Challenges for the Next Generation ECRIS

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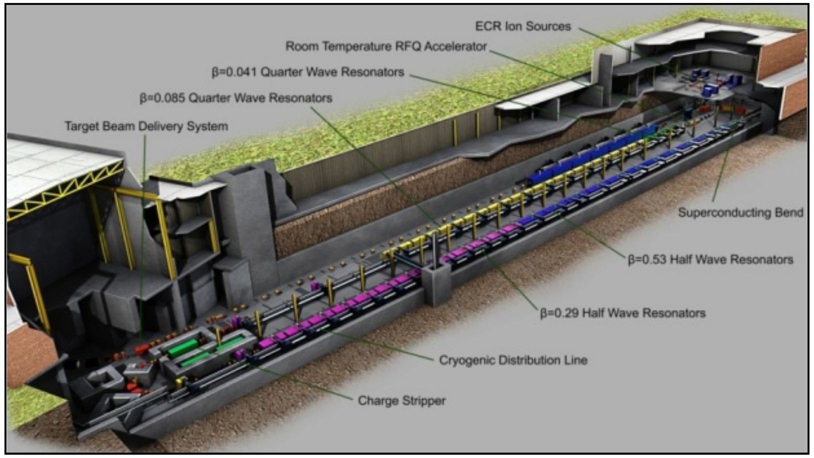
Outline

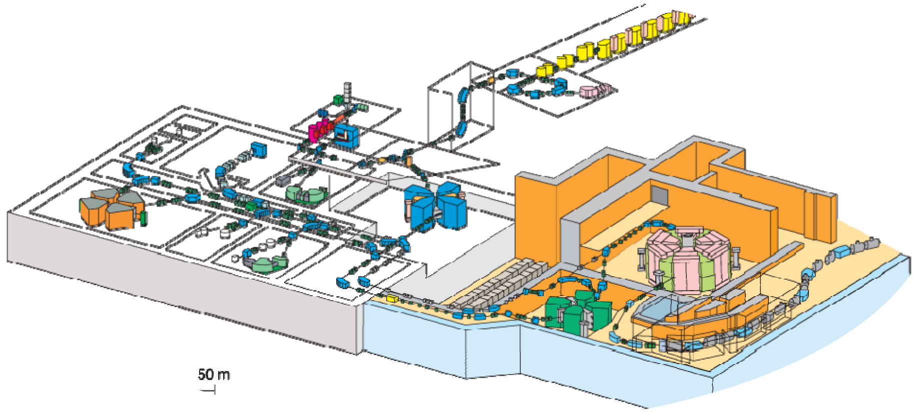
- **Why a next G. ECRIS?**
- **Development of a 3rd G. ECRIS**
- **What should be done to make a successful 4th G. ECRIS?**

Why a Next G. ECRIS?

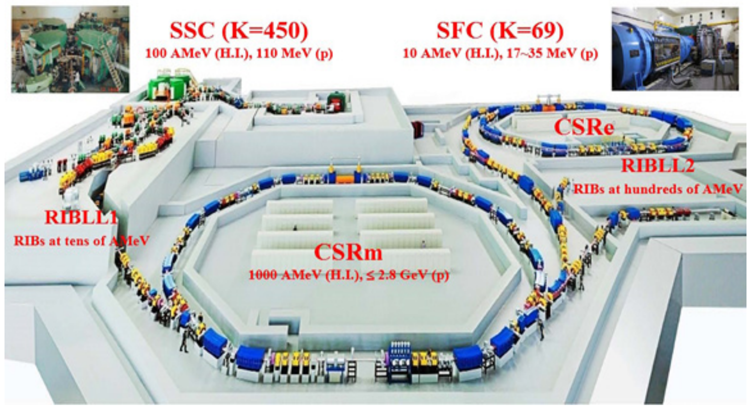
CW-intense highly charged heavy-ion-beams requested by accelerator complex



MSU FRIB U^{34+} 13 pμA/ CW



RIKEN RIBF U^{35+} 525 eμA/ CW

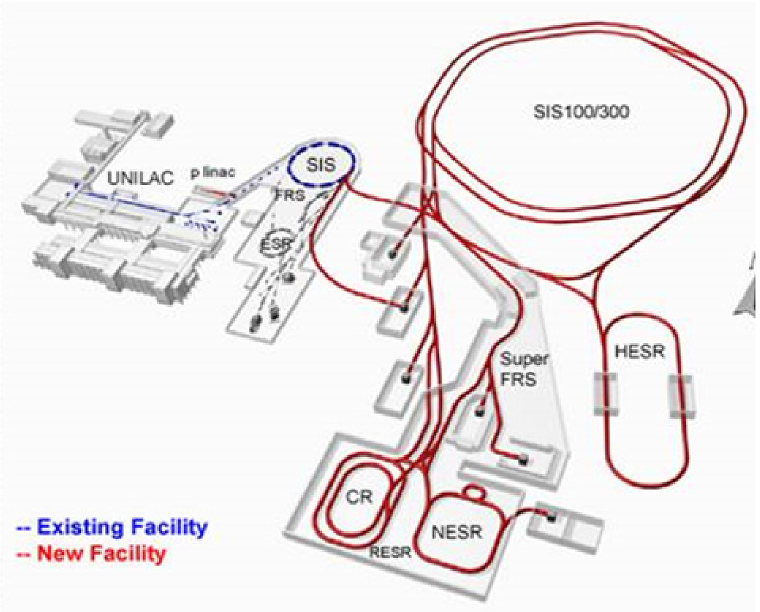


IMP HIRFL U^{41+} 100 eμA/ CW

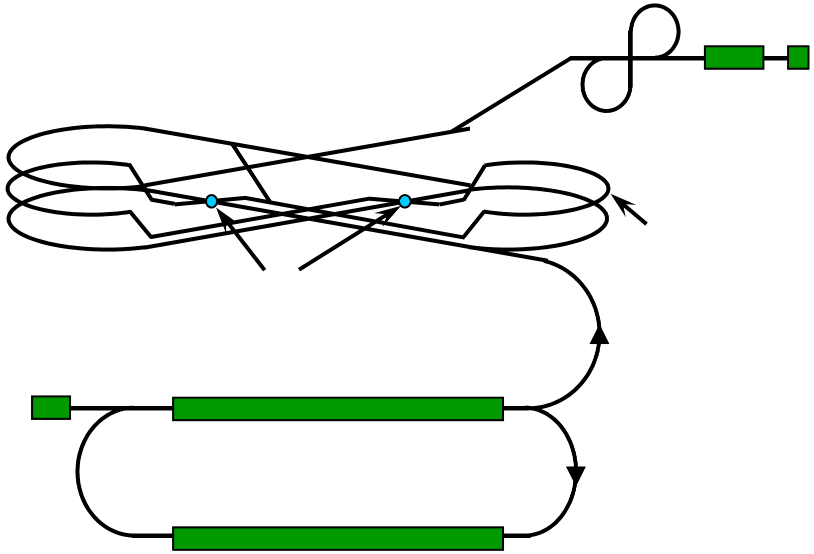
SPIRAL2 Ar^{12+} 1 emA/ CW

Why a Next G. ECRIS?

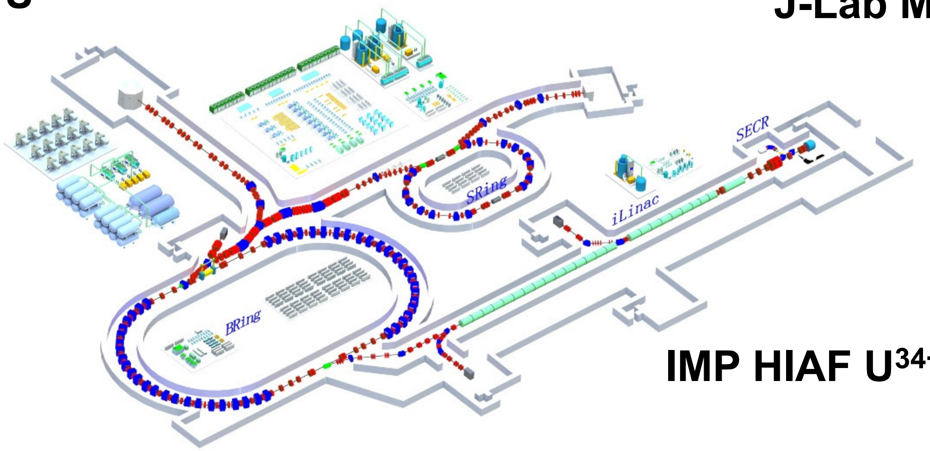
Pulsed-intense highly charged heavy-ion-beams requested by accelerator complex



GSI FAIR U^{28+}



J-Lab MEIC, U^{34+}



IMP HIAF U^{34+} 50 pμA/ 400 μs

Why a Next G. ECRIS?

Requirements of ion source for those high energy (GeV/u) high current heavy ion accelerators

Ion Source → Q: **$E \sim Q^2$ for cyclotrons**; **$E \sim Q$ for linac**

Ion Source → I_Q: **Higher power**; **Simpler injection mode**

Developing intense highly charged ion source is both performance-effective and cost-effective.

Why a Next G. ECRIS?

Why a Next G. ECRIS?

	$^{238}U^{34+}$	$^{238}U^{46+}$	$^{238}U^{55+}$
Injection E（MeV/u）	1.3	1.3	1.3
Output E（MeV/u）	100	100	100
Design I_{max}（emA）	1.0	1.0	1.0
SC cavity	HWR009+HWR015+ Spoke021	HWR009+HWR015+ Spoke021	HWR009+HWR015+ Spoke021
SC cavities	44+100+248=392	40+92+176=308	32+80+152=264
Solenoids	78	65	55
CRM Reduced		11	16
Total length（m）	288	225	197
Budget reduced		>70 M$ (MP not included)	>100 M$ (MP not included)

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SC cavity	HWR009+HWR015+ [illegible]	HWR009+HWR015+ [illegible]	HWR009+HWR015+ [illegible]
SC [illegible]	[illegible]	[illegible]	[illegible]
Solenoids	[illegible]	[illegible]	[illegible]
CRM Reduced		11	16
Total length（m）	288	225	197
Budget reduced		>70 M$ (MP not included)	>100 M$ (MP not included)

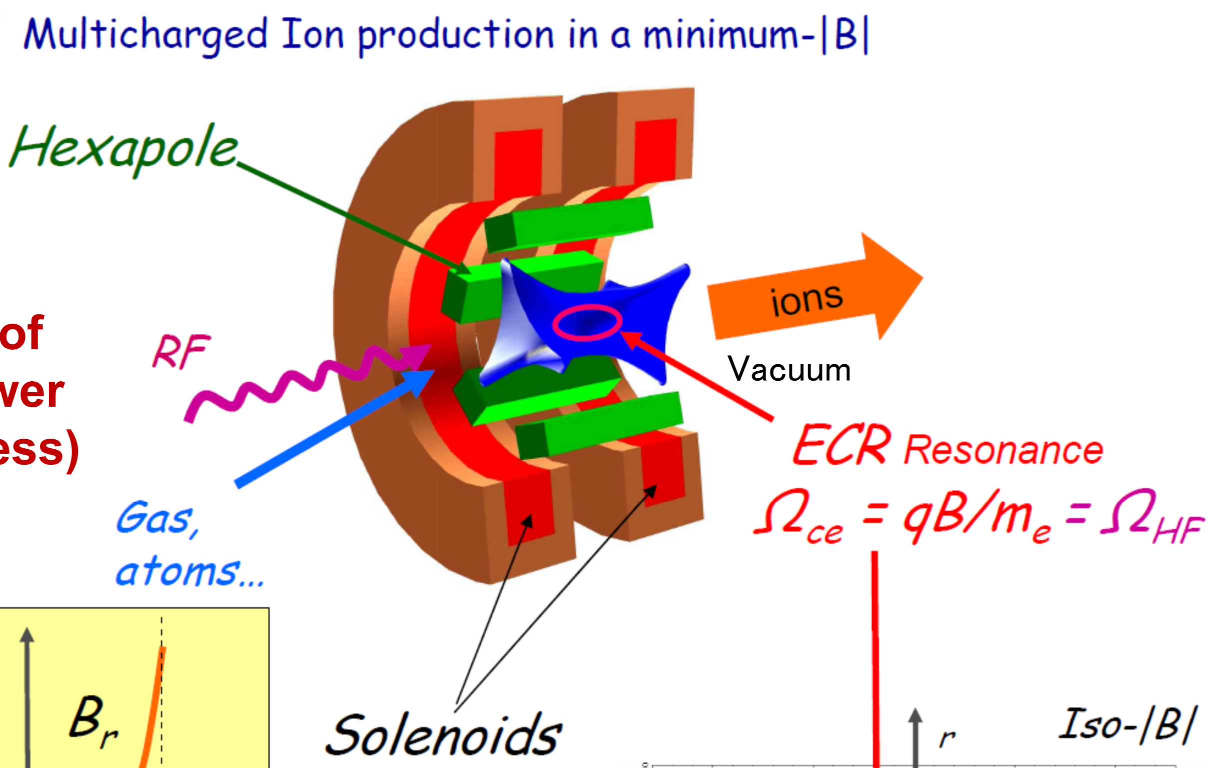
It is very much worthy of developing highly charged ion source aiming at very high charge state!!

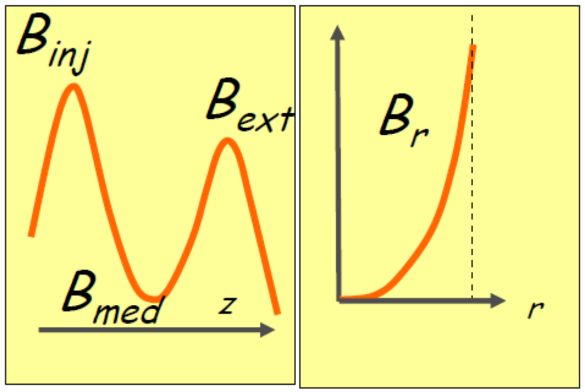
Why a Next G. ECRIS?

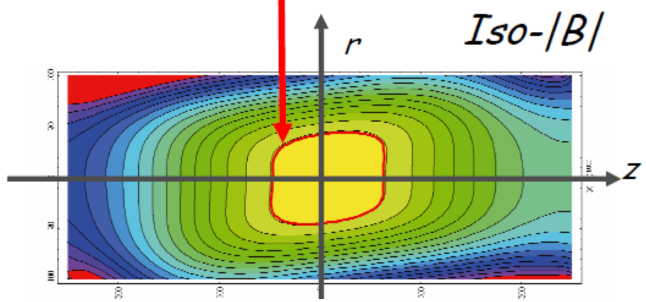
- EBIS or Electron Beam Ion Source
  - Invented by Dr. Donets in 1965
  - Control precisely and independently n_e, T_e and τ_i
  - Very high charge state pusled ion beams, such as 3.4×10^9 ppp Au^{32+} with RHIC-EBIS
- LIS or Laser Ion Source
  - Proposed by Dr. Bykovskii et al. and Peacock, Pease in 1969
  - Least control of the three key factors
  - Very intense short pulse medium charge state ion beams, typically $1\sim2\times10^{10}$ ppp Pb^{27+} with CERN/ITEP LIS
- ECRIS or Electron Cyclotron Resonance Ion Source
  - proposed by Prof. Geller in late 1960s
  - Reasonable control of the n_e, T_e and τ_i factors but not independently, and they are coupled
  - Most powerful machine for CW HCI beams and capable of delivering 10^{10} ppp or more intense pulsed beam with AG mode

Why a Next G. ECRIS?

Resonant Heating of electron by RF power (Stochasting process)







Why a Next G. ECRIS?

Why a Next G. ECRIS?

