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Electron Acceleration in a Gas-Discharge Capillary

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Over the last few years laser wakefield acceleration (LWFA) became a promising approach for generating quasi-monoenergetic electrons of several hundred MeV [1]- [4]. Moreover the LWFA process inherently supports bunch lengths of less than 10 fs, which cannot be achieved with conventional RF-accelerators. In LWFA the ponderomotive force of a laser pulse excites a plasma wave with electric field gradients of 10-100 GeV/m. These accelerate electrons to relativistic energies. If the laser pulse is short enough to fit into half a plasma wavelength and delivers relativistic intensities, it can drive a so called bubble [5]. This is an electron free positively charged cavity right behind the laser pulse where previously expelled electrons can be caught and accelerated. A longer laser pulse has to undergo nonlinear self-compression inside the plasma until it is short enough to drive a bubble. [7]

Most experiments so far have been conducted in a gas jet. Here the acceleration distance is limited to twice the Rayleigh length of the laser. In a waveguide the laser stays focused and therefore the acceleration length can be extended until the electrons outrun the laser pulse. This so called dephasing length L scales with $L \propto n_e^{-3/2}$ in the linear case [6], where n_e is the electron density. For higher laser intensities with the dimensionless laser vector potential $a_0 \approx 1$ this scaling is still valid with good approximation. According to this simple law the acceleration conditions can be sustained over more than 10 mm for electron densities of $n_e = 3 \cdot 10^{18}\mathrm{cm}^{-3}$ or less. This way 1 GeV quasi-monoenergetic electrons have been demonstrated in a 33 mm capillary discharge waveguide (laser properties: 38 fs, 40 TW) [4].

The experiments described below are conducted in a 15 mm long sapphire capillary with a diameter of 200 μm. A 20 kV discharge is applied to the hydrogen filled waveguide. The gas gets ionized and an electron density gradient is formed by the temperature difference between the center and the capillary walls. As the refractive index of plasma is mainly determined by the

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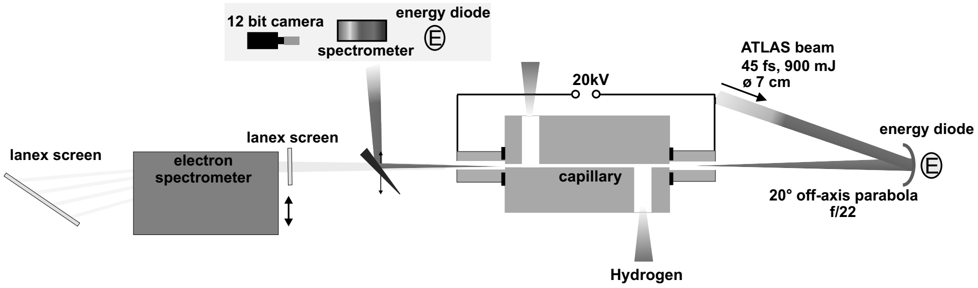

Figure 1: Experiment Setup

electron density, a parabolic refractive index profile is generated [8] that acts as a waveguide and keeps the laser focused over the length of the capillary.

The laser used for the experiments is the *Advanced Ti:Sapphire Laser* (ATLAS) at the Max-Planck-Institute of Quantum Optics in Garching, Germany. During the measurements it delivered approximately 900 mJ in 45 fs (20 TW) and was focused by an f/22 off-axis-parabola to a spot size of 22 μm which corresponds to the matched spot size of the plasma channel in a 200 μm capillary for the densities used [8].

The transmitted spectrum, beam profile and the energy throughput of the incident laser pulse is measured (Fig. 1). The electron bunch is dispersed by an electron spectrometer (425 mT, 37 cm long) and hits a rare earths scintillating screen (*CAWO OG 16*) that is observed with a 12-bit CCD camera. The absolute value of the charge contained in an electron bunch can be determined by cross-calibrating the scintillating screen to an image plate [9]. Alternatively, the pointing stability can be observed on a second screen 110 cm behind the capillary exit. With this screen in place it is not possible to simultaneously measure the electron energy. Simulations show that one screen scatters a perfect pencil-like 130 MeV beam up to 4 mrad r.m.s. and therefore degrades the spectrometer resolution significantly.

