



INFN/AE-09/1  
April 8, 2009

**STUDY OF THE BERNSTEIN WAVES HEATING IN THE WEGA STELLARATOR  
PLASMA AND POSSIBLE APPLICATIONS TO ECRIS – ECR ION SOURCES**

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**Abstract**

The Electron Cyclotron Resonance Ion Sources (ECRIS) are nowadays the most effective devices that can feed the particle accelerators in a continuous and reliable way, providing high current beams of multiply charged ions. The heating mechanism of the ECRIS plasma is based on the Electron Cyclotron Resonance, that is able to create multi-keV electrons useful for ionization and to produce a conspicuous number of electrons up to MeV energies, as demonstrated by recent experiments on 3<sup>rd</sup> generation sources. These electrons are completely useless for the production of highly charged ions (their ionization cross section is very low) and they are also detrimental for the source safety, because they increase the heat load on the superconducting magnets' cryostat, making the magnets operations problematic.

With the aim to study alternative plasma heating mechanisms for ECRIS, a series of experimental measurements have been carried out at Max Planck Institute for Plasma Physics of Greifswald, where a Stellarator for nuclear fusion research operates. In the last years it has been demonstrated that the Stellarator plasma can be efficiently heated by means of electrostatic Bernstein waves (BW), generated through an electromagnetic to electrostatic mode conversion mechanism named "OXB-conversion". We will show that a proper BW-heating strongly reduces the number of high energy electrons over a large range of pressure and power. A possible injection scheme for ECRIS-like devices has been designed on this basis and it will be proposed along with a preliminary modelling of the waves to plasma coupling and wave's path and absorption via OXB-conversion in ECR ion sources.

PACS.: 52.50.Dg, 52.50.Sw, 52.55.Hc, 52.55.Jd

## 1. Introduction

The different methods to heat a plasma may be considered to modify the EEDF (electron energy distribution function) in microwave discharge and Electron Cyclotron Resonance ion sources (MDIS and ECRIS). In ECRIS we are mainly interested to enhance the population of electrons with energy in the range 1-100 keV and to cancel, if possible, the ones with energy larger than 100 keV. Different authors have studied this problem either experimentally [1, 2] and theoretically [3, 4, 5].

An experiment has been performed on the WEGA stellarator operating at the Max Planck Institute for Plasma Physics of Greifswald, Germany, in order to investigate the mechanism concerning the electromagnetic mode conversion leading to an electrostatic wave (the Bernstein Wave - BW) propagating throughout an overdense plasma and there absorbed. The experiment aimed to the measurements of the emitted X-rays for different values of pressure and injected RF power. The scope was also to understand whether or not the emission of the X-rays is linked to the plasma density, and if the BW absorption is able to damp the production of high energy electrons. The Bernstein waves are very interesting for nuclear fusion devices because the plasma heating occurs in absence of any density cutoff, which is not the case for the ECR heating and for different modes propagating in the plasma.

For ECR heating in toroidal devices, Ordinary mode (O-mode) or Extraordinary mode (X-mode) are externally launched to the plasma from high or low field side of the torus. Both modes have a cutoff limit for propagation. However, Slow Extraordinary mode (SX-mode) waves may be converted into a BW mode if they reach the Upper Hybrid Resonance (UHR) layer. O-mode waves launched from low field side may be coupled to the SX-mode in the region of the O-mode cutoff layer, and then the SX-mode is coupled to the B-mode. This process is called OXB mode conversion and it was described in 1973 by Preinhaelter and Kopecky [6]. In their work, it was shown that the OXB mode conversion may be optimized in terms of O-mode insertion angle with respect to the external magnetic field direction. Under the conditions for the optimization of the mode conversion, the O mode is completely converted into a slow X mode, which then completely converts to BWs in the UHR layer. The region outside the UHR layer is evanescent for the EBW (electrostatic Bernstein waves). Thus, the EBW can not be directly launched outside of the plasma but they must be excited inside the region bounded by the UHR layer. There are two main techniques to generate EB waves in the center of the overdense plasma. The first is to launch an X-mode from the high field side of the given magnetic structure. The X-mode converts to the B-mode on the UHR layer, and then the B-mode propagates into the overdense plasma region.

The second way is via the OXB mode conversion process. In this case, as mentioned above, the microwave power is launched from the low field side of the torus in the O-mode. The O-mode converts to the SX-mode, the SX-mode to B-mode, and the B-mode propagates inside the plasma and heats the electrons. The Bernstein waves are absorbed at the cyclotron harmonics, and then they travel inside the plasma until they encounter the ECR or the higher order harmonics. For the first time, OXB conversion was shown experimentally in 1987 in Japan Institute of Plasma Physics at Nagoya University on the TPL device [7, 8]. In that case the heating wave was launched obliquely via a horn antenna. The conversion was proved by two-dimensional high frequency (HF) probes measurements. The OXB plasma heating and current drive with BW in an overdense plasma was demonstrated also in the Stellarator WEGA operating at Greifswald [9].

The main limitation of the WEGA Stellarator (and of many other plasma devices based on the ECR heating, like ECRIS) is the density cutoff. Without any mode conversion, in fact, the wave can not reach the cyclotron resonance region in the center of the plasma in O-mode as well as in the X-mode. The wave meets cutoff barrier at the edge of the plasma where electron density reaches its critical value  $n_{cutoff}$ . Such heating mechanism results in a relatively low plasma density (just slightly higher than the cutoff density) and it also provides a hollow profile of the electron density. In fact, the largest part of the injected RF power is absorbed in the plasma periphery and, because of transport issues, a considerable fraction of energy escapes from the inner plasma. In the plasma core

only a reduced fraction of energy arrives, and a hollow temperature and density profile is obtained. In addition, the higher is the fraction of RF power absorbed at the plasma edge, the higher will be the edge density, hence the lower is the fraction of power able to reach the plasma core, because of the cutoff. Similar problems exist for ECR ion sources, where the peripheral plasma heating reduces the maximum achievable density and increases the temperature of the high energy electron component. For ECRIS either PIC simulations [5, 10] and experimental results [11] demonstrate that the plasma can be divided into primary (corresponding to the near resonance region) and secondary plasma, the former having the highest density and temperature, with their maximum values just in proximity of the ECR layer.

Some experiments [12] performed on WEGA demonstrated that the cutoff density can be overcome without any induced mode conversion inside the plasma. The magnetic field was fixed, at the beginning of the experiment, to a value close to the ECR one. After the plasma ignition, the magnetic field was decreased down to  $0.5 BECR$ . In this way the density overcome the cutoff value, and a maximum was observed for  $B = 0.65 BECR$ . Similar results are shown in [13] and in [14]. In these cases the increase of the electron density was attributed to the second cyclotron harmonic absorption. This mechanism is still based on a single particle approach and does not take into account any collective motion of the plasma particles, neither the possible formation of electrostatic waves. However, the experimental results cannot exclude the presence of electrostatic BW absorbed at the cyclotron harmonics and it is worthwhile to determine their occurrence experimentally. Other evidences about the overdense plasma formation in under resonance field come from an experiment carried out at INFN-LNS [15] with a plasma reactor used for environmental studies. A systematic measurement of the electron density was performed along the entire plasma chamber and for different values of gas pressure and microwave power at 2.45 GHz. It was observed a creation of an upstream slightly overdense plasma (close to the microwave window) in the region where the magnetic field is well below the ECR value.

