Alternative plasma heating schemes within the classical ECR-heating scenario

Luigi Celona

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

Multi-frequency heating,
Broadband heating,
Phase relationship

Alternative mechanisms of plasma heating

1. Frequency tuning **(Gammino's talk)**
2. Two Frequency Heating
3. Two Closed Frequency Heating
4. "Flat B Field" heating
5. "Broadband" heating

Alternative heating schemes

STRONG INCREASE OF THE HEATING RAPIDITY

↓

Production of high energy electrons

The TWO Frequency Heating effect: a long history

1994 – First evidence of the TFH at LNBL, California

[Z. Q. Xie and C. M. Lyneis. Improvements on the LBL AECR Source. *in Proc. 12th Int. Workshop ECR Ion Sources, Tokyo, Japan*, 1995.]

→ CSD peak from 33+ to 36+ for ^{238}U, *current increased by a factor 2-4 for CS>35+*

2001 – TFH on the SERSE source at INFN-LNS; first evidence of the importance of TWT also in case of TFH

[S.Gammino, G. Ciavola, L. Celona, D. Hitz, A. Girard, and G. Melin. Operation of the SERSE superconducting electron cyclotron resonance ion source at 28 GHz. *Rev. Sci. Instr.* 72, pp. 4090-4097.]

→ 3 eμA of Sn^{29+} were produced with two KLY (1.4 +1.0 *kW*) @ *14.5 and 18 GHz. The same current with TWT 8-18 GHz @ 200 W*

2002 – Observation of TFH at ORNL, Argonne, together with FTE

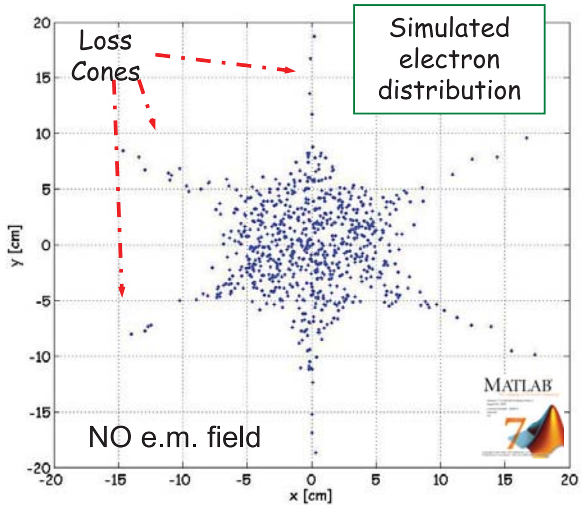
[R. C. Vondrasek, R. H. Scott, R. C. Pardo, and H. Koivisto. Operational improvements of the Argonne ECR sources. *in Proc. 15th Int. Workshop ECR Ion Sources, Jyvaskyla, Finland*, Jun. 12-14, 2002. p. 174.]

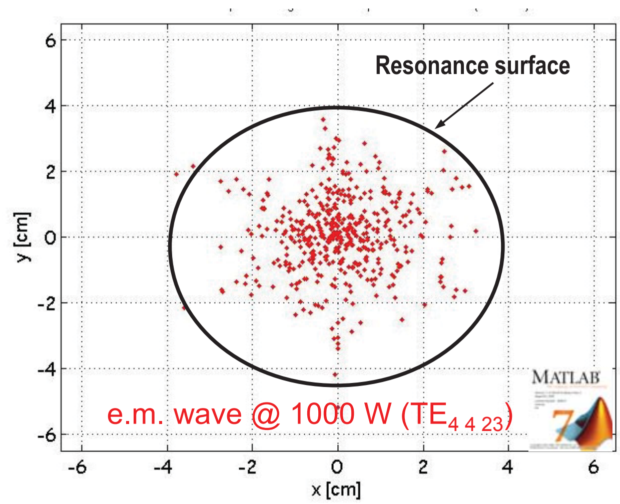
→ TWT (*60 W*) + Kly (*400 W*)
I = 66 eμA
Kly (*400 W*)
I = 39 eμA

neither the relationship between the two frequencies nor the respective power was univocally determined.

Simulations' Results for Single Frequency Heating

Plug-in & ECR plug Effect

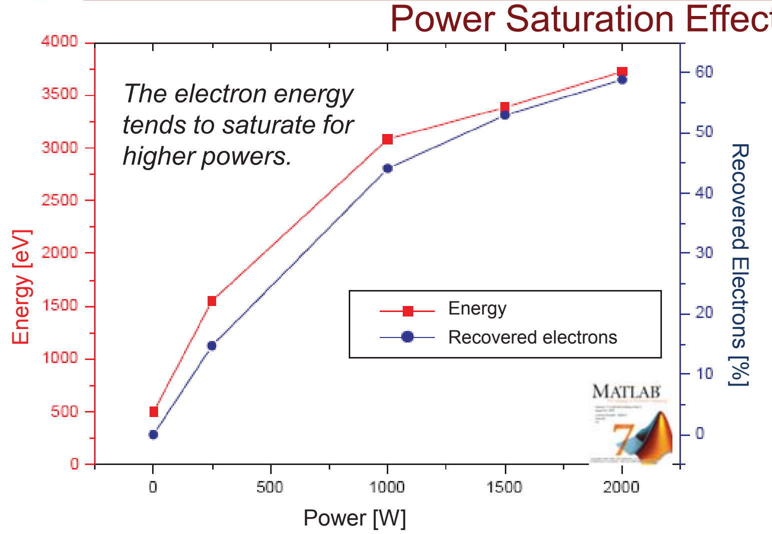




The e.m. field allows to confine up to 40% of electrons that otherwise go away from the plasma.

Simulations' Results for SFH

Power Saturation Effects



Heating process more difficult for higher powers:

-ECR zone crossing time is strongly reduced at higher energies

-Strongly confined electrons don't reach again the ECR zone

The Power saturation value seems to depend on:

E: Electric Field at the resonance point.

∇B: Magnetostatic Field Gradient

STRONG GRADIENTS limit the maximum achievable energy per time unit, thus reducing the ECRIS potentiality.

