An Advanced Superconducting ECR Ion Source SECRAL at IMP: First Results and Operation at 18 GHz

H.W.Zhao, L.T.Sun, X.Z.Zhang, X.H.Guo, Z.M.Zhang, P.Yuan, W.L.Zhan, B.W.Wei, W.He, M.T.Song, J.Y.Li, Y.C.Feng

Institute of Modern Physics (IMP), Chinese Academy of Sciences, Lanzhou, 730000, China

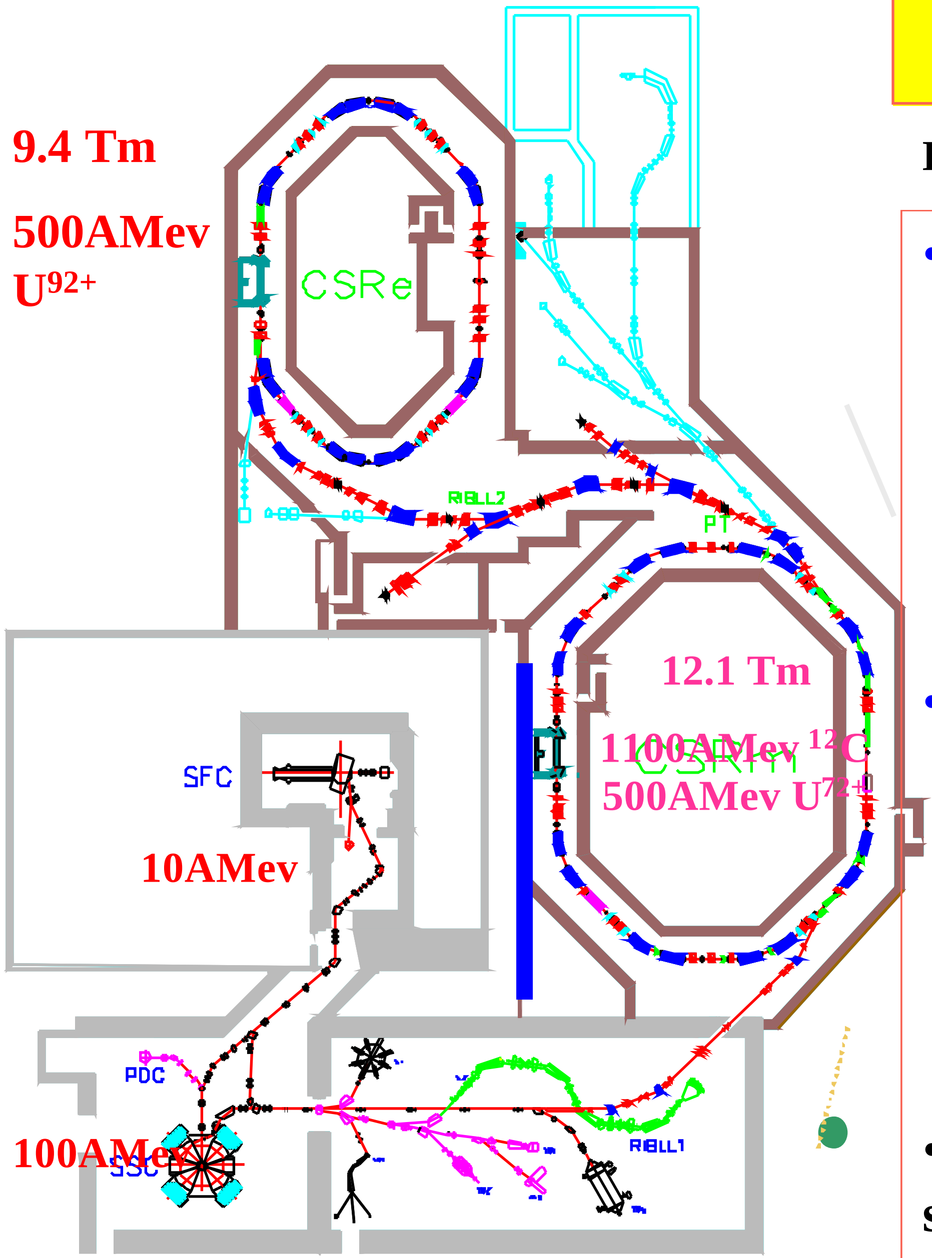
FRXCR02: Presented to CYCLOTRON2007 Sept.30- Oct. 5 , Italy

OUTLINE

SECRAL: **<u>S</u>uperconducting <u>ECR</u> ion source with <u>A</u>dvanced design in <u>L</u>anzhou**

- Goals for SECRAL
- SECRAL Structure and unique features
- Commissioning results and performance studies at 18GHz
- SECRAL operation for HIRFL accelerator
- Summary

HIRFL Layout and SECRAL Goals



HIRFL: Heavy Ion Research Facility in Lanzhou

- Achieve performance enhancement of HIRFL accelerator complex in order to satisfy the research requirements for super-heavy nuclei, RIB, and intense beam injection to the CSR.

- For cyclotron injector:
  - Ni^{19+}, Xe^{31+}, U^{41+}
    CW Beam: 50-100 e• A
    Pulsed Beam: 100-200 e• A
    More intense beam is required for heavy ion linac injector

•Develop a compact fully superconducting ECRIS

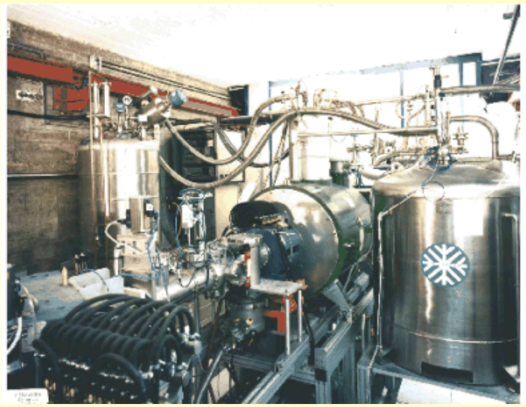
Fully Superconducting ECR Ion Source

$n_e \sim \bullet^2_{rf}$, $I \sim \bullet^2_{rf}$

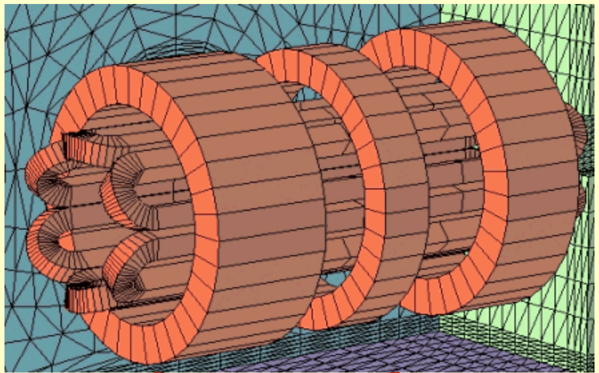
$B_{ecr} = \bullet_{rf} m_e/q$, $B_{inj} \bullet 2$ Becr

High B, $\bullet_{rf}$, P_{rf}

Conventional Structure



SERSE in Catania (14.5-18 GHz)



VENUS in Berkeley (18-28 GHz)

Advantage:

- Higher sextuple field;
- Larger plasma chamber;
- Higher rf power up to 10 kW;
- Higher frequency >28GHz

Disadvantage:

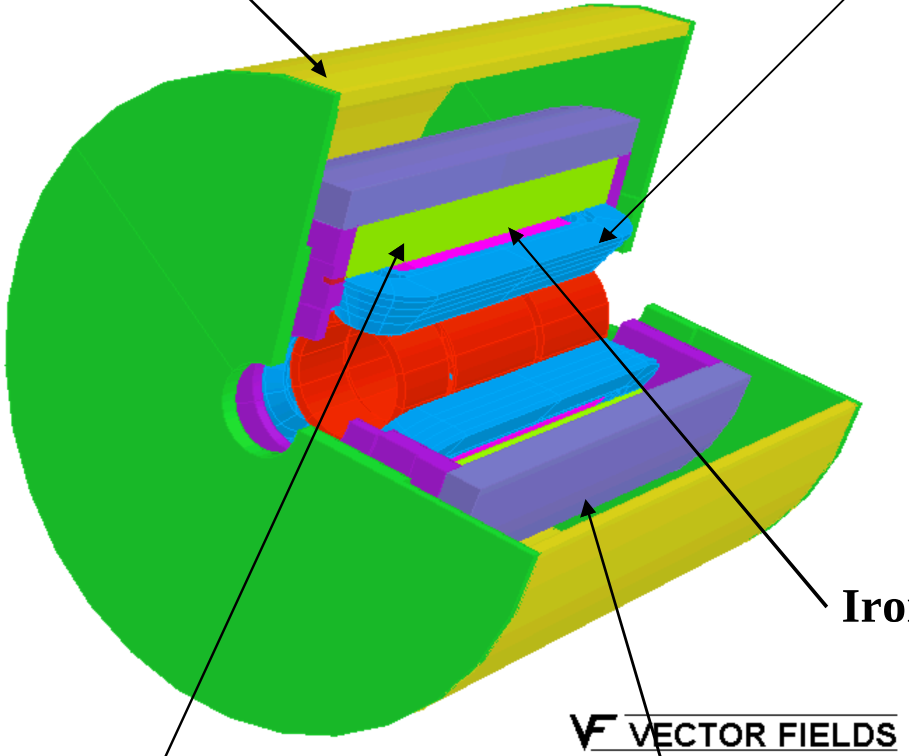
- Very strong interaction forces;
- Much longer sextupole;
- Bigger source body;
- Hard to build

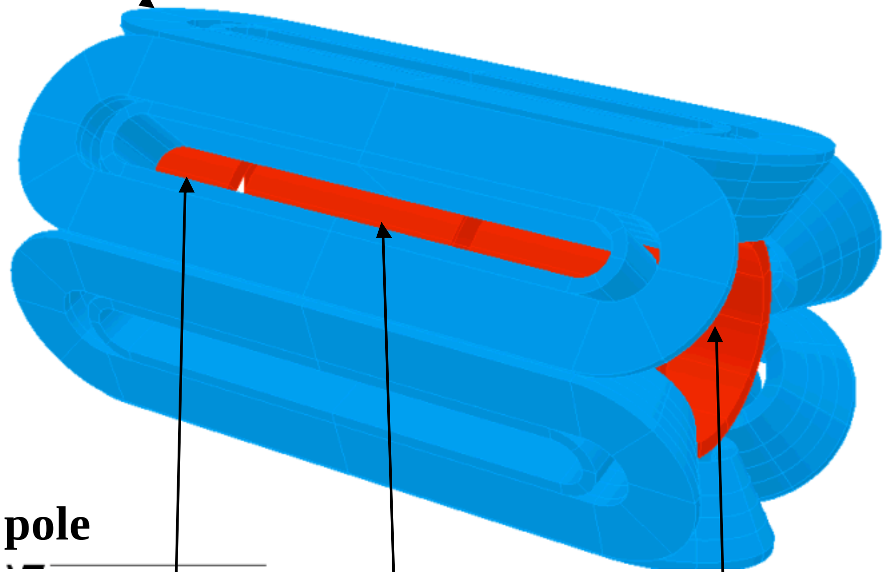
SERSE and VENUS are pioneers

MS-ECRIS, RIKEN SC-ECR, SuSi…

SECRAL Magnet Concept and Superconducting Coil Configuration

Completely new structure!
Reverse conventional coil configuration





Iron Yoke and Shielding

Sextupole Coil

Iron pole

Iron Segments as Sextupole field Booster and coil Clamping, also reduce the stray field

