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Proposals of quasi-optical grills for ITER and NSTX tokamaks

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1. ITER. In the current ITER operating scenario, LH waves are needed for current profile control in the outer regions of the plasma. The ITER RF design has reserved 2 ports (2.6×1.6m^2) for LH active passive structures operating at 5 GHz and 25 MW per port [1].

In [2] we have shown that the requirements for ITER design can be met by a new type of LHCD launcher - the quasi-optical grill [3]. For 5GHz and $N_\parallel = 1.8$, we designed a QOG with modular sections each containing two rows of 2×27 very massive rods to shield the structure from the neutron flux (the rods are $600\times600\times17$mm^3 and with 7.2mm gaps between them). Each structure is irradiated obliquely by LSE$_{3,7}$ mode ($\alpha = 41^o$) emerging from a compact waveguide structure which convert power from three 1MW klystrons into desired form. Such a structure has an excellent weighted directivity (-56%), a standard coupled power directivity (73%) and a moderate power reflection coefficient (9%) for a optimized box-limiter depth of 6mm. The box-limiter is introduced to lower the plasma density below the critical density in front of the grill and thus improve the directivity of QOG.

It is important to restrict the maximum electric field in the grill. Since the electric field is singular at sharp corners, we have determined the field for an infinite set of identical rods with rounded corners placed in front of an ITER plasma and irradiated obliquely by plane wave. We proved [4] that the weighted directivity sharply decreases with increasing radius of rounding so only small rounding radii will be practical. Also the amplitude of the standing waves increases both with the increasing radius of rounding and the width od rods. It seems that 17mm thick rods at slightly longer resonant length 6.06cm (+arbitrary multiple of $\lambda_{vac}/2$) gives acceptable directivity (-45%), reflection coefficient (22%) and the electric field at antinodes of standing wave $5\times E_{\rm inc}$ (6kV/cm at full power) and $6.8\times E_{\rm inc}$ (8kV/cm) at the corner 'hot spots' (Fig. 1). For a finite grill (2×27 rods) one can estimate that such rounding will not change efficiency of the structure significantly.

2. PAM for FTU. The estimated maximum electric field in our quasi-optical grill is rather high and we would like to compare it with the corresponding field in the passive-active structure. As a preliminary results we give in Fig. 2 the envelope of E_z ($|E_z/E_{incident}|$) for FTU PAM working at 8GHz [5]. From this study it follows that the maximum field is only about three times higher that the incident field. However, this question could be settled only if we finished computation for rounded septa. The shape of pyramidal region of 'turbulent' field in plasma in front of grill suggests that the non-linear effects are prominent (formation of density cavitons [6]) and the linear theory of coupling is not fully adequate.

2. NSTX. The very low magnetic field at the edge of NSTX (B_0=2.6kG) requires EBW for both heating and current drive. QOG (as well as its feeding structure) is well suited for the launch of 2cm waves. As a preliminary study of wave coupling we present here power absorption of linearly polarized wave incident obliquely on an NSTX plasma. For this purpose we use a code which determines the cold plasma surface impedance matrix $Z_{kl}, k, l = 1, 2$ by direct finite element integration of Maxwell equations in a tokamak plasma [7].

The dependence of the absorbed power on the angle γ between the direction of magnetostatic field B_0 and the plane of incidence and the magnitude of $N_\perp = k_\perp/k_{vac} = \sin\alpha$ is shown for two possible wave polarization (in the plane of incidence and perpendicular to this plane, see Fig.4). If we use the oversized hyperguide (eg. with the rectangular cross-section $b \times b$, b=15cm) for the launch of this wave, then γ is the angle between the side of the waveguide and $\mathbf{B_0}$ and $N_\perp = n\pi/(b * k_{vac})$. Either LSE$_{mn}$ or TE$_{mn}$ modes with $m \ll n$ produce the waves with required polarizations.

For a large distance between the plasma boundary and UHR the absorbed power (see Fig 7 a$_{1,2}$) coincides well with the WKB prediction [8] of full transmission of O-mode wave through the plasma resonance region at oblique incidence ($N_z = k_z/k_{vac} = (\omega + \omega_{ce})/\omega = 0.572$ for f=15GHz and $B = 2.6kG$). The density profile is assumed to have the form $n(x) = n_b + (n_c - n_b) * (1 - (|x|/a)^p))$, where a small radius a = 44cm, the central density $n_c = 4 \times 10^{13}$cm^{-3}, $n_b = 0.1 \times 10^{13}$cm^{-3}, $p = 1.2$. Because, for obliquely propagation to the magnetic field, the O-mode and the X-mode are elliptically polarized, they will both be excited by the incident linearly polarized wave. The X-mode is reflected at cutoff while the O-mode penetrates into the UHR where it is absorbed. If the incident wave is polarized in the plane of incidence then it will preferentially excite the O-mode which will then be absorbed.

