Tracing ultrafast field dynamics in laser-ion-acceleration

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Abstract: Using the ultra-low emittance of laser accelerated proton beams we investigate with 1D-spatial / 1D-energy resolved spectrograms the field dynamics of high intensity laser pumped thin foils.

Plasma creation with ultra-intense optical light fields has brought laser based acceleration of charged particles in the current research focus. The striking property of laser accelerated ion beams is their very low emittance, both in transversal and longitudinal direction. While the transversal beam characteristic has been successfully applied in projection based imaging application we concentrate here on longitudinal beam characterization and its application in ultrafast diagnostic of strong fields in plasma. The field dynamics is highly transient and the lifetime of the relevant fields is coupled to the laser pulse duration and depending on energy dissipation processes. Typically the time scale of these processes can extend over several times the pulse duration. Characterization of these fields is not only important to understand the basic physics involved but also to explore application of charged particle injection and cascaded acceleration. Here we investigate strong electrical and magnetic fields created at plasma vacuum interfaces of laser irradiated thin foils. These strong electrical fields play the key role in Target Normal Sheath Acceleration (TNSA) [1]. In further development of previous experiments [2] we focus on thin (below micrometer thickness) foils which optimize the TNSA-process [3,4] and reduce the scattering of penetrating probe particles. As a consequence the driving laser pulse needs a temporal envelope with a high contrast which acts back to the evolving field dynamics. The low transversal and longitudinal emittance [5] of laser accelerated ion beams is its predominant characteristic. Hence imaging and probing of strong fields with proton beams has been successfully applied [6]. Electrical fields have been mainly investigated with transversal [7] and magnetic fields with longitudinal [8] deflection geometry, respectively. As a measure for the longitudinal emittance we found recently a laser cycle based modulation in the velocity spectrum of proton beams [9]. These beams emerge from thin foils which have been irradiated with femtosecond laser pulses at relativistic light intensities and with very high temporal pulse contrast. As shown in Fig.1 we apply now these beams in a streak-like longitudinal probing geometry. Strong fields at plasma-vacuum interfaces change the velocity distribution of the probe beam abruptly and field dynamics becomes traceable.

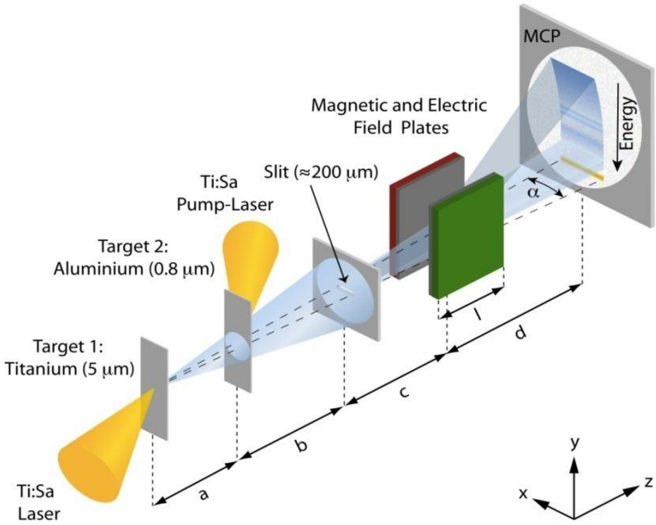

Fig.1 Experimental setup of longitudinal probing of fields in plasma sheets (distances cf. text)

The experimental setup and the probing geometry is depicted in Fig.1. Protons are registered with a modified Thomson spectrometer [2]: The entrance slit has a width of about 200 microns and a length of about 1 cm. The projection of the source (perpendicular to the slit length) to the detector is about (cf. Fig.1) b : (c+d) = 1:1.6. (a= 7.4 mm, b= 486 mm, c= 229 mm, d= 523 mm, l=50 mm (B-field = 0.34 T)). The resolution of the recorded kinetic energies concerning slit width, magnetic field strength and drift length is about 3% of calculated kinetic energy values. Detection of energy changes with this resolution correspond to a probing time of about 30 fs for protons of 1 MeV kinetic energy which probe localized (~ 500 nm extension) strong (~ 1 MV/micron) electric fields.