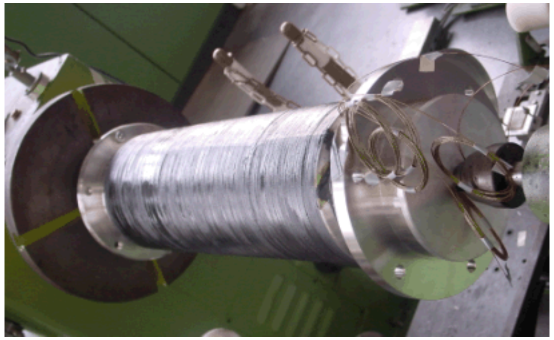
Aluminum Clamping Ring

Middle Solenoid

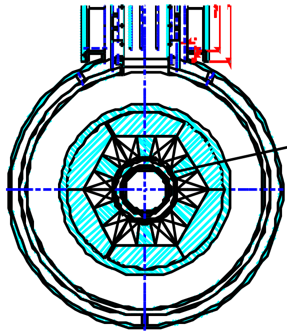
Extract. Solenoid

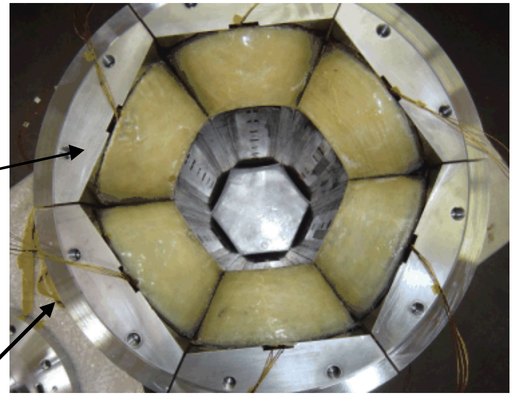
Inject. Solenoid

SECRAL Superconducting Magnet

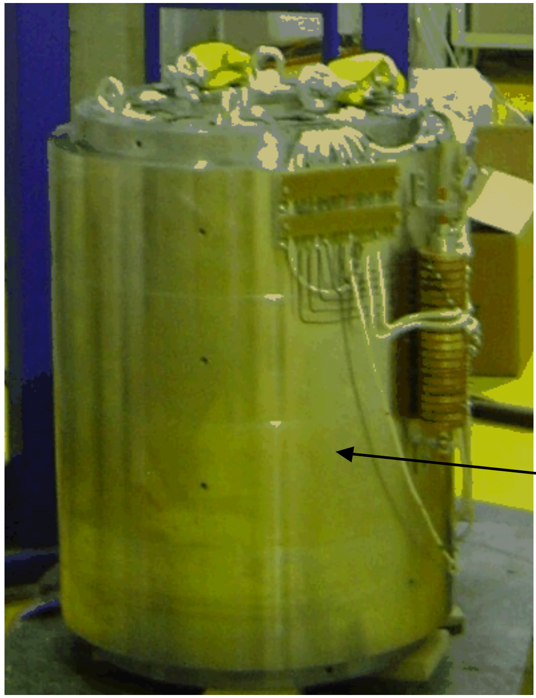


Three Solenoids

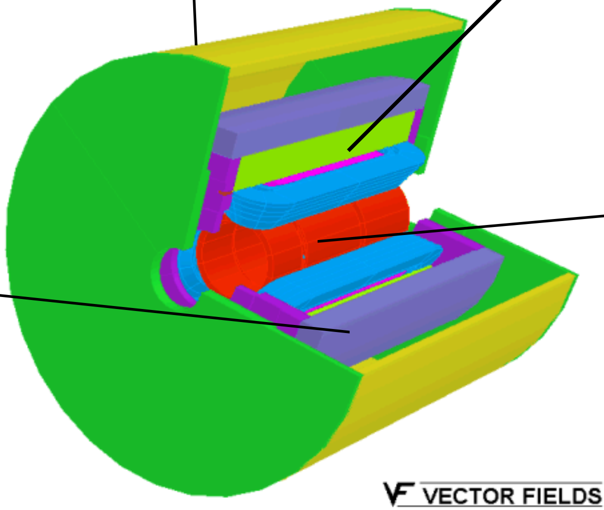


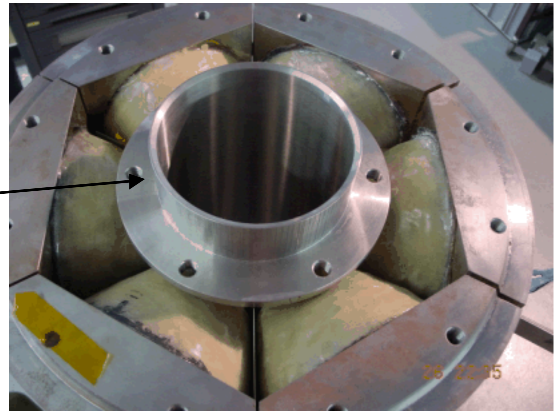


Sextupole



SECRAL Magnet





Sextupole + Three Solenoids

The magnet was fabricated by ACCEL

Unique Features for SECRAL

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

l Reduced interaction force → **Easier to build and cost-effective**

l Compact source body → **Efficient rf coupling and effective extraction**

l Lower rf power and higher power density → **Good long-term stability**

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

l Increase sextupole field

l Reduce stray field, easy support and suspend the cold mass

l Very simple clamping scheme

Ø **Disadvantage:**

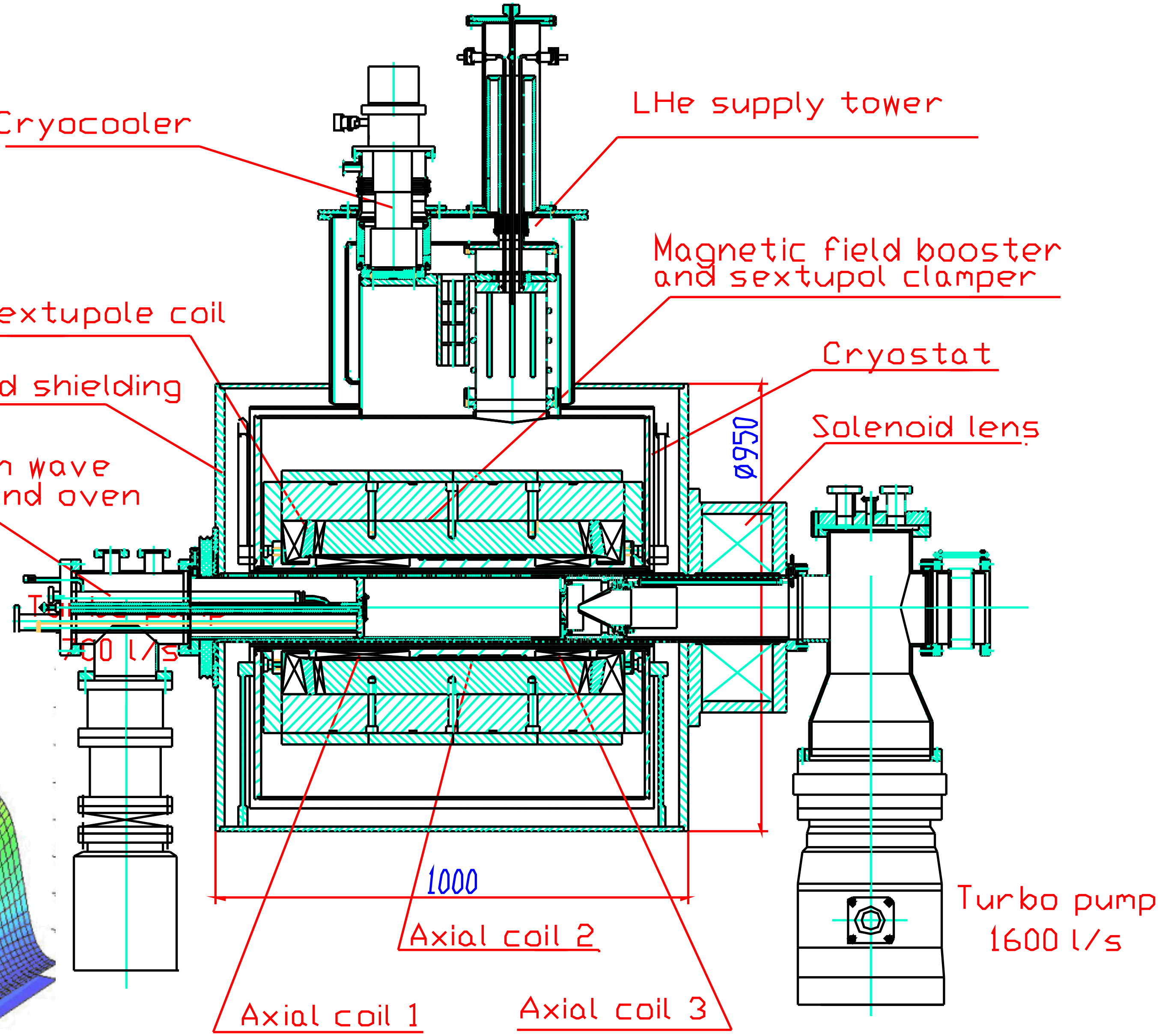
n **Plasma chamber and sextupole field are limited, not for >28GHz, chamber >130 mm**

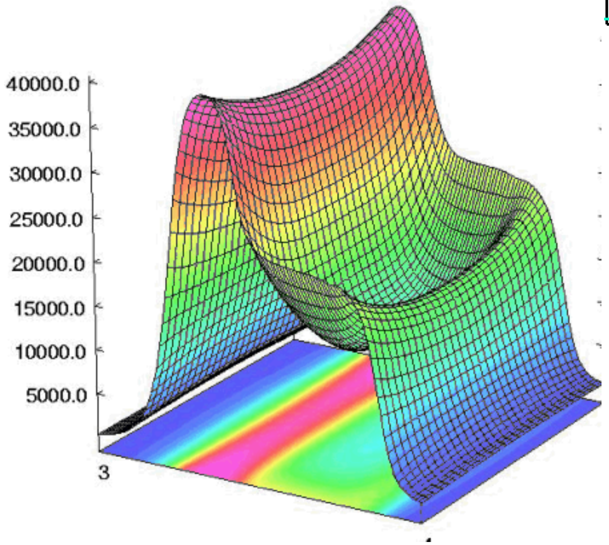
n **But: 3.7 T injection field, 2.0 T sextupole field at the wall and • 126 mm chamber, sufficient for 28 GHz, and higher power density!**

SECRAL Milestone and Status

- 09. 2000 • Project approved.
- 04. 2002 • Fabrication contract with ACCEL.
- 04. 2005 • SECRAL magnet reached 100% fields at ACCEL.
- 06. 2005 • SECRAL magnet installed at IMP in Lanzhou and reached 100% designed fields .
- 10,08. 2005 • First Analyzed Beam at 18 GHz.
- 08. 2005-08.2006 — Commissioning for intense highly charged beam production, some record beam intensities were produced.
- 08. 2006 — Moved to IMP cyclotron beam line.
- 05. 2007 — First beam provided to HIRFL continuously for one month.

