Specific Electrodynamic Features of a Plasma Channel Created in Gas by Powerful Femtosecond UV Laser Pulse

Application to the Problem of Guiding and Amplification of Microwave Radiation

A. V. Bogatskaya[1,2,3], A. M. Popov [1,2,3] and E. A. Volkova[2]

[1]*Department of Physics, Moscow State University, Moscow, 119991, Russia*

[2]*D. V. Skobeltsyn Institute of Nuclear Physics, Moscow State University, Moscow, 119991, Russia*

[3]*P. N. Lebedev Physical Institute, RAS, Moscow, 119991, Russia*

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Abstract: The evolution of strongly non-equilibrium plasma in a channel created in xenon by powerful KrF - femtosecond laser pulse is studied. It is demonstrated that such a plasma channel can be used as a waveguide for both transportation and amplification of the microwave radiation. The specific features of such a plasma waveguide are studied on the basis of the self-consistent solution of the kinetic Boltzmann equation for the electron energy distribution function in different spatial points of the gas media and the wave equation in paraxial approximation for the microwave radiation guided and amplified in the channel. The amplification factor in dependence on plasma channel radius, intensity and frequency of the input RF radiation is analyzed.

1 INTRODUCTION

Recent technological progress in photonics and materials science make it possible to obtain different type of sources of radiation in terahertz (THz) or subterahertz frequency range. Such sources of radiation are of significant interest in a number of research fields, such as chemistry (Skinner, 2010), molecular biology (Meister, et al, 2013), medicine (Titova, et al., 2013) and materials science (Grady, et al., 2013). The continuously increasing interest for terahertz and subterahertz radiation and its possible applications is caused by its ability to penetrate through a lot of materials (Jepsen, et al., 2011), which are usually opaque in the infrared and visible. Also, a number of physical and chemical processes (vibrational dynamics of macromolecules and crystalline lattices, reconstruction of hydrogen bounds, etc.) can be controlled and governed by this low frequency radiation.

The goal of our paper is to study the process of transportation of focused microwave pulses in subterahertz frequency band with low divergence and possibility of their amplification in a plasma channel at distances of order of 100 cm.

It is known, that if the electron energy distribution function (EEDF) in a plasma is characterized by the energy intervals with the inverse population, such situation can be used for amplification of the electromagnetic radiation (Bekefi, et al, 1961; Bunkin, et al, 1973). Such EEDF can be easily obtained in the process of multiphoton ionization of a gas by a high-intensity laser pulse under the conditions when the pulse duration is comparable or even less than the average time interval between the electron - atomic collisions. To realize the regime of amplification one needs the gas of atoms or molecules characterized by the transport cross section increment with the energy where the peak of photoelectrons is found to exist. Bogatskaya and Popov (2013) had demonstrated that such a regime of amplification of electromagnetic radiation can be obtained in a xenon plasma created by powerful (10^{10} - 10^{12} W/cm^2) excimer KrF laser pulse ($\hbar\Omega = 5$ eV) of femtosecond duration in subterahertz frequency band ($\omega < \nu_{tr}$, ν_{tr} is the transport frequency) at time duration up to 100 ns. In (Bogatskaya, et al, 2013) the possibility to amplify the subtrerahertz radiation in different gases was analyzed. The amplification regime in the air plasma was studied in (Bogatskaya, et al, 2014a). It was found that amplification in air plasma created by the

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third harmonic of the Ti:Sa laser is also possible, but positive value of a gain factor is found to exist only for rather short durations ~ 20 ps. Hence there is a possibility to amplify only extremely short radio-frequency pulses of 2-3 cycles duration.