Density gradient effects [9] play an important role in the propagation and absorption of waves for UHR-plasma boundary distances smaller then the wavelength. One consequence is the loss of symmetry with respect to $\pm N_y$ (Figs. 7b$_{1,2}$ - n_b =0.8 $\times 10^{13}$cm^{-3} and $p = 4$). The O-mode is now absorbed (Fig. 7b$_2$) at a different angle of incidence than in preceeding case (see Fig. 5) and it also has a different polarization. As a result, the incident wave must be polarized perpendicular to the plane of incidence. The X-mode is absorbed predominantly at normal incidence with the electric field perpendicular to B_0, where the width of the evanescent layer between the cutoff of this wave and UHR is a minimum (Fig. 7b$_1$) .

As was pointed out by A. Bers et al. [10], direct penetration of the X-mod through very a narrow evanescent layer at normal incidence in strongly inhomogeneous plasma dominates the absorption. Our results confirm this statement (Fig. 6 and Figs. 7**c**$_{1,2}$, where $n_b = 0.8 \times 10^{13}$cm^{-3} and $p = 8$). REFERENCES

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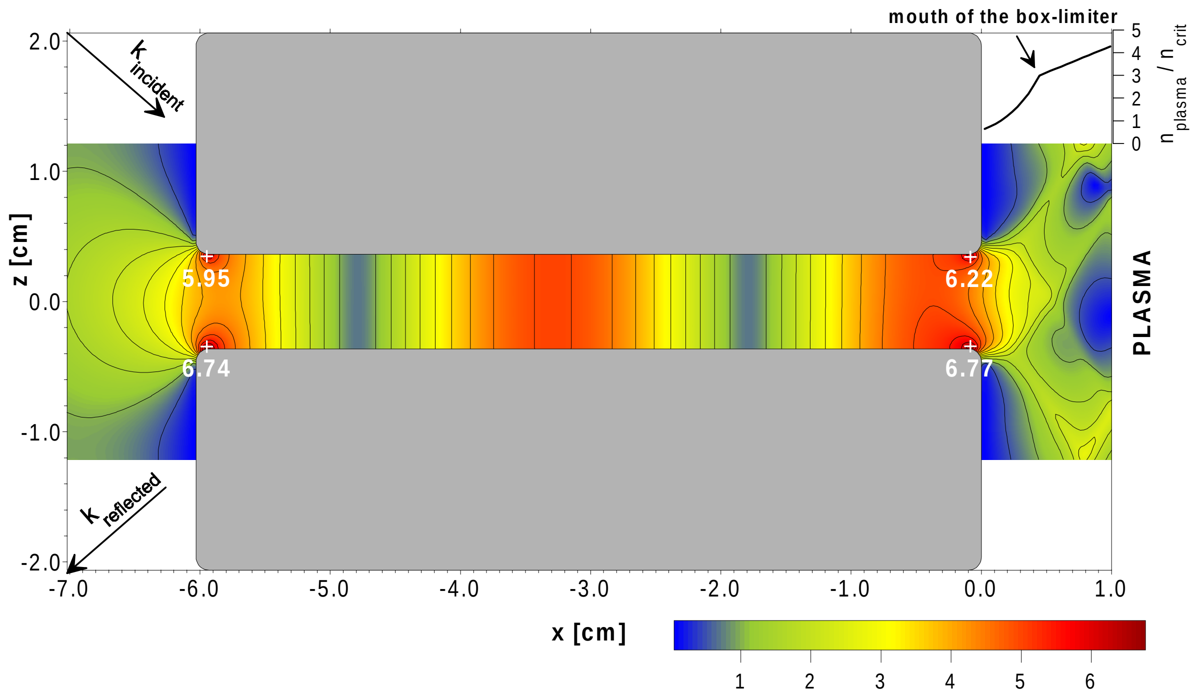

Fig. 1. Amplitude of E_z / E_{inc}. The wave is incident obliquely (α=41°) on rounded rods placed in front of ITER plasma (d=1.7cm, l=6.06cm , radius of rounding is 1 mm).

