39th ECPM

European Cyclotron Progress Meeting

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MICROWAVES TO PLASMA COUPLING TECHNIQUES ON THE AISHa SOURCE

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AISHa

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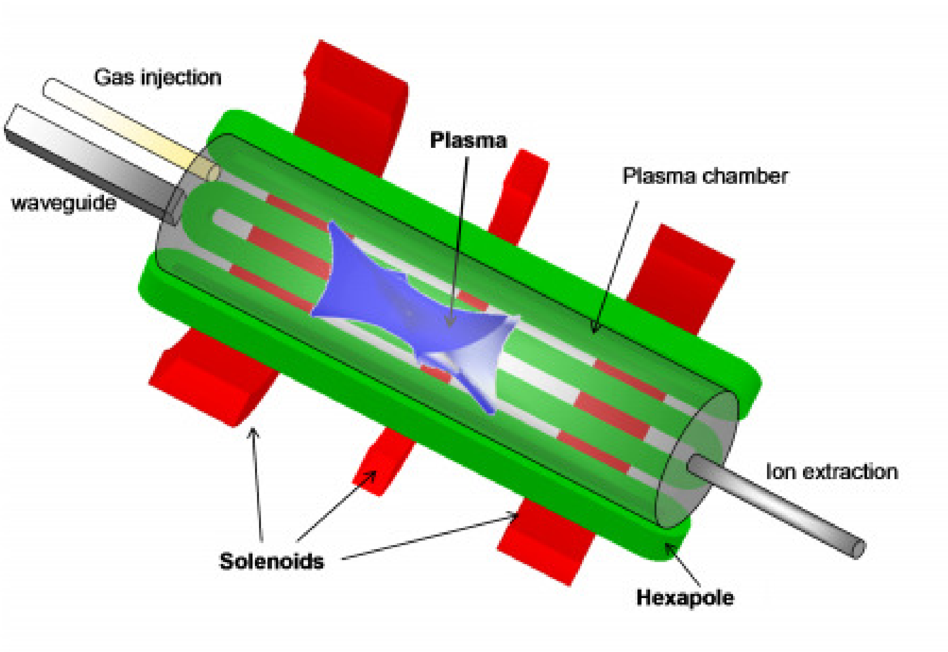
Electron Cyclotron Resonance Ion Source

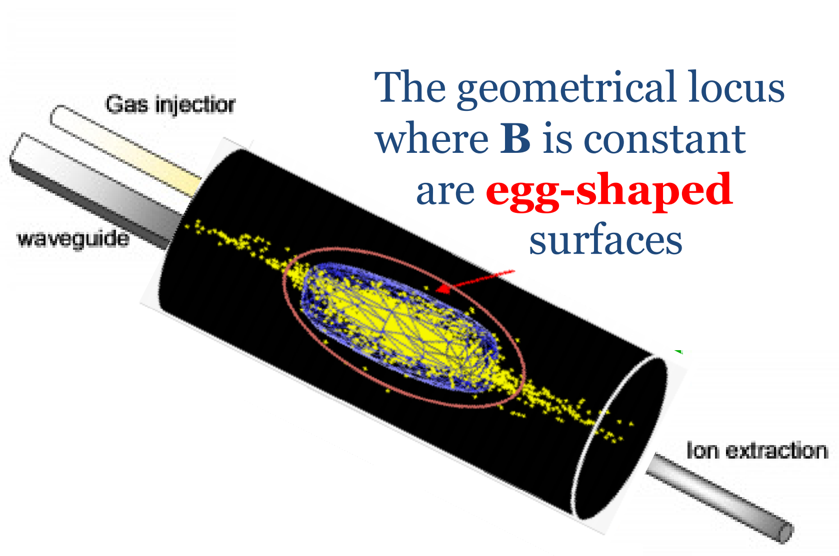


- long life-time
- low maintenance
- high stability
- intense CW or pulsed beams
- highly charged ions
- gaseous and metallic elements

An absorption of the wave energy occurs when the electrons cross the surface where the magnetic field fulfilled the ECR condition

