# Full wave modeling of Doppler backscattering from filaments

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**Introduction:** It is recognized that the filaments have a significant effect on the anomalous energy and particle transport in the tokamak periphery. They are actively investigated using various diagnostics in this regard. Recently studies of filaments using the Doppler backscattering (DBS) method have been performed in Globus-M [1] and ASDEX-Upgrade [2, 3]. Backscattering from filaments manifests itself as a burst of quasi-coherent oscillations of the signals of IQ detectors. Such signals are easy to describe theoretically within the Born approximation using the diagnostic weighting function [1]. However, the filaments in tokamaks differ noticeably in their size and intensity. With an increase in the amplitude of the filaments, it is necessary to consider the transition from linear scattering to nonlinear one and further up to the transition from backscattering to reflection from a moving over dens filament. This problem can be solved only using a full wave code. In this paper we present the results of two-dimensional full wave simulations of Doppler backscattering (DBS) from filaments in slab geometry.

**Numerical modeling:** 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 ($\delta n = \frac{A}{100\%} n_c exp(-((r-r_0)/l_c)^2)\exp(-((x-x_0)/l_c)^2)$, where $A$ is a filament amplitude in %, $n_c$ – critical density, $r$ – radial position, $r_0$ – radial position of the filament center, $x$ – poloidal position, $x_0$ – poloidal position of the filament center, $l_c$ is a half width of the filament) that allows freedom in choosing the size, amplitude and position of a filament in radial and poloidal coordinates, which are here identified in Cartesian coordinates used in our simulations. Two-dimensional full wave simulations are relevant knowing that the filament has a very long extension along the magnetic field line, and were done with finite-difference time-domain code IPF-FD3D [4] in slab geometry. The goal was to calculate the DBS responses depending on various filament amplitudes (0.1%, 1%, 5%, 50%, 100% and 150% of density at cut off of the probing wave) and size (0.5cm, 1 cm, 1.5cm, 3cm, 5cm and 6cm).

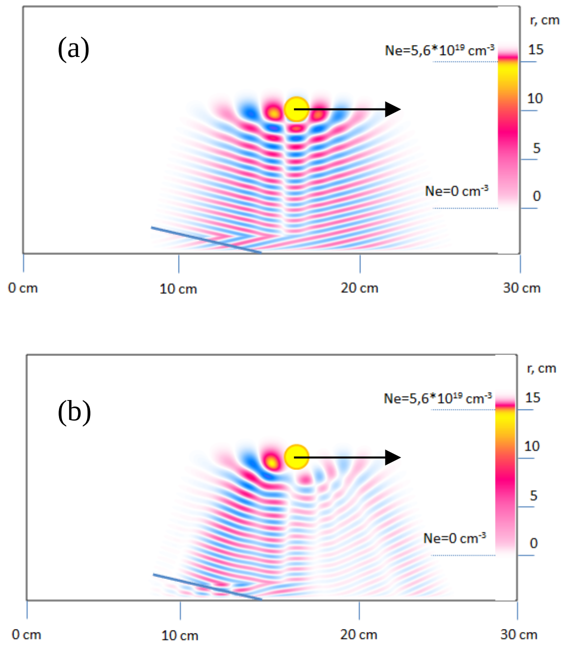


Figure 1. Electric field distribution for linear (a) and non-linear (b) regime.

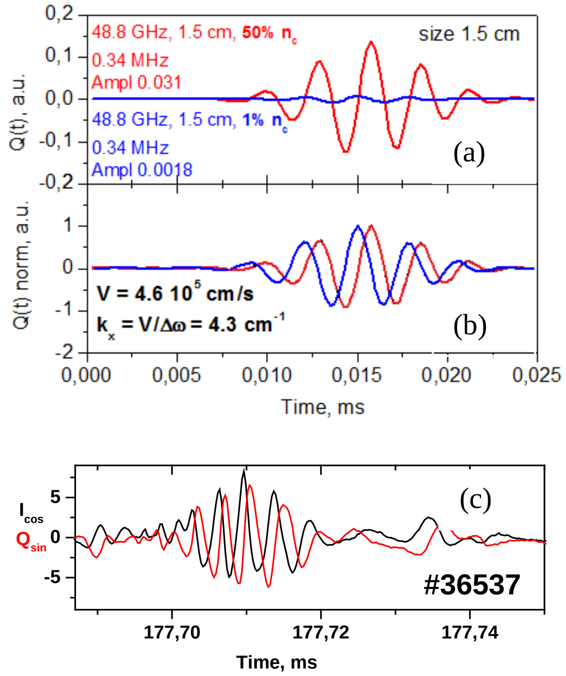


Figure 2. (a) Calculated Q(t) signals for linear (blue) and nonlinear(red) regimes; (b) normalized calculated signals; (c) I(t) and Q(t) DBS signals measured in Globus-M shot#36537, f=48GHz.

A) Amplitude: 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 velocity 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 and suppression of the specular reflection component is clearly seen in the nonlinear case. The modeling has shown that the bursts of quasi-coherent oscillations (BQO) are formed in both linear and non-linear regimes. In figure 2(a) the BQOs 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 BQOs look similar as it is shown in figure 2(b). It means that the signature for the filament is always the same in arbitrary units. 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. However simultaneous measurements of the DBS and the specular reflection component possess some potential for characterization of the filament amplitude which will be studied in further computations.