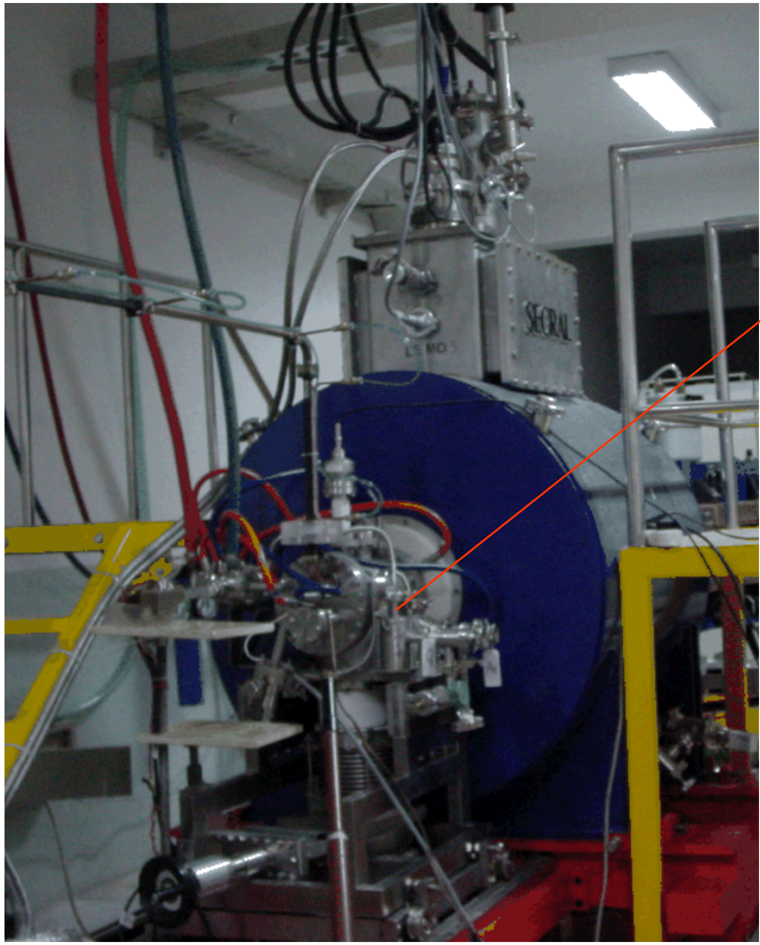
Achieved axial field: 3.7, 2.2T
Sextupole at the wall: 2.0 T
RF frequency: 18-28 GHz
Plasma chamber: • 126
Extraction voltage: 20-30 kV

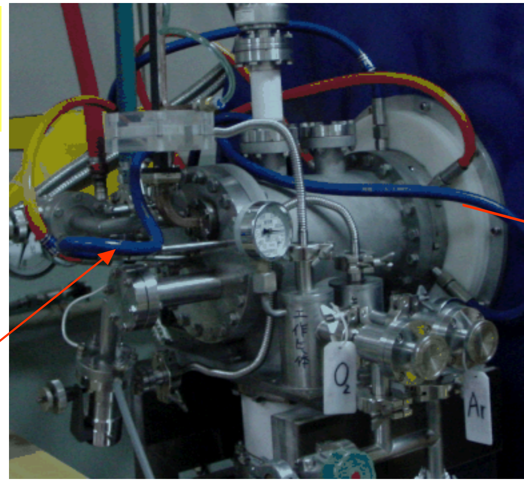


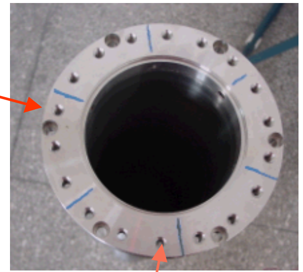


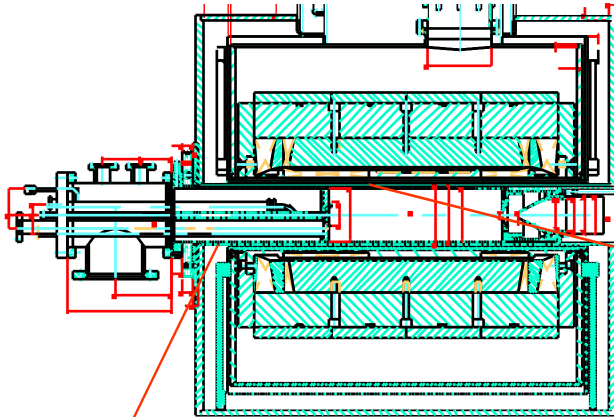
Schematic view of SECRAL ECR source

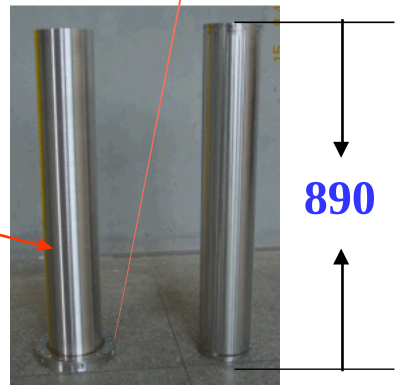
SECRAL and its components

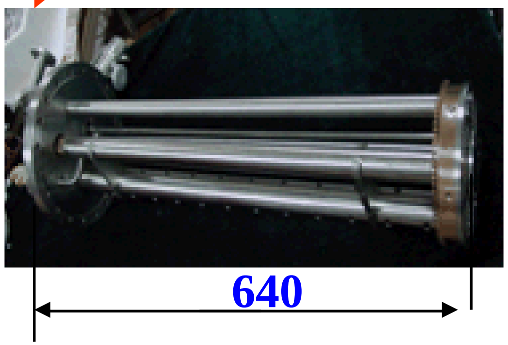


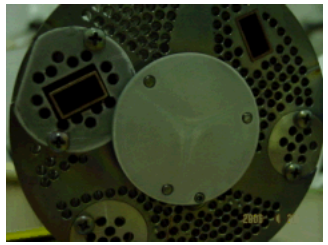








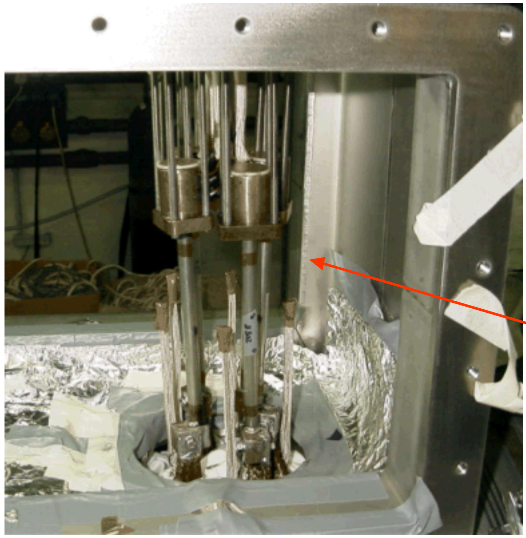




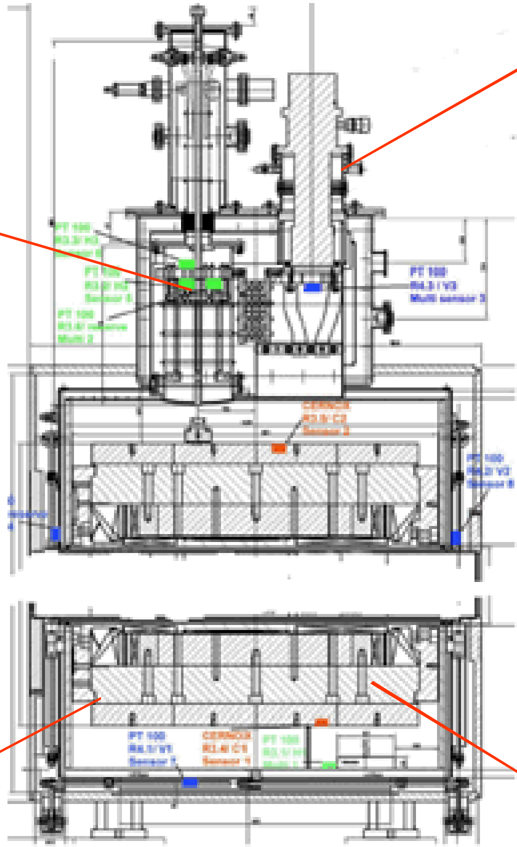
Experiences from SERSE and VENUS are helpful for design of conventional Components.