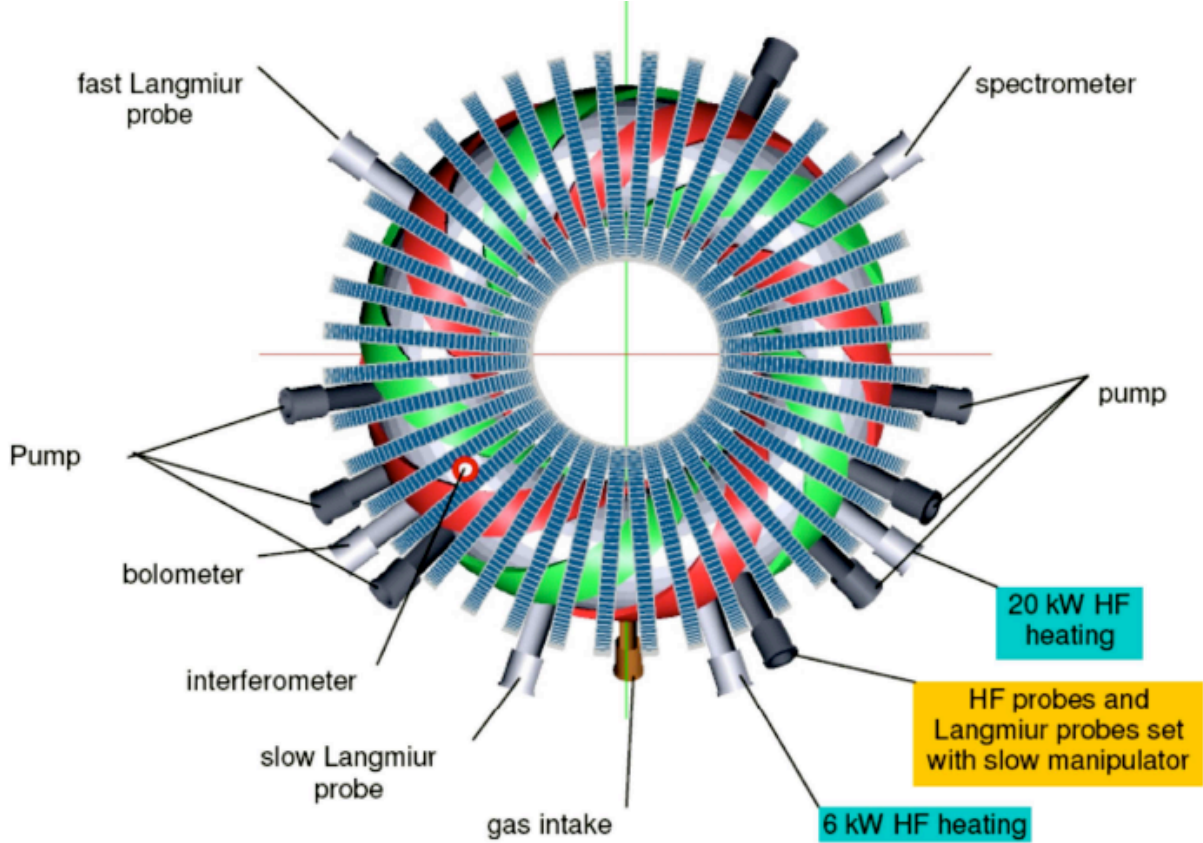
All the above mentioned results about the production of very hot electrons obtained recently on third generation ion sources [12] suggest that the ECR heating is not the best method to achieve high density with a small amount of high energy electrons. The ECR is an effective method to transfer energy from the waves to particles. Anyway, it works so well that electrons resonantly accelerated gain higher and higher energies thus limiting the number of lower energy particles that can be accelerated.

If we would like to increase the plasma density by suppressing the number of high energy electrons generated by the ECR, we should be able to use the OXB or the X-BW direct conversion in the plasma trap. Even if the technology advanced significantly since the time of pioneers, Golovanivsky and Dougar-Jabon, who used the BW excitation in 2.45 GHz plasma sources, this objective is still a challenge.

## 2. The experimental method and the set-up

WEGA is a classical mid-size stellarator, whose toroidal vacuum chamber has a major radius of  $R = 0.72 m$  and minor radius of  $r_0 = 0.19 m$  [12]. Hydrogen, Helium and Argon are used as working gas. The microwave pulse duration varies from a few seconds up to a few minutes depending on the magnetic field strength and hence the dissipated energy in the field coils. Short shots are used for high magnetic field experiments, the long time shots may be performed with magnetic field strength up to  $0.34 T$ . In this case the operation of WEGA in steady regime is possible. Three different types of coil are used for plasma confinement. In particular, the toroidal coils generate the field for the toroidal confinement, while the helical coils generate the poloidal field, essential to obtain the stabilization of the plasma confinement either in terms of the single particle and of fluidodynamics approach. Figure 1 shows the different tools used for the plasma diagnostics. In addition, during our experiment, a soft X-rays detector was used, in order to detect X-rays emitted by plasma electrons via bremsstrahlung with energies of  $500 eV$  or more. The plasma is ignited and

heated by ECR with a maximum power of  $20 + 6 \text{ kW}$  coming from two separate magnetrons operating at the frequency of  $2.45 \text{ GHz}$ . The microwaves are launched in the equatorial plane of the torus through A-ports at two positions shifted of  $36^\circ$ . Because of the low heating frequency, our experiment has been carried out with  $B \leq 0.0875 \text{ T}$  where  $0.0875 \text{ T}$  is the electron cyclotron resonant field for the  $2.45 \text{ GHz}$  heating frequency.



**Figure 1:** Design of the WEGA stellarator showing the helical, the toroidal field and the vertical field coils along with the several flanges for the location of plasma diagnostics.

The experiment with WEGA aimed to investigate the production of high energy electrons under extreme conditions of the Stellarator plasma, i.e. for maximum values of RF power and minimum pressure, in order to have a pressure and a power density comparable to the ECRIS ones. Typical values of plasma parameters like density and temperature are usually determined with the diagnostics shown in figure 1, and they are the following:

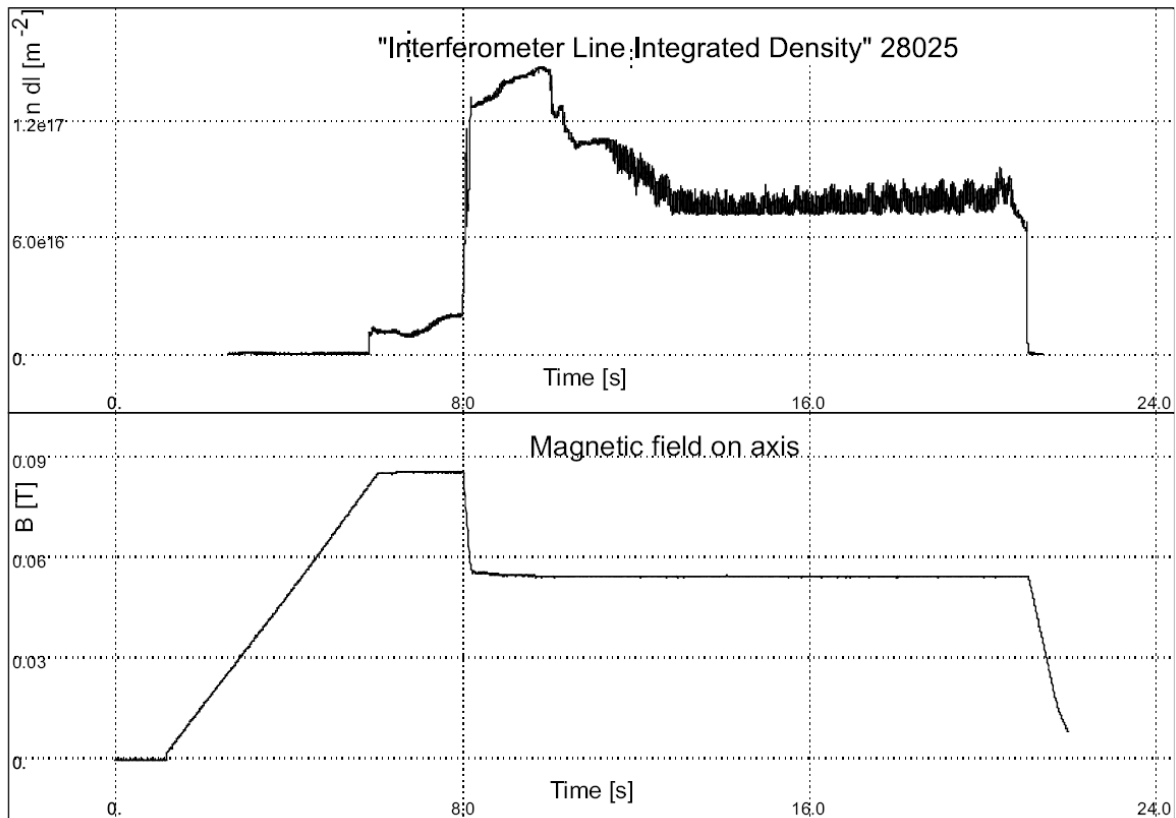
- Electron density:  $1 \cdot 10^{17} \text{ m}^{-3} < n_e < 5 \cdot 10^{18} \text{ m}^{-3}$ ;
- Plasma potential:  $15 \text{ V} < V_p < 60 \text{ V}$ ;
- Temperature of slow electrons:  $3 \text{ eV} < T_e^s < 12 \text{ eV}$ ;
- Temperature of fast electrons:  $T_e^f \sim 400 \text{ eV}$ ;
- Fraction of fast electrons:  $f_n < 5\%$

The values reported above point out that two typical plasma populations exist in WEGA. The higher energy one is named *suprathermal*, and it is of our interest to understand if some electrons belonging to this population goes till higher energies when the extreme conditions described above are satisfied.

