Моделирование эксперимента по генерации ТГц излучения при столкновении лазерных кильватерных волн в плазме

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Radiation mechanism

Let two Langmuir waves propagate in a cold uniform plasma in opposite directions along the same z-axis with equal phase velocities. In the linear approximation, the electrostatic potential can be written as the sum:

$$\Phi(t,\mathbf{r}) = \Phi_1(\mathbf{r}_\perp)e^{ikz-i\omega t} + \Phi_2(\mathbf{r}_\perp)e^{-ikz-i\omega t} + c.c.$$

Amplitudes of density and velocity perturbations for plasma electrons take the form:

$$v_{1\|} = -\frac{k}{\omega}\Phi_1(\mathbf{r}_\perp), \quad v_{2\|} = \frac{k}{\omega}\Phi_2(\mathbf{r}_\perp),$$
$$\delta n_{1,2} = \frac{1}{\omega^2}(\Delta_\perp - k^2)\Phi_{1,2}(\mathbf{r}_\perp).$$

Nonlinear interaction of these waves generates the longitudinal electric current

$$\mathcal{J}_\| = -(\delta n_1 v_{2\|} + \delta n_2 v_{1\|})e^{-i2\omega t} + c.c.,$$

which is able to radiate electromagnetic waves transversely to the propagation axis.

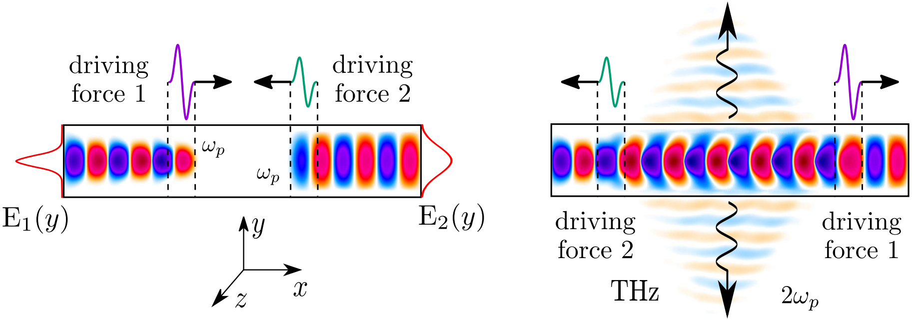
Radiation mechanism

The nonlinear current

$$\mathcal{J}_{\|} = \frac{k}{\omega^3}\left(\Phi_1 \Delta_\perp \Phi_2 - \Phi_2 \Delta_\perp \Phi_1\right)$$

can generate the $2\omega_p$-radiation if colliding Langmuir waves have differing transverse profiles

$$\Phi_1(\mathbf{r}_\perp) \neq \Phi_2(\mathbf{r}_\perp). \tag{1}$$



I.V.Timofeev, V.V.Annenkov, E.P.Volchok. Generation of high-field narrowband terahertz radiation by counterpropagating plasma wakefields. Phys. Plasmas **24**, *103106 (2017)*

Excitation of wakes by laser pulses

Axially symmetric gaussian laser pulses with the envelopes

$$a_s = a_{0s}\frac{\sigma_{0s}}{\sigma_s(z)}e^{-r^2/\sigma_s^2(z)}\sin^2\left(\frac{\pi(t \pm z)}{2\tau}\right),$$

$$\sigma_s(z) = \sigma_{0s}\sqrt{1 + z^2/\mathcal{R}_s^2}, \quad \mathcal{R}_s = \omega_0\sigma_{0s}^2/2.$$

act on plasma electrons through the ponderomotive force and excite plasma wakes with the following potential profiles

$$\Phi_s(r) = \Phi_s^w\left(\frac{\sigma_{0s}}{\sigma_s(z)}\right)^2 e^{-2r^2/\sigma_s^2(z)},$$

$$\Phi_s^w = \frac{3}{4}a_{0s}^2\frac{\sin\tau}{(4 - 5\tau^2/\pi^2 + \tau^4/\pi^4)}.$$

Optimal duration of laser pulses is $\tau \approx \pi/\omega_p$.

Radiation power

The amplitude of radially propagating THz wave at the plasma boundary ($r = R$) can be presented in the form

$$\mathcal{E}_0 = \frac{3\Phi_1^w\Phi_2^w\mathcal{F}_\sigma}{2\sqrt{(2\sqrt{3}RJ_1 - J_0)^2 + 16R^2J_0^2}}, \qquad (2)$$

$$\mathcal{F}_\sigma = \frac{\sigma_{01}^2\sigma_{02}^2\left|\sigma_2^2 - \sigma_1^2\right|}{(\sigma_1^2 + \sigma_2^2)^2}\exp\left[-\frac{3}{8}\frac{\sigma_1^2\sigma_2^2}{\sigma_1^2 + \sigma_2^2}\right], \qquad (3)$$

where $J_n = J_n(\sqrt{3}R)$ are the Bessel functions of the order n. The total radiation power is

$$\frac{P}{P_0} = \pi R\int \mathcal{E}_0^2 dz, \qquad P_0 = \frac{m_e^2c^5}{4\pi e^2} \approx 0.69 \text{ GW}.$$

These formulas allow to find the optimal overlapping of colliding wakes.

