Production of photoionized plasmas by the interaction of short FEL pulses with gaseous medium

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Overview

• Important to understand photoionization of gases with XUV radiation;
• Photoionized gas jets produce unique engineered plasmas with $n_e = 10^{18}-10^{20}$ cm$^{-3}$;
• Photoionization with $\sim$40 eV– few keV photons and long collision relaxation time leads to non-equilibrium plasma;
• Characterization of post-ionized plasma;
• Self Thomson scattering at various angles to probe non-equilibrium distribution and in future regular Thomson scattering to study relaxation to thermal distribution;
• Emission from non-equilibrium plasma;
• Plasma instabilities and turbulence
Experimental Parameters

He gas jet:
- $n_a = 5 \times 10^{18} \text{ cm}^{-3}$, 1 mm diameter, 10 Hz

FEL pulse:
- $N_\gamma = (1-5) \times 10^{12}$ – incident photons with $\hbar \omega = 40 \text{ eV}$
- pulse duration $\tau = 50 \text{ fs}$, bandwidth $\Delta \omega / \omega \approx 0.003 - 0.005$,
- $d = 20 \mu \text{m} –$ focal spot size, xuv intensity $\sim 10^{14} \text{ Wcm}^{-2}$

Plasma:
- weakly ionized, $N_\gamma \ll d^2 / \Sigma$
- xuv absorption length $l_{abs} = 1/n_a \Sigma \sim 1 \text{ mm}$
- electron energy $\varepsilon = mv_0^2/2 = \hbar \omega - I \cong 15 \text{ eV}$, electron-atom collision time $\sim 1 \text{ ps}$.

Planned programs $\rightarrow$ $\hbar \omega > 1 \text{ keV} \rightarrow$ comparative analysis for $\hbar \omega = 100, 300 \text{ eV}$
Physical processes

Integral cross sections for neutral He versus the energy of projectile (electron or photon):

1) Recombinational processes are not included because they are occur on a ns-time-scale.

2) Photoionization of ions He is disregarded, since the degree of ionization is assumed to be small.

3) Two-photon photoionization is ignored because its cross section is much smaller than $\Sigma$ since $N_\gamma \frac{d^2}{\Sigma}$.
The Monte Carlo model (I)

\[
\frac{d^2\sigma}{d\cos\theta d\varphi} = \Sigma(\hbar\omega) \frac{3}{4\pi} (\sin\theta \cos\varphi)^2
\]

\(\Sigma=3\text{Mb}, \ \hbar\omega=40\text{eV}\)

\(\Sigma=0.34\text{Mb}, \ \hbar\omega=100\text{eV}\)

\(\Sigma=0.015\text{Mb}, \ \hbar\omega=300\text{eV}\)

Homogeneous cylindrical x-ray beam. The behavior of electrons in He gas is calculated by MC direct simulation method with semi-infinite simulation box, \(Z>0\).

Time points of photoelectron production were randomly sampled with the same probability for \(\tau \geq t \geq 0\).

Electron photoproduction in gas medium \((z > 0) \sim \Sigma \exp(-\Sigma z)\)

The total number of primary photoelectrons: \(10^8, 5\times10^7, \text{ and } 10^7\);

Simulation times: 55.3 ps, 108 ps, and 244 ps

The simulation box is divided into the cells in the cylindrical coordinate system: partitions in \(z\)-direction (10 bins), sectoring (20 bins), and radial partitions (15 bins). The calculation in velocity space is performed by a three-dimensional model. The velocity space is not divided into cells while the code generates the averaged electron velocity component and the averaged squared electron velocity component for each space cell. There are no time steps, although the simulation time is broken into 50 time intervals for analysis purposes. This gives a total number of space-time cells of 150000. The code samples the elastic and inelastic mean free path and redistributes particles at the time point of electron collision in accordance with their coordinates and current time.
The Monte Carlo model (II)

1. Elastic electron collisions

\[ \cos \theta = 1 - \frac{2 \zeta}{1 + 8(1 - \zeta)E} \]  

(the scattering angle)

Here \( \zeta \) is a random number uniformly distributed in the interval \([0,1]\) and \( E \) is \( \varepsilon \) in AU.