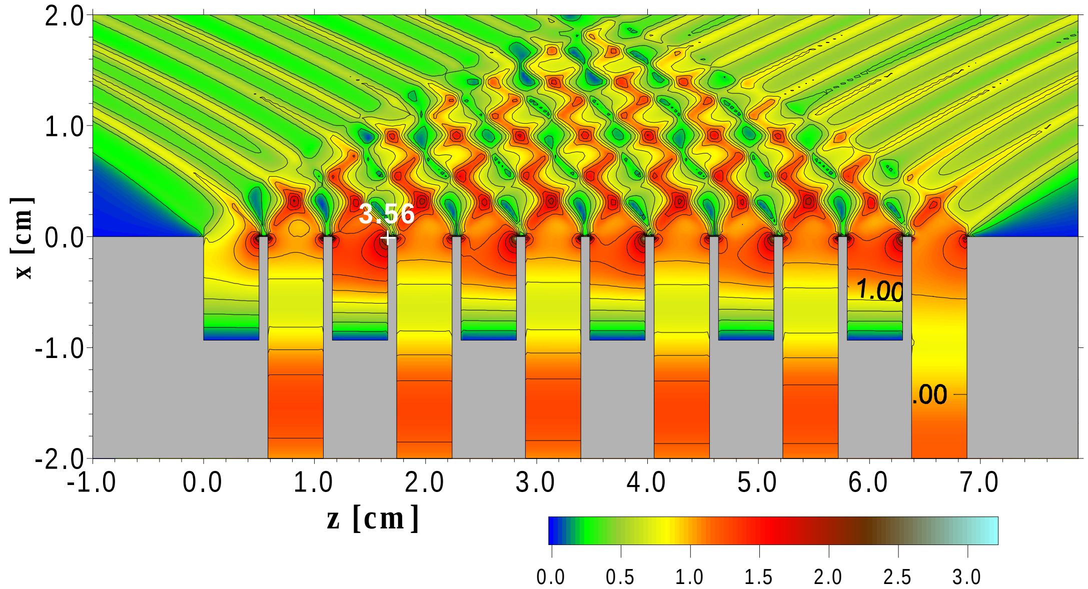

Fig. 2. PAM for FTU (8GHz). Amplitude of E_z / E_{inc}. The phase shift between incident waves in the adjacent active waveguides is 270°) , the vaccum gap is 0.5mm, N_z^{peak} = 2.39, -3.97, n_{wall} / n_{crit} = 2 dn /dx=1.6×10^{12}cm^{-4}

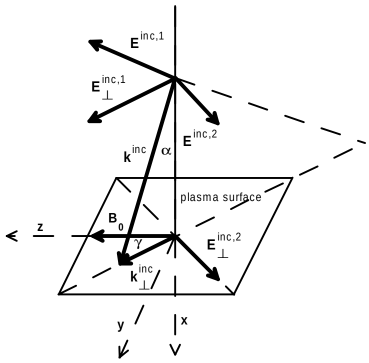

Fig. 4. Coordinate system for two polarizations of incident wave. $E^{inc,1}$ correspods to the wave with the electric field in plane of incidence and $E^{inc,2}$ is perpendicular to this plane.

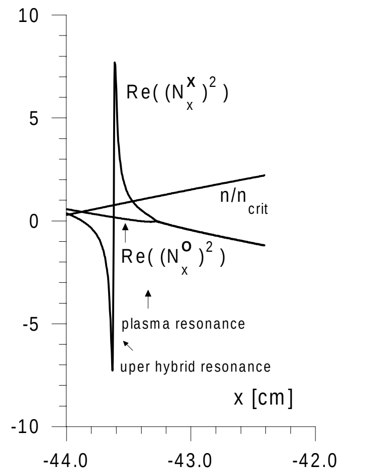

Fig. 5. WKB approximation with included density gradient effects. Depicted Re($(N_x^{X,O})^2$) correspond to Fig.4$\mathbf{b_2}$ maximum with N_y^{inc}=-0.13, N_z^{inc}=0.41, ν=0.01, B=2.6kG

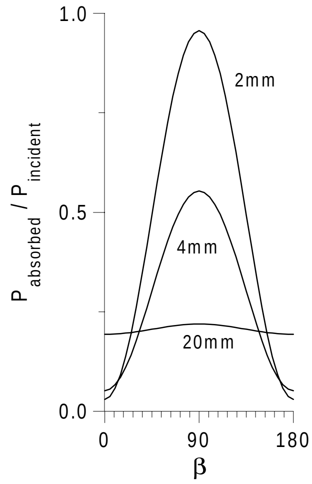

Fig. 6. Power absorbed in NSTX plasma at normal incidence. The distance from a plasma boundary to UHR is a parameter, β=∠($\mathbf{E_{inc}}$, $\mathbf{B_0}$).

