GAMMA-RAY MEASUREMENTS IN RELATIVISTIC INTERACTIONS WITH UNDERDENSE PLASMAS

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ABSTRACT

Fast electrons generated during laser-plasma interactions at relativistic intensities can be studied directly using electron spectrometers, or indirectly, detecting the gamma-ray bremsstrahlung radiation generated by the interaction of these electrons with matter. In a recent experiment carried out at the Rutherford Appleton Laboratory using the Vulcan laser, the propagation of a 75 J, 1 ps Chirped Pulse Amplified pulse (CPA) in a preformed plasma channel was studied using a variety of diagnostic techniques. High energy gamma ray detectors based on NaI(Tl) scintillator coupled to photomultipliers were used to detect bremsstrahlung emission from accelerated electrons. The gamma-ray yield was studied for different plasma channel conditions by varying the delay between the channel forming pulse and the main CPA pulse. These results are correlated with the interferometric images of the plasma interaction region.

Keywords: laser-plasmas, relativistic interactions, electron acceleration

1. INTRODUCTION

The interaction of ultra-short laser pulses with plasmas at relativistic intensities gives rise to very large electric fields which can accelerate charged particles [1-4]. Depending on the plasma density, several mechanisms can be activated which accelerate electrons to much higher energies than those due to the laser ponderomotive potential. Stimulated Raman forward scattering (SRFS) and self-modulated laser wake-field acceleration (SMLWFA) are some of the mechanisms proposed to explain the generation of a large number of >10 MeV electrons in recent experiments [4-9]. Theoretical studies also predict that energy conversion into energetic electrons should be favored when the laser pulse propagates in a cavitated structure such as a plasma channel. These issues may have important consequences on laser-driven plasma-based accelerators as well as on inertial fusion energy (IFE), particularly in the Fast Ignitor (FI) scheme. A major problem of laser-driven plasma-based accelerators is the short acceleration distance which is basically limited by laser beam diffraction [10]. Propagation in a plasma channel has been proposed as a way of overcoming this limitation. It is well established that channels can be produced [11,12] as a result of laser interaction with underdense plasmas. Several experiments [13,15] have also demonstrated that efficient guiding of ultraintense pulses in a channel is indeed possible. From the point of view of the fast ignitor approach to inertial fusion, the occurrence of non-ponderomotive acceleration mechanisms typical of the ultra-intense regime may result in a loss of energy if the stopping range of these electrons is much greater than the typical size of the compressed core of an IFE pellet. It is therefore important to assess the role of these additional acceleration mechanisms and their importance in the energy balance.

Fast electrons generated in laser-plasma interactions at relativistic intensities can be studied directly using electron spectrometers, or indirectly, detecting the gamma-ray bremmsstrahlung radiation generated by the interaction of these electrons with matter. The gamma-ray detection technique is particularly suitable when the energy of the fast electrons is expected to be very high (>>10 MeV) and traditional (magnetic) electron spectroscopy would require dedicated, large scale equipment. Here we report on a recent investigation carried out at the VULCAN laser facility, Rutherford Appleton Laboratory (UK) in which this technique was employed to study the effect of a precursor channeling pulse on the interaction VULCAN CPA laser pulse (75 J, 1 ps , 1.054 µm) with an underdense plasma. The generation of fast electrons during the interaction was monitored for different conditions of the preformed channel by varying the delay between the channel forming pulse and the main CPA pulse.

2. EXPERIMENTAL SET-UP

The plasmas were produced by using a well established technique [16] based upon the explosion of thin plastic foils (0.1, 0.3 or 0.5 µm thick) by two 600 ps, 0.527 µm Vulcan laser pulses at a total irradiance of about 5 10^{14} W/cm^2 (see Figure.1). After a suitable delay (typically of the order of 1 ns) the main CPA pulse was focused into the plasma. At this time the peak density of the plasma was below $n_c/10$ and its longitudinal extension was of the order of 1mm. With an f/3.5 focusing optics the CPA vacuum irradiance was up to 5 10^{19} W/cm^2 (about 50 J on target, with up to 50 % of the energy in a 10-15 µm focal spot). A fraction of the energy of the main CPA pulse was used to provide a prepulse, collinear with the main pulse. The prepulse could be focused into the preformed plasma before the main pulse and used to open a density channel. A further small fraction of the CPA pulse was frequency quadrupled and used as a transverse optical probe. Interferometry was performed along this line using a modified Nomarsky interferometer[17]. Other diagnostics included calorimetry of the energy transmitted through the plasma, imaging of the transmitted laser spot, forward and back-scatter spectroscopy.

