World-wide Development of Intense Highly-charged SC-ECR Ion Sources

(ECR: Electron Cyclotron Resonance)

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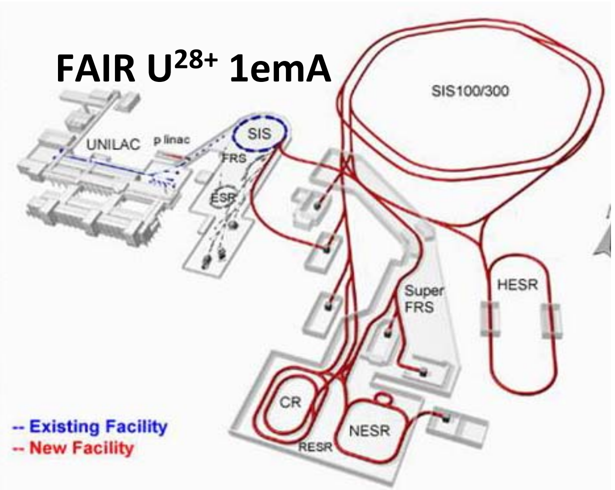
Outline

- ECR ion source brief introduction
- Review of SC-ECR development
- Future development

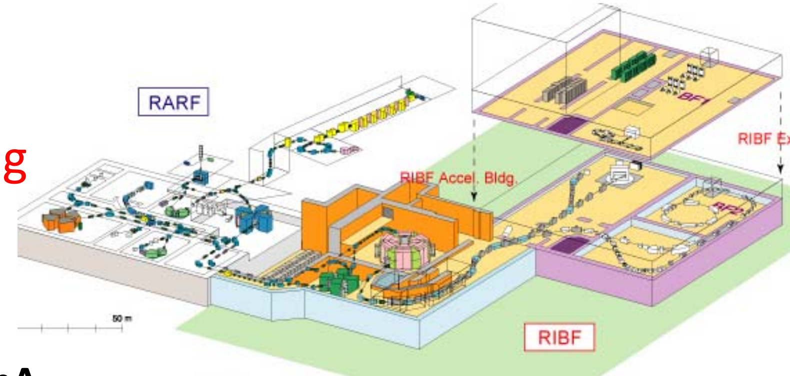
High Power Heavy Ion Accelerator is driving force for Intense Highly Charged Ion beams

FAIR U^{28+} 1emA

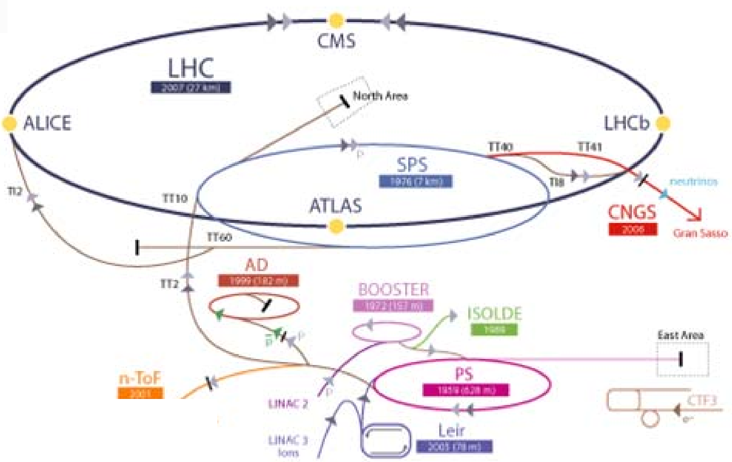


Demands to intense highly charged ion beams are increasing

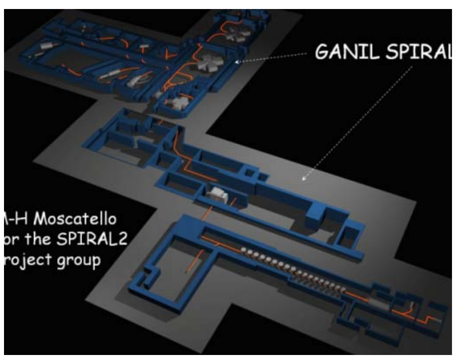
RIKEN RIBF U^{35+} 525e μ A



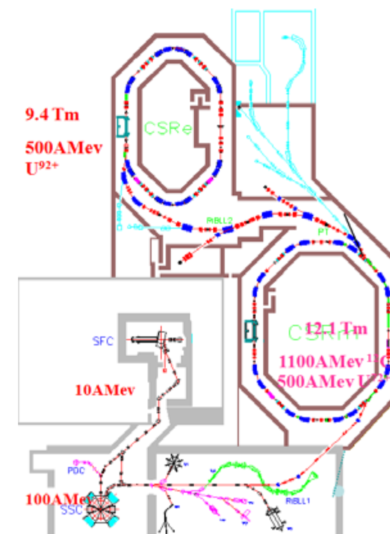
LHC Pb^{27+} 1 emA



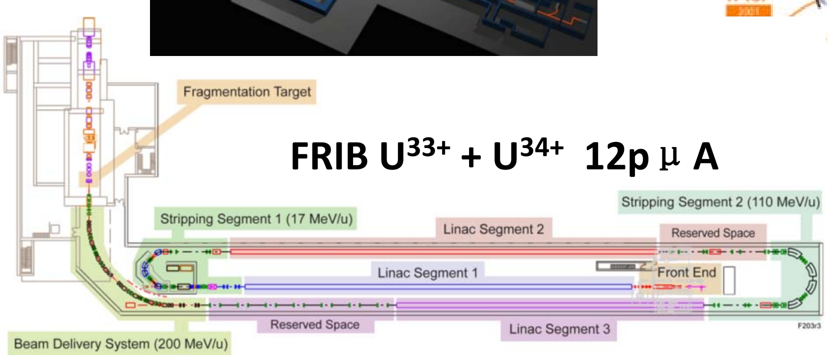
SPIRAL2 Ar^{12+} 1emA



IMP HIRFL U^{41+} 100e μ A



FRIB U^{33+} + U^{34+} 12p μ A



Except U^{33+} and U^{34+}, these beam intensities have not been achieved by any existing ECRIS .

Why Highly Charged Ion Beams

(Q: Charge Sate)

- **Higher Q, higher energy. E $\propto$ Q or Q^2**

- **Higher Q, higher energy gain, accelerator more compact and lower cost**

-2001, RIA project, U^{28+}, 400MeV/u, 400kW, cost range 950M$

-2009, FRIB project, $U^{33+}+U^{34+}$, 200MeV/u, 400 kW, cost range 550M$

- **Higher Q, more intense beam without stripping**

- RIKEN ECRIS is running U^{35+} directly for RIBF

- IMP SECRL is running Bi^{31+} directly for HIRFL

Ion Sources for Highly Charged Beam

- **ECRIS**

  CW and pulsed beam (～10ms), *I*: eμA-emA

- **EBIS-** Electron Beam Ion Source

  Only pulsed beam (10-50 μs), *I*: few emA-tens emA

- **LIS-** Laser Ion Source

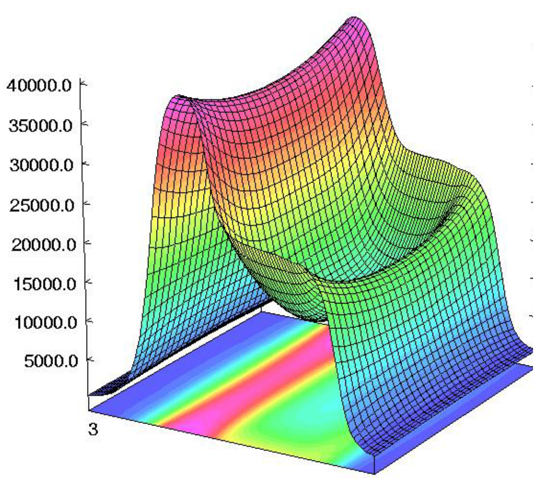
  Only pulsed beam (a few μs), *I*: few emA-tens emA

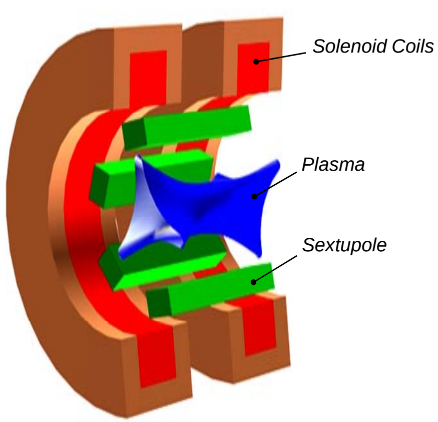
ECR Ion Source

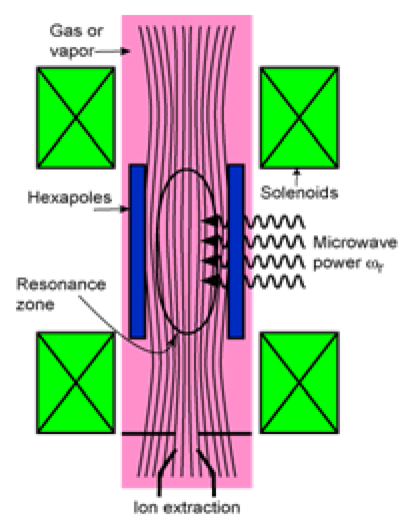
- Plasma device to produce intense highly charged ion beams
- Plasma is produced and heated by microwave (6 GHz-28GHz)
- Plasma is confined by minimum B structure－solenoids+sextupole
- Highly charged ions are produced by stepwise ionization process
- A resonant interaction between electrons and RF takes place when :

$$\omega_{HF} = \frac{eB(\mathbf{r})}{m}$$

- Plasma parameters: n_e - 10^{12} cm^{-3} Te – tens keV, τ_{ion} - ms
- To produce HCI beams, need high n_e, long τ_{ion} and low n_0







ECRIS physics is not completely understood!

ECR Ion Source

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- Plasma is produced and heated by microwave (6 GHz-28GHz)
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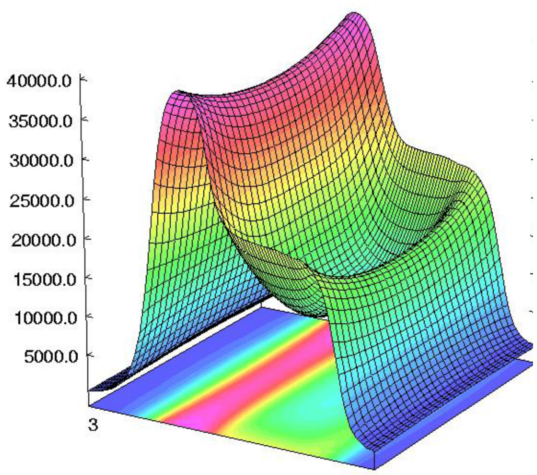
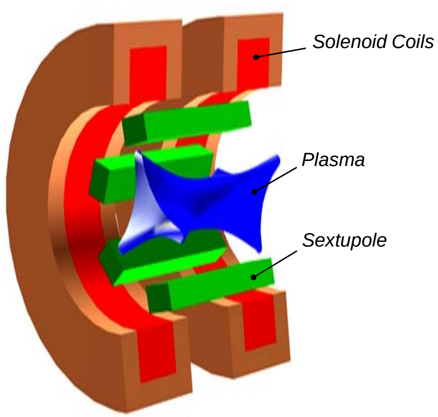
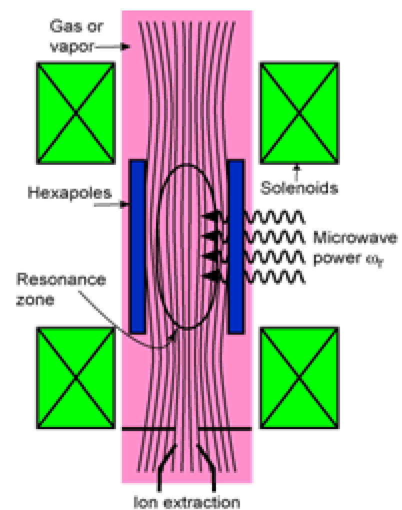
- Highly charged ions are produced by stepwise ionization process

Higher Q and higher I ⟹ Higher $n_e \tau_i$ ⟹ Higher ω_{rf} ⟹ Higher B
That is why we need to build SC-ECRIS, and also good device to study ECRIS physics.

- **To produce HCI beams, need high n_e, long τ_{ion} and low n_0**







ECRIS physics is not completely understood!

ECR Ion Source Development

- In the Beginning   Supermafios in 1974
- First generation 6 to 10 GHz sources
  - Minimafios, ECRVIS , LBL ECR, RT-ECR …
- Second generation 14 to 18 GHz
  - CAPRICE, AECR-U, LECR ………
  - RIKEN 18 GHz
  - SERSE 18 GHz Superconducting
  - A-PHOENIX
  - GTS 18 GHz Grenoble
- Third Generation 24 to 35 GHz
  - VENUS Operating at 28 GHz Berkeley
  - SECRAL Operating at 18 -24GHz Lanzhou
  - MS-ECRIS Under construction for 28 GHz for FAIR
  - RIKEN SC-ECR Operating at 18 GHz for RIBF
  - MSU-NSCL   SUSI Operating at 18 GHz
- Fourth Generation ,35GHz-60GHz??

