PROPOSAL OF QUASI-OPTICAL GRILL FOR ITER TOKAMAK

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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 ($2.6 \times 1.6 \text{m}^2$) for LH active passive structures operating at 5 GHz and 25 MW per port [1,2]. Here, we will show that the requirements for ITER design can be met by a new type of LHCD launcher -the quasi-optical grill (QOG) [3-5, 8].

To minimize the theoretically not well understood effects of the poloidal inhomogeneity of plasma in front of grill we propose to use for ITER 8 modular section each only 60cm high and 70cm wide.

It is supposed that each section has its own feeding structure [6] (see Fig. 1.). The power from each 1MW-klystron must be divided into one row of 8 standard rectangular waveguides ($47.5 \times 22.1 \text{ mm}^2$, the first and the last ones have the half width - 11.05 mm). These waveguides must be flared to ($200 \times 22.1 \text{ mm}^2$) in horn-like sections (the power reflection from this sections is negligible and the modal purity - 99% of TE_{10} - can reached for an 1m long horns). The LSE_{37} mode will be exited in the junction of three rows of these waveguides with an auxiliary hyperguide ($600 \times 320 \text{ mm}^2$) (the modal purity is absolute and only 0.2% of power will be reflected). The electric field in the feeding structure reaches 7kV/cm in standard waveguides, 3kV/cm in flared waveguides and only 1.75kV/cm in auxiliary hyperguide (at maximum incident power - 3MW). The power losses in an 70m long auxiliary hyperguide made from copper are below 7%. At the junction of active auxiliary hyperguide and the passive auxiliary hyperguide of the same dimension with the main hyperguide ($600 \times 660 \text{ mm}^2$) the incident LSE_{37} mode creates a plane which irradiate obliquely 27 rods (the angle of incidence is $\alpha = 41°$) (see Fig. 5) [6].

The neutron shielding calls for rather massive rods (they must create equivalent of 0.8m thick wall composed from 60% of metal and 40% of cooling water). For this purpose we make use of the periodicity of the diffraction problem with respect to increase of length of the rod cross-section in the direction of propagation by integer multiple of half wavelength [5]. So our rods are more plates than rods ($10 \times \lambda_{\text{vac}} \times 600 \times 17 \text{mm}^3$). Moreover, the gaps between the rods are so narrow that the evanescent modes are able to penetrate only 1cm deep between the rods and thus the diffraction properties of rods are fully independent on the shape of gaps - narrow waveguides - in central region. So we can bend slightly these waveguides to prevent the neutron streaming (see Fig. 5).

To have good directivity the plasma density in front of quasi-optical grill must be lower than critical. For this purpose we must place, at the grill mouth, a so called box-limiter (the moveable rectangular ring from beryllium slid on the mouth of the grill covering waveguide) [7]. The exponential density profile in the box-limiter (see Fig. 2) has the scale length given by $L_n = \sqrt{2Db_{tor}/v_{\text{s}}}$ (where D is the anomalous diffusion coefficient, b_{tor} is the toroidal

width of the grill and $v_{\mathrm{s}} = \sqrt{k_{\mathrm{B}}(T_e + T_i)/m_i}$ is the ion sound velocity). For ITER parameters ($T_e = T_i$=25eV, b_{tor}=66, $D \sim 0.3\mathrm{m}^2\mathrm{s}^{-1}$) we obtain an estimate of $L_n \approx 2.7$mm. In Fig. 2 we suppose that that plasma density at the grill mouth without any box-limiter would be equal to $2n_{\mathrm{crit}}$ and the density gradient in front of box-limiter is $7.3 \times 10^{11}\mathrm{cm}^{-4}$.