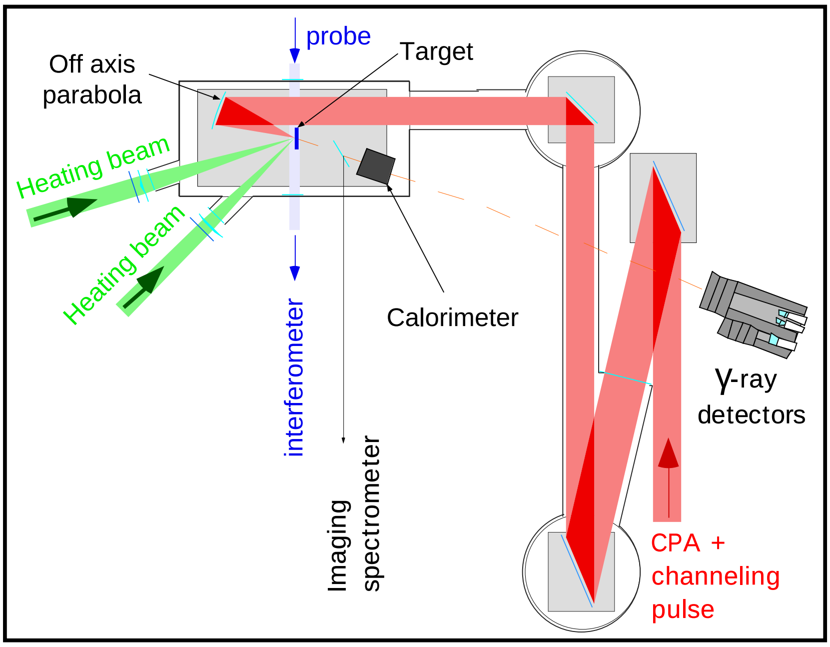


Figure 1 - Experimental arrangement showing the configuration of the laser beams for the explosion of the thin Al foil for the production of the preformed plasma. Also shown is the path of the two CPA pulses which interact with the preformed plasma and the main diagnostics activated for the characterisation of the interaction.

A set of detectors with the thickness of the scintillating crystal ranging from 12.5 to 50.1 mm was placed along the direction of the incident CPA pulse while two additional 50.1 mm detectors were placed at 45° and 90° respectively. All scintillators were shielded from side-scattered radiation by a 50 mm lead case. Lead slabs were also used to reduce the signal below the PM saturation level. According to numerical simulations performed using the code GEANT4[18], the total mass density placed along the line of view of the detectors ensures that primary electrons with energy up to several hundreds of MeV do not reach the detectors. In other word we can assume that the signal of the scintillators is mostly due to gamma-ray photons generated by bremsstrahlung of primary electrons.

3. EXPERIMENTAL RESULTS AND DISCUSSION

A preliminary survey of the data indicates that a large number of very high energy electrons were generated mostly in the forward direction. Assuming a given direction of the primary electrons (i.e. the direction of CPA), the comparison of simulation with the experimental data obtained from the scintillators allows a correlation to be established between the number of electrons and their energy. This calculation, combined with the condition set by the energy conservation principle indicates that the electron energy must be >10 MeV which may correspond to a maximum of 10^{13} electrons accelerated. On the other hand our data are also compatible with a flux of 10^7- much more energetic electrons. Further analysis is being carried out to clarify this point.

Another measurement concerns the gamma-ray emission yield for different preformed channel conditions. Figure 2 shows the dependence of the gamma-ray yield as a function of the delay between the channel forming pulse and the main CPA pulse for three different values of the thickness of the scintillating crystal. The "zero" delay position in this plot corresponds to the interaction of the main CPA pulse with the unperturbed preformed plasma (no channel-forming pulse). The increase of the detected energy with the thickness of the scintillating crystal indicates that the attenuation length of detected gamma-ray photons reaching the crystal is greater than the 25mm. The signal at "zero" delay shows large shot-to-shot fluctuations (≈100%) with an average value ranging from 1 to 1.3 pJ for the three typed of detectors. The signal drops to a minimum (detection level) around 20 ps and then increases again over the entire range of delays explored.