- $I_i^q = \frac{1}{2}\frac{n_i^q\, q\, e V_{ex}}{\tau_i^q}$ 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 : $(n_e T_e) \approx (\frac{m_e \varepsilon_0 \omega_{rf}^2}{e^2}) m_e c^2$ **$I^q \propto \omega^2_{ECR}$**
- Plasma Stability condition : $\beta = \frac{n_e k_b T_e}{(\frac{B^2}{2\mu_0})} < 1$ As $n_e \nearrow$ $B \nearrow$

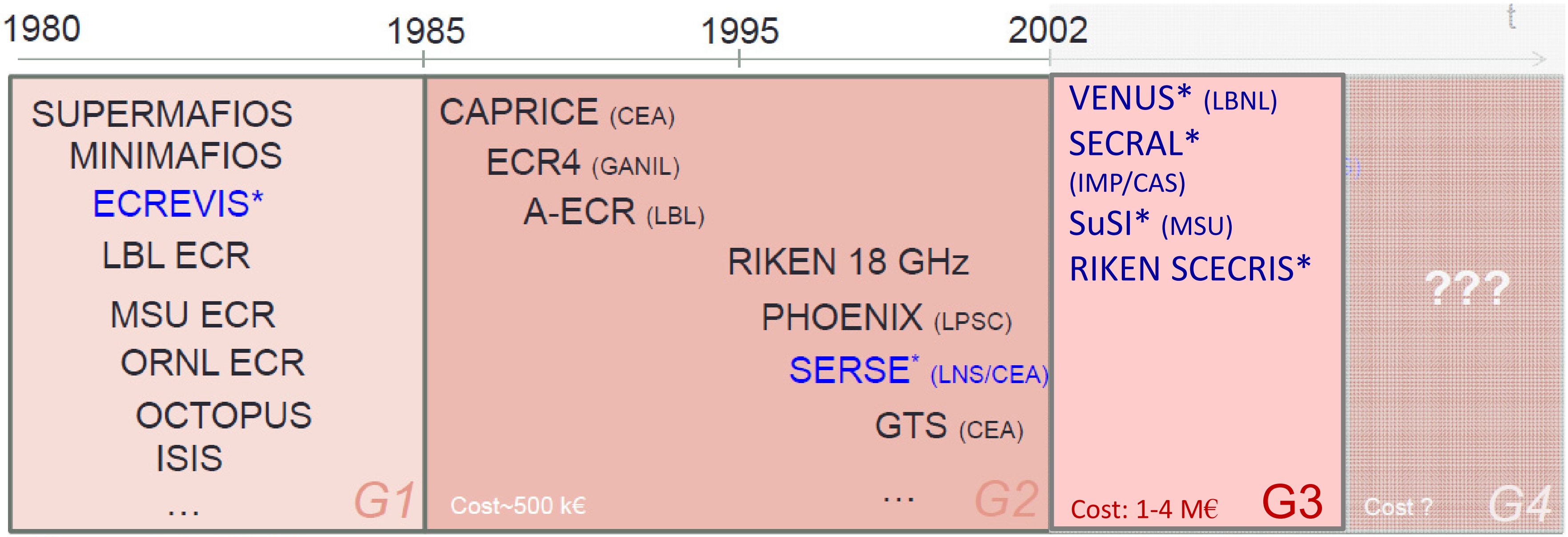
- B_{inj} ~ 3 - 4 B_{ecr} on axis
- B_{ext} ~ 2.2 B_{ecr} on axis (T)
- B_{rad} ~ $2B_{ecr}$ on plasma chamber wall
- Last closed Bmod inside chamber is ~2 B_{ecr}

Semi-empirical rules

f_{ECR}	B_{ECR}	B_{inj}	B_{rad}
14 GHz	0.5 T	2 T	1 T
28 GHz	1 T	4 T	2 T

Why a Next G. ECRIS?

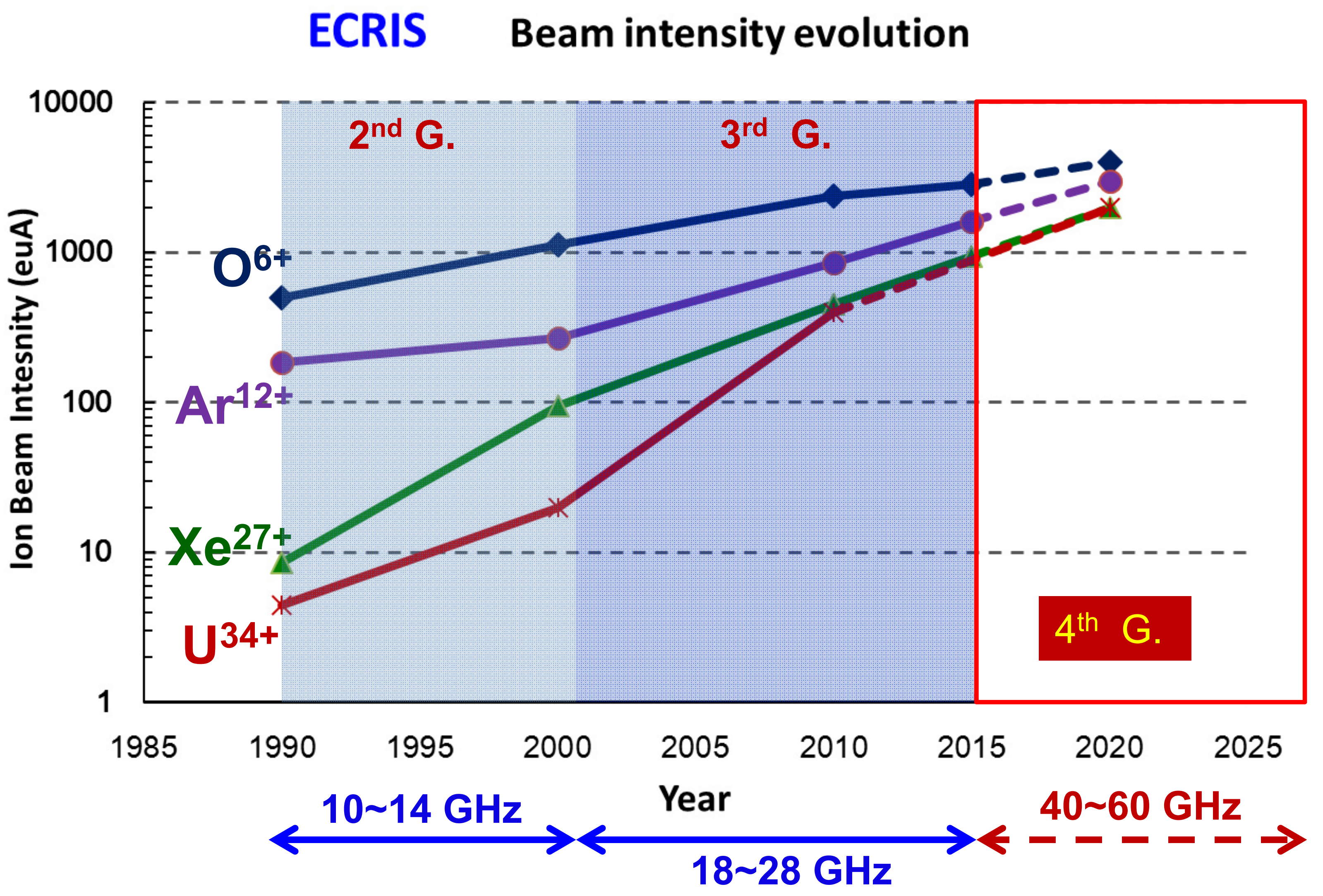
All permanent magnet ECRIS	Classical RM ECRIS	Hybrid SC-ECRIS	Fully SC-ECRIS
Nanogan series ion sources	GTS source	RAMSE, SHIVA	SERSE 18 GHz
BIE series ion sources	AECR-U	A-PHOENIX	VENUS 28GHz
LAPECR1, LAPECR2	LECR2, LECR3	PKDELIS	SECRAL 18~28 GHz
Kei1, Kei2	RIKEN 18 GHz	Dubna 18 GHz	SUSI 18~24 GHz
SOPHIE	ECR4, Caprice		RIKEN SCECRIS 28 GHz
Operated 2.45 ~ 14 GHz	Operated 10 ~ 18 GHz	Operated 14 ~ 28 GHz	Operated 18 ~ 28 GHz



*Superconducting ECRIS

From T. Thuillier's slides at CERN Accelerator School 2012

Why a Next G. ECRIS?



3RD G.

BACK TO THE FUTURE

4TH G.

SERSE@INFN

Available in 1997

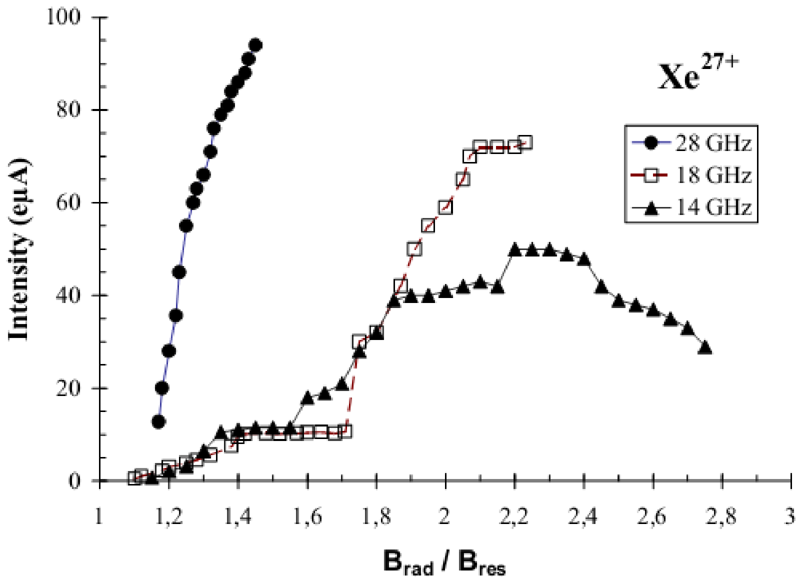
Frequency	18 + 14.5 GHz
Type of launching	WR62, off-axis
Mirror length	490 mm
B_{inj}	2.7 T
B_{min}	0.3-0.6 T
B_{ext}	1.6 T
L_{ecr}	< 100 mm
$L_{hexapole}$	700 mm
B_{rad}	1.55 T max.
Ø plasma electrode	8 mm
Ø puller	12 mm
Extraction voltage	30 kV Max.

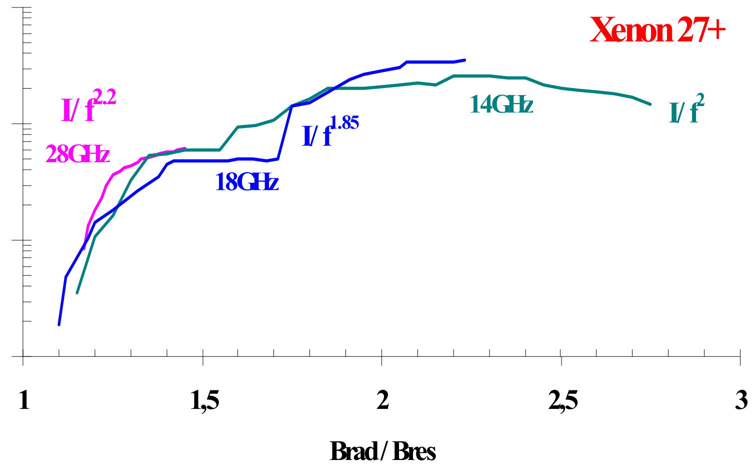
Development of a 3rd G. ECRIS

What we learn from SERSE:

- 28 GHz operations seem to give more current
- TE_{01} mode works with ECRIS
- Higher extraction voltage is essential
- Lots of technical problems…
- LHe boil-off
- X-ray radiation problems
- Poor extraction and transport
- Time consuming and expensive

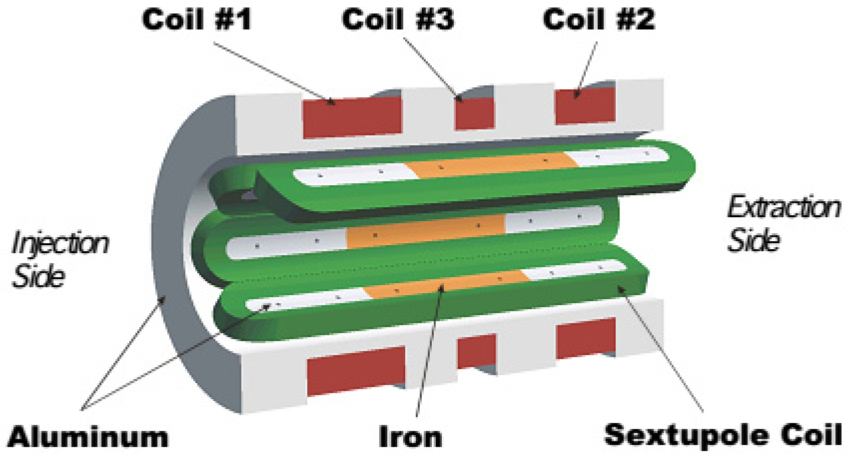
S. Gammino@FRIB Ion Source Review 2009





Results in 1999

Development of a 3rd G. ECRIS



VENUS——First 3rd G. ECRIS

Achieved magnetic fields
Binj ≤4 T, Bext ≤ 3 T, Brad≤2.2 T

Sextupole-in-Solenoid

- ***cost effective***
- ***reliable***
- ***scaleable to 56 GHz***

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

C. Lyneis@Lecture of Brightness Award 2009

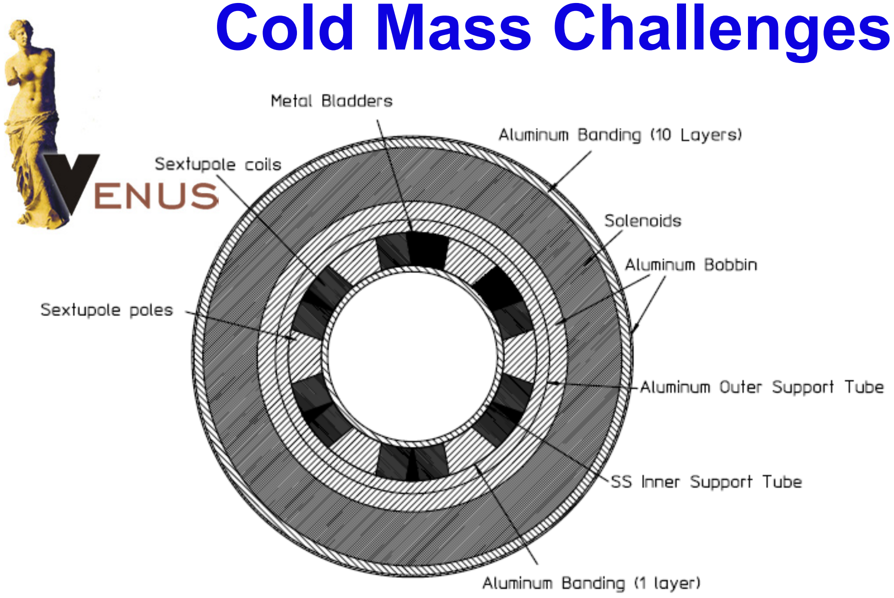
Development of a 3rd G. ECRIS

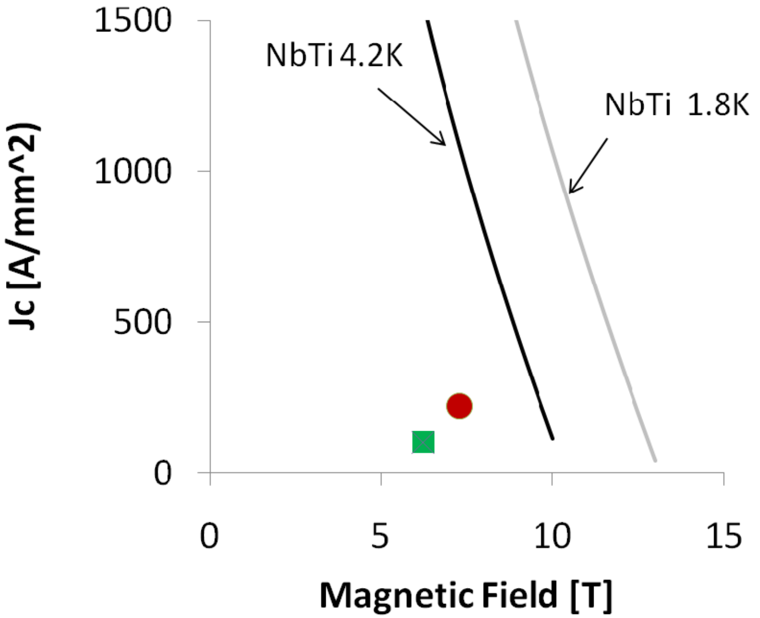
- 1996-1997-Prototype sextupole/solenoid built and tested with directors fund
- 1997-Decision to build production magnet
- 1999-ISOL Task Forces selects 400 kW Uranium Driver for US radioactive beam project
- 1999-Production magnet trains to full field
- 2001-Installed and successfully tested in cryostat
- 2002-First Plasma--18 GHz Operation
- 2003-Sep--160 eμA Bi^{24+}
- 2004-May--First 28 GHz Operation

VENUS Team: D. Leitner, C. Taylor, C. Lyneis, M. Leinter
S. Abbott (not shown)

