EVOLUTION OF ELECTRON CYCLOTRON RESONANCE ION SOURCES

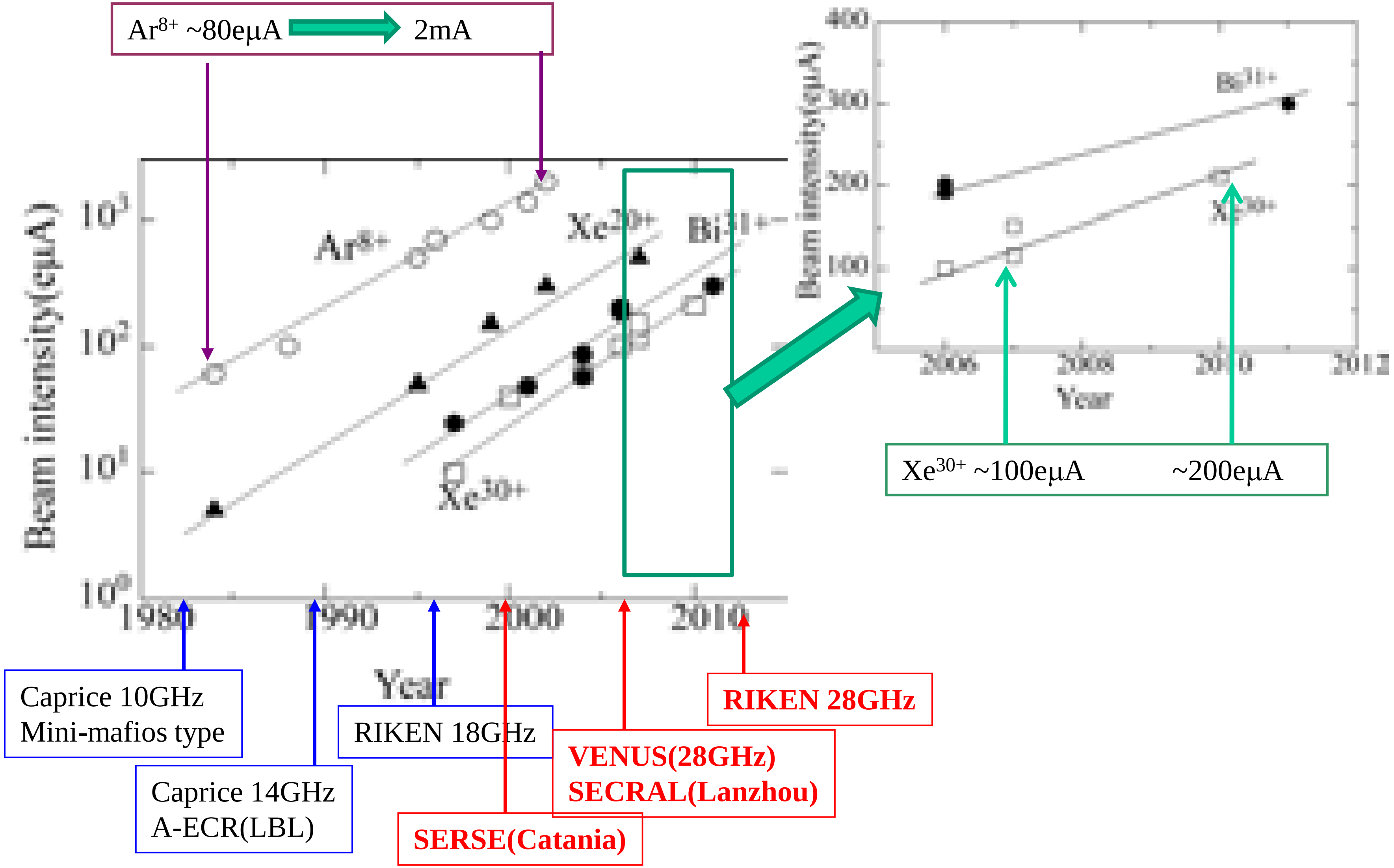
Luigi Celona

Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud
Via S.Sofia 64
95123 Catania, ITALY

E-mail: celona@lns.infn.it

Contents

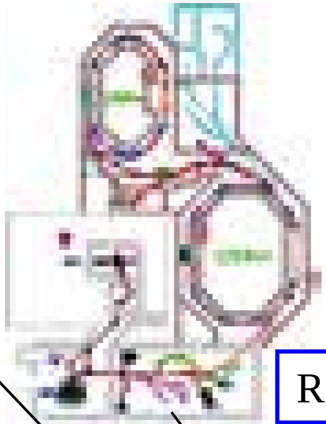
Time evolution of the beam intensity



Heavy ion accelerator facility

GSI (Germany)

Lanzhou (China)

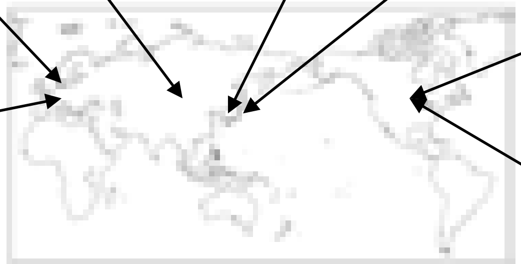


RIKEN RIBF (Japan)

MSU (USA)

SPIRAL II (France)

RIBF (South Korea)

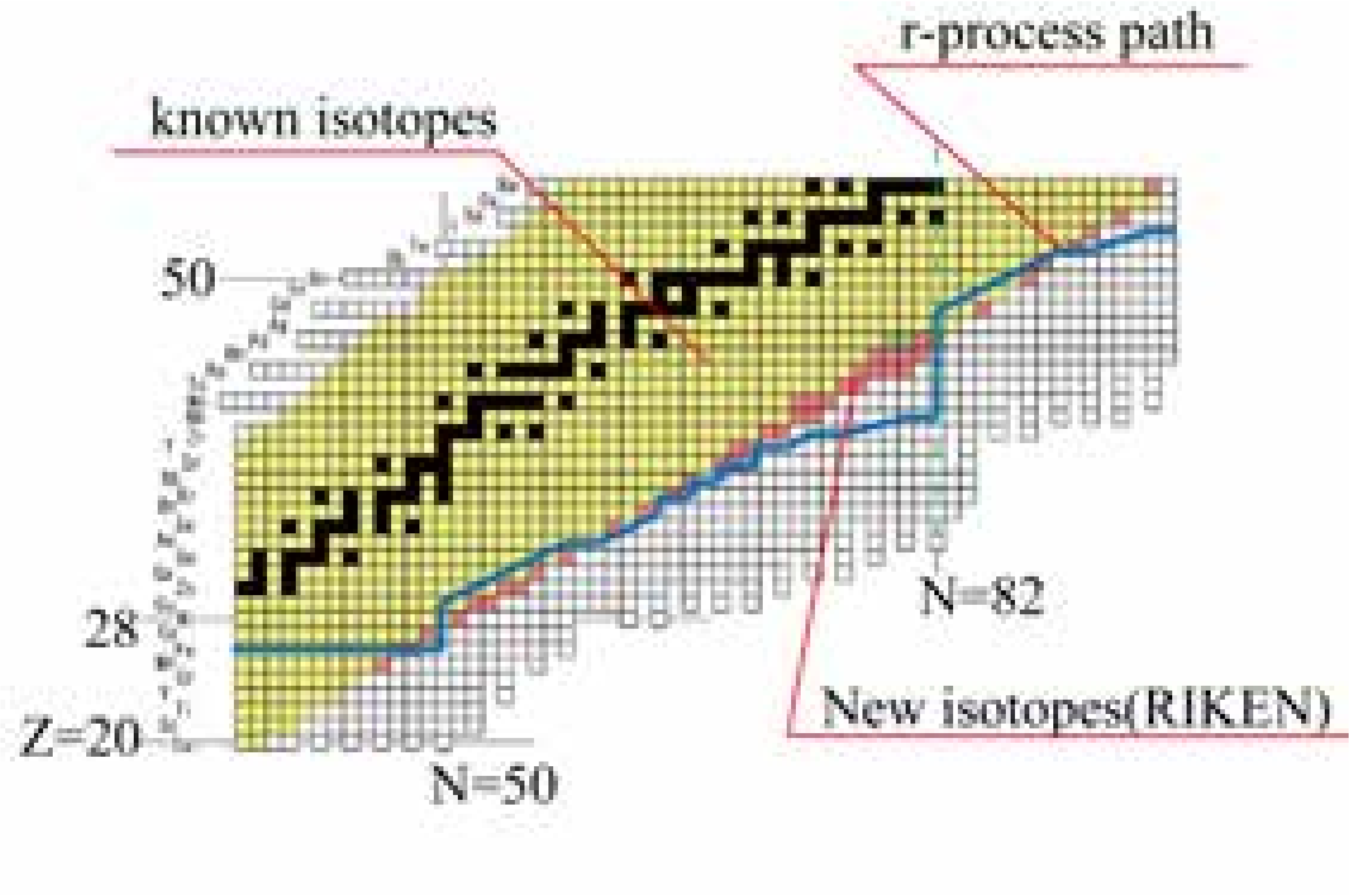


FRIB (USA)

Require intense beam of highly charged heavy ions

~15pμA of U^{35+}, 1mA of Ar^{12+}

RIKEN new isotopes



U beam intensity (~0.8pnA) 345MeV/u

S. Nishimura et al, PRL. 106(2011)052502

State of art of ECR ion sources

1. Introduction

2. Main parameters of the traps for production of highly charged heavy ions

Geller's scaling laws
High B mode concept
Experimental evidences
Frequency tuning

3. Technology of SC-ECR ion sources

4. Directions to future

Magnetic system and frequency role

- *1987* **Geller's scaling laws:**

$$I \propto \omega^2 M^{-1} \qquad q_{opt} \propto \log(B^{1.5})$$

- ***1990 High B-mode concept***

  14GHz, 18 GHz, 28GHz confirmations

$$\frac{B_{max}}{B_{ECR}} > 2$$

- ***2000 Ecris standard model***

$$\begin{cases} B_{inj} \approx 3\, B_{ECR} & \text{or more if possible} \\ B_{rad} \geq 2\, B_{ECR} & \text{(on plasma chamber wall)} \\ B_{ext} \approx B_{rad} & \text{competitive process...} \end{cases}$$

18 GHz

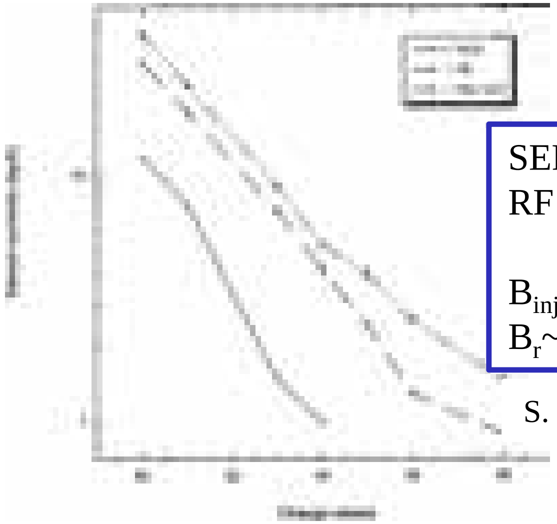
$$\begin{cases} B_{ECR} = 6361\, G \\ B_{inj} \geq 1.9\, T \\ B_{rad} \geq 1.3\, T \\ B_{ext} \geq 1.3\, T \end{cases}$$

28 GHz

$$\begin{cases} B_{ECR} = 9896\, G \\ B_{inj} \geq 3\, T \\ B_{rad} \geq 2\, T \\ B_{ext} \geq 2\, T \end{cases}$$

Use of SC or HTS coils is mandatory for last generation ECRIS

Frequency scaling

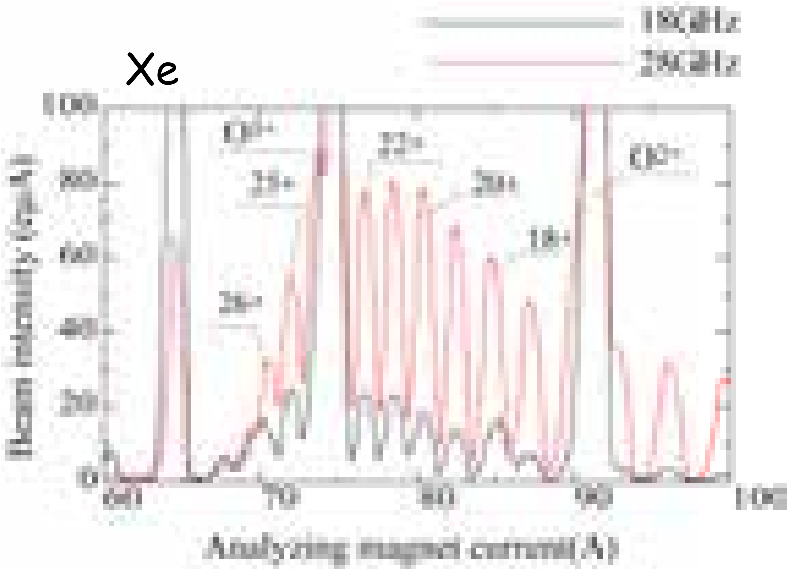


SERSE
RF power 1.8kW

B_{inj}~3.5B_{ecr},B_{min}~0.8B_{ecr},B_{ext}~2B_{ecr}
B_r~2B_{ecr}

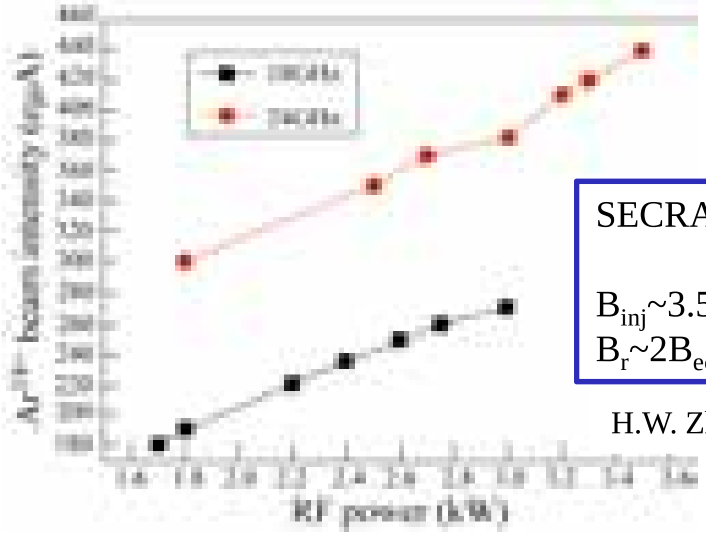
S. Gammino, RSI., Vol. 70, 1999,3577

Xe



	B_{inj}	B_{min}	B_{ext}	B_r	
28GHz	3.15	0.62	1.83	1.86T	
18GHz	2.1	0.4	1.18	1.2T	(18/28)

Y. Higurashi et al, RSI 83(2012)02A333

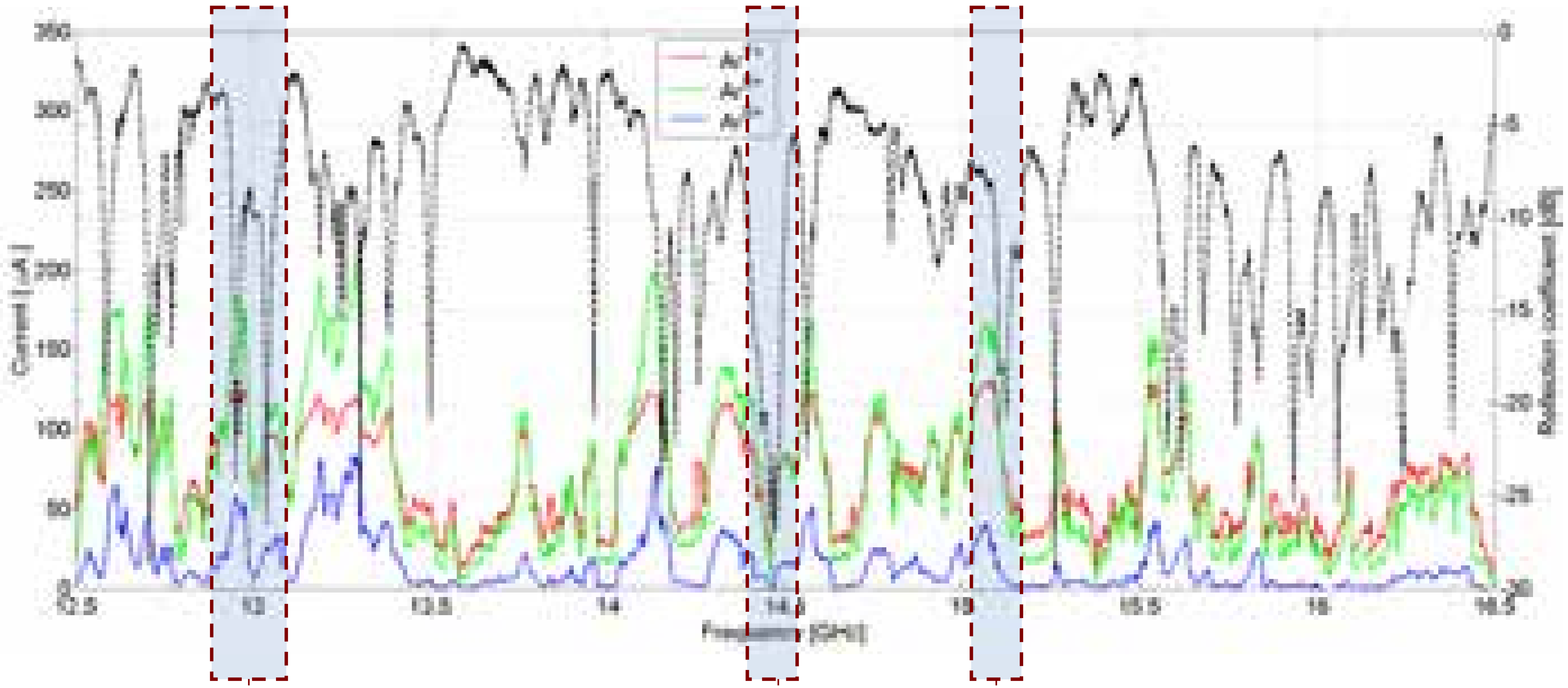


SECRAL

B_{inj}~3.5B_{ecr},B_{min}~0.8B_{ecr},B_{ext}~2B_{ecr}
B_r~2B_{ecr}

H.W. Zhao et al, RSI 81(2010)02A202

Frequency tuning



Minima of reflection coefficient are cavity modes.

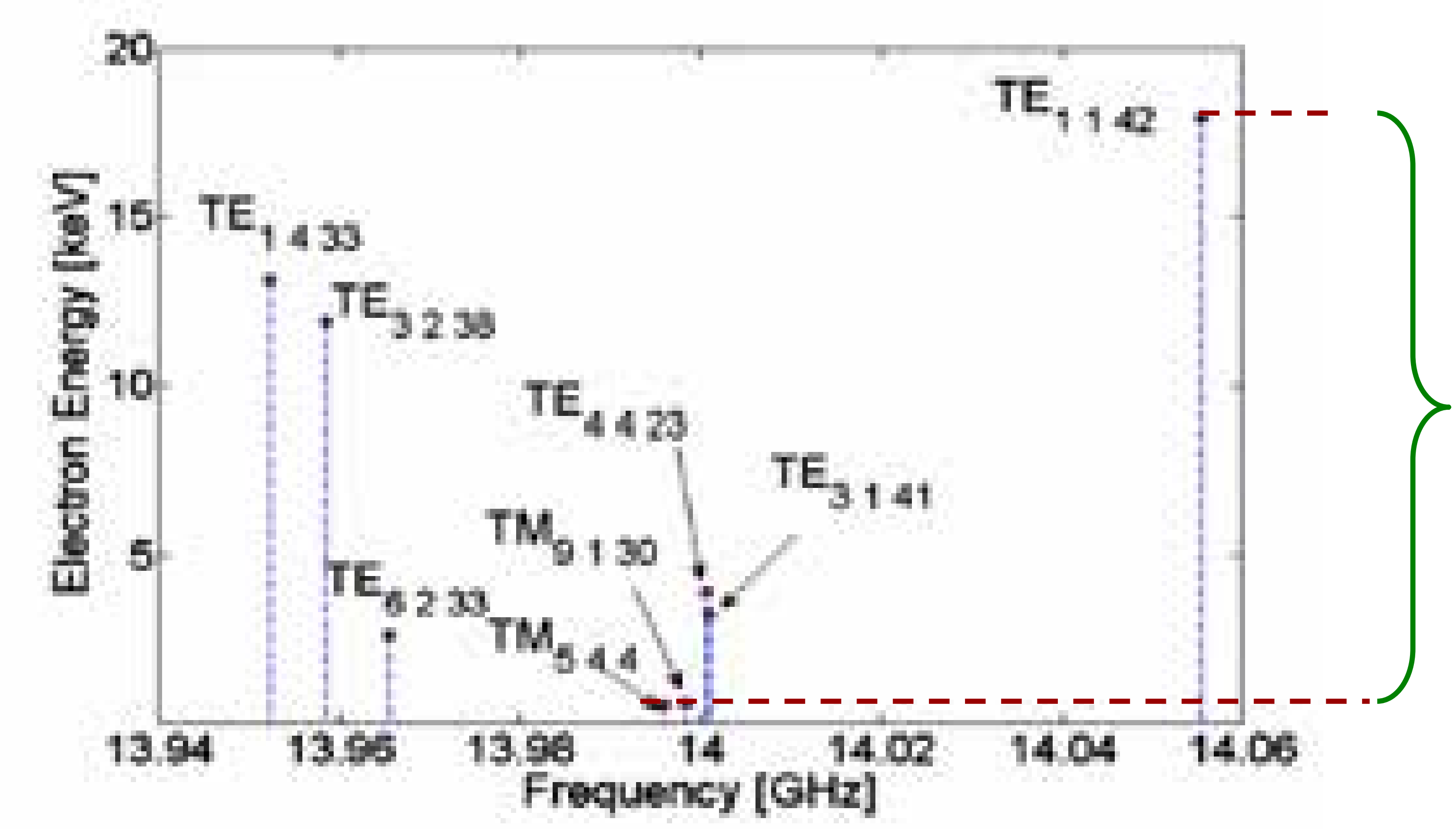
Often to resonant modes correspond current's peaks

But...
it is not a rule!

Some freq. are coupled with cavity but they do not match properly with plasma!!!

L. Celona ,REVIEW OF SCIENTIFIC INSTRUMENTS **81, 02A333 2010**

Frequency tuning

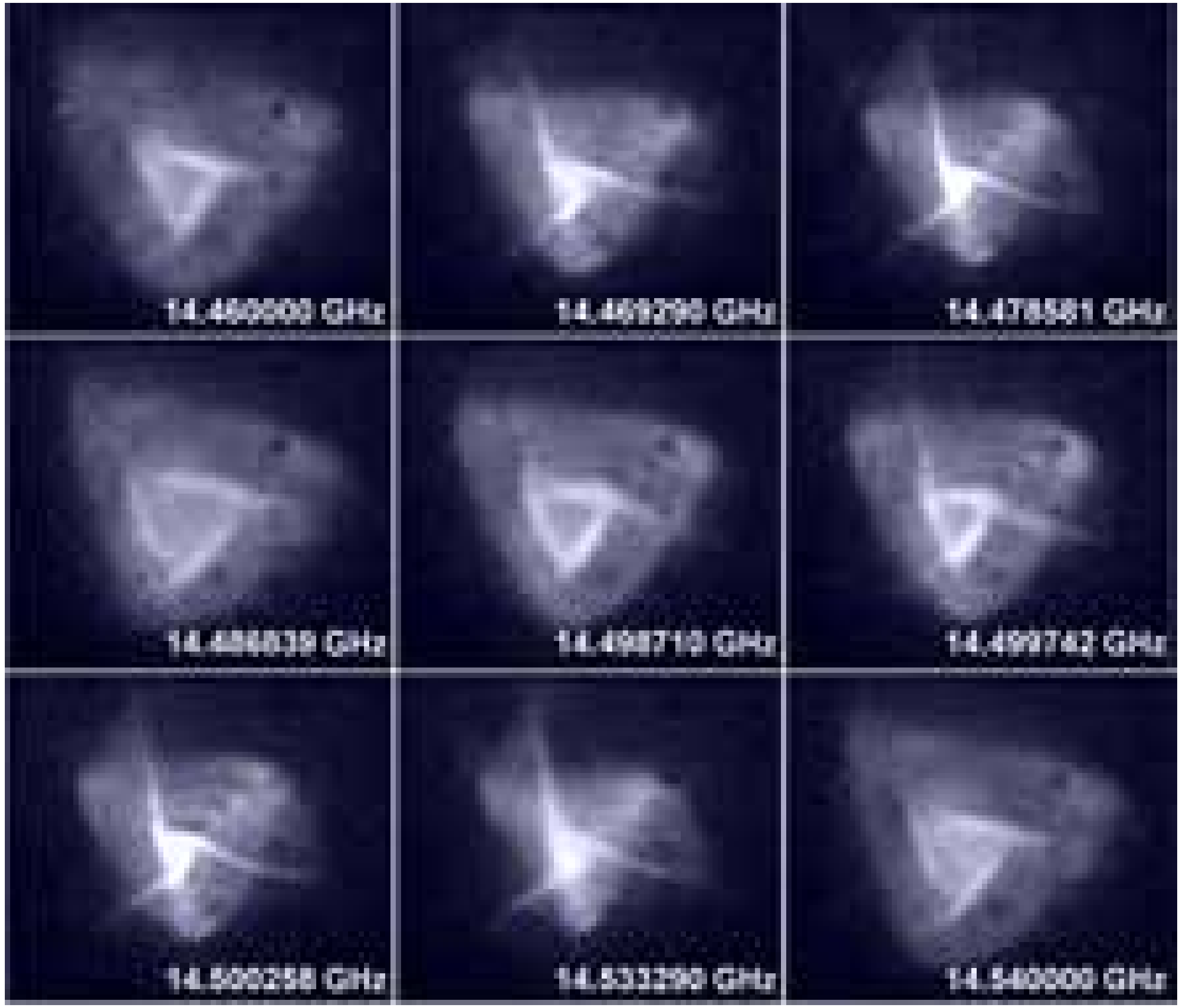


Strong fluctuations of heating rapidity for different excited modes inside the plasma chamber

F. Consoli, L. Celona, G. Ciavola, S. Gammino, F. Maimone, S. Barbarino, R.S. Catalano, D. Mascali, Rev. Sci. Instrum., 79, 02A308 (2008).

Frequency tuning

Viewer located 25 cm far from the extraction electrode without any focusing element in between.



L. Celona et al., REV. SCI. INSTRUM. **79, 023305, 2008**

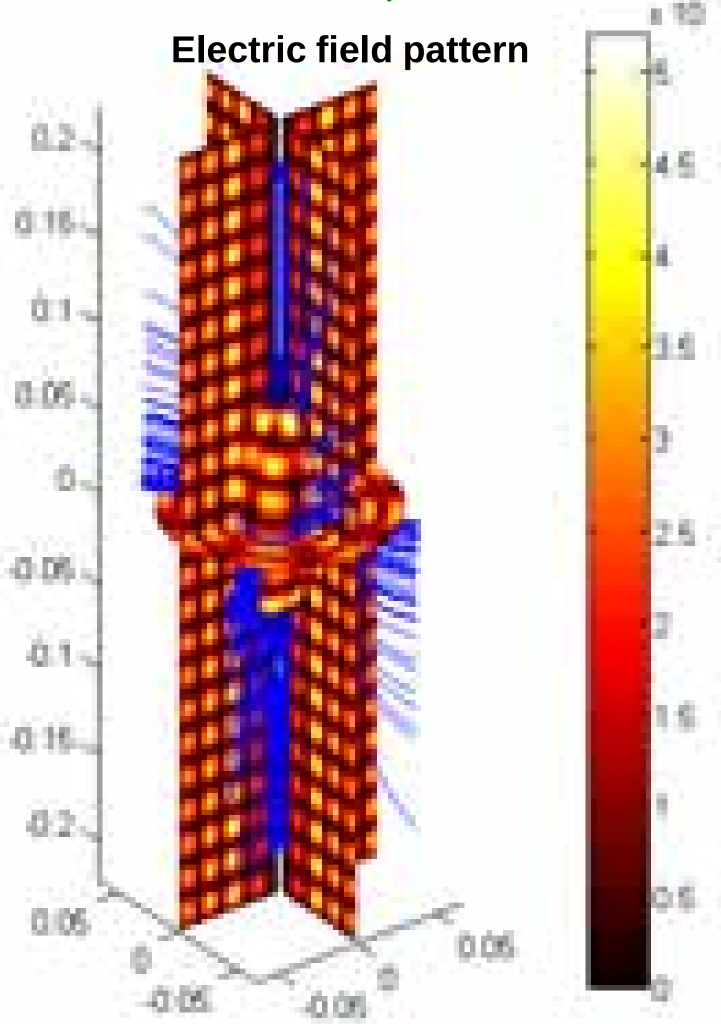
He GAS
Freq sweep: 14.5 GHz±40 MHz
Sweep Time: 150 sec (x10)

500 W MICROWAVE POWER
INJECTION PRESSURE OF
$4.3\cdot10^{-6}$ mbar

Electron and Ion dynamics

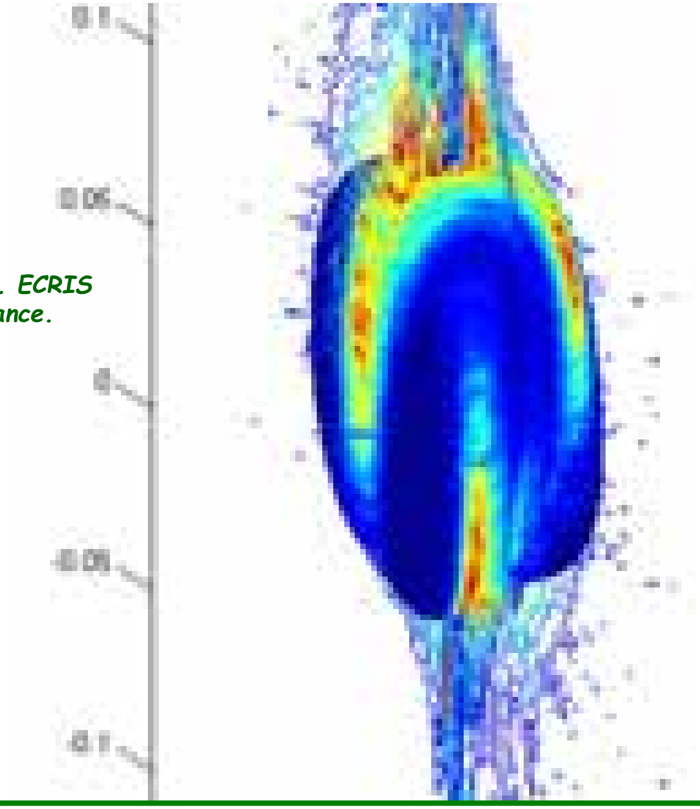
The pattern of the electromagnetic field
influences also the plasma density distribution

Electric field pattern



D. Mascali et al., Proc. ECRIS 2010, Grenoble, France.

Plasma density distribution in proximity of ECR surface



NOTE that the plasma is almost completely confined inside the resonance surface

State of art of ECR ion sources

1. Introduction

2. Physics of ECR plasma for production of highly charged heavy ions

3. Technology of SC-ECR ion source

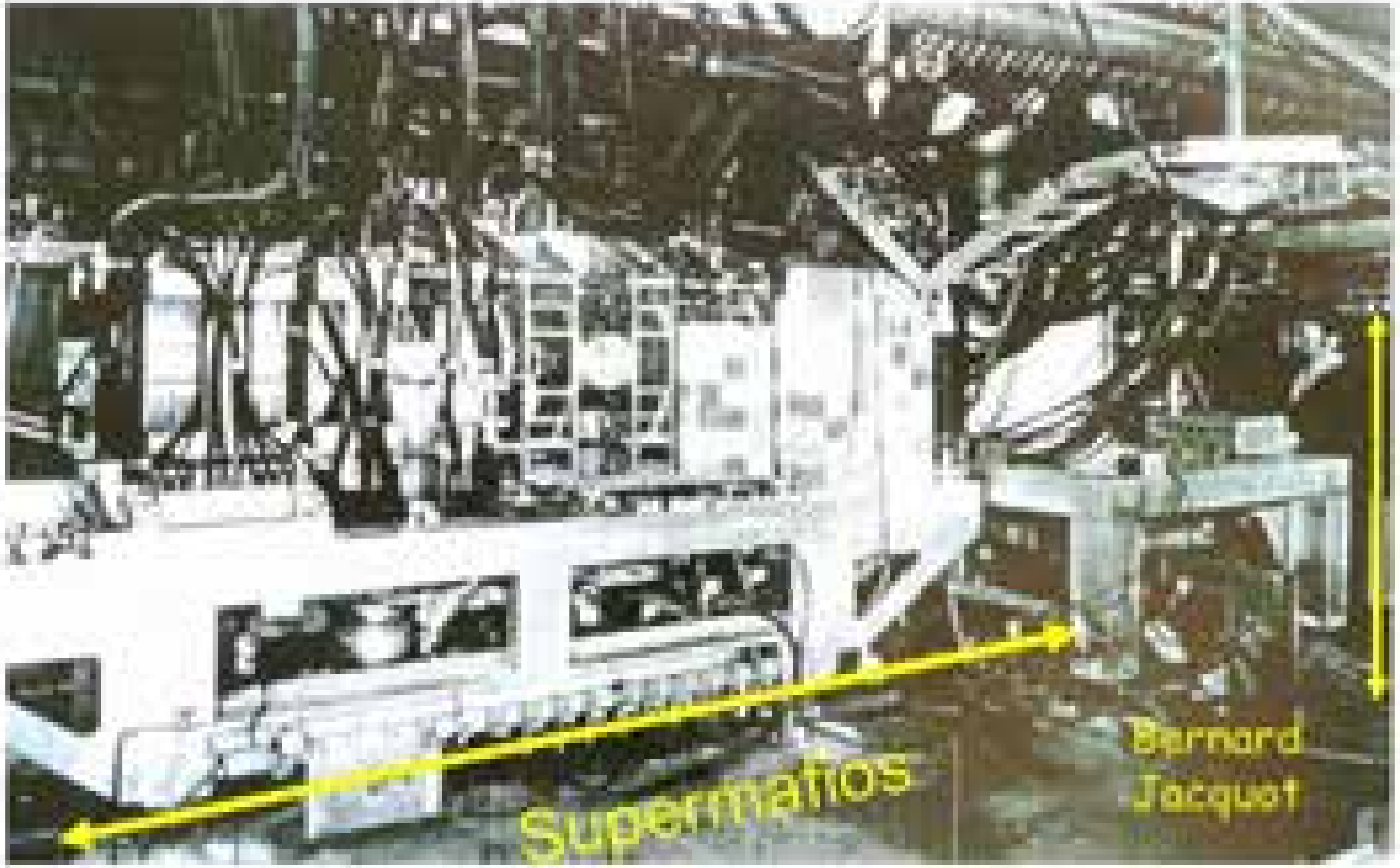
High performance SC-ECRIS
X-ray heat load
SC-Coils

4. Directions to Future

Pioneeristic work

The First Multicharged ECR Ion Source : SUPERMAFIOS 1975

- Invented at CEA Grenoble by R. Geller



R. Geller

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

Pioneeristic work

- SUPERMAFIOS, a Two Stage ECR Ion Source
  - The first ECRIS were very long (≥ 1m) and featured a complicated two stage ECR plasma
  - Stage 1: high frequency, high pressure plasma in an axi-symetric magnetic field to pre-ionize the atoms
  - Plasma diffusion between stage 1 and stage 2 in a magnetic gradient
  - Stage 2: main plasma heated at a lower frequency but in a large volume chamber equipped with a min-B structure (Iofee bar hexapole + axial coils mirror) providing good confinement time for ions.
  - The ion extraction was done very far away from the last magnetic mirro peak (never do that!)

