Simulation of reflectometry Bragg backscattering spectral responses in the absence of a cutoff layer ^a

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Abstract

Experimental reflectometry signals obtained in the absence of a cutoff layer, and with the possibility of *interferometric* operation excluded, show a coherent and recurrent frequency spectrum signature similar to an Alfvén cascade signature. A possible explanation resides in the modulation of a resonant Bragg backscattering response by an Alfvén mode structure located at the center of the plasma whose frequency of oscillation modulates the backscattered signal in a conformable way. This situation is modeled and simulated using an O-mode full-wave Maxwell finite-differences time-domain code and the resulting signatures are discussed.

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I. INTRODUCTION

Alfvén eigenmode instabilities and Alfvén cascades (AC) in particular are an important topic of research in nuclear fusion due to the capacity to expel α particles which reduces plasma self-heating and may result in damages to the first wall. Reflectometry has contributed to reveal the radial structure of the AC modes [1] and, working as an interferometer, to monitor the discrete spectrum of ACs [2]. New experimental results obtained at ASDEX Upgrade during the current ramp-up phase with early NBI heating (2.5 MW) clearly show a rich presence of coherent modes whose signatures are compatible with the ones observed in an Alfvén cascade. These responses have been obtained when the electronic density of the plasma is still too low to allow the existence of a cutoff layer (no reflection present). An interferometric-like operation, such as obtained, for instance in JET [2] is also ruled out since the particular setup and geometry of the ASDEX Upgrade reflectometer do not permit this type of response: In a homodyne system the minimum detectable signal is determined by the Tangential Signal Sensitivity (TSS) of the detector, defined as the minimum signal required for offset the output baseline until it becomes even with or tangential to the output noise peaks [3], a value that in our case is around -45 dBm. The detector load will set a compromise between video bandwidth and sensitivity, increasing this value to -35 dBm. With an estimated 40 dB loss in the free space propagation path and a maximum of 0 dBm of power launched from the antennas, it is therefore impossible to receive any detectable signal reflected from the inner wall heat shield. These facts are supported by in-vessel tests with a plane metallic mirror[4]. This is a new type of response and in this work we explore a possible explanation for the presence of these signatures which consists in the modulation of a resonant Bragg backscattering response by an Alfvén mode structure located at the center of the plasma. The oscillation of this mode modulates the Bragg backscattered signal in a conformant way and therefore a signature is obtained without the need of reflection. In order to check the validity of such hypothesis we constructed a model and simulated this scenario. In section II a succinct description of the code is made and the model used explained. The results of the simulation appear in section III and we conclude with a discussion in section IV.

II. CODE AND MODEL

To simulate the reflectometry experiments we resort to a two-dimensional full-wave finite-differences time-domain (FDTD) Maxwell code describing the propagation of a transverse magnetic mode (O-mode propagation) in a plasma. FDTD have been successfully used to simulate reflectometry experiments [5], [6], [7]. The differential equations describing the propagation of the wave were discretized using a Yee schema and are coupled to the plasma through the response of plasma density current which depends on the electronic density $n_e(\mathbf{r}, t)$. The plasma is thus described by defining n_e , which in the model used admits a term $n_{e0}(\mathbf{r}, t)$ accounting for the plasma density profile, the Alfvén-like mode $\delta n_{eMOD}(R, t)$ and a term describing the turbulence $\delta n_{eTRB}(\mathbf{r}, t)$.

