ELECTRON INJECTOR FOR MULTI-STAGE LASER-DRIVEN PLASMA ACCELERATORS

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Abstract

An electron injector in the 50-200 MeV range, based on laser wakefield acceleration, is studied in the context of multi-stage laser plasma acceleration. Test experiments carried out at the UHI100 laser facility show that electron bunches in the 100 MeV range, generated by ionization-induced injection mechanism, and accelerated by laser driven wakefield in a mm-scale length plasma can be transported using a magnetic line and precisely analysed. A comparison with simulation results provides insights on electron dynamics and indicates ways to optimize the injector.

CONTEXT

Laser wakefield acceleration capability to sustain fields in excess of 100 GV/m and produce short pulse, accelerated electron bunches, makes it a promising way towards compact high energy accelerators for a wide range of applications. Additionally, multi-stage acceleration schemes have the potential to provide scalability and control, and are actively investigated for the development of future accelerators. Multi-stage schemes are under development in France at the APOLLON CILEX [1] laser facility and under design in the frame of the EUPRAXIA project [2].

In these schemes, an optimized electron injector that produces a high quality electron beam with narrow energy spread and small emittance is one of the key issues. As shown by simulations [3] using experimentally achievable parameters, energy spread and emittance can be improved by injecting plasma electrons created locally in the accelerating plasma wave to minimize their transverse momentum, by limiting the distance of propagation over which electrons are injected, and by shaping self-consistently the energy distribution during the acceleration process. Another crucial element for electron injection into a second plasma is the stability of the electron beam pointing at its entrance.

A specific experimental room has been developed in one of the two target areas of the UHI100 facility at CEA-Saclay to study laser-plasma acceleration. A laser plasma electron beamline, composed of an electron source in the 100 MeV range, followed by magnetic components to image and analyse the electron beam is used to study electron acceleration mechanisms and test several elements necessary for external injection of electrons into a plasma accelerator. In this paper we report on the use of the magnetic line, tuned to operate at 70 MeV, to characterize and analyse the properties of electron bunches generated in a short gas cell by ionisation induced electron injection. Experimental results are compared to simulation results obtained with the particle-in cell (PIC) code WARP.

LASER PLASMA ELECTRON SOURCE AT UHI100 FACILITY

Relativistic electron bunches are generated in a gas cell through the interaction of the focused laser beam delivered by a 100TW class- Ti:Sapphire UHI100 laser system as illustrated schematically in Fig. 1. The UHI100 beamline is opened to users in the frame of the ARIES Transnational Access program [4].

Linearly polarized laser pulses of 25 fs duration full width half maximum (FWHM) at 800 nm center wavelength and 10 Hz repetition rate are delivered to a target area in vacuum. After wave front correction with a deformable mirror, laser pulses are focussed using a 1.1 m focal length off-axis parabola to a spot size of 16 µm (radius at $1/e^2$) to a peak intensity $I_L = 4.8\times10^{18}$ Wcm^{-2} which corresponds to a normalized laser amplitude a_0 = 1.5.

A short gas cell filled with hydrogen and 1% of nitrogen is used to generate electrons using ionization induced injection [5]. Fluid simulations were performed with OpenFOAM [6] and the solver SonicFoam in order to determine the distribution of gas density in the cell along the laser propagation axis: the profile is shown as the graph with blue area in Fig. 1. The peak density is achieved in the central part of the cell of width 500 µm. The density decreases at the edges of the gas cell on the laser propagation axis, which has an impact on the non