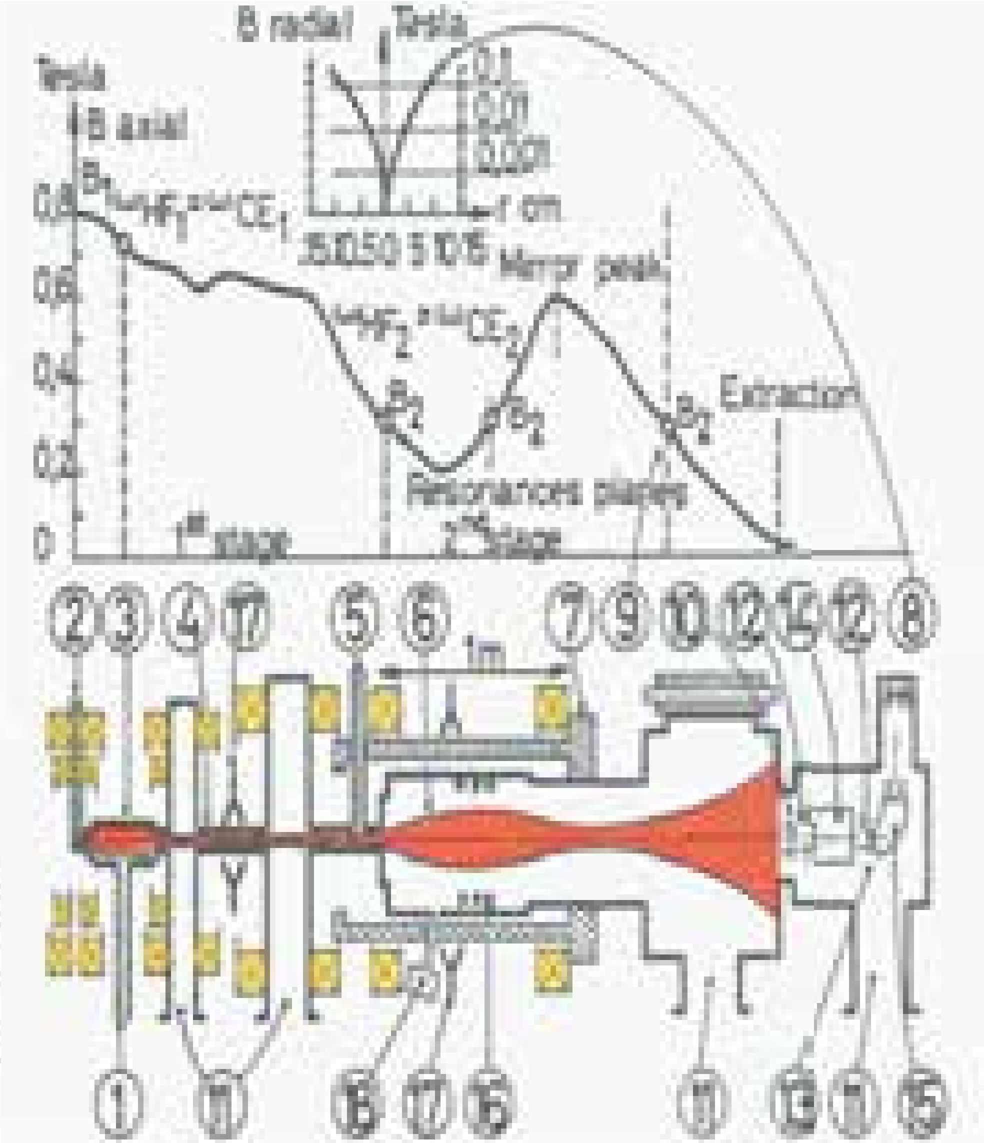
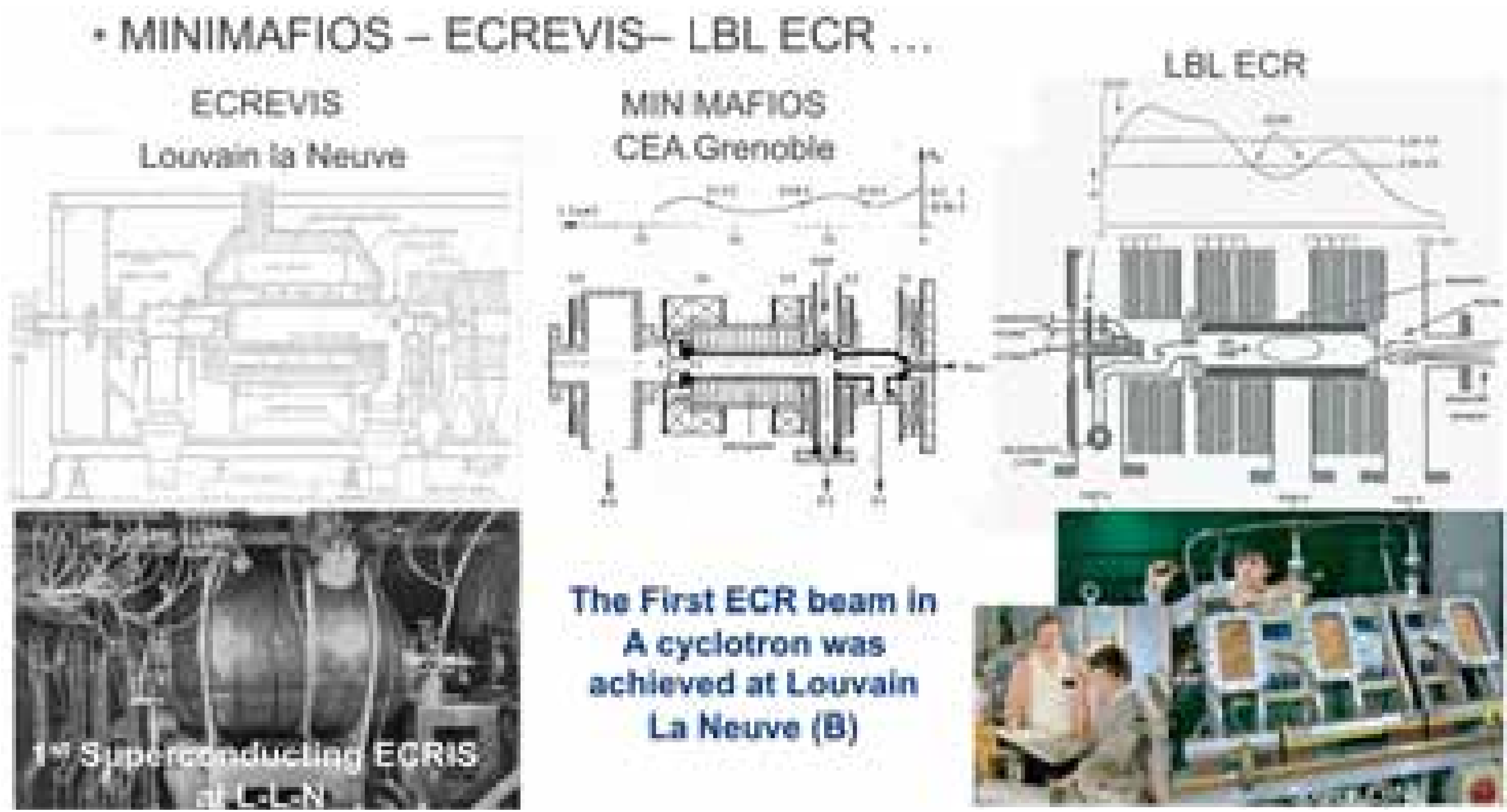


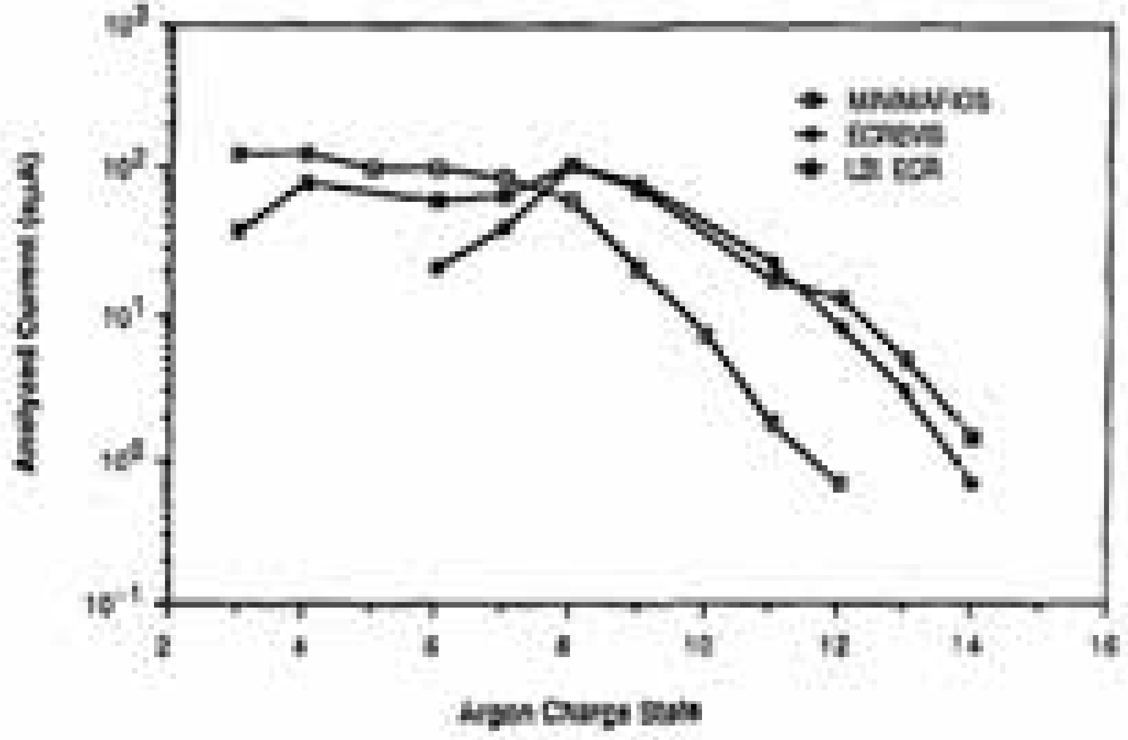
Fig. 1. 1) Gas injection; 2) Wave guide for RF_1 (16 GHz); 3) UHF cavity – source of plasma to be injected; 4) Diffusion zone; 5) Wave guide for RF_2 (8 GHz); 6) Accumulation zone for hot plasma; 7) Hexapole field coils; 8) Radial magnetic field; 9) Axial magnetic field; 10) Ion extraction; 11) Vacuum pumping; 12) Retractable faraday cup; 13) Ion abundance measurement; 14) Wien filter; 15) Energy analyzer; 16) Diamagnetic loop; 17) Microwave 8 mm interferometer for density measurements; 18) Beryllium window for X ray measurements.

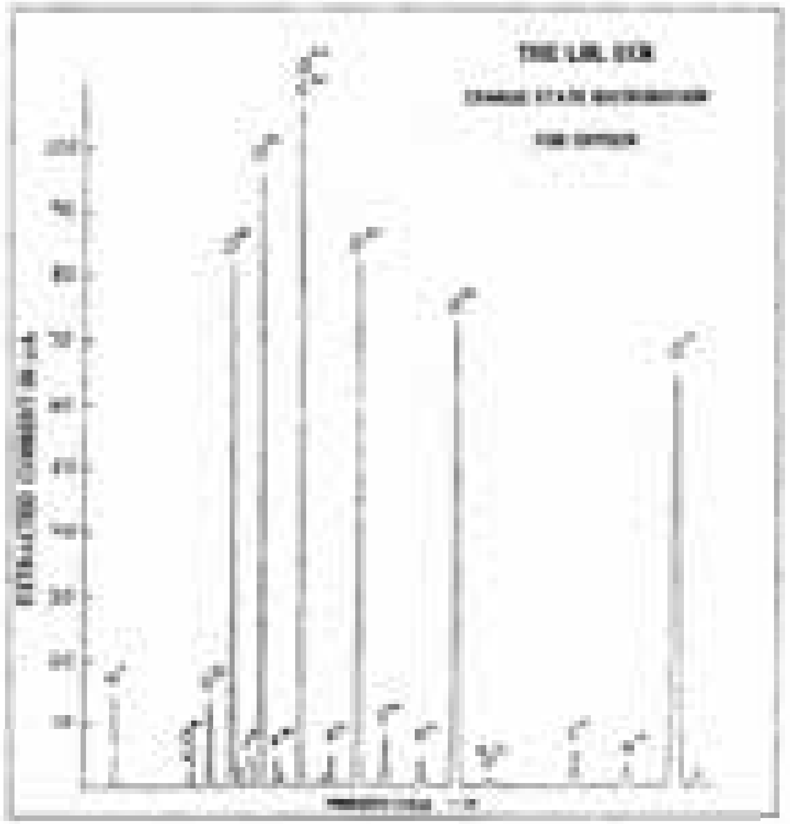
The 70's&80's: First Generation ECRIS



First generation ECRIS performances

- International competition for results was already there!
- First International Workshop on Ion sources in Berkeley





Typical beam performance of G1:
~100 µA Ar^{8+}
~100 µA O^{6+}

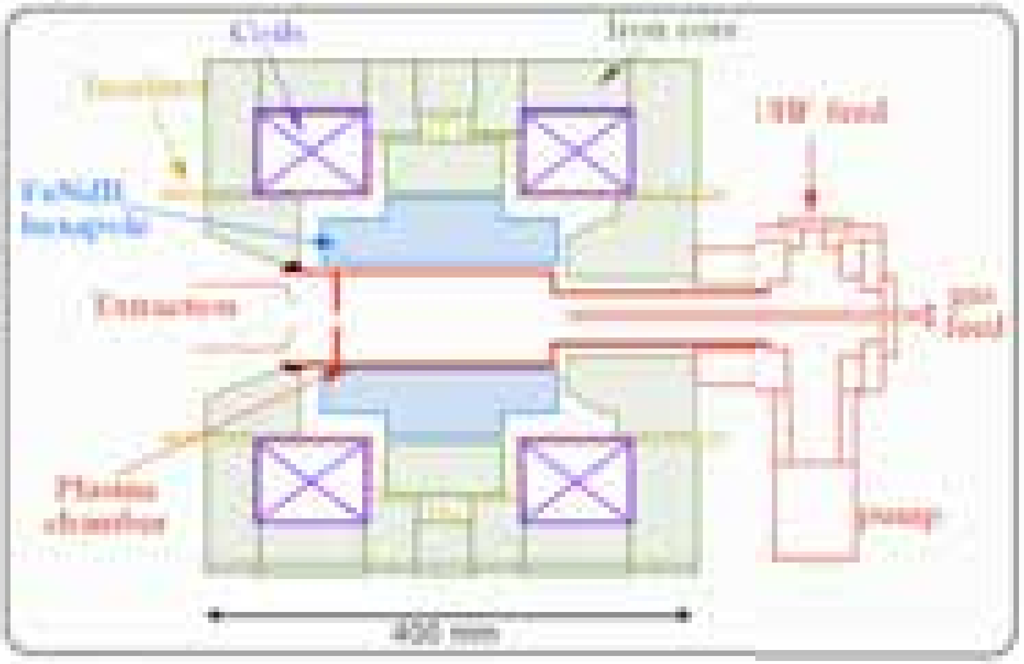
Second generation ECRIS

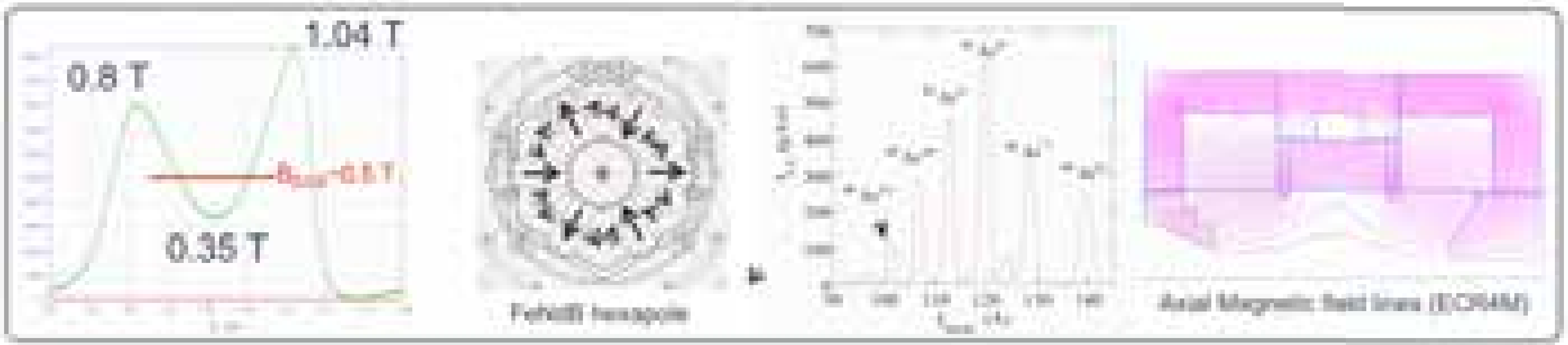
- Generalization of ECRIS used as cyclotron injectors or low energy atomic physics facility in the 80's and the 90's
  - Dramatic increase of plasma performance by improving the know-how in RF injection, magnetic confinement and ion beam extraction
  - The first plasma stage is abandonned => simplification of the design
  - It is the time for more compact an economical ion source using permanent magnets for hexapole
  - Numerous nuclear physics results obtained thanks to ECR Ion Sources

*Superconducting ECRIS

ECR4, GANIL (1989)

- f=14.5 GHz-1.5 kW (B_{ECR}=0.64 T)
- Coaxial RF coupling from a cube located outside the source, equipped with a movable rod (not shown) able to adapt RF impedance to the ECR cavity, inherited from CAPRICE source design
- Axial Mirror: 1.04 T – 0.35 T – 0.8 T
- Hexapole: 1 T FeNdB HallBach type
- Typical Ion Beam: ~650 μA Ar^{8+}
- Chamber volume (Ø64 mm×L200 mm) V~0.5 liter

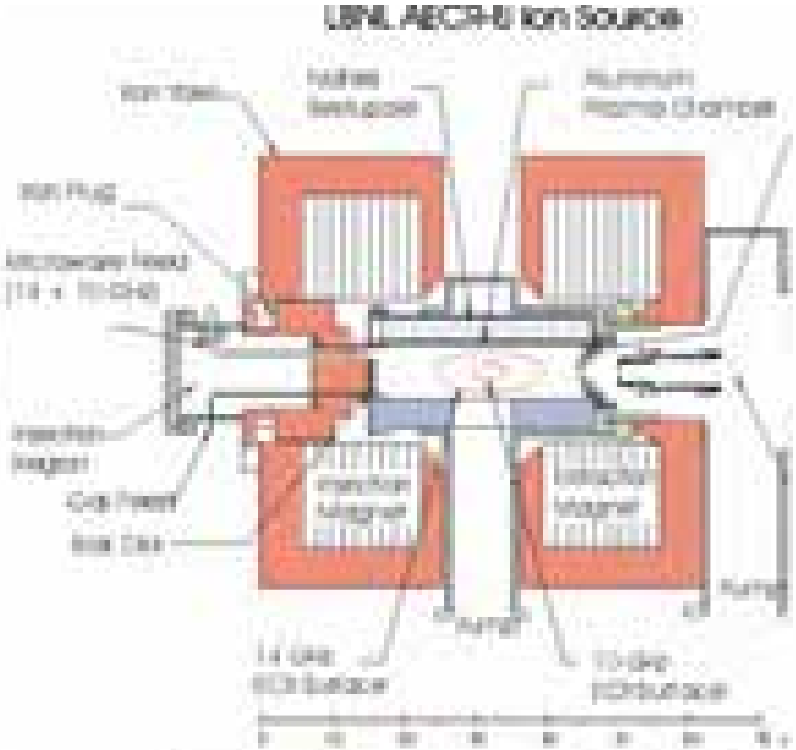


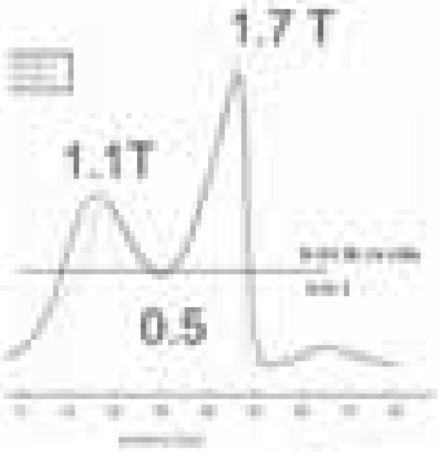


AECR-U LBNL (1996)

- Introduction of double frequency heating (+10-20% beam)
  - f=10+14 GHz / 2 kW
- Volume V~1.36 liter
- Hexapole with radial slots access between poles for pumping
- Iron Plug at injection to boost injection field to 1.7 T
- Bias disk to boost charge states (see picture next slide)
- Aluminum plasma chamber (higher charge state)
- Axial field 1.7-0.5-1.1 T
- Radial Field 0.85 T
- Movable extraction system
- Typical beam 840 μA O, 120 μA Ar

hexapole





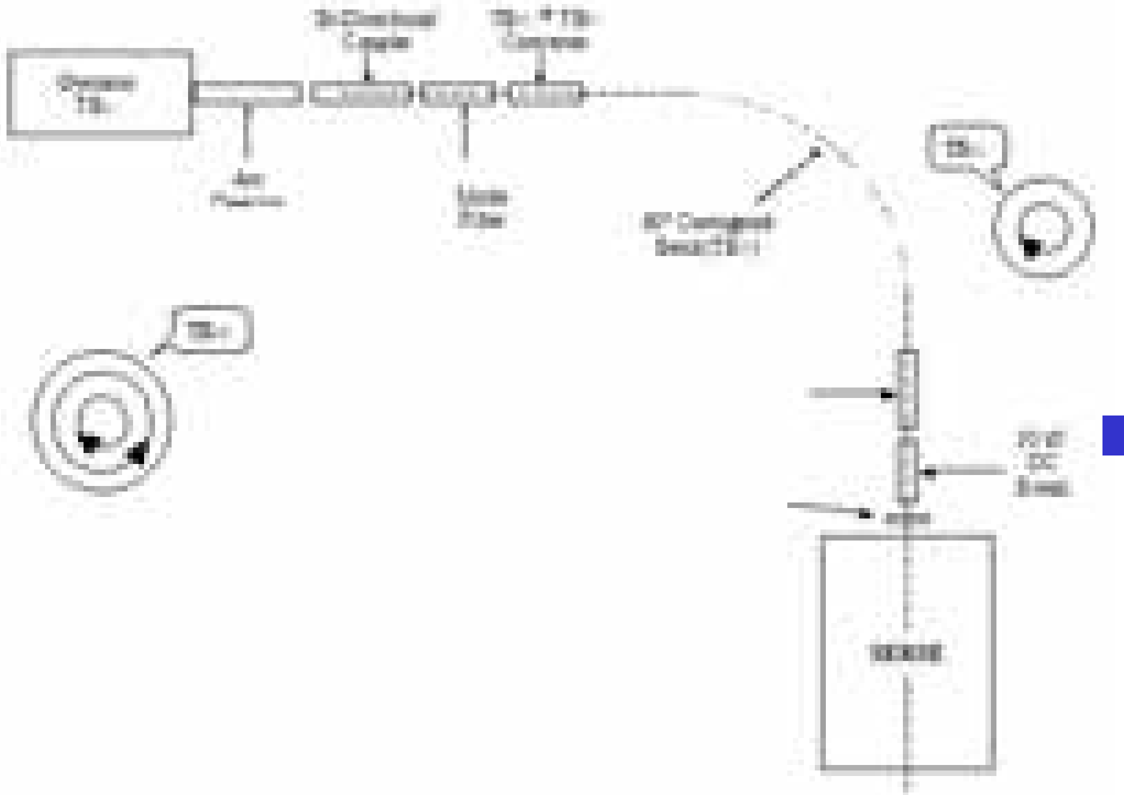
Axial magnetic field

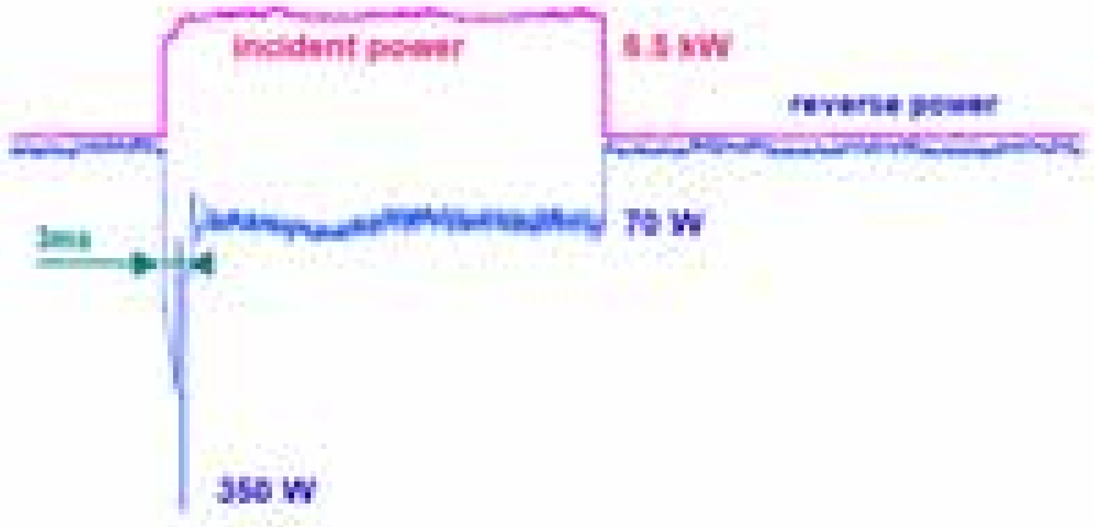
SERSE ion source

Beam	[illegible]	Beam	[illegible]	Beam	[illegible]
O[illegible]	[illegible]	Kr[illegible]	[illegible]	Au[illegible]	[illegible]
O[illegible]	[illegible]	Kr[illegible]	[illegible]	Au[illegible]	[illegible]
O[illegible]	[illegible]	Kr[illegible]	[illegible]	Au[illegible]	[illegible]
Ar[illegible]	[illegible]	Kr[illegible]	[illegible]	Au[illegible]	[illegible]
Ar[illegible]	[illegible]	Kr[illegible]	[illegible]	Au[illegible]	[illegible]
Ar[illegible]	[illegible]	Xe[illegible]	[illegible]	Au[illegible]	[illegible]
Ar[illegible]	[illegible]	Xe[illegible]	[illegible]	Au[illegible]	[illegible]
Ar[illegible]	[illegible]	Xe[illegible]	[illegible]	Au[illegible]	[illegible]
Kr[illegible]	[illegible]	Xe[illegible]	[illegible]	Au[illegible]	[illegible]
Kr[illegible]	[illegible]	Xe[illegible]	[illegible]	Au[illegible]	[illegible]
Kr[illegible]	[illegible]	Xe[illegible]	[illegible]	Au[illegible]	[illegible]
Kr[illegible]	[illegible]	Xe[illegible]	[illegible]	Au[illegible]	[illegible]

Ref.: S. Gammino, G. Ciavola, L. Celona et al., Rev. Sci. Instr. 70(9), (1999) 3577

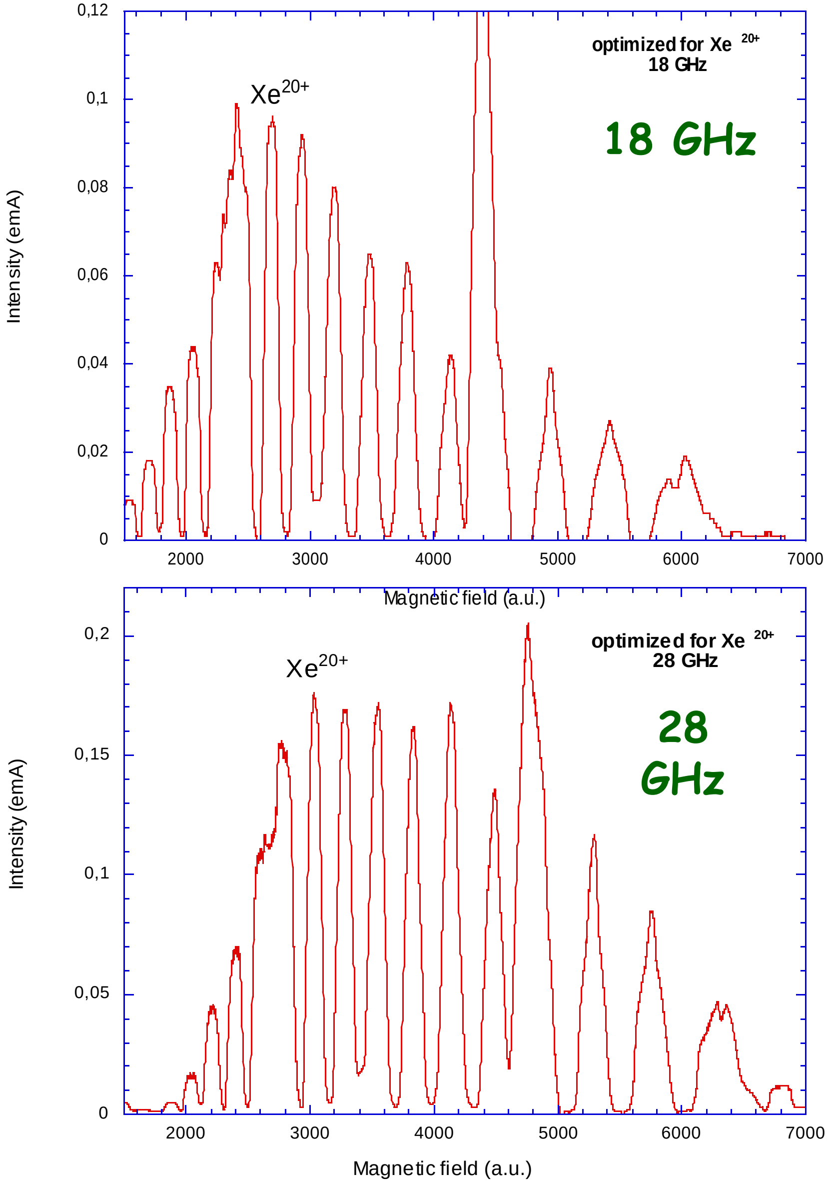
SERSE 28 GHz

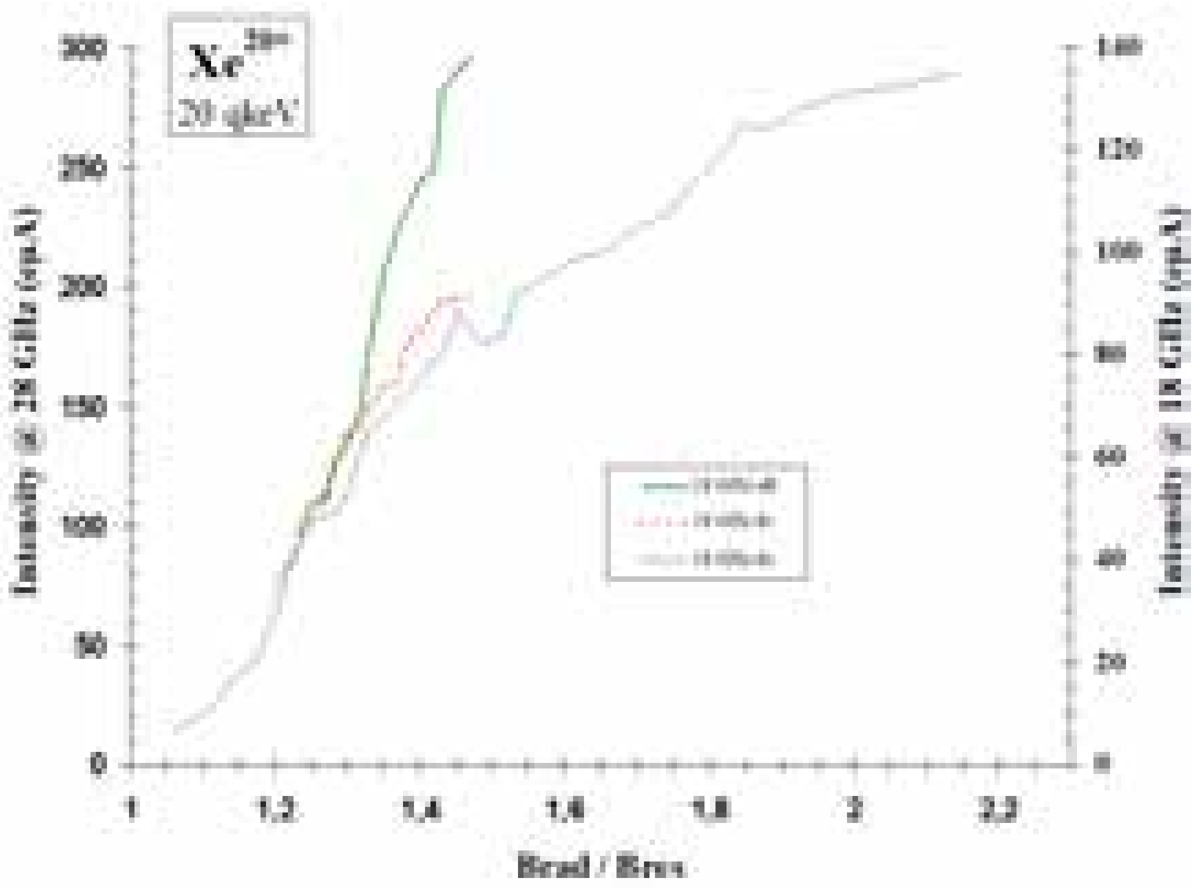




Reference design for all third generation ECRIS

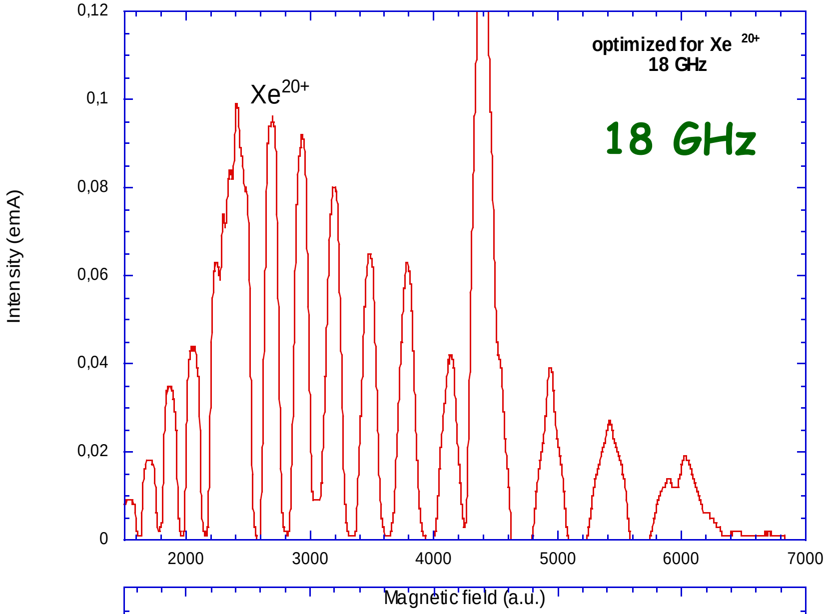
SERSE 28 GHz

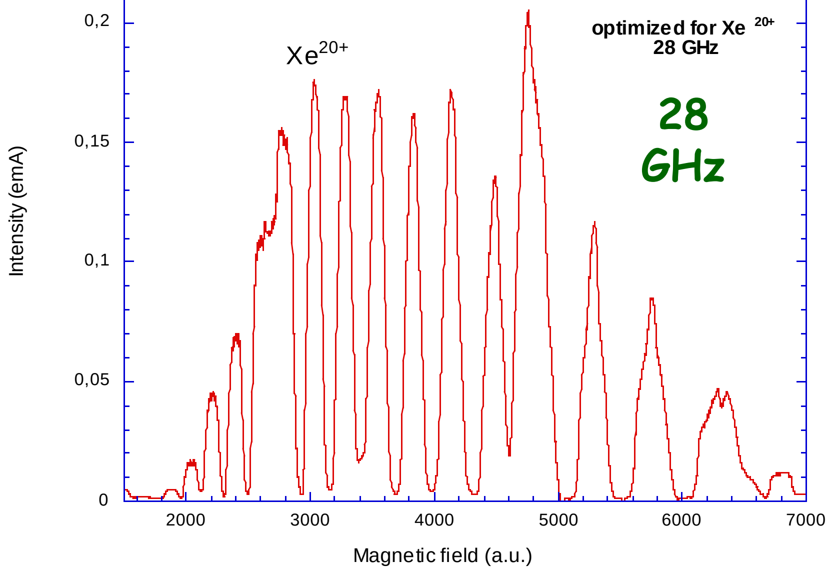


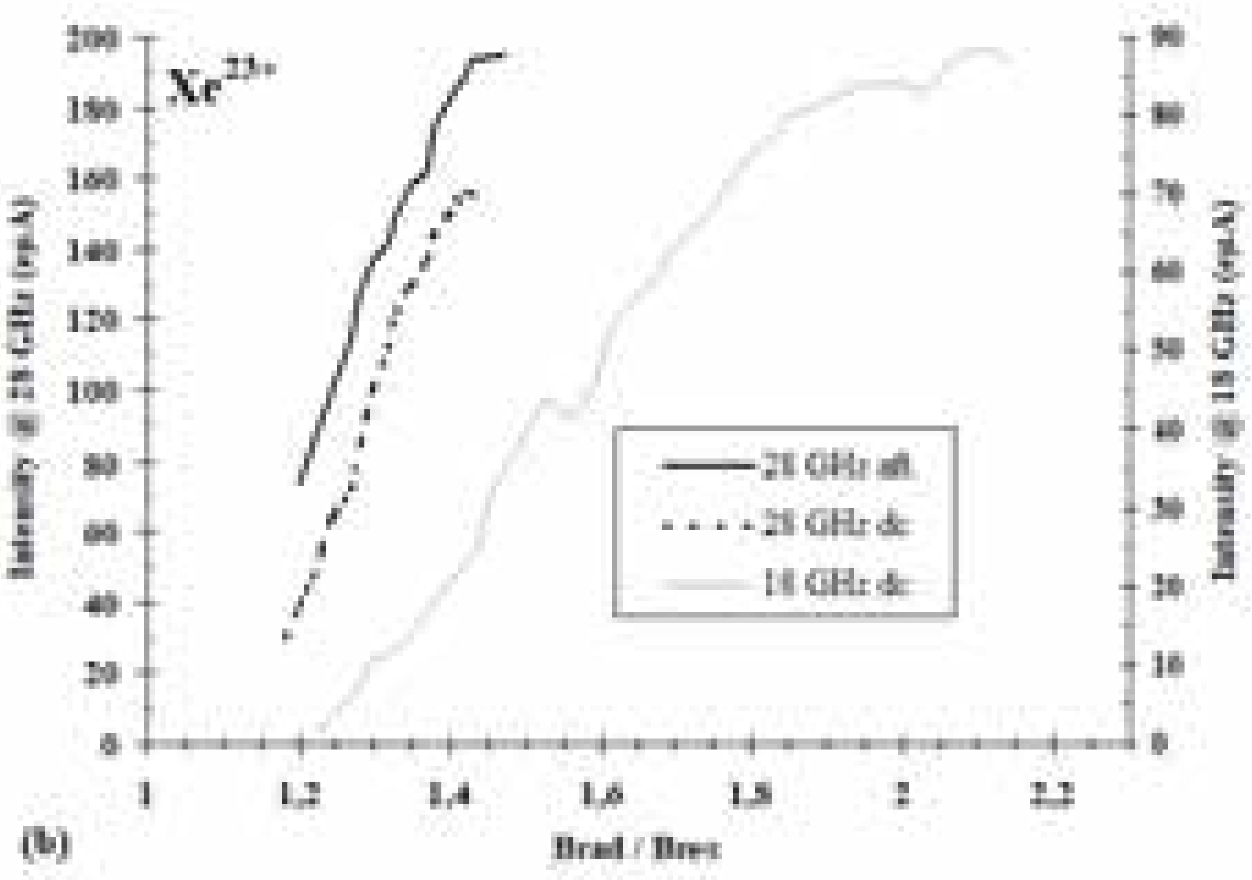


Ref..: S. Gammino, G. Ciavola, L. Celona, D.Hitz, A. Girard,G. Melin, Rev. Sci. Instr. 72(11), (2001) 4090

