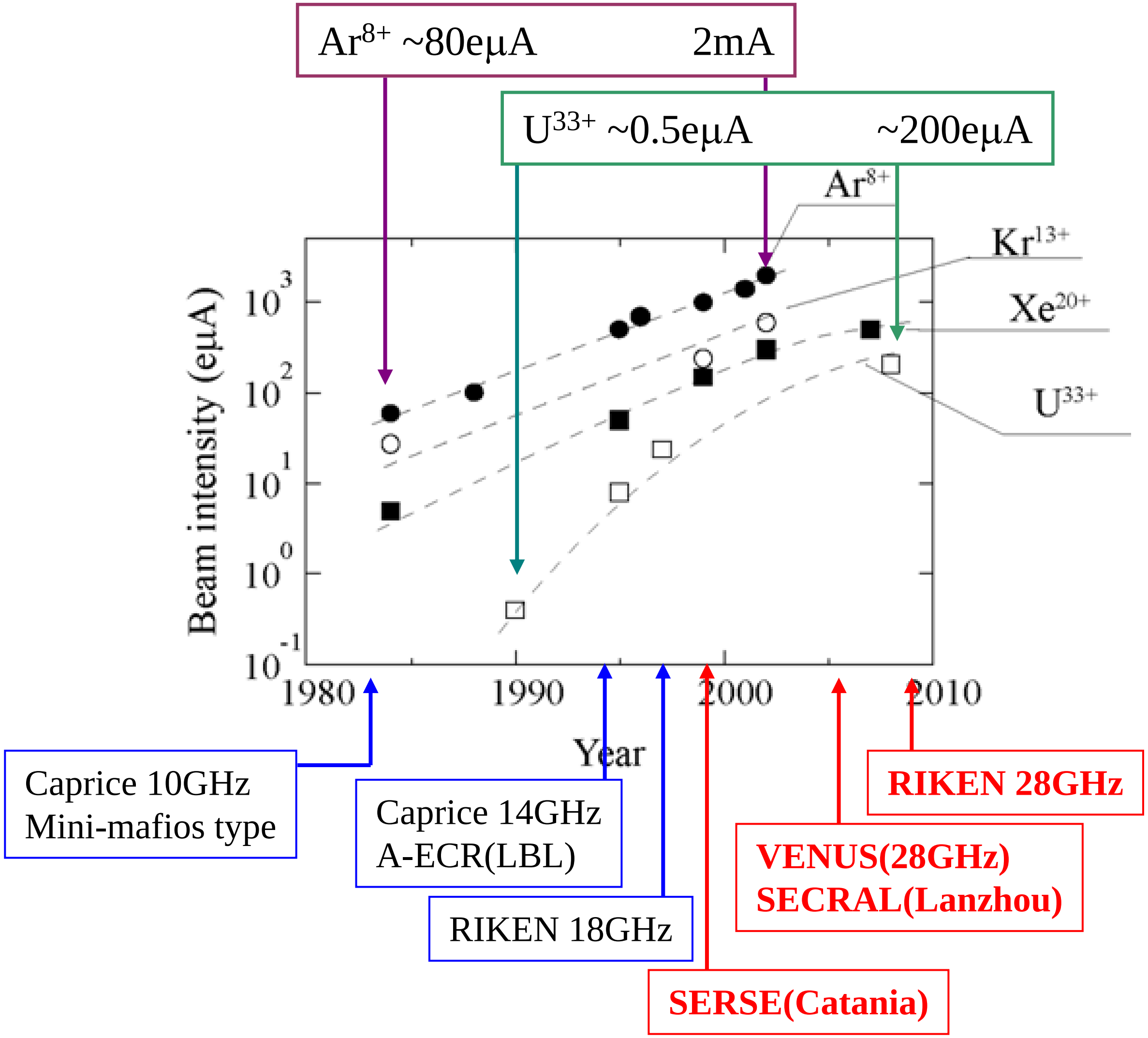
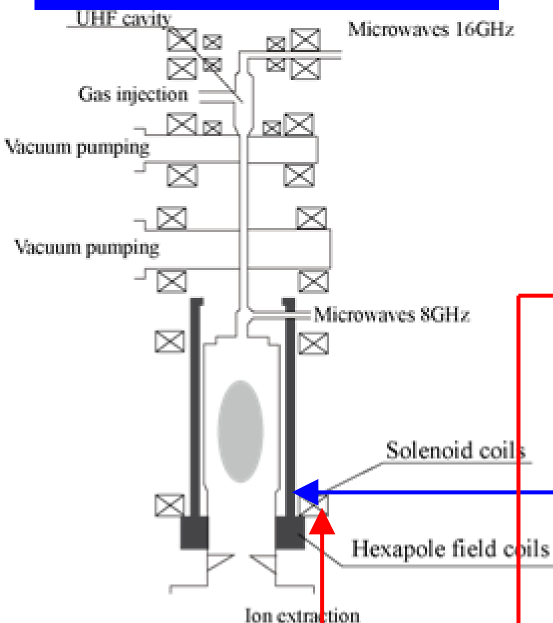
Time evolution of beam intensity from ECRIS

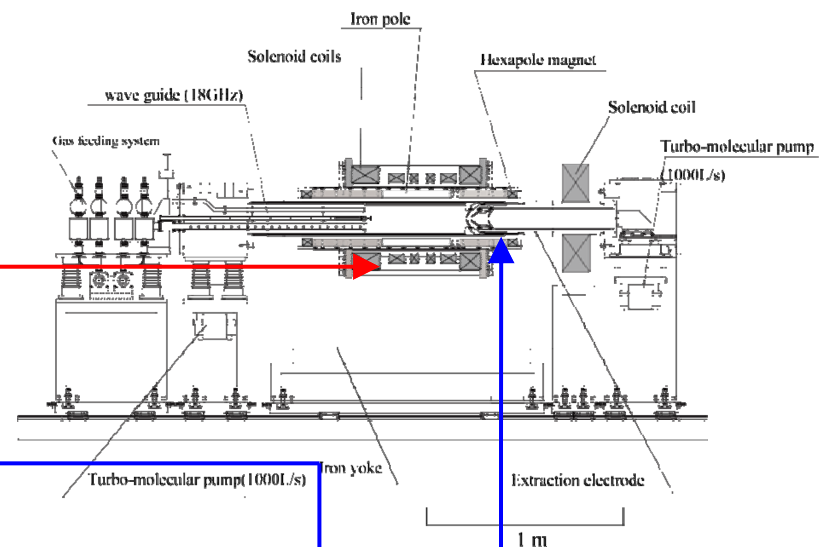


Structure of the ECR ion sources (1970~2009)

Supermafios (1970's)



RIKEN 28GHz(2009)



Mirror magnetic field

Hexapole magnetic field

"Minimum B" configuration

Against the plasma instability

1)Long plasma confinement
2)Production of highly charged heavy ions

Ar^{8+} ~80eμA 2mA (factor of 250)

U^{33+} ~0.5eμA ~200eμA (factor of 400)

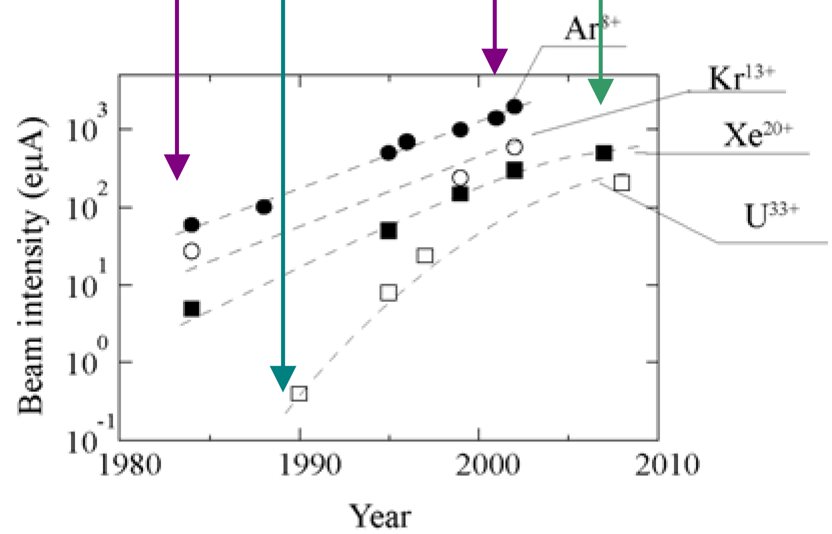
Key words

1)Understanding ECR plasma

Effect of key components(magnetic field configuration, RF power etc) on the beam intensity and ECR plasma

2) Progress of technology

- Superconducting magnet
- Permanent magnet



ECR ion sources

: Brief History and Look into the next generation

T. Nakagawa (Nishina center, RIKEN)

1. ***Physics of ECR plasma***

   Effect of key components on the ECR plasma and beam intensity

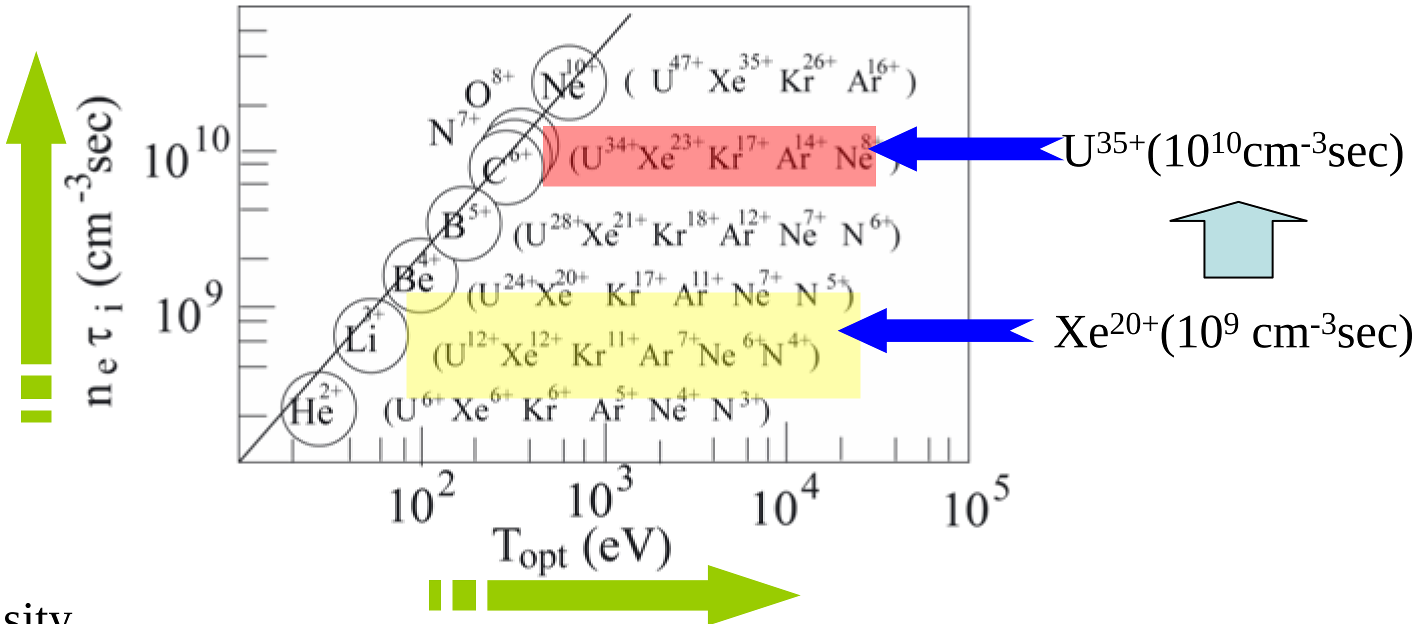
2. ***Technology of the ECR ion sources***

   Permanent magnet
   super-conducting magnet
   Example of most advanced ECR ion sources

