Superconducting Magnets for High Performance ECR Ion Sources

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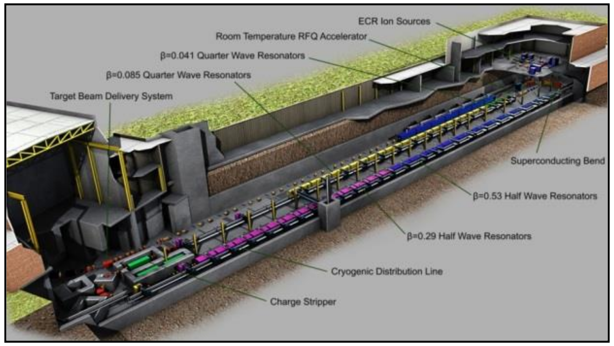
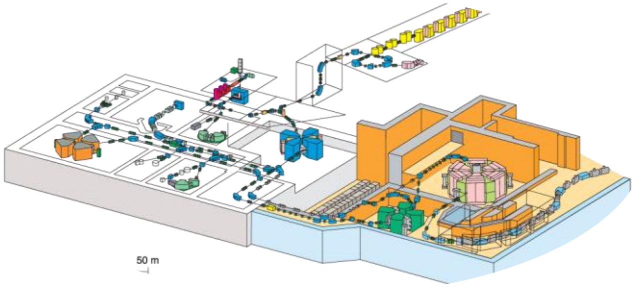
Outline

- Introduction
- Worldwide SC-magnet development for 3rd G. ECRIS
- Development of SC-magnet for 4th G. ECRIS

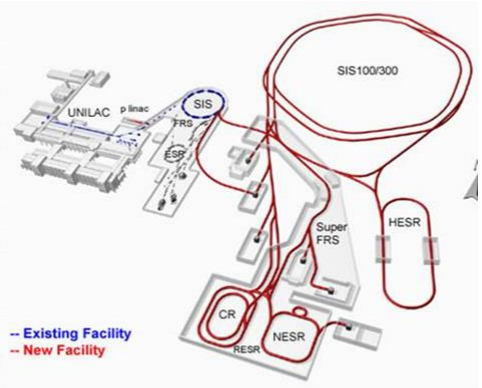
Worldwide Large Scale Heavy Ion Facilities



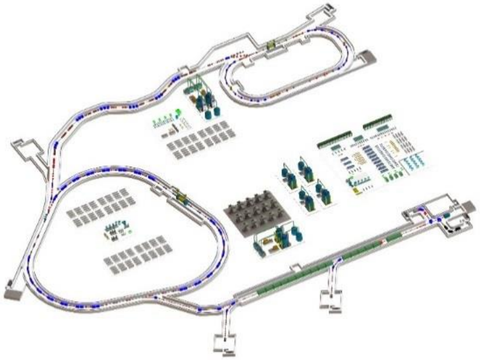
MSU FRIB U^{34+} 440 eμA/ CW



RIKEN RIBF U^{35+} 525 eμA/ CW

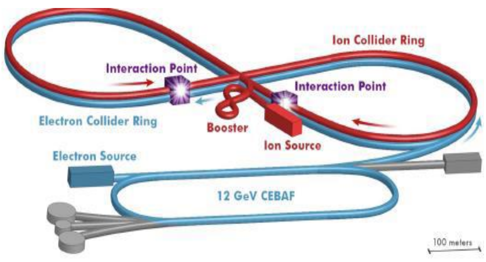


GSI FAIR A/q ≤6.0 1emA/CW



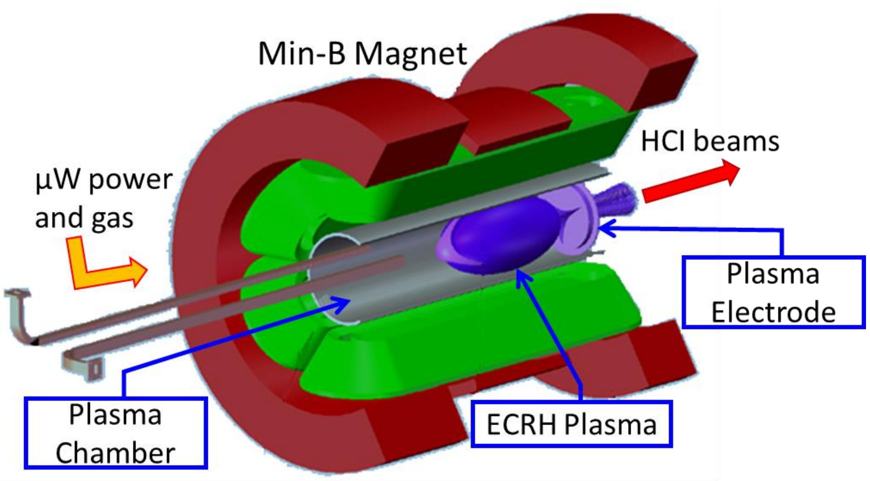
HIAF IMP U^{35+} 700 eμA/CW & 1750 euA/Pulsed

