Generation of laser-driven femtosecond electron beams for secondary photon sources with 7 TW Ti-sapphire laser system at PALS

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Introduction

Relativistic electron beams have been successfully accelerated by the laser wakefield mechanism [1, 2]. Such beams can be used for a broad range of applications, such as radiotherapy [3], electron radiography of dense materials and the measurement of electric and magnetic fields [4, 5, 6], or they can serve as sources of femtosecond, collimated and point-like X-ray radiation [7, 8].

In parallel with efforts of creating new state-of-the-art systems, there is a quest for producing an inexpensive and cost-efficient stable electron and X-ray source (in comparison with conventional sources). In this paper, a possibility to build such a source is investigated in a small laboratory equipped with an affordable femtosecond few-terawatt laser system.

Experimental setup

The Ti:sapphire laser system at the PALS laboratory provides laser pulses with a maximum power of 25 TW and a central wavelength of 808 nm with a designed repetition rate of 10 Hz. Nevertheless, in this experiment, laser pulses with a duration of 50 fs and an energy of 600 mJ (on target) were used for the electron acceleration in the single shot regime. An off-axis parabolic mirror with f/# = 6.5 was used. The focal spot contained 60 % of the pulse energy, which in total equals to 360 mJ and corresponds to a power of 7 TW, and its size was close to the diffraction limit without the use of a deformable mirror. The focal spot was elliptical with a size of 14x11 μm.

During the experiment, dry air, and a mixture of helium and argon were used as supersonic gas jet targets. In both cases, the backing pressure was set in a range of 3-20 bar. The approach to use air was chosen to test the possibility as accelerating medium as an inexpensive gas jet option apart from previously used noble gases [9, 10] and nitrogen [11], which allows to further lower the cost of the electron and X-ray source and its operation. Argon was mixed with helium in a ratio of 1:99 in an attempt to increase the charge of the accelerated electron beams using the ionization injection regime. In the case of dry air, the electron beam was injected into an accelerating phase by self-injection and probably also by ionization injection when laser self-focusing appeared. In the second case, using Ar admixture in He, the ionization injection regime was used. The intensity of the laser pulse is in the order of magnitude of 10^{18} W/cm^2. While helium can be easily fully ionized at such intensity, the argon has only upper levels stripped. However, a higher level of ionization can be achieved due to laser self-focusing, which allows a higher intensity to be reached. These extra electrons can be subsequently trapped and accelerated. The analogous injection technique also takes place for dry air containing nitrogen and oxygen atoms.

Moreover, in order to increase the injected charge, a razor blade was used to create a steep density gradient at the front of the target.

Results

It is crucial to monitor plasma parameters and parameters of produced electron and X-ray beams in order to achieve stable accelerating conditions, in which electrons emit betatron radiation. One of the key parameters of every laser wakefield accelerator is the plasma density, which was monitored by Mach-Zehnder interferometer. The most stable conditions for electron acceleration and betatron X-ray generation were found for a density of 2.5x10^{19} cm^{-3} for the He-Ar mixture and 5.0x10^{19} cm^{-3} for dry air.

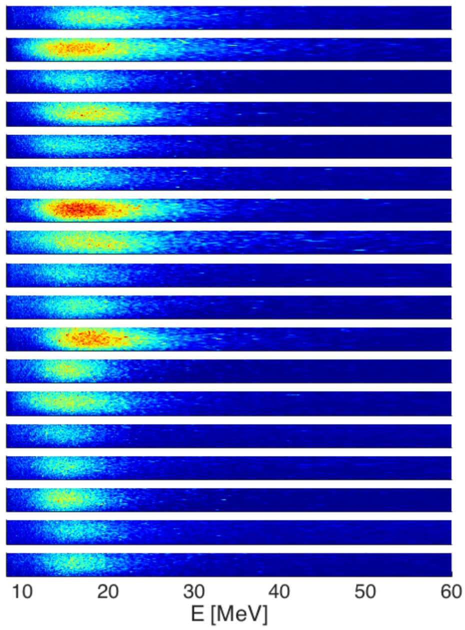

Fig. 1: Electron spectra obtained using the dry air target, showing high stability in energy E = (17.4 ± 1.1) MeV.

Besides the accelerator parameters, the electron beam parameters, such as pointing stability, energy and energy spread, were also monitored. Pointing stability was monitored using a small Lanex screen placed few centimeters downstream the electron source. It was found that the pointing instability is (40 ± 20) mrad for both gas targets. The energy and energy spread of electron beams were measured using a magnetic spectrometer consisting of a dipole magnet creating a uniform magnetic field of 0.27 T and a Lanex screen imaged by a CCD camera; energy was corrected to the electron beam pointing. The setup of the spectrometer allowed energy measurement in the range from 8 to 120 MeV. Electron acceleration using dry air showed remarkable stability in energy (as can be seen in Fig. 1) with a peak electron energy of (17.4 ± 1.1) MeV, as well as shot-to-shot stability in electron bunch generation, which reached about 85 %. The achieved electron energy for the He-Ar mixture was up to 80 MeV (as shown in Fig. 2).

These accelerated electrons can serve as a source of betatron X-ray radiation. For this purpose, a CCD camera operating in the single photon counting mode [12] in a distance of 300 cm from the source was used. The photon flux was attenuated to the desired intensity by an appropriate aluminum filter. This radiation was observed only for the He-Ar mixture and had a critical energy of about 1.6 keV (see Fig. 2).

