Prospects and challenges of the next generation highly-charged ECR ion source

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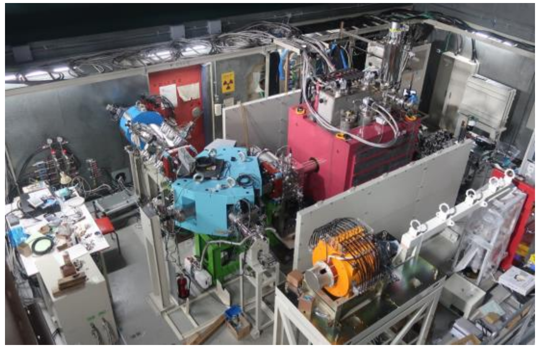
High performance 3rd generation ECRIS

VENUS@LBNL: 28+18 GHz

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



SCECRIS@RIKEN: 28+18 GHz

FRIB-SCECRIS: 28+18 GHz

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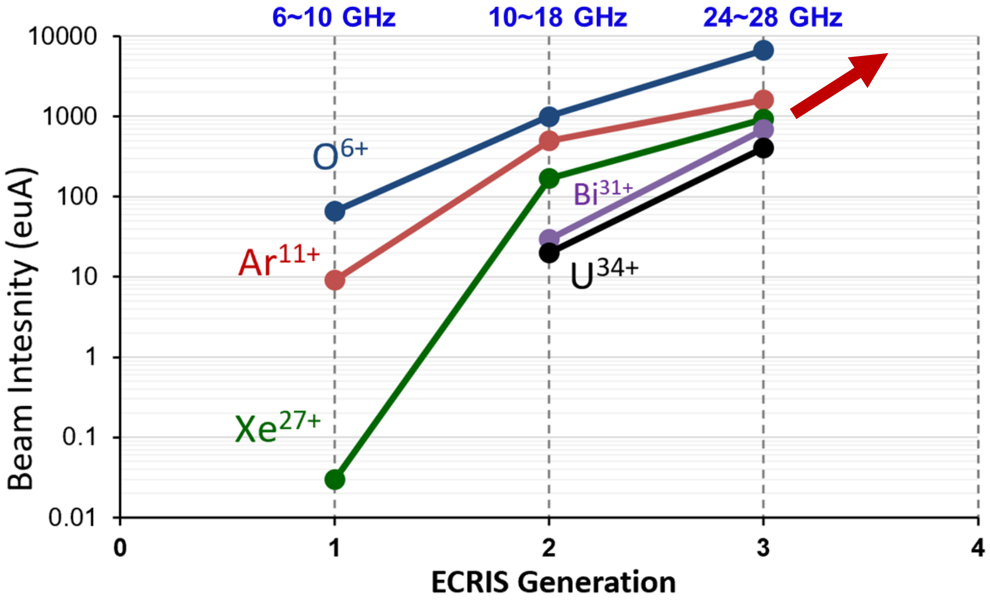
30 years continuous development

State of the art ECRIS:

- ω_{rf}: 24~28 GHz
- Microwave power: 3~12 kW

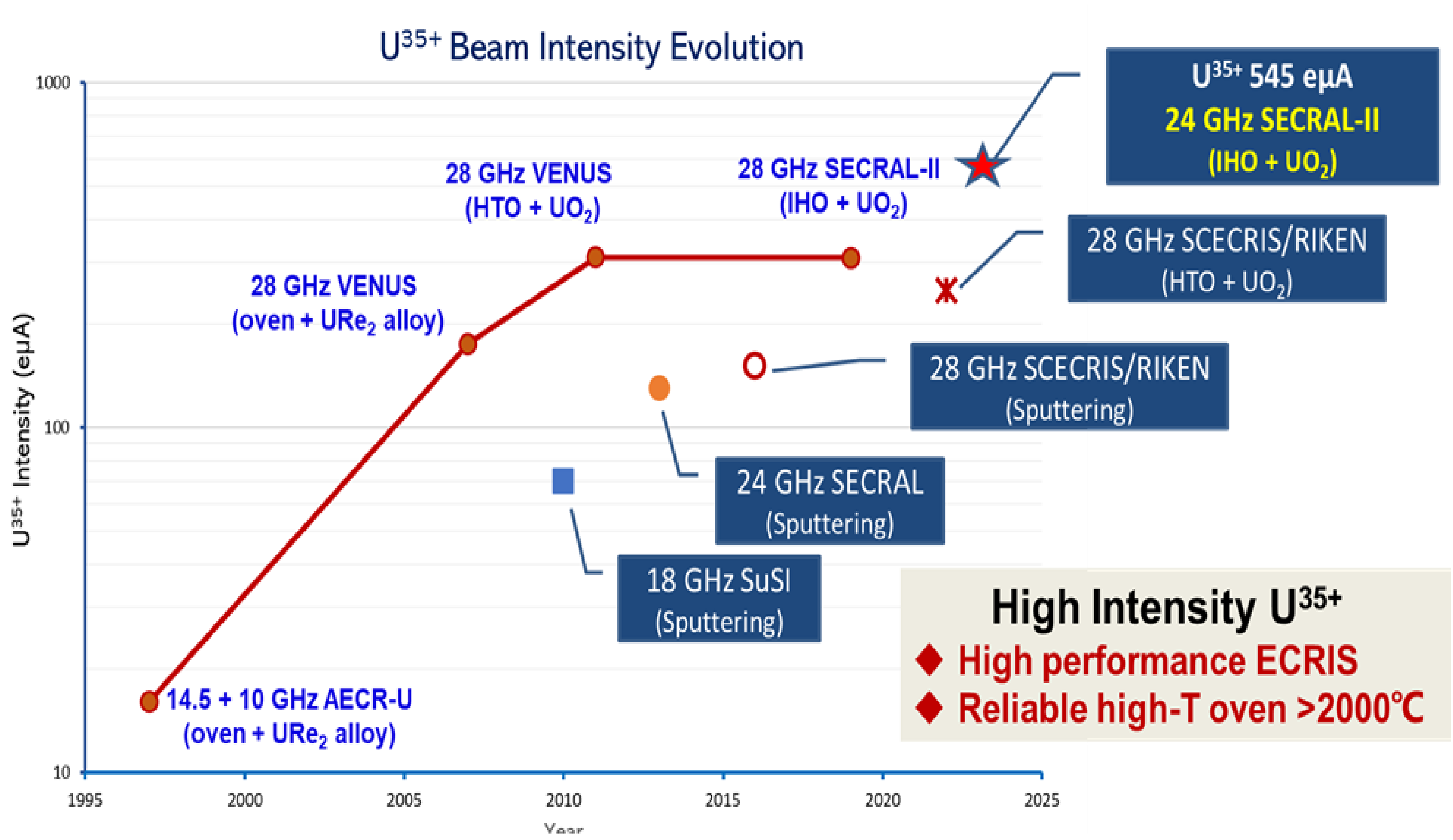


G1	G2	G3
(1970~1980)	(1980~1990)	(2000~now)

Very successful development and operation !

Uranium beam record intensities produced by the 3rd G. ECRIS

Intense U beam production with technology advancement

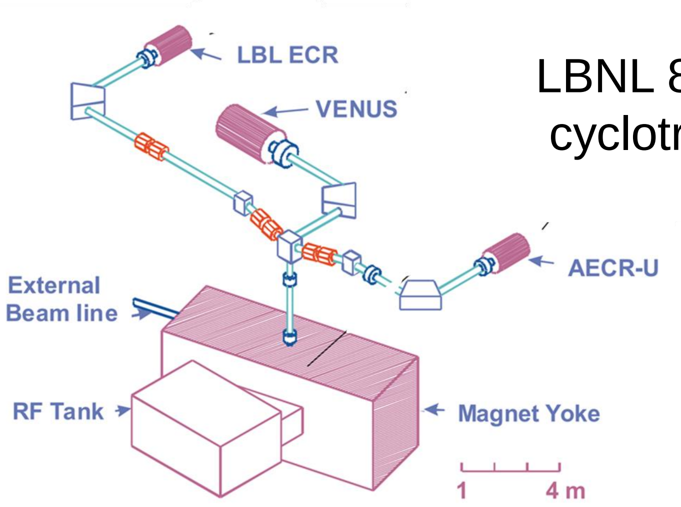


Record uranium beam intensities produced by the 3rd G. ECRISs

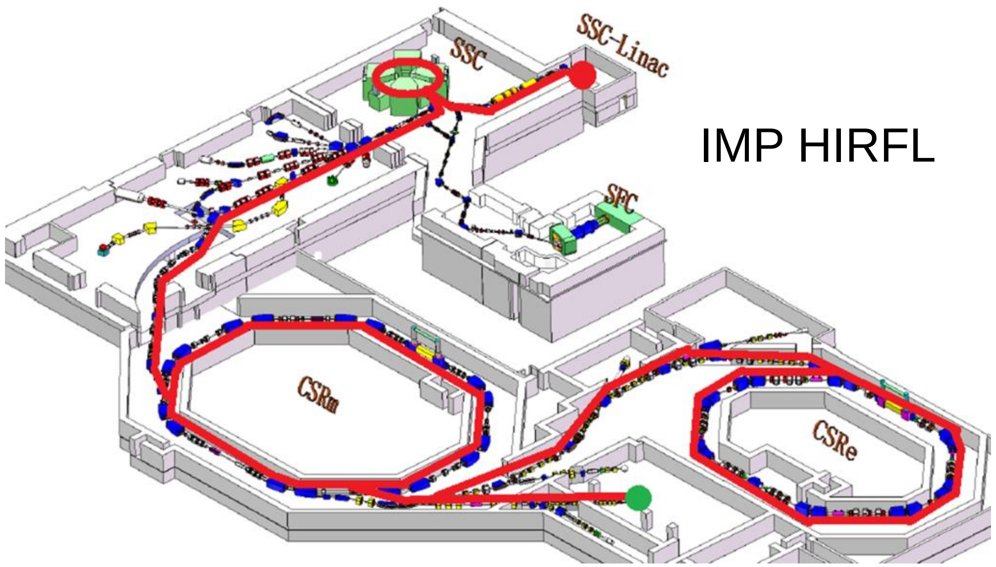
U beam Charge State	SECRAL-2023 (eμA)	Records as of 2022 (eμA)	Contributors as of 2022
33	640	450	SECRAL-II/IMP[1]
34	620	400	VENUS/LBNL[2]
35	545	310	VENUS/LBNL，SECRAL-II/IMP
42	100	62.6	SCECRIS/RIKEN[3]
46	61	36.2	SCECRIS/RIKEN
50	38	20.1	SCECRIS/RIKEN
54	19	10.4	SCECRIS/RIKEN
56	9.5	0.9	SECRAL-II/IMP
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*