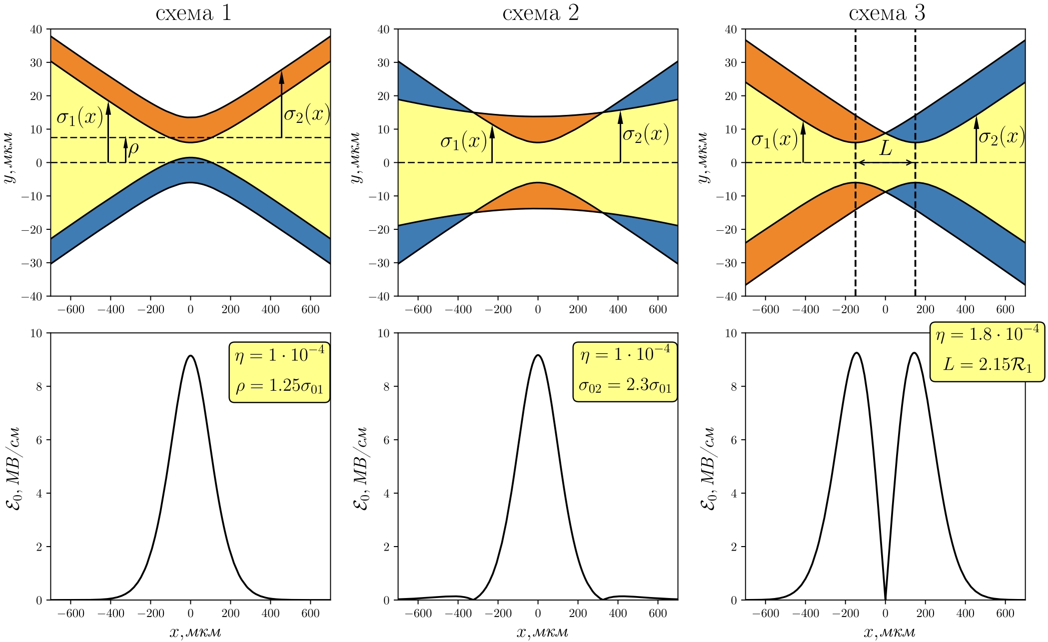
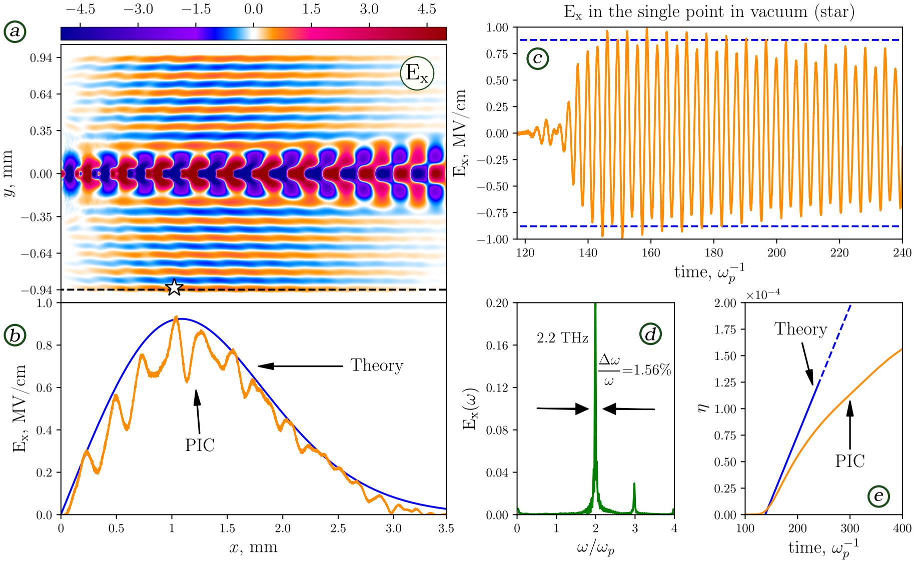
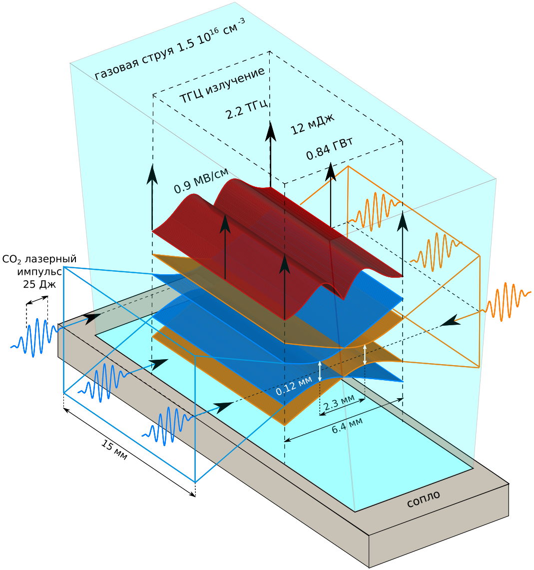


схема 1
схема 2
схема 3
y, мкм
x, мкм
$\mathcal{E}_0$, МВ/см
$\sigma_1(x)$
$\sigma_2(x)$
ρ
L
$\eta = 1 \cdot 10^{-4}$
$\rho = 1.25\sigma_{01}$
$\eta = 1 \cdot 10^{-4}$
$\sigma_{02} = 2.3\sigma_{01}$
$\eta = 1.8 \cdot 10^{-4}$
$L = 2.15\mathcal{R}_1$
40
30
20
10
0
−10
−20
−30
−40
−600
−400
−200
0
200
400
600
10
8
6
4
2
0

We have confirmed our theoretical predictions by PIC simulations in plane geometry (two 500 fs CO$_2$ laser pulses with equal amplitudes $a_{1,2} = 0.7$ are injected into the uniform plasma layer with the density $1.5 \cdot 10^{16}$ cm^{-3}).



