IPAC19

High Performance ECR Sources for Next-Generation Nuclear Science Facilities

Daniela Leitner

Lawrence Berkeley National Laboratory

BERKELEY LAB

VENUS

Outline

- ECR Ion Sources Overview
- Next Generation Facility Requirements
- Design Parameters and Challenges
- Uranium Beam Production
- 3rd Generation ECR Ion Sources
- Towards 4th and 5th Generation ECR Ion Sources

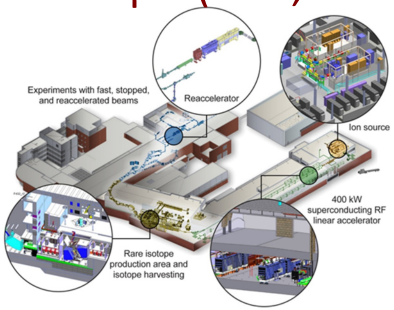
View into the plasma chamber of the VENUS ECR Ion Source

Demands For Higher Charge State Ions Continue To Drive ECR Ion Source Development

- The requirements of next generation heavy ion beam facilities are barely met by current state-of-the-art ECR ion sources.
- Particular challenge: High intensity uranium beams and the versatility of beams required

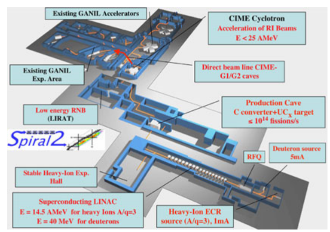
VENUS - II

540 eμA (U^{32+}, U^{33+})



Facility for Rare Isotope Beams, East Lansing, US

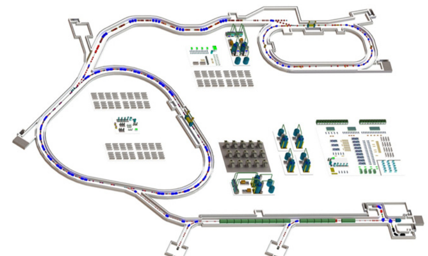
1mA Ar^{12+}rt



SPIRAL 2, GANIL, France

SECRAL and FECR

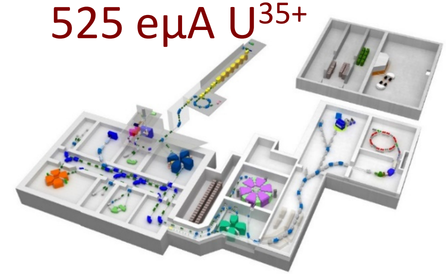
1.0emA(U^{35+} - U^{46+})



IMP, Lanzhou, China

SC-ECRIS

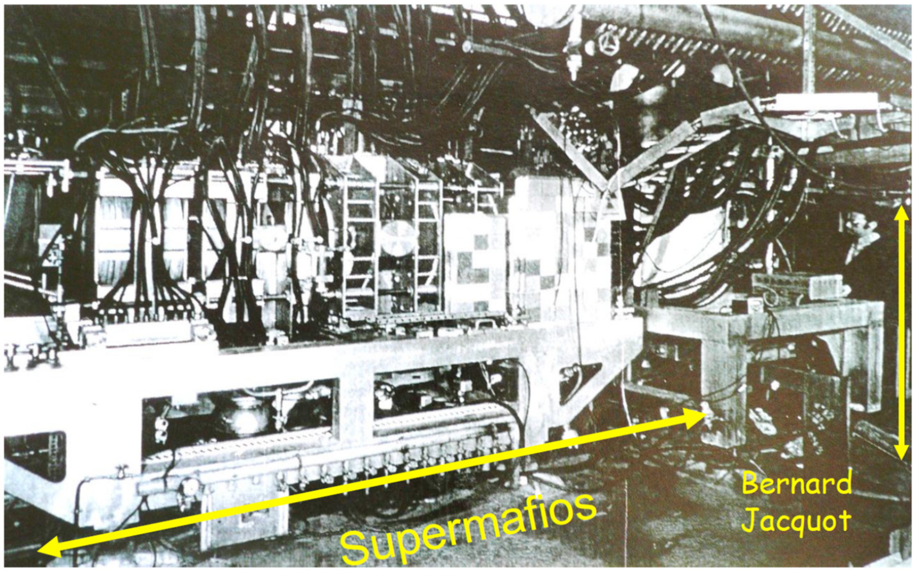
525 eμA U^{35+}



RIKEN Rare Isotope Beam Factory, Japan

Electron Cyclotron Resonance Ion Sources - History

Starting in 1972 R. Geller in Grenoble converted fusion plasma devices into the first ECR ion source.

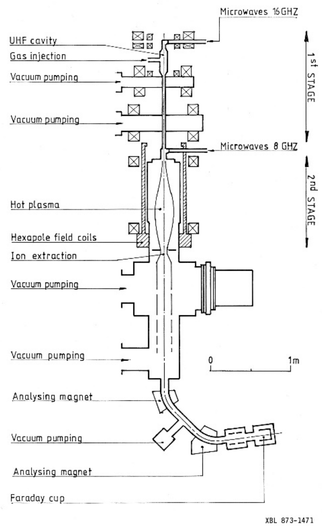


- A 3 MW modified fusion machine (CIRCE) to produce ion beams
- The legend says that, at first power switching, an electrical black out occurred on half of Grenoble city!

Supermafios (Geller, 1974)
15 eμA of O^{6+}

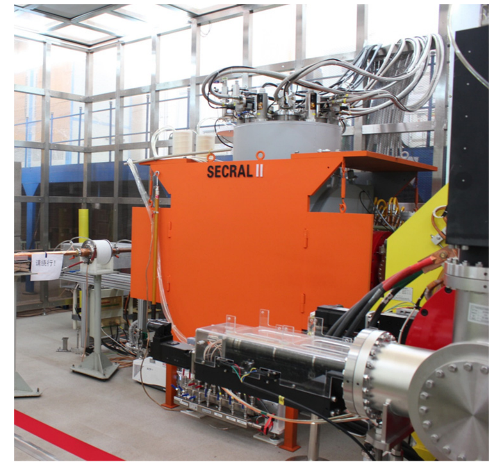
Electron Cyclotron Resonance Ion Source Development

Supermafios (Geller, 1974)
15 eμA of O^{6+}



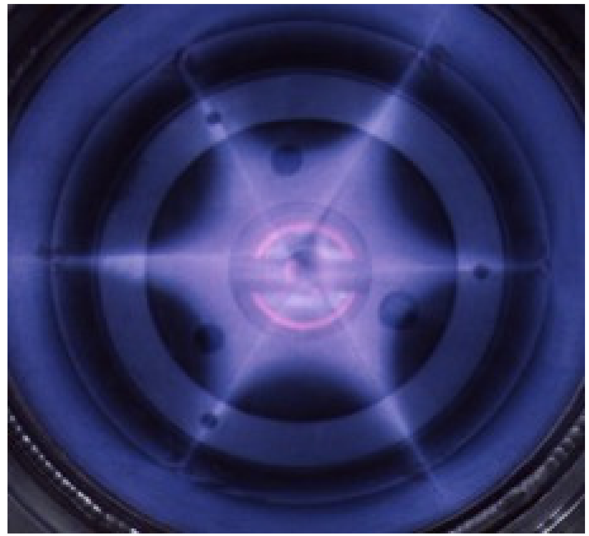
VENUS (2004)
4500 eμA of O^{6+}

SECRAL-II (2016)
6100 eμA of O^{6+}



Fully superconducting NbTi ECR ion sources operating at 28 GHz Microwave plasma heating frequency are now the state-of-the-art injector sources for heavy ion facility.