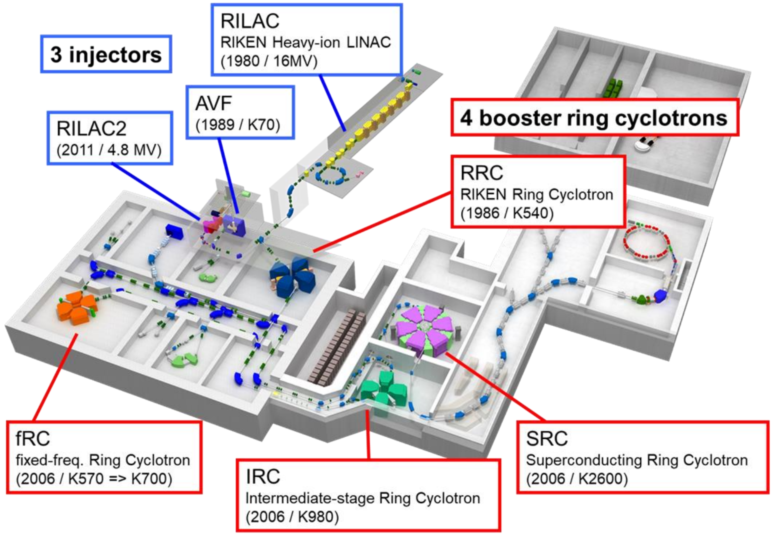
The 3rd G. ECRIS enhances performance of HI accelerators significantly



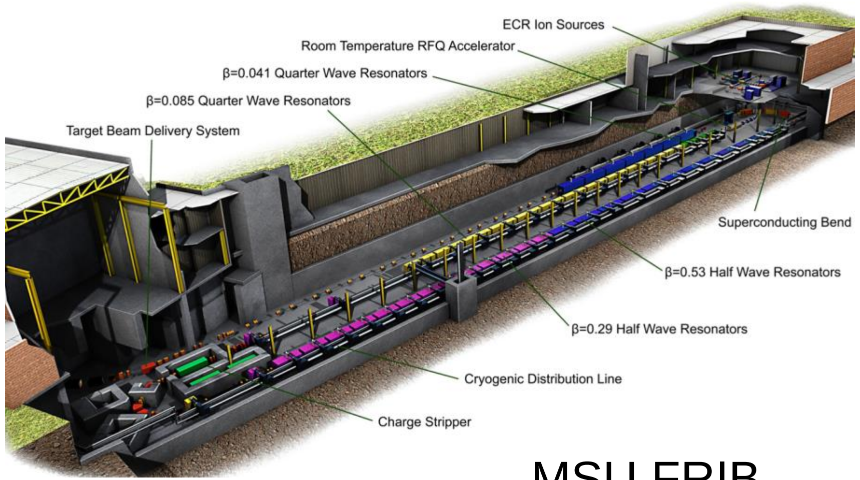
LBNL 88-inch cyclotron



IMP HIRFL

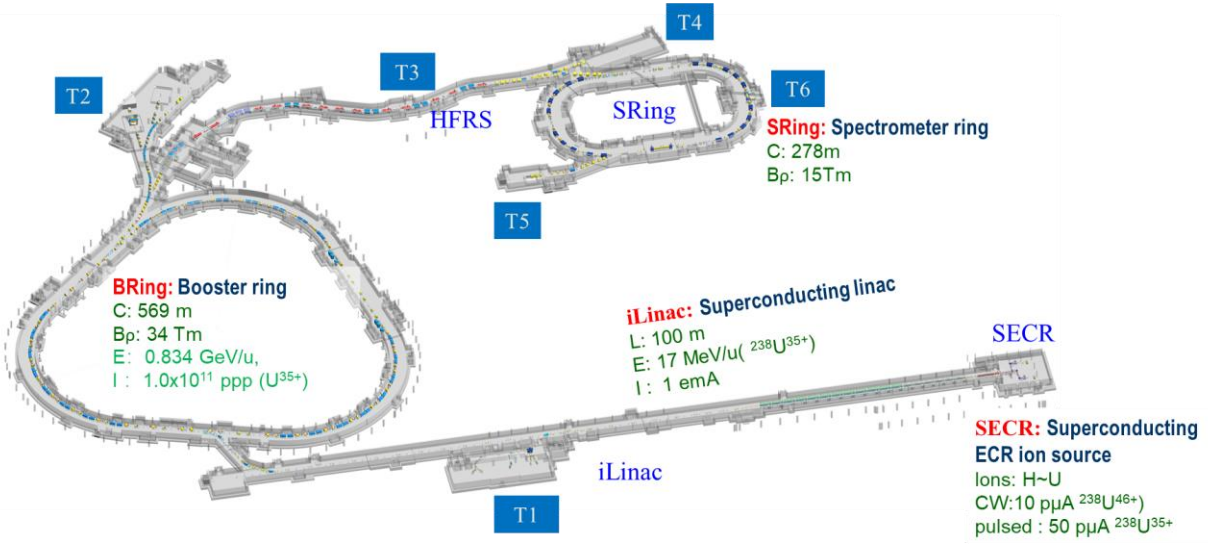


RIKEN RIBF



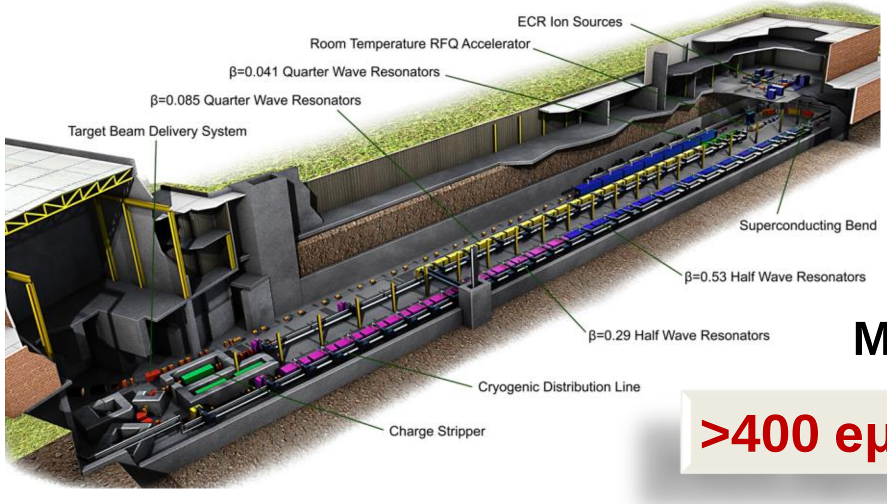
MSU FRIB

Global heavy ion accelerators need more intense HCI beams



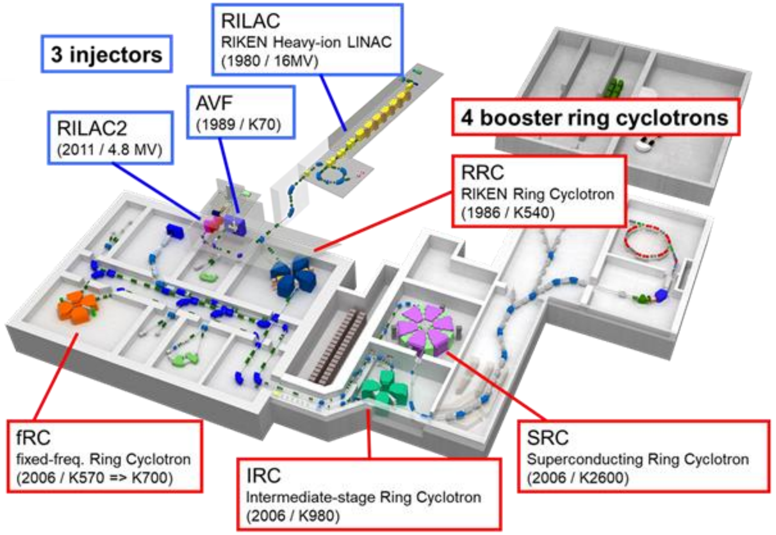
IMP HIAF (under construction)

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



MSU FRIB

>400 eμA U^{35+}, CW



RIKEN RIBF

>500 eμA U^{35+}, CW

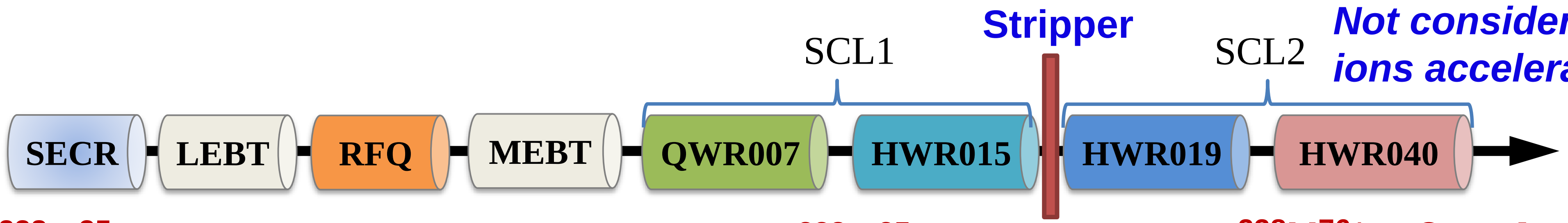
The 3rd G. ECRIS is not able to routinely deliver these beams for long-term operation!

HCI ECRIS can improve performance-cost effectively for a new HI accelerator

A CW SRF heavy ion linac for 150 Me/A Uranium beam, What ECRIS would be built?