Improvement of the electron heating

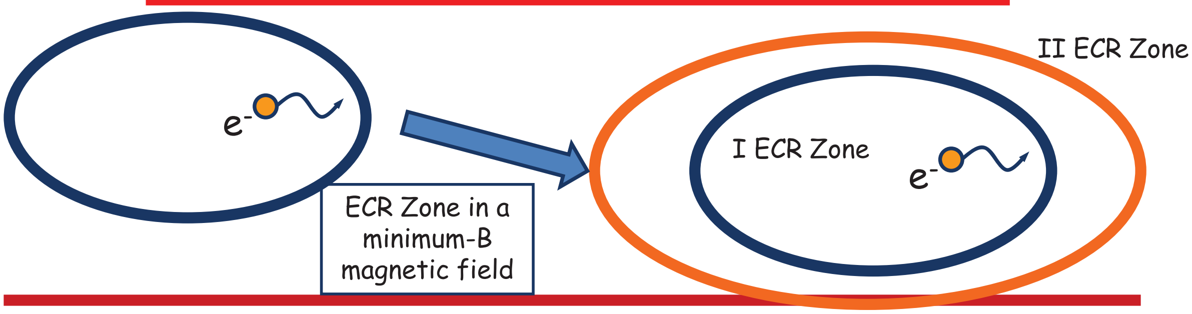
The possibility of Two Frequency Heating - TFH

Strong ECR plug effect and plug-in

Energy and "recovering mechanism" saturation with the RF power

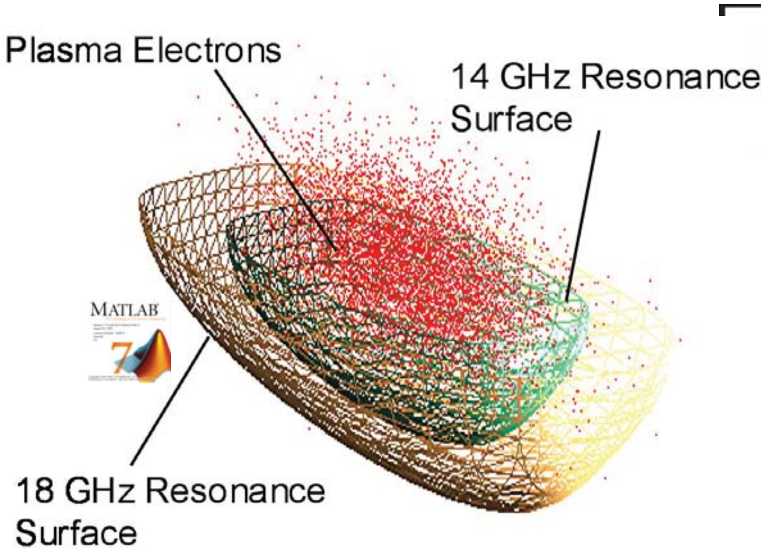
plasma heating with two electromagnetic waves instead of one, by using two medium or low powers

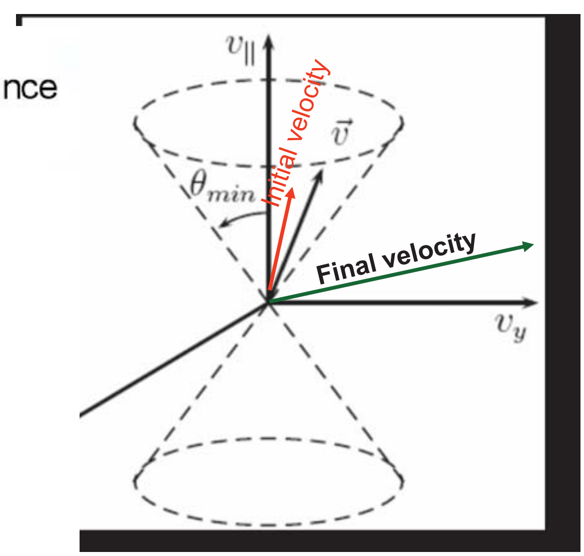
possibility to optimize the plasma heating by efficiently transferring the electromagnetic energy



Improvement of the electron heating

The possibility of Two Frequency Heating - TFH

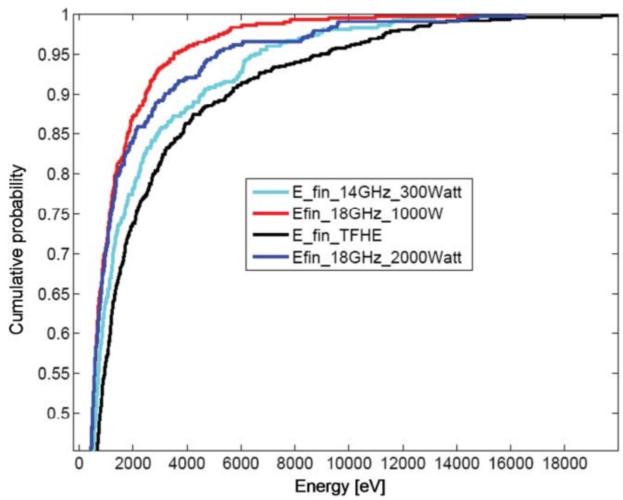




Electrons passing just one time across the resonance have a high probability to be strongly accelerated (the acceleration affects the perpendicular component of the velocity). Hence they are expelled by the loss cone and recovered by the electromagnetic field.

Simulations of the Two Frequency Heating

	$(14+18)GHz$, $(1000+300)W$	$18\ GHz$, $2000\ W$	$18\ GHz$, $1000\ W$	$14\ GHz$, $300\ W$
Recovered electrons [%]	38.2	35.2	19.2	12.9
Energy (keV)	1.9589	1.2612	1.0141	1.5509

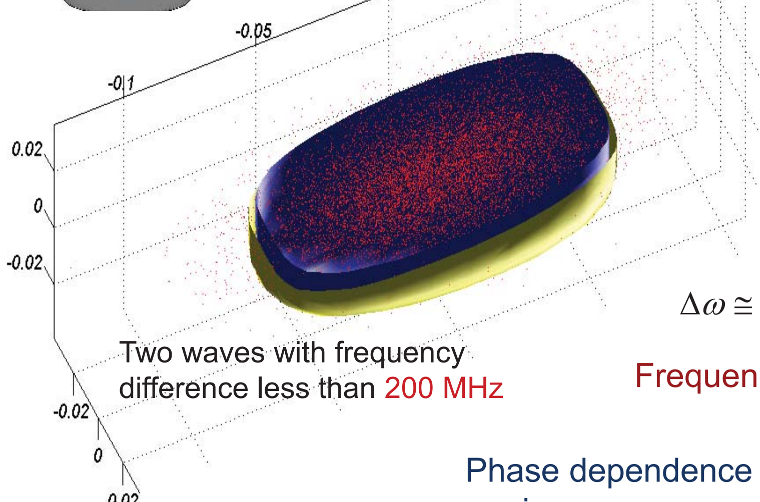


MATLAB 7

1. Strong increase of the confined fraction in the case of TFH;
2. Strong increase of the mean electron energy;
3. TFH @ 1300 W more efficient than Single Frequency Heating (SFH) @ 2000W;
4. Electron Energy for @ 300 W – 14GHz higher than @ 2000 W – 18 GHz.

[D. Mascali et al. *Enhancement of the electron confinement and temperature by means of the two frequency heating in ECR ion sources plasmas*. in Proc. Eur. Phys. Soc. Conf. Plasma Phys., Warsaw, Poland, 2007. vol. 31F, p. O2:013.]