SPIRAL2 Ar^{12+} 1 emA/ CW Bi^{30+} 1 emA/CW



J-Lab JLEIC Pb^{30+} >500 euA/pulsed

Introduction



Plasma Magnet Microwave

Electron Cyclotron Resonance
Ion Source

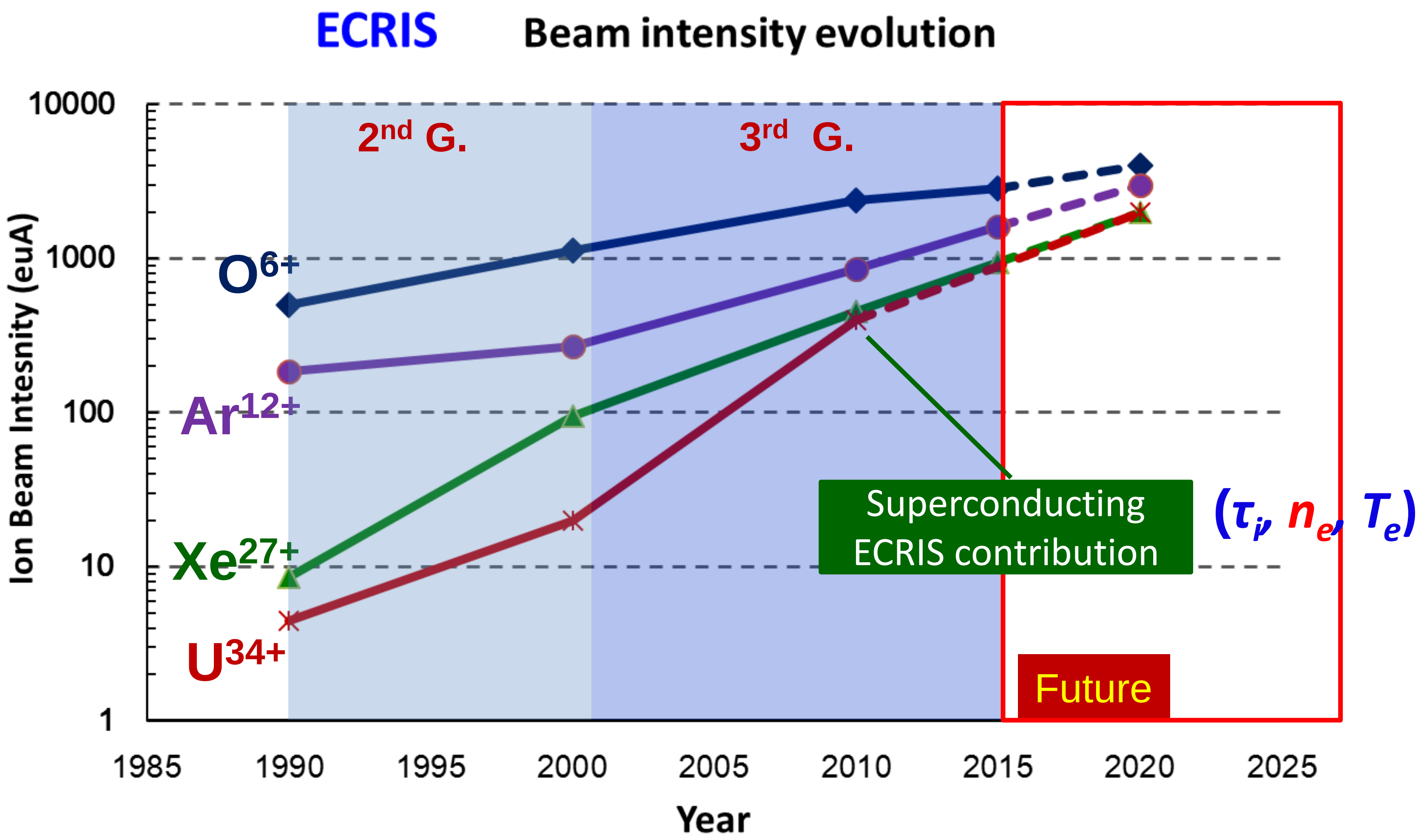
$$B_{ecr} = \frac{\omega_{rf} m_e}{e}$$

- $I_i^q = \frac{1}{2}\frac{n_i^q\, q\, e V_{ex}}{\tau_i^q}$ n_i^q ion density for species i charge q; τ_i^q Confinement time for species i charge q; $\sum_{i,q} n_i^q\, q_i = n_e$ (Plasma neutrality)

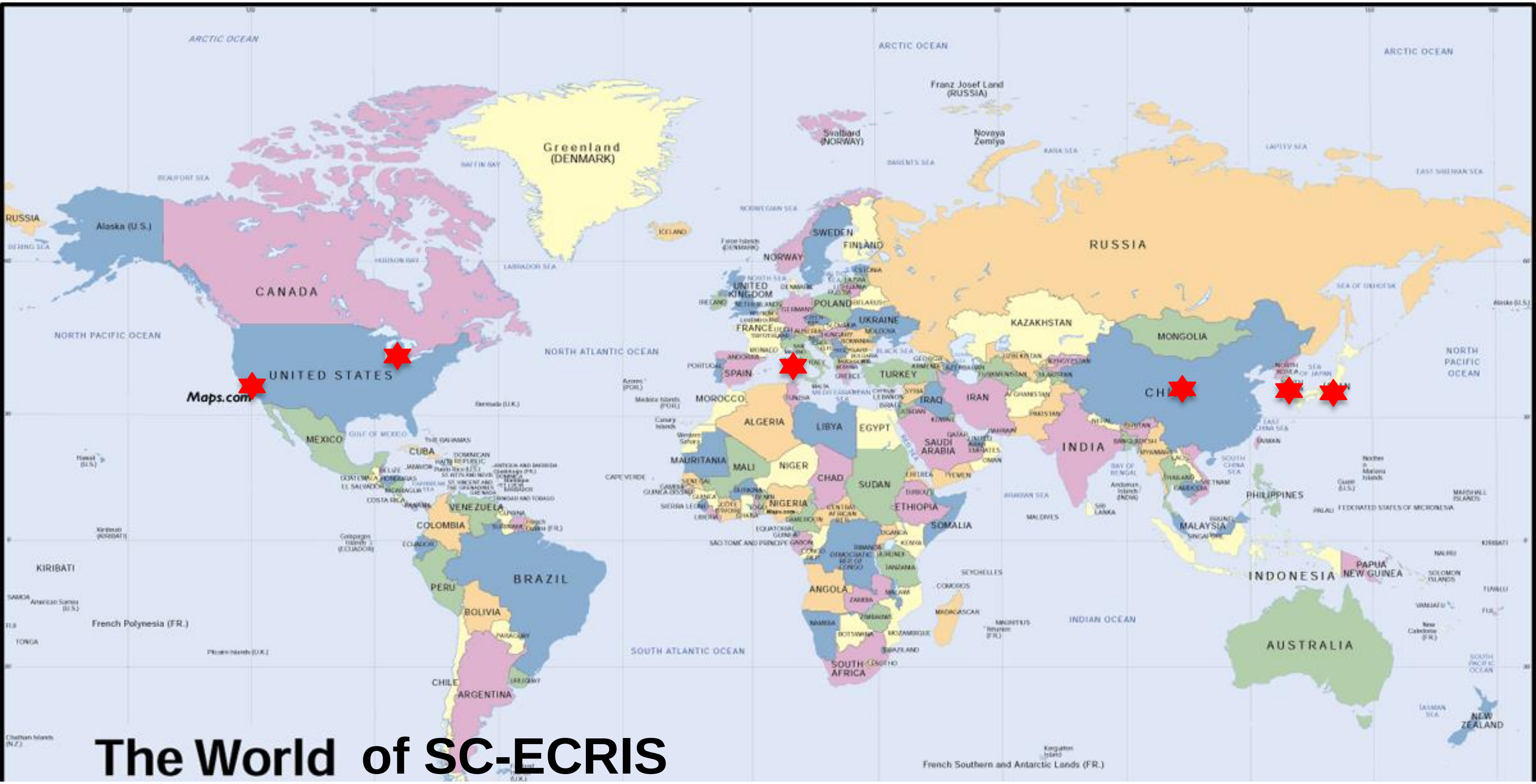
- RF dispersion equation at resonance : $(n_e T_e) \approx (\frac{m_e \varepsilon_0 \omega_{rf}^2}{e^2}) m_e c^2$ $I^q \ \alpha\ \omega^2_{ECR}$

- Plasma Stability condition : $\beta = \frac{n_e k_b T_e}{(\frac{B^2}{2\mu_0})} < 1$ As $n_e \nearrow$ $B \nearrow$

