ECR ion sources (ECRIS) for high-intensity heavy ion beams

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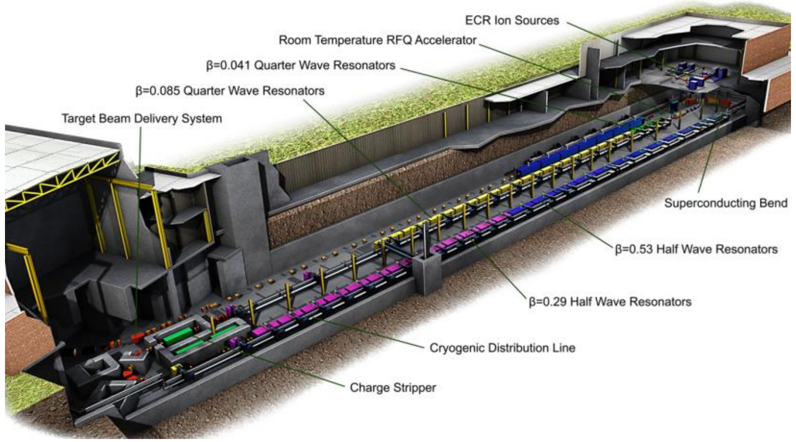
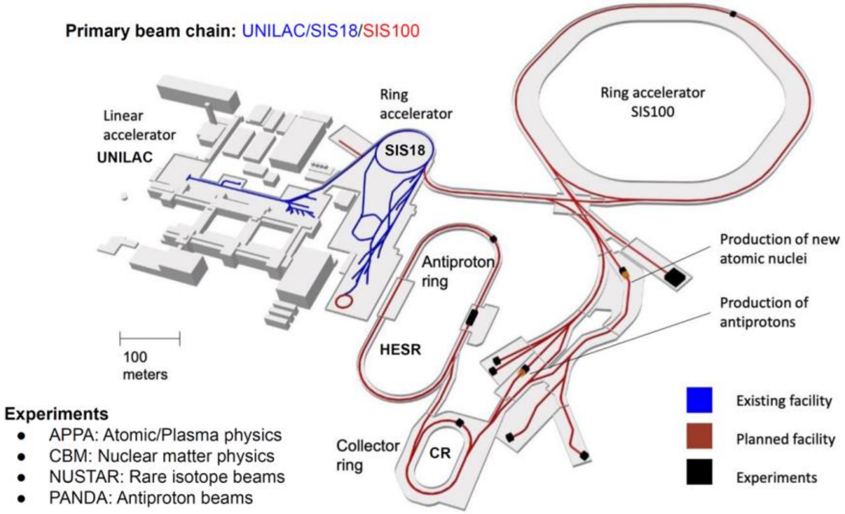
Outline

- Worldwide high performance ECRIS development
- Recent ECRIS development at IMP
- Next generation ECRIS

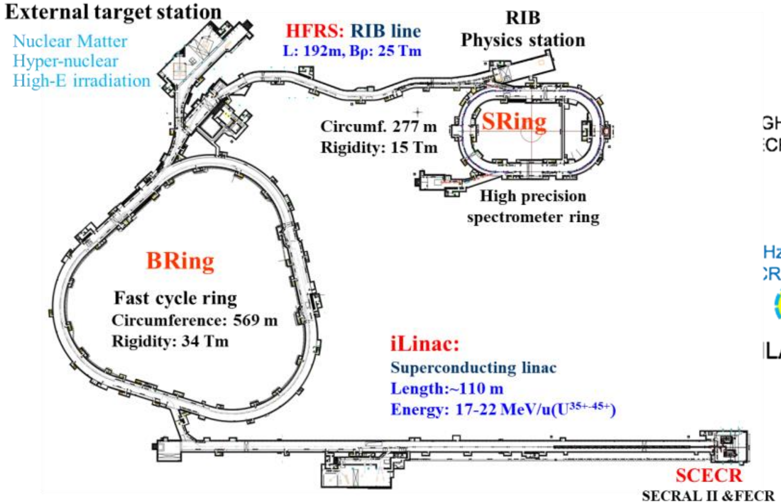
Worldwide heavy ion linacs need high-intensity highly-charged ECRIS



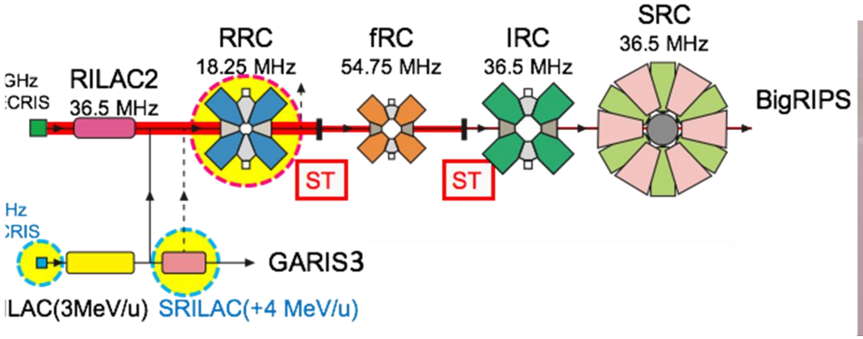
MSU FRIB



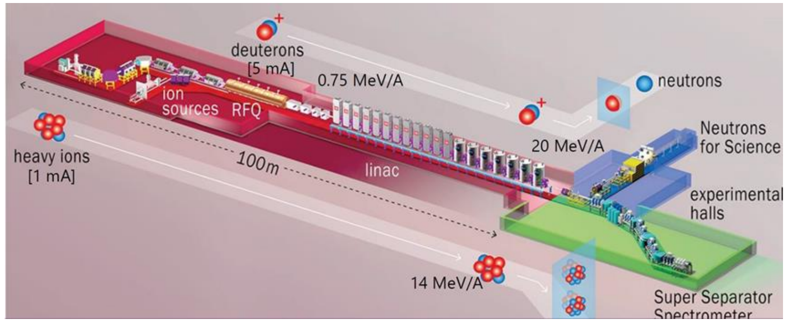
GSI@FAIR UNILAC



IMP HIAF iLinac

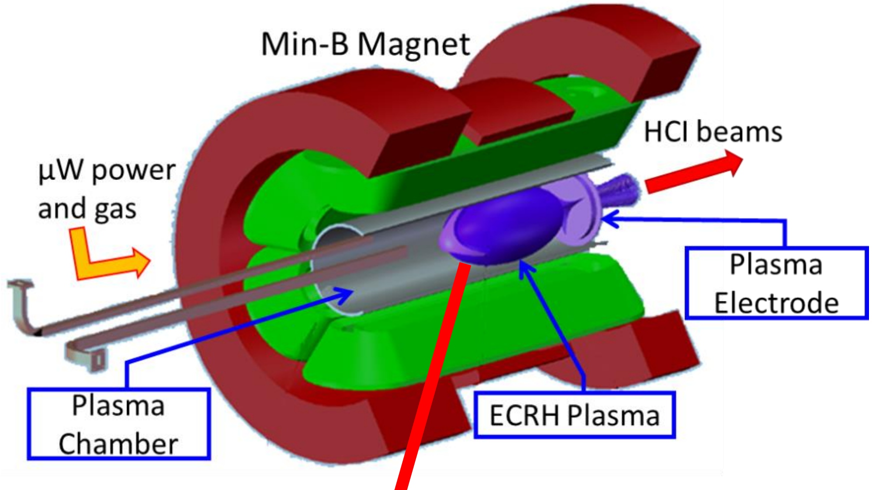


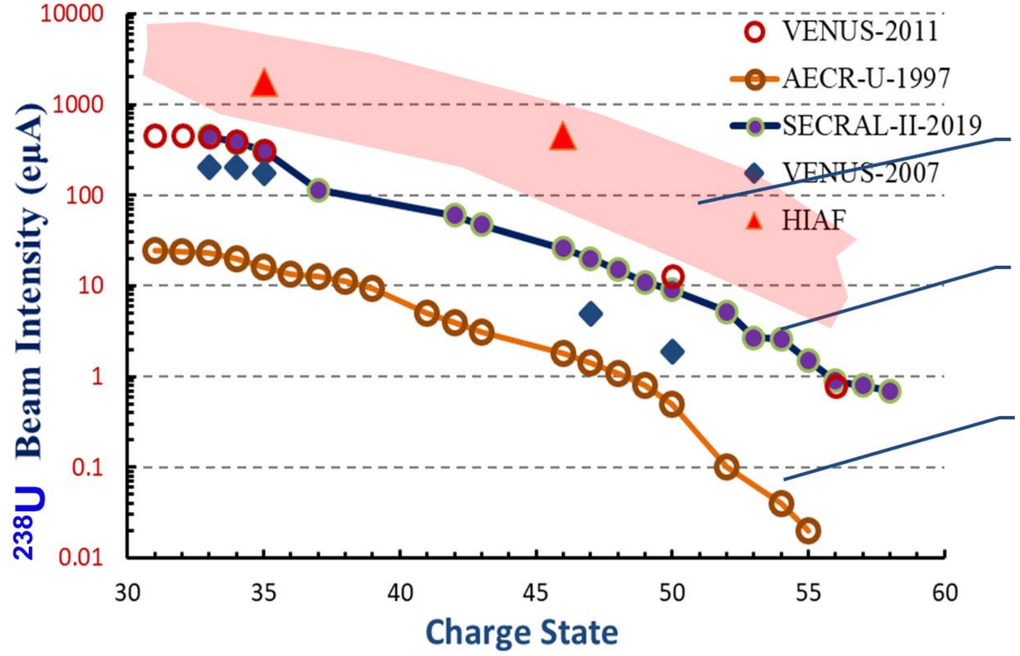
RIKEN RIBF RILAC



GANIL SPIRAL 2

High-intensity highly-charged ECRIS





ω_{ECR} **B$_{ecr}$**

4th G ECRIS	45-60 GHz
3rd G ECRIS	24-28 GHz
2nd G ECRIS	14-18 GHz

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

$$I_q \propto \omega_{\mathrm{ECR}}^2$$

High-intensity heavy ion linac needs higher frequency/higher magnetic field ECRIS