The experiments were performed with the "High Field Laser" system at Max-Born-Institute Berlin which consists of two separate Ti:Sapphire amplifier chains being optically synchronized and seeded with a XPW-frontend. A laser accelerated proton beam, the probe, is used to propagate along the surface normal direction through a laser irradiated 800 nm thick Al-foil, the pumped region. Laser probe and pump intensities are ~ 10 x 10^{19} W/cm^2 and ~ 1 x 10^{19} W/cm^2, respectively. Due to different architecture of the amplifier chains laser pulses with different temporal contrast and pulse duration can be used, both for the probe and for the pump: A 100 TW-arm (called laser arm A) delivers pulses with 25 fs duration at an ASE background level of 10^{-10} - 10^{-9}. A 70 TW-arm (called laser arm B) delivers pulses with 35 fs duration at an ASE background level of 10^{-11} - 10^{-10}.

Results are discussed for the case of two laser pulses created due to splitting of the "lower contrasted" laser pulse (beam A). The pump – probe proton spectra are displayed in Fig.2. The temporal adjustment of the pump laser pulse corresponds to the arrival time of 1.5 MeV protons of the probe beam at target 2 (cf. Fig.1). A pronounced gap in the distribution for protons of the probe results in an energy range between 1.2 MeV and 1.5 MeV. Arriving protons within this energy range interact with the strong field set up by the pump laser pulse and their kinetic energy is changed due to acceleration or deceleration in the field. When the central region of the pump laser interaction with target 2 is probed (upper half in Fig.2) a characteristic double peak feature arises on the high energy side of the gap.

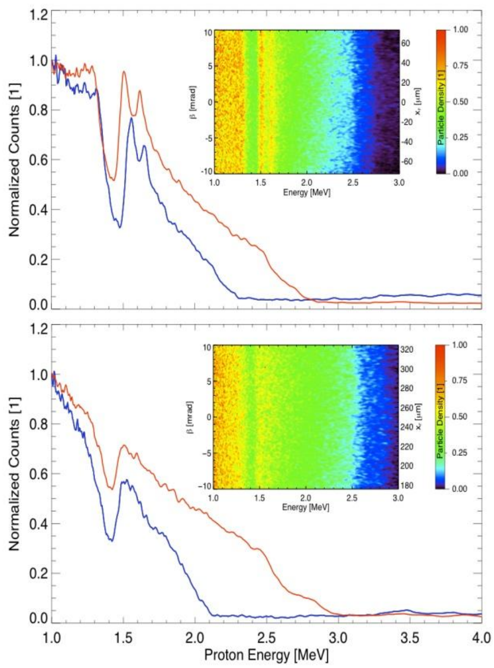

Fig.2 Proton beam "probing" of a laser "pumped" interaction center (upper half) and 250 microns aside (lower half) at target 2 using laser arm A (parameter cf. text): Color coded inserts show processed 2D-spectrogramms. Lineouts are spectrograms integrated along the x-axis (cf. Fig.1). Red and blue lines show two independent laser shots.

Applying a model calculation [10] one can show that an effective field pointing in one direction along the target normal of sufficient strength (15% of the laser electrical field strength ~ 1 x 10^{12} V/m) and a certain lifetime accounts for the double peak feature. The peak separation is connected to the field lifetime and from our observation a duration of about 100 fs can be concluded.

The situation changes when a laser with even higher contrast is applied as pump (cf. Fig.3).

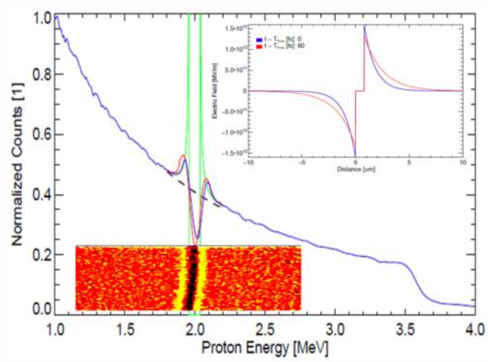

Fig.3 “Probing” the interaction centre of target 2 “pumped” with laser arm B (cf. text): Colour coded insert – cut of measured spectrogram, function insert - symmetrical fields used to ray trace the interaction of the proton probe resulting in the left-right peaked green curve, main graph: red curve – with instrument function, blue – experiment;

Again the typical gap in the spectrum occurs. But now the two peaks emerge at the low energy side of the gap and at the high energy side. The higher temporal pulse contrast of laser arm B initiates a close to symmetrical field configuration concerning target front and rear side and a simple model field to ray-trace the proton probe beam through the “pumped” field can reproduce the finding.

Summarizing we investigated how proton probing of localized and strong fields in a longitudinal geometry can trace field dynamics at ultrafast timescale. Analysis of the findings need appropriate analytical models being justified with numerical simulation. Our results show possibilities for beam manipulation in cascaded acceleration schemes.

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