(1). 28 GHz ECRIS. Low efficiency and lifetime problem for the stripper

Not considering Multi-charge ions acceleration



150 MeV/A
>2 pμA U beam

$^{238}U^{35+}$
12 pμA

3rd G. ECRIS

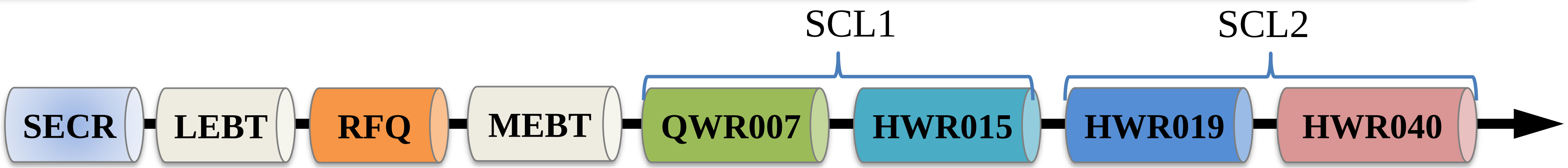
$^{238}U^{35+}$

η~20%
Lifetime?

$^{238}U^{76+}$, >2 pμA

Cavity numbers difference 5%-8%

(2). 45-60 GHz ECRIS, higher charge state. Without stripper



150 MeV/A
>2 pμA U beam

$^{238}U^{56+}$
2.5 pμA

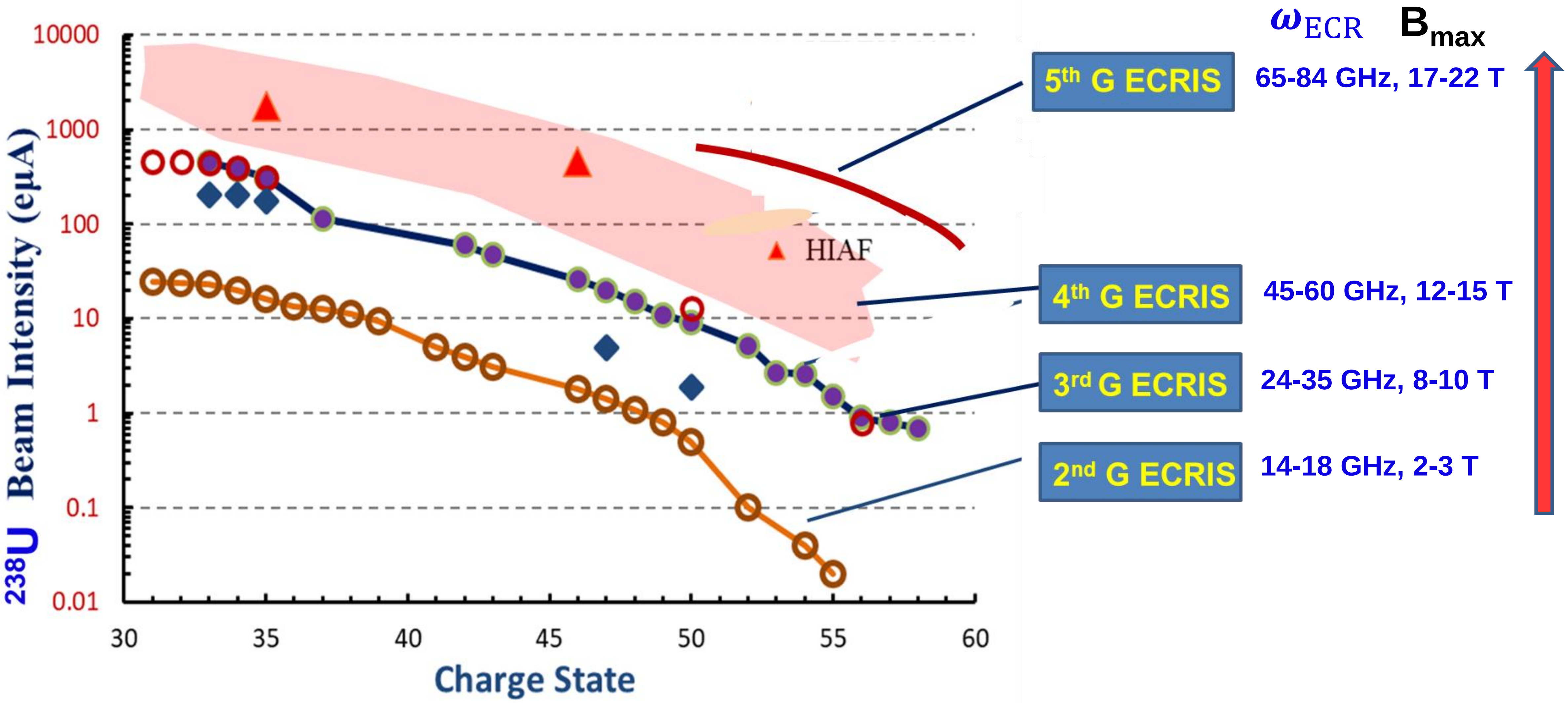
4th G. ECRIS

$^{238}U^{56+}$

$^{238}U^{56+}$, >2 pμA

HCI ECRIS generation evolution in terms of frequency and magnetic field

The next generation high-intensity HI accelerator demands the 4th even 5th G. ECRIS



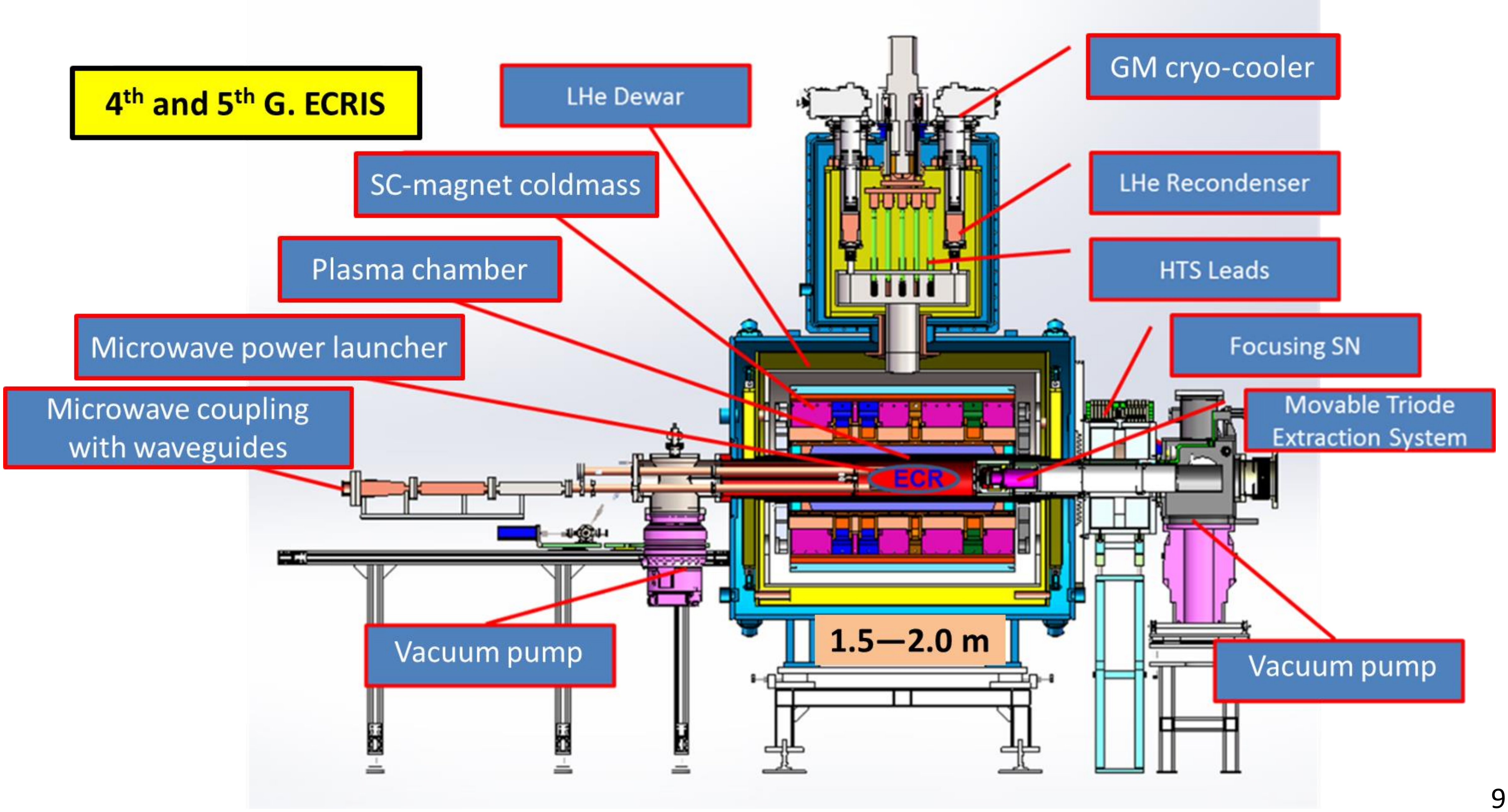
The 4th and 5th G. ECRIS only for very high charge state and current

Estimated beam intensities produced by the 4th and 5th Gen. SC ECRIS

Ion species	Charge state	4th Gen. SC ECRIS 45-60 GHz/20-30 kW [eμA]	5th Gen. SC ECRIS 65-84 GHz/50-60 kW [eμA]
^{40}Ar	16+	~1000	
	18+	~100	~300
^{129}Xe	30+	~1000	
	42+	~100	~300
	45+	~20	~60
^{209}Bi	35+	~1000	
	45+	~300	~1000
	55+	~80	~250
^{238}U	35+	~1000	
	46+	~250	~800
	50+	~160	~500
	56+	~60	~200
	60+	~10	~50

Actually most of heavy ion accelerators do not need the 4th and 5th G. ECRIS.
Only dedicated to high-intensity and high-power heavy ion accelerators