3. ***Next generation***

   Super-conducting ECR ion source (>28GHz)
   New type ECRIS

ECR plasma condition



Beam intensity

$$I_q = \frac{n_q \, q \, V}{\tau_c}$$

n_q : ion density

q : charge state

V : plasma volume

τ_c : ion confinement time

n_e	*Larger*
V	*Larger*
τ_c	*Shorter*
$n_e \tau_c$	*Constant (10^{10}(cm^{-3}s)*

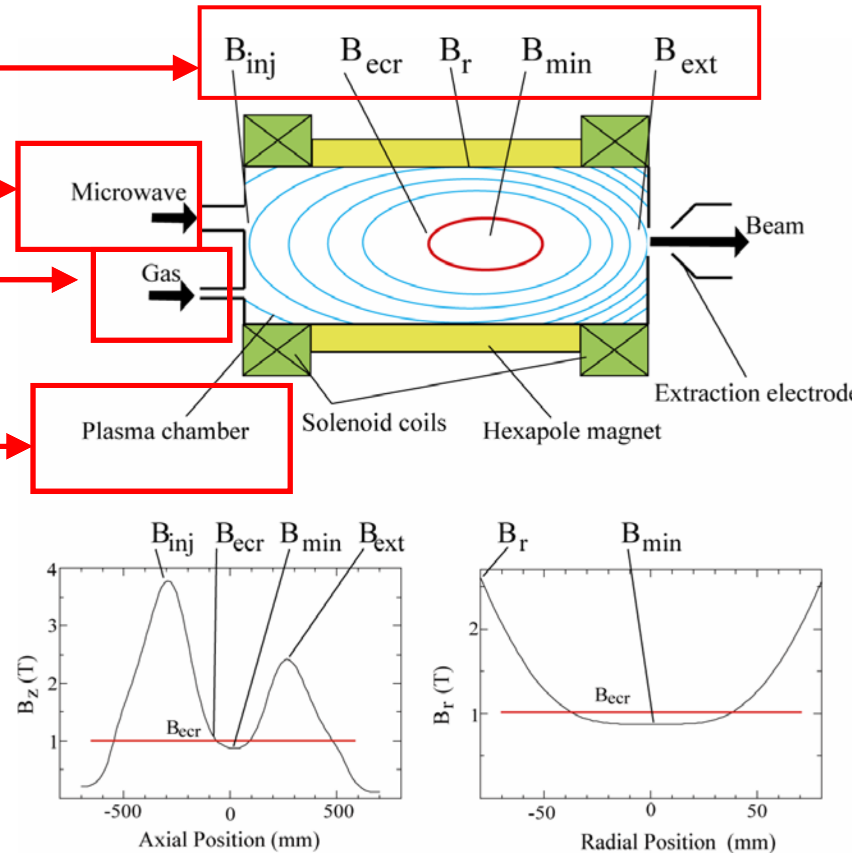
ECR ion source (structure)

1)Magnetic field configuration

2)Gas pressure

3)Microwave frequency

4)Plasma chamber size
Ion confinement time



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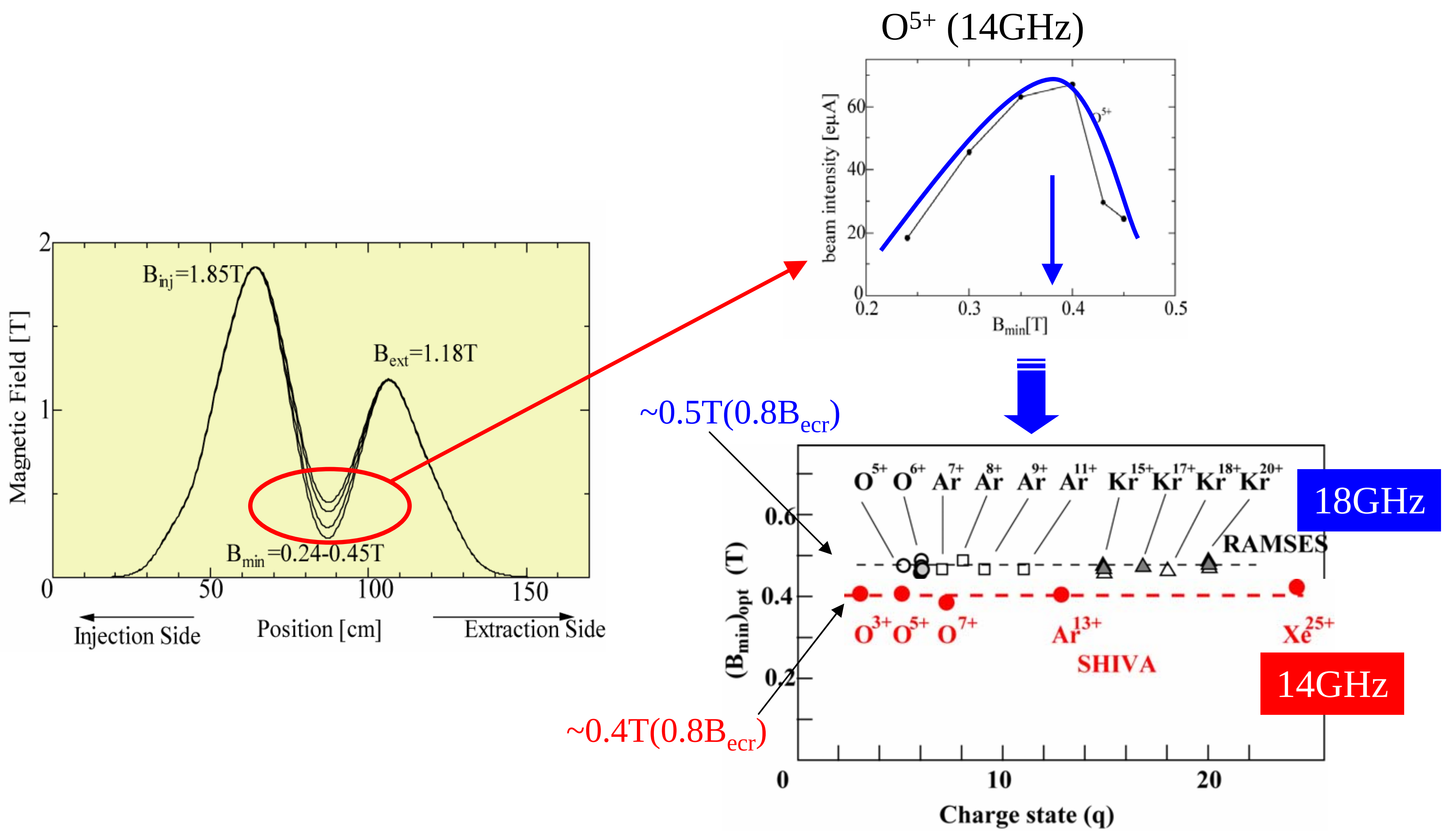
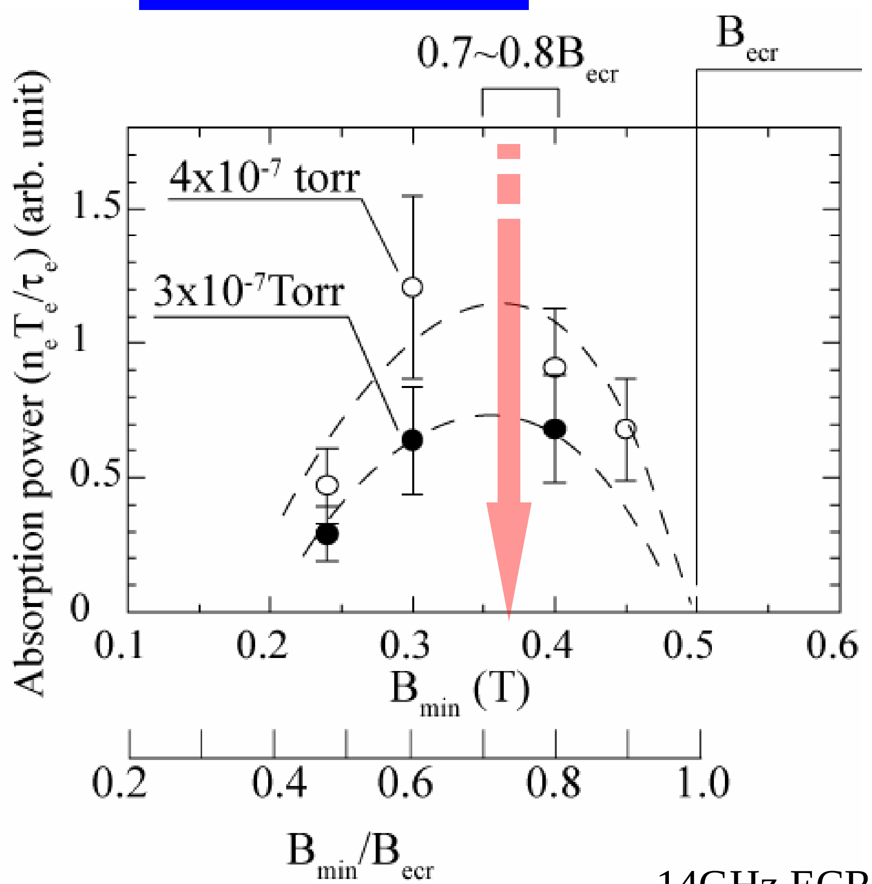
Magnetic field configuration I (B_{min} effect)



Magnetic field configuration I (B_{min} effect)

Absorption power



14GHz ECRIS

Energy absorption as a function of B_{min}

Total absorption power

Absorption power

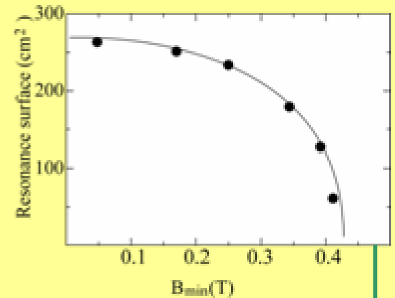
$$\frac{S_{abs}}{S_{inc}} = 1 - e^{-\pi\eta}$$

$$\eta = \omega_{pe}^2 / (\omega c|\alpha|),$$

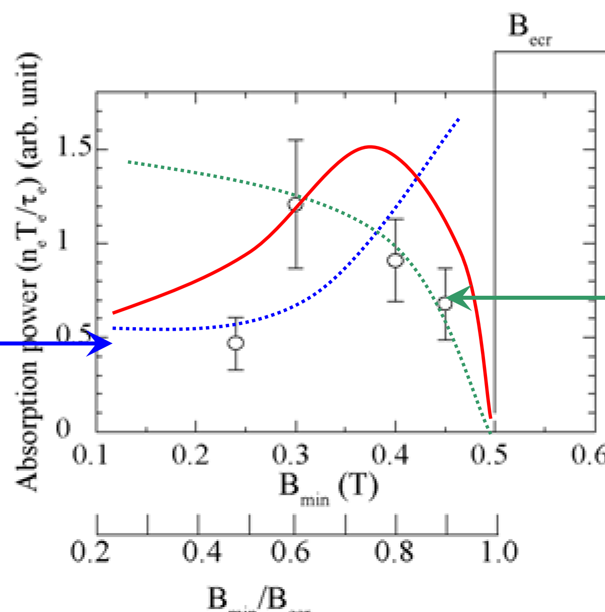
$$\alpha = (d\omega_{ce} / dz) / \omega_{ce}$$

X

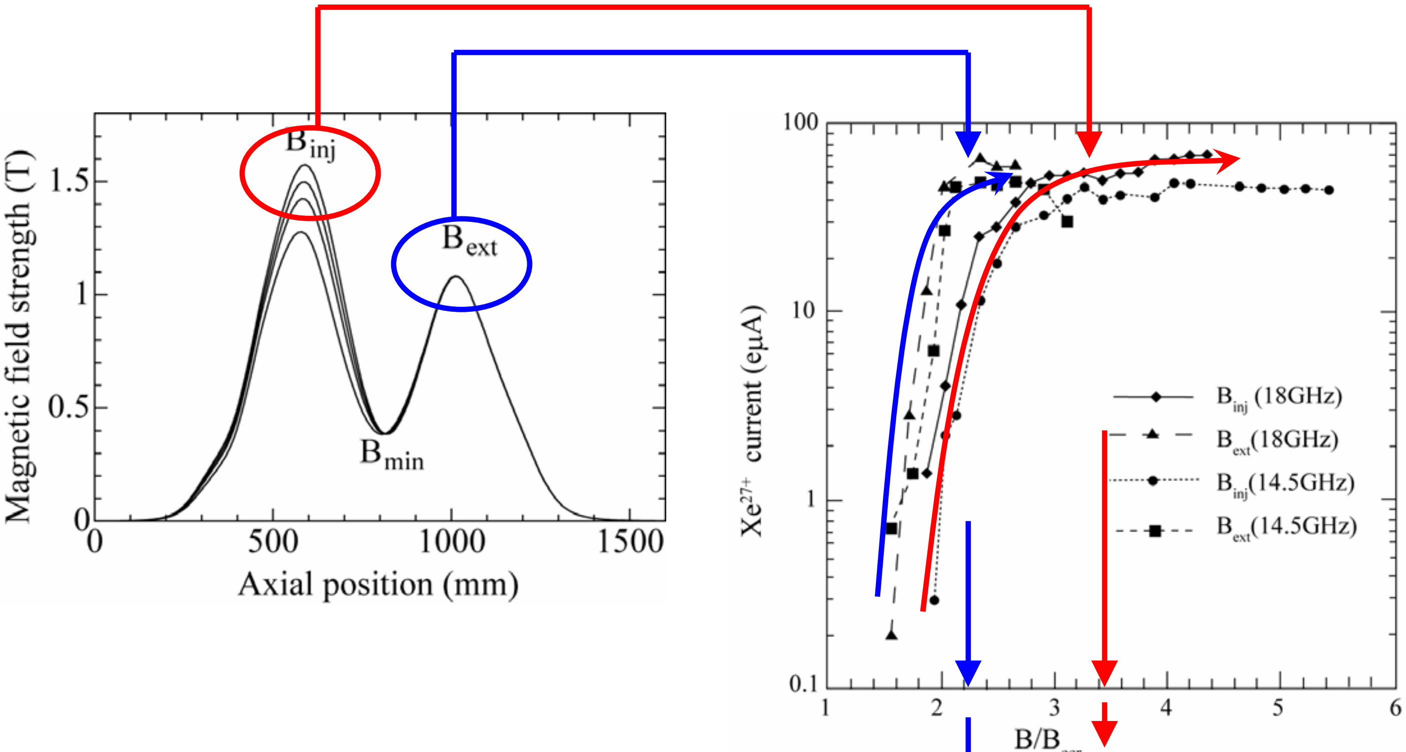
Resonance surface



Field gradient
At resonance zone



Magnetic field configuration II (Mirror ratio)

