ANNEX 14

Power flow induced by an amplified RF beam from a gyrotron

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INTRODUCTION

The development of the gyrotron as the dominant high-power source for fusion applications has been primarily motivated by the high-power demands – of the order of several MWs in Continuous Wave (CW) operation– required for efficient plasma heating and current drive in fusion reactors like ITER. Gyrotron oscillators employ a weakly relativistic electron beam propagating along a strong magnetostatic field in a microwave resonator. Part of the kinetic energy of the electrons is converted to electromagnetic (EM) energy resulting in efficient production of coherent EM radiation of up to about 1-2 MW, in the range of 100-200 GHz, required for electron-cyclotron heating and current drive in fusion plasmas. However, despite these achievements, an output power of more than 2 MW CW at the desired frequency range seems, at present, significantly difficult because of intrinsic physical and primarily technological limitations. To overcome these limitations and accomplish an even higher output power, an alternative configuration is proposed (which resembles the initial concept of the Quasi-Optical Gyrotron), which involves a sheet electron beam drifting along a magnetostatic field and intersecting with the RF beam at an appropriate angle. The perturbed electron motion excites an additional radiation field, whereas the two pairs of equations (for the electrons affected by the radiation and for the electromagnetic field excited by the electrons) formally constitute a self-consistent system of equations. This system is numerically integrated using an iterative procedure in which the radiated fields (or, the electron motion) are obtained using the latest approximation for the electron properties (or, the field distribution, respectively), with the procedure repeated, until convergence is finally reached [1].

INDUCED POWER FLOW

After assessing the optimal range of the operating parameters, a considerable production of simulation results was carried out for a number of initial conditions, combined with the corresponding global parameters governing the interaction. This was done in order to determine to what extent these parameters affect the evolution and the mechanism of the interaction and consequently the corresponding efficiency. In particular, after introducing the self-consistent procedure to obtain the final electron trajectories as well as the EM field components and the corresponding Poynting vectors [2], we focused our efforts on calculating the power flow. Initially, we calculated the power flow on every outer surface of the 3-D mesh, i.e. on the planes $\xi_0 = \xi_{in}, \xi_{fin}$, $\eta_0 = \eta_{in}, \eta_{fin}$, $\zeta_0 = \zeta_{in}, \zeta_{fin}$ respectively, and finally we calculated the total power flow out of the interaction area. In dimensionless notation, the EM power flowing through the surface, say $\zeta_0 = \zeta_{in}$, is given by the expression

$$p_{\zeta,\mathrm{in}} = \sum_j s_{\zeta,\mathrm{in}}(j)(-d\xi_j \times d\eta_j) \tag{1}$$

where j is the total number of the nodes of the surface, $d\xi_j \times d\eta_j$ is the infinitesimal surface area (composed of the corresponding axes intervals $d\xi$ and $d\eta$) normal to the Poynting vector's direction, and $s(j)$ is the Poynting vector calculated on the specific j node. The (–) sign is due to the orientation of the Poynting vector towards the $(-\hat{i}_x)$ direction, and the summation over j has replaced the integral representation [2]. In *Fig. 1* we present the power flow out of the six normal surfaces comprising the interaction area, in the form of contour plots.

Correspondingly, the energy balance requires that the total power flow through the entire area is equal to the power loss of the electron beam, meaning that (in dimensionless notation)

$$P_{MW,out} = \oiint_A \mathbf{s} \cdot d\mathbf{A} = \eta_e P_{EB} \;\Rightarrow\; \sum_n p_n = \eta_e (\gamma_0 - 1) 4\pi I_b / I_{Alf} \tag{2}$$

where p_n is numerically calculated from (1) (index n denotes the respective facet of the orthogonal area), γ_0 is the initial relativistic factor of the electrons, associated with the electron energy due to the accelerating voltage $V_b = (\gamma_0 - 1) mc^2 / e$, I_b is the electron beam current, and I_{Alf} is the Alfven current.