ECR Ion Sources Are Confined Plasma Devices



ECR Plasma

Ingredients of an ECR-Ion Source

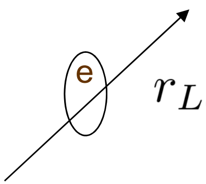
- The plasma must be confined (magnetic fields) and heated (RF) if it should be sustained for some time
- Microwave (GHz) used for plasma heating (electrons)
  - Hot Electrons
  - Cold Ions (good emittance)
- Plasma Ions: Gas injection, vapor from external devices (e.g. ovens), sputtering
- Charge balance is determined by the neutral gas pressure in the source, electron temperature and confinement time

ECR Ion Sources Are Confined Plasma Devices

Plasma electrons are resonantly heated with microwaves

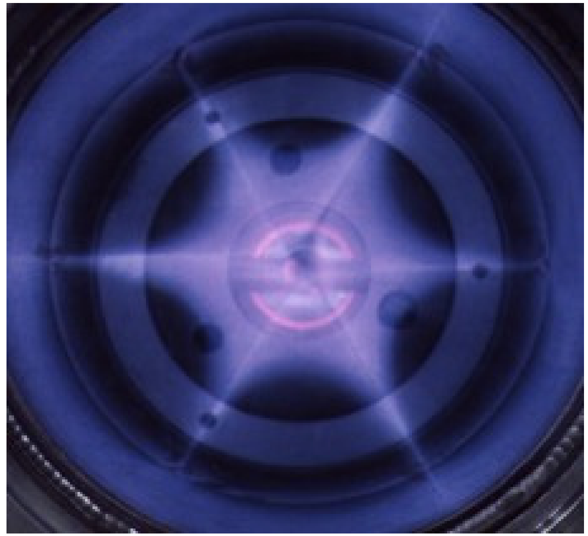
$$\omega_e = \frac{e \cdot B}{m} = \omega_{rf}$$

Magnetic flux line



$$r_{Lamor} = \frac{m \cdot v}{q \cdot B}$$

$$B = 1T$$
$$f = 28GHz$$
$$r_{Lamor} = 0.011mm$$



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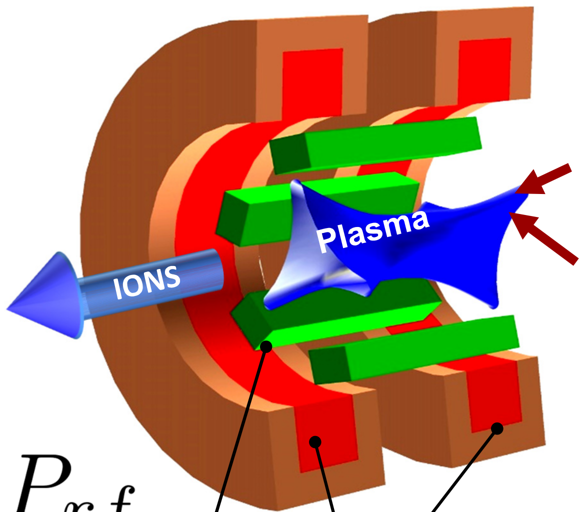
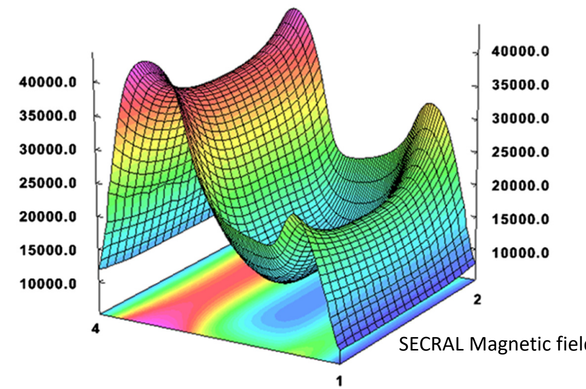
Key Parameters for an ECR Ion Source Performance

Minimum-B field confinement structure

$$n_e \cdot \tau_i$$



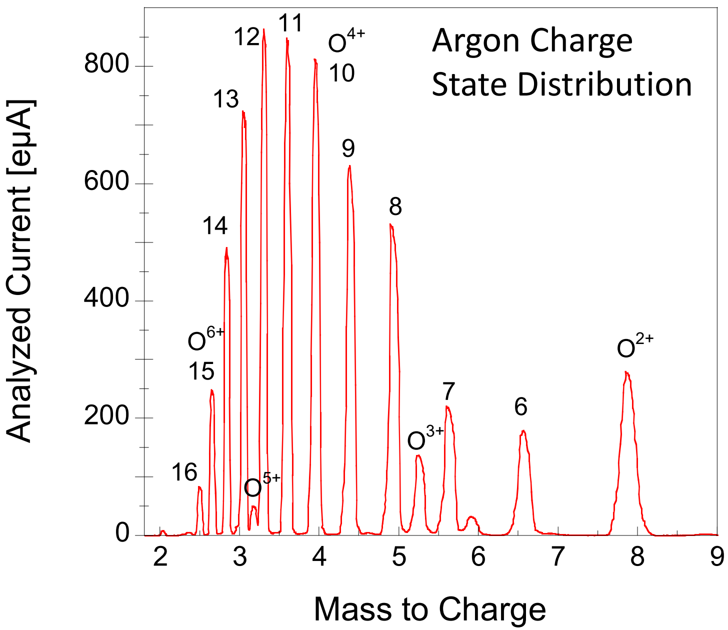


$$n_e \propto \omega_{rf}^2, P_{rf}$$

$$\tau_i \propto B_{avg}$$

Key parameters	
Ion confinement times τ_i	$\approx ms$
Plasma densities n_e	$10^9 - 10^{12}/cm^3$
Electron temperature T_e	$eV\ to\ MeV$
Charge exchange/ neutral gas density σ_{ex}	$q^{1.17} \cdot I_p^{-2.76} \cdot cm^2$

Leading 3rd Generation SC ECR Ion Sources Performance



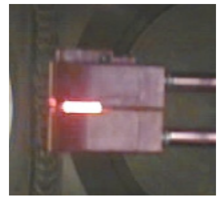
Beams (eμA)	VENUS * 28+18 GHz (2018, 10 kW)	SECRAL I+II** 24+18 GHz (2018, 10 kW)	Required Intensities (eμA)
O^{6+}	4750	6700	> 400
O^{7+}	1900	1750	> 400
Ar^{12+}	1060	1420	> 1000
Ar^{17+}	115	133	
Xe^{27+}	705	920	> 500
Xe^{38+}	26	N/A	
Bi^{30+}	310	710	>650
Bi^{61+}	0.1	N/A	
°U^{32+}	450	200	**>500**
°U^{35+}	300	N/A	**>500**
U^{47+}	5	N/A	**>1000**

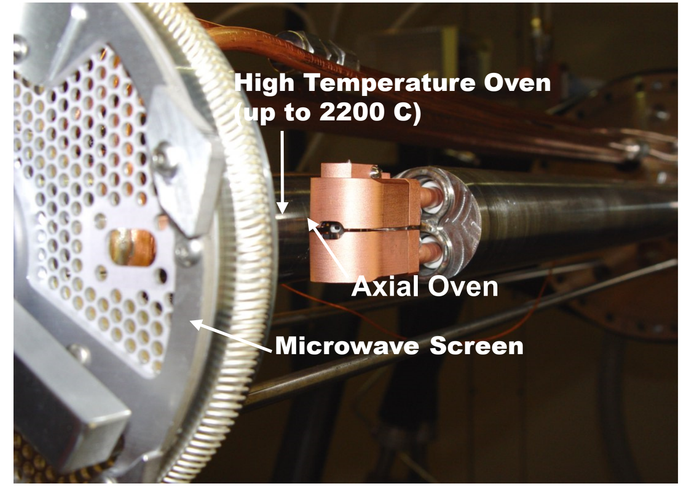
Demonstrated source performances and improvements show that next generation accelerator performance requirements are in reach, but challenges remain

*Dan Xie, ECRIS2018-MO02, Catania, Italy, 2018
°Janilee Benitez, ECRIS2012, Sydney, Australia, 2016
**Liangting Sun, ECRIS2018-TUA5, Catania, Italy, 2018

High intensity Metal Beams – Why is Uranium so challenging?