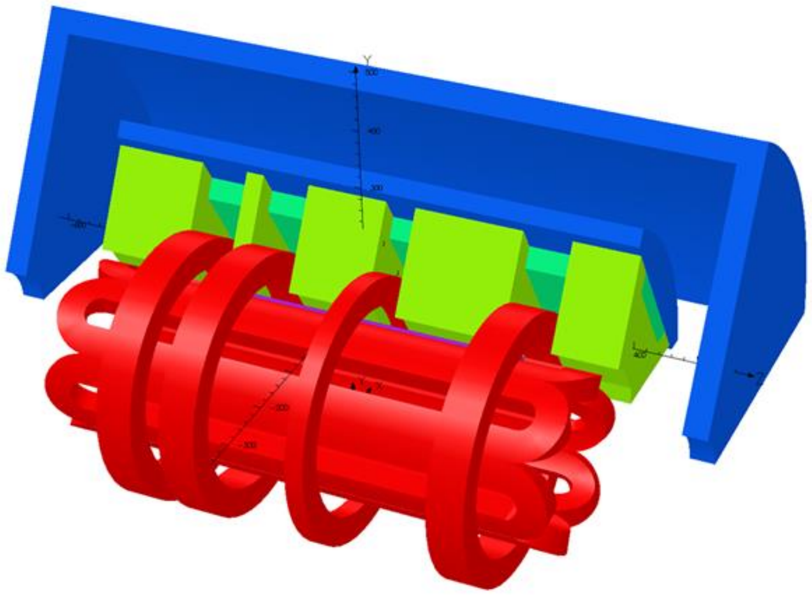
Schematic layout of the 4th and 5th Generation ECRIS



Technical Challenges of the 4th and 5th Generation ECRIS

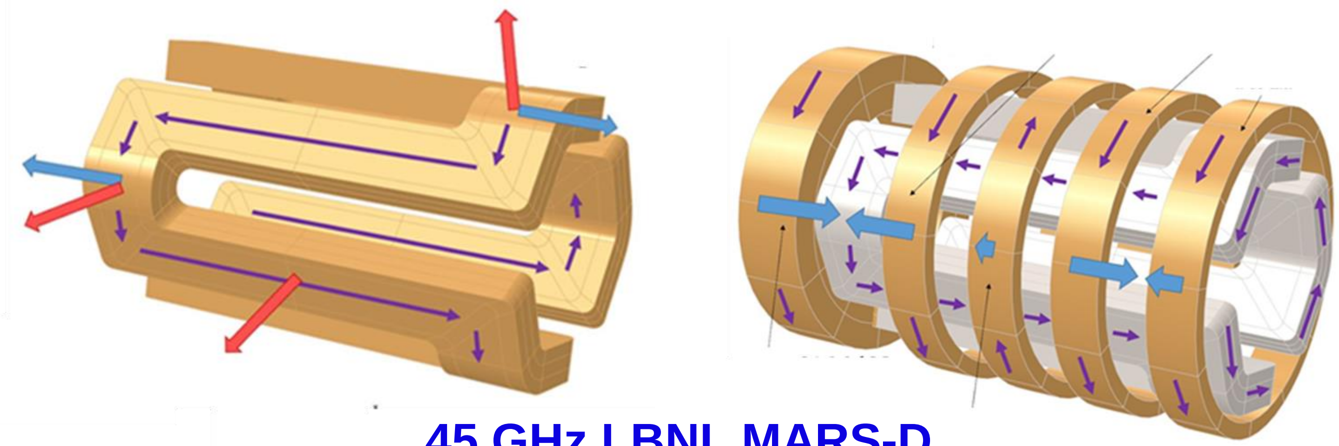
Key parameters	Unit	4th G.	5th G.	Challenges
frequency	GHz	45-60	65-84	■ High frequency high power microwave ECRH ■ High power chamber cooling
Operational RF Power	**kW**	**20~30**	**50-60 ?**	
B_{ECR}	T	1.6-2.1	2.3-3	■ Reliable high field SC magnet with min-B field configuration ★
B_{rad}	T	3.2-4.2	4.6-6	
B_{inj}	**T**	**6.5-8.8**	**9.3-12**	
B_{ext}	T	3.4-4.5	5.0-6.5	
Maximum B field at SC conductor	**T**	**12-15**	**17-22**	
Plasma Chamber ID	**mm**	**Ø150**	**Ø200?**	
U^{56+}	**pμA**	**1**	**4**	■ Intense highly-charged ion beam production with small emittances

SC magnet structure of the 4th Generation ECRIS



45 GHz IMP-FECR

- Conventional structure
- Nb_3Sn single-wire or mini-cable
- Brittleness and strain dependence
- Complicated mechanical-structure
- Sophisticated and challenging for quench protection



45 GHz LBNL MARS-D

- The closed-loop sextupole coil is worth exploring since it has many advantages.
- A successfully developed NbTi closed-loop coil may provide a new magnet structure for future ECRISs

- **Closed-loop sextupole coil – innovative structure**
- **Closed-loop coil provides radial + solenoid fields**
- **Higher field in hexagon "Corners" with hexagon chamber**
- **Complex, labor-intensive and challenging for winding**
- **NbTi or Nb_3Sn**

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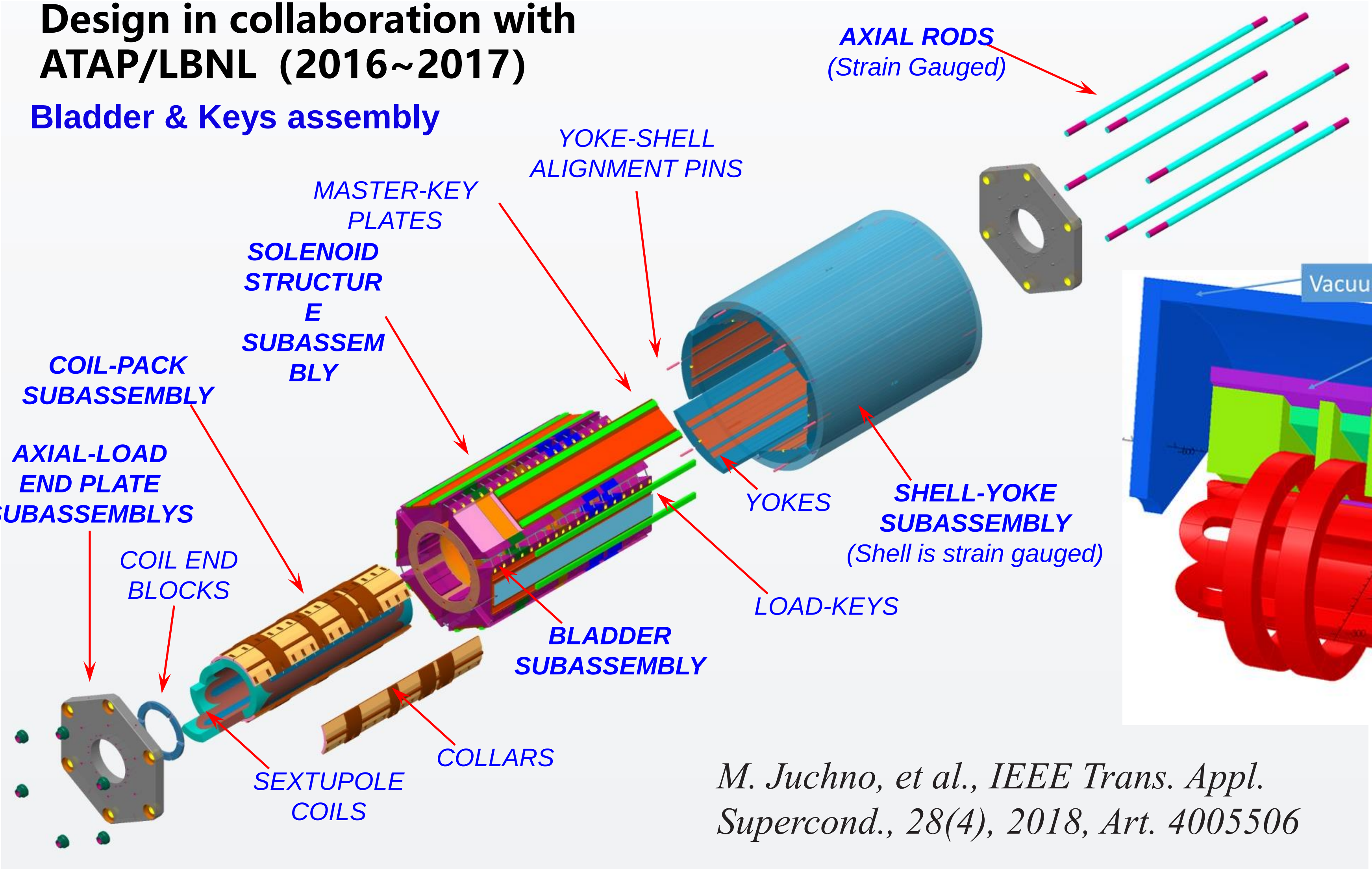
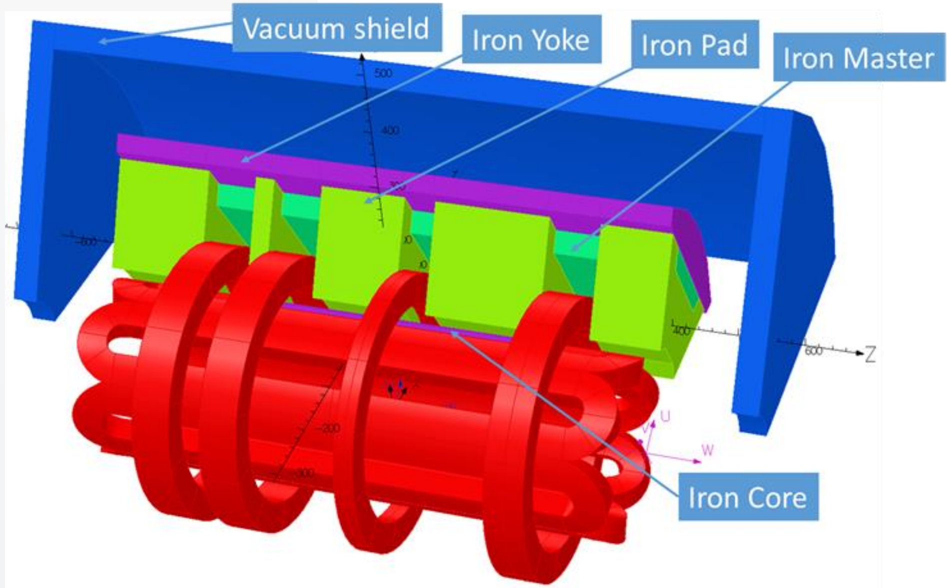
45 GHz FECR : Nb_3Sn Magnet Cold-Mass Structure