2. Ionization

\[ \sigma_I(\varepsilon) = \frac{q_0 A}{I^2} \left( \frac{I}{\varepsilon} \right) \sum_{\mu=0}^{\nu} (-1)^{\mu} \left( \frac{\nu}{\mu} \right) \left( \frac{\varepsilon I + 1}{2} \right)^{\Omega + \mu \nu - 1} - 1 \]  

\[ \frac{(\varepsilon I)^{-\mu \nu}}{\Omega + \mu \nu - 1}, \]

(Stolarski-Banks form)

The residual energy \( \varepsilon - I \) is shared between the energy, \( \varepsilon_1 \), of scattered electron and the energy, \( \varepsilon_2 \), of secondary (ejected) electron, \( \varepsilon_1 + \varepsilon_2 = \varepsilon - I \). This energy sharing depends on the differential ionization cross section, \( \sigma(\varepsilon, \varepsilon_2) \), which is taken as

\[ \sigma(\varepsilon, \varepsilon_2) = \frac{C(\varepsilon)}{1 + (\varepsilon_2 / \varepsilon)^{2.1}}, \]

\( C(\varepsilon) \) is a fitting function derived from experiments.

3. Atom excitation

\[ \sigma_j(\varepsilon) = \frac{q_0 A}{E_j^2} \left( \frac{E_j}{\varepsilon} \right)^{\Omega} \left[ 1 - \left( \frac{E_j}{\varepsilon} \right)^{\gamma} \right]^{\nu}, \]

(Grin-Stolarski form)

The energy of the electron after excitation of atom is \( \varepsilon - E_j \). The outgoing electrons are assumed to be isotropically distributed. Three main excitation levels, 1snp \((n=1,2,3)\), which provide sufficient accuracy of excitation modelling are taken into account.
EDF for $\hbar \omega = 40 \text{ eV}$
Electron density for $\hbar \omega = 40$ eV (I)

$\lambda_e = (n_a \sigma_e)^{-1}$ is comparable to the x-ray spot size. Hence, the nature of the electron transport is kinetic rather than diffusive. The electron flux along x-ray polarization direction dominates. Correspondingly, the initially produced circular cross-section plasma column takes an elliptical form. 0.28-0.55 (1), 3.9-4.4 (2), 9.4-10 (3), 53-55 (4) ps
Electron energy for $\hbar \omega = 40$ eV

The x,y spatial disparity is even more distinctly seen from evolution of $T_x$. 

Electron density for $\hbar \omega = 40$ eV (II)

This figure shows the electron density profiles along X- and Y-axes.
The excitation processes lead to formation of satellite lines in the electron energy spectrum which becomes quasi-multi-mono-energetic with corresponding energies \( (\hbar \omega - I) - nE_j \)

\[
E_j \approx (21.2 - 23.7) \text{ eV}
\]

\[
\nu_i \approx n_a (\sigma_i + \sum_j \sigma_j) \sqrt{\varepsilon/m_e}
\]
Unlike excitation processes, ionization provides a weak background of continuous electron spectrum. Asymptotically ($t \rightarrow \infty$) low energy electrons form isotropic band structure in energy space, at energies about 20eV, which is not enough to cause atom excitation. This band structure has a smoothed maximum at an energy $\sim 7-8$eV. This is because the excitation cross section dominates the ionization one for $\leq 30$ eV and the characteristic residual energy after atom excitation by the electrons with such energy is $\varepsilon - E_f \approx 7-8$ eV.
Asymptotic EDF band structure

Quasistationary electron energy spectra for interaction of 100 fs x-ray beam of 10 µm diameter and (1) 100 eV, (2) 300 eV (2), and (3) 500 eV photon energies with a gas jet having the density 10^{19} cm^{-3}.
Electron density for $\hbar \omega = 100$ eV

0.5-1.1 (1), 7.6-8.6 (2), 18-19 (3), 102-108 (4) ps
Electron density for $\hbar \omega = 300$ eV

The spatial asymmetry along and perpendicular to the x-ray polarization vector is distinct. It remains even for longer times than for the case of low energy EUV pulse (40 eV)

1.2-2.4 (1), 17-20 (2), 41-44 (3), 231-244 (4) ps
Electron energy relaxation

The EDF anisotropy disappears on a picosecond time scale. The characteristic time scale of the EDF isotropization, $\tau_e$, is defined by the effective collision frequency $\tau_e = (\nu_e + \nu_i)^{-1}$. For considered parameters this value is almost the same for both cases of low and high energy photons, $\tau_e \approx 3\text{ps}$
Dielectric tensor

\[ \varepsilon_{ij} = \delta_{ij} + \delta \varepsilon_{ij}^{(e)} + \delta \varepsilon_{ij}^{(i)} \]

