Quasi-continuous sub-millimeter optical discharge on Novosibirsk free electron laser: experiments and elementary theory

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Abstract

The first quasi-continuous optical discharge in near sub-millimeter spectral range was demonstrated on high-power Novosibirsk free electron laser. Experimental results and elementary theory of this phenomenon are presented.

Introduction

Optical discharge as interesting physical phenomenon is well known since 1963 year [1]. The first experiments on ruby lasers marked the appearance of new powerful impulse optical sources of laser type. When powerful cw CO_2 lasers have been created cw optical discharge was used also for demonstration of their high power [2].

In framework of the tradition the phenomenon has been produced on Novosibirsk free electron laser at the first time in near sub-millimeter range in cw regime as an illustration of its unique power parameters [3-5].

Experimental results

The first stage of the Novosibirsk free electron laser is based on the one-orbit 12 MeV electron accelerator-recuperator. After interaction with radiation in optical resonator with undulators the electron beam passes once more through the accelerating structure, returning the power, and comes to the beam dump at the 1.5 Mev injection energy. Now the FEL provides electromagnetic radiation in the wavelength range of 120 - 180 microns as continuous train of shot pulses about 60 ps duration at the average power up to 400 W and pulse power about of 1.2 MW at pulse frequency of 11.2 MHz.

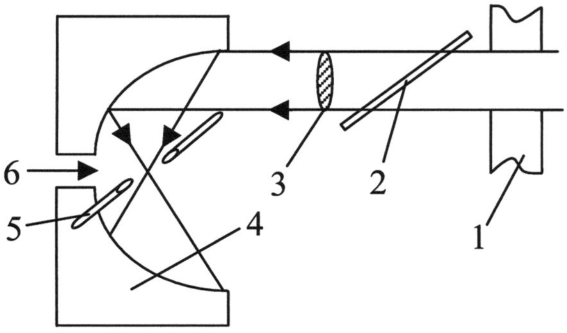

Fig. 1: Layout of the experiment with optical discharge: 1-FEL output mirror, 2- diamond window, 3-laser beam, 4-parabolic mirror, 5-ignition electrodes, 6-gas flow.

The first optical discharge has been created when average power was about of 100 W, pulse frequency - 5.6 MHz and wavelength - 140 μm. Layout of the experiment is shown in Fig.1. The FEL radiation from 8 mm output hole in mirror of optical resonator goes out in atmosphere through 0.8 mm CVD-diamond window. Near the window off-axial parabolic cupper mirror with focal distance of 10 mm was installed to focus radiation in spot ~ λ^2. We have possibility to change air atmosphere by expulsion argon gas through discharge volume. The additional high-voltage electrical ignition can be used in some experiments. Following experimental results have been found:

1) optical discharge appears without additional electrical ignition both in argon and in air atmosphere at laser output power about 100 W,
2) threshold laser power for argon is greatly less than for air,
3) use of electrical ignition decreases threshold power for both gases by a factor of 2-3,
4) optical discharge burns stationary at high power and can be pulsed at power which is near to threshold.

Photos of the optical discharge are shown in Fig.2. The first

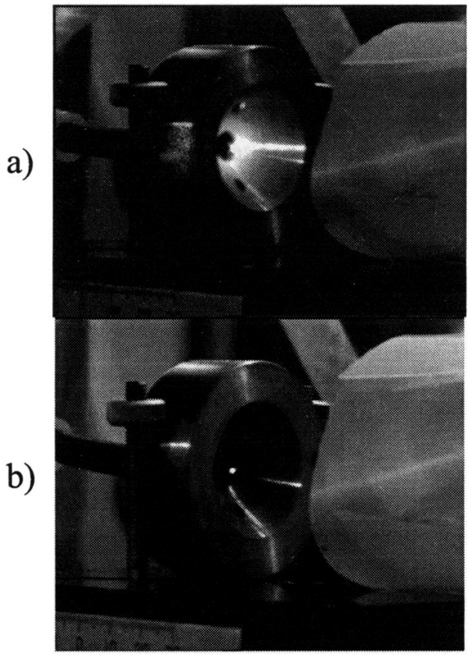

Fig. 2: Photos of the optical discharge.

one (a) is discharge at high power, the second (b) is discharge with smaller power and smaller discharge volume.

Elementary theory

We will create elementary theory our optical discharge on base well known theoretical and experimental moments described in [1]. For simplicity we will examine optical discharge in argon with discharge volume ~ λ^3 for radiation pulses Δt = 60 ps focused in spot ~ λ^2 at wavelength λ=140 μm (frequencies $\nu = 2.1 \cdot 10^{12}$ s^{-1}, $\omega = 1.3 \cdot 10^{13}$ s^{-1}).

