FECR Ion Source Development and Challenges

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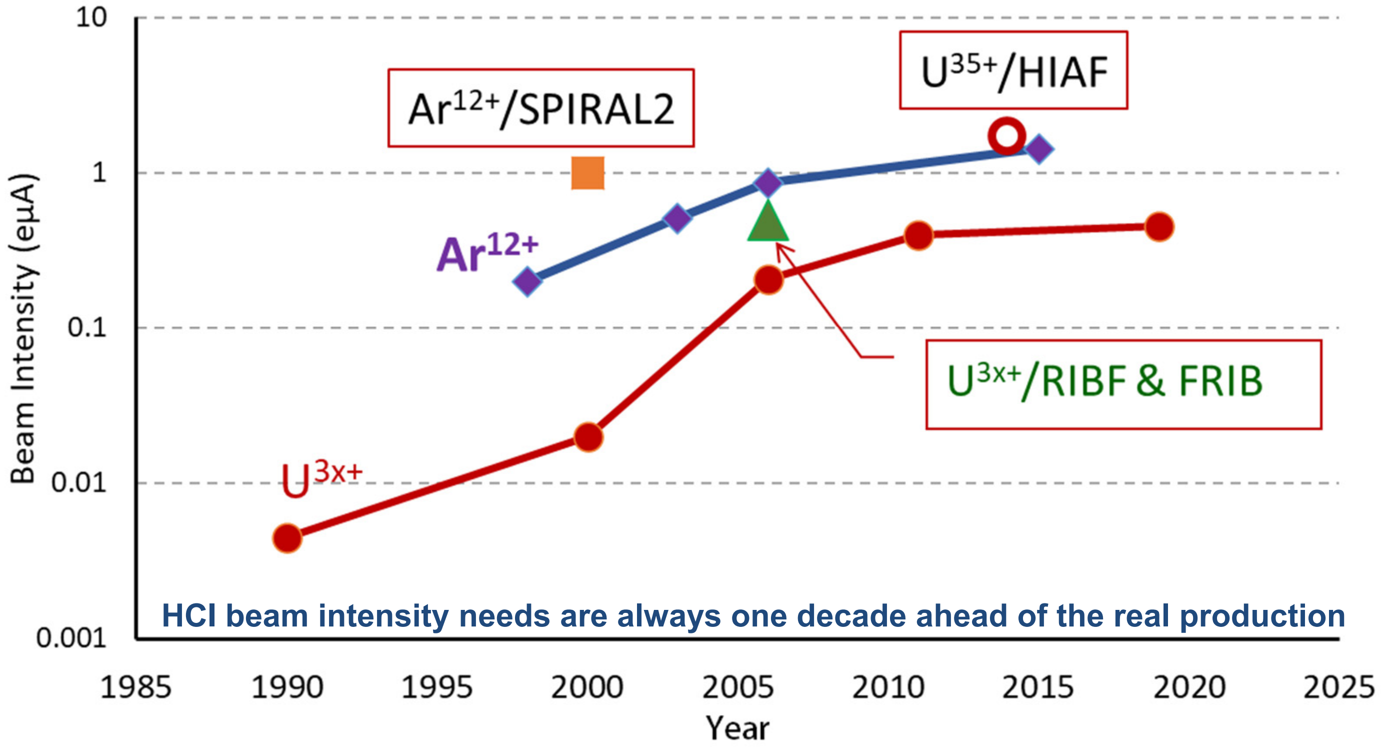
ECRIS'20, Sept. 28~30, 2020, Virtual Conference, hosted by MSU

Outline

- Intense HCI Beam Needs
- Status of Intense HCI Beam Production
- Perspectives of Next Generation ECRIS
- Status of FECR Development
  - 45 GHz Nb_3Sn Magnet Development
  - Conventional Ion Source Physics & Technologies
- Summary

Intense HCI Beam Needs by Accelerators

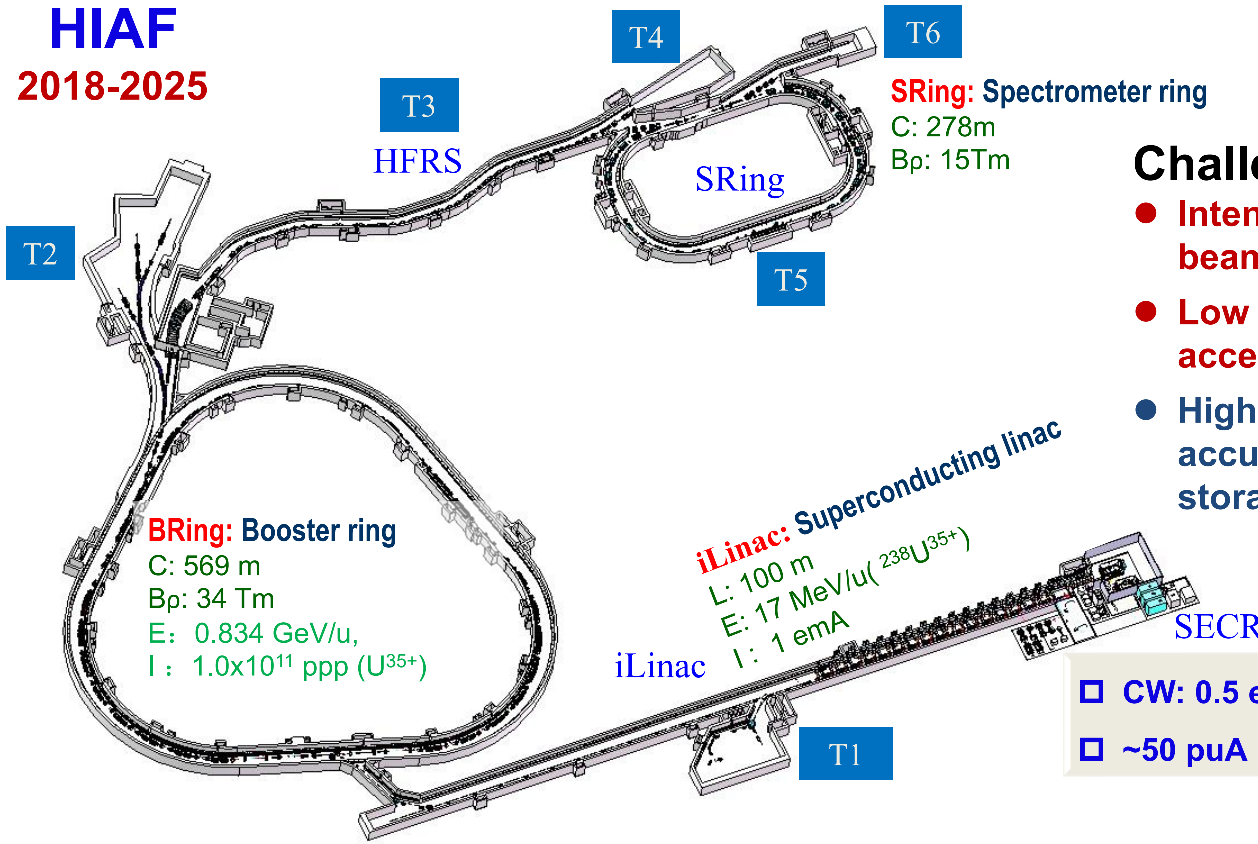
Ar^{12+} and U^{3x+} beam intensities evolution over years



Intense HCI Beam Needs of HIAF

HIAF

2018-2025

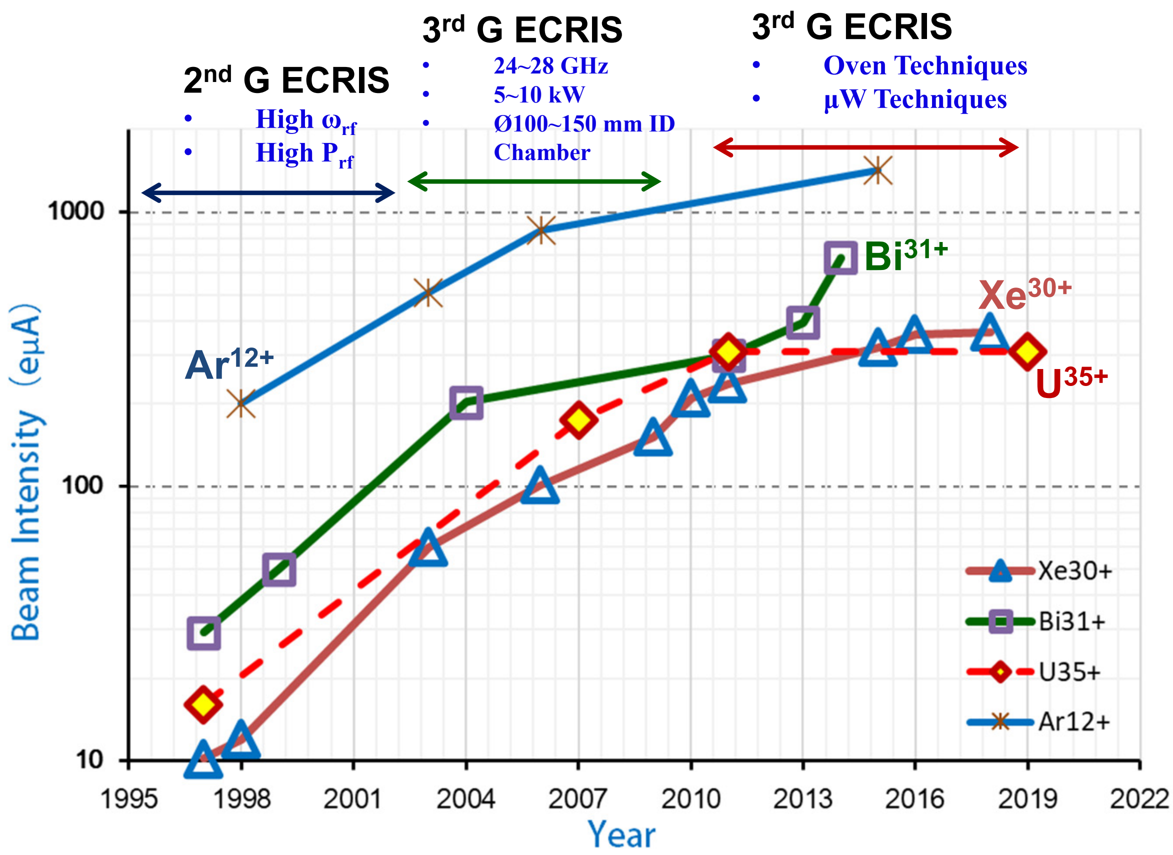


Challenges

- **Intense highly charged heavy ion beams production**
- **Low β intense heavy ion beam acceleration**
- **High intensity heavy ion beam accumulation, acceleration in storage ring**

