Simulation of localized THz-discharge supported by FEL radiation

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Introduction

A localized discharge supported by terahertz (THz) radiation in a jet of a noble gas is promising for use as a point-like source of extreme ultraviolet (EUV) radiation with a wavelength of about 10 nm, which is in high demand for the next generation chip manufacturing technologies [1]. The range of optimal plasma densities for the absorption of THz radiation coincides with the range of optimal transparency for EUV radiation [2, 3]. The experiments with such discharges were performed previously with a gyrotron as a plasma supporting power source [4, 5]. These experiments were limited by available gyrotron power up to 100 kW at 670 GHz and 250 kW at 250 GHz. Further increase of rf-power deposited into the plasma is possible with a free-electron laser (FEL). In [6] it was proposed to use THz radiation from FEL to support a point-like EUV-light emitting discharge in an inhomogeneous gas flow, in particular, for the facility running at the Budker Institute (NovoFEL [7]).

In the present paper, we develop a model of the breakdown and further evolution of a discharge in an inhomogeneous gas flow under the action of a pulse of high-power THz radiation specific to FELs. We perform simulation of such a discharge supported in xenon flow by radiation pulse of the prospective NovoFEL-3 (pulse 20 ps / wavelength 20 μm / instant power 10MW) which is to provide the longest pulse of high-power radiation with the optimal wavelength. Simulated discharge radiates 700 nJ per pulse in one of the technological wavelength ranges 11.2 nm$\pm$1%.

Model

We consider a flow of neutral xenon expanding from a nozzle into a vacuum camera (fig. 1). A sharp maximum of the gas density in the vicinity of the nozzle provides the discharge localization. An extremely focused beam of THz radiation propagates towards the flow and causes the gas breakdown. Then it supports a discharge with multiply charged ions radiating EUV light.

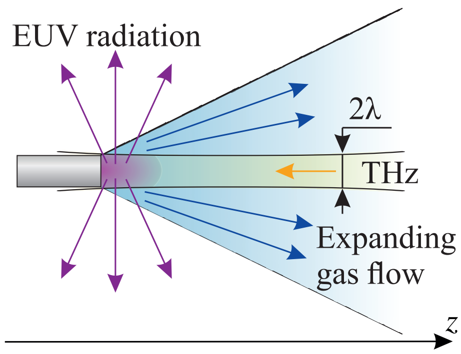

Figure 1: *Schematic of the discharge*

We develop a one-dimensional model of the discharge considering plasma parameters dependent on time t and one spatial coordinate z along the flow.

s	a_s	b_{sj}	c_{sj}	comment
1	$-\delta\sum_{j=0}^{j_{\max}} k_{cj} n_j \mathscr{E}_e$	0	0	elastic collisions
2	$-\sum_{j=0}^{j_{\max}}(I_j k_{ij}\underline{n}_j + \widetilde{I}_j \widetilde{k}_{ij}\overline{n}_j)$ $-(\mathscr{E}_e/n_e)dn_e/dt$	$-k_{ij}\underline{n}_j n_e$ $+k_{ij-1}\underline{n}_{j-1}n_e$	$-\widetilde{k}_{ij}\overline{n}_j n_e$ $+\widetilde{k}_{ij-1}\overline{n}_{j-1}n_e$	ionization
3	$\sum_{j=0}^{j_{\max}} \widetilde{I}_j k_{rj}\underline{n}_j n_e$	$-k_{rj}\underline{n}_j n_e^2$	$k_{rj+1}\underline{n}_{j+1}n_e^2$	recombination
4	$-\sum_{j=0}^{j_{\max}} E_{ej} k_{ej}\underline{n}_j$	$-k_{ej}\underline{n}_j n_e$	$k_{ej}\underline{n}_j n_e$	excitation
5	$\sum_{j=0}^{j_{\max}} E_{ej} k_{dj}\overline{n}_j$	$k_{dj}\overline{n}_j n_e$	$-k_{dj}\overline{n}_j n_e$	de-excitation
6	0	$A_j^*\overline{n}_j$	$-A_j^*\overline{n}_j$	UV radiation
7	Q_a	0	0	THz absorption

Table 1: *Coefficients of balance equations* (1). *Legend: k_j with indices* c, i, r, e, d *are coefficients of elastic collisions, ionization, recombination, excitation and de-excitation correspondingly, $\widetilde{k}_{ij}$ are ionization coefficients for excited ions, I_j are ionization energies, E_{ej} are transition energies, $\widetilde{I}_j = I_j - E_{ej}$ are ionization energies for exited ions, $\delta = 2m_e/m_i$ is the energy exchange coefficient for elastic collisions (m_e and m_i are electron and ion masses), Q_a is the absorbed THz power.*