### 3. Experimental Results

We started the experiment by looking to the variation of the electron density in typical conditions of background pressure and injected power. The power has been maintained constant during all the experimental acquisition; its maximum possible value was about  $18 \text{ kW}$ ; no more power could be injected into the plasma chamber as in the cases of lower pressures the reflected power increases dangerously.

Microwave shots lasting about  $40 \text{ sec}$  were used, and for each shot the pressure and the magnetic field were varied. In figure 2 the trend of the plasma density is shown; it is plotted versus the time during a single shot and in comparison with the current flowing in the toroidal coils. The maximum current value corresponds to the ECR field.

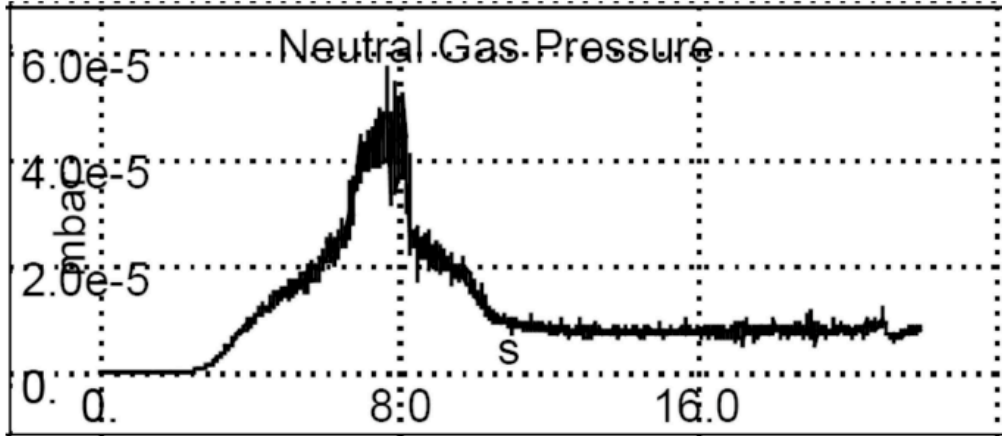


**Figure 2:** Trend of the electron density with respect to the time for a single shot compared with the coils current.

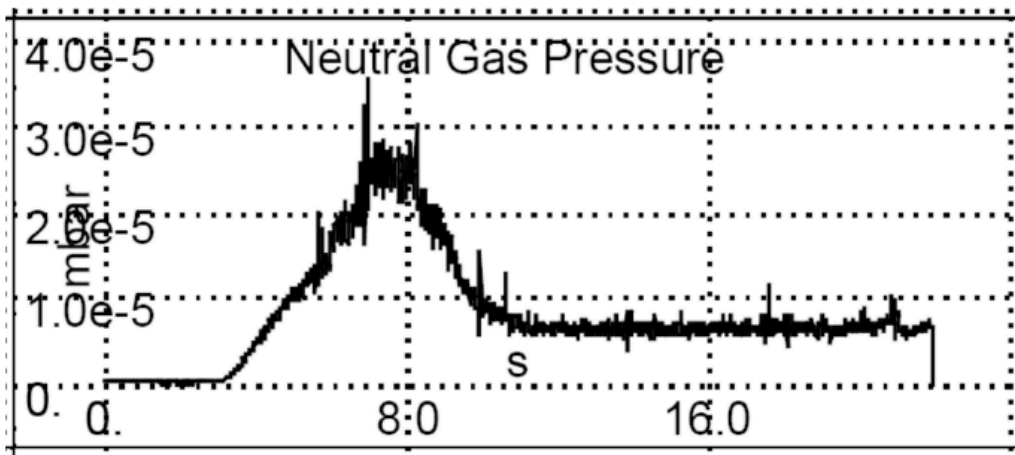
Note that when we decrease the magnetic field the density abruptly increases, as expected when the magnetic field is decreased below the ECR value; in particular the density increases above the cutoff value ( $n_{cutoff} = 7.5 \cdot 10^{10} \text{ cm}^{-3}$  for  $2.45 \text{ GHz}$ ). In this case the process is optimized by the OXB conversion driven by properly shaped antennas and microwave mirrors (see [16] for more details). Anyway the jump of the density occurs also without any optimization of the OXB process.

The density value shown in figure 2 has been obtained through the interferometer measurements. It gives an integrated density along the last closed magnetic field surface. A maximum density of about  $7.5 \cdot 10^{17} \text{ m}^{-3}$ , i.e. about one order of magnitude higher than the cutoff one, was obtained and even higher densities were obtained for higher background pressures. Under the conditions of figure 2, the soft X-ray detector, calibrated with a chromium-copper alloy used as anode for the internal X-ray source, did not give any signal around and above  $800\text{-}900 \text{ eV}$ .

Afterwards the inlet gas flow was decreased.

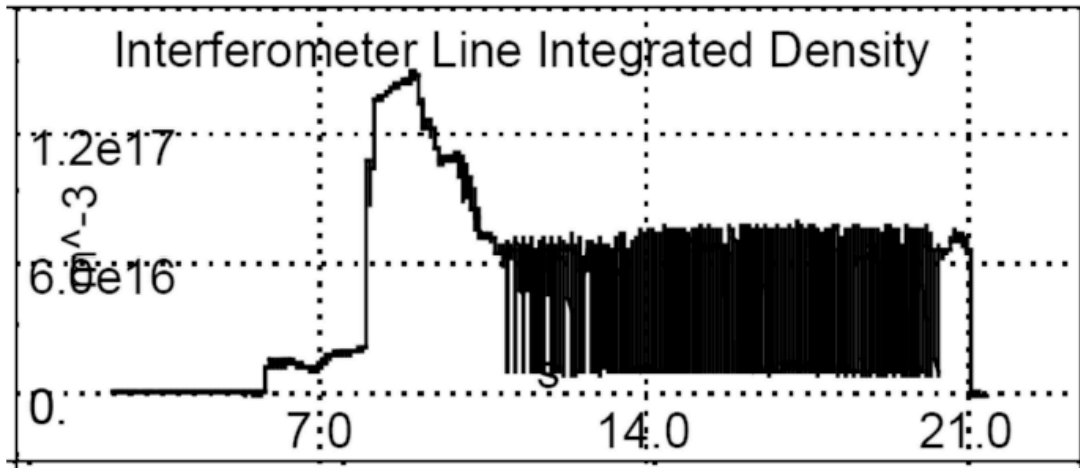


**Figure 3** Trend of the pressure versus the time for the shot #25.



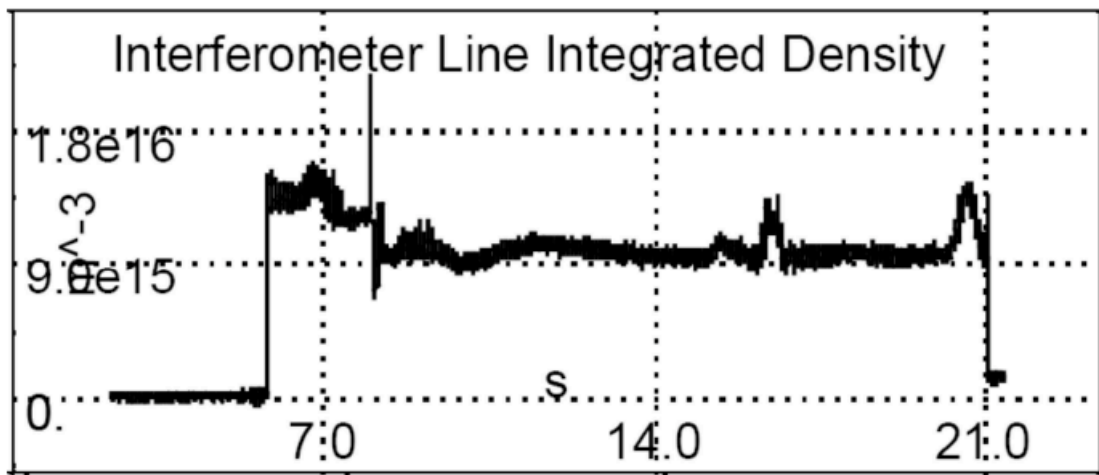
**Figure 4** Trend of the pressure versus the time for the shot #27. The inlet gas flow has been decreased, then the pressure is lower on average.

