Investigations of ultrafast charge dynamics in laser-irradiated targets by a self probing technique employing laser driven protons


Published in:
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
Link to publication record in Queen's University Belfast Research Portal

Publisher rights
© 2016 Elsevier B.V.
This manuscript version is made available under the CC-BY-NC-ND 4.0 licensehttp://creativecommons.org/licenses/by-nc-nd/4.0/, which permits distribution and reproduction for non-commercial purposes, provided the author and source are cited.

General rights
Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy
The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.
Investigations of ultra-fast charge dynamics in laser-irradiated targets by a self proton probing technique


*Centre for Plasma Physics, School of Mathematics and Physics, Queen’s University Belfast, BT7 1NN, UK

bDepartment of Physics E. Fermi, Largo B. Pontecorvo 3, 56127 Pisa, Italy

Institut für Laser-und Plasmaphysik, Heinrich-Heine-Universität, Düsseldorf, Germany

Abstract

The divergent and broadband proton beams produced by the target normal sheath acceleration mechanism, provide unique opportunity to probe, in a point-projection imaging scheme, the dynamics of the transient electric and magnetic fields produced during laser-plasma interactions. Commonly such experimental setup entails two intense laser beams, where the interaction produced by one beam is probed with the protons produced by the second beam. Here we studied ultra-fast charge dynamics along a wire connected to laser irradiated target by a ‘self’ proton probing arrangement - i.e. by connecting the wire to the target generating the probe protons. The experimental data shows that an electromagnetic pulse carrying a large amount of charge is launched along the wire, which travels as a unified pulse of 10s of ps duration with a velocity close to speed of light. The experimental capabilities and the analysis procedure of this specific type of proton probing technique are discussed.

Keywords:...
been the object of several previous studies employing
the standard proton probing technique (using two laser
pulses) [11, 12, 13, 14]. These studies revealed positive
target charge up to MV potential following intense irra-
diation, due to the escape of relativistic electrons from
the laser-irradiated region [11, 12, 15]. The targets were
then observed to discharge to ground on timescales of
10s of ps [11, 14]. The strong and sudden charge sep-
oration caused by the hot electron escape was also seen
to lead to the launch of a surface electromagnetic (EM)
wave along the target, expanding out from the interac-
tion point at nearly the speed of light [13, 12]. This
surface wave contributes to the target neutralization pro-
cess by carrying the positive charge away from the in-
teraction region. In this paper we show how an ap-
propriate arrangement allowed us to follow this surface
wave along a cm-long wire connected to the laser irra-
diated target, and to reveal its pulsed nature. We saw the
pulse propagating along the wire at a velocity close to
the speed of light, while retaining its pulse shape over
centimetres of propagation.

2. Experimental setup

The experiment was performed using the TARAN-
NIS laser at QUB [16], employing the CPA pulse of
~600fs pulse duration with energy ~5J on target. The
short pulse was focused by a f/3 off axis parabola onto
~10 µm thick and a few mm² gold foil at an intensity
~ 2 × 10¹⁹ W/cm². Following this interaction protons
are accelerated from the rear surface of the foil via the
TNSA process and are used as a charged particle probe
for a separate portion of the target. A schematic of the
experimental setup is shown in figure 1(a). A stack of
multilayer Radiographs films (RCF) of type HD810
[17] was used as a proton detector. Due to the Bragg
peak energy deposition profile of protons in matter, the
proton image produced in a given layer of RCF corre-
spends primarily to a narrow range of proton energy,
defined by the position of the RCF layer in the stack.