The discharge is described with the local equations of particle and energy balance: ion densities and mean electron energy at a particular position z evolve in time independently on the discharge evolution at any other position. The equations are written as

$$\frac{d\mathscr{E}_e}{dt} = \sum_s a_s\,, \quad \frac{d\underline{n}_j}{dt} = \sum_s b_{sj}\,, \quad \frac{d\overline{n}_j}{dt} = \sum_s c_{sj}\,, \quad n_e = \sum_j Z_j\left(\underline{n}_j + \overline{n}_j\right)\,, \tag{1}$$

where $\mathscr{E}_e$ is mean electron energy, $\overline{n}_j$ and $\underline{n}_j$ are densities of excited and unexcited atoms ($j = 0$) and ions Xe^{j+} ($j = 1...j_{\max}$), and n_e is an electron density calculates from the condition of quasineutrality. Here we neglect effects of particle diffusion and thermal conductivity for plasma as for the characteristic densities 10^{18} cm^{-3} and mean electron energy on the order of 100 eV provided by a FEL pulse the characteristic times of these processes exceed the times of the discharge development.

Coefficients a_s, b_{sj} and c_{sj} are given in table 1 and describe the elementary processes important in our range of plasma parameters and timescales, such as elastic electron-ion collisions, ionization, excitation, de-excitation of ions by the electron impact, three-body recombination and spontaneous line radiation of ions. Since bound-bound transitions are not equally probable, and for most ions, the Einstein coefficients of transitions from the ground electronic configuration to excited ones have distinguished maxima in a narrow range of transition energies, for simplicity we describe only one effective transition per ion with an averaged energy E_{ej} and summarized transition frequency A_j. Effective elongation of lifetimes of excited ions due to radiation trapping in the discharge volume is taken into account with the technique analogous to proposed in [3]; corresponding reduced Einstein coefficients are denoted as A_j^*.

The electromagnetic field is set as a monochromatic plane linearly polarized TEM wave propagating in a plane-layered medium. The electromagnetic wave period λ/c is short in comparison with all other times of the discharge. Thus, to find a spatial distribution of electromagnetic field, one can use the stationary Maxwell equations for complex amplitudes

$$\begin{cases} dE_x/dz = i\omega H_y/c \\ dH_y/dz = i\omega\varepsilon E_x/c \end{cases}, \quad \varepsilon(t,z) = 1 - \frac{\omega_\mathrm{p}^2(t,z)}{\omega^2 + \nu^2(t,z)}\left[1 - \frac{i\nu(t,z)}{\omega}\right], \tag{2}$$

where $\varepsilon(t,z)$ is a complex dielectric constant of cold plasma [8], ω is THz radiation frequency, $\omega_\mathrm{p}^2 = 4\pi e^2 n_\mathrm{e}/m_\mathrm{e}$ is the plasma Langmuir frequency squared, ν is the electron-ion collision frequency. Solution of (2) gives the absorbed power per electron

$$Q_\mathrm{a}(t,z) = \frac{P_0}{\pi\lambda^2 n_\mathrm{e}}\frac{d}{dz}\mathrm{Re}\left[E_x H_y^*\right], \tag{3}$$

where complex field amplitudes are normalized such that P_0 is the instant power of the incident THz radiation.

At $t = 0$, we define the gas density profile $n_0(0,z)$ and some seed background electron density $n_\mathrm{e} \ll n_0$ in order to initiate the electron avalanche. Then equations (1) and (2) form a closed set for the simulation of the discharge evolution at $t > 0$. The spatial inhomogeneity of $\mathscr{E}_\mathrm{e}$, $\overline{n}_j$ and $\underline{n}_j$ is determined by the initial conditions and the inhomogeneous power deposition profile of the incident FEL radiation.

Results

Simulations are performed for the parameters of radiation corresponding to the NovoFEL-3 project: the wavelength $\lambda = 20$ μm, the pulse duration $t_\mathrm{p} = 20$ ps and the instant power $P_0 =$ 10 MW. To provide the shortest possible time of the electron avalanche development, we set initial density of neutral xenon in the nozzle, $n_0(0,0) = 2.5\times10^{18}$ cm^{-3}, close to the cut-off density $n_\mathrm{cr} = 2.8\times10^{18}$ cm^{-3} for FEL radiation; this choice still lets sufficient multiply charged ion population before the electron density exceeds the cut-off. Initial ionization is $n_\mathrm{e}/n_0 = 0.01$.

