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Tracing ultrafast dynamics of strong fields at plasma-vacuum interfaces with longitudinal proton probing

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If regions of localized strong fields at plasma-vacuum interfaces are probed longitudinally with laser accelerated proton beams their velocity distribution changes sensitively and very fast. Its measured variations provide indirectly a higher temporal resolution as deduced from deflection geometries which rely on the explicit temporal resolution of the proton beam at the position of the object to probe. With help of reasonable models and comparative measurements changes of proton velocity can trace the field dynamics even at femtosecond time scale. In longitudinal probing, the very low longitudinal emittance together with a broad band kinetic energy distribution of laser accelerated ions is the essential prerequisite of the method. With a combination of energy and one-dimensional spatial resolution, we resolve fast field changes down to 100 fs. The used pump probe setup extends previous schemes and allows discriminating simultaneously between electric and magnetic fields in their temporal evolution. © 2014 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4891167]

The current interest in plasma based acceleration for charged particles manifests itself in the possibility to produce high electrical field strength in a small micrometer to millimeter sized plasma volume. Acceleration of charged particles over short distances might advance future accelerator technology. The strong force needed to drive the process can be provided by a short and intense laser pulse. Thus, the field dynamics is highly transient, and the lifetime of the relevant acceleration fields is coupled to the laser 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 fields created at plasma vacuum interfaces of laser irradiated thin foils, which 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-process3,4 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 emittance5 of laser accelerated ion beams is its predominant characteristic. Hence, imaging and probing of strong fields with proton beams has been applied.6 Electrical fields have been mainly investigated with transversal7 and magnetic fields with longitudinal8 deflection geometry, respectively. Laser produced proton (ion) beams have typically a broad velocity (kinetic energy) spectrum.1,5 The emission of protons with different energies is exactly ordered in time,3,9 which results in a low longitudinal emittance. The proton beam (ion pulse) shows a velocity (kinetic energy) distribution in time, which is similar to a negatively chirped optical beam (laser pulse). During a certain Time Of Flight (TOF), the differences in ion velocities lead to further temporal stretching of the ion pulse, the chirp increases. When an object is probed with such a beam, the temporal resolution of the deflection is determined by the velocity (kinetic energy) chirp of the probe beam at the object position. Deflection results if the velocity vector of the probe beam is oblique to the direction of the field to probe. Therefore, we call it simply transversal probing geometry. The ions being registered in a certain kinetic energy interval create the deflection picture and the energy interval with the related chirp determines the temporal resolution. Deflection pictures10 (or radiographs) which reflect snapshots in time could be obtained with down to 1 ps and application of a streak-like deflectometry setup2 with about 30 ps temporal resolution, respectively. Alternatively, the use of laser-accelerated electron pulses with relativistic energies and femtosecond pulse duration could verify laser initiated strong magnetic field dynamics at femtosecond time scale.11 In the present work, we address a longitudinal probing geometry where laser pulses with high temporal contrast establish strong electrical fields in normal direction to the surface of an irradiated thin foil. The essential difference to transversal probing establishes in the predominantly change...
of the velocity (kinetic energy) distribution function of the probe beam. Hence, the temporal resolution is now linked to the energy redistribution effects in the probe beam resulting from field dynamics. And just this situation can provide insight to ultrafast changes of the field if specific prerequis-

ites are fulfilled. A proton which probes an electric field of about 1 MV/μm strength receives a well detectable 5% change of its original 2 MeV kinetic energy within 50 fs and 1 μm acceleration distance in the field. An ambiguous situa-
tion arises from the fact that quite different field configuration may result in the same change. Therefore, restrictions in the model discussion and comparative measurement at different field location are necessary. The aim of this paper is to show a principle diagnostic with 1D-spatial against kinetic energy resolution which can trace field effects at ultra-short time scale. This approach and investigation of parameters being relevant for optimum laser–ion–acceleration (as very thin target foils of 30 nm and 800 nm thickness illuminated with pulses of high temporal contrast) extends experiments of a post-acceleration setup significantly. We can conclude on different field developments being a characteristic of laser contrast and can even extend the analysis for radial electric and magnetic fields. After providing the experimental layout data are discussed including numerical simulation and analytical model interpretation.