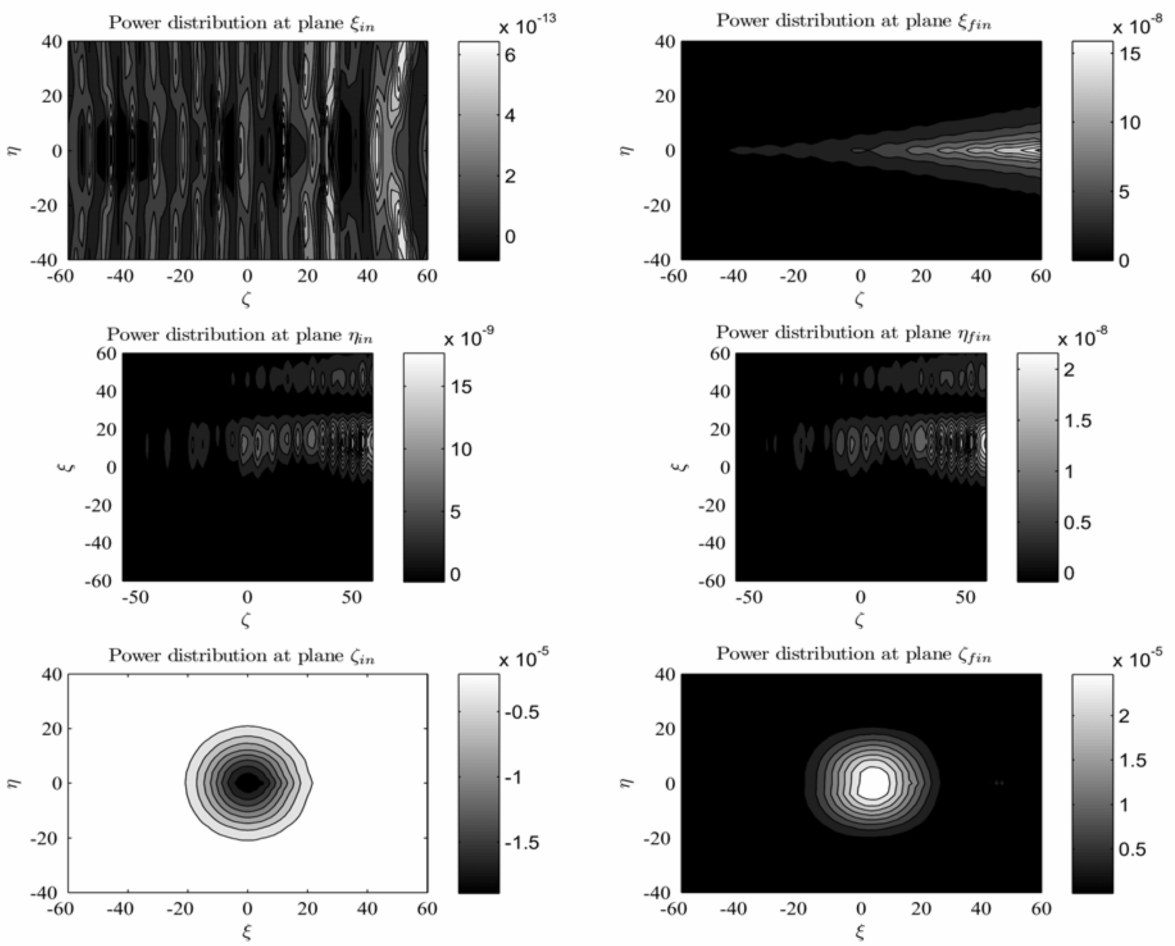

Fig. 1: Graphical representation of the power flowing out of the facets of the orthogonal interaction area. The negative values correspond to an inflowing (relatively to the specific facet) power. The simulation parameters are $\rho_0 = 20, \varepsilon_0 = 0.003, \delta = 0.025, a_0 = 1.5, \gamma_0 = 1.16$ *and* $I_b = 100A$.

DISCUSSION

As it is clearly shown in *Fig. 1*, the power flow through the planes ξ_{in}, ξ_{fin}, η_{in}, η_{fin} is three to five orders of magnitude smaller than the respective power flow through the planes ζ_{in}, ζ_{fin}. It is thus unlikely to cause any significant radiation effects along the axes ξ and η, and apparently they can be neglected as was already expected and discussed in [1], [2]. Considering the last two subfigures, we can conclude that the produced radiation field retains its Gaussian-shape distribution along the ξ-axis, while the power gain at the end of the output line is approximately 45%. Regarding the global energy balance though, we observed a relative inconsistency between the two values (i.e. the one obtained from the energy loss of the electrons and the one obtained from the radiated power) of the order of 12% for the specific case. This percentage may vary from 5-15% depending on the parameters used for each simulation and especially on the grid density. However, this discrepancy may be also due to any additional power consuming mechanisms which were not explicitly considered so far, e.g. space charge effects and radiation recoil energy. Further investigation in order to determine and implement the power transfer mechanism as well as its efficiency is currently under consideration.

REFERENCES

[1] G. Anastassiou and J. L. Vomvoridis, “Post-Amplification of a gyrotron RF beam by a sheet electron beam”, *IEEE Transactions on Plasma Science, Special issue on high-power microwave generation,* to be published June 2010.

[2] G. Anastassiou and J. L. Vomvoridis, “Post-Amplification of a gyrotron RF beam by a sheet electron beam”, *Annex XVIII* in *Fusion Project, Association EURATOM-Hellenic Republic, Annual report 2008.*