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O-X Mode Conversion Evaluations in FTU Tokamak for the Design of a New Launching System

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Introduction

The high-density plasma scenarios reached nowadays in FTU tokamak with the use of a Liquid Lithium Limiter (LLL), offer the possibility to operate at electron density above the standard Greenwald limit where the value $n_e=2.41*10^{20}m^{-3}$, corresponding to the O1-mode cut-off of the EC waves at 140GHz, is easily reached. Since also the X1-mode cannot access the inner side of the plasma, RF heating at the centre is prevented. Only longitudinal Electron Bernstein Waves (B-waves) [1], which have no density cut-off, can be excited in the plasma, typically through mode conversions. This led to envisage in FTU experiments on EBW heating through O-X-B mode conversion scheme [2]. O-X conversion efficiency is almost entirely responsible of the overall transformation of O-waves into B-waves. The B-branch turns out to be the natural extension of the SX-branch at the upper hybrid layer $\omega_{uh}=(\omega^2_{pe}+\omega^2_{ce})^{1/2}$, where $\omega_{pe}{}^2=n_e e^2/(\varepsilon_0 m_e)$, n_e is the electron density and $\omega_{ce}=eB/m_e$, and generally X-B conversion occurs with nearly 100% of efficiency. Usually an evanescent layer is present between O-mode and SX-mode cut-off. The size of this region, which depends on the density scale length $L_n = n_e/(\partial n_e/\partial r)$, can become null only in the case the parallel refractive index $|N_{//}|$ equals $N_{//,opt} = \sqrt{Y/(Y+1)}$, where $Y = \omega_{ce}/\omega$, in correspondence to the cut-off layer $\omega_{pe}= \omega$, while $N_\perp = 0$. In this case optimal O-X conversion can occur. When the power transmission function T_{OX} is described using a 1D slab model [3], i.e. magnetic field and density gradients are assumed to be parallel, its value is:

$$T_{OX}(N_{//},N_\perp) = \exp\left\{-\pi k_0 L_n \sqrt{\frac{Y}{2}}\left[2(1+Y)\left(N_{//,opt}-N_{//}\right)^2 + N_\perp^2\right]\right\} \qquad (1)$$

where $k_0=2\pi/\lambda$ is the wave number.

O-X Mode Conversion Evaluations in FTU

This model has been used to predict evaluations of O-X conversion efficiency in FTU. The ECWGB ray tracing code for EC-wave propagation, developed at IFP/CNR [4], has been used for calculations. Parameters of discharges performed with central magnetic field B_0=6T and plasma current I_p=500kA, have been considered for the calculations, but in a centered ECR scenario, by lowering via software the value of B_0 to 5.3T. High density plasma discharges, to be performed at 5.3T, will be tested during the present campaign of FTU. From ray tracing calculations, it turns out that to obtain O-X conversion on the central ray path of the injected beams, the toroidal launching angles needed are in the range 38°- 40°. Requested poloidal angles, instead, are always in a low range of values, because the high refraction experienced in the high density medium is such that the direction aiming approximately the center of the plasma is the only one which let the rays reach the O1-mode cutoff layer. The launching angular window, such that 50% of the power of an O polarized ray converts into X-wave, is very narrow, around 2° in both toroidal and poloidal directions. Its dimension depends from the value k_0L_n, as can be seen from (1), which for typical parameters of FTU is particularly high, being $200 \le k_0L_n \le 500$, mainly because k_0 is considerable at 140GHz. In the real case, the phenomenon of density fluctuations makes the plasma surface at cut-off become rough, with pejorative consequences on the efficiency of O-X conversion, because the actual value of $N_{//}$ is locally modified.

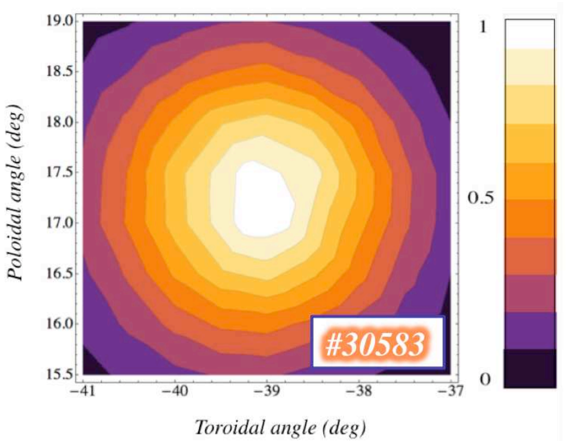

Fig.1: angular transmission window centered on the optimal launching angles. Each level corresponds to 10% of O-X conversion efficiency.

Following a statistical approach for the poloidal components [5], to evaluate the effects of the fluctuations on conversion efficiency and to describe the roughness of the cut-off layer, a probability density function can be written, as follow:

$$p(N_y) = \frac{\lambda_y}{\sqrt{2\pi}\sigma_x} \exp\left(-\frac{N_y^2\lambda_y^2}{2(1-N_y^2)\sigma_x^2}\right)\left(1-N_y^2\right)^{-3/2}$$

where λ_y is the poloidal correlation length and $\sigma_x = L_n \Delta n_e / n_e$ is the standard deviation of the fluctuation amplitude. This probability function can be used to weight the power

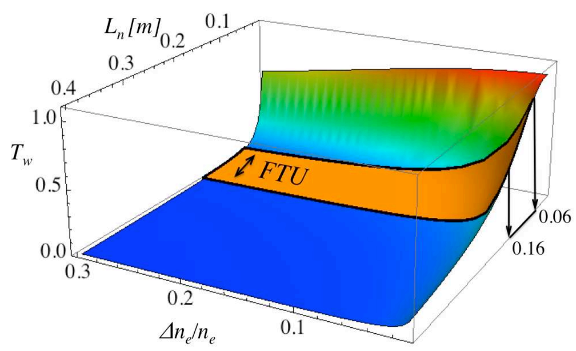

Fig.2: conversion efficiency versus relative density fluctuation amplitudes and density scale length L_n. The region defined by the range of L_n values obtained so far in FTU is shown (orange area).