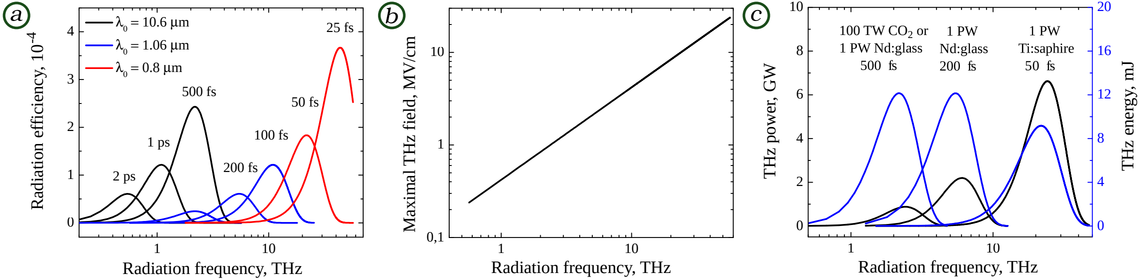

газовая струя 1.5 10^{16} см$^{-3}$
ТГц излучение
2.2 ТГц
12 мДж
0.84 ГВт
0.9 МВ/см
CO$_2$ лазерный
импульс
25 Дж
0.12 мм
2.3 мм
6.4 мм
15 мм
сопло

Tunability of radiation frequency

Radiation frequency $f_R = \omega_p/\pi \propto \sqrt{n}$

Laser pulse duration: $\tau \approx \pi/\omega_p \propto 1/\sqrt{n}$

Efficiency of plasma wake excitation $\propto \omega_p/\omega_0$.

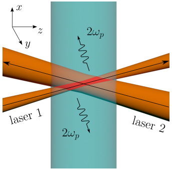


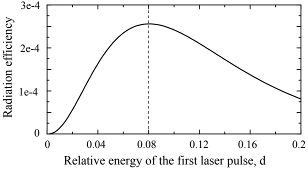
Optimal parameters for demonstration experiment

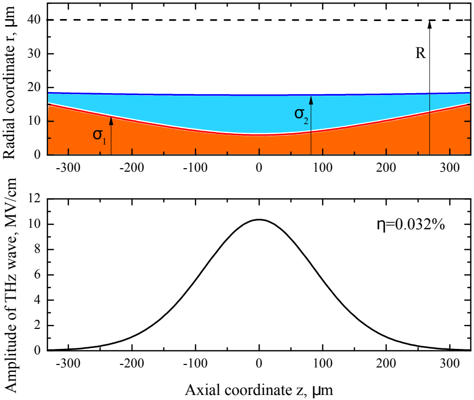
We propose to carry out a proof-of-principle experiment on the collision of two gaussian laser pulses in a supersonic gas jet using TW laser system ($\lambda_0 = 830$ nm, 0.2 J).

Parameter	Value
Laser wavelength, λ_0	830 nm
Energy of the 1st laser pulse, $\mathcal{W}_{L1}$	16 mJ
Energy of the 2st laser pulse, $\mathcal{W}_{L2}$	184 mJ
Spot-size of the 1st laser pulse, σ_{01}	6.3 μm
Spot-size of the 2st laser pulse, σ_{02}	18 μm
Maximal laser strength, a_{01}	0.67
Maximal laser strength, a_{02}	0.8
Duration of laser pulses, τ	39 fs
Density of plasma electrons, n_0	$2.5 \cdot 10^{18}$ cm^{-3}
Radius of plasma channel, R	40 μm
Length of radiating plasma channel	0.6 mm
Nozzle diameter	1.5 mm
Frequency of THz radiation, $2\omega_p/(2\pi)$	28.4 THz

I.V.Timofeev et al. Plasma Phys. Control. Fusion 62*, 045017 (2020)*







PIC simulations of experiment

Effects not accounted for in theory

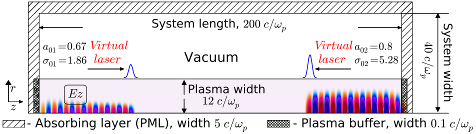
- Theory does not predict the duration of $2\omega_p$-radiation. It depends on
  - energy transfer from a primary wake to non-radiating harmonics due to electron nonlinearities ($\delta n \sim 0.5$),
  - ion dynamics (what gas is better to use?).
- What is the real size of a plasma channel produced by the field ionization and how does the nonuniform density profile influence on $2\omega_p$-emission?
- Effects of laser beams collision. What is the optimal delay between laser pulses?
- How does the radiation power depend on the collision angle?

