Experimental investigation of relativistic electron beam generation in glass capillaries under the action of ultra-intense laser pulse

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Introduction

Intense laser driven hard x-ray sources offer a new alternative to conventional electron accelerator bremsstrahlung sources. The temporal (few ps duration) and spacial (hundred μm spot size) characteristics of laser driven sources are significantly better than achievable with radiofrequency accelerator sources. There are many potential applications of these sources such as non-destructive control, high temporal dynamic processes investigation, medicine and others. For the most of the purposes, electrons with energies of several MeV are needed, but high x-ray dose levels are required to provide. A little attention so far has been paid to acceleration by picosecond laser pulses mainly for the reason of poor quality of generated electron beams.

As have been supposed by various authors the capillary target might provide the best interaction conditions to enhance generated electron beam quality. Inside a capillary tube, it is possible to create an axisymmetric plasma density distribution to efficiently confine the laser pulse, improve electron collimation and thus to increase on axis dose and improve reproducibility [1,2].

Experimental setup

Experiments on electron acceleration from capillary targets were performed on 30 TW picosecond laser facility (15 J, 0.8÷1 ps, $(2{,}5÷4{,}2)\times10^{19}$ W/cm^2). Inner diameter and length of the silica glass capillary targets was varied in the ranges of 50÷140 μm and 2÷10 mm correspondingly. The laser beam was focused at the entrance of capillary tube using an f/1.6 OAP mirror. Capillaries were aligned along the optical axis of laser pulse prior to an experiment. Accelerating plasma medium was created by ablating capillary inner walls with specially generated prepulse at 1.2 ns before the main pulse. The prepulse energy was varied in accordance to the presetted contrast (the relation of main pulse energy to prepulse energy) that could be chosen from 3 fixed values: 10, 100 and 1000.

The schematic view of the experimental arrangement is presented in figure 1. Accelerated electrons energy spectrum was measured by magnetic spectrometer, its entrance aperture was located at 250 mm from the target ($\Omega = 1{,}25\times10^{-5}$ sr). Electrons were detected on an image plate detector (IP BAS MS, Fuji) and signal was read out with scanner FLA7000 IP. Detector sensitivity to relativistic electrons (>1 MeV) was taken from available publications [3,4].

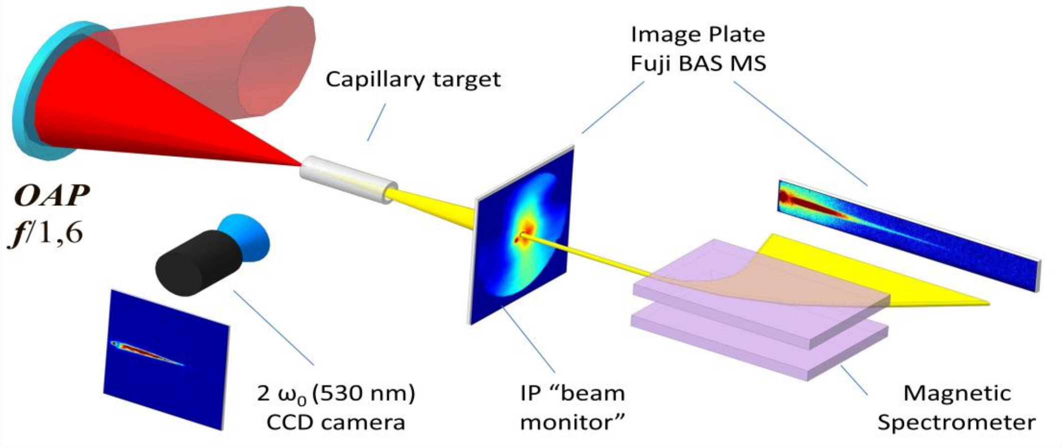

Figure 1. Experimental arrangement layout

In order to monitor angular divergence of the accelerated electron beam, an additional image plate («beam monitor») was mounted on the front face of the spectrometer. A hole in the beam monitor was punctured that was aligned with spectrometer entrance. Diameter of beam monitor is about 140 mm that corresponds to viewing angle of *~30°*. To protect beam monitor from laser light and low energy electrons it was covered by 100 μm Ni foil.