The “idea” of the Two Close Frequency Heating Effect



Two contiguous resonance surfaces ensure a sort of “electron surfing” on the two heating frequencies if the phase relationship is proper

Two waves with frequency difference less than 200 MHz

Frequency correlation

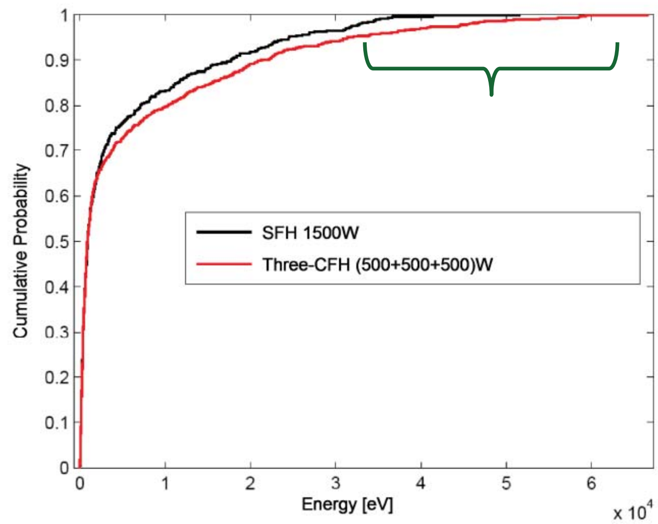
$$\Delta\omega \cong 1.4z\left(\frac{2k_2 q}{m}\right)\left(\frac{c}{\omega}\right)\left[\frac{\left(\frac{eE}{mc\omega}\right)^2}{\left(\frac{c}{\omega}\right)\left(\frac{\Delta B}{\Delta z}\right)\left(\frac{1}{B_{ECR}}\right)^3}\right]^{1/5}$$

Phase dependence on microwaves power

$$\Delta\vartheta \equiv \left(\frac{\pi}{2} - const\cdot\frac{\overline{\omega}}{P}\right)$$

S. Gammino, G. Ciavola, L. G. Celona, D. Mascali, and F. Maimone. *Numerical Simulations of the ECR Heating With Waves of DIfferent Frequency in Electron Cyclotron Resonance Ion Sources*. **Review paper on IEEE Transaction on Plasma Science**, 2008. vol.36, no.4.

Δϑ [°]	Confined Fraction	E final [keV]	ΔE/E [%]
0	0.916	4351	2.9
45	0.918	4815	13.9
80	0.907	4848	14.7
90	0.903	5045	19.3
100	0.894	4562	7.9
135	0.907	4383	3.7
180	0.920	4810	13.8
225	0.903	4703	11.2
270	0.908	5000	18.2
315	0.907	4934	16.7



Energy increase for TCFH (500+500 W) with respect to SFH @ 1000 W.

Final Energy increases up to 30% in Three Close Frequency Heating.

Possibility to exploit wave-electron energy transfer by means of the Multi Frequency Heating

Plasmas driven by Electrostatic Waves

Mode conversion and non-linear plasma heating in compact-size devices

Theory of EM to ES mode conversion: from X to Bernstein Waves

The dispersion relation for the X wave is:

$$\frac{c^2k^2}{\omega^2} = \frac{c^2}{v_\phi^2} = 1 - \frac{\omega_{pe}^2}{\omega^2}\frac{\omega^2 - \omega_{pe}^2}{\omega^2 - \omega_{uh}^2}$$

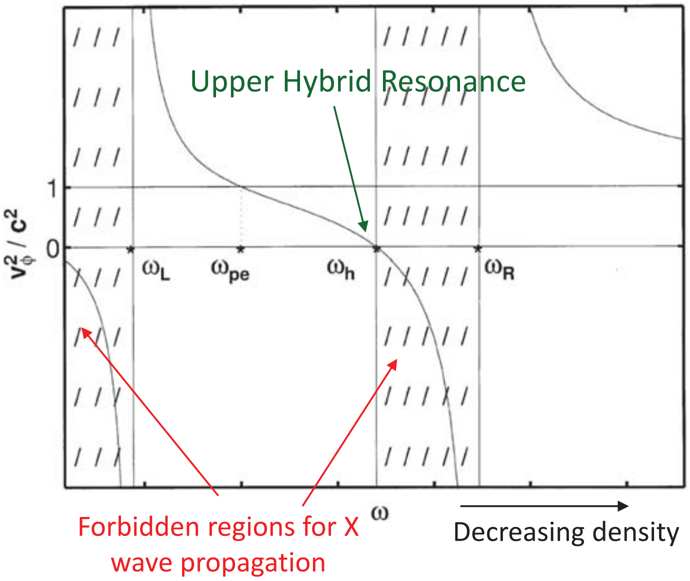
with:

$$\omega_{uh}^2 = \omega_{pe}^2 + \omega_{ce}^2$$

Upper hybrid frequency

$$\omega_{pe} = (n_e e^2/m_e \epsilon_0)^{1/2}$$

Plasma frequency



X waves are partially reflected and partially tunnel the R and L cutoffs

$$\omega_L = \frac{1}{2}\left(\omega_{ce} + \sqrt{(\omega_{ce}^2 + 4\omega_{pe}^2)^*}\right),$$

$$\omega_R = \frac{1}{2}\left(-\omega_{ce} + \sqrt{(\omega_{ce}^2 + 4\omega_{pe}^2)^*}\right)$$

If the UHR layer is embedded by to cutoffs then the X wave rebounce between them and adopts a standing wave behaviour.

At the UHR most of the X wave electric field is directed longitudinally to the wave vector k, thus exciting electrostatic wave oscillations

Theory of EM to ES mode conversion: from X to Bernstein Waves

Assuming that the electromagnetic wave has an even small, but still non negligible, k component oriented perpendicularly to the B field (oriented along the z axis), we can calculate the electric field of the X wave at the UHR.

It can be shown from the Maxwell equations that:

$$[\omega^2 - \omega_h^2]E_x + i\frac{\omega_{pe}^2\omega_{ce}}{\omega}E_y = 0$$

which at the UHR, where: $\omega = \omega_{uh}$ becomes:

$$E_y = 0 \Rightarrow \vec{E} = E_x\hat{x}$$

Since we assumed B directed along z, and the k vector of our interest as: $\vec{k} = k_x\hat{x}$

the wave becomes purely electrostatic, and since it propagates perpendicularly to the magnetic field it takes the name of **Bernstain electrostatic plasma wave**

$$C = C_{max}\cos^2\left(\frac{\phi}{2} + \theta\right)$$

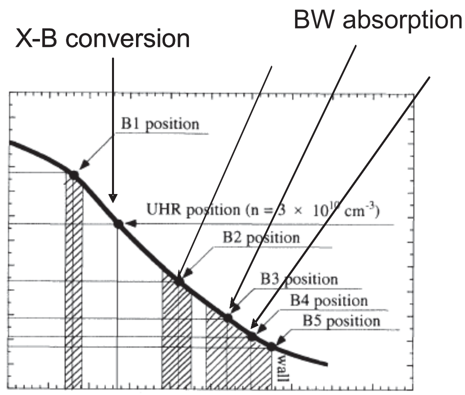
$$C_{max} = 4e^{-\pi\eta}(1 - e^{-\pi\eta})$$