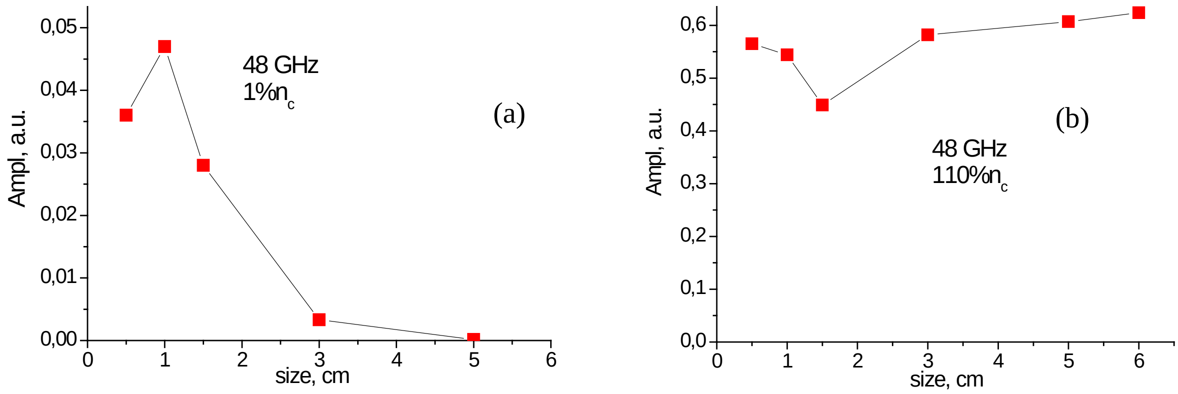


Figure 3. Signal amplitude on filament size dependence in linear (a) and non-linear (b) case.

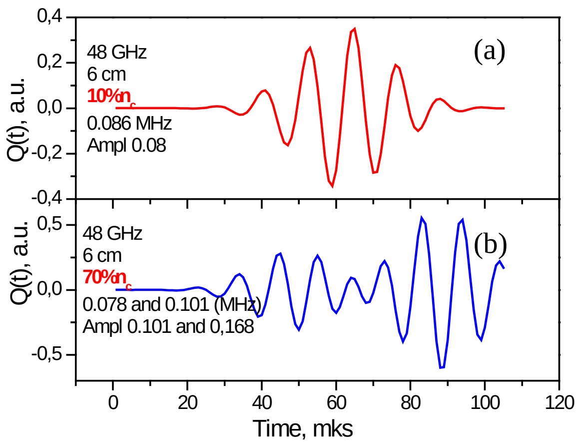


Figure 4. Calculated signal for 6cm filament diameter, 10% of critical density $n_c$ (a) and 70% of $n_c$ (b).

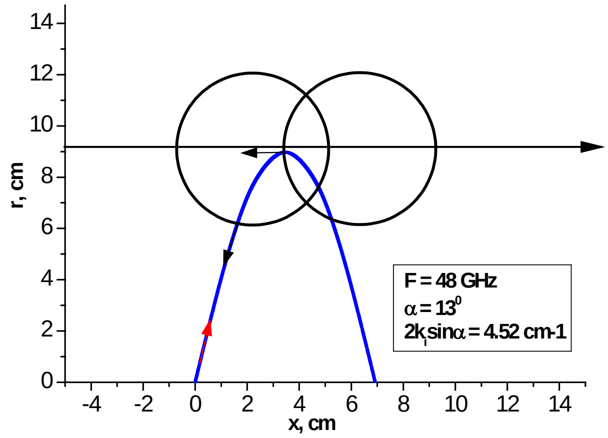


Figure 5. Ray tracing of the signal scattering off the filament 6cm.

B) Size and non-linear effects: The mechanism of BQO 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 of the non-perturbed electric field, see figure 1a), $\pi/k_i\sin\alpha$ ($k_i$ – free space probing wave number), the back scattering efficiency is expected to decay in Born approximation due to Fourier component suppression, as it is shown in figure 3(a). However, the BQOs can be still clearly observed in experiment. On contrary, the signal amplitude calculated using full wave code in non-linear case is only slightly depend on filament size as it is seen from figure 3(b). In figure 4 the result of signal calculation for the filament size 6cm >> $\pi/k_i\sin\alpha \approx 0.7$cm is shown. At small amplitudes (figure 4a), BQO is observed, similar to BQO in linear scattering. Double BQOs appear with large amplitude of the filament (figure 4b). This could be qualitatively explained with the use of raytracing, which did not take into account the density perturbation inside the filament, assuming the possibility of transition from backscattering to reflection, shown in figure 5.

**Conclusions:** Full-wave calculations have shown that similar BQOs are formed in case of scattering off from filaments 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. It was shown that the signal amplitude is independent on filament size in non-linear regime. The results obtained largely explain the similarity of the IQ detector data registered in different tokamaks.

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 simulation result 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 [5] are being processed currently.

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