Injection component with wave-guide, biased disk and oven

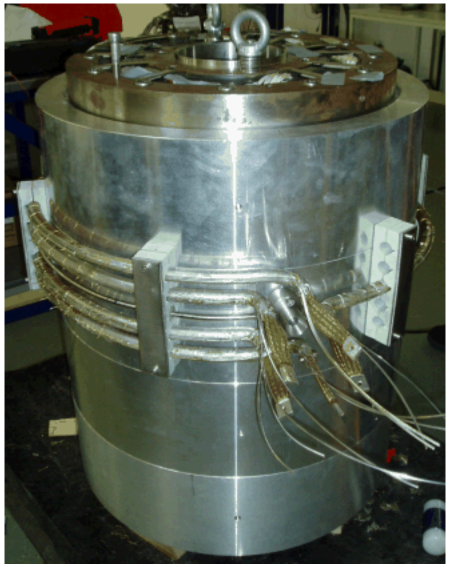
Cryogenics and Cold Mass



HTc Leads



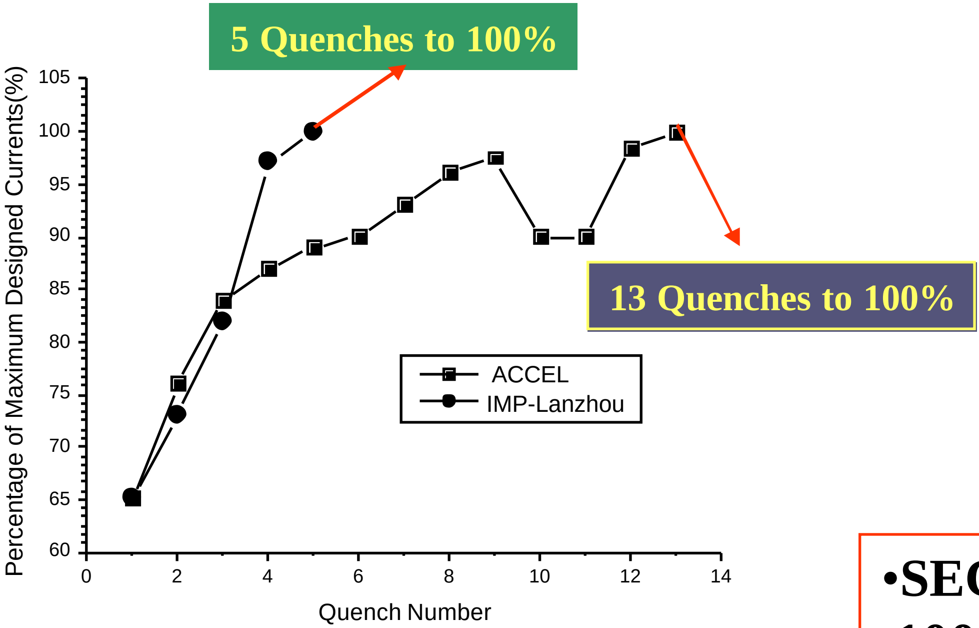
One Stage Cryocooler at 30-50K



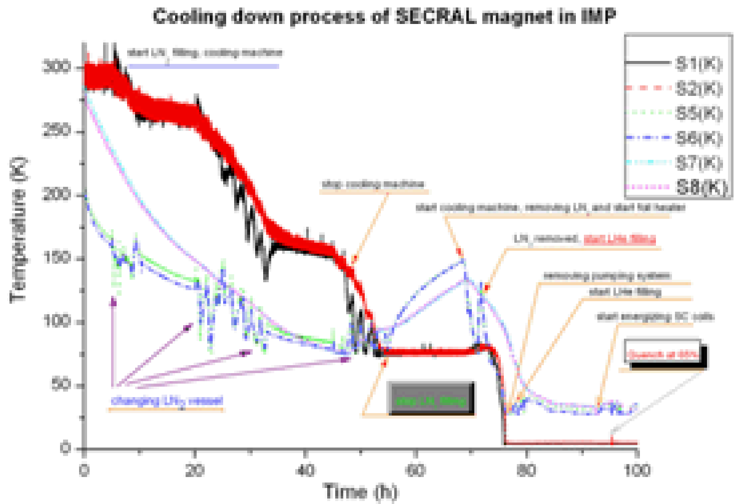
Magnet

Cold Mass

SECRAL Magnet Test and Measurements

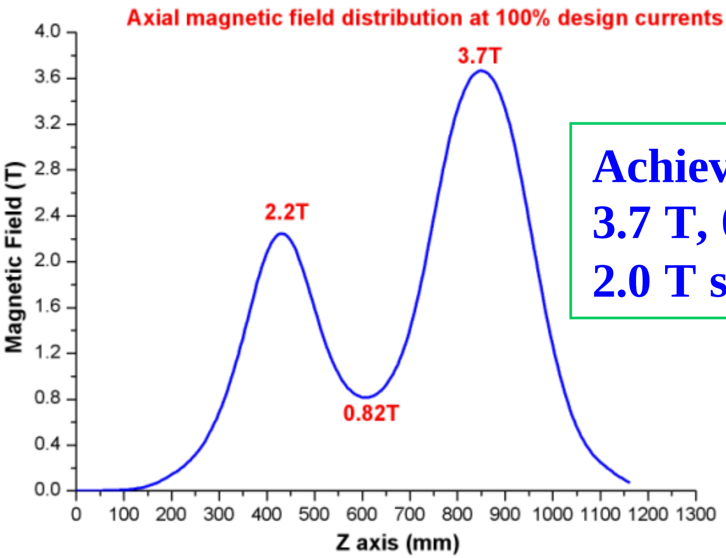


Quench History

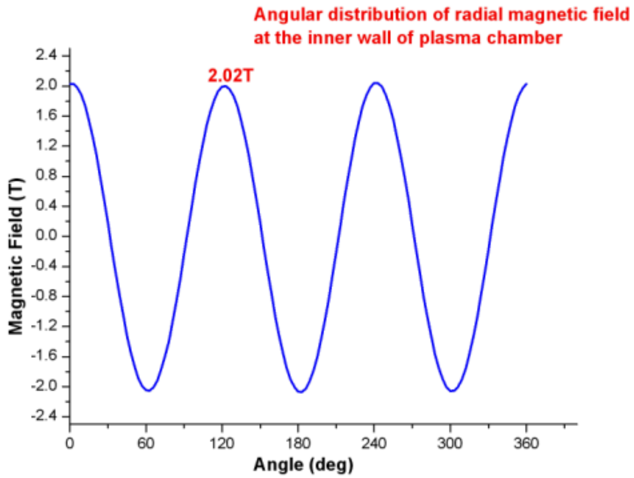


•SECRAL Magnet Has Reached 100% Designed Fields.

•Stable and Reliable!

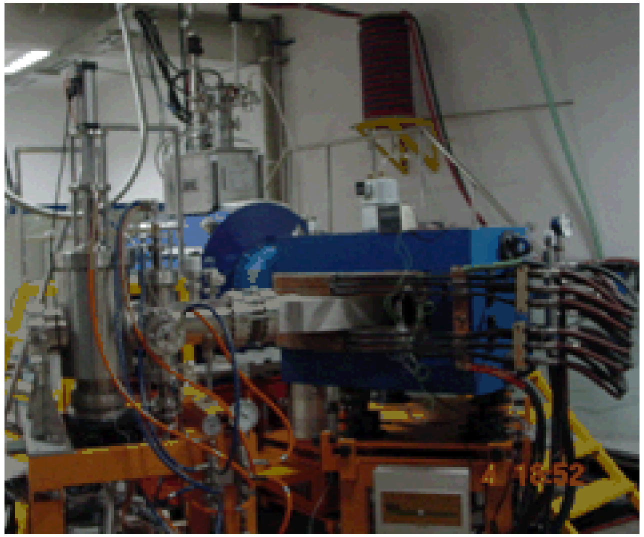


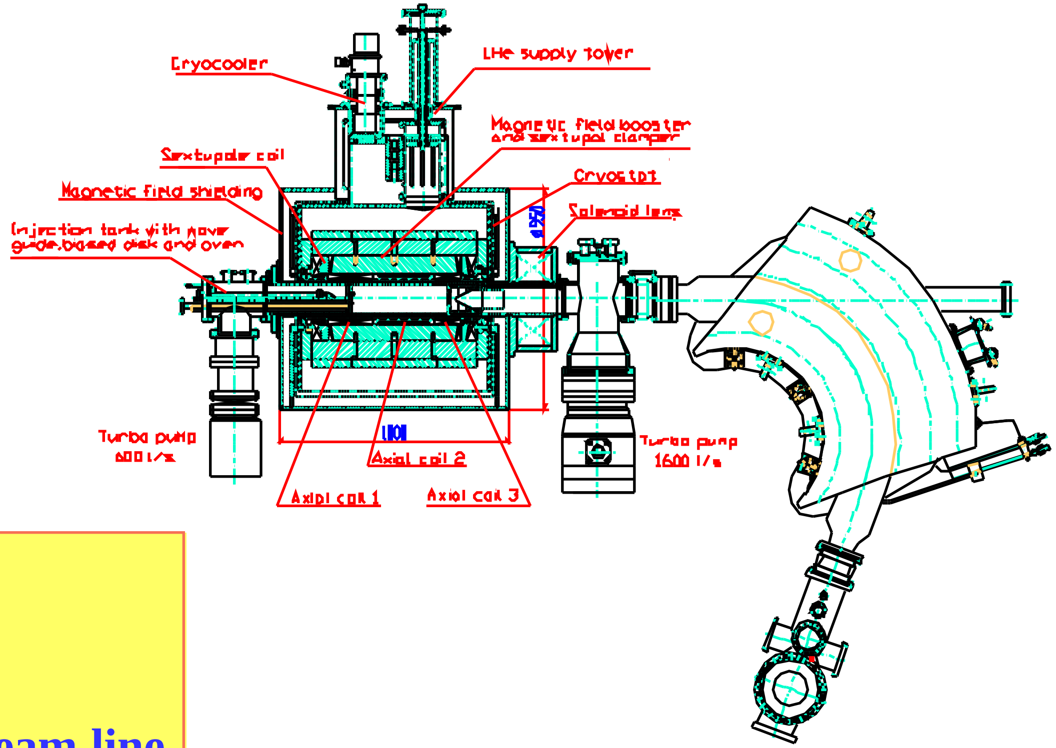
Achieved and measured fields:
3.7 T, 0.8 T, 2.2 T
2.0 T sextupole field at the wall



SECRAL Beam Transport Line

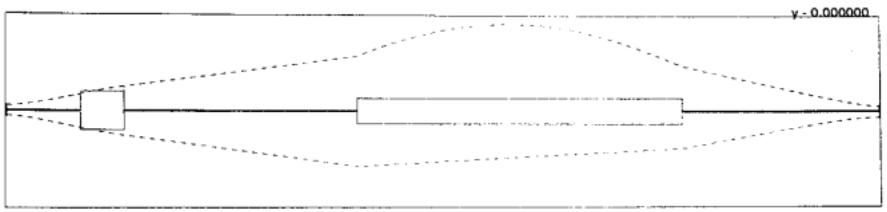
Designed for 15-20 mA total beam transmission at 20-30 kV extraction





Main Design Issues:

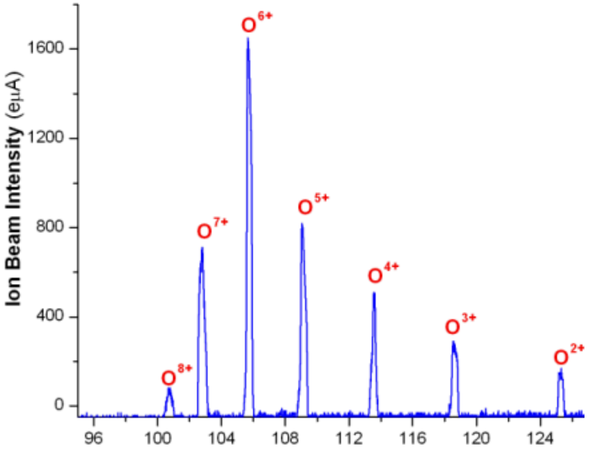
1. High transmission efficiency
2. High mass resolution (1/100)
3. Match with the axial injection beam line

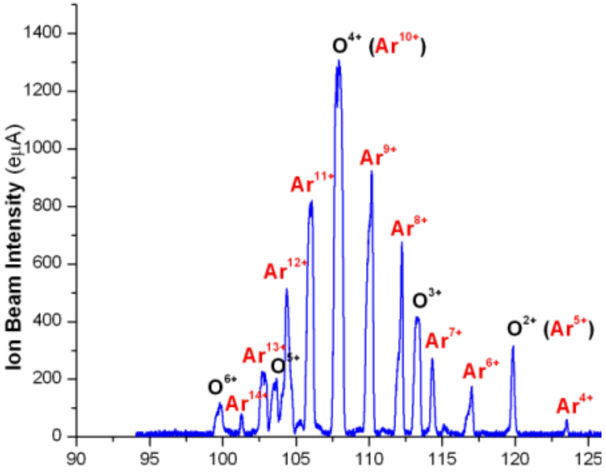


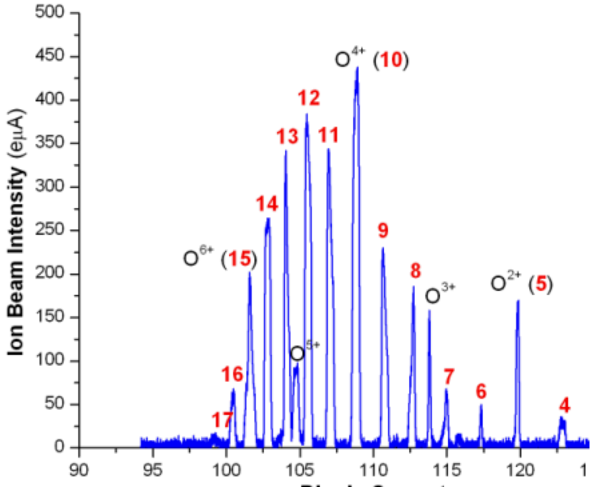
Analyzing magnet:
Bending angle: 110 degree
Bending radius: 600 mm
Pole gap: 120 mm