Simulation layout

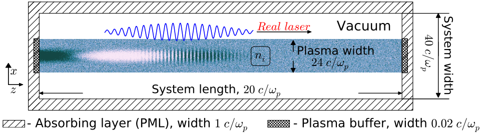
We use two numerical models:

- 2D3V axially symmetric PIC model with virtual laser pulses for full-scale simulations,
- 2D3V PIC model in Cartesian geometry with real laser pulses.

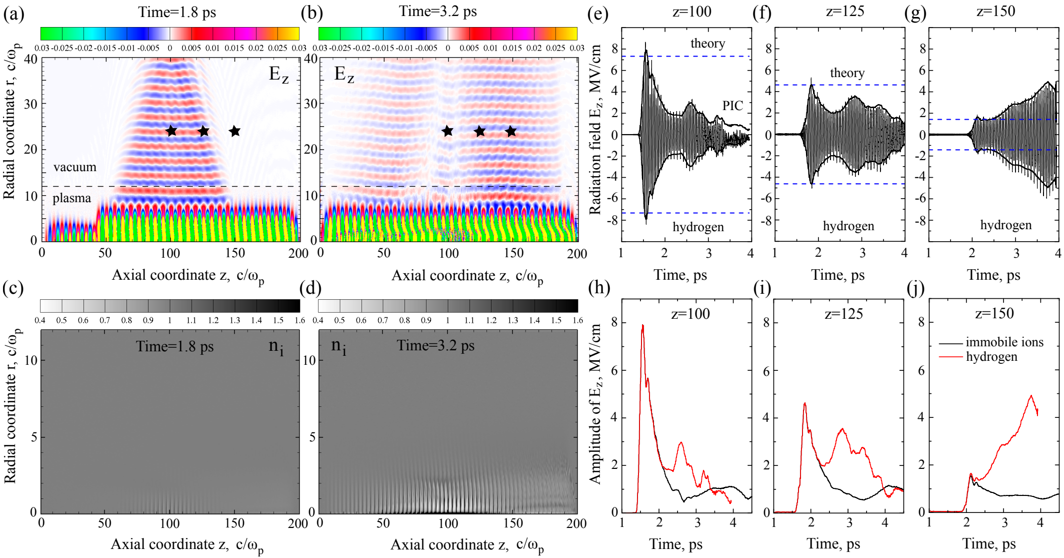
Axially symmetric



Cartesian



Effects of ion dynamics



Effects of ion dynamics

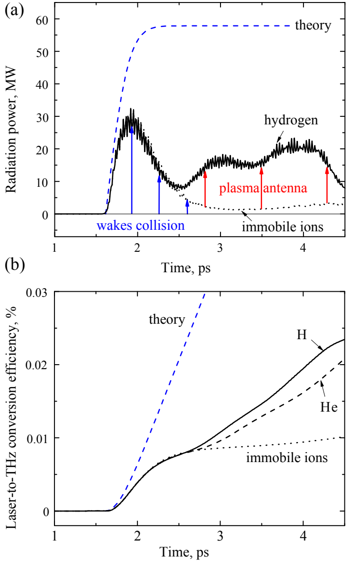
- Theory predicts correctly the amplitude of radiated THz wave in each spatial point, but the predicted amplitude profile is not simultaneously established along the whole radiating plasma length due to a small duration of $2\omega_p$-emission.
- Due to this effect, the total power emitted from the whole plasma volume turns out to be twice lower than the predicted value and reaches 30 MW.
- The duration of $2\omega_p$-emission due to the mechanism of wakes collision is limited by 1 ps.
- Finite-mass ions play the positive role by switching on the mechanism of plasma antenna:

$$(\omega, k) + (0, -q) \to (\omega, k-q)$$

$$(\omega, k) + (\omega, k-q) \to (2\omega, 2k-q)$$

Since $q = 2k$ in a standing wave, the nonlinear current radiates EM waves at 2ω transversely to the laser axis. Half of the total energy is radiated via the antenna mechanism. For light gases (H, He), the energy conversion efficiency reaches 0.02%.

We chose He as a target gas.



Field ionization of He

To calculate the probability of s-fold ionization of He

$$P_s = 1 - \exp\left(-\int_{t_0}^{t} W_s(t')dt'\right),$$

we will use the ionization rate $W_s(t)$ which goes through different regimes with increasing electric field:

$$W_s(E) = \begin{cases} W_{TI}(E), & E < E_1 \\ W_{BM}(E), & E_1 < E < E_2 \\ W_{BSI}(E), & E > E_2 \end{cases}$$

Tunnel ionization in a static field limit:

$$W_{TI} = \omega_a k_s^2 C_s \left(\frac{2}{F_s}\right)^{2n_s-1} \exp\left(-\frac{2}{3F_s}\right),$$

$$k_s = \sqrt{\frac{I_s}{I_H}}, \quad C_s = \frac{2^{2n_s}}{n_s\Gamma(2n_s)}, \quad F_s = \frac{E}{k_s^3 E_a},$$