- Uranium Vapor: Very high oven temperatures are needed to produce sufficient U flux into the plasma: 1900 °C to 2200 °C

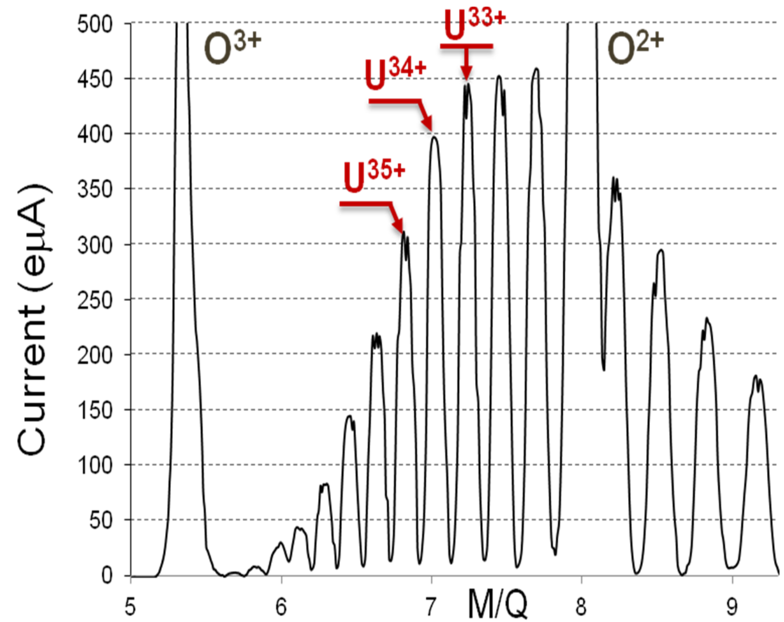




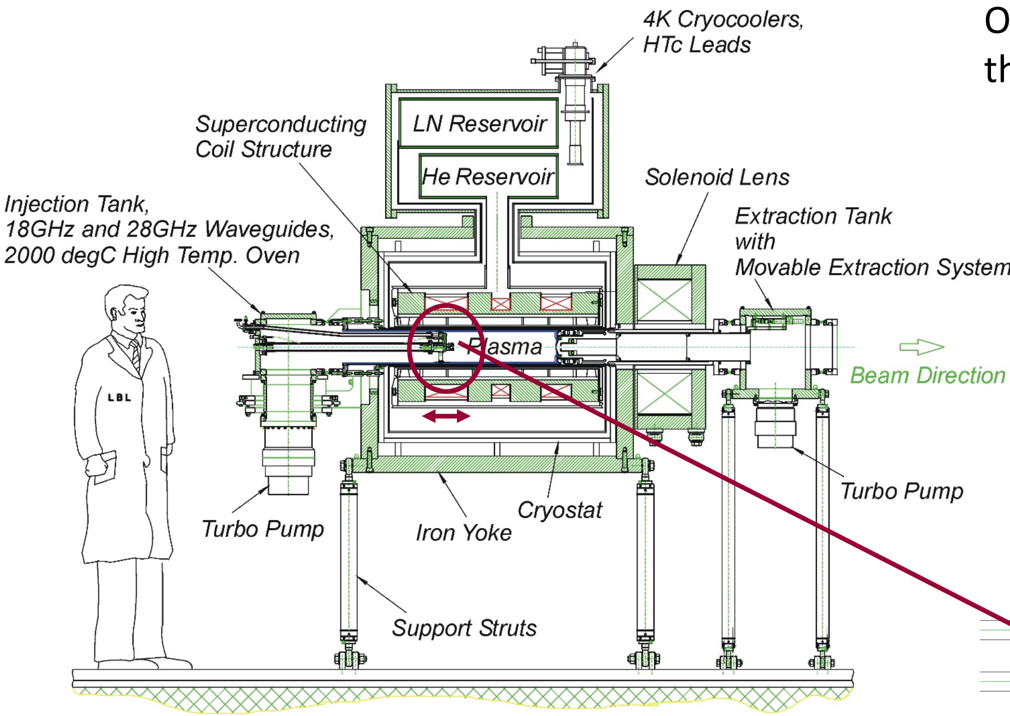
- High magnetic field at the oven location
- Reliability of the oven under these conditions (chemical reactions at high temperature, material fatigue)

Uranium Beam Development at LBNL

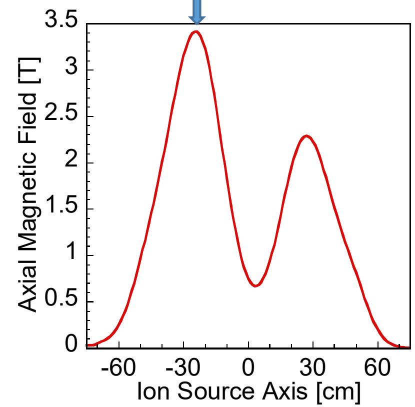
Materials tested at LBNL	
~~UF_6~~	High charge state ion performance terrible
~~U~~	Yttria crucibles, liquid - corrosive
URe_2	Works well in Re, Ta, W ovens, but not commercially available (1800- 2000 °C)
UO_2	Works well, readily available, 2-3 weeks production run completed in LBNL and RIKEN – Rhenium Oven (2000- 2300 °C)



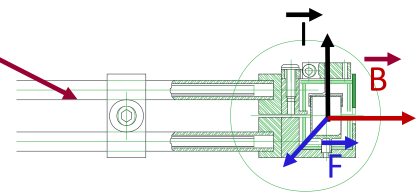
Strong Magnetic Field At The High Temperature Oven Location Results In Challenging Design Conditions



Oven is located close to the peak of the mirror field



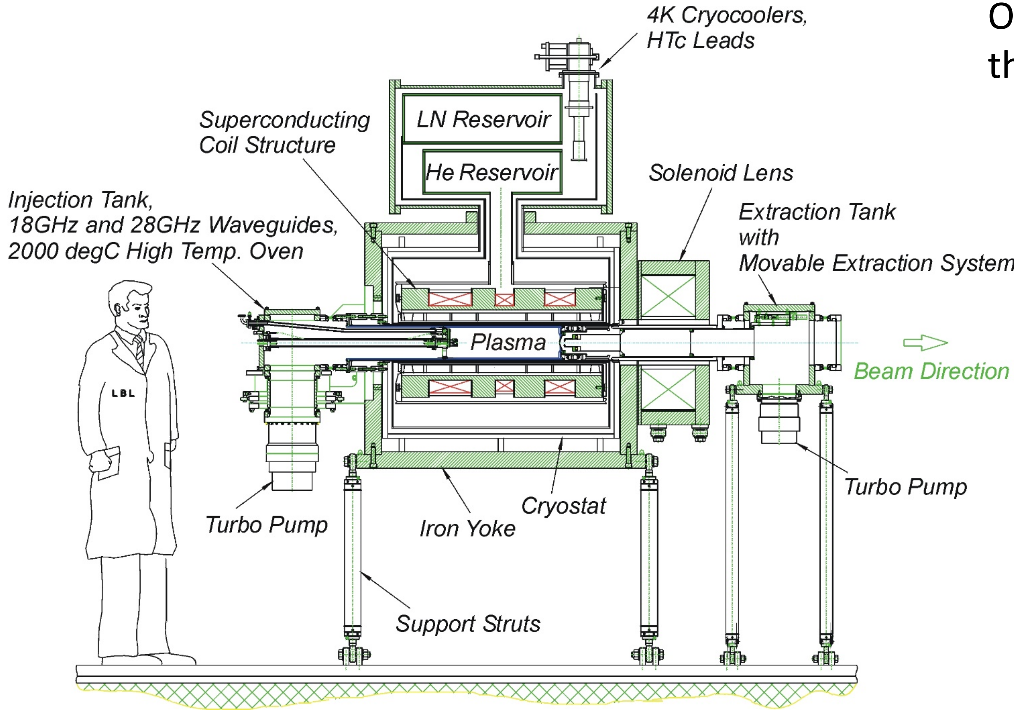
Force limits the temperature that can be achieved reliably in operation