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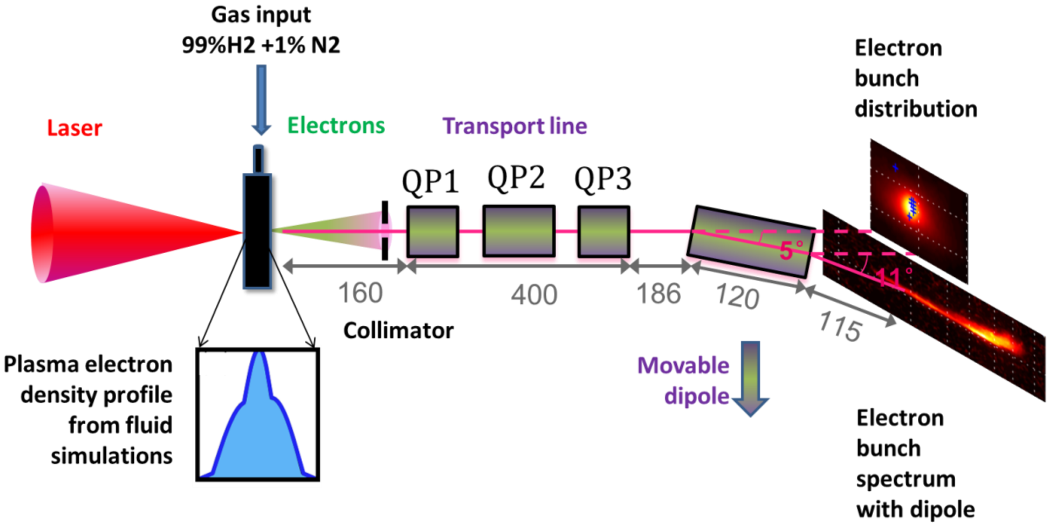

Figure 1: Schematic of experimental set-up; after exiting the plasma, electron bunches are imaged by a magnetic beam line (made of a triplet of quadrupoles labelled QP1 to 3), and analysed in energy when a dipole is moved in the beam.

linear focusing of the laser at the entrance of the cell [7]. For a plasma electron density of about 7×10^{18} cm^{-3}, and the above laser parameters, the injection process is controlled by tuning the initial position of the laser focal plane in vacuum relatively to the gas cell entrance.

The electron source generated in this regime is typically peaked in the range 50-100 MeV with a charge in this range of the order of 10 pC, a divergence of 6 mrad and shot-to-shot pointing fluctuations of the order or larger than 50% of the divergence.

TRANSPORT AND ANALYSIS OF ELECTRON BUNCHES

A transport line downstream of the gas cell optimized for an intermediate energy of 70 MeV was used to characterize electron beam properties such as energy distribution and angular divergence.

The transport line is composed of permanent magnets set-up in vacuum with a total length below one meter. In order to minimize the sensitivity to electron beam pointing, the transfer matrix from the gas cell to the observation point has the values R12 = R34 = 0 for the reference energy of 70 MeV.

Focusing is achieved with a triplet instead of a doublet in order to reduce the beam size in the quadrupoles and thus chromatic effects, and to have similar values of R11 and R33 at the observation point. A dipole can be inserted downstream of the triplet to achieve energy separation. The triplet is made of two 80-millimeter-long focusing quadrupoles and one 120-millimeter-long defocusing quadrupole with a distance of 48 mm in between.

The transport line and the dipole are mounted on separate motorized plates and can be removed in or out of the laser axis, allowing for laser and electron beam alignment in vacuum in the absence of magnetic component on the axis, or measurements with the triplet alone to measure electron beam distribution in space or energy. Angular clipping at 5 mrad is achieved by adding a collimator of diameter 1.5 mm set at the triplet entrance. A lanex screen is placed in the image plane of the transport line; the lanex emission is observed with an optical imaging system and recorded by a 16 bit CCD camera.

Figure 2 shows examples of a) the electron distribution imaged in a single shot on the lanex screen and of b) the spectrum when the dipole is in the beamline.

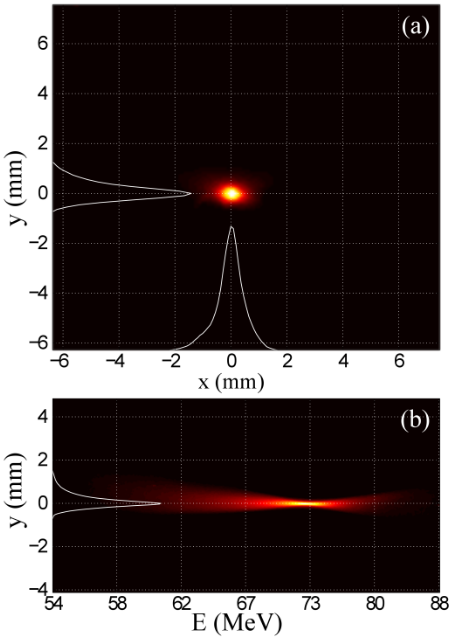

Figure 2: Image of the lanex emission in the image plane of the transport line a) electron distribution in space and b) with the dipole in the beam, dispersed in the horizontal direction.