Bogatskaya, et al (2014b) demonstrated also anomalous refractive properties of the strongly-nonequilibrium plasma produced by the short UV laser pulse. Such a plasma channel in the case of low-frequency radiation ($\omega < \nu_{tr}$) will be optically more dense in comparison with unionized gas, in contrast to the typical situation when plasma is an optically less dense medium. Just such a situation is of interest in respect to creation of a sliding-mode plasma waveguide (Zvorykin, et al., 2010). In the present paper we develop the self-consistent approach to the problem of transportation of the radio-frequency (RF) pulse in the non-equilibrium plasma channel. This approach is based on joint solution of the Boltzmann equation for the EEDF evolution in the strongly non-equilibrium plasma and the wave equation in the paraxial approximation for the transported through the channel RF pulse. The process of guiding and simultaneous amplification of the RF radiation in the plasma channel formed by a powerful KrF laser femtosecond pulse in xenon is studied in dependence of plasma channel radius and different parameters of the input RF pulse.

2 ELECTRODYNAMIC FEATURES OF A NONEQUILIBRIUM PLASMA CHANNEL

For the radiation with frequency ω electrodynamic features of a plasma channel are determined by complex permittivity $\xi_\omega = \xi_\omega' + i\xi_\omega''$ or complex conductivity $\sigma_\omega = \sigma_\omega' + i\sigma_\omega''$ which are related with each other by the expression

$$\xi_\omega = 1 + i\frac{4\pi\sigma_\omega}{\omega}. \quad (1)$$

The general expression for the complex conductivity in a relatively weak electromagnetic field when the two-term expansion for the EEDF $n(\varepsilon,t)$ is valid can be written in a form (Ginzburg and Gurevich, 1960; Raizer, 1977):

$$\sigma_\omega = \frac{\omega_p^2}{6\pi}\int_0^\infty \frac{\varepsilon^{3/2}(\nu_{tr}(\varepsilon)+i\omega)}{\omega^2+\nu_{tr}^2(\varepsilon)}\left(-\frac{\partial n(\varepsilon,t)}{\partial\varepsilon}\right)d\varepsilon. \quad (2)$$

Here $\omega_p^2 = 4\pi e^2 n_e/m$ is the plasma frequency squared, n_e is the electron density and $\nu_{tr}(\varepsilon) = N\sigma_{tr}(\varepsilon)\sqrt{2\varepsilon/m}$ is the transport frequency of electron-atomic collisions, $\sigma_{tr}(\varepsilon)$ is the transport cross section and N is the gas density. We should also mention that the evolution of the EEDF is rather slow in time and external electromagnetic field of frequency ω can be considered as the quasimonochromatic one. The EEDF in eq. (2) is normalized according to the condition $\int n(\varepsilon,t)\sqrt{\varepsilon}\,d\varepsilon = 1$.

If the transport frequency does not depend on energy the complex refractive index is the same for an any EEDF and for the case of weakly ionized plasma ($\omega_p << \nu_{tr},\omega$) can be written in the well-known form

$$n_\omega = n_\omega' + i\,n_\omega'' = 1 - \frac{\omega_p^2}{2(\omega^2+\nu_{tr}^2)} + i\frac{\omega_p^2\,\nu_{tr}}{2(\omega^2+\nu_{tr}^2)\omega}. \quad (3)$$

In particular, one derives from (3) that plasma is optically less dense medium in comparison with the unionized gas. Imaginary part of (3) determines the absorption coefficient of the electromagnetic radiation with frequency ω in plasma (Raizer, 1977):

$$\mu_\omega = 2\frac{\omega}{c}\times n_\omega'' = \frac{\omega}{c}\times\xi_\omega'' = \frac{\omega_p^2\,\nu_{tr}}{c(\omega^2+\nu_{tr}^2)} \quad (4)$$

For an arbitrary dependence $\nu_{tr}(\varepsilon)$ the definite expression for the EEDF is of importance. In this case more general expressions for refractive index should be used:

$$n_\omega' = 1 - \frac{2\pi\sigma_\omega''}{\omega} = 1 - \frac{\omega_p^2}{3}\int_0^\infty \frac{\varepsilon^{3/2}}{\omega^2+\nu_{tr}^2}\left(-\frac{\partial n}{\partial\varepsilon}\right)d\varepsilon,$$
$$n_\omega'' = \frac{2\pi\sigma_\omega'}{\omega} = \frac{\omega_p^2}{3\omega}\int_0^\infty \frac{\varepsilon^{3/2}\nu_{tr}}{\omega^2+\nu_{tr}^2}\left(-\frac{\partial n}{\partial\varepsilon}\right)d\varepsilon. \quad (5)$$

Typically the EEDF decreases with the increase of energy, i.e. $\partial n/\partial\varepsilon$ is negative and both of integrals in (5) are positive. Hence, for such a more general case plasma channel also appears to be optically less dense in comparison with unionized media and the absorption coefficient is positive, $\mu_\omega > 0$.

