Simulation of Doppler backscattering off filaments in the Globus-M spherical tokamak

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In this paper we present the results of two-dimensional full wave simulations of Doppler backscattering (DBS) from filaments in slab geometry. For simulation we have used a substitutional model of a filament of a Gaussian cross-section. The comparison of the simulation results and experimental data obtained at the tokamak Globus-M was performed.

Introduction. Filamentary-like plasma perturbations are routinely observed in many tokamaks. They are the result of non-linear development of some peripheral MHD instabilities in the region of the maximum plasma pressure gradient [1]. As soon as filaments can play a key role in the anomalous transport of particles and energy at plasma periphery studies of filaments are actively continuing in various tokamak experiments for better understanding of filament physics and extrapolating of filament parameters to the tokamaks of ITER scale [2]. Recently, authors proposed to use the Doppler backscattering method for filaments investigation [3, 4]. The results of backscattering from filaments can be easily interpreted within the framework of the linear backscattering or Born approximation. However, the description of the experimental data under the transition from linear to non-linear backscattering is a rather complicated task that could be solved with the help of full-wave simulations.

Numerical analysis. Instead of using complicated non-linear MHD codes for filament description we have used relatively simple model of a filament with a Gaussian cross-section that allows freedom in choosing the shape, size, amplitude and position of a filament. Two-dimensional full wave simulations were done with finite-difference time-domain code IPF-FD3D [5] in slab geometry. The goal was to calculate the DBS responses depending on

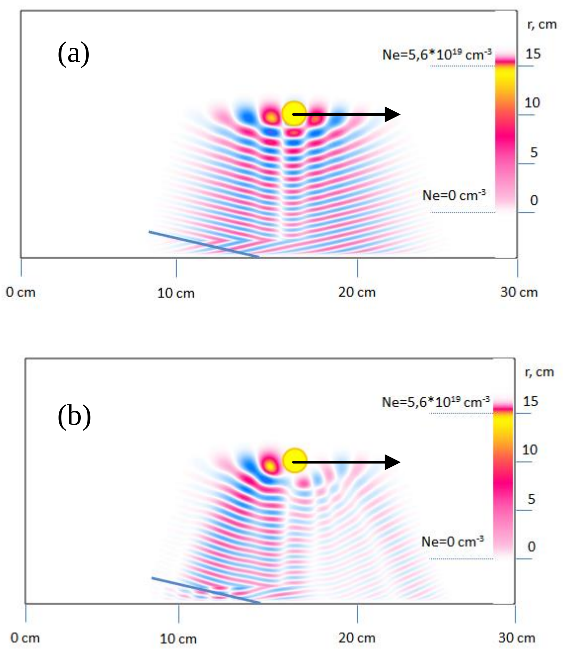

Figure 1. Electric field distribution for linear (a) and non-linear (b) regime.

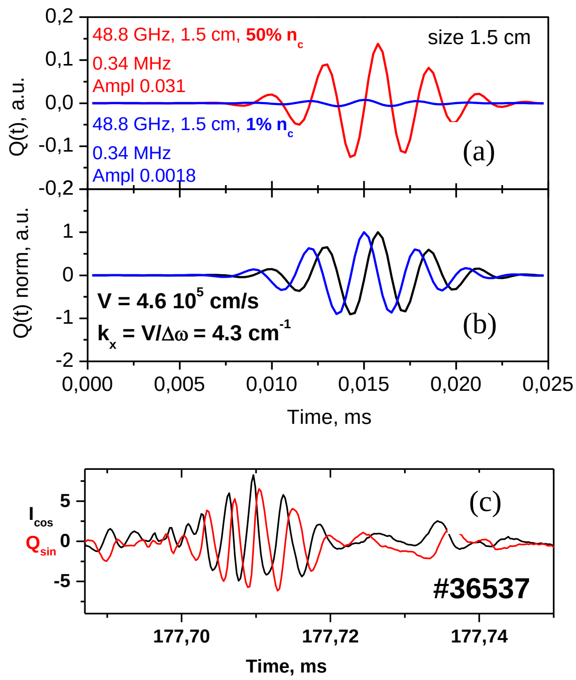

Figure 2. (a) Calculated Q(t) signals for linear (blue) and nonlinear(red regimes; (b) normalized calculated signals; (c) I(t) and Q(t) DBS signals measured in Globus-M shot#36537, f=48GHz.

