-Mass Structure

In collaboration with ATAP/LBNL (2016~2017)

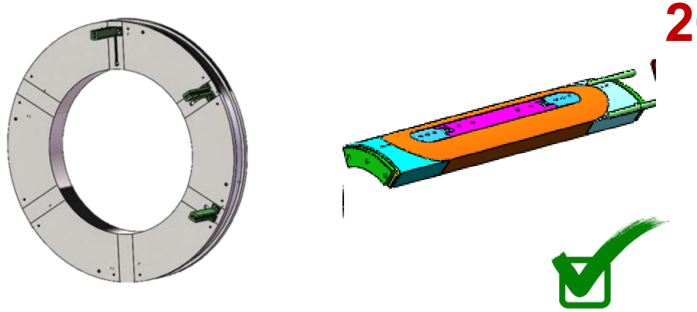


Key technologies and tests completed in close collaboration with XSMT in China (since 2016)

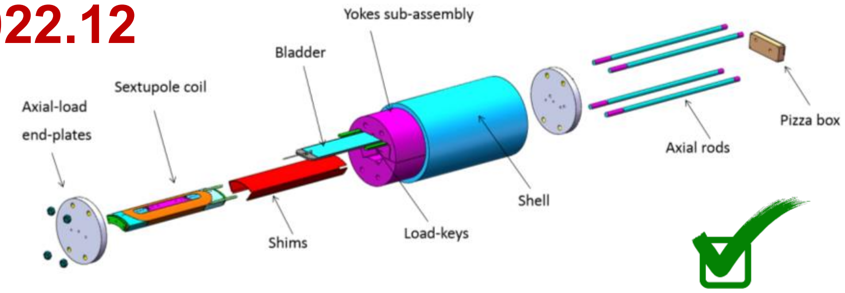
FECR: 4-Step Strategy of the Magnet Coldmass Development

From prototyping to operational magnet

2015.07~2022.12

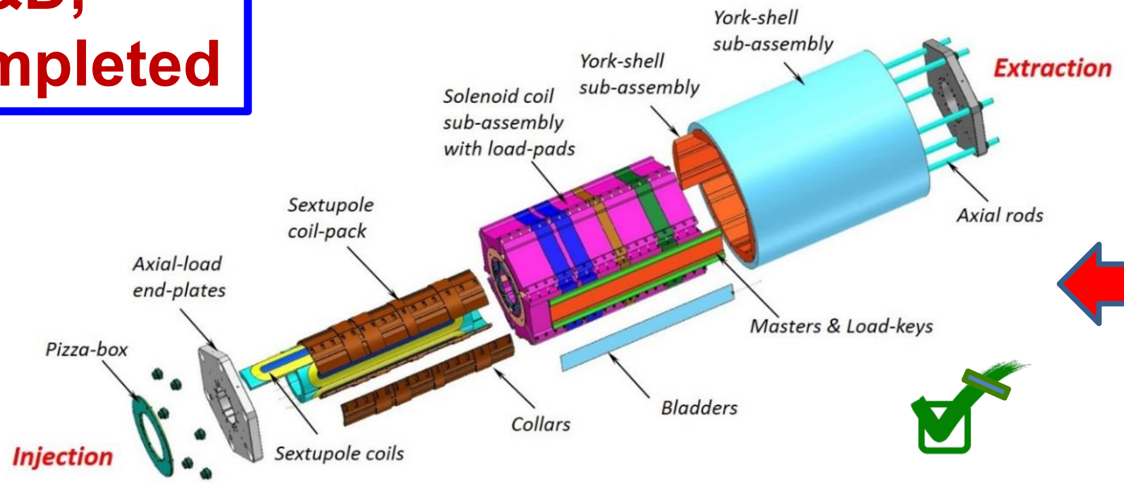


1.Prototyping single coils

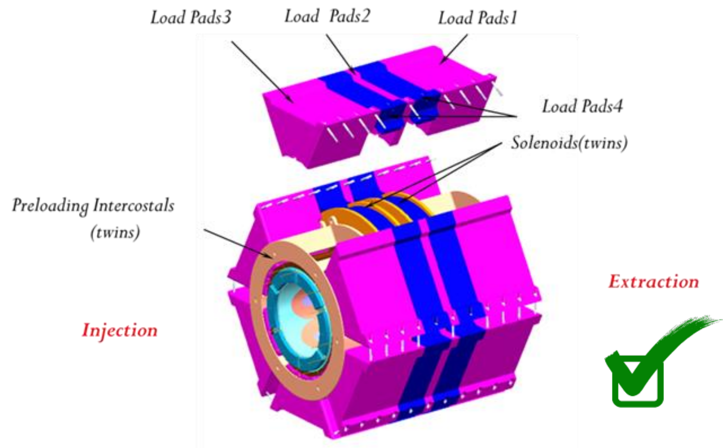


2.Key components and tech.

8 years R&D,
not yet completed

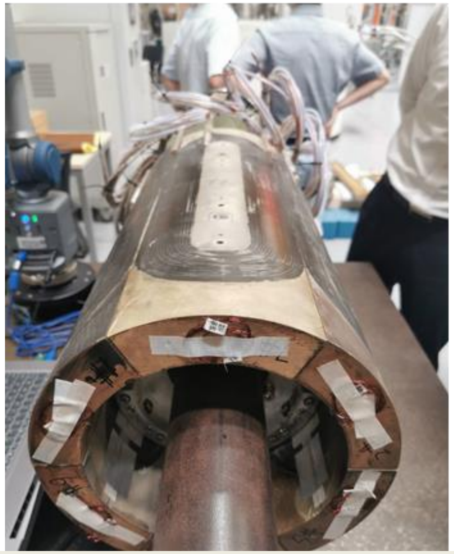


4. FECR coldmass full assembly
(2021.10-2022.05)

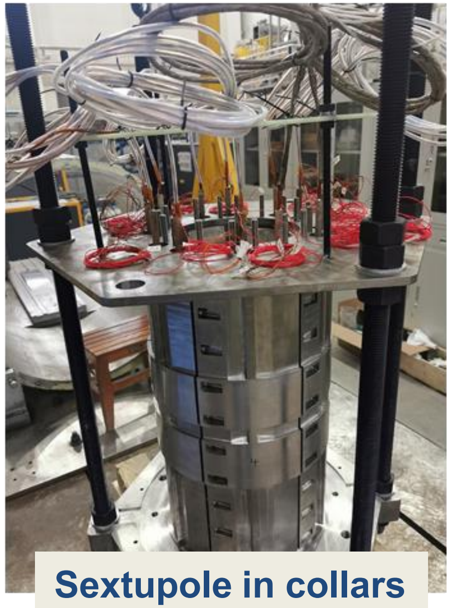


3. ½-length prototype
(2017.11-2021.12)