However, as the energy intervals with positive derivative $\partial n/\partial\varepsilon$ contribute negatively to the integrals (5), both of them may become negative. Hence, plasma turns out to be an amplifying medium. Also it can be optically more dense than the neutral gas. The conditions, when integrals in (5) can become negative are discussed in detail by Bogatskaya, et al., (2014b). In particular, in the energy range of inverse population in continuum for low frequencies ($\omega << \nu_{tr}$) the condition

$$\frac{d}{d\varepsilon}\varepsilon/\sigma_{tr}(\varepsilon) < 0 \qquad (6)$$

should be satisfied to obtain the positive gain factor in a plasma, i.e. transport cross section should grow up rapidly than the linear dependence. If the condition

$$\frac{d}{d\varepsilon}\varepsilon^{1/4}/\sigma_{tr} < 0 \qquad (7)$$

is fulfilled plasma will be optically more dense medium as compared with the neutral gas. The latter condition is much softer than the previous one and is fulfilled for a lot of atoms and molecules. If both of inequalities (6) and (7) are satisfied a plasma channel can be used as the waveguide for both transportation and amplification of the microwave radiation. For the xenon plasma at an atmospheric pressure such a guiding regime with amplification can be realized up to subterahertz frequency band.

To study temporal evolution of real and imaginary parts of plasma conductivity or permittivity in plasma channel the Boltzmann kinetic equation for the EEDF in two-term expansion was solved numerically taking influence of the transported RF field and electron – electron collisions into account. The details of the numerical procedure as well as the information on the set of cross sections used can be found in (Bogatskaya, et al., 2013).

For the case of multiphoton ionization of xenon by KrF laser radiation inelastic processes do not contribute to the evolution of the EEDF as the excitation potentials exceed the value of 8.31 eV while the position of the lowest photoionization peak is approximately 2.87 eV. At Fig.1 we present the calculations of temporal evolution of the gain factor per one electron and the real part of plasma permittivity for the RF frequency $\omega = 5\times10^{11}$ s^{-1} and for different electronic densities. First, we note that for rather low electronic densities both values are found to increase in time while photoelectron peak gradually shifts in time due to elastic collisions towards lower energies but still locates in the range where inequalities (6) and (7) are satisfied. Also it can be seen that for rather small time intervals the gain factor is proportional to the electronic density. As about the real part of plasma permittivity $\mathrm{Re}\,\xi_\omega - 1$, for small time intervals this value increases even faster than electronic density (see Fig.1b). On the other hand, the increment of the electron density leads to faster maxwellization of the EEDF which results in the rapid decrement of the time interval during which the gain factor is still positive and the real part of plasma permittivity is greater than unity.