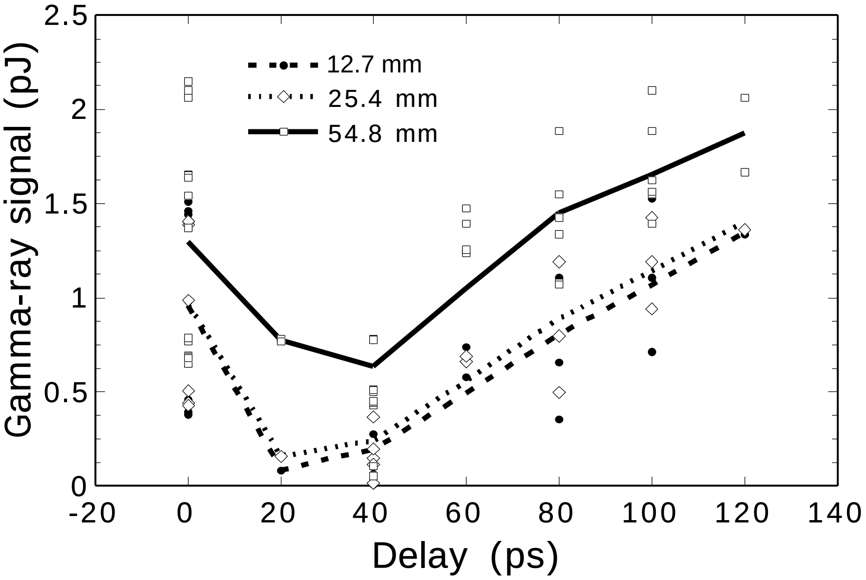
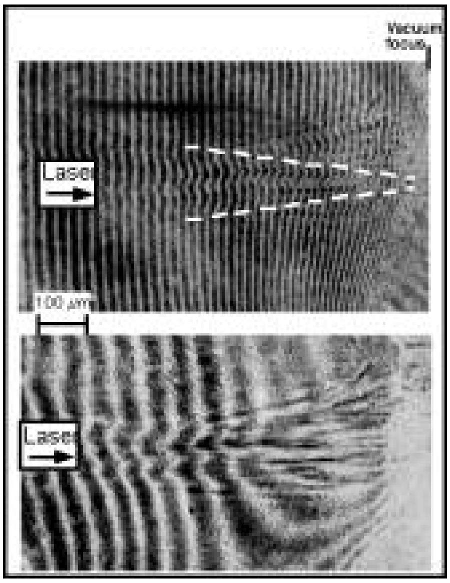


Figure 2. Energy released by the gamma-ray photons in the detector scintillating crystal as a function of the delay between the channel forming pulse and the main CPA pulse for three different values of the thickness of the crystal.

Simultaneous interferometric measurements have been carried out to monitor plasma channeling and the modifications induced on the preformed plasma density by the CPA interaction pulse. The interferogram of Figure.3 (left) shows that when the main CPA pulse interacts with the unperturbed preformed plasma ("zero" delay), the laser pulse breaks into many filaments. In this case a substantial fraction of electrons can be accelerated in the filaments where the effective laser intensity may be higher than the incident one. This effect may explain the large shot-to-shot fluctuations of the gamma-ray signal and the relatively high yield found in this condition. A correlation between forward electron acceleration and relativistic filamentation has already been claimed in a recent work by Wang et al.[19]. However, in that work, the laser intensity was weakly relativistic and the electron energies were of the order of a few MeV. In addition, in that work, the occurrence of relativistic filamentation was inferred by optical measurements of the laser pulse transmitted through the plasma. In our case the 0.25µm interferometry offers a direct evidence of filamentation as a local density perturbation.