Since optical discharge connected with process ionisation we need know or estimate following character values: ionisation energy of argon $\mathcal{E}_i$ =16 eV, frequency of elastic collision electron with Ar atoms for middle energy $<\mathcal{E}> \approx \mathcal{E}_i/2$ =8 eV at atmosphere pressure is $\nu_m = 5.0 \cdot 10^{12}$ s^{-1} , electron free path is L= 0.4 μm [1]. Since $L \ll \lambda$ electron life time in discharge volume is a diffusion time:

$$\tau_D = \lambda^2/4D = 3\lambda^2 \nu_m m_e/4\mathcal{E}_i = 50 \text{ ns} \qquad (1)$$

This time is much greater than pulse duration but some less than period of pulses T. Since the ionisation time must be more less than pulse duration this ionisation time is considerably less than diffusion time. As $\tau_D < T$ there is possibility of pulsed optical discharge, which has been observed in our experiments at small power when discharge volume is closed to λ^3.

Optical discharge correspond to the appearance ~ 10^{13} free electrons as been shown in many experimental investigations [1]. The electron avalanche can grows from the one initial electron appeared in air from cosmic rays and X-ray radiation of accelerator. Therefore a main criterion of the optical discharge is:

$$(\nu_i - \nu_D)\Delta t \approx \nu_i \Delta t = \ln(10^{13}) = 30 \qquad (2)$$

Thus from (2) we find that ionisation time (sum of time of electron heating and time of argon atom ionisation) must be 1/30 part of pulse duration $\tau_i = \nu_i^{-1}$ = 60/30 = 2 ps. For rough estimation we suppose time of electron heating and time of argon ionisation equal one to other. Then electron energy during Δt_h = 1 ps must increase up to value $\mathcal{E}_e \approx$ 25 eV for frequency of argon ionisation of 10^{12} s^{-1}. Using this value one can easy calculate necessary amplitude of electric intensity E_0 of the electro-magnetic wave $E = E_0 \sin \omega t$ by expression for collisional stochastic heating of electron [1]:

$$\mathcal{E}_e = \frac{e^2 E_0^2 \nu_m \Delta t_h}{2m_e(\omega^2 + \nu_m^2)} \qquad (3)$$

Thus we find the light intensity:

$$I = \frac{c m_e}{4\pi e^2} \frac{\mathcal{E}_e(\omega^2 + \nu_m^2)}{\nu_m \Delta t_h} \qquad (4)$$

From (4) we can determine threshold intensity I = 1.45 GW/cm^{-2} and the threshold FEL power:

$$P = I\lambda^2 \Delta t \cdot f = \frac{c m_e \lambda^2}{4\pi e^2} \frac{\mathcal{E}_e(\omega^2 + \nu_m^2) f \Delta t}{\nu_m \Delta t_h}, \qquad (5)$$

where f is pulse frequency. For f = 5.6 MHz we have P=97 W. This value is close to our experimental threshold power.

Let consider the condition of burning and maintenance of the optical discharge. The discharge starts from one initial electron and appearance of the electron in discharge volume has a statistical nature. Delay of the first ignition is shot enough. Estimation of the delay is ~1ms for typical density of initial electrons ~10^2 cm^{-3}. Between laser pulses (T = 180 ns) electron density in discharge volume will decrease as $T > \tau_D$. But electron concentration will be yet large enough for immediate discharge burning by next laser pulse. Thus we propose that our optical discharge has a quasi-continuous behavior. Deep of modulation of different parameters in the discharge is object of our future study.

Some recommendation for decrease of threshold power follows directly from expression (5). Optimal gas condition is $\nu_m = \omega$ Optimal pressure $p \sim \nu_m$ for argon gas is 2.6 bar and for xenon gas is 1.4 bar. Xenon is also more preferred then argon since it has some lesser ionisation energy ($\mathcal{E}_i$ =12 eV). But expulsion of xenon is expensive enough. Therefore we will use this gas in closed volume only.

In summary, one can see that all our experimental facts can be easy explained by the elementary theory.

Present activities and plans

Described above first simplest experiments with optical discharge was carried out directly in radiation-dangerous hall. Special user station in safe user hall is creating now both for more detailed experiments with optical discharge and for other light-material experiments with highest radiation intensity. Laser beam in user hall has large enough size ~100 mm to avoid diffraction divergence. Therefore parabolic mirror of the new user station will have large focal length of 100 mm. This gives us the additional possibility in investigation of large size samples. We plane to study various parameters of the optical discharge at different experimental conditions (gases, pressures, powers) and physical effects in solid materials under the action of powerful sub-millimeter radiation.

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