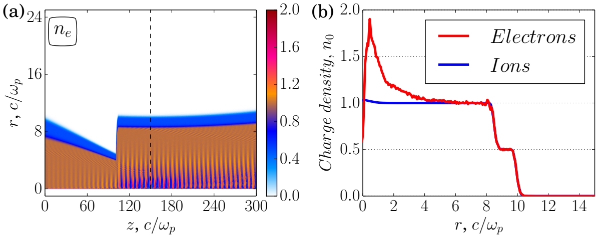
Bauer-Mulser ionization rate:

$$W_{BM} \approx 2.4\frac{\omega_a}{k_s^4}\left(\frac{E}{E_a}\right)^2.$$

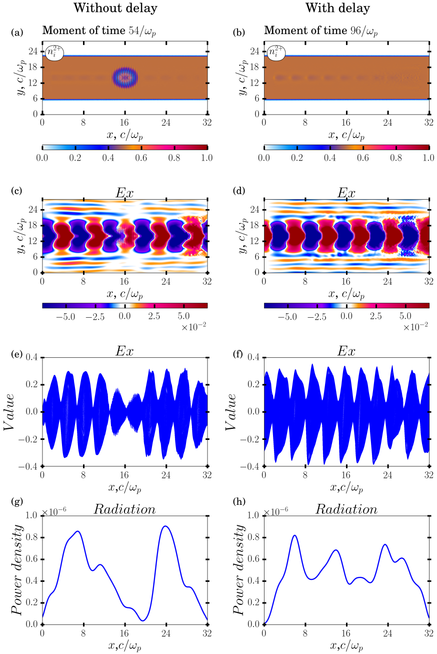
Barrier-suppression regime:

$$W_{BSI} \approx 0.8\frac{\omega_a}{k_s}\left(\frac{E}{E_a}\right).$$

Kostyukov et al. Field ionization rate for PIC codes. arXiv:1906.01358



The radius of fully ionized He plasma is large enough not to influence on wakes.



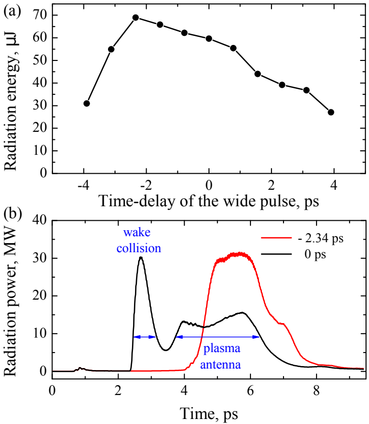
Overlapping of laser fields

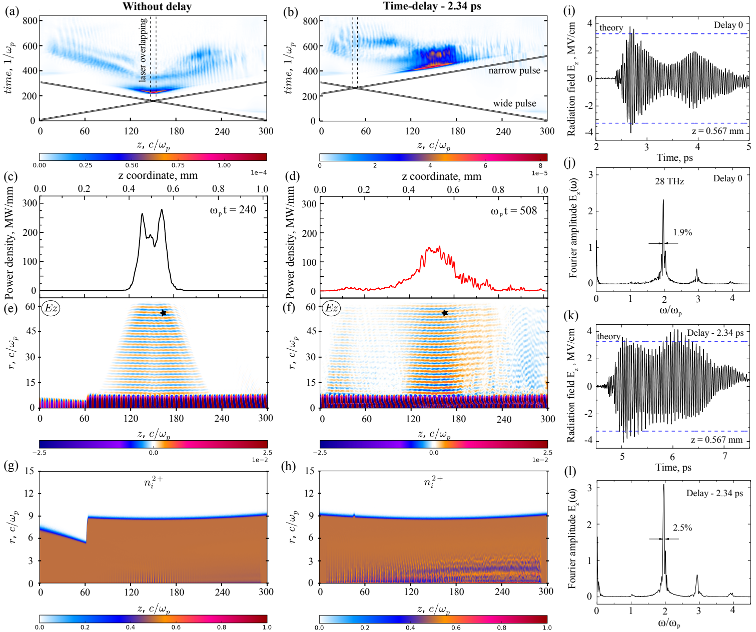
Ion density is rapidly modulated with the wavelength $\lambda_0/2$ by a standing EM wave in the overlapping region.

Both wakefields and $2\omega_p$-radiation inside this region is strongly reduced.

It is reasonable to shift this region from the focus.

Optimal time-delay





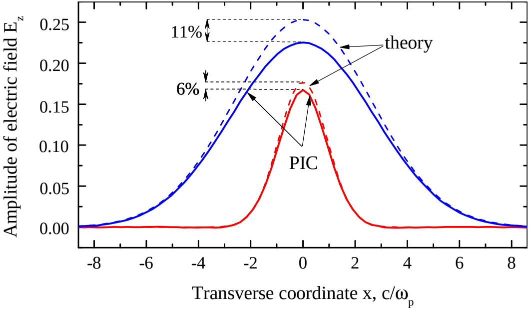
The use of helium allows to shift the region of laser beams overlapping far from the focus.

The narrow laser pulse should be delayed by 2-2.5 ps compared to the wide one in experiments.

The pulse of narrowband $2\omega_p$-radiation (28 THz with the line-width 2.5%) is predicted to reach the maximal power of 30 MW and total energy of 70 μJ.