The figures 3 and 4 feature the pressure trend versus the time for two different shots, labelled 25 and 27. Note that at the beginning the pressure is quite high; the plasma ignition occurs for relatively high values of the pressure, in order to avoid any excessive power reflection due to a strong decoupling of the incoming wave. Then, in order to investigate the extremely low pressure limit, we decreased the inlet gas flow. However, in case of figure 4 it is clear that the maximum value of the pressure is lower than for the shot 25, as well as the stabilized low value after 10-12 sec. The plasma density versus time is shown in figure 5. Note that in correspondence of the pressure decrease the density decreases as well; in addition,  $n_e$  begins to oscillate. This is a sign that a very unstable plasma state is established. In this case, some high energy X-rays were detected. Their energy lies in the range 0.9-2.5 keV, but a reduced number with an energy around 6.5-7 keV was detected. The maximum energy is much smaller than the ECRIS one, because of the pressure (two order of magnitude larger) and of the lower power density ( $0.04 \text{ W/cm}^3$  for WEGA and  $0.5 \text{ W/cm}^3$  for typical ECRIS). The presence of these X-rays when the density has such pronounced oscillations suggests that they are produced only in case of low densities, otherwise they should be detected also in case of non oscillating density. The plasma creation in conditions of strong fluctuations may be interpreted as a transition between an ECR-heated state (with low density and high electron energy) and an OXB-heated state characterized by high density and low electron energy.



**Figure 5** Trend of the electron density versus the time for the shot 27. Strong fluctuations are evident, in correspondence with the strong decrease of the background pressure.

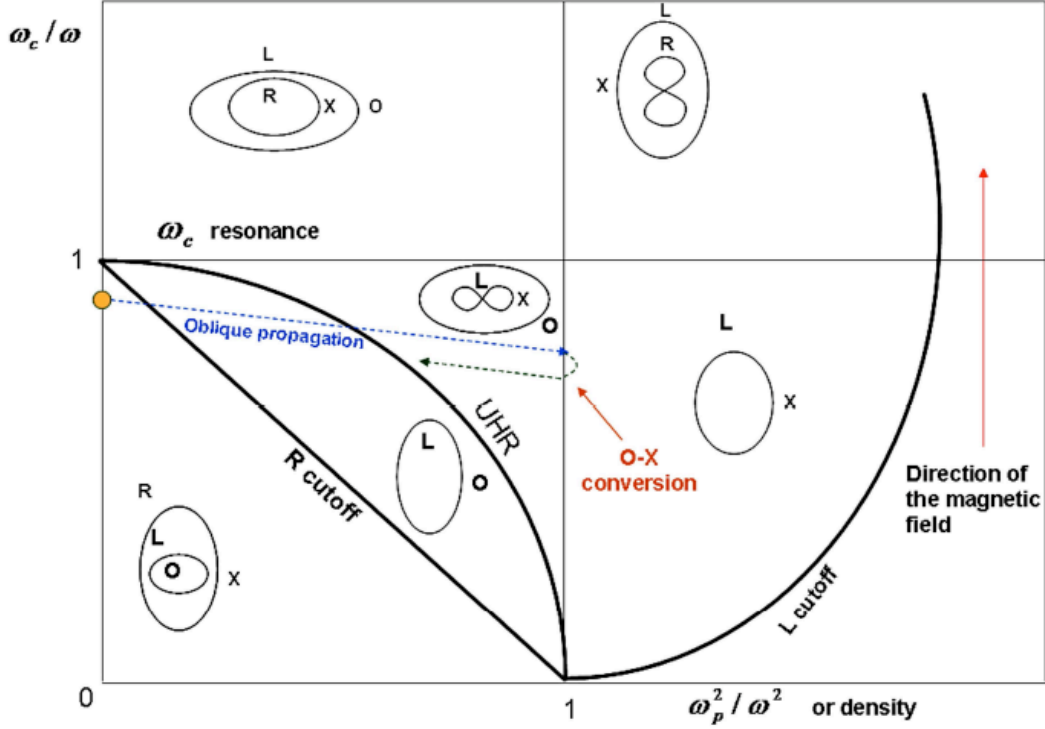
Hence, as expected, the low densities facilitate the electron heating up to high energies. On the contrary, in case of high pressures and high densities a great amount of electrons is generated through ionizing collisions and the wave energy is distributed among many particles; this leads to a reduction of the single particle energy. By keeping constant all the parameters except for the magnetic field, which was set at the ECR value for all the shot duration, and for the RF power, which was decreased down to 8 kW, the plasma density was again measured, and it is shown in figure 6.



**Figure 6** Trend of the electron density versus the time for the shot #69. The density remains well below the cutoff value for very low background pressures, which in addition was slightly decreased during the shot.

Note that the density remains well below the cutoff value at all the times, even when the pressure is decreased. This is the confirmation that when the ECR is active inside the plasma the overdense plasma state is not obtained. In addition, probably because of the low  $P_{RF}$ , no X-rays were detected. Measurements with the same set-up but with higher power levels were not possible because of the very high reflected power especially for the lower values of pressure.

#### 4. Modelling of a mode conversion experiment on an ECRIS-like device



**Figure 7** The CMA diagram showing the path of a obliquely launched O-mode with the following conversion in a X mode at the O cutoff.

The experimental results reported above permit to propose an experiment with modern ECRIS about the generation of BW via O-X-B or direct X-B conversion. The design of a BW heating for ECRIS requires a new approach: as mentioned above, the ECR surface must be placed outside from the plasma chamber, and a proper displacement of the O and X cutoffs, and of the UHR layer, must be chosen to generate BWs. The cutoffs and resonances of the various modes propagating in magnetized plasmas can be calculated according to the refraction indexes reported in table 1.

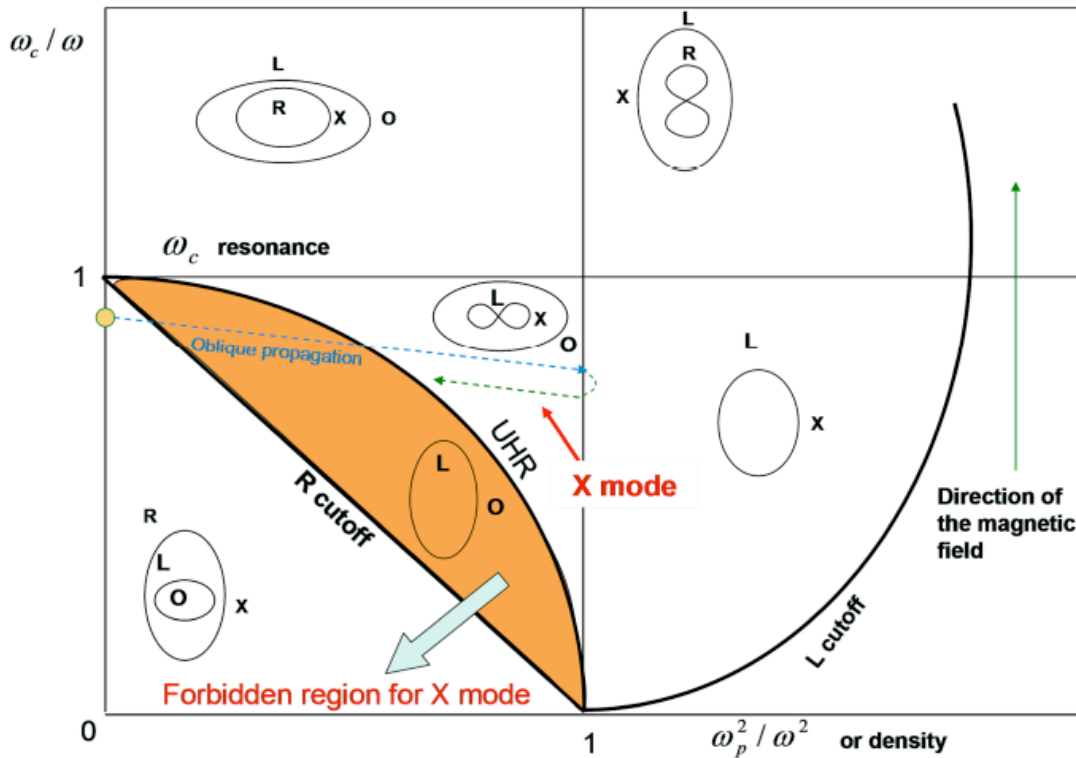
vectors orientation	refraction index	wave type
$\vec{B}_0 = 0$	$\omega^2 = \omega_p^2 + k^2 c^2$	light waves
$\vec{k} \perp \vec{B}_0, \vec{E} \parallel \vec{B}_0$	$\frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}$	O wave
$\vec{k} \perp \vec{B}_0, \vec{E} \perp \vec{B}_0$	$\frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2 \omega^2 - \omega_p^2}{\omega^2 \omega^2 - \omega_h^2}$	X wave
$\vec{k} \parallel \vec{B}_0$	$\frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2 / \omega^2}{1 - (\omega_c / \omega)}$	R wave
$\vec{k} \parallel \vec{B}_0$	$\frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_p^2 / \omega^2}{1 + (\omega_c / \omega)}$	L wave