- ☐ **CW: 0.5 emA U^{46+}**
- ☐ **~50 puA U^{35+}/ ≤5 Hz@0.2~2 ms**

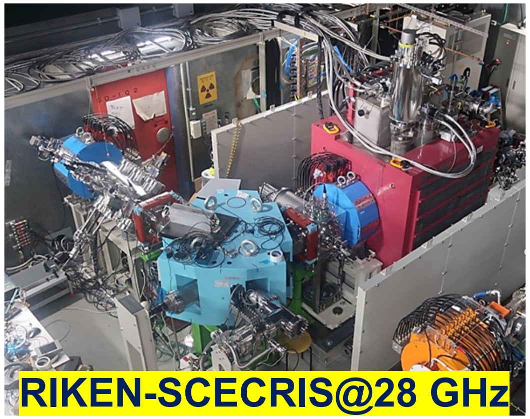
Status of Intense HCI Beam Production

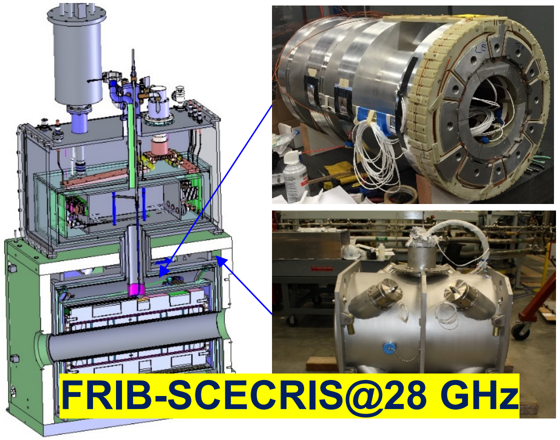


Status of Intense HCI Beam Production


VENUS@28 GHz

SECRAL-II@28 GHz


RIKEN-SCECRIS@28 GHz


FRIB-SCECRIS@28 GHz

Typical 3rd G. ECRISs for intense U^{3x+} beams

- U^{3x+}: 10~15 pμA
- 1/4~1/5 of HIAF needs

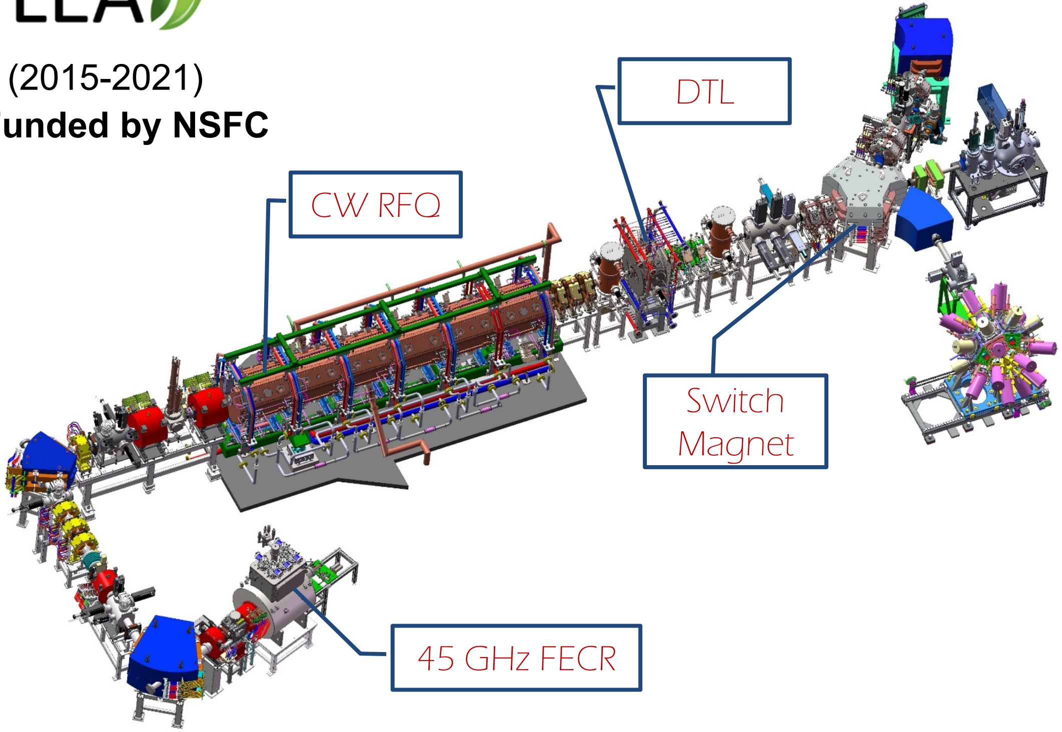
4th G. ECRIS

- U^{3x+}: 30~50 pμA
- U^{4x+}: 5~10 pμA

Perspectives of Next Generation ECRIS

LEA

(2015-2021)
Funded by NSFC



Significance:

Ultimate conditions for physics with low energy HCI beams:

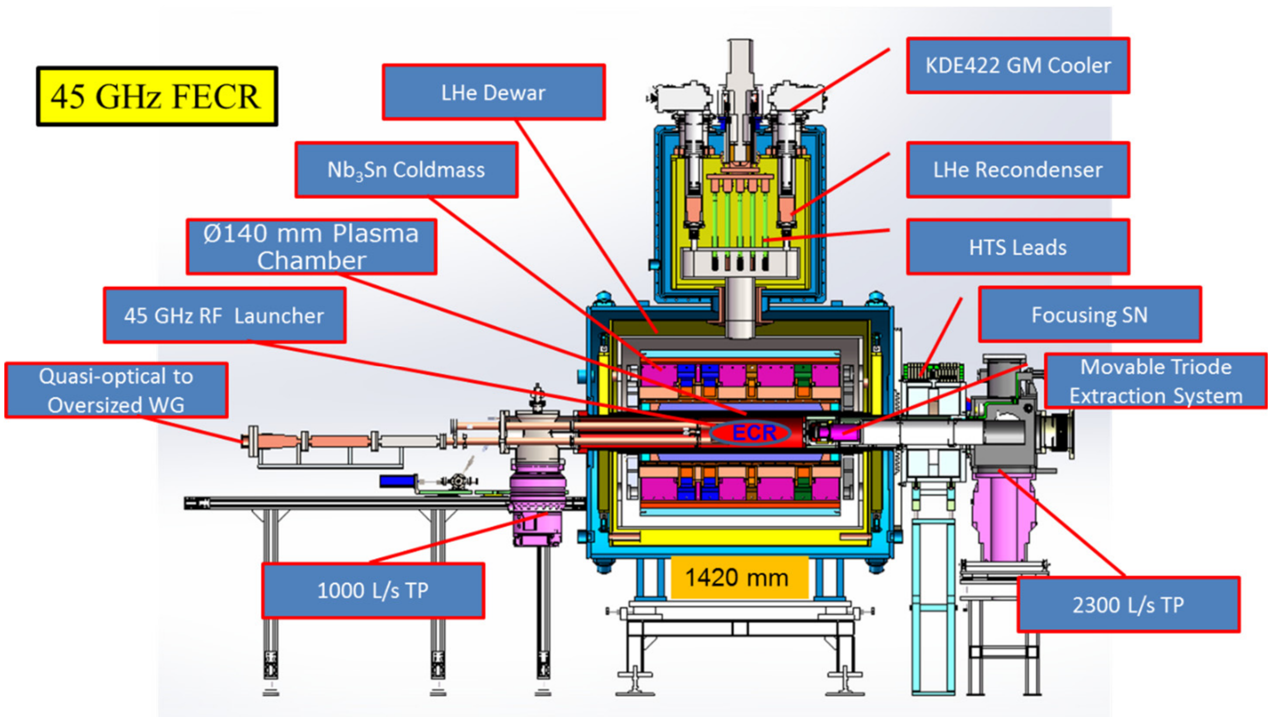
- Material irradiation research
- Highly charged atomic physics
- Low energy nuclear physics

Prototyping for HIAF:

- 45 GHz ECR Ion Source
- 81.25 MHz CW 4-vane RFQ
- Intense heavy ion beam production, transmission and acceleration

Perspectives of Next Generation ECRIS

FECR (First 4th generation ECR ion source)



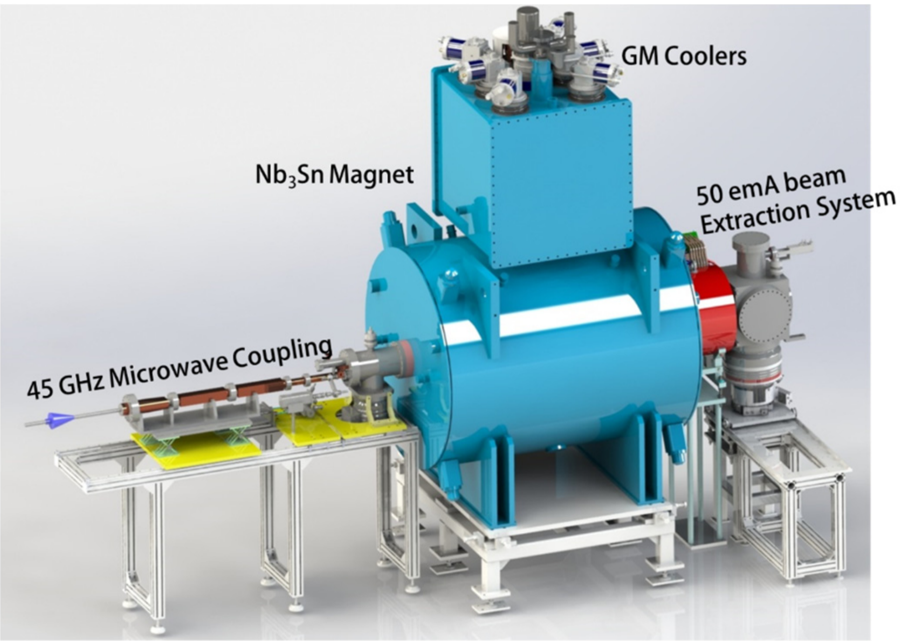
Specs. of FECR

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/mm²@12T
Cooling Capacity@4.2 K	W	>10.0

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

Perspectives of Next Generation ECRIS: Challenges

FECR (First 4th Generation ECR ion source)



- Reliable SC-magnet for 45 GHz plasma confinement
- Effective coupling to the plasma of 20 kW/45 GHz microwave power
- 20 kW microwave heated plasma operation reliability and stability: Plasma chamber and dynamic stability
- Strong bremsstrahlung radiation problems
  - Heat sink in cryostat
  - HV insulator degradation
  - Risk of coil epoxy degradation
- Intense high charge state ion beam (20-40 emA) extraction, transport and beam quality control
- Intense metallic beam production, especially of refractory materials: U, W, Ta, Mo, Ti, Ni…

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

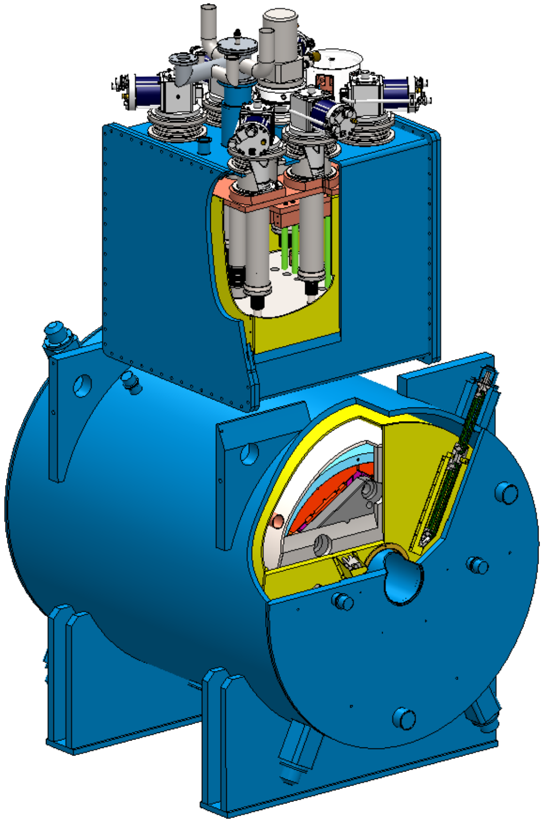
Status of FECR Development: Magnet

Cold mass

- High quality reliable Nb_3Sn sextupole coil production
- Precise and efficient pretension and clamping structure
- Fast quench detection and active protection

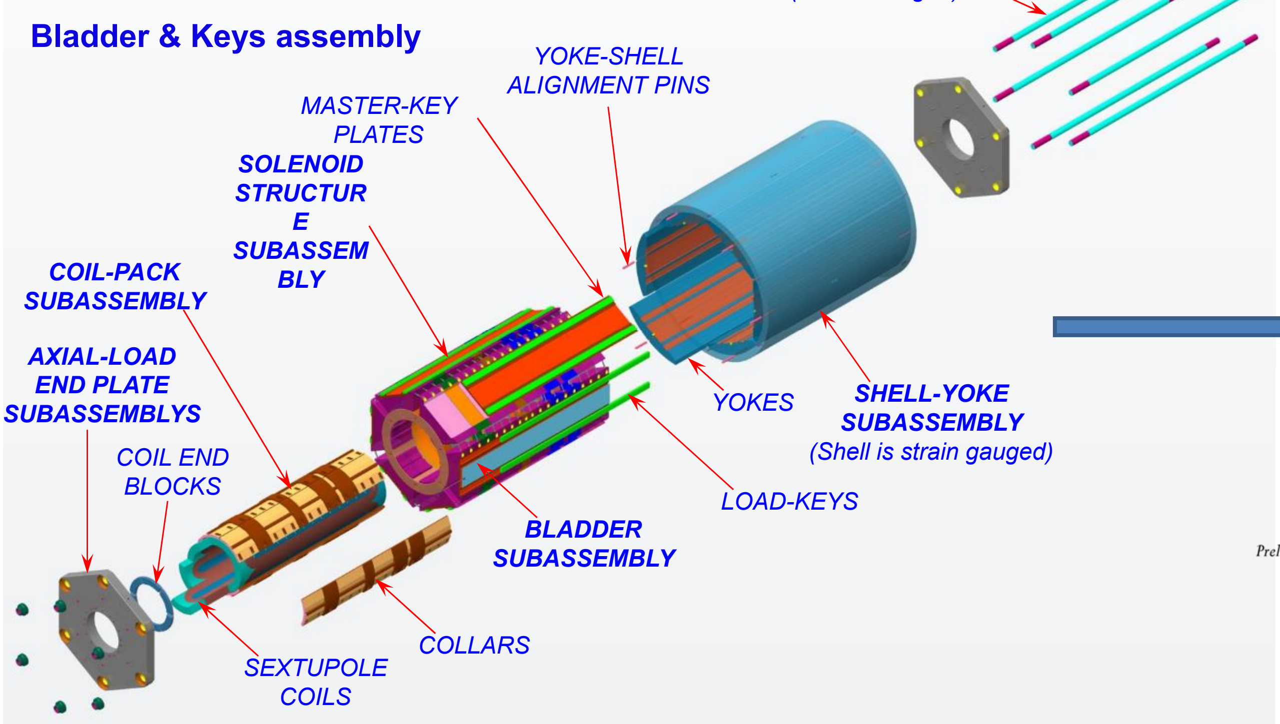
Cryostat

- Safe suspension system for operation and transport of 3.5 tons cold mass
- Precise installation and alignment of cold mass
- High voltage safe instrumentation
- Sufficient dynamic cooling power @4.2 K

