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Quasi-Monoenergetic Electron Acceleration: The Self-Modulated Multi-Bubble Regime

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The continuous rapid advance in the development of relativistic laser systems currently boosts the use of such devices in the creation of energetic particle beams. The ultra-high fields that emerge when femtosecond laser pulses are focussed on spots of only a few microns diameter exceed those of radio-frequency accelerators by at least four orders of magnitude. Matter located in such a laser focus is instantly ionized to a plasma, easily producing and supporting plasma waves with electric fields up to the TV/m-level, whereas conventional rf cavities are ultimately limited to fields of about 20 MV/m, where material breakdown sets in.

Because of these high fields and plasma waves, the concept of laser-plasma-acceleration was excogitated nearly 30 years ago [1]. In the meantime, many variations of such laser-plasma-accelerators where elaborated and demonstrated. Indirectly, not only electrons, but also protons and ions can be accelerated by the fields conveyed by the primary accelerated hot electrons. Durations, energies and focussed intensities of the driving lasers were varied and improved along with the progress in laser technique. It turned out that short, high-energy laser pulses are especially well suited, because the effects involved in the acceleration process are highly nonlinear. While only exponential particle energy spectra could be obtained for a long time, in the last two years major break-throughs were achieved by generating quasi-monoenergetic bunches of electrons with energies up to 170 MeV [2],[3],[4],[5], protons [6] and ions [7].

Certain types of laser-plasma production of quasi-monoenergetic electrons were predicted and can be explained by the so-called “bubble acceleration“ picture [8]. In this 3d picture, plasma electrons are expelled off the axis by the front of the incident relativistic laser pulse and form a bubble-like structure with longitudinal and transverse dimensions close to the plasma wavelength λ_p. This bubble is void of electrons at the beginning of the interaction and moves through the background plasma ions with a speed close to c. However, in the frame of the moving bubble, the net positive potential of the bubble core attracts electrons that fall back to the laser axis behind the cavity (see fig. 1). These electrons are captured and accumulated inside the bubble and are thus accelerated to high energies. The energy distribution of the bubble electron bunch is quasi-monoenergetic and its peak is given by

$$E_{\text{mono}} \approx \sqrt{\frac{P_{\text{pulse}}}{P_{\text{rel}}}} \times \frac{\tau_{\text{pulse}}[\text{fs}]}{\lambda[\mu\text{m}]} \times 0.1\,\text{MeV} \qquad (1)$$

where $P_{\text{rel}} = m_e^2 c^5 / e^2 \approx 8.5\,\text{GW}$ is the natural relativistic power unit and P_{pulse}, τ and λ are the laser pulse power, duration and wavelength, respectively [9].

The incident laser pulse, however, does not only have to be focussed to an intensity strong enough to expel all of the background electrons, but must also fit into the bubble structure in order to allow its stability. The ratio of laser pulse energy and duration that is at least needed can be described by [9]

$$P_{\text{pulse}} > P_{\text{crit}} \approx \left(\frac{\tau_{\text{pulse}}[\text{fs}]}{\lambda[\mu\text{m}]}\right)^2 \times 30\,\text{GW} \qquad (2)$$

which means that short pulses are best suited.

With laser pulses created by the Jena Ti:Sa-laser (JETI), adjusted to a pulse duration of 80 fs and an energy of 0.6 J on target, eq. (2) would not permit any generation of quasi-monoenergetic electrons via bubble acceleration. However, we made use of a well-known laser-plasma-effect, namely self-modulation of a laser pulse in a plasma, which leads to self-fragmentation of the incident laser pulse and to formation of discrete, ultra-short light bunches. The self-modulation can be triggered by an initial noise source such as the ionization front of the incident laser pulse and can evolve a feedback loop which leads to stimulated Forward Raman Scattering (FRS). This effect is promoted by high electron density and strong focusing as used in the setup depicted in fig. 2.

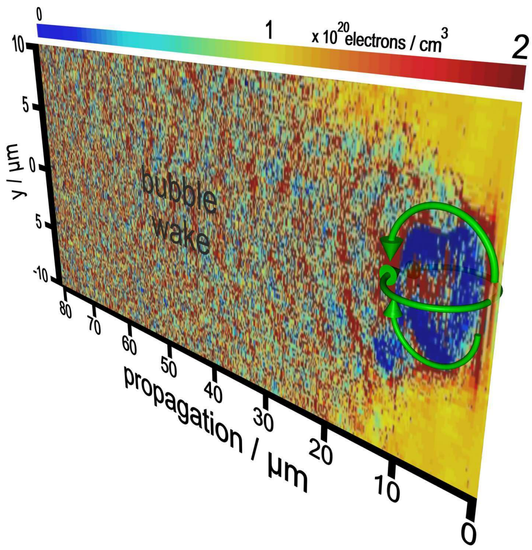

Figure 1: Bubble emerging from laser-plasma-interaction. Green arrows indicate the path of the electrons which are expelled from the laser axis by the laser pulse and fall back to the axis behind the cavity (blue). From here, electrons are drawn inside the bubble and form a high-density, high-energy electron bunch (red).