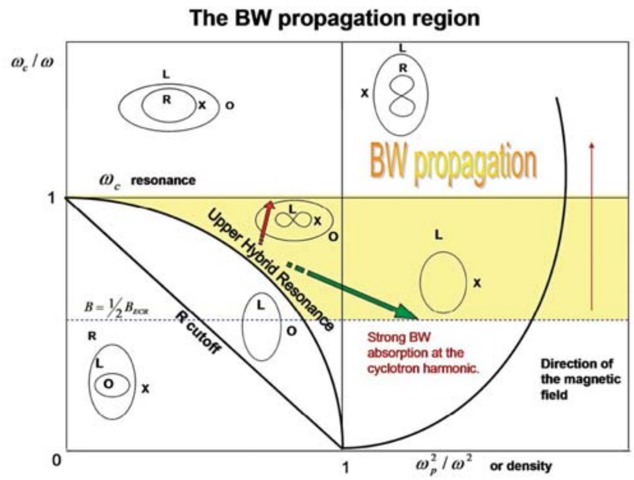
$$L_B \gg L_n$$

$$\eta \approx \frac{\omega_c L_n}{c\alpha}[\sqrt{1+\alpha^2} - 1]^{1/2} \qquad \text{with } \alpha = \left(\frac{\omega_p}{\omega_c}\right)\bigg|_{UHR}.$$

Phase term modulated by C_{max}

Plasma Heating at B<B$_{ECR}$: generation and absorption of BW





$$1-(k_x c/\omega)^2=(\omega_p/\omega)^2(\omega^2-\omega_p^2)/(\omega_p^2+\omega_c^2-\omega^2)\ ,$$

The X wavelength approaches the BW wavelength at the UHR, and a forward and backward propagating BW is generated

$$1+(k_B v_{\mathrm{th}}/\omega_p)^2=\exp(-k_B^2 r_L^2)I_0(k_B^2 r_L^2)-2(\omega/\omega_c)^2 \times\sum_q \exp(-k_B^2 r_L^2) \times I_q(k_B^2 r_L^2)/(q^2-\omega^2/\omega_c^2)\ .$$

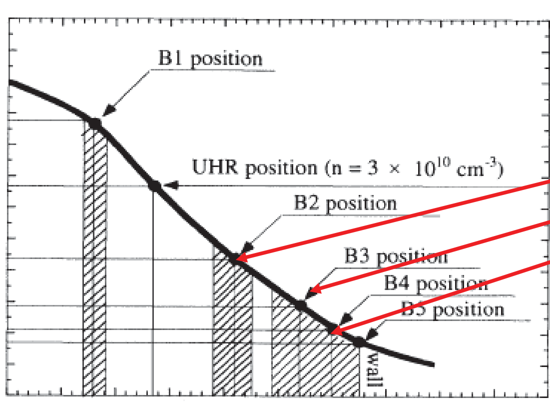
The BW dispersion relation predicts a resonance at the harmonics of Electron Cyclotron frequency, and a wave cutoff at UHR

Theory of EM to ES mode conversion: from X to Bernstein Waves

Mode conversion takes place when the incident EM-X wave encouters the UHR layer, where it is in spatial and temporal resonance with the nascent EB mode.

Dispersion relation for EBW

$$1+\left(\frac{k_B v_{th}}{\omega_p}\right)^2 = e^{-k_B^2 r_L^2 I_0\left(k^2 r_L^2\right)} - 2\left(\frac{\omega}{\omega_c}\right)^2 \sum_q e^{-k_B^2 r_L^2} \frac{I_q\left(k_B^2 r_L^2\right)}{q^2-\left(\frac{\omega^2}{\omega_c^2}\right)}$$

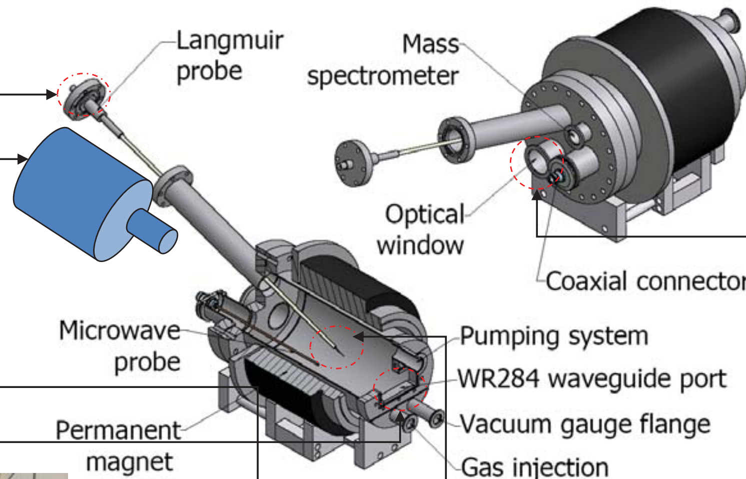


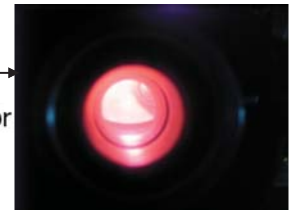
When: $B=\frac{1}{q}\frac{m}{e}\omega_{RF}$ **q=1,2,…,n**

(cyclotron harmonics) this term approaches zero and electron Bernstein waves can be absorbed by the plasma

Experimental apparatus for mode conversion detection

H-Ge X-ray detector





Optical window for direct observation of plasma

Tungsten probe tip: 4 mm length, 0.15 mm diameter

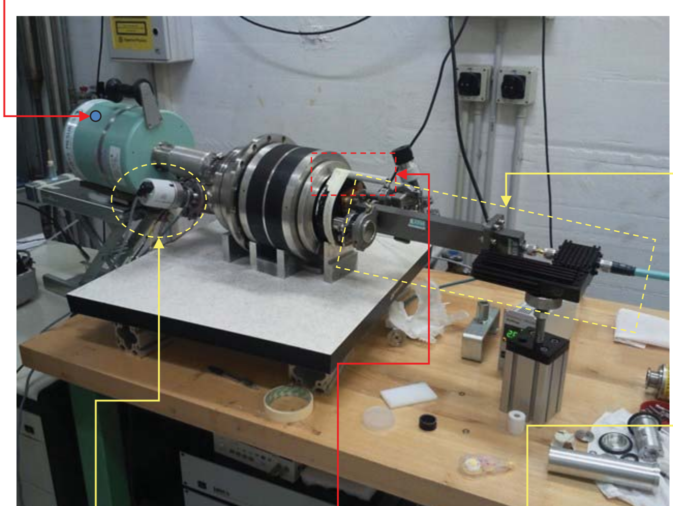
Travelling Wave Tube (TWT) able to erogate microwaves from 2.3 to 4.9 GHz