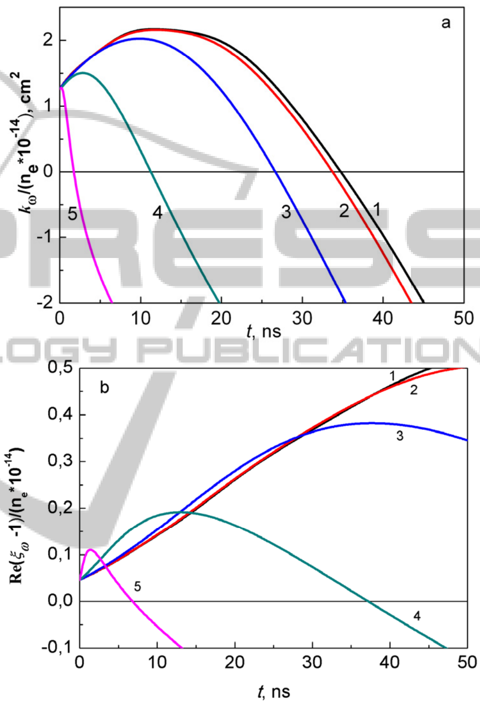

Figure 1: The gain factor (a) and the real part of plasma permittivity (b) per one electron in xenon plasma for different electronic concentrations (cm-3): 1 - 1010, 2 - 1011, 3 - 1012, 4 - 1013, 5 - 1014. Negative values correspond to absorption of a RF radiation in plasma.

Results of calculations of the gain factor for different values of radiation intensity with a frequency $\omega = 5\times10^{11}$ s^{-1} are presented at Fig. 2 and demonstrate that the time interval during which the gain factor is positive reduces from 20 to 2 ns with increase of RF intensity from zero to 10^3 W/cm^2. For the RF field intensity of 10 kW/cm^2 amplification in a plasma channel is possible for very short times about ~ 0.1 ns. From practical point of view it means that microwave pulses of 2 ns duration can be amplified up to the intensity of ~ 1 kW/cm^2. We also note that the amplification of RF pulse in the plasma channel results in a decrement of electron energy, i.e. an external electric field of a RF pulse leads to the cooling of the plasma electron component.

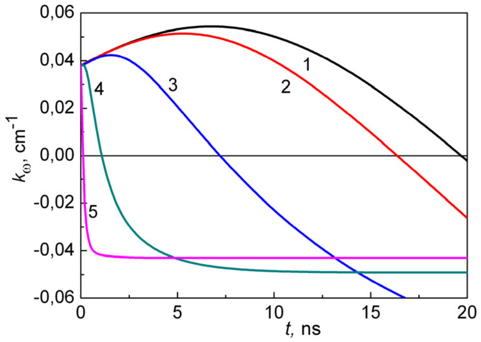

Figure 2: Time dependence of the gain factor of electromagnetic radiation for different intensities of the RF radiation (W/cm^2): I=0 (1), 10 (2), 10^2 (3), 10^3 (4), 10^4 (5). The data obtained for electronic density $n_e = 3\times10^{12}$ cm^{-3} and $\omega = 5\times10^{11}$ s^{-1}.

3 PROPAGATION AND AMPLIFICATION OF THE RF PULSES IN A PLASMA WAVEGUIDE

In this chapter we will discuss propagation of a short RF pulse in a plasma channel created in xenon by a femtosecond KrF laser pulse. Our analysis is based on the self-consistent solution of the wave equation for the RF pulse and the Boltzmann equation for the EEDF in a plasma channel in different spatial points. If the RF field is weak enough and do not influence on plasma parameters the set of Boltzmann equations can be solved independently from the wave equation. In this case the RF pulse propagates in a channel with given plasma properties slow varying in time. Much more complicated is the situation when the RF pulse is strong enough and produces significant effect on evolution of the EEDF. In this case the self-consistent analysis of the equations is mandatory.

As it is known, propagation of the electromagnetic radiation in the medium is described by the wave equation:

$$\nabla^2\vec{E} - \frac{1}{c^2}\frac{\partial^2\vec{E}}{\partial t^2} = \frac{4\pi}{c^2}\frac{\partial\vec{j}}{\partial t}. \qquad (8)$$

Here $\vec{E}$ is an electric field strength and $\vec{j}$ is a density of electric current in a plasma. Further we will suppose the field to be linearly polarized. To analyze the process of microwave pulse propagation qualitatively we use paraxial approximation for the solution of eq. (8) (for details see the monograph of Akhmanov and Nikitin (1997)). According to this approximation for the pulse propagation along z-direction electric field E should be represented as,