Only electrons contribute on the fs scale

\[ \delta \varepsilon_{ij}^{(e)} = \frac{\omega_{pe}^2}{n_e \omega} \int \frac{v_i \, d^3 v}{\omega - k \cdot v} \frac{\partial f}{\partial v_1} \left[ \left( 1 - \frac{k \cdot v}{\omega} \right) \delta_{ij} + \frac{k_i v_j}{\omega} \right] \]

Plasma dispersion equation:

\[ |c^2 (k^2 \delta_{ij} - k_i k_j) - \omega^2 \varepsilon_{ij}(\omega, k)| = 0 \]

\[ \delta \varepsilon^{(e)} = -\frac{\omega_{pe}^2}{\omega^2} \]

\[ \begin{pmatrix} \delta \varepsilon_{xx} & 0 & \delta \varepsilon_{xz} \\ 0 & \delta \varepsilon_{yy} & 0 \\ \delta \varepsilon_{zx} & 0 & \delta \varepsilon_{zz} \end{pmatrix} \]

\[ k \perp E \parallel OY \]

\[ c^2 k^2 - \omega^2 + \omega_{pe}^2 \delta \varepsilon_{yy} = 0, \]

\[ (c^2 k^2 - \omega^2 + \omega_{pe}^2 \delta \varepsilon_{xx})(\omega^2 - \omega_{pe}^2 \delta \varepsilon_{zz}) + \omega_{pe}^4 \delta \varepsilon_{xz} = 0. \]
Dispersion properties of photoionized plasma

For $\theta_0=0$ and $\theta_0=\pi/2$ dispersion equation is separated into two relations:

\[
\omega^2 = \omega_{pe}^2 \delta \varepsilon_{zz}, \quad \text{electrostatic}
\]

\[
\omega^2 = c^2 k^2 + \omega_{pe}^2 \delta \varepsilon_{xx}, \quad \text{electromagnetic}
\]

Undamped electrostatic mode for $\omega / kv_0 > 1$:

\[
\omega^2 = \omega_{pe}^2 \left(1 + \frac{3}{5} \frac{k^2 v_0^2}{\omega_{pe}^2}\right), \quad \omega_{pe}/kv_0 \gg 1 \\
\omega = kv_0 \left(1 + 2 \exp \left[\frac{-2}{3} \frac{k^2 v_0^2}{\omega_{pe}^2}\right]\right), \quad \omega_{pe}/kv_0 \ll 1
\]

\[
\omega^2 = \omega_{pe}^2 \left(1 + \frac{1}{5} \frac{k^2 v_0^2}{\omega_{pe}^2}\right), \quad \omega_{pe}/kv_0 \gg 1 \\
\omega = kv_0 \left(1 + \frac{3}{2} \frac{\omega_{pe}^2}{k^2 v_0^2}\right), \quad \omega_{pe}/kv_0 \ll 1
\]
Plasma Instabilities

Photo electron two stream (PETS) instability:

\[ \gamma_{\text{PETS}} = 0.21kv_0 \frac{3-(kv_0/\omega_{pe})^2}{\sqrt{1+1.1(kv_0/\omega_{pe})^2}}, \]

\[ \gamma_{\text{max}} = 0.31\omega_{pe} \text{ at } k \approx 0.82\omega_{pe}/v_0, \theta_0 = 0 \]

Photo electron Weibel (PEW) instability:

\[ \gamma_{\text{PEW}} = \frac{1}{4}kv_0 \frac{2-(kc/\omega_{pe})^2}{\sqrt{1+(kc/\omega_{pe})^2}}, \theta_0 = \pi/2 \]

\[ \gamma_{\text{max}} = 0.22\omega_{pe}(v_0/c) \text{ at } k \approx 0.7\omega_{pe}/c \]

2. PEW:

\[ G = (\gamma/\omega_{pe})(c/v_0), \]

\[ \theta_0 = 0, K = kc/\omega_{pe} \]

1. PETS:

\[ G = \gamma/\omega_{pe}, \]

\[ \theta_0 = \pi/2, K = kv_0/\omega_{pe} \]
2D PIC simulation of PITS instability

⇑ Classical TS instability ⇐

Linear regime ⇒
Saturation at the time of several $1/\gamma_{max}$ with $W_E \sim 5\% W_T$ ⇒
$W_E$ monotonous decreases up to initial noise

The modes with non-zero angle between $\mathbf{k}$ and $\mathbf{e}$ provide
 generation of magnetic field with energy $W_H \sim (10^{-2} - 10^{-3}) W_E$.