A particular target design (shown in Fig. 1(a)) was
used for studying the charge dynamics far away (≥ cm)
from the interaction region. A thin (≈ 75 µm diam-
ter) and several centimeters long Copper wire was con-
ected to the proton-generating gold foil. In order to
maximize the length of wire that could be observed
within the field of view of the probe beam, the Cu wire
was folded in to a square wave pattern (SWP) in front
of and parallel to the interaction foil, as shown in the
Fig. 1(b). There were 8 segments in the SWP, as shown
in Fig. 1(b), where the length of each horizontal wire
segment was ~2.5mm and the vertical spacing between
two segments was ~600µm. The distance between the
proton source and the centre of the SWP was ~2.4 mm,
whereas the RCF stack detector was placed at ~20 mm
from the proton generating foil, providing a magnifica-
tion of ~8.3 in the point-projection arrangement. The
length of the Cu wire from the Au foil to the top of the
winding in the SWP was approximately 12 mm, so that
a EM wave launched by the interaction and travelling

Figure 2: (a), (b) and (c) shows the raw proton images of the charge flow along the SWP at different probing times, obtained in a single shot from different RCF layers in the stack detector, corresponding to Bragg peak proton energy of (5.6, 4.5 & 3.2)±0.5 MeV protons (as labelled in the bottom left side of each image). The probing time mentioned at the top-right corner of each image correspond to the time of arrival of respective energy protons at the centre of their field of view on the plane of the SWP. The line segments in the proton images are labelled and the arrows indicate the direction of the charge flow through the SWP, from top to bottom. The red dashed lines provide eye-guide for the width of the proton deflected region around different wire segments for the respective probe proton energies labelled on the image. The insert at the bottom right of (a) shows part of the target image shown in Fig 1(b), with the circle representing the field of view of the probe protons.
along the wire at a velocity close to the speed of light, 
would be intercepted by the probe proton beam.

3. Time resolved detection of EM pulse propagation

Fig. 2 shows the data obtained in three consecutive 
layers of RCF in the stack detector, which show the 
propagation of the EM pulse in different segments of 
the SWP at different probing times. The darkness in the 
RCF images is proportional to the incident flux of protons 
of the given energy arriving at the RCF. For an electric-
ally neutral metal wire, a proton radiograph would 
show a shadow (proton depleted region) of the wire due 
to multiple-small angle scatterings of the probe protons 
in the wire. In this case, the width of the shadow on 
the RCF will be equal to the product of the diameter 
of the probe wire and the geometrical magnification 
(M = L/l, where l and L represent the distance from the 
proton source to the probe wire and the RCF respecti-
vely). If the wire is positively charged, the probe pro-
tons will experience a strong Coulomb deflection. The 
width of the proton depleted region on the RCF will in 
this case be related to the strength of the electric field 
around the wire and the energy of the probe protons.

As can be seen in Fig. 2(a), the segment S2 appears 
to be charged to some positive potential, while the next 
wire segment, S3, remains electrically neutral. The con-
ical shape of the proton depleted region around the seg-
ment S2, as highlighted by the red dashed line, indicates 
the rise of the electric field as positive charge moves 
along the wire from its left hand side, the side which 
is connected to the laser irradiated target. At a later 
probing time, as shown in Fig. 2(b), the segment S3 has become positively charged as evident from the in-
crease of the width of the proton depleted region around 
S3. This suggests that the charge front associated to 
the surface wave has flown from S2 to S3 during the 
time elapsed between the snapshots shown in Fig. 2 (a) 
and (b). In the following time frame (Fig. 2 (c)), as 
expected, the charge appears to have entered into the 
line segment S4. However, it is interesting to observe 
that the line segment S1 and half of the line segment S2 
are back to being electrically neutral at this time. The 
proton depleted region around S2 takes the form of a 
reverse conical shape, with the narrower side towards 
the laser irradiated target. The data therefore are consis-
tent with the propagation of a localised pulse, with a 
finite temporal width and carrying positive charge. The 
propagation of this pulse is consistent with the previous 
observation of a surface EM wave generation and prop-
agation discussed in [12], and confirms separate obser-
vations reported in [18]. In response to the sudden, po-
sitive charge-up of the laser-irradiated area of the target, 
the propagation of EM pulses away from the interaction 
regions contributes to lowering the target potential to-
wards neutrality by carrying excess positive charge to 
remote regions of the target assembly or to ground.