The white curves in Fig. 2 represent the emission along one axis (y or x) integrated over the other variable (x, y or E). For this example, the spot size is 0.8×0.6 mm² measured FWHM. Over 10 shots the size average is (1.4±0.7) mm and a charge of (3.6±1.3) pC is in the energy range 70 MeV ±5%. The shot-to-shot pointing stability is measured to be of the order of 0.2mm, 14% of average size. The energy distribution is pinched at 70 MeV as expected for the tuning of the magnetic line used during this experiment.

COMPARISON TO SIMULATIONS

The dynamics of electron acceleration driven by laser wakefield in a plasma cell is modelled using the PIC code WARP [3]. Simulations performed with parameters close to the experimental case reproduce the main features of the electron spectrum.

In Fig. 3 is plotted a spectrum measured in the image plane of the triplet and averaged over two successive shots for an electron density of 6.6×10^{18} cm^{-3} (plain blue line with error bars); the lower detection threshold is at 40 MeV. Spectra resulting from simulations for an electron density of 5×10^{18} cm^{-3} (red dashed curve), and an electron density of 6×10^{18} cm^{-3} (plain red curve), are also shown. All spectra are normalized to their maximum.

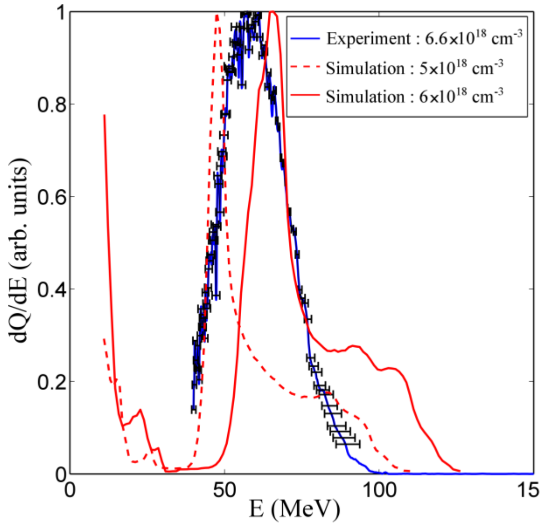

Figure 3: Accelerated electron spectra measured and averaged over 2 shots (plain blue line with error bars) and simulation results for two values of electron plasma density indicated in the legend.

The measured spectrum is peaked at 59 MeV with a relative energy spread FWHM Δ=0.5. Simulated spectra exhibit a peak with centre energy of 50 MeV and Δ=0.1 for the low density case, and a peak with centre energy of 65 MeV and Δ=0.3 for the high density case.

The comparison of these spectra shows that simulations reproduce qualitatively the spectra measured using the transport line and that the shape of the spectrum is sensitive to the value of plasma density. As the density is not measured on each shot, the value during the shot is known with a precision of 10% at most. Although simulated and experimental spectra are similar some notable differences are observed: in simulations, the peak width FWHM is smaller and the shape of the distribution exhibits a high energy wing, not present in the measured spectrum. A detailed analysis of simulation results shows that the peak is largely composed of electrons issued from the creation of N^{6+}, whereas N^{7+} electrons contribute to the higher energy wing. The evolution of these populations of accelerated electrons in the plasma depends on the time of injection of each electron in the wakefield and is thus strongly dependent on the plasma density, the shape of the density profile, and the initial laser intensity, as all these parameters determine the non linear evolution of the laser pulse during its propagation. Several scenarios can thus be proposed to optimize the electron source which will be the subject of future work.

CONCLUSION

An electron beamline was implemented at the UHI100 facility suitable for testing electron injector development for multi-stage laser plasma acceleration schemes. This beamline is able to operate with a broad band electron source. The transfer line was optimized for a reference energy of 70 MeV and was shown to deliver a stable beam with a charge of several pC in the image plane. A precise measurement of the beam spectrum was performed using this beamline, and compared to simulations. The tuning of the electron source should lead to an increase of the absolute charge delivered by the beamline.

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