Emission properties of a point-like discharge in an inhomogeneous gas flow supported by sub-THz radiation

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The latest developments of the powerful and reliable gyrotrons of the sub-terahertz range opens up new opportunities in research. In particular, detailed studies of the gas discharge in a focused beam of terahertz frequency range in an inhomogeneous gas flow were carried out recently [1–3]. This paper presents the results of experimental studies of point-like plasma emission in three spectral ranges: 112 - 180 nm, 18 - 50 nm, and 13 – 17 nm. The discharge was induced in a nonuniform gas flow (Ar, Kr, Xe) under the action of a focused beam of sub-terahertz waves. Two gyrotron complexes were used as the radiation source. They were 40 kW at 670 GHz and 250 kW at 250 GHz. An absolutely calibrated photomultiplier and an absolutely calibrated solid state detector with a set of filters were used to measure light properties.

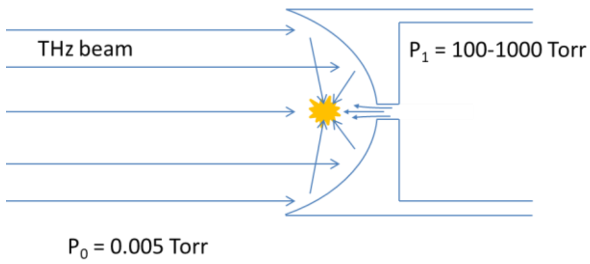

Fig. 1. The principal scheme of the experiment.

The principal scheme of the experiment is presented on Fig. 1. The goal is a source of extreme ultraviolet radiation, that is why we need to keep background pressure at the level below few millitorr to make it transparent for the EUV light. But for the THz waves this pressure is much too small. The optimal pressure for the THz discharge is close to atmospheric pressure. And to produce plasma with density about 10^{15} - 10^{16} cm^{-3} it is necessary to breakdown gas with pressure below 1 Torr. Estimations show that electric field of more than 100 kV/cm is needed for this [4]. And the discharge conditions should be fulfilled only in the small area. To fulfill all the conditions the nozzles with 50-300 μm in diameter used to have a small region of high density of particles and low background pressure. A point-like discharge with a size of not more than 1 mm (see Fig. 2) and a plasma density of more than 3×10^{16} cm^{-3} with valuable emission in extreme ultraviolet band was demonstrated [2].

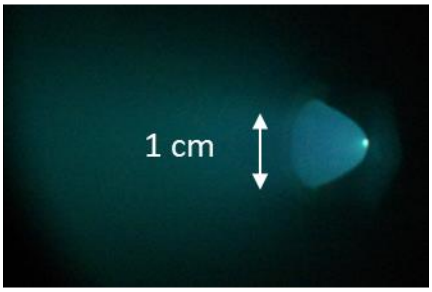

Fig. 2. Photo of the point-like discharge.

Result of experiments on the study of a point-like plasma heated by radiation with a frequency of 670 GHz and a power of up to 40 kW shows that argon has the maximal light emission power in the spectral band of 112-180 nm. Fig. 3 shows the oscillogram of absolutely calibrated photomultiplier. The luminosity of the point-like plasma in the range 112-180 nm reached 10 kW.

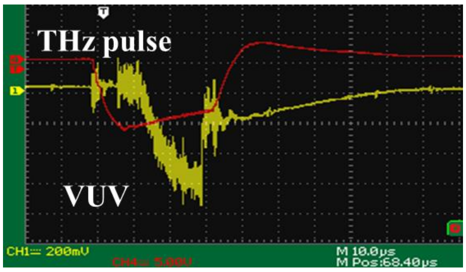

Fig. 3. The luminosity of the point-like argon plasma in the range 112-180 nm.

In the case of using xenon as a plasma-forming gas the luminosity of the discharge in the range 13-17 nm (double Mo/Zr filter [5]) was 0.11 W (100 W/cm^3). The luminosity in this spectral range appeared only at the end of the heating pulse.

The second source of microwave radiation, which was used in the described experiments, has a much higher power level. The heating of a point-like plasma by radiation with a frequency of 250 GHz and a power of up to 250 kW made it possible to investigate in detail the dynamics of the luminosity of the plasma. The optimal conditions for maximal luminosity in different bands differ. The maximum luminosity of the point-like plasma in the range 18-50 nm (double Al/Si filter [5]) was achieved in argon with heating power of

180 kW. Fig. 4 shows the oscillogram of the detector signal in this case. It can be seen that most part of the light belongs to deep UV range. Luminosity of argon plasma in the range 13-17 nm was almost zero.

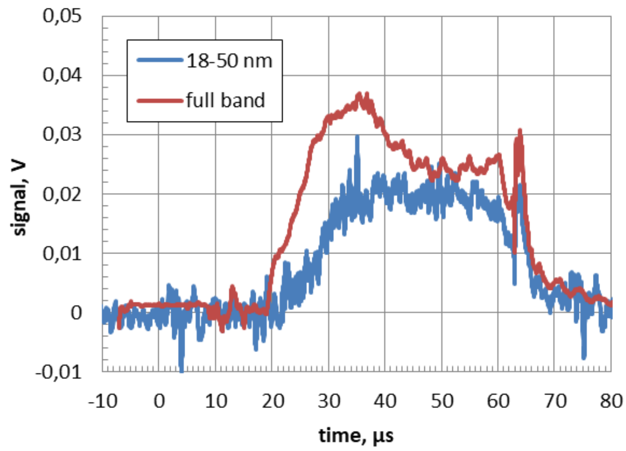

Fig. 4. Oscillogram of the luminosity of argon point-like plasma. Heating power 180 kW.

The luminosity of xenon plasma was observed in both spectral bands 13 – 17 nm and 18 – 50 nm. The luminosity of the plasma increased with time and reached a maximum value at the end of the heating pulse.

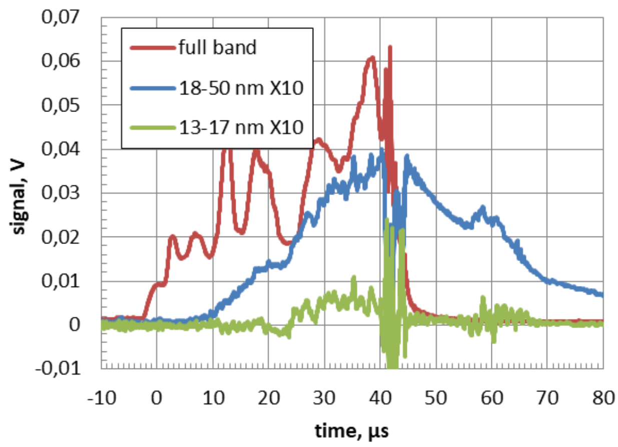

Fig. 5. Oscillogram of the luminosity of xenon point-like plasma. Heating power 250 kW.

The maximal EUV light power was of 1.5 W in the band 13-17 nm. Heating power was 250 kW, nozzle diameter 150 µm, background pressure 4 mTorr, pressure behind the nozzle was 0,4 bar. The maximal light power of xenon point-like plasma in the band 18-50 nm was of 20 W.

Such a plasma object can be a promising source of extreme ultraviolet light for high-resolution projection lithography.

Further increase in the conversion efficiency of the heating radiation into the extreme ultraviolet light can be achieved by the improving coupling of the heating wave and point-like plasma. One of the possible ways to increase the coupling is to increase the frequency of the heating wave. In the case of heating radiation with a frequency of 1-3 THz, the size of the plasma formation will correspond to the possible waist size of the beam. In this case most of the radiation could be absorbed in the plasma, which will increase the conversion efficiency.

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