Superconducting ECRIS
3rd and 4th Gen. ECRIS

The most significant development of HI - HC ECRIS

Worldwide High Performance ECRIS Development: LBNL VENUS

- Continuous development on high intensity highly charged ion beams production
- Routine operation with highly charged ion beams

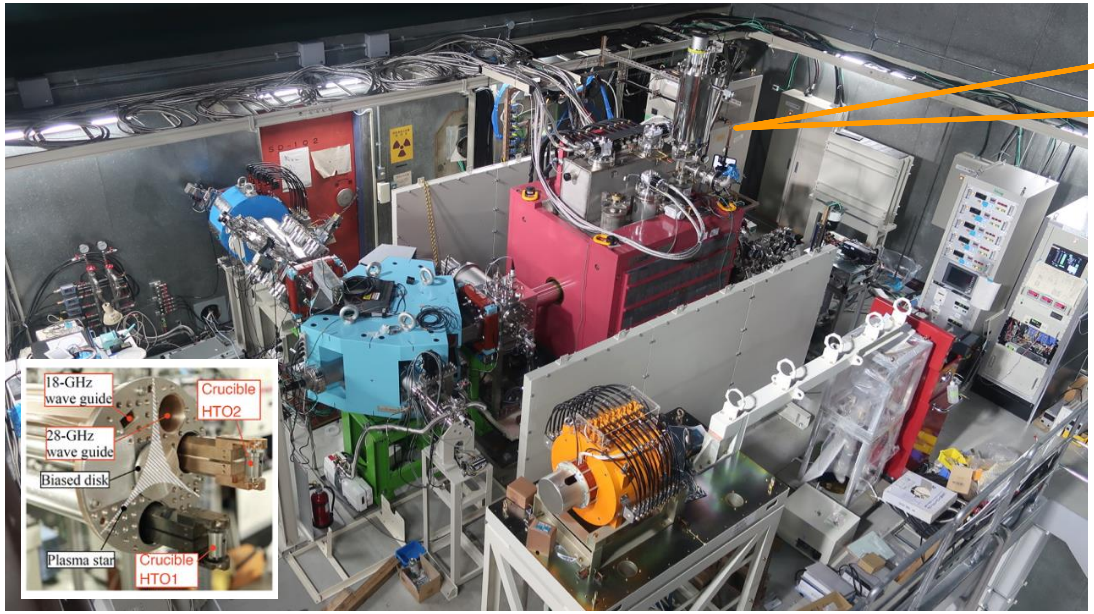
Courtesy of D. Xie@ICIS2021

(Quoted currents are in unit of eμA)

	≤2015	> 2015
$^{16}O^{6+}$	2850	4750
O^{7+}	850	1900
$^{40}Ar^{12+}$	860	1060
Ar^{16+}	270	525
Ar^{17+}	37	120
Ar^{18+}	1	4
$^{78}Kr^{18+}$		^{84}Kr 770
Kr^{23+}	88	420
Kr^{28+}	25	100
Kr^{32+}		7
$^{129}Xe^{27+}$	400	705
Xe^{38+}	7	26
Xe^{45+}		0.8
$^{197}Au^{47+}$	4	$^{197}Au^{51+}$ 5
Au^{52+}	0.8	4.7
Au^{58+}		0.6
$^{209}Bi^{45+}$	18	63
Bi^{50+}	5.3	27
Bi^{55+}		7.2
Bi^{59+}		0.7
$^{238}U^{33+}$	450	
U^{36+}	220	

Record beam intensities

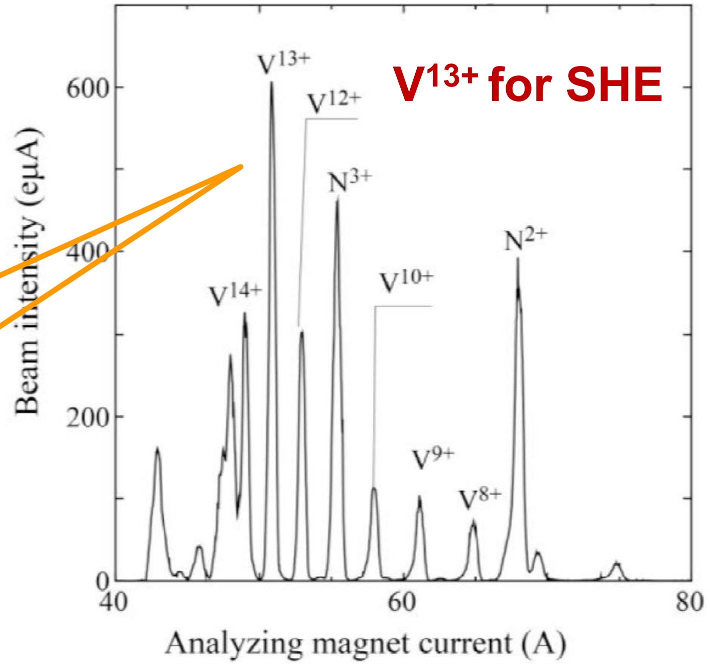
Worldwide High Performance ECRIS Development: RIKEN SCECRIS



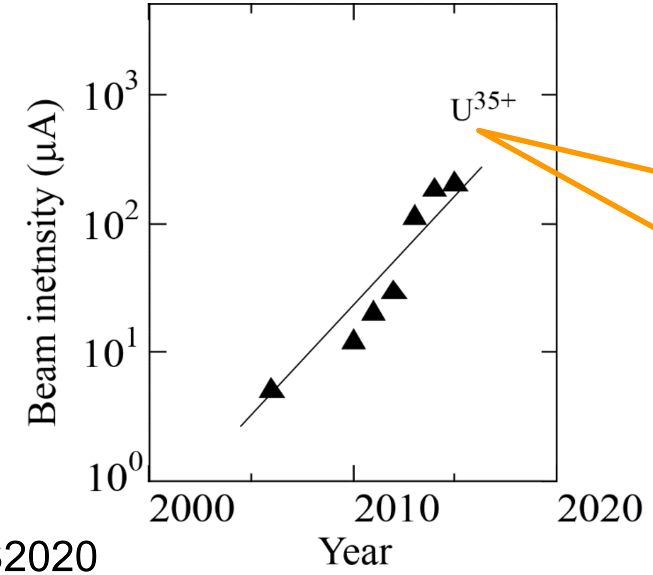
Courtesy of Y. Higurashi & T. Nagatomo @RIKEN

RIKEN 28 GHz SCECRIS dedicated to high intensity beam delivery for SHE

V^{13+} 400 eμA at 2.5 kW RF one month operation continuously. Very good long-term reliability!



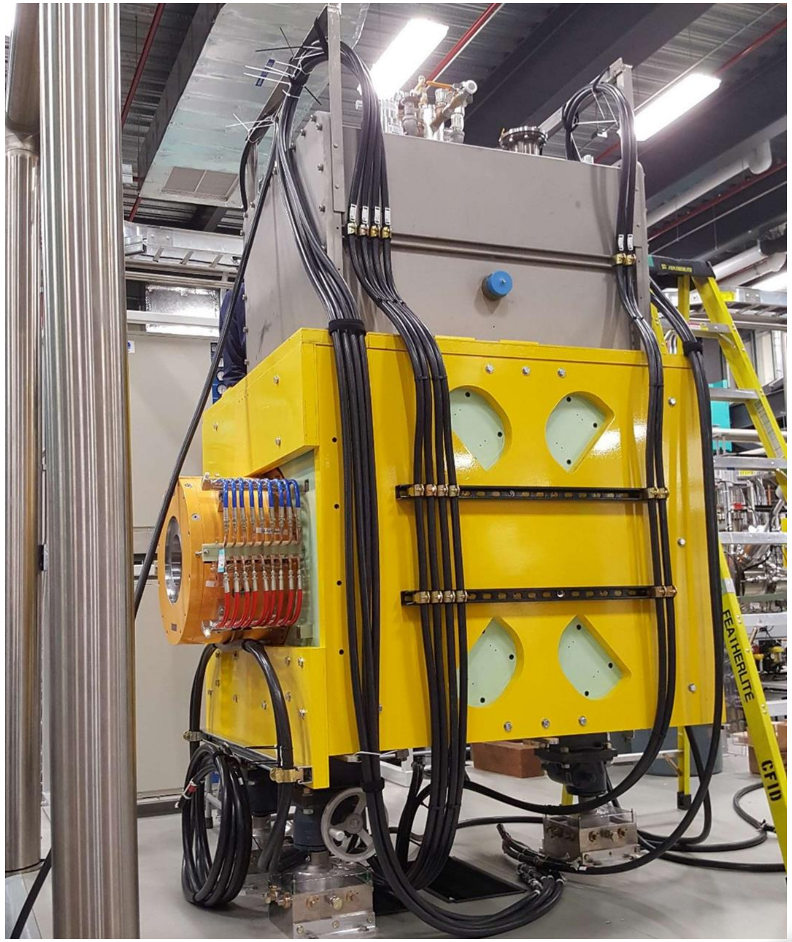
- High performance 28 GHz SCECRIS development
- Reliable high temperature oven development
- High intensity metallic ion beam long-term operation