SERSE 28 GHz

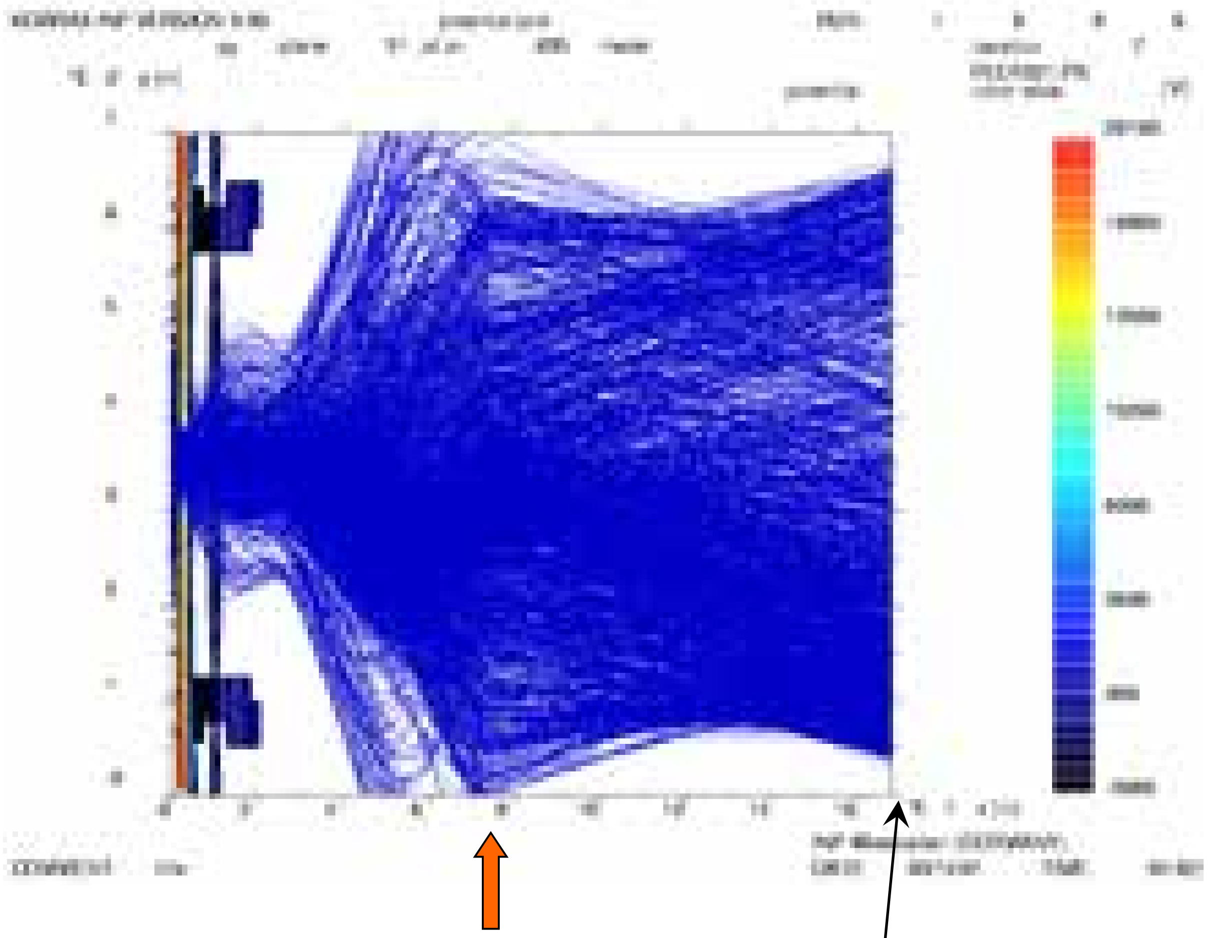






Ref..: S. Gammino, G. Ciavola, L. Celona, D.Hitz, A. Girard,G. Melin, Rev. Sci. Instr. 72(11), (2001) 4090

SERSE 28 GHz



Focusing Solenoid

Magnet gap=54 mm

MAIN Issues:

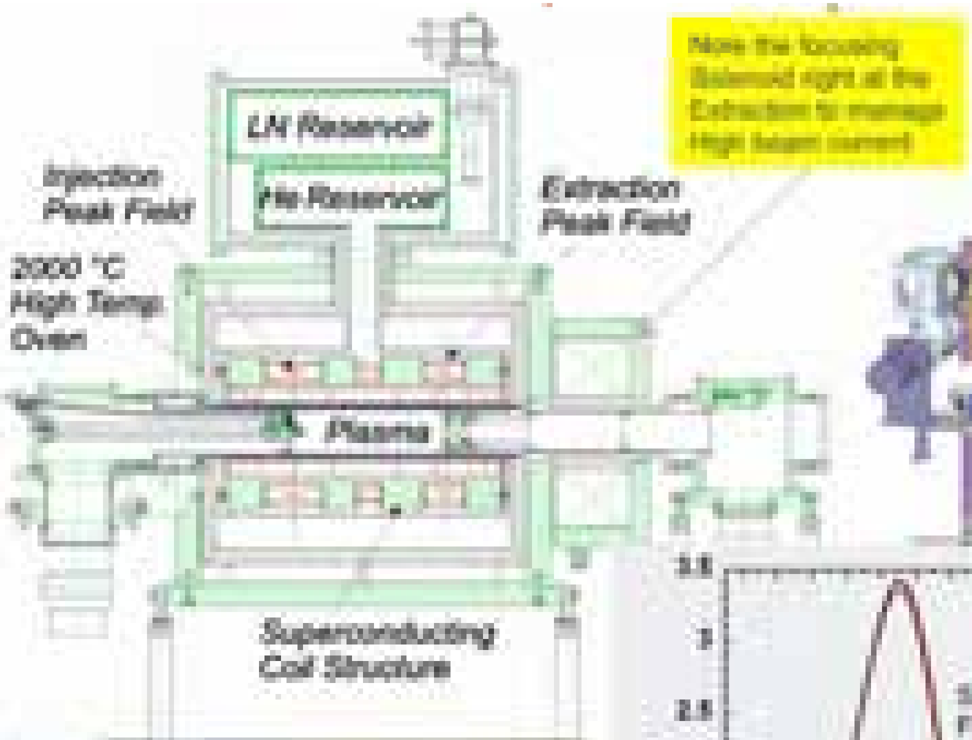
- Beam Transport losses
- Plasma chamber cooling
- Increase of X-ray heat load in the cryostat

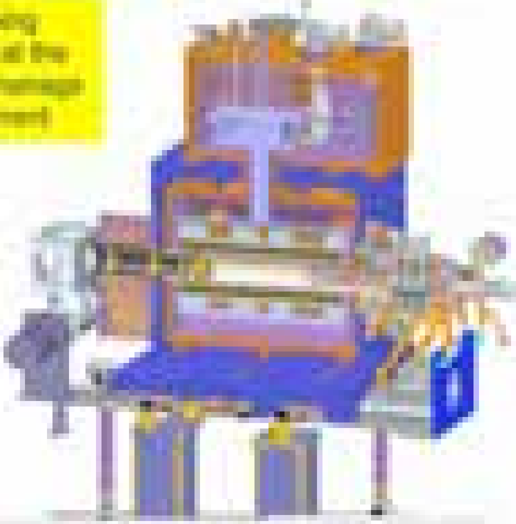
Third generation ECRIS

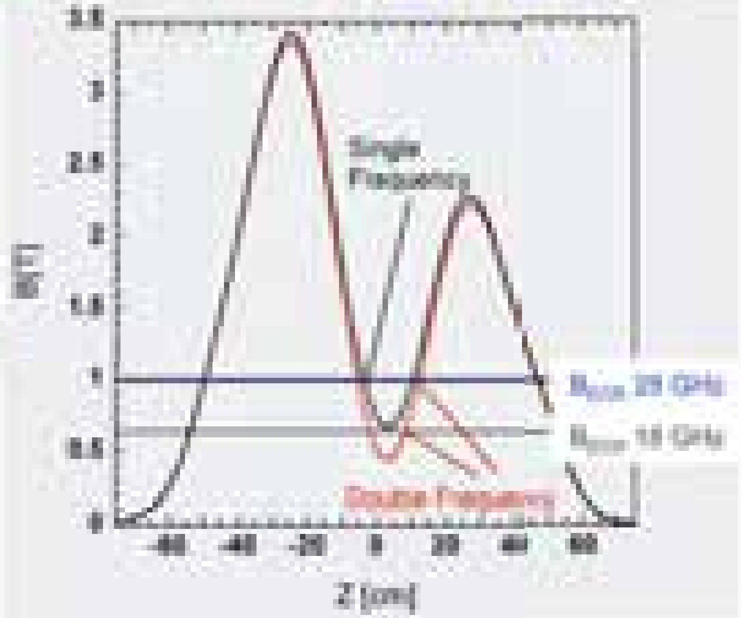
- The new high performance ECR ion sources are optimized for ECR frequency 18 <f< 28 GHz
- The high magnetic field intensity required to confine the plasma (~2-4×B_{ECR}~2-4) makes the use of copper coil technology unreasonable in term of electrical power consumption (2T hexapole in Cu technology=> 3-4 MW electrical power).
- New ECRIS are preferably fully superconducting, with a large plasma volume to produce very high charge states for Cyclotrons or High intensity LINAC
- The beam current dramatically increases when the source is operated at higher frequency, and new technical challenges have arisen….

VENUS

- f=18÷28 GHz - (2÷6) kW
- B_{ECR}=1 T
- Fully superconducting ECRIS
  - NbTi-Cu wire technology
  - 4K LHe + thermal 40 K shield
  - 4×1.4 W cryocooling
- Axial profile 3.5-0.35-2.2 T
- Radial hexapole at wall Br=2.2 T
- Dedicated to very high intensity very high charge state applied to cyclotron acceleration
- Plasma Chamber volume V~8.5 liter
  - Ø~15 cm , L~50 cm
- V=25 kV
- Typical beams: 3 mA O^{6+}, 0.86 mA Ar^{12+}

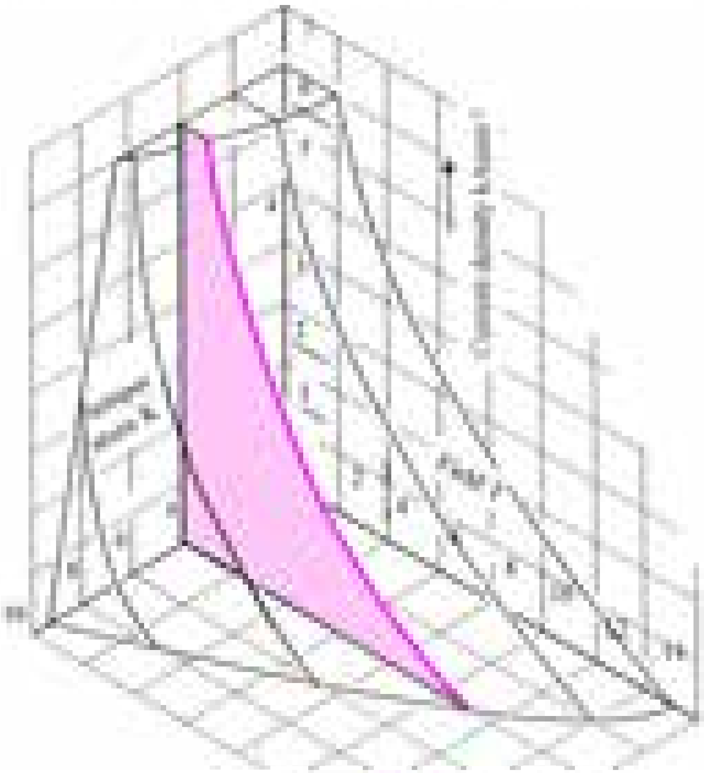


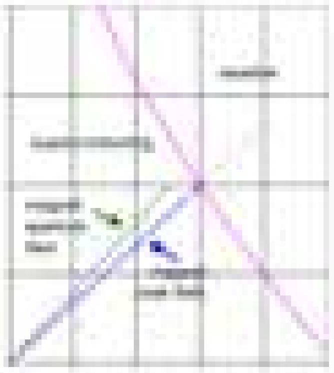


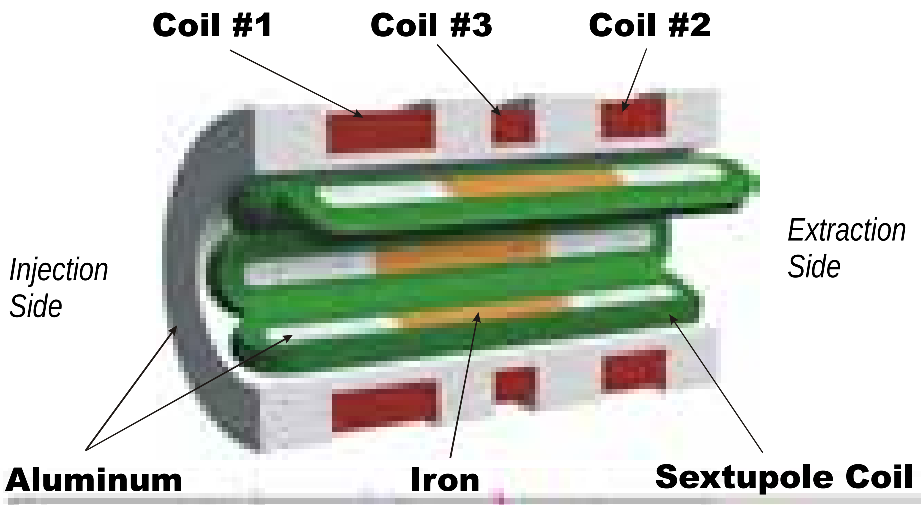


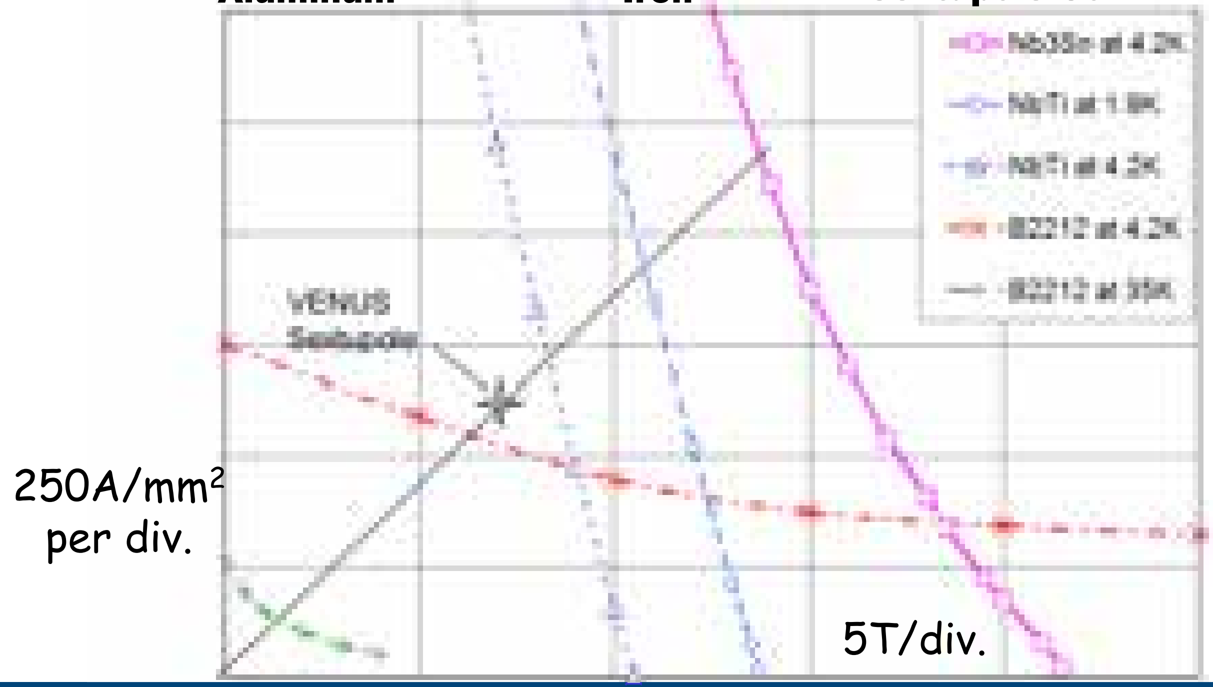
27

VENUS SC magnetic system

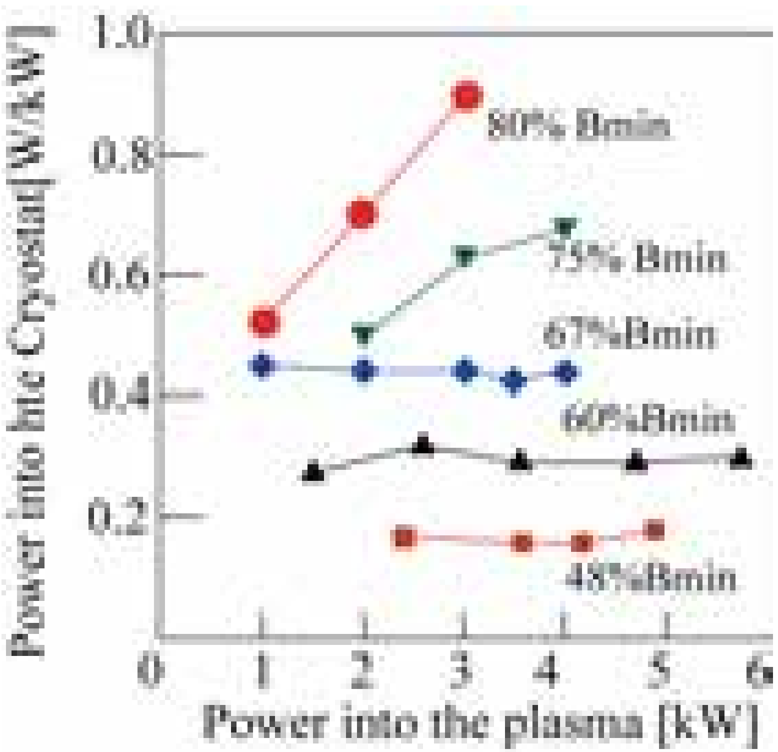




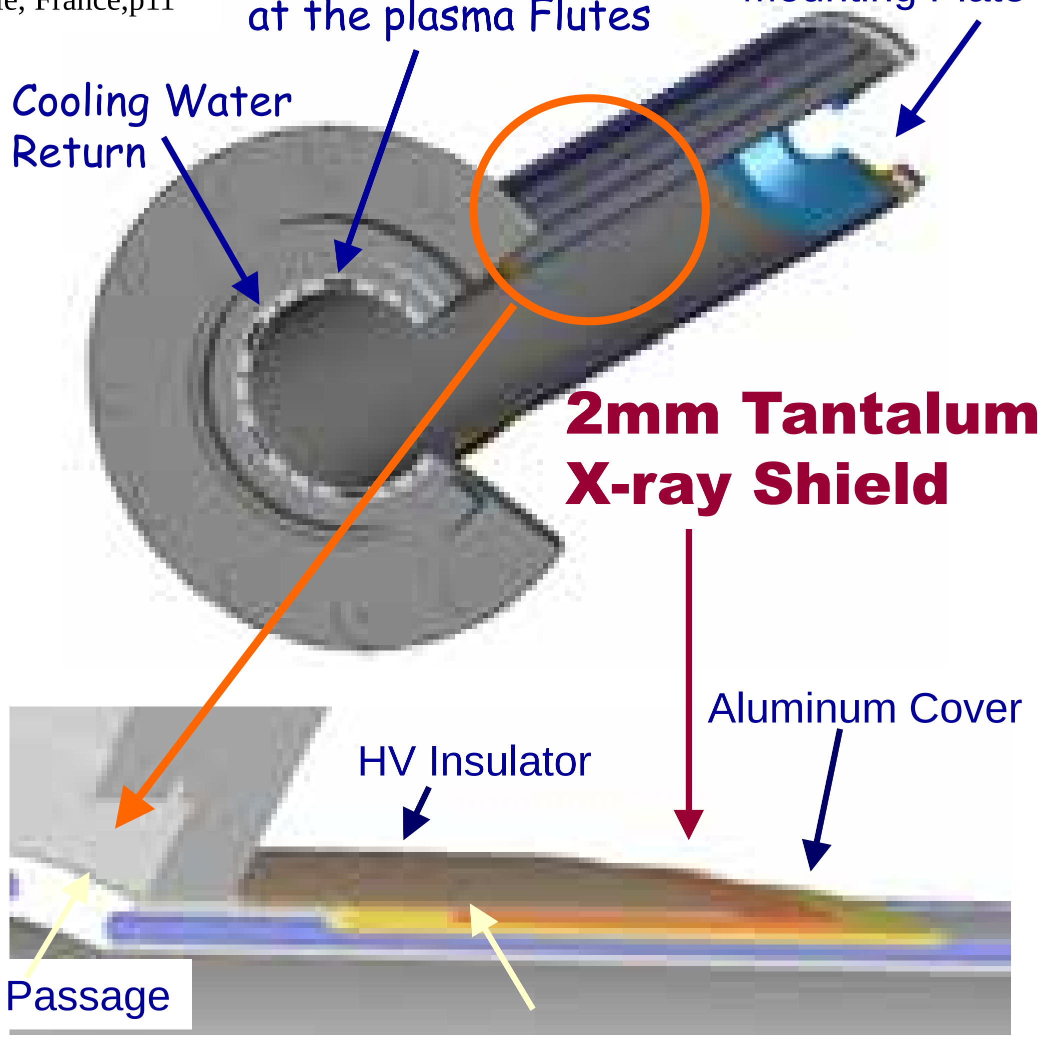




VENUS Plasma Chamber with X-ray Shielding



D. Leitner , et al, Proc. Int. Workshop on ECR ion sources, 2010, Grenoble, France,p11



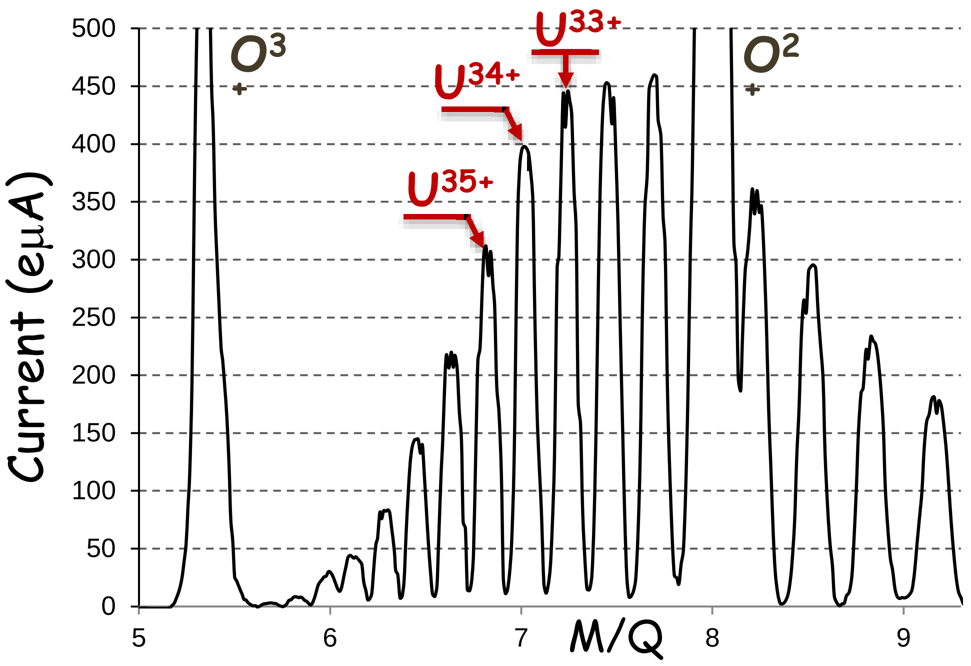
Higher B_{min}
Low gas pressure

→ Intense beam of highly charged heavy ions

→ Strong X-ray heat load

Uranium beam intensity

- ^{238}U Intensity



- FRIB Requirement

Q ECR	I ECR (eμA)	I ECR (pμA)
33	432	13.1
34	445	13.1

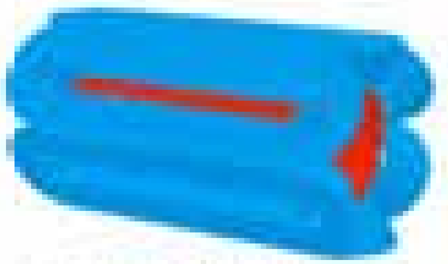
- Beam Measurements with VENUS

Q ECR	I ECR (eμA)	I ECR (pμA)
33	443	13.42
34	400	11.76

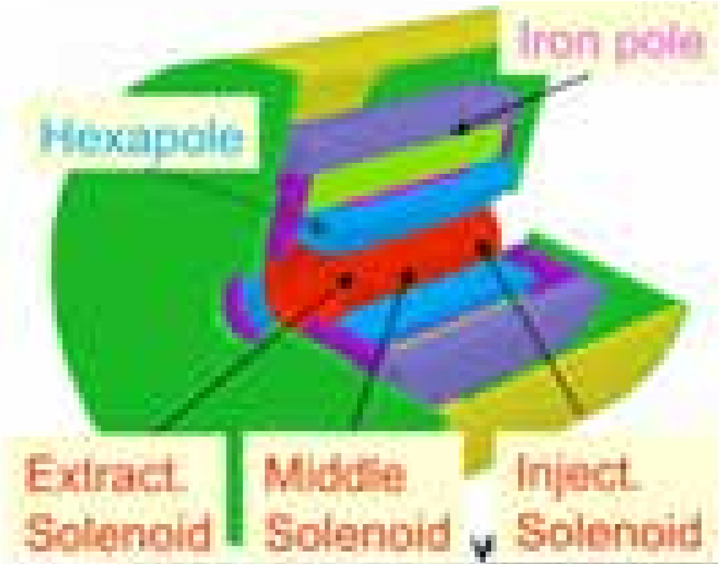
- Up to 8.3 kW Coupled to the VENUS ECR ion source
  - 28 GHz from gyrotron: 6.5 kW injected out of 10kW
  - 18 GHz from Klystron: 1.8kW (Maximum available)
- Total extracted current exceeded 9 emA for a transmission of 55%
- High intensity production was maintained for about 10 hours.
- New record beam intensity obtained with VENUS exceeds for U33+ the intensity needed to reach 400kW on target by accelerating only one chare state
- Beam emittance 95% within FRIB requirement (0.9pi.mm.mrad)

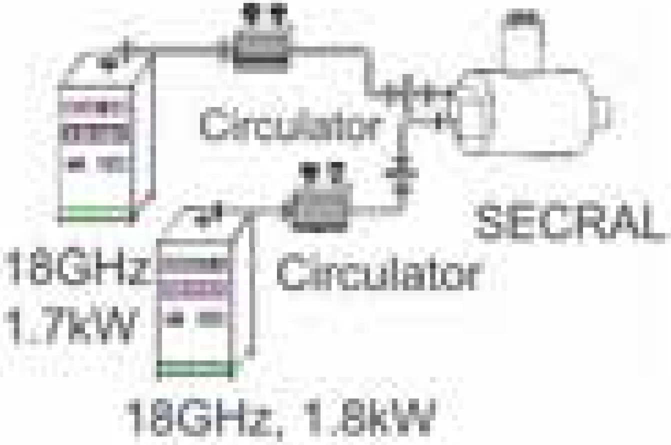
SECRAL 24GHz (IMP CAS, Lanzhou)

- Fully Superconducting ECRIS (2004)
- Original design hexapole outside the axial coils
  - Magnetic intensity boosted by large iron yoke around the large hexapole
- f=18+24 GHz / ((1.7+1.8)+7) kW
- Brad=1.8 T
- Axial Field 3.7-0.82-2.2 T
- Ø120 mm, L 42 cm ; V~4.7 liter
- Typ. beam: 2.3 mA O^{6+} ; 510 μA Ar^{12+}

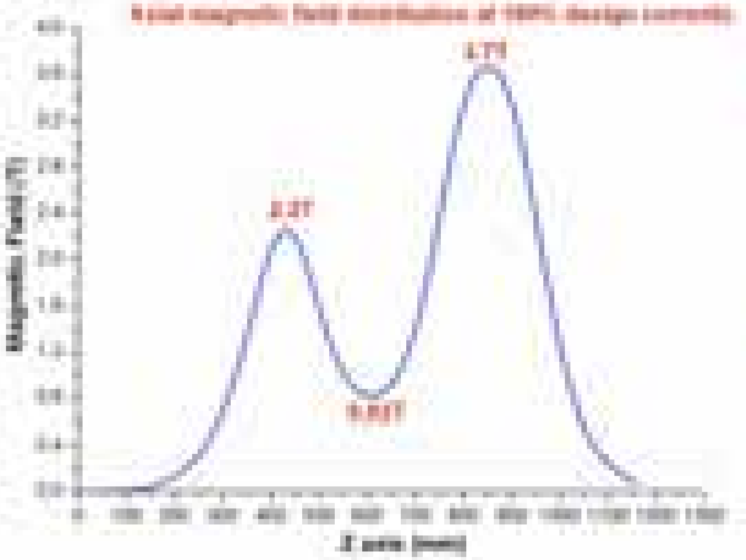


-SC Hexapole outside The solenoids





Sum of 2 ×18 GHz Klystron power



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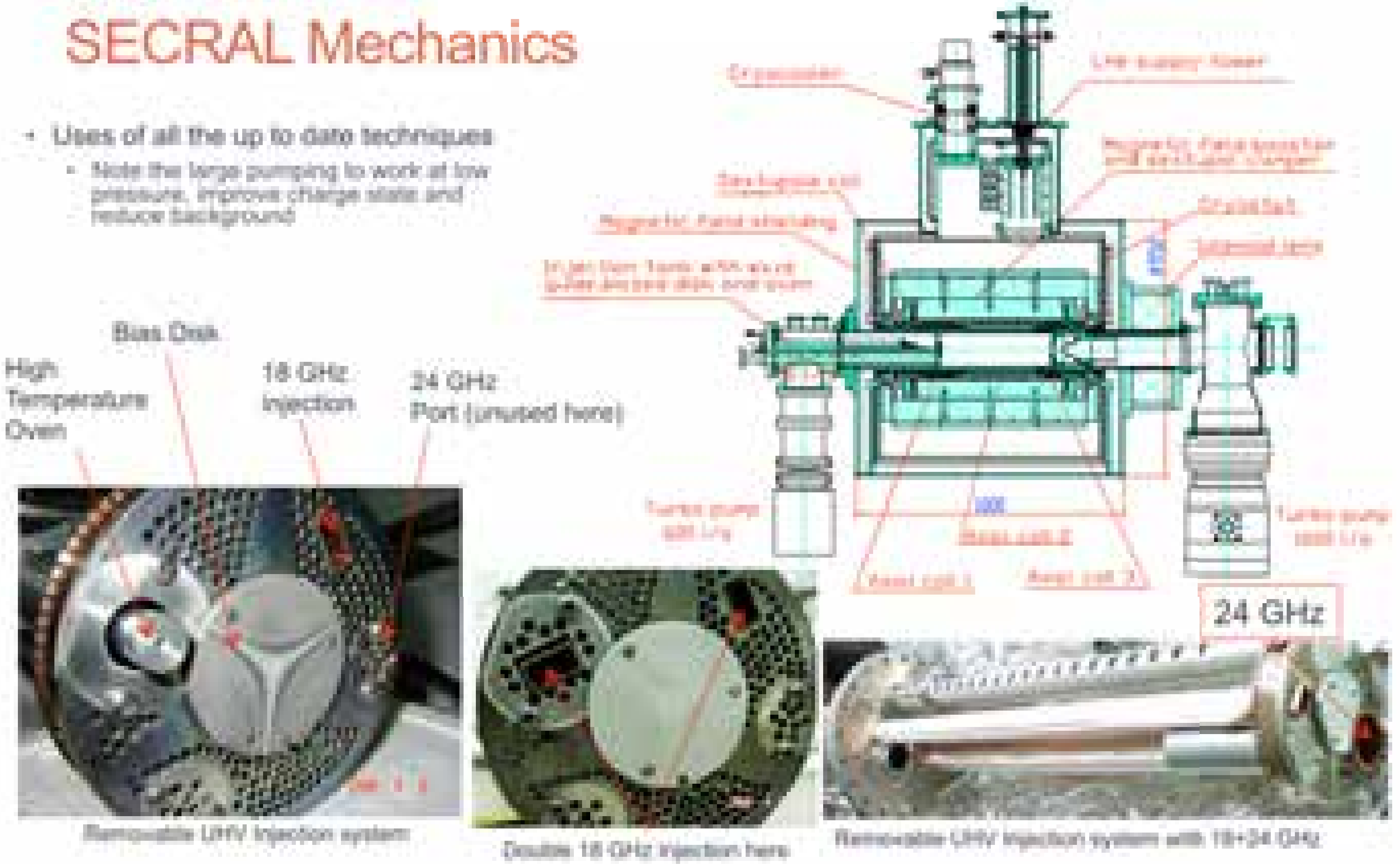
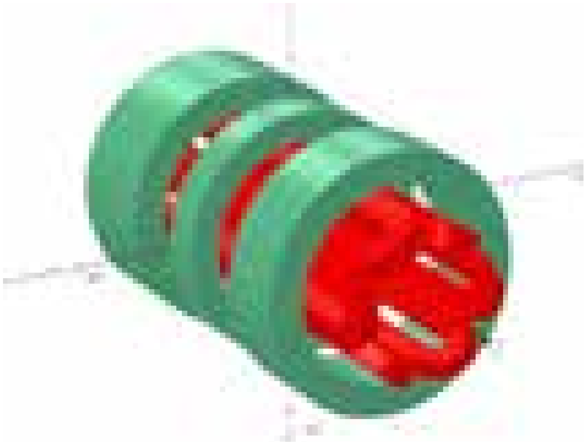
SECRAL Mechanics



SC Coils – Magnetic system

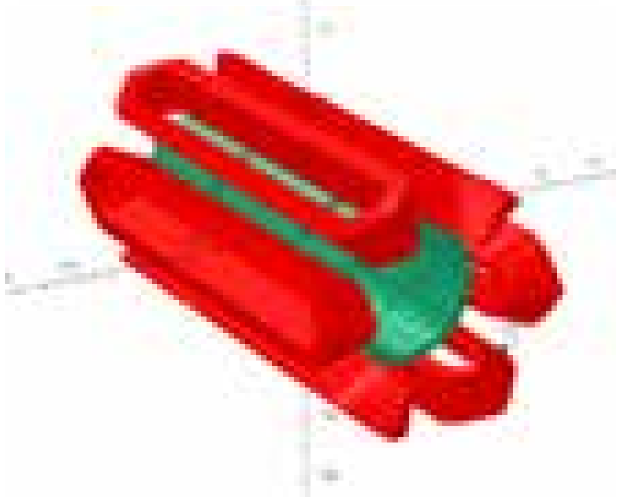
Sextupole-in-solenoid:

☺ Efficient use of the radial field (minimizes the peak field in the sextupole)
☹ Solenoid field causes strong asymmetric forces on the sextupole coil ends.
☹ Bulky magnet size and cryostat