Typical beam intensity enhancement in the last 10-30 years

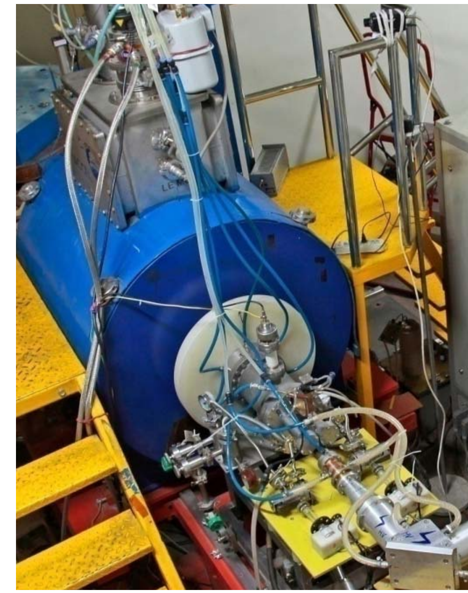
Ions	Year Intensity By ECRIS	Year Intensity By ECRIS	By factor
O^{6+}	1974, 15 e μ A Supermafios	2004-2006, >2000 e μ A IMP SECRAL LBNL VENUS	30 ys >130
Xe^{30+}	1997-1998, 10-15 e μ A, RIKEN 18 GHz, LBNL AECR-U	2008, >150 e μ A, IMP SECRAL	10 ys >10
Xe^{35+}	1997, 1.5 e μ A LBNL AECR-U	2009, >45 e μ A IMP SECRAL	10 ys >30
U^{34+}	1997, 20 e μ A, LBNL AECR-U	2006, >200 e μ A LBNL VENUS	10 ys >10

IMP ECRIS Evolution from Normal Conducting to Superconducting Magnet

Xe Beam Current from IMP ECRIS

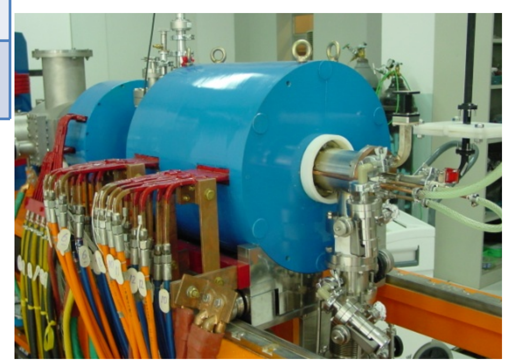
Ions	LECR1 10GHz eμA	LECR3 14.5GHz eμA	SECRAL 18-24GHz eμA
Xe^{20+}	20	160	505
Xe^{27+}	*	50	455
Xe^{30+}	*	7	152
Xe^{35+}	*	*	45
Xe^{42+}	*	*	3

Superconducting

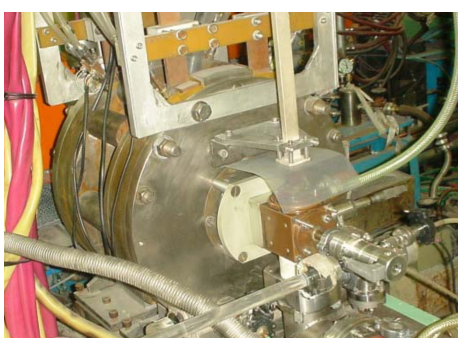


SECRAL(2005), 3.7T, 5-7 kW, 18-24GHz

Normal Conducting

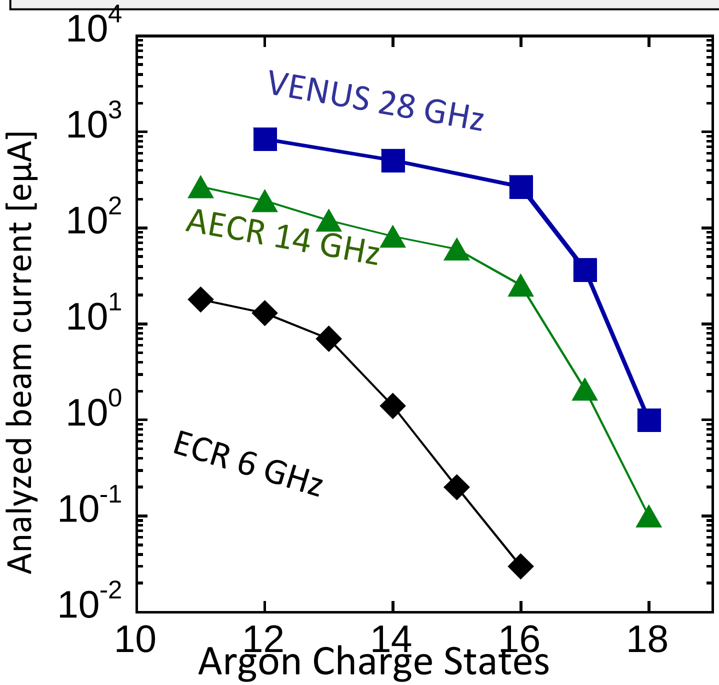


LECR3(1999), 1.5T, 1.5 kW, 14.5GHz



LECR1(1991), 0.8T, 0.5 kW, 10GHz

LBNL ECRIS Evolution from Normal Conducting to Superconducting Magnet



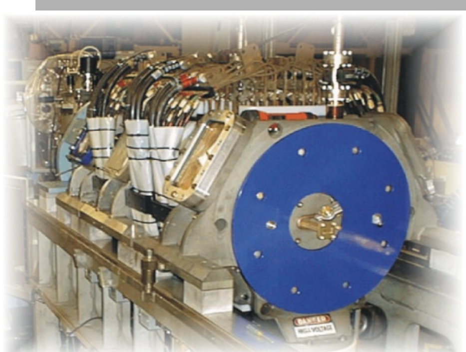
Normal conducting

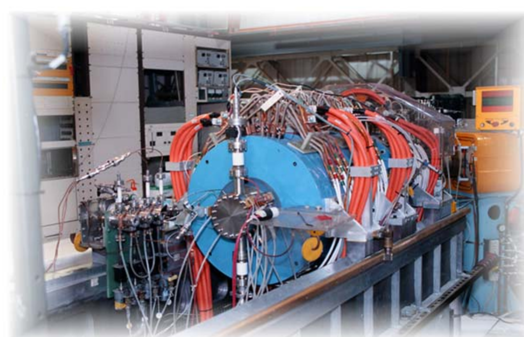
Super conducting

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



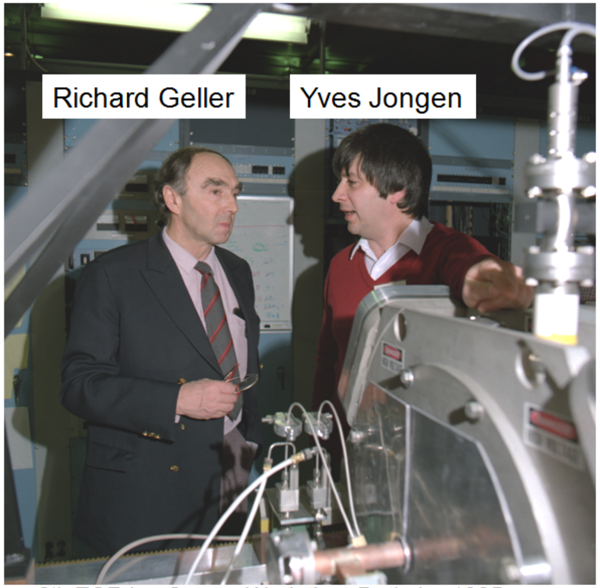


Slide from C.Lynies and D.Leitner talk at ICIS09

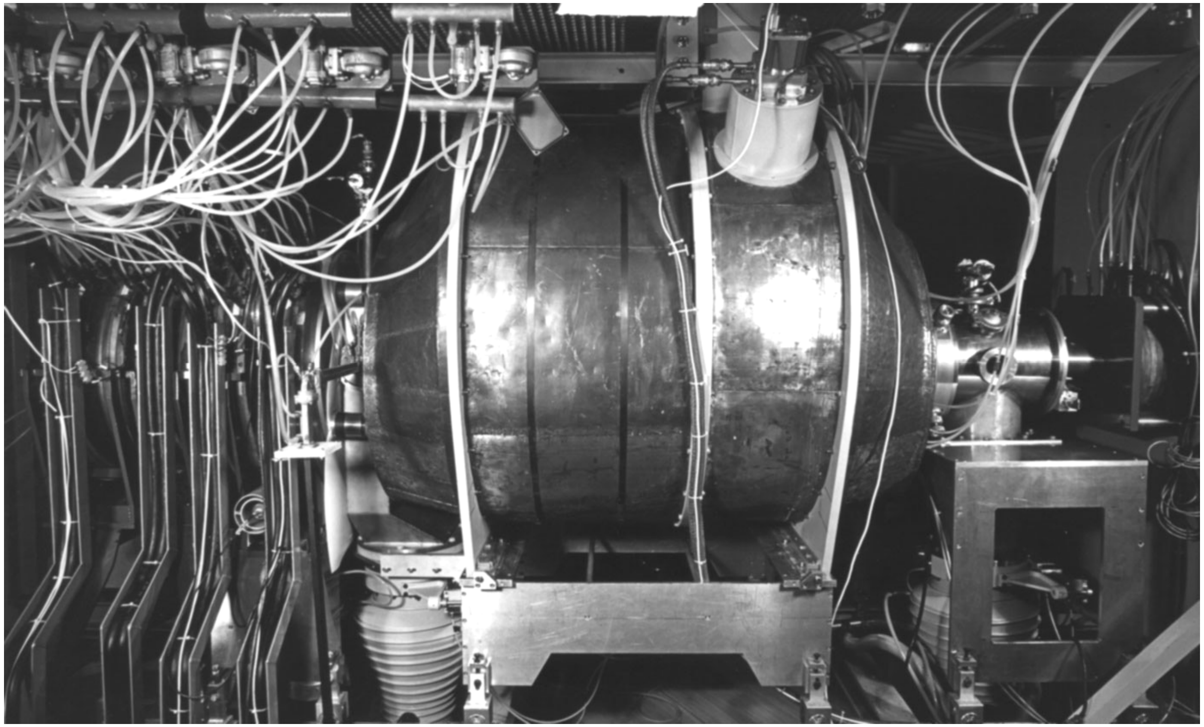
First successful SC ECR ion source

ECREVIS circa 1983

ECR Ion Source Pioneers



6th ECR Ion Source Workshop Berkeley 1985



Yves Jongen, Louvain-la Neuve, Belgium

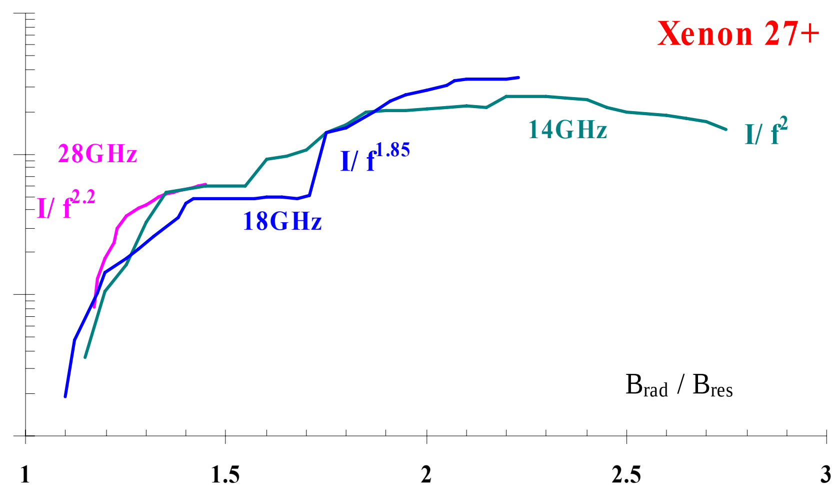
Slide from LBNL C.Lyneis talk at ICIS09

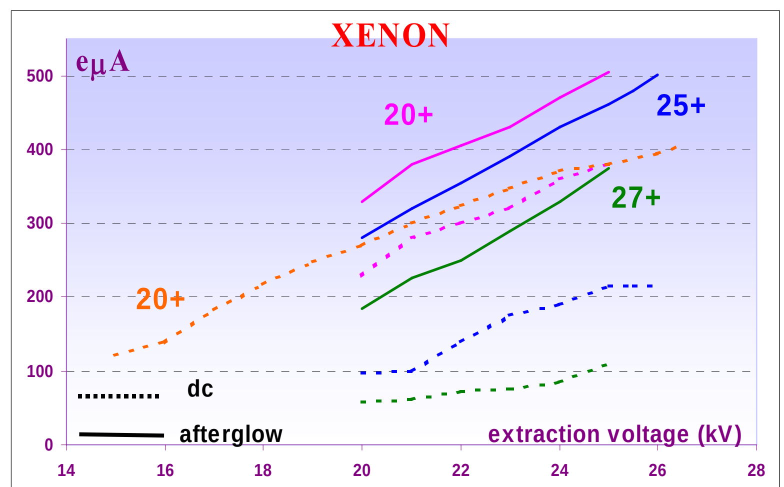
SERSE in INFN-LNS Catania

Built by collaboration between CEA-Grenoble and INFN-LNS

G. Ciavola, S. Gammino,IFN-LNS,Catania

First test at 28GHz in 2000 and demonstrated frequency scaling up to 28 GHz



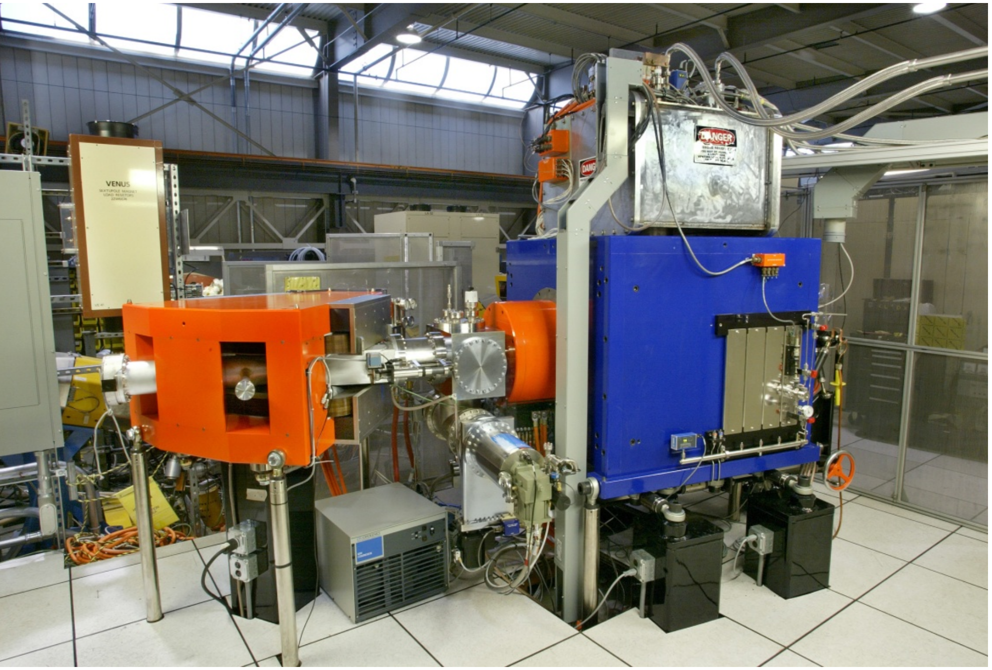


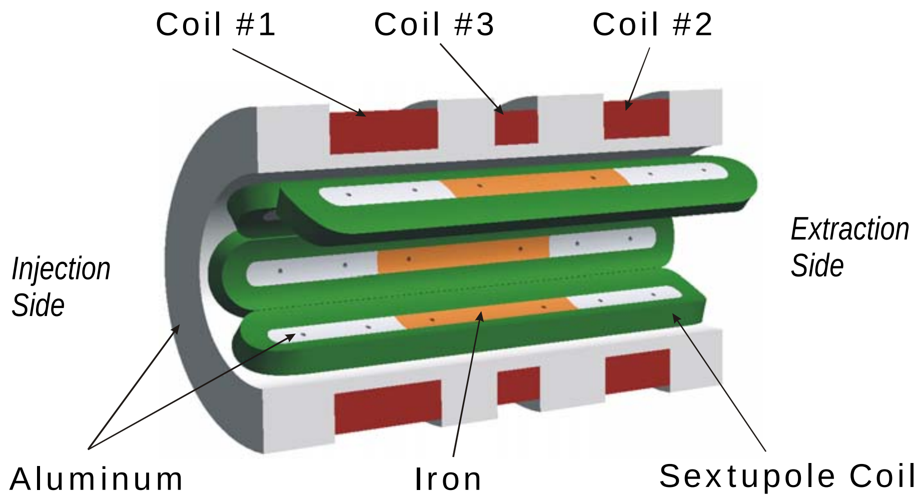
Superconducting ECR designed for 18 GHz

Tested at 28 GHz

- **I ~ f^2 , from 18 GHz to 28 GHz**
- **P ⩾ 3 kW**
- **Optimum B_{rad} at 28 GHz > 1.45 T**