4. Characterisation of the charge pulse profile

Quantitative information about the charge pulse tem-
poral profile can be obtained from the data shown in 
Fig. 2. The energy (E_proton) with which each of the 
RCF layers shown in Fig. 2 is labelled refers to protons 
reaching their Bragg peak in the layer, as obtained from 
SRIM [20] simulations. The probing times labelled at 
the top right hand corner of the RCF images shown in 
Fig. 2 correspond to the time of arrival of protons with 
this energy at the centre of its field of view (see Fig. 3 for 
a schematic of the geometry involved in our SPP setup). 
The probing time for different points on the SWP varies 
within a few ps due to the different path lengths trav-
elled by the probe protons. The absolute probing time 
at a given location on the plane of the SWP (x, y, z = l) 
(see fig. 3) can be calculated by,

\[ t_{\text{proton}}(E_{\text{proton}}, x, y, z = l) \approx \sqrt{\frac{x^2 + y^2 + l^2}{2E_{\text{proton}}/m_p}} \]  

(1)

where \( m_p \) represents the mass of proton. Assuming the 
charge pulse is travelling down the wire with a constant 
speed \( v_{\text{charge}} \), the time of arrival of the charge pulse 
at the point P can be written as \( t_{\text{charge}} = l_{\text{delay}}/v_{\text{charge}} \), 
where \( l_{\text{delay}} \) is the length of the wire from the proton
source to the given point P. Therefore, by measuring the charge density at different points on the SWP at different times, the charge pulse profile can be obtained by plotting the charge density with respect to the relative probing time \( t = t_{\text{proton}} - t_{\text{charge}} \).

The proton deflection by an electrically charged segment will depend on both the charge density and the probe proton energy. Therefore the 3D particle tracing simulations were carried out in order to estimate the charge density from proton deflection. The first step of the analysis was to measure the transverse width of the proton depleted region across the SWP. Although the image obtained in a given RCF layer is produced primarily by the protons having their Bragg peak in that layer, the image also contains a fractional contribution from higher energy protons in the probe beam. Therefore each RCF image contains an impression of the images produced by the higher energy protons deeper in the stack [13]. For instance, the gray dotted line around the segment S3 and S2 in Fig. 2(b) and (c), respectively, represent the width of the proton deflection region produced by the higher energy protons, probing the SWP at earlier times, compared to that produced by the protons reaching their bragg peak in the respective layers (marked by the red dotted line). Due to the ultra-fast (close to the speed of the light [12]) propagation of the charge pulse along the wire, these artefact (“ghost”) impressions becomes an integral part of the proton images produced in the RCF. By considering the dynamics of charging/discharging of a given line segment from the images obtained in different RCF layers, one can identify the actual proton deflection for a given layer from the overlying ghost impressions. The red dashed lines in Fig. 2 provide eye-guides for the width of the proton deflections around different wire segments in different layers.

In order to find out the local charge density from the width of the proton deflected region, a series of particle tracing simulations using the PTRACE code [21] were carried out. The code was setup to simulate probing of a metallic wire with uniform linear charge density by monoenergetic protons, while using the same geometry and dimensions as per the experimental setup. The simulated proton images were rendered as a two dimensional proton density map at the designated RCF plane in the experiment, i.e. on the plane at a distance \( L \) from the proton source. The linear charge density \( \lambda \) of the wire segment was varied until the width of the proton depleted region matched with the experimental results.

The particle tracing code PTRACE simulates the propagation of the protons from the source through the interaction region and up to the detector. There is a differential equation solver at the core of the PTRACE which computes the trajectory of the particles in presence of electric and magnetic fields. The numerical solver is a Runge-Kutta fourth-order algorithm coupled with an adaptive step-size monitoring routine. The adaptive step-size routine assures that the time steps at which the dynamics are sampled are adequately small so that computational resources are well managed during the simulation for large field strengths. The radial electric field at a given point in space due to the electrically charged wire was calculated by \( E(r) = \frac{\lambda}{2\pi \epsilon_0 r} \), where \( r \) is the radial distance between the given point and the wire and \( \epsilon_0 \) is the permittivity of vacuum.