Design in collaboration with ATAP/LBNL (2016~2017)

Bladder & Keys assembly

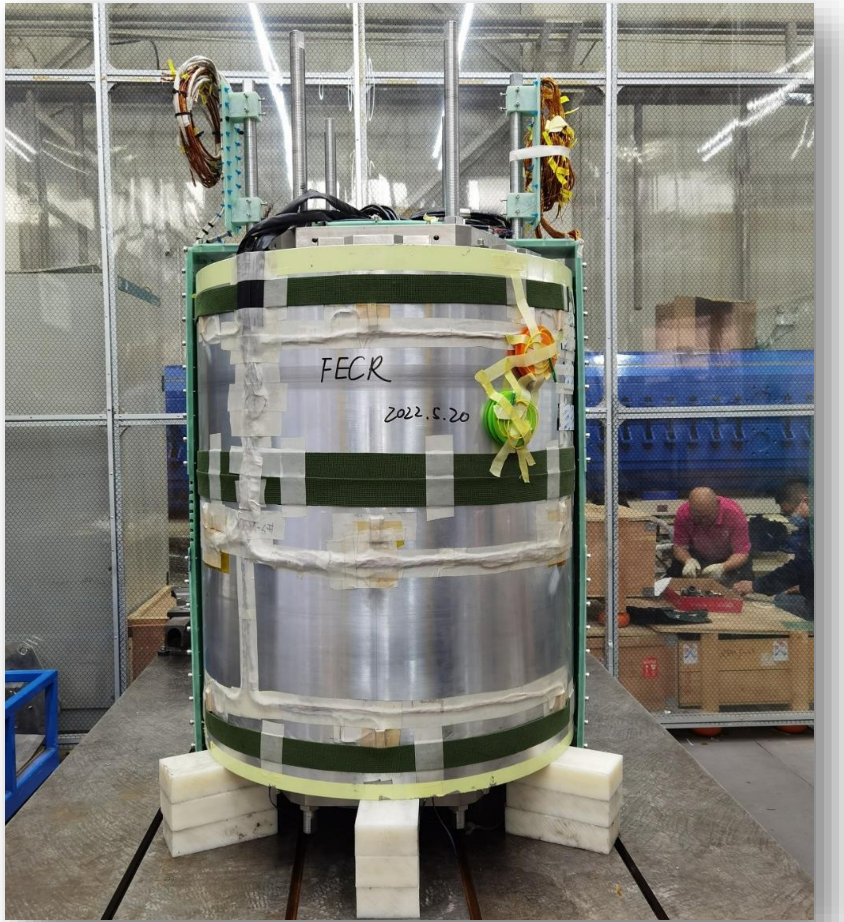




M. Juchno, et al., IEEE Trans. Appl. Supercond., 28(4), 2018, Art. 4005506

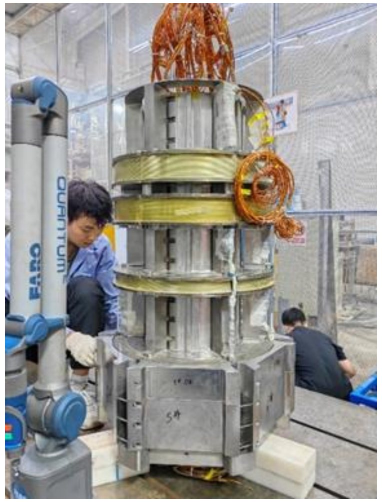
Key technologies and tests completed in close collaboration with XSMT in China (since 2016)

45 GHz FECR : Completed full-scale SC magnet Coldmass



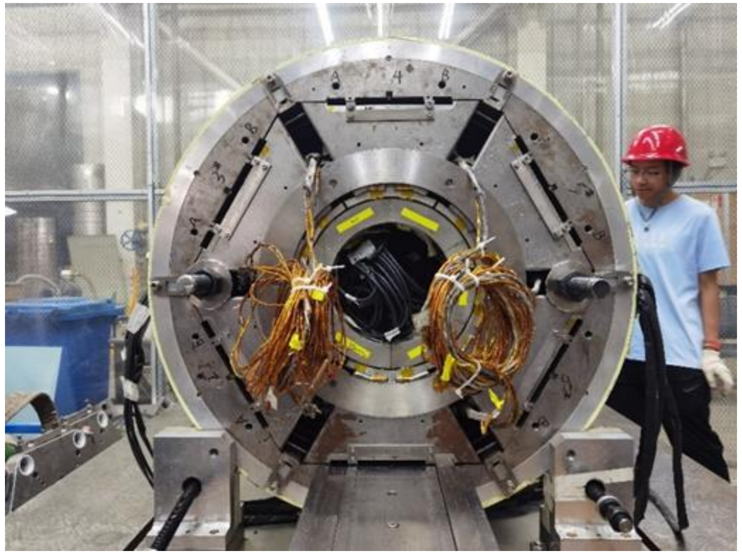
Completed full-scale FECR Nb_3Sn magnet coldmass

- Stress over-shoot during pre-loading (assembly)
- Sextupole coil leads broken



Nb_3Sn solenoids

NbTi sextupole



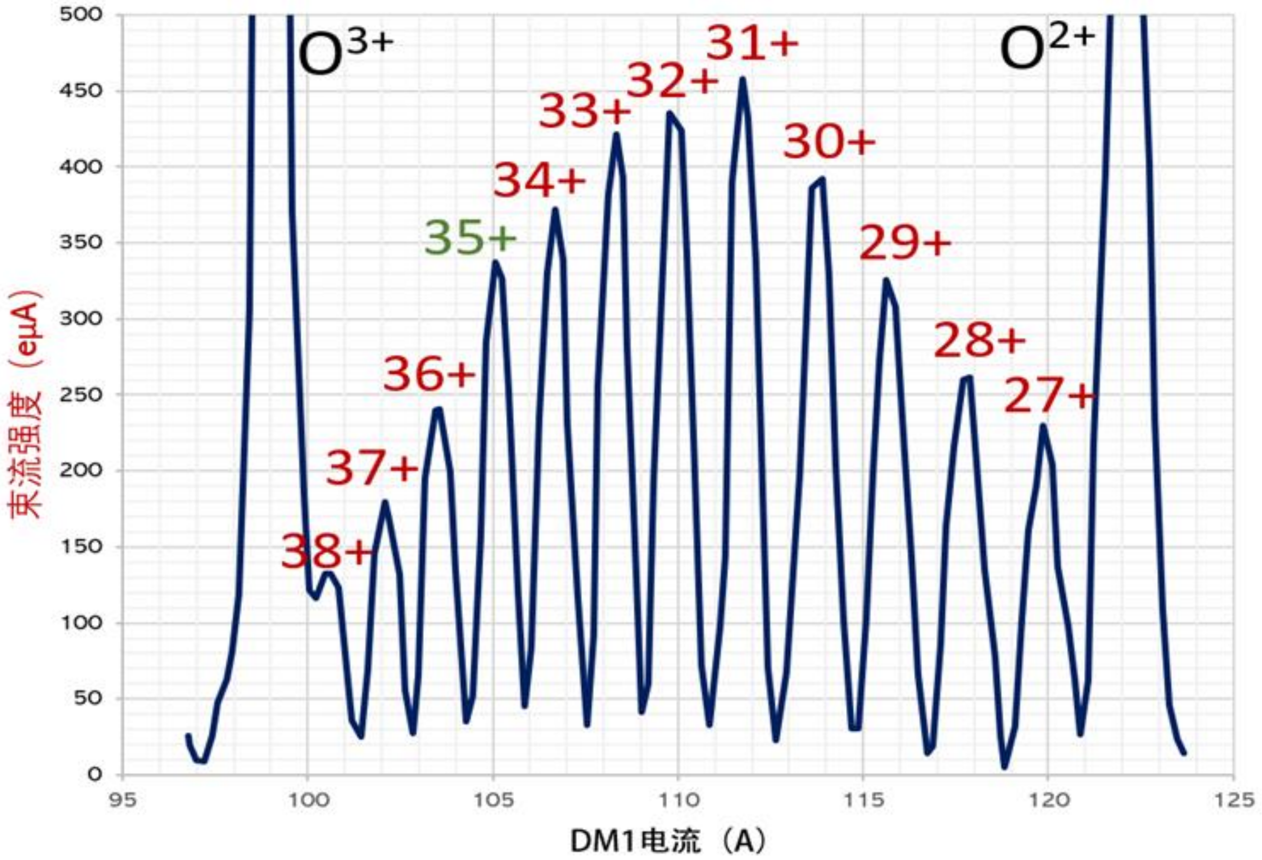
Full-scale FECR Nb_3Sn+NbTi hybrid-magnet coldmass