ECR surface

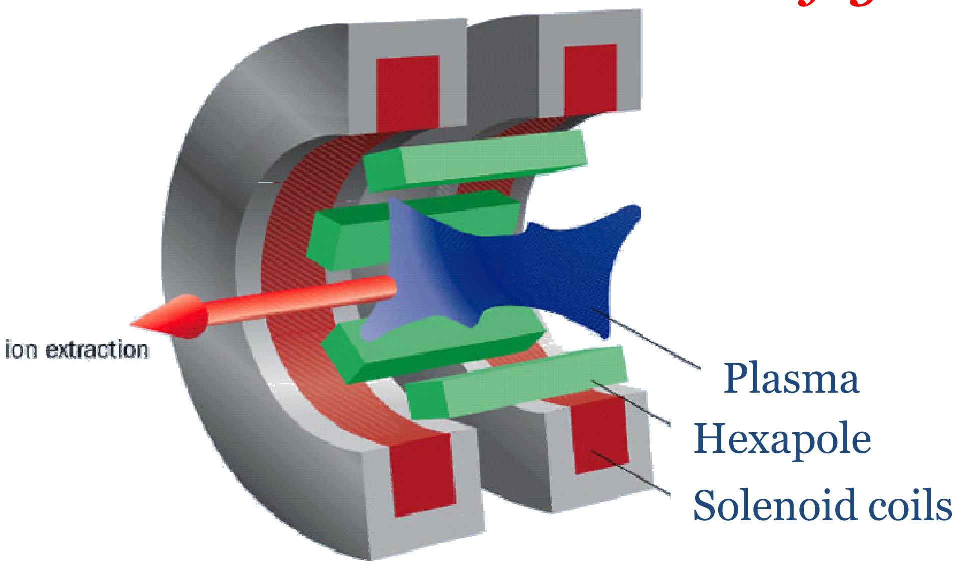
$$B_{ECR} = 2\pi \frac{m_e}{e} f$$

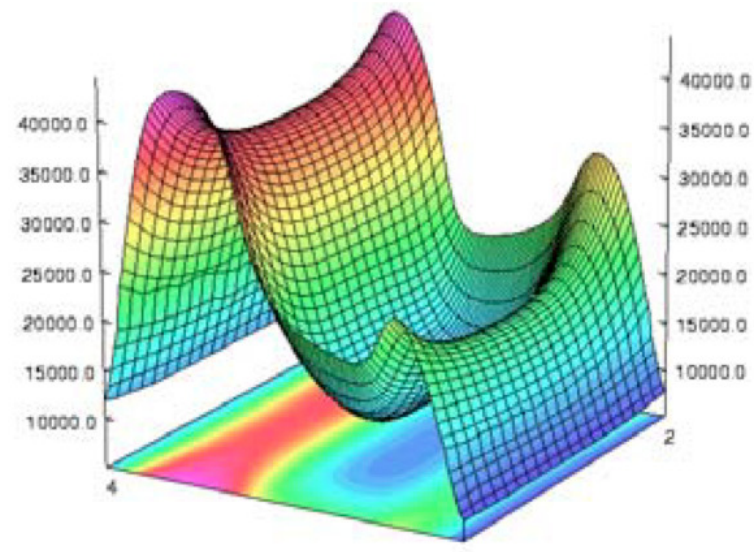


The geometrical locus where **B** is constant are **egg-shaped** surfaces

ECRIS: fundamental aspects

Minimum-B Configuration





*High-B Mode concept**

$$\frac{B}{B_{ECR}} \geq 2$$

$$f = 18\ GHz$$
$$n_e \approx \left[10^{12}\ cm^{-3}\right]\ \tau_i \approx [ms]$$

The possibility to operate with variable magnetic field allows the source performance to be optimized

*S. Gammino and G. Ciavola, Plasma Source Sci. Technol, May 1996. 5, 19-27

ECRIS: fundamental aspects

Waves in plasma:

- by external microwave generator
- Self-generated electrostatic oscillations

The propagation of e.m. waves is possible if ε>0

For cold plasma approximation $(T_e = T_i \sim 0)$

$$\varepsilon(\omega) \approx 1 - \frac{\omega_p^2}{\omega^2}$$

plasma frequency

$$\omega_p^2 = \frac{4\pi n_e e^2}{m_e}$$

cut-off density

$$n_{cutoff} = 4\pi^2 \frac{m\epsilon_0}{e^2} f_p^2$$

cut-off frequency

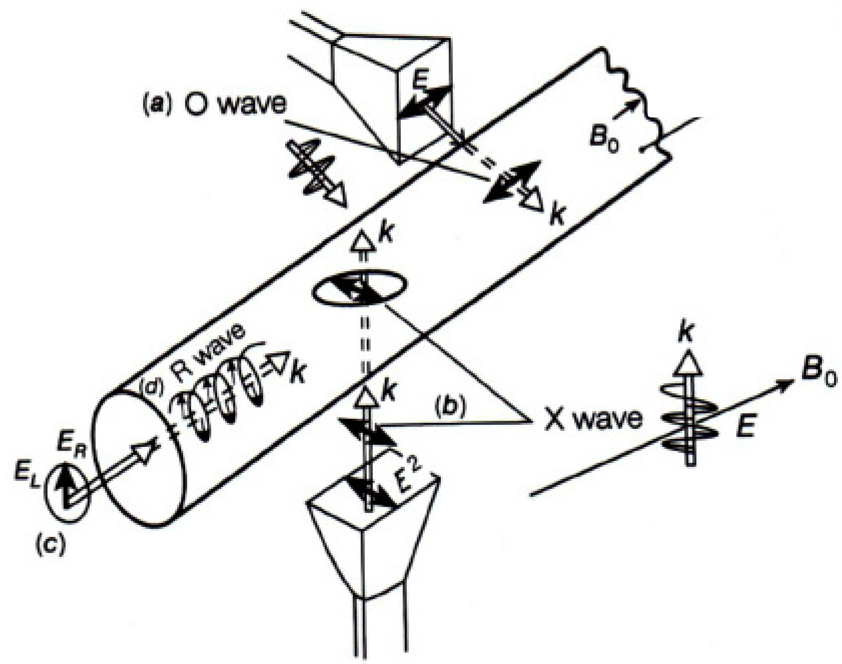
$$\omega = \omega_p$$

Above the cutoff the wave cannot propagate!