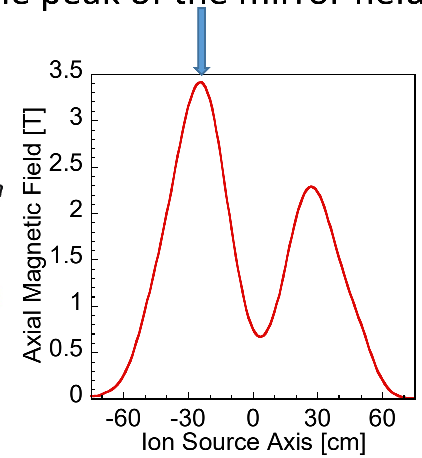
F=IxB
300A, 4T
2.5cm length, 30N

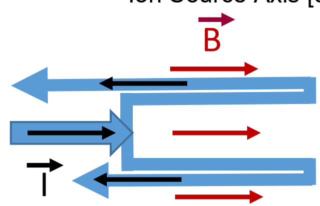
Possible solution: Use of AC heating currents – needs to be tested and optimized

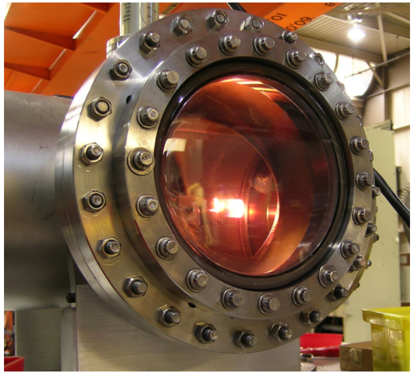
Possible Solution Is A Coaxial Oven: The Heater Current Flow Is Parallel To The Magnetic Flux Lines

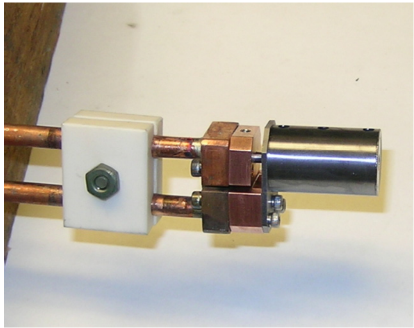


Oven is located close to the peak of the mirror field



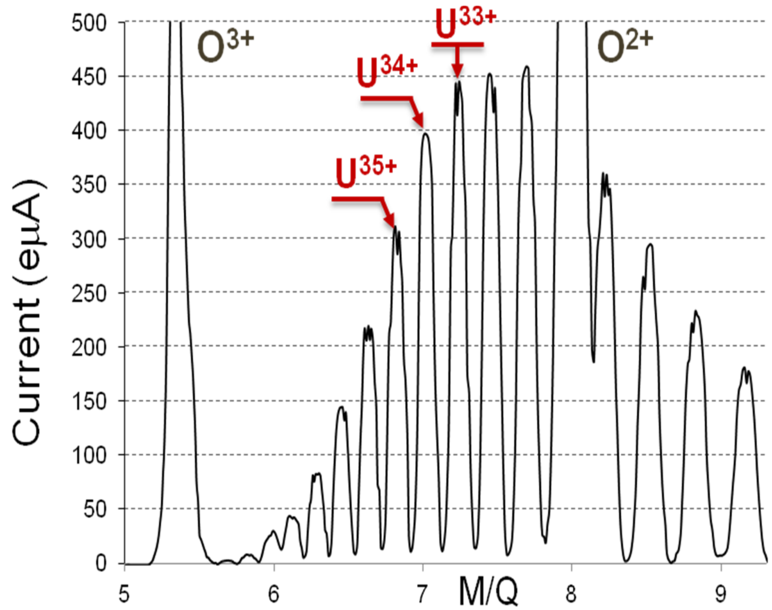






Needs testing and development to achieve the reliability required for operations

Leading 3rd Generation SC ECR Ion Sources Performance



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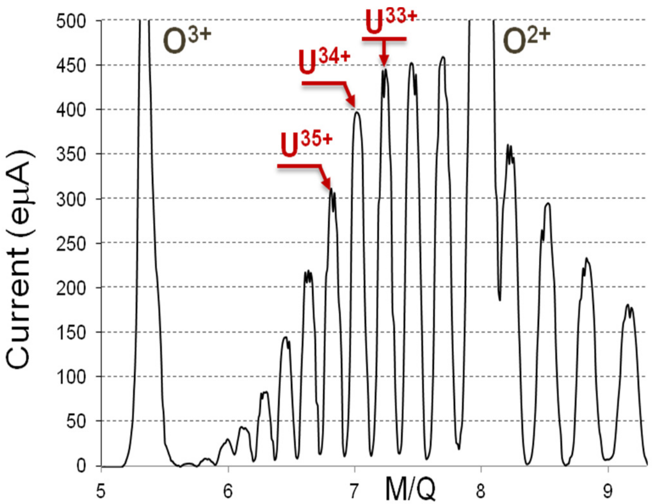
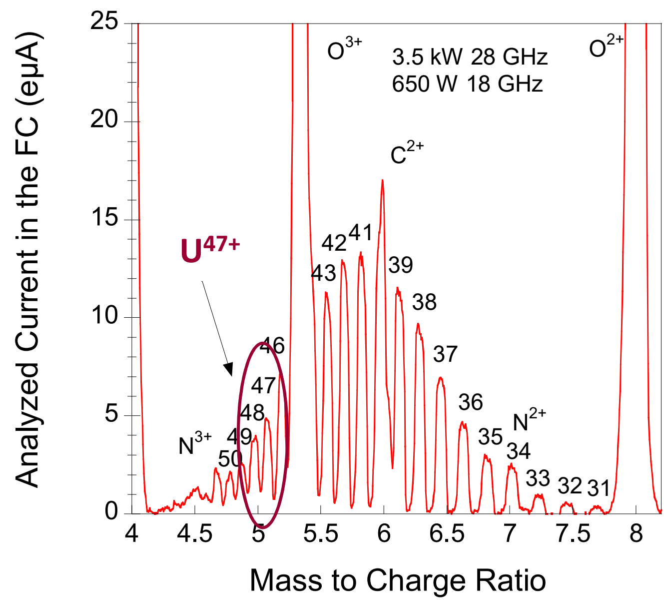
The Ion Beam Intensities Needed For Future Heavy Ion Facilities Require Development of 4th and 5th Generation ECR Ion Sources

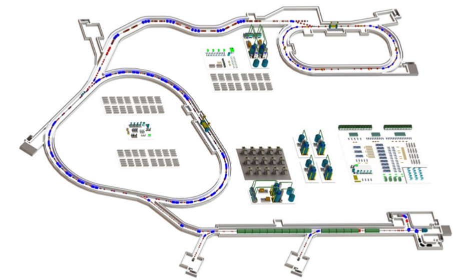
Uranium Medium Charge States*



Uranium High Charge States



Heavy Ion Research Facility (HIRFL), Lanzhou China



1000 eμA(U^{35+} - U^{46+})

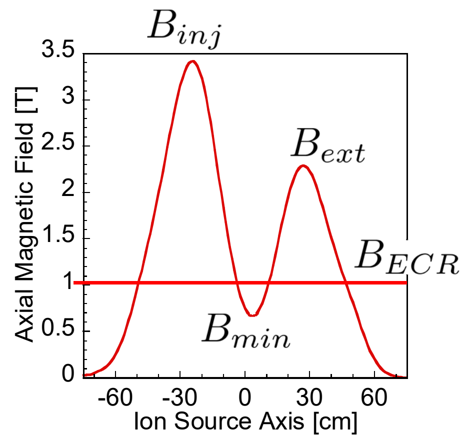
VENUS Performance: 450 eμA U^{33+}, 10 eμA U^{46+}