SECRAL Commissioning Results and Performance Studies at 18GHz

Beams Obtained with two 18GHz RF Generators





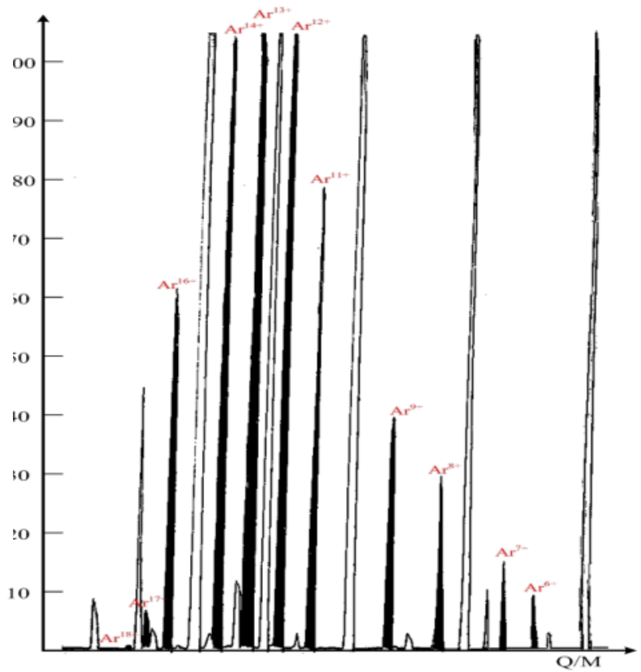


O^{7+}: 810 eμA (2.5 kW,23- 25 kV)
B_r1.23 T, B_{inj} 2.2T, B_{ext}1.36T, B_{min}0.46 T

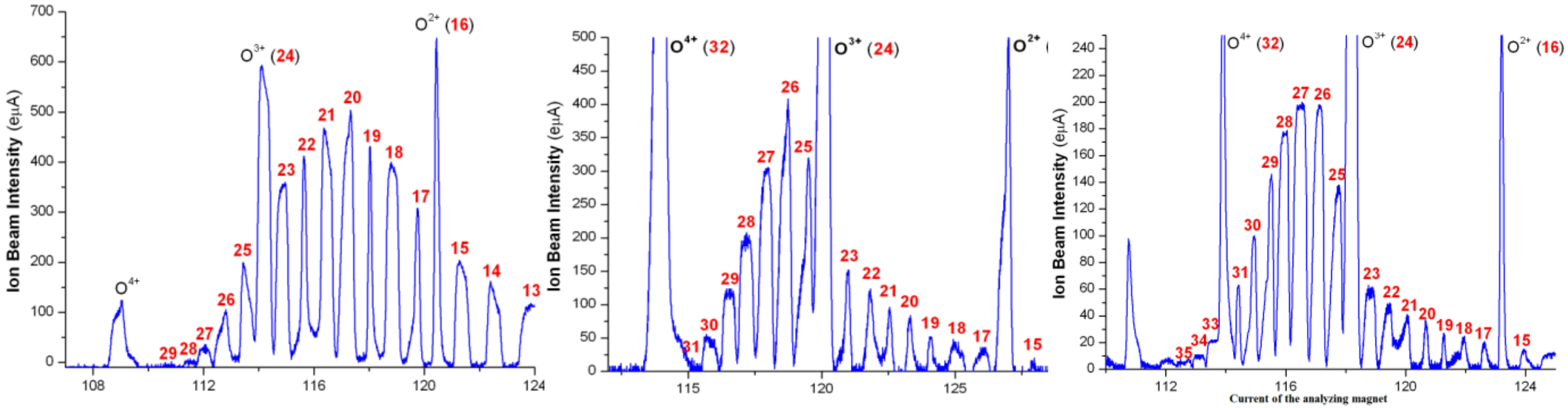
Ar^{11+}: 810 eμA (3.15 kW, 23-25 kV)
B_r1.18 T, B_{inj} 2.20T, Be_{xt}1.20T, B_{min}0.455 T

Ar^{14+}: 270 eμA (3.2 kW, 23-25 kV)
B_r1.30 T, B_{inj} 2.48T, B_{ext}1.33T, B_{min} 0.516 T

Ar^{16+}: 73 eμA (2.8 kW, 23-25 kV)
B_r1.49 T, B_{inj} 2.65T, B_{ext}1.53T, B_{min} 0.55 T
Better results are expected for higher Q



Beams Obtained with Two 18 GHz RF Generators



$^{129}Xe^{20+}$: 505 emA (2.75 kW, 23-25 kV)

B_r1.09 T, B_{inj} 2.23T, B_{ext}1.27T, B_{min} 0.47T

$^{129}Xe^{27+}$: 306 emA (2.85 kW, 23-25 kV)

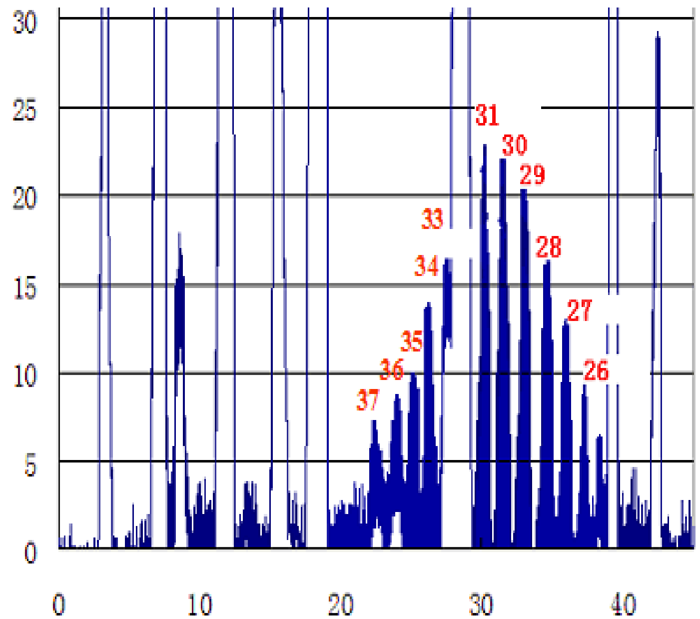
B_r1.29 T, B_{inj} 2.52T, B_{ext}1.41T, B_{min} 0.529T

$^{129}Xe^{30+}$: 101 emA, $^{129}Xe^{34+}$: 21 emA , $^{129}Xe^{38+}$: 2.4 emA

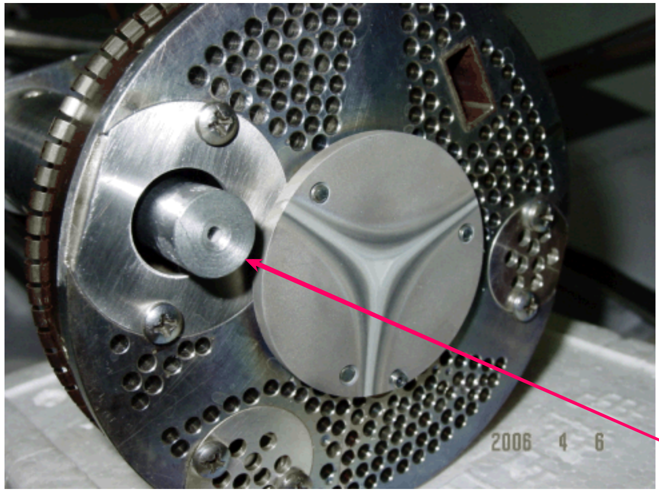
(3.2 kW, 23-25 kV)

B_r1.29T, B_{inj} 2.52T, B_{ext}1.41T, B_{min} 0.536T

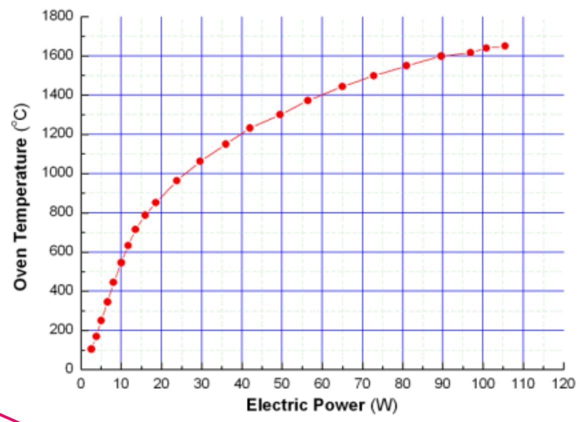
Better results are expected for higher Q

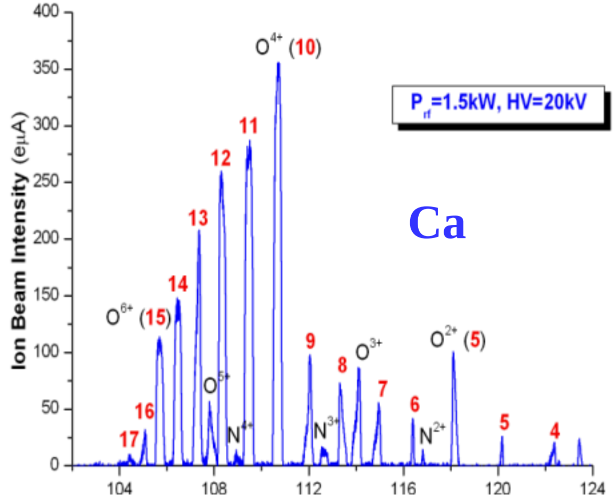


Preliminary Test of Metallic Beams from SECRAL at 18GHz



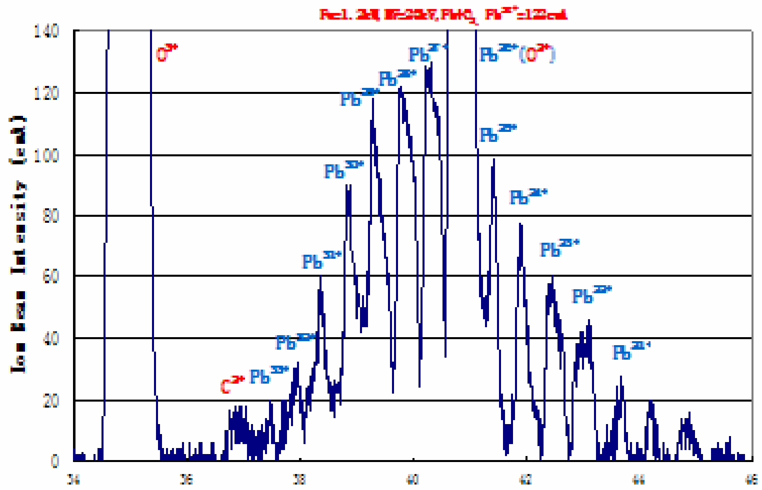
Micro-oven





With maximum P_{rf} =1.6kW, some preliminary but very promising metallic ion beams were produced:

287e• A Ca^{11+}, 162e• A Ca^{14+} , 75 e• A Ca^{16+},
20e• A Ca^{18+}, 2.3e• A Ca^{19+}
35 e• A $^{58}Ni^{17+}$, 10 e• A $^{58}Ni^{19+}$
180e• A Pb^{25+}, 173e• A Pb^{27+}, 65 e• A Pb $^{31+}$



Results not so good, test time too short(10 days)

Better results of very high Q are coming for Ca, Ni, Pb, Bi and U next year, firstly modify injection part and aslo use Al chamber.