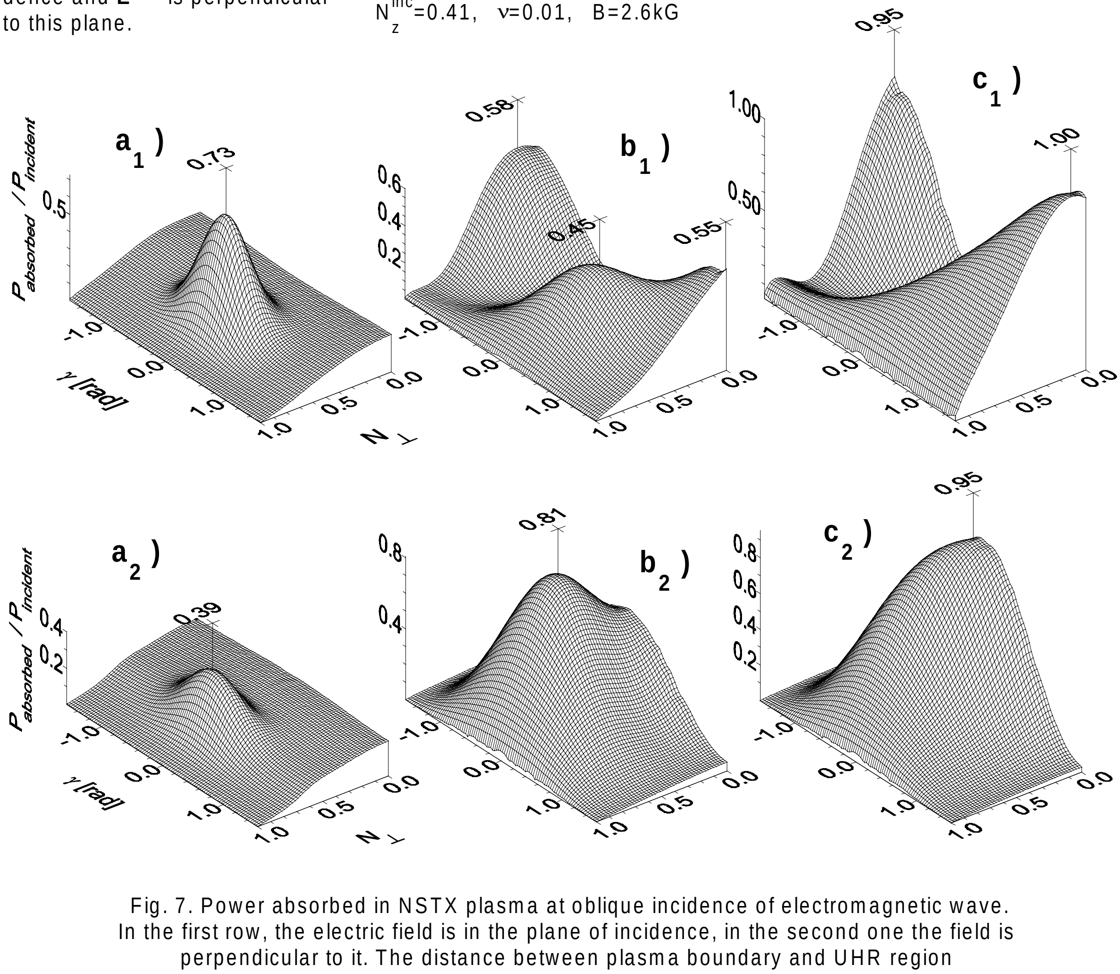

Fig. 7. Power absorbed in NSTX plasma at oblique incidence of electromagnetic wave. In the first row, the electric field is in the plane of incidence, in the second one the field is perpendicular to it. The distance between plasma boundary and UHR region is 20 mm for $\mathbf{a}_{1,2}$, 4mm for $\mathbf{b}_{1,2}$ and 2mm for $\mathbf{c}_{1,2}$