**Table 1** Refraction indexes for the different modes propagating in magnetized plasmas.

It is well known that for the resonances the refraction index becomes infinite, whereas for cutoffs it tends to zero. The CMA diagram is a powerful method to trace the path of a wave propagating



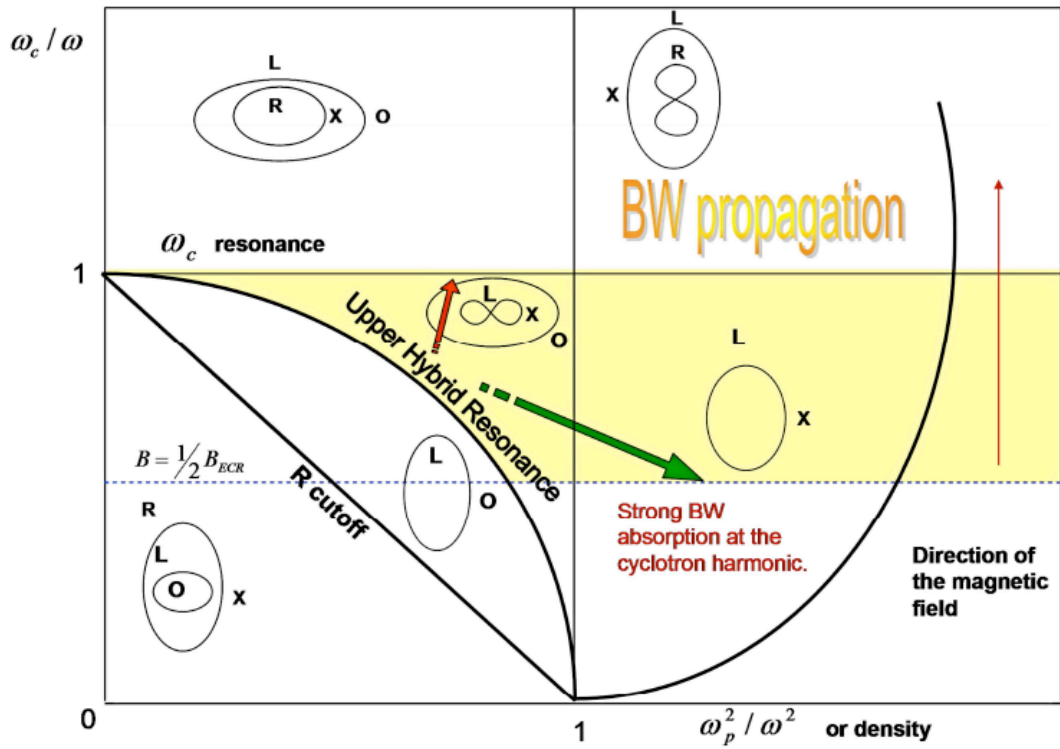
inside the plasma for different values of density and magnetic field. Cutoffs and resonances are traced in this diagram which is separated in different areas. The figure 7 shows the path of an obliquely launched O mode (oblique with respect to the magnetic field direction), travelling from a higher to a lower magnetic field towards the O cutoff. If the injection angle is proper, the O mode converts in a X mode at the O cutoff layer. The X mode comes back to the UHR layer, where it may be converted in a pure electrostatic wave, the Bernstein wave. Note that the starting point of the O mode is well below the ECR field. Once generated, the BWs can propagate in the shadowed region shown in figure 9.



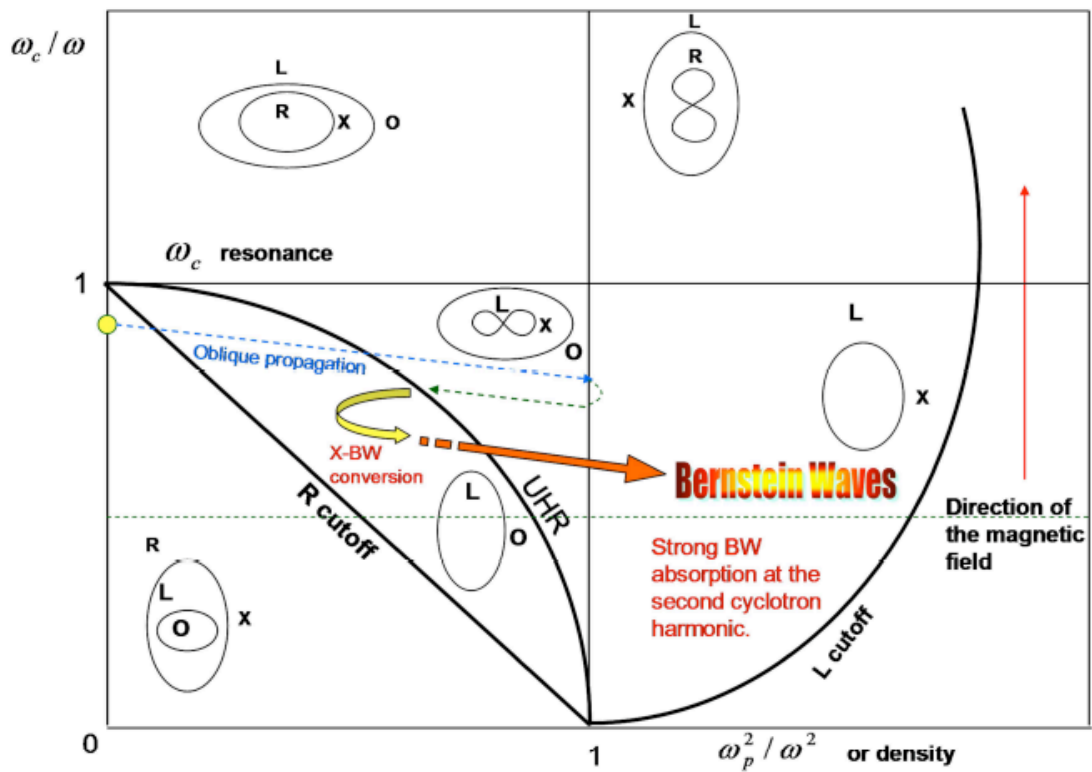
**Figure 8** Forbidden region for the X-mode, that is converted into a B-mode at the UHR layer.

Being the maximum field below the ECR, the BW propagating towards higher  $B$  fields cannot be absorbed. Therefore we can consider only the BW which propagate towards the plasma core. Supposing that in the plasma core the density is well above the cutoff, and the magnetic field has a very slow decrease near the center of the plasma chamber, then the BWs travel towards the plasma core and they are absorbed at the second cyclotron harmonic, provided that the condition  $B_{\min} < \frac{1}{2} B_{ECR}$  holds. This situation is shown in figure 10 on the CMA diagram.

For minimum-B structures the constant field surfaces are closed [10]. In addition, according to the PIC simulations and to the MHD stability principles [10], we can say that the constant field surfaces are also constant density surfaces. To determine the possible path in the real space (i.e. inside the plasma chamber of an ECRIS) of the O, X, and B modes, we can suppose that a given density profile has been established inside the plasma chamber; after we determine the waves' paths, and we may suppose that the density profile is achieved self-consistently in the transition to the OXB process.