SECRAL Commissioning Results at18GHz and Beam Intensity (emA)
Comparison with other ECRIS

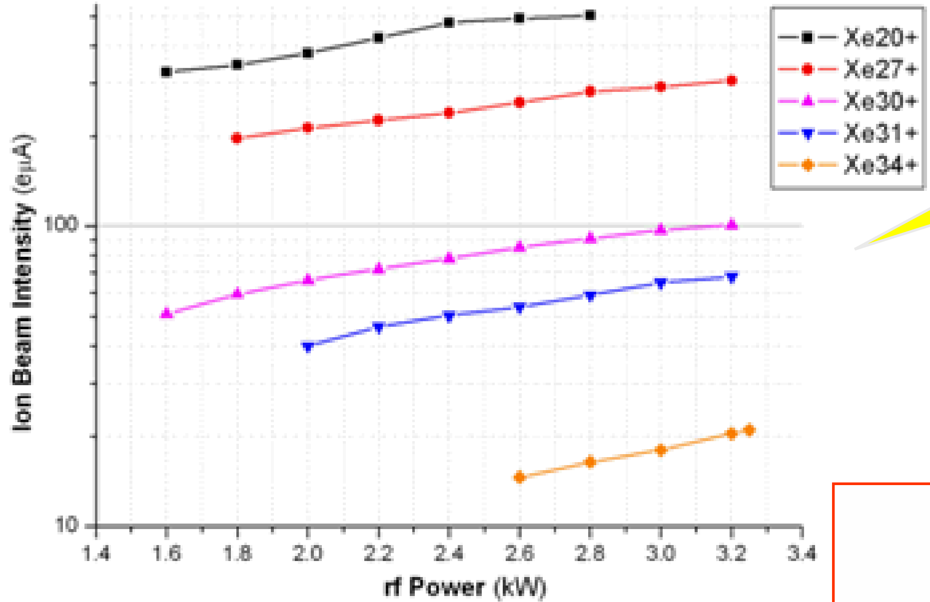
By Al chamber and 28 GHz/5kw ↗ by 2-2.5

f (GHz)		SECRAL *18*	VENUS *28 or 28+18*	GTS *18*
^{16}O	6^+	2300	**2850**	1950
	7^+	810	600	
^{40}Ar				
	11^+	810		510
	12^+	510	860	380
	14^+	270	514	174
	16^+	73	133	50
	17^+	8.5	14	4.2
^{129}Xe	20^+	505	**320**	310
	26^+	410	**290**	228
	27^+	306	**270**	168
	30^+	101	**116**	60
	31^+	68	**67**	40
	33^+	31		15
	34^+	21	40	8
	35^+	12	28	5.4
	37^+	5	12	2.3
	38^+	2.4	8	1

Table III. Comparison of key parameters between SECRAL and VENUS

Key parameters	SECRAL	VENUS
Designed RF frequency(GHz)	18-28	18-28
Axial mirror magnetic fields (Tesla)	3.6, 2.2	4.0 , 3.0
Sextupole field at the chamber wall (Tesla)	2.0	2.4
Mirror to mirror space (mm)	420	500
Magnet length (mm)	1000	~ 1500
Plasma chamber diameters (mm)	• 126	• 140-150
Plasma chamber length (mm)	890	~1400
Material of the chamber in commissioning	St. Steel	Al
Volume of plasma chamber (liter)	~ 5	~9
RF frequency in commissioning (GHz)	18	18, 28+18
Maximum rf power coupled into chamber so far (kW)	3.2	6.0-9
Maximum rf power density achieved (kW/liter)	0.64	0.67-1.0

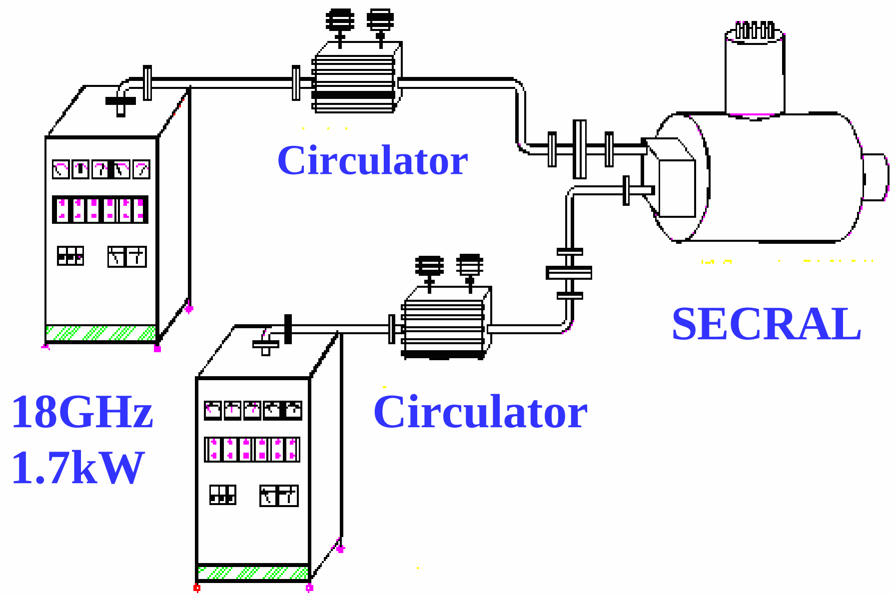
SECRAL Performance in Dependence of rf Power



Obvious increment of Xe ion beam with the increase of P_{rf}

To reach better results, SECRAL needs higher power up to limit 5 kW and 24-28 GHz rf frequency.

- **$I_{0.8kw+0.8kw}$ • $I_{1.6\ kw}$ typically 10%higher**
- **Beam more stable and total reflected power much lower with two generators.**

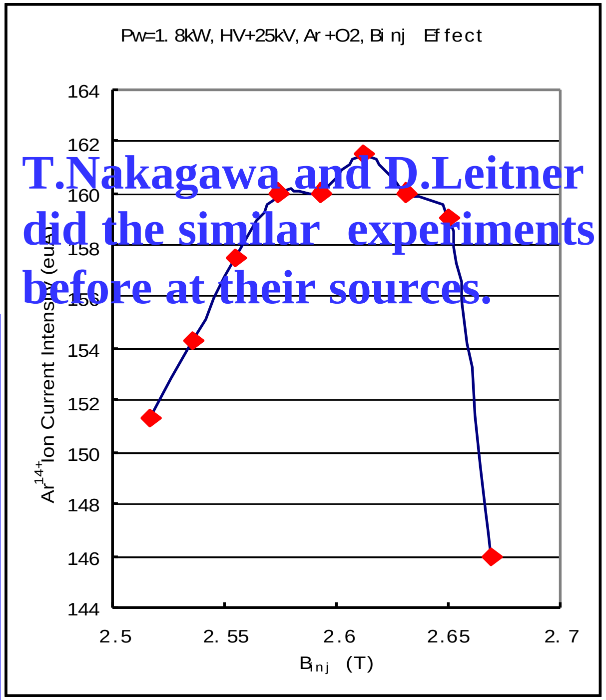


Beam intensity VS Magnetic fields

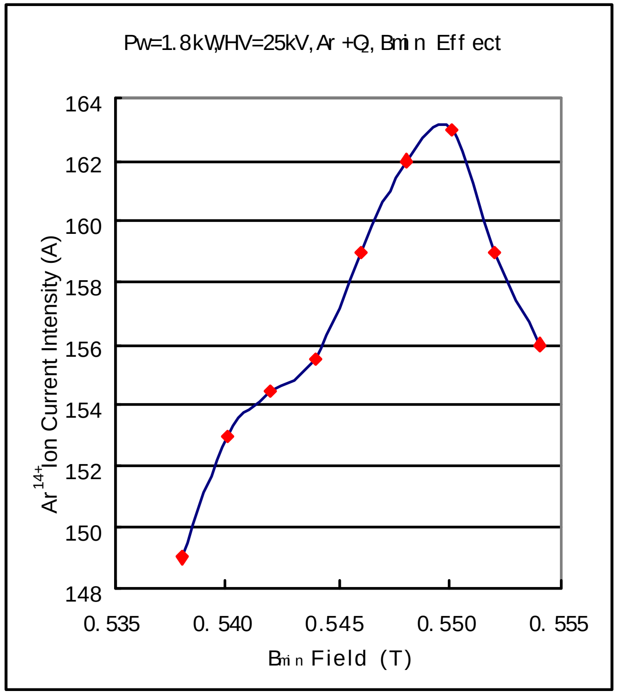
- For optimum fields, good agreement with the scaling laws:

B_{inj}~$4B_{ECR}$, B_{rad}~$0.8B_{ECR}$, $B_{rad} \geq 2B_{ECR}$

- But for different rf power, the optimized fields are different
- As expected, higher Q needs higher B



T.Nakagawa and D.Leitner did the similar experiments before at their sources.



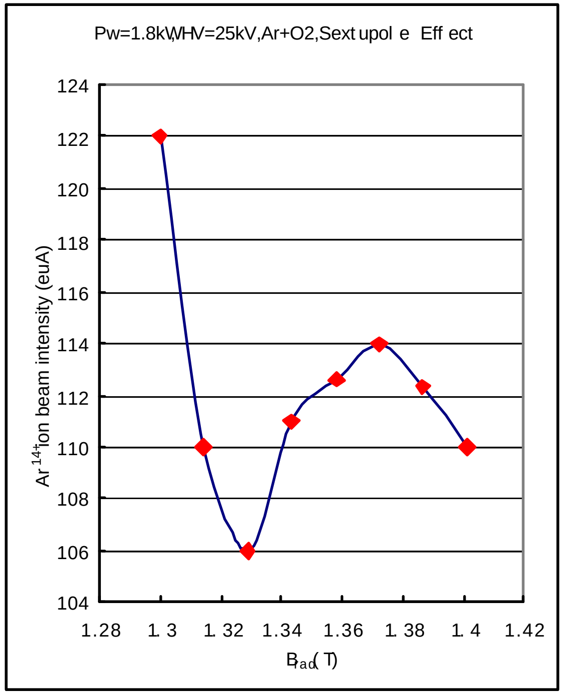
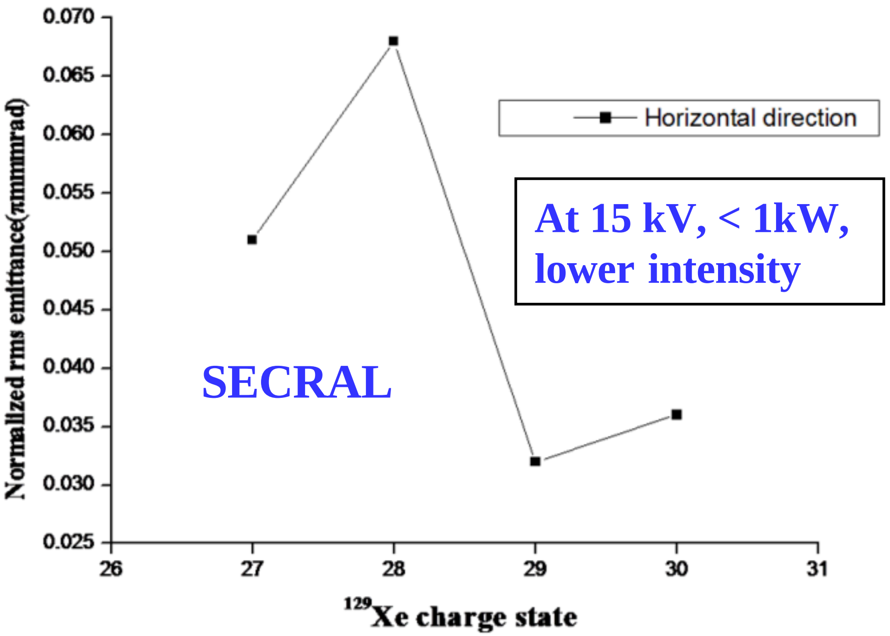


Table II. Typical beam intensities produced by SECRAL at the optimized magnetic field configuration and the coupled rf power.