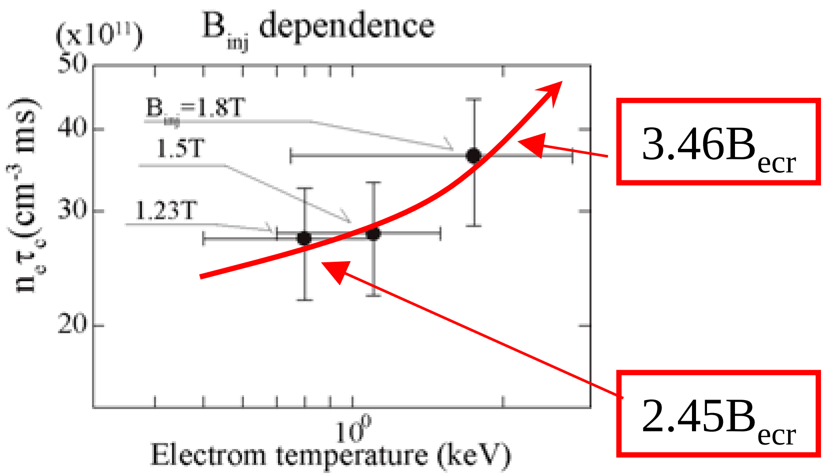


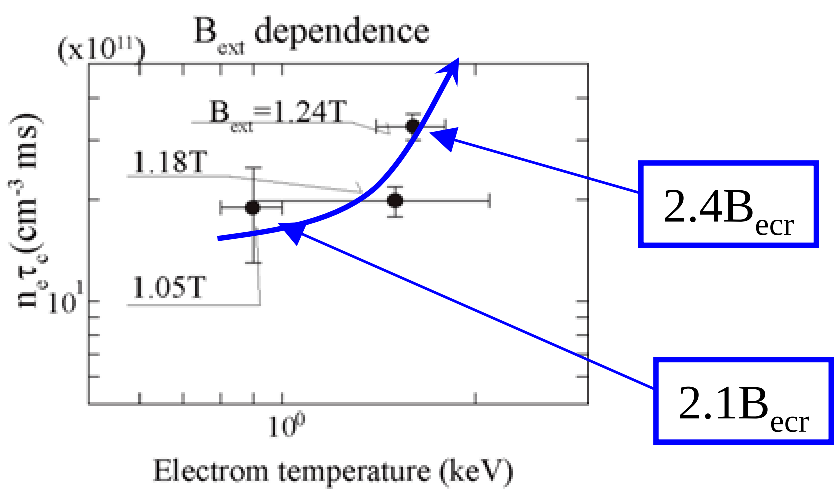
B_{inj}~$3.5B_{ecr}$

B_{ext} ~$2B_{ecr}$

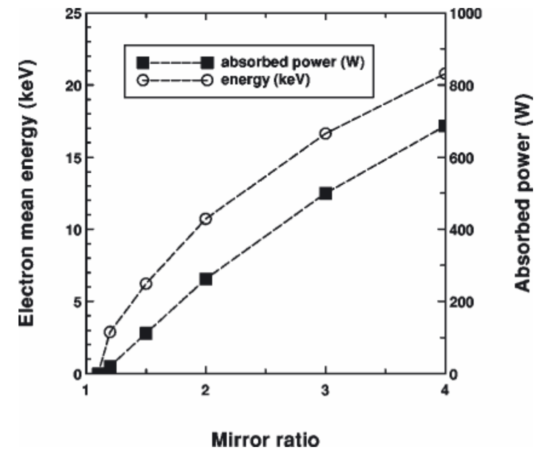
G. Ciavola et al, RSI 63(1992)2881

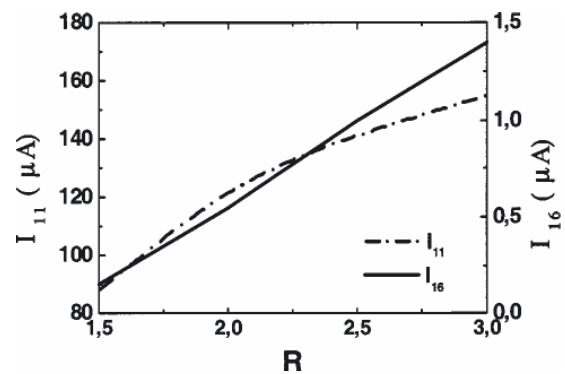
Magnetic field configuration II (B_{inj} effect)





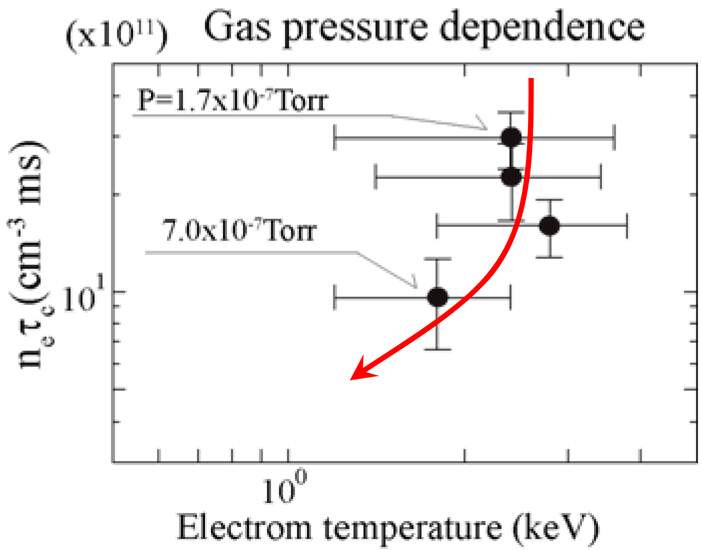
Fokker-Planck equation

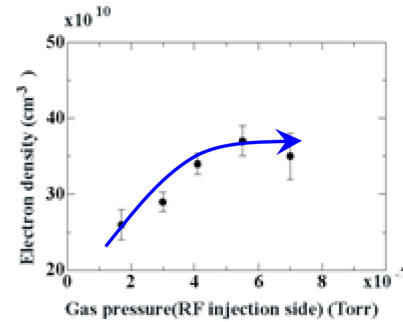




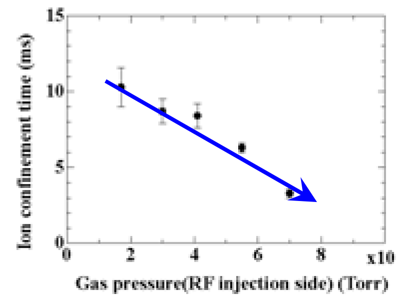
A. Girard et al J. Comput. Phys. 191(2003)228

Gas pressure effect

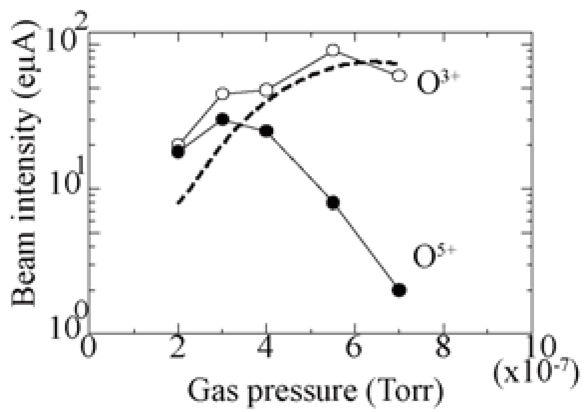


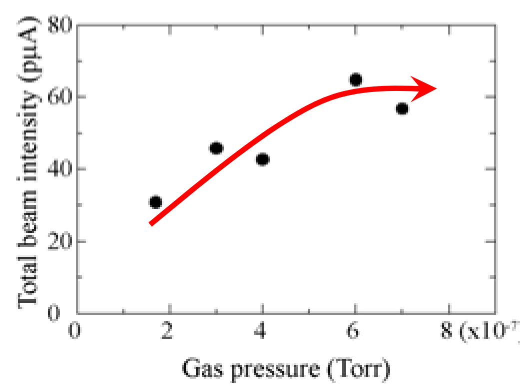


Electron density



Ion confinement time





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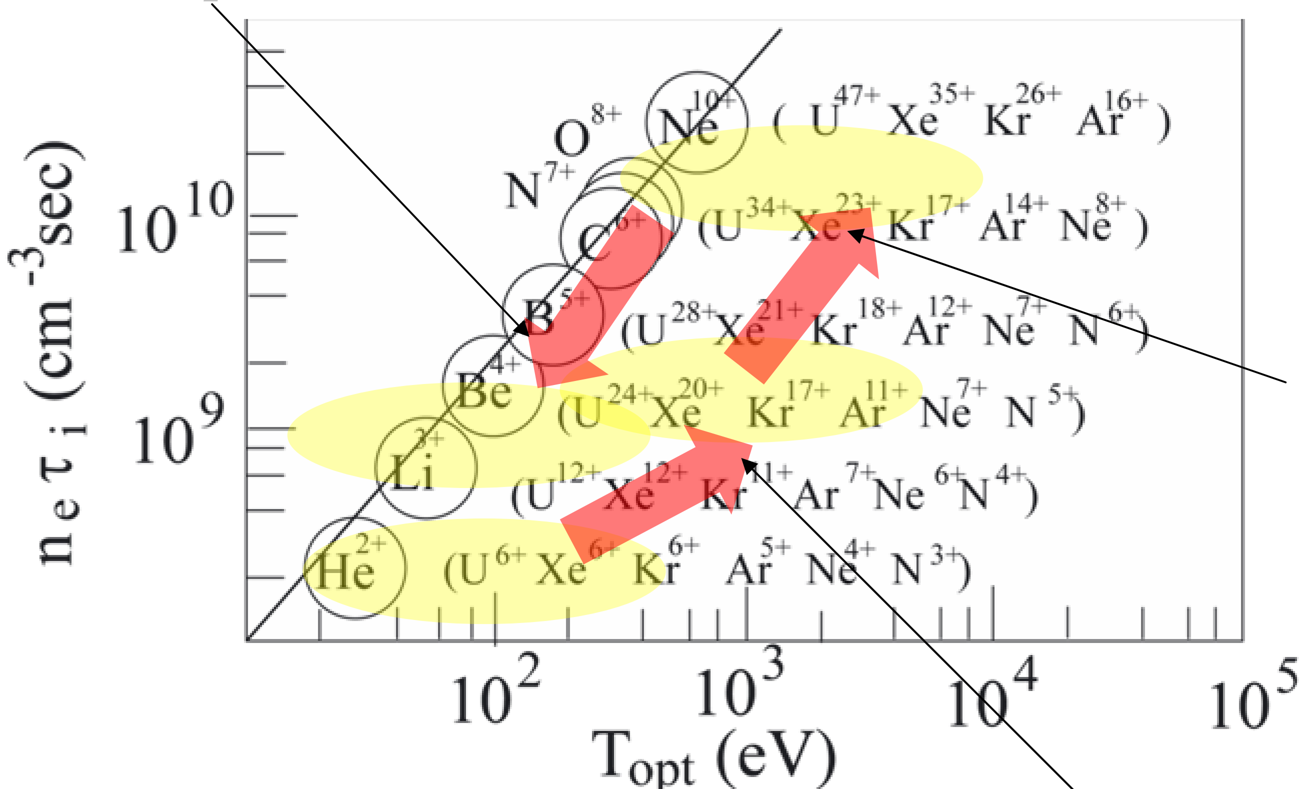
Scenario to increase the beam intensity