Introduction

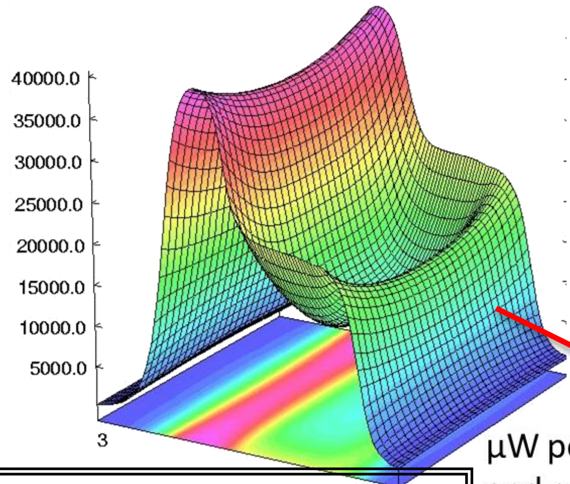


Introduction

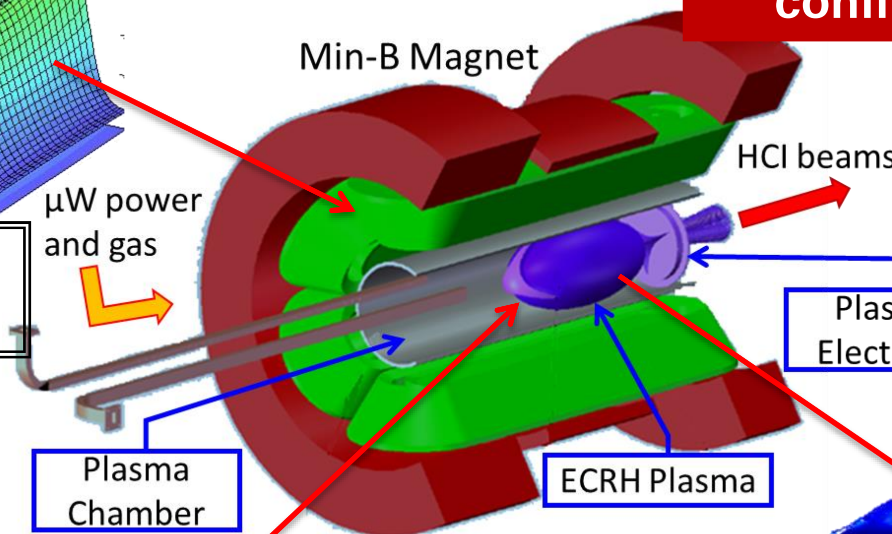


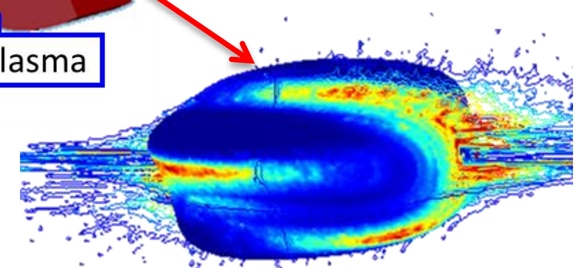
SC-Magnet Development for 3rd G. ECRIS

- ECRIS performance not determined by the magnet structure
- As long as sufficient confinement realized



$|B|_{min}$ configuration magnetic confinement

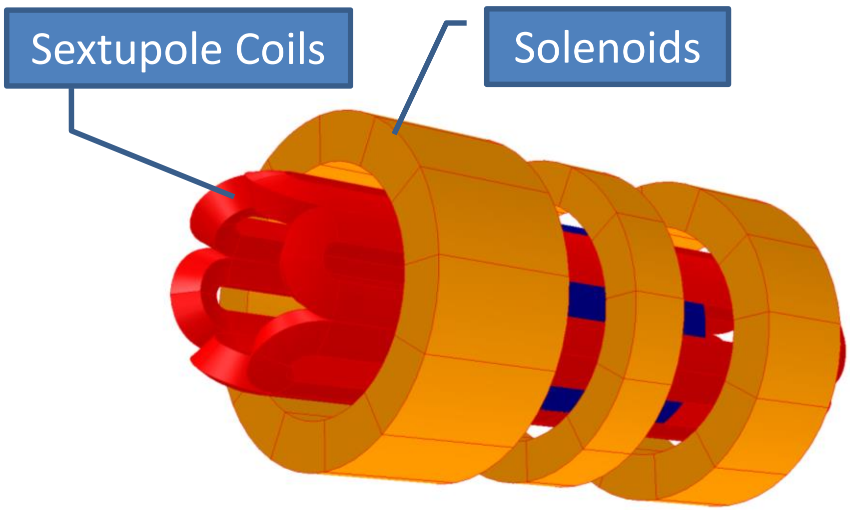


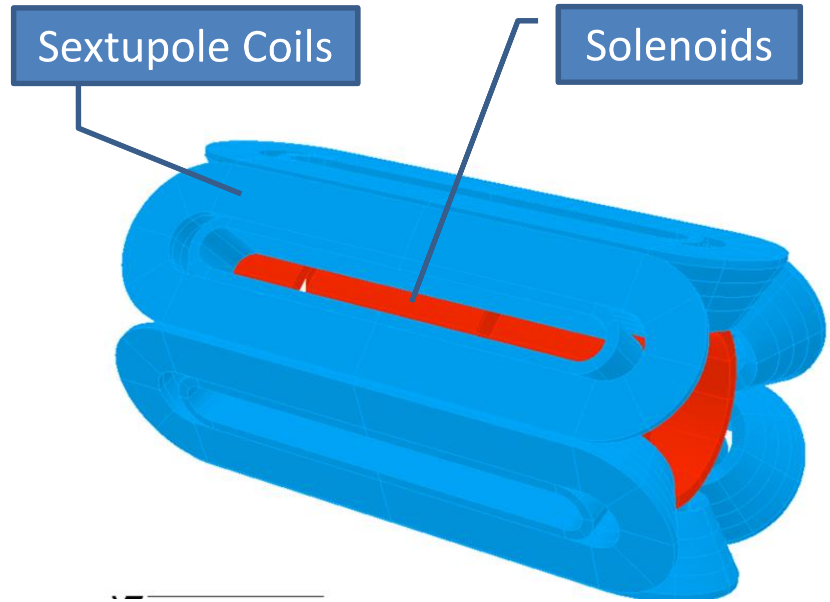


Dense hot plasma and HCIs production

Stochastic heating of electrons through ECRH $W_{ecr} = \frac{eB_{ecr}}{m_e}$

SC-Magnet Development for 3rd G. ECRIS





Conventional Structure

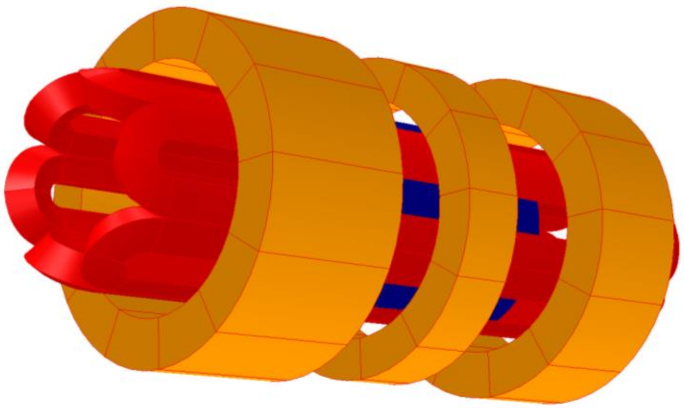
- SERSE INFN/Catania
- VENUS LBNL
- SuSI NSCL/MSU
- SCECRIS RIKEN
- FRIB SCECR FRIB/MSU
- RAON SCECR RISP
- Busan SCECR KBSI/Busan