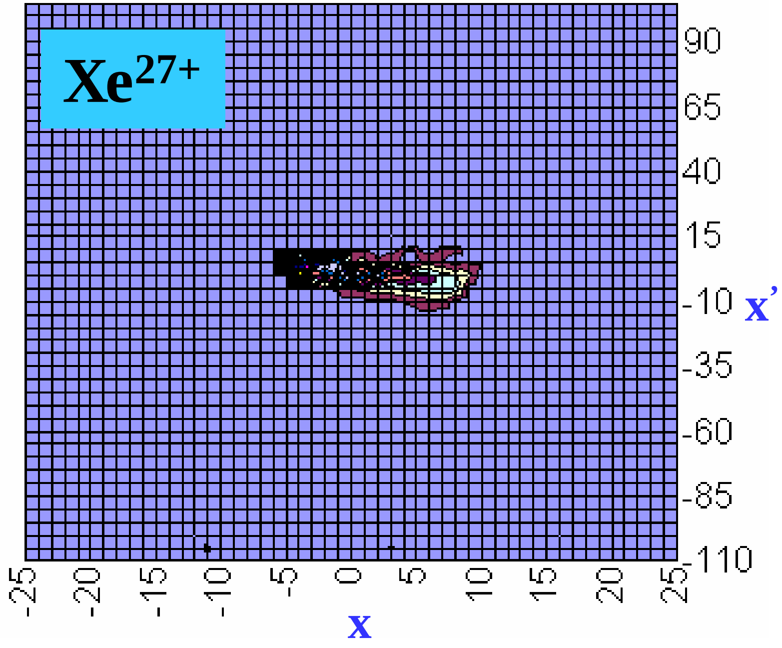
Ion	Beam intensity (eμA)	Coupled RF power (kW)	B_{inj} Tesla	B_{extr} Tesla	B_{min} Tesla	B_{rad} Tesla
O^{7+}	810	2.5	2.20	1.36	0.46	1.23
Ar^{11+}	810	3.15	2.20	1.20	0.46	1.18
Ar^{16+}	73	2.8	2.65	1.53	0.55	1.49
Xe^{20+}	505	2.85	2.23	1.27	0.47	1.09
Xe^{27+}	306	3.1	**2.52**	1.41	0.53	1.29