LBNL VENUS 28 GHz — The first 3rd generation ECRIS





Sextupole-in-Solenoid
Conventional coil structure

Achieved magnetic fields

$B_{inj} \leqslant 4$ T, $B_{ext} \leqslant 3$ T, $B_{rad} \leqslant 2.2$ T

18-28GHz, >9 kW rf power

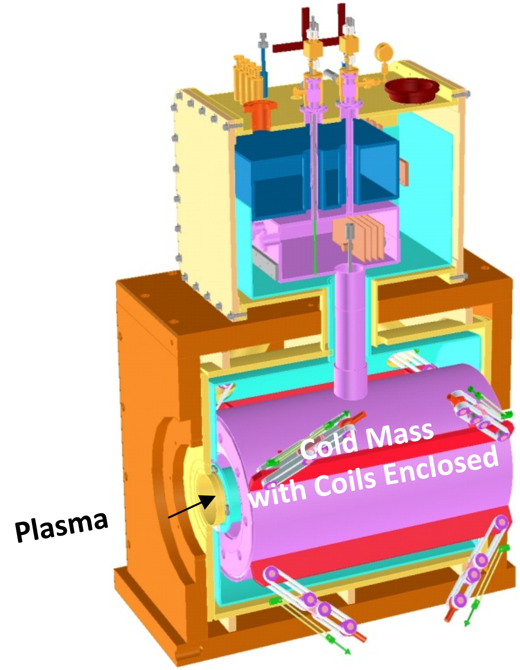
Courtesy of C.Lyneis and D.Leitnerat LBNL

- **1997 : Magnet prototype**
- **2002: The first test at 18GHz**
- **2006-2007: The best results achieved at 28GHz**

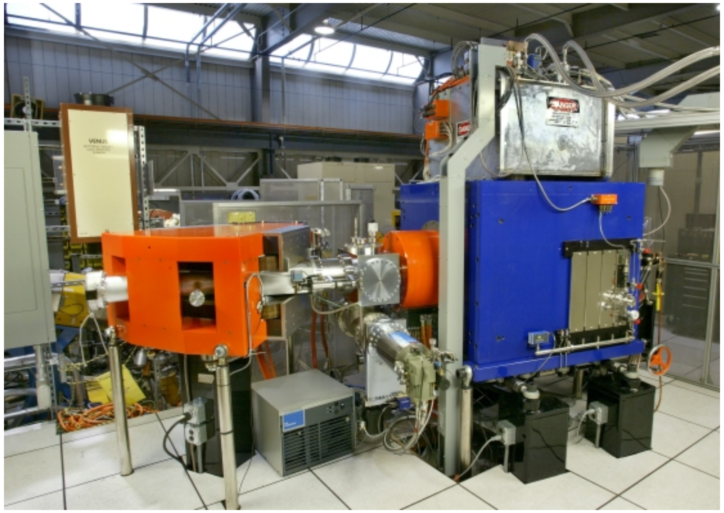
- **10 years from construction to the best results.**
- **Sextupole lead was burned in Jan.2008 and has taken more than two years to repair! It will be online test soon.**

VENUS has addressed many of technologies and challenges firstly Now being incorporated into other 3rd Generation Sources

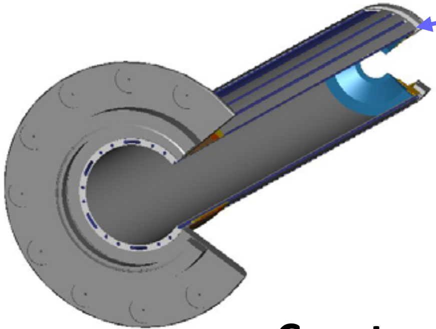
Advanced cryostat with cryocoolers



Beam transport with high transmission dipole magnet

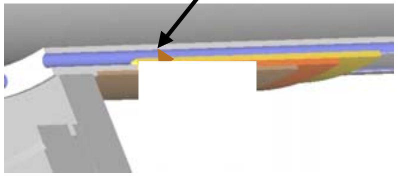


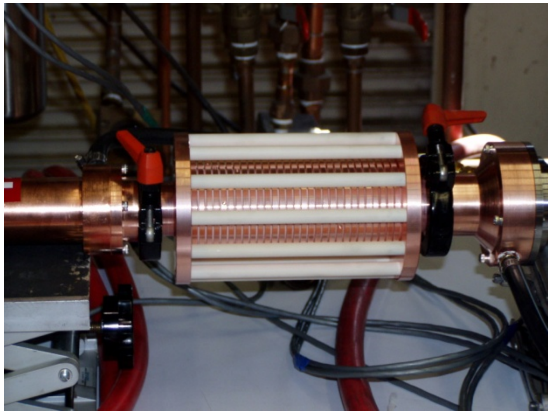
Aluminum plasma chamber for high power operation with incorporated tantalum x-ray shield



Water cooling for high power

Ta X-ray shield



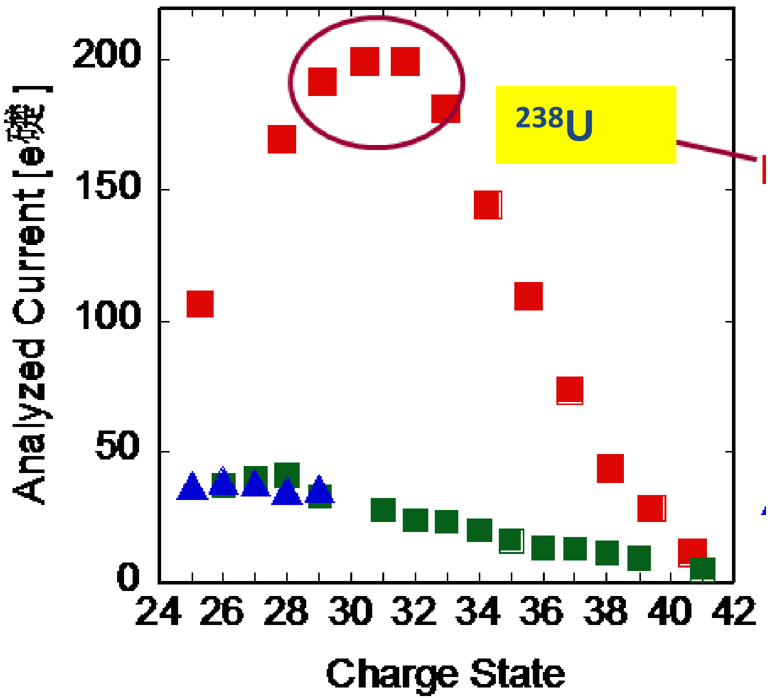


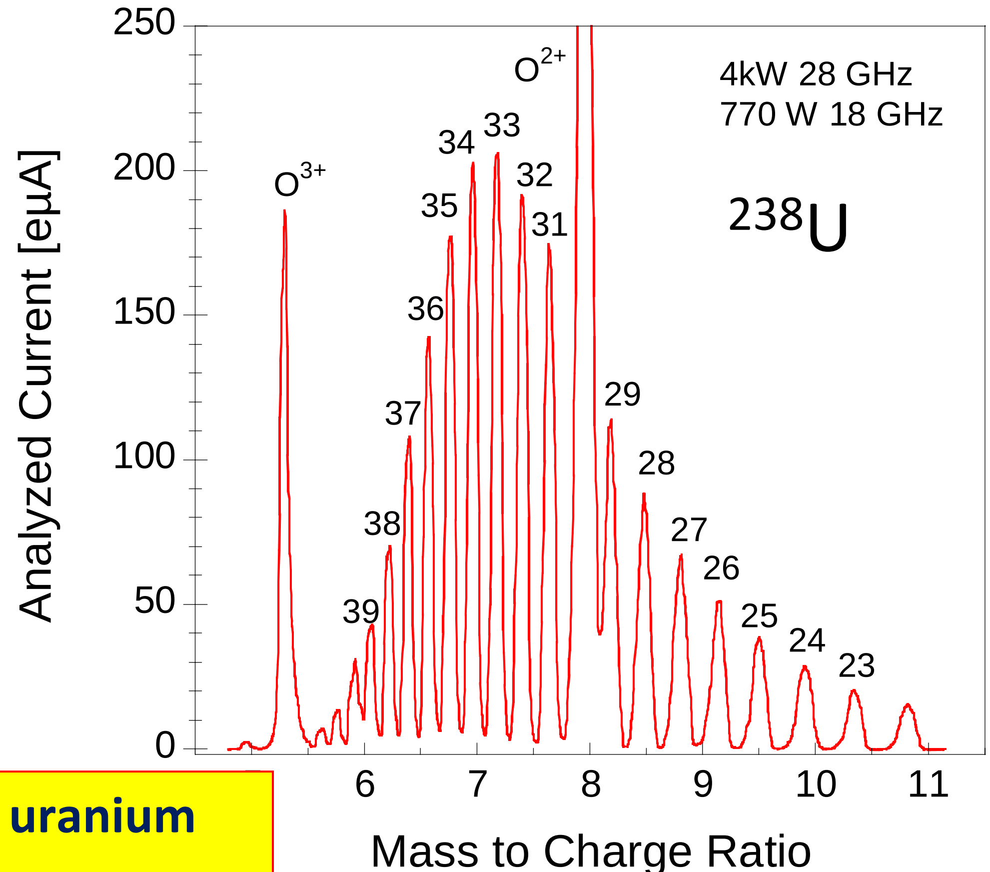
28 GHz ceramic HV break

Courtesy of C.Lyneis and D.Letner at LBNL

LBNL VENUS: Achieved the best uranium performance

U^{34+} 200 eμA, U^{47+} 5 eμA



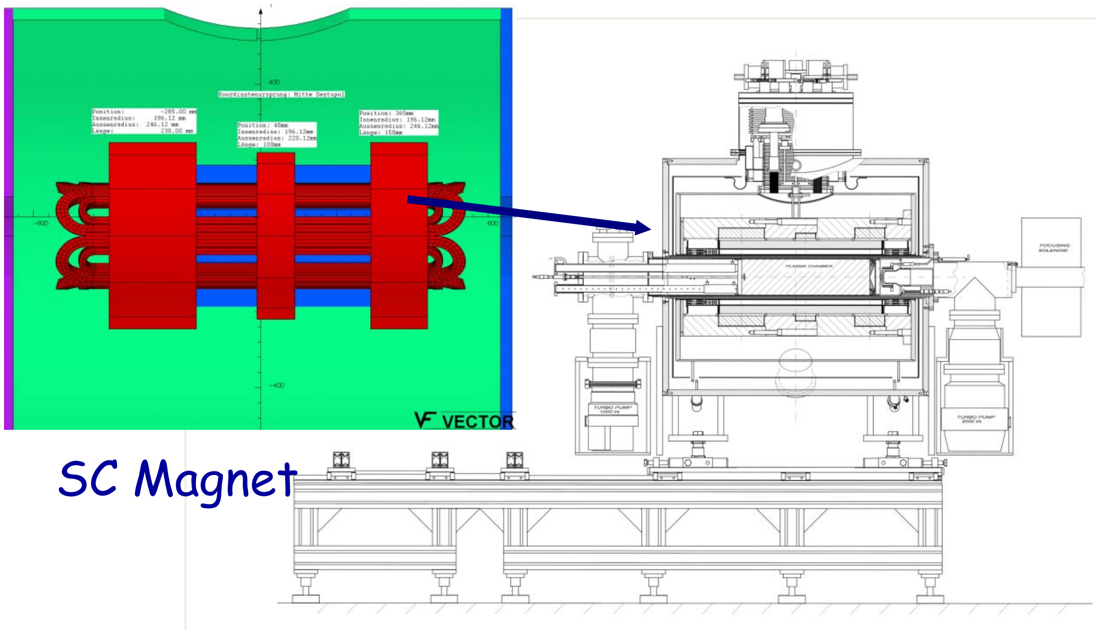


Production of intense highly charged uranium beams more challenging!