Simulations were performed on a box of dimensions $134 \lambda_{40\text{GHz}} \times 91 \lambda_{40\text{GHz}}$, where $\lambda_{40\text{GHz}}$ is the wavelength of $f = 40 \text{ GHz}$ in a vacuum, and includes the signal excitation setup (antenna and focusing lens), a vacuum region and the plasma. A unidirectional transparent source (UTS) [8] is used allowing one to decouple the weak backscattered signal from the much stronger main emission. The plasma has a radial dimension of $L = 88 \lambda_{40\text{GHz}}$ with the profile given by $n_{e0}(R) = n_{eMAX} \{1 - [(R_{MAX} - R)/(R_{MAX} - R_0)]^n\}^m$ with $n = 2$ and $m = 0.5$. Turbulence with a broadband amplitude spectrum is generated using a model of summation of modes [9] and added to the profile. The turbulence added enables Bragg backscattering as its wavenumber amplitude spectrum contains the wavenumber k_f which are resonant with the probing wave local wavenumber $k(r)$, according to the Bragg rule $k_f = 2k(r)$ [10]. In the flatter part of the density profile, at $x_f = 123 \lambda_{40\text{GHz}}$, corresponding to the center of the plasma, a coherent fluctuation mode with a Gaussian shape along the radius R with width $l = 16 \lambda_{40\text{GHz}}$ is placed. The amplitude $A_f(t)$ of the mode oscillates with a frequency $\nu_B = \nu_0(1 + t/T_s)$, where T_s is the simulation time, according to $A_f(t) = A_{MAX} \sin(2\pi\nu_B t)$ with $A_{MAX} = 5\%$. This core coherent mode will modulate the backscatter signal. This plasma setup is shown in Fig. 1. We can note that the maximum amplitude of the density corresponds to a plasma cutoff frequency below 36 GHz. Since our simulation uses a probing fixed frequency of $f = 40 \text{ GHz}$ it is clear that no cutoff is present in the system.

The ASDEX Upgrade fixed frequency reflectometer has a single ended homodyne detection. To replicate, in the simulations, the experimental conditions in which the reflectometry signal is obtained, the numerical microwave electric field returned to the antenna is regis-

tered and a numerical homodyne detection performed. The reflectometry signals are then analyzed, with the same signal processing tools used in ASDEX Upgrade, to recover the information they convey, namely the signature of the mode.

III. SIMULATION RESULTS

In addition to the main simulations with the oscillating mode ($n_e(t) = n_{e0} + \delta n_{eTRB} + \delta n_{eMOD}(t)$), two control simulations were made, one with only the *base profile* ($n_e = n_{e0}$) and the second with turbulence but without the oscillating mode ($n_e(t) = n_{e0} + \delta n_{eTRB}$). These were used to assess and contrast to the full response. Fast Fourier Transforms of the homodyne detected signals were performed and the results are shown in Fig. 2. We observe quite clearly the mode signature appearing in the amplitude spectrum covering a band of $\Delta f = 2$ GHz. Comparing with the spectra obtained from the unmodulated signal (without mode but with turbulence) we see that the base level is the same since in both situations there is backscattered power, but only with the mode present is the signal modulated showing a spectral signature. The power in the signature is higher because as the slope of the density profile is modified by the pulsating mode better conditions of coupling with turbulence are achieved and the scattering becomes more efficient. The spectrum of the signal obtained with the *bare* profile shows a returned power ≈ 30 dB below the floor of the other two spectra (≈ 20 times less power). This weak signal is due to the transition of media at the vacuum-plasma boundary and not to the existence of a cutoff. In fact its amplitude is 130 times smaller than the amplitude of the injected power. When a cutoff is present the ratio of amplitude between the injected signal and the reflected one is much better (≈ 10), thus confirming that the simulation is being performed in the right conditions. A frequency distribution analysis of the modulated backscattered signal, using a Sliding FFT technique, is shown in Fig. 3.

IV. DISCUSSION

The simulations with this model permit to credit Bragg backscattering as one possible explanation for the mode cascades observed at ASDEX Upgrade. In our simulations, also in a situation without cutoff or interferometric operation, a response compatible with experimen-

tal results is obtained. Although this validates Bragg backscattering as a likely explanation for this kind of experimental response, other scenarios may be possible. For instance, a second viable hypothesis rests on the radial movement of a turbulent wavefront, which induces a Doppler effect representative of its velocity at the location where the Bragg backscattering occurs. Assuming a constant radial velocity, the backscattered signal frequency increases as the front approaches the edge of the plasma. The wavenumber spectrum of the wavefront needs to be wide enough to allow backscattering along its trajectories. The induced frequency shift will be a function of the wavefront position and velocity. This situation will be the subject of a subsequent study and it is expected that its results together with the ones presented will allow a better understanding of the experimental scenario.

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FIG. 1. Model of the plasma density $n_e(R, t)$ used in the simulation. The vertical scales show the electronic density of the plasma (left) and the corresponding plasma frequencies. For a probing frequency of $f = 40$ GHz no cutoff is present. At the flatter part of the density profile an oscillating mode modulates the Bragg backscattered signal.

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FIG. 2. Fast Fourier Transforms of the homodyne detected signals.

FIG. 3. A frequency distribution analysis of the modulated backscattered signal using a SFFT.