various filament amplitudes (0.1%, 1%, 5%, 50%, 100% and 150% of density at cut off of the probing wave). This dependence was calculated for various filament positions in relation to the cut off and filament shapes (circle and elongated ellipse in radial direction). The parameters of the computations are as following: antenna tilt angle 13°, antenna horn mouth 5.5 cm, Gaussian beam with flat wave front in the antenna mouth. Computations have been performed for the frequencies 16GHz, 24 GHz, 32GHz, 40GHz, 48GHz, 56GHz, 64GHz in O-mode that corresponds to the frequency range used in the Globus-M tokamak DBS diagnostics (20GHz, 29GHz, 40Ghz and 48GHz). Experimental plasma density profile used for the computations close to linear, $n_e = 5.6 \cdot 10^{19}$ cm^{-3} at r = 15 cm (shot#36569 at Globus-M) is shown in figure 1 by color bar. The filament moves in poloidal direction at r=9.2cm, the direction of motion is shown in figure 1 by an arrow. The antenna horn mouth is shown by a solid line; the yellow circle shows the position and circular shape of the filament. The imitation of the filament motion was simulated by independent snapshots with a spatial step 1.3 mm. If a time interval assigned to this step the speed of filament and IQ signals can be determined. For each snapshot IQ signal was calculated (amplitude and phase) modeling a ‘time dependency’. In figure 1 the electric field distribution calculated for filament width 1.5cm at probing frequency 48GHz in case of linear scattering regime, figure 1(a), filament amplitude 0.1% from the density at cut off, and non-linear scattering regime, figure 1(b), filament amplitude 50%. Field distortion is clearly seen in the nonlinear case.

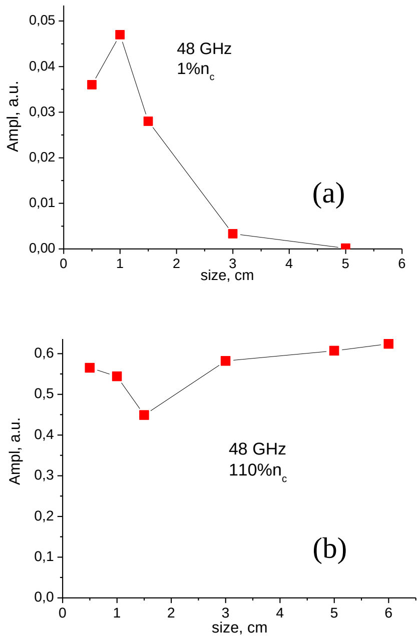

Figure 3. Signal amplitude on filament size dependence in linear (a) and non-linear (b) case.

The modeling has shown that in both linear and non-linear regimes the bursts of quasi-coherent fluctuations (BQF) are formed. In figure 2(a) the BQFs calculated for the 1.5cm circular filament moving along the cut off for linear (1% of the critical density) and non-linear (50% of the critical density) scattering are shown. After normalization BQFs look similar as it is shown in figure 2(b). The calculated signals can be compared to the DBS signals measured in Globus-M experiment shown in figure 2(c) qualitatively resulting in fact that unfortunately it is not possible to determine the filament amplitude from DBS data since it is measured in arbitrary units. The mechanism of BQF formation can be easily explained in a frame of Born approximation: if the size of a filament exceeds the spatial period of the weighting function (spatial distribution the non-perturbed electric field Fig. 1a) ($\pi/2k_i\sin\alpha$) (k_i – probing wave number) the back scattering efficiency is expected to decay in Born approximation due to averaging process, as it is shown in figure 3(a). However the BQFs can be still clearly observed in experiment. The signal amplitude calculated using full wave code in non-linear case does not depend on filament size as it is seen from figure 3(b). Despite this fact the DBS technique is able to provide