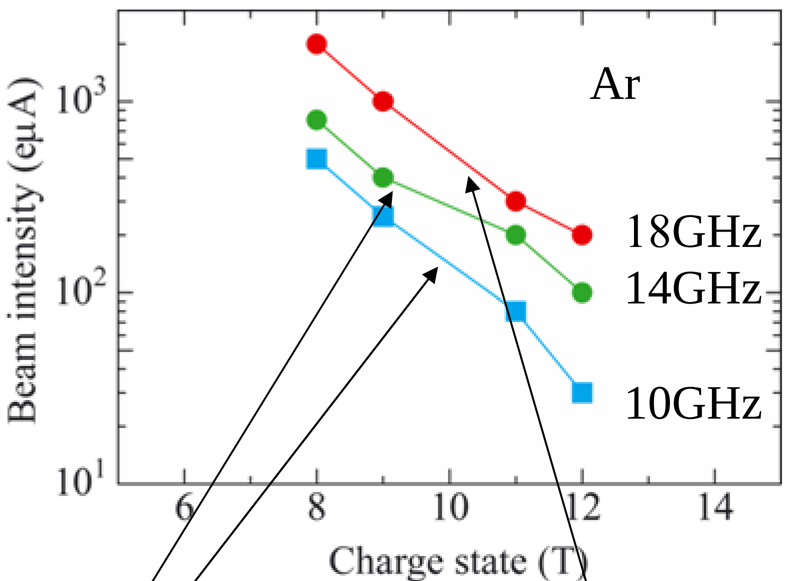
Gas pressure



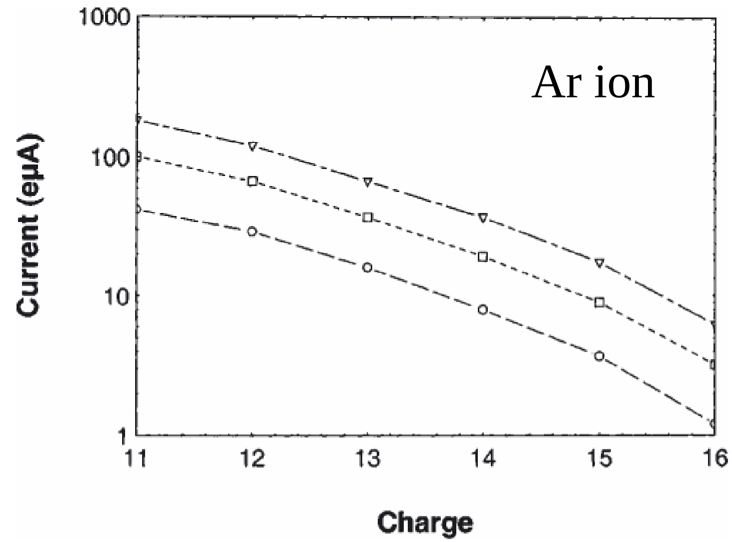
Optimization of magnetic mirror

Optimization of B_{min}

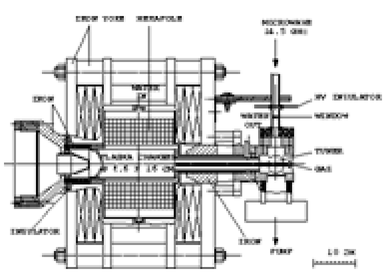
Frequency effect



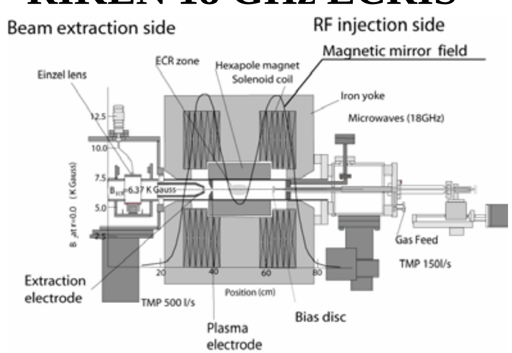
Fokker-Planck equation



Caprice (10, 14 GHz)



RIKEN 18 GHz ECRIS

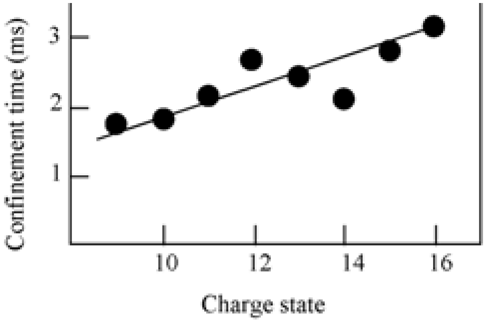


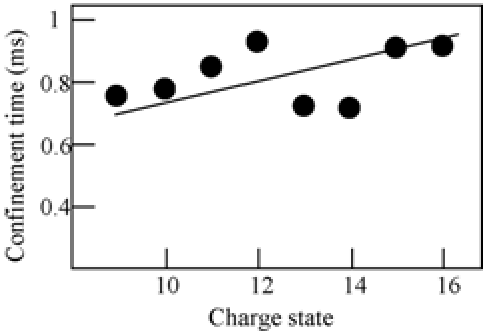
Chamber size effect (ion confinement time)

$$\tau_q = 7.1\times10^{-20} Lq \,\mathrm{Ln}\,\Lambda \sqrt{A}\frac{n_e q_{\mathrm{eff}}}{T_i^{3/2} E}$$

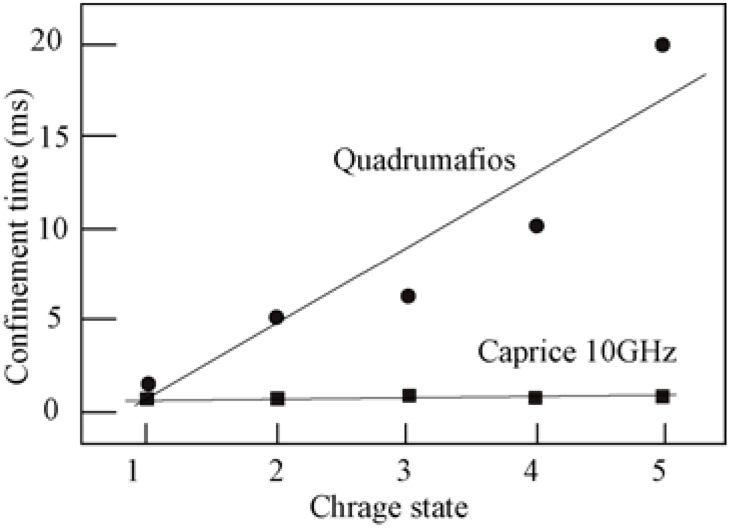
q: charge state
L: chamber length

Caprice 10GHz



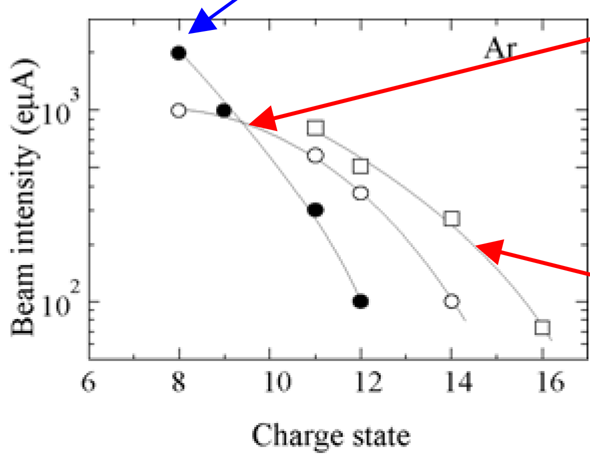


Chamber size (quadrumafios)
10times larger than caprice



1. B_{inj} >3.5B_{ecr}, B_{ext}~2B_{ecr}, B_r~2B_{ecr}, B_{min}~0.8B_{ecr}
2. Gas pressure — Highly charged heavy ions ⇨ Good vacuum
3. RF frequency — Higher ⇨ Intense beam
4. Chamber vol. — Larger ⇨ Highly charged heavy ions

Ar ion beam



RIKEN 18 GHz
B_{max}~1.4T(2Becr)
Chamber vol.~ 1L
RF ~600W (600W/L)

8+	2mA
9+	1mA
11+	300eμA

SuSi (MSU)
B_{max} <3.6T(6Becr)
Chamber vol. ~3L
RF
~1.5kW(18+14GHz)(500W/L)

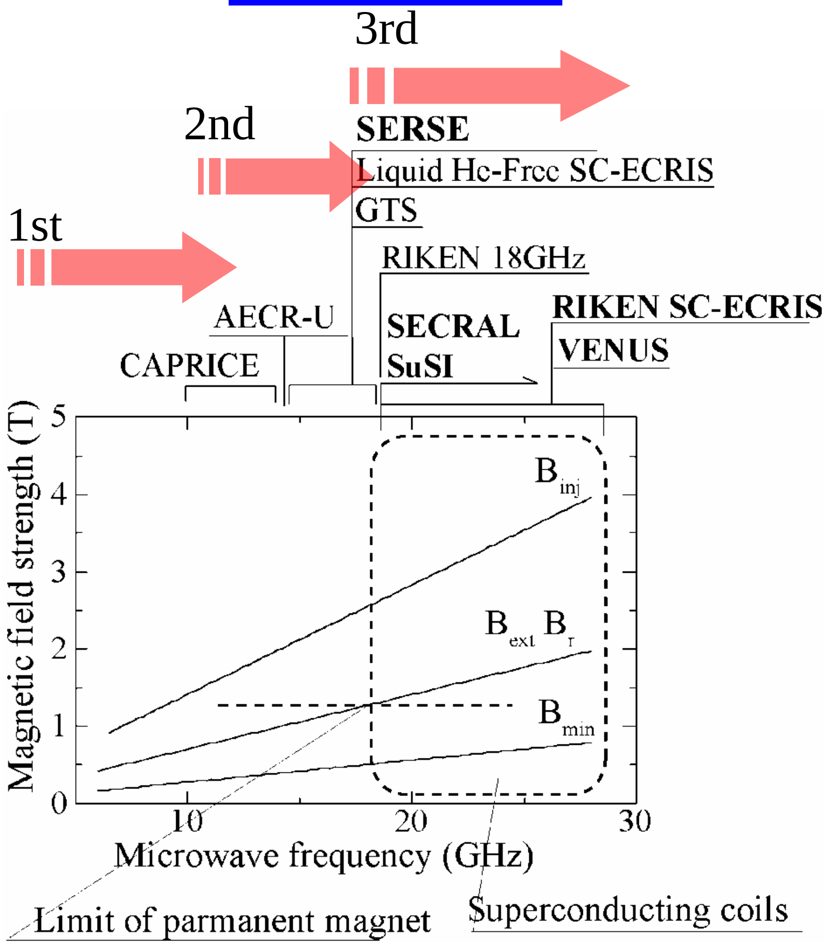
11+	540eμA
14+	100eμA

SECRAL (Lanzhou)
B_{max}~2.4T(4Becr)
Chamber vol. ~5L
RF ~3kW(600W/L)