The spatial power spectrum of waves radiated by quasi-optical grill can be approximated by the discrete spectrum of infinite grill determined from Floquet's theorem $N_{z,s} = N_z^{\mathrm{inc}} + \frac{2\pi s}{k_{\mathrm{v}} z_{\mathrm{QOG}}^{\mathrm{period}}}$, $s = 0, \pm 1, \pm 2, \ldots$, where $N_z^{\mathrm{inc}} = k_z^{\mathrm{inc}}/k_{\mathrm{v}} = \sin \alpha$ and α is the angle of incidence of a vacuum wave on the rods in the (x,z)-plane (The rods are parallel to the y-axis, while the toroidal magnetic field is in the z-direction). The periodicity length $z_{\mathrm{QOG}}^{\mathrm{period}}$ is the sum of the gap between rods and the rod diameter. The zero diffraction order does not contribute to the spectrum of waves in a plasma (since $\mid N_z^{\mathrm{inc}} \mid < 1$) and thus the most important are the orders $s = -1$ and $s = 1$. The main peak is $s = -1$ so the structure radiates in opposite toroidal direction than the incident ray.

For ITER LH scenario it is usually considered that main peak $N_{z,-1} = -2$ but QOG works better if it radiates longer waves. So we start to find optimum for $N_{z,-1} = -1.8$. The results for $N_{z,-1} = -2$ would be slightly poorer.

As the main parameter determining the grill quality we take the N_z-weighted directivity defined in [2] or [5]. We also mentioned the coupled power directivity. This quantity determine this part of normalized coupled power which is radiated in useful direction.

The maximum electric field in the structure determines the maximum power which could be transmitted through it without electric breakdown. It is not clear how large it could be for 5GHz in ITER, but on TdeV tokamak maximum electric field reached 7.5kV/cm at 3.7GHz and 1MW applied power. The requirement of ITER group - 3kV/cm for maximum electric field - is very low and it cannot be fulfilled by strongly resonant launching structure as QOG with large standing waves. The situation will be better if it will be possible to use 8GHz. The relevant electric field in figures describing results for infinite grill is the field in the main hyperguide (1.2kV/cm). The field in auxiliary hyperguide (1.75kV/cm) is relevant as incident field in the results for 27 rods in hyperguide.

The optimum width of rods and the optimum box-limiter depth for one row structure it is seen from Fig. 3 which is based on infinite grill theory. The rods must be rather thick (19mm) with 5mm gaps between them. The density in front of grill must about $0.65n_{\mathrm{crit}}$ for the box-limiter depth 4mm (at the box-limiter mouth we have $3n_{\mathrm{crit}}$) and the electric field $6 \times E_{\mathrm{inc}}$. The weighted directivity of finite structure having 27 rods (one row) is only -40% and the power reflection coefficient is 15%.

To improve the directivity we tested the grill made from slanted rods. We confirmed the increase of directivity about 10% for previously studied case by F. Santini of a low angle of incidence ($\alpha = 25^\circ$ $\beta_s = \beta_p = -25^\circ$) but for our case of the angle of incidence ($\alpha = 41^\circ$) the effect is small (2-3%) (Fig. 4). This approach could be useful for future structure at 8GHz where lower angels of incidence would be acceptable.

Practically the only way how to increase the directivity of QOG without an increase of maximum electric field in the structure, is to use of two rows of rods. The distance between rows is determined so that the constructive interference of the incident primary wave and the doubly reflected wave is supported. We derived for this distance distance Bragg formula $L = (\lambda_0/2) \cos \alpha \approx 25$ mm but in many cases it must be determined from optimization

(L=23.75mm for spectrum given in Fig. 7). For this purpose it sufficient to use infinite grill theory modified to accept double row systems. In Fig. 6 we present results for two rows system, for the rod width $d_1 = d_2$=17mm and gaps $b_1 = b_2$=0.7mm.

The main results of these preliminary estimates is a proposal of two row system having 27 rods in each row (rods in both rows are identical $600\times600\times17$mm^3 with 7.2mm gaps between them, see Fig. 5). Such a structure has an excellent weighted directivity (-56%), a standard coupled power directivity (73%) and a moderate power reflection coefficient (9%) for a optimum box-limiter depth 6mm. The maximum electric field in the structure is $4.3\times E_{inc} \approx 7$kV/cm. The better weighted directivity and better shape of power spectrum of this structure (see Fig. 7) than those for active-passive structure [1] is mainly caused by the presence of the box limiter (an evanescent layer suppresses higher modes substantially).