$$E(\vec{r},t) = E_0(\rho,z,t)\cdot\exp(i(kz-\omega t)). \qquad (9)$$

Here E_0 is the envelope of the RF pulse, $k=\omega/c$ is the wave number and ρ is the perpendicular spatial coordinate. If we neglect temporal dispersion, the expression for the current density can be written in a simple form $j(\vec{r},t)=\sigma_\omega E(\vec{r},t)$. Assuming that $|\partial\sigma_\omega/\partial t| << \omega|\sigma_\omega|$, $|\nabla\sigma_\omega| << k|\sigma_\omega|$, i.e. plasma conductivity is a slow-varying function in time and space, one derives from (8) the following equation for RF pulse envelope in the paraxial approximation

$$ik\left(\frac{\partial E_0}{\partial z} + \frac{n_\omega}{c}\frac{\partial E_0}{\partial t}\right) = -\frac{1}{2}\nabla_\perp^2 E_0 + \frac{2\pi\sigma''_\omega}{\omega}k^2E_0 + i\frac{1}{2}kk_\omega E_0 + \frac{2\pi}{c^2}\left(E_0\frac{\partial\sigma_\omega}{\partial t}\right) \qquad (10)$$

where $k_\omega = -\mu_\omega = 4\pi\sigma'_\omega/c$ is the plasma gain factor (if $k_\omega < 0$ plasma absorbs the radiation), and $n_\omega = 1 + i\,2\pi\sigma_\omega/\omega$ is the complex refractive index. The first term in the right part in Eq. (10) stands for the diffraction divergence of the electromagnetic field, the second one describes plasma focusing (defocusing) features and the third term represents the absorption (amplification) process. The last term in the right part of (10) is small in comparison with previous ones and gives some corrections to the focusing/defocusing and amplification/absorption of the wave field.

The case of our study is the situation when $k_\omega > 0$ and $\sigma''_\omega < 0$. Such a situation is of interest with respect to creation of the plasma waveguide being capable to amplify the transported radiation. Actually, the amplification duration τ_{ampl} corresponds to the amplification distance of about $c\times\tau_{ampl}$ (τ_{ampl} is the time interval of the positive gain factor existence) which equals to tens of centimetres. The same is for focusing properties of the plasma, but the guiding length is typically several times longer. So, a laser pulse creates the plasma channel characterized by an amplifying and a guiding «trails» (see Fig. 3). If we launch a laser pulse and a RF pulse just one after another simultaneously, the last one will continually locate in the amplifying and guiding zones of a laser pulse.

It can be seen from Eq. (10) that in the case $\mathrm{Re}\,n_\omega = 1 - 2\pi\sigma_\omega''/\omega > 1$ the plasma channel can partly suppress the diffraction divergence of the RF radiation. If the condition

$$(\mathrm{Re}\, n_\omega - 1)k^2 R^2 > 1 \qquad (11)$$

(here R is the plasma channel radius) is satisfied the channel will look like the waveguide and can transport the radiation without divergence. For $\omega = 5 \cdot 10^{11}$ s^{-1} and $k = \omega/c \approx 16.7$ cm^{-1} and $\Delta n_\omega = \mathrm{Re}\, n_\omega - 1 \sim 0.001$ (see Fig. 1b) the guiding regime of propagation will be realized for $R > 2$ cm. It means a laser pulse in order to create such a plasma channel with electron density $n_e \sim 10^{12}$ cm^{-3} should have the power at least in sub-Terawatt level.

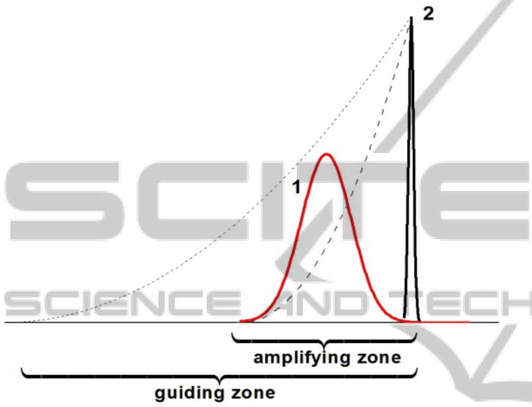

Figure 3: Spatial structure of radio (1) and laser (2) pulses for a given instant of time. Dash curves are spatial profiles of the gain factor and the refractive index.