45 GHz FECR preliminary commissioning results with hybrid magnet

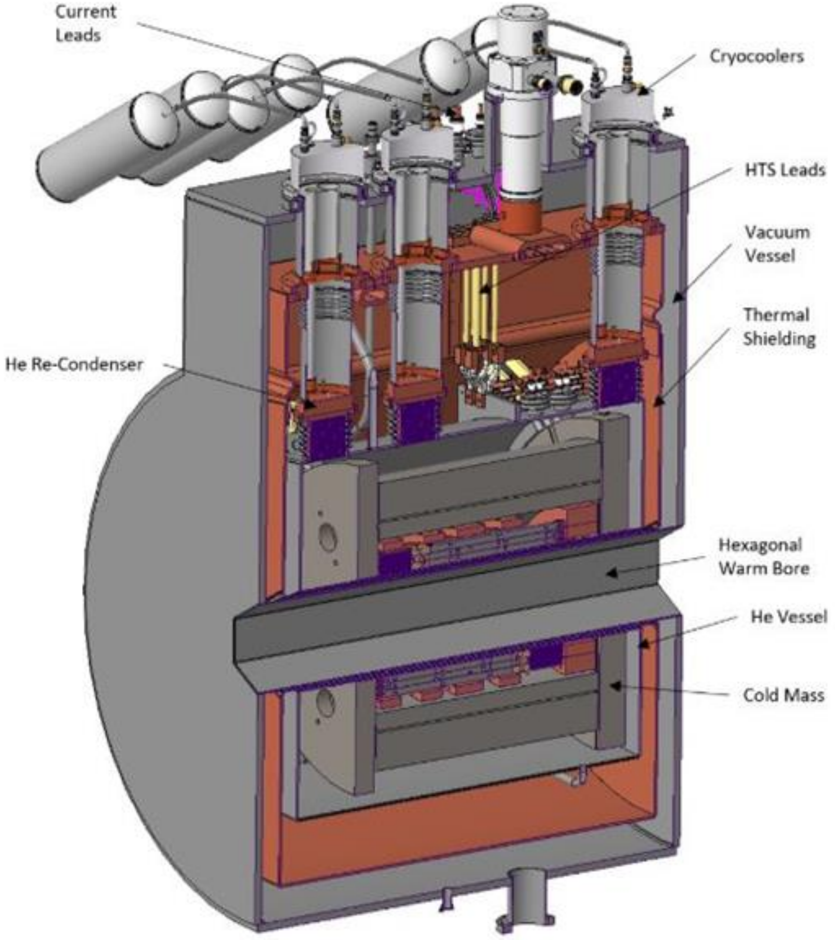
45 GHz FECR

350 eμA $^{209}Bi^{35+}$

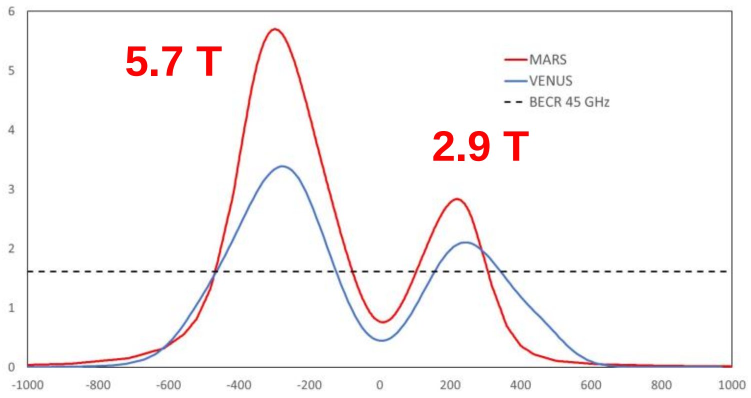
6.5 kW 45GHz+ 5.0 kW 28GHz

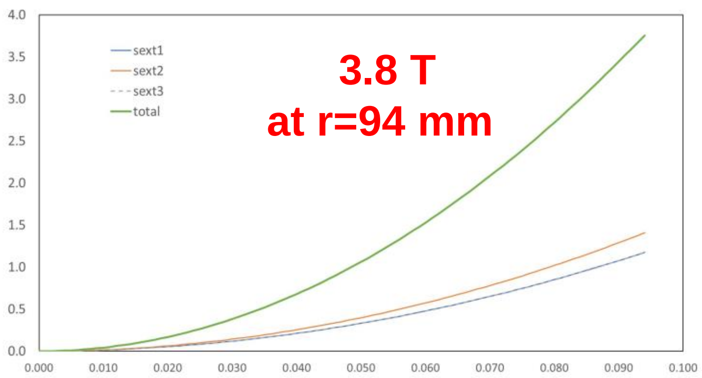


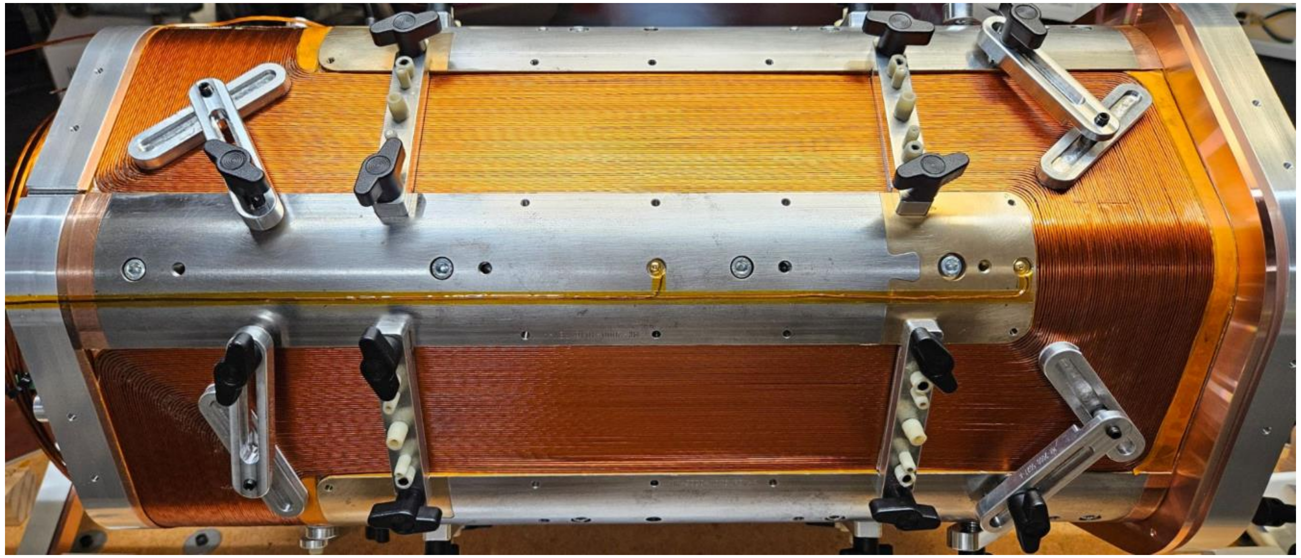
45 GHz LBNL MARS-D ECRIS NbTi-magnet under construction



45 GHz LBNL MARS-D







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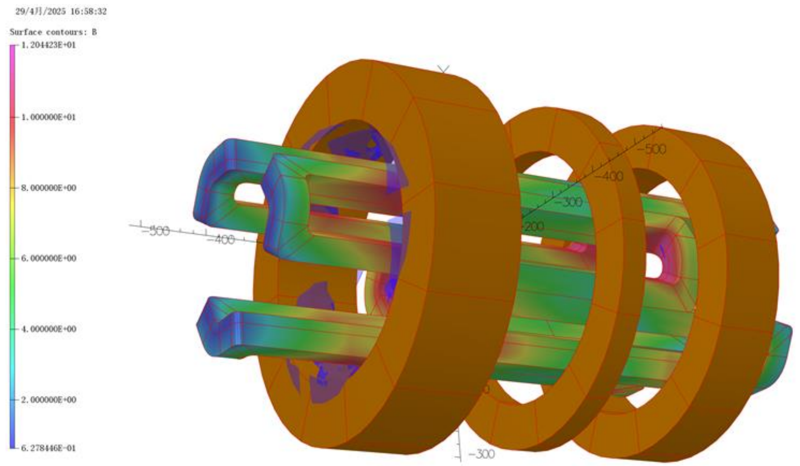
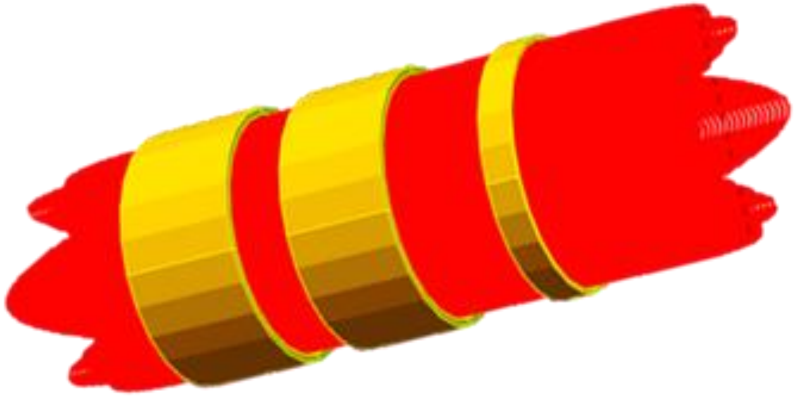
SC magnet structure of the 5^{th} Generation ECRIS

Nb_3Sn single-wire or mini-cable only for 65 GHz

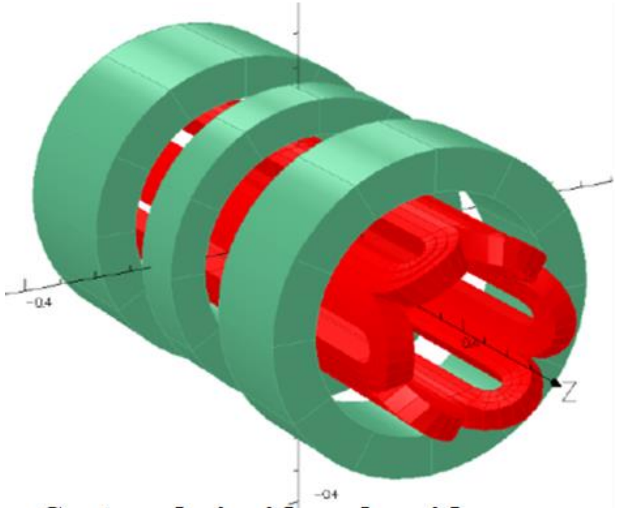


Optimized closed-up coil structure (MARS-D upgraded version)

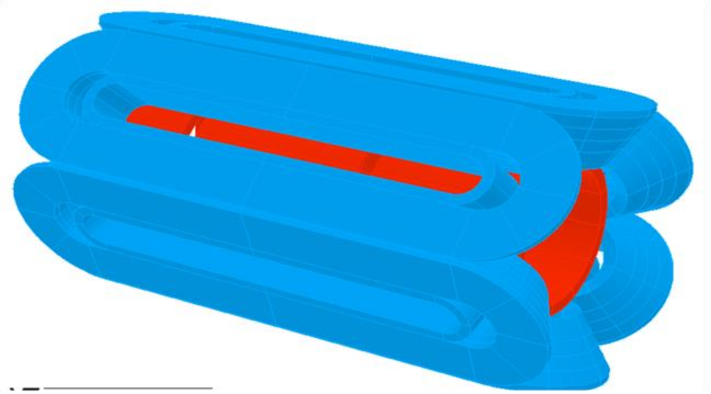


CCT or DCT sextupole under study
(Canted or Discrete Cosine Theta)