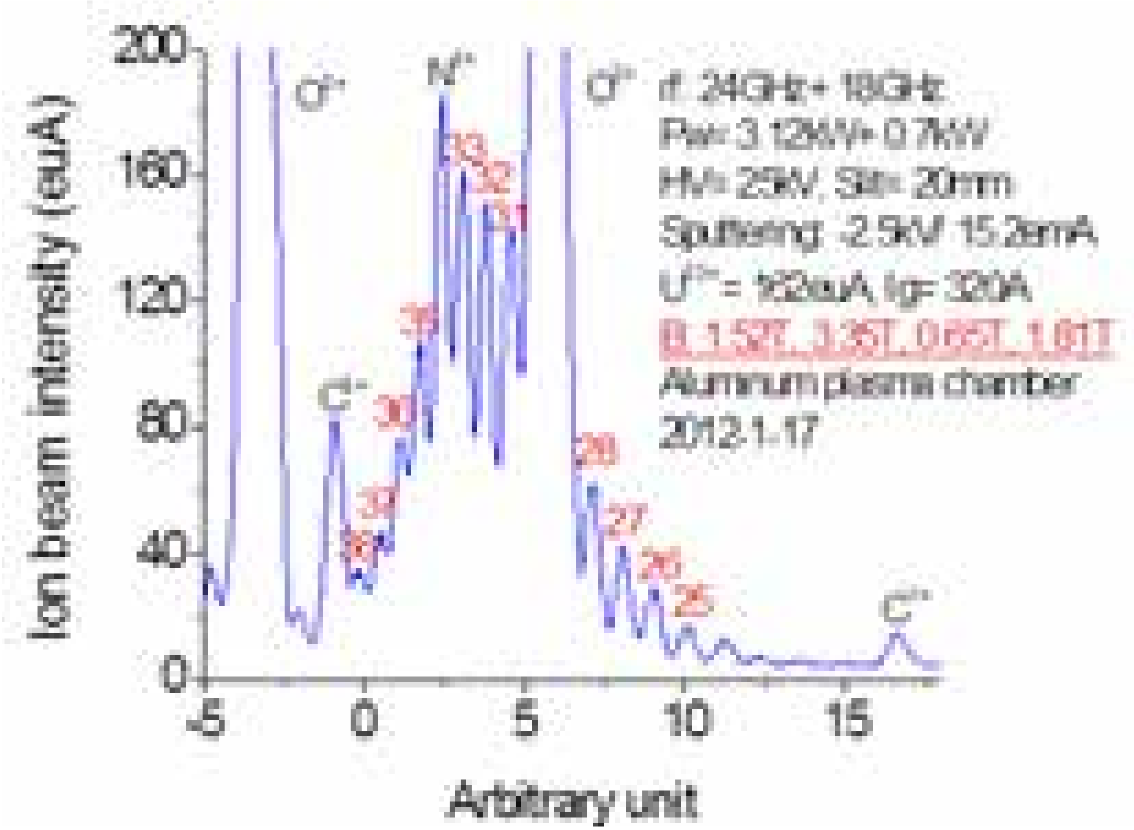


Solenoid in sextupole:

☺ Minimizes the influence of the solenoid on the sextupole coil field and forces
☺ More compact. Lower cost.
☹ Inefficient use of the radial field (larger radius, higher field in the sextupole coil)



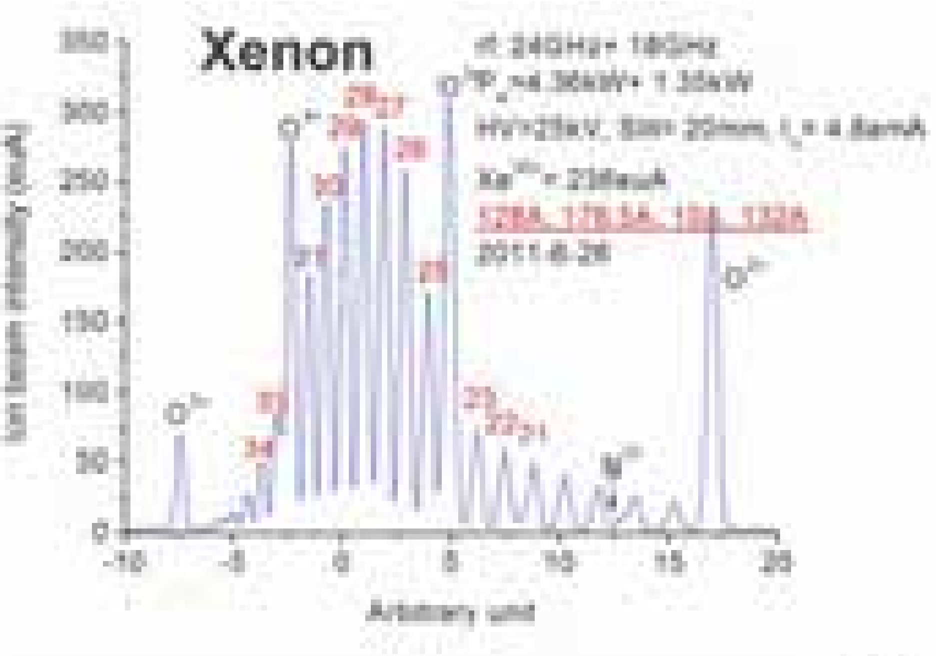
Uranium production by sputtering at SECRAL

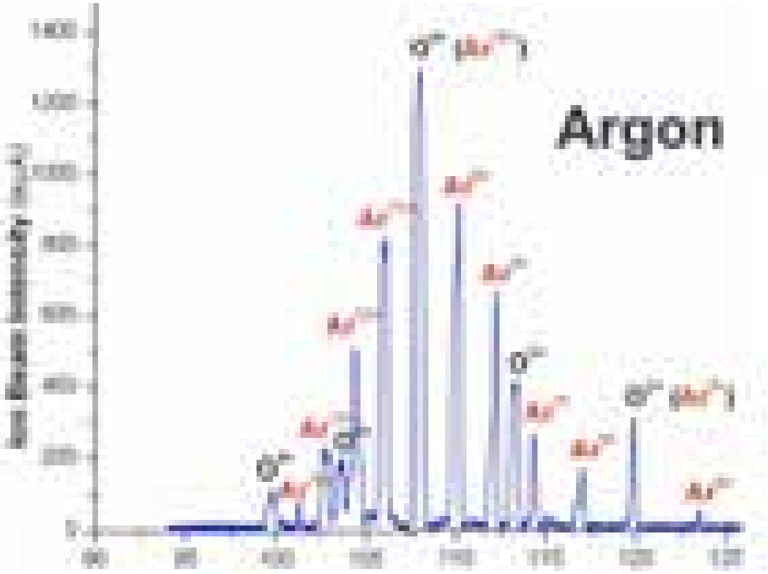


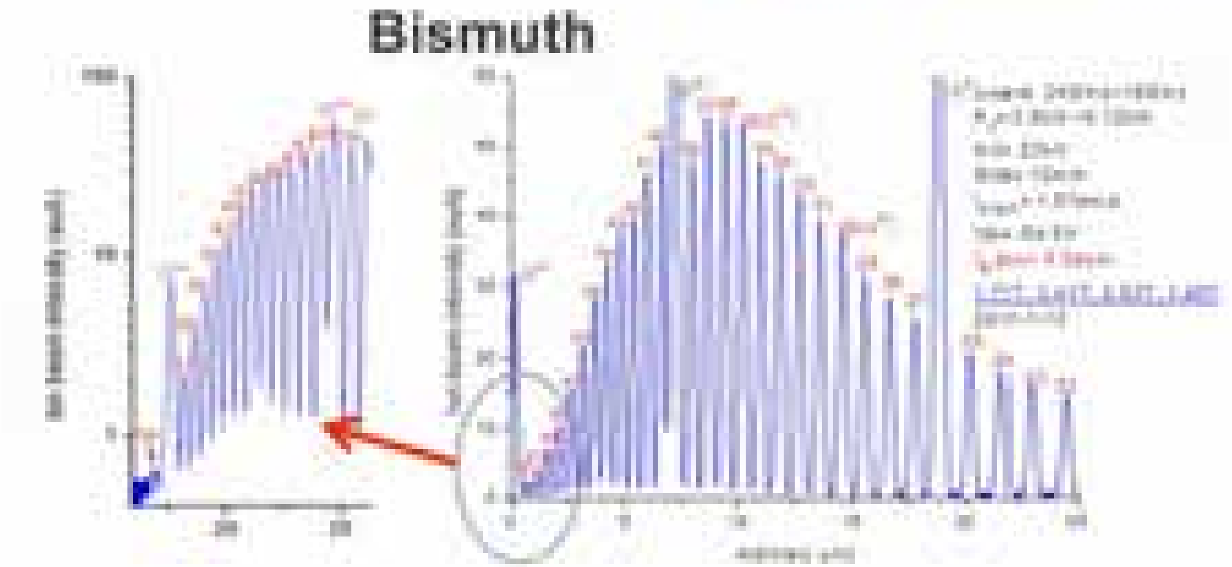
- Beam intensity still responding well with μW power increase
- >200 euA U^{33+} is possible provided time and power

$^{238}U^{33+}$ 162 eμA at 3.1kW+0.7kW with 24GHz+18GHz

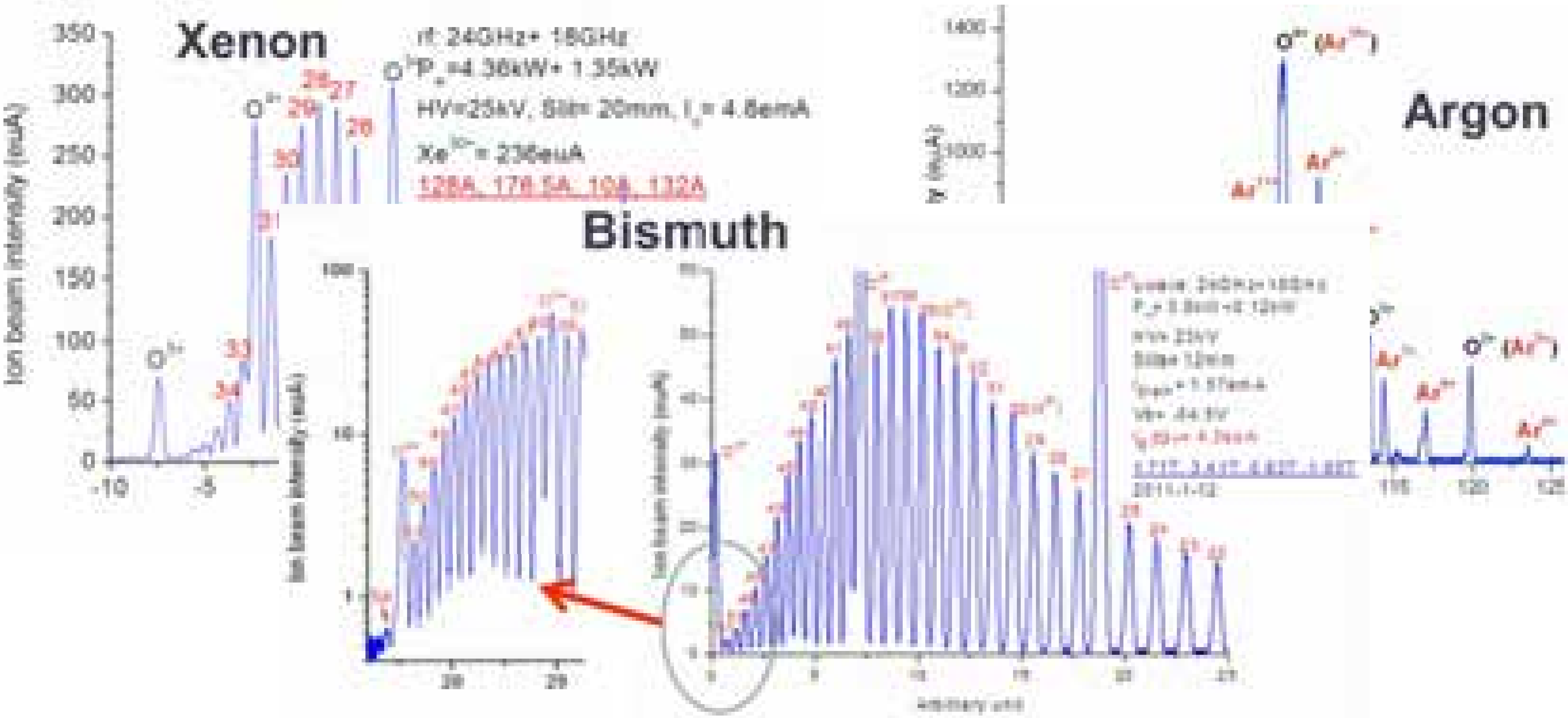
SECRAL beam performance



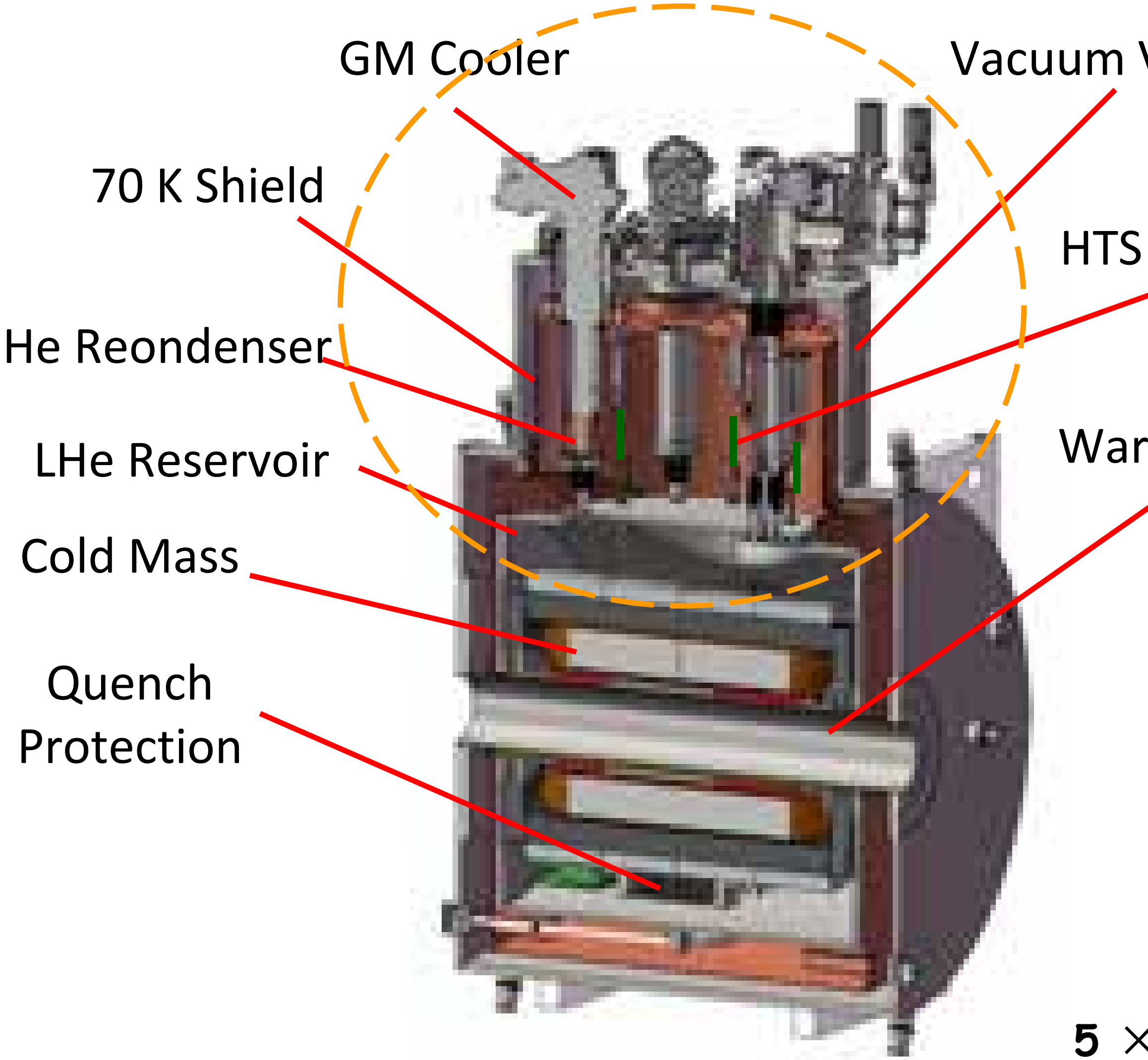


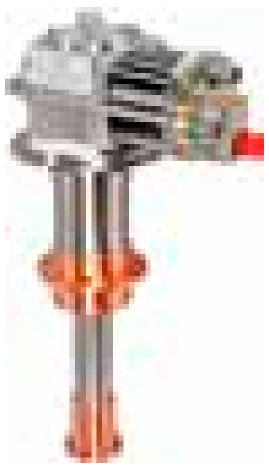


SECRAL beam performance



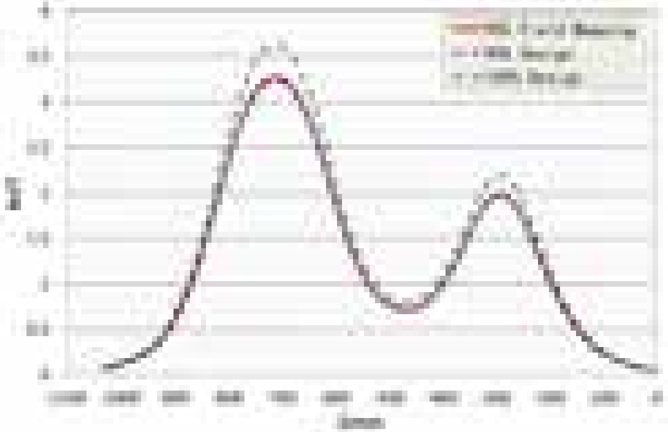
SECRAL II



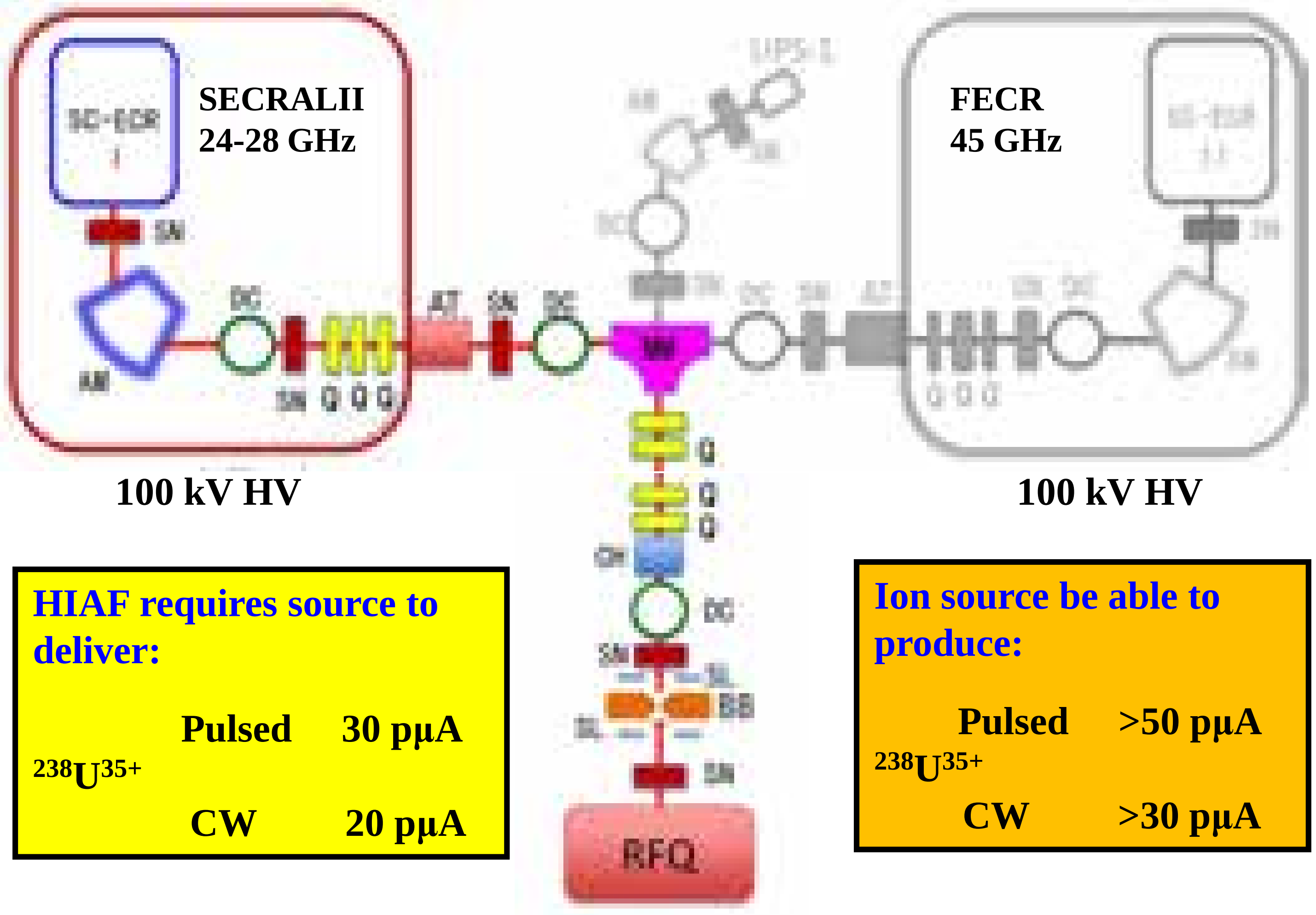


5 × RDK-415 D
Sumitomo

Based on SECRAL Design



SECRAL II requirements



HIAF requires source to deliver:

$^{238}U^{35+}$		
	Pulsed	**30 pμA**
	CW	**20 pμA**

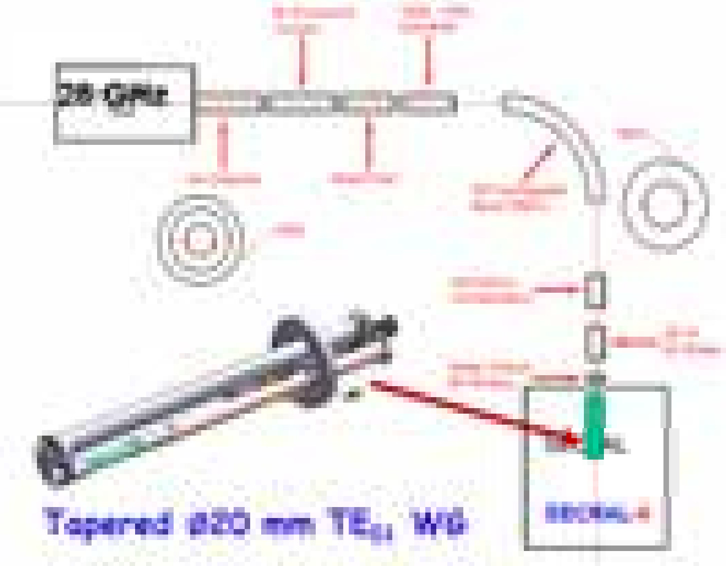
Ion source be able to produce:

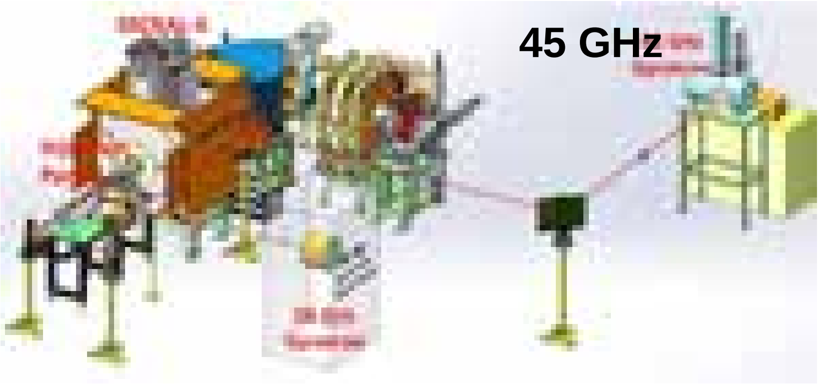
$^{238}U^{35+}$		
	Pulsed	**>50 pμA**
	CW	**>30 pμA**

Challenging requirements !!

SECRAL II

Tube Type	Company	Frequency (GHz)	Bandwidth (MHz)	Max. Output (kW)	Output Mode	ECR Coupling Mode
Klystron	CPI	18	50	2.4	TE_{10}	TE_{10}
Gyrotron	CPI	28	<0.5	10.0	TE_{02}	TE_{01}
Gyrotron	GyCOM	45	<0.5	20.0	TEM_{00}	TE_{01}



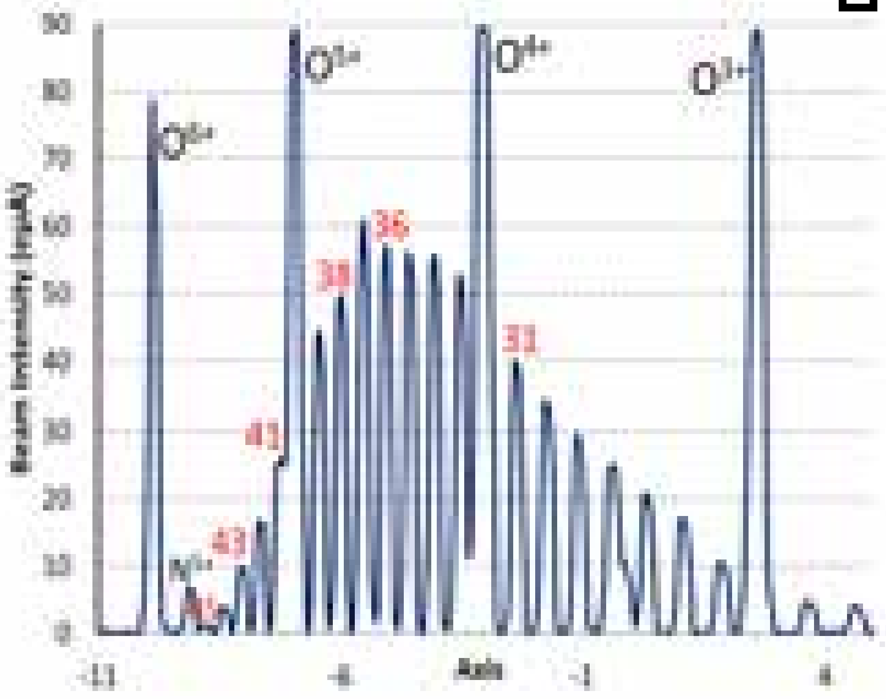


Quasi-optical→Oversized WG of Ø32 mm TE_{01}

No.	Frequencies (GHz)	Main Frequency (GHz)	Max. Power (kW)	Used Power (kW)	Note
1	18	18	2.4	1.5	√
2	18+28	28	12.4	12.4	√
3	28+45	28	30	7.4	√
4	18+ 28 + 45	28	32	7.3	√
5	45	45	20	4.0	√

SECRAL II

16.7 eμA Xe^{42+}



45 + 28 + 18 GHz

- Linacs
- Synchrotrons
- Cyclotrons
- HCI Physics

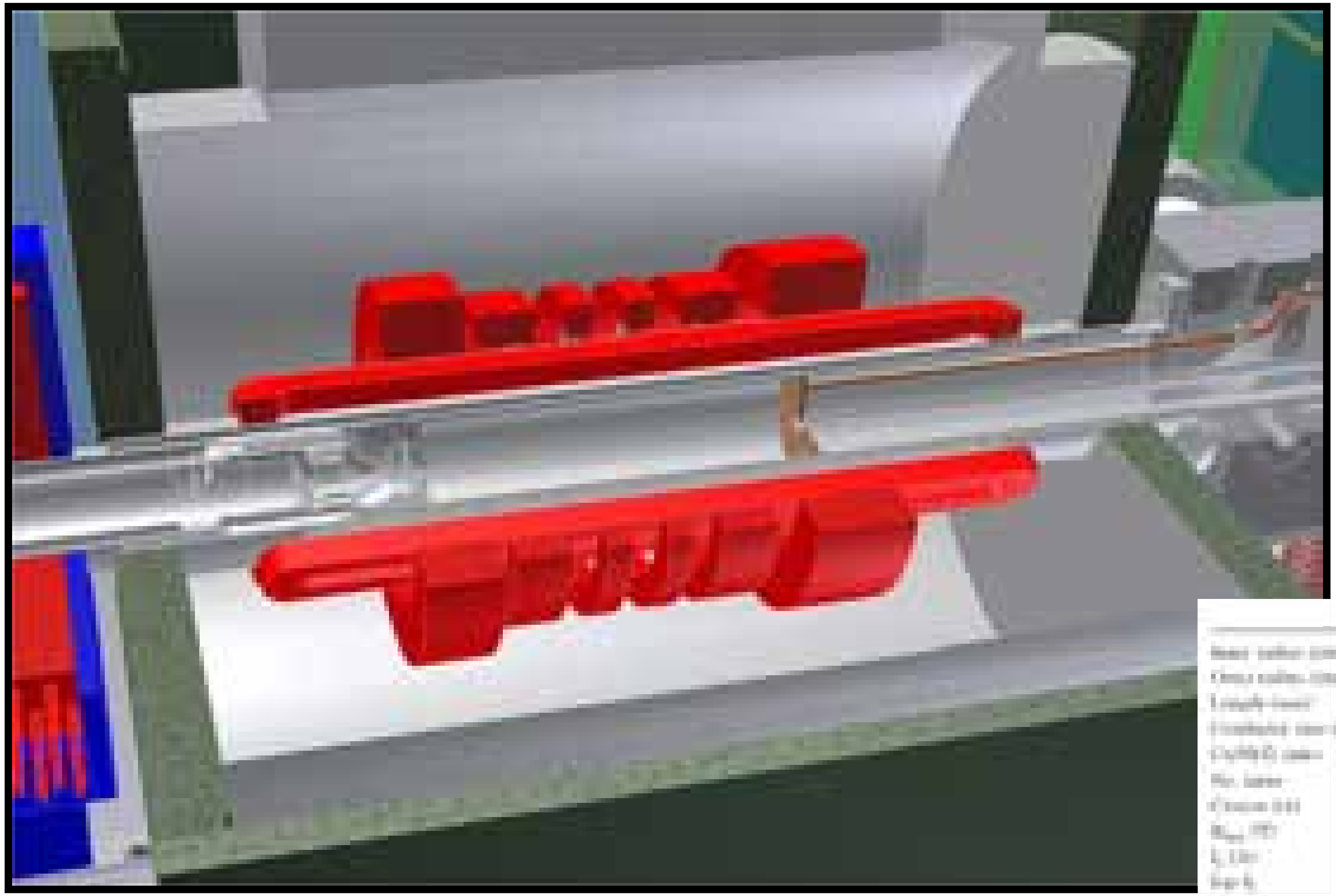
Very Intense Beams (emA)

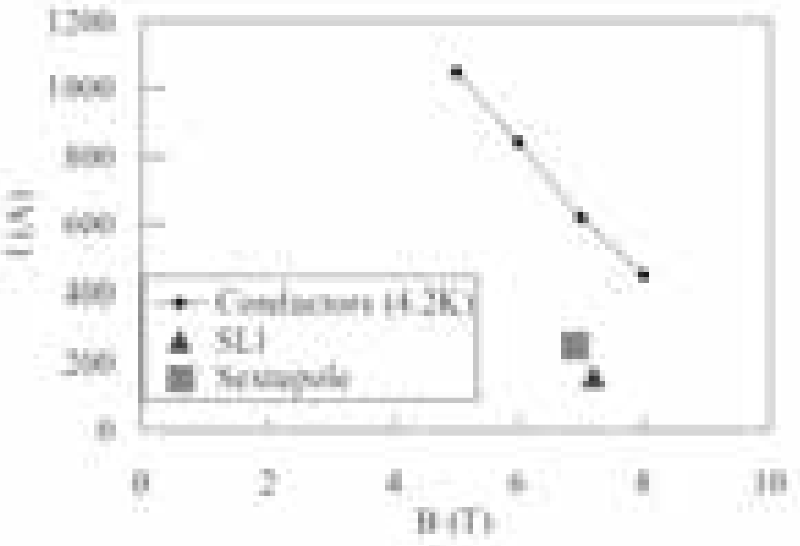
Ion	VENUS -2017*	SECRAL -2016	SECRAL-II
O^{6+}	4.75	2.3	6.7
O^{7+}	1.95	0.81	1.75
Ar^{9+}	/	/	1.75
Ar^{12+}	1.06	1.42	1.19
Kr^{18+}	0.77	/	1.03
Xe^{20+}	/	0.5	0.82

Highly Charged Beams (eμA)

Ion	VENUS -2017*	SECRAL -2016	SECRAL-II
Ar^{17+}	120	50	133
Ar^{18+}	4	/	14.6
Kr^{28+}	100	/	146
Kr^{31+}	17	/	7
Kr^{33+}	/	/	0.5
Xe^{38+}	26	22.6	56
Xe^{42+}	6	12	16.7
Xe^{45+}	0.88	0.1	1.3

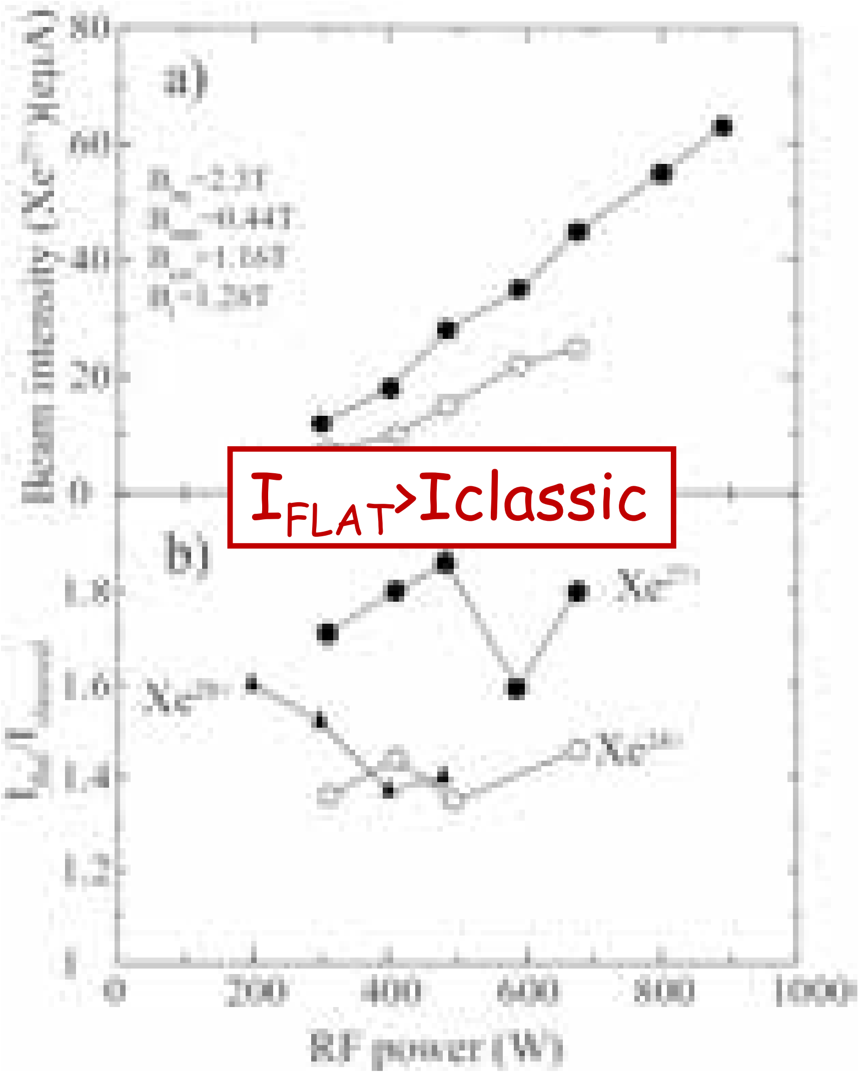
RIKEN 28 GHz





1200
1000
800
600
400
200
0
I (A)
0
2
4
6
8
10
B (T)
Conductors (4.2K)
SL1
Sextupole

ECR zone size, field gradient effect

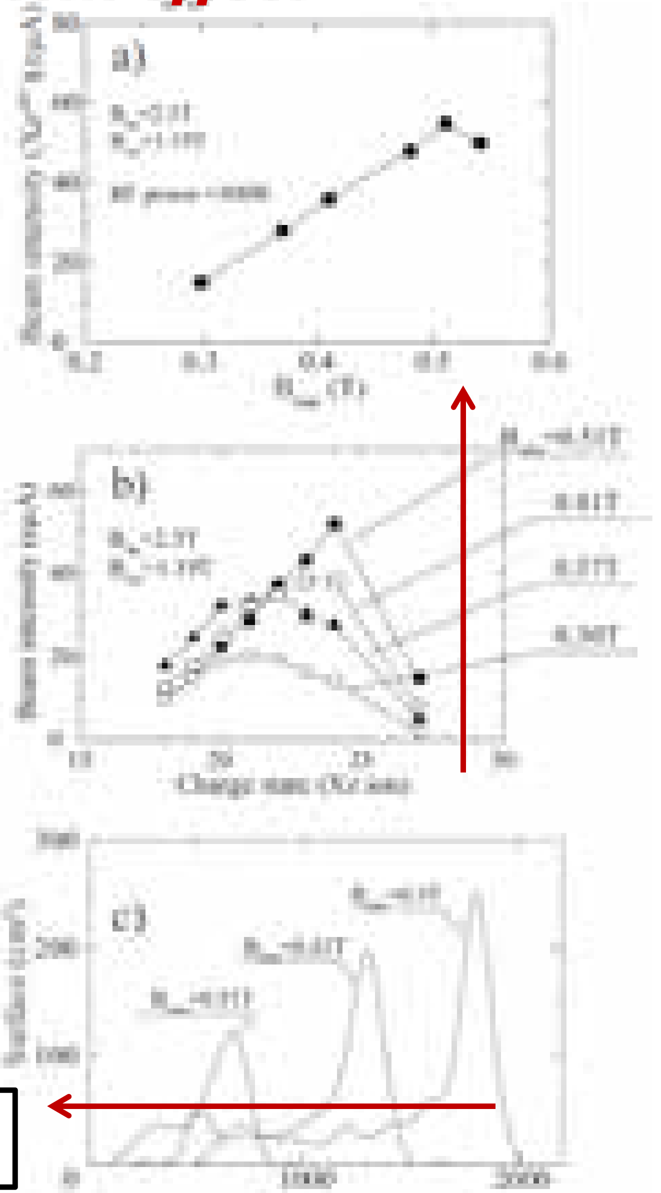


I_{FLAT}>Iclassic

Flexible magnetic field (from “classical” to “flat “ B_{min})

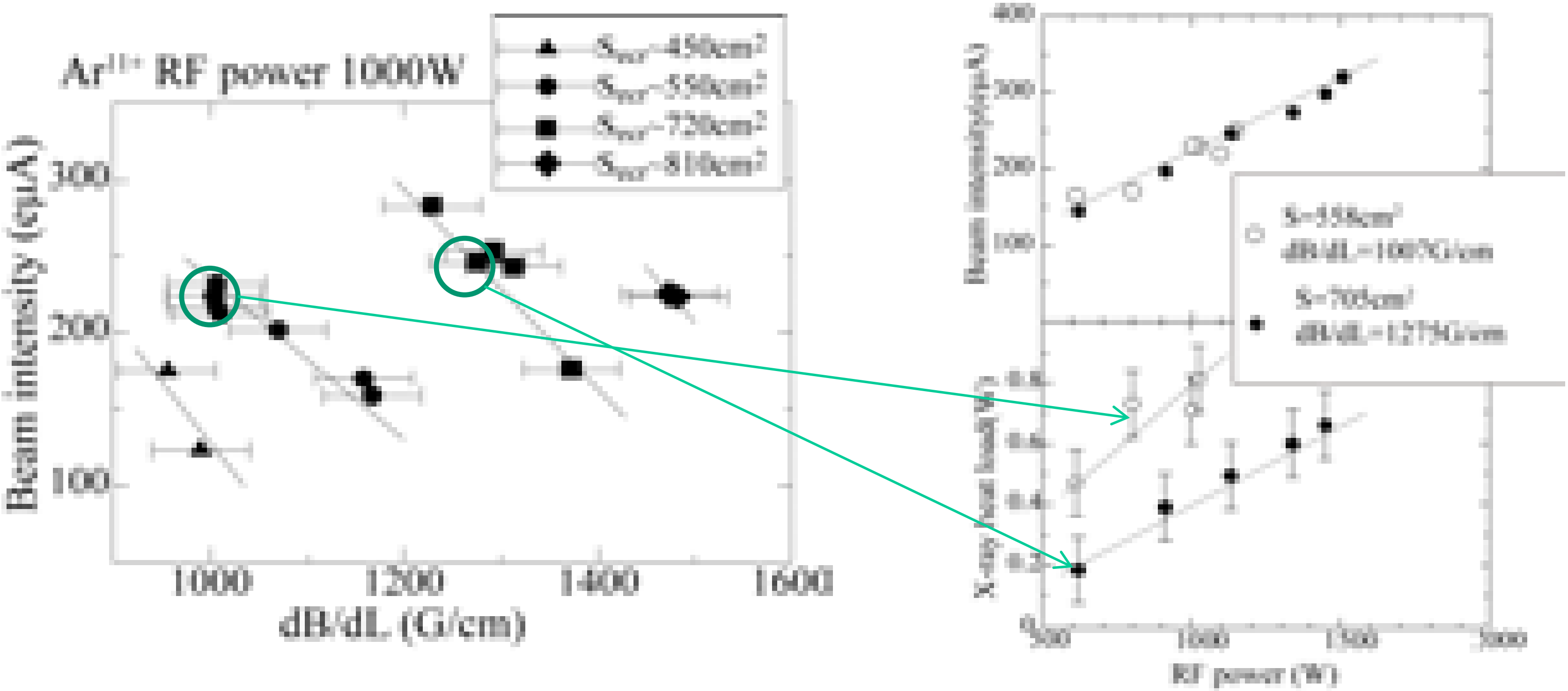
Higher Bmin improves CSD

Gentler grad gives larger energy to el.