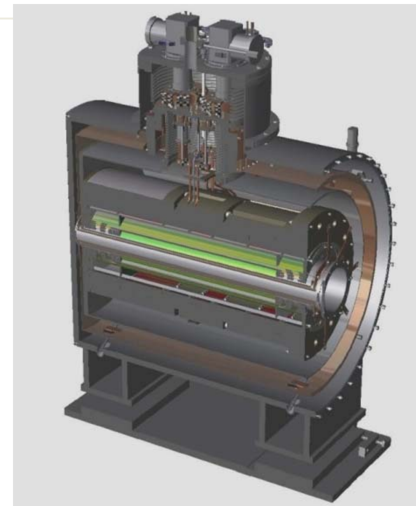
C.Lynies and D.Leitner at LBNL, talk at ICIS09

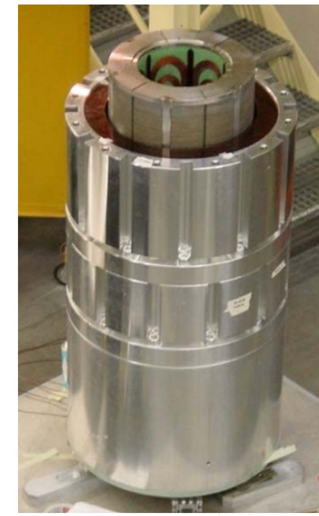
MS-ECRIS for FAIR

— The third Generation ECRIS collaborated by 9 EU institutions



SC Magnet



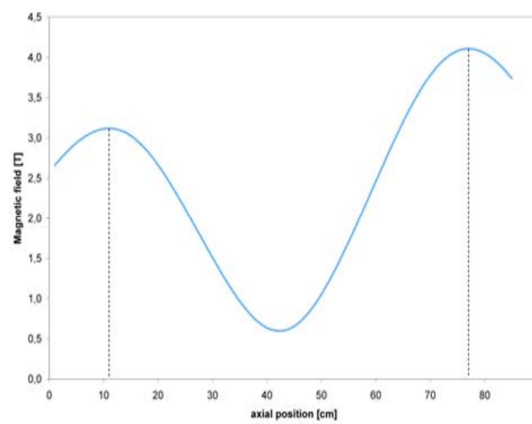


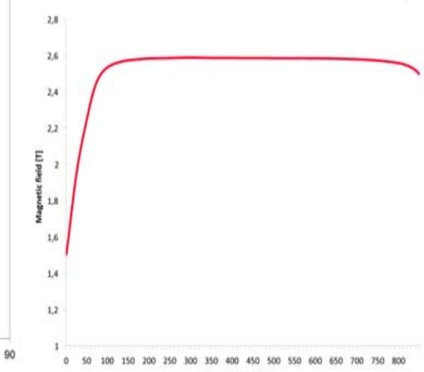
Fabrication of magnet started in 2007

- **Designed specifications**

  28GHz, B_{inj} 4.5 T, B_{ext} 3.2 T, B_{rad} 2.7 T

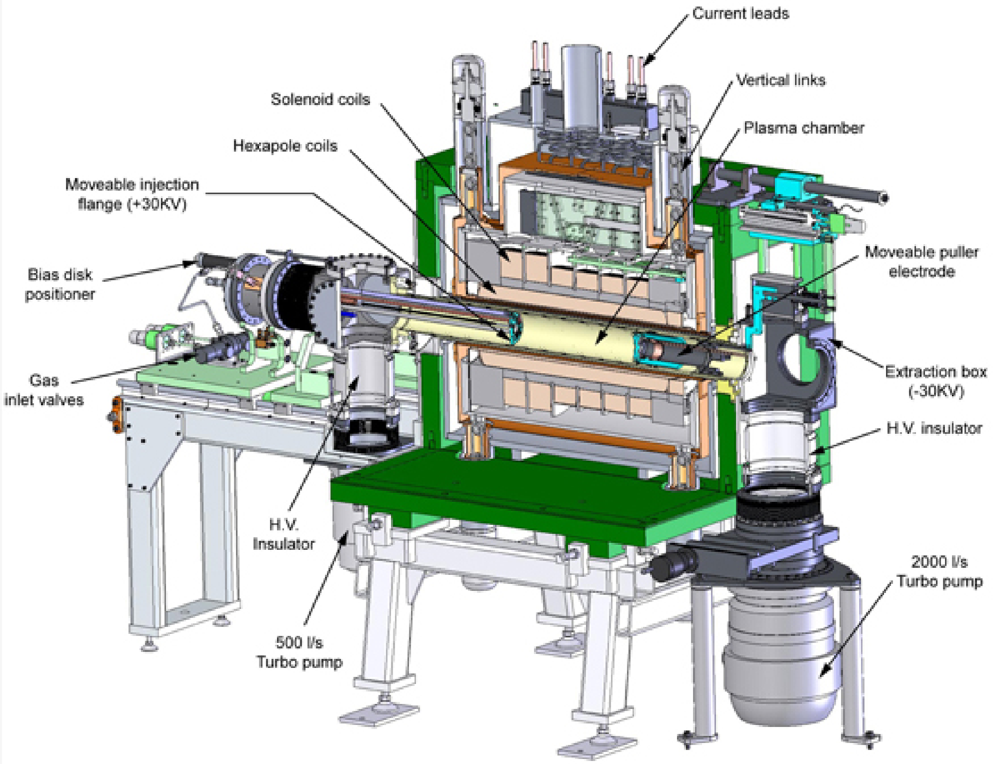
- **All single coils reached the specified demands .**
- **But the whole magnet system quenched randomly with different ramping strategies (50% maximum)**
- **Restarted mechanical modification recently**

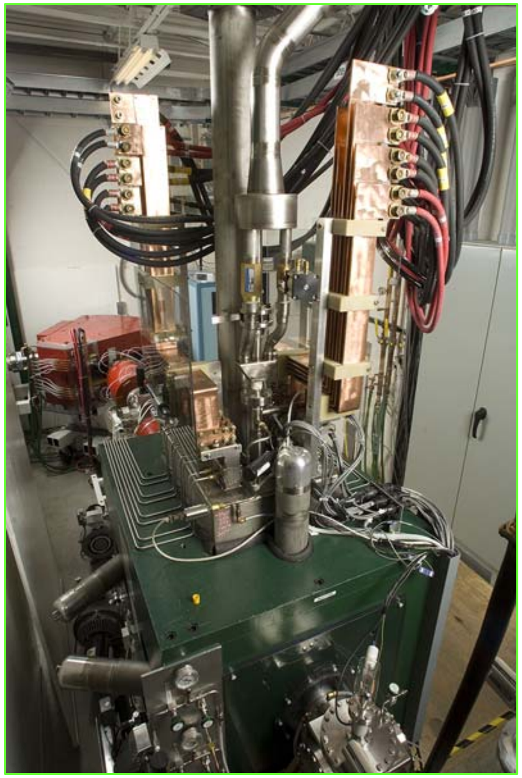


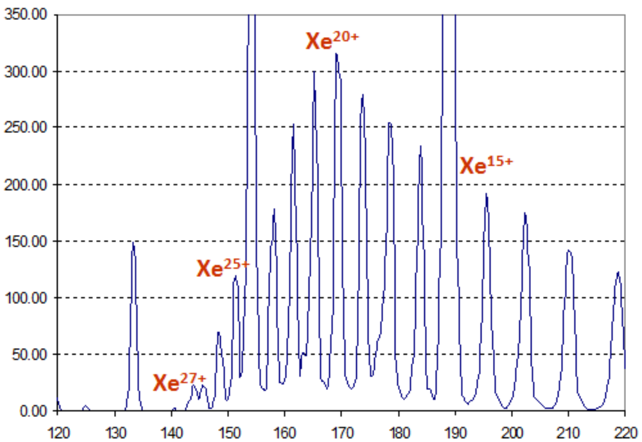


Courtesy G. Ciavola, S. Gammino,IFN-LNS,Catania

SUSI ECRIS at NSCL/MSU





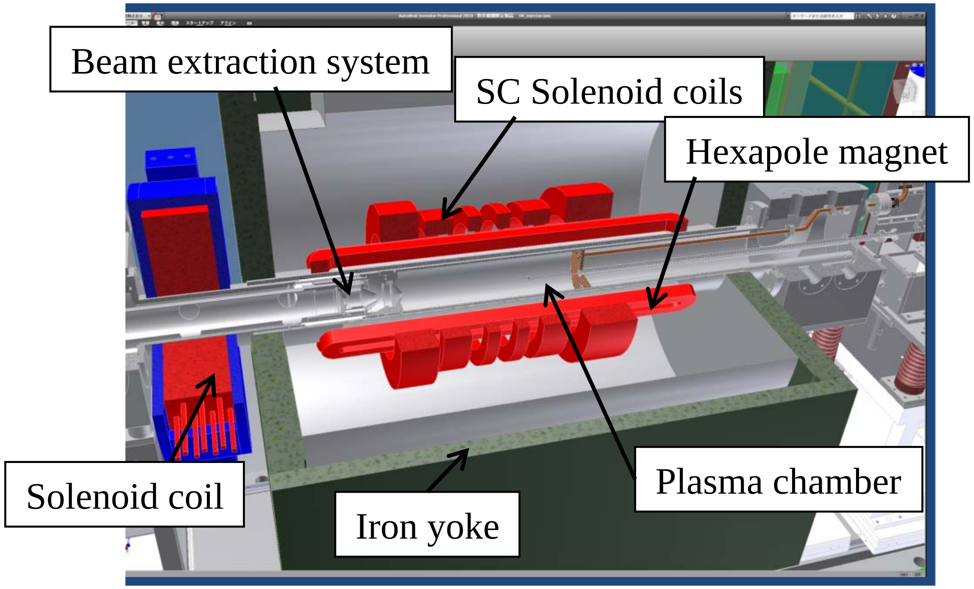


^{129}Xe : optimized on Xe^{20+} :335euA
1.7kW 18GHz, 300W 14.5GHz

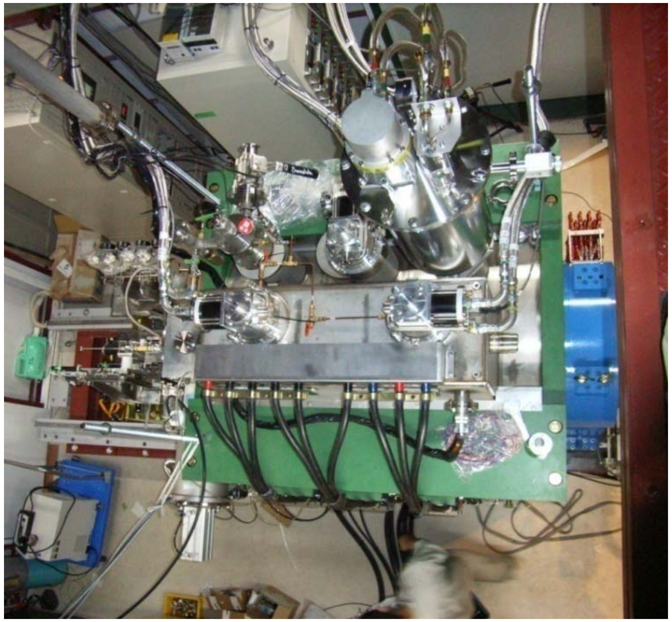
- **Achieved magnet field (lower field):**
  18- 24GHz, B_{inj} 2.5 T, B_{ext} 1.4 T, B_{rad} 1.5T
- **Unique feature : Flexible axial field distribution with 6 solenoid coils**
- **chamber volume adjustable from 3.1 to 3.9 l**
- **Started operation for accelerator at 18GHz**

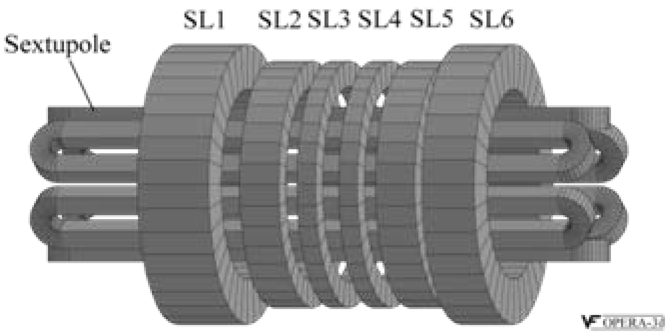
Courtesy of G.Machicoane at MSU

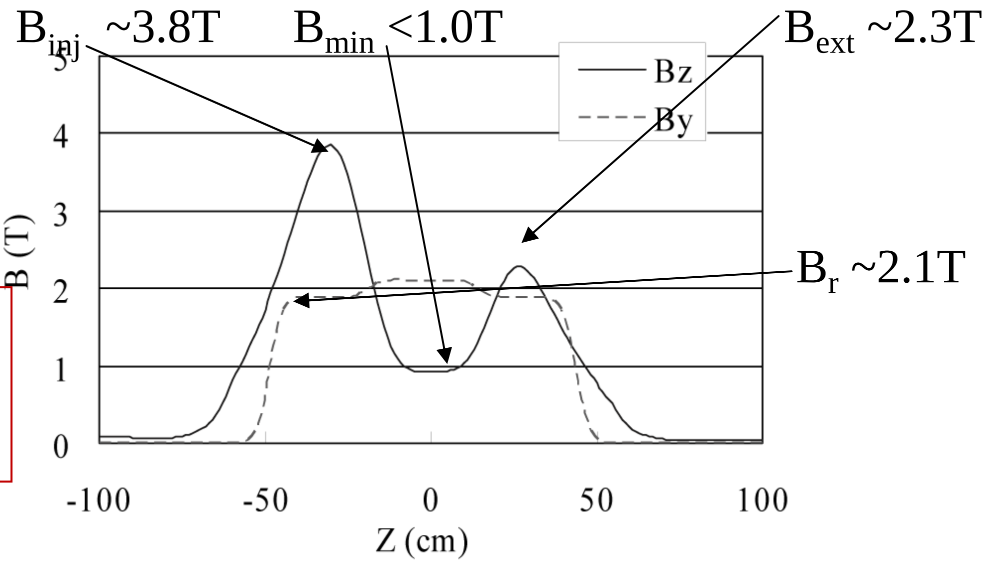
RIKEN 28GHz SC-ECRIS —The fastest construction 3rd Generation ECR



2 years from construction to the first beam.