Electron energy anisotropy dramatically reduces to just several
percents and $k$-spectrum enrich oneself by long wavelengths.

periodic boundary conditions;
"quiet start" algorithm;
$n_e=510^{18} \text{cm}^{-3}$;
$\varepsilon=40 \text{ eV}$;
Electromagnetic field generation

\[
\frac{\partial f}{\partial t} + v \frac{\partial f}{\partial r} - \frac{e}{m} \left( E + \frac{1}{c} \mathbf{v} \times \mathbf{B} \right) \frac{\partial f}{\partial \mathbf{v}} = \frac{3}{4\pi} \frac{\partial n_e}{\partial t} \frac{(\mathbf{e} \cdot \mathbf{v})^2}{v^4} \delta(v - v_0)
\]

\[
\left\{ \begin{aligned}
\frac{\partial j}{\partial t} + \frac{e}{m} \nabla \cdot \Pi - \frac{e^2 n_e}{m} E &= 0, \\
\Pi_{ij} = m \int d^3 \nu v_i v_j f &= P_{ij} + n_e m u_i u_j
\end{aligned} \right.

\]

Quasistationary magnetic field

\[
\Pi = \mathbf{P}
\]

\[
\frac{\partial \mathbf{E}}{\partial t} = \frac{c^2}{\omega} \nabla \times \nabla \times \mathbf{E} + \omega_{pe}^2 \mathbf{E} = \frac{4\pi e}{m} \nabla \cdot \Pi,
\]

\[
\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E},
\]

\[
\omega_{pe} \tau, L \omega_{pe}/c \gg 1
\]

\[
\nabla \times \mathbf{P}/\nabla \cdot \mathbf{P} = \text{ thermo-EMF }
\]

\[
\frac{\partial \mathbf{B}}{\partial t} = -\frac{c}{e} \nabla \times \frac{1}{n_e} \nabla \cdot \mathbf{P}
\]

\[
P_{ij} = P \delta_{ij}
\]

\[
\frac{\partial \mathbf{B}}{\partial t} \propto \nabla n_e \times \nabla T
\]
Quasistationary magnetic field generation

\[
\frac{\partial}{\partial t} \left( \mathbf{B} - \frac{c^2}{\omega_{pe}^2} \mathbf{B} - \frac{c^2}{\omega_{pe}^2} \nabla \cdot \ln n_e \times \nabla \times \mathbf{B} \right) = -\frac{c}{e} \nabla \times \frac{1}{n_e} \nabla \cdot \mathbf{P}
\]

- sausage type plasma speckle \( l \gg d/2 \)
  \[
  \frac{\partial}{\partial t} \left[ \left( 1 + \frac{4 c^2}{\omega_{pe}^2 r^2} \right) \mathbf{B}_x + \frac{c^2}{\omega_{pe}^2} \left( \frac{\partial \ln n_e}{\partial r} - \frac{1}{r} \frac{\partial}{\partial r} \right) \frac{\partial B_x}{\partial r} \right] = \frac{-2 c e}{5 e} \sin 2 \varphi \left( \frac{r}{\partial \varphi} \frac{1}{\partial r} \frac{\partial \ln n_e}{\partial r} \right)
  \]

- pancake type plasma \( l \ll d/2 \)
  \[
  \frac{\partial}{\partial t} \left[ \left( 1 + \frac{c^2}{\omega_{pe}^2 r^2} \right) \mathbf{B}_y + \frac{c^2}{\omega_{pe}^2} \left( \frac{\partial \ln n_e}{\partial x} - \frac{\partial}{\partial x} \right) \frac{\partial B_y}{\partial x} \right] = \frac{4 c e}{5 e} \cos \varphi \frac{\partial^2}{\partial r \partial x} \ln n_e,
  \]

\[\mathbf{E} \parallel OZ \]
\[\mathbf{k} \parallel OX\]

**B contour plot:**

\[n_e = n_0(t)(1 + r^2/r_0^2 + x^2/l^2)^{-1}\]