As long as $n_\mathrm{e} < n_\mathrm{cr}$, the electrons are efficiently heated. Since there are no losses of particles, the energy of electrons is spent only for the ionization and ion excitation, and the excess is stored in the mean energy $\mathscr{E}_\mathrm{e}$. When the electron density exceeds the cut-off value, most of the incident electromagnetic energy is reflected. The electron heating stops, but the energy stored in the electrons is still spent for the ionization and excitation of ions while the plasma cools down.

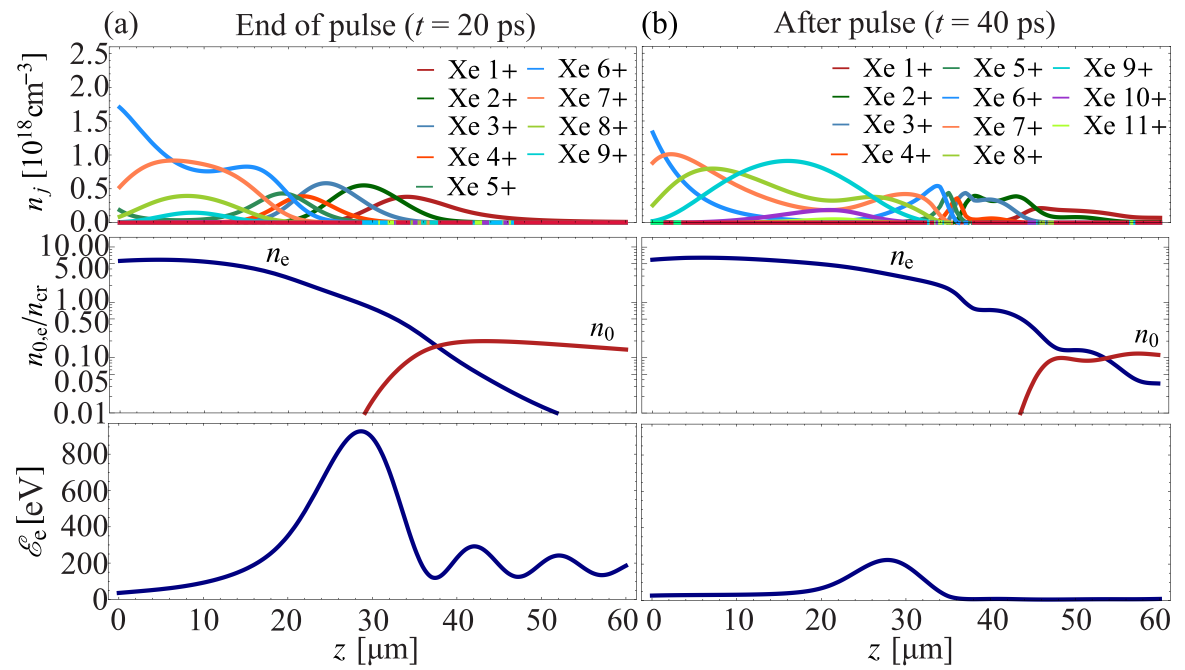

Figure 2: *The discharge parameters at 20 ps (a) and 40 ps (b) after the start of the FEL pulse.*

The overdense multiply charged plasma spot is of 30 μm in length at the end of the THz-pulse (fig. 2a). This spot radiates 50 kW of power in the EUV range including 1 kW in 11.2 nm±1% band. After the THz-pulse, the ionization process continues resulting in even higher ion charges (fig. 2b). The EUV radiation power is maximal at 40 ps reaching the level of 25 kW in 11.2 nm±1% of 250 kW in total (fig. 3). After 80 ps, cooled enough plasma stops emitting EUV light in 11.2 nm±1% range. The total emitted energy in 11.2 nm±1% is 700 nJ per one THz-pulse.

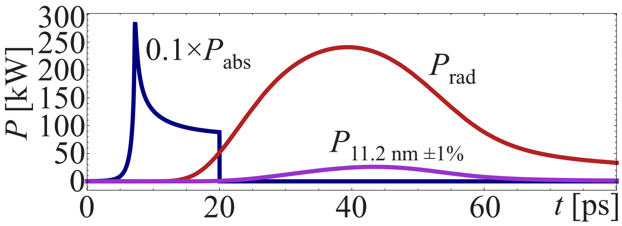

Figure 3: *Absorbed power* (P_{abs})*, total* (P_{rad}) *and in-band* ($P_{11.2\text{nm}\pm1\%}$) *EUV radiation power.*

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