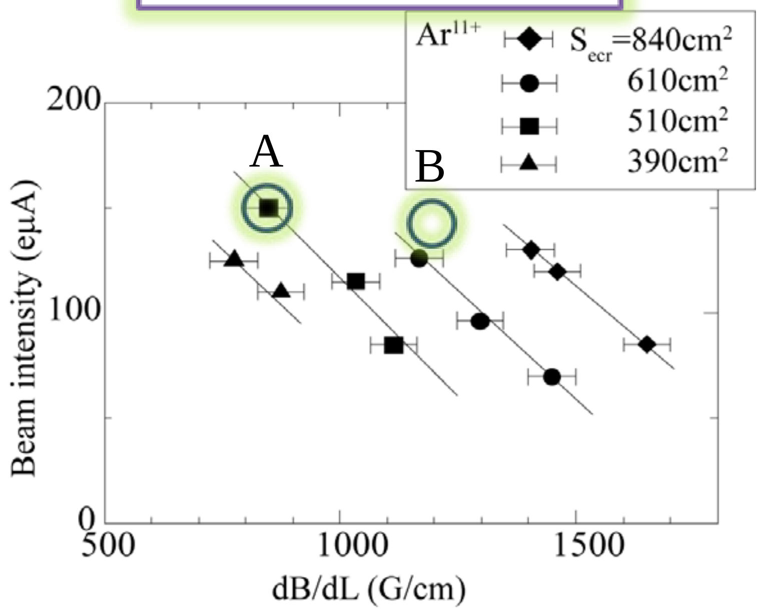


- **Started operation at 18GHz**
- **28GHz test and operation planed in 2010**
- **6 solenoid coils for flexible field**

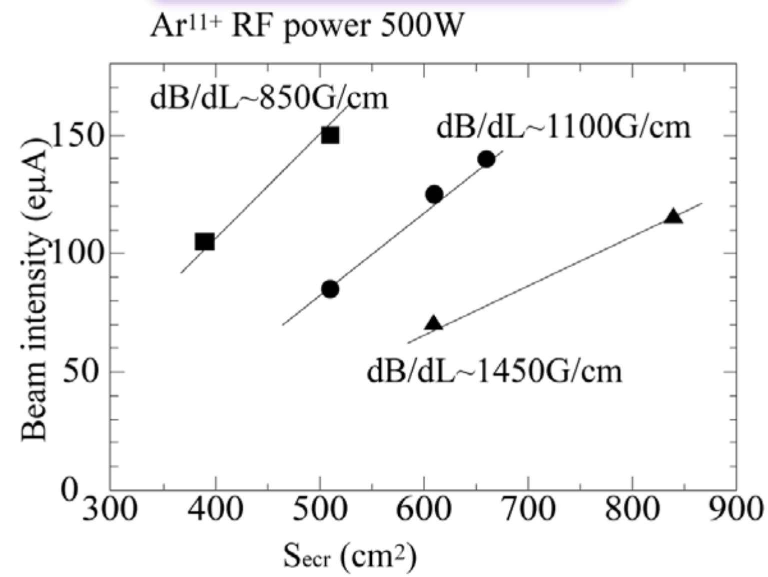
Courtesy of T.Nakagawa at RIKEN

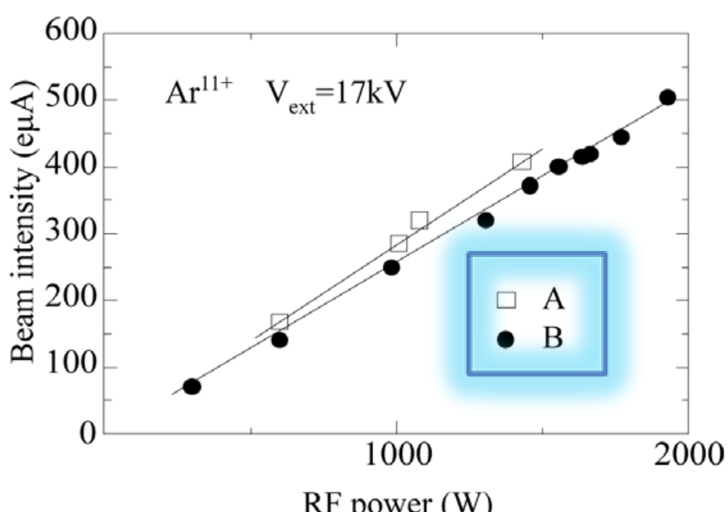
RIKEN SC-ECRIS — Very nice device to study ECRIS physics

Effect of field gradient



Effect of surface size





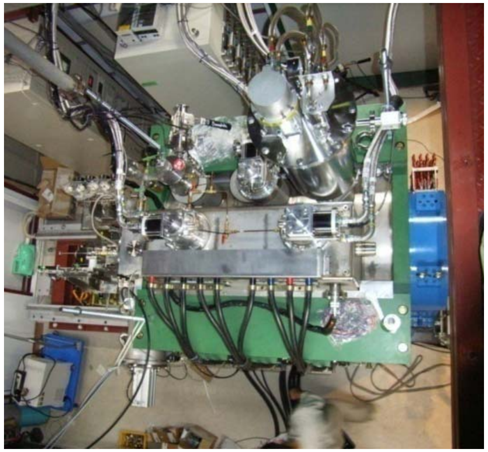
- **Effect of magnetic field configuration**
- **Effct of ECR zone and its size**

Courtesy of T.Nakagawa at RIKEN

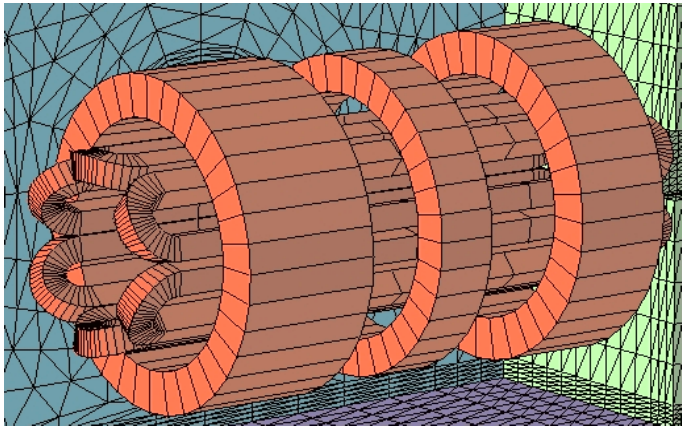
All existing or under-construction SC-ECRIS utilize conventional magnet structure

ECREVIS, SERSE,VENUS, SUSI, MS-ECRIS, RIKEN SC-ECR....

Conventional Structure:
Sextupole-inside-Solenoid



RIKEN SC-ECRIS (18-28 GHz)



VENUS in Berkeley (18-28 GHz)

Advantage:

- Higher sextuple field;
- Larger plasma chamber;
- Higher rf power.

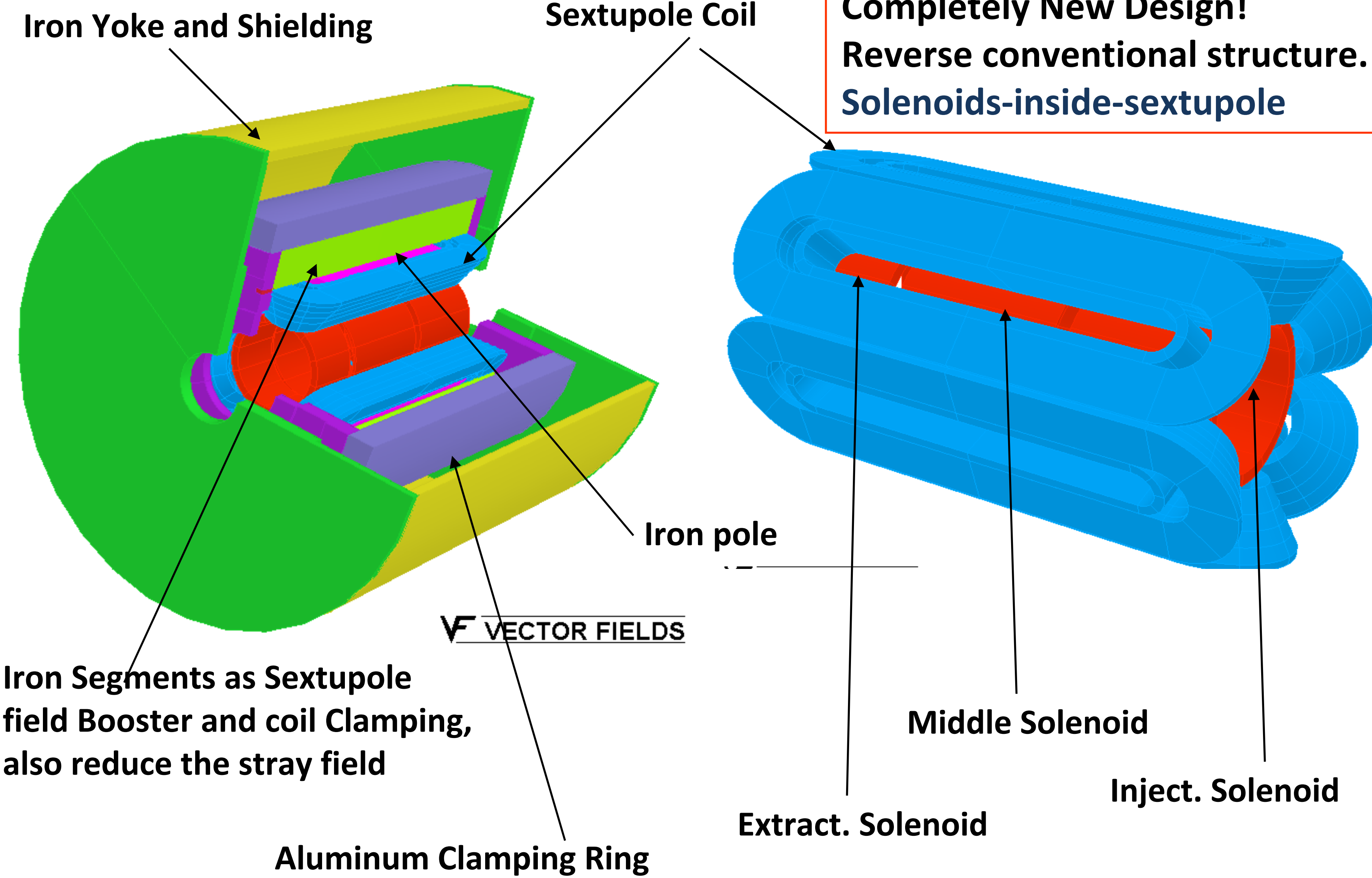
Disadvantage:

- Very strong interaction forces;
- Much longer sextupole;
- Bigger source body;
- Hard to build

That is why SERSE and VENUS took so many years to build and MS-ECRIS magnet failed .

IMP SECRAL Utilizes a New Magnet Concept and an Innovative Superconducting Coil Configuration

Completely New Design!
Reverse conventional structure.
Solenoids-inside-sextupole



Unique Features for SECRAL

✓ **Axial solenoids are located inside of sextupole**

- Reduce interaction force → Easier to build and cost-effective
- Compact source body → Efficient rf coupling and effective extraction
- Lower rf power and higher power density → Good long-term stability

✓ **Cold iron structure with iron segments as field booster and coil clamping**

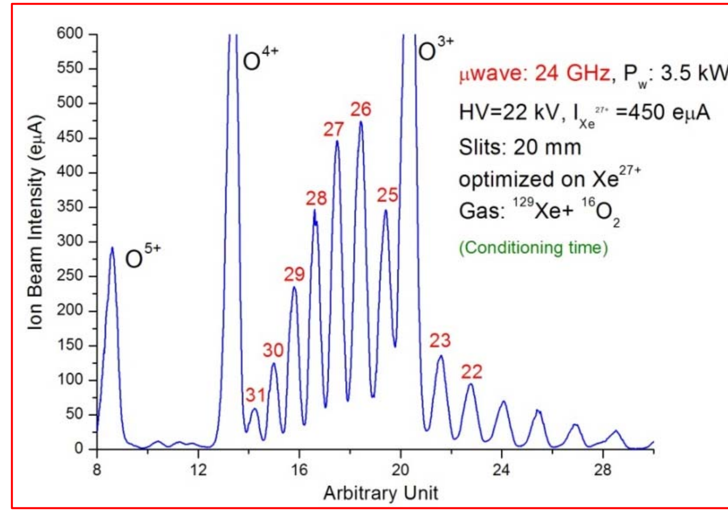
- Increase sextupole field
- Reduce stray field, easy support and suspend the cold mass
- Very simple clamping scheme

➢ **Disadvantage:**

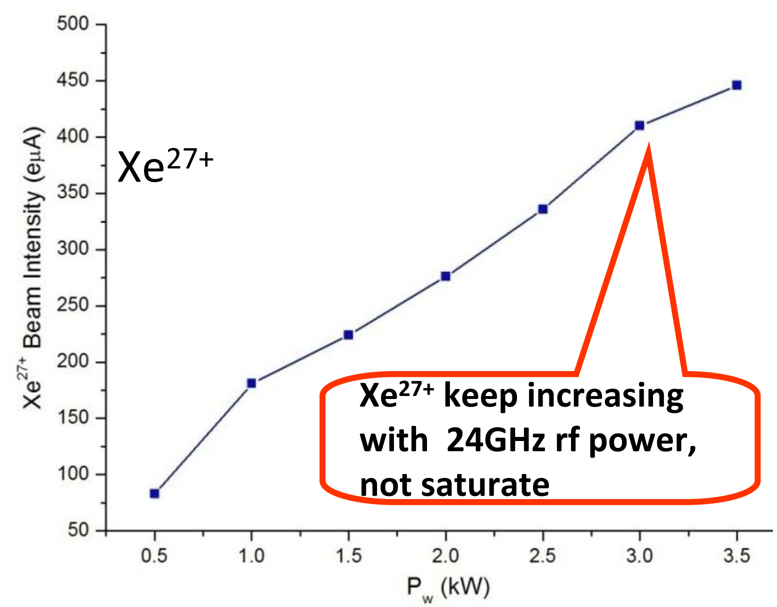
- **Plasma chamber and sextupole field are limited.**
- **But: 3.7 T injection field, 2.0 T sextupole field at the wall and Φ 126 mm chamber, sufficient for 28 GHz, and higher power density!**

Open questions: Do we need very big plasma chamber with very high rf power?

SECRAL 24GHz/7kW — the first 3rd generation ECRIS being operated to deliver thousands-hours-beam for accelerator



- **Achieved magnet field:**
  18- 24GHz, B_{inj} 3.7 T, B_{ext} 2.2 T, B_{rad} 2 T
- **2002, fabrication**
- **2005, the first beam at 18 GHz**
- **2009, the first test at 24 GHz**
- **SECRAL beam commissioning at 24GHz is just at initial stage. Better results will be coming up.**



The best results from SECRAL and VENUS

- SECRAL and VENUS have led the way in developing implementations of 3rd Gen ECRIS, and have demonstrated feasibility and the nice source performance of the 3rd Gen ECRIS , and have provided new opportunities for related research and heavy ion accelerators.