C. Lyneis@Lecture of Brightness Award 2009

Cold Mass Challenges

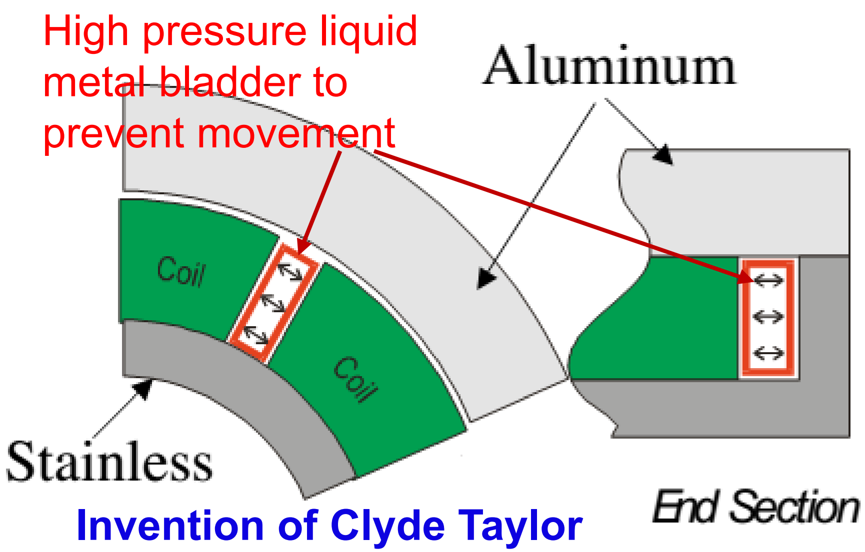




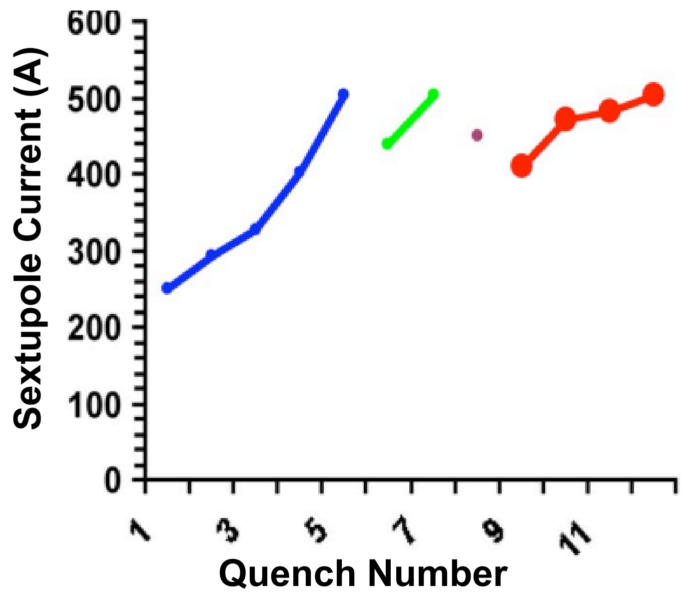
- **Strong clamping with metal bladders**
- **Shell construction to exert sufficient pre-stress**
- Difference to other designs: **3:1 Copper content in the sextupole wire**, which provides thermal stabilization and might damp micro movements of the coil.
- Might help also in preventing quenches initiated by x-ray heating
- Conservative approach for maximum field values and current densities to keep enough safety margin

D. Leitner@FRIB Ion Source Review 2009

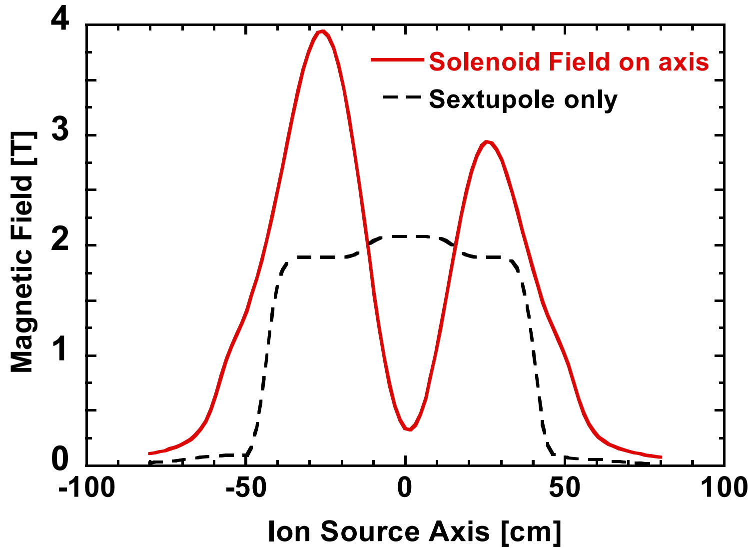
Development of a 3rd G. ECRIS



Invention of Clyde Taylor



- Only magnet that can be independently energized
- No retraining required after warm up



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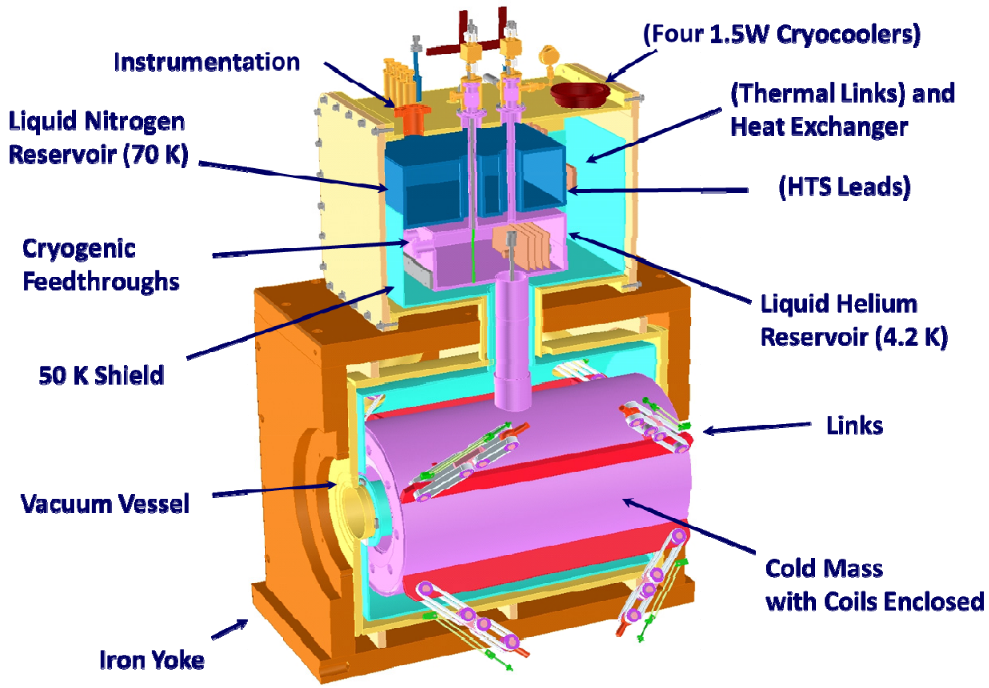
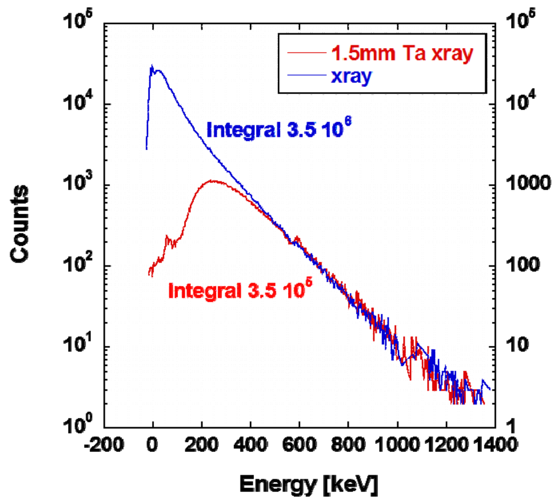
Development of a 3rd G. ECRIS

Cryogenics

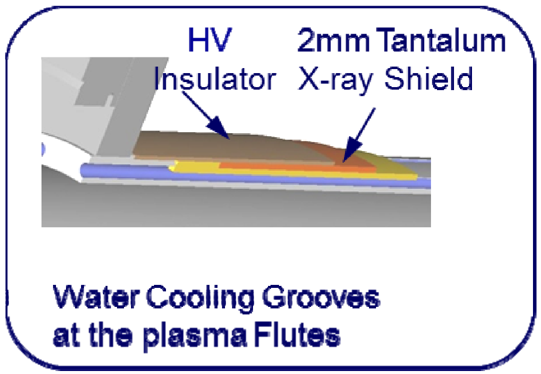
VENUS



- A LHe recirculation system reserves the conditions for the continuous operation of the magnet
- Bremsstrahlung radiation causes strong 4.2 K heat sink
- High voltage insulation deteriorates in the high x-ray flux
- X-ray flux is strongly dependent on the heating frequency
  - 1.5 W~1.0 kW@28 GHz



Shielding plan

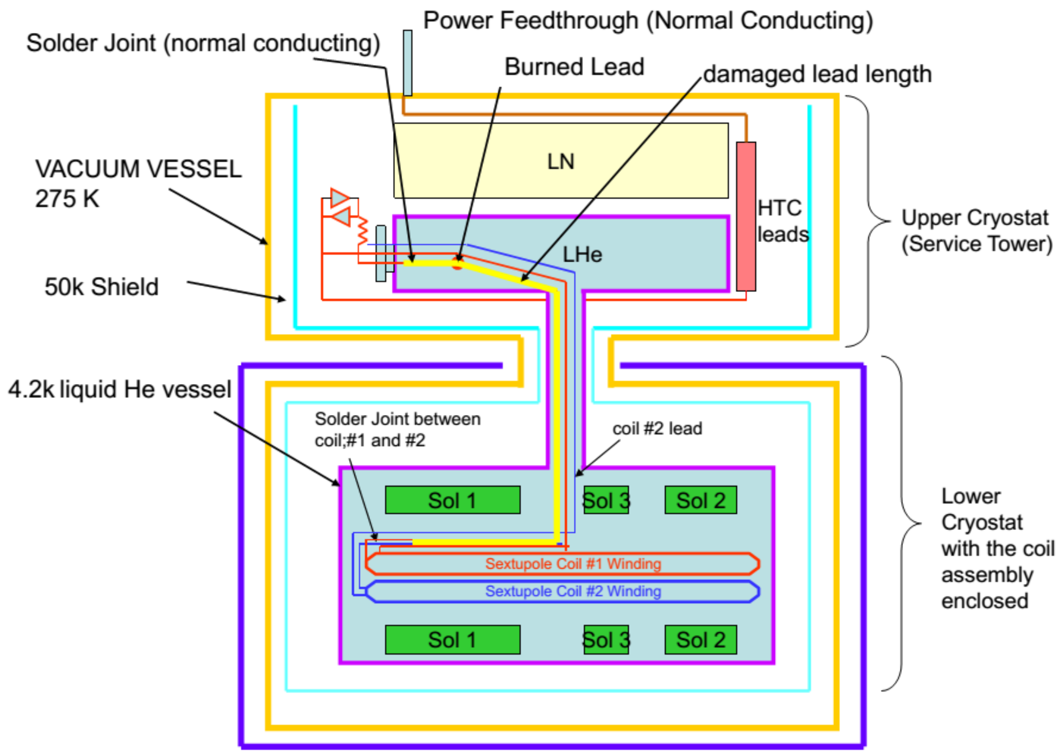


D. Leitner@FRIB Ion Source Review 2009

Development of a 3rd G. ECRIS

Major Events of the VENUS Project

09/97	Prototype Magnet Completed
09/01	Final Magnet Test
06/02	First Plasma@18 GHz
05/04	First 28 GHz Plasma
08/06	220 euA $U^{33+, 34+}$
01/08	Quench/Lead burnout
07/10	First plasma after repair

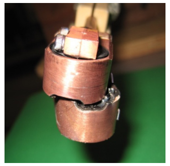
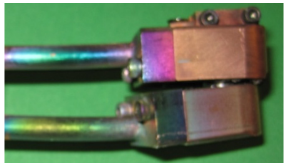


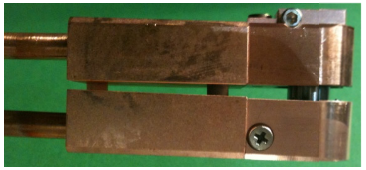
Trouble shooting diagram

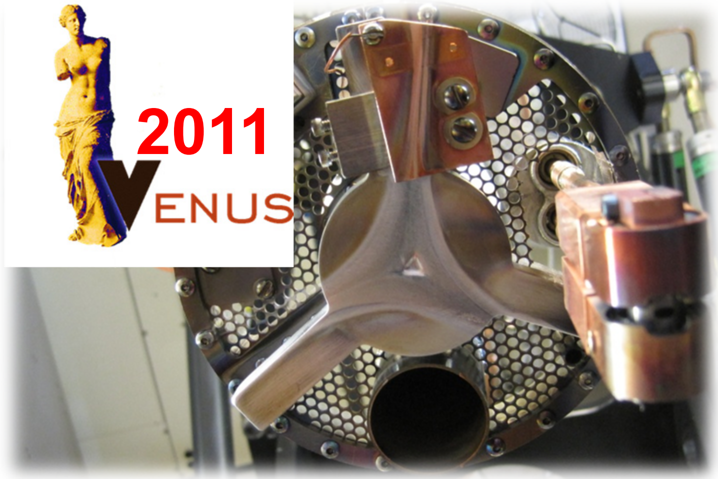
D. Leitner@ECRIS2010, Grenoble

Development of a 3rd G. ECRIS

- Operates 650° C-2300° C to vaporize metals
- Improved cooling
- Expands VENUS' metal production capability

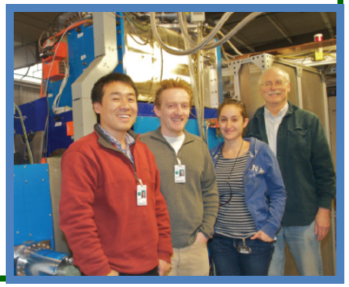


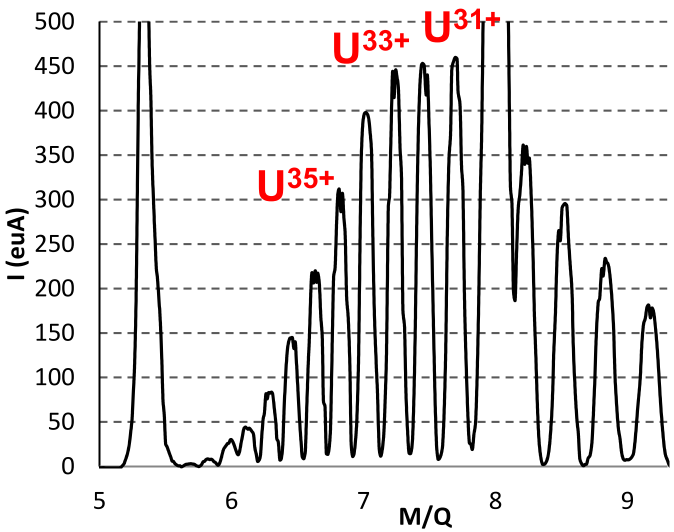


Uranium Development: High Intensity

- Uranium beams will be one of the most important and challenging beams for projects like FRIB, RIBF, HIAF…
- U sublimes @ 2000° C, 1000W!
- FRIB needs 440eμA of $^{238}U^{33+,34+}$ combined