Spectrum analyzer for inner plasma electromagnetic waves detection

Experimental apparatus for mode conversion detection

H-Ge X-ray detector

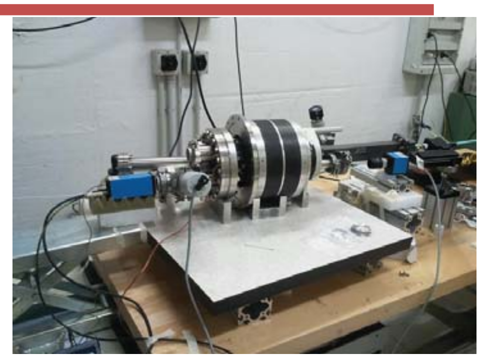
Set-up for X-ray spectroscopy and CCD imaging



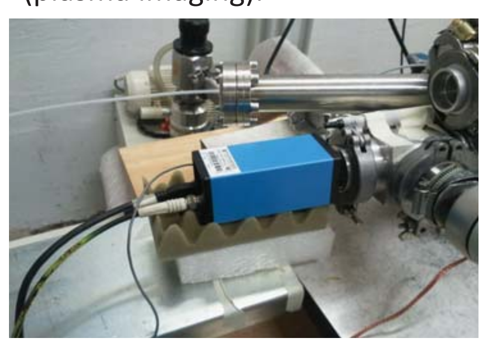
Pressure gauge

Hall probe for measurement of the magnetic field

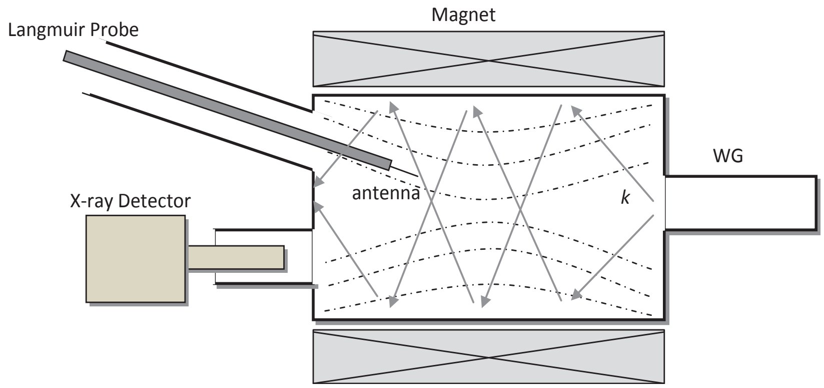
Microwave line with insulator

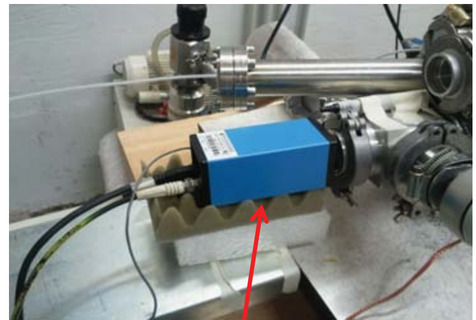


Positioning of the CCD for the pass-band filters measurements (plasma imaging).

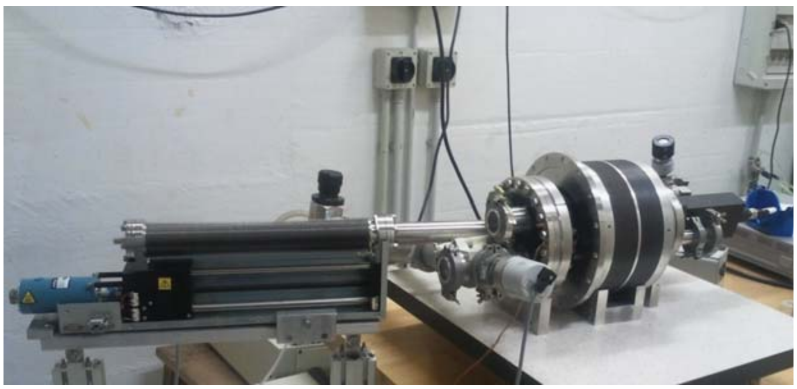


Experimental apparatus for testing Mode Conversion

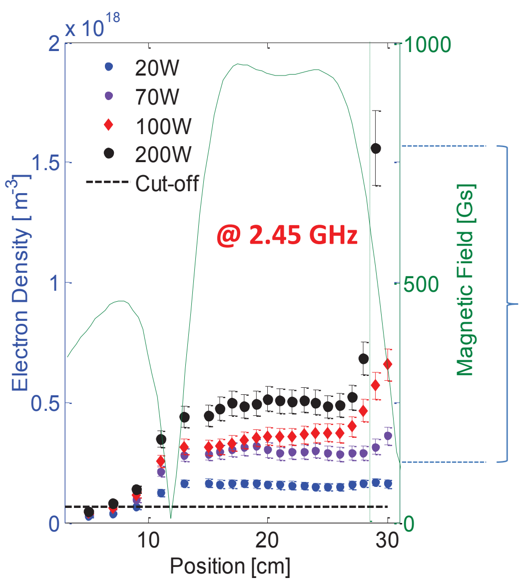




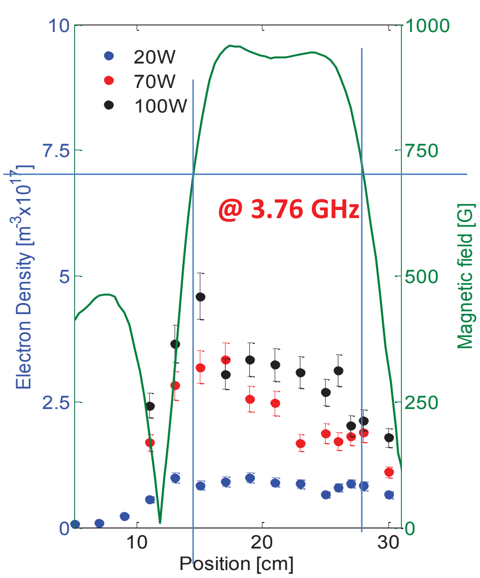
CCD camera for optical characterization



Plasma density @ 2.45 and 3.76 GHz measured by ES probe



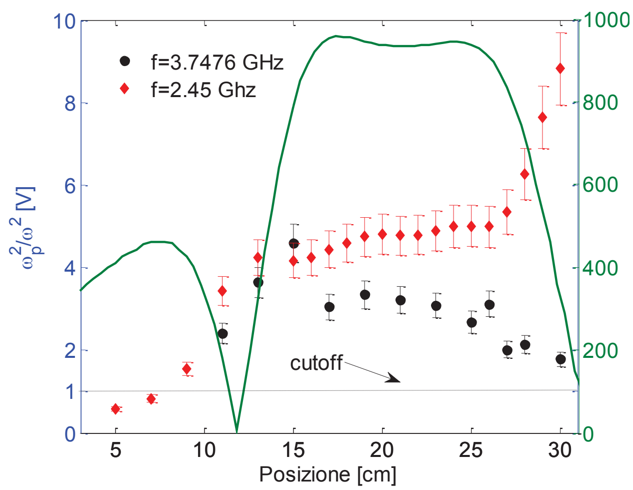
Enhancement of plasma density of one order of magnitude at the 1° harmonic of the cyclotron field !!!