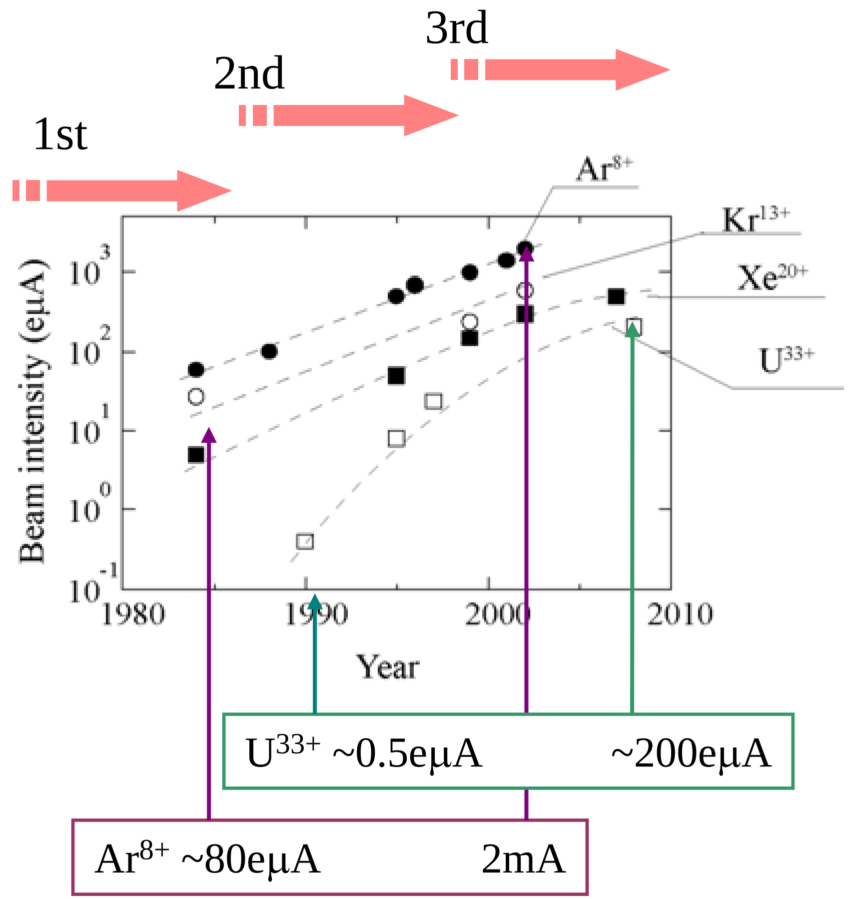
11+	810eμA
14+	270eμA

Technology of the ECR ion source

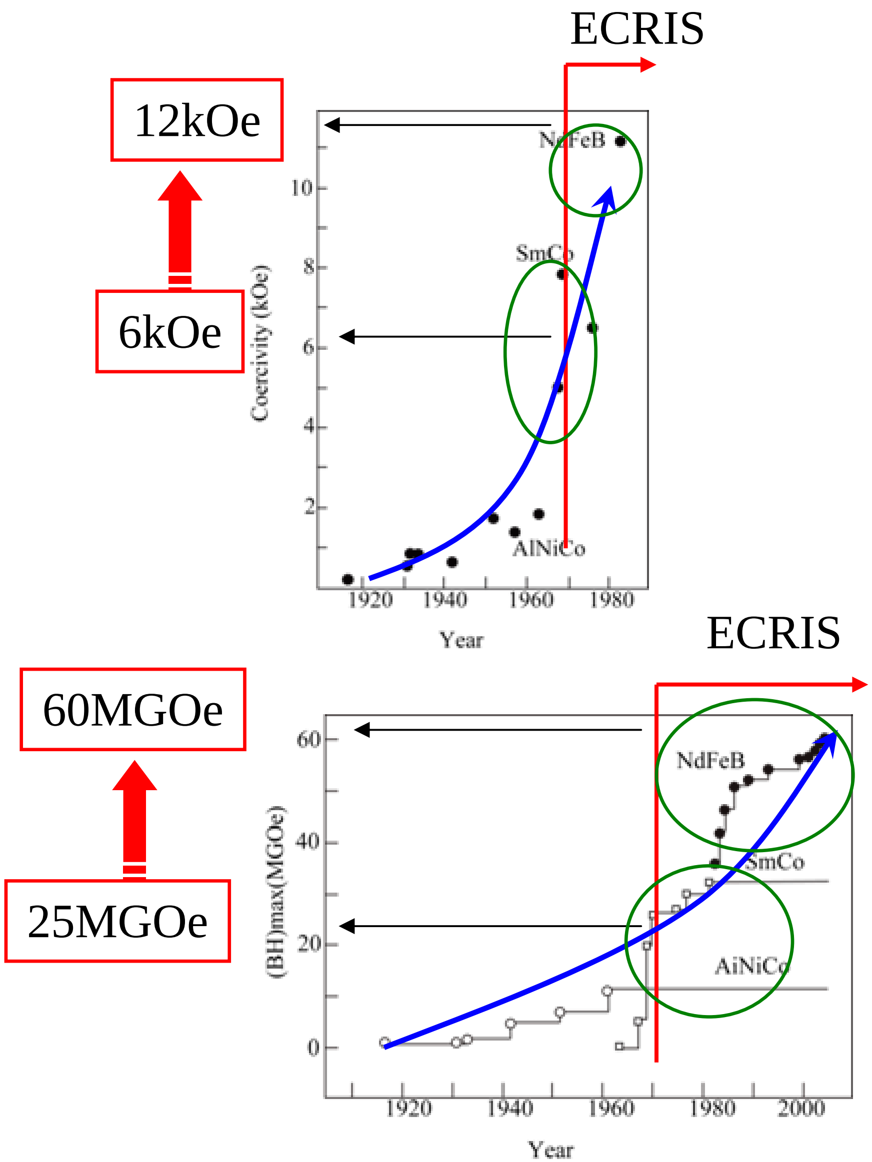
Magnetic field



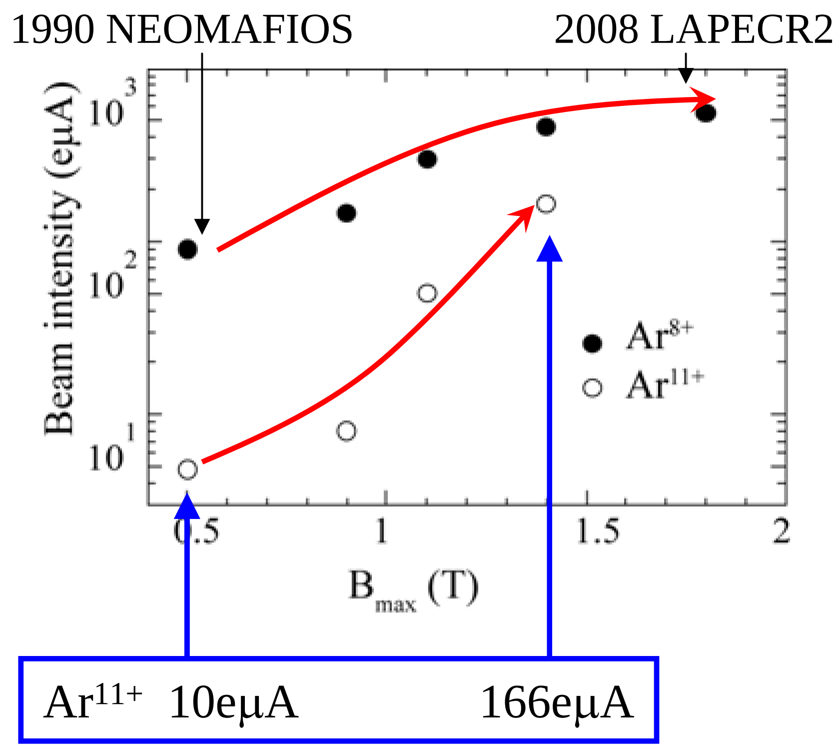
Time evolution



Permanent magnet technology



All permanent magnet ECR ion source



All permanent magnet ECR ion source (LAPECRIS2)

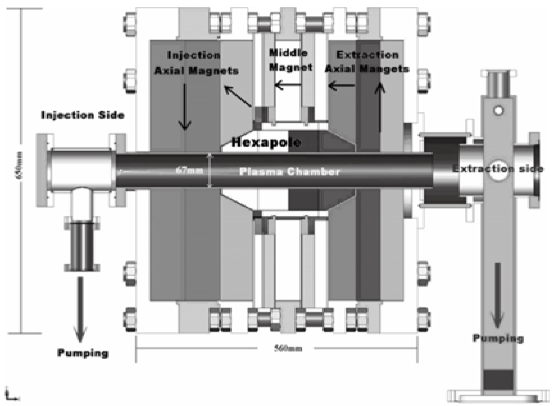
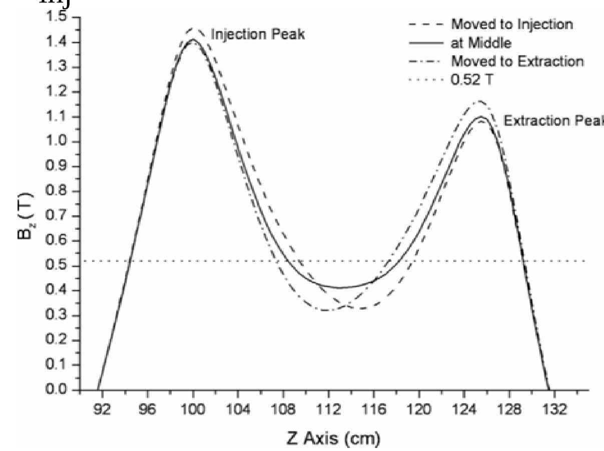


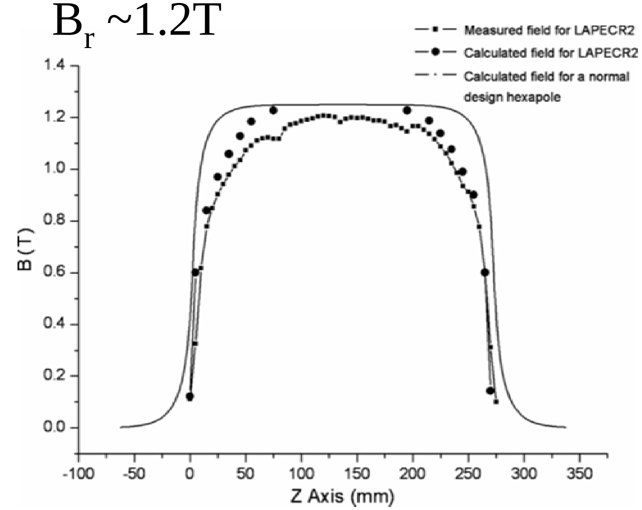
Table 2
Typical performances of LAPECR2 in comparison with LECR2

Ion	LAPECR2 (eμA)			LECR2 (eμA)
O^{6+}	1000	1.0 kW	24 kV	610
O^{7+}	130	1.0 k W	24 kV	140
Ar^{8+}	460	0.9 kW	24 kV	460
Ar^{9+}	355	0.9 kW	24 kV	–
Ar^{11+}	166	1.08 kW	25 kV	185
Ar^{12+}	62	1.08 kW	25 kV	105
Ar^{14+}	16.7	1.05 kW	23 kV	12
Ar^{16+}	2	1.0 kW	25 kV	–
Ar^{17+}	0.33	1.08 kW	23 kV	–
Xe^{20+}	85	1.0 kW	23 kV	–
Xe^{26+}	40	1.05 kW	24 kV	50
Xe^{27+}	24	1.05 kW	24 kV	25
Xe^{30+}	5.3	1.05 kW	24 kV	–
Xe^{31+}	2	1.05 kW	24 kV	–

B_{inj}~1.4T

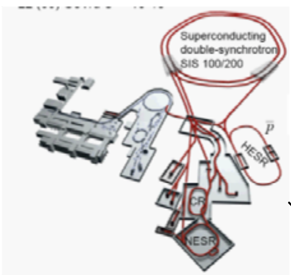


B_r ~1.2T

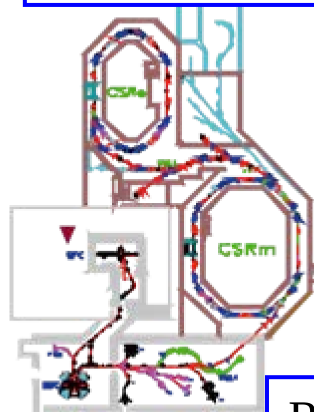


Heavy ion accelerator facility

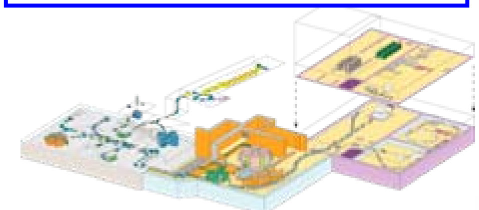
GSI (Germany)



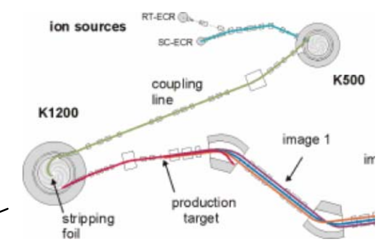
Lanzhou (China)



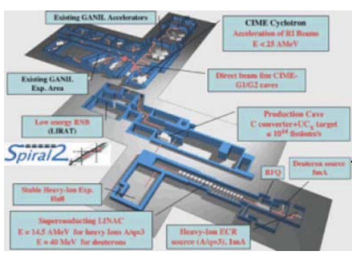
RIKEN RIBF (Japan)



MSU (USA)