$^{238}U^{33+}$	450eμA
$^{238}U^{34+}$	400eμA
$^{238}U^{50+}$	13eμA



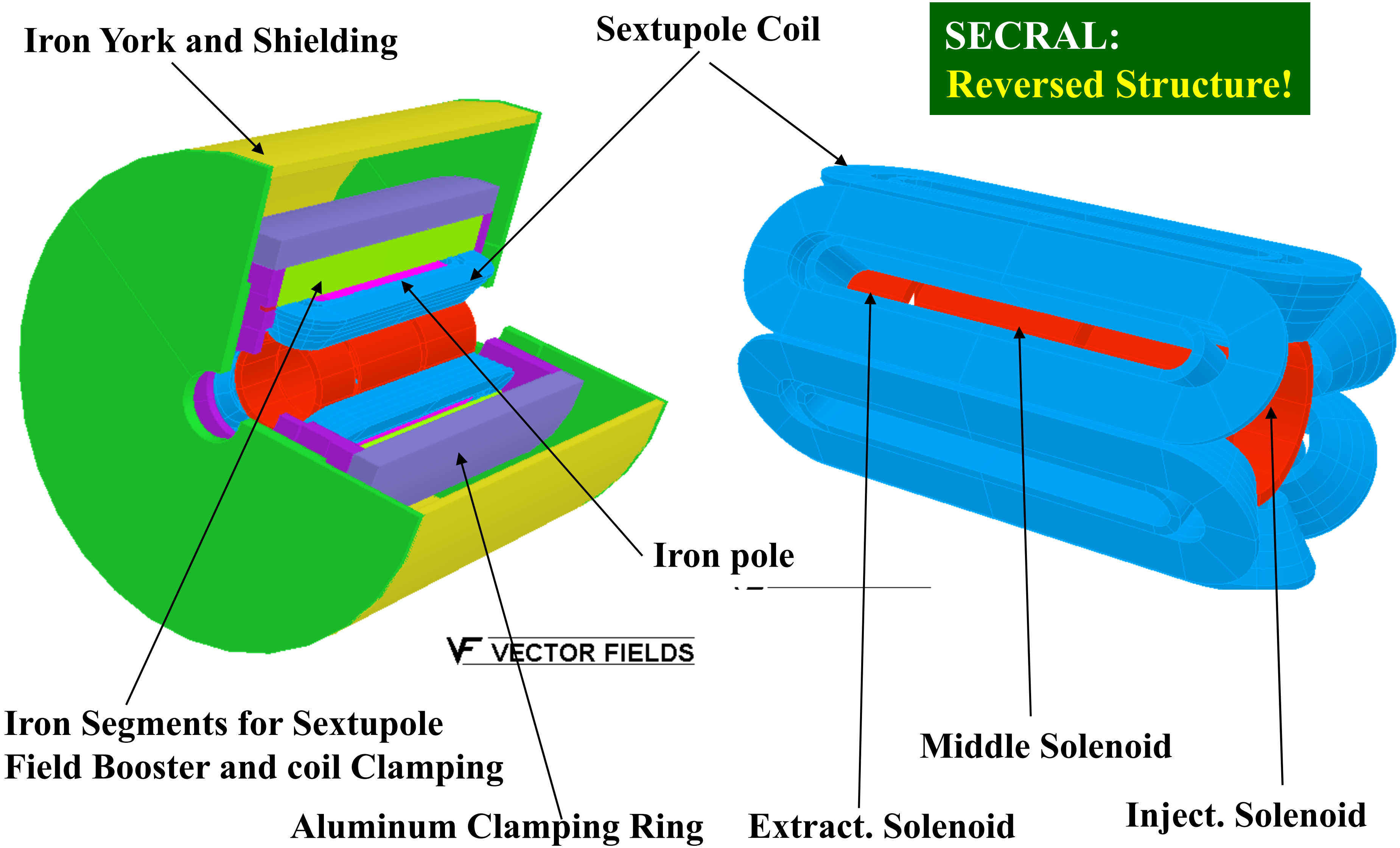


10 years from 1st plasma

J. Benitez@ICIS2011, Giardini Naxos

Development of a 3rd G. ECRIS

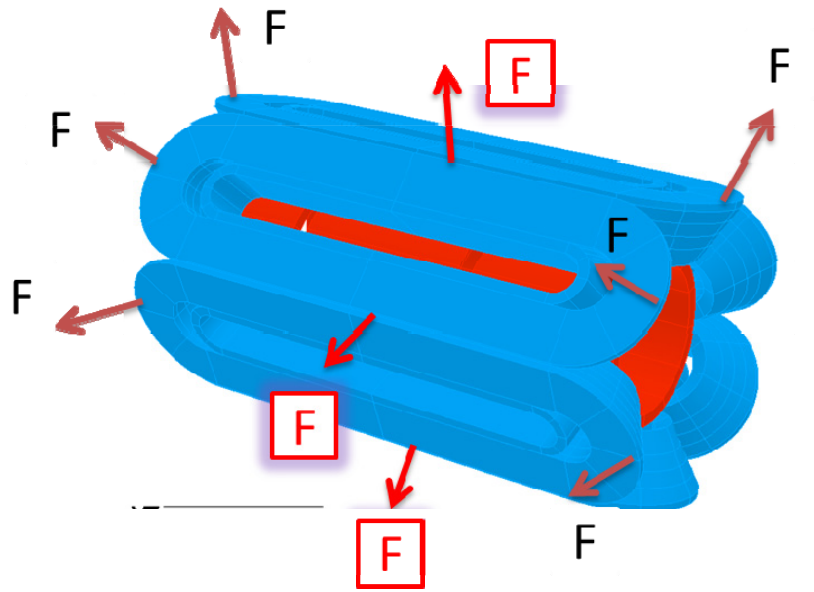
SECRAL: Reversed Structure!



Development of a 3rd G. ECRIS

Pros

- Lower/simpler interaction forces;
- Smaller magnet size and cryostat;
- Simpler fabrication and somewhat a bit lower cost.

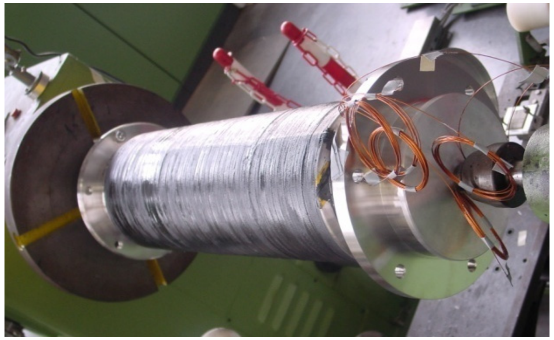


Con

- Inefficient utilization of the radial field.

Comments:

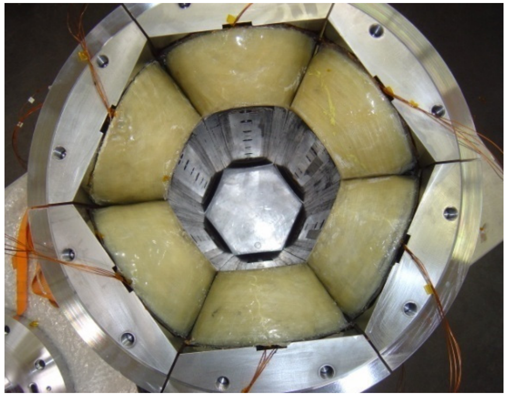
- **Will this new structure work in terms of HCI production?**
- **Is this still a conventional ECR ion source?**
- **Engineering feasibility?**



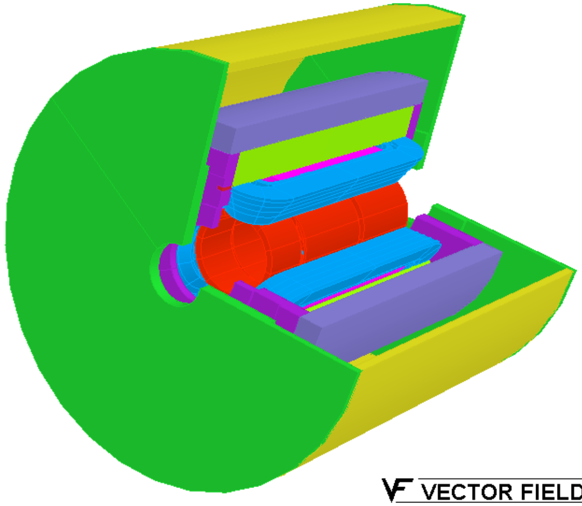
Three Solenoids

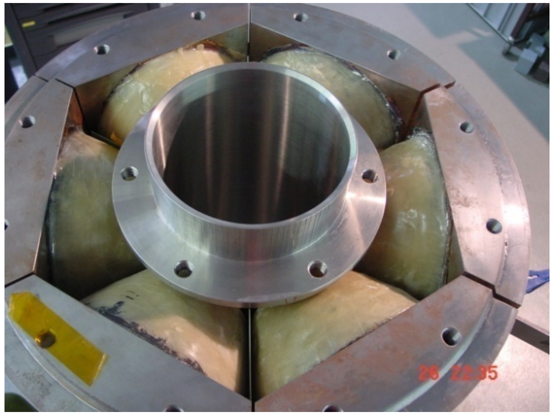
Cold Mass in ACCEL:
(2002-2005)

- No problems with winding and installation
- Difficulty in effective clamping solution



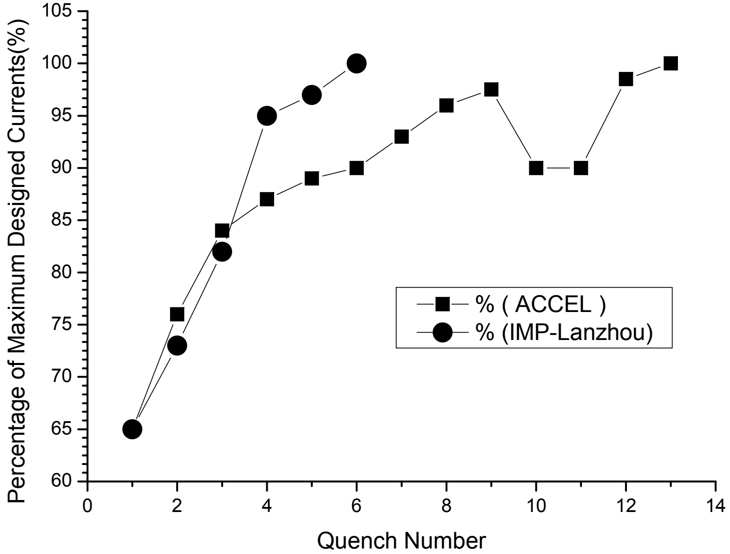
Sextupole

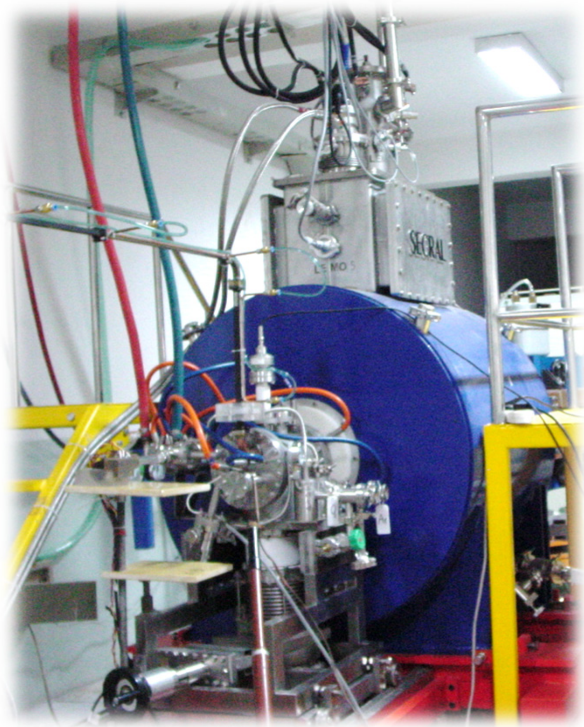


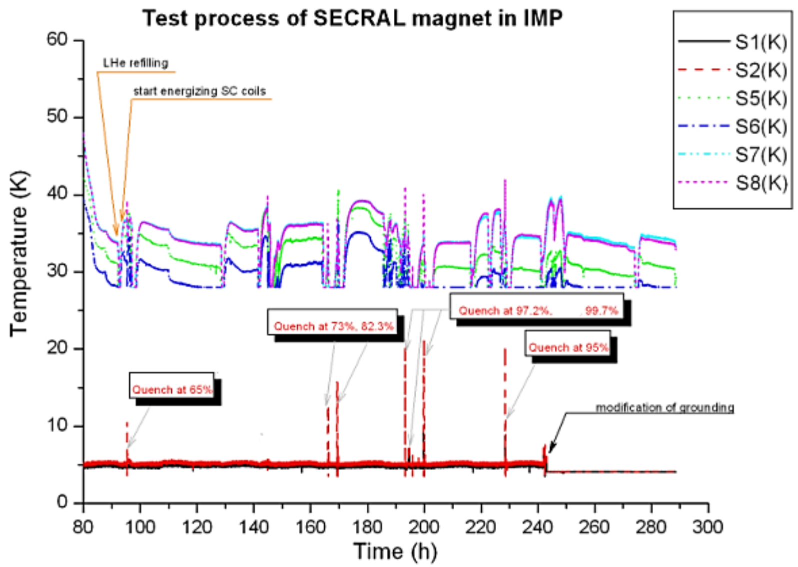


Sextupole + Three Solenoids

Development of a 3rd G. ECRIS

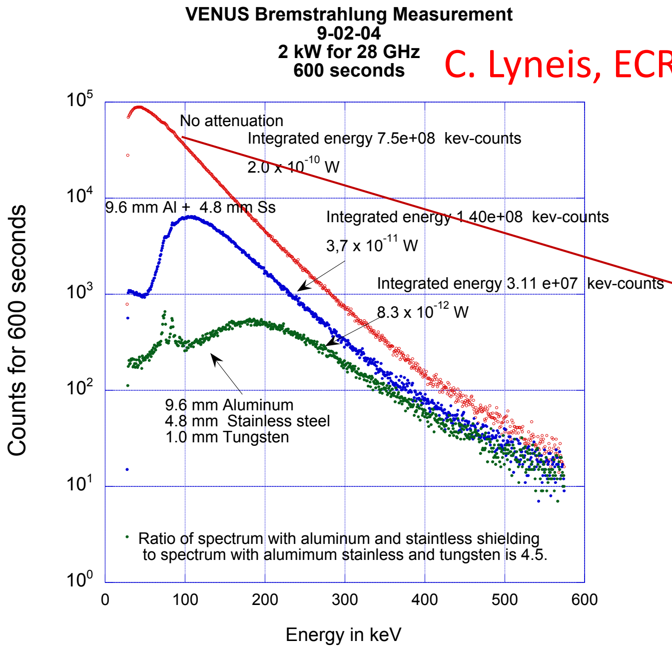




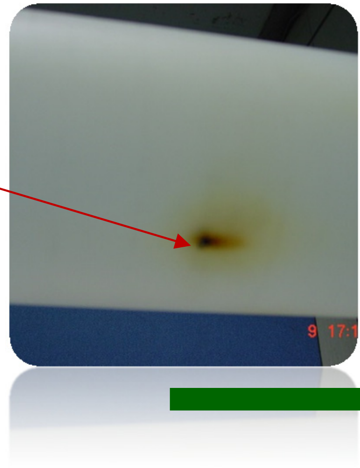


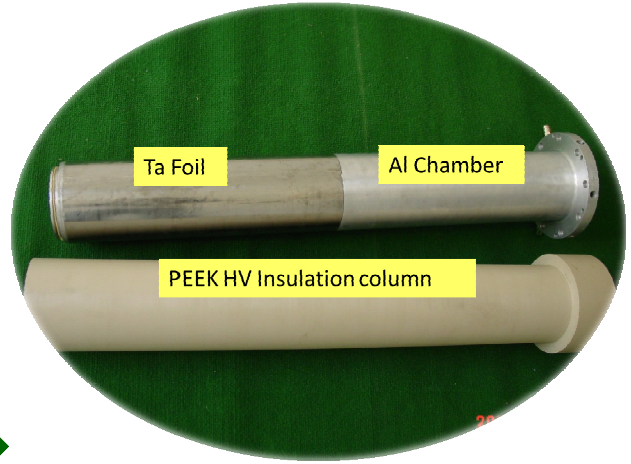
- **Retraining process is needed after every warm-up**
- **Both warm-up and cool-down procedures are very time consuming and has many technical details**