Ex., “Flat B_{min} “ structure
G. D. Alton and D. N. Smithe,
Rev. Sci. Instrum. 65 (1994) 775

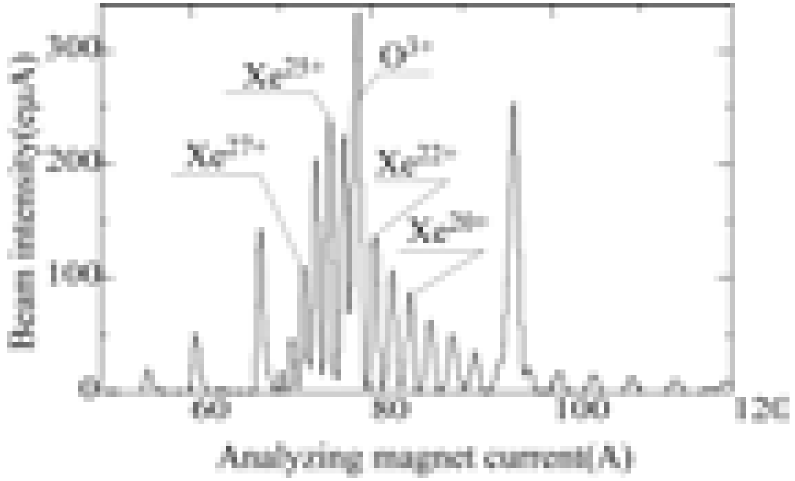
ECR zone size, field gradient effect

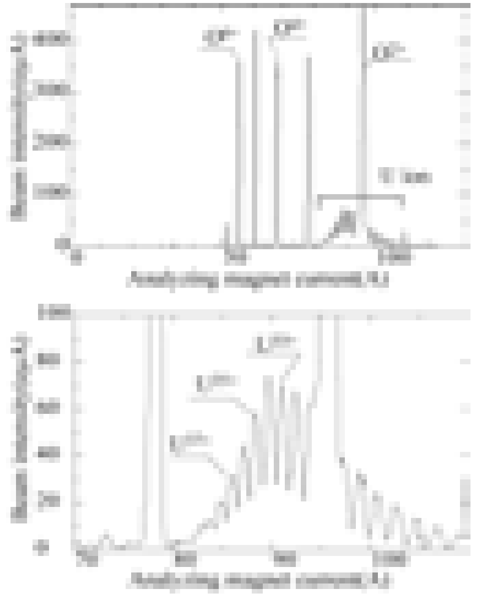


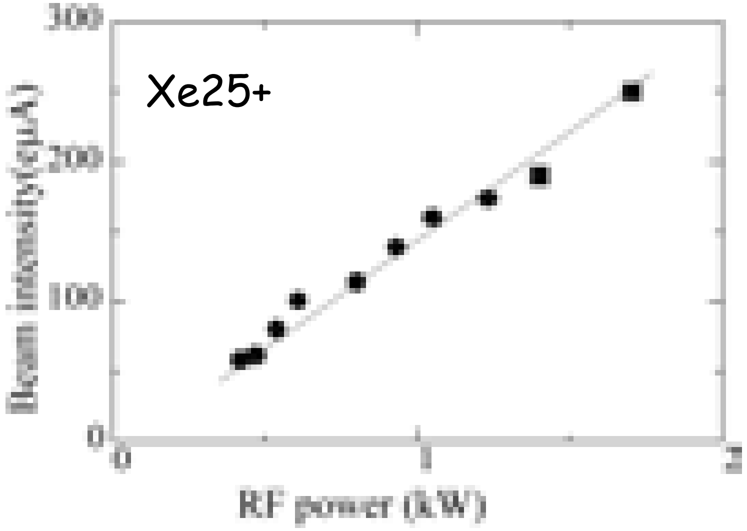
- With same Bmin and magnetic field gradient the source has better perfomance when tuned for larger ECR surfaces
- Slight change in the magnetic field gradient can significantly change the ion beam production when the ECR surface and Bmin are not changed
- X-ray heat load strongly depend from ECR surface dimensions, magnetic field gradient (similar observations at NSCL-MSU)

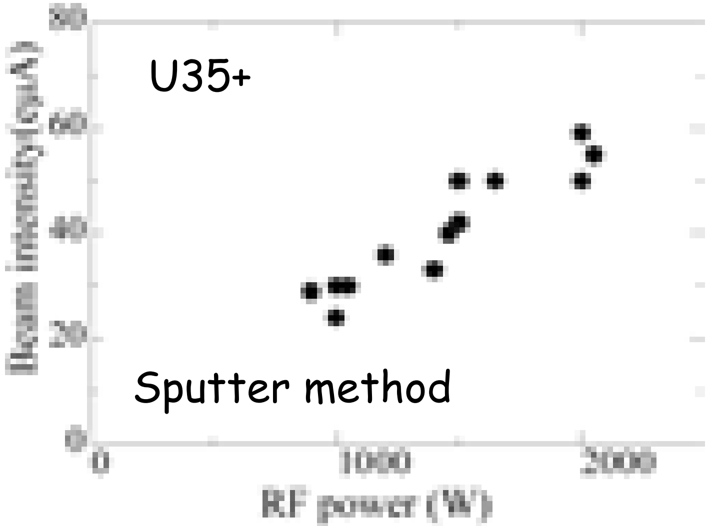
Flexible magnetic field structures important to optimize ECRIS performances

Xe, U ion beam production (28GHz)

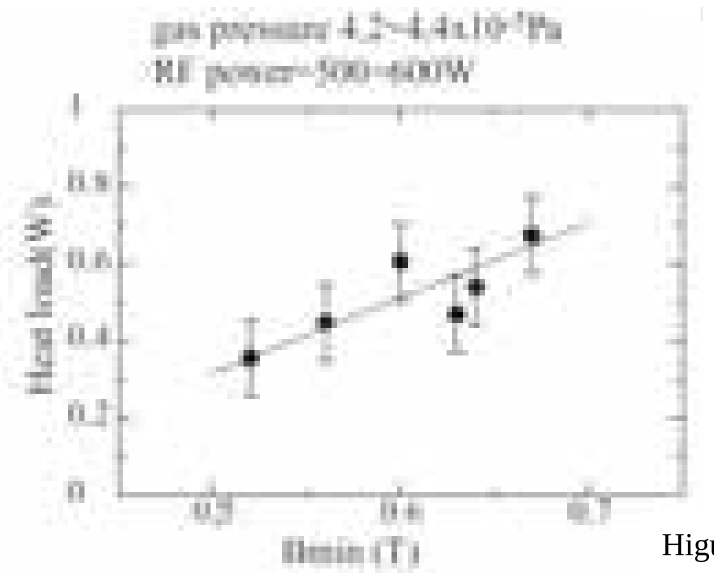




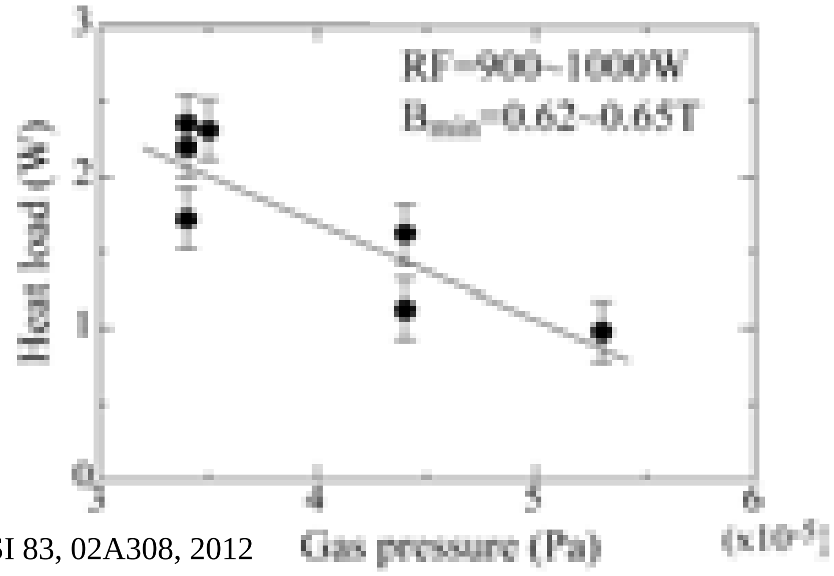


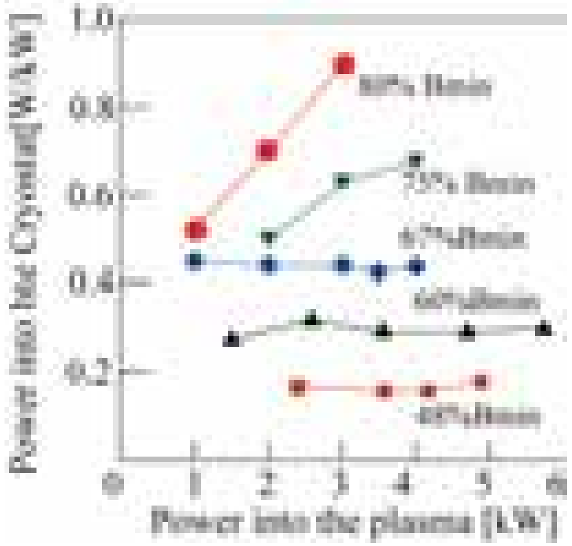


X-ray heat load I



Higurashi et al, RSI 83, 02A308, 2012





D. Leitner et al, Proc. Int. Workshop on ECR ion sources, 2010, Grenoble

Strong X-ray heat load

Higher B_{min}
Low gas pressure

Intense beam of highly charged heavy ions

Outline

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Fourth Generation ECR Ion Sources

- 3^{rd} Generation f ≤ 30 GHz
- 4^{th} Generation 30< f < 60 GHz

Confinement criterion

$$\begin{cases} B_{inj} \approx 3.5\, B_{ECR} & \textit{on axis} \\ B_{ext} \geq 2\, B_{ECR} & \textit{on axis} \\ B_{rad} \approx B_{ext} & \textit{at wall} \end{cases}$$

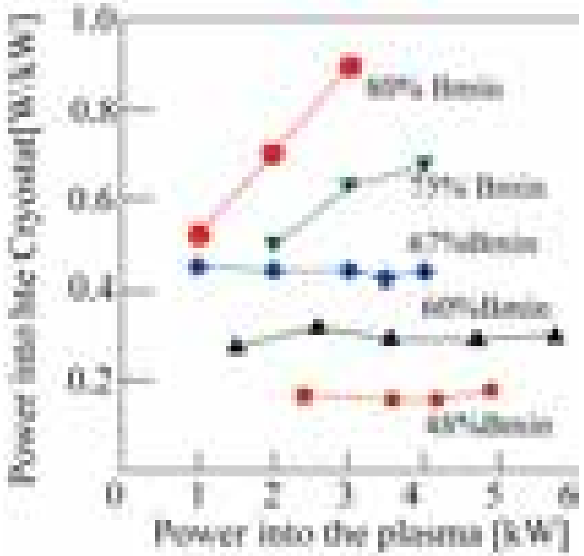
Exceed the critical current of ... at 4.2K

28 GHz	36 GHz	42 GHz	56 GHz
B_{ECR} ~ 1 T	B_{ECR} ~ 2 T	B_{ECR} ~ 2 T	B_{ECR} ~ 2 T
B_{inj} ~ 3.5 T	B_{inj} ~ 4.5 T	B_{inj} ~ 5.3 T	B_{inj} ~ 7 T
B_{ext} = 2 T	B_{ext} = 2.6 T	B_{ext} = 3 T	B_{ext} = 4 T
B_{rad} = 2 T	B_{rad} = 2.6 T	B_{rad} = 3 T	B_{rad} = 4 T

At > 40 GHz magnetic field is a significant challenge and requires Nb_3Sn superconducting magnets

Fourth Generation ECR Ion Sources

- Gyrotrons at 53, 60 and 70 GHz at 200 kW for 100 ms can be run at 30 kW cw. “No problem” to extend to 50 kW cw.
- Power requirements and chamber cooling
  - The heat deposition on the plasma wall is highly non-uniform and ‘burnout” is the major concern.
- Bremsstrahlung heating of the cryostat will require significantly more cryo-cooling power.



10kW RF power

↓

~10W heat load (28GHz)

>28GHz
We need higher cooling power (>10W)

↓

GM-JT cryo-cooler (~5W at 4.2K)

Why is this the time to develop a 4th Generation ECR Ion Source?

- Heavy ion driver requirements are beyond the reach of 3rd Generation Source performance

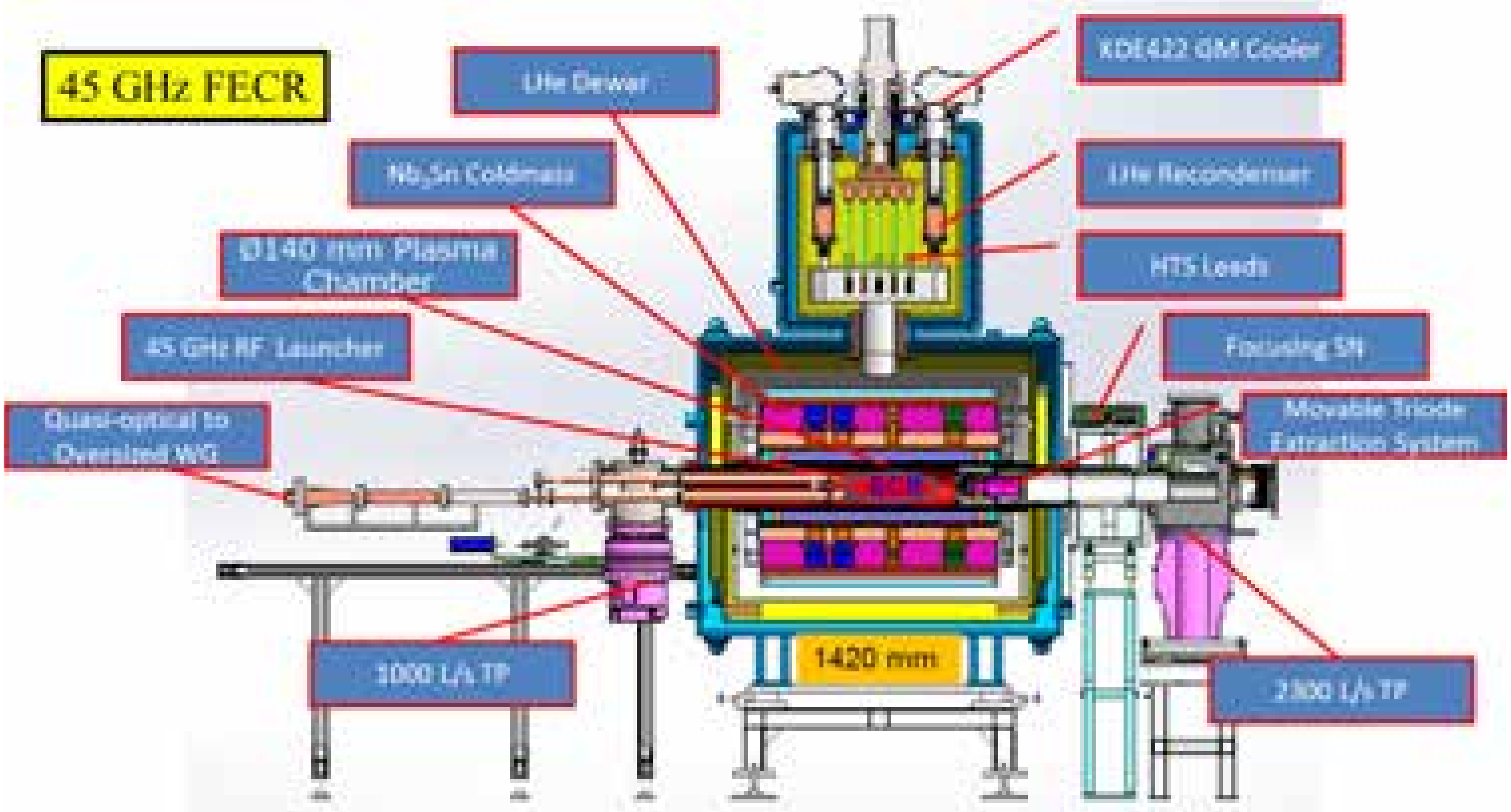
- The R&D time needed for a new generation source is quite long. Example: VENUS (9 years from proposal to 28 GHz operation)

- High Energy Physics is driving the technology for Nb3Sn magnets—LHC upgrade—
  - **Nuclear physics can take advantage of these developments**

- While the magnets are the most demanding technical challenge—The design studies show it is feasible to build an 4th Generation source at f ≥ 50 GHz

- The cost of such a source should only be about 2 or 3% of the cost of a state-of-the-art Rare Isotope Beam facility

FECR: first 4th generation ECRIS



IMP CAS – FECR

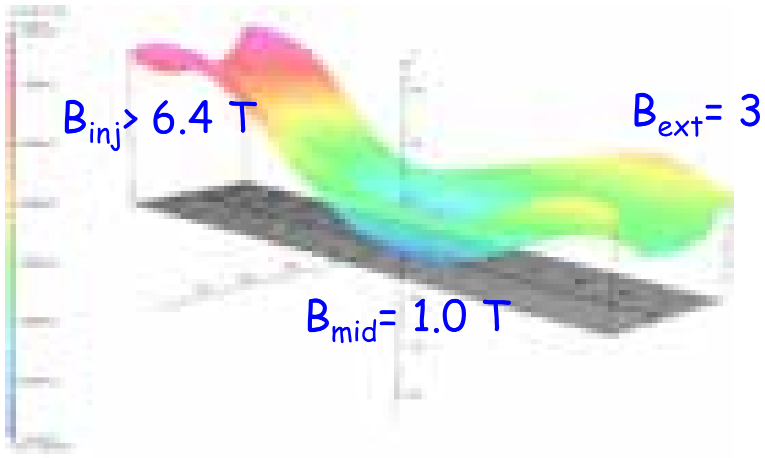
Key parameters – Intensities expected

Microwave	45 GHz/20 kW
Magnet conductor	Nb_3Sn
Axial fields (T)	6.5/1.0/3.5
Sextupole field (T)	3.8T@r=75 mm
Maximum field (T)	11.8 T
Maximum stress (MPa)	150
Magnet bore (mm)	>Ø160
Stored energy (MJ)	1.6
Extraction (kV)	50
Typical beam	1.0 emA U^{35+}

	Nominal engineering current density J_e (A/mm²)	Nominal wire current I_e (A)	Nominal peak field B_{peak-n} (T)	Load factor (%)
Sext.	320	654	11.3	**75.9**
Inj.	365	692	11.8	**78.2**
Mid.	-200	380	5.0	**36.5**
Ext.	330	626	9.7	**67.3**

$^{129}Xe^{30+}$	>1000 μA
$^{129}Xe^{45+}$	> 50 μA
$^{209}Bi^{31+}$	>1000 μA
$^{209}Bi^{55+dd}$	> 50 μA
$^{238}U^{35+}$	>1000 μA
$^{238}U^{41+}$	> 200 μA
$^{238}U^{56+}$	> 30 μA

51

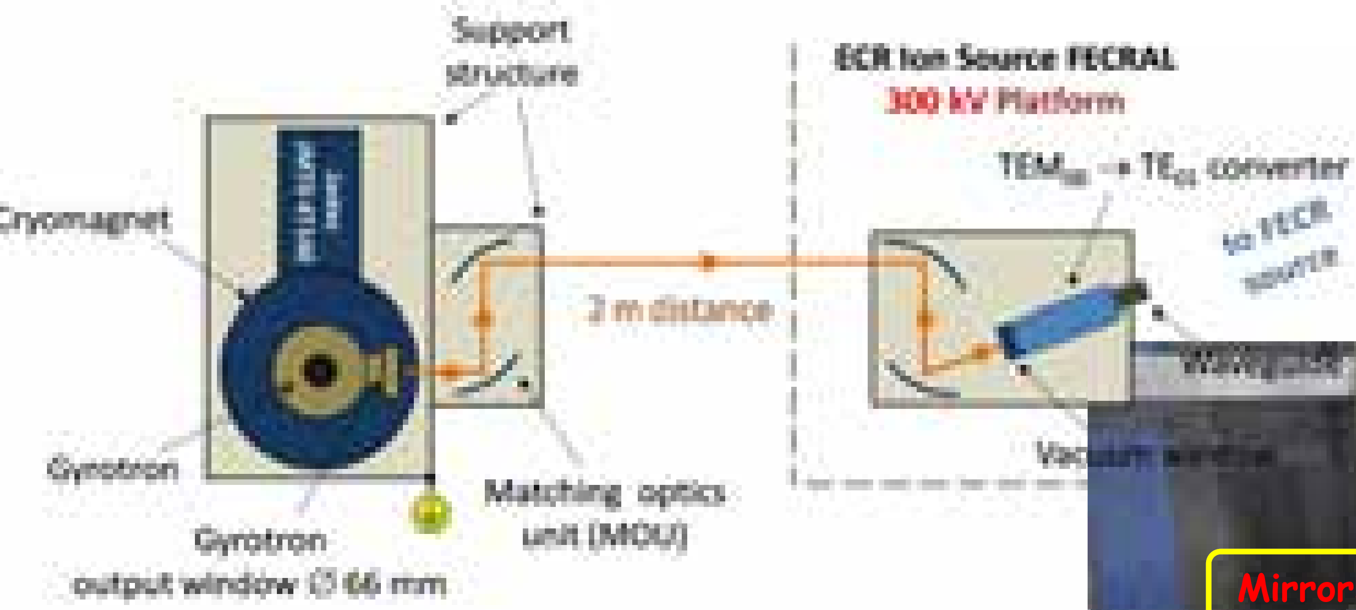


Nb3Sn Sextupole coil

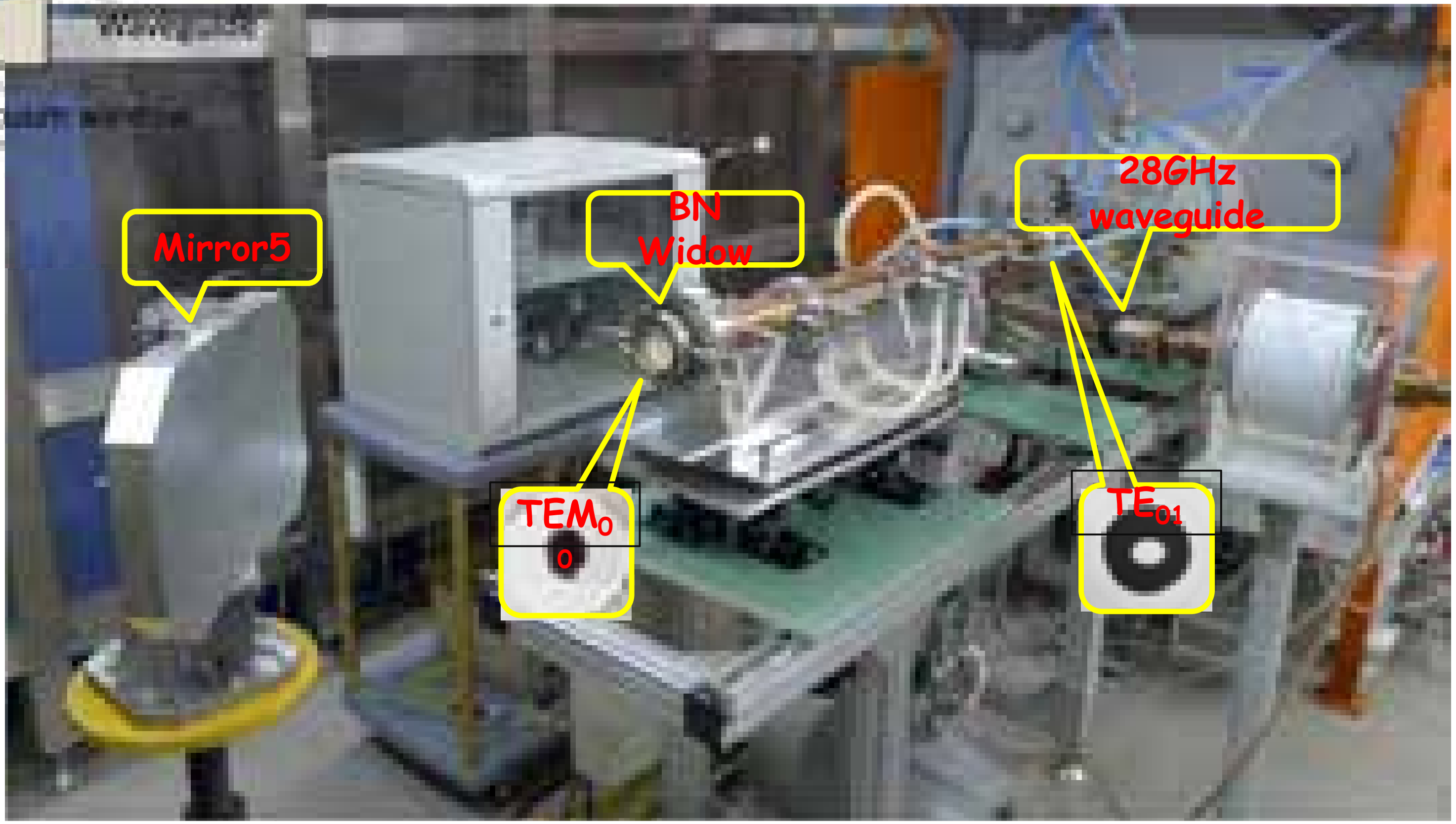
- Coil winding
- Pre-curing
- Heat treatment
- Epoxy impregnation
- Coil insulation check
- Coil cryogenic and quality test

- Test of the first ½ length sextupole coil failed due to insulation damage.
- The second coil is being built with improved winding tooling by two companies.

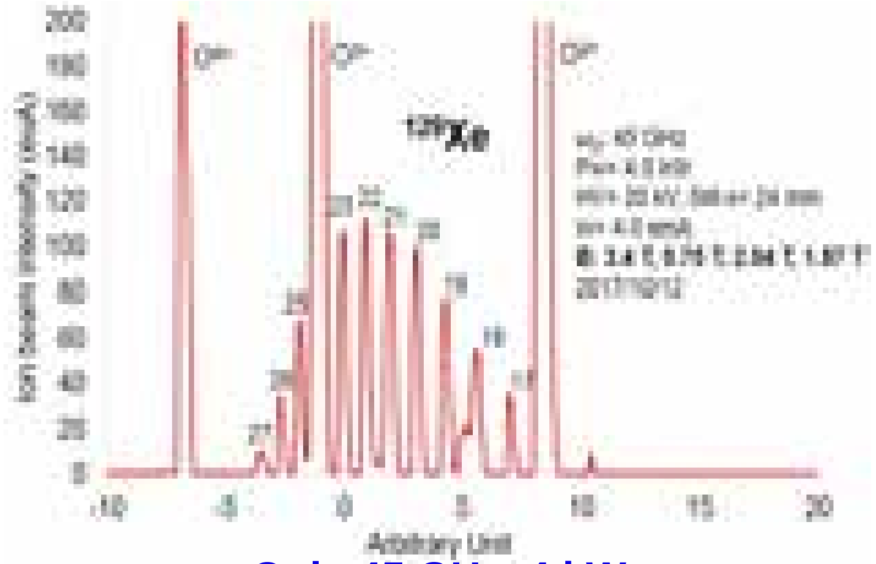
45 GHz quasi optical coupling



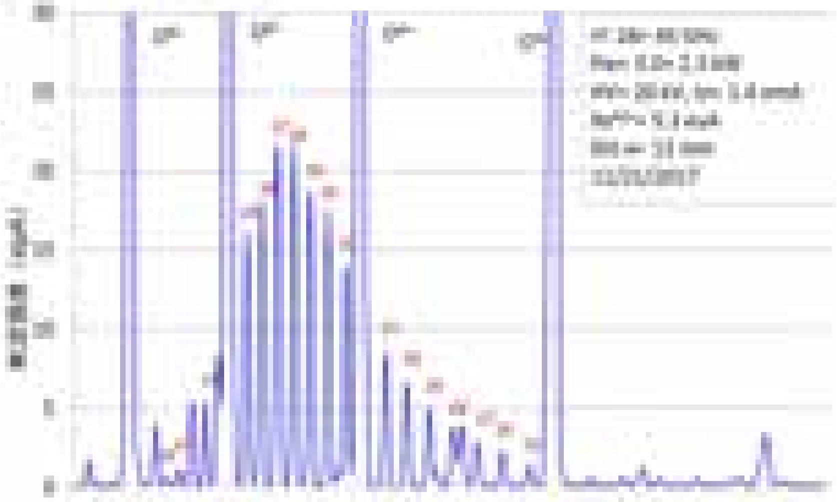
Total efficiency of quasi-optical transmission line and mode converter is about 97%.