FECR : ½-length Nb_3Sn magnet Cold-Mass Assembly

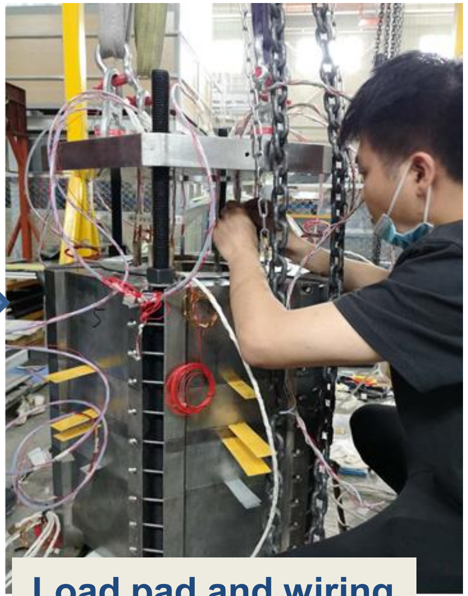


Sextupole pre-assembly

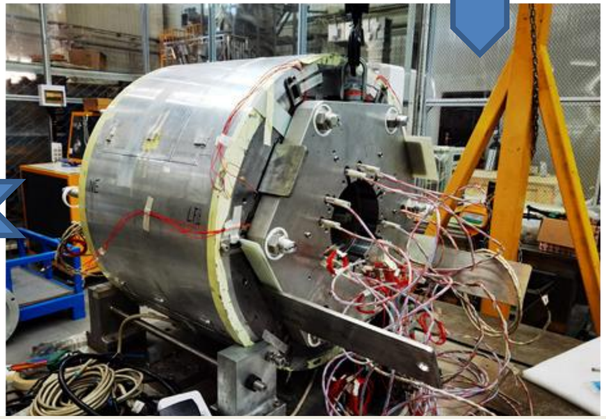


Sextupole in collars

Sextupole & solenoids



Load pad and wiring



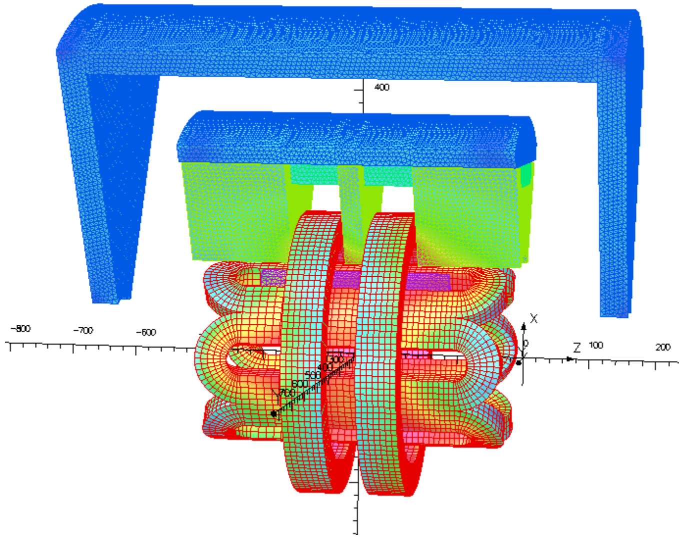
Radial preload with bladder & keys

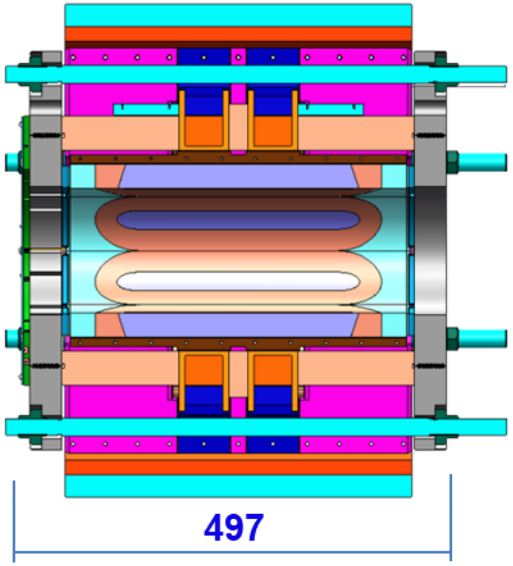
Axial preload with pistons

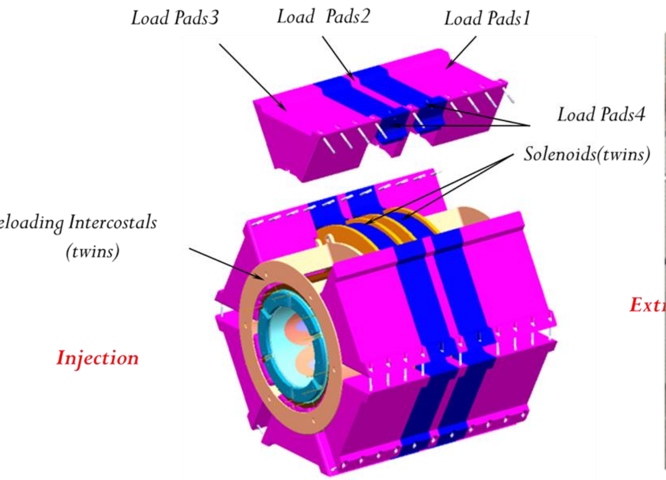
Successful ½ -length prototype

Instrumentation in Pizzabox

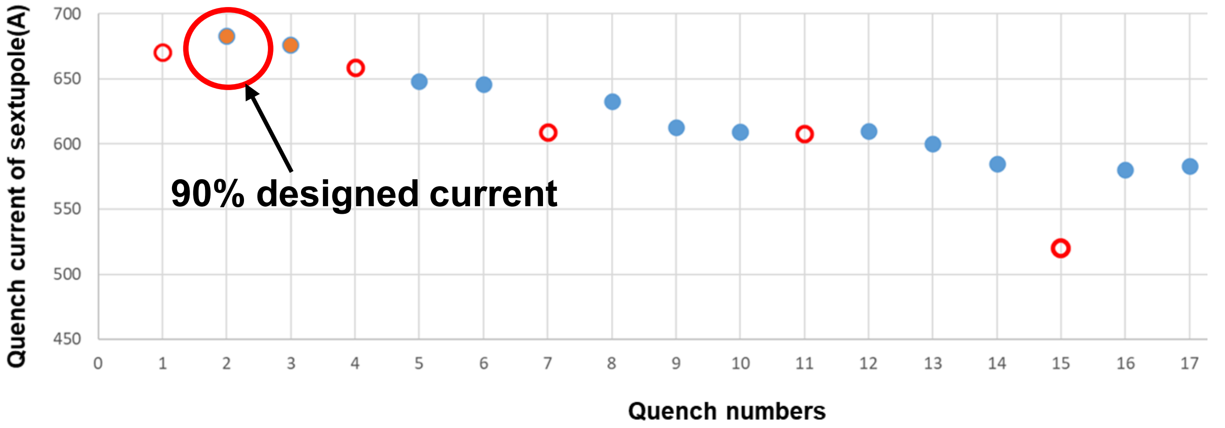
FECR: Cryogenic test of 1/2-length Nb_3Sn magnet cold-mass



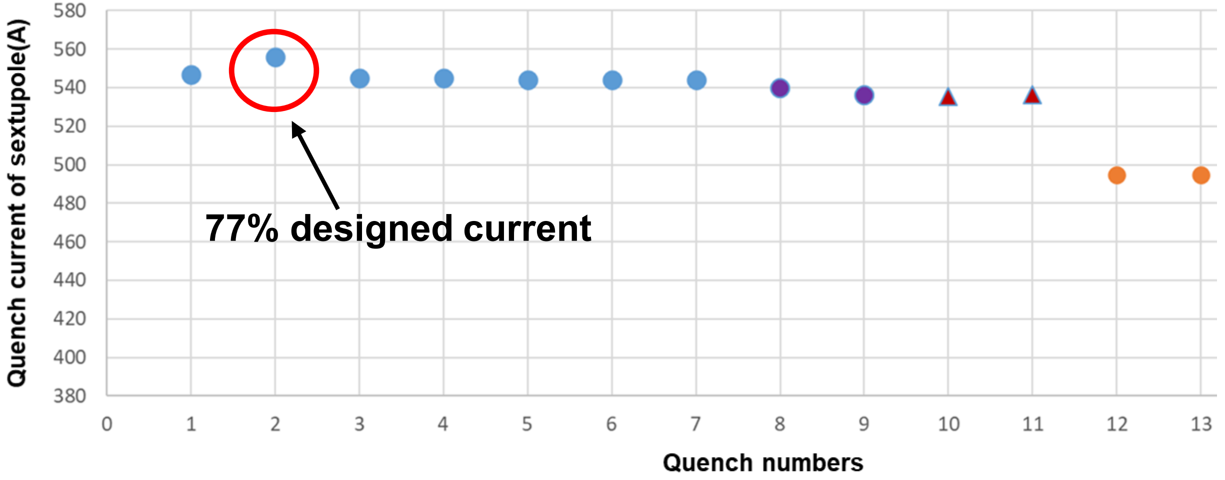




- Sextupole was energized only



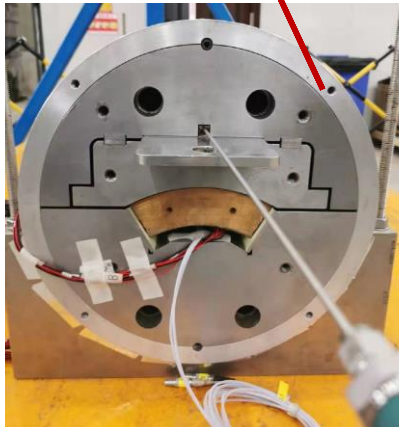
- Sextupole and one solenoid were energized



- The sextupole quenched at 70%-90%, sextupole+one solenoid reached 77% design current
- 2 of the 6 sextupole coils turned out to have performance degradation or minor damage
- Validated and verified the magnet structure and the key technologies
- Learned a lot of lessons and experiences, manufacturing, assembling, quench protection, flux jump, ….