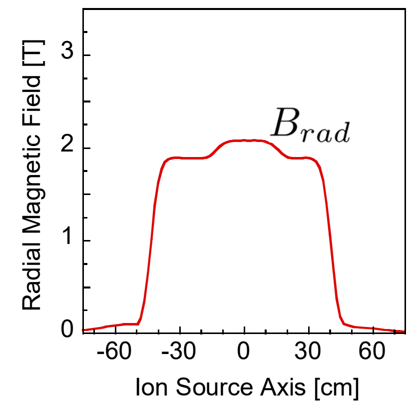
*Janilee Benitez, ECRIS2012, Sydney, Australia, 2016

Increasing Both Magnetic Fields And Frequencies Are The Key To Improved Performance

$n_e \propto \omega_{rf}^2 \propto I$ Beam Current

$q_{opt} \propto log B^{3/2}$ Average Charge State

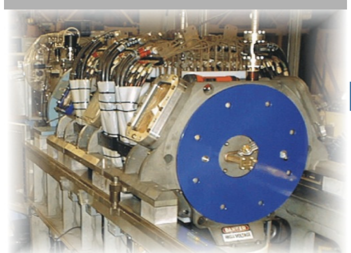




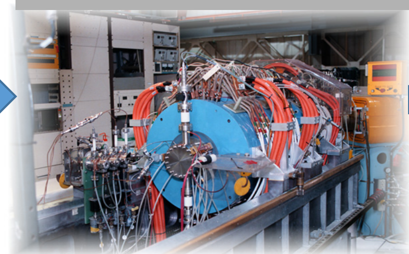
20 eμA Ar^{12+}

200 eμA Ar^{12+}

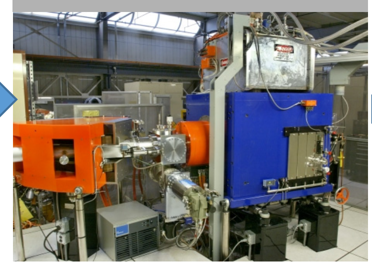
ECR (1983)
0.4 T, 0.6 kW, 6.4 GHz



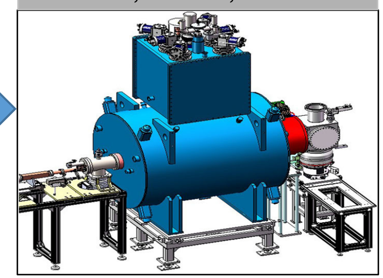
AECR-U (1996)
1.7 T, 2.6 kW, 10 + 14 GHz



VENUS (2001)
4.0 T, 14 kW, 18 + 28 GHz



4th Generation (2025?)
6-8 T, 30 kW, >45 GHz



NORMAL CONDUCTING

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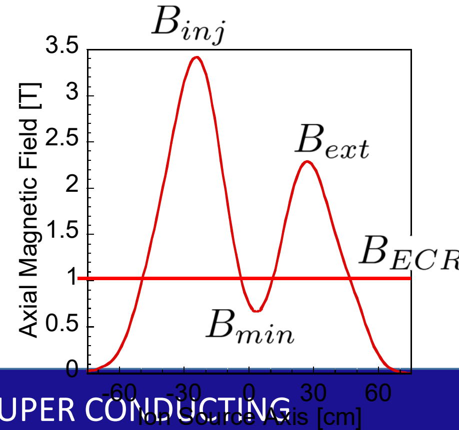
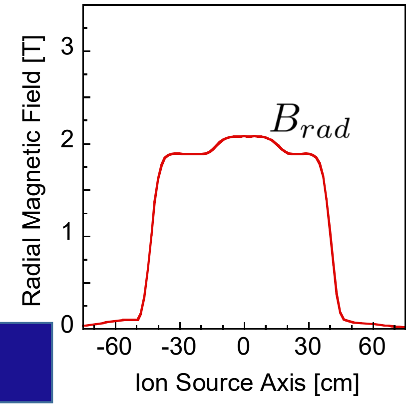
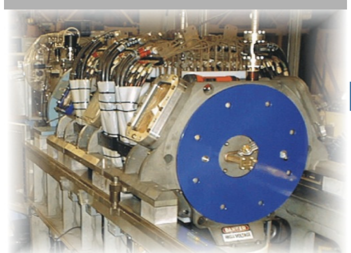
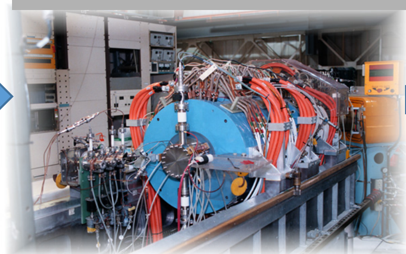


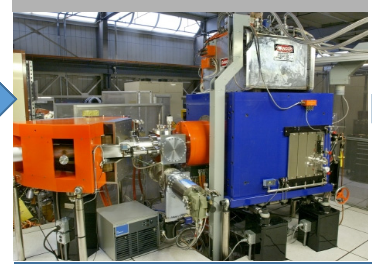


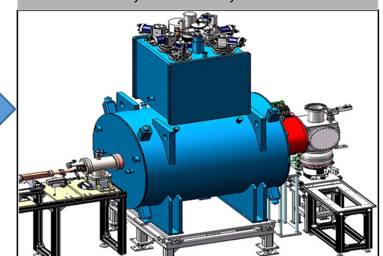
SUPER CONDUCTING

20 eμA Ar^{12+}	200 eμA Ar^{12+}	1000 eμA Ar^{12+}	3000 eμA Ar^{12+} ?
ECR (1983) *0.4 T, 0.6 kW, 6.4 GHz*	***AECR-U (1996)*** *1.7 T, 2.6 kW, 10 + 14 GHz*	***VENUS (2001)*** *4.0 T, 14 kW, 18 + 28 GHz*	***4th Generation (2025?)*** *6-8 T, 30 kW, >45 GHz*









NORMAL CONDUCTING → SUPER CONDUCTING

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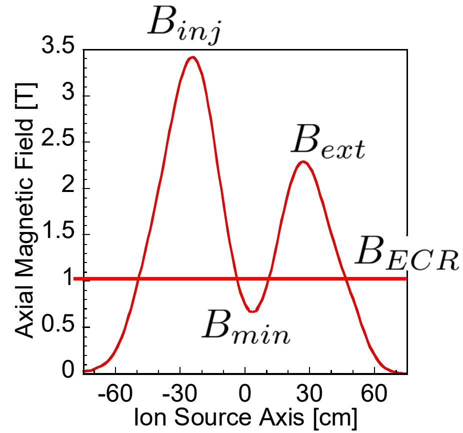
Increasing Both Magnetic Fields And Frequencies Are The Key To Improved Performance

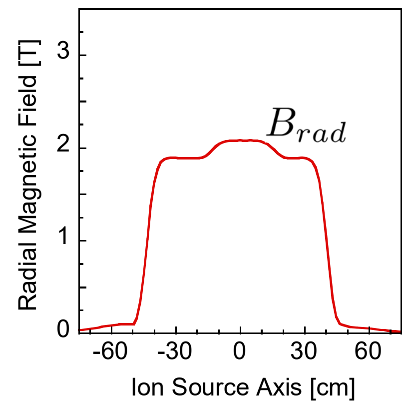
$$B_{inj}/B_{ECR} = 4$$

$$B_{ext} \approx 0.9 \text{ to } 1.2 B_{rad}$$

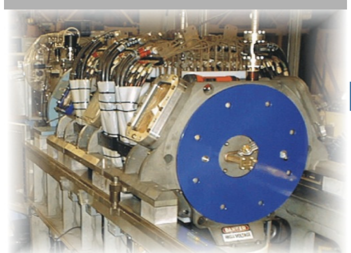
$$B_{rad}/B_{ECR} = 2$$

$$0.4 < B_{min}/B_{ECR} < 0.8$$





ECR (1983)
0.4 T, 0.6 kW, 6.4 GHz



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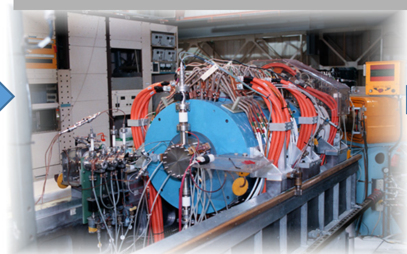
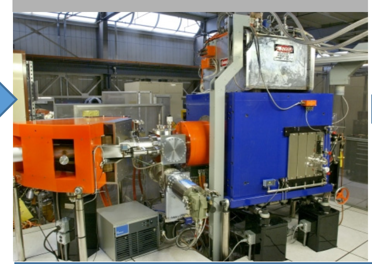
1.7 T, 2.6 kW, 10 + 14 GHz