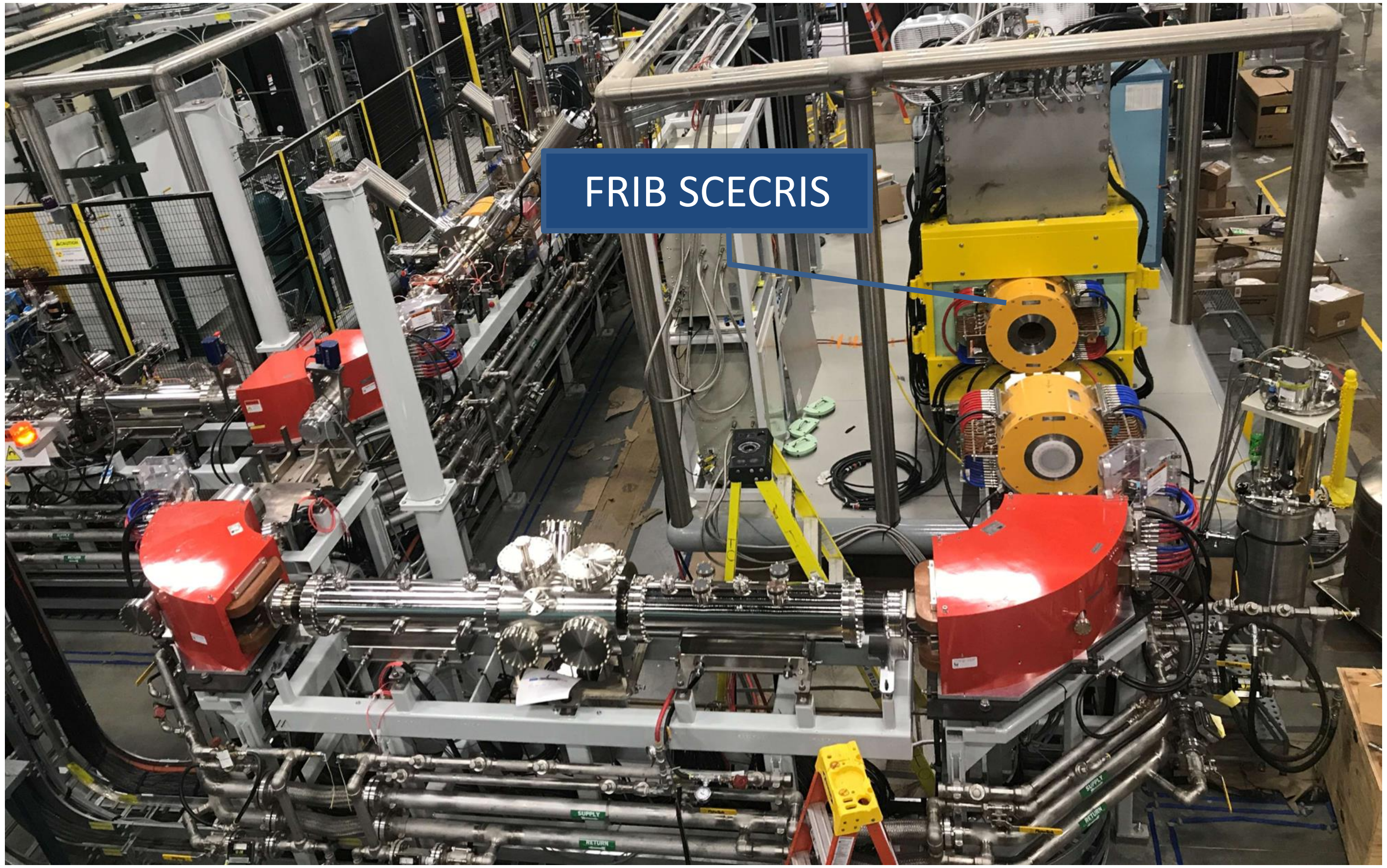
Takashi Nagatomo, RIKEN, ECRIS2020

U^{35+} 104-140 eμA 33 days operation continuously for RIBF in April 2022

Worldwide High Performance ECRIS Development: FRIB SCECRIS

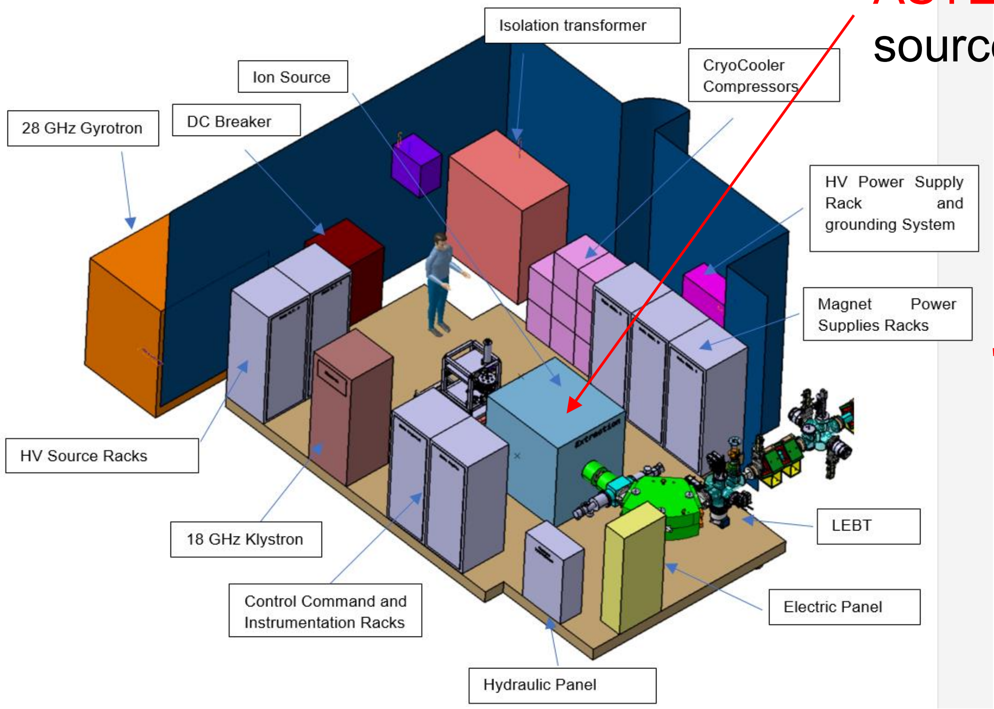


Courtesy of Haitao Ren@ICIS2021

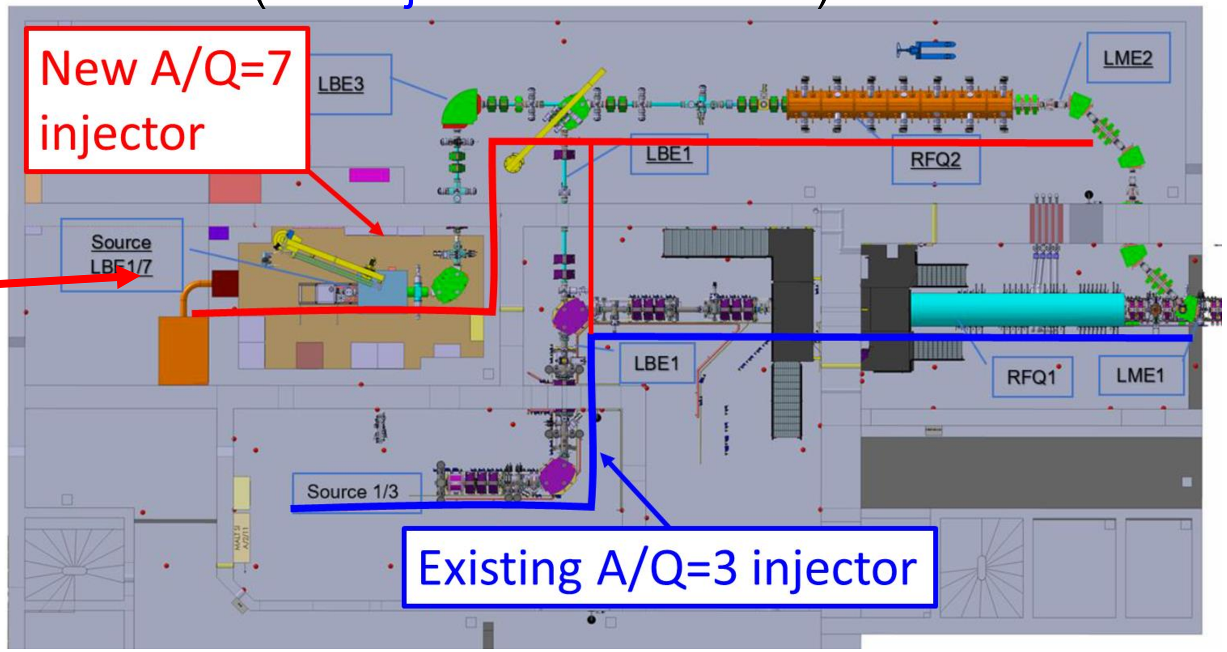


- **FRIB SCECRIS in position with 100% design operation fields**
- **First plasma at 18 GHz tested (2022)**
- **First plasma at 28 GHz scheduled at early 2023**

Worldwide High Performance ECRIS Development: GANIL ASTERICS



ASTERICS: A new 28 GHz Superconducting ion source for NEWGAIN (new injector for SPIRAL 2)

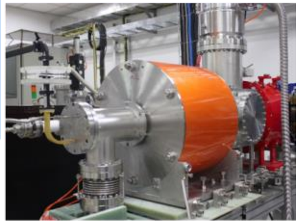


- Fully superconducting ECR ion source@28 GHz
- Typical beams: 15 pμA Ca^{11+}, ≥5 pμA U^{34+}
- Potential: Ion source on a 70 kV platform
- Project period: 2023~2028

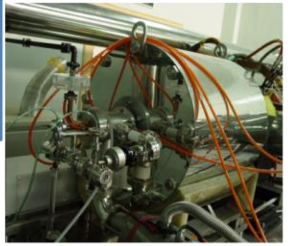
Courtesy of T. Thuillier@LPSC

ECRIS Development at IMP

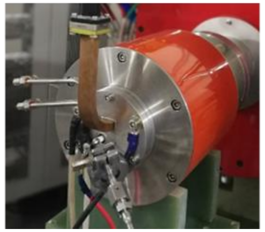
LAPECR3
14.5 GHz (2012)



LAPECR2
14.5 GHz (2005)

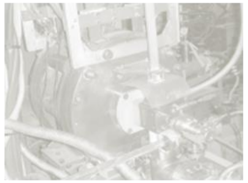


LAPECR1
14.5 GHz (2002)



Application series
(permanent magnet ECRISs)
10~14.5 GHz

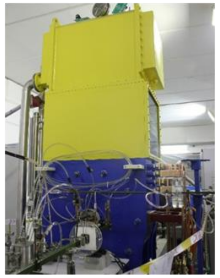
LECR1
10 GHz (1990)



LECR2
14.5 GHz (1997)

LECR3
14.5 GHz (2000)

LECR4
18 GHz (2013)



LECR5
18 GHz (2019)

Traditional series
(room temperature ECRISs)
10~18 GHz

SECRAL
18~24 GHz (2005)