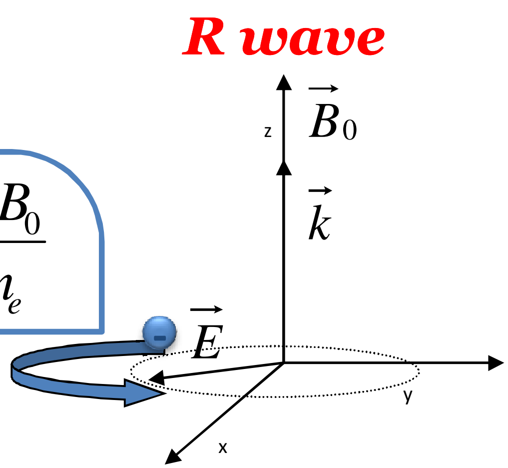
ECRIS: fundamental aspects

$$\bar{\bar{\varepsilon}} = \varepsilon_0 \bar{\bar{\varepsilon}}_r$$

$$\epsilon_r = \begin{pmatrix} \epsilon_{xx} & \epsilon_{xy} & 0 \\ \epsilon_{yx} & \epsilon_{yy} & 0 \\ 0 & 0 & \epsilon_{zz} \end{pmatrix}$$

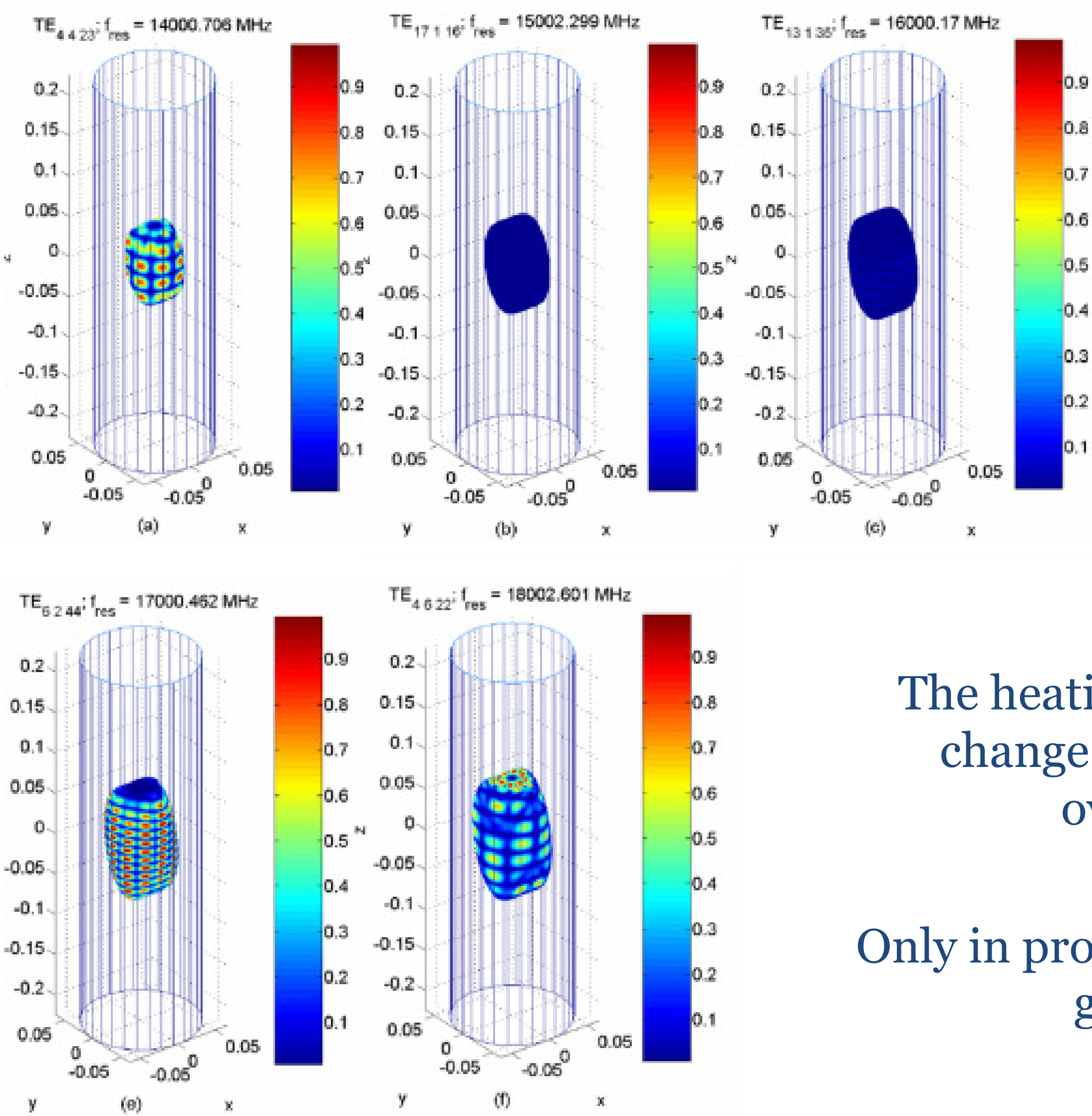


$$\omega_c = \frac{q_e B_0}{m_e}$$



A resonance occurs when the direction of rotation of the plane of polarization of the wave is the same of the direction of the gyration of the electrons around the lines of the magnetic field