- Now almost all record beam intensities are produced by SECRAL and VENUS

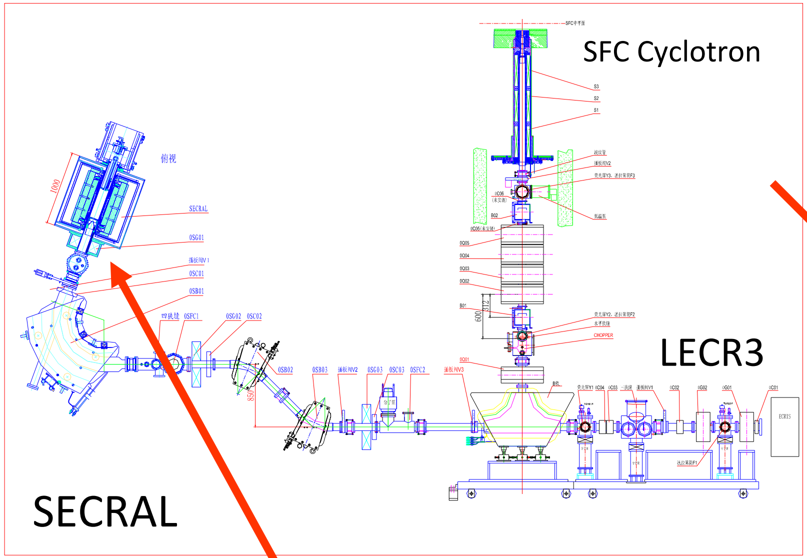
- SECRAL performances at lower frequency and lower power could be comparable or even better than those of higher frequency and higher power ECR sources.

  SECRAL with an innovative magnet structure and unique features may open a new way for developing high performance and compact SC ECR ion source.

	Q	SECRAL *18 GHz* *<3.2 kW* *μA*	SECRAL 24GHz *3-4 kW* *μA*	VENUS *28 GHz* *5-9kW* *μA*
^{16}O	6+	2300		2860
	7+	810		850
^{40}Ar	12+	510	650	860
	14+	270	440	514
	16+	73	149	270
	17+	8.5	14	36
^{129}Xe	20+	505		320
	27+	306	455	270
	30+	101	152	116
	31+	68	85	67
	34+	21	60	40
	35+	16	45	28
	38		17	7
	42+	1.5	3	0.5
	43+	1		
^{209}Bi	28+	214		240
	30+	191		225
	41+	22		15
	44+	15		7.7
	48+	4.2		1.4
	50+	1.5		0.5

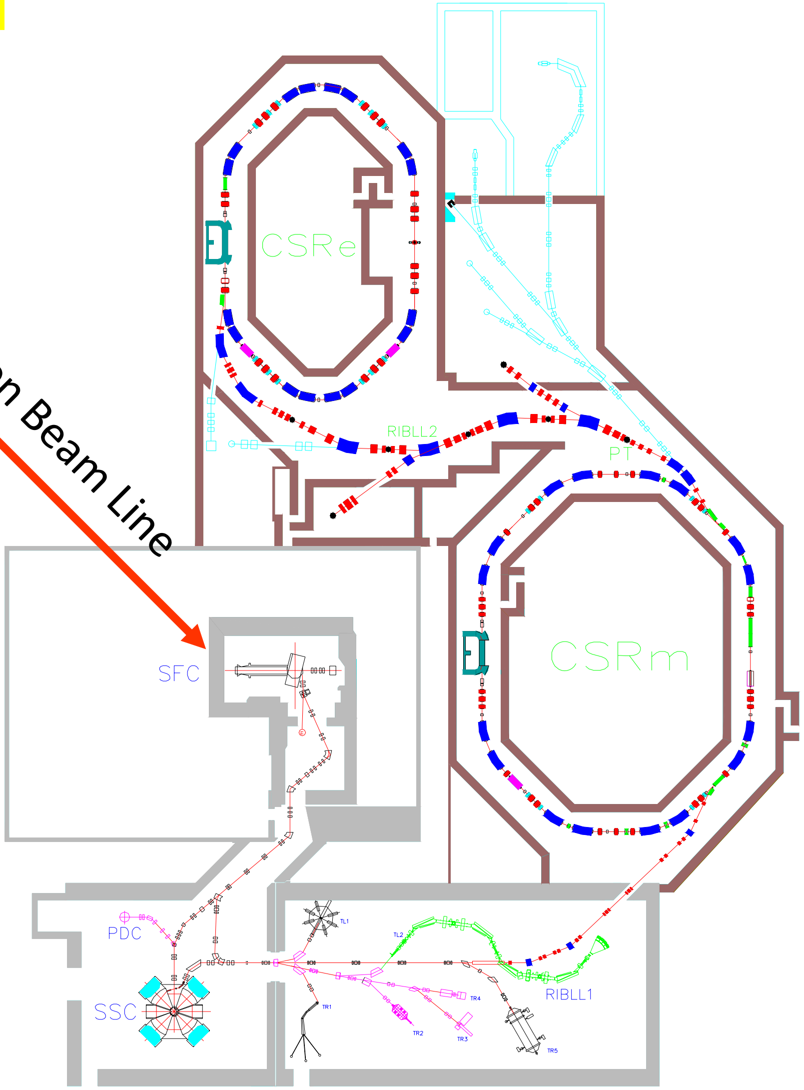
SECRAL Operation for HIRFL Accelerator since May 2007

SECRAL is dedicated only for operation of highly charged heavy ion beams.



Axial Injection Beam Line

HIRFL Accelerator Complex at IMP lanzhou



SECRAL Operation for HIRFL Accelerator

- Typical Beams delivered to HIRFL accelerator:

  $^{209}Bi^{31+}$, $^{129}Xe^{27+}$, $^{78}Kr^{19+}$, $^{58}Ni^{19+}$

  typical beam current: 120-150 eμA for Bi, Xe, Kr (V>15kV)
  50-70 eμA Ni^{19+}(9.8kV)

- **Total beam time from SECRAL for HIRFL: >3000 h**

- **SSC cyclotron Xe beam intensity was increased by a factor 50**

- **With ^{78}Kr beams at CSRe, 9 new nuclides (^{63}Ge, ^{65}As, ^{67}Se…) were identified firstly in the world with $\Delta m/m=10^{-5}$-10^{-6}**

Significant issues during design , construction and operation of high field high performance SC-ECRIS

- **Only if you need high current and high charge state heavy ion beams, go to superconducting ECRIS.**

- **To build a high performance SC-ECRIS, you have to achieve a good compromise among those key issues, such as rf frequency, rf power, magnetic field configuration, plasma chamber size, expertise of SC magnet and cryogenics , reliability, long-term operation, cost , construction time and risk.**

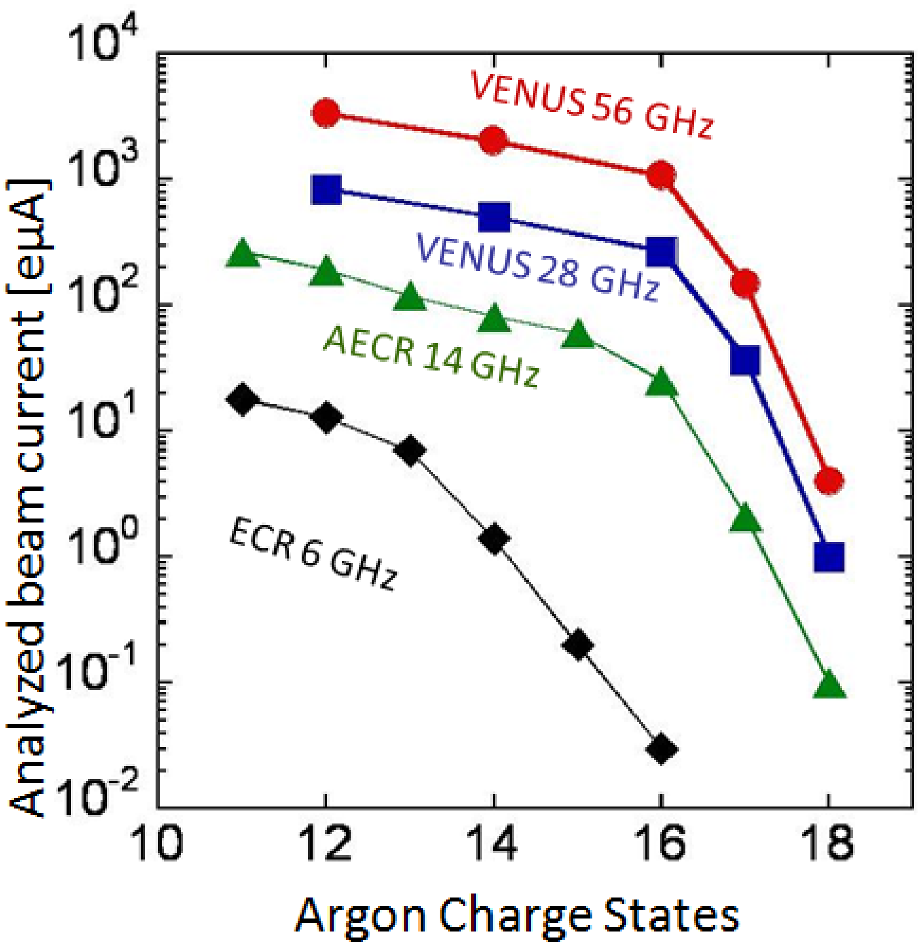
- **Challenges to build high field SC-magnet for the 3rd generation ECR:**

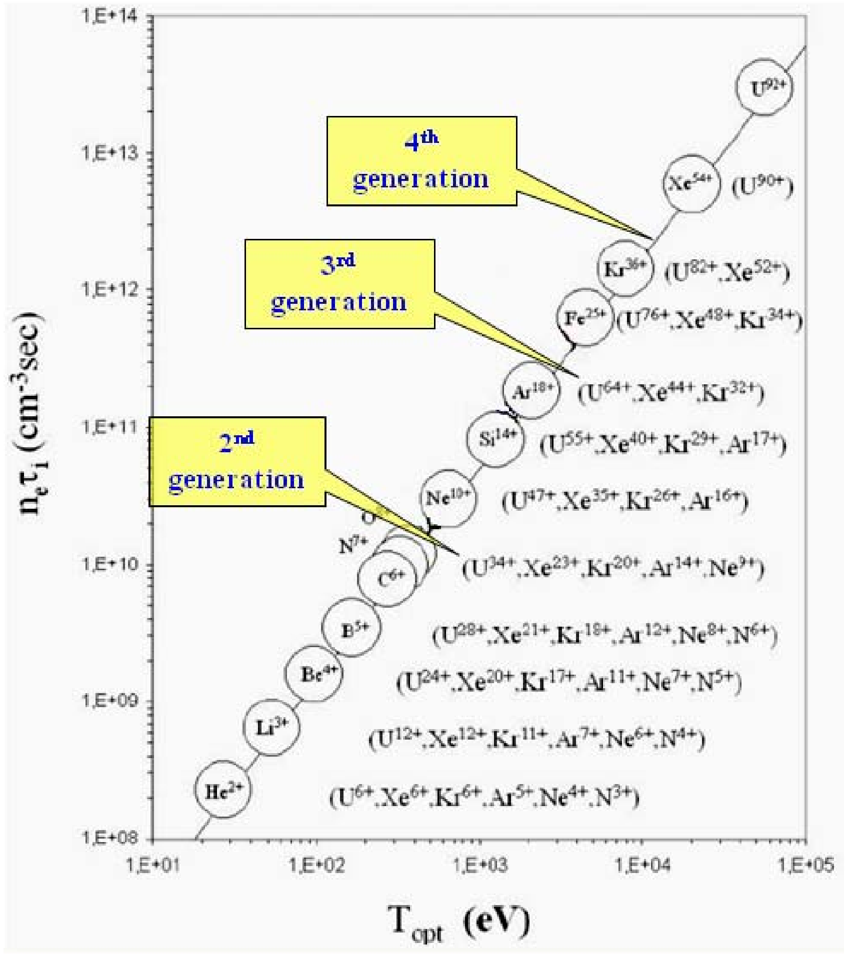
- Need to keep enough safety margin for maximum fields and critical current
- Try to reduce the interaction forces and design a reliable clamping system to prevent the wires and the coils from moving.
- Stability and reliability of the SC-magnet are the most important for SC-ECR

Significant issues during design , construction and operation of high field high performance SC-ECRIS

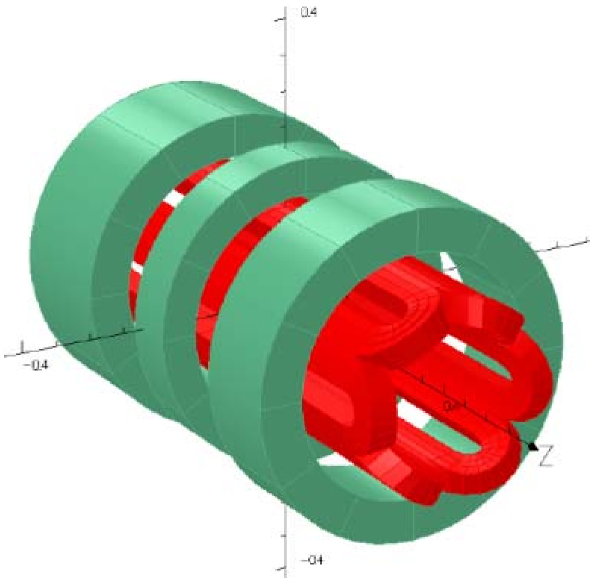
- **Challenges to design and operate cryogenics system for the SC-magnet of the 3rd generation ECRIS.**
  - Very strong x-ray with energy tens keV to MeV has to be taken into account in cryogenics design. Keep in mind that heat load from x-ray: 1 W/kW, much higher than that from magnet itself. X-ray flux and energy increase with rf frequency and power.
  - High power two stage cryocoolers or close-loop liquefy machine must be installed for long-term operation of the 3rd generation ECRIS.
- **Beam quality from the 3rd generation ECRIS and beam formation, beam transmission should be studied carefully. We only need high brightness beam.**
- **Reliable interlock and alarm system is very crucial.**
- **It is hard to build high field 3rd generation ECRIS. Sometimes it may take more than 5 years.**

The 4th Generation ECRIS—Future Development

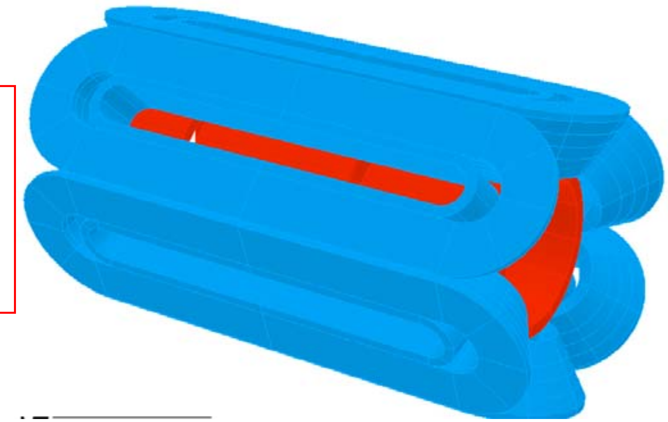




What SC-magnet structure shall we design for 4th generation ECRIS?