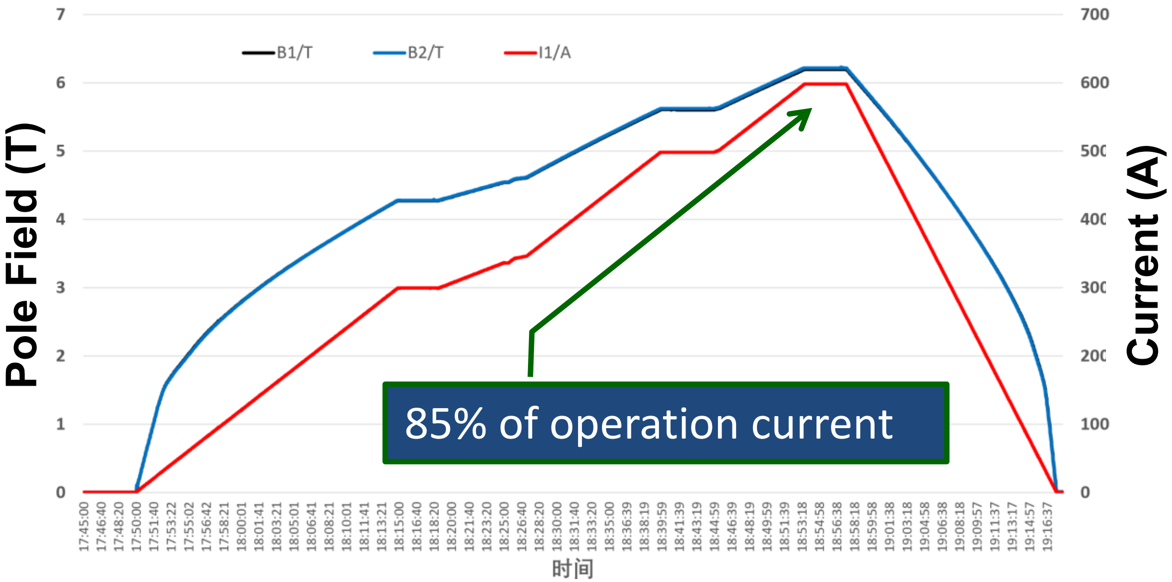
FECR : Full Length Nb_3Sn Sextupole Coil Test

Full length Nb_3Sn sextupole coils manufacturing and tests



Tested full-sized mirror structure

Test of full-sized sext. coil

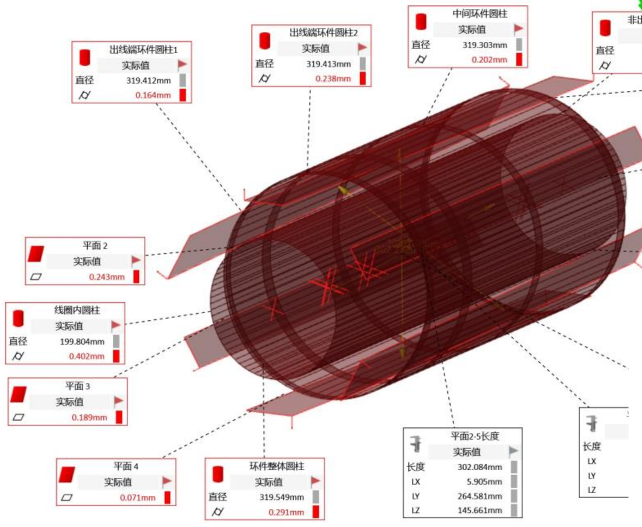


- **Full-sized sextupole coil energized to 85% design current with no quench**
- **Single coil performance demonstrated**

L. Zhu, et al., *IEEE Transactions on Applied Superconductivity*, Art no. 4006905 (2022).

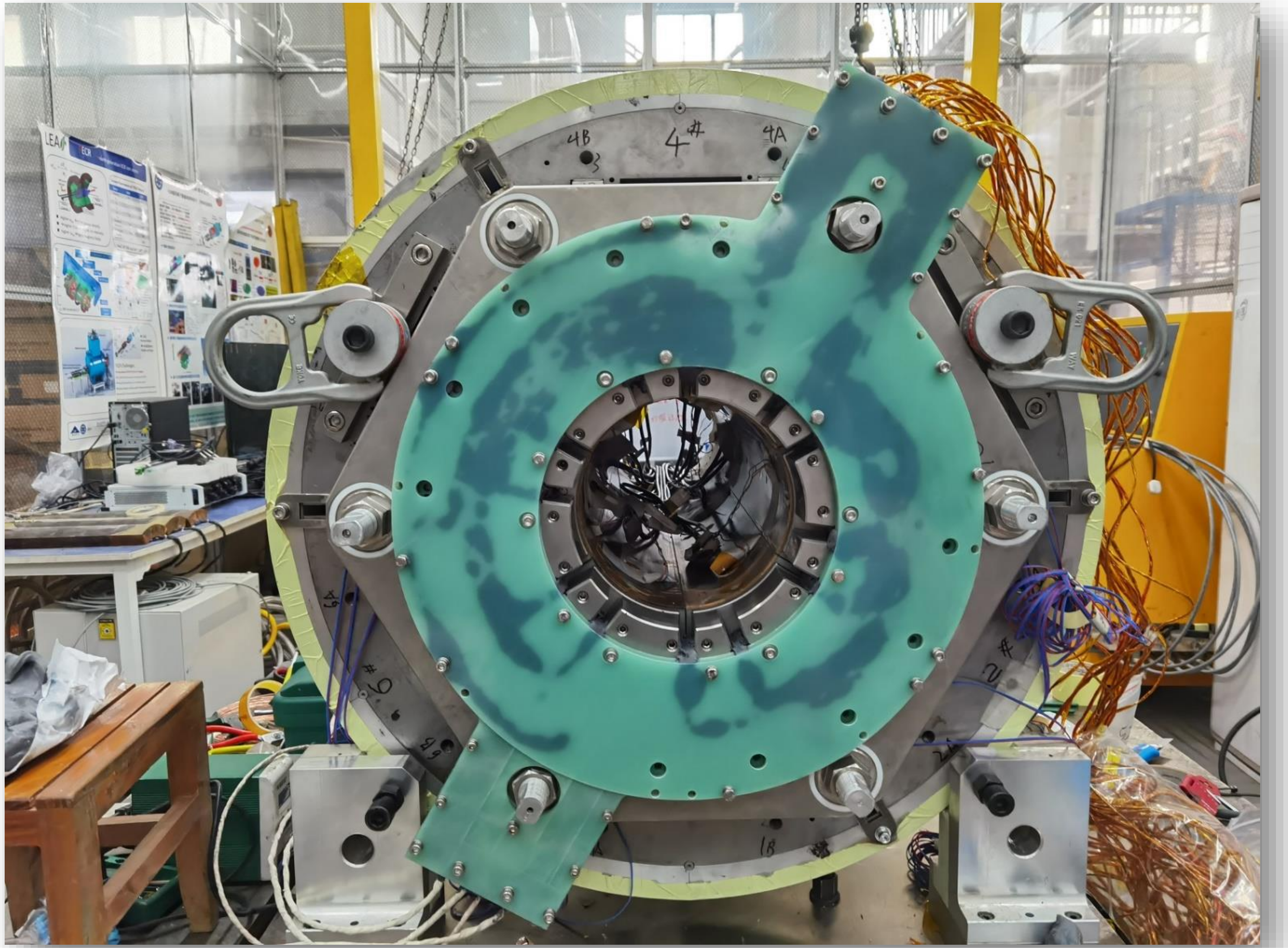
FECR : Full Length Nb_3Sn Sextupole Cold-mass Assembly