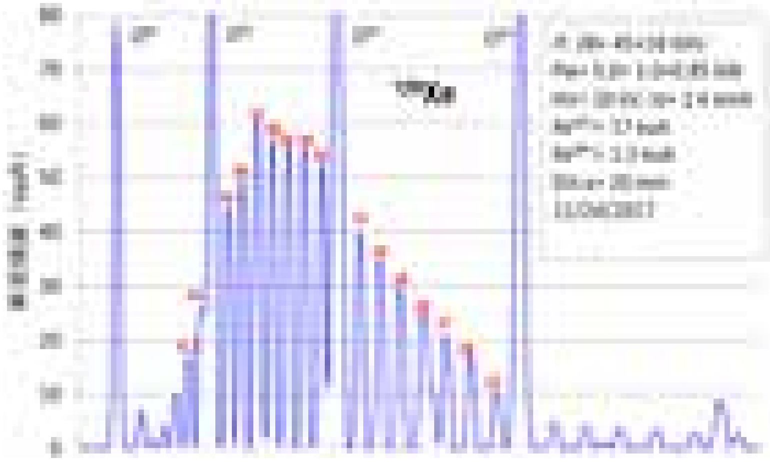
Beam production



Only 45 GHz, 4 kW



28+ 45 GHz, 3.0+2.3 kW



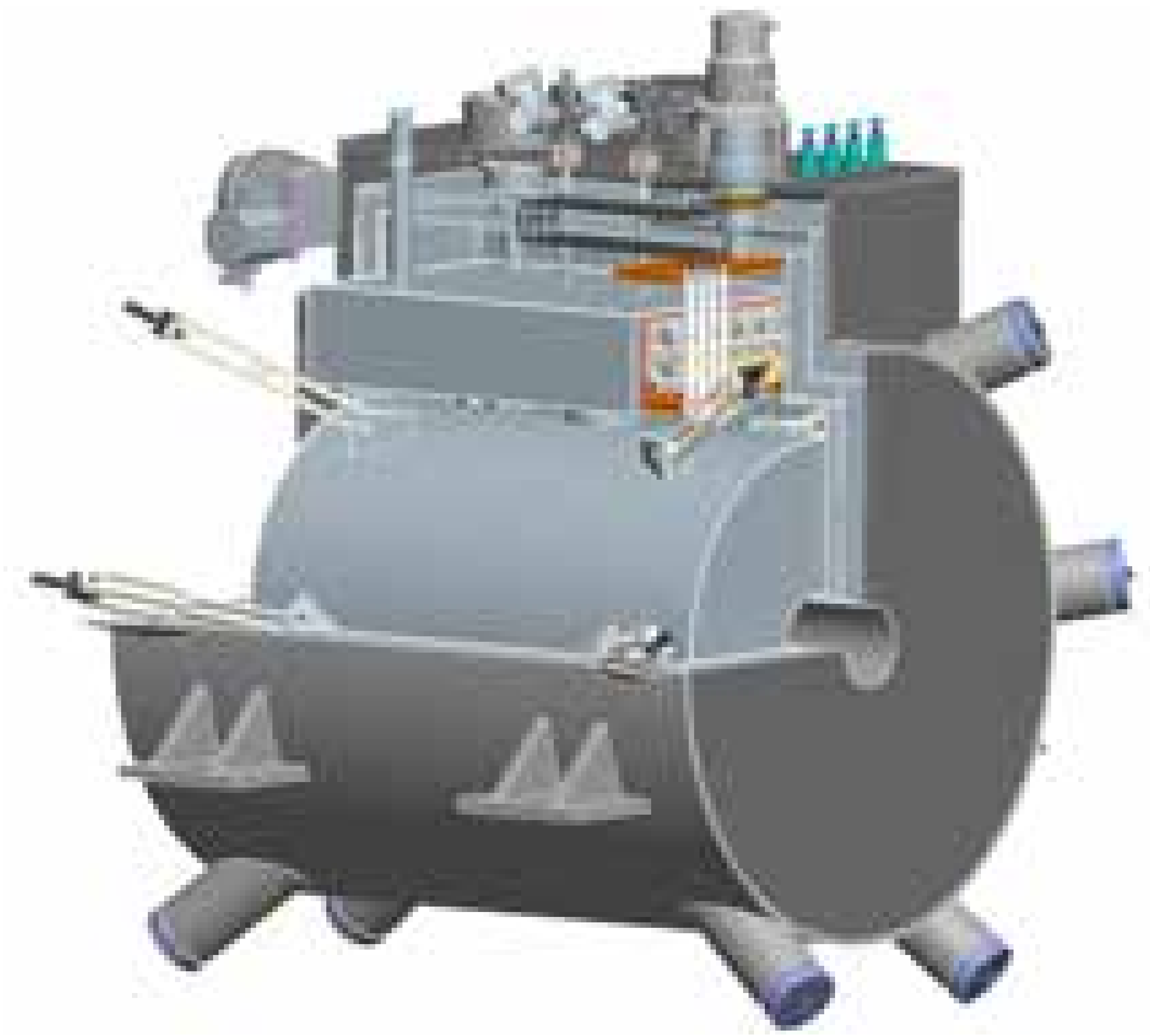
28+45+18 GHz, 5.0+1.0+0.85 kW

Ion	VENUS 28+18 GHz (eμA)	SECRAL 24+18 GHz (eμA)	SECRAL-II 45+28+18 GHz (eμA)
^{129}Xe [illegible]	26	22.6	53
Xe [illegible]	6	—	17
Xe [illegible]	2	1	3.9
Xe [illegible]	0.88	0.1	1.3

H.W. Zhao, et.al. RSI, (2018)

Total microwave power is different for the three cases

LBNL – ECRIS 56 GHz



- Two 5 W GM-JT cryocoolers at 4.2 K
- One shield cryocooler 6 W at 20 K and 120 W at 77 K
- High Tc leads
- Static heat load 1.5 W
- Magnets on + 0.15 W
- Warm bore 170 mm ID

Plasma chamber	140 mm ID	
Cryostat warm bore ID	170 mm ID	
Sextupole coil ID	200 mm ID	262 mm OD
Sextupole length	1000 mm	
Injection solenoid	326 mm ID	429 mm OD
Extraction solenoid ID	326 mm ID	425 mm OD
Middle solenoid	326 mm ID	429 mm OD
Inj-ext coil separation	500 mm	
Axial fields for 56 GHz	Inj. 8 T	Ext. 5 T
Sextupole field r = 70 mm	4.2 T	
B_{mod} closed surface	>3.8 T	

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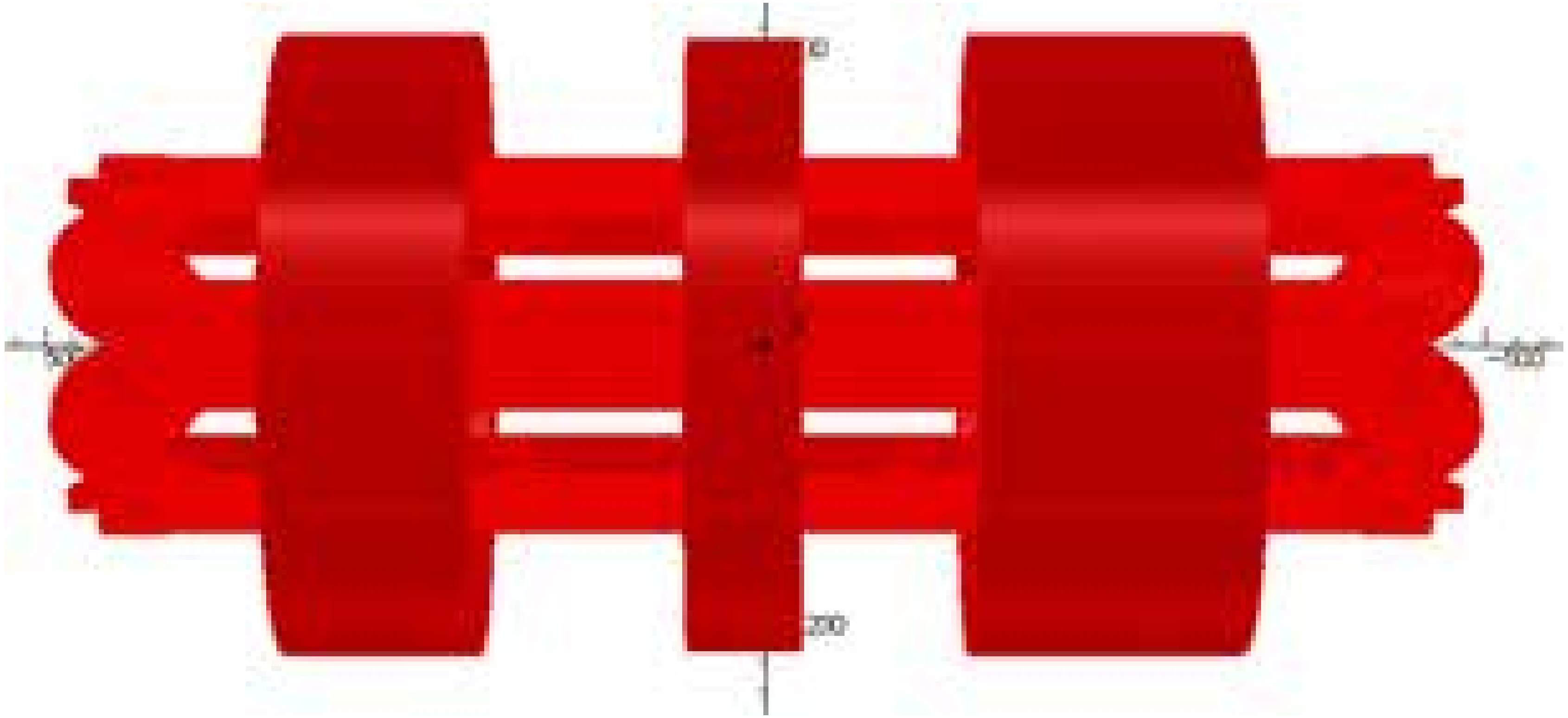
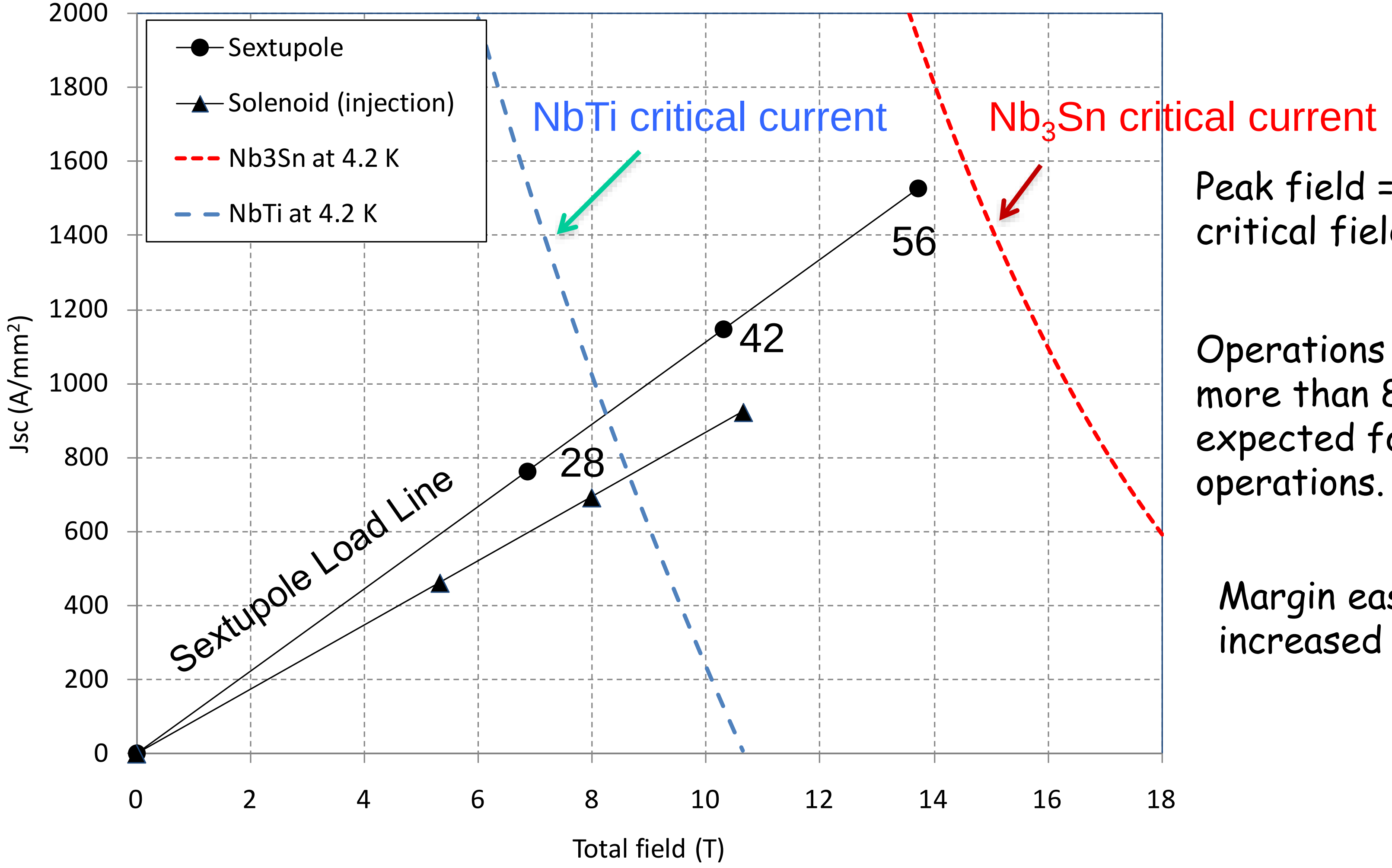
LBNL ECRIS 56 GHz

Starting point—VENUS Geometry
Frequency---56 GHz (twice that of VENUS)



Operational condition at 28 – 42 – 56 GHz (Binjection = 3.5 Becr)

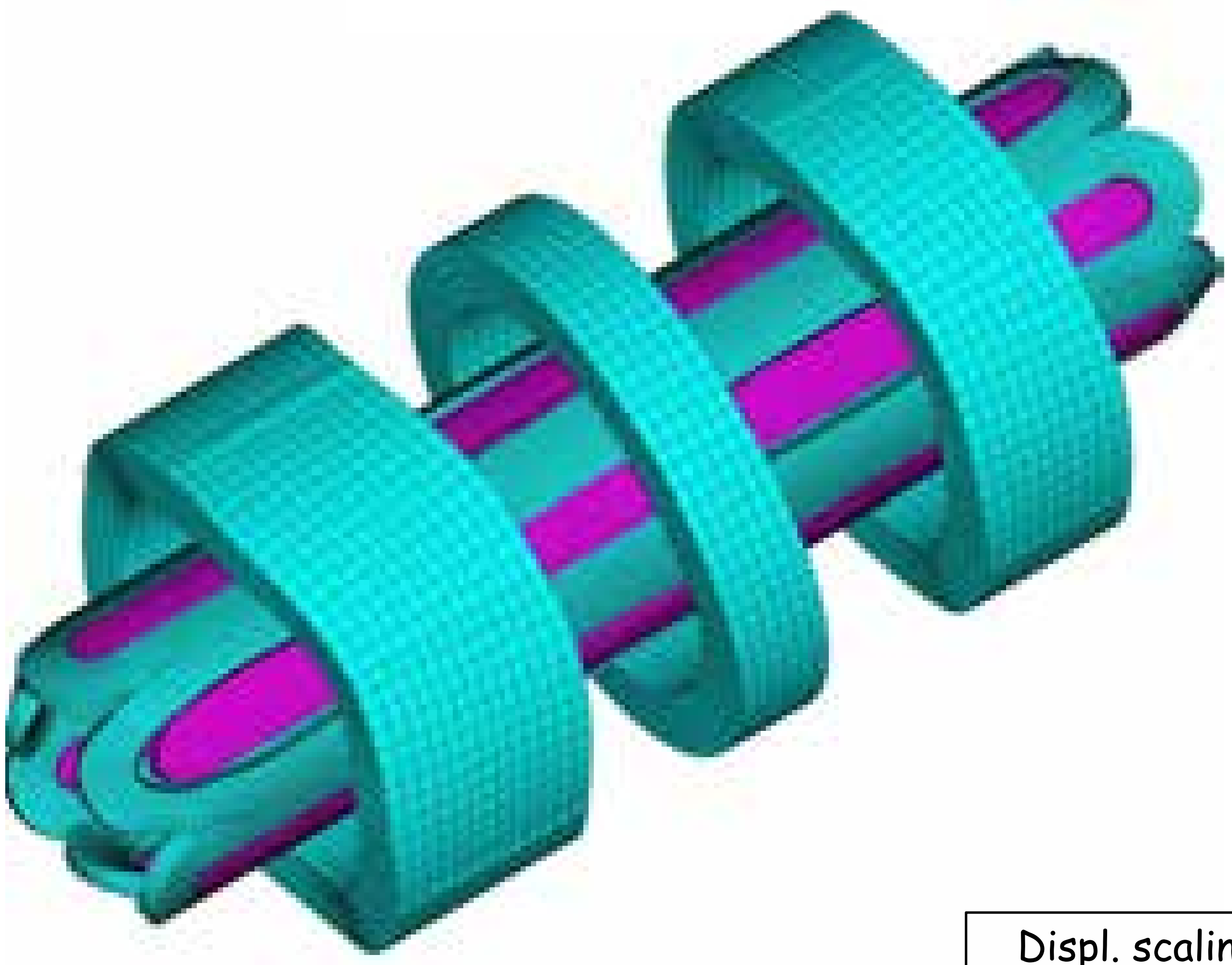


Peak field = 94% of critical field

Operations at no more than 85% are expected for stable operations.

Margin easily increased

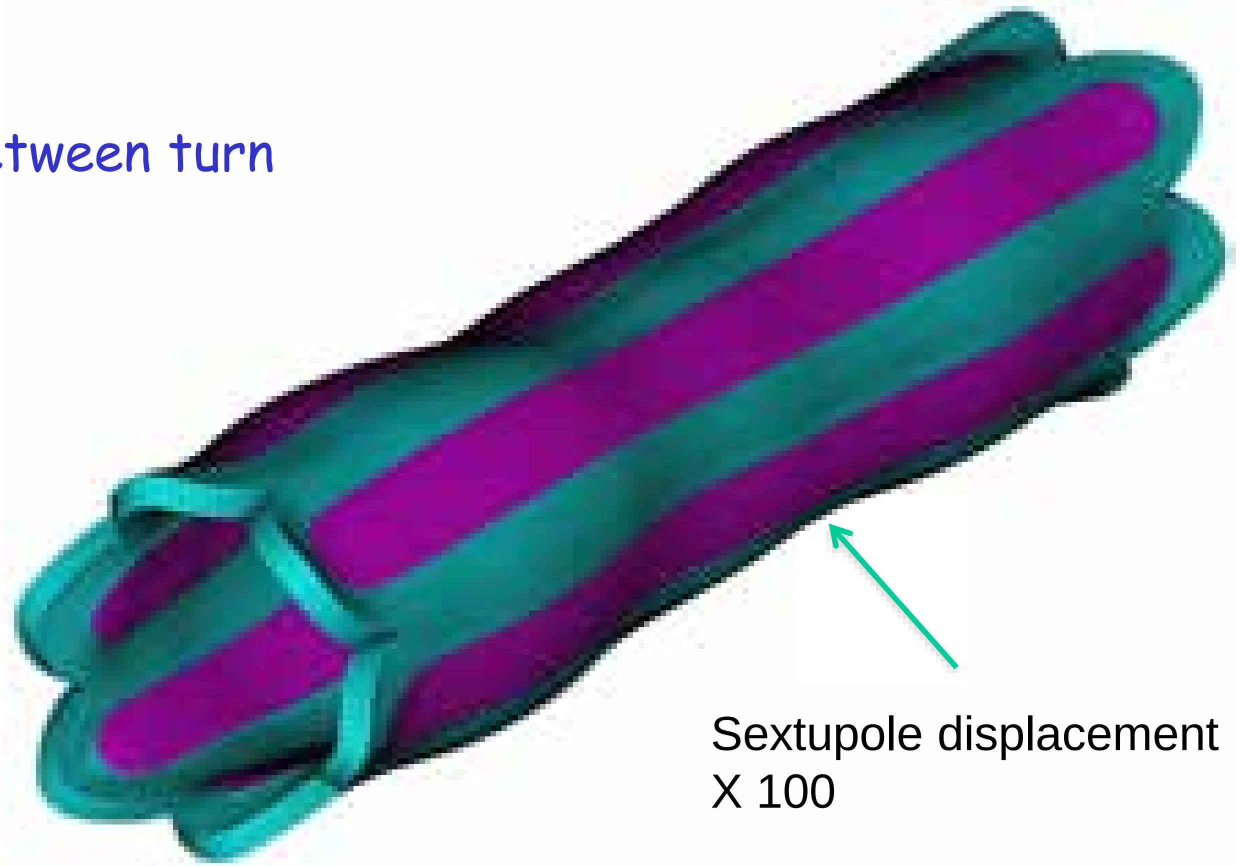
Sextupole and solenoid e.m forces Deformed shape



Displ. scaling = 100

3D analysis with real structure

- All the components of the impregnated coil bonded
  - Both sextupole and solenoids
- Output
  - Peak stress --OK
  - Bonding tension between turn and pole
    - <20 Mpa--OK

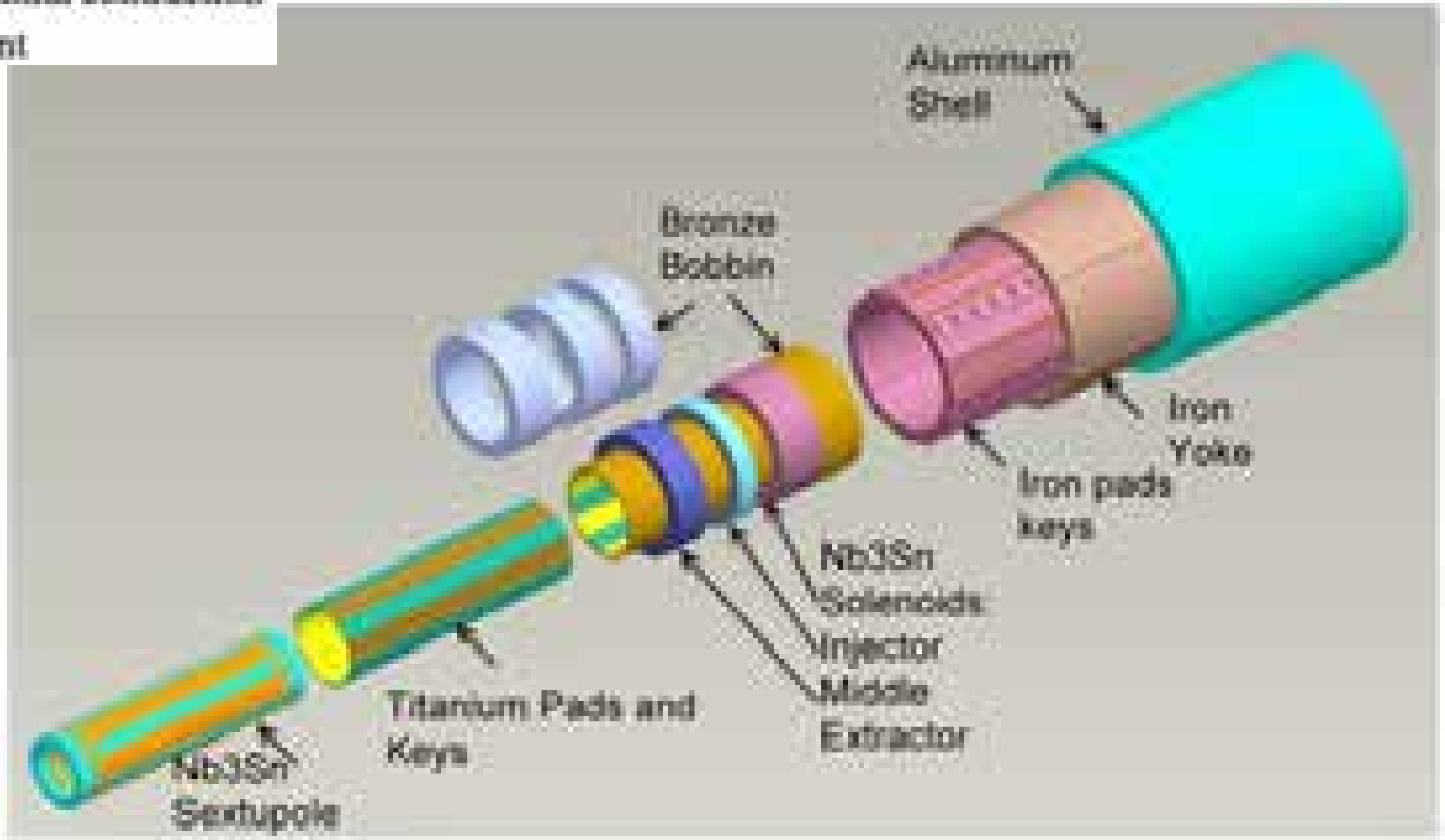


Sextupole displacement
X 100

Magnet support structure

Shell structure and keys to prestress

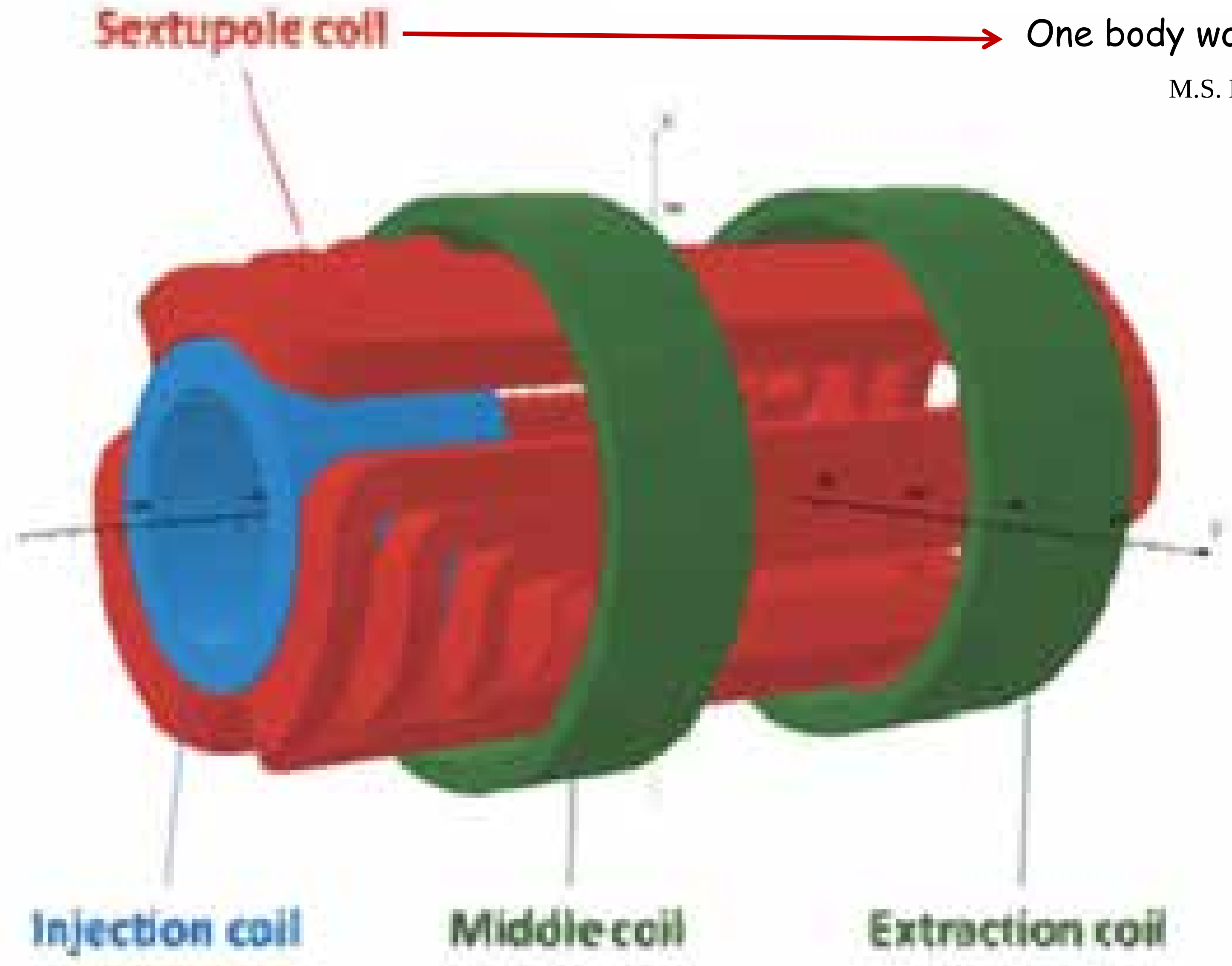
- Primary mechanical support is provided by a thick Aluminum shell
- Assembly (warm) pre-load by pressurized bladders and interference keys
- Pre-load increase at cool-down due to shell-yoke differential contraction
- The coils remain in compression up to the operating point



Because of large e.m. forces acting on the SC material, the magnets require precise control of the preload in order to minimize conductor motions at 4.2 K.

S. Prestemon, F. Trillaud, S. Caspi, P. Ferracin, G. L. Sabbi, C. M. Lyneis, D. Leitner, D. S. Todd, and R. Hafalia, IEEE Trans. Appl. Supercond. 19(3), 1336 (2009)

MK1 new approach to 4th generation ECRIS



One body wound closed loop multipole using Ioffe bars.

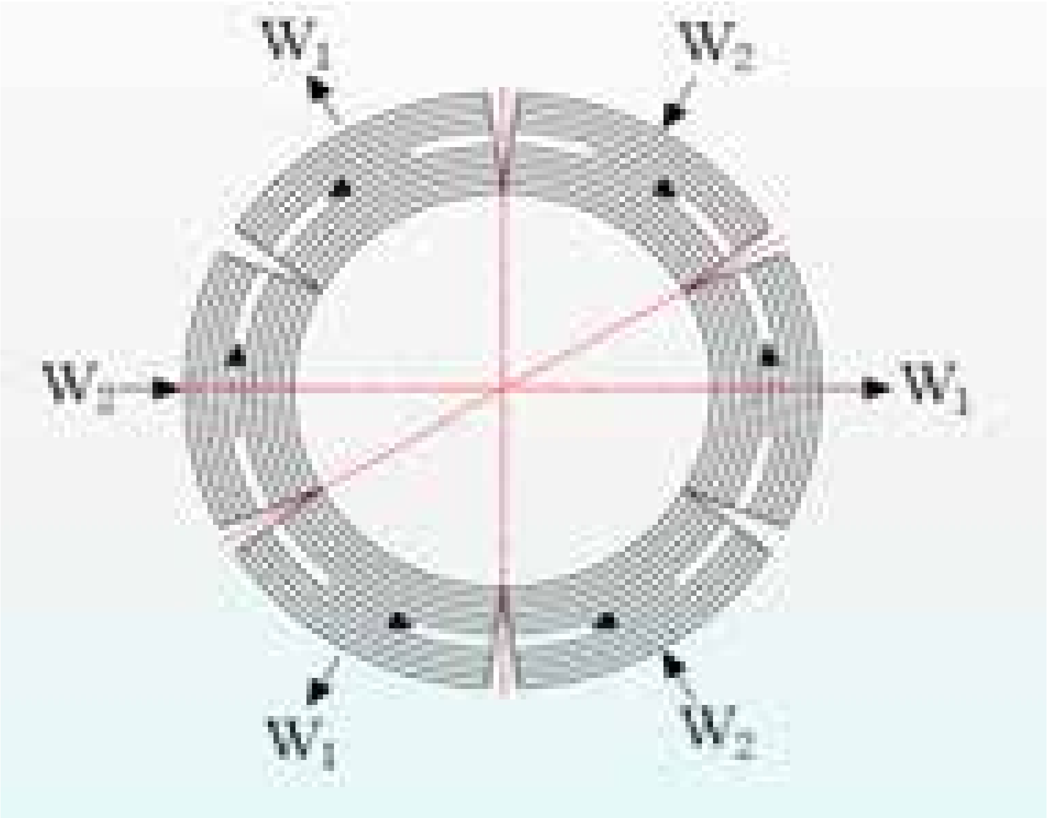
M.S. Ioffe and B.B, Kadomtsev, Sov. Phys. Usp. 13, 225 (1970)

6 rect. bars

All of the Azimuthal Currents Flows in the same Directions!

No Repulsions between the Solenoids and the Sextupole Ends

Classical hexapole structure of 6 racetrack coils



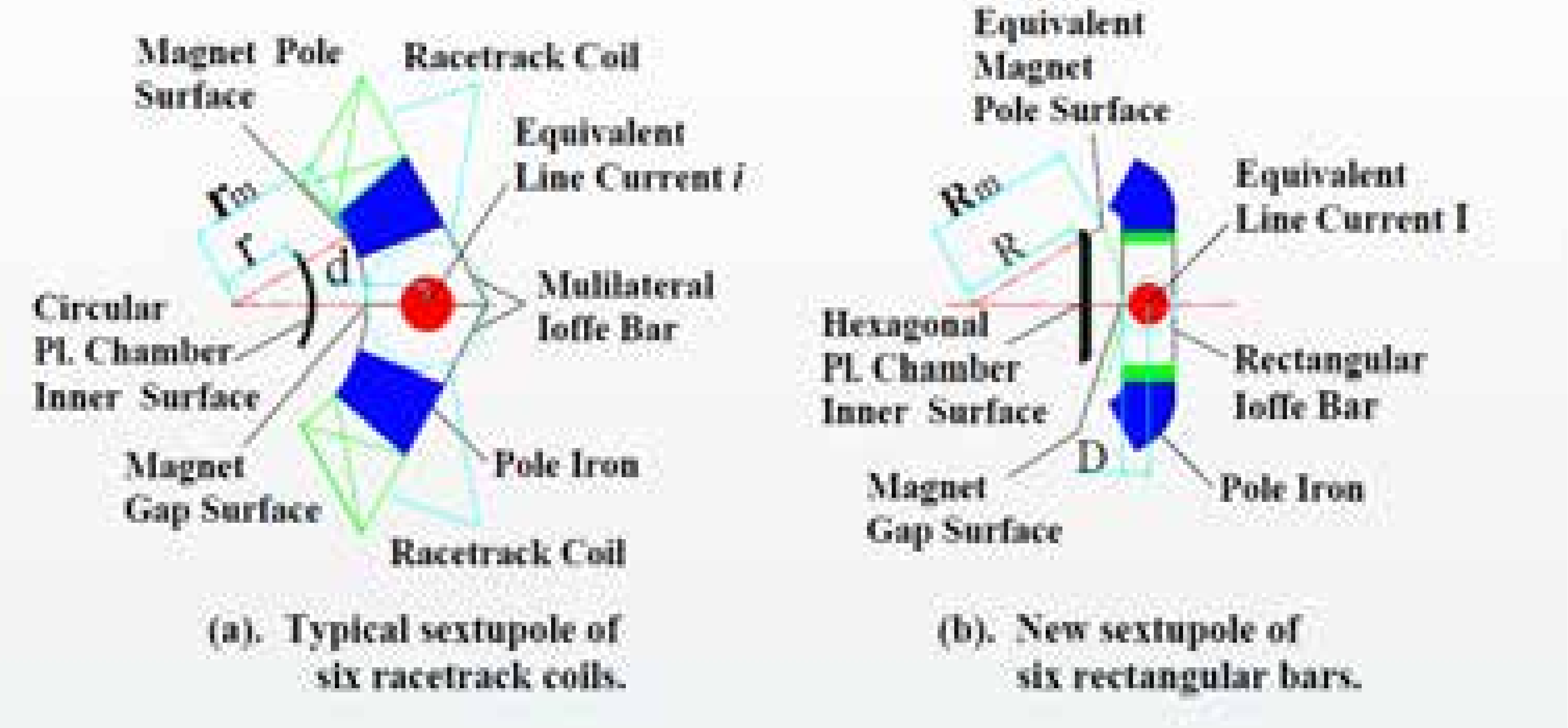
- No Axial Field Contributions due to the opposite end turn currents
- The alternating current flow interacts with the axial fields resulting in a set of strong radially outward W1 and inward W2 forces, as well as axial repulsions and attractions on the solenoids

Sextupole ends have to be axially extended

Bulky magnet and cryostat, higher radial repulsions

62

Rectangular Ioffe bars yields better form factor

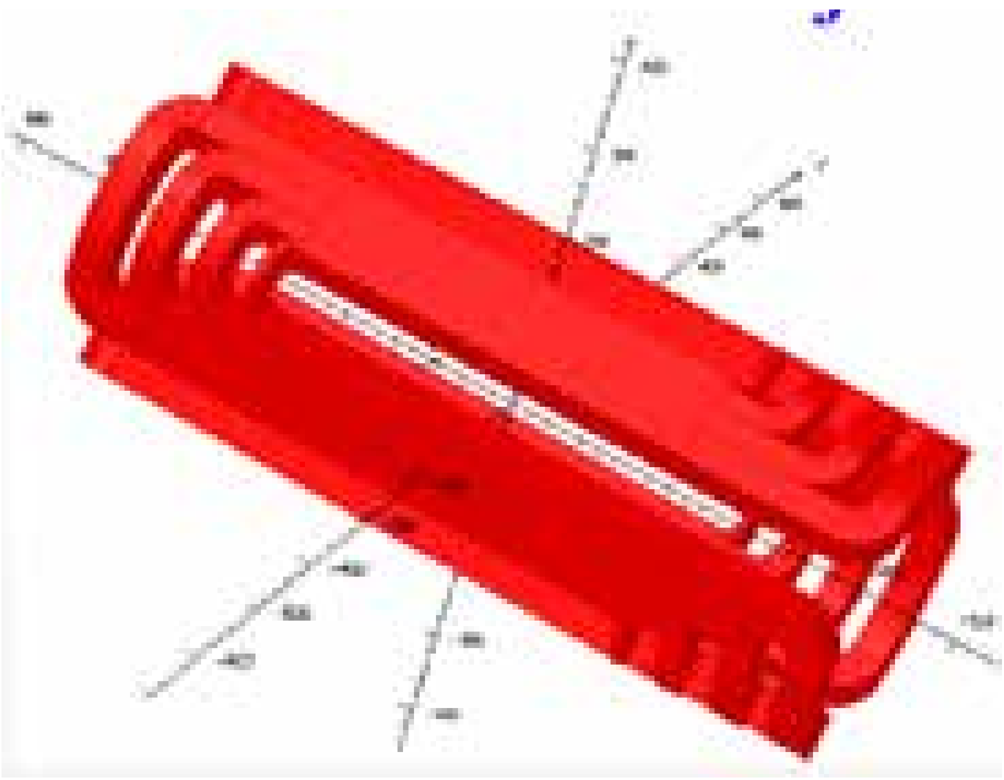


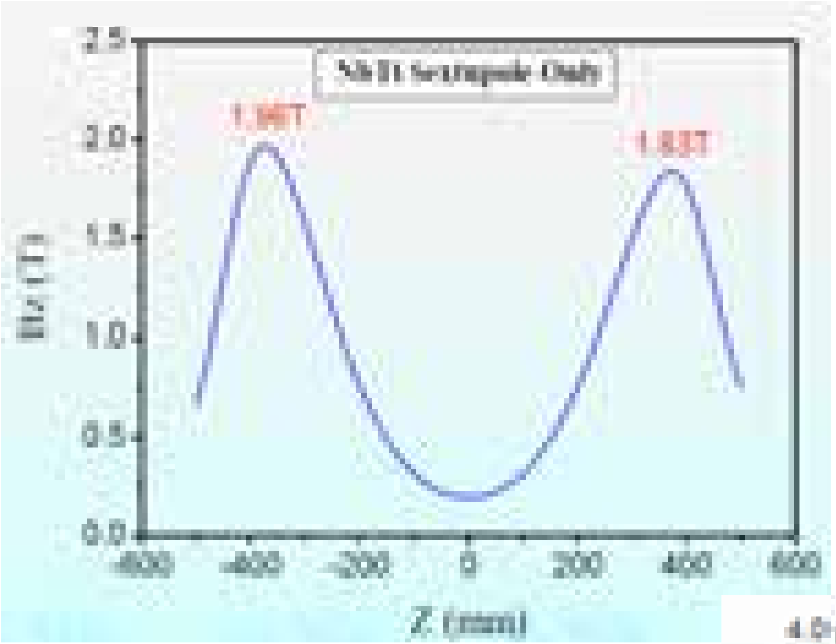
(a). Typical sextupole of six racetrack coils.

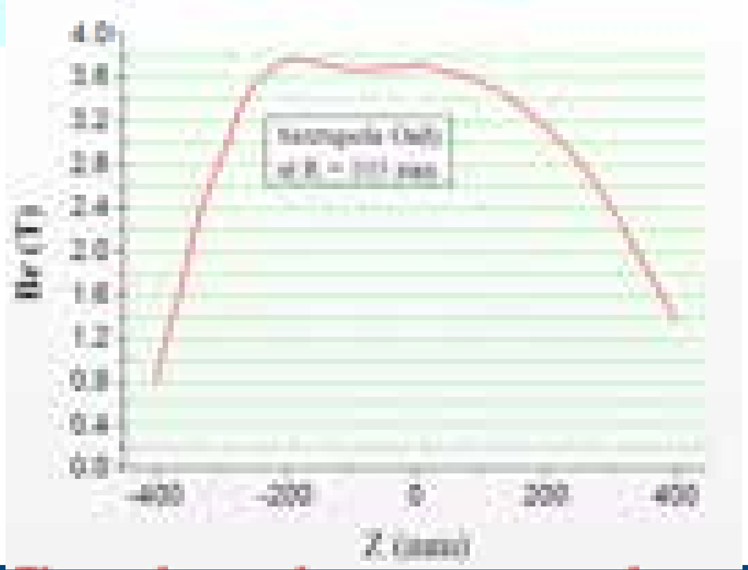
(b). New sextupole of six rectangular bars.