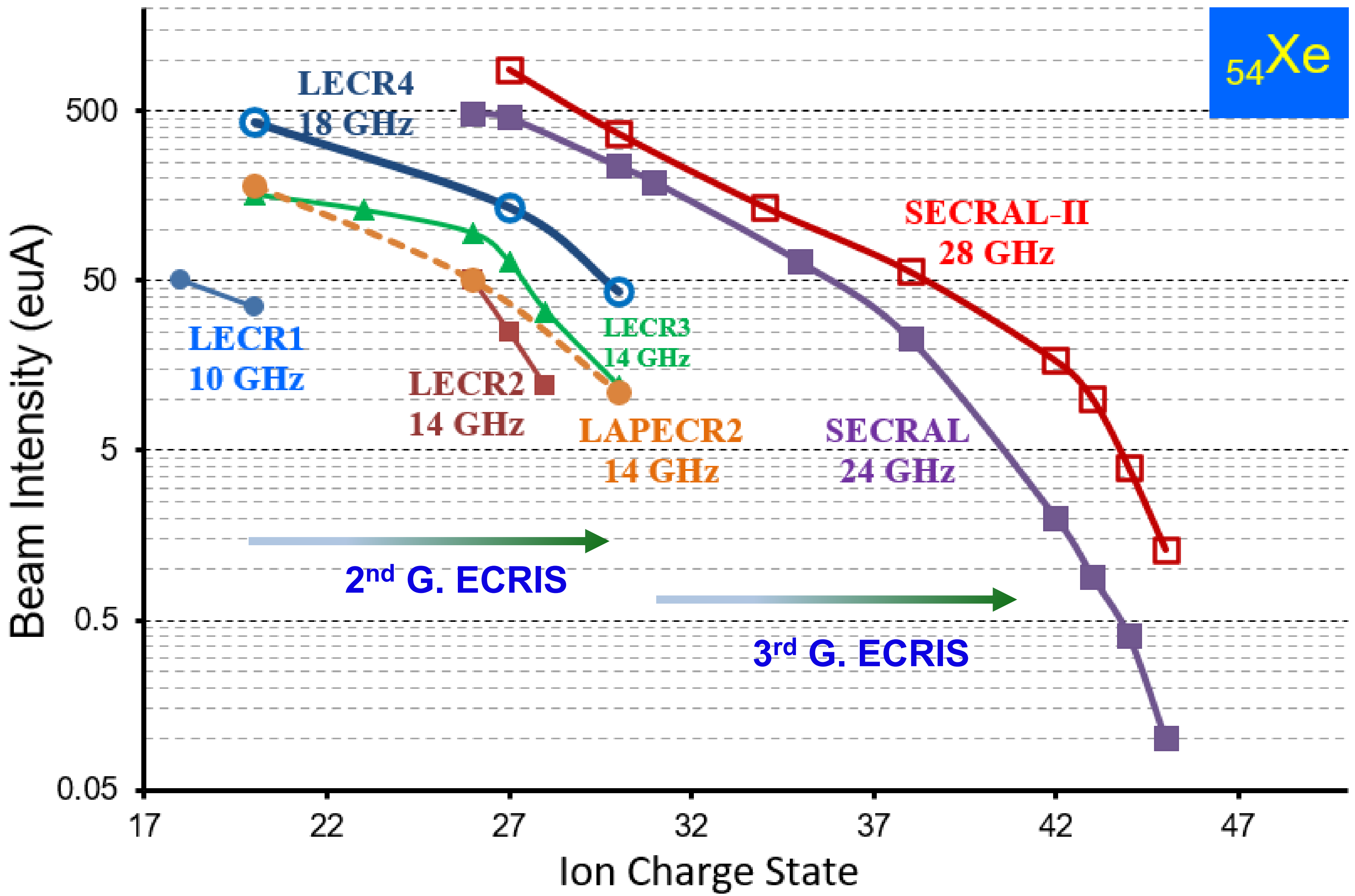
SECRAL-II
18~28 GHz (2016)

SECRAL-I
18~28 GHz (2019)

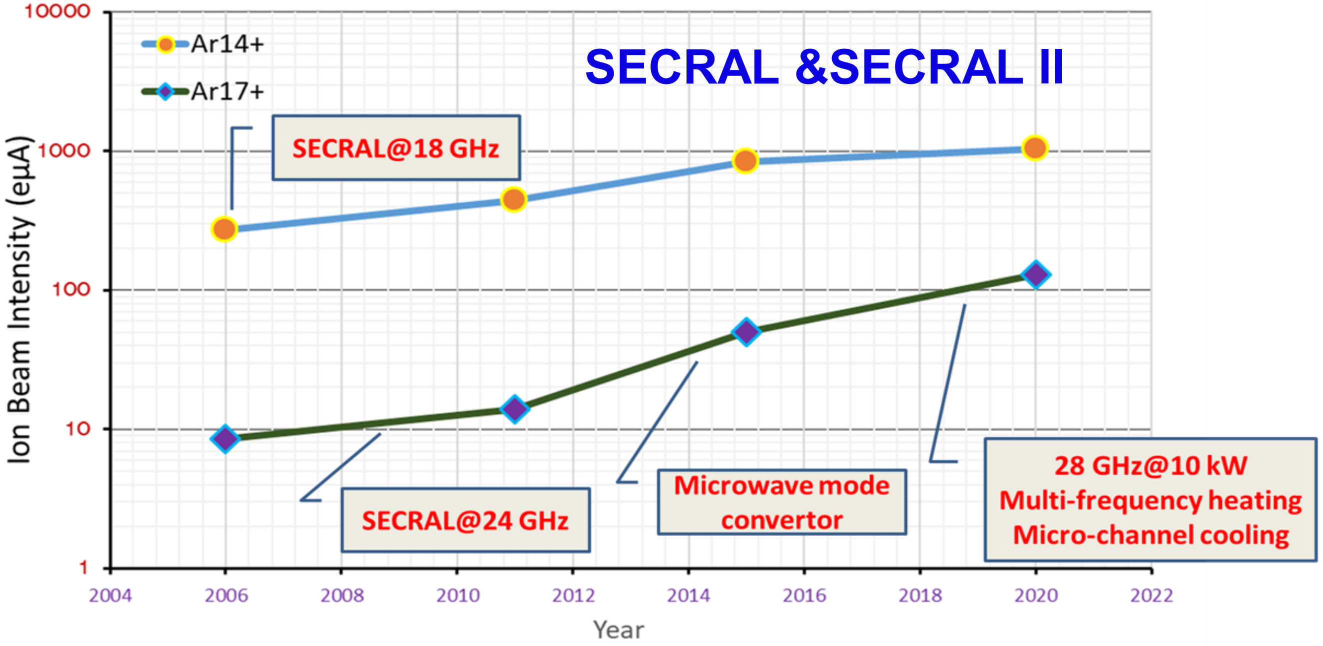
High performance series
(Superconducting ECRISs, 3rd G.)
18~28 GHz

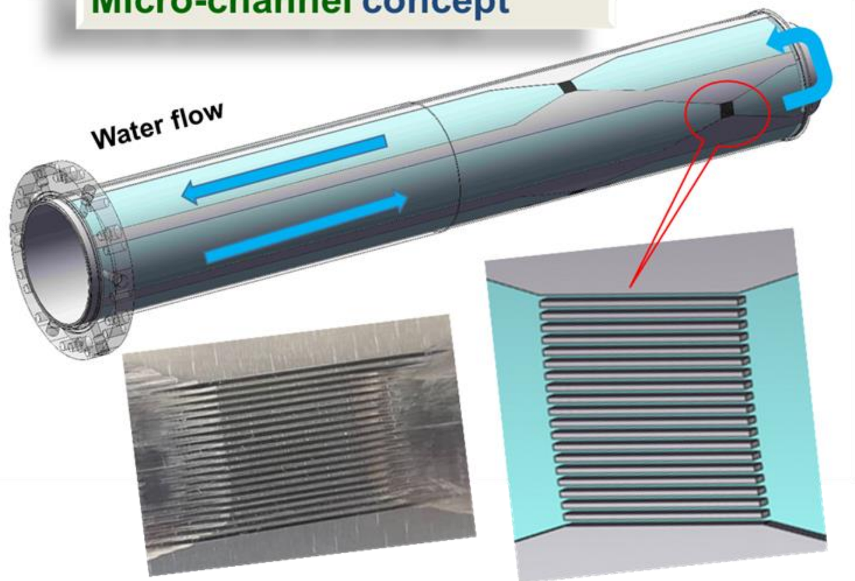
L. Sun, et al., Rev. Sci. Instrum. 91, 023310 (2020)

ECRIS Development at IMP: Beam intensity evolution



ECRIS Development at IMP: Technical advancement

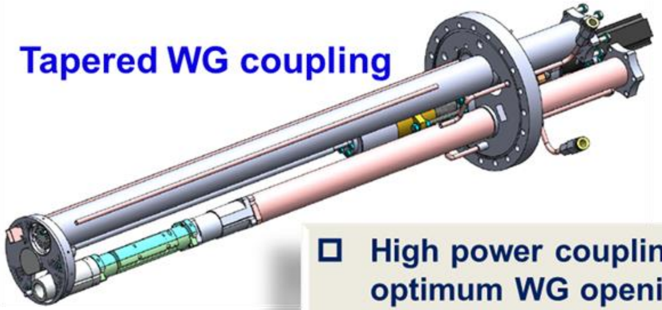




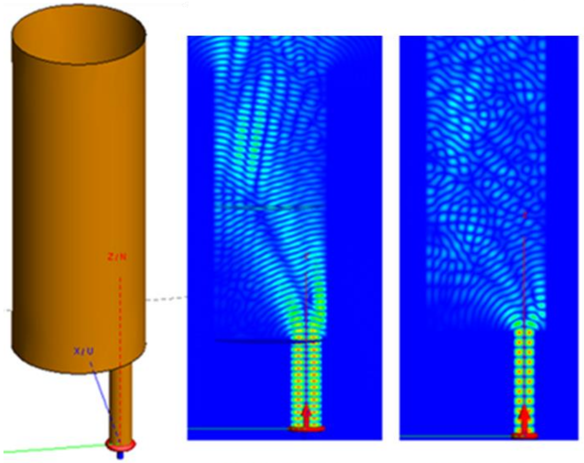
- High power operation safe
- Long-term reliability