ECRIS: fundamental aspects



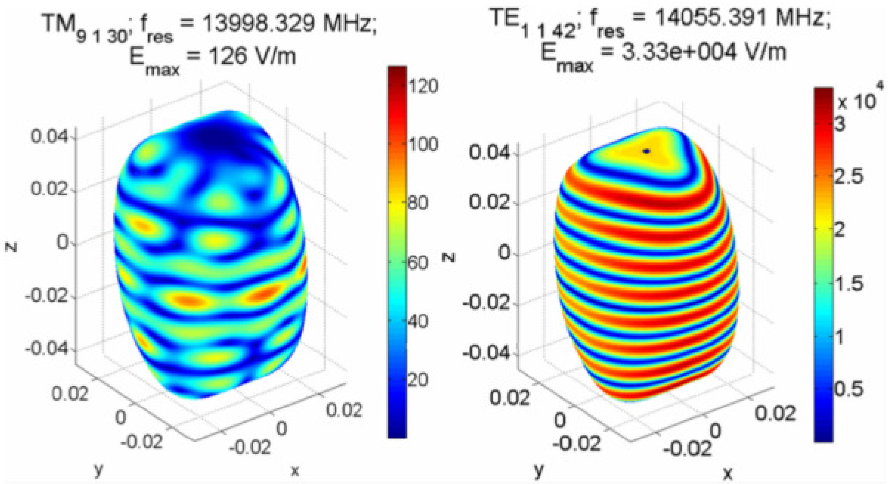
*The plasma chamber is a **resonant cavity** for the electromagnetic waves*

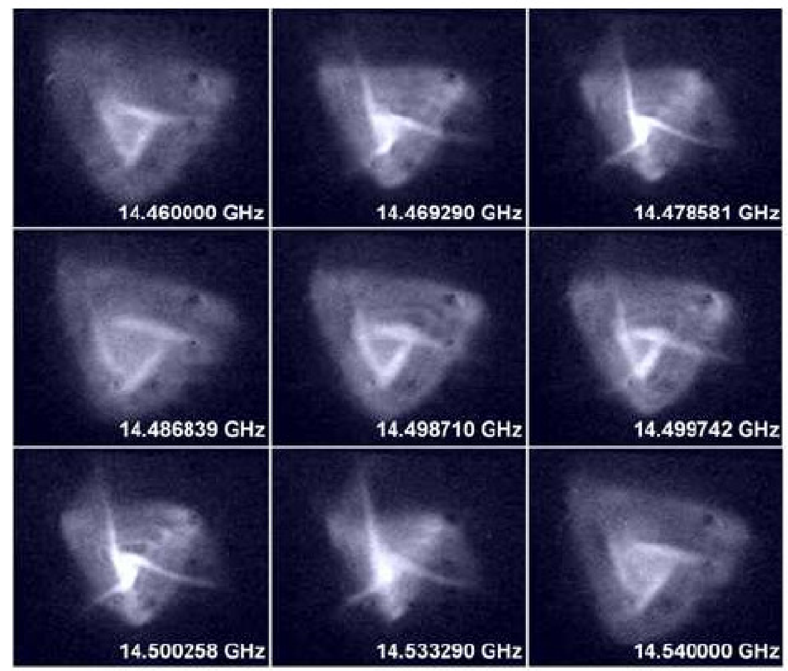
The heating and the ionization process change with the e.m. field distribution over the resonance surface

Only in proximity of high field the electron gained very high energies

Microwaves to Plasma Coupling Techniques

Frequency Tuning Effect (FTE)

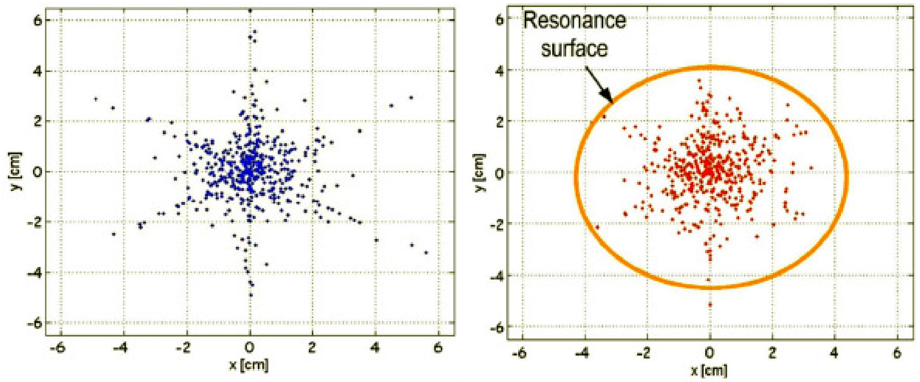




Celona et al.,Rev. Sci. Instrum., 79 (2008) 023A305

Slight variation (~MHz)
of the exciting frequency produces
strong changes in the electric field distribution
over the resonance surface,
therefore on the ionization rate, and finally,
on the output beam shape

Microwaves to Plasma Coupling Techniques

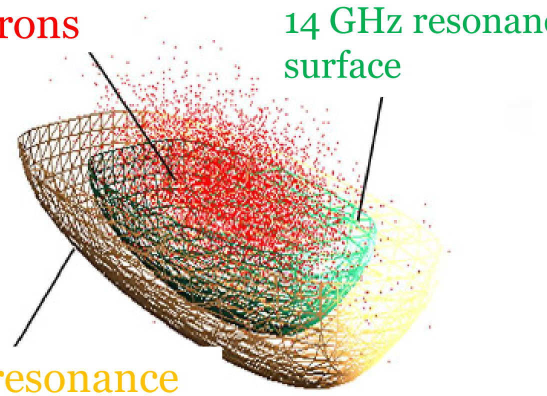


Two Frequency Heating(TFH)

If the electron are subject only the magnetostatic field it would escape from loss cones

The effect of the second frequency is to increase the electron temperature and improve the electron confinement

