EFFECT OF TJ-II COMPLEXITY ON EFFICIENCY OF ELECTRON BERNSTEIN WAVE HEATING

[1]F.Castejón, [1]A.Cappa, [1]A.Fernández, [2]K.A. Sarksyan, [2]M.A.Tereshchenko, [3]N.V.Matveev, [2]N.K.Kharchev

[1]*Asociación Euratom - CIEMAT para Fusión, 28040 Madrid, Spain*
[2]*General Physics Institut, Russian Academy of Sciences, Moscow, Russia*
[3]*State Unitary Enterprise "All-Russian Electrotechnical Institute", Moscow, Russia*

e-mail: francisco.castejon@ciemat.es

The feasibility of heating TJ-II plasmas by electron Bernstein waves is studied. The ray tracing code TRUBA, that has been adapted to the TJ-II geometry, has been used to perform detailed calculations. The final result is that it is possible to heat plasmas overcoming the cut-off density of electromagnetic modes injecting O mode and having O-X-B conversion. The optimum characteristics of the beam are obtained by considering ray tracing for a bunch of rays distributed perpendicularly over the wave front at the point where the beam enters the plasma.

1- Introduction and Motivation.

The limit of density to which an Electron Cyclotron (EC) electromagnetic wave can penetrate in magnetized plasmas can be overcome by means of mode conversion into electrostatic waves, the electron Bernstein waves (EBW), characterised by having large refractive index. The EBW can propagate at high densities and are strongly absorbed near the cyclotron resonance layer.

The possibility of obtaining high density plasmas in TJ-II using EBW has being explored in [1]. This heating smethod is very promising for overcoming cut-off density limit ($n_e(0) \approx 1.7\ 10^{19}\ m^{-3}$) and getting good plasma targets for neutral beam injection heating, as has been shown in previous experiments in W7-AS [2] and H-J [3] stellarators. In particular, ray tracing calculations have been performed, using the ray tracing code TRUBA [4], to look for the optimum positions and scenarios for EBW heating in TJ-II. Such calculations show two possible heating schemes at first harmonic, using a 28 GHz gyrotron available in CIEMAT, namely O-X-B1 (O mode is converted into X mode which in turn is converted into EBW, absorbed at first harmonic) and X-B1 (X mode is converted into EBW). The complicated geometry of TJ-II poses specific problems on using this heating method and special consideration must be given to those related to the hardware design [5]. The former heating scenarios imply the use of a complicated launching system, including a movable mirror located inside the vacuum chamber.

The task of optimising launching angle in LHD was dealt in Ref. [6] where the range for having an efficient EBW absorption in that device was obtained. The problem appears to be more complicated in TJ-II due to the strong inhomogeneity of magnetic field. In the O-X-B1 scheme, the properties of the beam must be chosen in order to maximise the mode conversion without losing power absorption. For the X-B1 scheme the critical layer is the upper hybrid resonance and the characteristics of the beam must be optimised at such layer.

In this work, a study of the optimum characteristics of the beam is performed. The obtained information will be an input for the design of the last mirror. The sensitivity of this design to the plasma density profile evolution will be also considered. Finally, this paper is organised as follows. Sect 2 is devoted to the consideration of the specific problems of TJ-II geometry. Ray calculations are presented in Section 3 while beam optimization is shown in Section 4. Conclusions come in Section 5.

2.- EBW in TJ-II geometry

In a previous work [1], it has been shown that the only heating schemes that can be suitable for TJ-II are X-B1 and O-X-B1 at f =28 GHz. The first one may be troubled in high-density plasmas (n_{max} > 1.3 x 10^{19} m^{-3}) because the central region is opaque for X-mode and peripheral propagation suffers from strong refraction. Therefore, the second scheme will be used in TJ-II.