To observe laser produced plasma inside the capillary a CCD camera viewing capillary from side was implemented. The CCD registered plasma emission at 527 nm ($2\omega_0$).

Experimental results

21 experiments have been performed in all. Accelerated electron energy distribution $d^2N/dE/d\Omega$ was reconstructed from the raw spectrum recorded by magnetic spectrometer. Integrating this energy distribution we obtained number of electrons n_{sp} emitted into the entrance slit of spectrometer. The total charge of electron beam Q_{beam} in every experiment was estimated on the base of beam monitor image:

$$Q_{beam} = n_{sp}\frac{\sum I}{I_{sp}},$$

where $\sum I$ – is overall beam footprint brightness on beam monitor, I_{sp} is a mean brightness in the region around collimation hole. It should be noted that this assessment supposes that electron energy distribution does not depend on angle. It is clear that if the relativistic electron beam has a complicated angular distribution the above beam total charge estimation doesn't give accurate result.

All detected relativistic electron beams had exponential spectrum with maximal particle energy in the range of 3÷22 MeV and with effective temperature in the range of (0.5÷2.5) MeV.

All experiments with 50 μm capillaries gave extremely non-uniform electron beam angular distribution. Increase of capillary inner diameter to 140 μm improved angular distribution substantially (figure 2).

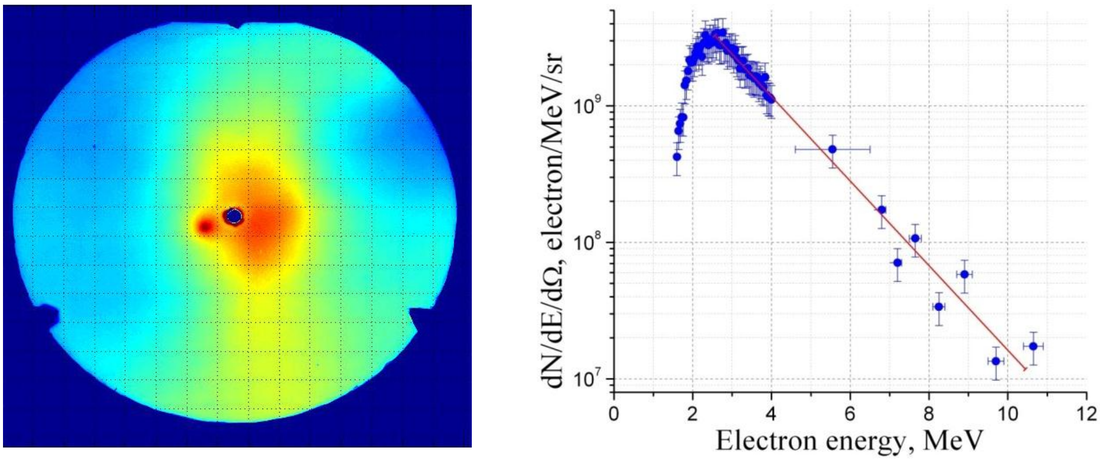

Figure 2. Experimental results (Ø140мкм×10мм, k=10, E_{max}=10 MeV, T_{hot} = 1.4±0,15 MeV, Q_{beam}=30±10 pC)

High quality electron beams were generated in experiments with Ø140 μm×2 mm capillaries (figure 3). The typical electron beam footprint has a tight axial symmetric form with opening angle of ~40 mrad (FWHM). The highest measured electron energy is about 22 MeV.