At present we found QOG structure with excellent directivity, acceptable power reflection coefficient, excellent neutron shielding but with the maximum electric field about 7kV/cm in the worst 21 gap between rods. We hope that it will be possible to find out an optimum where the field will be about 5kV/cm.

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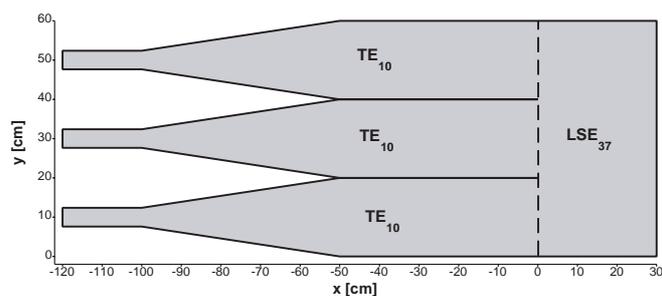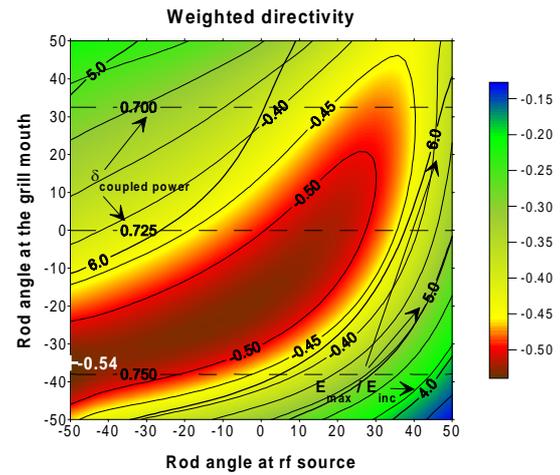

