Laser-driven plasma wakefield electron acceleration and coherent femtosecond pulse generation in X-ray and gamma ranges

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Abstract. The laser wakefield acceleration (LWFA) of electrons in capillaries and gas jets followed by inverse Compton scattering of high intensity femtosecond laser pulses is discussed. The drive and scattered pulses will be produced by the two-channel multi-terawatt laser system developed in ILP SB RAS.

At the present time, the impressive progress in laser wakefield acceleration (LWFA) of charged particles gives grounds to consider LWFA as a perspective method of electron beam production in the GeV energy range [1, 2]. Electrons of this energy can be used in advanced light sources for future application. Combining the LWFA of electrons and Compton backscattering of a probe light beam on them opens the possibility to create a tabletop source of femtosecond light beams in X-ray and gamma ranges [3, 4]. This kind of source can have high coherence and polarization, quasi-monochromatism, and tunability of radiation parameters.

LWFA experiments are currently prepared at the Institute of Laser Physics (ILP) in collaboration with Budker INP. The experiments are based on the two-channel multi-terawatt femtosecond high contrast, high angle stability laser system with the pulse repetition rate 10 Hz, which is developed at ILP [5].

Traditionally, there are two basic schemes of LWFA (figure 1). In one scheme, the acceleration occurs in plasma filled dielectric capillaries. Highest electron energies are obtained this way in wide capillaries with preformed plasma that has the density minimum on the axis. In another scheme, a supersonic gas jet is used.

The capillaries (or narrow waveguides) can prevent laser beam diffraction directly by reflection of the pulse from the walls and extend acceleration length up to many Rayleigh lengths [6, 7]. We study metallic capillaries. This scheme can be considered as an extreme case of the plasma-walled capillary and can lead to high energies of accelerated electrons at moderate laser beam powers [7]. In this case, metal walls behave like a cold dense plasma with a sharp boundary. We have experimentally studied propagation of high-intense (up to $10^{17}$ W/cm$^2$) high-contrast ($<10^{-8}$) 50 fs laser pulses through the 20 mm long 50 mkm wide triangular copper channel (figure 2a) in vacuum and in helium ($\sim 1\div1000$ mbar) [8].
The main results are:

- Relative transmission 70% through the channel (15 Rayleigh lengths) is measured;
- Single mode regime of pulse propagation is demonstrated;
- No difference between vacuum and helium inside the capillary is observed;
- Decrease of the transmission to zero after hundreds or thousands of pulses is observed (figure 2b), which is caused by local plug formation [9].

As a result, we can conclude that plasma filled metal capillaries have perspectives as accelerating structures and deserve further studies, but high repetition rate sources of electrons need another LWFA scheme in its basis.

To pursue further studies of laser-based acceleration techniques, a specialized experimental facility was designed. Main parts of the facility (Laval nozzle with pulse valve, laser beam compressor and parabolic mirrors, electron beam diagnostics) will placed into three vacuum chambers: the chamber for the laser pulse compressor, the chamber for a supersonic jet and focusing mirrors, and the chamber for electron beam diagnostics and beam dump. A sketch of the latter two chambers is shown in figure 3. In the default scenario, the same sub-PW high-contrast femtosecond laser pulse will be responsible for gas ionization and formation the plasma channel, wakefield excitation, and trapping of plasma electrons by the wave. This scenario and design are traditional for LWFA devices.
Figure 3. Two experimental chambers (without the compressor chamber): 1 – supersonic gas jet, 2 – focusing mirrors, 3 – laser beam for diagnosing the jet density, 4 – electron spectrometer magnet, 5 – Faraday cup, 6 – luminophor screens, 7 – electron beam, 8 – driving laser beam, 9 – scattered laser beam.

The numerical analysis of electron trapping and acceleration shows the following:

- For effective electrons trapping, we require to focus the laser beam down to the diameter \( \sim 10 \text{ mkm} \). Rayleigh length and effective length of acceleration will be about 0.5 mm.
- The optimum plasma density is \( 3\div5\cdot10^{18} \text{ cm}^{-3} \).
- In the case of the laser pulse energy 0.3 J, the maximum electron energy can reach 100 MeV. For the laser pulse energy 0.1 J, we can obtain \( \sim 65 \text{ MeV} \) electrons at best.
- The maximum energy of Compton \( \gamma \)-quanta can reach 240 keV and 100 keV, respectively (figure 4a), and the main part of the scattered radiation will be in the angle \( \sim 1/\gamma \), where the relativistic factor of electrons \( \gamma \sim 150\div200 \) in our conditions, as it is shown in figure 4b.
- The supersonic gas jet is necessary to produce a flat top density profile of the jet, as required for minimizing the energy spread of electrons.

Figure 4. Energy (a) and angle (b) distributions of Compton \( \gamma \)-quanta. Estimations are performed for head-on scattering of monoenergetic electrons and 810 nm photons.

Numerical analysis of the gas flow shows that we can use a simple conical Laval nozzle with the waist diameter 0.3÷0.4 mm, output diameter 1.5 mm, and cone angle 14°. In this case, we can obtain the jet density up to \( 10^{19} \text{ cm}^{-3} \) and Mach number 4 with the input gas pressure below 10 atm. We use the fast pulse valve Festo that enables jet operation with the frequency up to 10 pulses per second.
Several variants of nozzles were produced and tested (figure 5), and now the gas system with the fast pulse valve is complete. Measured jet parameters are close to simulated ones.

![Figure 5](image)

**Figure 5.** A Laval nozzle with the pulse valve installed at the testing stand (a), and the measured jet density profile (b).

Faraday cup (FC) and magnetic spectrometer are chosen as the basic electron diagnostic. The Faraday cup (figure 6) is designed for full stopping of 100 MeV electrons with minimized backscattering. FC is a cube-like capacitor of the size ~ 20 cm in each dimension. One plate of the capacitor is made of 6 cm thick tungsten with 1 cm thick aluminium cover plate. The capacity is as low as to 14 pF. This FC allows measuring charge of ultrashort electron bunch ($\tau \leq 1$ ps) with high precision ($\leq 1$ pC) without any additional complicated electronics and does not need special calibration procedures. The Faraday cup is fabricated and successfully tested under 120 MeV beam of VEPP-5 accelerator complex at Budker INP, Novosibirsk (figure 7).

![Figure 6](image)

**Figure 6.** Faraday cup in the experimental hall of VEPP-5 accelerator complex at Budker INP during tests under the electron beam.

![Figure 7](image)

**Figure 7.** Signals from the Faraday cup measured during tests: single electron bunch of charges 72.3 pC (a) and 14 pC (b).
The electron beam spectrometer is based on the magnetic analyzer with the deflecting field 0.75 T. The analyzer is made from permanent magnets (figure 8). The deflected beam is detected by the Renex luminophor screen and registered by a special CCD camera. At present, both devices are fabricated and being tested under the real high-energy electron beam at Budker INP.

![Figure 8. The deflecting magnet of the electron spectrometer. Permanent magnets are replaced by dielectric imitations for preliminary assembling.](image)

The main immediate aim of the experimental work is producing LWFA-accelerated electrons with energies up to 100 MeV. The next stage is to produce high-energy Compton backscattered gamma-quanta with the maximum energy up to ~ 200 keV.

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