Under the condition of equal field strength at the magnet pole and gap surfaces, the rectangular bars can be designed with shorter distance from the bar center to the gap surface.

Closed loop sextupole



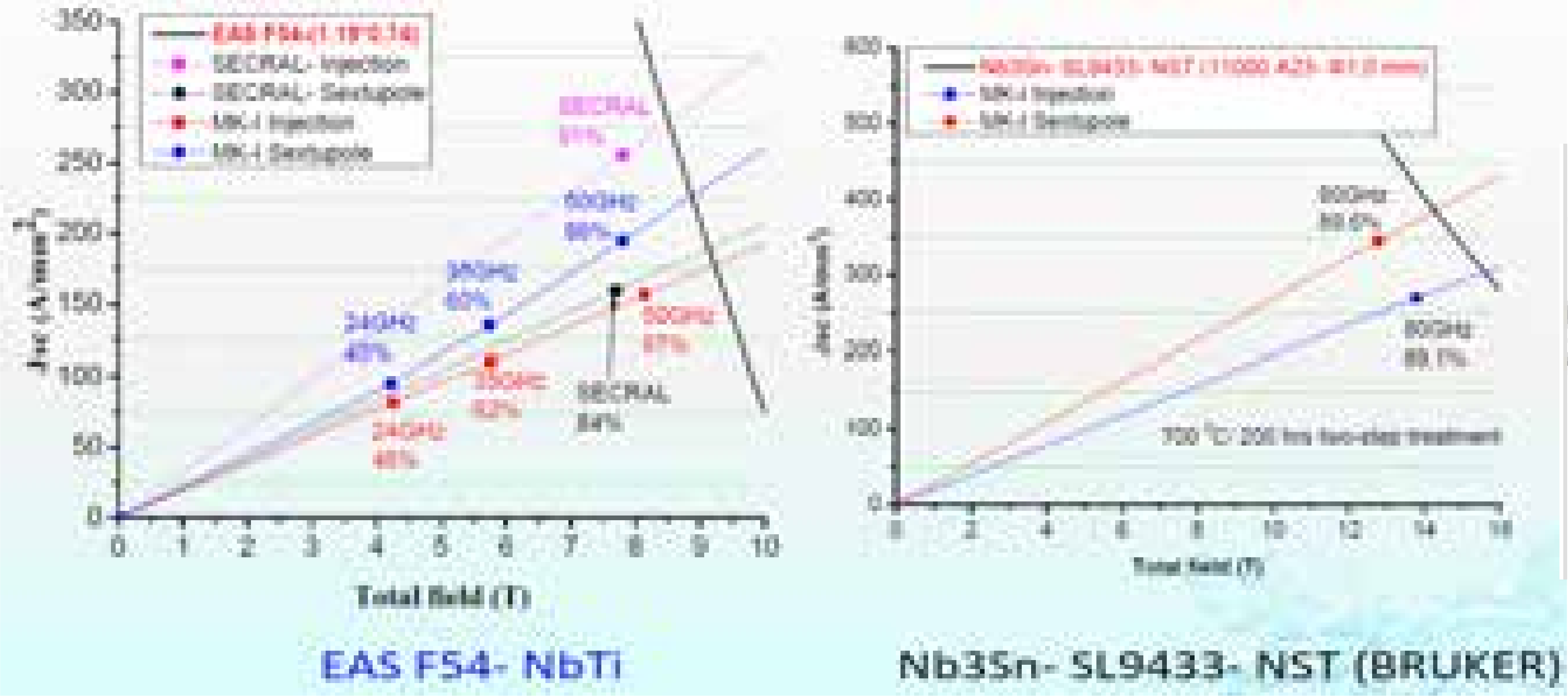


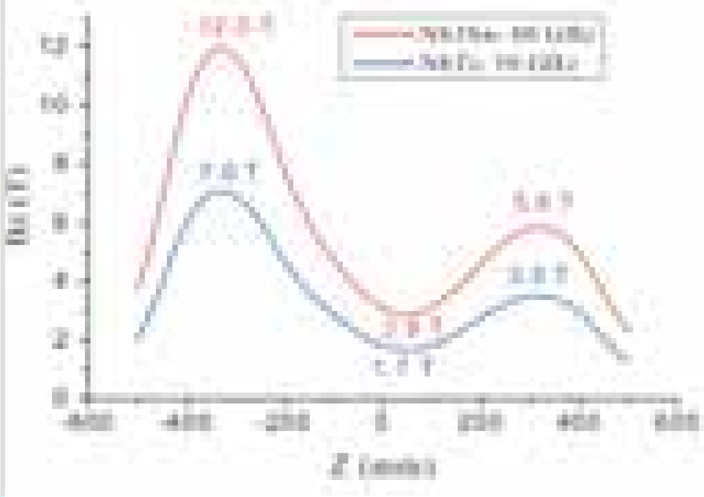


The closed-loop sextupole axial contributes almost 30% of the injection and more than 50% of the extraction mirror fields.

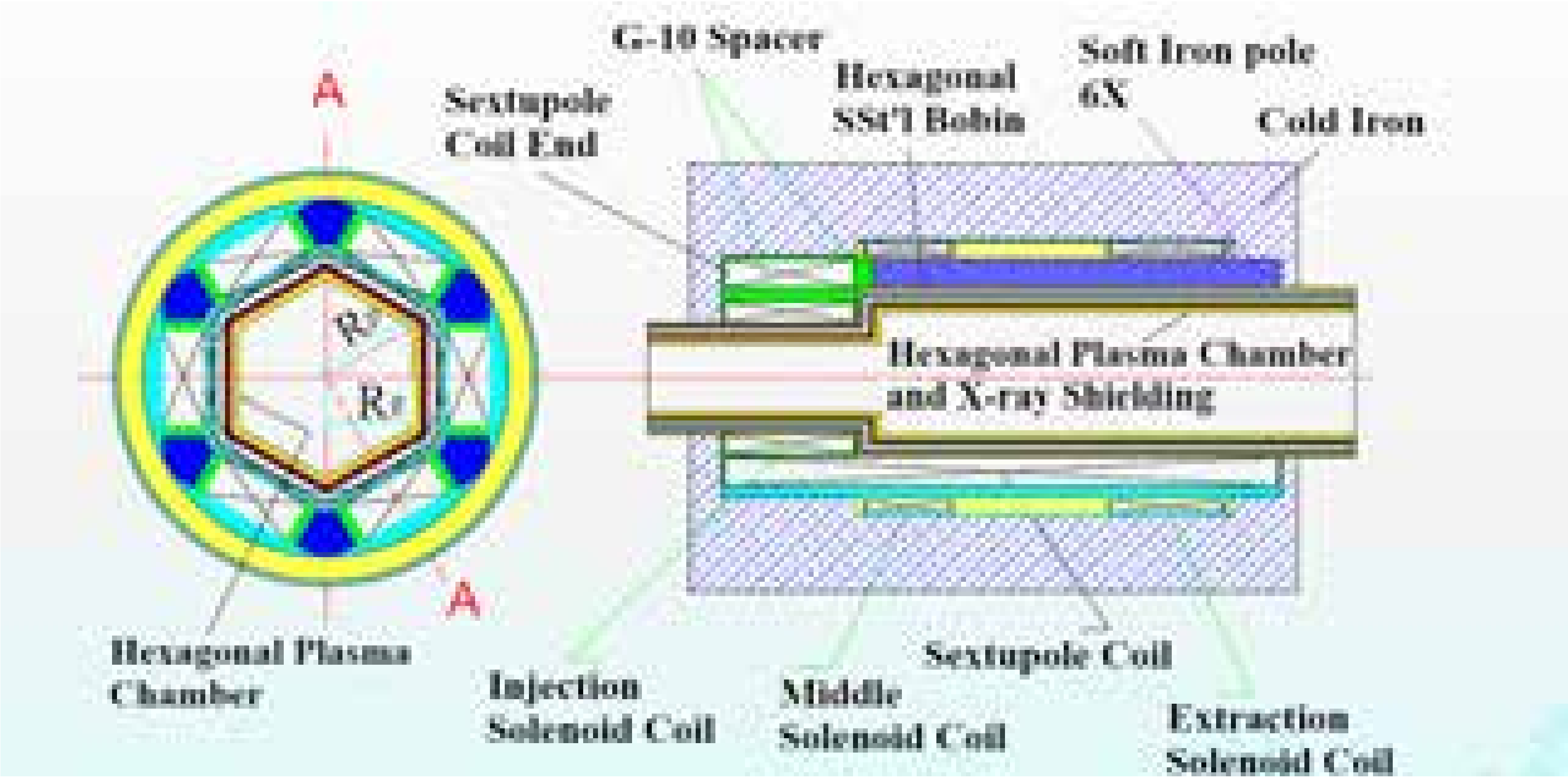
WIRE TENSION ISSUE

Current Loading of NbTi and Nb3Sn Wires





The new magnetic structure



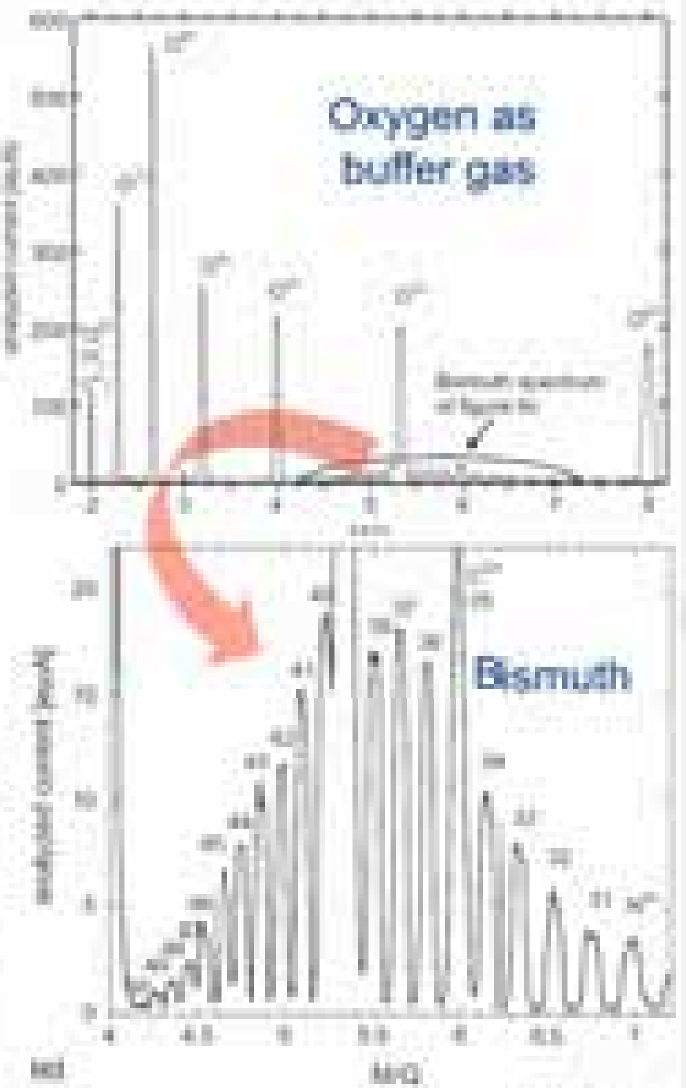
Pro: A very promising new magnet structure for higher-field ECRIS with many advantages over the existing magnet structures

Cons: Needs a stepped cryostat with partial hexagonal warm bore and plasma chamber; Complexity of the new sextupole winding

GAS MIXING

Gas Mixing

- Discovered at KVI (Holland)
- Add He or O_2 gas helps improving high charge state production in an ECR Ion Source
  - Usually He is used for mixing with atomic masses A<16 (O)
  - Usually O is used to mixing with heavy masses A>16
- The extra O or He injected is used as the main buffer gas that sustains the plasma
- The other compound to be highly ionized is injected in low quantity with respect to the buffer gas
- the charge state distribution of the atom of interest shifts to very high charge state (eg fully stripped Ar^{18+} beam)



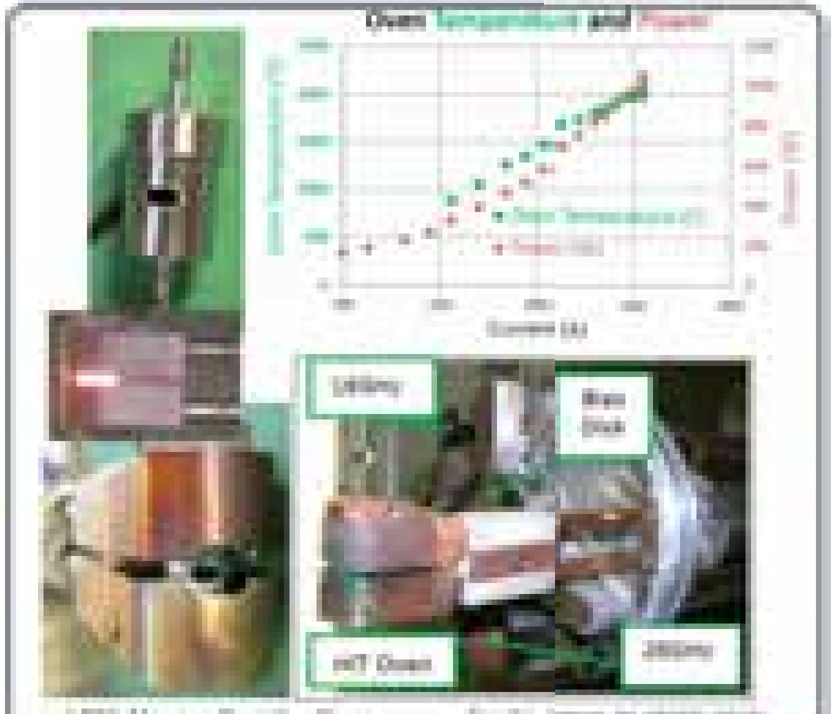
Very high charge states obtained in VENUS with the gas mixing technique

- The high plasma density of ECR ion Sources features a short mean free path for 1st ionization of atoms: $\lambda_{0\to1+} \sim 1 - 10\ cm$
- On flight ionization of condensable or refractory atom can be performed by severa techniques in ECRIS
  - **Oven technique**: An miniature oven is inserted in front of the ECR plasma and heated up to the temperature at which a condensable atom evaporates under vacuum
  - **Sputtering technique**: when the evaporation temperature is unreachable, a sample of condensable is introduced inside the plasma which sputters the material. The sample can be biased to negative voltage to increase sputtering yielc.
  - **MIVOC technique** (Metal Ions from VOlatile Compounds): condensable atoms are chemically inserted in an organic molecule that is gaseous under vacuum. The gas diffuses to the plasma.
  - **Wall heating**: It is complementary of oven or sputtering technique. A refractory cylindrical metallic liner (Mo, Ta, W) is placed around the plasma chamber with a weak thermal interaction with the water cooled wall. The liner temperature increases due to RF and plasma heating. The sticking time of condensable is reduced, which allows wall recycling and improve the global ionization efficiency.

Production of metallic beams

Metallic ovens for ECRIS

- **Massive resistive oven**
  - The crucible is directly the heated resistor (Tungsten)
  - Large oven (~4 cm), large metal capacity
  - Requires large DC current 350 A/3V
  - T_{MAX}~2000-2300°C
  - Large current through leads may generate electromagnetic force in the magnetic field of the ECRIS:
    - F~iB
    - Thermo-mechanical calculation required



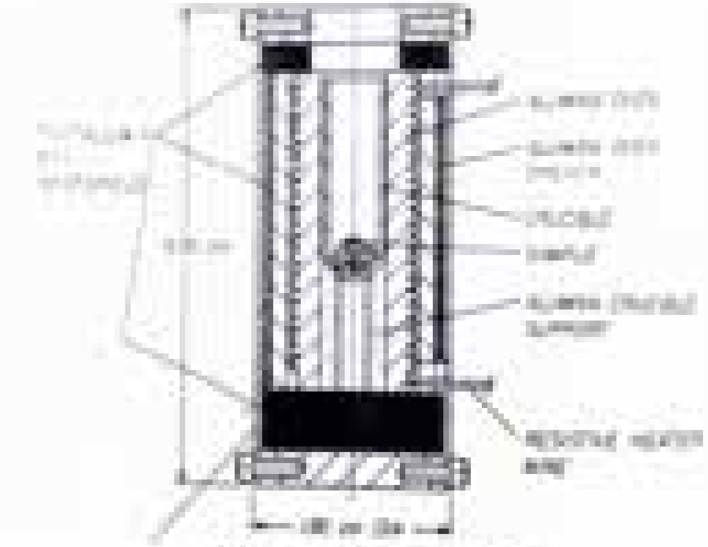
LBNL Massive Resistive Oven

- **Inductive oven**
  - The metallic crucible is inductively heated by a water-cooled excitation coil
  - T_{MAX}~2000-2600°C (Mo melting)
  - The tricky part is the external pulsed current generator to excite the coil (f~100-200 kHz P~1 kW)
  - Ø~25 mm

Production of metallic beams

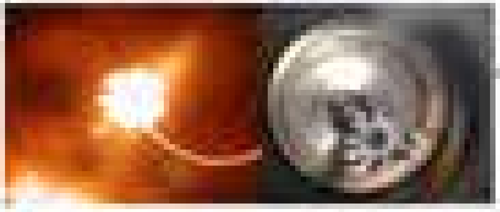
Metallic ovens for ECRIS

- **Resistive Filament Oven**
  - Helicoidal W filament inserted bewteen an inner and outer insulator (alumina)
  - Can be very compact (Ø~10-20 mm)
  - T~1400-2000°C max
    - Depending on design
    - The Alumina crucible melts at 2050°C
  - Possibly radiation reflector foil on the outside to improve heating



MSU Resistive Filament Oven

- **Resistive Foil Oven**
  - The filament is replaced by a Ta Foil
  - The alumina crucible is replaced by a Mo one
  - T_{MAX}~2000-2600°C (Mo melting)
  - Ø~20 mm
  - Requires a careful thermal design study



JYFL Resistive Foil Oven

Production of metallic beams

- Metal consumption~0.1-10 mg/h depending on the tuning and the source
  - Consumption is a concern when expensive elements like ^{48}Ca is requested
- Global ionization efficiency of oven is ~10%
- Hot liner Recycling helps to reach ~ %
- Run duration ~days to ~weeks depending on the crucible volume and the metal consumption

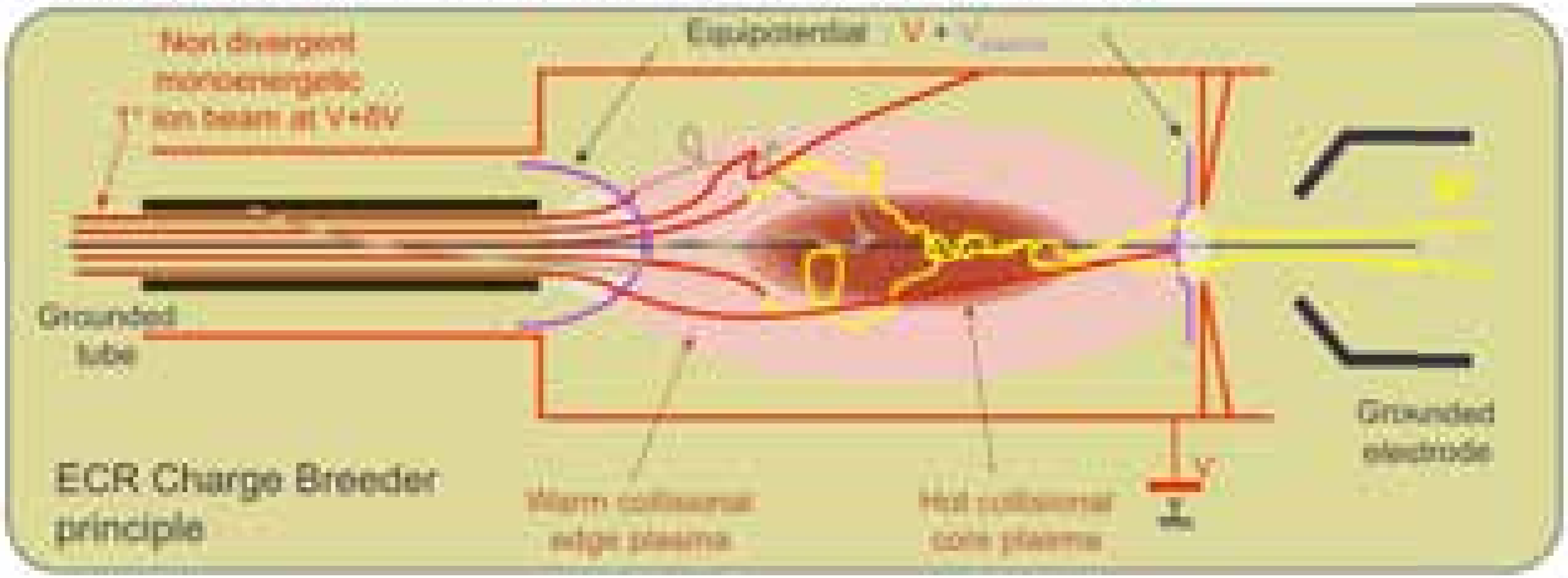
Uranium Sputtering stick
Inserted on the plasma
Axis to make U beam
On SECRAL

Production rate of RI beam

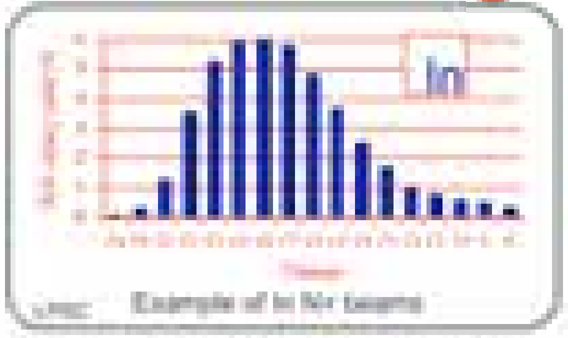
1+N+ Method in ECRIS

- Dedicated to Radioactive Ion Beam post-acceleration

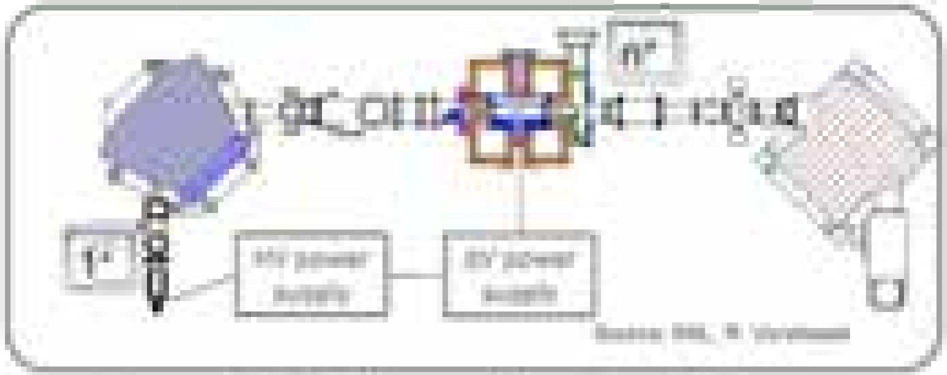
- Invented by R. Geller at Grenoble
- Method under development in many laboratories GANIL(SPIRAL1→2), ANL(CARIBU), TRIUMF (ISAC2), KEK(TRIAC), LNL(SPES)...



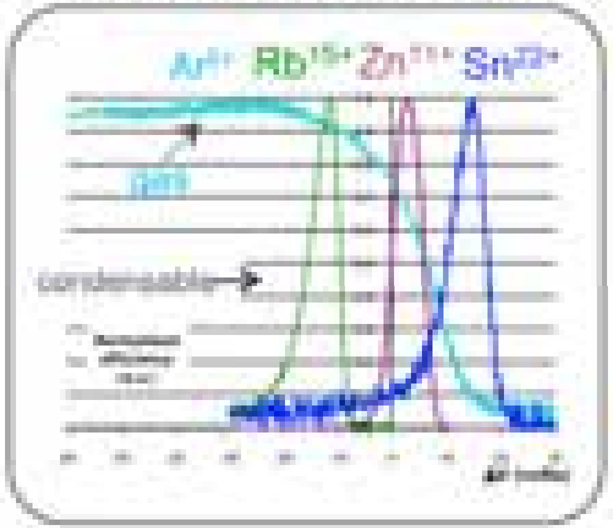
ECR Charge breeding – Efficiency - ΔV

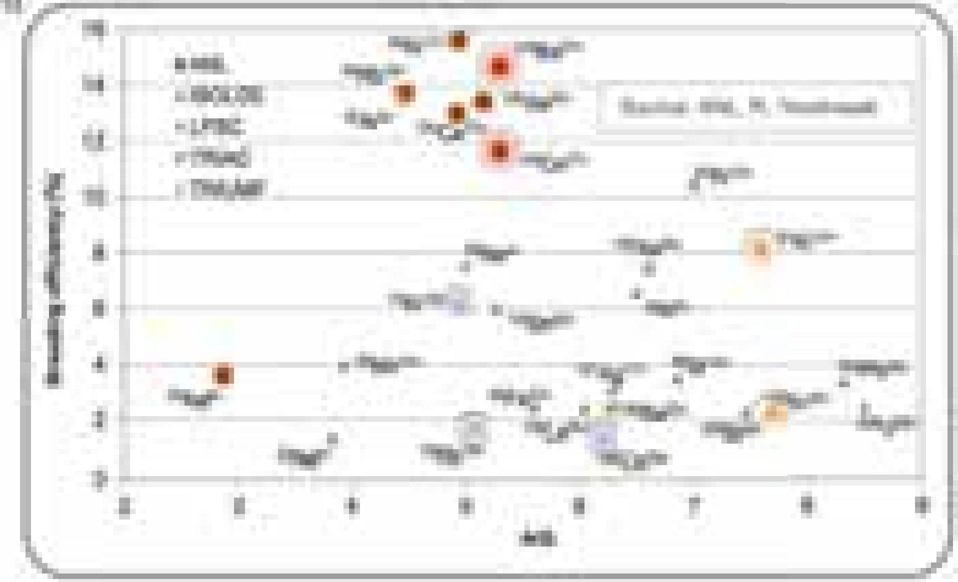


Example of In N+ beams



- Efficiency for n+ ion: $\eta_n = \frac{I^{n+}}{n I^{1+}}$
- The 1+ ions should be accurately decelerated to match the plasma capture condition (ΔV curve=function of both source plasma potential)
- Today, the main limitation comes from the beam contamination with impurities (from plasma chamber walls)
- Small intensity RIBS may be hidden by a nearby Q/A contaminant

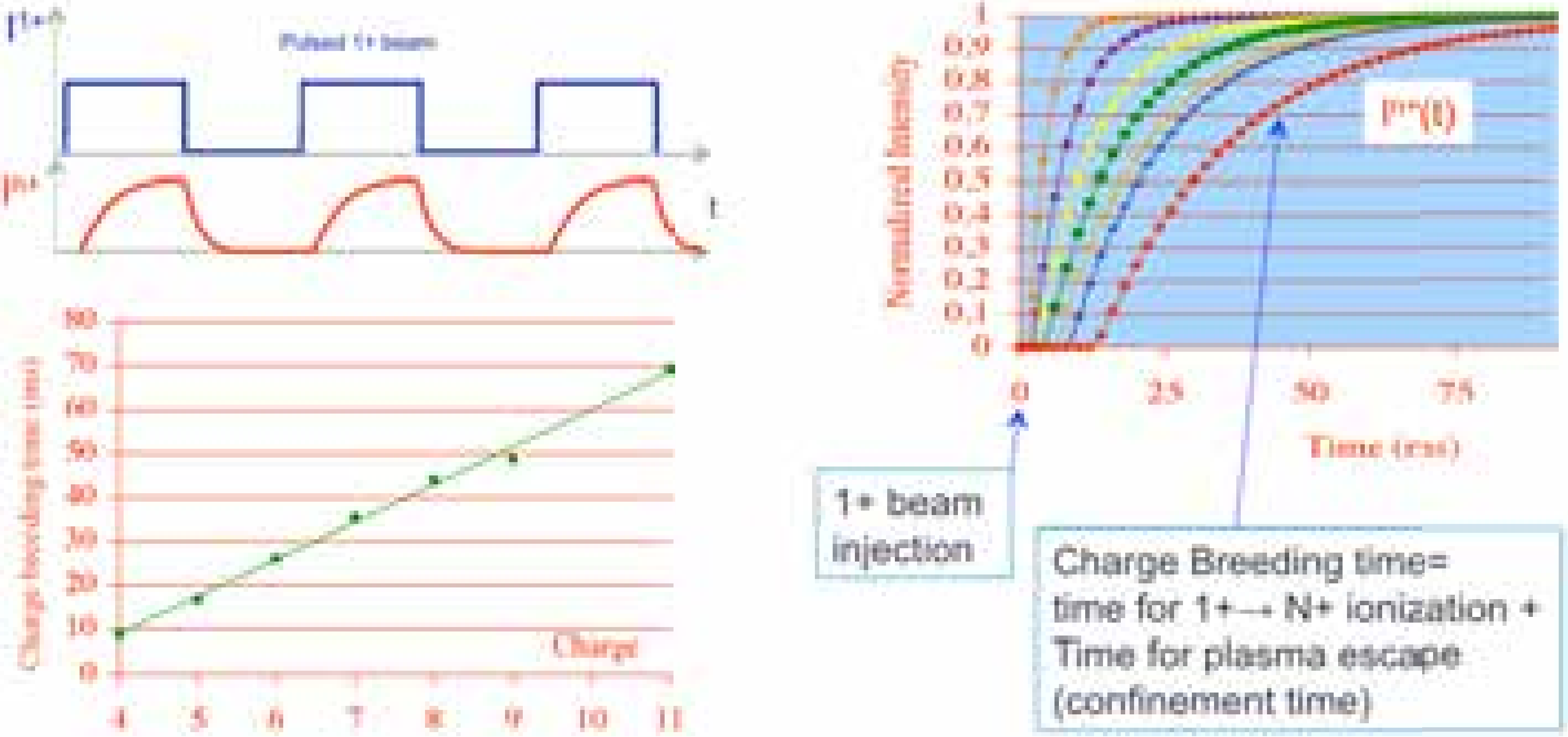




Production rate of RI beam

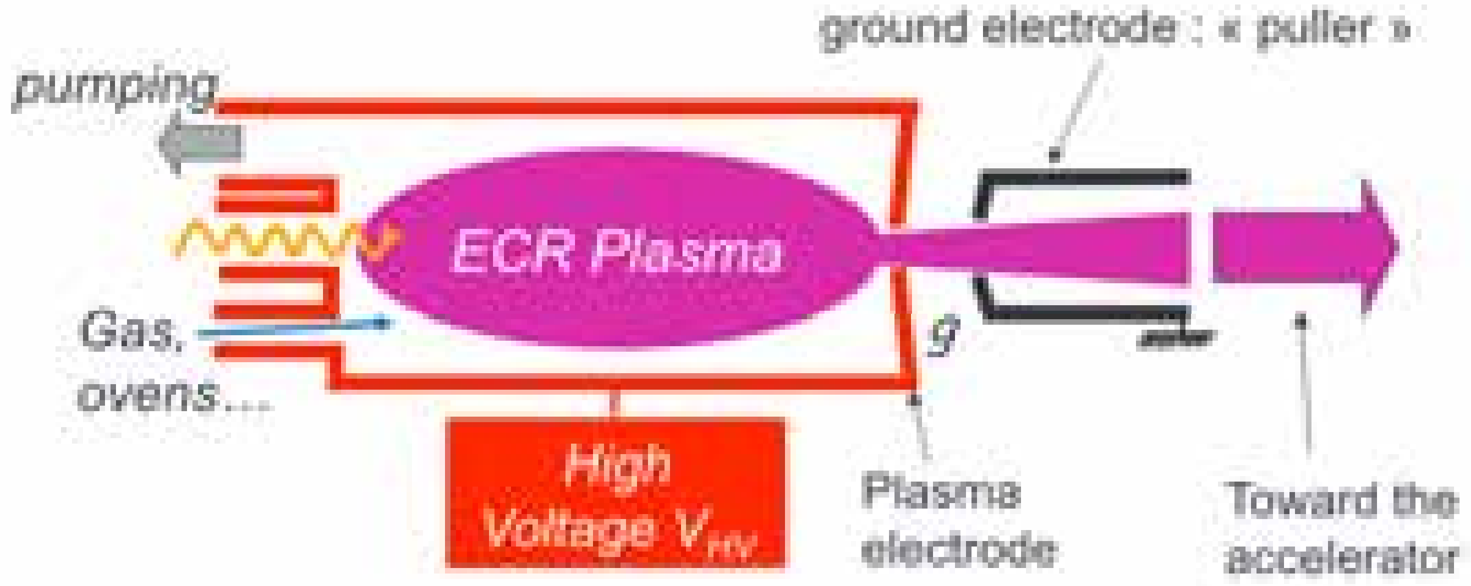
ECR Charge breeding as a plasma probe

- Evidence of step by step ionization process in the ECR plasma



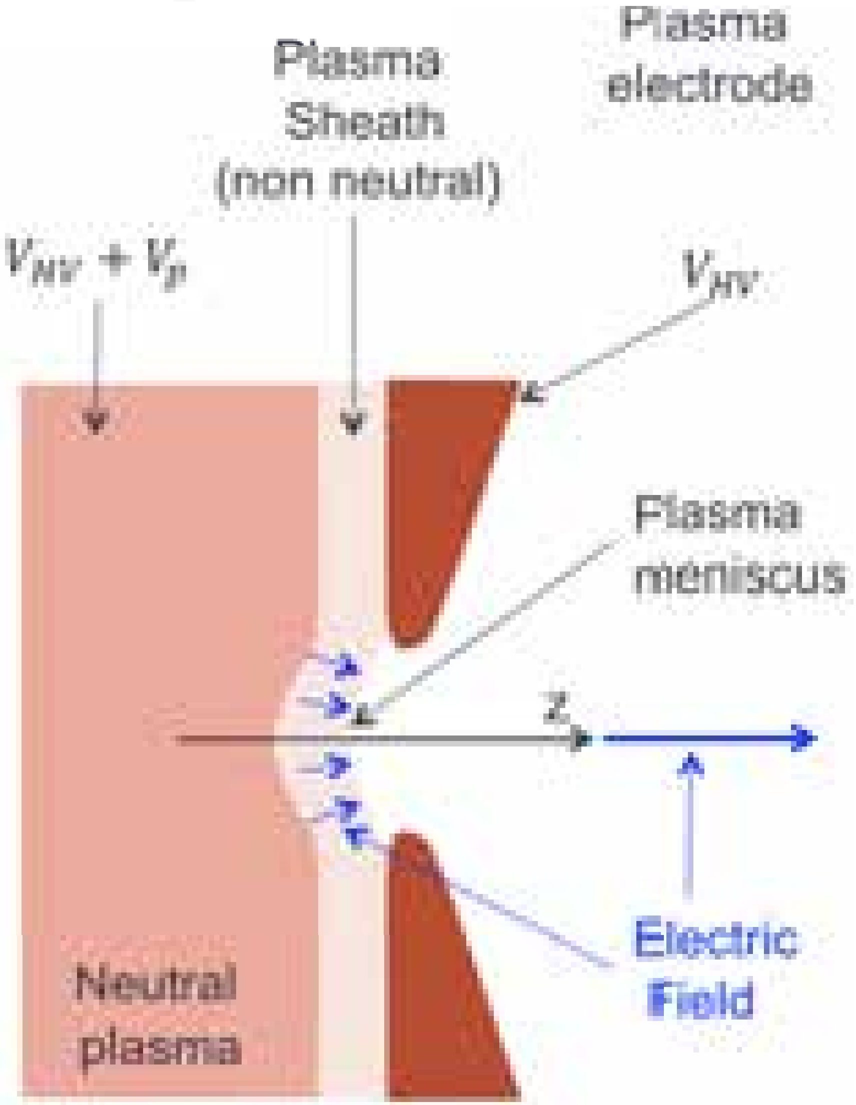
Beam Extraction from ECR Ion Sources

- The ion beam is extracted by setting the plasma chamber to high voltage V_{HV}~15-60 kV
- A plasma electrode is closing the cavity on the extraction side, it is equipped with a circular hole with diameter Ø~5-13 mm
- A puller electrode, set to ground potential, is placed in front of the plasma electrode
- The electric field in the gap *d* enables to accelerate the low energy ions from the plasma while hot electrons are repelled back to the source