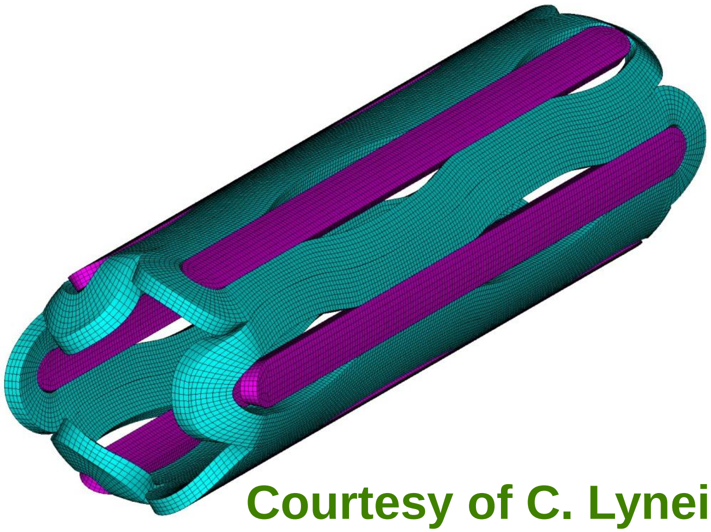
Reversed Structure

- SECRAL IMP/Lanzhou
- SECRAL II IMP/Lanzhou

SC-Magnet Development for 3rd G. ECRIS

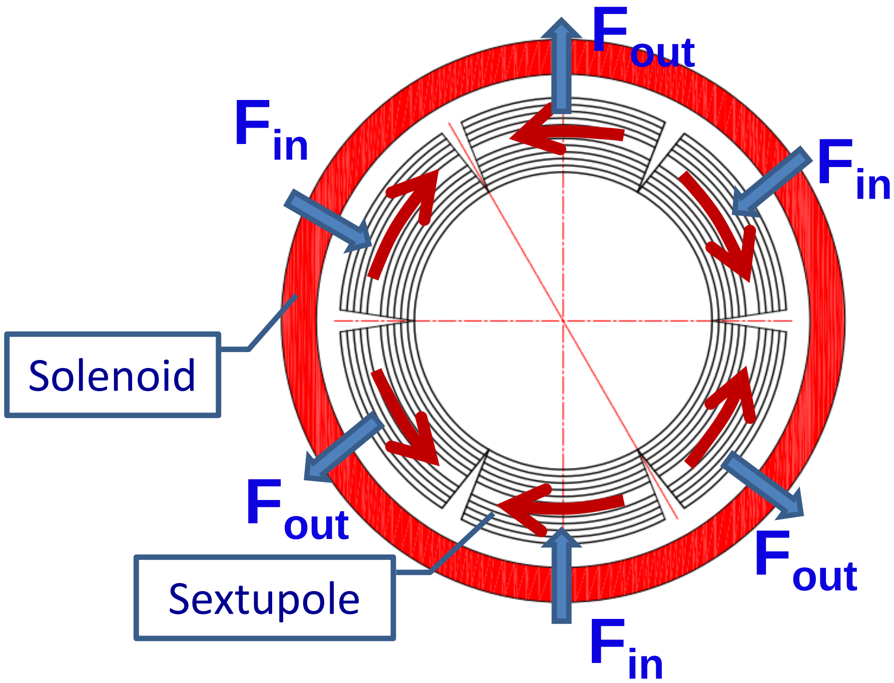
Conventional structure





Courtesy of C. Lyneis

Exaggerated displacement for illustration (×100)



- Complicated EM forces and stresses
- Sophisticated installation fixture, tooling and clamping structure
- Bulky magnet and high cost
- High radial field efficiency