transmission function: $T_w(N_{//}) = \int_{-1}^{1} T(N_{//}, N_y) p(N_y) dN_y$. Fig.2 shows how testing O-X scheme using 140GHz is not trivial, being the efficiency of the conversion strongly lowered by the turbulences of the plasma, at least in the range of L_n considered so far. Evaluations of conversion have been also performed using a 2D model, still being developed [6]. A more realistic geometry is used in this case to describe the magnetic field strengths and plasma density gradients, than in the 1D case. The 2D theory predicts a dependence of the conversion efficiency from the sign of $N_{//}$, from the poloidal positions of the launching points and from

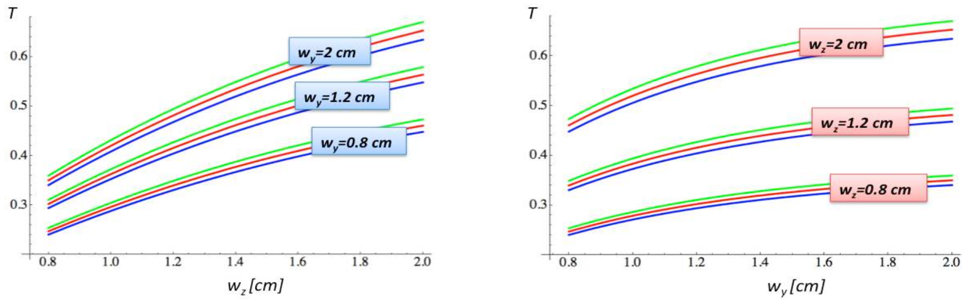

Fig.3: O-X conversion evaluations for FTU case, based on a 2D model versus different values of waist sizes w_z and w_y for an incident Gaussian electric field distribution $E \propto \exp\left(-z^2/w_z^2 - y^2/w_y^2\right)$. Green and blue lines represent the cases of "optimal" and "non-optimal" direction of the beam respect to the magnetic field (i.e. different signs of $N_{//}$ or, equivalently, symmetric poloidal launching points, as described by the 2D theory). Red lines show the results of a 1D slab geometry case, including the *k*-spectrum influence on the conversion.

the incident beam geometry. Some results for FTU are showed in Fig.3. It can be seen that the predictions are slightly different for opposite signs of the toroidal injection angles (or equivalently for symmetric poloidal launching points), at fixed magnetic field. These values turn out to be centered around the efficiency calculated using a slab geometry, considering the *k*-spectrum influence of a beam steerable with the new launcher under construction [7-8].

New ECRH Launching System for FTU

Being the present launcher capable to inject beams only in a set of fixed toroidal angles, with a maximum limit of ±30°, no tests on O-X conversion could be performed so far. The angular steering requests and the precision needed for these experiments have been taken into account in the design of the new launcher, together with the requirements needed to test real-time MHD stabilization. The launcher will be in a front steering configuration. It is thought to be plugged-in the vessel of the machine and it will be capable to inject/detect two independent beams from poloidally symmetric positions, using small movable mirrors put in the plasma proximity. In particular, real-time MHD stabilization with FTU parameters needs the launcher to be able to scan 1 cm in 10 ms, with 0.5 cm as maximum instantaneous error [9]. This leads to a system that is faster than in ITER, with a mirror angular acceleration requested of $\approx 10^3$ rad/s^2. EBWH experiments and detection of radiation coming from B-X-O conversion will become feasible thanks to the possibility of the launcher to finely tune the beams injection and detection around precise toroidal angles up to ±40° with a continuous scan. A real-time

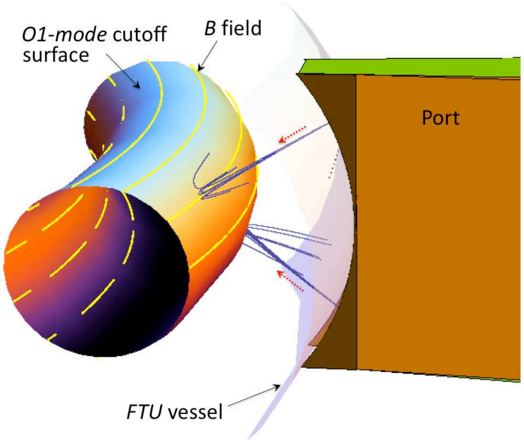

Fig.4: 3D poloidal view of FTU region where the new launcher will be installed. O1-mode cutoff layer and B field have been reconstructed using real high density plasma parameters of FTU. The paths of some rays, calculated using ECWGB ray tracing code, are also shown, showing the perfect poloidal and toroidal symmetry of the launcher (used as a launching system in the case considered in the figure).

tracking of the best launching angles for conversion is foreseen, using in feedback the stray radiation signal measured by probes, and also a zooming system will be available in the launcher, capable to change the beam radius in the range 17-28 mm. These performances will enable to test the influence of the beam structure on O-X transmission and the asymmetries expected for O-X/X-O efficiencies, by receiving signals on two poloidally symmetric lines.

Conclusions

The requirements to test O-X-B conversion at 140GHz have been shown. The purpose for the next campaign of FTU will be the achievement of a plasma target with density gradients as steep as possible, to obtain the largest conversion angular window. The precise control in feedback of the new launcher on the injection angles turns out to be of utmost importance.

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