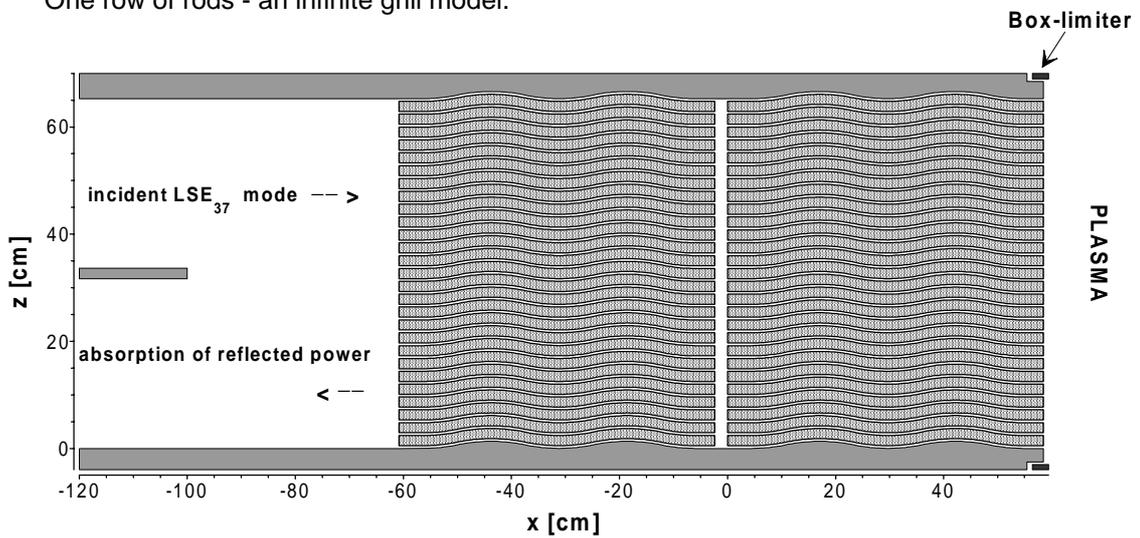**Fig. 1.** Side view of the feeding structure.
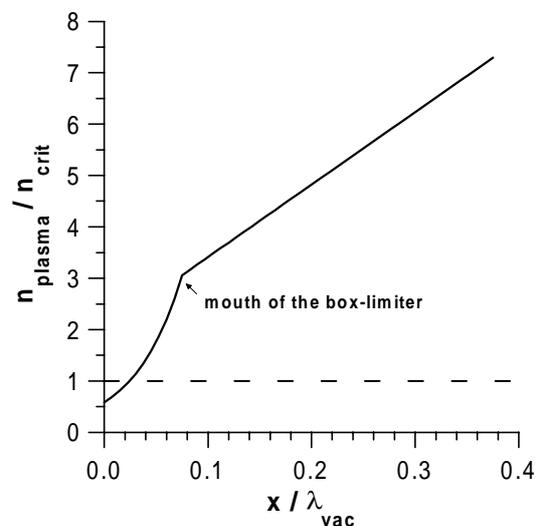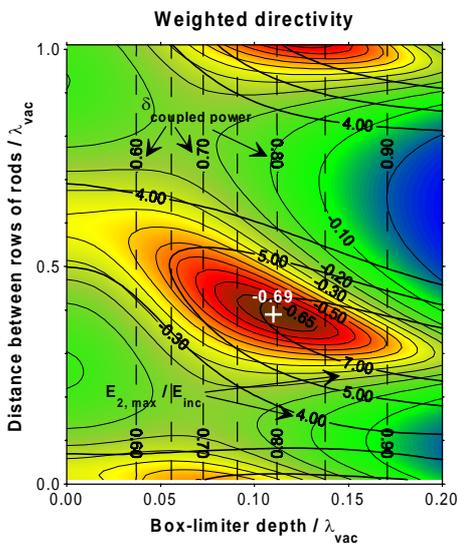

Fig. 2. Box-limiter density profile.
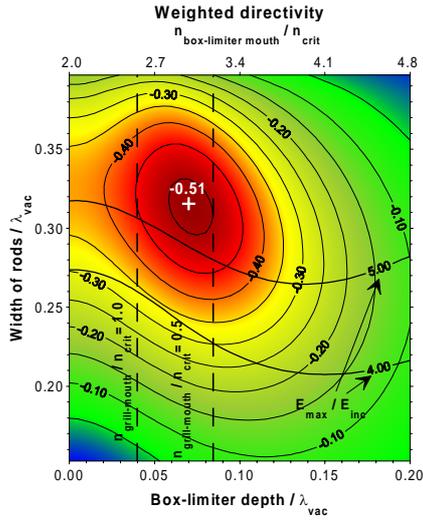
Fig. 3. N_z-weighted directivity.
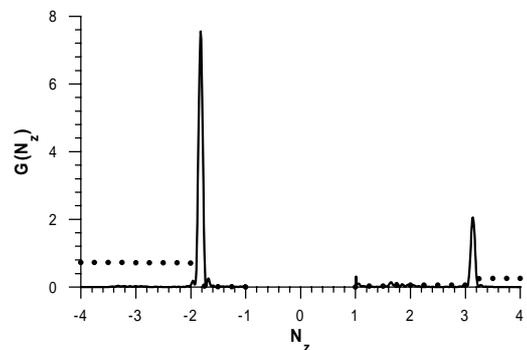One row of rods - an infinite grill model.

Fig. 4. N_z-weighted directivity for slanted rods.

Fig. 5. Poloidal section through one module of ITER QOG structure having two rows of 27 rods.

Fig. 6. N_z-weighted directivity.
Two rows of rods - an infinite grill model.

Fig. 7. Spatial power spectrum
of two rows of 27 rods structure.