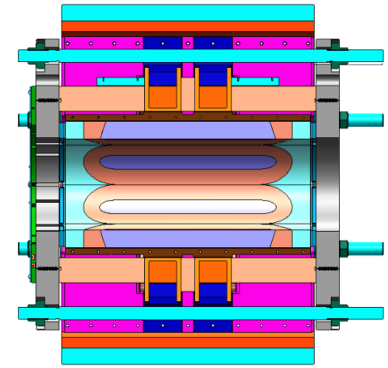


Status of FECR Development : Nb_3Sn magnet

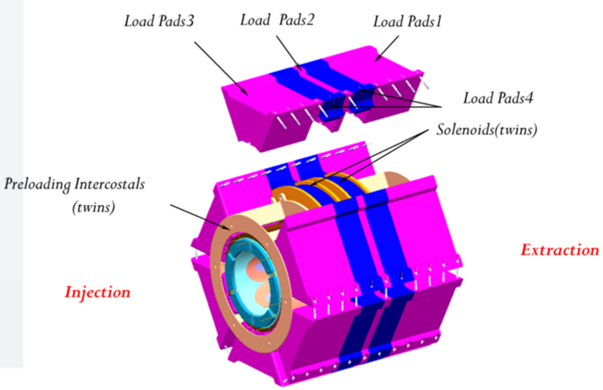
The coldmass mechanical structure was designed by collaboration with ATAP magnet group at LBNL (2015~2016)



M. Juchno, et al., IEEE Trans. Appl. Supercond., vol. 28, no. 3, Apr. 2018, Art. no. 4602806

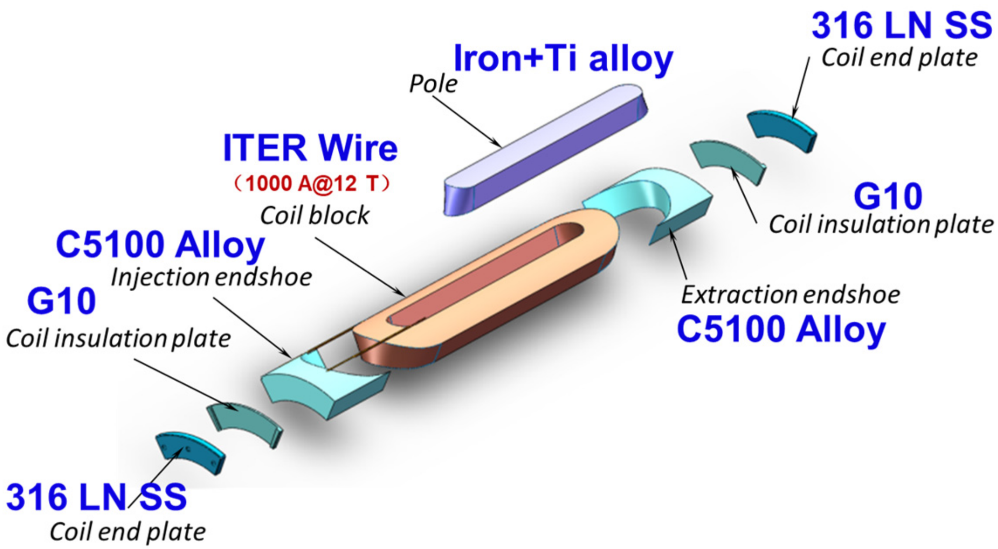


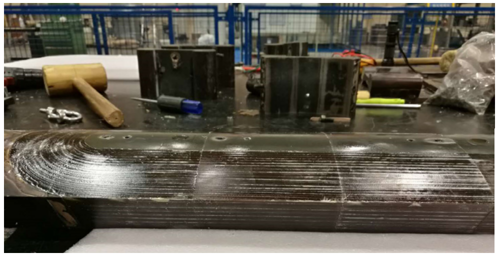
½ length prototype



R&D: 2017~now

Status of FECR Development : Nb_3Sn Coil

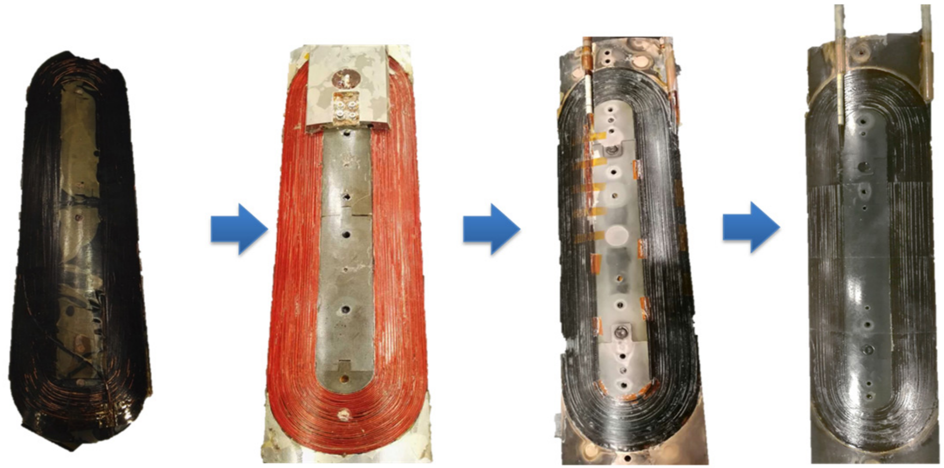


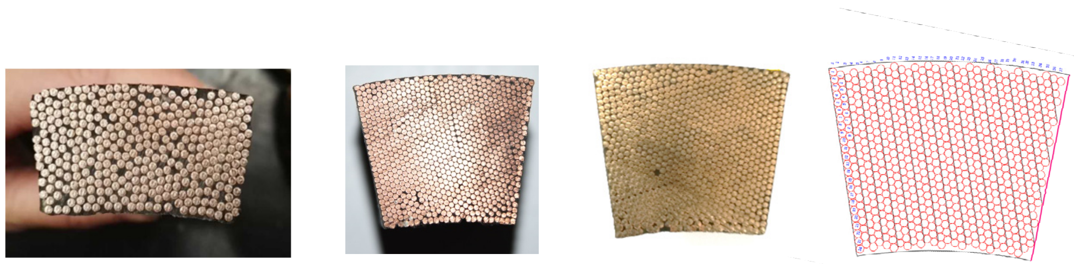


Prepared Coil

- Mechanical mapping
- Detailed Q/A

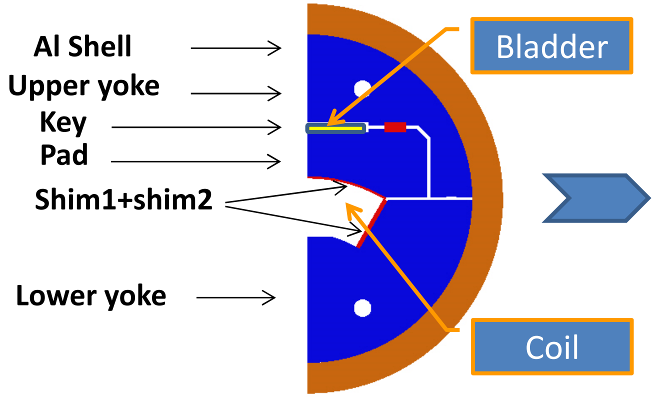
Status of FECR Development : Nb_3Sn Coil

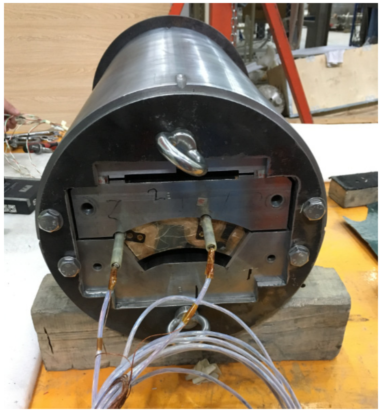


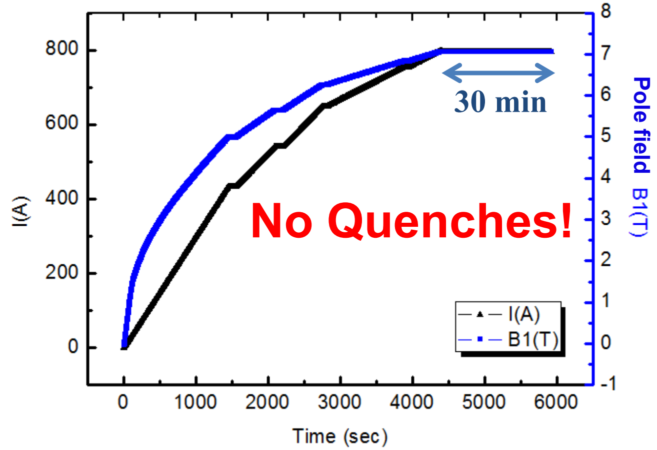


2016.12 **Journey of coil R&D** **2018.12**

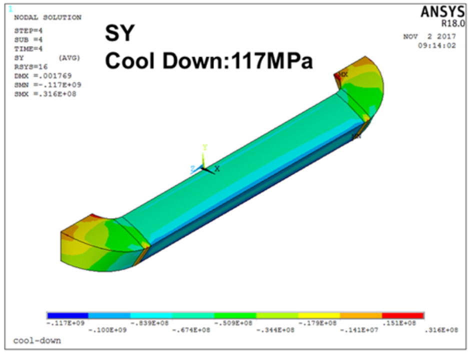
Status of FECR Development : Nb_3Sn Coil