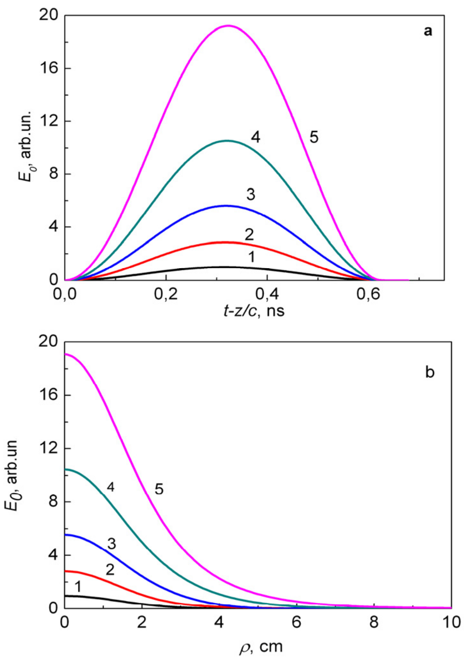

Figure 4: Temporal (1) and radial (2) profiles of the electric field envelope of the amplifying pulse at different propagation distances z: 1 – 0 cm, 2 – 30 cm, 3 – 60 cm, 4 – 90 cm, 5 – 120 cm. Initial peak intensity is 0.1 W/cm^2.

First, we discuss the results of numerical integration of the wave equation (10) for the case of weak field when the contribution of the amplified RF pulse to the EEDF evolution in the plasma channel can be neglected. We assume that the RF pulse is characterized by the sine-squared temporal envelope $E_0(t) \sim \sin^2(\pi t/\tau_p)$, where $\tau_p = 50T$ $(T = 2\pi/\omega)$ is the pulse duration. Typical distributions of the electric field envelope $\left|E_0(\rho, t - z/c, \tau)\right|$ for the initial RF field and electron density distribution in plasma channel Gaussian profiles, characterized by the radius $\rho_0 = 2$ cm versus the variable $\tau = t - z/c$ (for $\rho = 0$) and the radial variable ρ (for $\tau = \tau_p/2$ that corresponds to the maximum of the envelope of the initial pulse) are presented at Fig. 4. The first of these distributions can be considered as the temporal envelope of the pulse at different fixed values of z or as a distribution over z - coordinate at a fixed instant of time. For the RF pulse duration $\tau_p = 50T$ the spatial length of the pulse is equal to $c\tau_p \approx 1.9$ cm. For such a pulse $k_\omega \approx 0.04$ cм$^{-1}$ and can be considered to be nearly constant during the all propagation time (see Fig. 2). The electric field E_0 increases with propagation length approximately exponentially $E_0 \sim \exp(hz)$ with $h \approx 0.024$ cm^{-1}. This value is even little larger than $k_\omega/2 \approx 0.019$ cm^{-1}, this difference arises from the partial focusing effect during the propagation of the RF pulse in the plasma waveguide. As about the radial distribution (see Fig. 4b) it is nearly Gaussian one for all instants of time.

The case of the initial RF pulse with relatively high intensity when the guiding RF field contributes significantly to the evolution of the EEDF in the plasma channel is more interesting. The results of such calculations for the initial RF intensity $I_0 = 10^3$ W/cm^2 are presented at Fig. 5. It can be seen for the same propagation length 120 cm there is an increase in the peak intensity of the RF pulse just only approximately six times. The pulse shape is found to be distorted significantly, mainly because of the dominant enhancement at the leading edge of the pulse. As about the trailing edge of the pulse it can be seen at fig.6a that for the propagation distances of 60 cm and more the significant absorption of the RF intensity is observed due to dramatic reconstruction of the EEDF by the RF pulse. As a result, the shorter RF pulse with leading peak and broader spectrum is formed in such a propagation regime.