15.6 * 15 mm
Fins: 0.4 mm*19
Channel: 0.4 mm *20

Tapered WG coupling

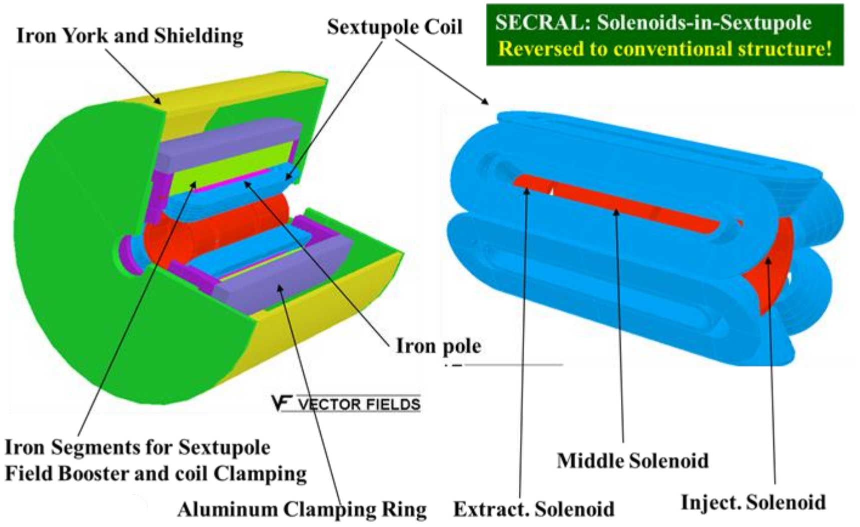


- High power coupling via optimum WG opening
- Homogenous ECR surface microwave power radiation

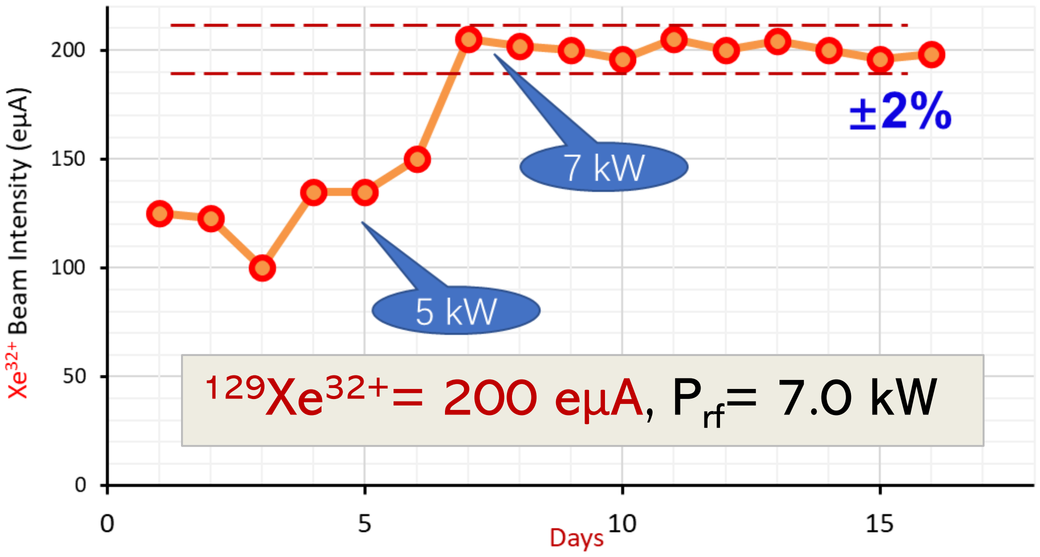


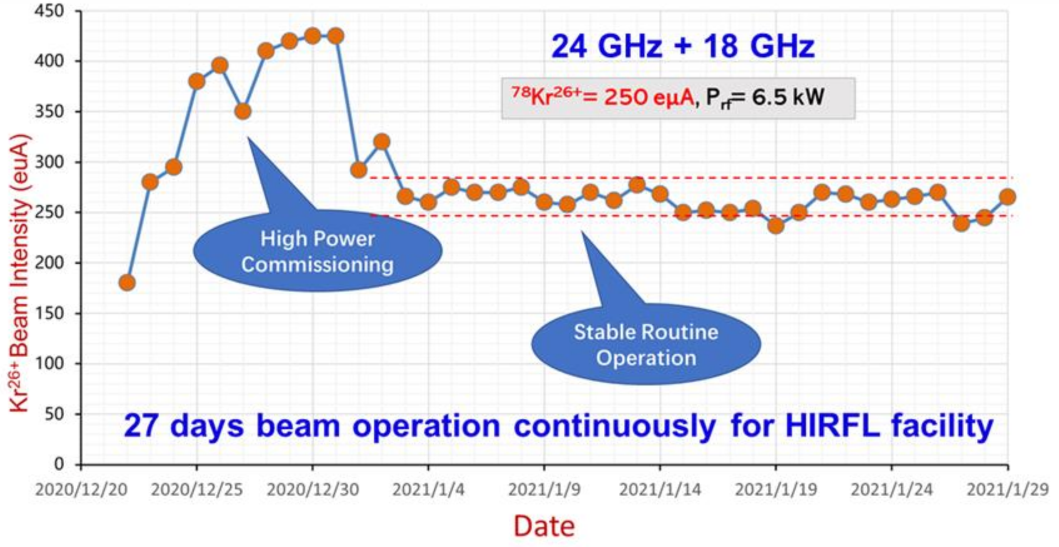
Ø32 mm TE_{01} Ø20 mm TE_{01}

Record beam intensities and long-term operation by SECRAL -II



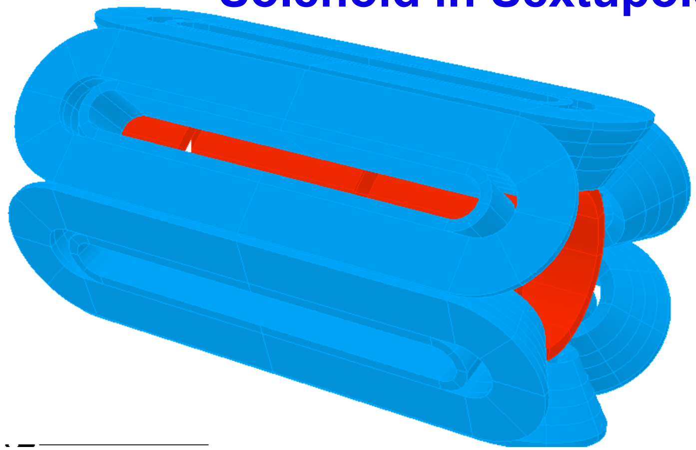
Ion Beam	SECRAL (eμA) (2015-2019)
$^{16}O^{6+}$	6700
$^{40}Ar^{12+}$	1420
$^{40}Ar^{16+}$	620
$^{40}Ar^{18+}$	15
$^{78}Kr^{18+}$	1030
$^{78}Kr^{28+}$	146
Xe^{26+}	1100
Xe^{30+}	365
Xe^{42+}	16
$^{209}Bi^{31+}$	680
$^{209}Bi^{41+}$	100
$^{238}U^{33+}$	450
$^{238}U^{35+}$	315



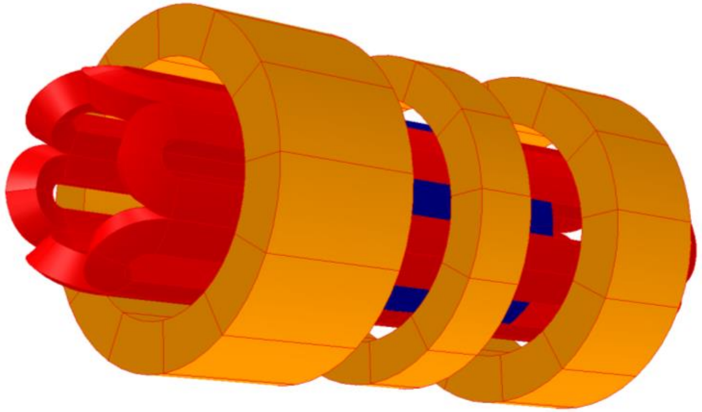


Next Generation ECRIS: Magnet structure

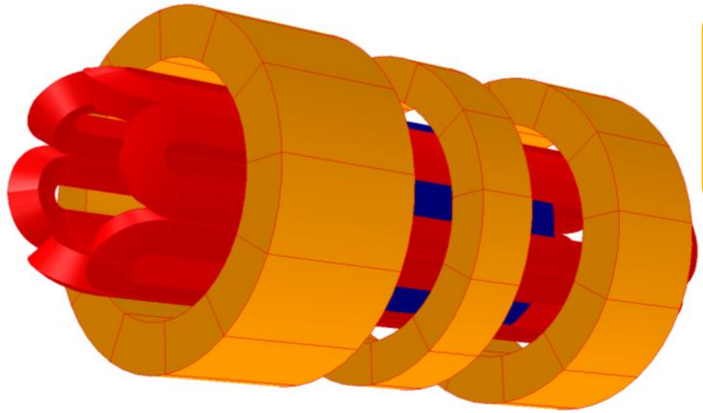
Solenoid in Sextupole--SECRAL



Sextupole in Solenoid--VENUS

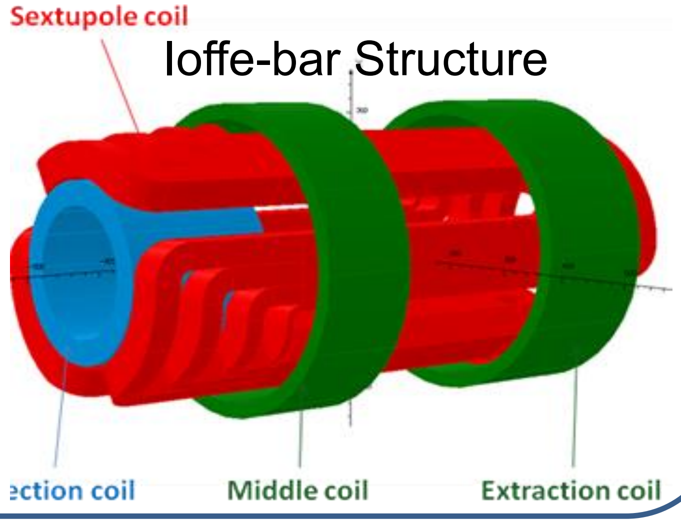


3rd G. ECRIS
(24-28 GHz)