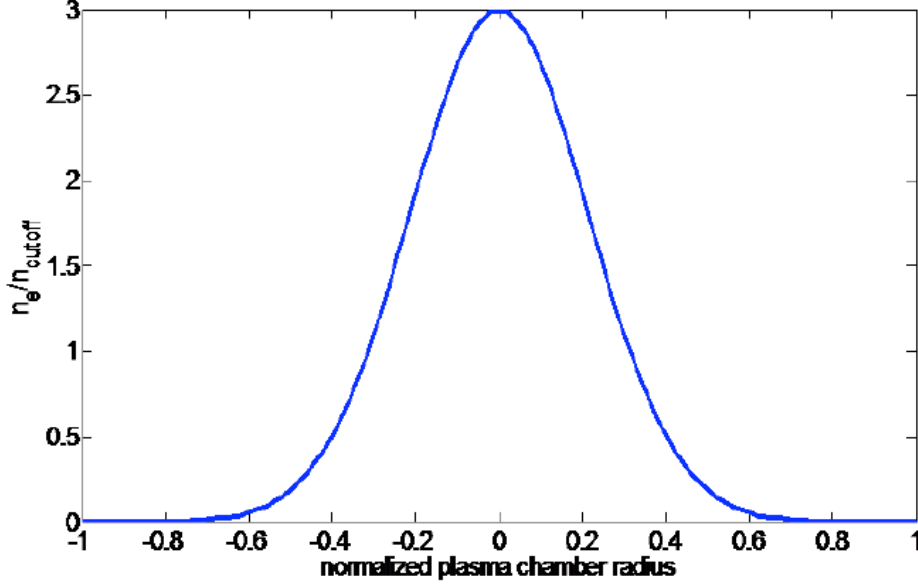


**Figure 9** Representation on the CMA diagram of the region of possible propagation for the Bernstein waves.



**Figure 10** Description of the complete O-X-B conversion mechanism, with the trajectory followed by the BWs, effectively absorbed at the first cyclotron harmonic.

We may determine the locations of the cutoffs and resonances with the profile shown in figure 11. If the displacement of these layers is proper, the assumed density profile can be achieved self-consistently during the plasma ignition. The cutoffs and resonances layers, for the given density profile and for different magnetic field configurations, have been simulated by means of a MATLAB numerical code [10].



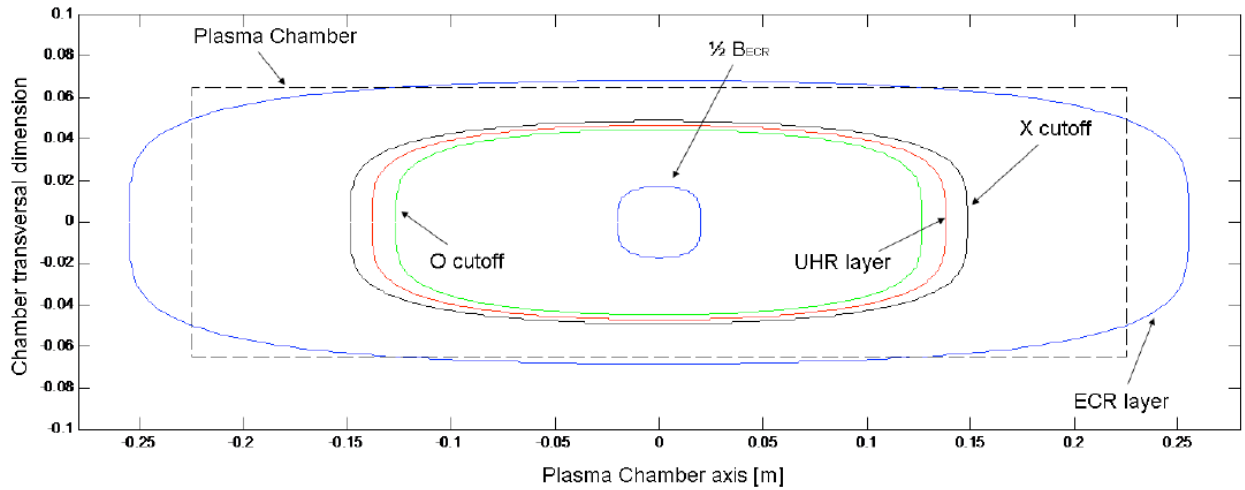
**Figure 11** Assumed profile of the electron density inside an ECRIS with respect to the chamber normalized radius.

This code solves the equations reported in table 1 with the magnetic field given by the equations:

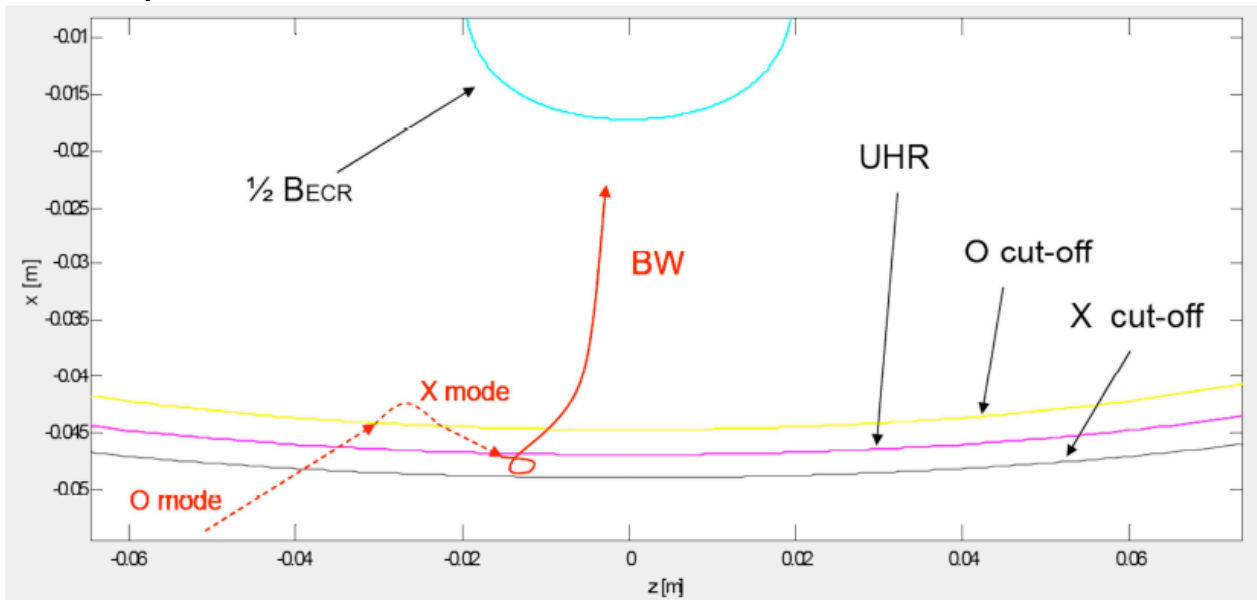
$$\begin{aligned} B_x &= -B_1xz + 2Sxy \\ B_y &= -B_1yz + S(x^2 - y^2) \\ B_z &= B_0 + B_1z^2 \end{aligned}$$

where  $S$  is a constant which indicates the gradient of radial field increase,  $B_0$  is the minimum field in the trap and  $B_1$  is connected with the longitudinal magnetic gradient. Figure 12 shows the localization in the real space of the cutoffs and the resonances that may permit to exploit the OXB. The plasma chamber dimensions and the features of the magnetic field structures are similar to those of SERSE, the ECR source operating at INFN-LNS. The location of the different layers is shown in figure: the ECR surface is outside the plasma chamber, thus avoiding any single particle absorption of wave energy.

The UHR layer is bounded outward by the X cutoff surface, and inward by the O cutoff. This displacement ensures that the O mode, coming from regions outside the plasma edge, converts in the X mode at the O cutoff for a particular injection angle. The detailed tracing of the wave path inside the plasma is shown in figure 13. According to the path on the CMA diagram shown in figure 10, the X waves travels towards the UHR layer, i.e. in regions of lower density and higher magnetic field.



**Figure 12** Real cutoffs and resonance localization for the different modes propagating inside the plasma of a future ECRIS able to exploit the OXB conversion mechanism. The second cyclotron harmonic layer is also shown.