One important parameter in the experiment is the delay between the discharge and the arrival of the laser at the capillary. Fig. 2 shows three different spectra of the transmitted laser pulse and a vacuum laser spectrum for comparison. Depending on the timing the plasma channel is not yet readily formed, is stable or already decays due to recombination, when the laser arrives. If the channel is developed, two different situations can be observed. The laser beam energy transmission can be more than 90% with a noticeable but comparably low change in the spectrum. This means that there is almost no interaction between laser and plasma. In the other case the laser is intense enough to excite strong plasma waves which causes a red shift of the spectrum. In this regime electrons can be accelerated and the laser energy transmission drops due to the high energy transfer to the plasma. Whether this necessary intensity is reached depends on the

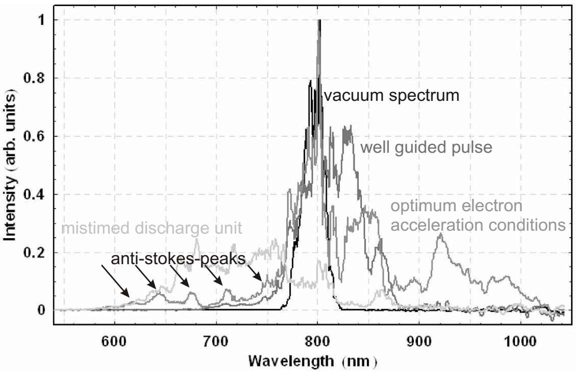

Figure 2: Spectra of transmitted laser light

complicated interplay of channel quality, and therefore gas density and delay, and duration and energy of the laser pulse. The exact correlations are currently being investigated. For even later delays recombination starts, the pulse is not guided. Without guiding the laser intensity seems to be low enough for ionization-blueshift to occur. From the anti-Stokes peaks in the spectrum the electron density can be estimated as $n_e = 7.1 \cdot 10^{18} \mathrm{cm}^{-3}$. That is in close agreement with the value that is predicted by scaling laws deduced from interferometric measurements [8].

Fig. 3 shows different electron spectra. The one on the left side was measured with a calculated

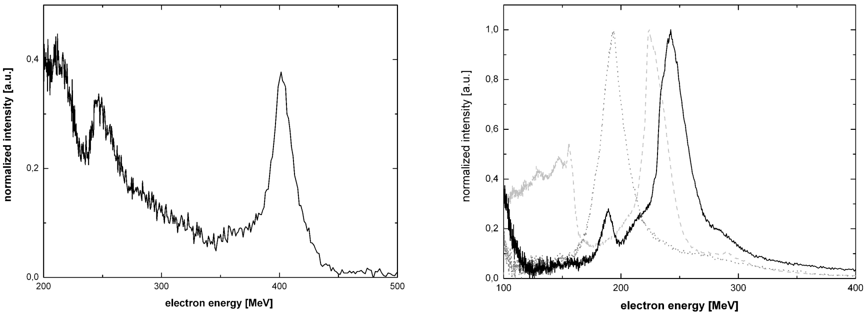

Figure 3: Electron Spectra

on axis electron density of $n_e = 7.3 \cdot 10^{18}$ cm^{-3}. A monoenergetic peak at 400 MeV with an FWHM energy spread of 5 % is shown. The r.m.s. error of the energy can be determined from the electron bunch pointing stability measured in front of the spectrometer. A given pointing stability of 4.8 mrad r.m.s. in the dispersion direction of the spectrometer results in an error of $\pm 11\%$ for the 400 MeV peak. This high error reflects the fact that the spectrometer was not designed for such high energies. The perpendicular pointing stability is 8.4 mrad r.m.s. That direction coincides with the laser polarisation axis. The divergence of the electron bunch can be determined from the width of the monoenergetic feature on the screen perpendicular to the dispersion direction taking into account the focusing properties of the spectrometer. For the 400

MeV shot the divergence is 0.3 mrad r.m.s. To the best of our knowledge this is a factor of 5 smaller than the lowest divergence from LWFA reported up to date. Simulations suggest that the source size is less than 10 μm which results in a normalized emittance smaller than 2.4 mm mrad r.m.s. The peak contains approximately 0.3 pC.

All spectra on the right side of Fig. 3 are taken under the same laser and plasma conditions (calculated electron density $n_e = 4.9 \cdot 10^{18}\mathrm{cm}^{-3}$, delay δt =194 ns). The FWHM energy spread in each case is around 10%, but the peak energy varies between 190 and 250 MeV (±6%) and the charge between 5 and 10 pC. The energetically unstable acceleration might be accredited to the relatively low energy of the *ATLAS* laser. Increased laser energy could probably help to stabilize the process.[10]

The first steps towards an *ATLAS* driven quasimonoenergetic electron source for further table-top experiments have been done. Reasonable energy spreads and very low beam divergences have already been demonstrated. Further investigations of the parameter space might lead to improved control over different beam properties like peak energy, charge and pointing.

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