The 3D study of the microwave behaviour shows a strong variation of $N_{||}$ along the ray trajectories. Considering the dispersion function

$$H = \mathrm{Re}\left[\det\left(N^2\vec{I} - \vec{\mathrm{N}}\vec{\mathrm{N}} - \vec{\varepsilon}_h\right)\right] \tag{1}$$

that depends on $q=(\omega_p/\omega)^2$, $u=(\omega_c/\omega)^2$), T_e, $N_{||}$ and $N_\perp$, one can write the Hamiltonian ray tracing equations:

$$\frac{d\vec{r}}{ds} = -\frac{\partial H}{\partial \vec{N}} = -2\left[\frac{\partial H}{\partial N_\perp^2}\vec{N} + N_{||}\left(\frac{\partial H}{\partial N_{||}^2} - \frac{\partial H}{\partial N_\perp^2}\right)\hat{b}\right]$$

$$\frac{d\vec{N}}{ds} = -\frac{\partial H}{\partial \vec{r}} = \left(\frac{\partial q}{\partial \psi}\frac{\partial H}{\partial q} + \frac{\partial T_e}{\partial \psi}\frac{\partial H}{\partial T_e}\right)\vec{\nabla}\psi + 2\frac{u}{B}\frac{\partial H}{\partial u}\vec{\nabla}B + 2N_{||}\left(\frac{\partial H}{\partial N_{||}^2} - \frac{\partial H}{\partial N_\perp^2}\right)\vec{N}\cdot\left(\vec{\nabla}\vec{b}\right) \tag{2}$$

where $\boldsymbol{B}$ is the magnetic field, $\boldsymbol{b}$ is a unit vector parallel to the magnetic field and $\psi(\vec{r})$ is the magnetic flux. The vector notation: $\vec{N}\cdot\left(\vec{\nabla}\vec{b}\right) = N_i\,\partial b^i/\partial\vec{r}$.Noting that $\vec{B}\cdot\vec{\nabla}\psi = 0$, we obtain:

$$\frac{dN_{||}}{ds} = \left(\vec{N}\cdot\vec{\nabla}\vec{b}\right)\frac{d\vec{r}}{ds} + \vec{b}\cdot\frac{d\vec{N}}{ds} = 2\frac{u}{B}\frac{\partial H}{\partial u}\vec{b}\cdot\vec{\nabla}B - 2\frac{\partial H}{\partial N_\perp^2}\vec{N}\cdot\left(\vec{N}\cdot\vec{\nabla}\right)\vec{b}$$

(3)

Outside the vicinity of ECR, the EBW refractive index satisfies that $N_\perp^2 >> 0$. Using this approximation the dispersion relation is given by:

$$H = N_\perp^4 \left\{ 1 - 2q \sum_{n=1}^{\infty} \left[\frac{n^2}{1-n^2 u} R_n\left(N_\perp^2 / \mu u\right) \left(1 + N_\parallel^2 \frac{1+3un^2}{\mu(1-n^2 u)^2} \right) \right] \right\}$$

(4)

Where $R_n(x) = x^{-1} e^{-x} I_n(x)$ and $\mu = mc^2 / T_e >> 1$. This expression implies that $\left|\partial \tilde{H} / \partial u\right| \sim N_\perp^2 \left|\partial \tilde{H} / \partial N_\perp^2\right|$. From this condition, it follows that the two terms of the RHS of (3) are of the same order. This fact means that when the magnetic ripple is large, what happens in TJ-II, the value off $N_\parallel^2$ will suffer a fast increase whenever $N_\perp^2$ goes up, giving a strongly Doppler-shifted absorption of EBW with $N_\parallel^2 \geq 1$. This result conflicts with the objective of central plasma heating. So, longitudinal inhomogeneity of magnetic field should be very small in the region of the plasma from the zone of UHR layer crossed by the beam, where mode conversion happens, towards the heated plasma core. The only region accessible from LFS with those characteristics in TJ-II is at toroidal angles in the range ϕ=21º-25º. Therefore this must be the starting point for developing EWB scenarios.

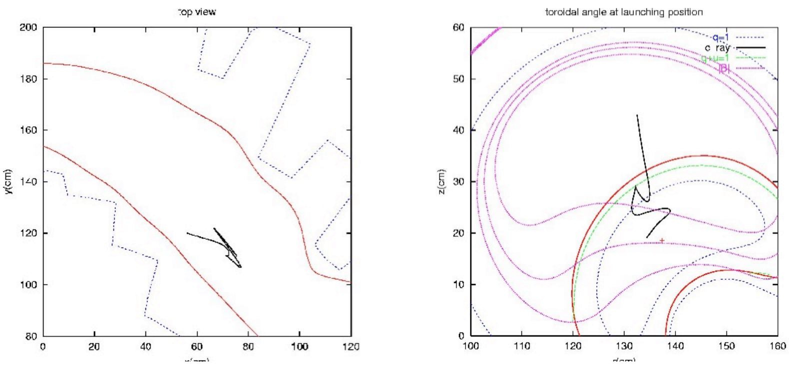

Figure 1: Ray trajectory .in toroidal and poloidal plane for n_{e0}=1.7 x 10^{19} m^{-3} and T_{e0}=700 eV.