The line charge density was varied in the simulation in order to reproduce the experimentally measured width of the proton depleted region around the wire. Fig. 4 shows the comparison between the experimental and a simulated proton flux profiles across a wire segment shown in Fig. 2. By converting the proton deflection to linear charge density, the effect of proton energies on the net deflection produced in different RCF layers was eliminated. This procedure was followed to estimate the local charge density at several points on the segments S2, S3 and S4 wire segments for different probing times.

In order to reconstruct the temporal profile of the charge pulse, the charge densities estimated at different points along the SWP from different RCF layers were plotted as a function of the relative probing time \( t = t_{\text{proton}} - t_{\text{charge}} \). The relative probing time accounts for \( t_{\text{charge}} \), which depends on the speed of the charge pulse along the wire \( v_{\text{charge}} \). Since \( t_{\text{delay}} \) for each analysed point on the SWP was measured directly from the target images taken prior to the shot (as shown in

![Figure 4: Figure showing the comparison between the experimental and simulated proton flux profiles (as shown in inserts) across a proton depleted region around one of the wire segment shown in Fig. 2.](image-url)
Figure 3.7: Charge density profile, obtained by referring the probing time to the field arrival time at different points along the wire. The charge density values follow from the uncertainty in measuring the width of the proton deflection from the RCF data.

The error in the charge density values follows from the uncertainty in the SWP measured by the SPP technique. The graph shows the line charge density measured at different points across different line segments probed by the proton beam with respect to the relative probing time \( t = t_{\text{proton}} - t_{\text{charge}} \). The error on the time values is dominated by the width of the Bragg-peak for protons in different RCF layers.

The error in the charge density values follows from the uncertainty in measuring the width of the proton deflection from the RCF data.

Acknowledgements

The authors acknowledge funding from EPSRC, [EP/J002550/1-Career Acceleration Fellowship held by S.K., EP/L002221/1, EP/K022415/1, EP/J500094/1 and EP/1029206/1], SBF-TR18 and GRK1203, EC-GA284464 and Invest Northern Ireland (POC-329).

References


Fig 1(b)), the charge velocity remains a free parameter in the data set. By varying the value of \( v_{\text{charge}} \) in the data points, it was possible obtain a fairly consistent pulse shape centred at \( t=0 \) as shown in Fig. 5. The agreement between the data points, obtained for different line segments at different probing times, was attained for a charge pulse velocity \( v_{\text{charge}} = (0.96 \pm 0.04)c \), where \( c \) is the speed of light in vacuum, which agrees well with that reported in ref [12]. The error in the velocity measurement is primarily due to the uncertainty in defining the location of the peak of the charge pulse with respect to the relative probing time. Although a limited number of temporal snapshots were obtained in this shot, one can broadly define the charge pulse as having a full width at half maximum of \( \sim 25 \) ps, which is consistent with the previous measurements of the neutralization times of electrically charged targets [11, 12].

5. Summary and Discussions

In summary, a slightly different approach to the typical proton radiography technique is discussed. The technique was used for characterising the charge flow dynamics in a wire connected to a laser irradiated target, which itself provided the probe protons for the radiography. The experimental results illustrate that positive charge flows along the wire as a high amplitude pulse of a few tens of ps duration. Furthermore, it is found that the charge can be transported over a long wire (a few cm) away from laser interaction region, which may be important for future developments of schemes useful for controlling and optimising the laser driven proton beams. The electric field associated to such travelling pulse is strong enough to steer MeV protons, and hence can be used to manipulate the laser driven MeV proton beams[15]. For instance, allowing the EM pulse to travel along a helical path around the proton beam, the transverse and longitudinal components of the electric field produced inside the helical coil can act simultaneously on a selected bunch (depending on the coil diameter and pitch) of the transiting protons to produce strong focusing and post-acceleration effects [22].