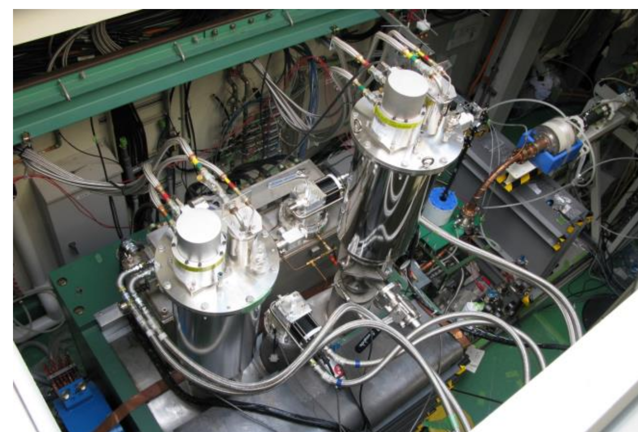
SC-Magnet Development for 3rd G. ECRIS

Conventional structure SC-ECRISs

SERSE-18 GHz: 1997

VENUS-28 GHz: 2002

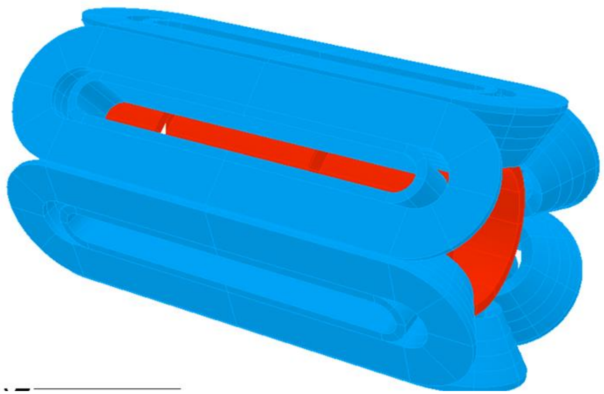
SuSI-24 GHz: 2007

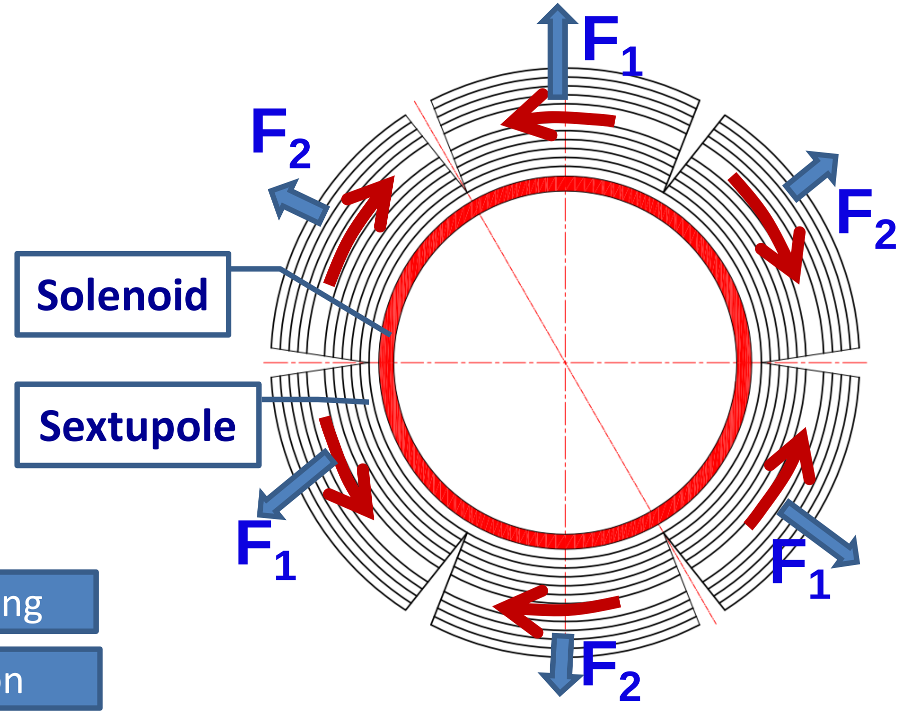


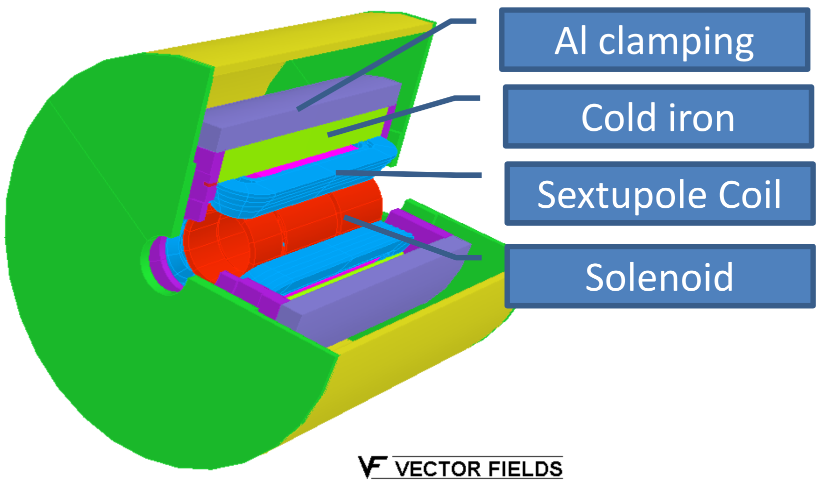
SCECRIS-28 GHz: 2009

SC-Magnet Development for 3rd G. ECRIS

Reversed structure



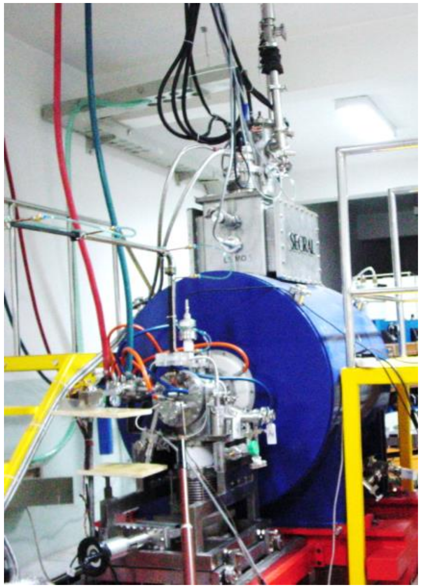




SECRAL magnet structure

- Lower/simpler interaction forces
- Easier tooling and clamping structure
- Compact magnet and lower cost
- Lower radial field efficiency

SC-Magnet Development for 3rd G. ECRIS

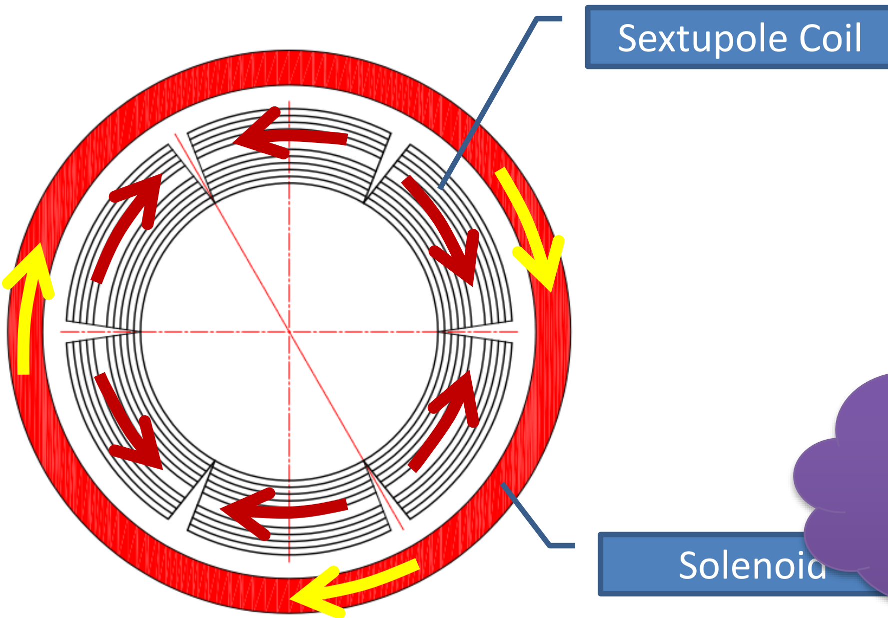


SECRAL-24 GHz: 2005

SECRAL II-28 GHz: 2016

See Tue-Af-Or16-04 by Tongjun Yang

SC-Magnet Development for 3rd G. ECRIS

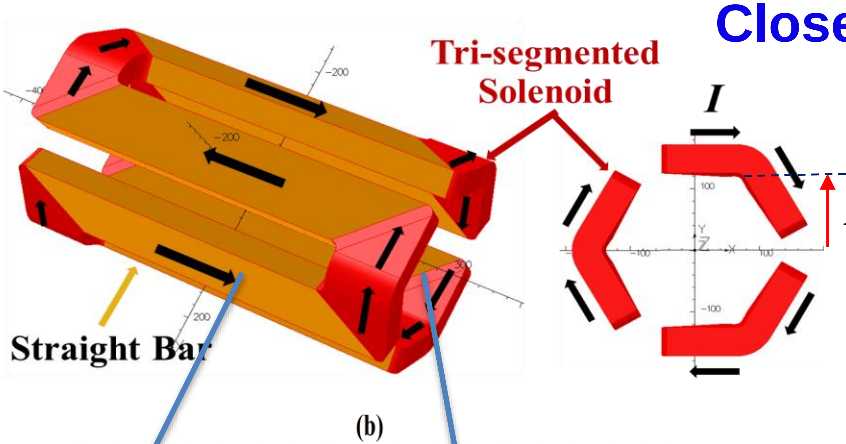


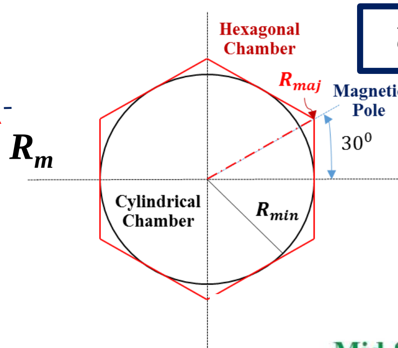
Sextupole coil ends having … elled solenoidal components

- **Lower field efficiency**
- **Higher end forces between … ext … ole coils and solenoids**