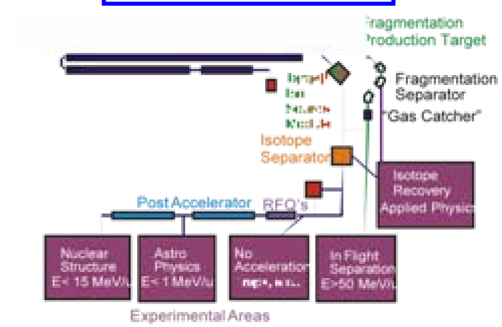


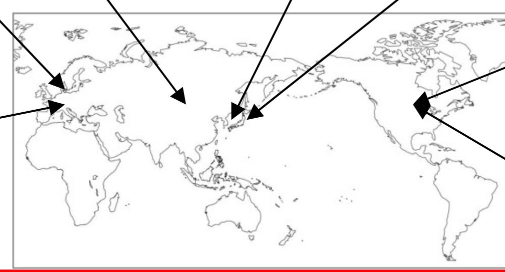
SPIRAL II (France)



RIBF (South Korea)

FRIB (USA)

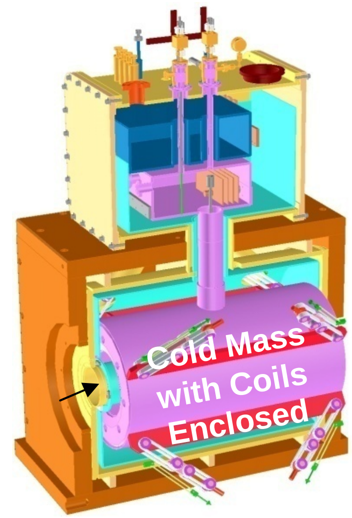




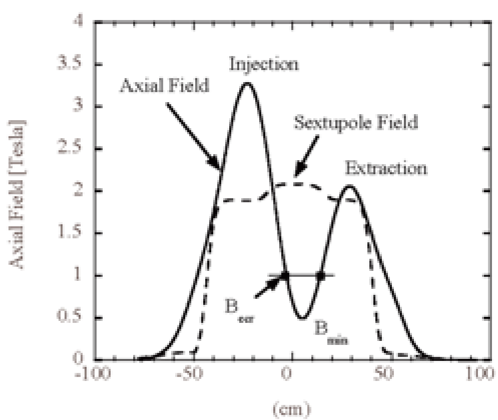
Require intense beam of highly charged heavy ions

~6pμA of U^{33+}, 1mA of Ar^{12+}

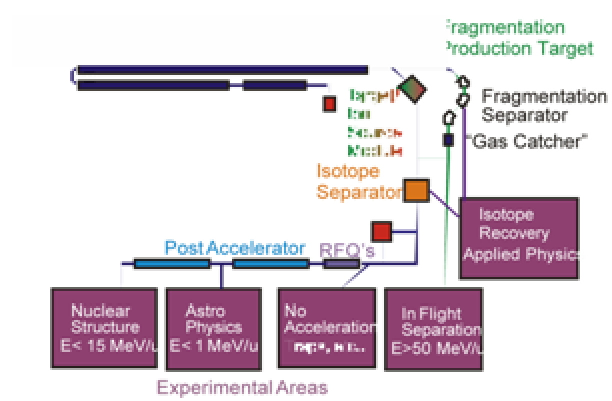
Advanced ECR ion source I (VENUS)



B_{inj}/B_{ecr}	~ 4
B_{ext}/B_{ecr}	~ 2
B_{min}/B_{ecr}	~ 0.5 to 0.8
B_{rad}/B_{ecr}	≥ 2
B_{ext}/B_{rad}	≤ 0.9 to 1



		VENUS			
f(GHz)		28 or18 +28			
^{16}O	6^{+}	2850	^{129}Xe	28^{+}	222
	7^{+}	850		29^{+}	168
^{40}Ar	12^{+}	860		30^{+}	116
	14^{+}	514		31^{+}	86
	16^{+}	270		34^{+}	41
	17^{+}	36		37^{+}	12
	18^{+}	1		38^{+}	7
				42^{+}	.4
^{238}U	33^{+}	205			
	34^{+}	202			
	35^{+}	175			
	47^{+}	5			
	50^{+}	1.9			



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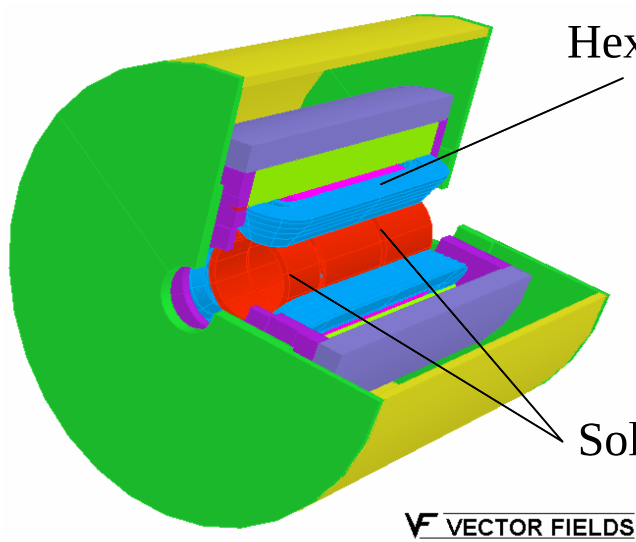
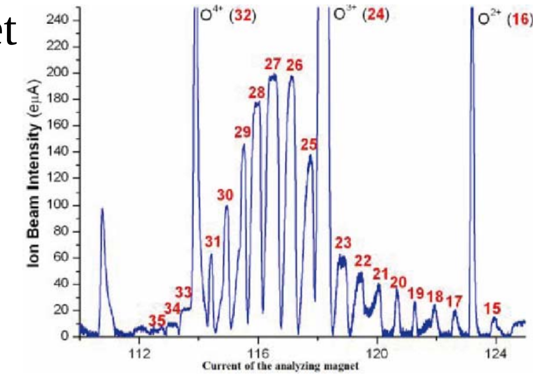
Advanced ECR ion source II(SECRAL)



B_{inj}~3.6T B_{ext}~2.2T, B_r~2.0T
Chamber vol. 5L

Solenoid coils are located inside of the hexapole magnet

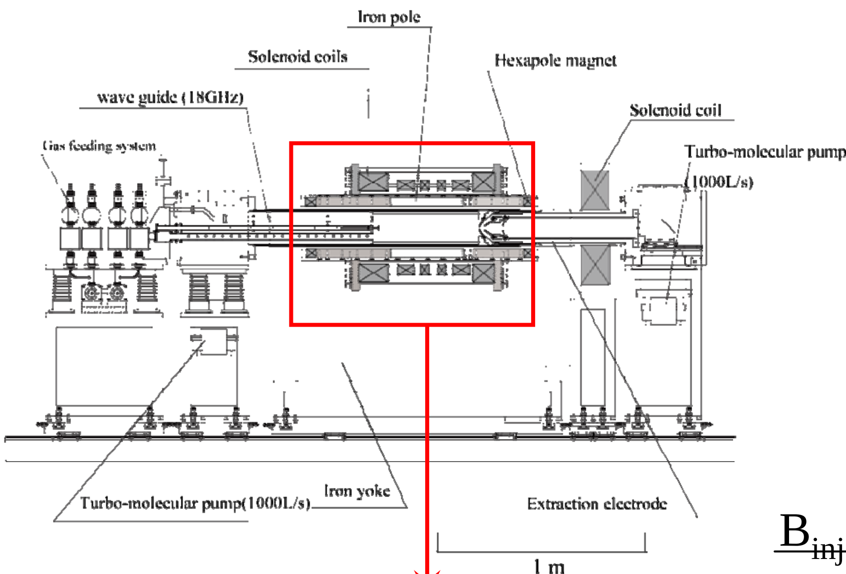
Reduce the interaction force between hexapole coils and solenoid coils

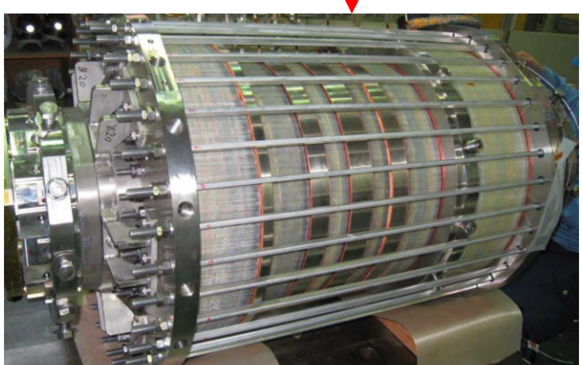


18GHz RF

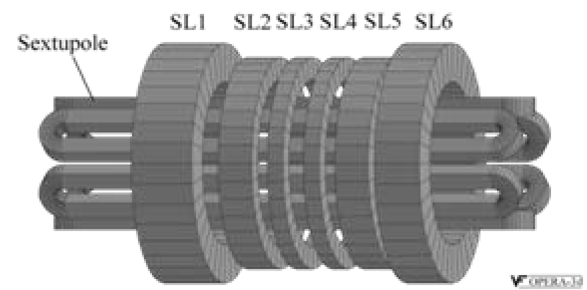
f (GHz)	Q	SECRAL[12] 18
O	6^{+}	2300
	7^{+}	
Ar	11^{-}	810
	$12^{\cdot}$	510
	14^{-}	270
	$16^{\cdot}$	73
	17^{-}	8.5
Xe	$20^{\cdot}$	505
	26^{-}	410
	$27^{\cdot}$	306
	$30^{\cdot}$	101
	31^{-}	68
	33^{-}	31
	34^{-}	21
	35^{-}	12
	37^{-}	5
	38^{-}	2.4