Development of a 3rd G. ECRIS



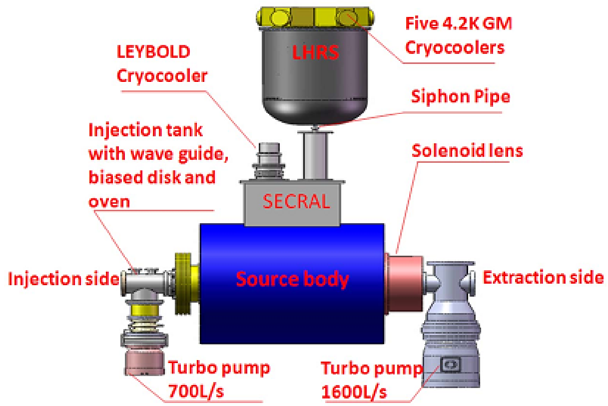
C. Lyneis, ECRIS'04



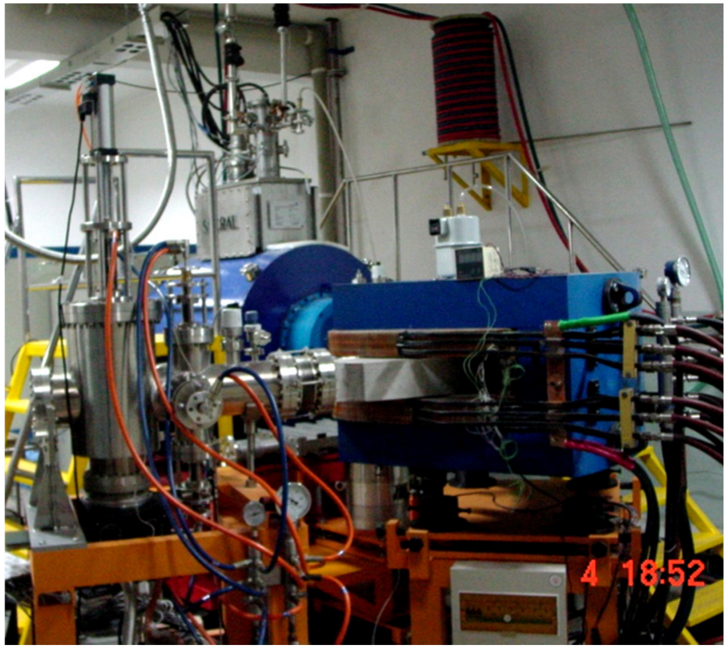


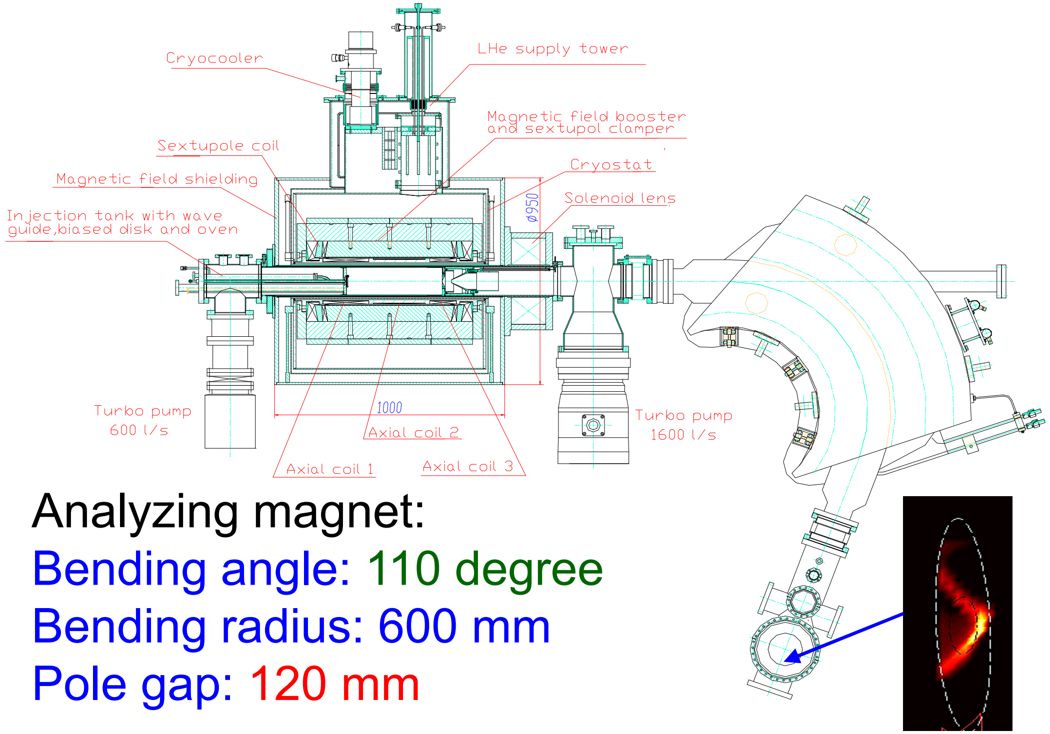
- Main insulator failure at high X-ray flux radiation
- Insufficient μW power density → Dual 18 GHz feeding
- High dynamic 4.2 K heat load at gyrotron frequency (~1W/kW)

External LHe circulation sys.



Development of a 3rd G. ECRIS





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

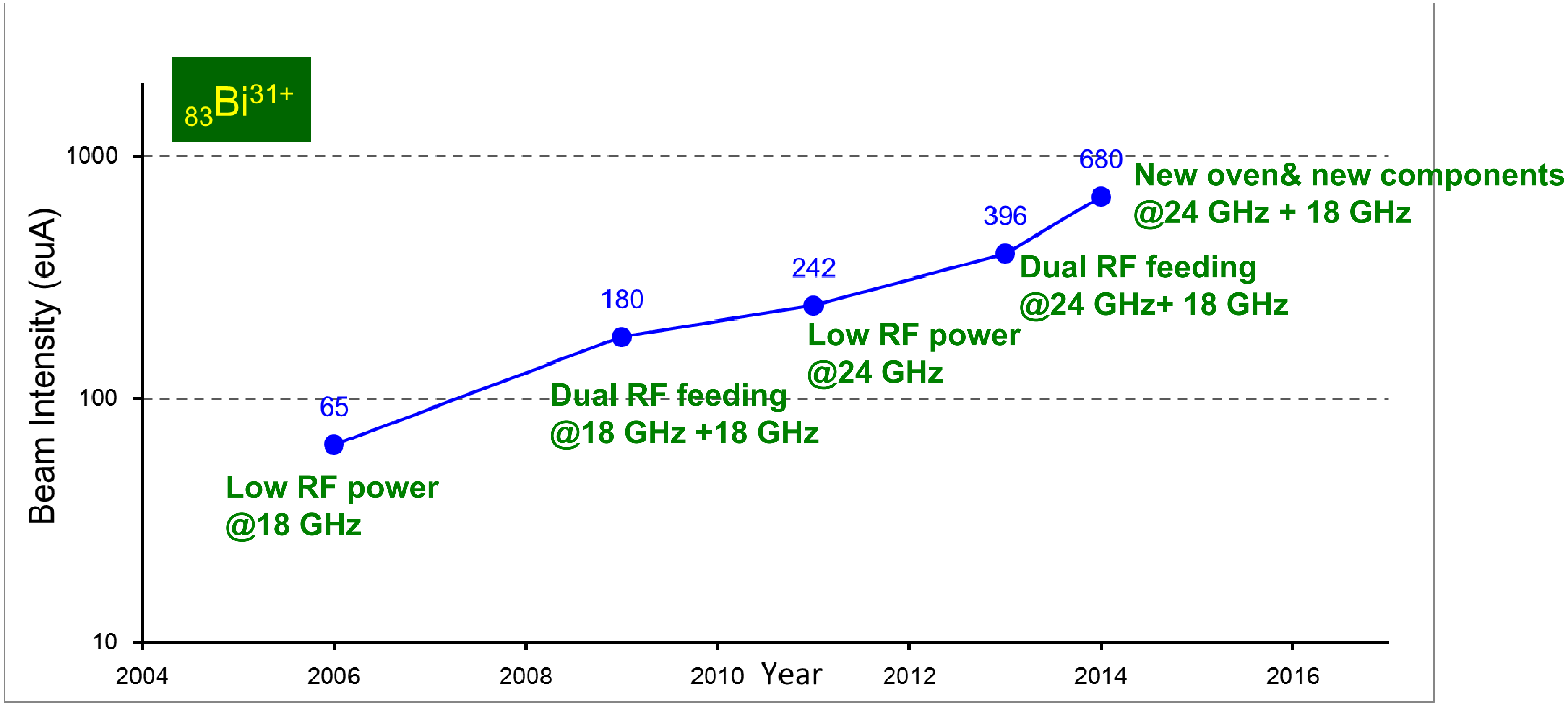
- **High mass resolution analyzing system is important for high charge state heavy ion beam production**
- **Large gap dipole magnet is essential to have high transmission efficiency and high order aberration control**
- **Space charge Effect dominates intense beam extraction that needs optimum design**

Milestone of the SECRAL Project

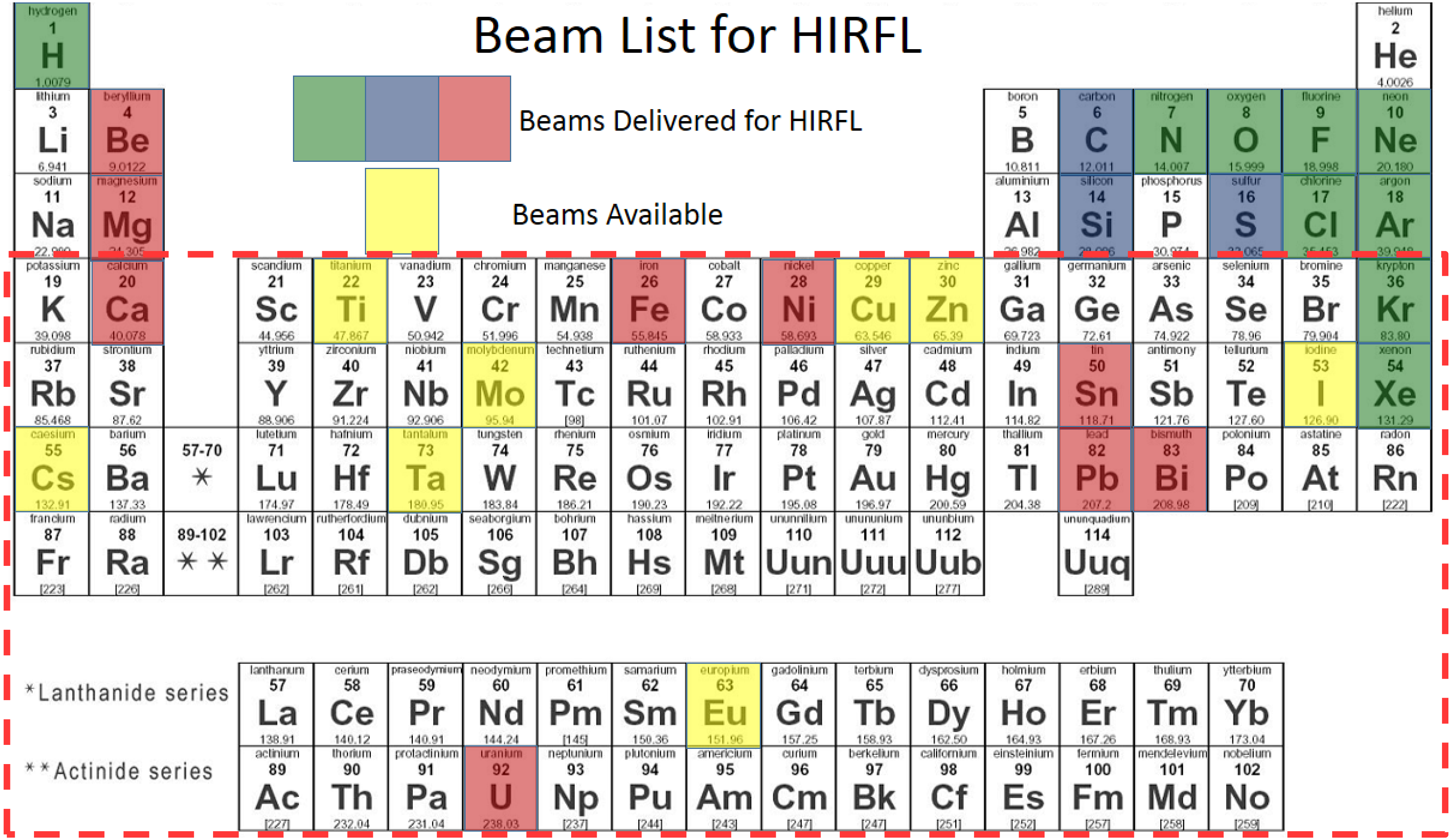
- 09. 2000 – Project approved.
- 04. 2002 – Magnet fabrication contract with ACCEL
- 08. 2005 – First Analyzed Beam at 18 GHz
- 2005~2006 – Commissioning at 18GHz, many record beam intensities were produced
- 05. 2007 – First operation beam to HIRFL accelerator
- 08. 2009 – First beam test at 24GHz
- 09. 2011 – first uranium beam delivered for HIRFL
- 11. 2011 – External LHe recycling system put into operation with SECRAL
- 06. 2014 – 680 eμA Bi^{31+} produced
- 05. 2015– 1420 eμA Ar^{12+} produced
- Up to Now → more than 20,700 hours for routine operation.

Development of a 3rd G. ECRIS

SECRAL beam current increasing with the technologies



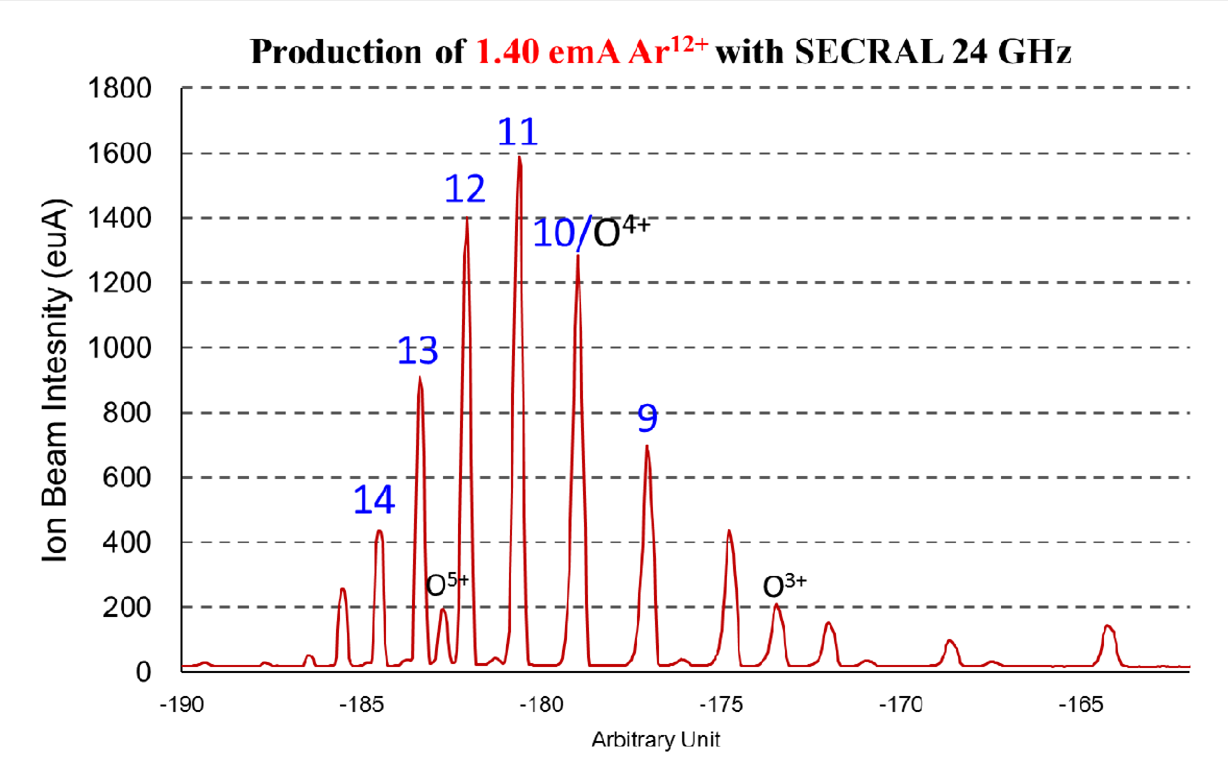
Development of a 3rd G. ECRIS



A< 40: LECR1, 2 & 3, A≥ 40: SECRAL

Development of a 3rd G. ECRIS

SECRAL@2015



Ion	Intensity (euA)
Ar^{11+}	1620
Ar^{12+}	1420
Ar^{13+}	930
Ar^{14+}	846
Ar^{16+}	350
Ar^{17+}	50
Xe^{26+}	1100
Xe^{27+}	920
Xe^{30+}	322
Xe^{34+}	90

Challenges to Develop a 4th G. ECRIS

Challenges to Develop a 4th G. ECRIS

- Reliable SC-magnet running at optimum fields for 4th G.
- Effective coupling to the plasma of 10-20 kW/40-60GHz microwave power
- Strong ECR plasma bremsstrahlung radiation problems
  - Heat sink in cryostat
  - HV insulator degradation
- Intense high charge state ion beam (20-40emA) extraction and transmission and beam quality control
- Ion beam quality and stability from the ion source working at 10-20 kW/50-60 GHz is unknown
- Intense metallic beam production, especially ion beams of refractory materials

Challenges: SC-Magnet

4^{th} G. ECRIS Goal

- >1.0 emA very heavy ion beam, Bi^{31+}, U^{34+}…

Ion	Ar^{12+}	Xe^{27+}	Bi^{31+}	U^{34+}
18 GHz	735	380	270	180
24/28 GHz	1460	920	680	400
Gain factor	2	2.4	2.5	2.2

Contributions from: SECRAL, VENUS and SuSI

$$I^q \ \alpha \ \omega^2_{ECR}, \ G_q \sim (28/18)^2 = 2.4$$

→ 45 GHz~ G_q=2.6: 1.0 emA U^{34+}(2.0 emA with Afterglow)

Why not 56 GHz?