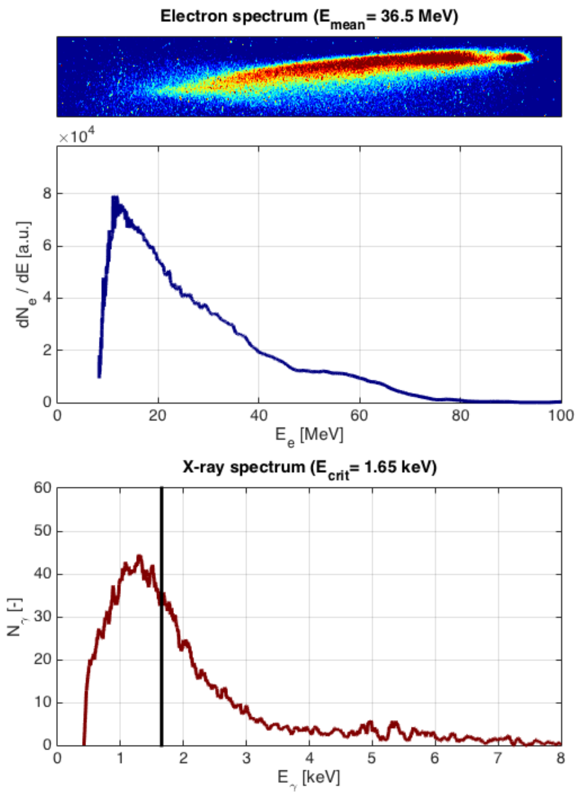

Fig. 2: The electron signal (top) and electron spectrum (middle) with the electron energy up to 80 MeV and corresponding betatron X-ray spectrum with a critical energy of 1.6 keV.

Experimental results were supported by particle-in-cell simulations, which were done in the EPOCH 2D code [13] with ADK model for ionization [14]. Initially neutral atoms (only oxygen and nitrogen were considered as components of dry air) were in the simulation ionized by the laser pulse. The parameters of the laser pulse and plasma were chosen according to the measured experimental values mentioned above.

The simulations showed a peak energy of 17 MeV for the dry air target (see Fig. 3) and 24 MeV for the He-Ar mixture, and formation of non-linear wake waves (Fig. 4). In the latter case, the wake wave starts to form an ion cavity and electrons wiggle in the typical betatron motion with a radius of about 2 μm, indicating a possibility of the generation of X-ray pulses. All these figures also show an agreement between the simulations and the experimental data in terms of the spectrum shape and the energy.

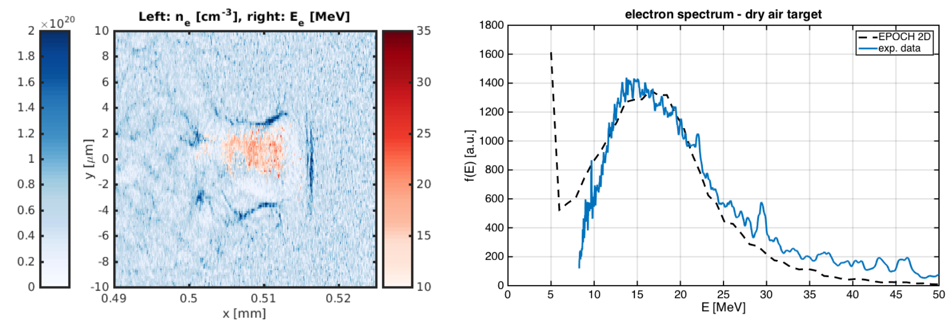

Fig. 3: Electron acceleration using dry air. Left: A 2D map of the electron plasma density showing the shape of the non-linear wake wave. Right: The comparison of experimental data with simulations for the electron spectrum. The maximum in the number of electrons in the low energy range obtained from simulations is caused by including the electrons which are momentarily displaced by the laser pulse.

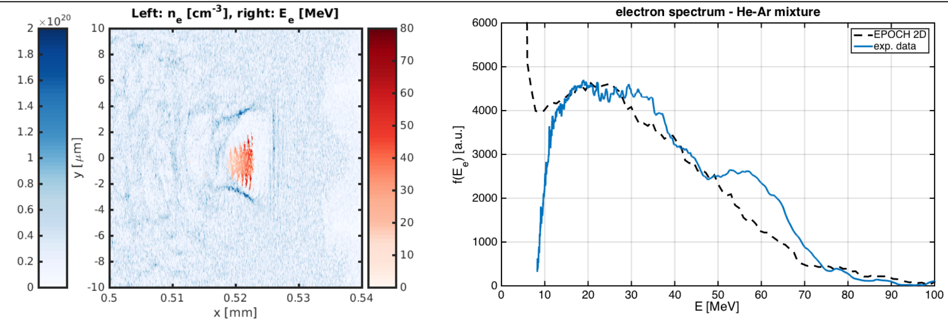

Fig. 4: Electron acceleration using the mixture of helium and argon (99:1). Left: A 2D map of the electron plasma density showing the forming ion cavity and electrons undergoing betatron oscillations. Right: The comparison of experimental data with simulations for the electron spectrum. The maximum in the number of electrons in the low energy range obtained from simulations is caused by including the electrons which are momentarily displaced by the laser pulse.

Conclusions

The electron beams and betatron X-ray pulses were produced using a few-TW femtosecond laser system with focus on the low costs and inexpensive operation. Offline diagnostics were used to monitor the focal spot and laser pointing stability, and online diagnostics were utilized for monitoring of the electron pointing stability, electron energy, energy spread and plasma density. Two types of supersonic gas target – dry air, and a mixture of He and Ar – were tested. Electron beams were generated with a pointing instability of (40 ± 20) mrad with both targets. Dry air proved to be an efficient option to create a stable electron source in terms of energy and energy spread. Using this target, stable electron bunches were produced with an energy of (17.4 ± 1.1) MeV. On the other hand, the He-Ar mixture, while not as stable in electron energy, was proved to be more suitable for reaching high electron energies (up to 80 MeV), and for generation of betatron X-ray pulses with a critical energy of 1.6 keV.

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