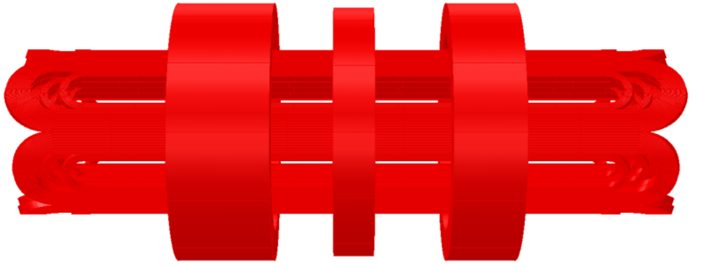
Some new configuration ?

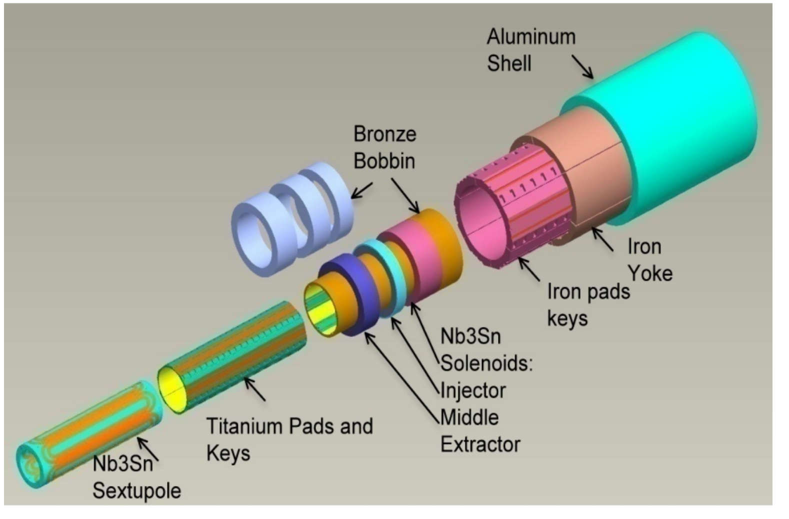


1. Sextupole-inside-solenoid **2. Some new structure?** **3. Solenoid-inside-sextupole**

The **continuing demand of higher beam intensities** makes the development of 4th Generation ECR ion sources necessary

4th Gen ECRIS 56 GHz design at LBNL





Study supported by FRIB R&D funds

Courtesy of D.Leitner at LBNL

The most challenging tasks in 4th generation ECRIS

1. **SC-magnet with the max field at the coil 15-17 T and the huge interaction forces between the solenoids and the sextupole(>few tens tons).**

2. **Laboratory available 50-60GHz /10-30 kW gyrotron system operated at both CW and pulse mode. Long-term stability and reliability are crucial.**

3. **Extremely strong X-ray flux to insulation material and very strong head load to the cryogenics system. Online close-loop LHe liquefy machine may have to be utilized.**

4. **40-60 mA mixed highly charged ion beam transmission issues.**

Technical R&D is absolutely necessary and should be supported .

Studies on ECRIS physis for intense highly charged ion beam formation are urgent

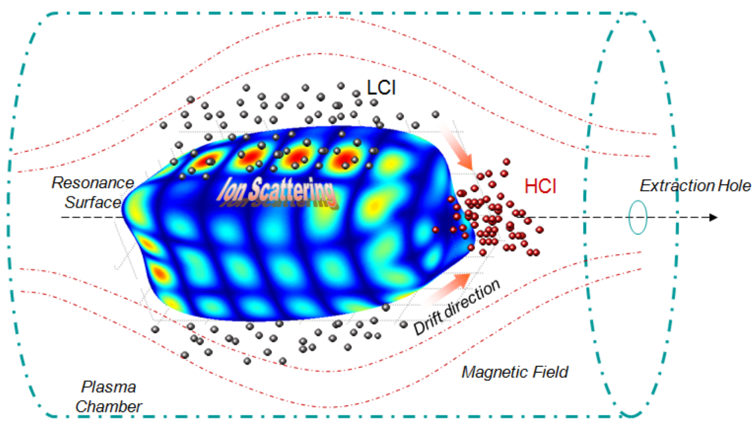
■ECRIS physics for intense highly charged ion beam formation is far from understanding because it is so complicated.

■Design of high performance ECRIS still remains semi-empirical and tricky.

■ECRIS physics study is extremely slower that than experimental progress.

■That is why there has been no big significant breakthrough in the past 20 years although great progress has been made.

■High performance ECR ion source is becoming a very big machine and too much rely on high technology instead of new ideas.



Graph courtesy of S.Gammino at LNS

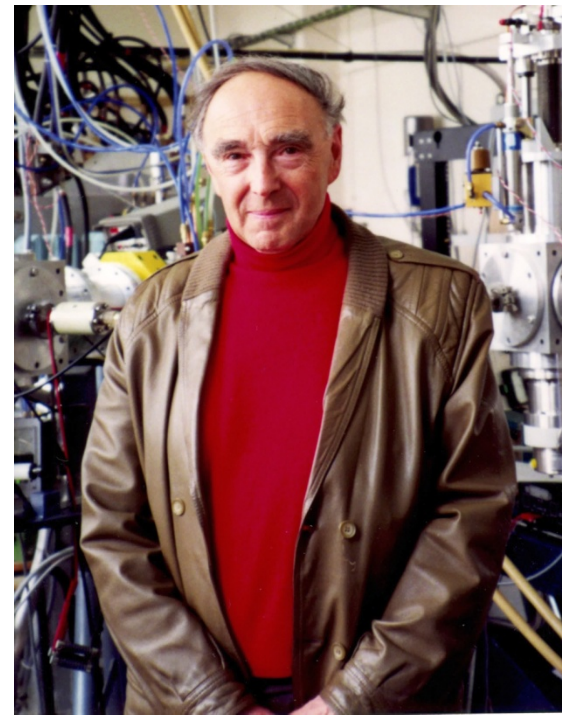
Original and innovative ideas that may result in great breakthrough for HCI beam production are extremely significant at present

We are still under “ECRIS father” Prof. Geller’s guideline established more than 30 years ago!

“… we propose a bolder extrapolation.
…**With a 56 GHz generator, TRIPLEMAFIOS should furnish up to U^{50+} ions**!”

Richard Geller, IEEE-Trans NS-23, 1976

“New microwave power generators (called gyrotrons) in the range up to 120 GHz will be commercially launched in the next five years. Combined with superconducting stripping stages they will enable the production of completely stripped heavy ion beams for cyclotron injection.”
Richard Geller, IEEE Trans NS-26, 1979



courtesy of C.Lyneis at LBNL

Acknowledgement

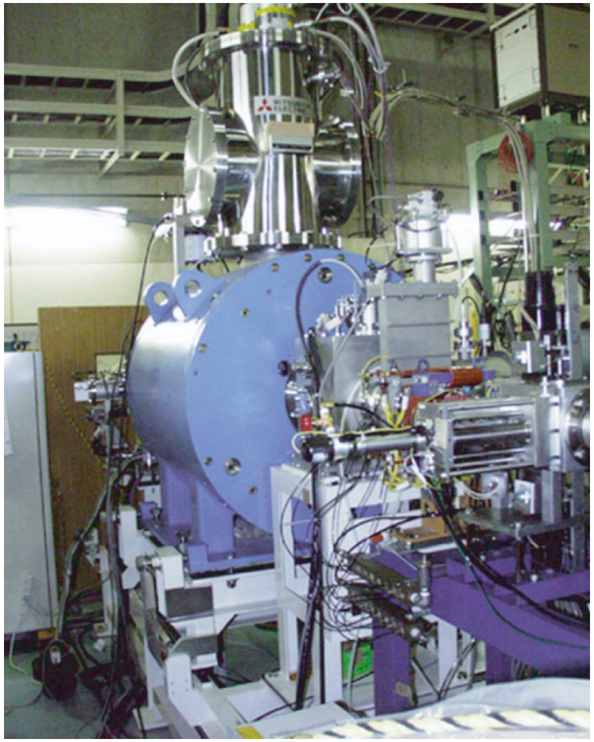
I do appreciate for those colleagues in ECRIS community who sent me their slides:

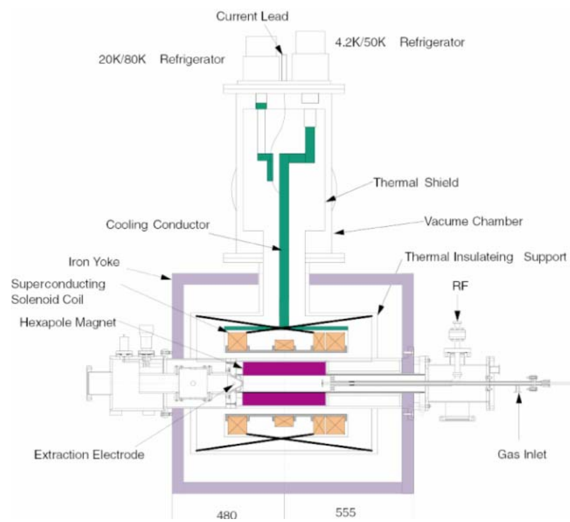
Claude Lyneis, Daniela Leitner, LBNL, US
Takahide Nakagawa, RIKEN, Japan
Santo Gammino, LNS/INFN, Italy
Guillaume Machicoane, NSCL/MSU, US
Amit Roy, IUAC/New Delhi, India

Thanks for fruitful discussions with Dan Zuqi Xie.

Thank you for your attention !

Hybrid SC-ECRIS: SC solenoid+NdFeB sextupole

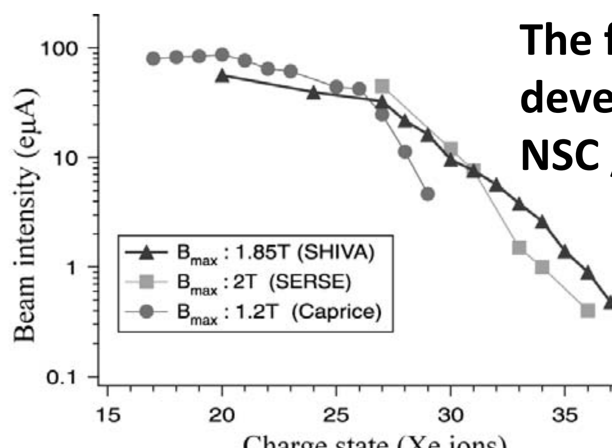




Courtesy of T.Nakagawa at RIKEN
And A.Roy at NSC/New Delhi

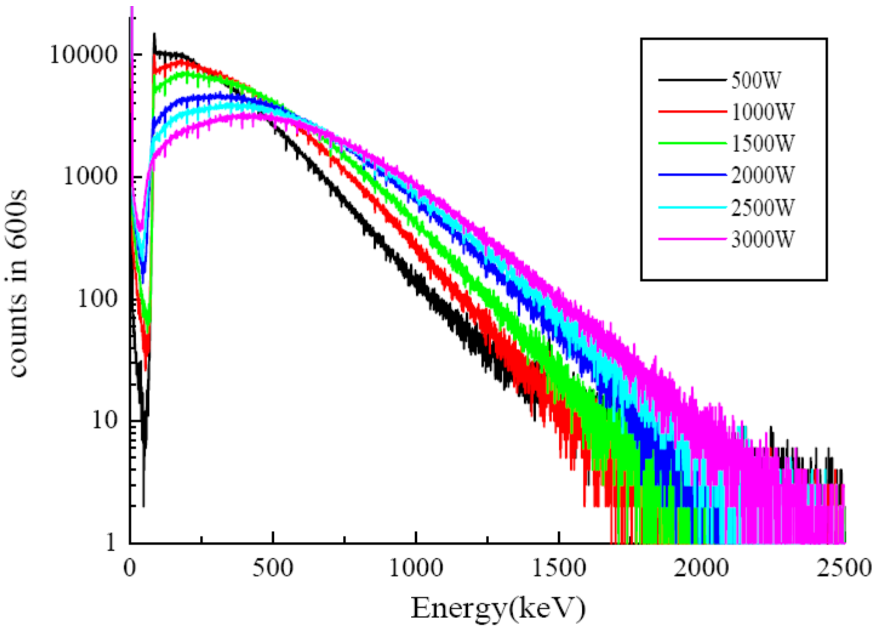
The first LHe–free hybrid ECRIS developed by RIKEN . 18GHz

- Performance of such hybrid ECR is nice, but beam current for high Q is not so good because of low field.
- Be careful to demagnetization of sextupole due to solenoid Br

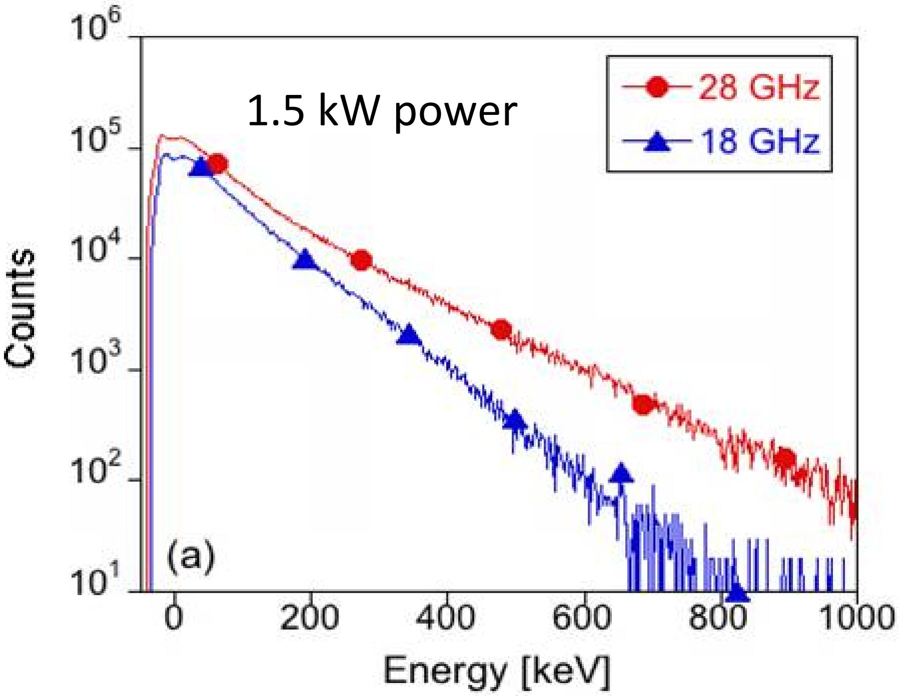


The first high Tc HTS ECRIS developed by Pantechnik and NSC /New Delhi . 18GHz

Bremsstrahlung spectra measurement and study are important to ECRIS physics and particularly crucial to cryogenics design of the SC-magnet