This means that also the ion confinement time increases and the extracted ion beam has higher charge states and currents



Microwaves to Plasma Coupling Techniques

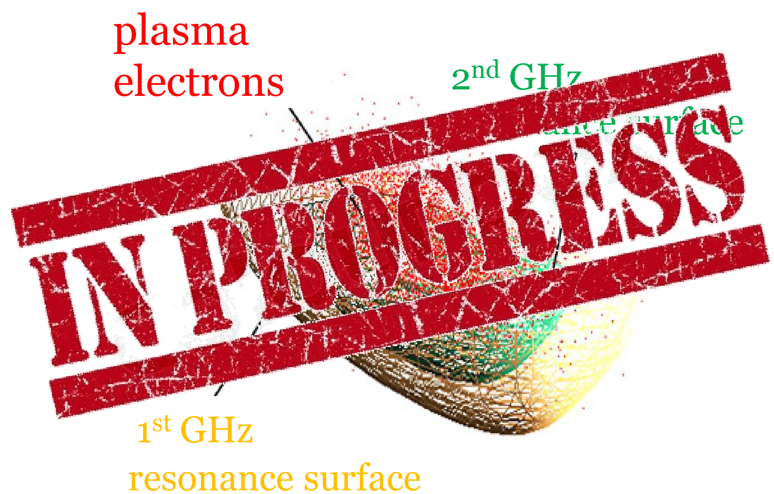
The electrons that leave the first ECR zone
may be accelerated by the second one
depending on the phase shift between the two waves

$$B_{ECR} = \frac{m_e}{e}\omega_{RF}$$

$$\Delta\omega_{RF} \simeq 1.4z\left(\frac{2k_2 q}{m}\right)\left(\frac{c}{\omega}\right)\left[\frac{\left(\frac{eE}{mc\omega}\right)^2}{\left(\frac{c}{\omega}\right)\left(\frac{\Delta B}{\Delta z}\right)\left(\frac{1}{B_ECR}\right)^3}\right]^{\frac{1}{5}}$$

$$\Delta_{\omega_{RF}} \approx 250\ MHz$$

Two Close Frequency Heating(TCFH)



S. GAMMINO et al., IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 36, NO. 4, AUGUST 2008

Microwaves to Plasma Coupling Techniques

Scaling laws

$$q_{opt} \propto \log B^{\frac{3}{2}}$$
$$I^{q+} \propto f^2 M_i^{-1}$$

$$\langle q \rangle \propto n_e \tau_i$$

High charge state

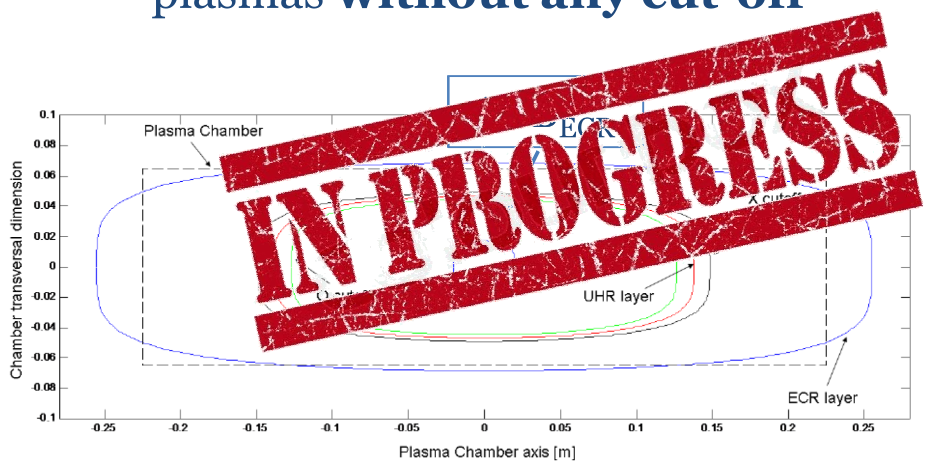
$$I \propto \frac{n_e}{\tau_i}$$

High current

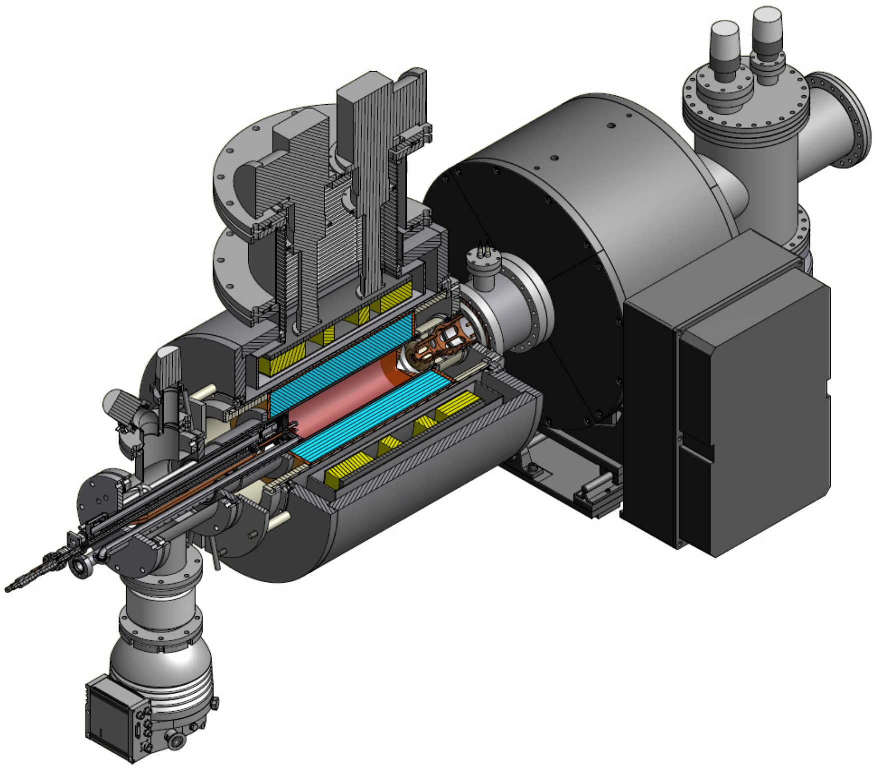
$$n_{cut-off} = \frac{m_e \varepsilon}{e^2} \omega_{RF}^{\ 2}$$