8 sextupole coils for full assembly



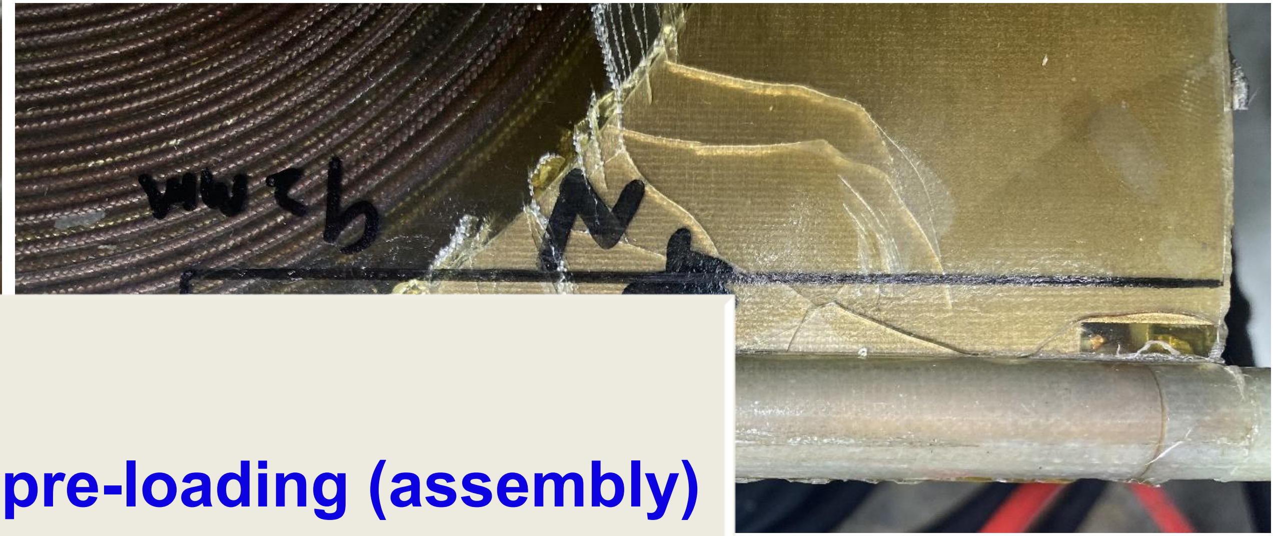
With Quantum Max FaroArm

FECR : Completed Nb_3Sn magnet Coldmass



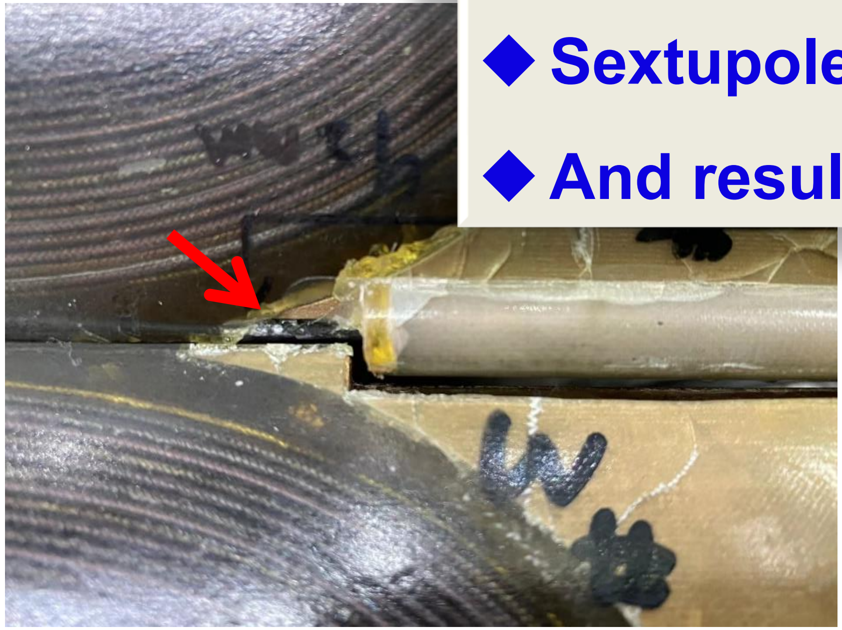
Completed FECR Nb_3Sn magnet coldmass

FECR : Problems and Risks in Full-length Magnet Assembly

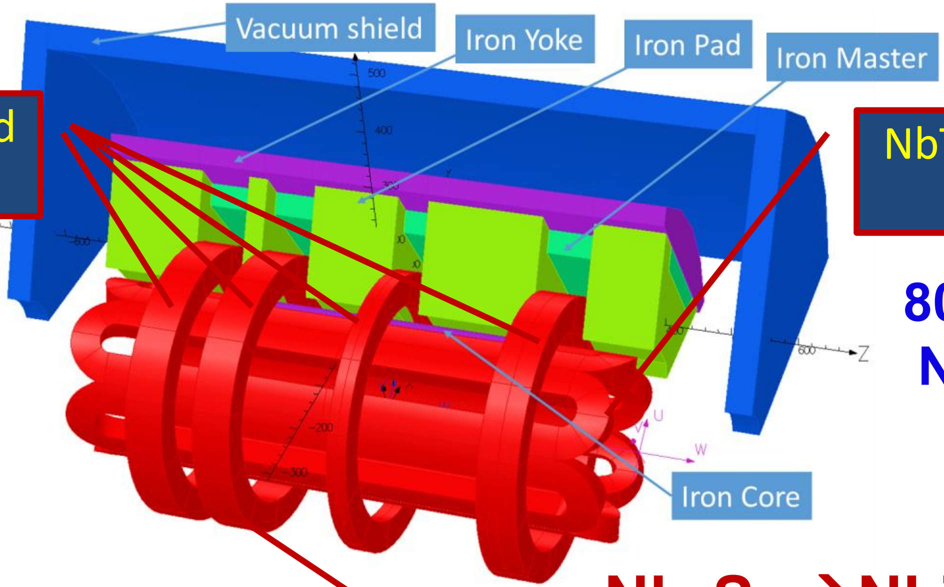


Full-sized coldmass:

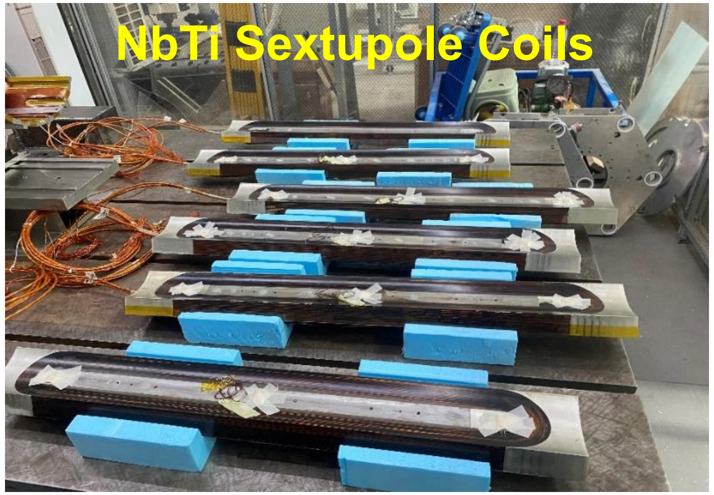
- ◆ Over-stressed during pre-loading (assembly)
- ◆ Sextupole coil leads broken
- ◆ And resultant insulation risk



