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EBW launching optimization in TJ-II

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1 Introduction: EBW in TJ-II

Launching of Electron Bernstein waves (EBW) into TJ-II has been investigated [1] and is currently in the final design stage [2]. The ray tracing code TRUBA [3], which includes automatic mode conversion and tunneling efficiency calculation, has been used to determine the optimum launching conditions for the O-X-B1 ($f = 28$ GHz) scenario, that is, the best launching position and direction, in terms of power absorption, and the optimum Gaussian beam, in terms of transmission efficiency.

2 Launching position optimization

To determine the best launching position, a single ray has been traced from different starting points that cover a wide toroidal and poloidal range. This range is limited by the need for low longitudinal inhomogeneity of the magnetic field in order to have low Doppler-shifted absorption [1] and by the internal mirror design requirements. For each point, located after the O-mode cut-off surface a distance along ∇n_e much smaller than the wavelength ($\lambda \approx 1.07$ cm), the ray is launched with its optimum parallel refraction index, given by $N_{||}^{opt} = \sqrt{s/(1+s)}$ where $s \equiv \omega_c/\omega$. The local transmission efficiency is given by

$$\eta = \exp\left(\frac{f(s)}{c}\left[{N_\perp}^2 + 2(1+s)(N_{||} - N_{||}^{opt})^2\right]\right) \quad (1)$$

where $f(s) \equiv -\pi\omega(n_e/|\nabla n_e|)(s/2)^{1/2}$ and hence every ray is launched with full transmission efficiency ($\eta = 1$). The calculations have been performed for a standard TJ-II magnetic configuration where the magnetic field intensity is the one needed for second harmonic X-mode on-axis power deposition with $N_{||} = 0$ ($f = 53.2$GHz). The density and temperature profiles are $n_e = 1.7(1-\psi^{1.375})^{1.5}$ and $T_e = 0.7(1-\psi^{1.125})^{1.25}$. The central density is chosen close to the low density second harmonic X-mode cut-off. Almost all the launching positions considered provide complete EBW absorption. However, only

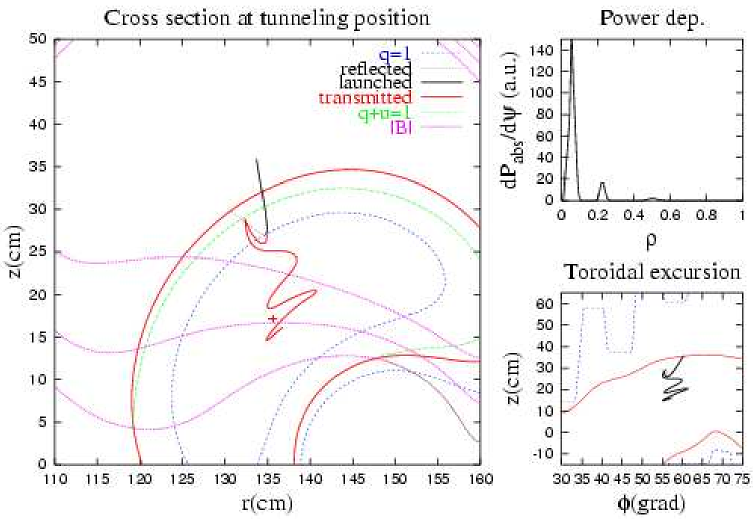

Figure 1: *Ray trajectory for the optimum launching position. The O-mode cut-off surface ($q \equiv (\omega_p/\omega)^2 = 1$) and the uhr layer ($q + u = 1$, with $u \equiv s^2$) are represented. The power deposition profile shows centred EBW absorption.*

a few of them show central deposition. The power absorption profile of the optimum position, together with the ray trajectory are plotted in Fig 1. Once the optimum inner point is determined, a ray is launched backwards with opposite **N** from an outer point placed before the O-mode cut-off surface a distance along ∇n_e also smaller than λ. In this way, the launching direction for that position, that must be fulfilled by the internal mirror, is determined. The optimum curvature parameters of this mirror, that is, the optimum launched gaussian beam, are treated in the next section.

3 Optimum Gaussian beam

In the following, we shall define the origin of the beam field to be the centre of the internal mirror (Fig.2). For a given frequency, the beam is defined by two parameters: w_0, which is the beam waist and z_0, the waist location along the propagation direction. At first, in order to calculate its transmission efficiency, the gaussian beam is viewed as composed of rays, traced independently of each other along the local group velocity direction, i.e perpendicular to the approximately spherical wave fronts and centred at z_L with radius of curvature R_1,

$$R_1 = z_1 - z_0 + \frac{a^2}{z_1 - z_0} \qquad z_L = z_1 - R_1 \quad (2)$$

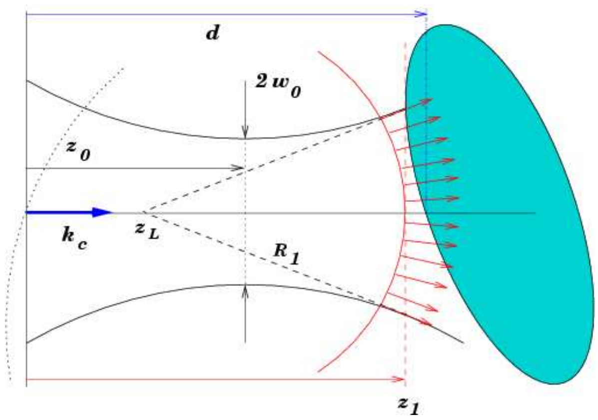

Figure 2: *Beam optimization parameters. Plasma is plotted schematically. In the calculations, d=203 mm*