Electrostatics Waves Heating (EWH)

The **Electron Bernstein Waves** are electrostatics waves propagating in over-dense plasmas **without any cut-off**



Advanced Ion Source for Hadrontherapy- AISHa

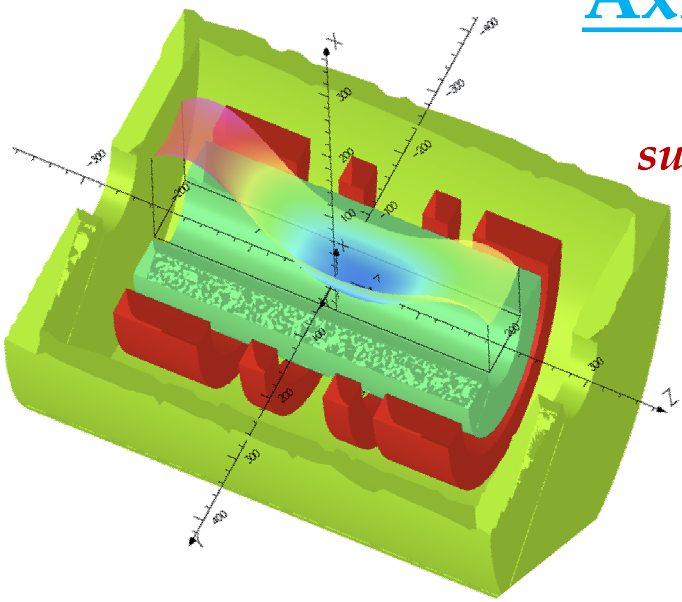


Chamber diameter	92 mm
Chamber length	357 mm
Operating Frequency	18 GHz
Operating Power (max)	1.5 kW
Extr Voltage (max)	40 kV
Weight	600 kg
Axial Magnetic Field	$(B_{INJ}/B_{MIN}/B_{EXT})$ 2.7 T/ 0.4 T / 1.6 T
Radial Magnetic Field	1.3 T

AISHa source was designed in order to adapt a high performance ECR ion source to hospital facilities needing multiply charged ion production with high reliability and brightness, easy operations and maintenance

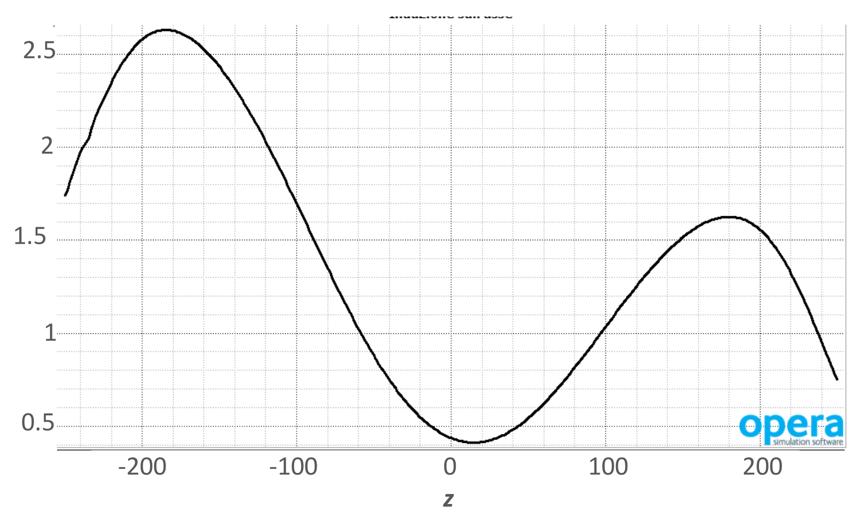
Advanced Ion Source for Hadrontherapy- AISHa

Axial Confinement



Helium-free superconducting magnets

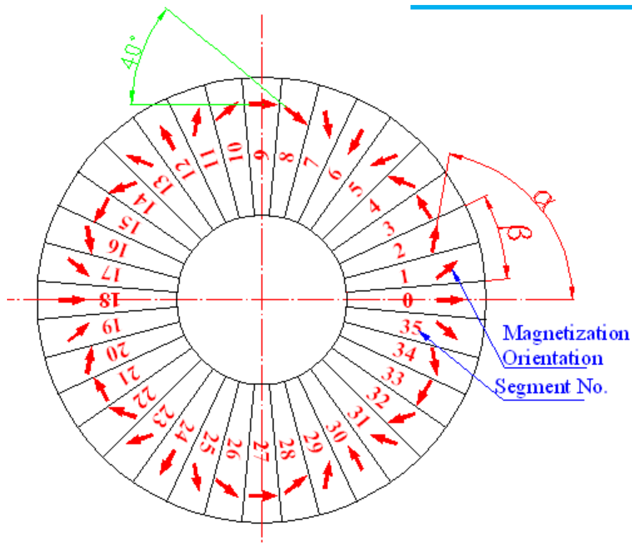
Axial Field	(INJ/MID/EXT) 2.6 T/ 0.4 T / 1.7 T			
SC coil	INJ	Med1	Med2	Extr
ID (mm)	260	260	260	260
OD (mm)	340	340	340	340
Length (mm)	100	30	30	90
Current (A/mm²)	165	143	143	115