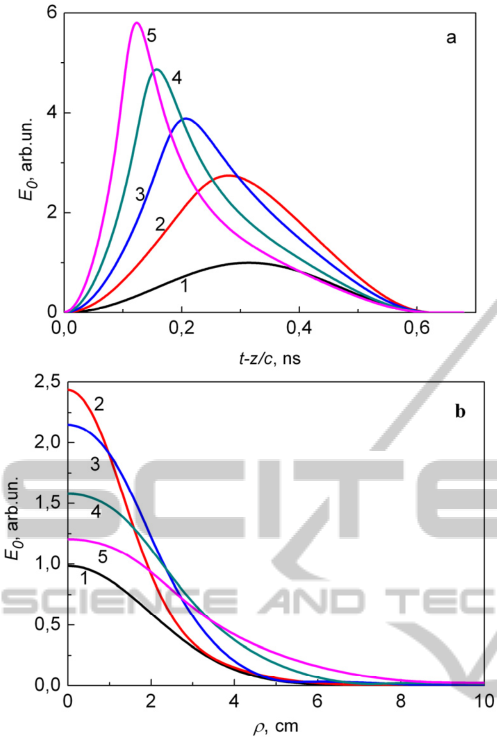

Figure 5. Temporal (1) and radial (2) profiles of the electric field envelope of the amplifying pulse at different propagation distances z: 1 – 0 cm, 2 – 30 cm, 3 – 60 cm, 4 – 90 cm, 5 – 120 cm. Initial peak intensity is 10^3 W/cm^2.

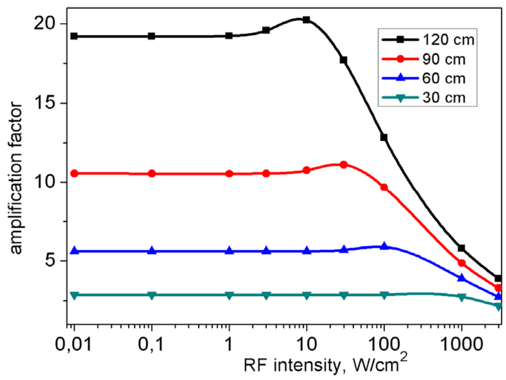

Figure 6: Field amplification factor in dependence of the input RF intensity for different propagation lengths (30, 60, 90 and 120 cm). Electronic density is $n_e = 3\times10^{12}$ cm^{-3} and $\omega = 0.5$ THz, channel radius is 2 cm.

Let us now discuss the results of simulation obtained for different initial parameters of an input RF pulse (its peak intensity and frequency) and the radius of the plasma channel. The dependence of the field amplification factor $g = E_0(z)/E_0(z=0)$ for different propagation lengths in dependence on peak input RF intensity is presented at Fig. 6. In low intensity limit the amplification factor do not depend on the input intensity and reaches the value $g \approx 20$ for the propagation length $L = 120$ cm. It means that output intensity increases ~400 times in comparison with the input one. In the range of input intensities above 100 W/cm^2 the g-factor drops dramatically. This results-due to the rapid relaxation of the EEDF in the presence of RF field and decrement of the gain factor in the plasma channel. We also note the local maximum which is well pronounced at the input intensity 10 W/cm^2 for the L=120 cm. This maximum appears to exist due to the additional focusing effect of a plasma arising in the process of EEDF relaxation at moderate intensities.

The dependence of the field amplification factor on radius of a plasma channel is presented at Fig. 7. The most important is the fact that in agreement with (11) effective amplification of the RF pulse takes place only for plasma channels of radius $R \geq 2$ cm. For $R < 1$ cm both effects of amplification and plasma focusing cannot compensate the diffraction divergence of the pulse and its intensity decreases along the propagation length. The increment of the channel radius above 2-4 cm leads to the saturation of amplification factor at a level $g = \exp(k_\omega L/2)$.