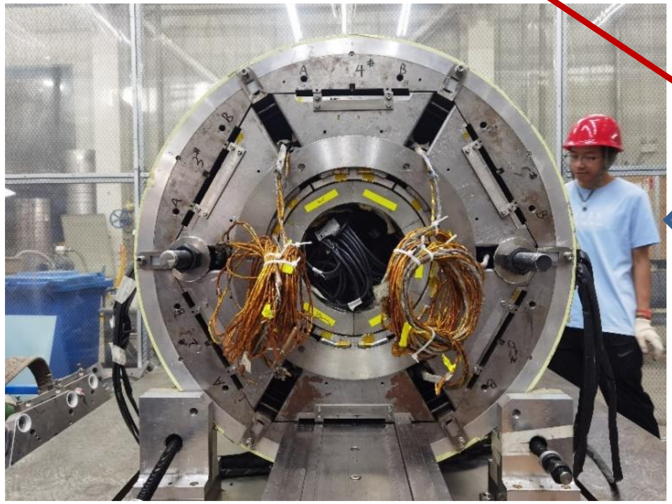
FECR : Nb_3Sn magnet Coldmass to Hybrid

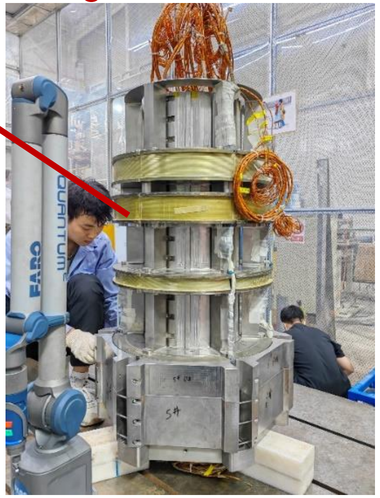


80% B field of the Nb_3Sn magnet

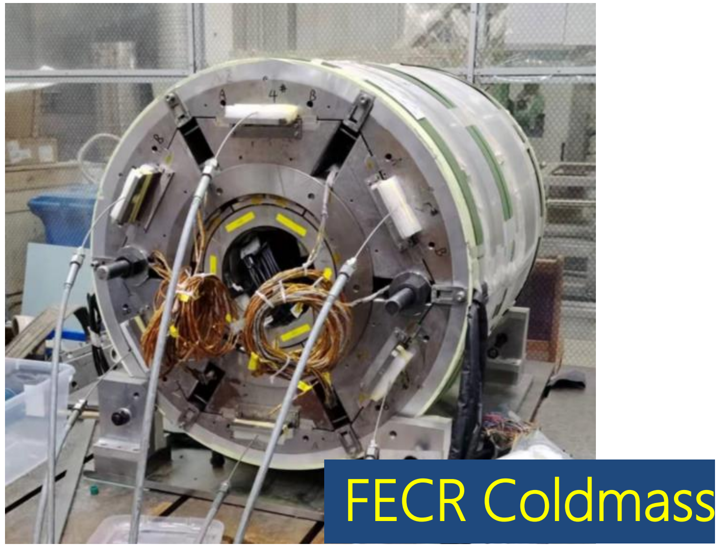


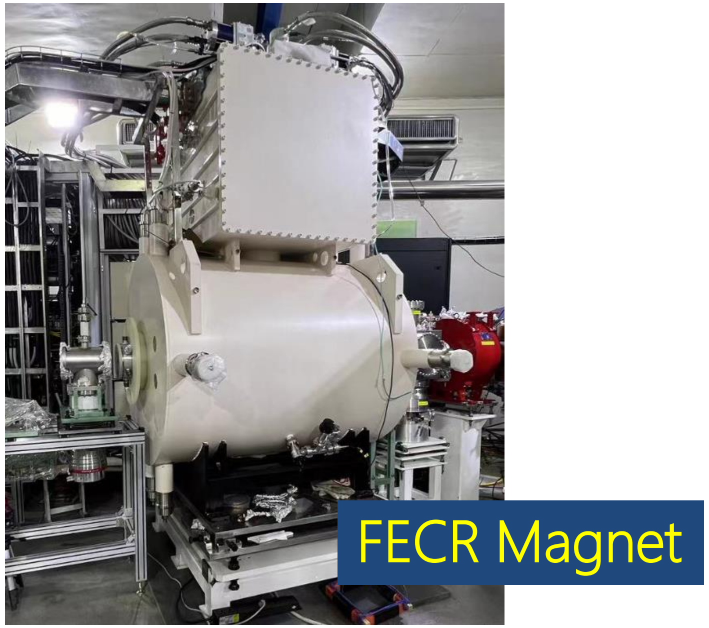
Nb_3Sn→NbTi sextupole coils, Structure unchanged