Under certain conditions, these ultra-short light pulses have durations of only a few fs but still high powers, so that eq. (2), scaling with the squared pulse duration, can be fulfilled. Thus, they are capable to trigger bubble acceleration, generating electron bunches with durations of the order of 5 fs. The energy of these self-modulated bunches is in good agreement with eq. (1),

which demonstrates the robustness of the effect and its scalings. Fig. 3 shows examples of such electron spectra which were recorded on
electron-sensitive image plates (IP).

The appearance of more than one quasi-monoenergetic spike in some of the spectra is supposed to be caused by more than one laser fragment being strong enough to evoke bubble formation as indicated by the frame (taken from a simulation with the ILLUMINATION-PIC-Code) at 400 fs in fig. 2. In this case more than one bubble is formed, leading to ultra-short electron pulses with different quasi-monoenergetic energies and distances of the order of the plasma wavelength $\lambda_p \approx 15\,\mu$m. Defining the electron bunch brightness in analogy to the term "brightness" frequently used for x-ray pulses as $B = I/(\gamma\beta\varepsilon)^2$, where the normalized emittance ε is $<$ 10 mm mrad, the small bunch duration leads to high values of the order of $0.5\,\mathrm{A/mm^2mrad^2}$, despite of the relatively low electron numbers.

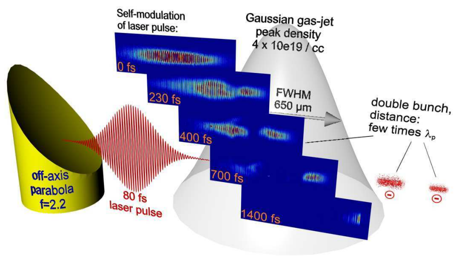

Figure 2: Strong focusing and dense gas jet promote the self-modulation process, leading to fragmentation of the laser pulse and creation of multi-bubbles and ultra-short electron bunches and distances.

In terms of electron bunch length (few fs) and well-defined bunch succession time ($\approx$ 50fs), this self-modulated multi-bubble-process has several qualities beyond what is feasible with conventional accelerators. However, in order to use the phenomenon for practical applications, several problems caused by electron bunch separation and guidance have to be addressed. If this can be done, several interesting applications seem to be feasible.

First, one would want to isolate the electron bunches from the γ- and x-ray background emitted in a forward cone on the laser axis, and second, one might want to separate the successive electron bunches. This can be achieved by applying magnetic fields, at the same time enabling energy-selection and further monochromization of the bunches, but also leading to different electron trajectories and flight times, resulting in higher effective divergences and lower brightnesses. Despite the small divergence of the observed electron bunches (< 10 mrad), refocusing the beam spatially using electron lenses, e.g. quadrupole triplets, would lead to additional, significant reduction of brightness. Therefore, any experimental set-up that wants to make use of such electron bunches in well-defined, ultra-short succession, e.g. for time-resolved electron diffraction, has to take these effects into account and has to be very carefully designed.

A 50 MeV electron bunch with a maximal FWHM of 4 MeV like the one observed in fig. 3 smears out by about 50 fs on a distance of 1 m, while a 100 MeV-bunch with such a FWHM would smear out only by about 7 fs, at the same time being supposed to have better divergences and energy spread, which would reduce the impact of the mentioned problems significantly.

Thus, considerable engineering is necessary to stabilize the process, improve its reproducibility and increase the energy and number of multi-MeV-electrons.

Besides possible medical applications such as VHEE beams for radiation therapy [10], ultra-fast electron beam pump and probe-experiments which make use of the well-defined successive electron bunches, look most promising, but also challenging.

Laser-plasma-interaction can drive itself towards the bubble regime and its quasimonoenergetic electron bunches, even if the initial parameters are not sufficient. The key effect is self-modulation of the incident laser-pulse, and leads to the most welcome side-effect of the generation of ultra-short electron bunches of the order of 5 fs and the possibility of creating multiple such electron bunches with well-defined distances on the fs-scale.

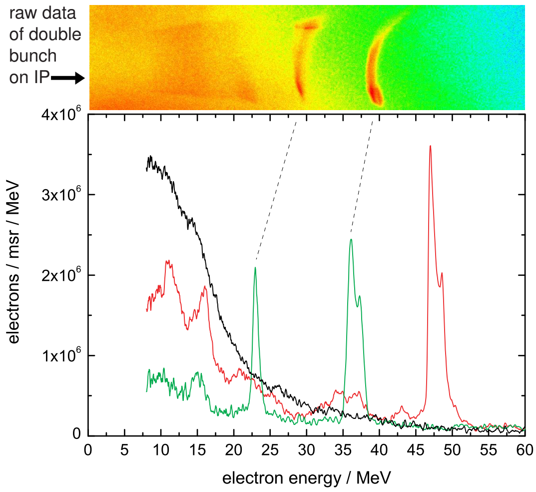

Figure 3: Three types of electron spectra have been observed: exponential (black line), quasi-monoenergetic (red line) and spectra showing the signature of multi-bubbles (e.g. two bunches, green line).

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