RIKEN 28GHz ECR ion source

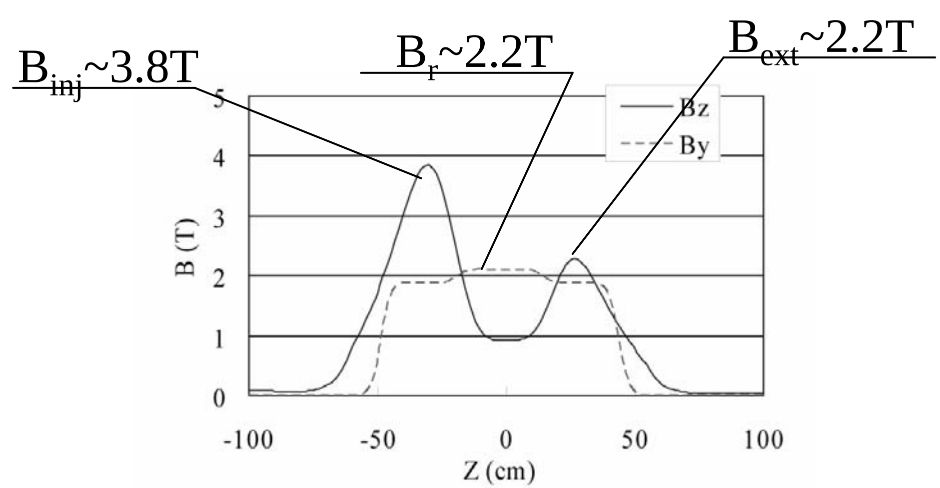




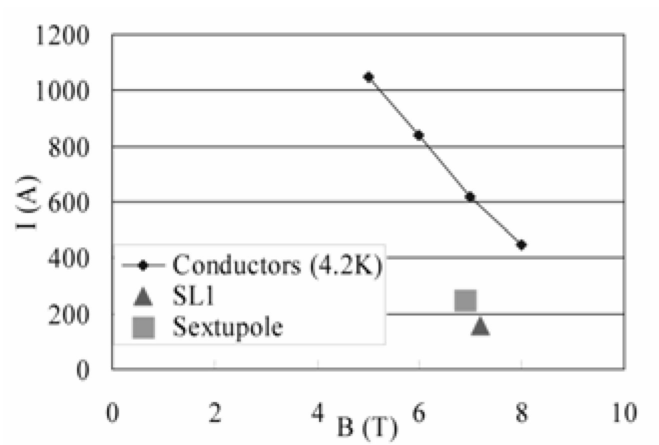
Coil arrangement



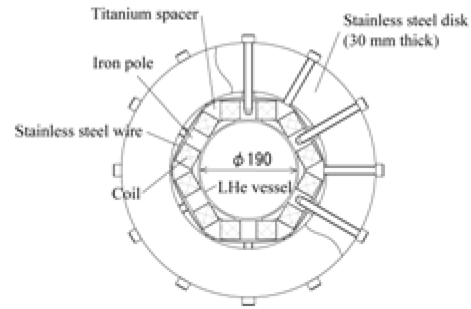
Magnetic field strength

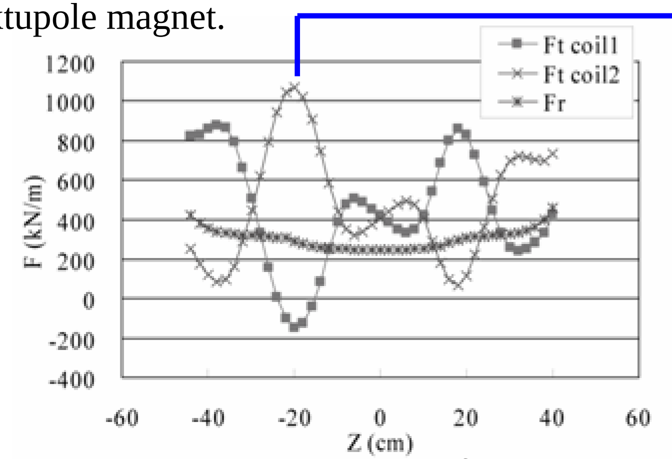


Structure of SC-Coils

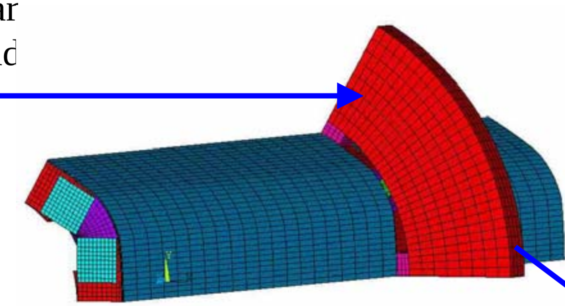


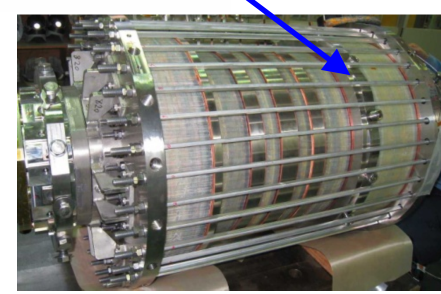
I_c performance of the conductor with a rectangular shape and the load points for the solenoid SL1 and sextupole magnet.





The longitudinal distributions of the magnetic force acting on the straight region of the hexapole coils.





Size of ECR zone vs. B_{min} (field gradient)

Field gradient effect

$$\Delta W \sim \frac{\pi e^2 \left|\vec{E}\right|^2}{m_e \nu \omega \frac{1}{B_{res}} \left(\frac{dB}{dZ}\right)_{res}}$$

Surface size effect

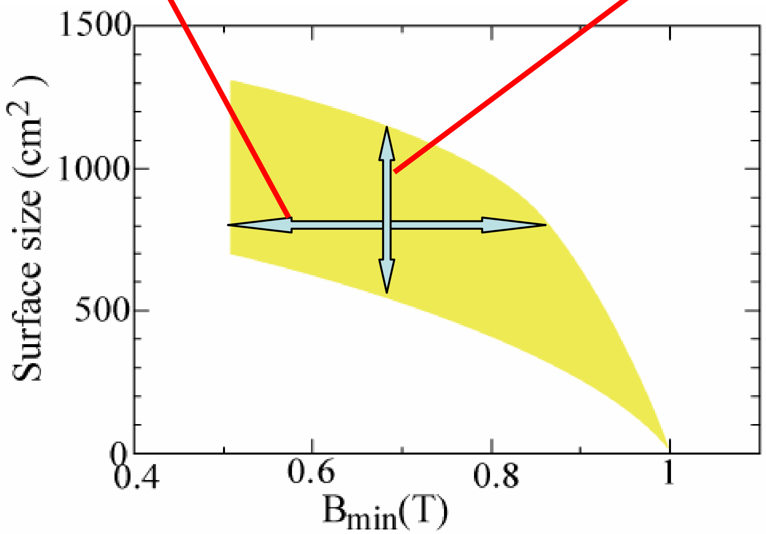
$$I_q = \frac{n_q\, q\, V}{\tau_c}$$

n_q : ion density

q : charge state

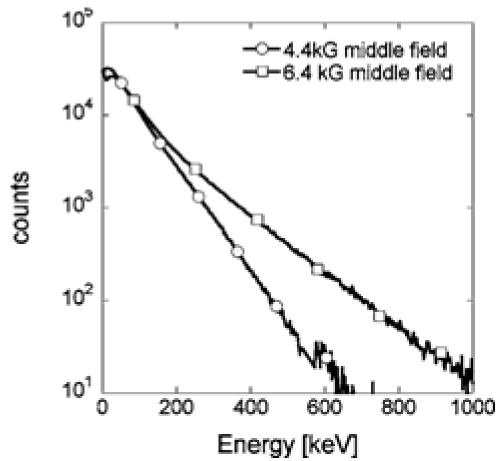
V : plasma volume

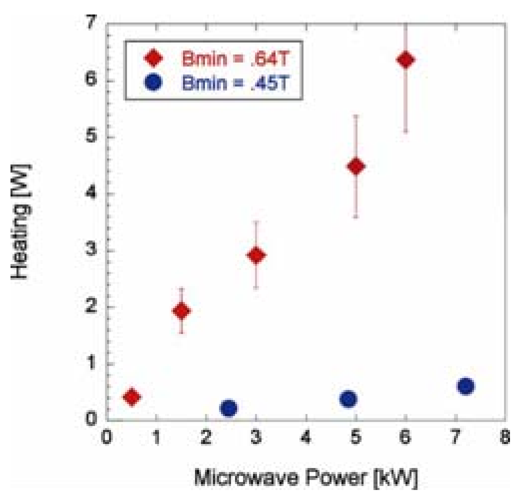
τ_c : ion confinement time



Heat load (x-ray form plasma)

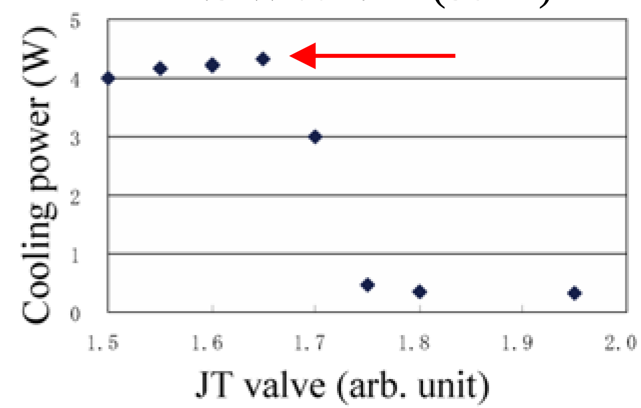
Rev. Sci. Instrum. 79(2008)033302 D. Leitner et al,





GM-JT refrigerator

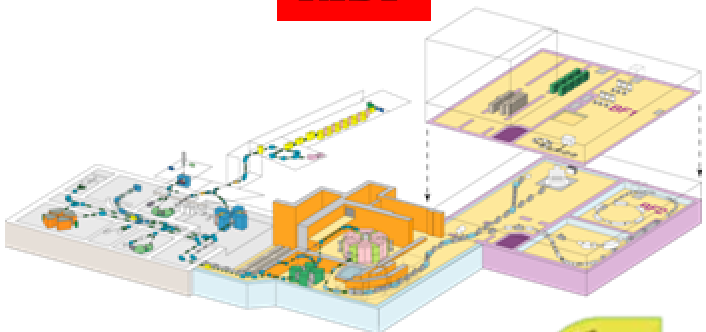
~4.5 W at 4.2K (50Hz)

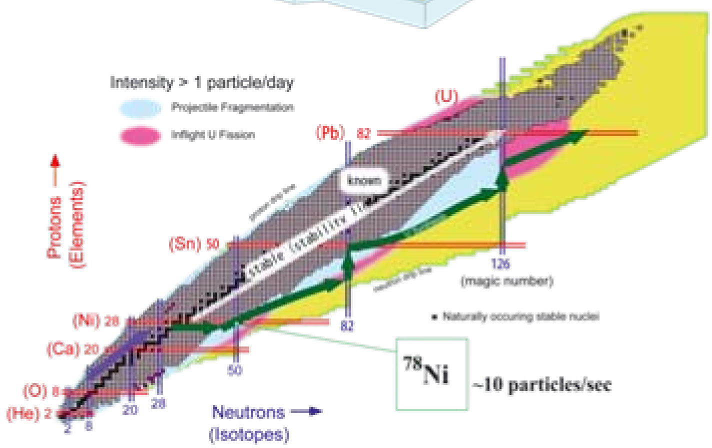


2 GM-JT refrigerator is installed for
Cooling the SC-Coils of RIKEN SC-ECRIS

Next generation (requirements)

RIBF



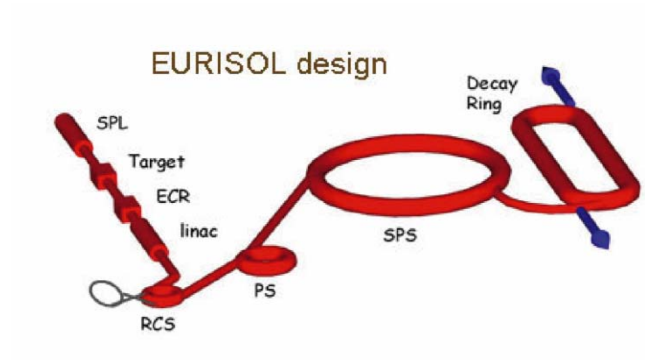


1pμA U beam on target

>15pμA of U^{35+} from ion source

New ECR ion source

Beta beam



Required beam intensity from ion source

^{6}He= 2 10^{13} atoms per second
^{18}Ne= 8 10^{11} atoms per second

High ionization efficiency

New 60GHz ECRIS

Next generation (Superconducting magnet technology)

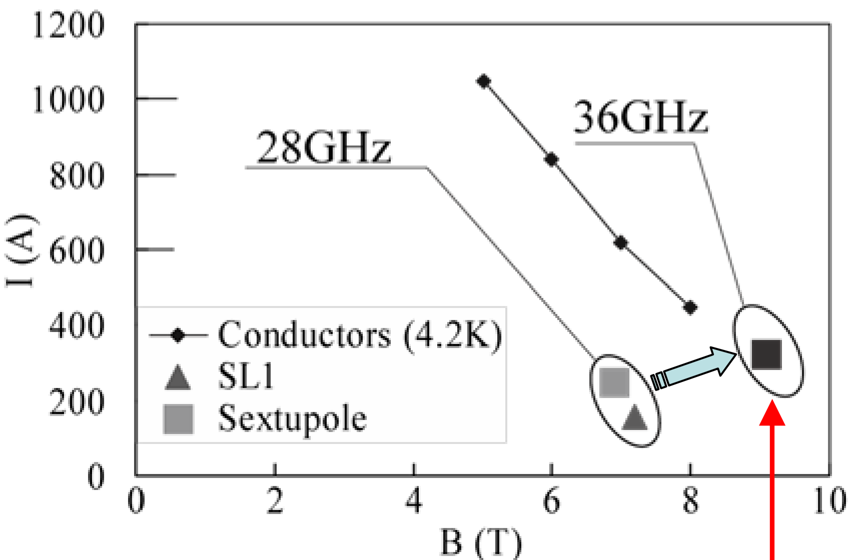
36GHz ECRIS

Required magnetic field strength

B_{inj}	~ 5T
B_r	~2.7T
B_{ext}	~2.7T
B_{min}	0.8~1.2T

Example of RIKEN 28GHz ECRIS

28GHz ⇨ 36GHz



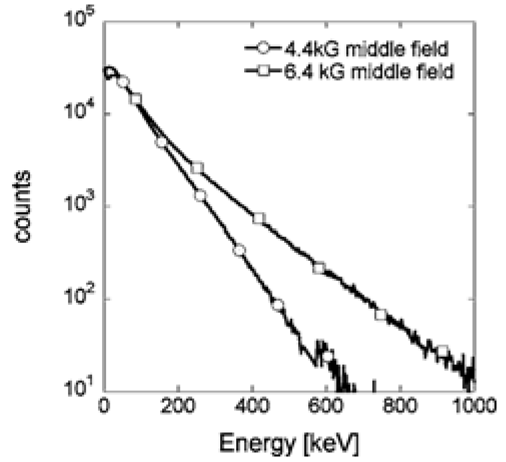
Exceed the critical current of NbTi wire at 4.2K