1. Electron Density measurements show that the plasma is largely overdense everywhere above 70-80 W of power either at 2.45 and 3.76 GHz!!

1. Experimental Results @ 2.45 GHz and 3.76 GHz collected with electrostatic probe

Change of the plasma density shape with the frequency!!!

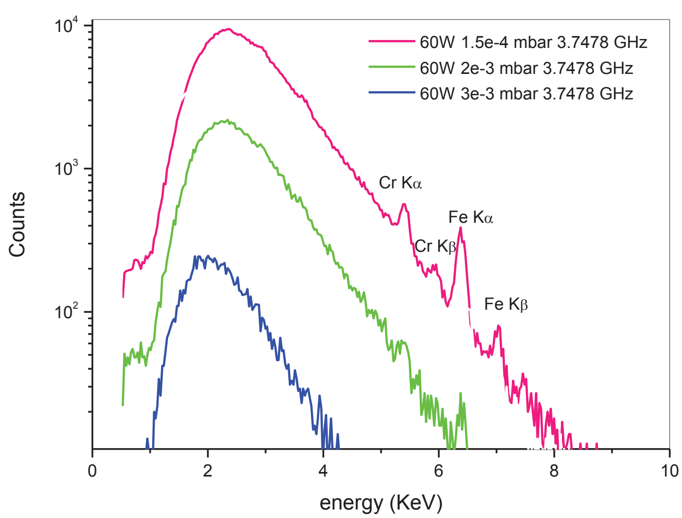


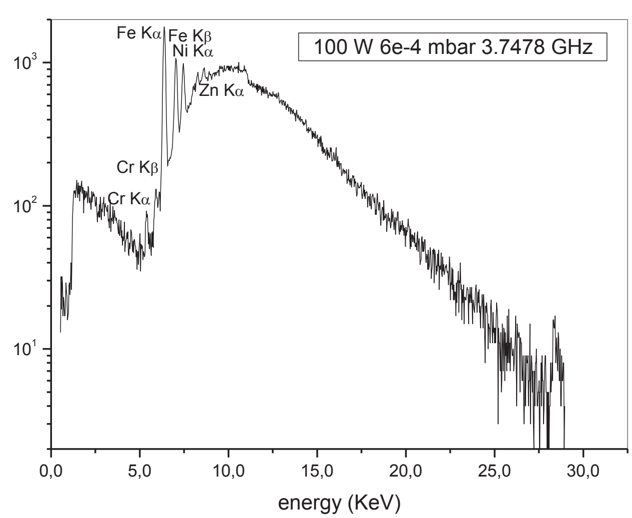
The plasma density is peaked at the relative 1st harmonic of the two frequencies. The peak position changed with the frequency, confirming that the mode conversion is "frequency sensitive".

The non parallel component of the k vector with respect to B is in fact provided by the resonator!!

1. **Values up to 10 times the cutoff density have been measured!!!**

X-ray spectra during EM-ES conversion



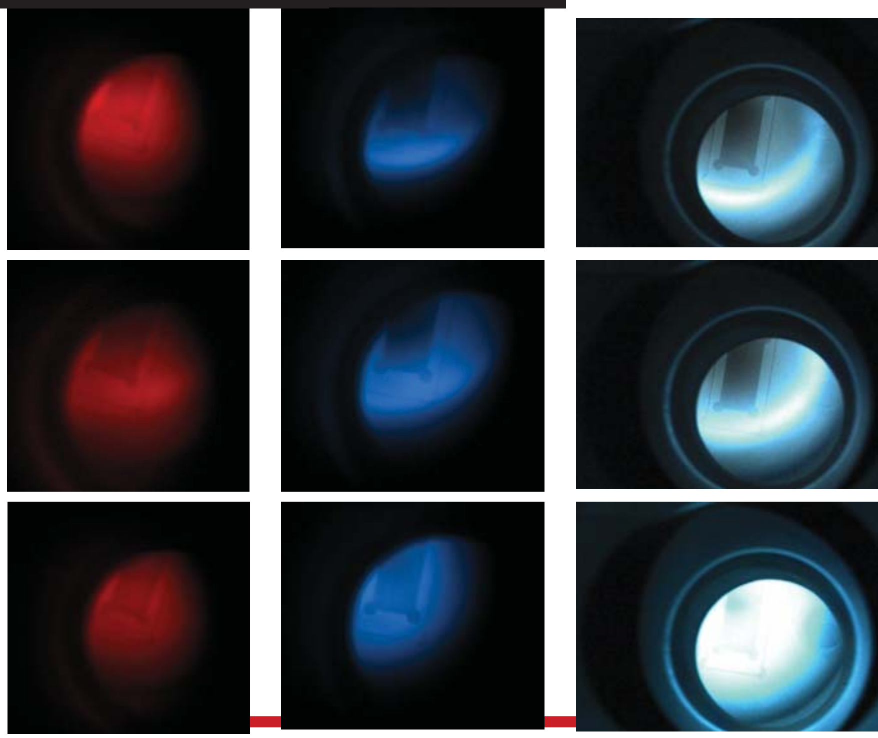


1. **Boost of X-ray energy** for low pressures;
2. The plasma exhibits a **threshold-like behavior**: at 1.5E-4 mbar **hot electrons are generated for P_{rf}>80 W;**
3. In the same RF power domain, a **plasma hole appears** and it is observable in the visible range.

Spontaneous formation of a plasma hole

Rotating plasma and enhancement of ion transport

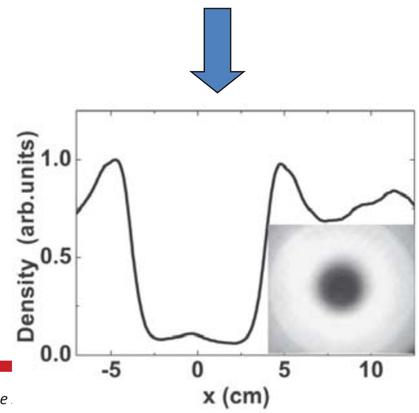
[redacted] No filters



Neutrals 1+ Ions

Filters reveal that the ions are mostly concentrated around the hole.