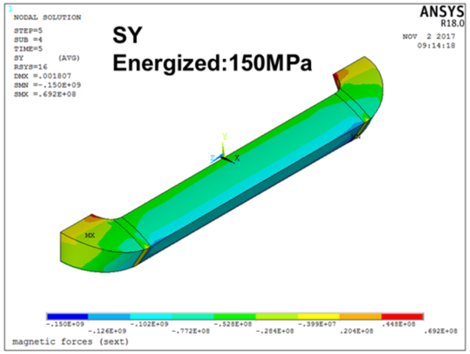


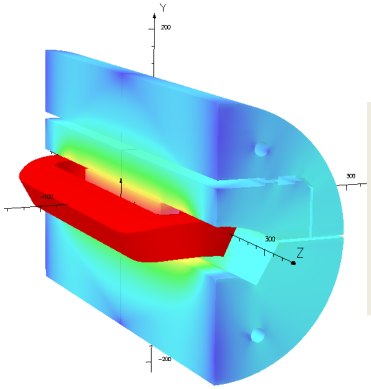




A Mirror Structure for sextupole cold test



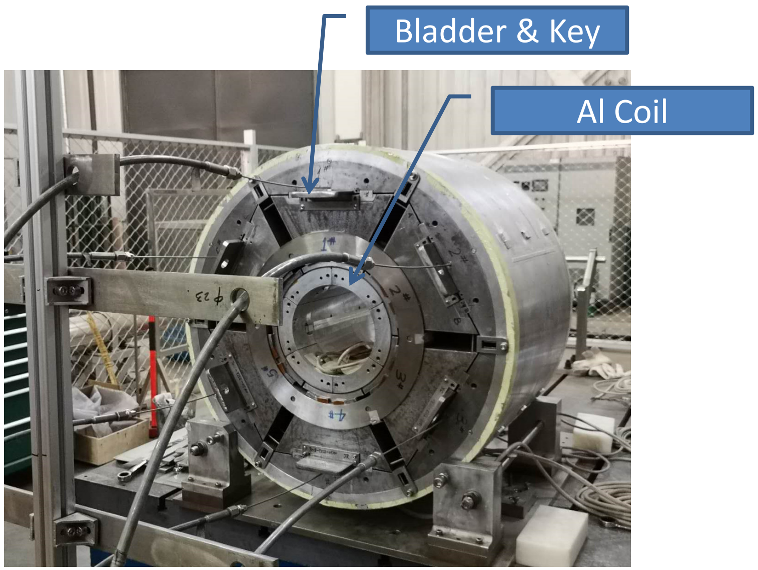




- Highest field in superconductor: 10.4 T
- LF : 80% of short sample

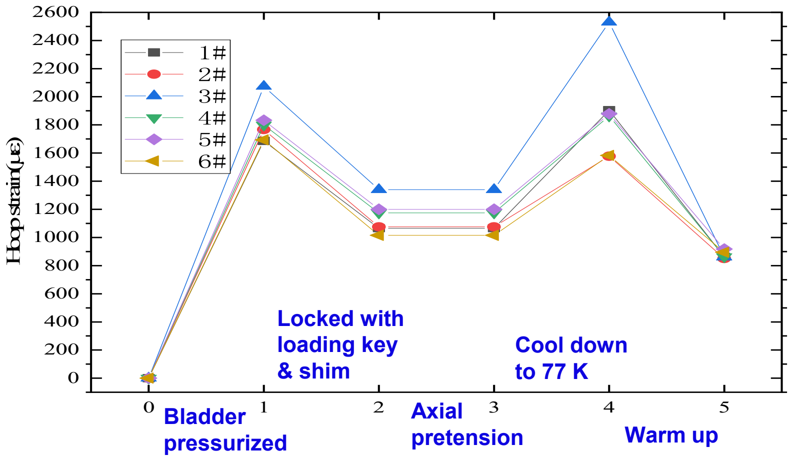
Yuquan Chen, et al., IEEE Trans. Appl. Supercond., vol. 31, no. 1, Jan. 2021, Art. no. 4100105

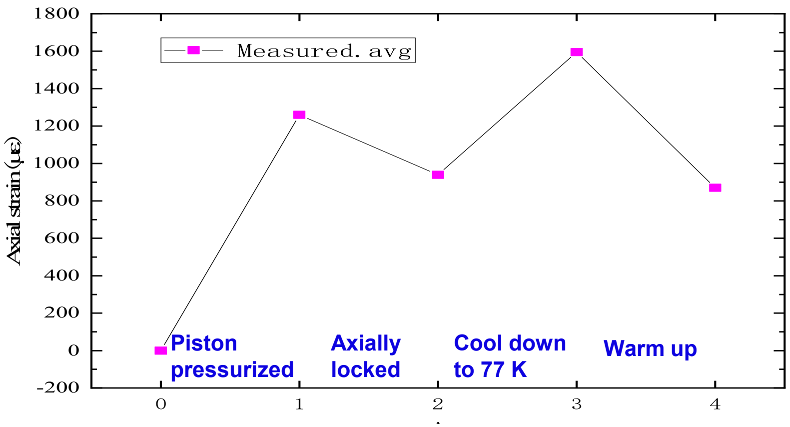
Status of FECR Development : structure



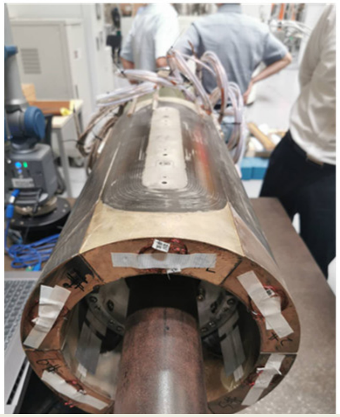
½ prototype with Al dummy coil mockup

Whole process Strain- Guaged

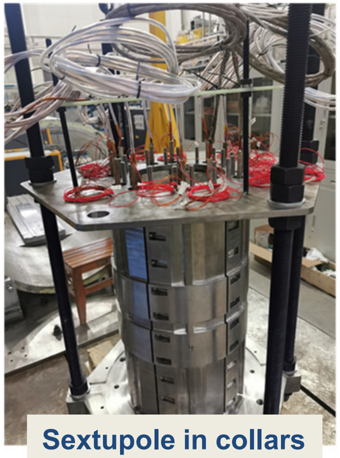




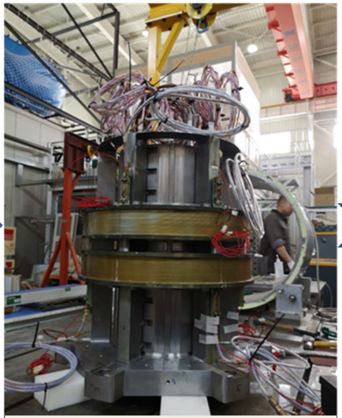
Status of FECR Development : ½ coldmass



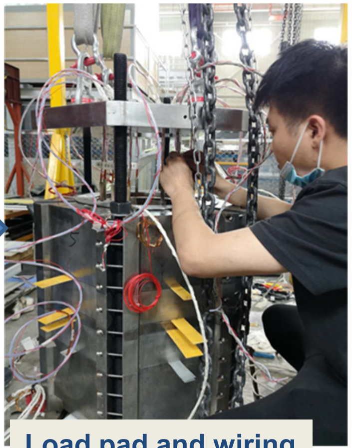
Sextupole pre-assembly



Sextupole in collars



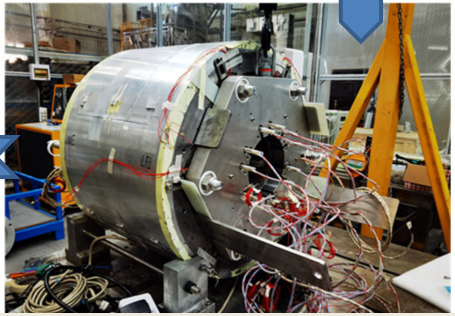
Sextupole & solenoids



Load pad and wiring

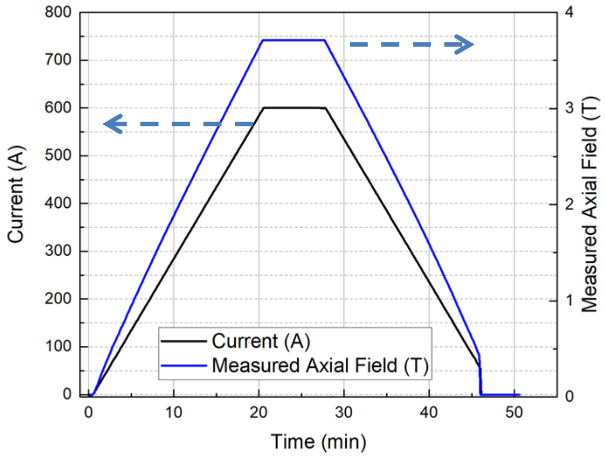
Instrumentation in Pizzabox

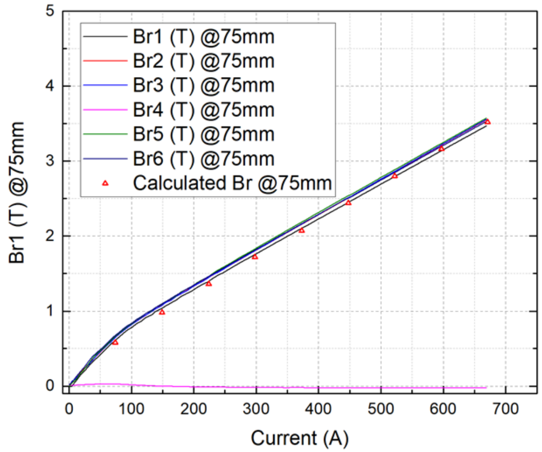
Axial preload with pistons



Radial preload with bladder & keys

Status of FECR Development : Cold Test



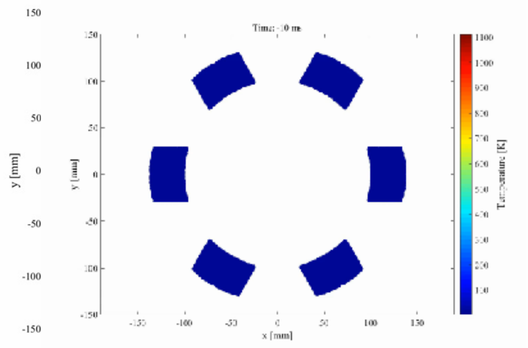


- **Solenoid only energized to 100% design current 600 A**
- **No quenches!**
- **Field consistent with calculated**

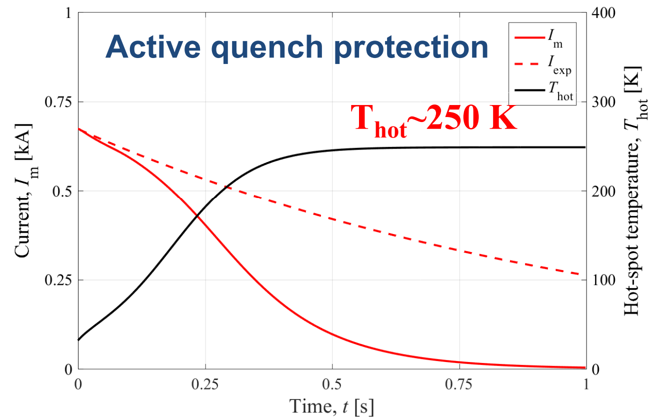
- **Sextupole only energized to 90% design current= 671 A (power supply malfunction)**
- **No quenches!**
- **Field consistent with calculated**

Status of FECR Development : Quench protection

Sextupole passive quench protection

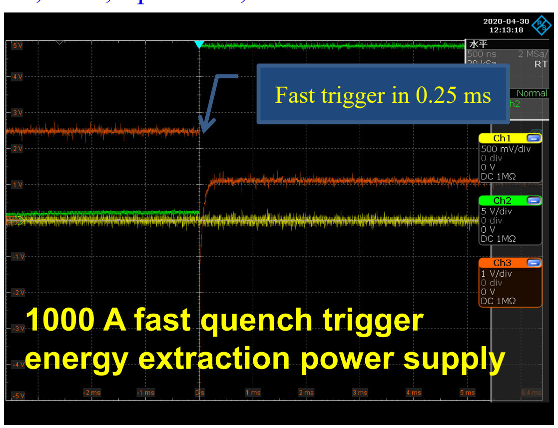


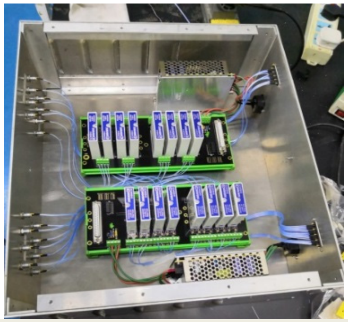
E. Ravaioli, et al., IEEE Trans. Appl. Supercond., vol. 28, no. 3, April 2018, Art. no. 4700906