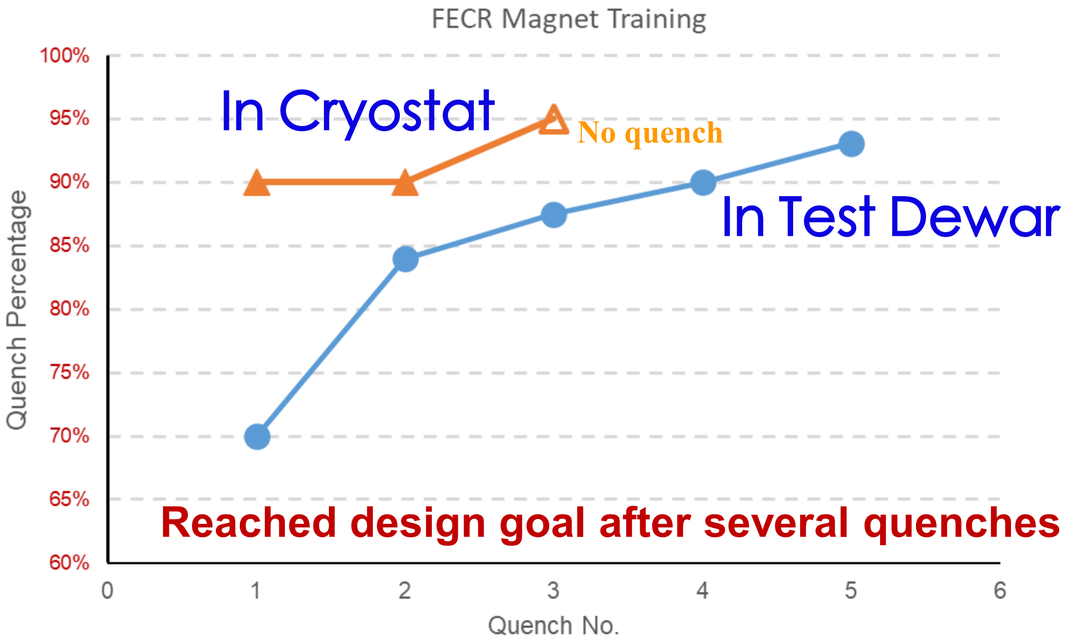




FECR : Completed the Hybrid Magnet and Cryogenic Test



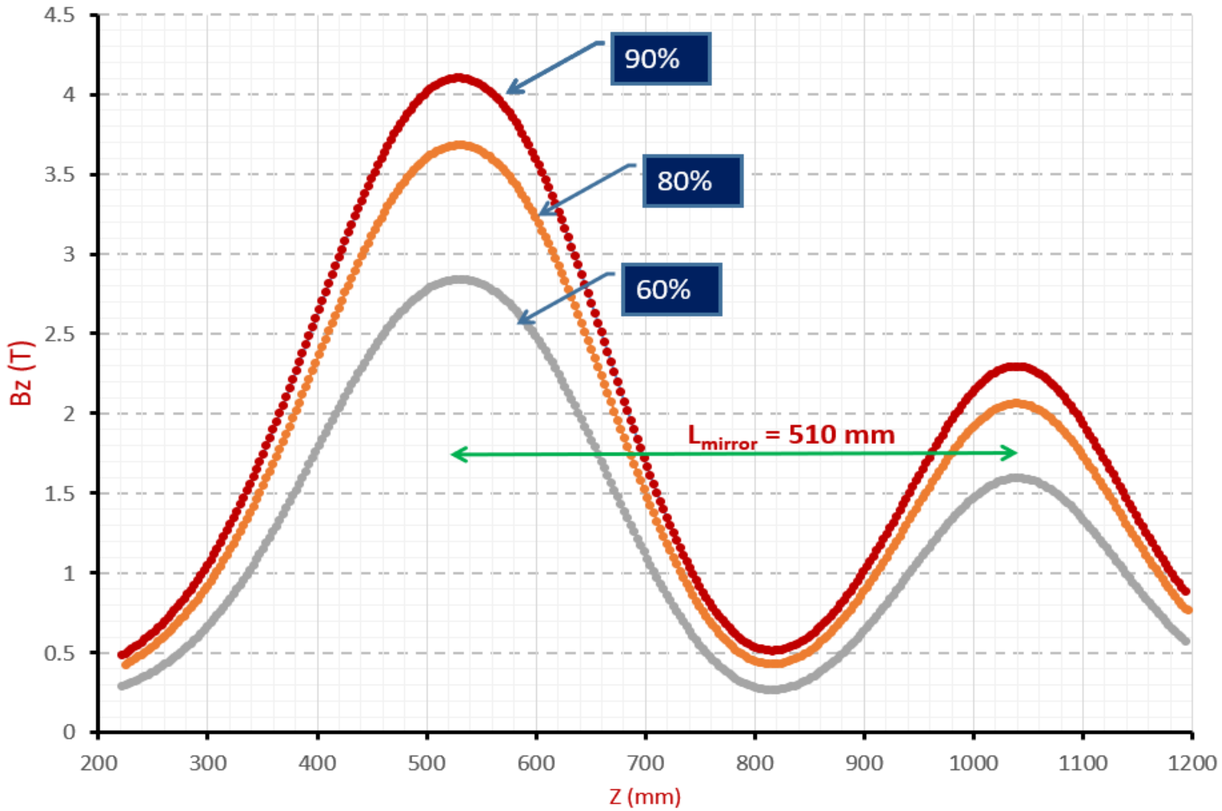


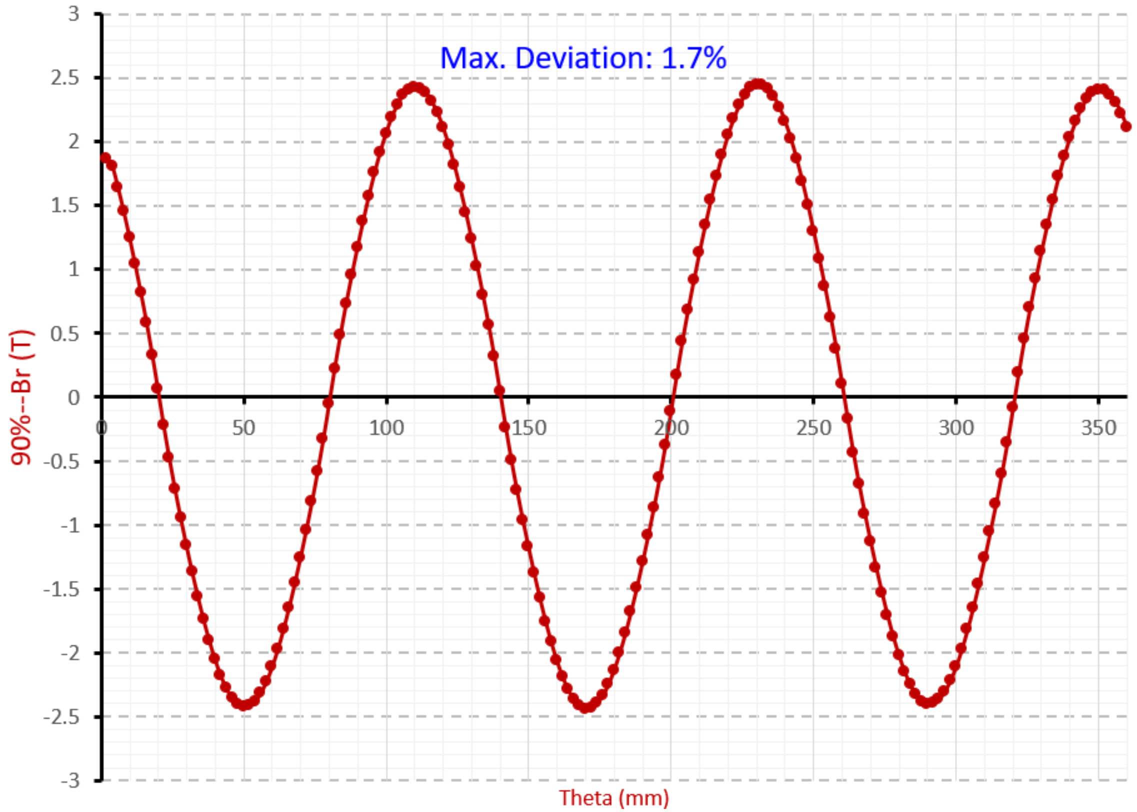


FECR with Nb_3Sn+NbTi coils:

- **High precision fabrication**
- **High precision assembly**
- **Successful operation against Flux Jumps**
- **ECRIS magnet with highest magnetic fields**

FECR : Hybrid-magnet Field Mapping



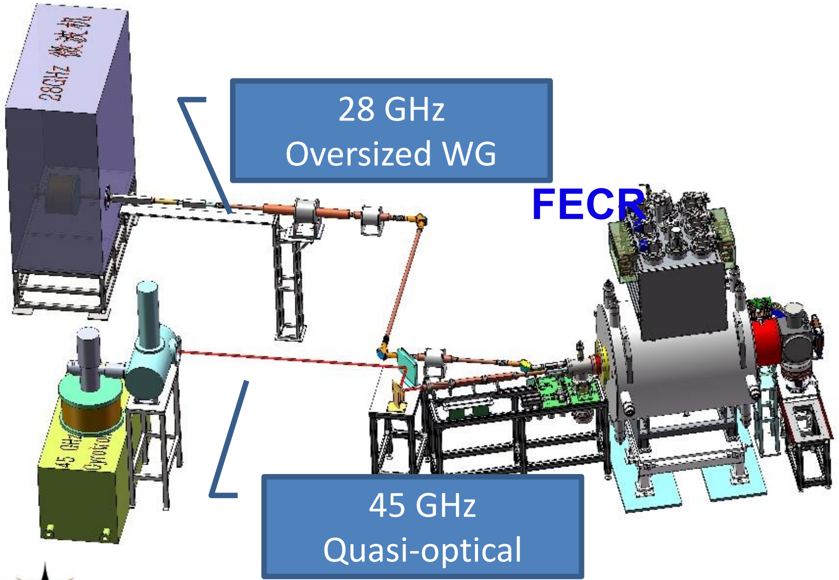


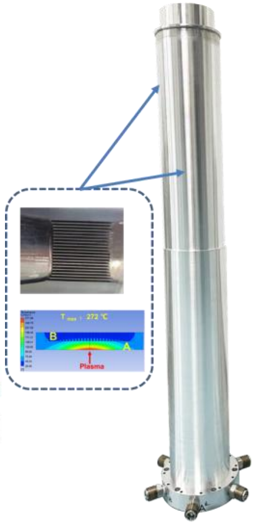
Robust structure

- Decision going to hybrid → successful coldmass = 9 months
- Magnetic fields precision well controlled
- Sextupole B_{max} reaches the 93% loading factor of NbTi conductor

FECR : First Beam Commissioning Results

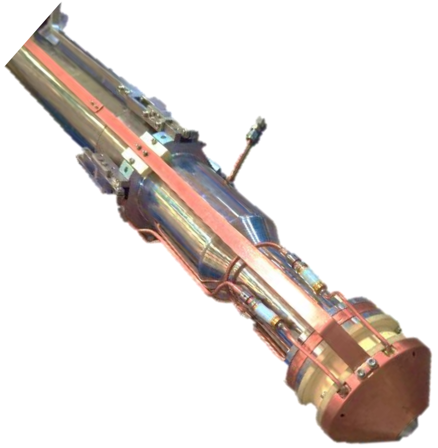
Parameters	Value
Microwave	**45 GHz + 28 GHz**
45 GHz Power	**5-8 kW**
28 GHz Power	**5-6 kW**
Typical operation fields	**Mirror peaks: 3.9 T/2.1 T** **B_r= 2.3 T**
Commissioned ions	**O, Xe, Bi**
Operation voltage	**25 kV**