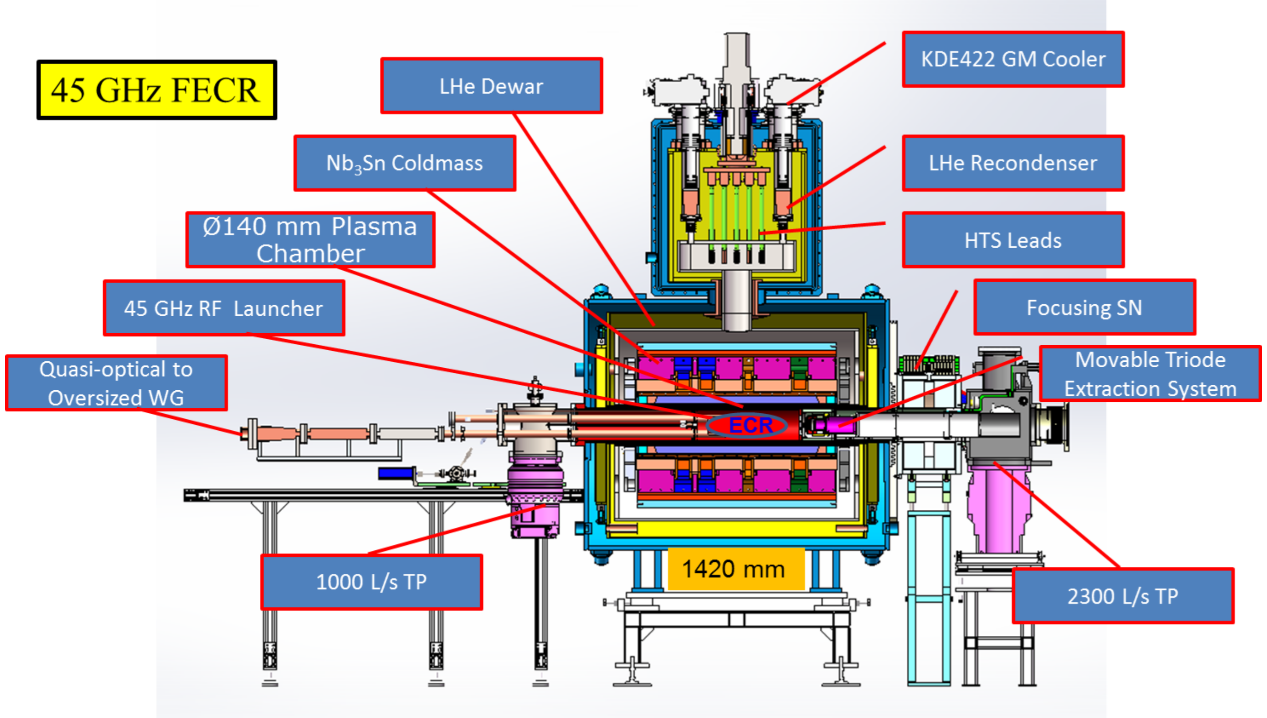
Sextupole in Solenoids with Nb_3Sn

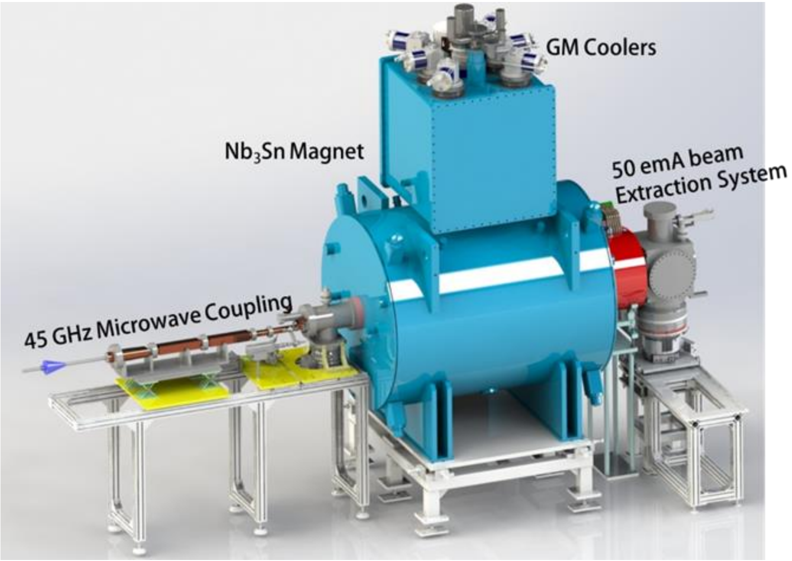
New structure with NbTi proposed by D. Xie LBNL



4th G. ECRIS
(45-60 GHz)

The world first 4th generation ECR ion source FECR at IMP





FECR key parameters

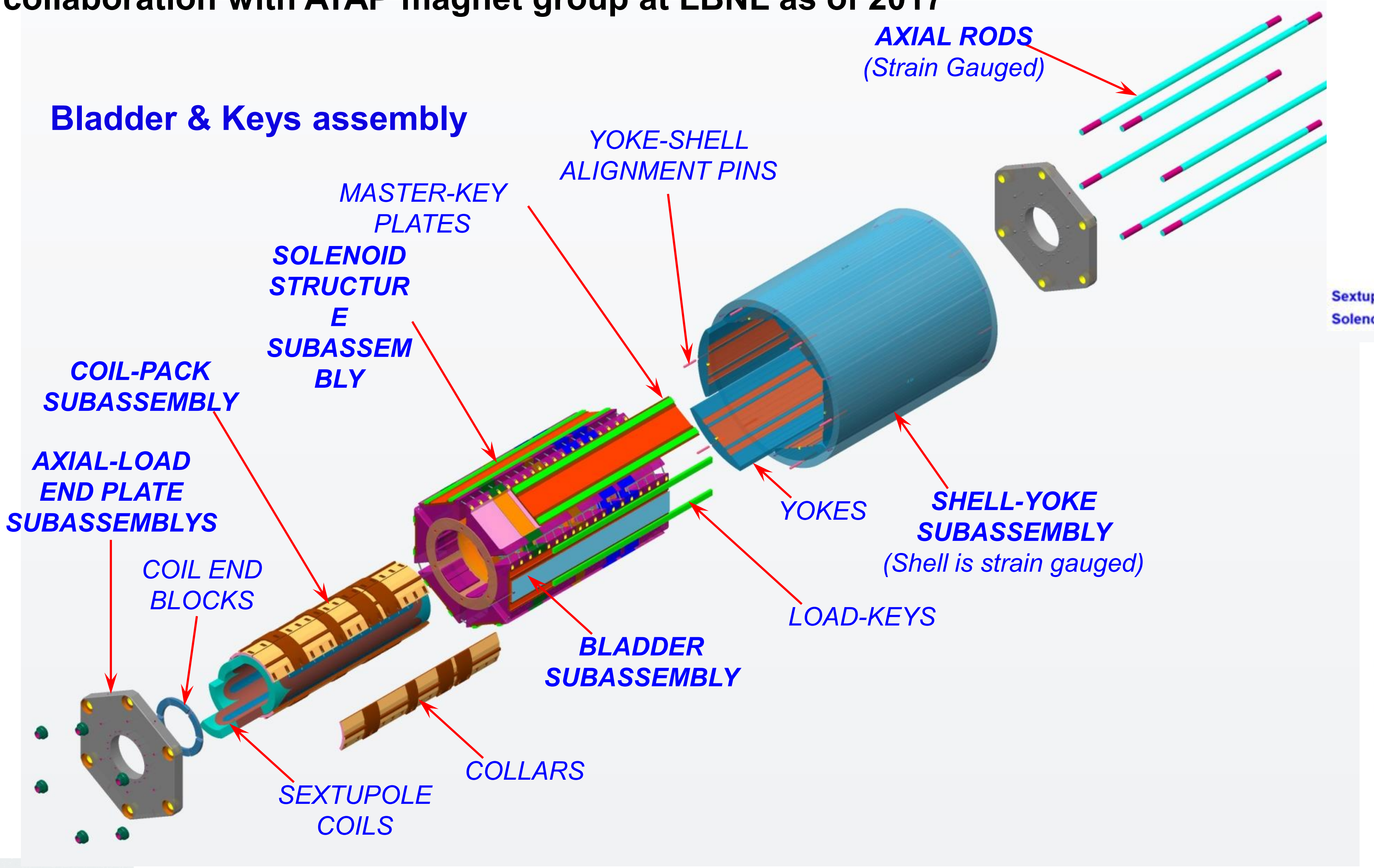
Microwave	45 GHz/20 kW
Magnet conductor	Nb$_3$Sn
Axial fields (T)	6.5/1.0/3.5
Sextupole field (T)	3.8@r=75 mm
Maximum field (T)	11.8 T
Maximum stress (MPa)	150
Magnet bore (mm)	>Ø160
Stored energy (MJ)	1.6
Extraction (kV)	50
Typical beam	1.0 emA U^{35+}

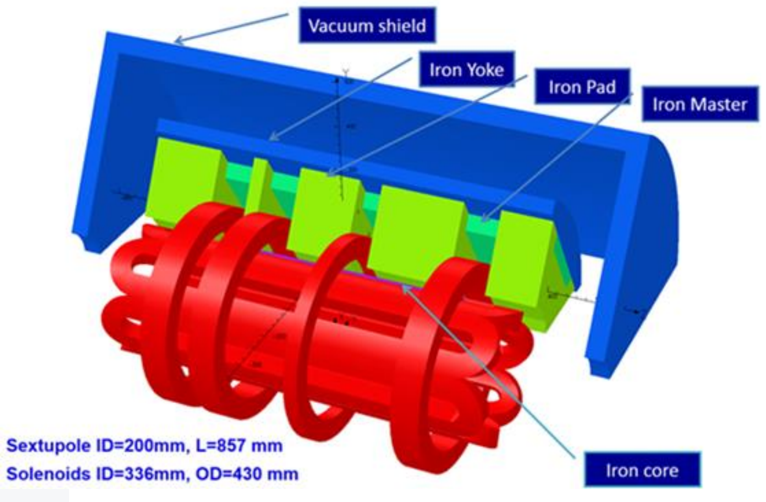
- **Beams and intensities expected from FECR**
- **3-5 times higher than existing record beam intensities**