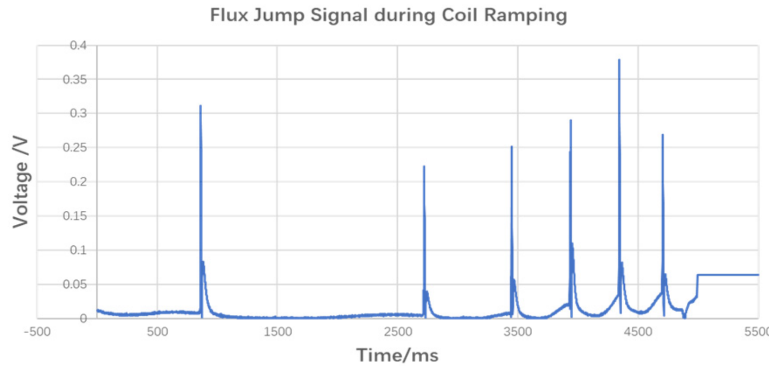
I_0=673 A
R_{EE}=2.4 Ω
U_{EE}=1650 V

Fast quench detection, validation and triggering energy extraction in: 17 ms





Fast quench detection (~20 mV, 10 ms) system based on FPGA

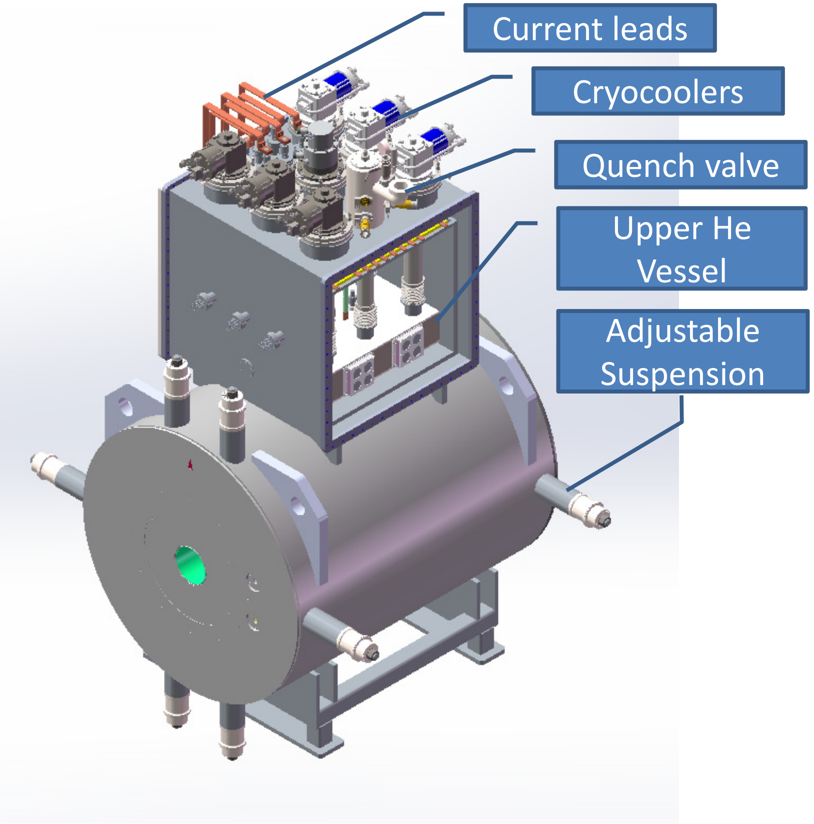


Flux jump adds additional difficulty to quench protection and coil safety

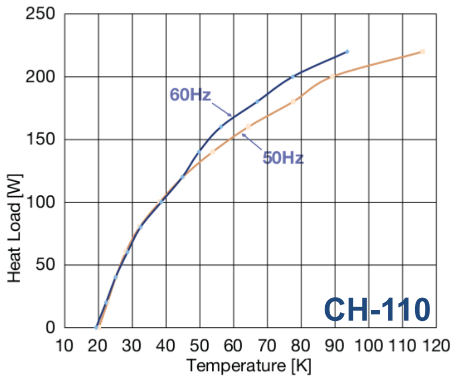
Status of FECR Development : Cryogenic system

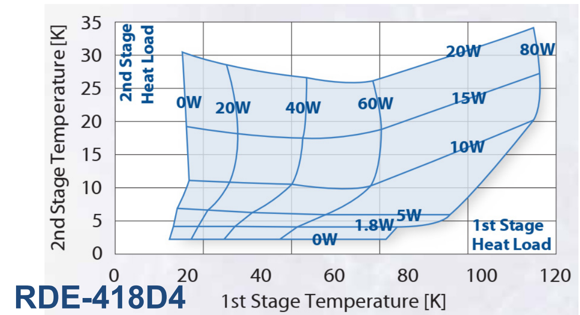
Key parameters of FECR cryostat

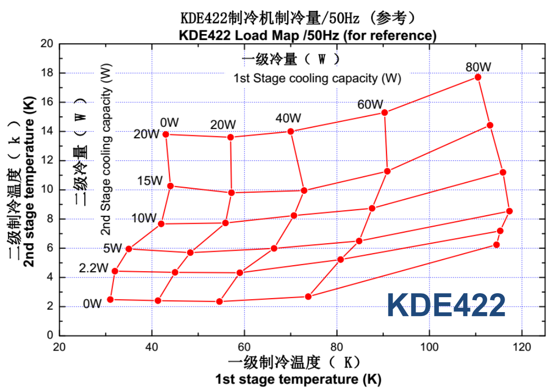
Parameters	Value	Note
Operation Temp. (K)	4.3 K	
Magnet Cooling	LHe bathing and "0" boiling-off	
Stored Energy (MJ)	~1.6	100% currents
Required heat load (W)	≥ 12	~2 W static at 100% currents
Warm Bore (mm)	Ø162	
LHe Volume (L)	~330	
Cryocoolers	6 two-stage + 1 single stage coolers	Cold service enabled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



Status of FECR Development : Cryogenic system

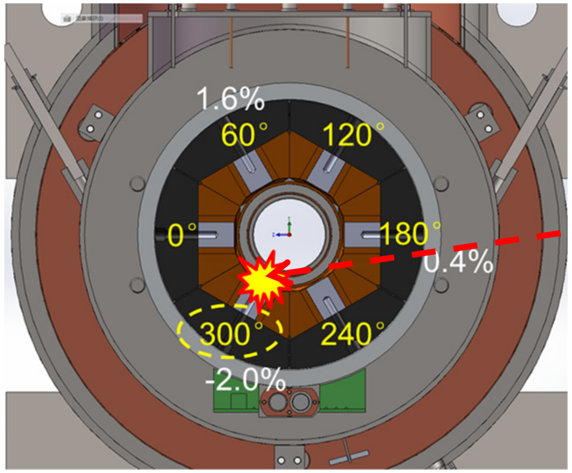


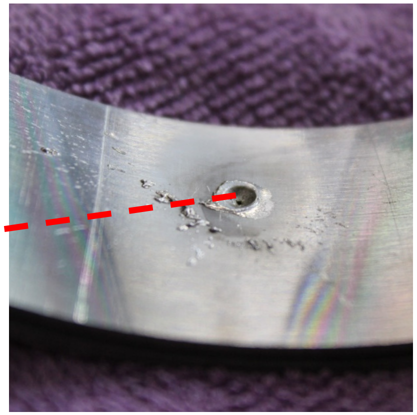


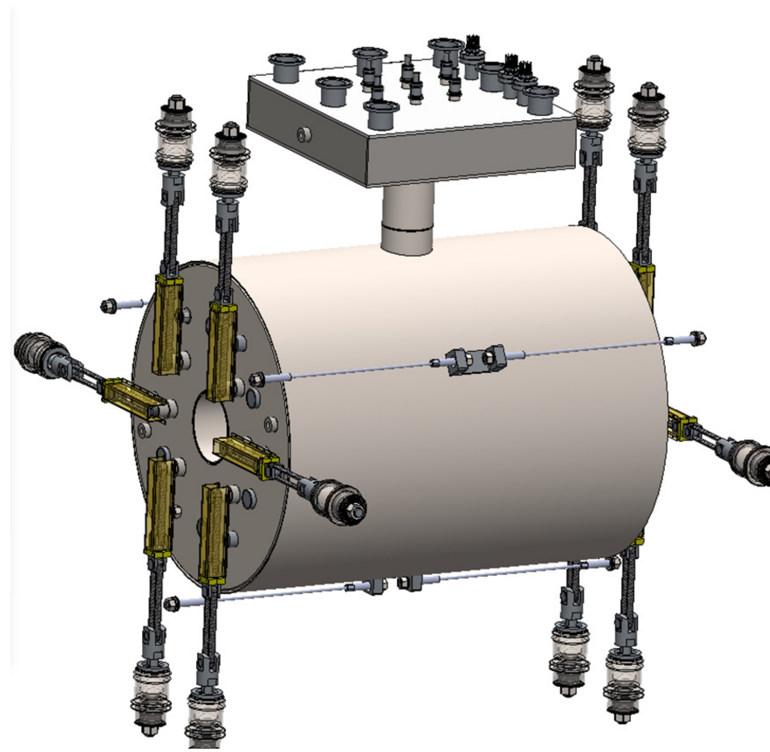


Model	1st Stage	2nd Stage
CH-110	130 W@50 K	N/A
KDE422	~20 W@50 K	≥2.2 W@4.2 K
RDE-418D4	~42 W@50 K	≥1.8 W@4.2 K
Total	~316 W@50 K	≥12 W@4.2 K

Status of FECR Development : Cryogenic system







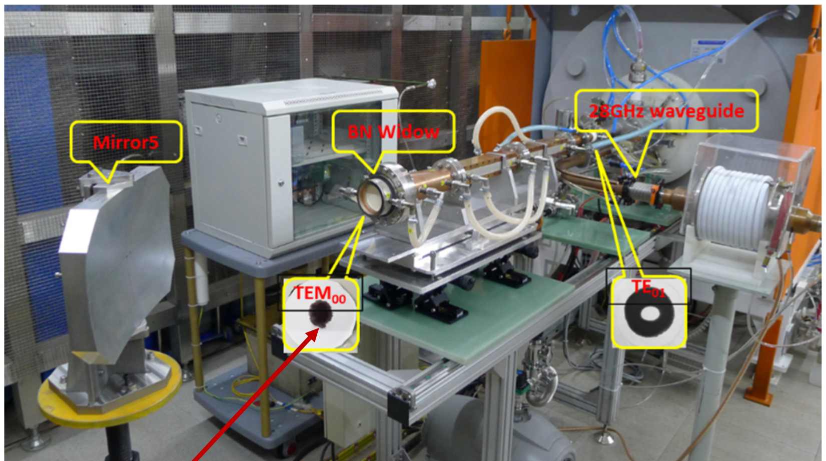
- Localized heat sink strongly related to field homogeneity
- Field homogeneity:
  - <1% → concentricity Δr< 0.4 mm
  - <0.5% → concentricity Δr< 0.2 mm

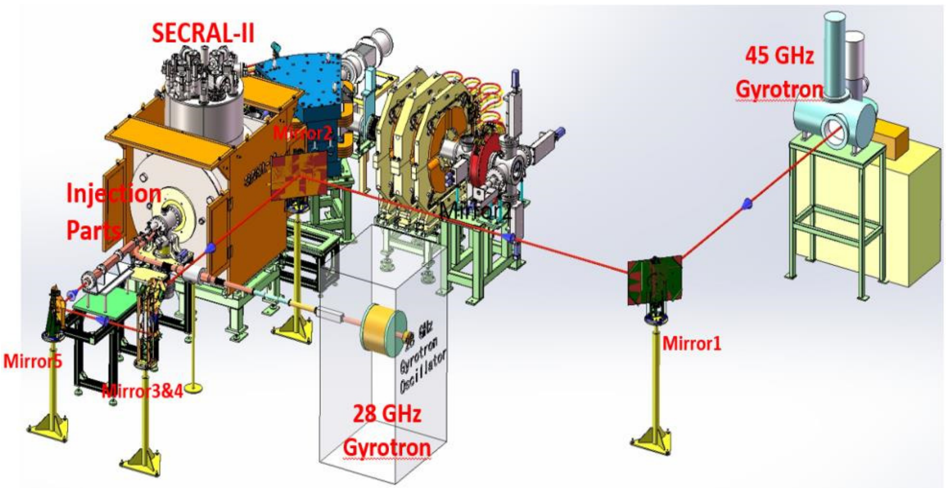
Status of FECR Development : Conventional Parts

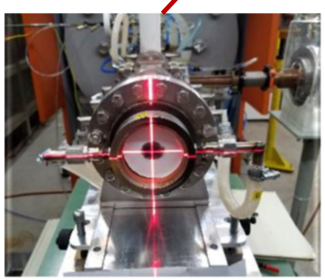
Parameters	3rd G. ECRIS	45 GHz FECR	Increased by
Microwave Power (kW)	~10	>20	>2
Ts (keV)	50~60	80~100	>1.5
Microwave Length (mm)	~10	~6	/
Max. Plasma Density (cm^{-3})	~$1X10^{13}$	~$2.6X10^{13}$	>2.6
Total Beam Available (mA)	10~20	26~52	>2.6