The parameter $a = \pi {w_0}^2/\lambda$ is the confocal distance and z_1 is defined as the position of the plane perpendicular to $\mathbf{k}_c$ that is adjacent to the plasma (see Fig.2). Each beam is simulated by a bunch of rays distributed on the wave front that intersects the z-axis at z_1, directed perpendicularly to this surface, with components $(k_x, k_y, k_z) \equiv (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$ where θ and ϕ are the usual spherical coordinates angles. The maximum value of θ is $\theta_{max} = \tan^{-1}(w_1/R_1)$ where w_1 is the beam size at z_1. Every ray trajectory in the plasma is calculated with TRUBA and its single tunneling efficiency is determined. The total efficiency of the beam is defined as

$$T \equiv T_{\{w_0,z_0\}} = \sum_1^{N_r} \eta_j \rho_j \Big/ \sum_1^{N_r} \rho_j \tag{3}$$

where N_r is the number of rays used in the simulation and η_j is the transmission efficiency of ray j (eq.(1)), which is weighted proportionally to the wave power over the wave front

$$\rho_j \equiv \frac{1}{{w_j}^2} \exp(-2({x_j}^2 + {y_j}^2)/{w_j}^2) \tag{4}$$

where $(x_j, y_j, z_j) \equiv (R_1 \sin\theta_j \cos\phi_j, R_1 \sin\theta_j \sin\phi_j, R_1 \cos\theta_j)$ are the launching coordinates of ray j and w_j is the beam size at $z = z_j$. 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 in the angular spectrum which has its wave vector $\mathbf{k}$ along that direction [4]. For these conditions, the approximation used 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 $f = 28$ GHz and $w_0 = 2$ cm) the results obtained for beam waists placed near plasma must be understood very carefully and particularly when the beam is strongly focused (small waist). In fact, in this case, a better aproximation is to consider each plane wave contributing to the beam at this point. The local plane wave spectrum of a non-astigmatic Gaussian beam at $z = z_0$ is given by

$$\mathbf{A}(k_x, k_y; z_0) = \mathbf{C}(z_0) \exp(-{w_0}^2({k_x}^2 + {k_y}^2)/4) \tag{5}$$

where $\mathbf{C}(z_0)$ is a complex vectorial quantity that depends on beam power and polarization. Figure 3 shows schematically the ray distribution used to simulate the beam when $z_0 = z_1$. Many rays are launched from each point of the wave plane front (three points are represented in the figure). The transmission efficiency is calculated as previously but now each ray is weighted with $\alpha_j = A_j \rho_j'$ where $A_j \equiv \exp(-w_0^2({k_{x,j}}^2 + {k_{y,j}}^2)/4)$ takes into account the plane wave spectrum and ρ_j' is again proportional to the beam power in the $z = z_0$ cross section. Therefore,

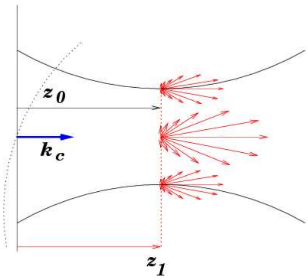

Figure 3: *Beam simulation for $z_0 = z_1$. Plane wave spectrum is now considered.*

$$\alpha_j' = \exp\left[-2({x_j}^2 + {y_j}^2)/{w_0}^2 - {w_0}^2({k_{x,j}}^2 + {k_{y,j}}^2)/4\right] \quad (6)$$

4 Results and Discussion

The transmission efficiency for different beam waists is plotted in Fig. 4. The most efficient beam is the one with $w_0 = 0.03$ m, focussed beyond the critical layer, since it is the most robust against density changes and for this waist the calculations based on the two different approximations give similar results. For more focussed beams ($w_0 = 0.02$ m) the value of T close to the critical layer appears overestimated in the far field approximation, since $T \approx 0.68$ is obtained when considering the plane wave spectrum. For higher beam waists ($w_0 = 0.04$ m) the bigger size of the beam spoils its transmission efficiency due the non homogeneity of plasma and magnetic field, despite the $N_{||}$ of the central ray is the optimum.

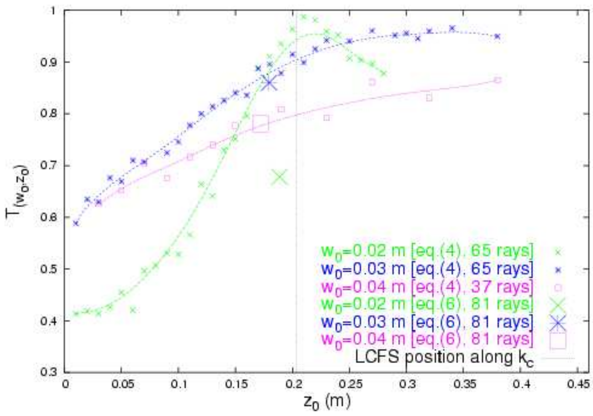

Figure 4: *Beam transmission efficiency T, calculated with* (4)*, for $w_0 = 0.02, 0,03$ and $0,04$ m vs. z_0. Transmission efficiency calculated with* (6) *(only for $z_0 = z_1$) is also represented. The maximum z_0 for each w_0 is given by losses requirements due to the internal mirror size.*

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