HTS option for 70-84 GHz

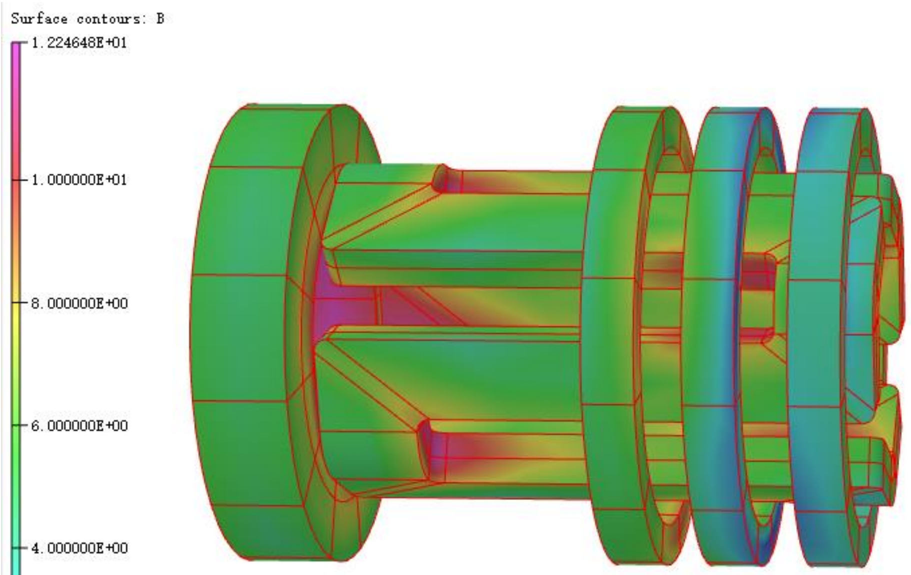


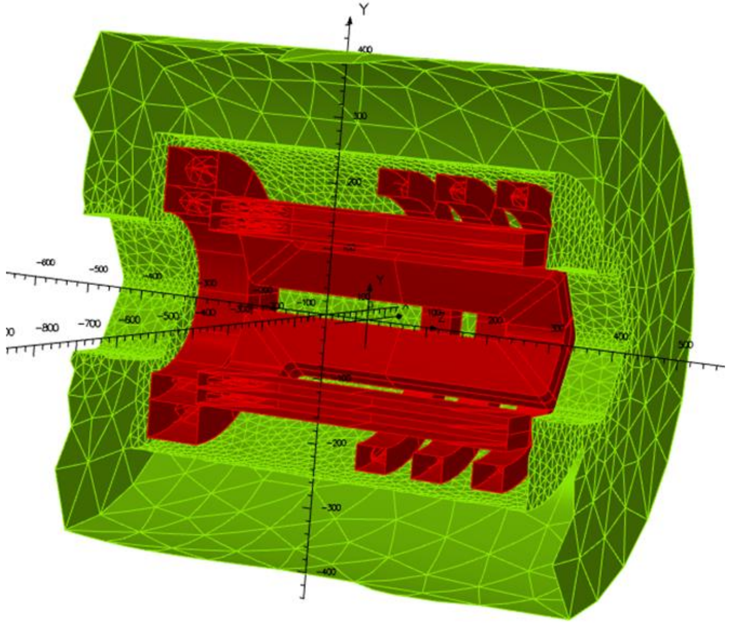
Sextupole-inside-solenoid



Solenoid-inside-sextupole

Optimized closed-up coil structure for the 65 GHz 5th G. ECRIS





Optimized on basis of 45 GHz MARS-D

Both solenoids and sextupole coils are 2×4 Ruthford mini-cable with Ø0.62mm Nb_3Sn strand

B_{peak} =12.2 T on Injection Solenoid

Inject Sol: J= 280/165 A/mm^2

Mid Sol: J= 400 A/mm^2

Extra Sole： J= 300 A/mm^2

Stored Energy = 1.94 MJ

Sextupole hexagonal coil dimensions:

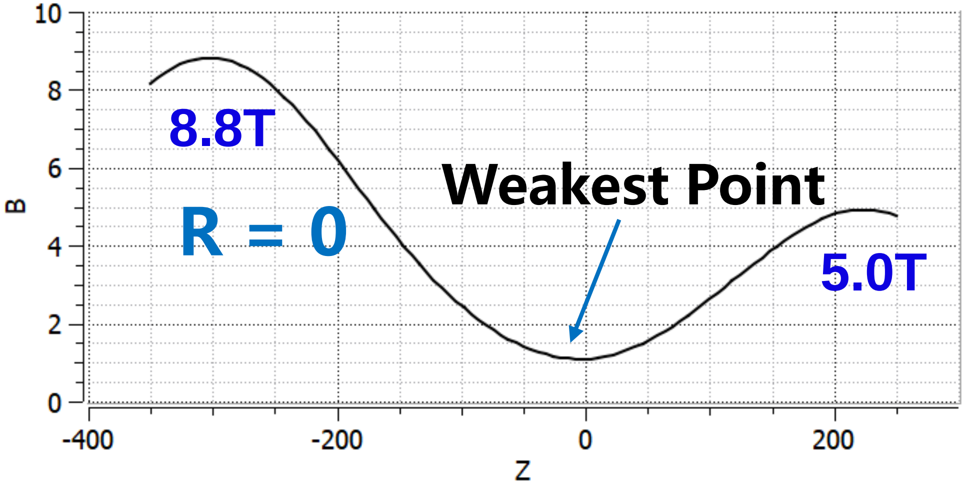
Minor ~ 110 mm, Major ~ 127 mm

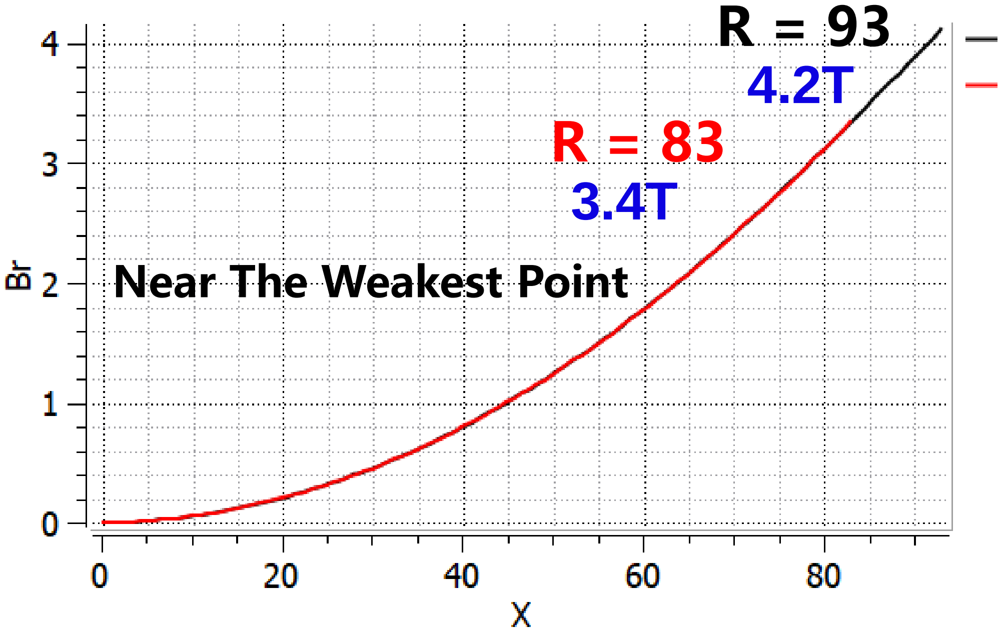
Hexagon chamber: Min: 83 mm and Maj: 93 mm

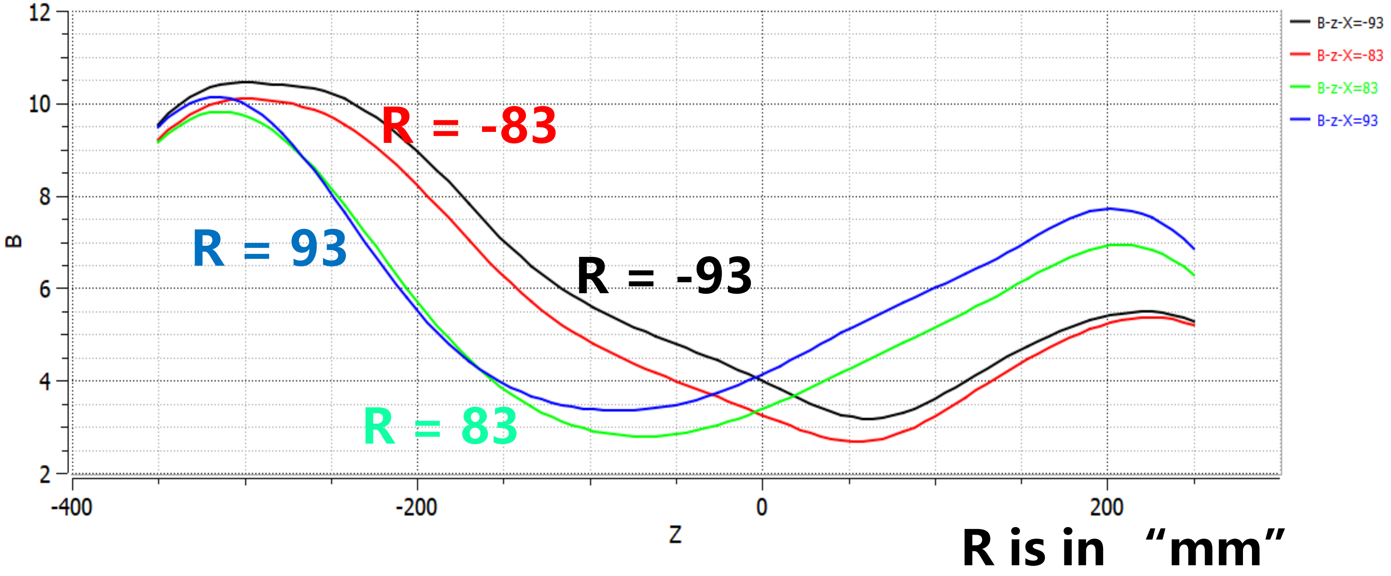
Take advantages of the "V-shape" Sextupole and the hexagon plasma chambet