Status of FECR Development : µW coupling

45 GHz Microwave System for FECR



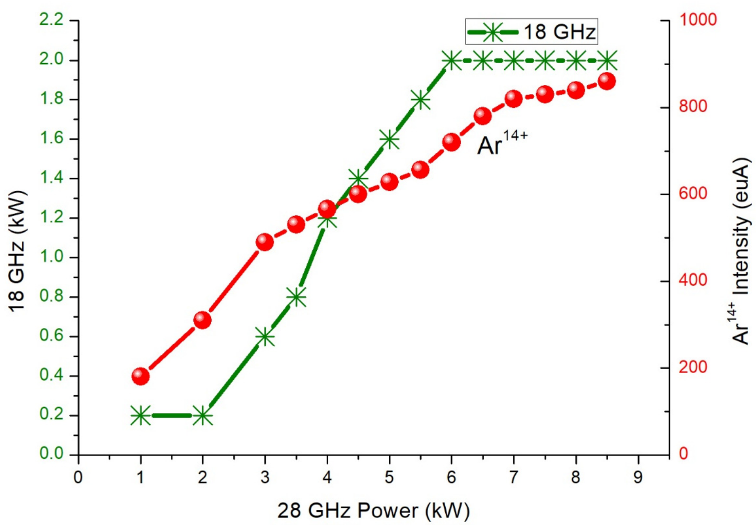


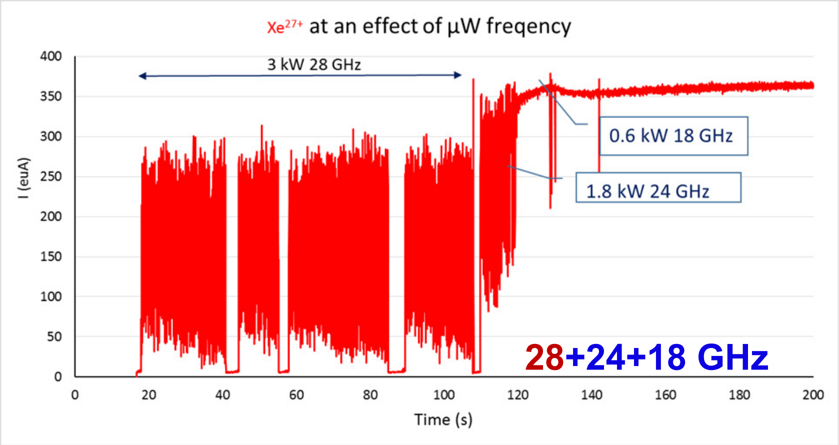


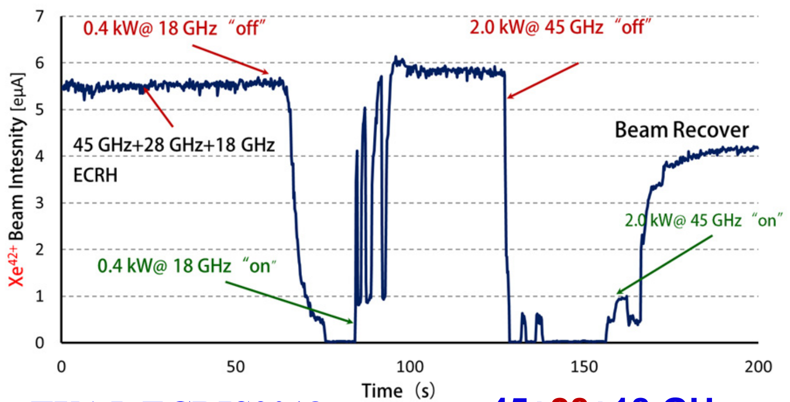
- 45 GHz/20 kW microwave transmission system based on Quasi-optical design
- First 45 GHz ECR plasma with SECRAL-II ion source
- Efficient transmission and coupling demonstrated

J. W. Guo, et al., AIP Conference Proceedings **2011**, 090001 (2018)

Status of FECR Development : μW coupling







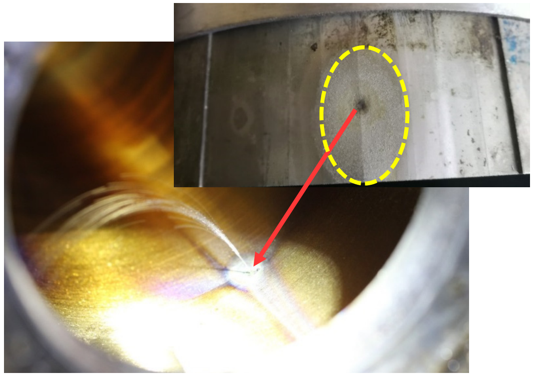
45+28+18 GHz

About multi-frequency ECRH

- Secondary or multi-frequency ECRH is essential
- Optimum frequencies to suppress kinetic instabilities?
- Needed power? (4~5 kW)

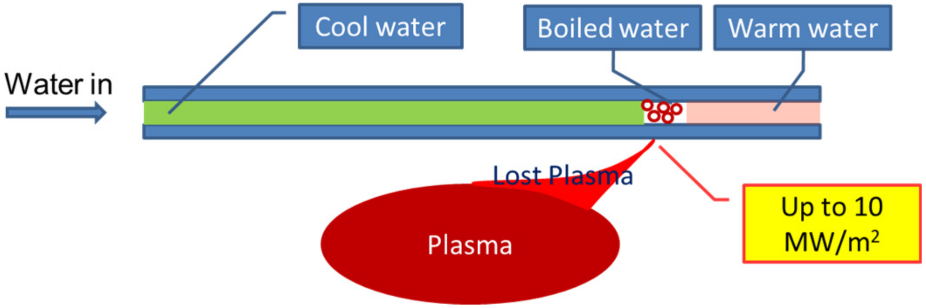
L. Sun, TUA5, ECRIS2018

Status of FECR Development : Plasma Chamber

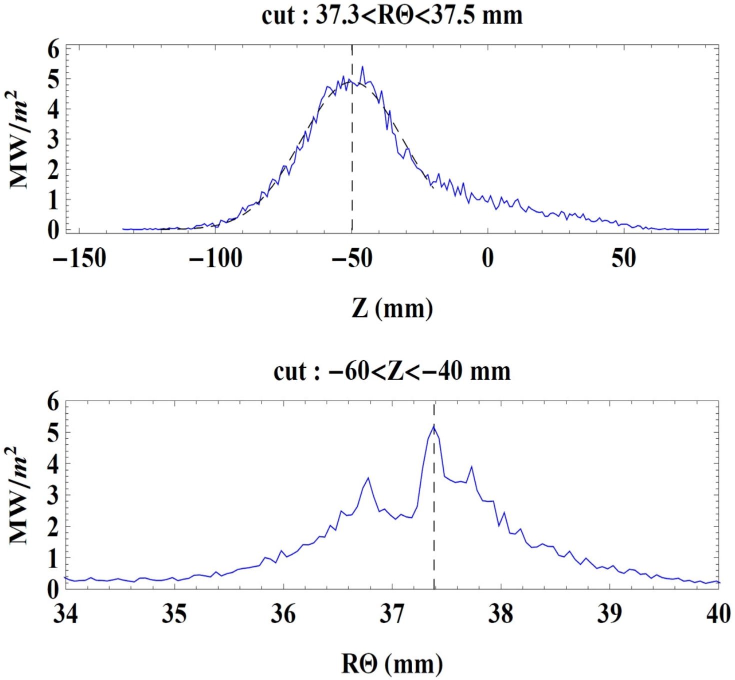


Chamber burnt with SECRAL-II
Typically：>7 kW

Chamber burnt with VENUS



LCW pressure of 6 kg/cm^2, water BP =150~160℃



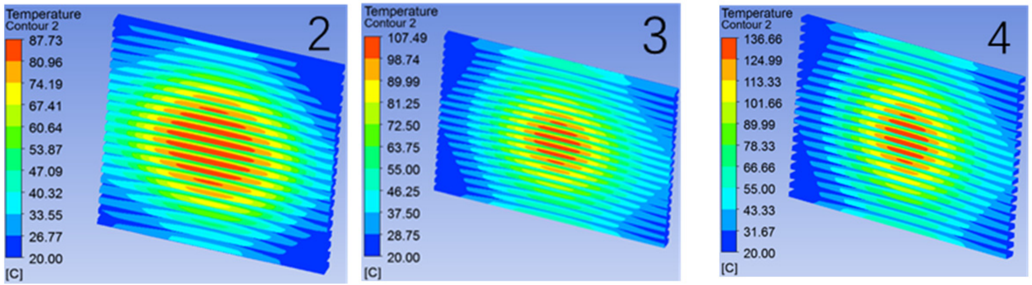
1 kW μW~1.25 MW/m^2 heat sink

T. Thuillier et al., Review of Scientific Instruments **87**, 02A736 (2016)

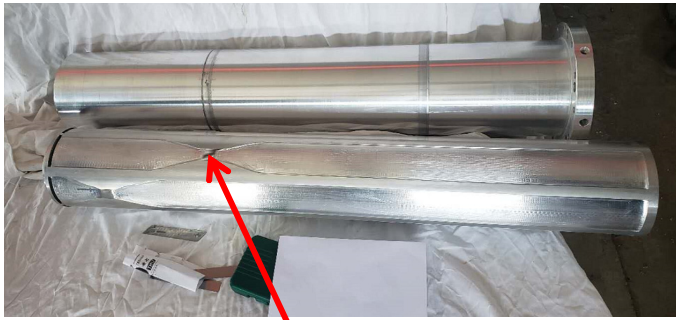
Status of FECR Development : Plasma Chamber

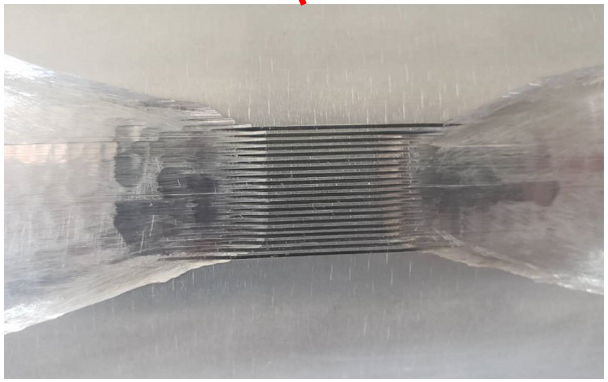
	P_{rf} (kW)	T_{max} on Al wall	T_{max} of water at the hottest point
1	10： averagely distributed	174℃	88℃
2	10： Gaussian distributed	159℃	78℃
3	15： Gaussian distributed	229℃	107℃
4	20： Gaussian distributed	299℃	137℃

Water flow rate: 7 L/min with micro-channel



Water temperature distribution at the chamber wall of weakest plasma confinement point

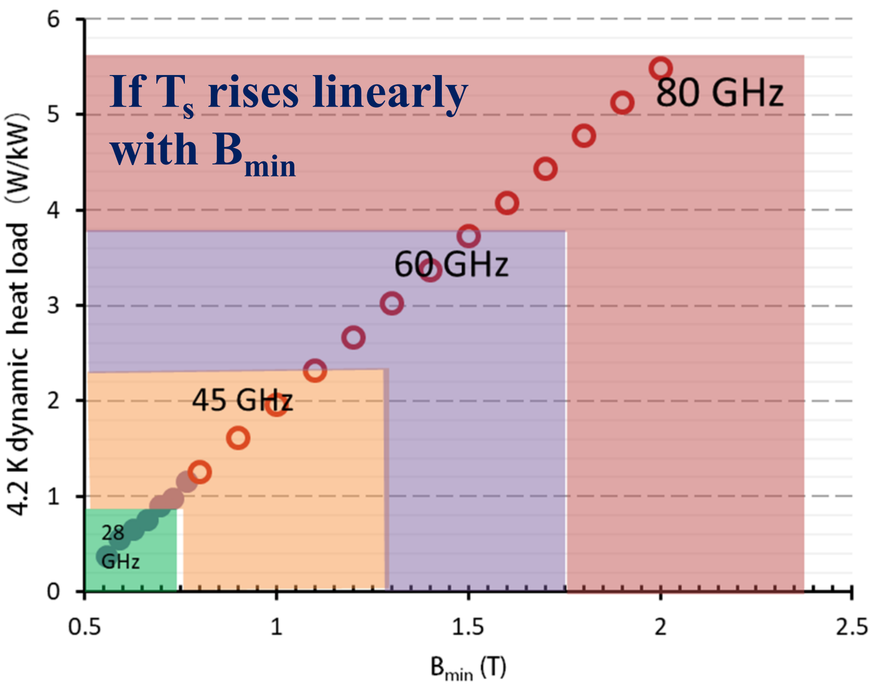


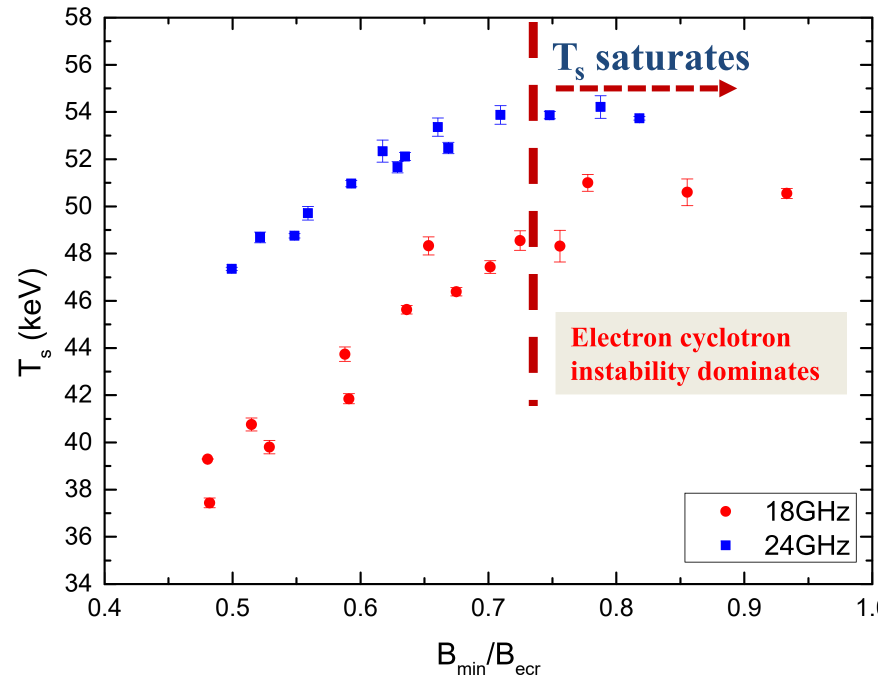


Micro-channel structure of 0.4 mm×20

Please see Guo's talk 1147 on Tuesday

Status of FECR Development : Bremsstrahlung





- ~0.6 W/kW@28 GHz, 1~2 W/kW@45 GHz?
- 20 kW@45 GHz ~ >20 W@4.2 K?