A similar structure was observed by Nagaoka et al. *Phys. Rev. Lett.* 89, 075001 (2002).



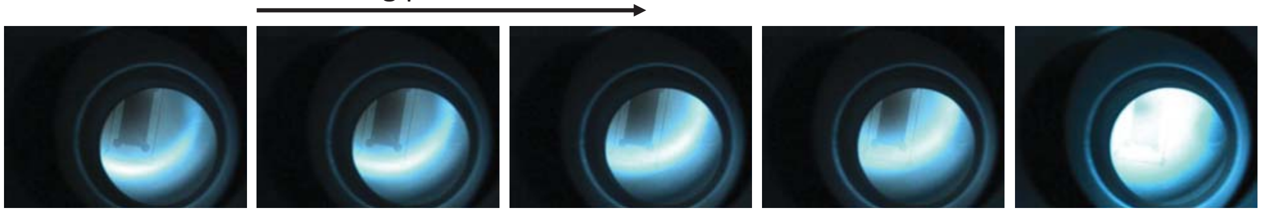
CCD imaging during plasma startup at different P_{RF}

200 μs 400 μs 600 μs

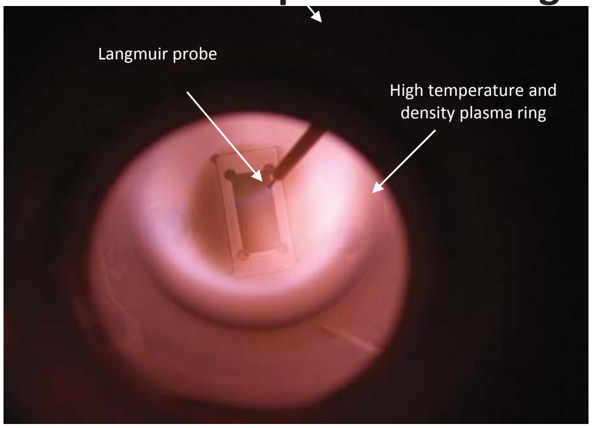
PLASMA HOLE FORMATION

The formation of the overdense plasma, which takes to strong X-ray emission and electromagnetic spectral broadening, also causes a marked change in plasma shape.

20 W Increasing power 90 W



Additional proofs of X-B mode conversion and plasma heating through BW (July 2010)

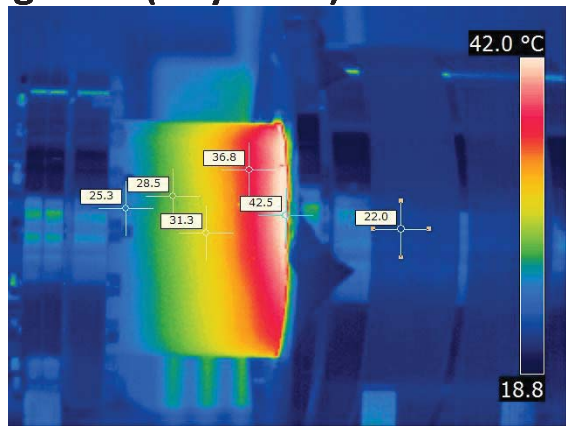


Plasma viewed through the optical window

Where the Bernstein waves are absorbed (at EC harmonic) the **electrons flow rapidly perpendicularly to the magnetic fled**.

This flow violates locally the quasineutrality condition and an ambipolar electric field arises. **An E x B drift generate the plasma rotation around the plasma chamber axis.**

Viscosity accumulates plasma peripherically, like in case of water vortexes.



Plasma chamber infrared image

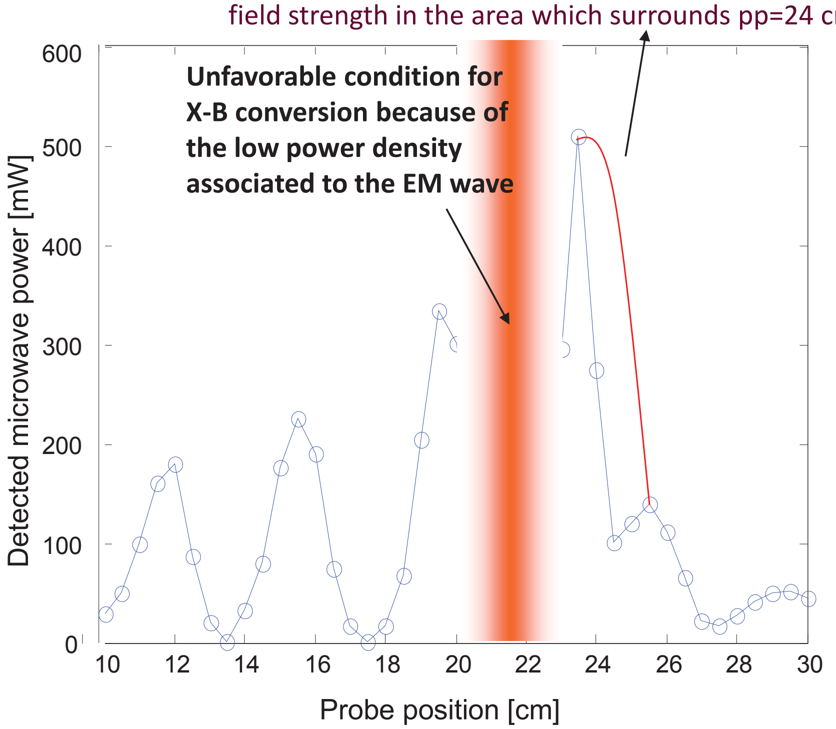
Effects of the **high energy electron ring formation are evident also on the heating of the plasma chamber walls**.

In one hour of continuous operations **the temperature was close to 50 °C**, that is **dangerous for the demagnetization of our magnet**

When the probe tip was left 3-4 minutes at pp=20 cm (corresponding to maximum BW absorption) it was almost completely disintegrated by the plasma