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 thin foil, the pumped region. Laser probe and pump intensities are \( \sim 10 \times 10^{19} \) W/cm\(^2\) and \( \sim 1 \times 10^{19} \) W/cm\(^2\), respectively. Resulting focal intensities are based on calculation with pulse energies measured in front of the grating compressors, measured relative transmission of grating compressors and beam-lines inclusive focusing optics, pulse compression as well as the measured focal spot sizes with encircled energy content. The proton “probe” stems from laser irradiated Ti-foils (5 μm thick) and its adherent CH-contamination. 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 Amplified Spontaneous Emission (ASE) background level of \( 10^{-10} \)–\( 10^{-9} \). It is a commercial system from Amplitude Technology \(^{12}\) and lines up with a regenerative amplifier inclusive spectral steering. A 70 TW-arm (called laser arm B) delivers pulses with 35 fs duration at an ASE background level of \( 10^{-11} \)–\( 10^{-10} \), as self-made construction, and it consists of multi-pass amplifier sections only. A pulse from one arm (either A or B) was divided with a semi-transparent mirror and used for the probe (80% pulse power) and the pump (20% pulse power). Due to the dispersion of the glass substrate, the duration of the transmitted pulse (used for the pump) changes either from 25 fs to 87 fs or from 35 fs to 62 fs.

The experimental setup and the probing geometry are depicted in Fig. 1. Protons are registered with a modified
Thomson spectrometer. The entrance slit has a width of about 200 \( \mu \)m and a length of about 1 cm. The projection values are related to used distances ("pumped" rear or "pumped" front) in Fig. 1: \( a = (5 \text{ or } 20) \text{ mm}, b = (3 \text{ or } 16) \text{ mm}, c = (470 \text{ or } 440) \text{ mm}, d = 228 \text{ mm}, e = 515 \text{ mm}, \) and \( l = 50 \text{ mm} \) (B-field = 0.34 T)). Inserting of a beam mask allows detection of deflection along x-direction. 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/\( \mu \)m) electric fields. If the electrical field plates in the spectrometer are switched off, the dominating proton signal is covered with a carbon ion background signal. This influence is marginal for our probe beam and has been checked if only the faster protons in respect to slower carbon ions have been recorded with appropriate gating of the voltage of the phosphorous screen. Due to our choice of pump conditions in respect to the probe excitation (laser energy relation 1:4) pictures are obtained which are only partly overlaid with proton emission from the second (pump) target.

First, results are given 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 setup 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. The traces in Fig. 2 represent different laser shots in order to illustrate the reproducibility of the phenomenon.

Applying a model calculation as outlined in a previous paper, 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 \( \sim 1 \times 10^{12} \text{ V/m} \)) and a certain lifetime accounts for the double peak feature. The peak separation is connected to the field lifetime and a duration of about 100 fs can be concluded.

Such an effective field represents the combined action of two anti-symmetric fields located at the front and the rear of target 2. It is substantiated from a 2D-PIC simulation of the pump illumination of target 2 which uses a temporal contrast of laser arm A with residual influence of weak pre-pulses. In order to account for the contrast, the simulation starts with a Gaussian pulse envelope in time at a laser intensity of \( 10^{-3} \) peak level and 60 fs in front of the peak. Start conditions for the plasma surface are six times ionized Al at solid density, 100 eV electron temperature and a plasma density gradient of 1/40 laser wavelength. Electrical field distributions at front and rear side differ and as a result an effective strong field points into direction of the proton "probe" beam propagation and accounts for the double peak feature in Fig. 2, a specific finding being not observed in other setups.

The field strength declines with increasing distance from the interaction center. In the experiment, the field of view at target 2 is 120 \( \mu \)m. Within this range, the observed effect is similar. Moving the observation zone more far away ~250 \( \mu \)m have been applied here, the drop of the field becomes significant and the double peak feature is not any longer detectable (cf. Fig. 2, lower half). If one would analyze only one observation alone one might also conclude (and can model) that a weaker but longer living field at picosecond order can account for the observation. Such a long living field should extend radially also over larger distances, e.g., 300 \( \mu \)m correspond to a field extension time of 1 picosecond. But we observe already at such a distance a clear change of the probe beam redistribution. This suggests a fast field dynamic below 1 ps, which manifests also in strong field changes within several hundred microns of spatial separation. That means the characteristic of the electrical fields at target front and rear side depends sensitively on the contrast of the field driving laser pulse. Theoretical and experimental work has studied these processes in relation to ion acceleration and to electric as well as magnetic field generation.