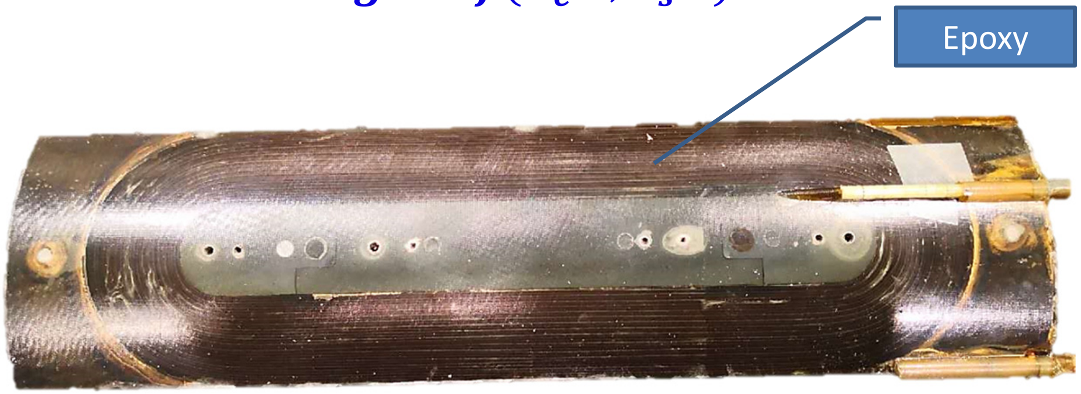
J. B Li, et al., Plasma Phys. Control. Fusion **62** (2020) 095015

Also see two Li's talks 1122 & 1082 on Tuesday & Wednesday

Status of FECR Development : Insulators

Yellowish PEEK insulator after high power operation (1.5 mm Ta shielding)

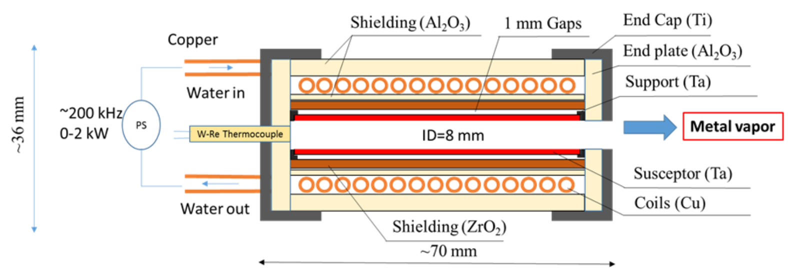
$$damage = f(n_e \uparrow, T_s \uparrow)$$

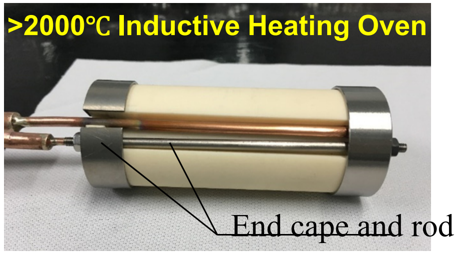


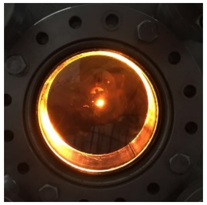
- ☐ Main insulator is replaceable
- ☐ What if Coil epoxy degrades after long time exposure, which literally needs high quality of insulation property (5 kV standard)

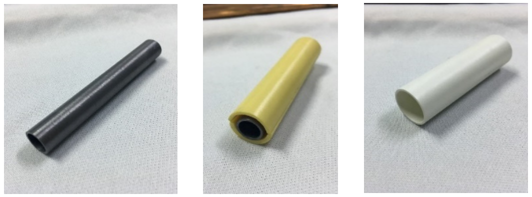
Status of FECR Development : Uranium Beam

Uranium beam production with HTO





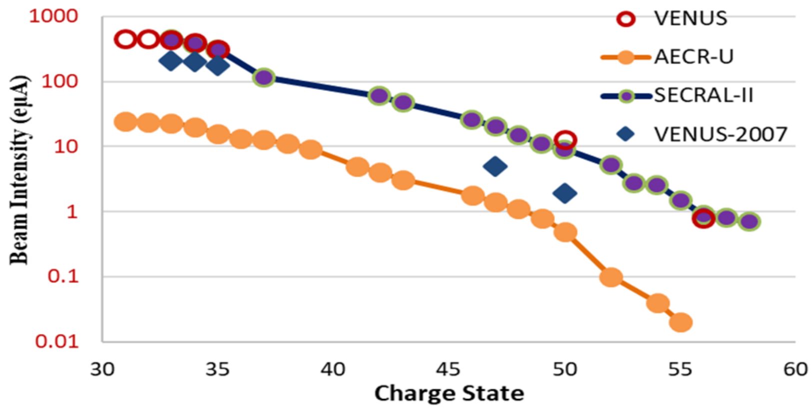


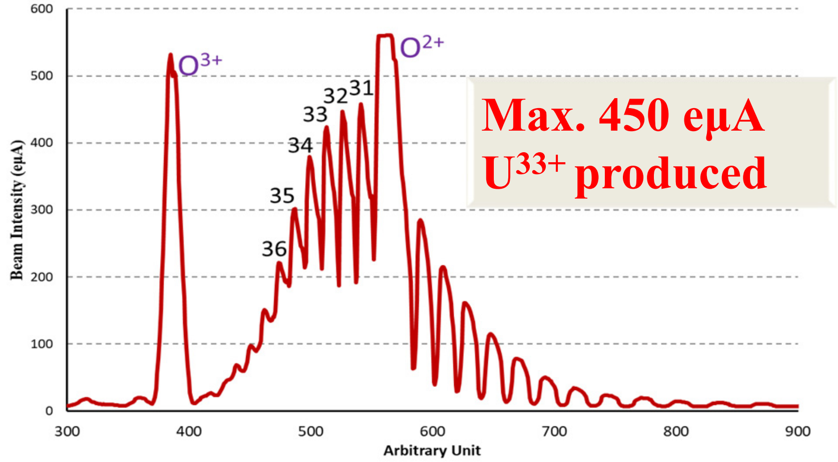


Crucible、Thermal Shield & Insulator

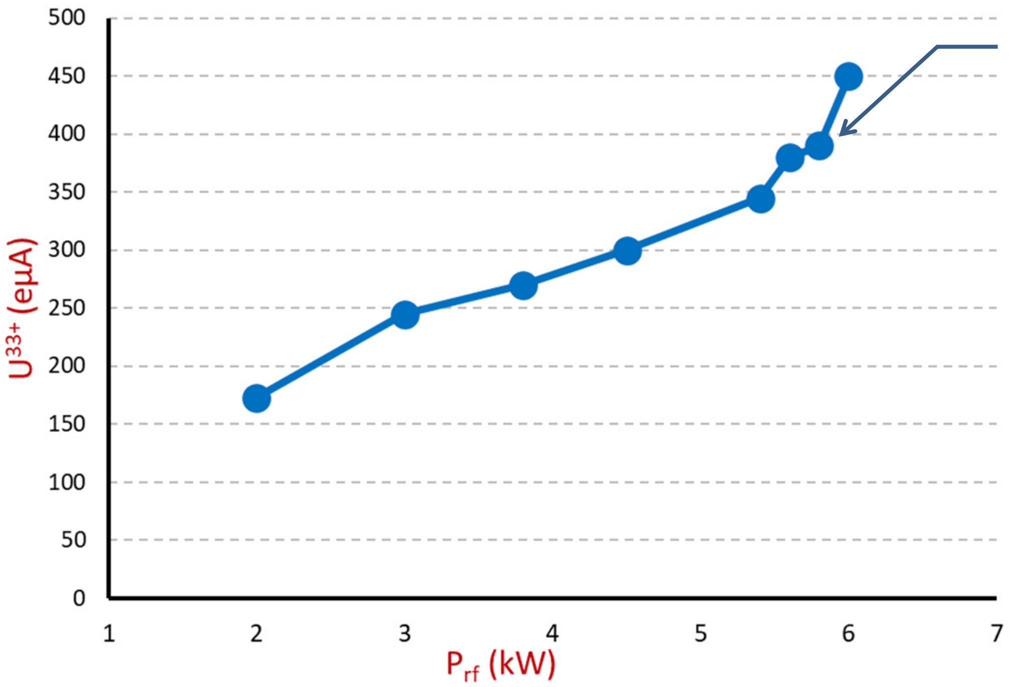
Off-line Test

Wang Lu @ talk 1155, on Tuesday

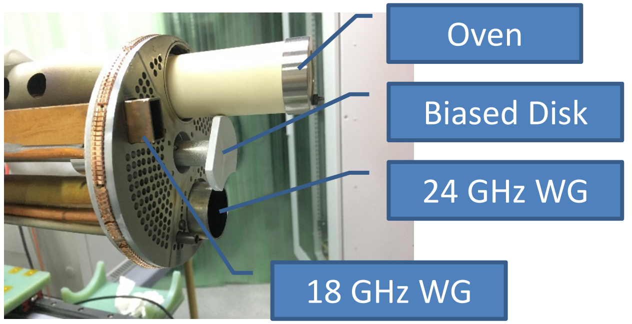




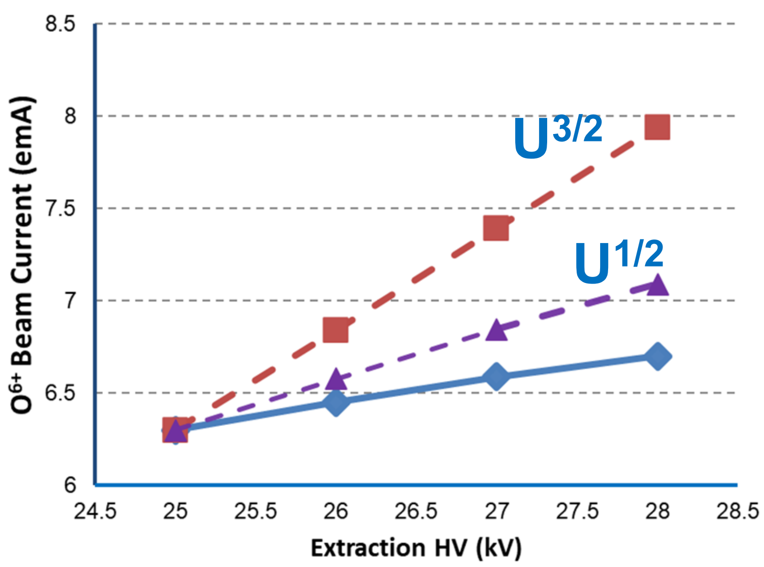
Status of FECR Development : Uranium Beam