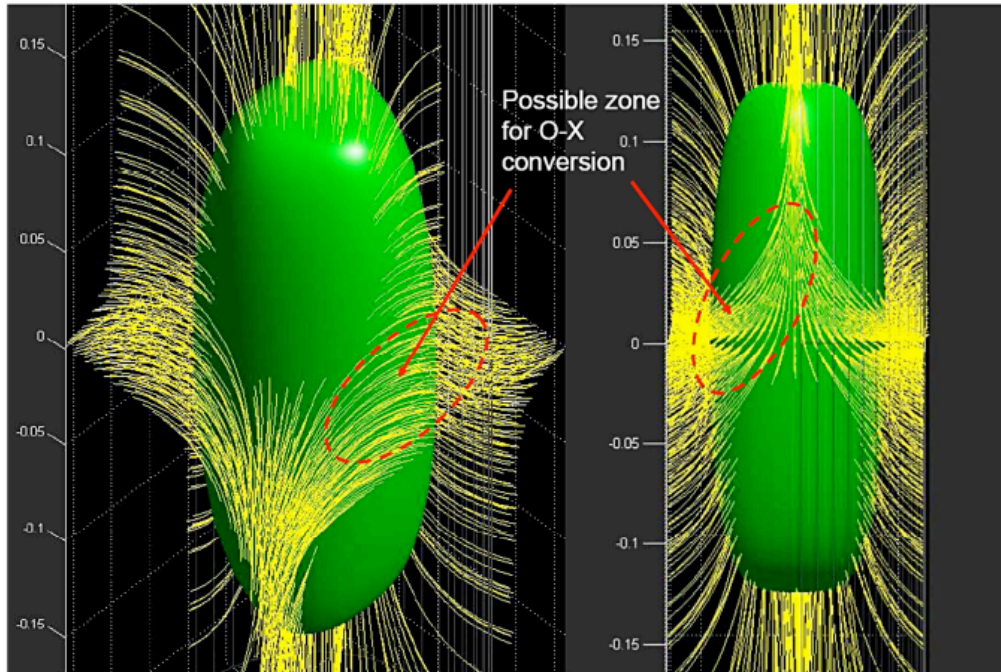
**Figure 13** Tracing of the different mode propagation paths with the relative conversion and absorption layers in a SERSE-like ECRIS system.

This means that, in real space, it will come back from the O cutoff layer to the UHR surface (see again figure 13). There, the X mode converts in a B mode; as shown in figure 10, the BW will move towards the lower magnetic field region without any density cutoff. It will be absorbed only when it encounters one of the cyclotron harmonic resonances. In figure 13 the first cyclotron harmonic is located near the center of the plasma. This means that the BW are centrally absorbed and the central heating ensures, because of transport reasons, an effective heating of a great amount of particles, up to densities well above the cutoff one.

The required profile for the magnetic field is:  $B_{min}=0.32 T$ ,  $B_{inj} = B_{ext} = 0.63 T$  and  $B_{hex} = 0.6 T$  for a heating frequency of  $18 GHz$ .

The other required condition to optimize the OXB is that the magnetic field lines be almost parallel to the constant density surfaces, especially in the case of the O cutoff layer. This condition is not so easily satisfied in minimum-B structures; anyway, some regions approximatively satisfy this condition.

Something about the mutual orientation of the field lines with respect to the O cutoff surface is shown in figures 14 and 15. Note that in the lateral part of the O cutoff the field lines curvature is less pronounced, and for some centimeters the quasi-parallel condition among the force lines and the O surface is satisfied.

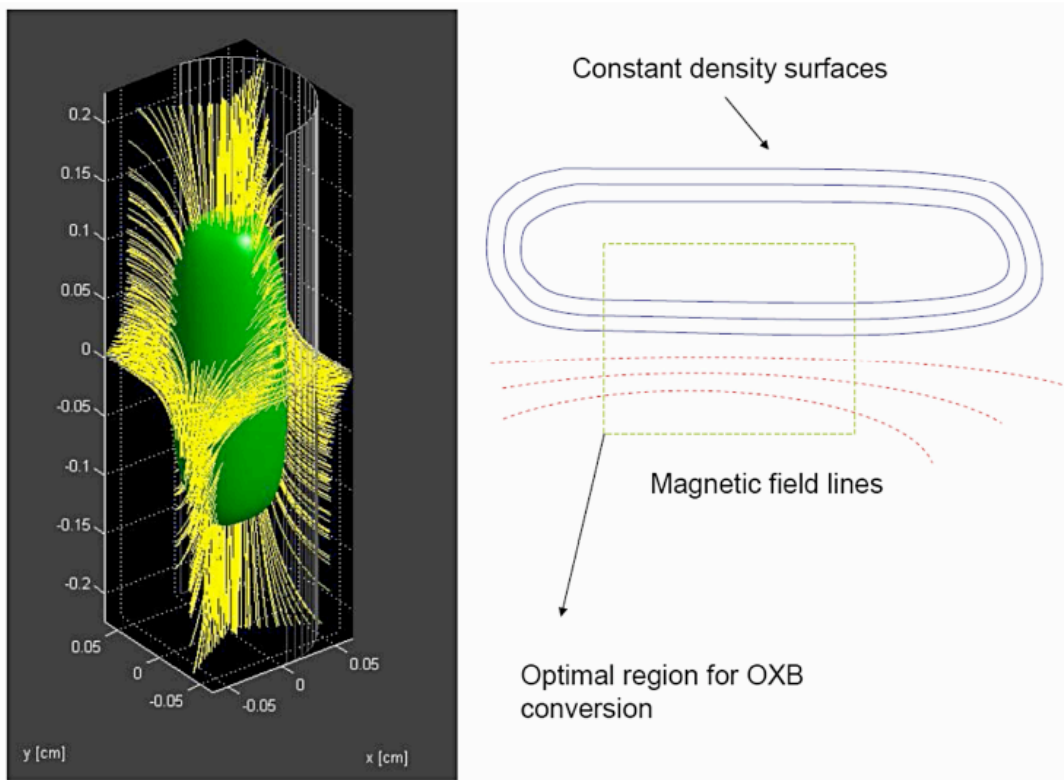


**Figure 14** Three dimensional views of the O cutoff surface (in green) together with the field lines (in yellow). The region of possible optimized mode conversion is indicated.

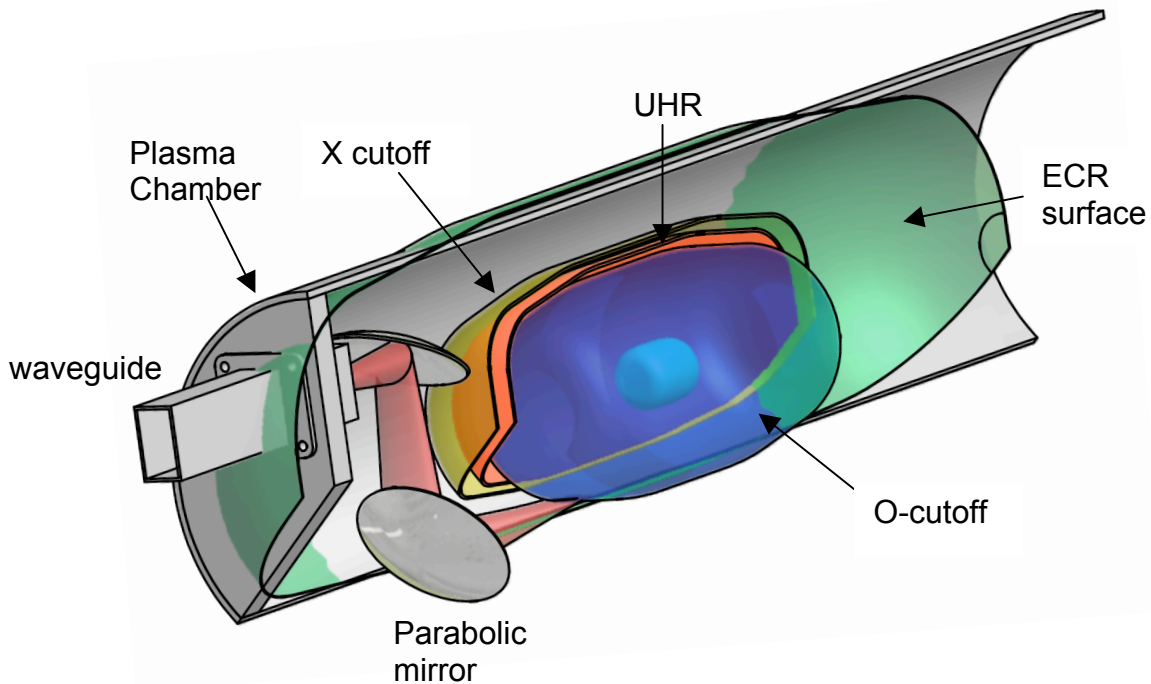
Hence the main question is the following: how to bring the O wave just in the required region? The microwave injection in ECRIS is usually provided by waveguides located in the injection flange. Hence we need a direct injection of the wave towards the O cutoff layer, with a proper angle and in an adequate region of the cutoff surface, as shown in figure 15. This can be obtained by means of two different injection schemes. The simplest one consists of a single cut antenna, with the cut oriented so that the emitted wave directs towards the O cutoff layer. However in this way the great amount of the power reaches the cutoff surface with a non optimal angle, as the microwave beam is not focused. Moreover the space to locate the waveguide between the chamber walls and the O cutoff surface is very small. An improved scheme can be designed, requiring two metallic parabolic mirrors for the microwaves, placed as in figure 16. Now the microwaves are brought towards the O cutoff layer through the two parabolic (focusing) mirrors. The mirrors displacement should be adapted to launch the microwaves towards the O cutoff surface region.