SC-Magnet Development for 3rd G. ECRIS

Closed-Loop Coil (CLC) structure

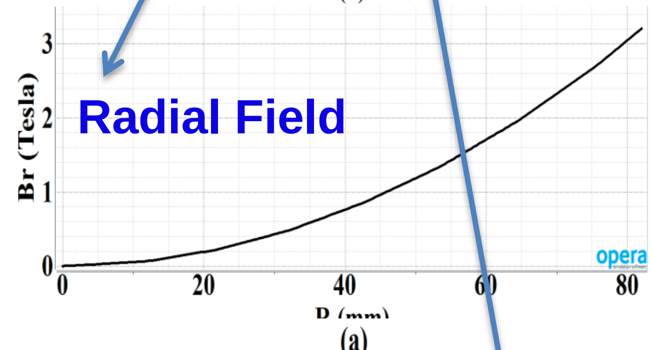


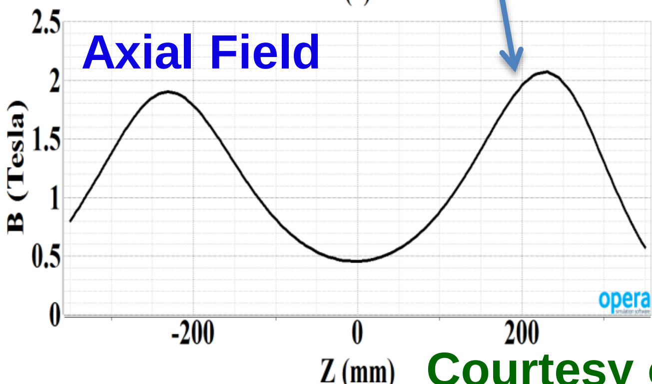


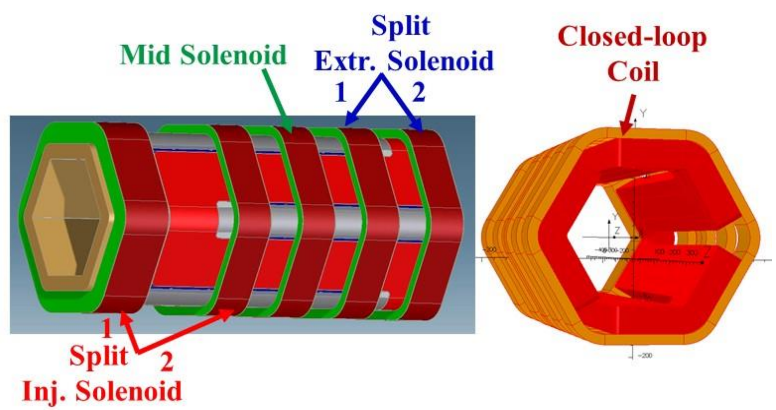
Use a hexagonal plasma chamber

$B_r/B_m = (R_{maj}/R_m)^2$ ~ 66%

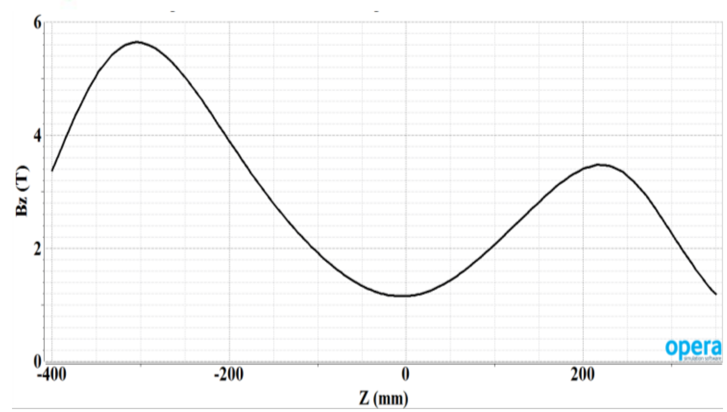
$B_r/B_m = (R_{min}/R_m)^2$ ~ 50%







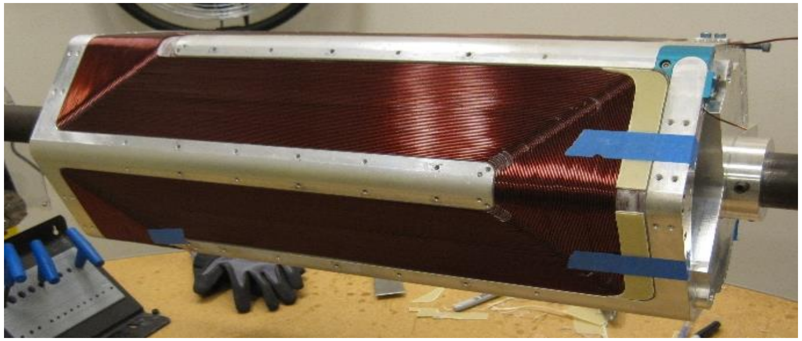
Practical Axial Field



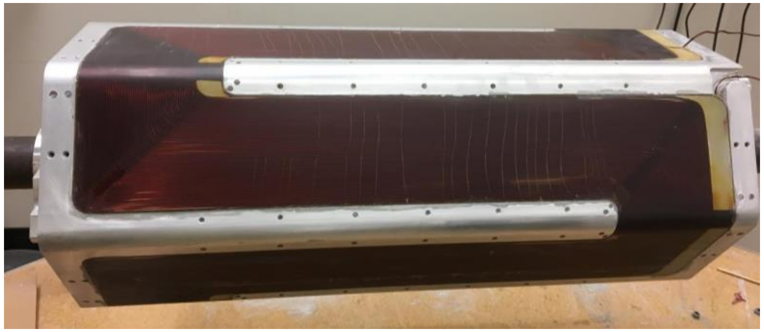
Courtesy of D. Xie

SC-Magnet Development for 3rd G. ECRIS

CLC structure



Closed-loop-coil with Cu wire finished on the winding fixture



Closed-loop-coil after potting with epoxy

Proof of principle completed with Cu wire

- Winding and potting
- Field mapping

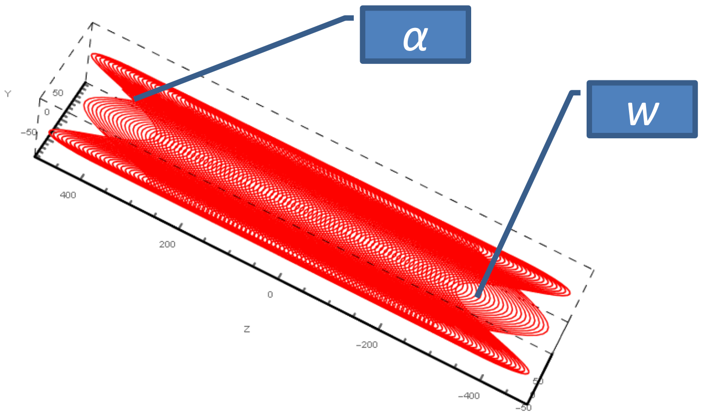
Challengeable aspects

- Hexagonal inner bore cryogenic system
- Hexagonal plasma chamber
- Magnet assembly

Intense R&D work in LBNL led by Dr. D. Xie

SC-Magnet Development for 3rd G. ECRIS

Canted Cosine Theta (CCT) Design



$$\begin{pmatrix} B_{ri} \\ B_{\theta i} \\ B_{zi} \end{pmatrix} = \frac{\mu_0 I_0}{2w} \begin{pmatrix} \cot(\alpha)\left(\frac{r}{a_i}\right)^{n-1} \sin(n\theta) \\ \cot(\alpha)\left(\frac{r}{a_i}\right)^{n-1} \cos(n\theta) \\ 2(-1)^i \end{pmatrix}$$

Each CCT module

- **Pure sextupole field**
- **Solenoidal field**

Extra solenoids

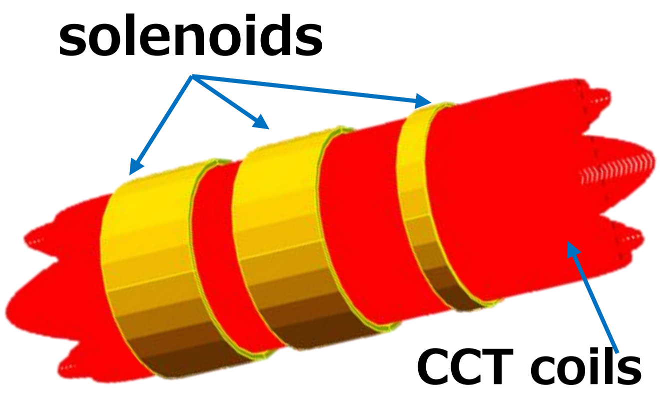
- **Mirror field configuration**
- **Flexible tuning for ECR operation**

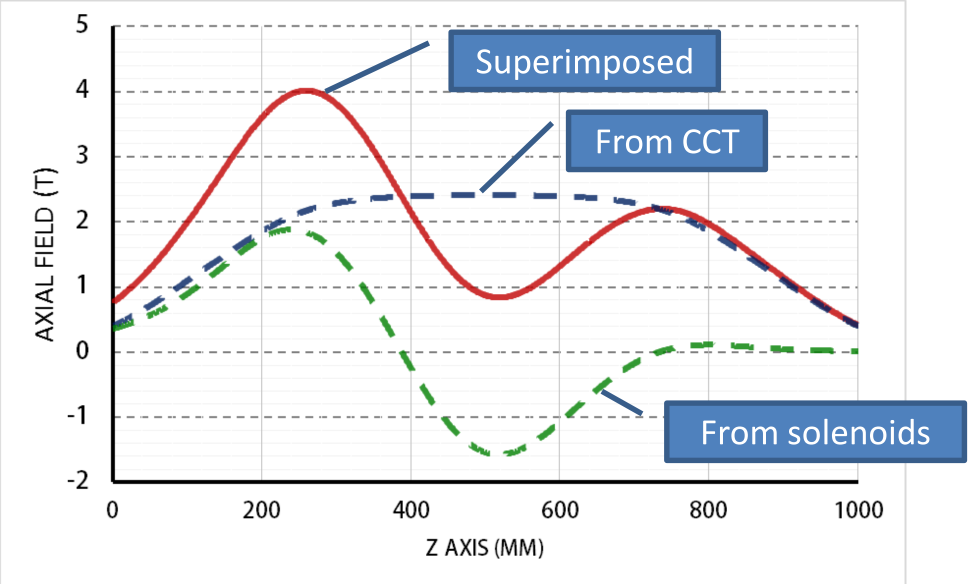
Reference:

- D.I. Meyer, and R. Flasck, Nucl. Instrum. Meth., pp. 339-341, 1970.
- S. Caspi, et al., IEEE Trans. Appl. Supercond, Vol. 17, part 2, pp. 2266-2269, 2007.
- Brouwer, Lucas Nathan, ProQuest Dissertations And Theses; Thesis (Ph.D.)--University of California, Berkeley, 2015

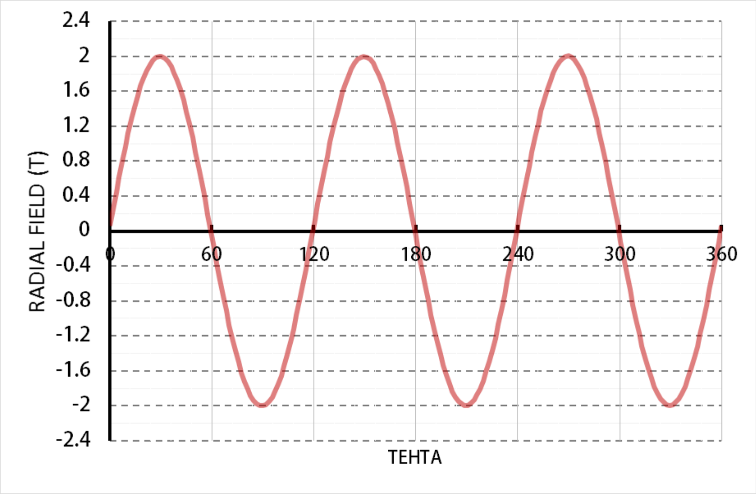
SC-Magnet Development for 3rd G. ECRIS

Canted Cosine Theta (CCT) Design





Axial field@r=0 mm



Sextupole field@r=63 mm

- **4 modules + 3 solenoids**
- **1 module= 24 turns**
- **2 inner modules → solenoidal field + pure sextupole field**
- **2 outer modules → pure sextupole field**

SC-Magnet Development for 3rd G. ECRIS

Comparison of the 4 designs for a 28 GHz ECRIS

Key Para.	Conventional	Reversed	CLC	CCT
Frequency (GHz)	28	28	28	28
Warm bore (mm)	170	142	>160	>140
$B_r/B_{inj}/B_{ext}$ (T)	2.0/4.0/2.8	2.0/3.7/2.2	2.2/4.1/3.0	2.0/4.0/2.2
Mirror Length (mm)	500	420	420	500
Max. Je (A/mm^2)	200	255	270	625
Stored Energy (kJ)	760	700	212	<1000
#Wire length (km)	38.6	34.2	16.9	<20.0
#Loading Factor	87%	91%	72%	~90%
Engineering Difficulty	High	Medium	Very high	Low

#Based on WST 1.20X0.75 mm^2 NbTi wire

SC-Magnet Development for 4th G. ECRIS

General Parameters of A 45 GHz 4th G. ECRIS Magnet

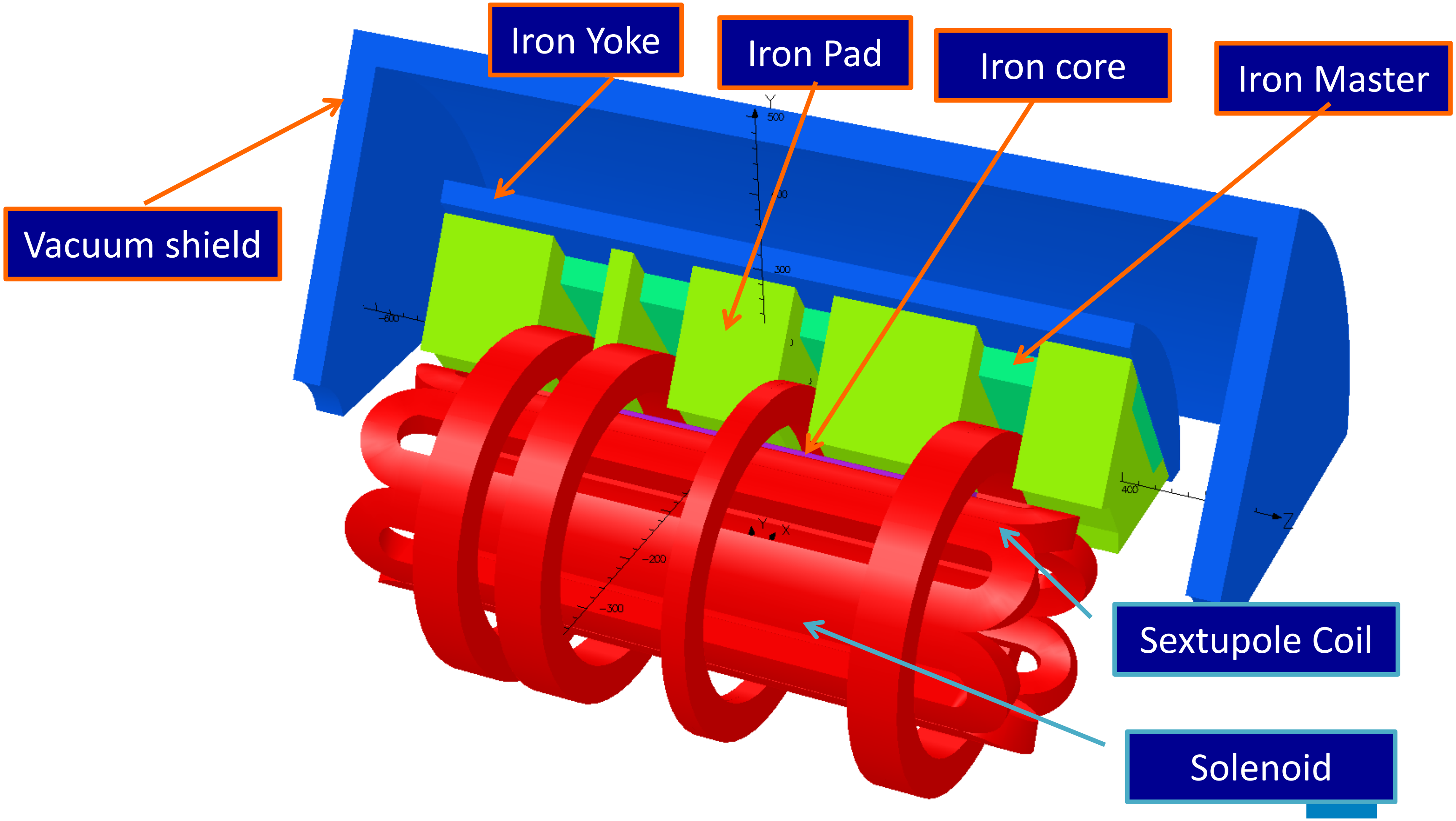
Specs.	Unit	State of the art ECRIS	FECR
frequency	GHz	24-28	45
B_{ECR}	T	0.86~1.0	1.6
B_{rad}	T	1.8~2.2	≥3.2
B_{inj}	T	3.4~4.0	≥6.4
B_{min}	T	0.5~0.7	0.5~1.1
B_{ext}	T	1.8~2.2	≥3.4
Warmbore ID	mm	120~170	≥160
Mirror Length	mm	420~500	~500
Cooling Capacity@4.2 K	W	0~6.0	≥10.0