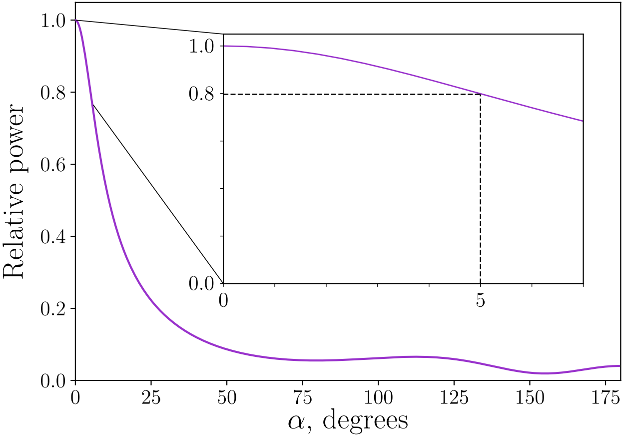
(Timofeev et al. submitted to Phys. Plasmas)

Accuracy of the ponderomotive approach



The model of virtual laser pulses overestimates the efficiency of laser-to-THz energy conversion by no more than 30% (> 20 MW, > 50 μJ).

Effects of finite collision angle and angular distribution of $2\omega_p$-emission



In the far zone, the angular distribution of radiation power is calculated as

$$\frac{dP}{d\Omega} = \frac{P_0 k}{8\pi^2 \omega \epsilon} \left| \int [\mathbf{J} \times \mathbf{k}] \, e^{-i\mathbf{kr}} d^3 r \right|^2 ,$$

where $\mathbf{k} = (\sqrt{3}\sin\theta\cos\varphi, \sqrt{3}\sin\theta\sin\varphi, \sqrt{3}\cos\theta)$ is the wavevector of radiated EM wave and $\epsilon = 3/4$ is the plasma dielectric constant. It is seen that

- the total radiation power decreases monotonically with the increase of angle
- at small angles $< 5^\circ$, this decrease does not exceed 20%

Head-on collision

Boundary problem

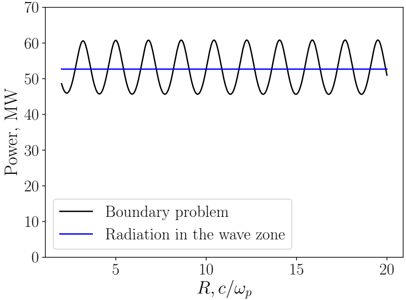
$$\frac{P}{P_0} = \frac{9\pi R}{4} (\Phi_1^w \Phi_2^w)^2 \int dz \frac{\mathcal{F}_\sigma^2}{(2\sqrt{3}RJ_1 - J_0)^2 + 16R^2 J_0^2}$$

$$\mathcal{F}_\sigma = \frac{\sigma_{01}^2 \sigma_{02}^2 \left|\sigma_2^2 - \sigma_1^2\right|}{(\sigma_1^2 + \sigma_2^2)^2} \exp\left[-\frac{3}{8}\frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2}\right]$$

Infinite plasma (far zone)

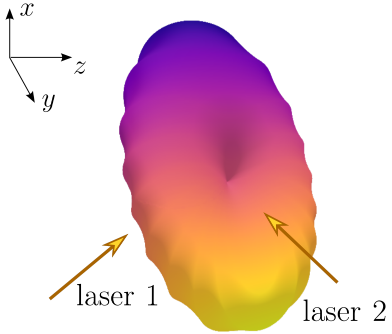
$$\frac{P}{P_0} = \frac{9\sqrt{3}}{256} (\Phi_1^w \Phi_2^w)^2 \int d\Omega \sin^6\theta \left|\mathcal{F}_\sigma e^{-i\sqrt{3}z\cos\theta} dz\right|^2$$

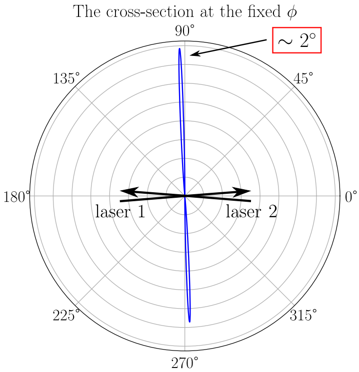
$$\mathcal{F}_\sigma = \frac{\sigma_{01}^2 \sigma_{02}^2 \left|\sigma_2^2 - \sigma_1^2\right|}{(\sigma_1^2 + \sigma_2^2)^2} \exp\left[-\frac{3}{8}\frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2} \sin^2\theta\right]$$

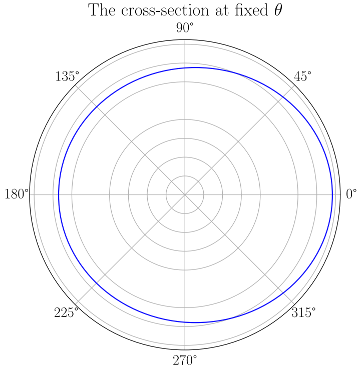


Angular distribution at $\alpha = 5^\circ$

- the direction of radiation propagation rotates together with a more narrow laser pulse