\(l = 2r_0\)

\[|B|_{\text{max}} = \frac{v_0 c e r_0}{5 \omega_{pe}} \left| \frac{\partial}{\partial r} \frac{1}{r} \frac{\partial}{\partial r} \ln n_e \right|, \quad l \gg d/2 \]

\[\frac{|B|_{\text{max}}}{\sqrt{8 \pi n_e \varepsilon}} = \frac{2 v_0 c e r_0}{5 \omega_{pe}} \left| \frac{\partial^2}{\partial r \partial x} \ln n_e \right|, \quad l \ll d/2 \]

**generation rate:**

\(~3 \text{ kG/ps} \quad \varepsilon = 30 \text{ eV}\)
\(~50 \text{ kG/ps} \quad \varepsilon = 500 \text{ eV}\)

~ \(d/l\) times higher for pancake type plasma
**Electromagnetic emission**

**T-ray pulse**

cylindrical plasma speckle

\[ n_e = n_a [1 - \exp(-t/\tau_0)] \eta(r_0 - r) \cos^2(\pi r/2r_0) \]

\[ \mathbf{B} = \{ B_x, 0, 0 \} \quad \mathbf{E} = \{ 0, E_x, E_z \} \]

plasma antenna has an angular directedness

\[ \propto \sin 2\varphi \]

video-pulse

in the \( B_0 \)-units

\[ 2\pi B_0 = (T_\perp/mc^2)^{1/2} (4\pi n T_\perp)^{1/2} \]

\( \varphi = \pi/4; \ r = 10.6r_0, 19.5r_0 \)

The optimum conditions for effective EMW generation

\[ \omega \sim 1/\tau_0 \]

\[ c\tau_0 \sim c\omega^{-1} \sim k^{-1} \sim r_0 \gg c/\omega_{pe} \]
Parametrization of the T-emission

\[
\int (d\omega_p/2\pi) \int (d\varphi 4\pi) (r\omega_p/2\pi c) |\mathbf{E} \times \mathbf{B}|/B_0^2
\]

\[\omega-k\] matching:

\[c\tau_0 \sim c/\omega \sim 1/k \sim r_0 \sim c/\omega_{pe}\]

\[\text{dimensionless linear energy density}\]

\[
\int (d\omega_p/2\pi) \int (d\varphi 4\pi) (r\omega_p/2\pi c) |\mathbf{E} \times \mathbf{B}|/B_0^2
\]

\[\text{peak EMW energy flux}\]

\[
\int (d\varphi 2\pi) (r\omega_p/2\pi c) (|\mathbf{E} \times \mathbf{B}|/4\pi B_0^2)
\]

\[\text{EMF pulse-duration (}\Delta T\text{)}\]

For example, at the distance \(r = 100r_0\) intensity is \(I \approx 0.02 \times (cB_0^2/4\pi)\)
for the conditions \(\tau_0 = \omega_p^{-1}, r_0 = 8c/\omega_p\). For \(\tau_0 = 100\text{ fs}, r_0 = 15 \mu\text{m}\),
\(n_a = 10^{19}\text{ cm}^{-3}\) this gives the intensity \(I \approx 3\varepsilon^2(\text{W/cm}^2\), where \(\varepsilon\) is in eV\)
of the ~5THz emission at the distance \(r = 1.5\text{ mm}\) from the plasma source.

For 30 eV photoelectrons this is equivalent to peak electric field of ~400 V/cm
at the detector.
Conclusion

• Using the Monte Carlo method the electron distribution function and electron transport in gas medium were studied;
• These results are particularly important for the study of the EDF by using either self-Thomson x-ray scattering or Thomson scattering of a probe laser beam;
• On the time scale of electron collisions the energy anisotropy disappears and, depending on the photon energy, the initial monoenergetic EDF either holds (low energy photons, ) or splits into several broadened energy lines (high energy photons, ), i.e. taking a form of quasi-multi-monoenergetic EDF;
• For hard EUV photons, the EDF evolves asymptotically in time to an isotropic distribution of bell-shaped form with a maximum of 7-8 eV;
• The spatial symmetrization of plasma across FEL beam happens on a much longer time scale (t>100 ps), because it depends on the particle transport. The circular section of the initially produced plasma channel takes an elliptic shape.
• This underdense plasma at ~ps time scale will serve as a test bed for studying non-equilibrium plasma phenomena including
  – Plasma antenna
  – Photo electron two stream instability
  – Photo electron Weibel instability