3.- Numerical Results.

In the cases with strong spatial dependence of dispersion properties of the plasma the multiple ray tracing method can work properly. The ray trajectory in toroidal and poloidal plane is plotted Figure 1 for O-X-B1 scenario, while the power deposition profile is plotted in Fig. 2. All the estimations have been done for the following density profile: $n_e(\psi) = n_{e0}\left(1-\psi^{1.375}\right)^{1.5}$. One should note that when n_{e0} drops below 1.1 x 10^{13} cm^{-3}, O-X conversion fails with the subsequent total loss of efficiency of this scheme. Therefore, ECH must be used to get high densities and an extra gas puffing is needed to achieve the necessary density. In more dense plasmas the behaviour of O-X-B1 trajectories remains almost unchanged as n_{e0} rises, and for $n_{e0} \geq 1.5$ x 10^{13} cm^{-3} the single ray efficiency of O-X-B1 heating scheme is stably high (not less than 75%).

Extensive single ray tracing calculations have been performed to evaluate the optimum launching position in the chosen sector of the machine. In this way, the optimum launching direction, along which the centre of the mirror must be positioned, is determined. It still remains to estimate the optical properties of the mirror.

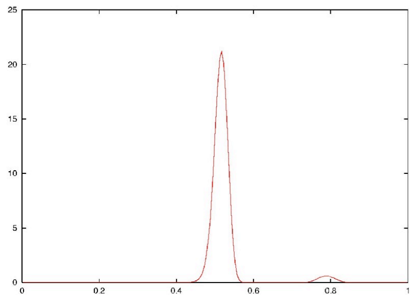

Figure 2: Power deposition profile (a. u.) for the case of Fig. 1

4.- The optimum characteristics of the beam.

Electron Bernstein wave heating in the O-X-B scheme needs a very precise beam launching direction for which the tunneling efficiency T_{eff} of O-mode radiation through the evanescent layer is maximum (and very close to 1). But this is only true for a single direction represented by a single ray. Actually, the power is launched through quasi-optical means and it is the tunneling efficiency of the real Gaussian beam that must be adressed. Our goal is to calculate T_{eff} for any non-astigmatic launched beam and find the design parameters of the last mirror that maximize its value.

In the following, we shall define the origin of the beam field to be the center of the internal mirror (see Fig. 3). For a given frequency, the beam is defined by two parameters, the minimum waist, w_0 , and its location along the propagation direction, z_0. The position of the mirror respect to the plasma (d), that is another free parameter of the calculation, is restricted by the relatively low frequency and the small space available inside and outside vacuum vessel. Therefore, we choose this distance as d=135 mm for our analysis.

In order to calculate its tunneling efficiency, the Gaussian beam is viewed as composed of rays, traced independently, along the local group velocity direction, i.e perpendicular to the approximately spherical wave fronts S_1, centered at z_L with radius of curvature R_1. These two quantities satisfy: $R_1=z_1-z_0+a^2/(z_1-z_0)$ and $z_L=z_1-R_1$, being $a=\pi w_0^2/\lambda$ the confocal distance and z_1 the position of the plane perpendicular to the central ray that is adjacent to the plasma. Every pair (w_0 , z_0) defines a beam that will be simulated by a bunch of rays distributed on the surface S_1 (that intersects z-axis at z_1) and directed perpendicularly to this surface and, hence, every ray is defined by $\mathbf{k}=\left(k_x,k_y,k_z\right)= \left(\sin\theta\cos\phi,\sin\theta\sin\phi,\cos\theta\right)$ where θ and ϕ are the usual spherical coordinates angles that give the starting point of the ray in the wave front. The wave vector of the central ray is $\mathbf{k_c}$=(0,0,1). The maximum value of θ is $\theta_{max}=tan^{-1}(w_1/R_1)$, where w_1 is the beam size, defined as the point where the amplitude of the field is 1/e the maximum, at the position z_1. Every ray trajectory in the plasma is calculated using TRUBA and its single tunneling efficiency is determined. The total efficiency of the beam is estimated as:

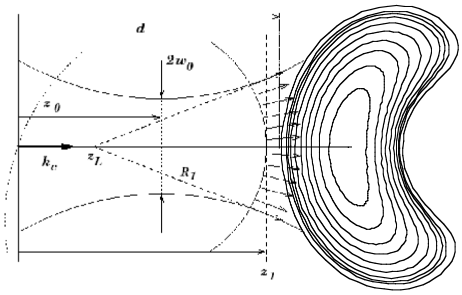

Figure 3: Schematic view of beam launching

$$T_{eff}=\sum_1^{N_r} t_j\rho_j(z_1)\Bigg/\sum_1^{N_r}\rho_j(z_1)$$

where N_r is the number of rays used in the simulation and t_j is the tunneling efficiency of ray jth which is weighted proportionally to the electric field amplitude over S_1:

$$\rho_j=\frac{1}{w(z_{1,j})}\exp\left(-\left(x_{1,j}^2+y_{1,j}^2\right)/w(z_{1,j})^2\right)$$
$$x_{1,j}=R_1\sin\theta_j\cos\phi_j$$
$$y_{1,j}=R_1\sin\theta_j\sin\phi_j$$
$$z_{1,j}=R_1\cos\theta_j$$

For the moment, with N_r=25, these preliminary calculations show that the optimum beam is obtained for (w_0,z_0)=(0.02, 0.136) (see figure 4), with a transmission efficiency of 0.95.

In the far-field region of the beam, the main contribution to the field amplitude in a particular direction is given essentially by the plane wave that has its wave vector along that direction. For these conditions, the approximation used here to simulate the beam is reasonably valid. Since the far-field region is defined for z values such $|z-z_0|>>a$ ($a \approx 0.1$ m, for $f \approx 28$ GHz and $w_0 = 2$ cm), the results obtained when $z_1 \approx z_0$ (the beam is simulated near its waist) must be understood carefully. In fact, a better approximation should include the amplitude of each of the infinite plane waves contributing to the beam at every point of the wave front, whose shape can always be assumed spherical. In this case, in order to simulate the beam, many rays should be launched from each point of the constant phase surface. For the moment we have restricted our considerations to the beams where the minimum beam waist occurs before or after reaching the plasma.

5.- Conclusions.

The possibility of using EBW for heating plasmas in TJ-II has been explored in this work using the ray tracing code TRUBA. The O-X-EBW1 scheme had been found to be effective for densities $n_{e0} \geq 1.1 \times 10^{19}$ in previous works. We have found here the optimum launching direction by performing extensive ray tracing calculations. The structure of the beam and, therefore, the optical properties of last mirror of transmission line have been determined. The main conclusion of this simulation is that beam waist can be positioned in a wide range of distances, still having an acceptable transmission efficiency.

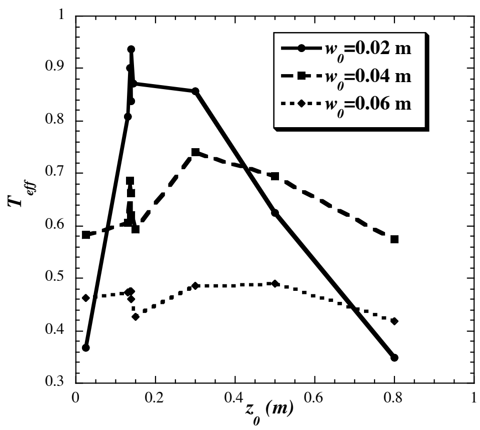

Figure 4: Transmission efficiencies for three beams.

References

[1] F.Castejón et al. "Electron Bernstein Wave heating calculations for TJ-II plasmas". Fusion Science and Technology (In press, 2004)
[2] H.Laqua et al. "Electron Bernstein wave heating and current drive in overdense plasmas at the W7-AS stellarator". Nuclear Fusion, 43 (2003)
[3] K.Nagasaki et al. "Electron Bernstein wave heating in Heliotron Systems". Proceedings of the EC12. Aix-en-Provence. France (2002)
[4] M.Tereshchenko et al. "Development of 3D Gaussian Shaped Beam Tracing code for Plasma Heating by Bernstein Waves in TJ-II". Proceedings o the 30th EPS conference. St. Petersburgo, 2003.
[5] A. Fernández et al. "Design of electron Bernstein Wave heating system in TJ-II". Fusion Science and Technology (In press, 2004)
[6] K.Nagasaki and N. Yanagi. Plasma Physics and Controlled Fusion 44 (2002) 409