Solution

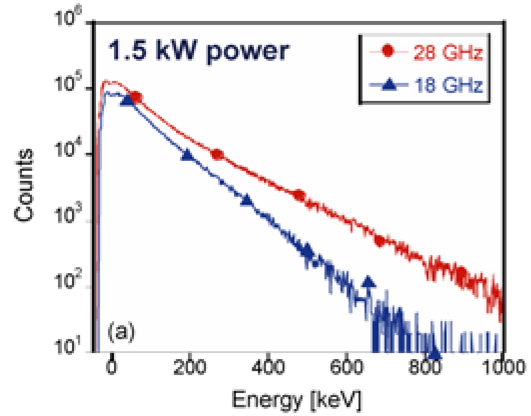
1) Use of NbTi wire at low temperture (<4.2K)

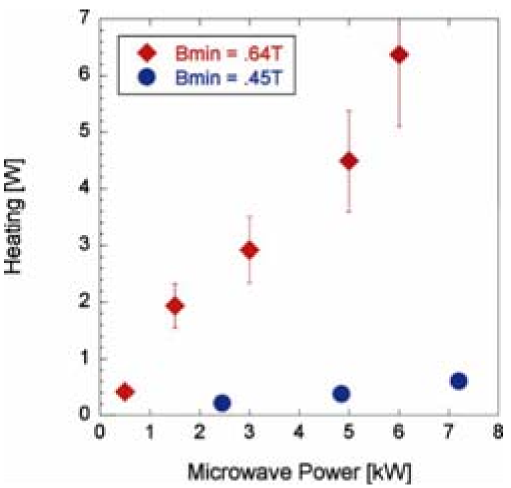
2) Use of other super-conducting wires (Nb_3Sn)

Next generation (Heat load from X-ray)



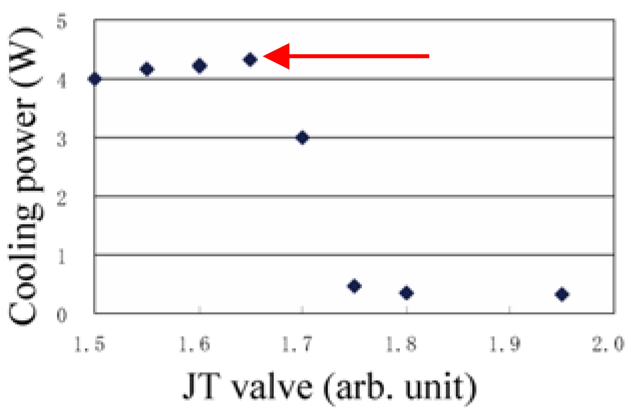
Frequency effect





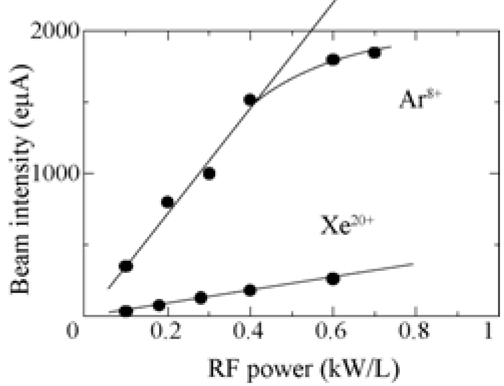
GM-JT refrigerator

~4.5 W at 4.2K (50Hz)

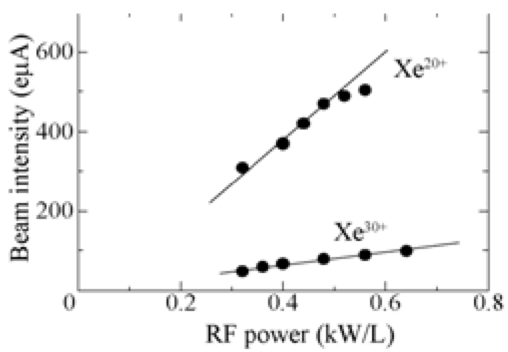


Next generation (Limitation of injected RF power)

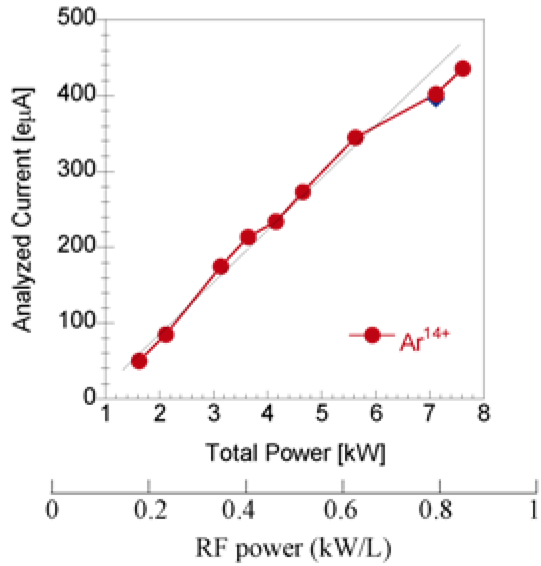
RIKEN 18GHz



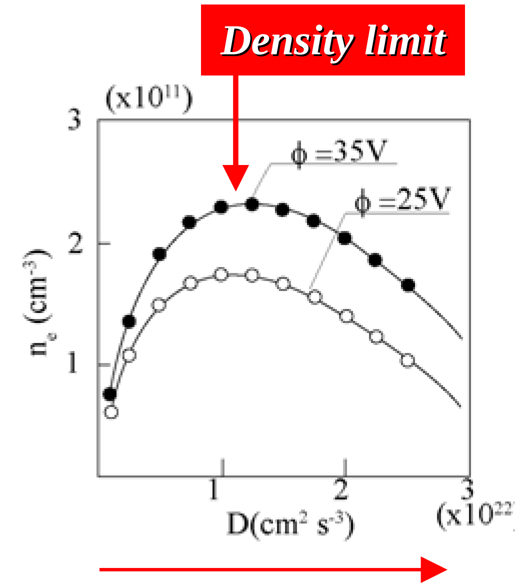
SECRAL 18GHz



VENUS 28GHz



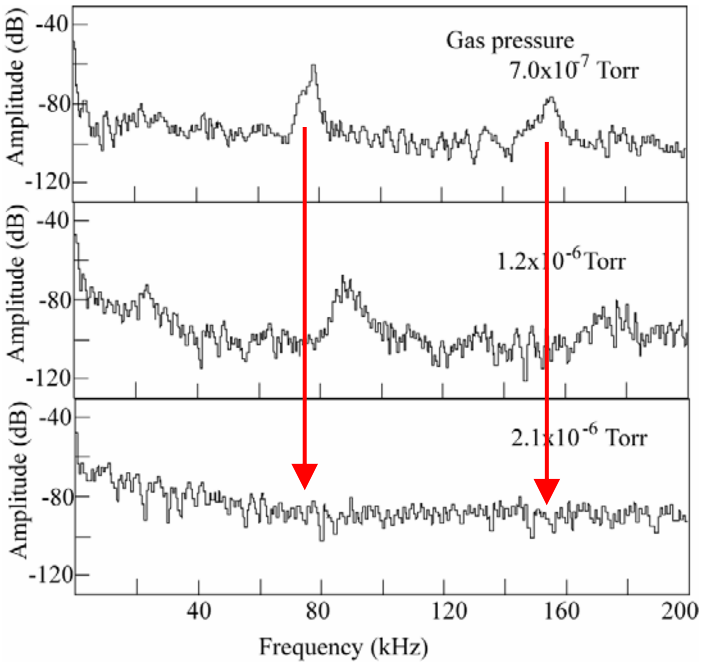
Fokker-Plank equation

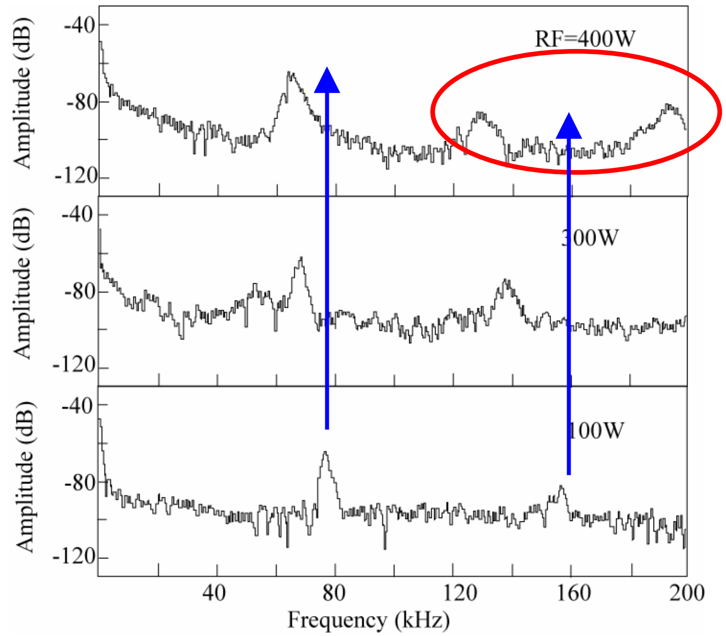


RF power

Next generation (Plasma instability)

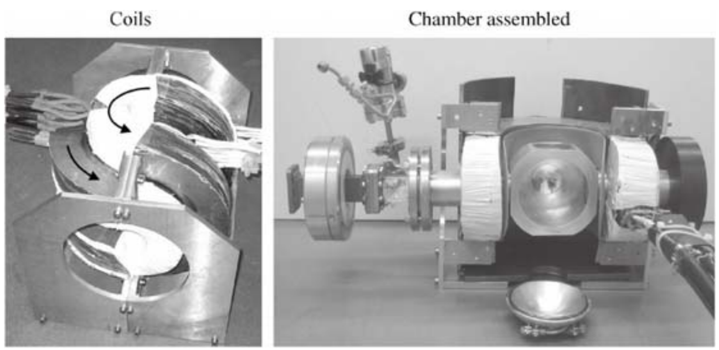
Beam from ECRIS

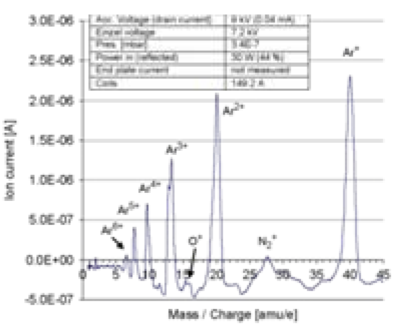


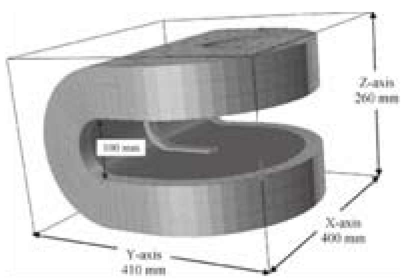


Next generation (New type ECRIS)

ARC ECRIS

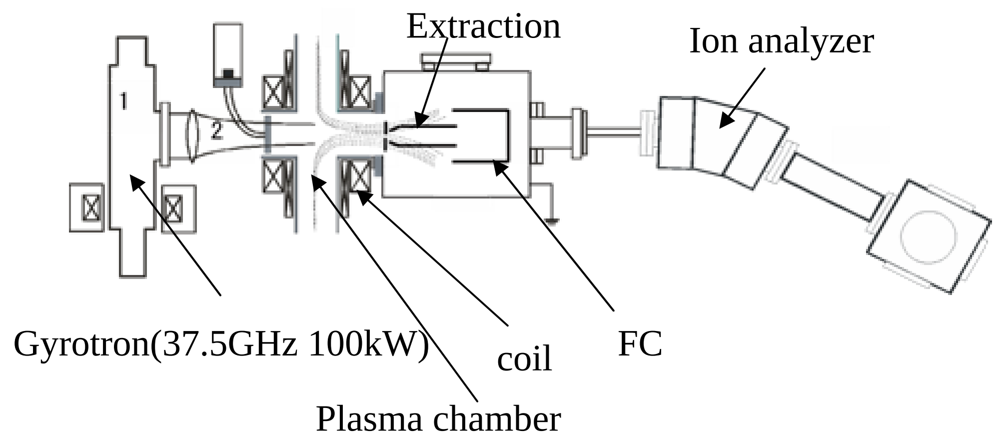




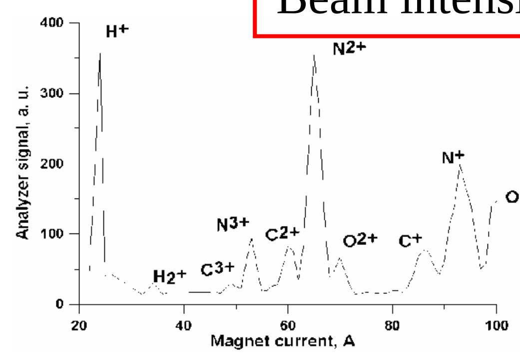


NIM A578(2007)370

Gas dynamics ECRIS



Beam intensity Few A/cm^2



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