Bremsstrahlung spectra dependence on rf power from 0.5 to 3.0 kW at 24GHz SECRAL

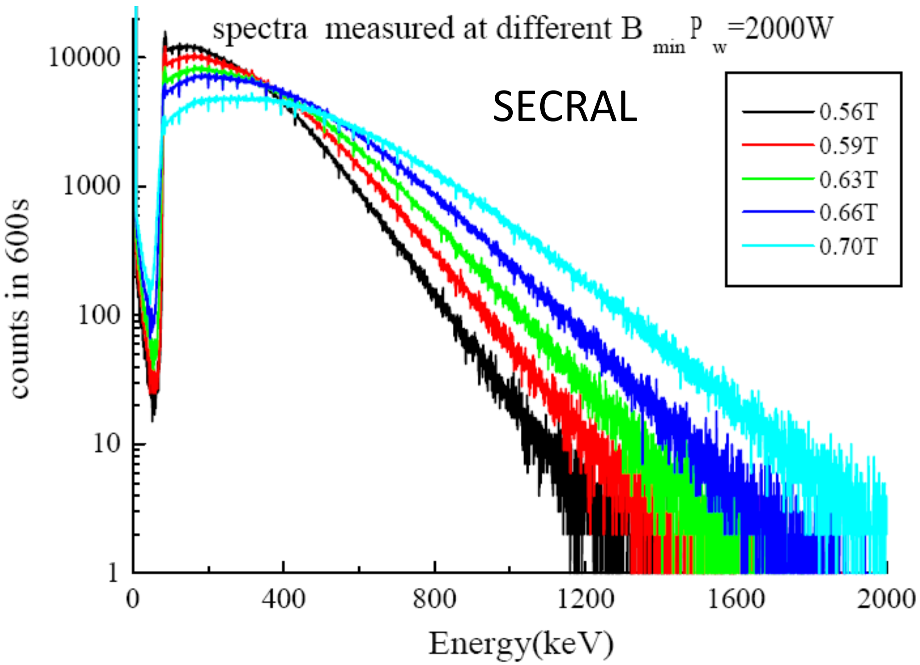


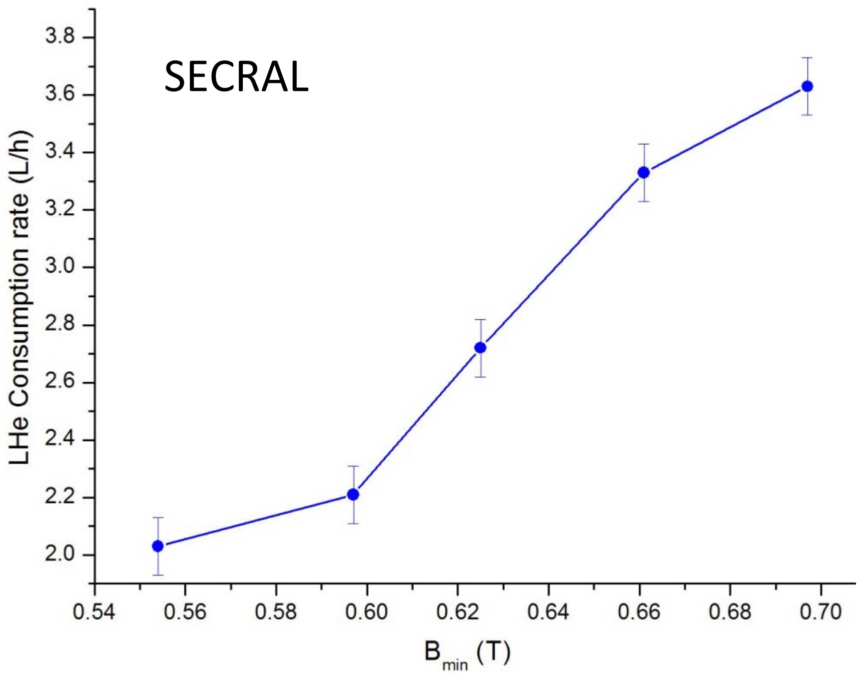
Bremsstrahlung spectra dependence on rf frequency at 18-28GHz VENUS

Courtesy of C.Lyneis at LBNL

The total X-ray flux increases with increasing RF power and frequency. Very stong heat load to the cryostat of SC-magnet. 24-28GHz results from VENUS and SECRAL: 1W/kW rf power, rf power could be more than 10 kW. Typical heat load from magnet itself is less than 1 W.

The gradient of magnetic field at the resonance zone influences the X-ray flux and energy strongly



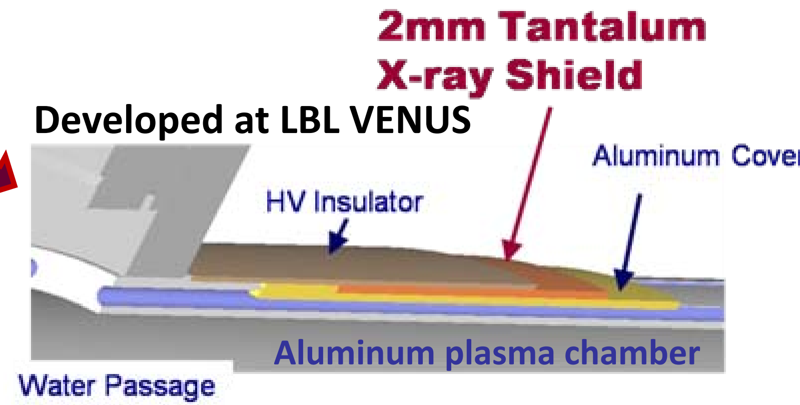


The X-ray flux and energy of the Bremsstrahlung spectra increase with the decreasing field gradient at the resonance zone strongly, which indicates that the ECR heating is more efficient with a gentle gradient at the resonance. As a consequence, the heat load and LHe consumption are higher at a gentle gradient (higher B_{min}).

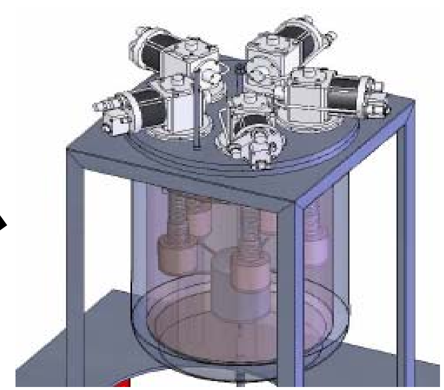
The heat load induced by Bremsstrahlung is one of the major challenges for the development of high field SC-ECRIS, and what can we do aiming at this challenge?

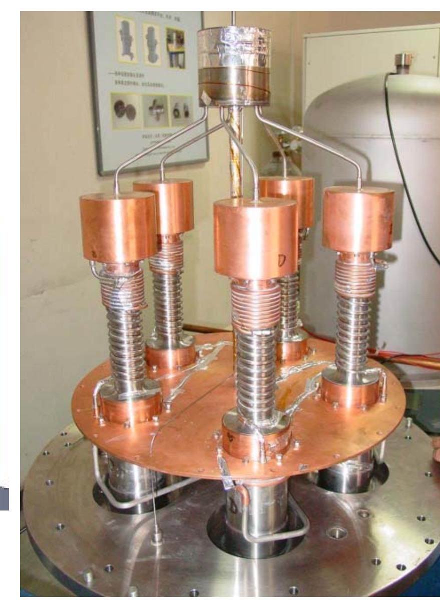
- **Shielding between plasma chamber and cryostat, but there is no efficient shielding material above 500 keV.**
- **Double frequency heating with strong field gradient at ECR zone and aluminum plasma chamber may reduce Bremsstrahlung radiation.**
- **More powerful cryocoolers or close-loop LHe liquefy machine.**

Developed at LBL VENUS



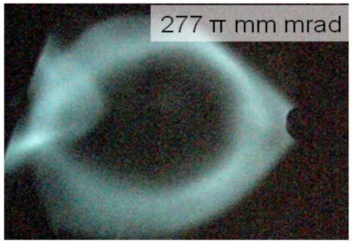
Courtesy of C.Lyneis at LBNL



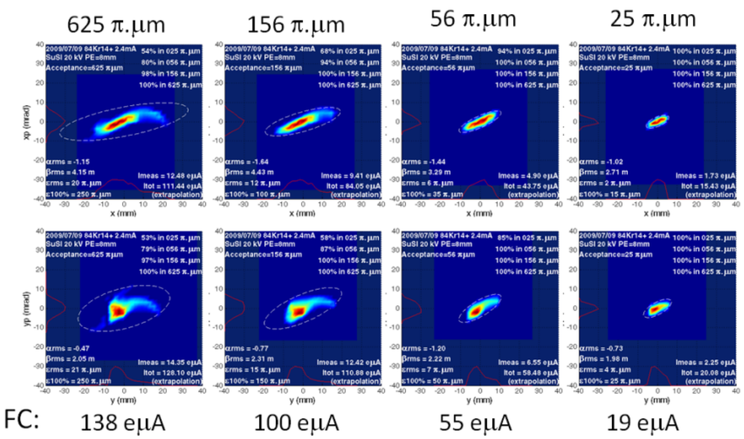


Five cryocoolers installed at SECRAL

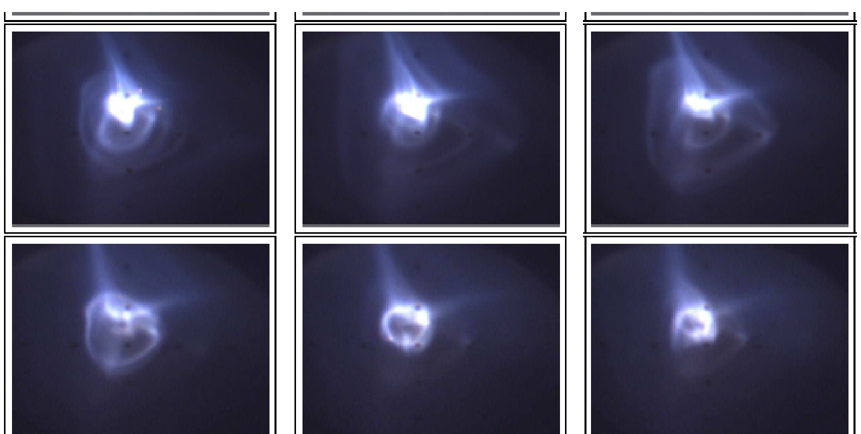
Beam quality, beam formation and transmission



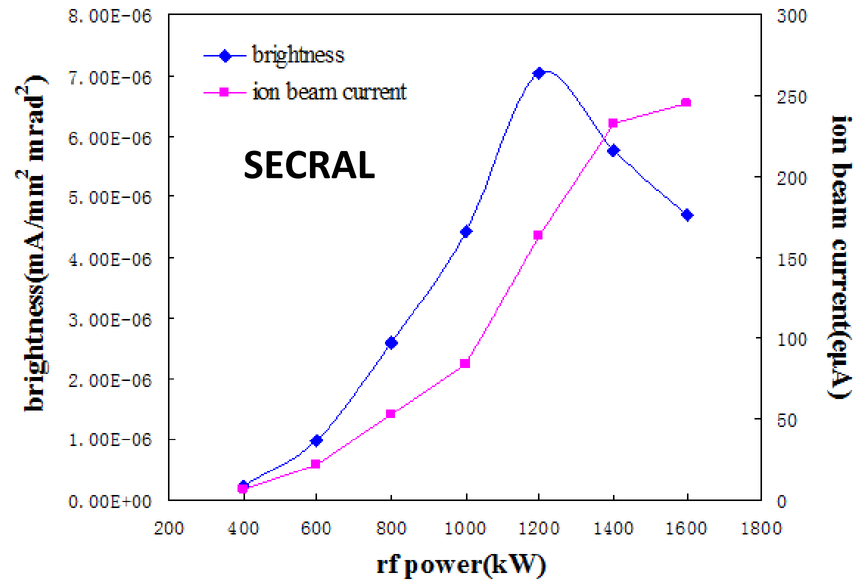
JYFL 14GHz ECRIS, Ar8+ beam, H.Koivisto talk at ICIS09



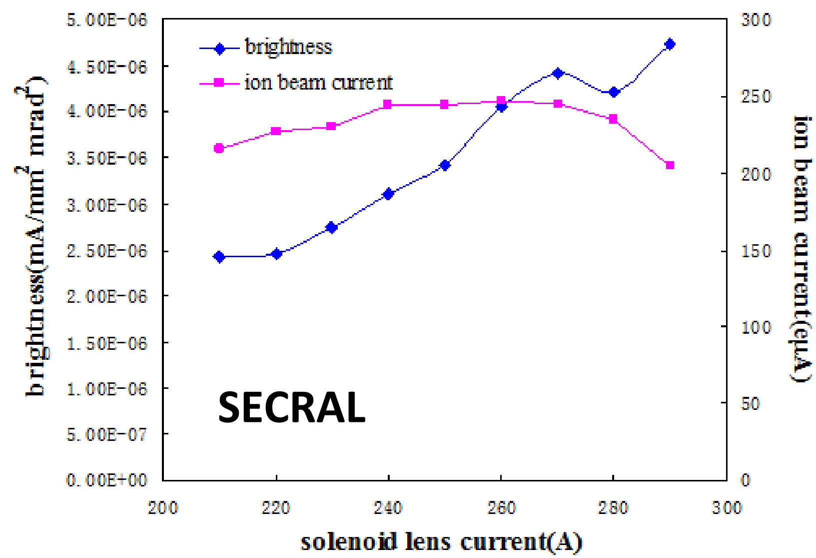
Beam collimation at SUSI beam line



SECRAL Ar beam at different settings of the focusing solenoid.



Xe^{25+} beam current and brightness vs rf power



Xe^{25+} beam current and brightness vs solenoid lens setting