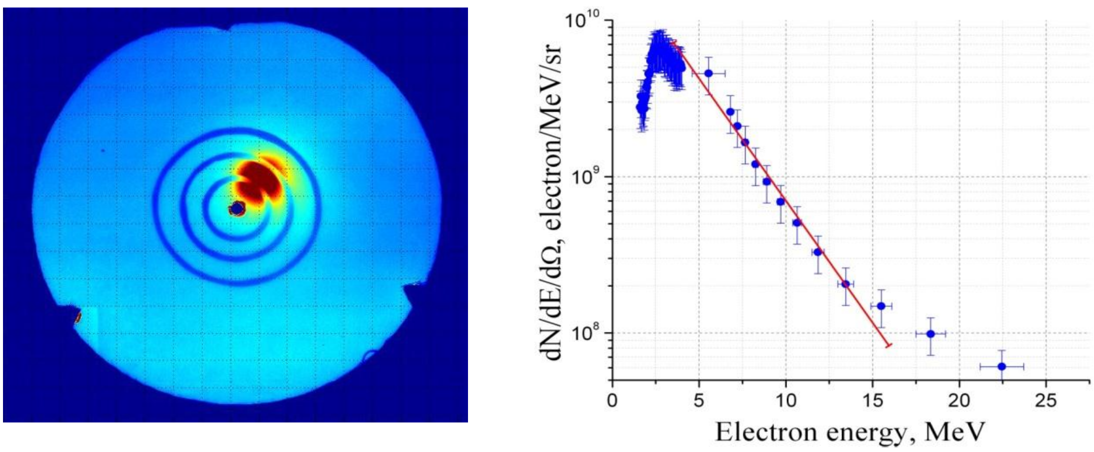

Figure 3. Experimental results (Ø140 μm×2mm, k=10, E_{max}=22 MeV, T_{hot} = 2.8±0.2 MeV, Q_{beam}=200±54 pC)

Side view camera image is shown in figure 4 (left). One can see bright light emission on the capillary tube exit. Authors of [5] have observed the similar emission in their experiments.

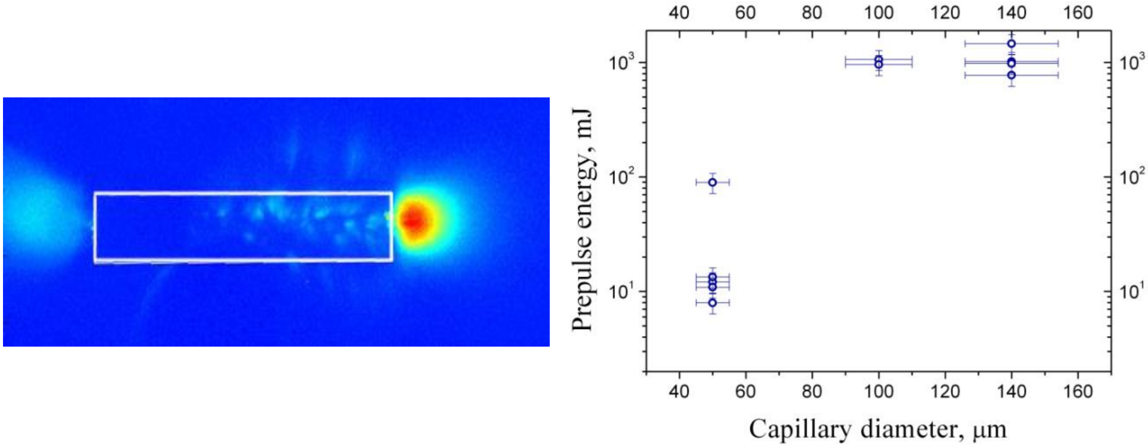

Figure 4. (Left) The capillary target (Ø140 μm×2 mm) experimental side view image. (Right) The parameters of experiments with successful electron beam acceleration conditions.

Parameters of experiments where accelerated electrons were observed are plotted on the figure 4 (right). It is clear that optimal prepulse energy for generation of relativistic electron bunch increases for larger capillary inner diameter.

Conclusion

On 30 TW picosecond laser facility, the series of experiments on generation relativistic electron beams in glass capillary tubes have been performed. The plasma acceleration medium inside capillary targets was created by ablating their inner walls by special produced picosecond prepulse.

We detected relativistic electron beams of exponential spectrum with energies of up to 20 MeV, ~50 mrad divergence angle and total charge of ~200 pC.

The opening angle of generated beams corresponds to aspect ratio of capillary target.

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