Options for 4th G. ECRIS

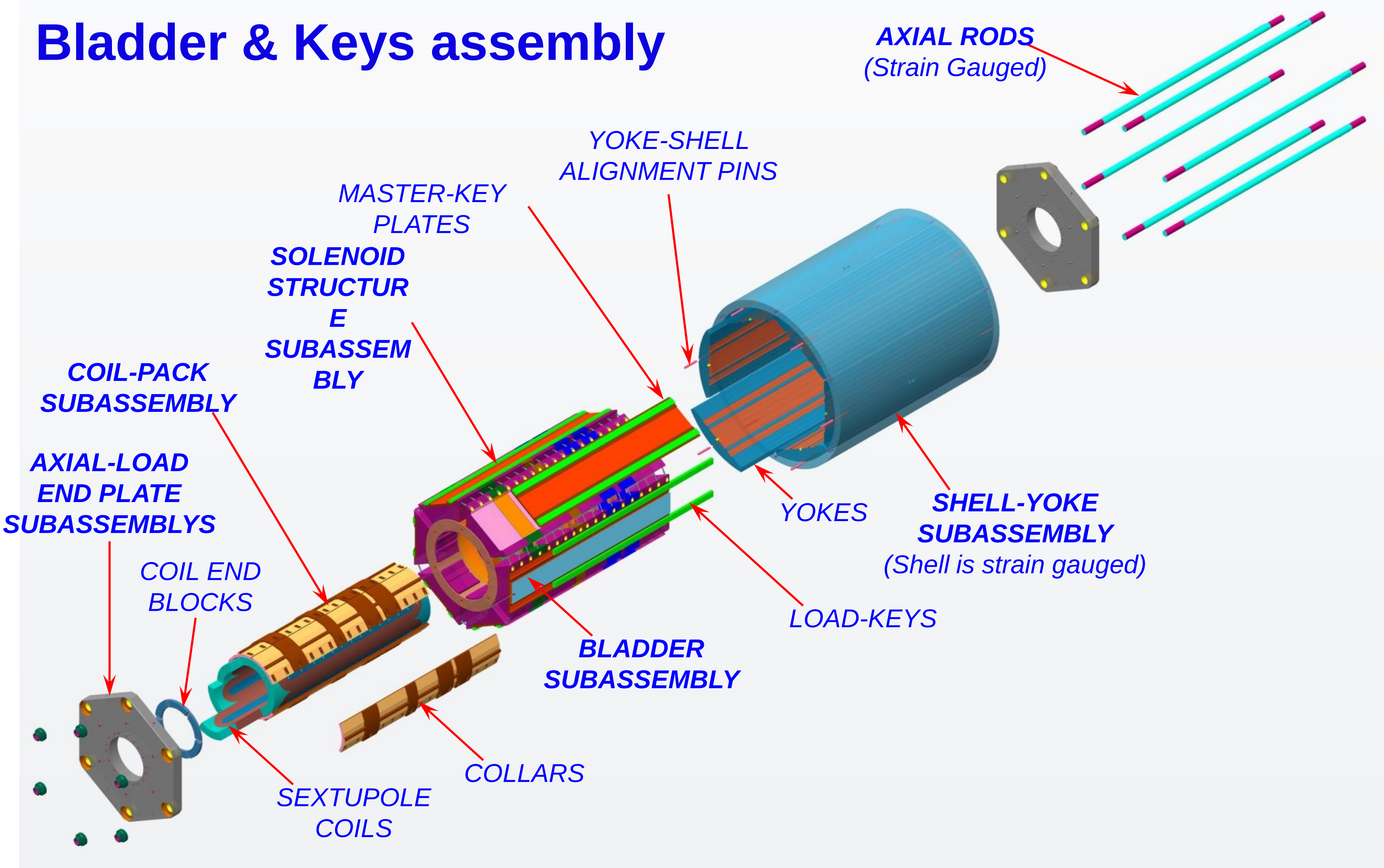
Issues	Conventional	Reversed	Ioffe-bar	CCT
Frequency	<50 GHz	<42 GHz	>56 GHz	<50 GHz
Wire	Nb_3Sn	Nb_3Sn	Nb_3Sn+NbTi	Nb_3Sn
Challenges	Coil fabrication Quench protection Clamping, assembly	Insufficient fields Coil fabrication Quench protection Clamping, assembly	Not technically verified Cryogenic system complexity	Not technically verified
Stored Energy	1.7 MJ	1.7 MJ	0.8 MJ	~2.0 MJ
Feasibility	✓	✗	✗	✗

SC-Magnet Development for 4th G. ECRIS

Magnetic Structure Design of FECR



SC-Magnet Development for 4th G. ECRIS



See Mon-Af-Po1.01-09 [09] by M. Juchno

SC-Magnet Development for 4th G. ECRIS

Challenges in the magnet development

Coil fabrication

- Nb_3Sn wire winding
- curing with precise configuration
- Large number of current leads

Integration*

- Precise fabrication and assembly
- Tolerance control

Quench protection#

- Uni-strand wire design
- Quench detection and protection for 10 coils system

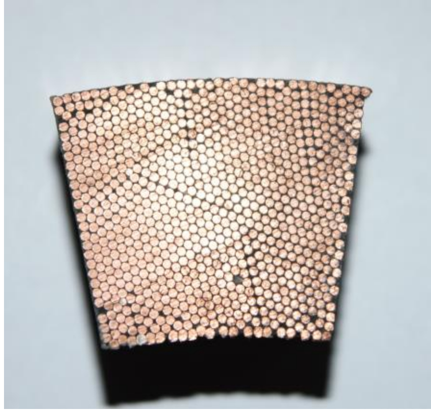
*See Mon-Af-Po1.01-09 [09] by M. Juchno
#See Thu-Af-Po4.09-03 [140] by E. Ravaioli

SC-Magnet Development for 4^{th} G. ECRIS

Sextupole Coil Prototyping

Solenoid Prototyping

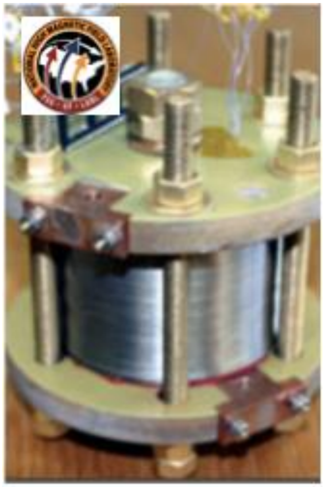
Water bladder test setup



SC-Magnet Development for 4th G. ECRIS

Explore higher field reliable sextupole magnet…

- Feasibility of HTS materials in ECR sextupole magnet
  - Bi2212 wires
  - REBCO tapes/cable
- Conductor:
  - Stronger Bi2212 wire
  - Quasi-isotropic YBCO cable
- Coil:
  - ◆ Race track, saddle, CCT,... ?
  - ◆ Mechanical support
  - ◆ Quench protection



Bi2212: OST

REBCO: Superpower

Conclusion

- Superconducting magnet community has provided strong support for ECR ion source technology development
- ECRIS community still needs more robust and economical SC-magnet for high performance sources
- 4th G. ECRIS development is unique in the state of the art SC-magnet technologies

Acknowledgement

- Hongwei Zhao, Wang Lu, Wei Wu, Enmin Mei from IMP, CAS
- GianLuca Sabbi, Daniel Xie from LBNL

Thanks for your attention!