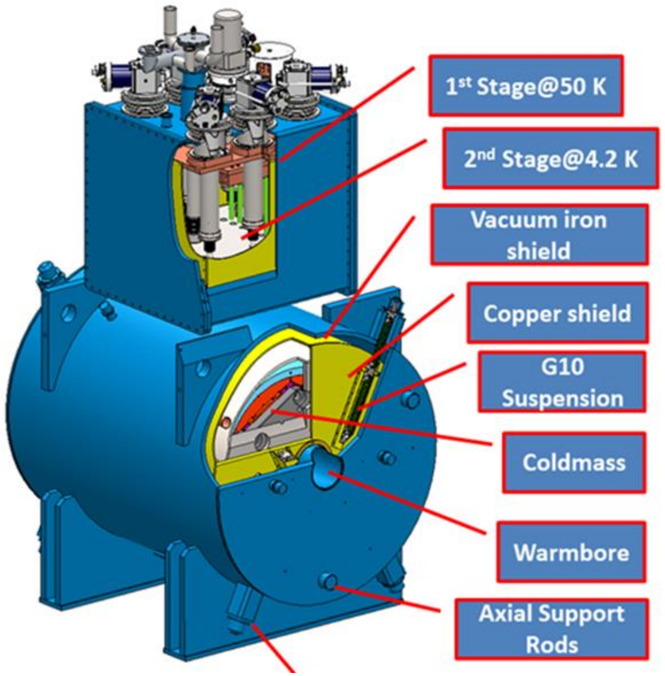
$^{129}Xe^{30+}$	>1000 μA
$^{129}Xe^{45+}$	> 50 μA
$^{209}Bi^{31+}$	>1000 μA
$^{209}Bi^{55+}$	> 50 μA
$^{238}U^{35+}$	>1000 μA
$^{238}U^{41+}$	> 200 μA
$^{238}U^{56+}$	> 30 μA

FECR Nb_3Sn magnet

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

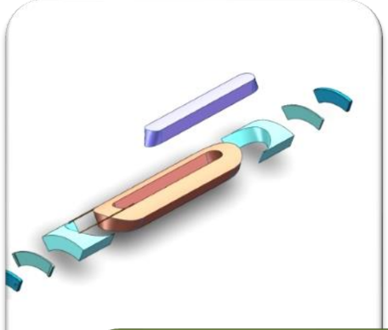






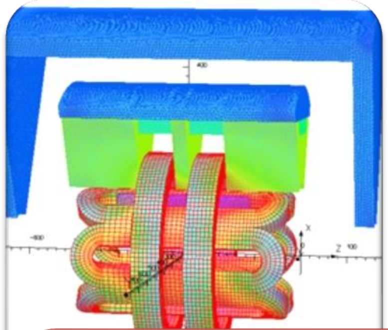
FECR Nb_3Sn magnet development

From prototyping to operational machine (2016-2022)



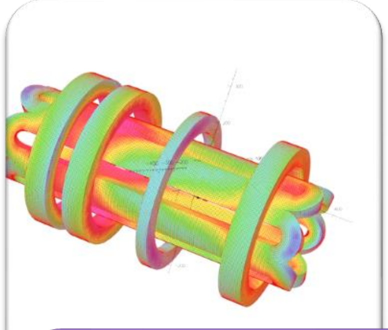
Key technologies

- Coils fabrication
- Keys & Bladder
- Quench protection
- Know-how of Nb_3Sn coil



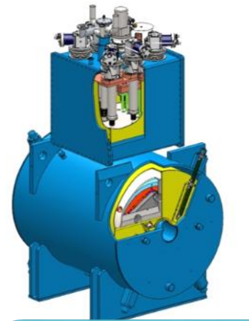
½ Prototype Coldmass

- Quality control and analysis
- SG assisted mechanical assembly
- Quench protection
- Reliability



Full Sized coldmass

- Quality control of mass production
- Quench protection
- Reliability
- System integration



FECR Magnet

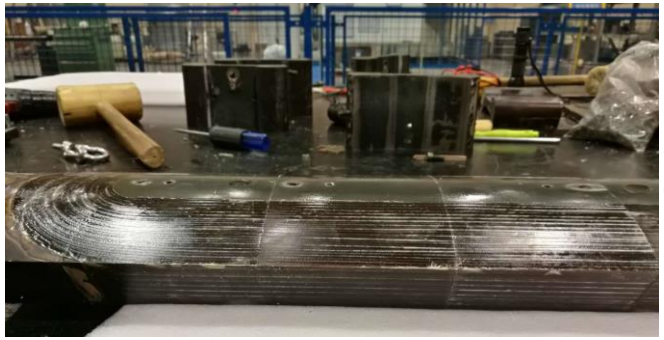
- System integration
- Coldmass alignment
- Reliable operation

To demonstrate 80~85% of FECR coldmass performance

Operational FECR Nb_3Sn magnet

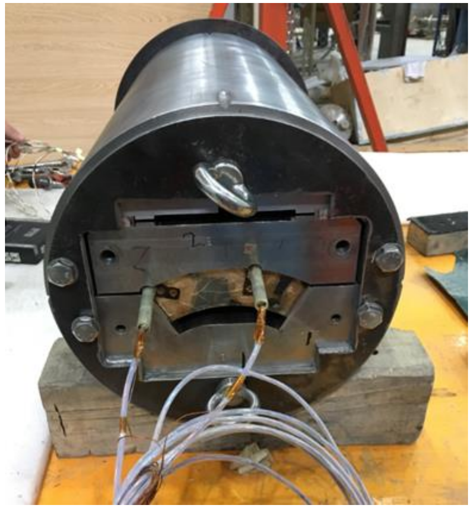
FECR Nb_3Sn magnet : Prototyping sextupole coil

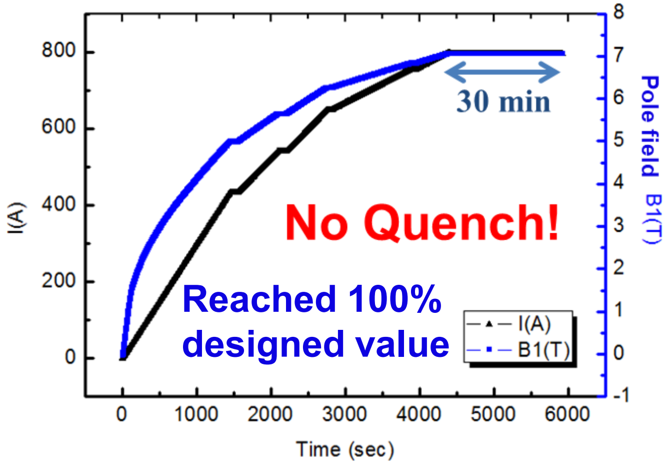
Development of prototyping ½-sized sextupole coil