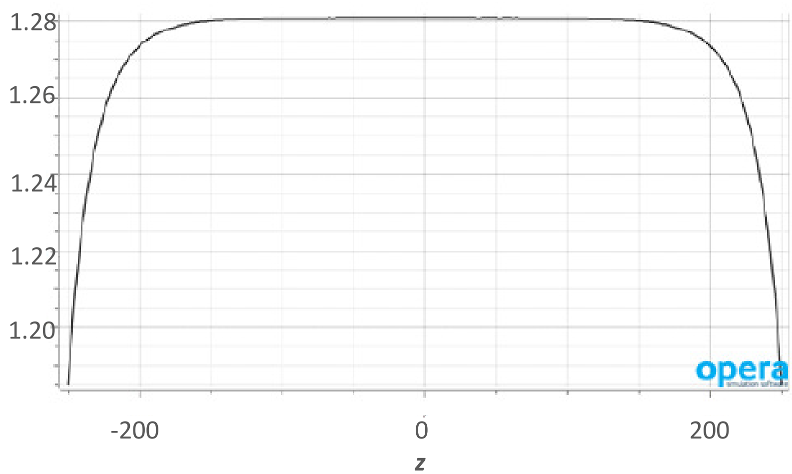


ECRIS Standard Model
@ 18 GHz

Advanced Ion Source for Hadrontherapy- AISHa

Radial Confinement





36 sgm Halbach-type Hexapole

inner radius	51 mm
outer radius	110 mm
length	400 mm

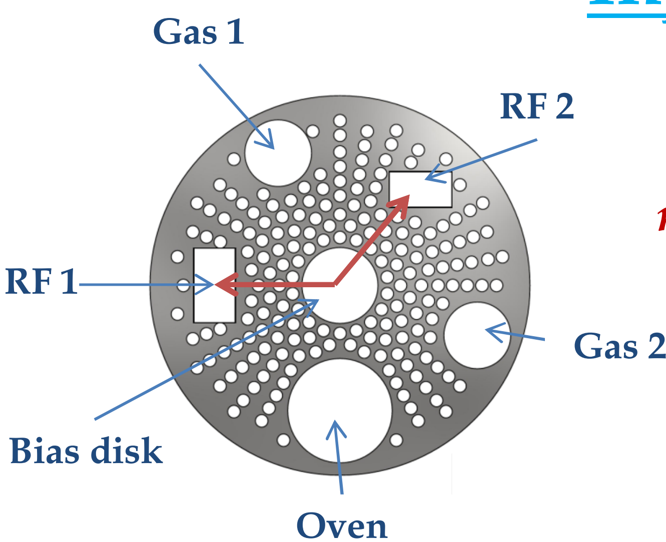
VACODYM 745/677 HR

Hcj =1.195×10^{3} kA/m

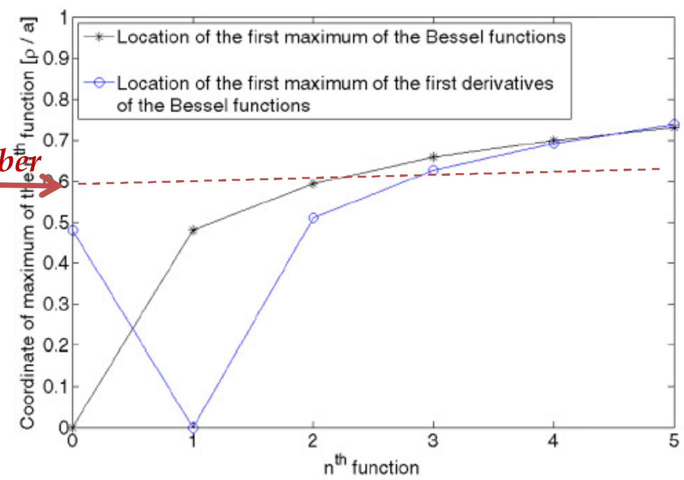
9 directions of magnetization

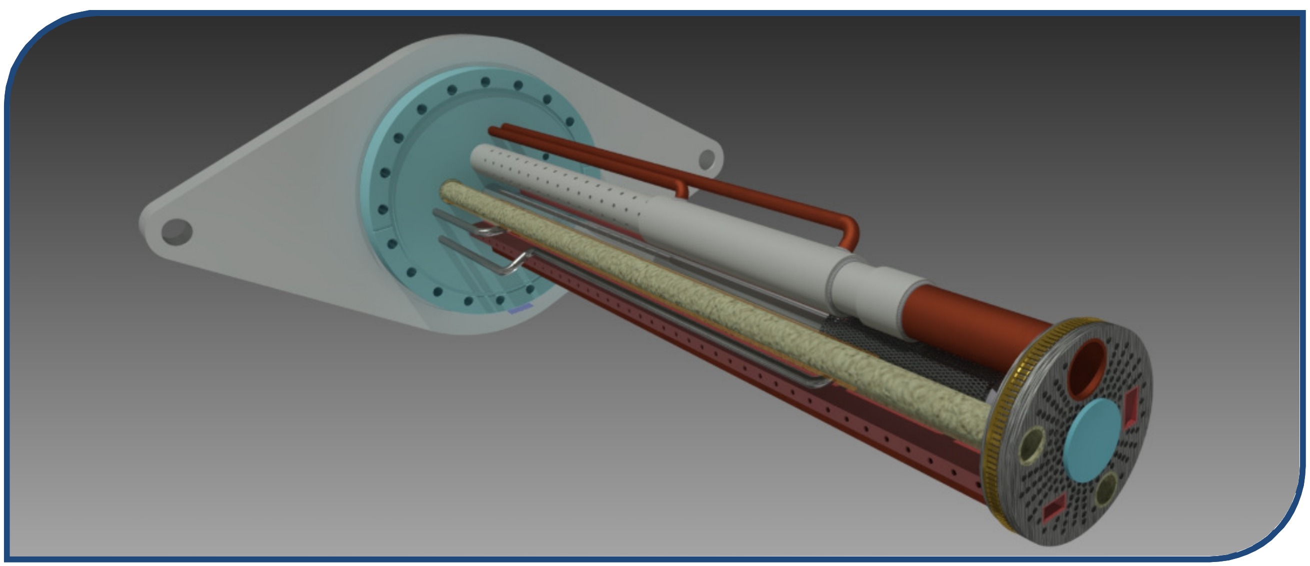
1.3 T on plasma chamber walls along whole length

Injection System



r_{wg}=0.6 $r_{chamber}$

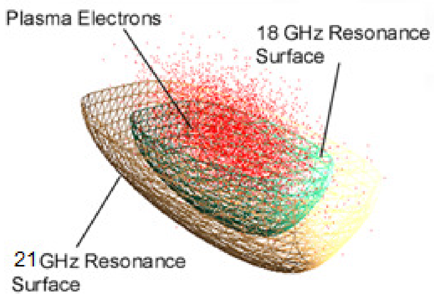




Advanced Ion Source for Hadrontherapy- AISHa

Microwave Injection

High Power Klystron Amplifiers
RF1 [17.3 - 18.4 GHz]
RF2 [21 - 22 GHz]



TFH

- multi-staged depressed collectors
- up to 2.4 kW output power
- 50 MHz of instantaneous bandwidth
- precise tuning of up to 24 channels
- Fast Digital Tuner System

chamber	ϕ=92 mm l=357 mm
# modes	391
Δf_{avg}	~3 MHz

FTE

Advanced Ion Source for Hadrontherapy- AISHa

Expected Currents

Ion beam production (eμA)

Ion	Supernanogan (14 GHz)	AISHa (18 GHz + TFH)
H^+	2000	4000
H_2^+	1200	2000
H_3^+	1000	1500
$^{3}He^+$	800	2000
$^{12}C^{4+}$	250	800
$^{6}Li^{2+}$ - $^{7}Li^{2+}$	//	800
$^{10}B^{3+}$ - $^{11}B^{3+}$	//	600
$^{18}O^{6+}$	400	1000
$^{21}Ne^{7+}$	120	500
$^{36}Ar^{12+}$	20	150

AISHa - Conclusion

- Several ***variation to the classical ECR-heating*** mechanism have been proposed in order to increase the current and average charge state produced.

- The set of four superconducting coils independently energized will permit to realize a ***flexible magnetic trap,*** fundamental to study alternative heating schemes.