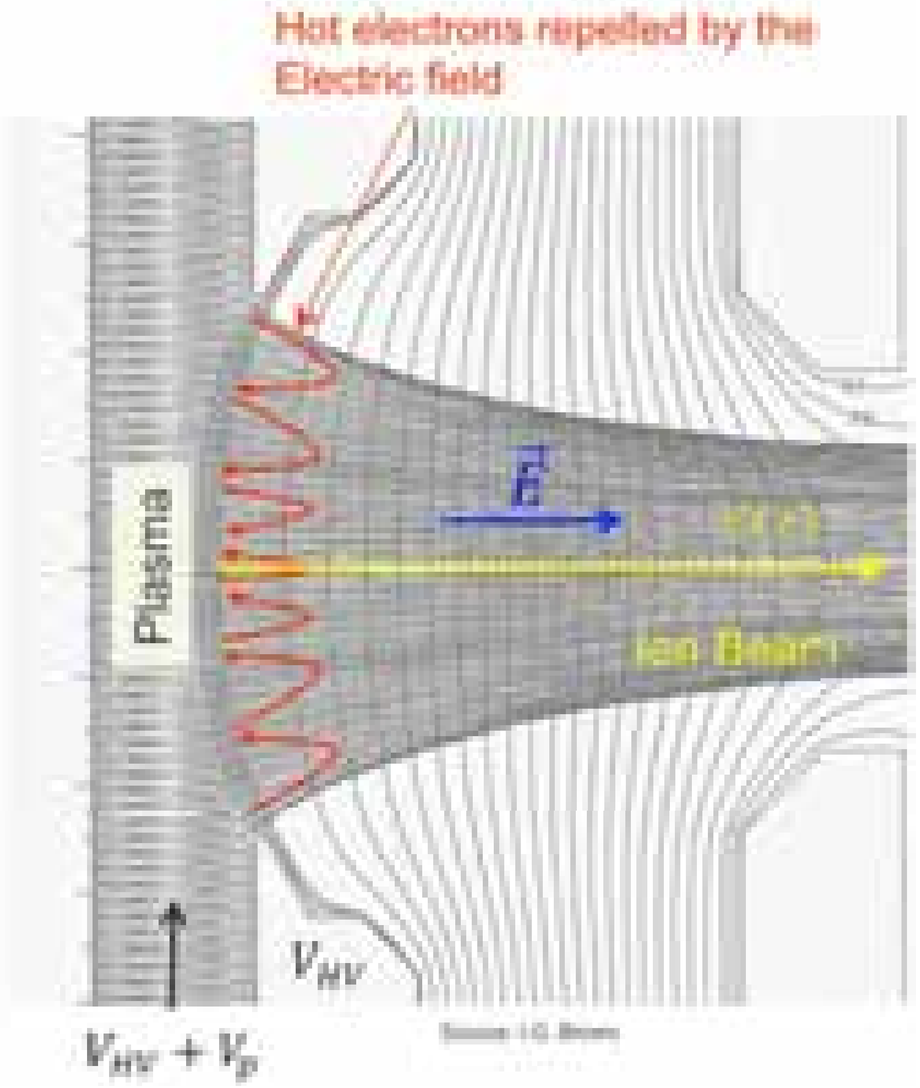
Ion Extraction from the plasma

- The plasma potential is $V_p > 0$ (usually ~5-50 eV)
- The plasma meniscus is the natural curvature of the plasma in front of the circular electrode hole
- The plasma meniscus shape is not predictible. A concave meniscus is optimum for ion extraction.
- The ions are extracted from the plasma sheath (non neutral area, see appendix).
- The ions incident velocity in the early sheath can be modelized by the Bohm criterion:
  - $v_i = \sqrt{kT_e/m_i}$
- Ions extracted have escaped the magnetic mirror, so their initial velocity angle θ with respect to $\vec{B}$ are distributed in the loss cone ruled by the Axial Mirror ratio $R = \sqrt{B_{max}/B_{min}}$:
  - $v_z = v\cos\theta$
  - $\sin\theta \leq \frac{1}{\sqrt{R}}$



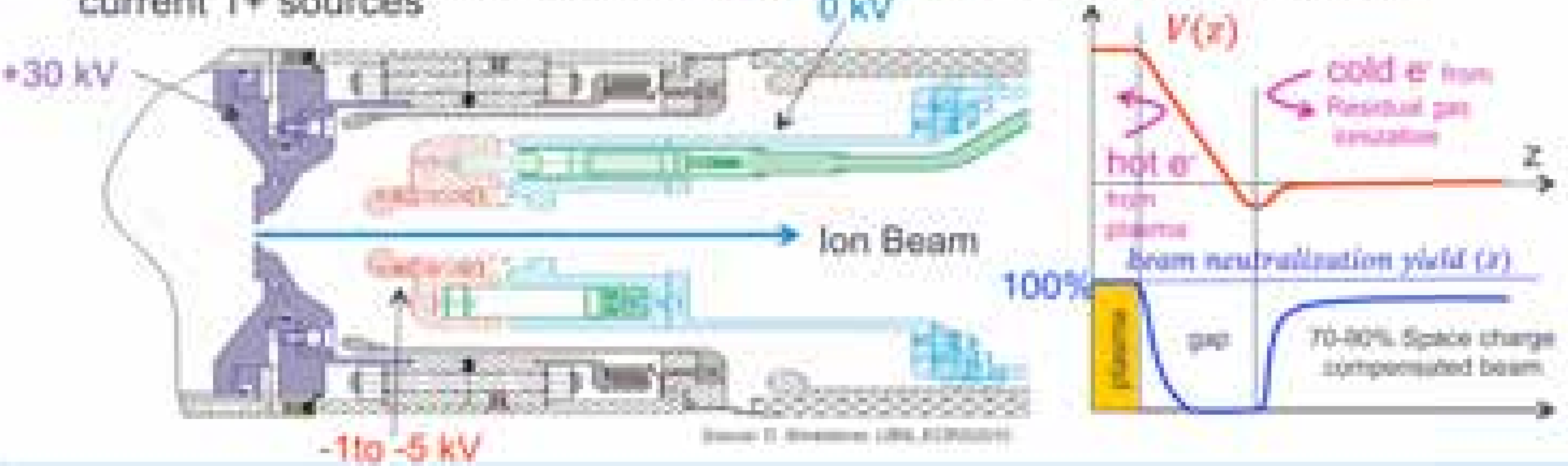
Hot electrons contribution to the emittance

- The hot electrons of ECRIS play an important role in the early beam formation, when the ions have very low energy
- Hot electrons ($kT_e \sim 1-5\ keV$) penetrate into the extraction gap and neutralize partially the space charge induced by the ions, until a point where they are reflected back to the source
- The electron density in the ECR plasma sheath is usually approximated by the Boltzmann distribution function, assuming a gaussian electron distribution function:
- $n_e = n_{e0} e^{\frac{e(V(z)-V_{HV}-V_p)}{kT_e}}$
  - n_{e0} is the electron density in the neutral plasma
  - $V(z)$ is the local potential at position z in the extraction area
  - V_P is the plasma potential, V_{HV} the High Voltage



Example of Extraction system

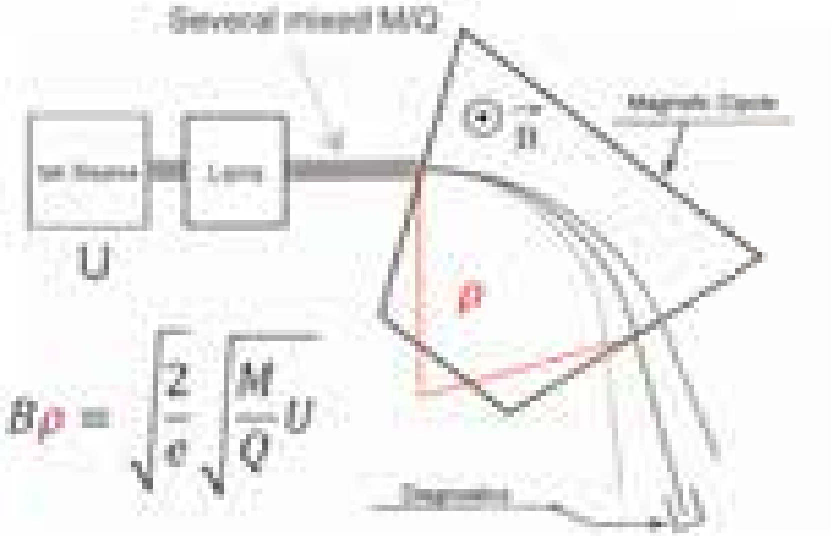
- ECR ion sources used to extract I~1-2 mA of Ion beams,with a low divergence and negligible space charge effects
  - Classical extraction feature diode system with a plasma electrode and a grounded puller (as shown earlier)
- New generation high performance ECRIS produce high intensity beams of multicharged ions: the total current extracted increases typically to the range I~2-20 mA where the space charge is highly dominant
- ECRIS extractor was modified to a Triode system used fo decades in high current 1+ sources



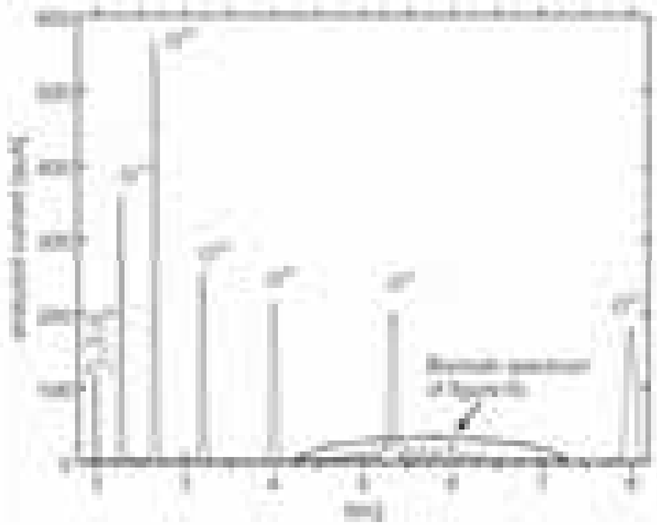
Beam transport and separation

- The ECRIS beams are composed of several charge states of several atomic species. These beams are extracted all together, and their number is in the range ~10-50. A bending magnet with a mass separation $M/\delta M$ ~100 is necessary to cleanly separate the beam of interest from its M/Q neighbours.

- The dramatic increase of total current extracted from today high performance multicharged ECRIS (I~5-20 mA) requires a dedicated high performance Low Energy Beam Transfer Line, usually equipped at least with a focusing lens right at the exit of the source, a large acceptance beam line ($\varnothing_{pipe}$≥100 mm), and a large bending magnet (~100 mm vertical gap and a large ~200 mm horizonthal aperture).



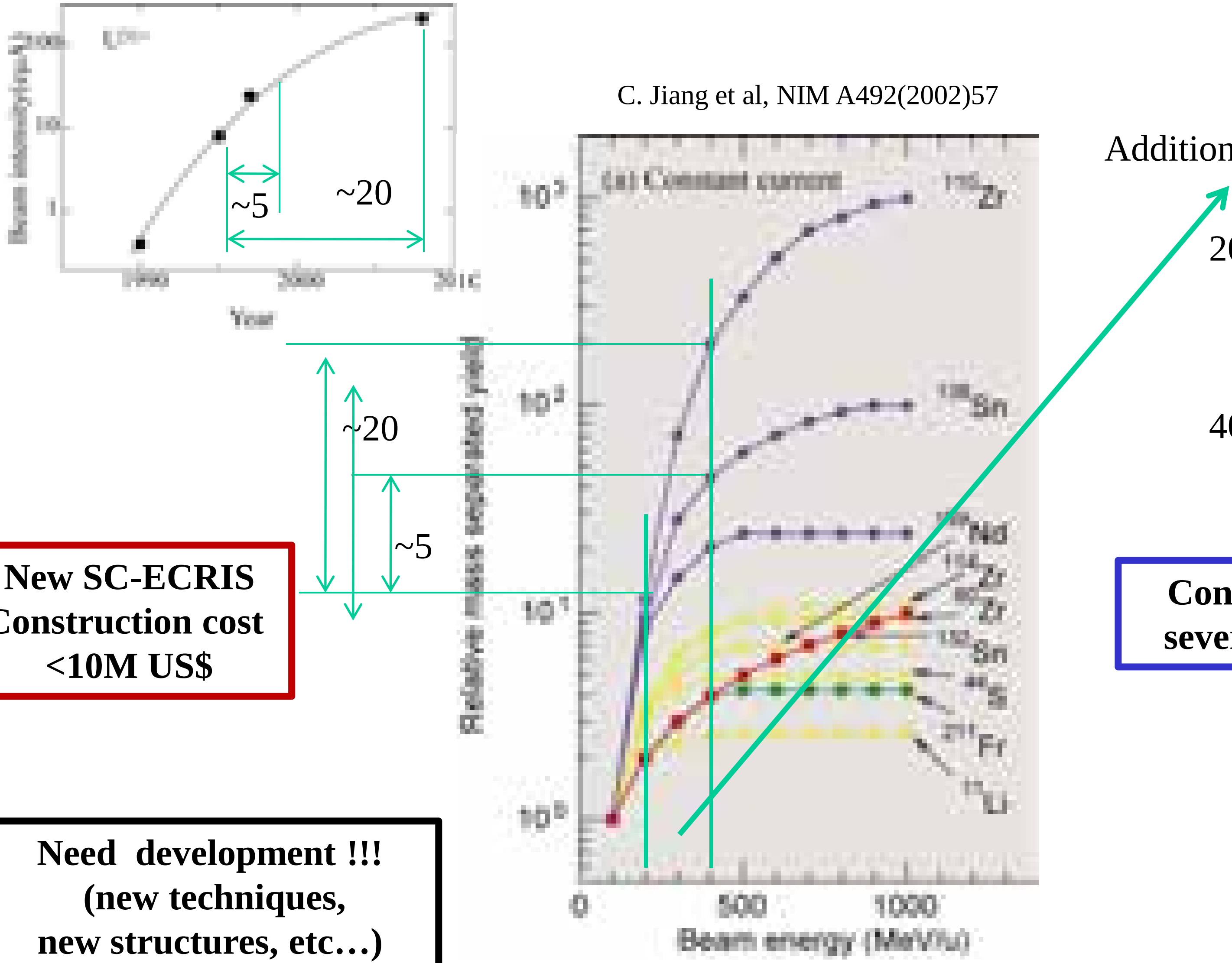
$$B\rho = \sqrt{\frac{2}{e}}\sqrt{\frac{M}{Q}U}$$



Example of an ion spectrum from VENUS, LBNL.

Production rate of RI beam

C. Jiang et al, NIM A492(2002)57



Additional accelerator

200MeV/u

400MeV/u

New SC-ECRIS
Construction cost
<10M US$

Construction cost
several 100M US$

Need development !!!
(new techniques,
new structures, etc…)

Therefore….

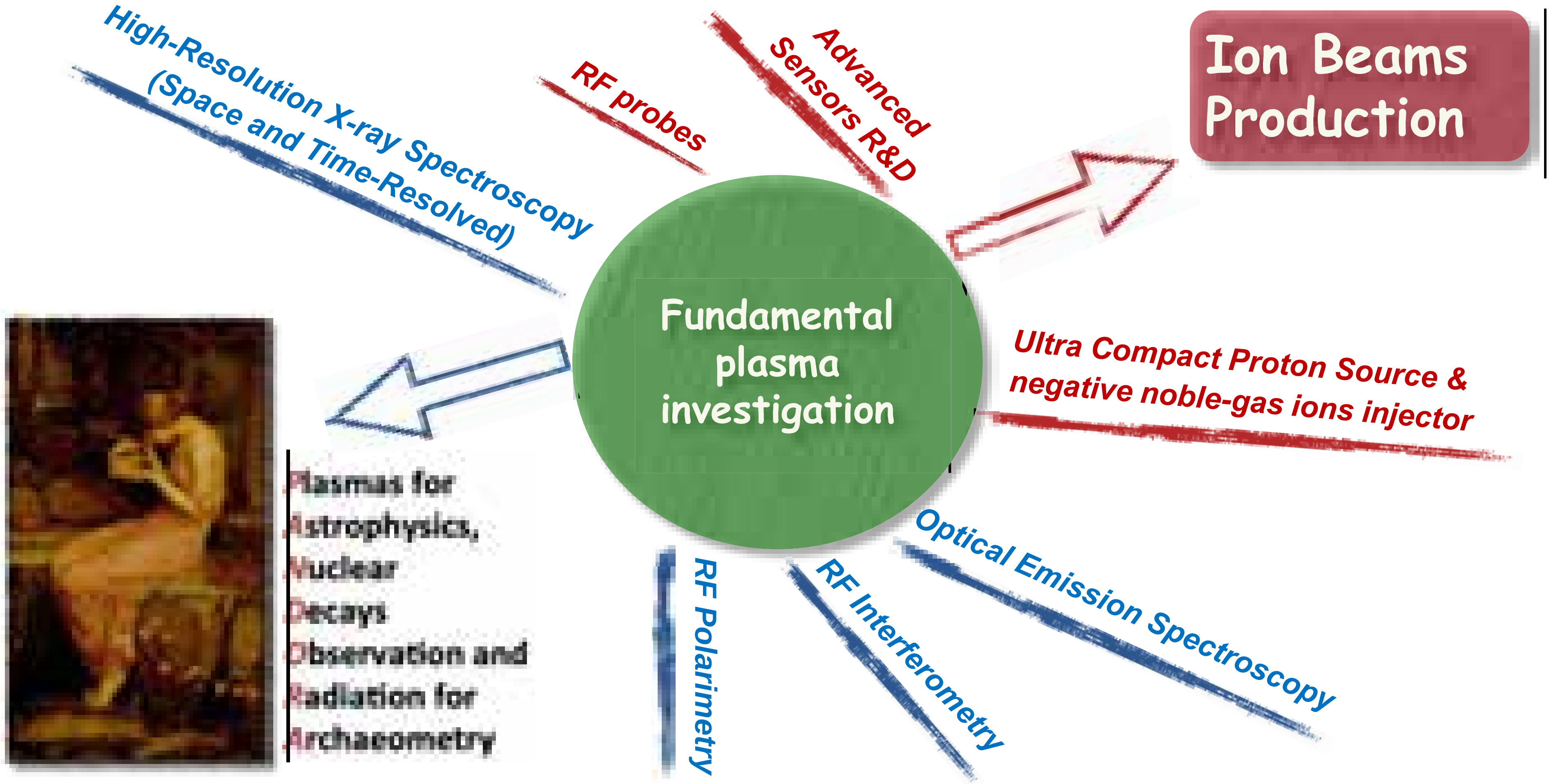
- As Geller predicted, frequency scaling promises us higher intensity and higher charge states
- The design and construction of a magnet structure for a 4th Generation ECR is the most challenging task.

Fourth Generation ECRIS: an old idea!
"… 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

BUT…

Laboratory magnetoplasmas in compact traps are historically used for ion beams production



Laboratory magnetoplasmas are suitable and interesting for other researches

BUT…

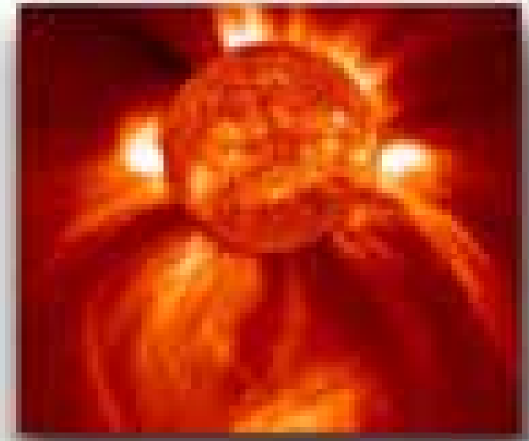
- **In stars, matter is in the plasma state,** with temperatures ranging from thousands to hundreds millions of °K, implying that the **atoms are strongly ionized**;

- **s and r-processes branching points depend on the "competitive" rates of neutron capture vs. β-decays**; However…

Reaction rates are typically measured in lab and done on neutral matter!!

- **Possible modifications of β-decaying radio-isotopes lifetimes is however expected by models in strongly ionised atoms!!**

PANDORA

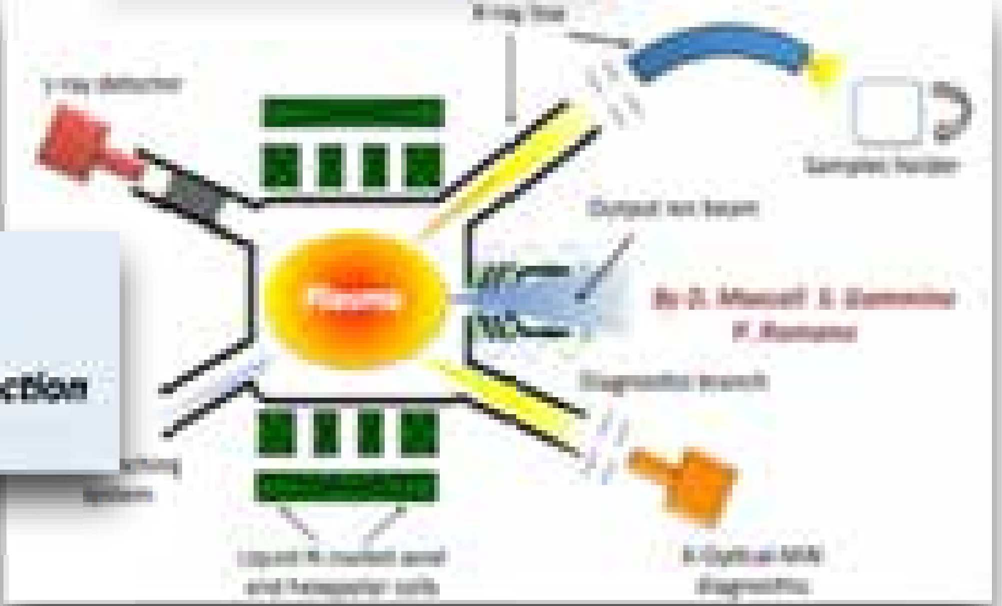


- Solar nucleosynthesis occurs *in-plasma*
- Primordial nucleosyntesis occurs *in-plasma*
- s-process nucleosynthesis occurs *in-plasma*
- Visible to X-ray radiation is generated *in-plasma*
- Magnetized plasma in stars is extremely peculiar

But on *Earth* (or underground at LNGS) we perform nuclear reactions and decay rate measurements by using solid-gas-liquid samples

To be investigated

^{7}Be half-life has ***never*** been measured in-plasma

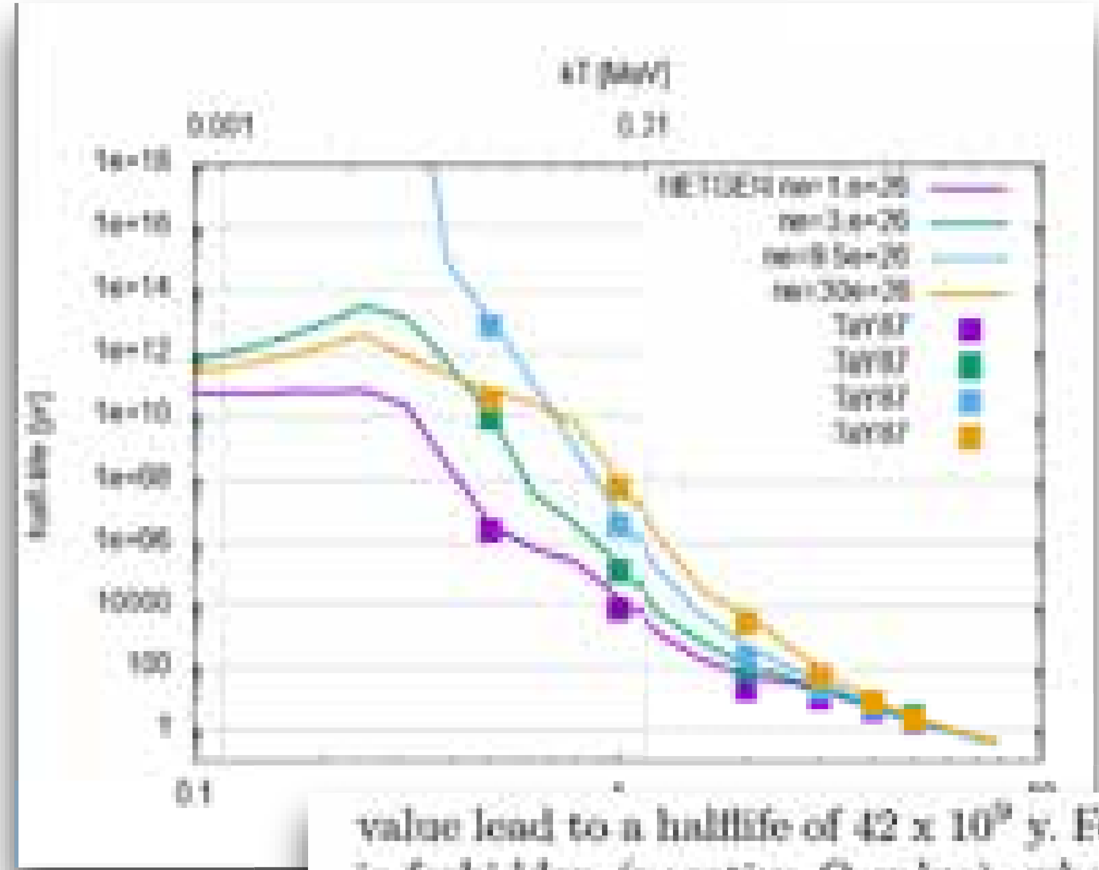


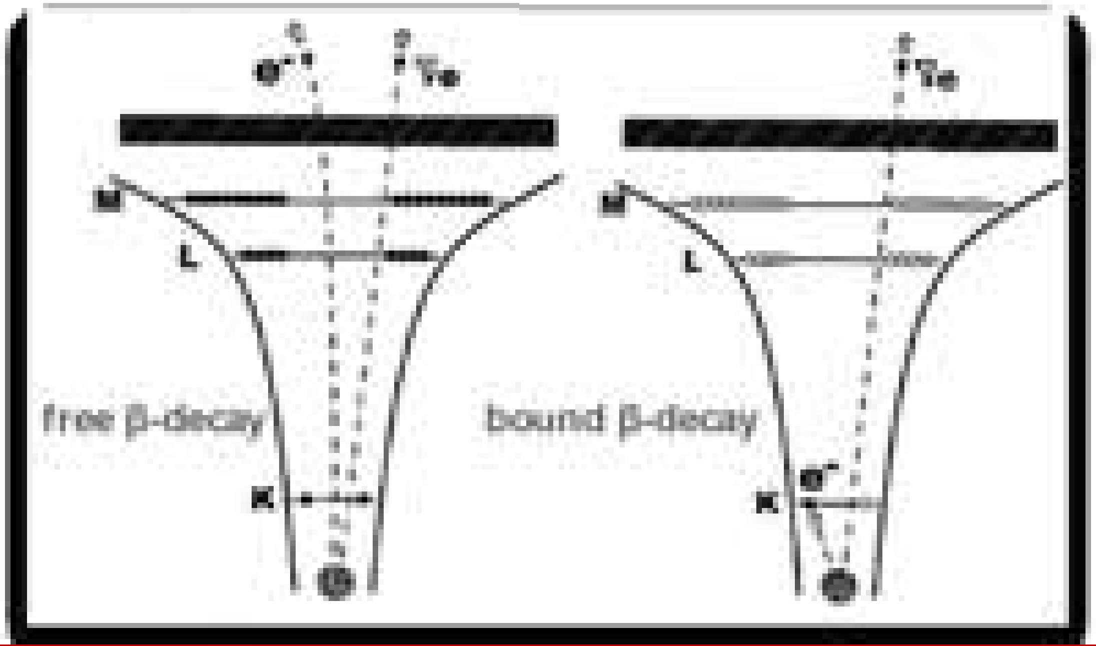
The PANDORA goal:

Trap radionuclides in magnetoplasmas and study their decay times as a function of ioalzation states

Bound-electron beta decay activation in ionized species;

The collapse of 187Re lifetime





For ^{187}Re a lifetime variation of 9 orders of magnitude (!!) was observed in Storage Rings

value lead to a halflife of 42 x 10^9 y. For *fully ionized* ^{187}Re the continuum β^- decay is forbidden (negative Q value), whereas bound-state β^- decay with the electron bound in the K shell becomes possible. The dominant decay branch, a nonunique first forbidden transition, feeds the *first excited state* in ^{187}Os at 9.75 keV excitation energy. This effect dramatically decreases the half-life of bare ^{187}Re, as measured at the ESR (see next section), to 33 y only. The figure is taken from [42].

HIE-ISOLDE

Storage ring facility at HIE-ISOLDE

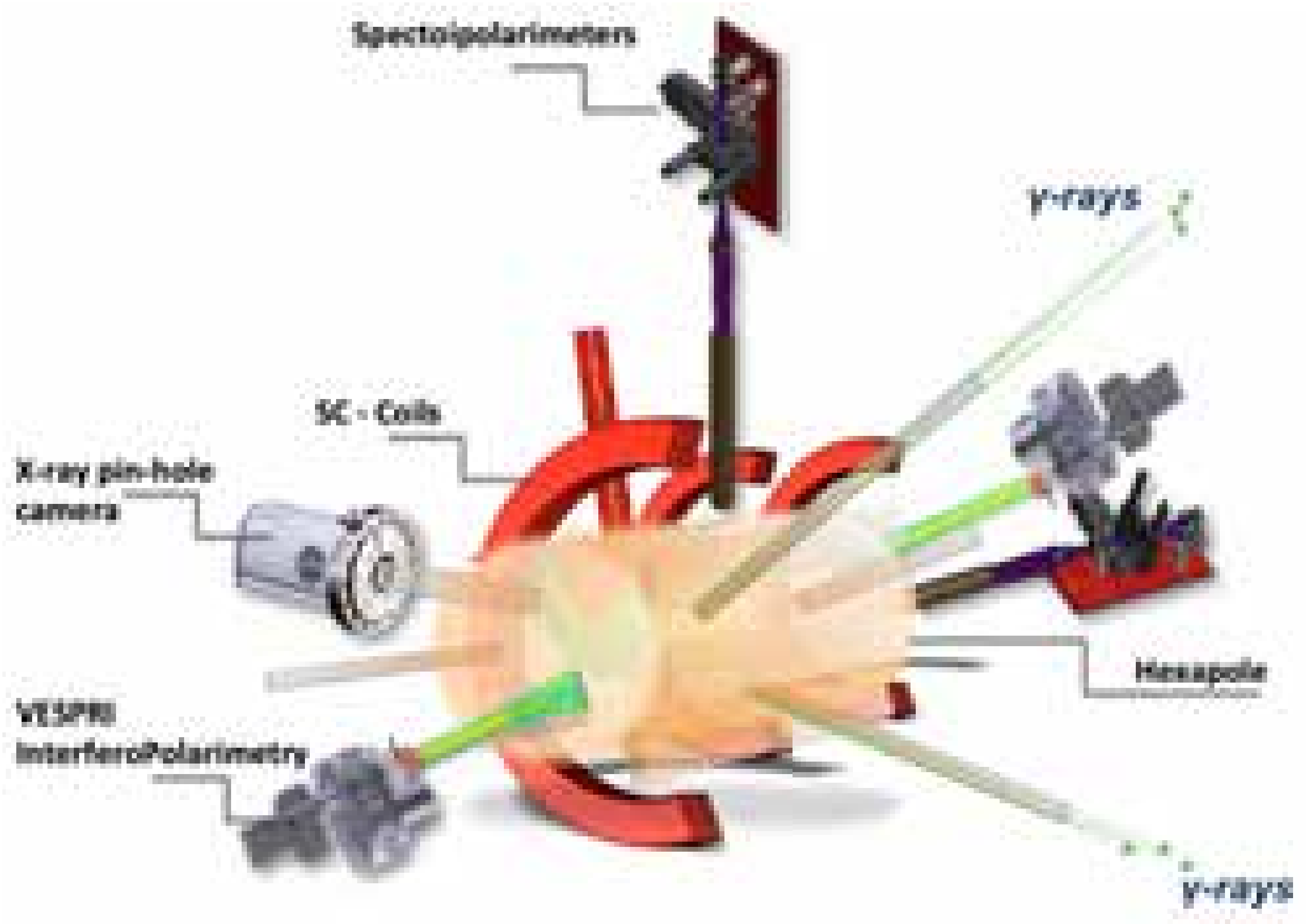
Technical Design Report

Half-lives of ^{7}Be in different atomic charge st-

Attempts to obtain the "true" terrestrial half-life of ^{7}Be are done in numerous experiments in which ^{7}Be atoms are implanted in different chemical environments, see, e.g., recent expe- fields [9, 10]. The motivation for studying this decay is its impact for Solar physics, where th- probability of ^{7}Be plays a crucial role for the neutrino fluxes from the ^{7}Be EC- and ^{8}B [11] (see Figure 2). Although the main decay channel of ^{7}Be in the Sun's interior is the fre- capture, Iben, Kalata & Schwartz [12] have shown that bound electrons can significantly in- decay probability. Theoretical predictions exist indicating that about 20% of ^{7}Be in the center might have a bound electron [12, 13]. A longer lifetime of ^{7}Be in the Sun would increase the p-

^{7}Be, ^{26}Al lifetime variations at different charge states are among hot-topics for HIE-ISOLDE storage ring

PANDORA conceptual design



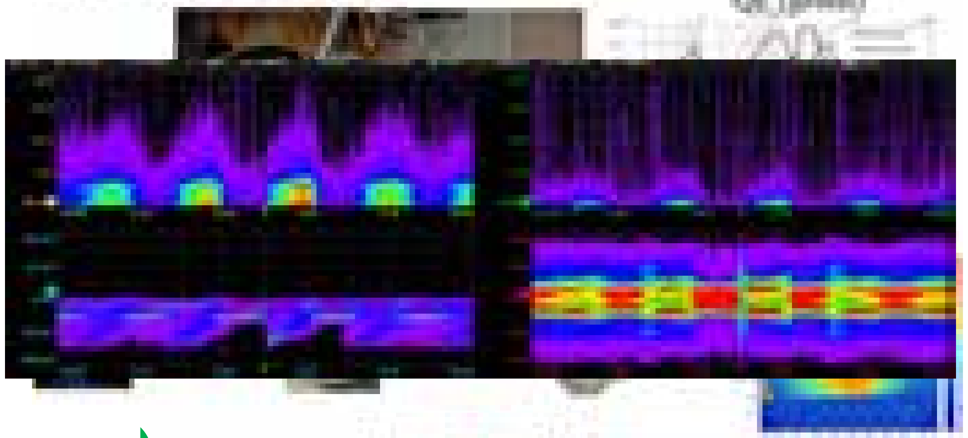
- A "buffer plasma" is created by He, O or Ar up to densities of 10^{13} cm^{-3}
- The isotope is then directly fluxed (if gaseuous) or vaporized by appropriate ovens and then fluxed inside the chamber to be turned into plasma-state
- Relative abundances of buffer vs. isotope densities range from 100:1 (if the isotope is in metal state) to 3:1 (in case of gaseous elements)

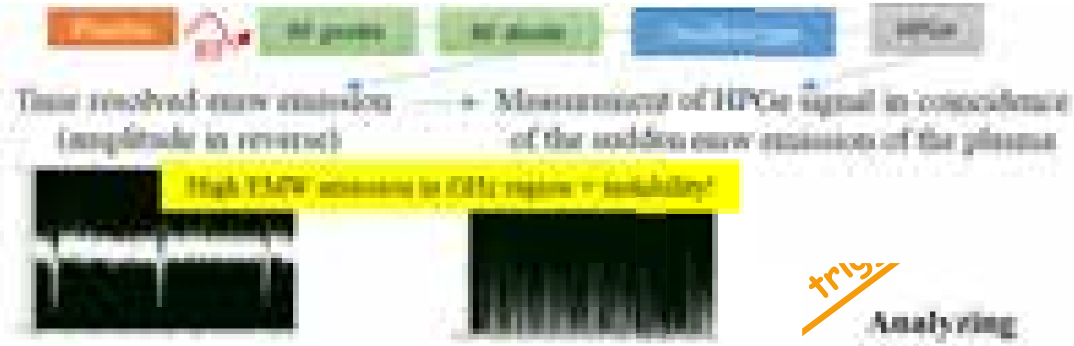
The plasma is maintained in dynamical equilibrium by equalizing input fluxes of particles to losses from the magnetic confinement

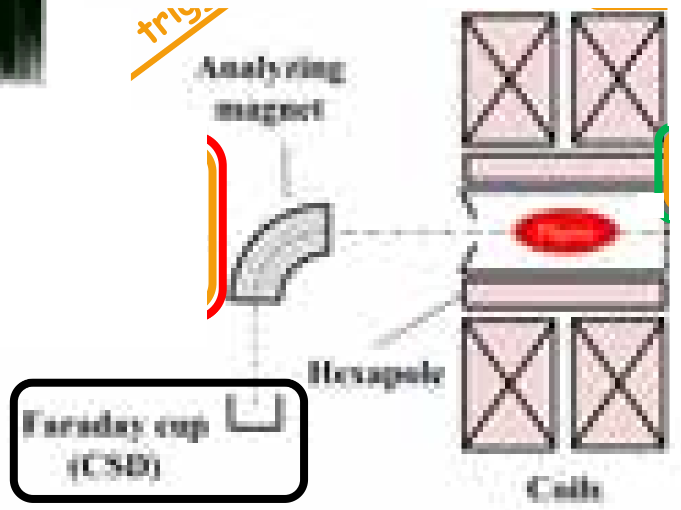
PANDORA multi diagnostic setup

- Mass spectrometry: evaluation of CSD
- SDD: probing volumetric soft X-radiation in the 2 – 20 keV domain
- HPGe: providing time integrated X-ray spectra in the 30 - 300 keV domain
- VL camera: probing volumetric optical radiation in the 1 – 12 eV domain
- Pinhole camera: providing plasma structural in the range 2 - 20 keV
- RF probe + Spectrum analyzer: plasma radio-emission analysis

Time resolved spectra with 6 ms resolution if triggered by RF probe







Thanks for your attention !!!

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