Electromagnetic wave absorption at pp=24 cm is a clear sign of mode conversion

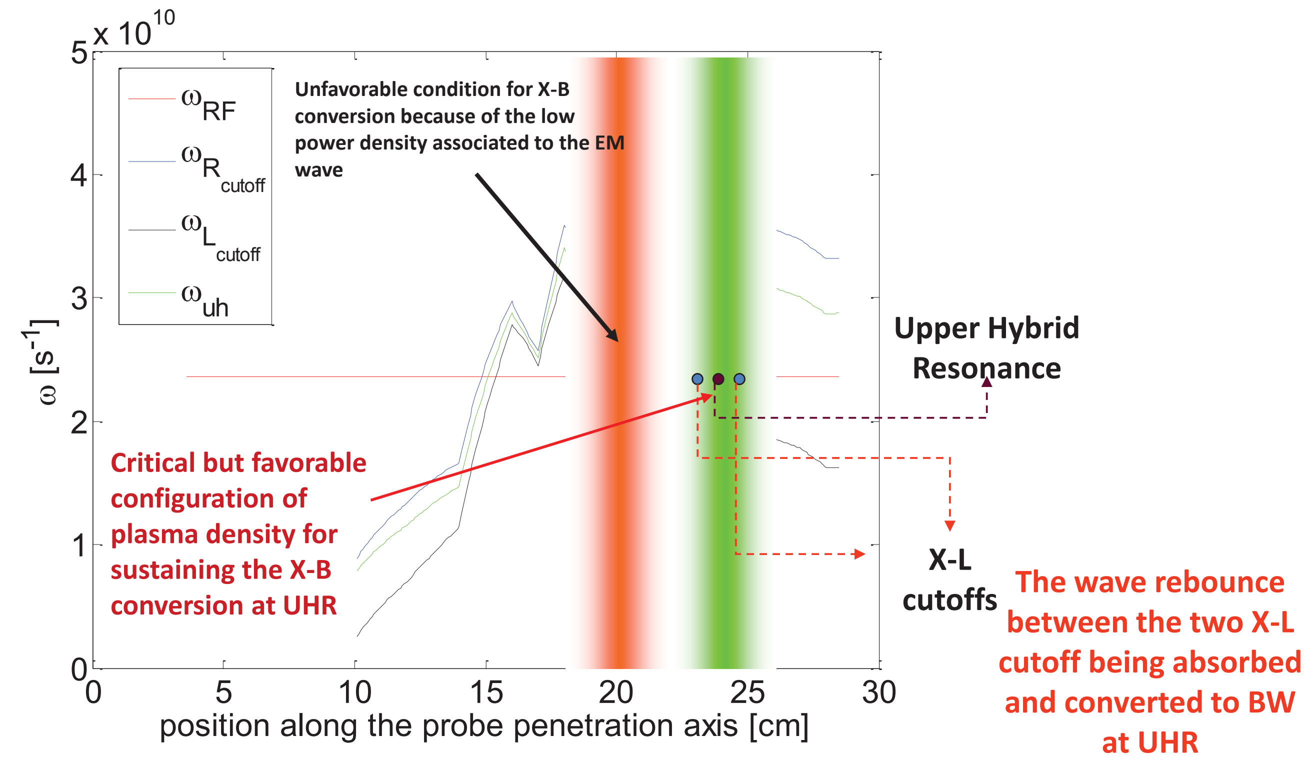
Estimated theoretical trend of the electromagnetic field strength in the area which surrounds pp=24 cm



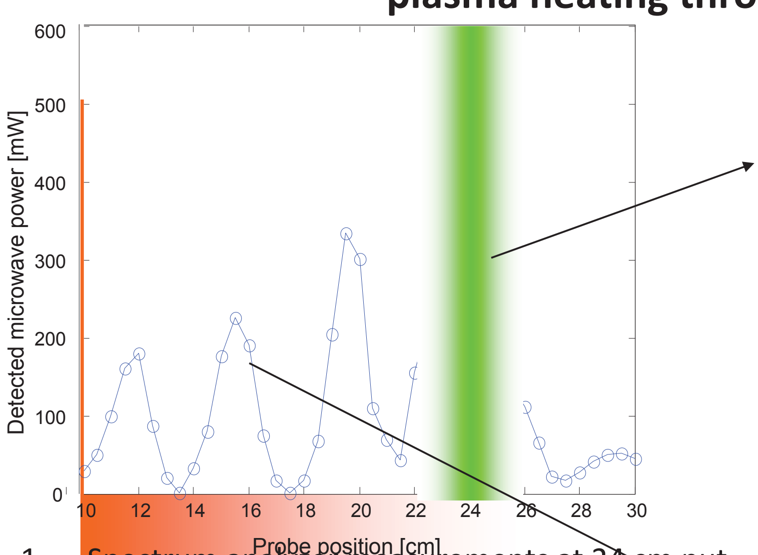
Electromagnetic wave measurements show that:

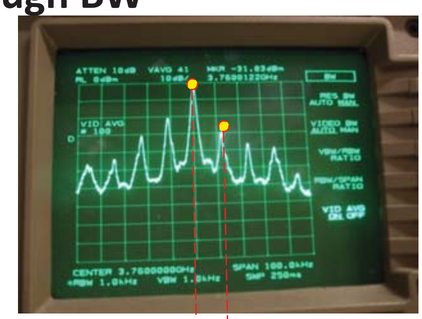
1. The EM forms a standing wave inside the resonator although the presence of an absorbing mean like the high density plasma
2. The EM is partially absorbed at pp=24 cm and no other layers of EM to plasma energy transfer are evident
3. The EM-ES conversion at 24 cm is critical because the detected EM power oscillates strongly

Details about direct X-B conversion inside the Plasma Reactor



Additional proofs of X-B mode conversion and plasma heating through BW





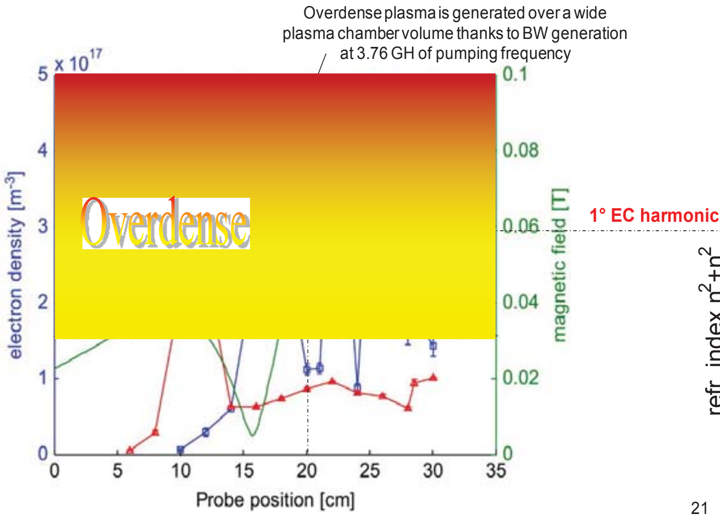
$$\Delta\nu \approx 10\,kHz$$

1. Spectrum analyzer measurements at 24 cm put in evidence the existence of **non linear effects** typical of X-B conversion, which leads to the formation of **sidebands in EM spectrum**
2. **Sidebands disappear far away from 24 cm** position

BOOSTING OF EBW-heating to overcome density limitations

Measurements with the Plasma Reactor @ LNS already showed the formation of an overdense plasma in case of UHR active inside the chamber and EBW absorption in higher harmonics of the cyclotron field

Generation of overdense plasma when f=3.76 GHz, with $2\pi f>(qB_{max})/m$



. [D. Mascali et al., *Nuclear Instruments and Methods in Physics Research, Section A*, in press]

The UHR is accessible through the tunneling of the X cutoff. The wave encounters the UHR and it is there converted.