Here, we have changed the contrast condition either by using laser arm A or B for both the pump and the probe beam. Measurements with a 3rd order correlator show differences concerning the Amplified Spontaneous Emission by one order and different residual short pre-pulses. A result

![Graph](image-url)
of a pump–probe experiment with laser arm B (higher contrast) is displayed in Fig. 3. The color coded 2D-
spectrogram (a clipped part is inserted) and the respective
integrated lineout show again the typical gap in the
spectrum. But now two peaks, one at the low energy side of the
gap and one at the high energy side, occur. They are located
differently in comparison to the result with laser arm A. The
higher temporal pulse contrast of laser arm B initiates a close
and symmetrical field configuration concerning target front
and rear side which has been deduced also from ultra-high
contrast laser driven proton acceleration experiments\textsuperscript{1,4} and
respective simulation. Such a field configuration (cf. also
inset in Fig. 3) is used as a simple model field to ray-trace
the proton probe beam. The model calculation shows that
now neighbor peaks arise close to the gap position in the pro-
ton probe spectrum. Two symmetrical strong electrical fields
peak at the order of 1.5 MV/\textmu{}m and decline with a half width
time of about 100 fs, which account for the experimental
observation.

This observed feature is similar to another previous
experiment,\textsuperscript{12} which aimed to investigate the possibility of
staged TNSA acceleration,\textsuperscript{15} and measurement of energy
redistribution was perused. The current work extends this
specific former one-dimensional approach\textsuperscript{12} which cannot
resolve different field components. In contrast to that we
have developed a method allowing to investigate the real
evolution of fast rising field components in time and its
transversal projection (cf. Fig. 1). Our approach gave us the
possibility to study the influence of laser contrast on field
dynamics for interesting post-acceleration schemes which
need much more detailed investigation. Specifically, we
investigated the fields responsible for proton acceleration
using different targets irradiated with very high and interme-
diate pulse contrasts. A beam mask forms beamlets and
transversal deflection of protons becomes detectable. This
allows discriminating simultaneously between electric and
magnetic fields: Radial electrical fields cause outward bend-
ing along x-direction and magnetic fields can result in inward
bending, respectively.

Results shown in Fig. 4 demonstrate the change of field
components when different temporal contrast of the laser is
applied. Lower contrast values favor magnetic field genera-
tion being different at front and rear.\textsuperscript{16} Thus, their influence
becomes measurable. A high contrast results in symmetric
magnetic fields\textsuperscript{16} which compensate probe beam deflection.
But this does not hold for radial electric fields which cause
deflection in the same direction at rear and front side.

In conclusion, the experimental findings show that
longitudinal probing of strong electrical fields with laser pro-
duced proton probe beams can trace strongly peaking fields
within a temporal duration in the order of 100 fs. The princi-
ple of the method is based on sensitive energy redistribution
within a broad band proton beam with a well-defined kinetic
energy chirp. Moreover, our method allows with help of
field symmetry predictions from simulation, ray tracing of a
model field, and comparison of measurements at different
field localization to discriminate simultaneously between
electric and magnetic fields, their temporal-spatial change
and their dependence on laser pulse parameter.

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Framework Program). A.A.A. acknowledges the provided
computation resources of JSC at project HBUIS.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig3}
\caption{“Probing” (without beam mask) the interaction center of target 2
(800 nm aluminum) “pumped” with laser arm B (contrast level of
ASE ~ 10^{-10}). Color coded inset—cut of measured spectrogram, function
inset—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 included instrument function, blue curve and dashed black curve are
the measurement results with the “pump” laser pulse on or off, respectively;
Laser “pump” irradiates rear of target 2.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig4}
\caption{Proton probing of a “pumped” 30 nm formvar foil with inserted
beam mask: (a) outward bending (pump laser B—contrast level of
ASE ~ 10^{-10}) indicates radial electrical fields, (b) inward bending (pump
laser A—contrast level of ASE ~ 10^{-9}) shows deflection due to an effective
magnetic field, calculated iso-contour lines illustrate the effect; Laser
“pump” irradiates front of target 2.}
\end{figure}

\begin{thebibliography}{10}
\bibitem{Hatchett}
Mackinnon, D. M. Pennington, M. D. Perry, T. W. Phillips, M. Roth, T. C.
Sangster, M. S. Singh, R. A. Snavely, M. A. Stoyer, S. C. Wilks, and K.
\end{thebibliography}