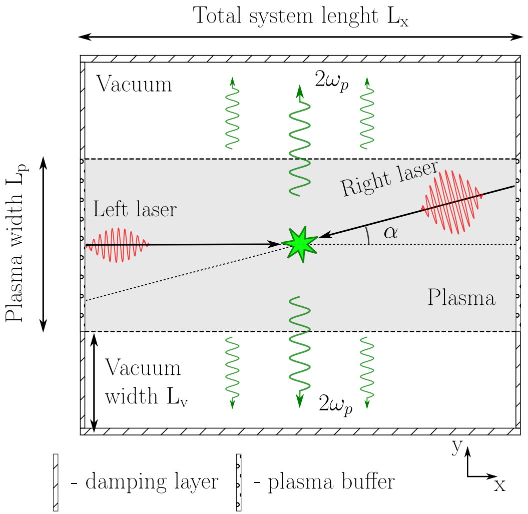


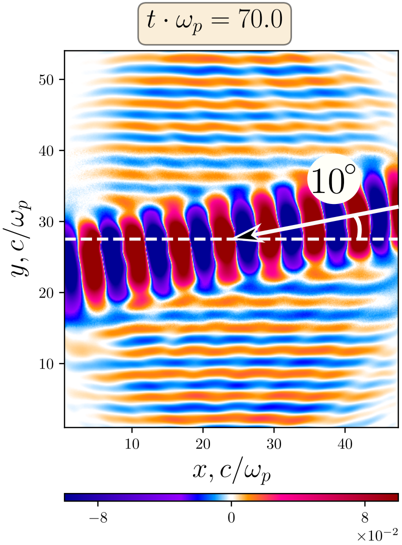




E.P.Volchok et al. Electromagnetic emission due to nonlinear interaction of laser wakefields colliding in plasma at an oblique angle // submitted to Plasma Phys. Control. Fusion

Emission angle in PIC simulations



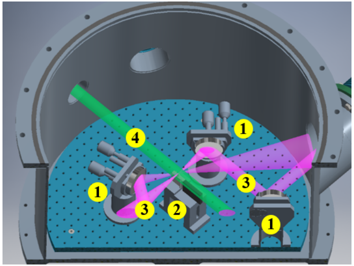


Laser system

We use two-channel multi-terawatt femtosecond laser system based on OPCPA in BaB_2O_4 (BBO) and LiB_3O_5 (LBO) crystals operating at the wavelength 830 nm with the pulse energy 0.2 J, duration 20 fs and repetition rate 10 Hz. A feature of this system is the high angular stability of the output radiation (5-7 μrad).

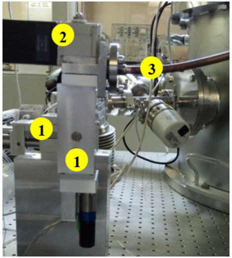
Institute of Laser Physics SB RAS (Novosibirsk)

Experimental setup



Layout of experimental setup (without the THz diagnostic). 1 – remote controlled 2D-turn parabolic mirrors, 2 – remote controlled 3D-move supersonic jet device, 3 – high-power laser beam, 4 – interferometer beam.

Vacuum chamber with a pumping system is ready to operation. Level of $2 \cdot 10^{-6}$ mBar is reached.

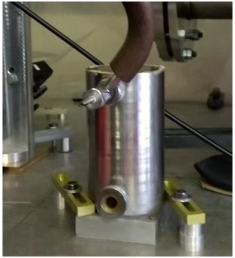


Testing of supersonic jet device prototype. 1 – vacuum translation stage, 2 – de Laval nozzle and fast pulsed gas valve, 3 – gas input tube.

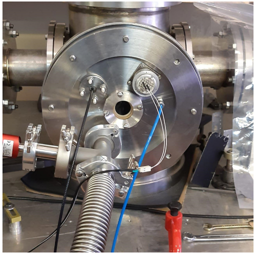
Design parameters of a gas flow are obtained (with nitrogen): diameter of flat region ~ 1.2 mm, density $10^{18} - 10^{19}$ cm^{-3}, Mach number ~ 4, backpressure is up to 9 atm.

Diagnostic of $2\omega_p$-emission (28 THz, 10-11 μm)

CaHgTe detector

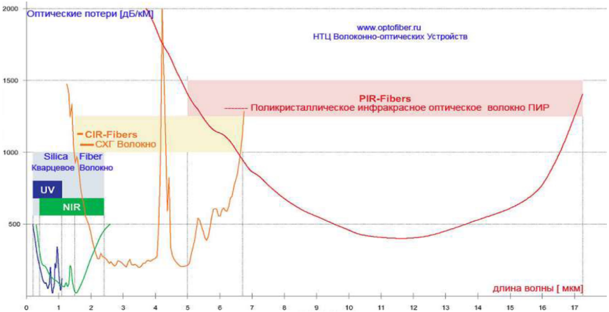


AgCl:AgBr waveguide



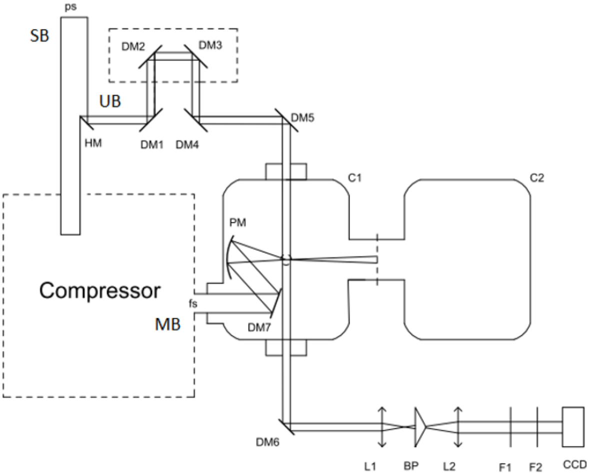
Technical parameters of detector	Resistor	Diode
Wavelength of peak sensitivity, μm	14.9	9.9
Long-wavelength limit of spectral sensitivity by $0.1\lambda_{0,1}$, μm	19	11.7
Response time, ns	160	70
Threshold power in peak sensitivity, W·Hz$^{-0.5}$	10^{-13}	10^{-12}

$2\omega_p$-radiation will be transmitted from a given spatial point inside the chamber to the cooled CaHgTe detector by the AgCl:AgBr waveguide with the following spectral dissipation



Options of resistor type and diode type detectors are considered. The construction, testing and calibration of the complete measurement system is started. Detailed study of system properties is planning at the Novosibirsk FEL.