Micro-channel plasma chamber

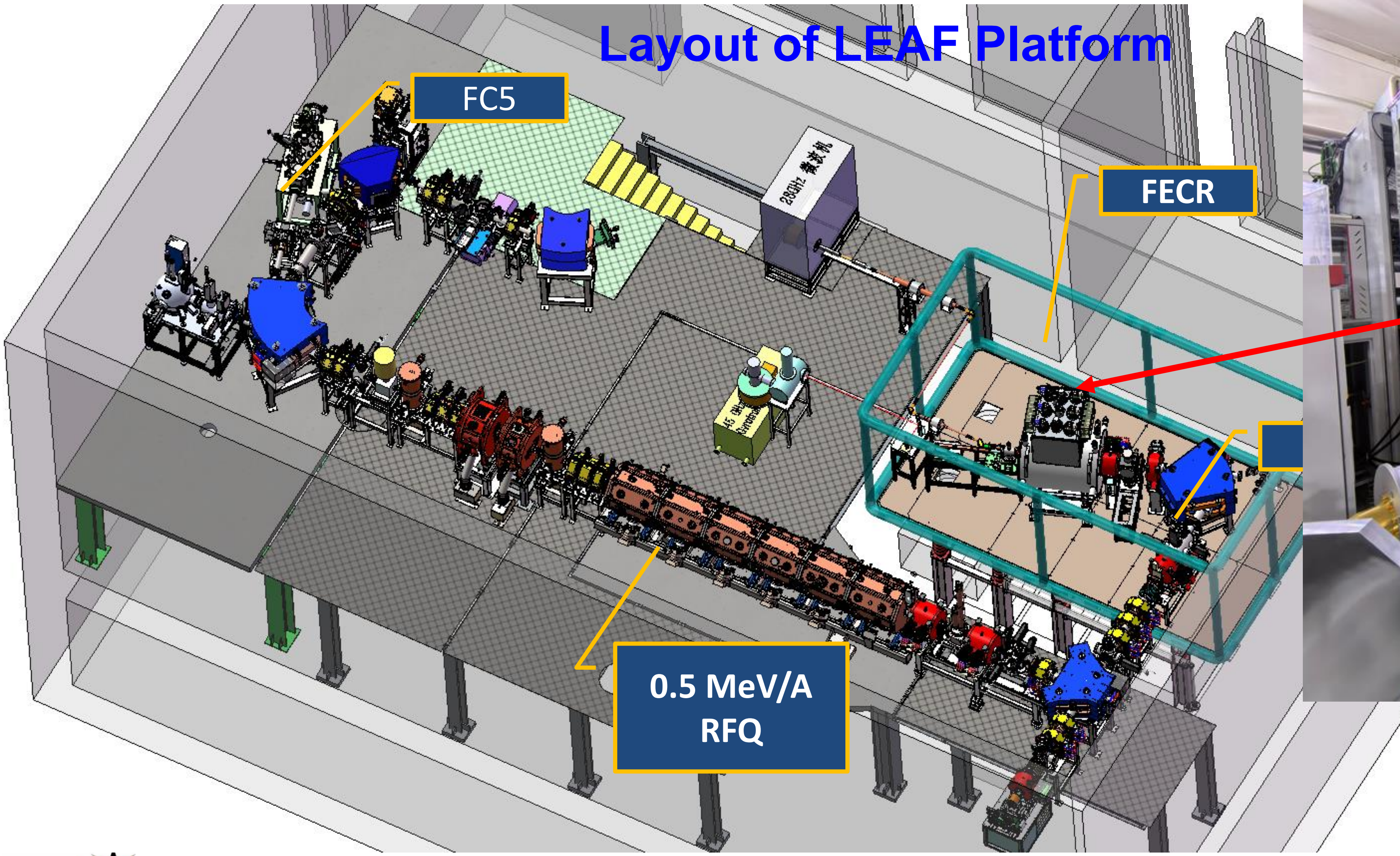
Conventional Injection setup

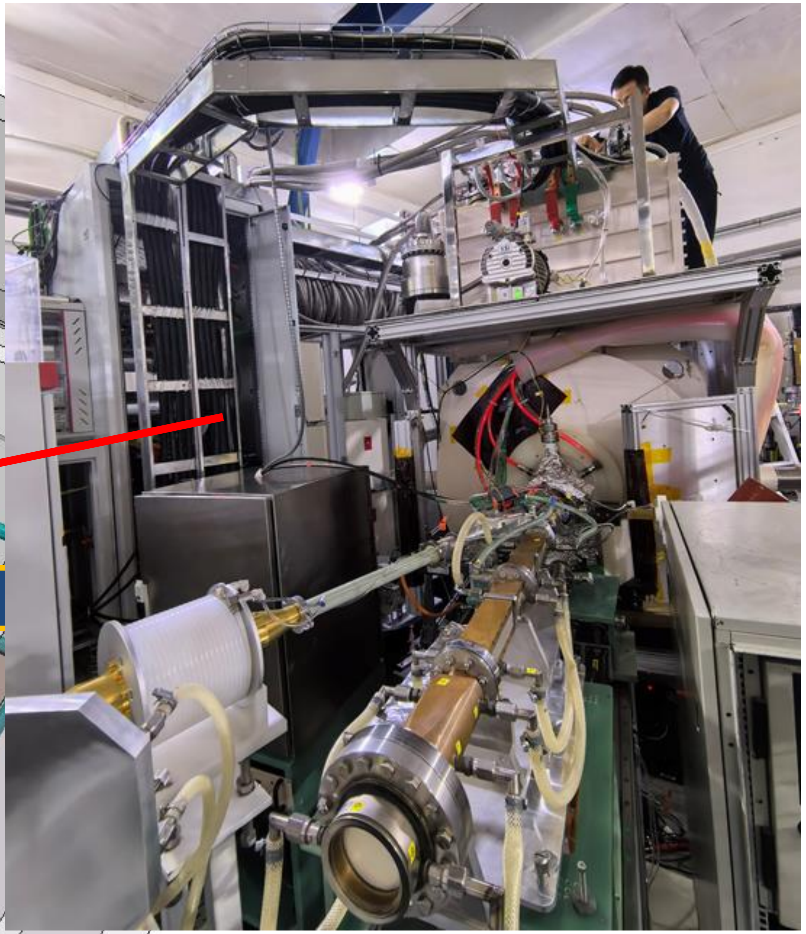


Movable Extraction electrodes

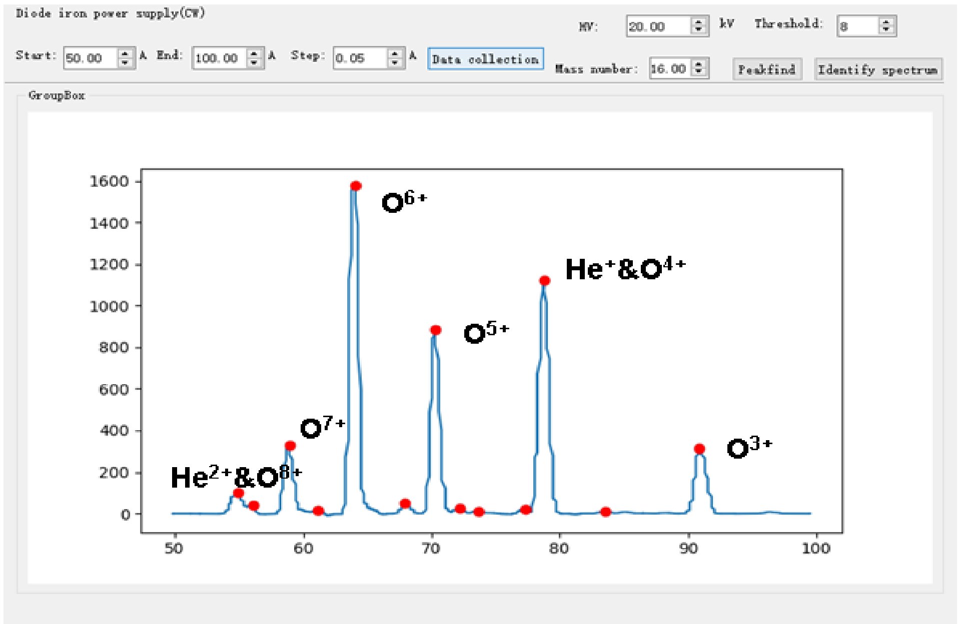
FECR: Joint Test at LEAF

LEAF: Low Energy high intensity highly-charged heavy ion Accelerator Facility

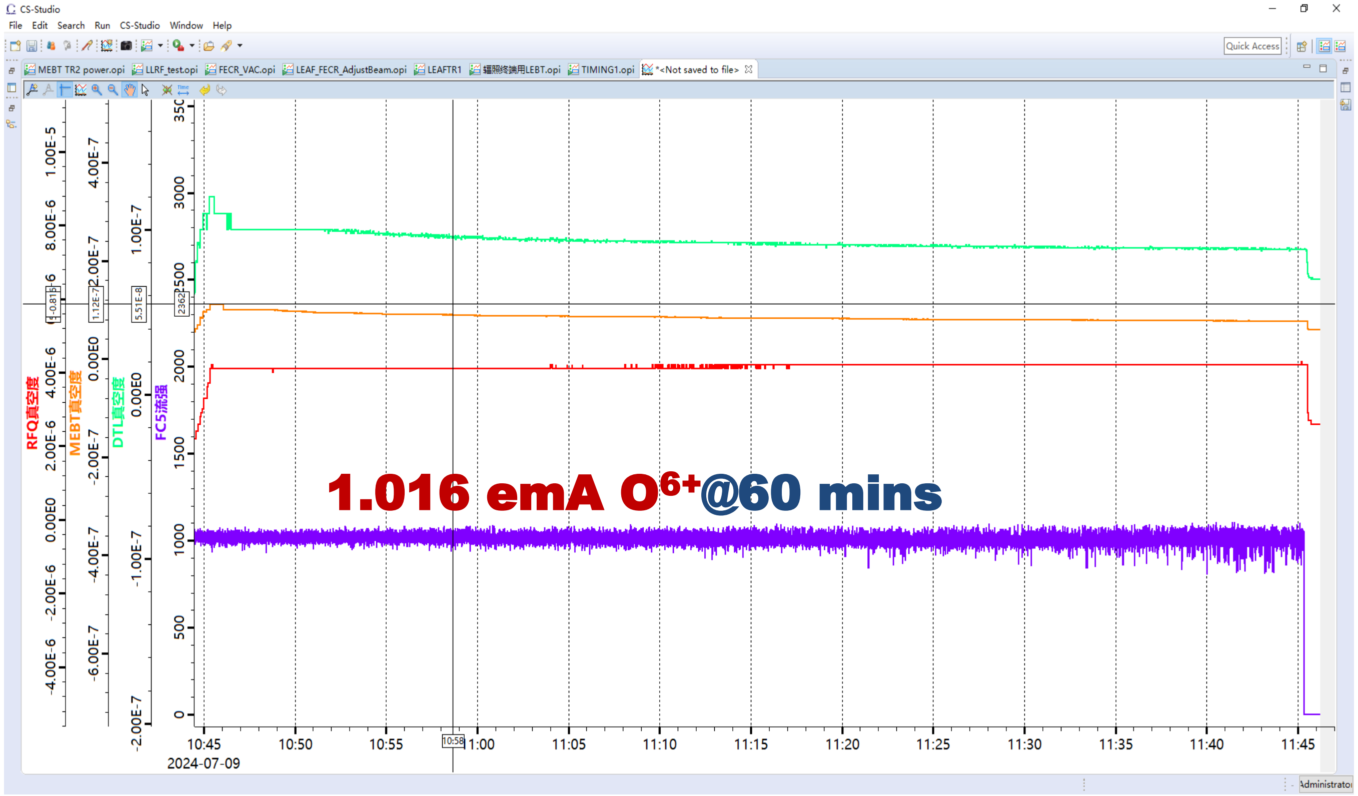




FECR: Joint Test at LEAF and the First Results

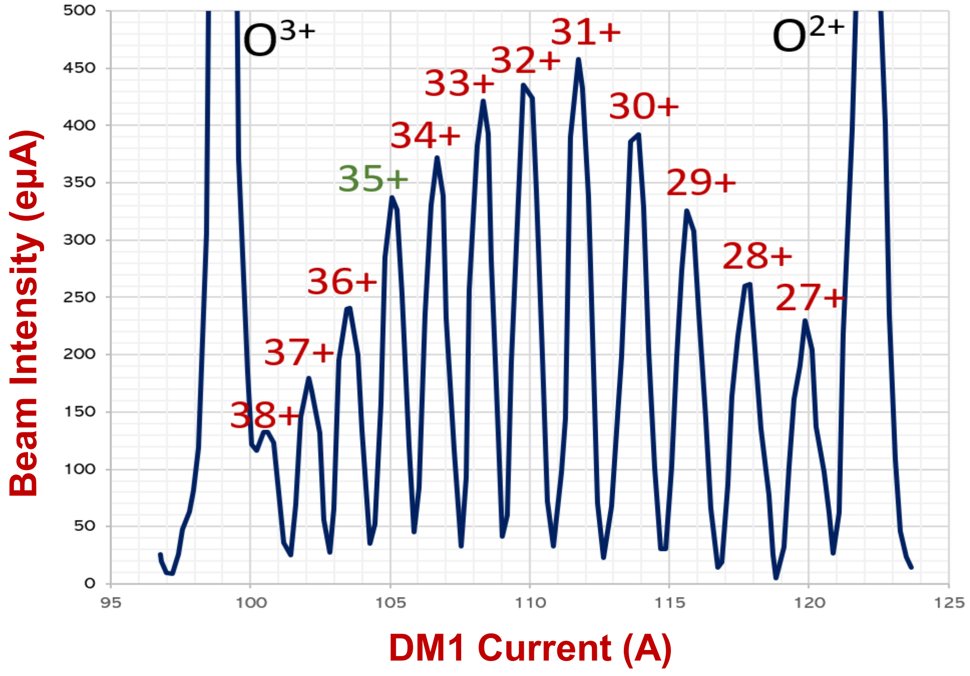


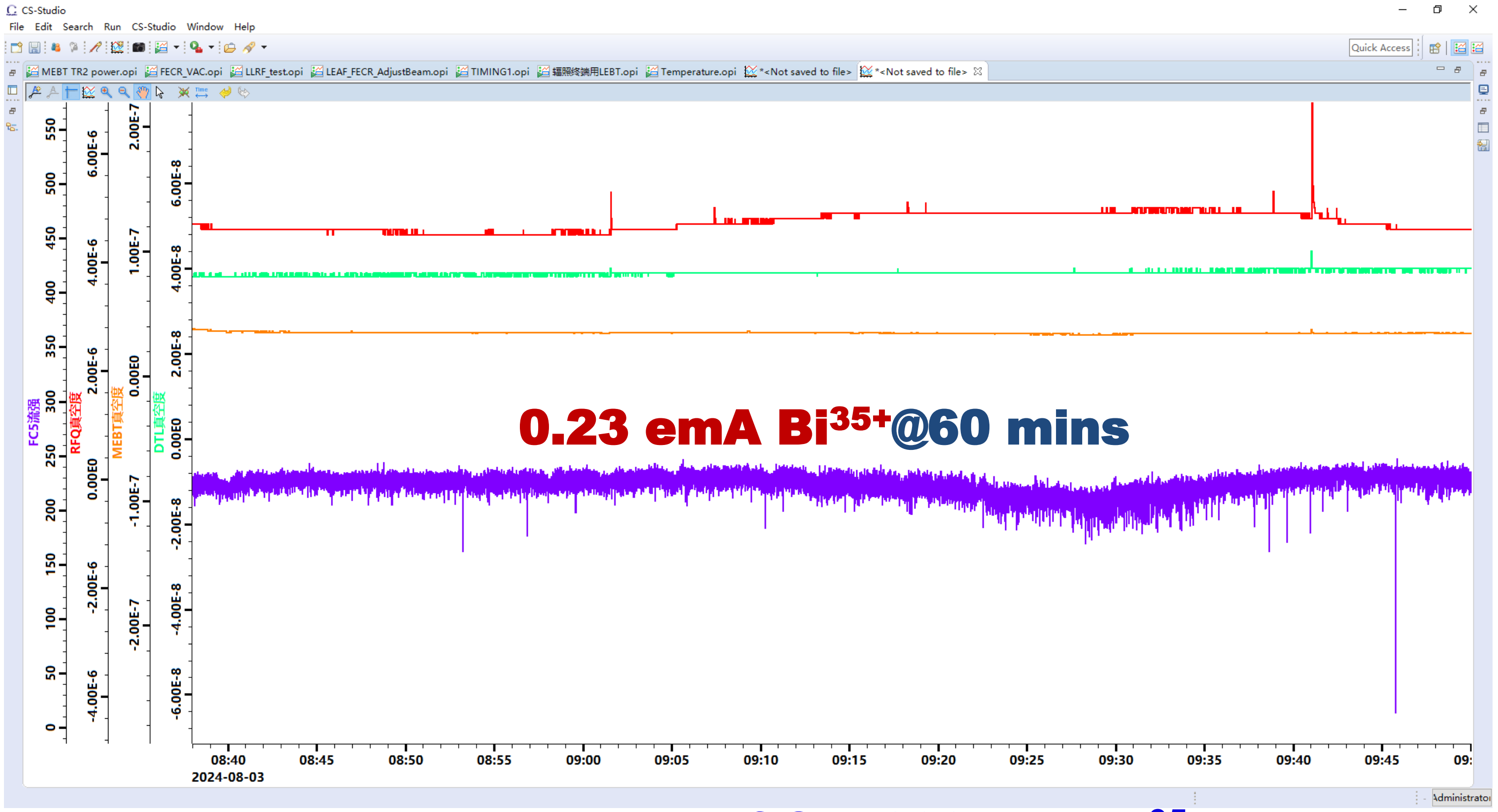
FECR: 1.6 emA O^{6+}



1 hour stability demonstration of CW 1.0 emA O^{6+} beam accelerated by the LEAF-RFQ. Record intensity for HI RFQ

FECR: Joint Test at LEAF and the First Results





FECR: 350 eμA $^{209}Bi^{35+}$
6.5 kW 45GHz+5.5 kW 28GHz

1 hour stability demonstration of CW 230 eμA Bi^{35+} beam accelerated by the LEAF-RFQ. Record Bi intensity for HI RFQ

Surprising and not understandable results: The magnetic field B_z peak 3.9 T, B_r at the wall 2.3 T, 28 GHz B field. But 45 GHz power played an significant role for rasing the beam intensity? 45 GHz power was higher than 28 GHz power

Summary

- New techniques are the engines to extract more intense HCI beams with ECRISs
- Still need fundamental study and understanding towards the behavior of the magnetic field confined ECR plasma, especially for high field, high rf frequency
- The first version of FECR completed and produced beams
  - High power 45 GHz + 28 GHz ECR plasma at lower B field reliable, the first results.
  - FECR produced 350 eμA Bi^{35+} with hybrid magnet and 45+28 GHz
  - Two month beam commissioning results and phenomena interesting and need to be studied in detail.
  - LEAF with FECR delivered 2 weeks Xe and O beams for users demonstrating nice reliability
  - Full Nb_3Sn FECR under development

Thanks for your attention and comments