- The use of a ***broadband microwave generator*** will permit to efficiently tune the frequency improving the source performances.

- The injection system was designed in order to ***optimize the microwave to plasma coupling*** taking into account the need of space to house the ***oven for metallic ion*** beam production.

Thanks for your attention!

AlSHa

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ECRIS Standard Model

- the radial magnetic field value at the plasma chamber wall must be $B_{rad} \geq 2B_{ECR}$;
- the axial magnetic field value at injection must be $B_{inj} \sim 3B_{ECR}$ or more;
- the axial magnetic field value at extraction must be about $B_{ext} \sim B_{rad}$;
- the axial magnetic field value at minimum must be $0.30 < B_{min}/B_{rad} < 0.45$.
- the optimum power increases with the volume of the plasma and with the square of the frequency.

At power, magnetic fields and microwave frequencies used up to now obey to the Standard Model: the extracted current strongly increases as the microwave frequency increases, but only the increase of mirror ratio can exploit the performances, making effective the increase of electron density with frequency

High-B Mode

ECRIS: fundamental aspects

$$\bar{\bar{\varepsilon}} = \varepsilon_0 \bar{\bar{\varepsilon}}_r$$

$$\epsilon_r = \begin{pmatrix} \epsilon_{xx} & \epsilon_{xy} & 0 \\ \epsilon_{yx} & \epsilon_{yy} & 0 \\ 0 & 0 & \epsilon_{zz} \end{pmatrix}$$

k depends on the angle formed by the incoming wave with the magnetic field direction

There are two electromagnetic waves traveling in an arbitrary direction θ with different propagation constants

k'_θ ordinary wave

k''_θ extraordinary wave

$$\omega_g = \frac{q_e B_0}{m_e}$$