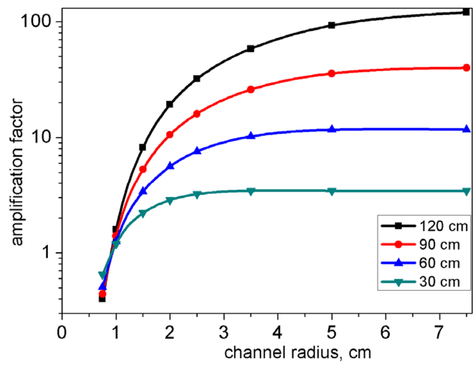

Figure 7: Field amplification factor in dependence of the plasma channel radius for different propagation lengths (30, 60, 90 and 120 cm). Electronic density is $n_e = 3\times10^{12}$ cm^{-3}, $\omega = 0.5$ THz and input RF intensity is 0.01 W/cm^2.

It should be mentioned that there is an existence of the optimal value of frequency for effective RF pulse amplification for a given channel radius (see data at Fig. 8). For R=2 cm this frequency is rather close to $\omega = 5\times10^{11}$ s^{-1}. The decrement of the frequency and, hence, increment of the microwave radiation wavelength leads to the violation of the inequality (11) determining realization of the guiding regime. On the other hand, the amplification factor also falls down for high frequencies. When the condition $\omega \geq \nu_{tr}$ is fulfilled the gain factor becomes negative and amplification regime is impossible for any radius of the plasma channel. In the situation under study the regime of amplification can be realized for microwave frequencies $\omega \leq 1.8$ THz.

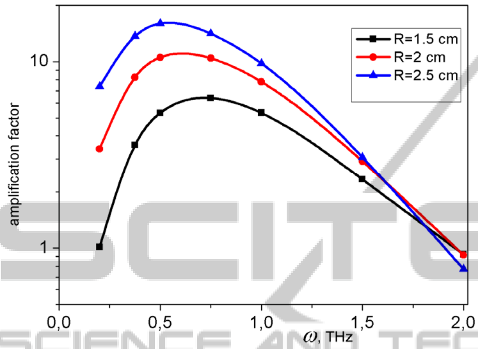

Figure 8: Field amplification factor in dependence of RF pulse frequency for different channel radius *R*. Electronic density is $n_e = 3\times10^{12}$ cm^{-3}, input RF intensity is 0.01 W/cm^2 and propagation length is *L*=90 cm.

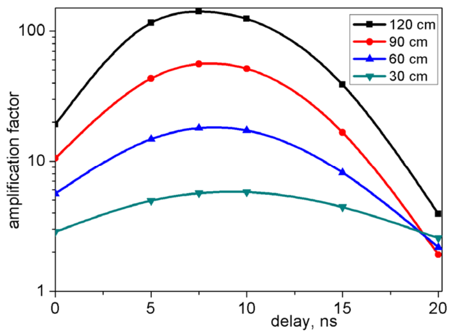

Figure 9: Field amplification factor in dependence of the time delay between laser and RF pulses for different propagation lengths (30, 60, 90 and 120 cm). Electronic density is $n_e = 3\times10^{12}$ cm^{-3}, input RF intensity is 0.01 W/cm^2 and *R*=2 cm.

All discussed above data were obtained for the zero delay between optical and RF pulses. On the other hand, the data presented at Fig. 1 lead to the conclusion that in order to increase the amplification factor we should introduce the time delay between laser and microwave pulses. The value of this delay depends on the electronic density in the channel and for $n_e = 3\times10^{12}$ cm^{-3} this delay should be of order of 10 ns. The data presented at Fig. 9 confirm the above conclusion. The optimal delay in our situation is ~7.5 ns. Due to increment of the gain factor and refractive index during the initial period of the EEDF evolution (see Fig. 1) such a delay value allows to increase the amplification factor approximately five times.

4 CONCLUSIONS

Thus, in this paper it is shown that the nonequilibrium plasma channel created in xenon by powerful femtosecond KrF laser can be used to guide and amplify the RF pulses till subterahertz frequency band. There is an opportunity to reach significant amplification by the launching of the laser and RF pulses, so that the RF pulse is continually located in the guiding and amplification zones of the laser pulse. Optimal parameters of radio-frequency pulse for guiding and amplification are discussed.

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