VENUS (2001)
4.0 T, 14 kW, 18 + 28 GHz



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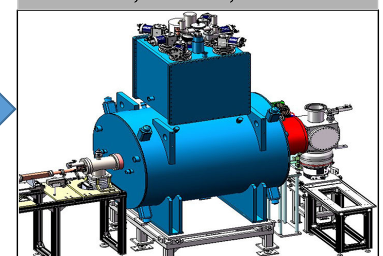


NORMAL CONDUCTING → SUPER CONDUCTING

Increasing Both Magnetic Fields And Frequencies Are The Key To Improved Performance

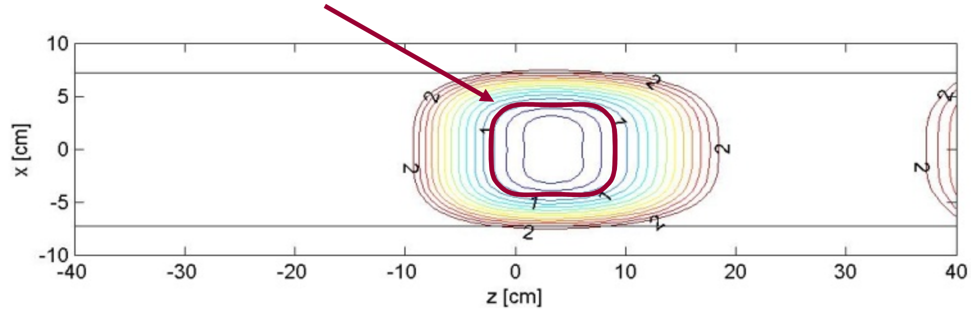
$$B_{inj}/B_{ECR} = 4$$

$$B_{ext} \approx 0.9 \text{ to } 1.2 B_{rad}$$

$$B_{rad}/B_{ECR} = 2$$

$$0.4 < B_{min}/B_{ECR} < 0.8$$

$$B_{ECR}(T) = \frac{F_{rf}(GHz)}{28(GHz)} \cdot T$$



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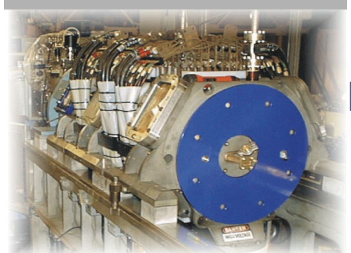

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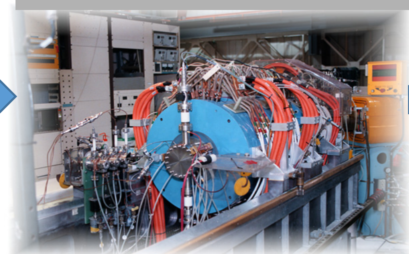

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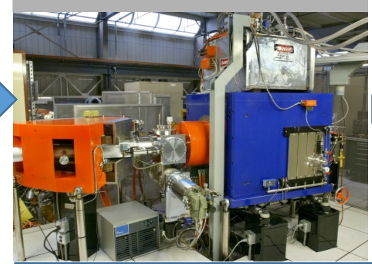
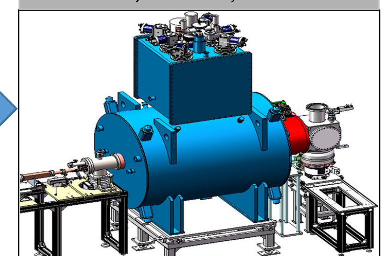


4th Generation (2025?)
6-8 T, 30 kW, >45 GHz

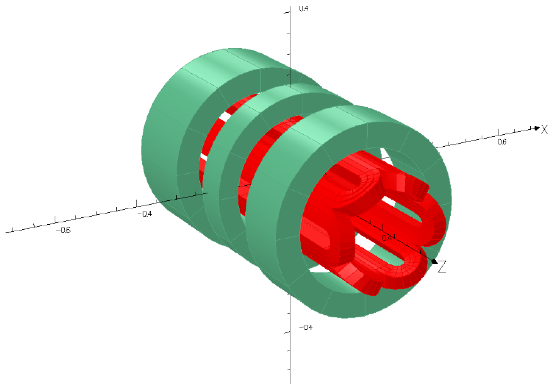


NORMAL CONDUCTING → SUPER CONDUCTING

Third Generation SC ECR Ion Sources: NbTi

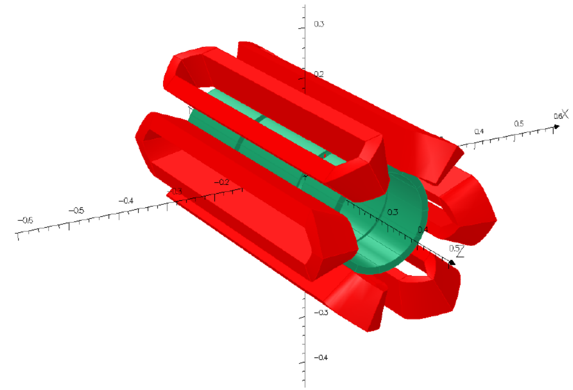
Two geometries have been successfully realized to create the min-B field

Sextupole-in-Solenoid Classic Geometry (VENUS, VENUS II, SC-28 RIKEN I+II, SuSI)



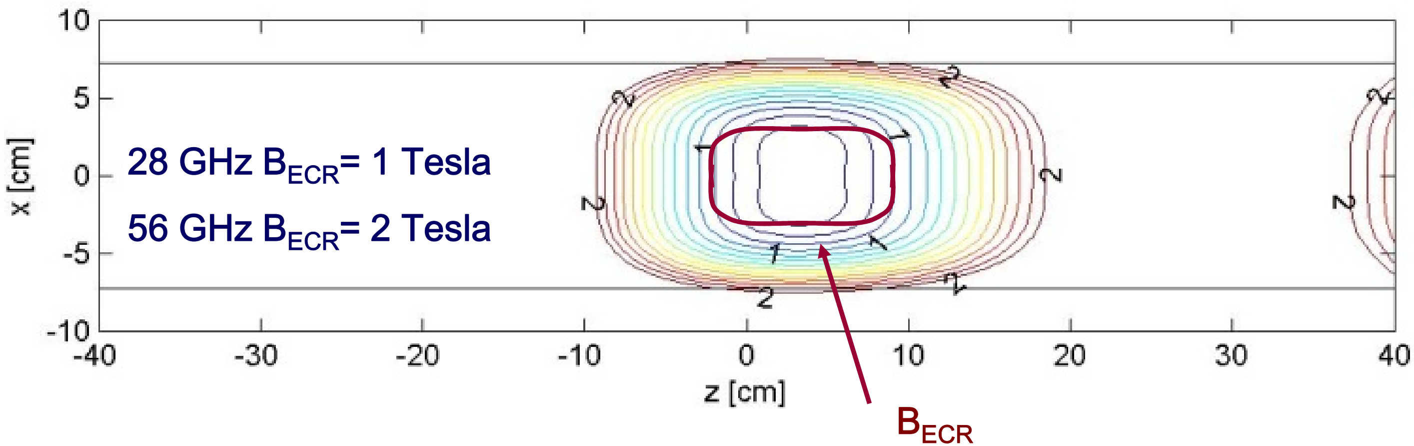
- Minimizes the peak fields at the coils
- Strong influence (forces) of the solenoid field on the sextupole ends