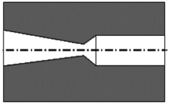
Scheme of interferometric measurements



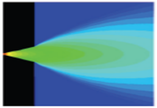
Jet: diameter is $1.2 \div 1.5$ mm, gas density is $10^{18} \div 10^{19}$ cm^{-3}, Mach number is $3 \div 4$, pulse duration ~ 6 ms.

Optical diagnostic of the gas density is on $\lambda =$ **532 nm**.

de'Laval nozzle

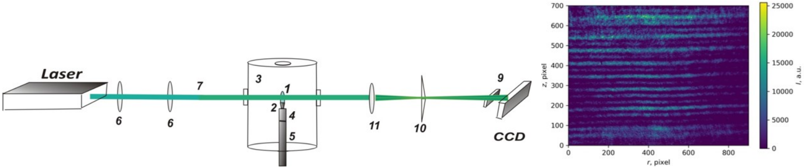


Supersonic jet

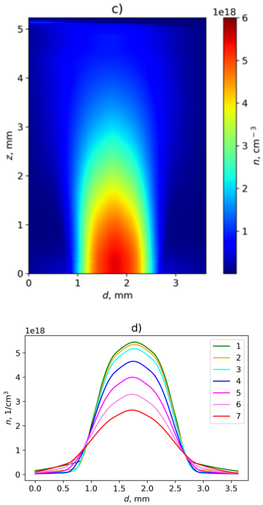


Scheme of the interferometric diagnostic; C1, C2 – vacuum chambers, SB – ps laser beam , MB – main fs laser beam, PM - parabolic off-axis mirror, SSJ – supersonic jet, UB – ps probe beam, HM – hot mirror, DM1 – DM6 – dielectric mirrors, L1, L2 - lenses, BP – Fresnel biprism, F1 – neutral density filter , F2 – selective filter, CCD camera.

Interferometric study of supersonic jet characteristics



The experimental setups with a biprism interferometer: 1 is a supersonic nitrogen jet, 2 is the de'Laval nozzle, 3 is the vacuum chamber, 4 is the pulse valve, 5 (Laser) is the Nd-YAG laser, 6 are lenses of a telescope system, 9 is a neutral density filter, 10 is a Fresnel biprism, 11 is a focusing lens.



(c) The retrieved gas density maps of the nitrogen supersonic jets after 6 ms delay relative voltage pulse to a valve, and (d) gas density radial distributions after 7 ms delay at various distances from the nozzle exit: 1 – 0.01 mm, 2 – 0.46 mm, 3 – 0.67 mm, 4 – 1.13 mm, 5 – 1.58 mm, 6 – 2.04 mm and 7 – 2.5 mm; the backing pressure is 9 bar.

S.V. Avtaeva, K.V. Gubin, V.I. Trunov, and P.V. Tuev. Algorithm for supersonic gas jet density profile retrieval from interferometric measurement// JOSA A, 2019, Vol. 36, No. 5 , pp. 910-917

Заключение

- Предложены оптимальные параметры лабораторного эксперимента, который должен продемонстрировать возможность генерации $2\omega_p$-излучения с узкой спектральной линией $\Delta\omega/\omega < 3\%$ за счёт лобового столкновения двух плазменных кильватерных волн, возбуждаемых в сверхзвуковой струе гелия парой гауссовых лазерных импульсов с длиной волны 830 нм, длительностью 40 фс и полной энергией 0.2 Дж.

- С помощью аналитической теории и PIC моделирования показано, что фокусировка встречных лазерных пучков в пятна различных размеров (6 и 18 мкм) с несоосностью $< 5^0$ создаёт в газовой струе канал полностью ионизованной плазмы с диаметром > 50 мкм, внутри которого нелинейное взаимодействие кильватерных волн генерирует импульс $2\omega_p$-излучения (28 ТГц) с характерной длительностью 3 пс, полной мощностью ∼20 МВт и энергией 40 мкДж, что соответствует эффективности преобразования энергии $2 \cdot 10^{-4}$. В дальней зоне источника генерируемое излучение направлено поперёк оси тонкого лазерного пучка и имеет весьма узкий угловой разброс 2^0. Максимальная эффективность $2\omega_p$-эмиссии достигается, если тонкий пучок приходит в точку фокуса на 2-2.5 пс позже, чем толстый.

- Экспериментальная установка на стадии сборки: получены необходимые вакуумные условия, разработана схема интереферометрических измерений плотности газа и плазмы, начата калибровка детектора излучения с длиной волны 10 мкм на ЛСЭ.