The interaction changes completely when the channel preforming pulse is present. For small delays, when the plasma channel is beginning to develop, the gamma-ray signal drops rapidly and reaches a minimum at 20ps. For larger delays the signal increases again reaching the value of 1.9 pJ for the 50.1 mm crystal at the maximum delay of 120 ps used in our experiment. On the other hand, interfermometric measurements show that the presence of a channeling pulse, no filamentation takes place, regardless of the delay. In other words, the presence of a precursor, lower intensity CPA pulse, prevents filamentation of the main, high intensity CPA pulse. This circumstance may explain why the gamma-ray signal drops rapidly as soon as the channeling pulse is turned on. As the delay increases further, the CPA pulse interacts with a well-formed channel whose radius reaches a saturation level of 100µm for delays greater than 40 ps. The interferogram of Figure.3 (right), taken at 45 ps delay, shows a fully-developed channel of approximately 100µm radius. The behaviour of the gamma-ray signal shown in Figure.2 suggests that the interaction of the CPA pulse with a well-formed channel is again favourable for the acceleration of electrons. Also, the absence of filamentation and the smaller shot-to-shot fluctuations observed in this case (<40%) suggest that a new acceleration regime is being accessed, different from the acceleration in the filaments considered above.



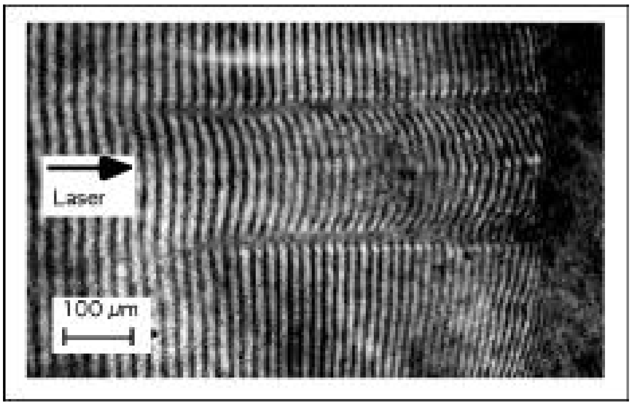


Figure.3. left: Details of an interferogram taken 5 ps after the propagation of a 50 TW pulse through a laser beam. The two images (from the same interferogram) both show the interaction region. Laser-break-up and formation of filaments are clearly visible. Right: Interferogram of the channel taken 45 ps after its formation

Guiding of the CPA pulse in the channel may occur which may extend the laser-plasma coupling in the longitudinal direction, leading perhaps to a more efficient coupling. The role different acceleration processes proposed so far in relativistic interactions of CPA pulses with underdense plasmas, including the traditional and self-modulated laser wakefield as well as other more recent models is being carried out. However, this preliminary survey of our recent data clearly shows that the presence of a channeling pulse in this class of experiments may have a strong effect on the interaction dynamics and, ultimately, on the interplay between laser driven instabilities and electron acceleration processes.

4. REFERENCES

1. K.W.D.Ledingham et al., Phys. Rev. Lett. **84**, 899 (2000)
2. T.E.Cowan et al., Phys. Rev. Lett. **84**, 903 (2000)
3. K. Krushelnick et al., Phys. Rev. Lett., **83**, 737 (1999)
4. L. Gremillet et al, Phys. Rev. Lett., **83**, 5015, 1999.
5. A.Pukhov et al, Phys. Plasma, **6**, 2847, 1999
6. K.C.Tzeng et al., Phys. Rev. Lett.**79**, 5258 (1997)
7. E.Esarey et al., Phys. Rev. Lett., **80**, 5552 (1998)
8. T. Tajima and J.M. Dawson, Phys. Rev. Lett., **74**, 267 (1979)
9. F. Amiranoff et al., Phys. Rev.Lett., **81**, 995 (1998)
10. W.P. Leemans et al., Phys. Plasmas. **5**, 1615 (1998)
11. M.Borghesi et al., Phys. Rev. Lett., **78**, 879 (1997)
12. V. Malka et al., Phys. Rev. Lett., **79**, 2979 (1997)
13. K.Krushelnick et al., Phys. Rev. Lett., **78**, 4047 (1997)
14. A.J. Mackinnon et al., Phys. Plasmas, **6**, 2185 (1999)
15. R.Wagner et al., Phys. Rev. Lett. **78**, 3125 (1997)
16. L.A.Gizzi et al, Phys. Rev. E, **49**, 5628 (1994)
17. R. Benattar, C.Popovics and R.Siegel Rev.Sci.Instrum. 50 1583 (1979)
18. GEANT4: LCB Status Report/RD44, CERN/LHCC-98-44, 1998
19. X. Wang et al, Phys. Rev. Lett., 84, 5324 (2000).