Solenoid-in-Sextupole Geometry (SECRAL I, SECRAL II)



- Minimizes the influence of the solenoid on the sextupole field
- Significantly higher field required for the sextupole magnet due to the larger coil radius
- Strong forces on the solenoid coils

Superconducting Magnets: ECR Design Rules

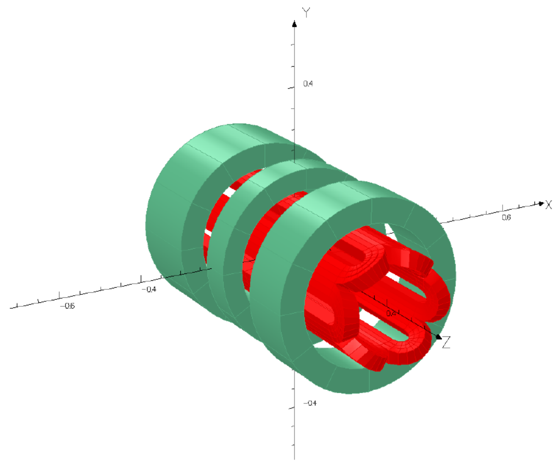


	28 GHz	56 GHz
$B_{inj} \sim 4 \cdot B_{ecr}$	4T	8T
$B_{min} \sim 0.8\ B_{ecr}$	.5-.8 T	1-1.6 T
$B_{ext} \sim B_{rad}$	2T	4T
$B_{rad} \geq 2\ B_{ecr}$	2T	4T

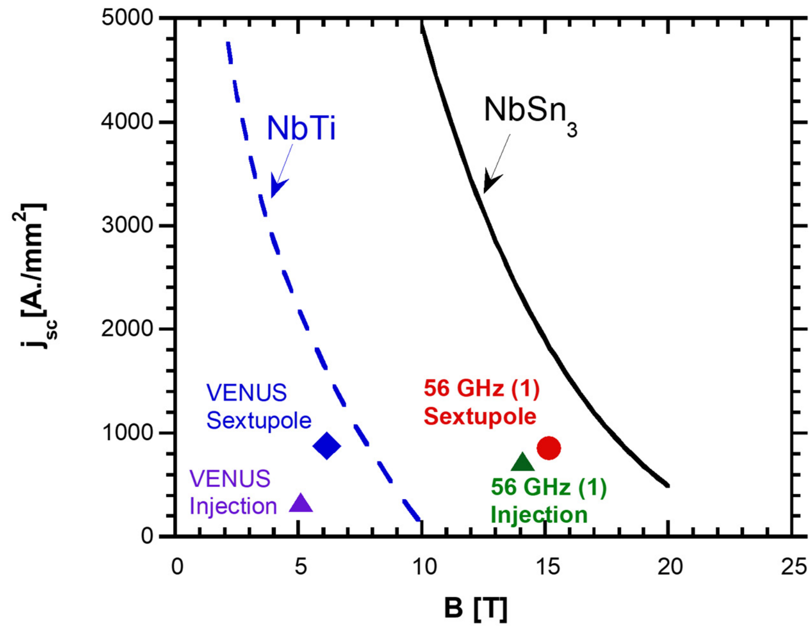
Magnetic Design		28 GHz	56 GHz
Max solenoid field	on the coil	6 T	12 T
	on axis	4 T	8 T
Max sextupole field	on the coil	7 T	15 T
	on plasma wall	2.1 T	4.2 T
Superconductor		NbTi	Nb_3Sn

LBNL Has Developed A Conceptual Design For A 56 GHz Nb_3Sn ECR Magnet Based On The VENUS Geometry

Sextupole-in-Solenoid Classic Geometry



- Minimizes the peak fields in the coil
- Strong influence (forces) of the solenoid field on the sextupole ends

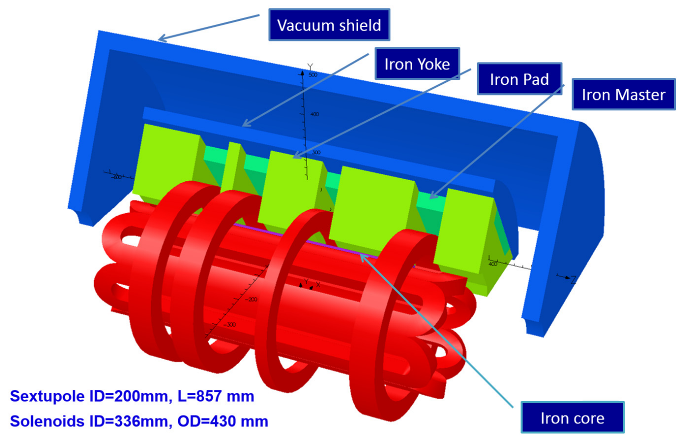


P. Ferracin et al.,Rev. Sci. Instrum., vol.81, 02A309 (2010)

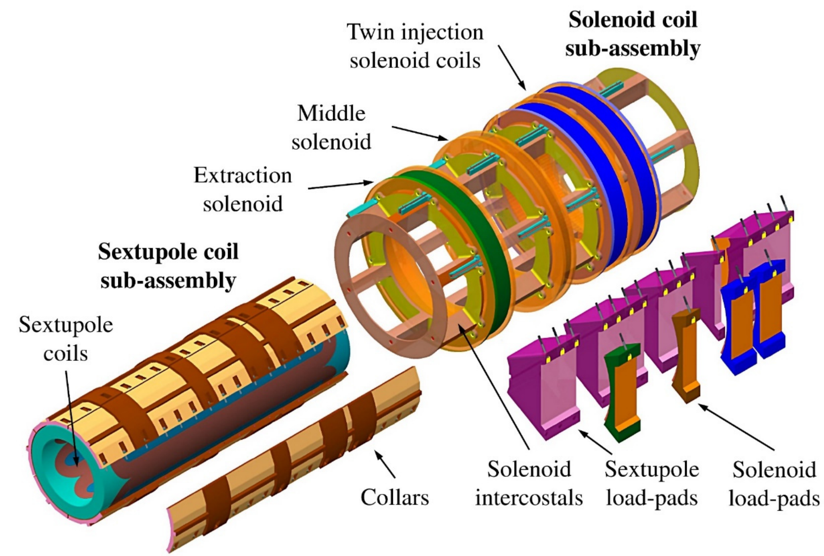
Fourth Generation Nb_3Sn ECR Ion Sources Are Emerging

45 GHz ECR Magnet Design has been developed in a collaboration between LBNL and IMP

FECR Magnetic Design *



FECR Nb3Sn magnet mechanical structure**



R&D/ Prototype Phase

*H.W. Zhao et.al ECRIS2018, Catania, Italy, 2018
*H.W. Zhao et. al.,Rev. Sci. Instrum., vol.89, 052301 (2018)
**M. Juchno et al.,IEEE Trans.Appl.Supercond., 28, 4602806(2018)

Fourth Generation Nb_3Sn ECR Ion Sources Are Emerging

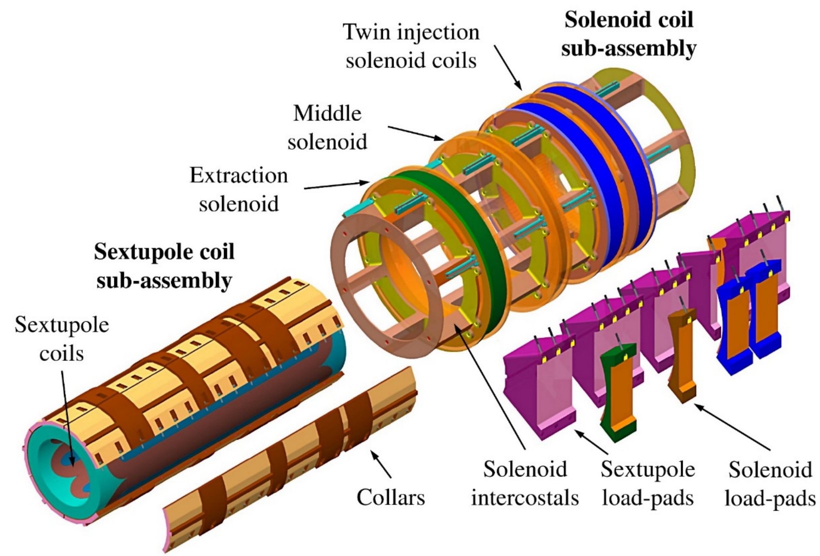
45 GHz ECR Magnet Design has been developed in a collaboration between LBNL and IMP

Design is based on several years of experience with the design and fabrication Nb_3Sn at LBNL within the LARP program and the HILUMI project to develop high field quadrupoles (Rutherford Cables) for the LHC upgrade.