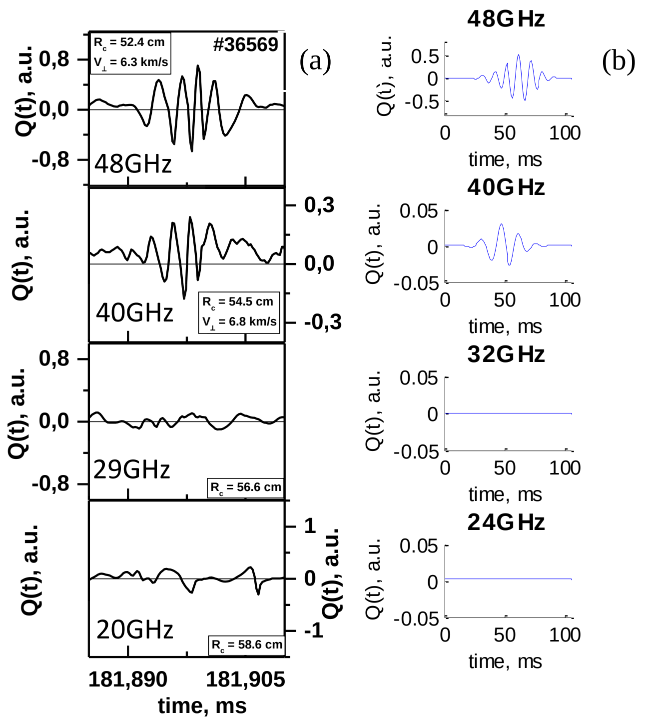

Figure 4. DBS experiment signals shot #36569 Globus-M (a), calculated signals for filament size 3cm (b)

information on filament size in radial direction when using multiple-frequency probing. Such a technique is used in Globus-M tokamak. In figure 4(a) the DBS signals obtained in Globus-M experiment (shot #36569) are shown. It is seen that there is no DBS signal at f=29GHz and f=20GHz. The radial size of the filament can be estimated as ≈2cm (distance between cut offs for f=48GHz and f=40GHz). The BQF at f=40GHz is shifted comparing to the BQF at f=48GHz, the same effect can be observed in figure 4(b) showing the result of numerical simulation for filament size 3cm in radial direction. To obtain precise information on filament size in radial direction more probing frequencies for DBS signals measurements needed.

Conclusions. Full-wave calculations have shown that similar BQFs are formed in case of scattering off from filament either in case of linear or non-linear regimes. As soon as the signal amplitude is measured in experiment in arbitrary units it is not possible to extract information on filament amplitude from experimental data. Nevertheless it is possible to determine the filament size in radial direction in case of multi-frequency probing. As it was expected the signal amplitude decreases with growing filament size in linear regime and in non-linear regime the signal amplitude is independent on filament size.

The calculations have been performed in O-mode using simple slab model and have not taken into account complicated magnetic field configuration taking place in real experiment. Such a task that is difficult even in the optical approximation is particularly relevant for tokamaks with a low aspect ratio. Moreover in presented computation turbulence effects are not taken into account as well. Despite the difficulties described above the comparison of the simulation result and experimental data obtained at the tokamak Globus-M was performed and has shown in particular the amplitude at which transition to the non-linear regime occurs. Also the preliminary calculations using full-wave finite-difference time-domain code REFMULF [6] are being processed currently.

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[1] Spolaore M et al 2017 Nucl. Mater. Energy 12 844

[2] Snyder P B et al 2009 Nucl. Fusion 49 085035

[3] Bulanin V V et al 2011 Tech. Phys. Lett. 37 340

[4] Bulanin V V et al 2019 Nucl. Fusion in press https://doi.org/10.1088/1741-4326/ab2cdf

[5] Lechte C et al Plasma Phys. Contr. Fusion, 59 (7) 075006, 2017

[6] da Silva F et al Proc of the 13th International reflectometry workshop, 2017, NFRI, KOREA