Pros: potential Beam intensity gain by a factor of 1.5

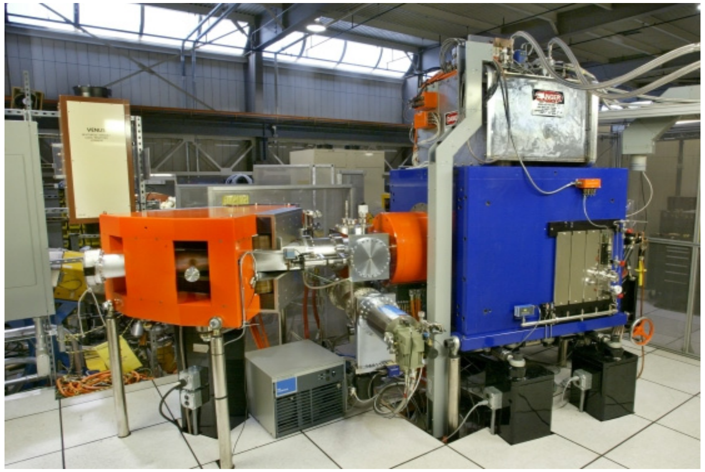
Cons:

- Highest Field ~15 T (limit of Nb_3Sn Tech.)
- Lorentz Force by a factor of 1.5 (longer sextupole)
- Engineering cost and risk > a factor of 1.5?

General Parameters of A 45 GHz ECRIS

Specs	Unit	State of the Art ECRIS	45 GHz ECRIS
frequency	GHz	24~28	45
B_{ECR}	T	1	1.6
B_{rad}	T	2	>3.2
B_{inj}	T	3.6~4	>6.4
B_{ext}	T	2~2.5	>3.4
Chamber ID	mm	100~150	150
Warmbore ID	mm	140~180	170
Mirror Length	mm	400~500	500

Challenges: SC-Magnet



VENUS

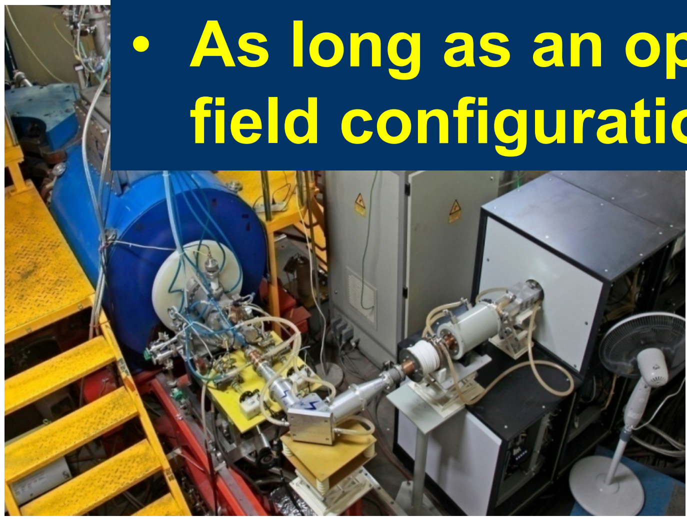
SECRAL

A Few Example Beams from SECRAL and VENUS

	Q	SECRAL *18 GHz* *<3.2 kW* *μA*	SECRAL 24GHz *3-4 kW* *μA*	VENUS *28 GHz* *5-9 kW* *μA*
16O	6+	2300		2860
	7+	810		850
40Ar	12+	510	650	860
	16+	73	149	270
	17+	8.5	14	36
129Xe	27+	306	455	270
	35+	16	64	28
	42+	1.5	3	0.5
209Bi	31+	150	242	310
	41+	22	50	15
	50+	1.5	4.3	5.3
238U	31+			460
	35+			311

As of 2012

Challenges: SC-Magnet



SECRAL

A Few Example Beams from SECRAL and VENUS

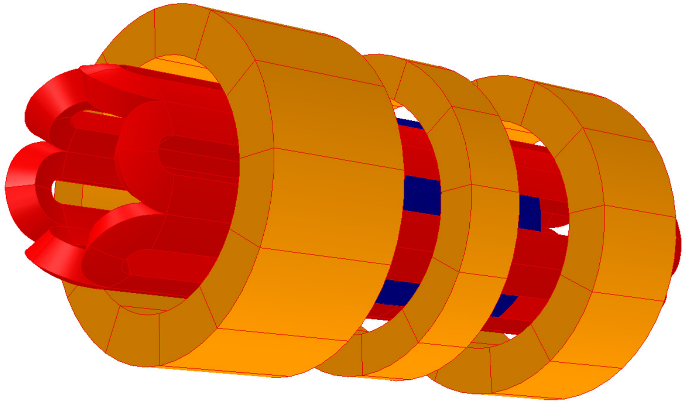
	Q	SECRAL *18 GHz* *<3.2 kW* *μA*	SECRAL 24GHz *3-4 kW* *μA*	VENUS *28 GHz* *5-9 kW* *μA*
16O	6+	2300		2860
				850
				860
				270
				36
				270
				28
	42+	1.5	3	0.5
209Bi	31+	150	242	310
	41+	22	50	15
	50+	1.5	4.3	5.3
238U	31+			460
	35+			311

- **ECR ion source is not picky on the magnet structure**
- **As long as an optimum nested min-B field configuration is created**

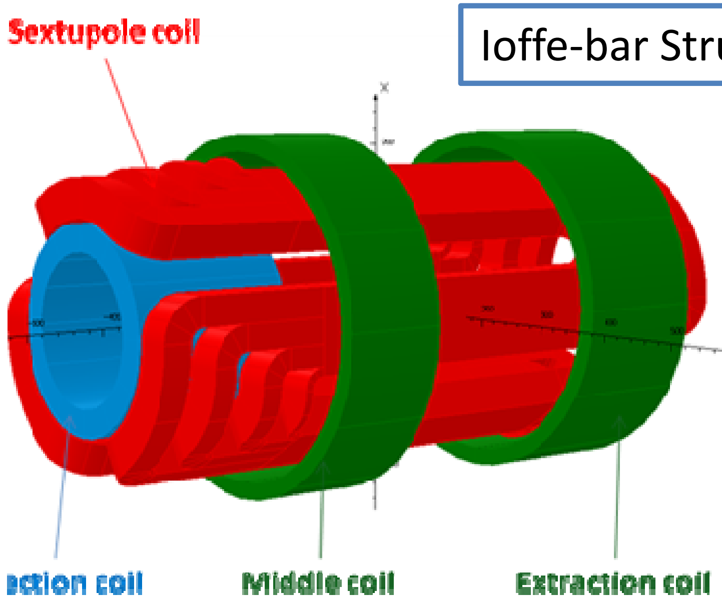
As of 2012

Challenges: SC-Magnet

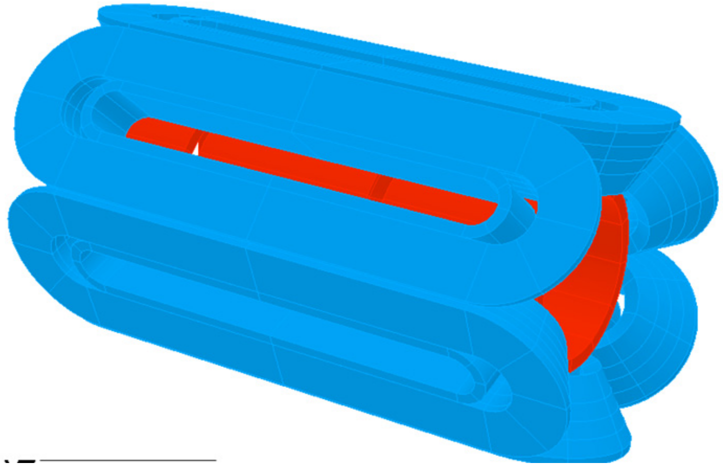
Conventional Structure: VENUS, SuSI, RIKEN-SCECRIS…



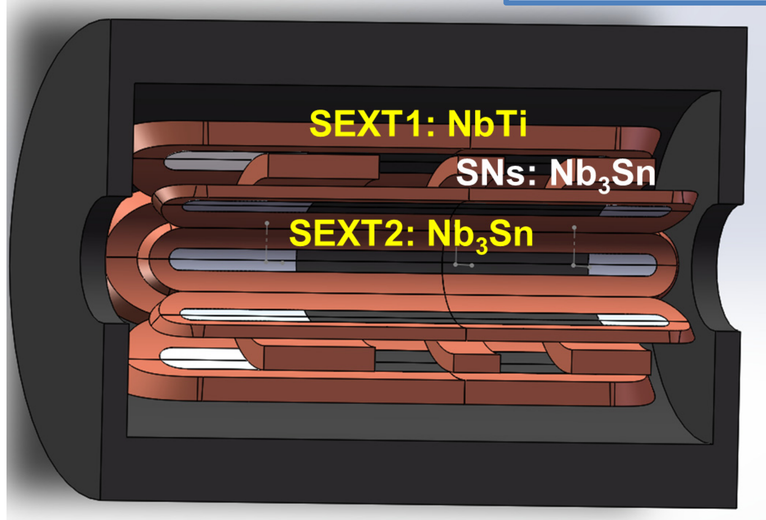
Ioffe-bar Structure



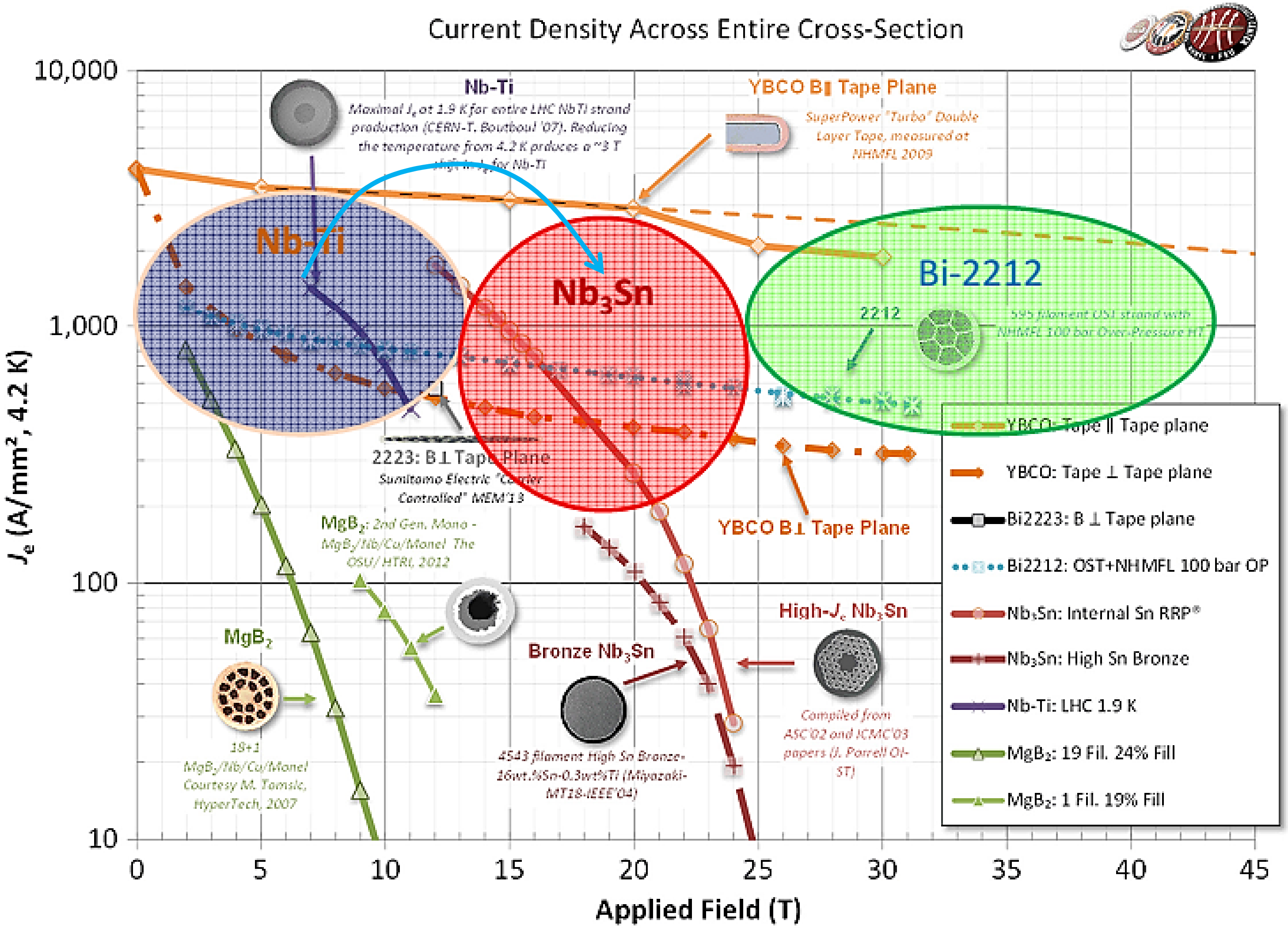
SECRAL Structure



Hybrid Structure



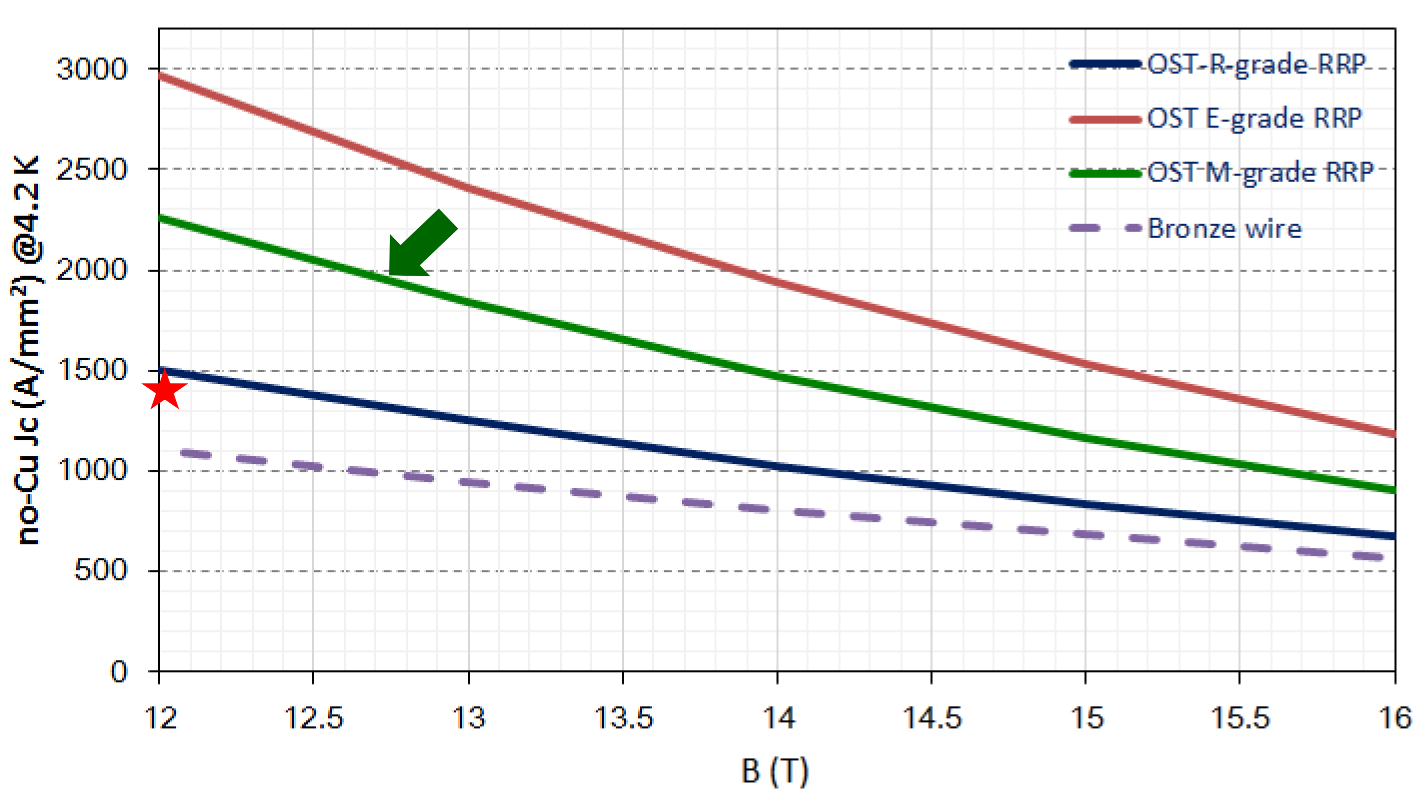
Challenges: SC-Wire



3rd G. : ~700 A/mm²@7 T

4th G. : 1400 A/mm²@12 T

Selection of SC-conductors



- **A 45 GHz ECRIS magnet designed at 12 T@1400 A/mm^2 to have ≤85% loading factor**
- **M-Grade RRP wire from OST gives more safety margin**

Challenges: SC-Wire

Wire

Pros:

- No extra cabling process
- Lower power supply currents (<1000 A)
- Simpler HTS current lead solution
- HV platform feasible
- Cost efficient

Cons:

- Sophisticated quench protection issues
  - ~1.7 MJ stored energy
  - Insulation limit 1000 V, T_{quench} rise ?
- Superconducting joints
- Higher failure risk

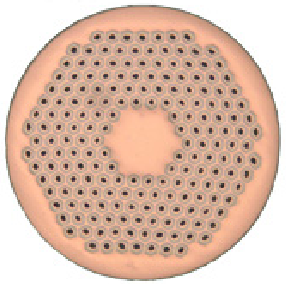
Cable

Pros:

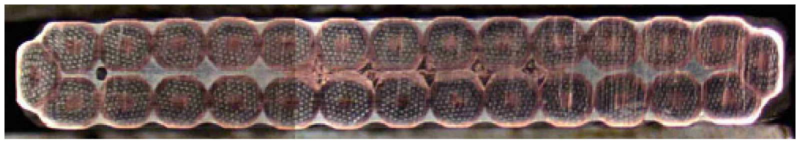
- Successful examples of Accelerator magnets
- Good reliability
- Easier quench protection sys.