A more simple design is shown in figure 17 and it consists of a single cut antenna, with the cut oriented so that the emitted wave directs towards the O cutoff layer. However in this way the great amount of the power reaches the cutoff surface with a non optimal angle, as the microwave beam is not focused. Moreover the space to locate the waveguide between the chamber walls and the O cutoff surface is very small. Despite of these problems, this scheme could be the first set-up to be tested in the next months.

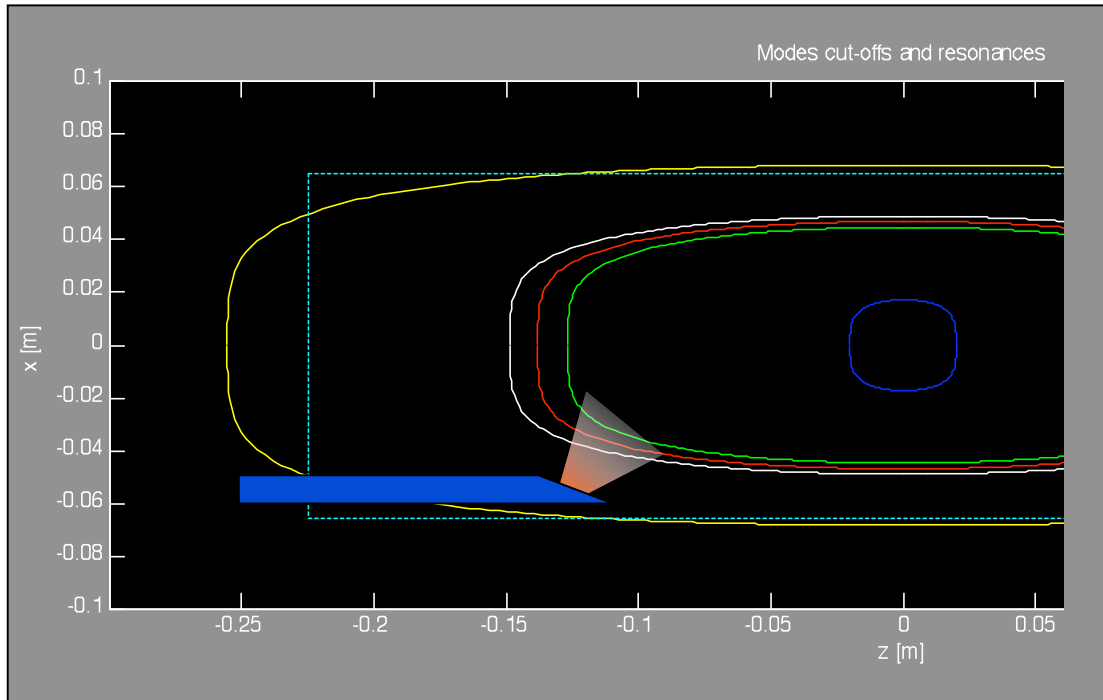
Ray tracing of the electromagnetic waves travelling inside the plasma is also required in order to design an experiment based on such a launching system. For a further optimization of the O-X-B conversion, the wave should be left hand elliptically polarized, with the main axis of polarization along the magnetic field direction.



**Figure 15** 3D view of the O cutoff layer together with a two dimensional representation of the constant density layers. The optimal region for the O-X conversion is emphasized.



**Figure 16** Improved design of the microwave injection for O-X-B conversion. Two parabolic mirrors are used to bring a focused microwave beam in the optimal region of the O cutoff layer.



**Figure 17** Scheme of simple scheme for microwave injection in order to have the O-X conversion at the O cutoff layer. The dimensions of the SERSE source are considered as an example.

A proper design of the cavity walls may be helpful for oblique launching: grid reflectors on the chamber walls may be used instead of single-cut antenna and/or parabolic mirrors, but further investigation are needed in order to design the best launching system.

## 5. Discussion

The main unknown phenomena about the OXB in ECRIS are the plasma start-up and the MHD stability. The assumed density profile could be achieved self-consistently immediately after the plasma ignition, but at the beginning the various cutoffs and resonance layers (except for the ECR and the first cyclotron harmonic, which do not depend on the density) are located differently with respect to the ones shown in the previous pages. This may limit the heating till overdense plasmas and a sort of two stage heating, initially by means of the ECR, may be helpful.

The main advantages of the OXB conversion is obviously represented by the strong increase of the electron density and the experiment on WEGA here reported confirms that the higher is the density, the lower is the number of high energy electrons. However, in order to obtain highly charged ions, electron temperatures on the order of  $keV$  or tens of  $keV$  are needed. Much lower temperatures were observed on WEGA, because of the lower power density with respect to the ECRIS one (in a SERSE-like ECRIS it is almost one hundred times the WEGA's one). Although no well known scalings of the temperature with the power are available, it is reasonable to suppose that temperatures on the order of few  $keV$  in ECRIS are obtainable in case of BW heating. The main point in achieving high density and high temperatures is the power balance. The problem is that the radiation losses goes with the square of the density. This could be the limiting factor. In order to reach high temperatures, one has to control the density by the neutral pressure.

Many problems may arise by the point of view of the plasma confinement, as the mirror ratios must be strongly reduced. This problem can be treated by the two usual different points of view: the single particle and the macroscopic (fluid) dynamics. The main question concerns the MHD

equilibrium and stability, which may result seriously damaged. We will need to experimentally determine a new "stability island". One possible technique to avoid any plasma instability may be to increase the periphery magnetic field once achieved the overdense plasma state, that is possible because of the high versatility of the magnetic system in ECRIS; however the effects of the ECR layer coming again into the plasma cannot be easily predicted and must be checked experimentally. Another key point is the possible formation of HEL-Hot Electron Layers observed by Golovanivsky and co-workers in an experiment based on the BW heating of 2.45 GHz plasmas [17]. They observed a strong absorption of BW at the cyclotron harmonics, leading to very high energy electrons, above 700 keV. However, their microwave launching scheme was quite different with respect to the mechanism here proposed. They launched an X wave perpendicularly with respect to the plasma chamber axis, and the magnetic field was more similar to that used in MDIS instead of ECRIS: it decreased from the center to the periphery of the plasma chamber. BW were generated by means of the direct X-B conversion and they were reflected by the UHR layer, moving exactly in the opposite direction with respect to the incoming X-mode, i.e. towards the periphery of the plasma chamber. In this way the power is deposited in the plasma halo leading again to the formation of an hollow shape of the electron density and, because of transport, to a poorly efficient heating of the plasma core. A great amount of energy is deposited in small layers, correspondingly to the cyclotron harmonics, involving few particles which can reach very high energies. With the scheme proposed in figure 16 the HELs formation should be avoided, thus depositing the RF power centrally.

## 6. Conclusions

The results obtained with WEGA about the OXB conversion, have opened new frontiers for the design of ion sources based not only on the ECR-heating, but also on the Bernstein waves heating. In collaboration with the Max Planck Institute, a preliminary test will be carried out in the second half of 2009 about the applicability of the OXB conversion on ECRIS-like devices. On the basis of the obtained results, a "dream machine" may be designed, able to operate with overdense plasmas without any limitation due to the production of high energy electrons. In addition it is clear that such a machine will operate with relatively low magnetic fields, if compared with those ones used nowadays for 3<sup>rd</sup> generation ECRIS. The extraordinary advantages coming from the completely different heating mechanism should overcome the disadvantages due to the worsening of the confinement even if the RF power may be larger than 10 kW. Finally, the possibility to tailor the EEDF (avoiding the formation of excessively high energy electrons, with a great amount of particles in the warm population), seems to be possible and it may be the key for further increases of ECRIS performances in the next ten years.

## Acknowledgments

The support of the 5<sup>th</sup> National Committee of INFN (INES and HELIOS experiments) is warmly acknowledged. The authors wish to thank L. Allegra for the technical support.

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