Prepared Coil

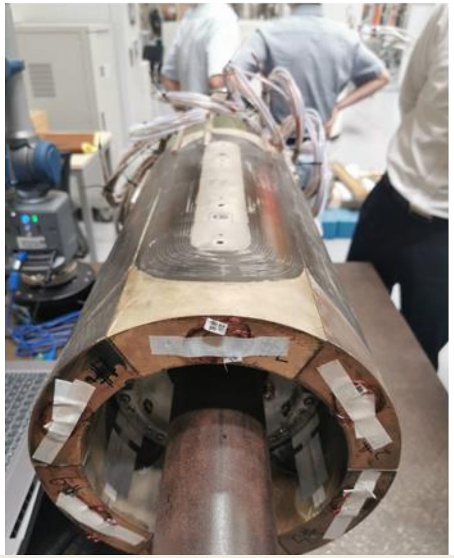
- Mechanical mapping
- Detailed Q/A



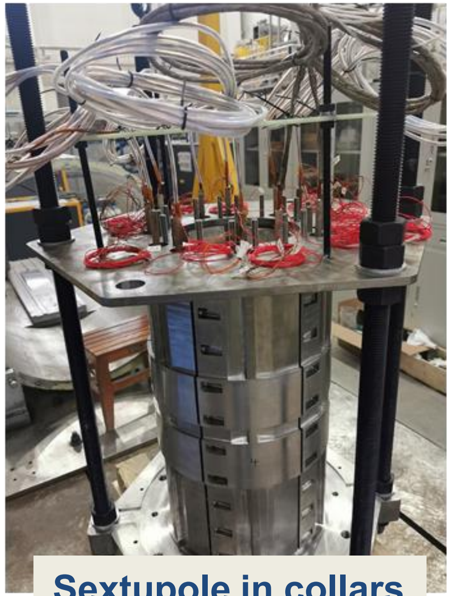


A Mirror Structure for sextupole cold test

FECR Nb_3Sn magnet : ½-sized prototype coldmass assembly

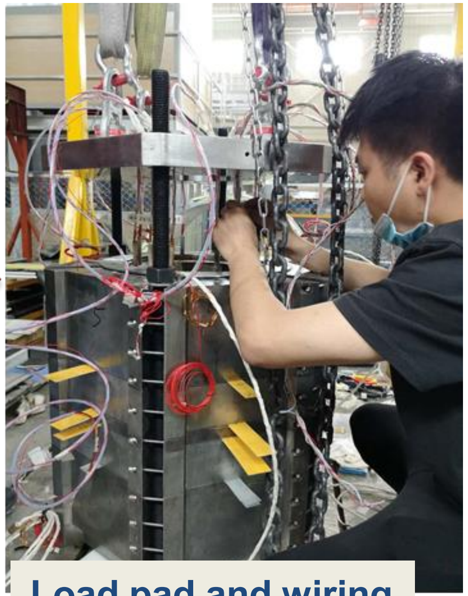


Sextupole pre-assembly

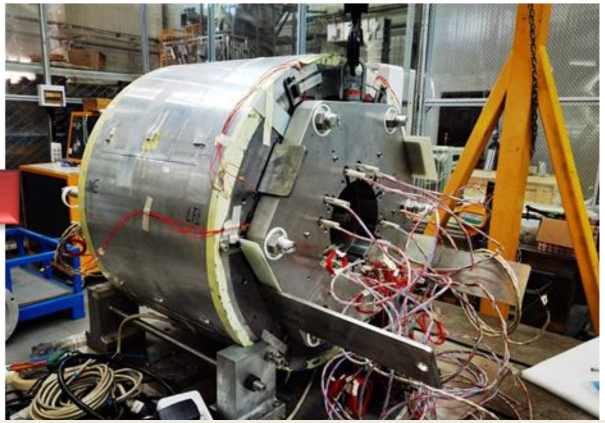


Sextupole in collars

Sextupole & solenoids



Load pad and wiring

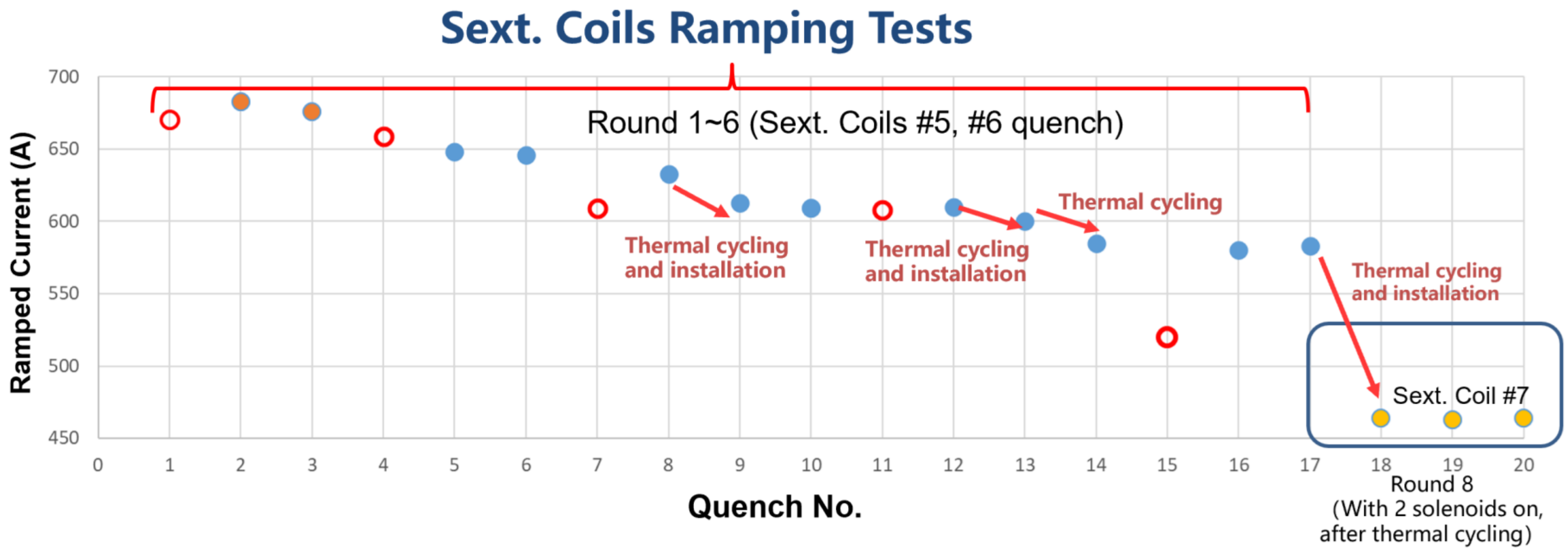


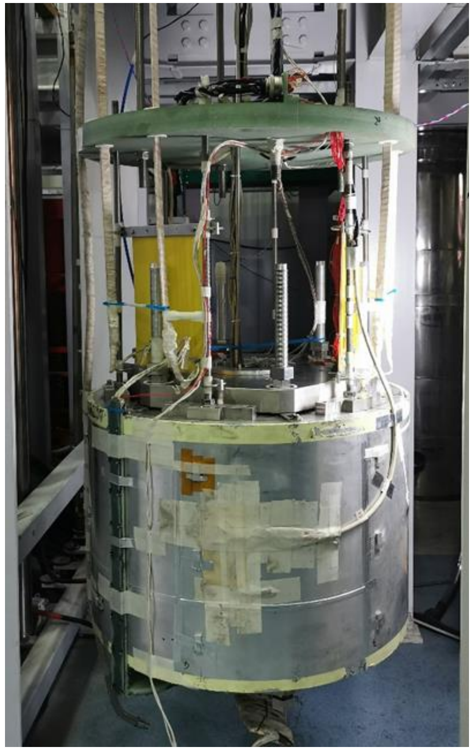
Radial preload with bladder & keys

Axial preload with pistons

Instrumentation in Pizzabox

FECR Nb3Sn magnet : ½-sized prototype coldmass test





Technical challenges

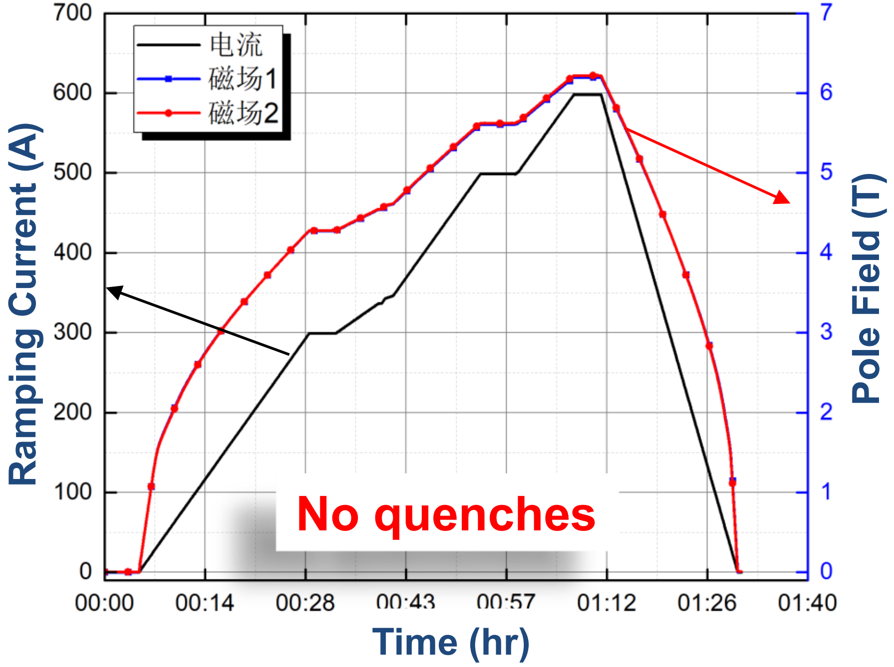
- Precise installation and stress control
- Reliable active quench protection system
- >1.0 kV quench voltage circuit
- Strong Flux Jump interference
- Sextupole degradation reason

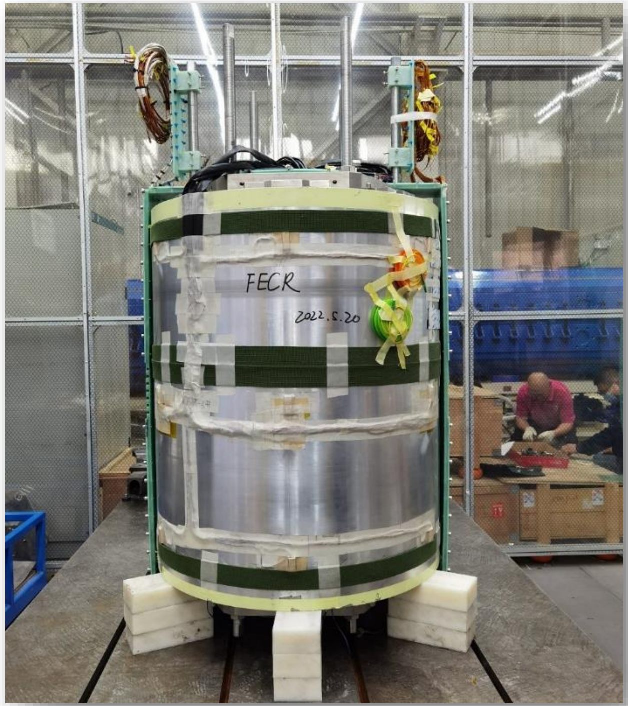
Test results

- 8 rounds energizing tests of the ½ prototype coldmass
- The sextupole quenched at 70%-90%, sextupole+one solenoid reached 77% of design current.
- 2 of the 6 sextupole coils turned out to have performance degradation or minor damage.
- Learned a lot of experiences and lessons

FECR Nb3Sn magnet : Full-sized coldmass

Full-sized sextupole coil reached 100% of designed current





- Full-sized coldmass almost ready for test
- Quench protection remains challenging

Summary and Conclusion

- High-intensity heavy ion linac needs high-intensity highly-charged ECRIS.
- Development trend of high-intensity highly-charged ECRIS towards higher RF frequency, higher RF power, higher confinement magnetic field, the 3rd and 4th Gen. ECRIS, which means higher cost and more technical challenge. Breakthrough needs new ideas and new technology.
- Development of the 3rd Gen. ECRIS has demonstrated very good performance with higher charge state, higher beam intensity and good long-term reliability.
- The next generation (4th Gen.) high-intensity highly-charged ECRIS is under development. IMP 45 GHz FECR Nb_3Sn magnet almost ready for cryogenic energizing. The FECR first beam commissioning could be in Feb. 2023.

Acknowledgement

Thanks to my colleague Liangting Sun for preparing many slides !

Thanks for all those progress and slides from LBNL VENUS, RIKEN SCECRIS, FRIB SCECRIS, GANIL ASTERICS.

Thank you for your attention !