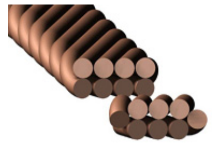
Cons:

- Not feasible for HV platform
  - 100~300 kV
  - 10 kA PSs on Platform
- Cryogenic solution ?
- Higher cost
- Performance degradation after cabling



OST RRP wire

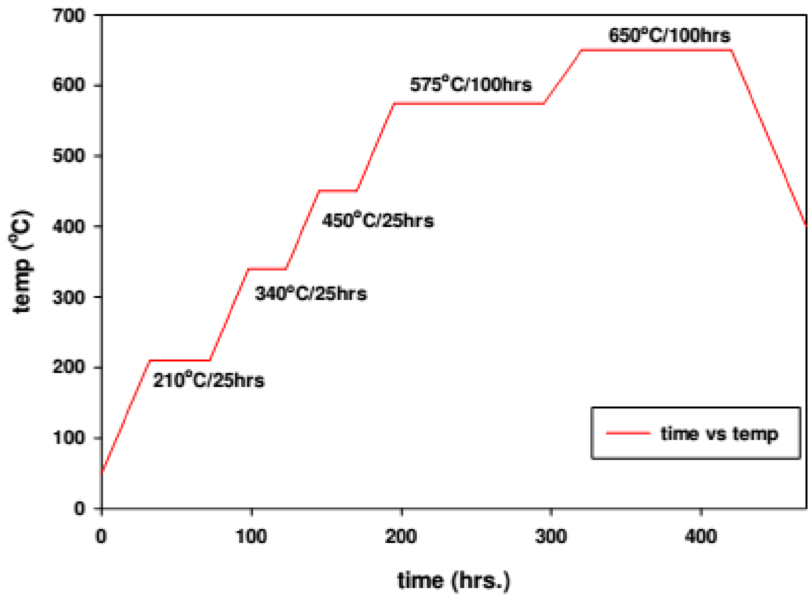




Rutherford Cable

Characteristics of Nb_3Sn Magnet

- Sophisticated and time consuming heat treatment sequence
- Performance is greatly heat treatment related
- Brittle
- Performance is strain sensitive
  - Mechanical stresses in windings
  - Magnet design
  - Reversible degradation >150 Mpa
  - Permanent degradation >200 MPa



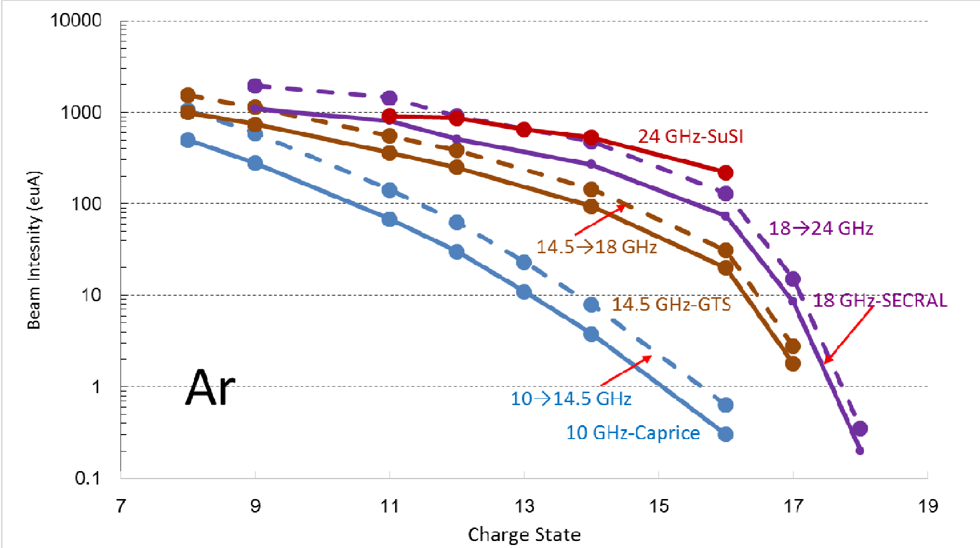
Example heat treatment sequence for ITER wire

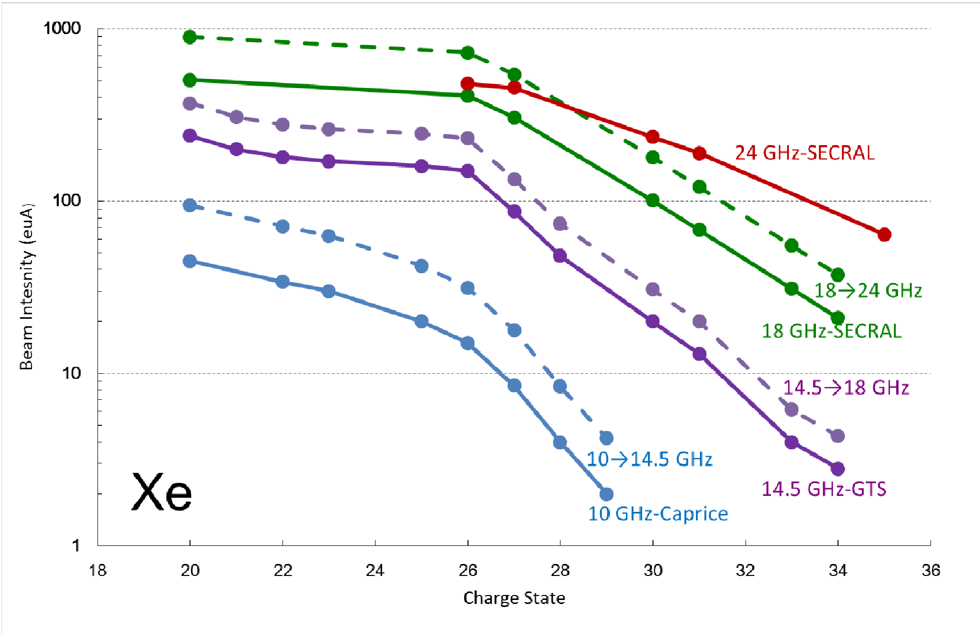
Challenges: Microwave Coupling

$$I_i^q = \frac{1}{2}\frac{n_i^q\, q\, e\, V_{ex}}{\tau_i^q}$$

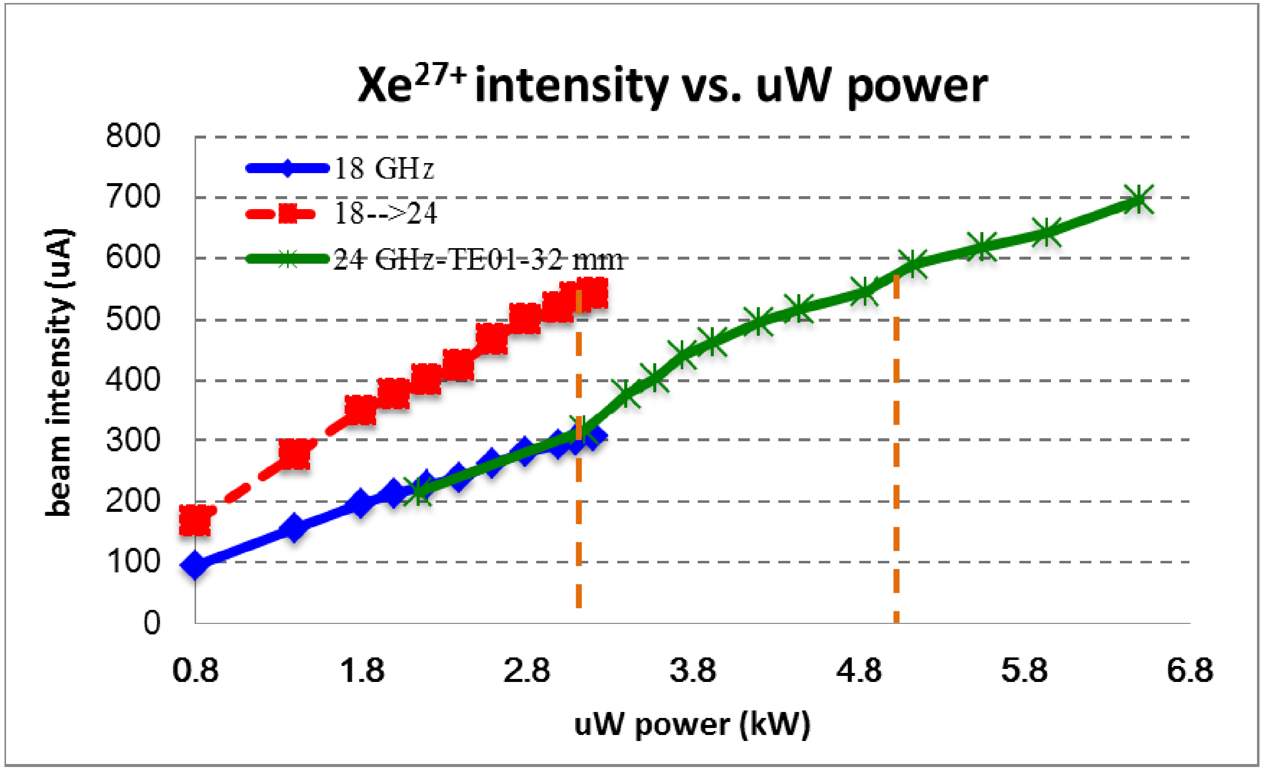
$n_i^q \sim \omega^2$, $V_{ex} \sim$ volume effect

- **10~18 GHz：ion source performance consistent with scaling laws:**
  - ✓ **ω^2 scaling**
  - ✓ **Extra gain from plasma volume effect & high P_{rf} at 18 GHz**
- **24/28 GHz generates better performance than 18 GHz:**
  - ✓ **Much Higher P_{rf}**
  - ✓ **Frequency effect for higher Q**
- **Gyrotron frequency is not working as efficient as Klystron frequency:**
  - ☐ **Empirical scaling laws applicable still?**
  - ☐ **μW coupling issue?**





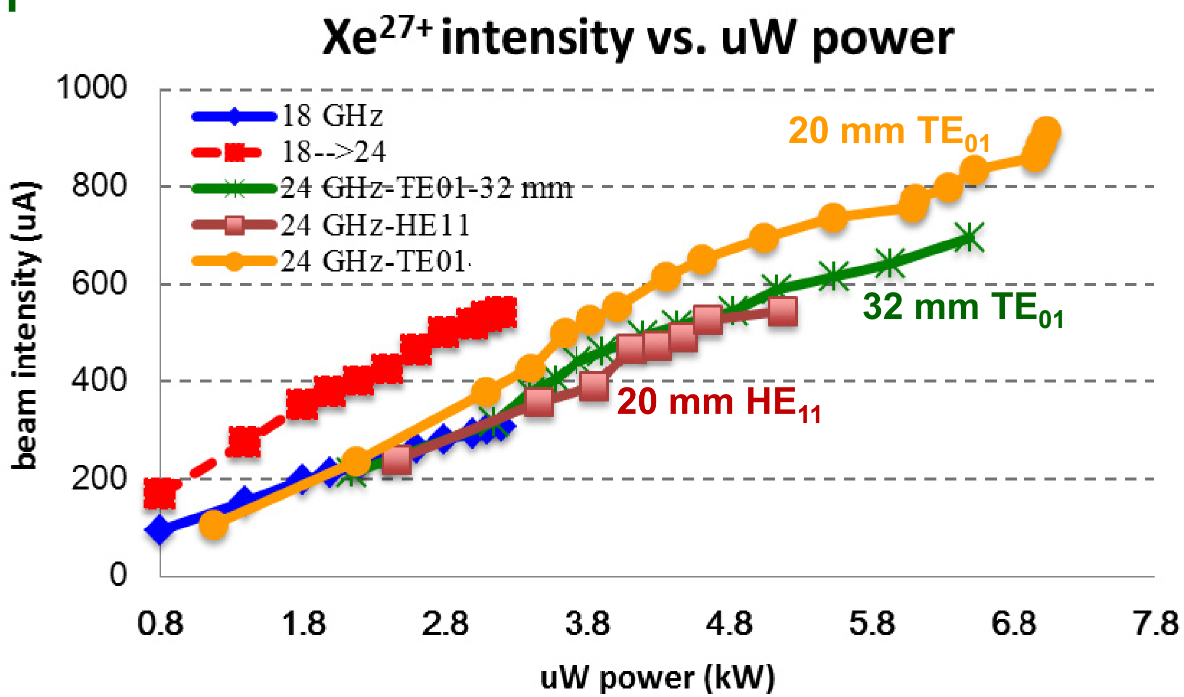
Challenges: Microwave Coupling



- 5.0 kW@24 GHz TE_{01} to get the extrapolated results from 18 GHz expected at 3.0 kW
- A coupling efficiency of <60% compared to 18 GHz?

Challenges: Microwave Coupling

- **Ø20 mmTE$_{01}$ show obvious advantage in HCI production at high power level**
- **Power efficiency is further improved with new Waveguide design**
- **Better understanding towards optimum μW coupling is essential so as to avoid:**
  - → **Weak higher frequency effect**
  - → **Higher power is needed which means reinforced cooling and more 4.2 K heat load mitigation**



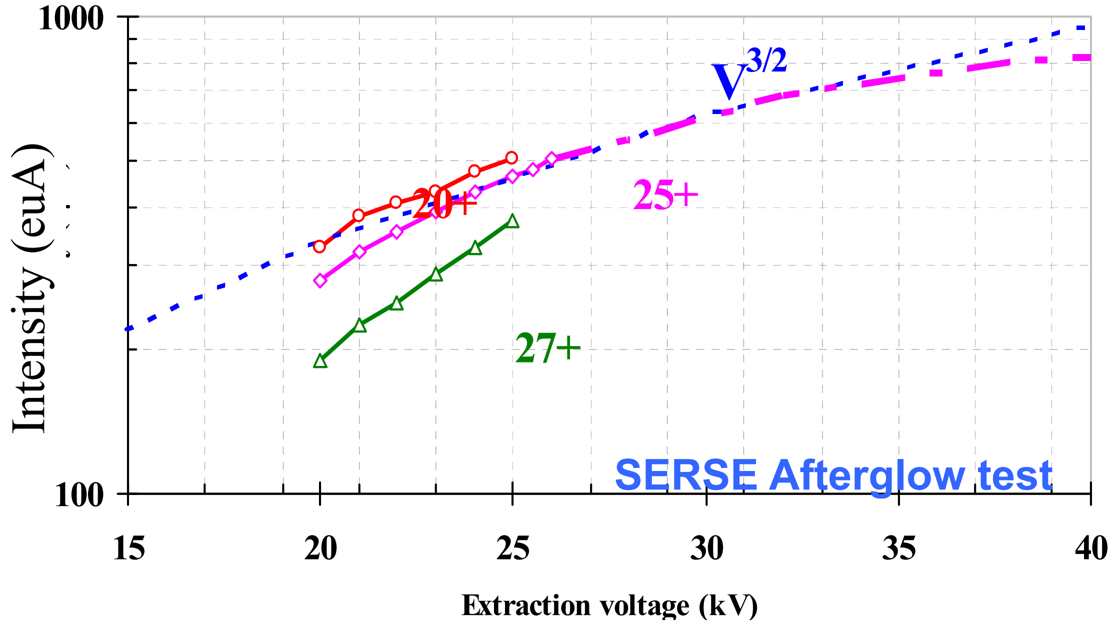
Recent progress on μW coupling understanding

Challenges: Intense beam extraction

Child-Langmuir Law:

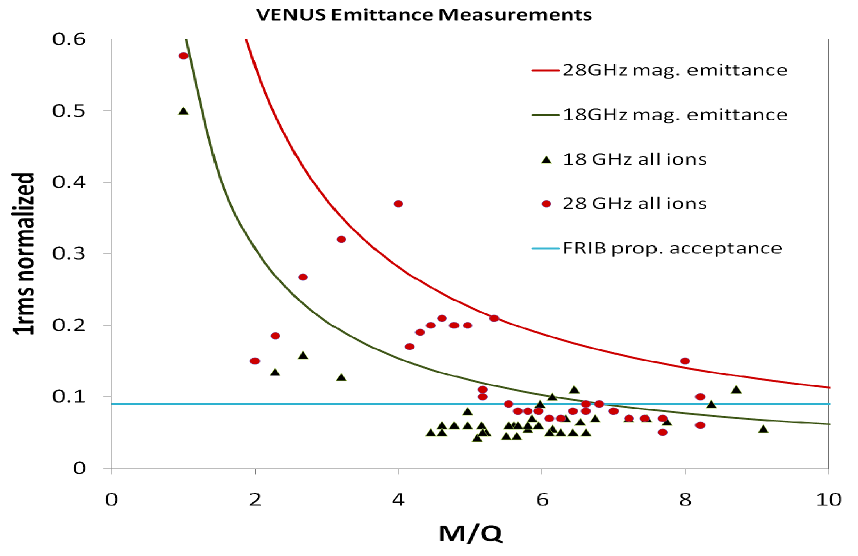
$$j = \frac{4}{9}\varepsilon_0\left(\frac{2q}{m_i}\right)^{0.5} U^{1.5}/d^2$$

- When more ions produced, higher extraction voltage is desired, i.e. >30 kV



$$\varepsilon_{ecr} \propto r_i \cdot B_{ext} \cdot \sqrt{Q_i/M_i}$$

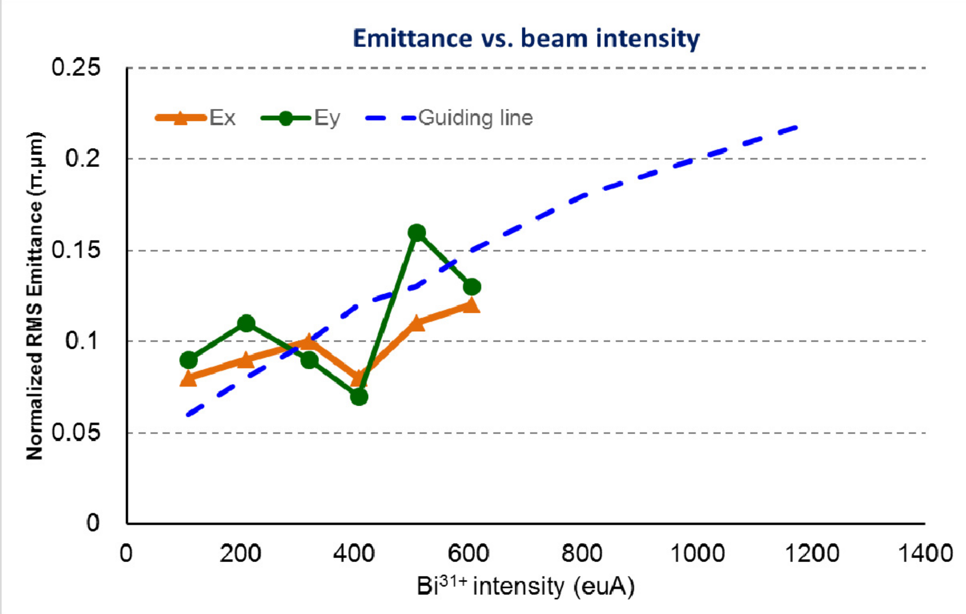
- Applicable for medium charge ions
- Very highly charged ions intrinsically features lower ε
- SPC may have stronger impact



Challenges: Intense Beam Transmission

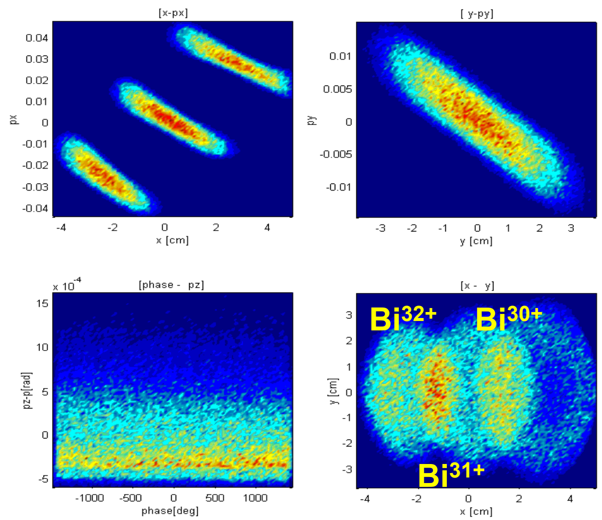
Increased beam intensity:

- ~20 emA mixing beams and ~1.0 emA analyzed beam
- SPC results in higher beam envelope → bigger gap dipole
- Unwanted beams
  - ☐ Better pumping to improve vacuum
  - ☐ Watered cooling at beam loss region



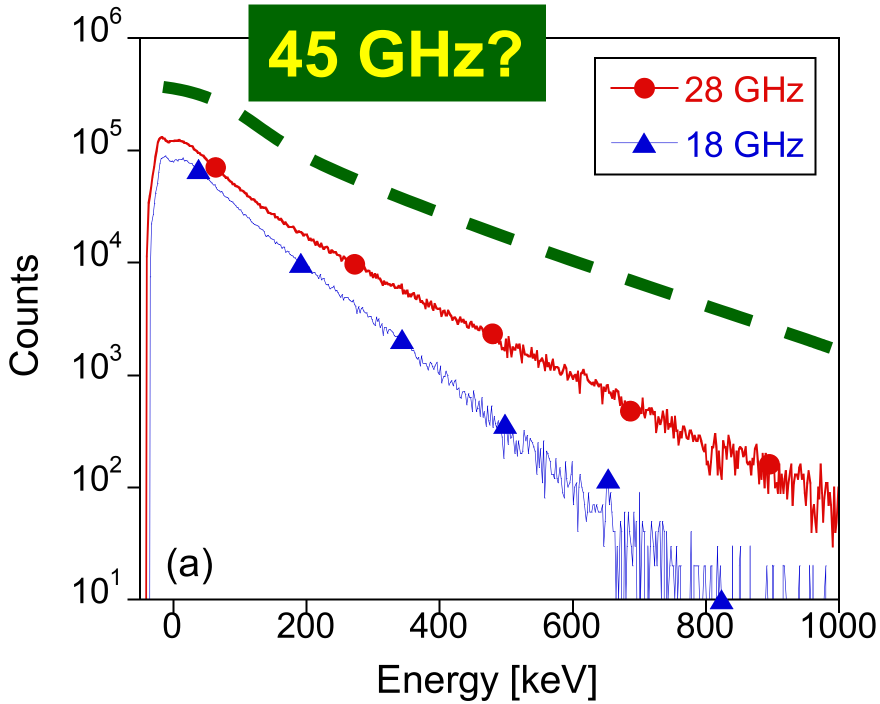
Beam quality control:

- Avoid higher order aberration
- Space charge compensation
- SPC effect results in mass resolution degradation of the M/Q analyzing system
- Transverse decoupling solution

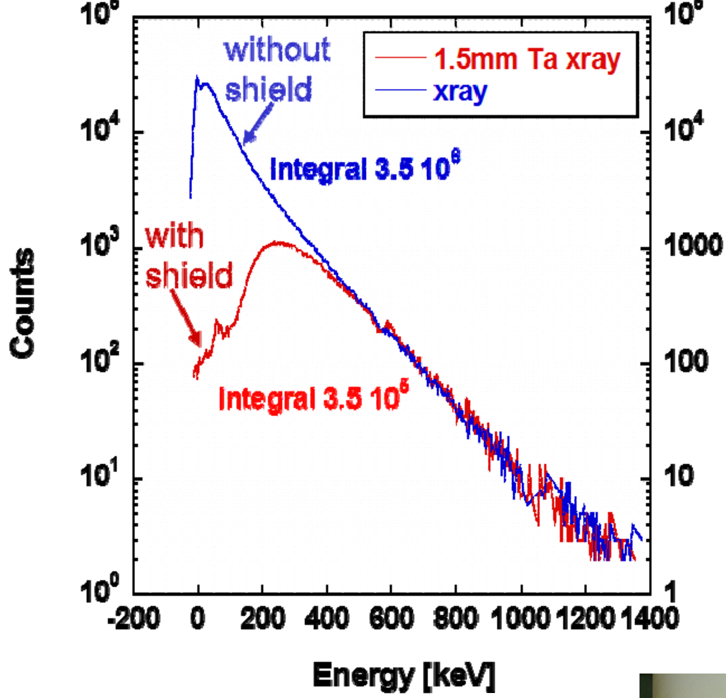


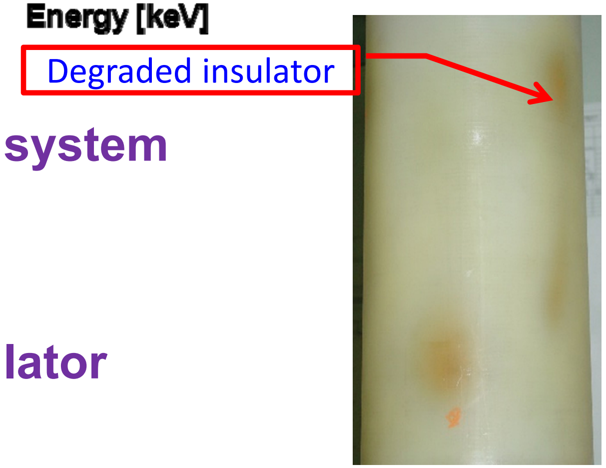
SPC caused degradation of M/Q resolution

Challenges: Bremsstrahlung Radiation and Cryogenics



D. Leitner@FRIB Ion Source Review 2009

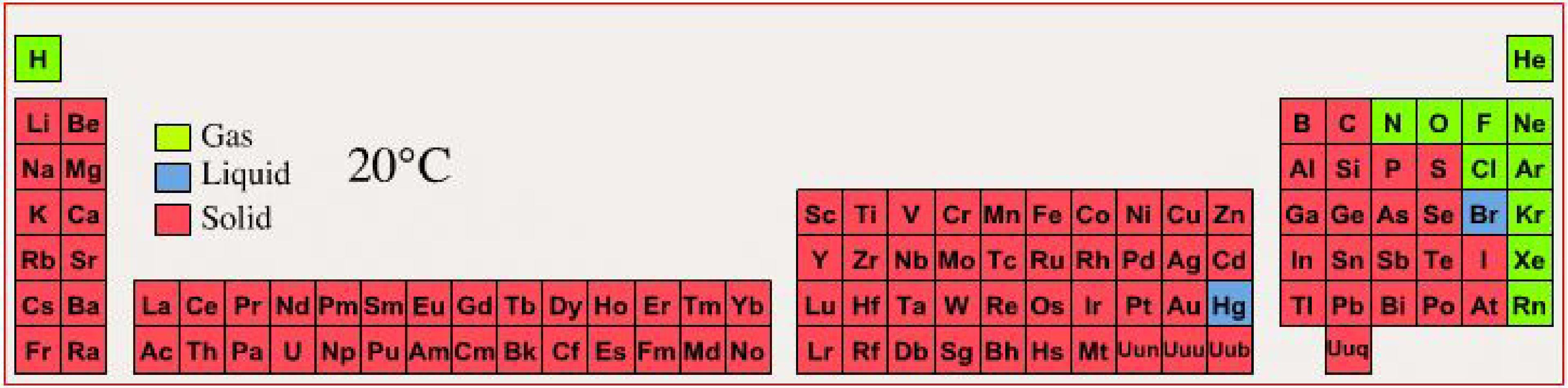


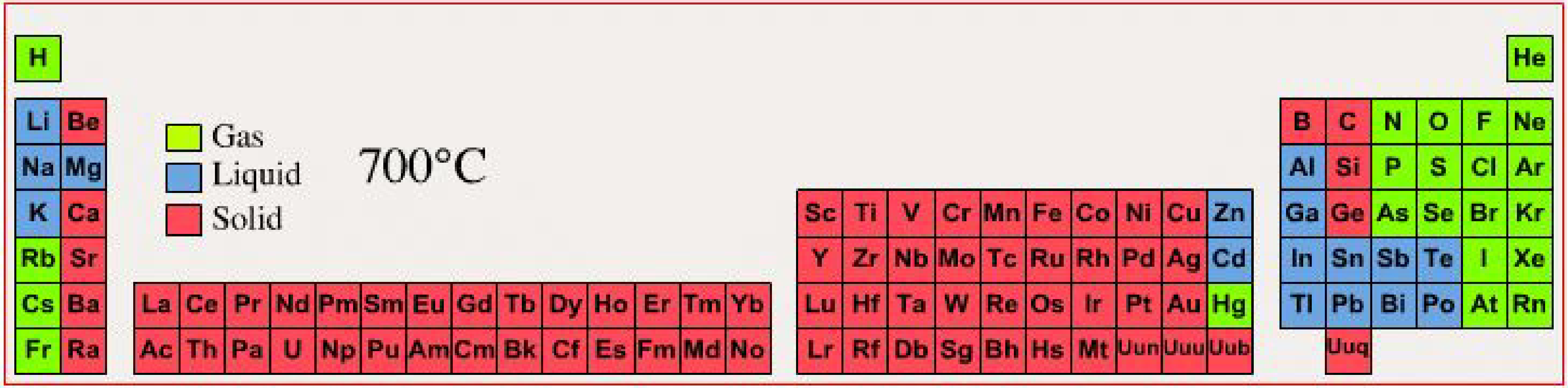


Higher X-ray flux and higher X-ray energies:

- **Higher 4.2 K cooling capacity or LHe refilling system**
- **Main insulator life span**
  - * **Heavy metal shielding can work, thickness?**
  - * **How fast insulator material degrades?**
- **Will superconducting magnet epoxy and insulator material be affected?**

Challenges: Metallic Beam Production





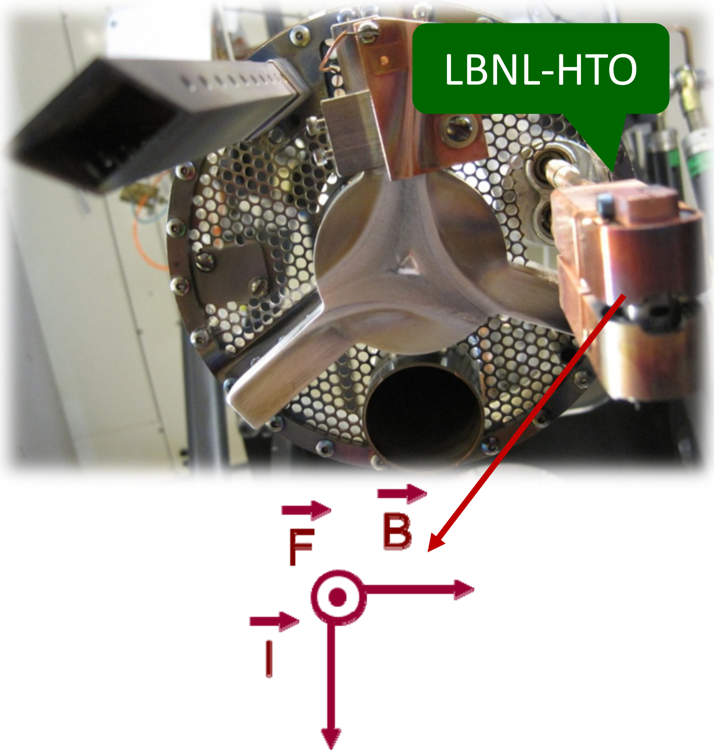
For mA metallic beams, oven is the only solution

- <700℃--LTO
- <1500 ℃--RHO
- <2200 ℃--HTO

Challenges: Metallic Beam Production

For emA U^{34+} beam production:

- Stronger Lawrence force because of higher B field
  - Forces increased 4th G./3rd G. = 45/28 ~1.6
- Higher temperature to get more vapor
- Will LBNL-HTO survive?
- Alternative solution is desired



For low melting point metals:

- Large capacity oven
  - 400 euA Bi^{31+}~11 mg/hr→1 emA Bi^{31+}~27.5 mg/hr→4.6 g/week
- Plasma chamber contamination after beam time

Long term operation stability of the ovens

Destroyed oven by Lawrence Forces

Summary

3rd G. ECRISs are still moving towards their peak performance, and dispensable for the corresponding facilities;

What a 4th G. ECRIS look like?

She is a "GIRL"

Acknowledgement

Ion Source Group:
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Accelerator Physics Group:
Y. J. Yuan

Thanks for your attention

谢谢！

HPPA Mini-workshop 2015

October 13-15, 2015, IMP, Lanzhou, China

Topics:

✧Status reports and new developments of high power proton and heavy ion linac accelerators.

✧Beam dynamics

✧RFQ accelerator

✧SRF and superconducting linac, and related topics such as cavity processing, rf coupler, frequency tuning and so on

✧LLRF, control system and machine protection

✧Beam diagnostics

✧Proton and heavy ion sources

✧RF power source for proton and heavy ion linac

✧Some other topics related to proton and heavy ion linac