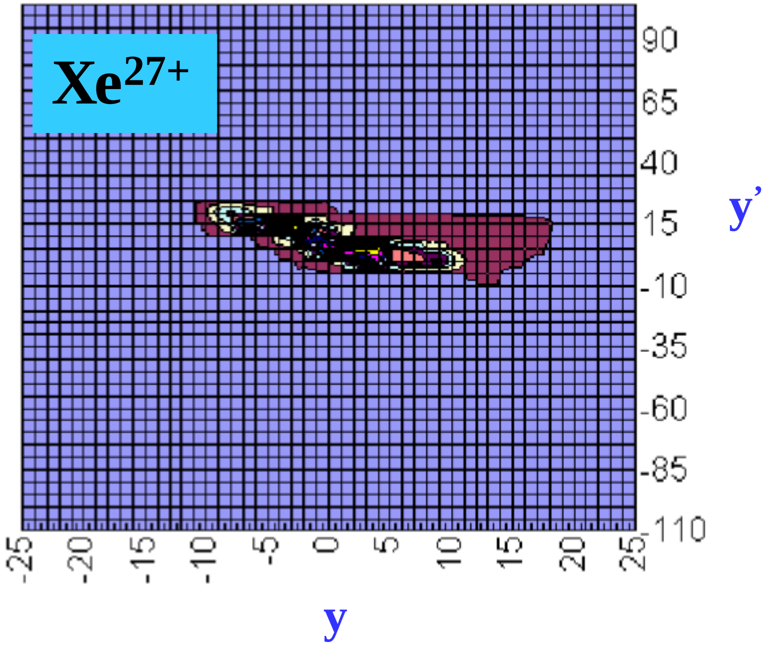
Preliminary emittance measurement

IMP Allison-type emittance scanner.
Located after the analyzing magnet

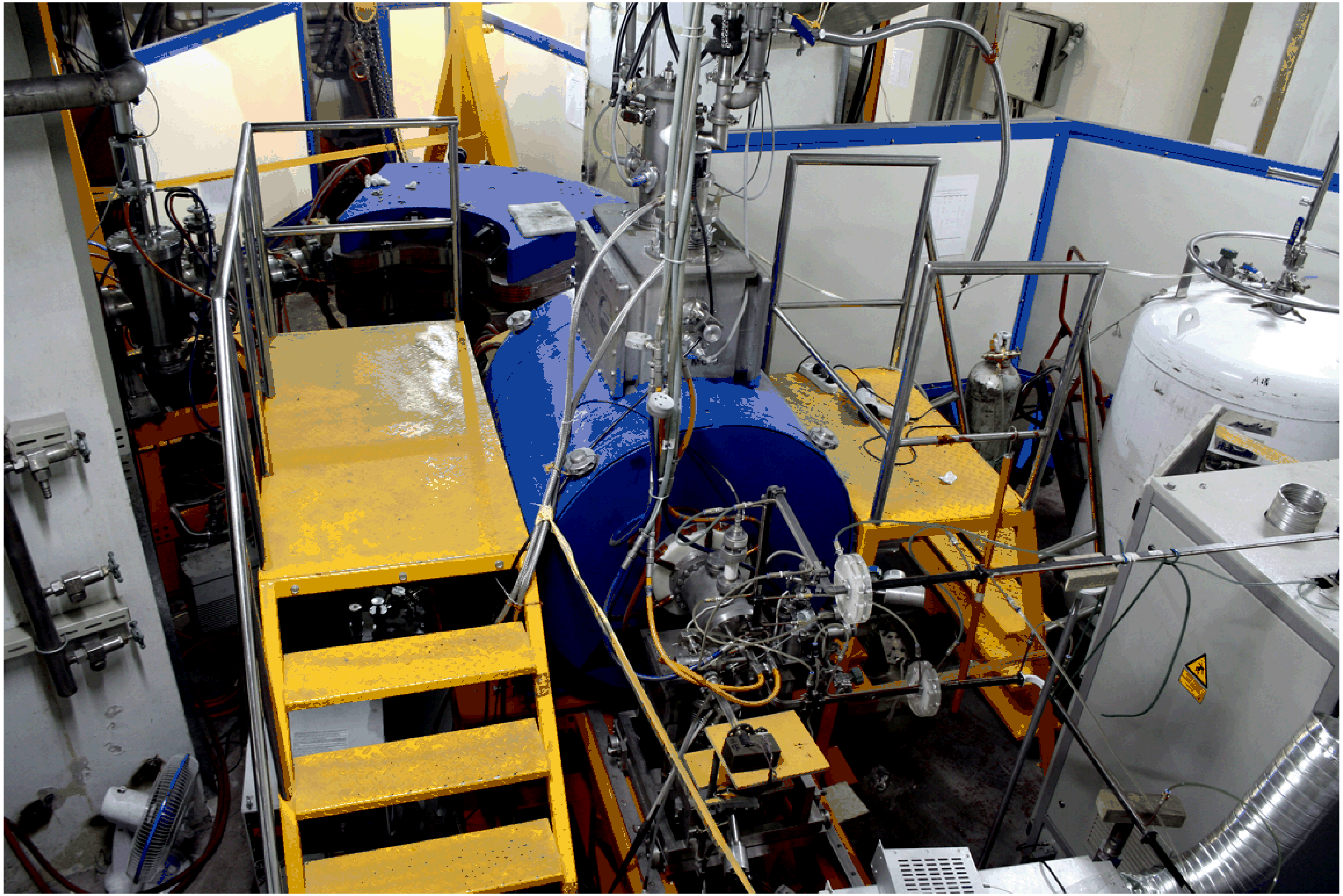


Use M. Stockli's code to process data





SECRAL at the Axial Injection Beam Line of IMP Cyclotron



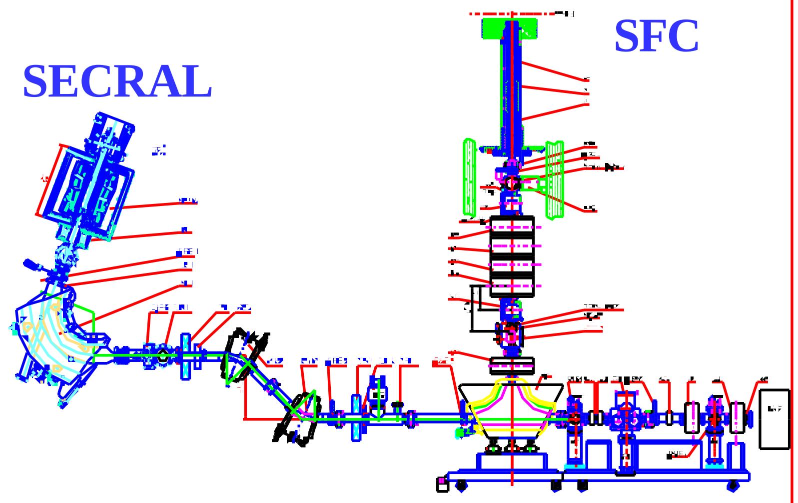
SECRAL Operation for HIRFL Accelerator

- The first beam: $^{129}Xe^{27+}$, extraction voltage: 22 kV,

  rf power 1.5-2.0 kW,

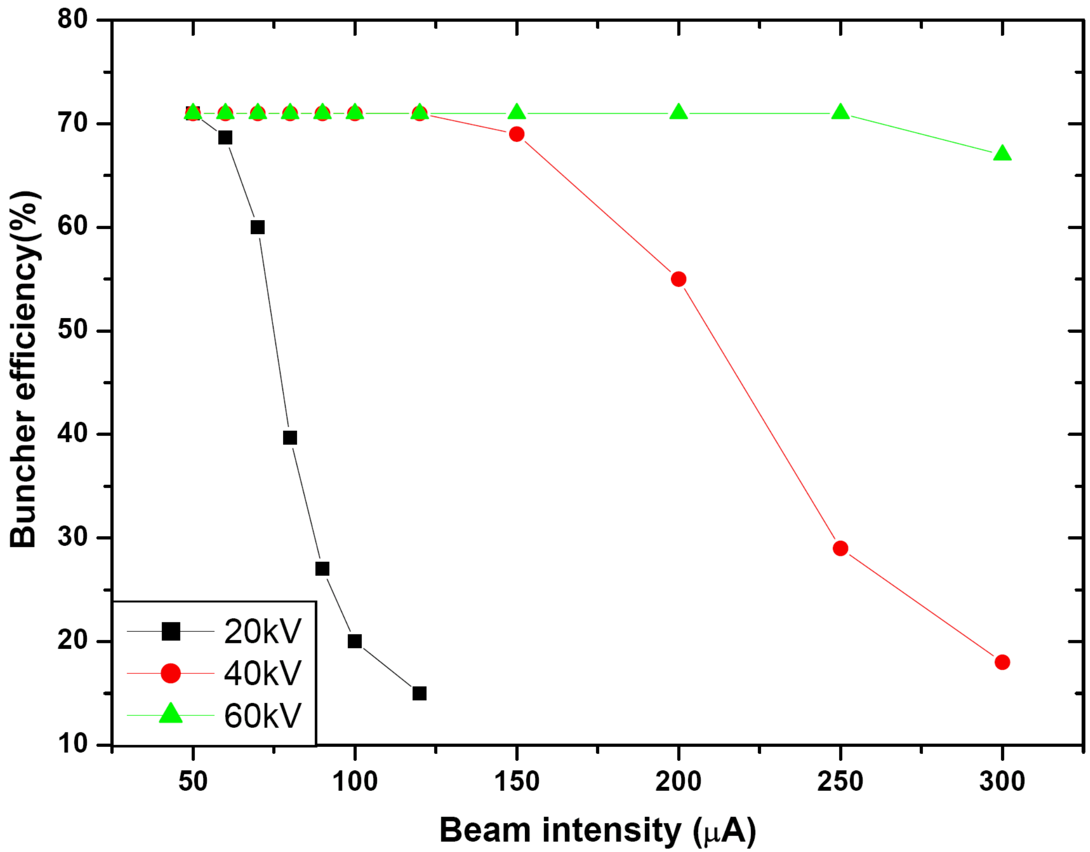
  Beam intensity: 130-160 eμA,

  Continuously operated for more than one month.
- Dedicated to commissioning of IMP new project HIRFL-CSR.
  - SFC Xe beam increased by factor 10
  - SSC Xe beam increased by factor 50
  - CSRm accelerated Xe^{27+} beam to 235 MeV/u, accumulated beam intensity up to 500 eμA (1×10^8 pps), the heaviest ion and the biggest beam intensity achieved for a heavy ion synchrotron with a cyclotron injector, impossible without SECRAL.



SFC : Xe^{27+} 2.9 MeV/u,
extracted intensity: 5-6 eμA
But SECRAL: 130-160 eμA
Low transmission effciency.

One of reasons for low transmission: longitudinal space charge effect may reduce the buncher efficiency.
If at higher extraction voltage up to 60 kV, the buncher efficiency could be improved and may achieve a better transmission efficiency.



Longitudinal acceptance of SFC $(\Delta f = 10^0, \frac{\Delta W}{W} = 4\%)$

Summary and Conclusion

1. A superconducting ECR ion source SECRAL with an innovative magnet structure has been successfully built. The unique features of SECRAL have resulted in some significant advantages , which may open a new way for developing a compact and high performance 18-28 GHz superconducting ECR ion source.

2. Commissioning results at 18 GHz are promising and some record beam intensities have been produced. Beam intensities are still increasing linearly with rf power and better results should be coming up with Aluminum chamber, higher rf power and higher rf frequency 24-28GHz.

3. SECRAL has been put into routine operation for HIRFL accelerator since May 2007. It has demonstrated SECRAL has a nice long-term stability, reliability with higher beam intensity for highly charged ions.

Acknowledgement

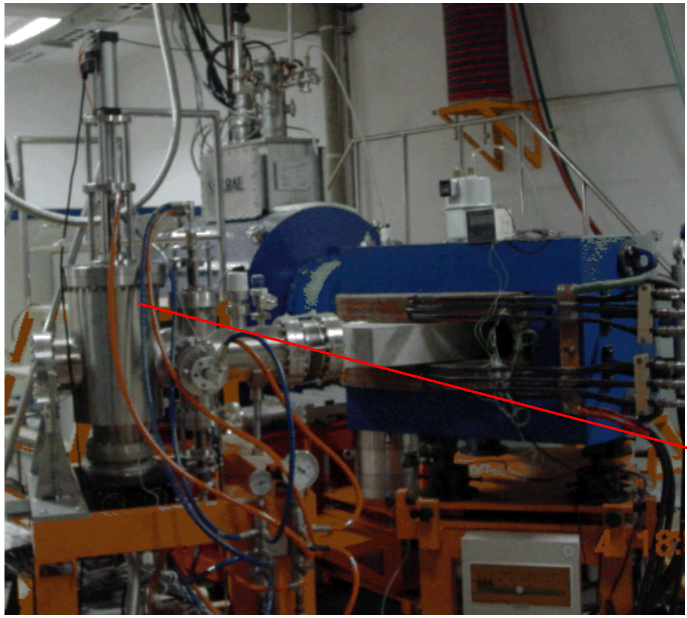
- Thank ACCEL for fabrication of the magnet.

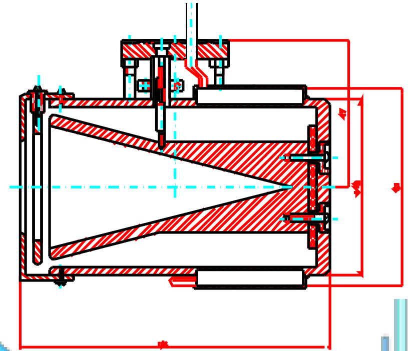
- Many thanks go to the following colleagues for their kind help and fruitful discussions during design and commissioning of SECRAL:

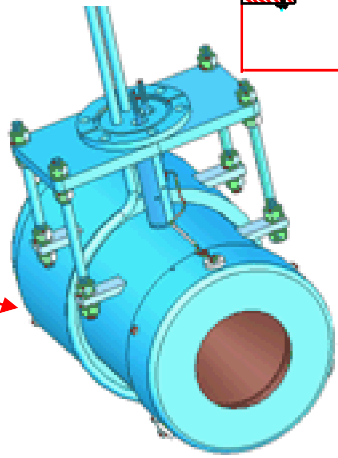
  Dan Xie, Denis Hitz, Claude Lyneis, Daniela Leitner, Santo Gammino, Luigi Celona, T.Nakagawa, A. Efremov, Weijiang Zhao, A.Drentje….

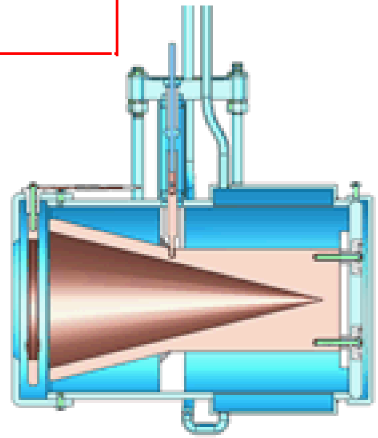
Thank you for your attention !

Faraday-cup to measure beam current



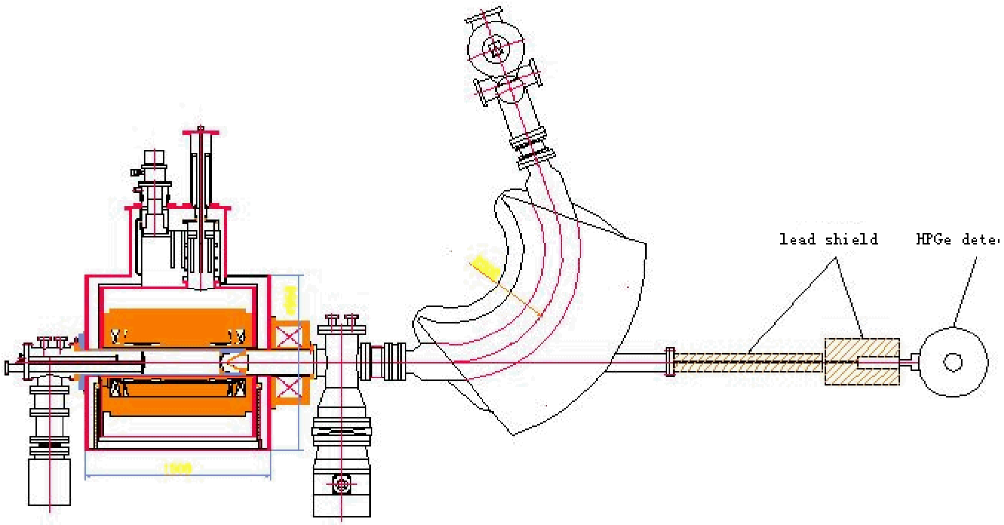


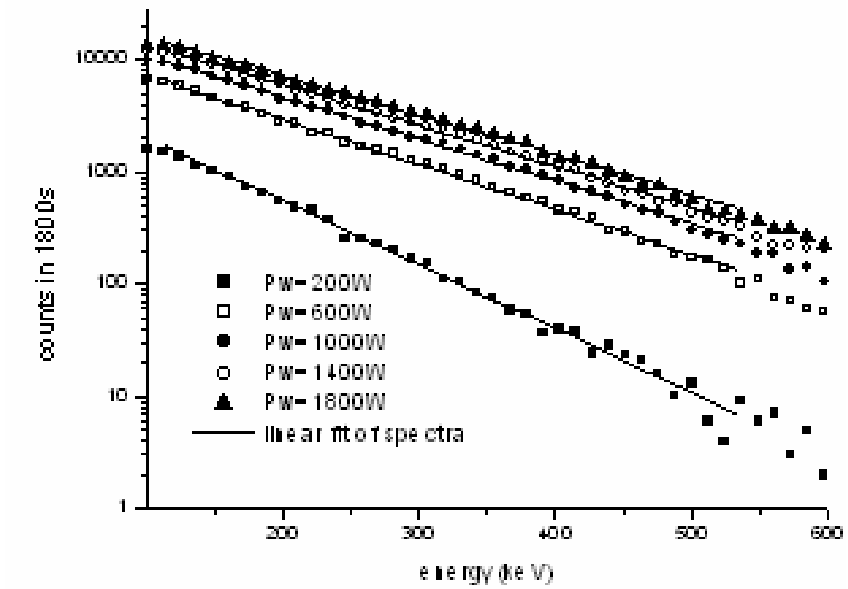




- Good shielding to the ground.
- Water cooled down through BeO.
- Suppressor electrode -150 ~-200 V.
- Cone-shape cup prevents from electrons coming out.

Bremsstrahlung Measurements





•Increase $B_{inj,}$ B_{min}; Reduce $B_{extr,}$, • stronger X ray, Might be related to dB/dz,

•LHe consumption:

90% Bmax (no plasma) : <1.5 l/h;
1.0 kW, 18GHz: <1.5 l/h;
1.0-2.0 kW, 18GHz: 1.5-2.0 l/h
2.0-3.0 kW, 18GHz: 2.0-2.5 l/h