Challenges:

- Combined magnet functionality (Solenoid and Sextupole)
- Single Strand SC Wire

FECR Nb3Sn magnet mechanical structure**

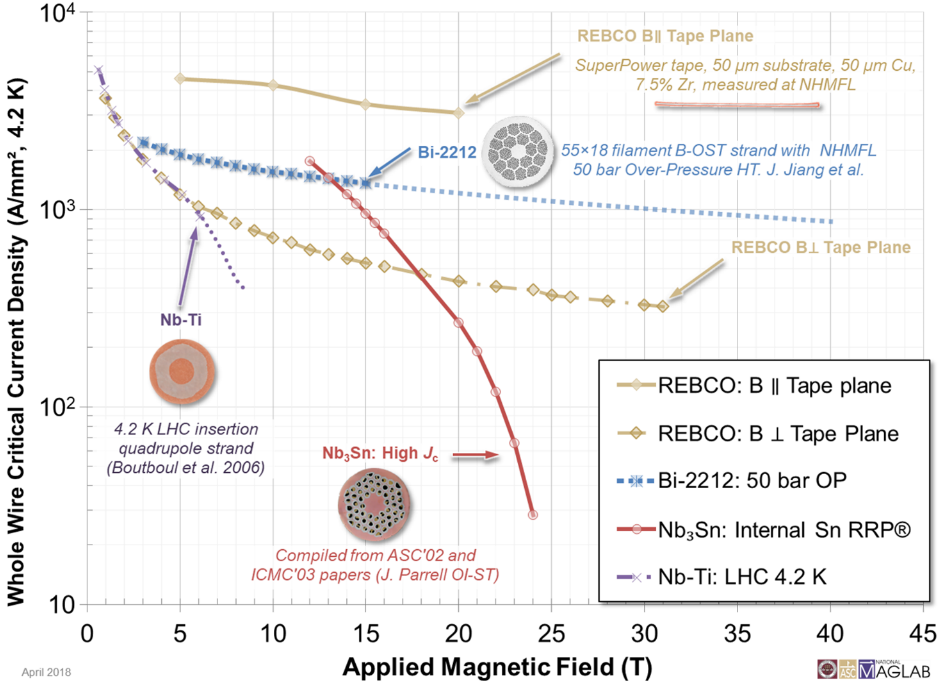


Technology is within reach in the next 5-10 years

*H.W. Zhao et.al ECRIS2018, Catania, Italy, 2018
*H.W. Zhao et. al.,Rev. Sci. Instrum., vol.89, 052301 (2018)
**M. Juchno et al.,IEEE Trans.Appl.Supercond., 28, 4602806(2018)

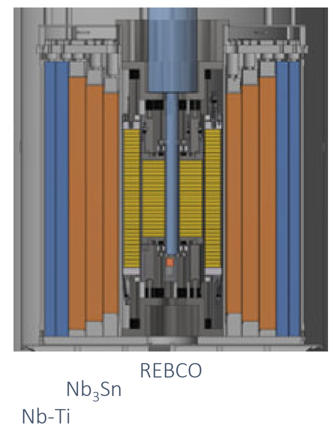
Fifth Generation ECR Ion Sources for 80 to 100 GHz

High critical current density and operation at T>4K makes HTS materials an attractive candidate for frequencies beyond 56 GHz



32 T all superconducting solenoid was recently developed

40 mm



S. Hahn, Supercond. Sci. Technol.21, 105017 (2016)

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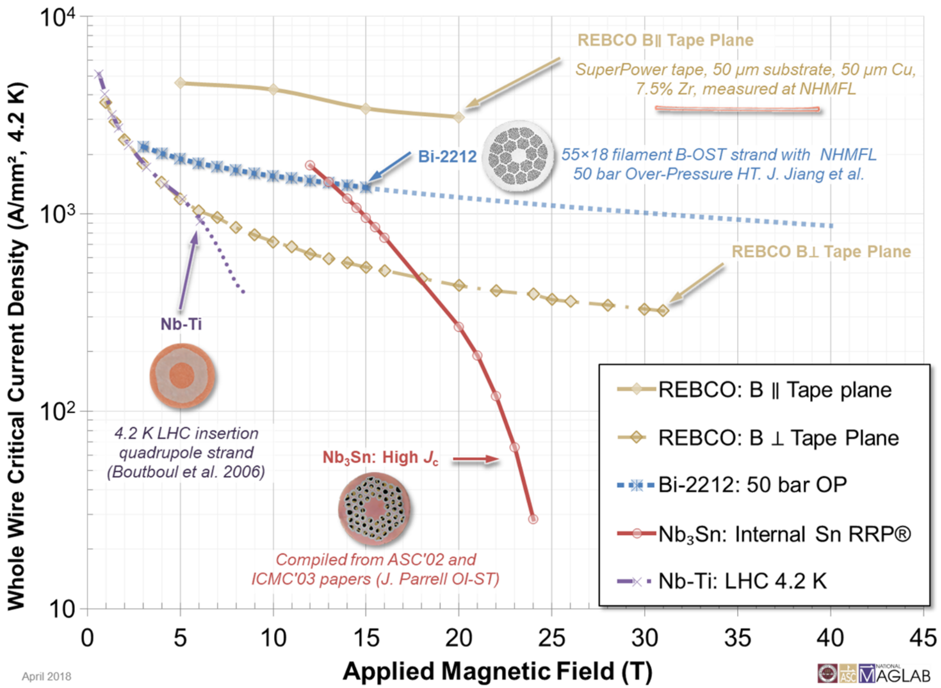

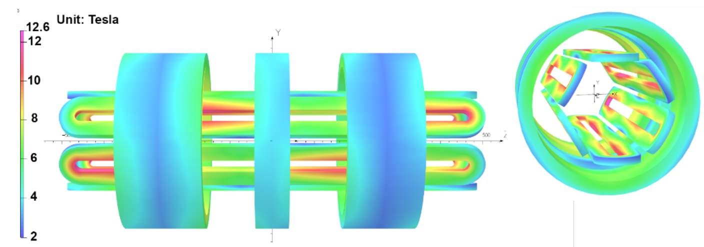

T. Shen, et al.,ECRIS'18, Catania, Italy,(2018)

Technology is within reach in the next 10-15 years

S. Hahn,Supercond. Sci. Technol.21, 105017 (2016)

Conclusion

- ECR ion source performance continues to improve for 3rd Generation ECR ion sources
- Technological challenges remain for high power operation of these sources and the production of high temperature, high intensity heavy ion beams (Uranium)
- The ion beam intensities needed for future heavy ion facilities require development of 4th and 5th generation ECR ion sources
- Nb_3Sn structures are the most promising candidates for building ECR magnets to be operated using microwave frequencies beyond 45 -56 GHz
- HTS technology is emerging as a promising option for 5th Generation ECR magnet structures for operations beyond 56 GHz

Acknowledgements

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