Preliminary magnetic field calculation for the 65 GHz 5th G. ECRIS (1)

Axial and Radial Fields

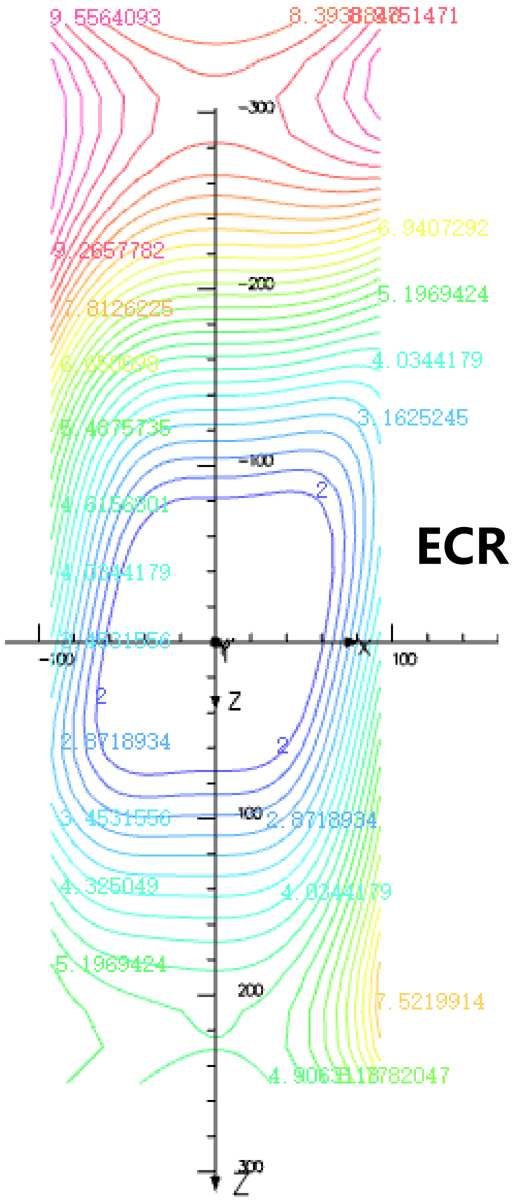




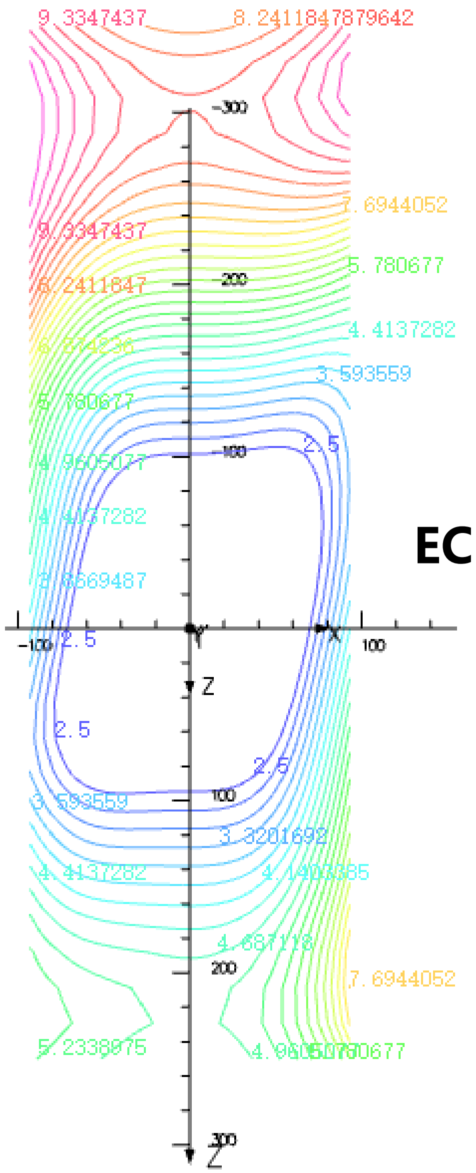


Preliminary magnetic field calculation for the 65 GHz 5th G. ECRIS (2)

3D field contour



56 GHz
ECR Surface：2T



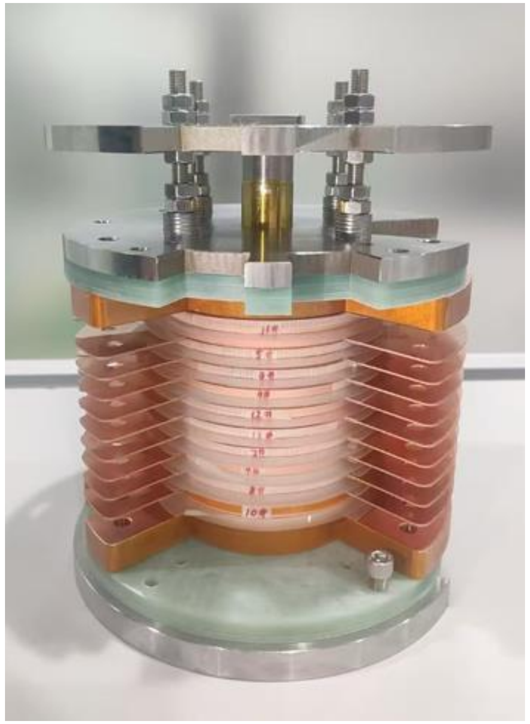
65 GHz
ECR Surface：2.3T

HTS magnet for the 5th Generation ECRIS >65 GHz

- Possible to realize J_c >1000 A/mm^2 , B > 20T, T > 20K
- HTS conductors: REBCO, BSCCO (Bi-2223, 2221), IBS
- REBCO (+ BSCCO) commercially available, although expensive
- Interests from other communities (eg. fusion, NMR, high-field science)

  Demonstrations with REBCO high-field solenoids:

  solenoids (28 T Bruker; 27 T IPP-CAS) , toroidal coils (20 T)
- Key issues: degradation, quench losses and quench protection, cost
- ECRIS demands: field quality, reproducibility, stability
- Develop/validate REBCO cable + learn how to wind, insulate, load, cool, quench protection
- Many labs over the world involved in high field HTS magnet development



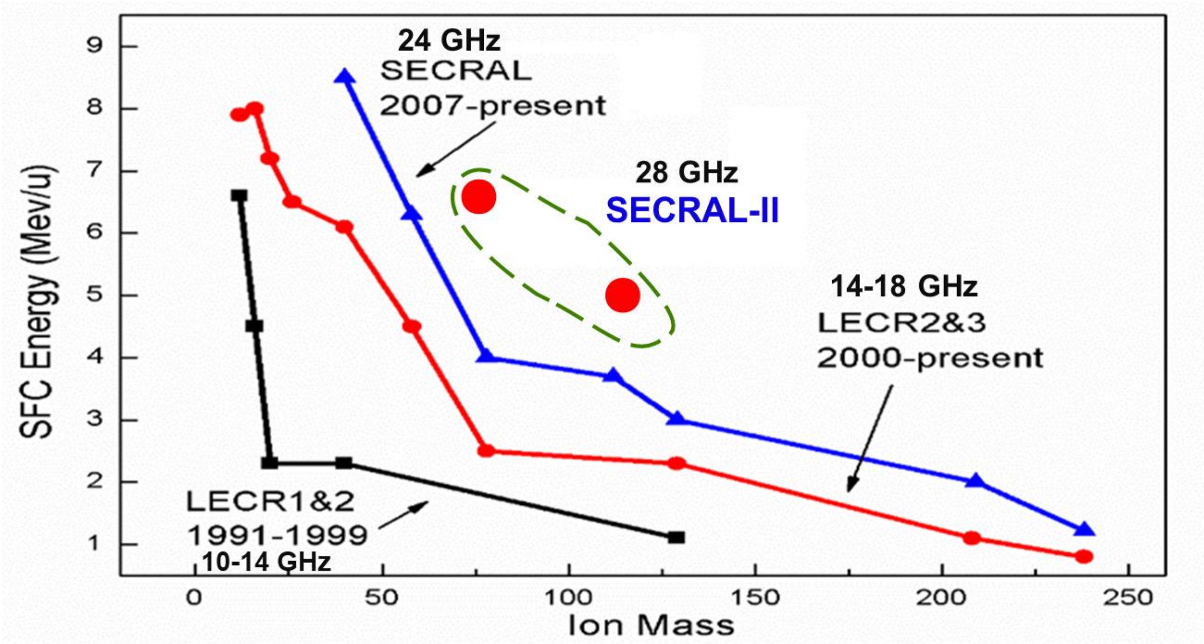
REBCO solenoid by IPP-CAS.
27 T, Ø20 mm

Conclusion

- Very successful development for the 3rd G. ECRIS (28 GHz) since 2000, being operated and had enhanced performance of the world-wide HI accelerators.
- The next genenration high-intensity HI accelerator demands the 4th (45-60 GHz) even the 5th (65-84 GHz) G. ECRIS for higher intensity and charge state with performance-cost effectiveness.
- Gyrotrons up to 100 GHz/100 kW are achievable .
- The 4th G. ECRIS could rely on LTS Nb_3Sn technology or innovative magnet-structure with NbTi technology, which are quite challenging technically for both option.
- The 5th G. ECRIS (> 65 GHz) can only rely on HTS magnet technology which needs very intensive R&D world-wide.
- The current engineering path by increasing magnetic field and operation frequency to enahnce performance of the highly-charged ECR source may end soon unless HTS magnet technology would achieve significant breakthrough.
- Fundamental physical path is the only way to continue the ECRIS future development on both the charge state and beam intensity

Thank you for your attention !

28 GHz SECRAL-II operation improved E & I of HIRFL significantly



HIRFL-SFC cyclotron (k=69) used as an injector to SSC or CSR

SECRAL-I delivered $^{238}U^{46+}$ beam to increase energy and intensity from SSC-linac and SSC.