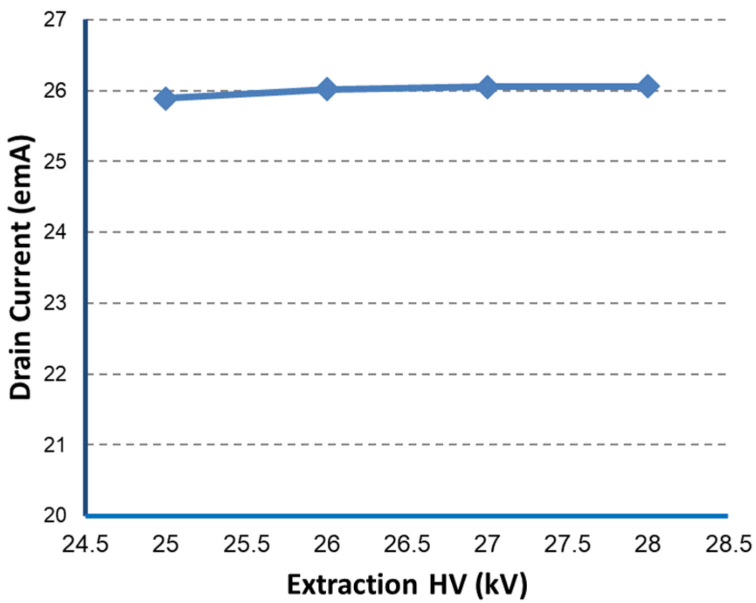


- Plasma heating contribution obvious
- Oven temperature still has margin
- Potentials at 28 GHz, limited by power limit in 2019 (chamber damage at high power)



Status of FECR Development : Beam Extraction

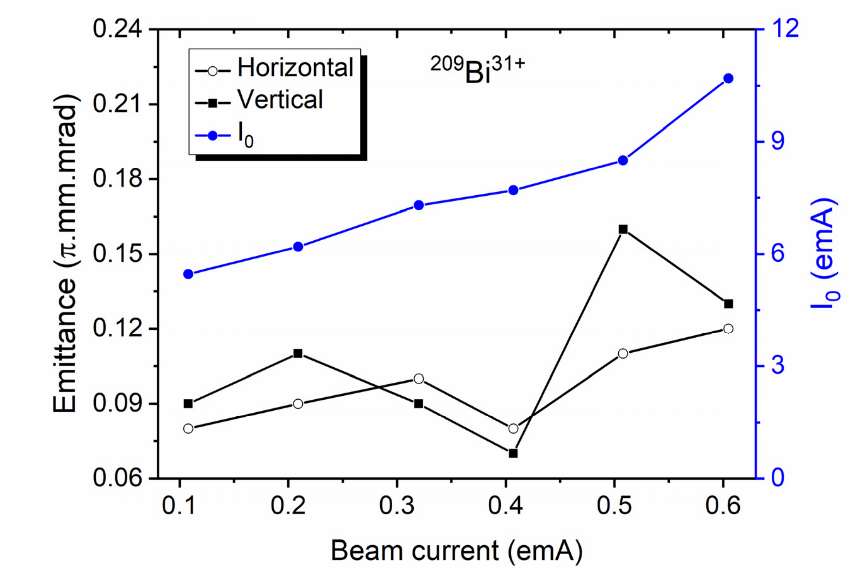


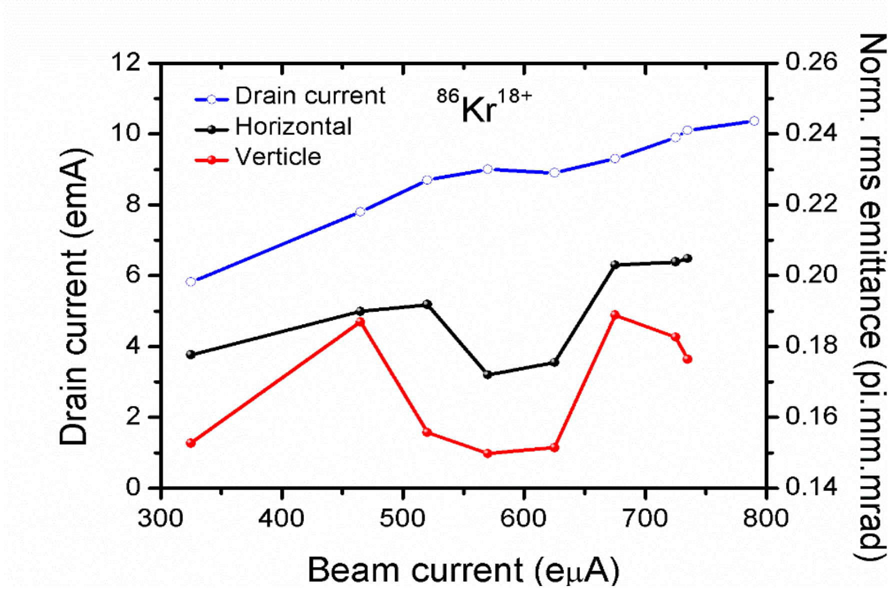


Higher extraction voltage==

- **Higher beam transmission efficiency**
- **Better beam quality in terms of SPC**

Status of FECR Development : Beam Extraction

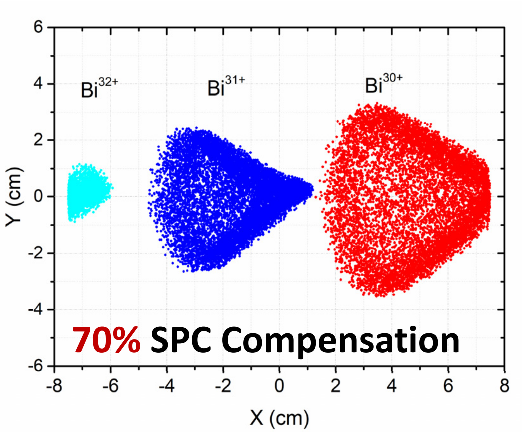


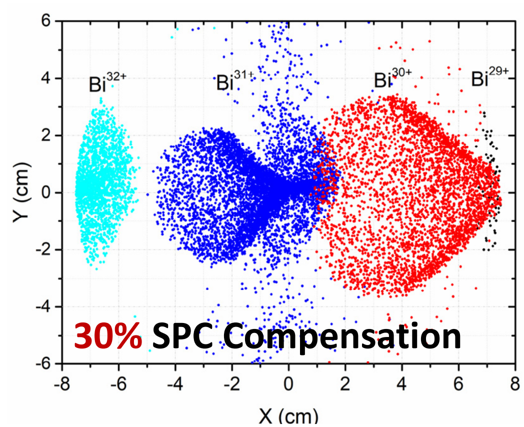


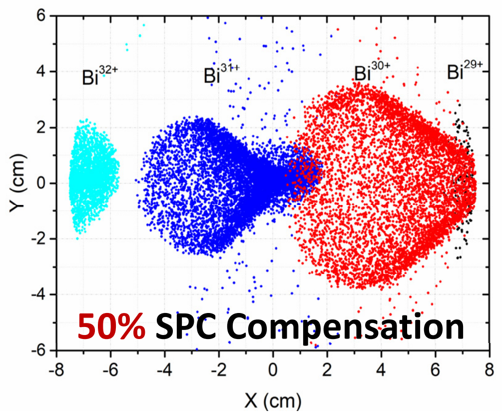
- **Beam emittance degradation not proportional to I_q**
- **Space charge not dominant at extraction and transmission**
- **Plasma condition and beam extraction critical**

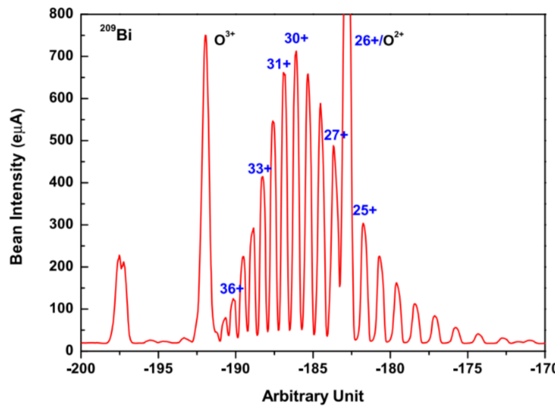
Y. Yang, et al., Phys. Rev. Accel. Beams, **22**, 110101 (2019)

Status of FECR Development : Beam Extraction





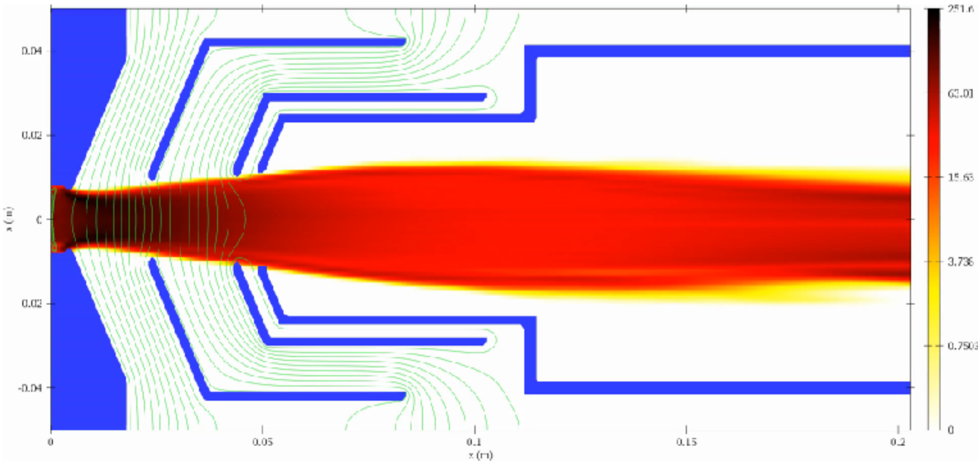


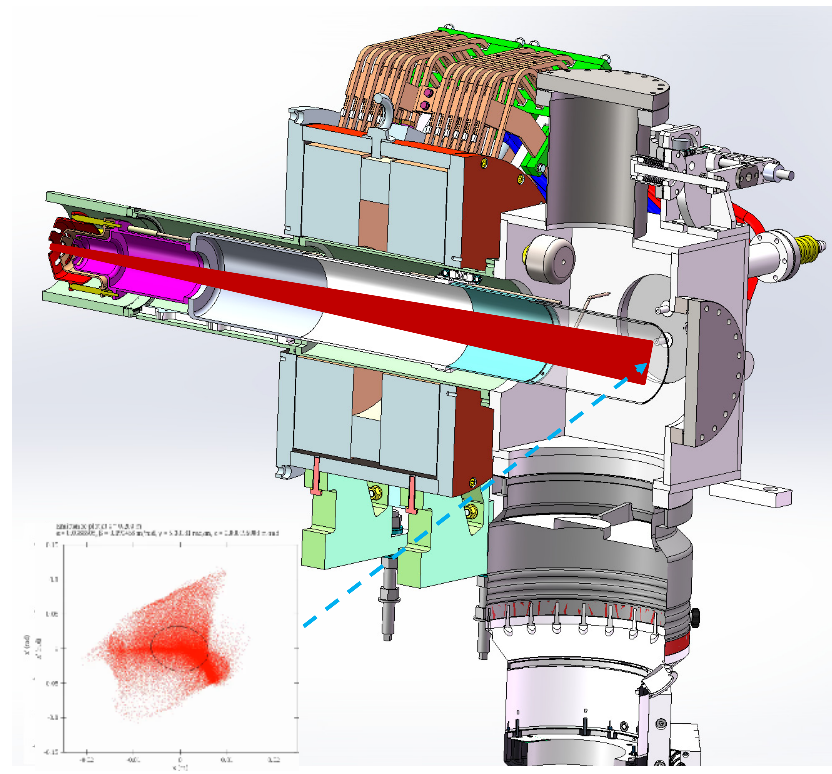


- I_{total}=13 emA, I_{Bi31+}=0.65 emA.

Evidence of SPC not dominant in ion source extraction and transmission

Status of FECR Development : Beam Extraction





- Max. 50 kV extraction voltage
- 4-electrode extraction system
- Variable beam extraction optics
- Dural-solenoid solution before dipole magnet
  (independent control of beam focusing and matching)

Z. Shen @ talk 1142, on Wednesday

Summary

- Reliable and safe SC-magnet for 45 GHz plasma confinement
- Effective coupling to the plasma of 20 kW/45 GHz microwave power
- 20 kW microwave heated plasma operation reliability and stability:
- Strong bremsstrahlung radiation problems
- Intense high charge state ion beam (20-40 emA) extraction, transport and beam quality control
- Intense metallic beam production, especially of refractory materials: U, W, Ta, Mo, Ti, Ni…

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- Cold mass fabrication and assembly

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- Nb_3Sn Wire

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

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

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

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

Lawrence Berkeley National Laboratory
- Coldmass structure design

RIKEN
- High temperature oven

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O. Tarvainen, E. Ravaioli, X. J. Liu, W. Kasparek

Welcome collaborations and Postdoc research !!