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Experimental Observations of the Weibel Instability in High Intensity Laser Solid Interactions

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1. Introduction Recently, there has been a great interest in the study of fast electron propagation in the solid density plasmas due to its potential application to ignite the fusion spark in the fast ignition scheme [1]. When the fast electron beam generated by a high intensity short pulse laser near the vacuum plasma interface penetrates into a solid target, the return current induced in the bulk cold plasmas effectively balances the fast electron current so that currents larger than the Alfven current limit can propagate. Two counter propagating streams are subject to the well-known Weibel instability [2], which can generate strong magnetic fields transverse to the fast electron beam direction. These magnetic fields cause the electron beam to break up into small filaments. Linear analysis of the Weibel instability in the two-fluid model has studied the dynamics of this instability [3,4]. Considerable numerical simulation work has been done on the fast electron propagation and the related magnetic channels formation in the overdense plasmas [4,5,6]. An essential feature of these simulations is the break-up of the current into small filaments in the overdense plasma and the subsequent coalescence of these filaments.

The single highly collimated electron beam has already been confirmed experimentally inside the transparent glass targets and at the rear surface of the plastic targets in high intensity laser solid interactions [7]. However, until now, the filamentary structures resulted from the Weibel Instability have not yet been observed from the experiments.

In this paper, we present the first experimental observations of the fine structures of the Weibel instability induced by high intensity laser produced fast electron beam. The speckle-like off-normal electron filaments have consistently been observed in our high intensity laser interactions with thin gold foil targets.

2. **Experimental set-up and diagnostic tools** The experiments were performed at the Rutherford Appleton Laboratory using the Vulcan Nd:glass laser operating in the CPA mode. The 1.054 μm laser beam, 1ps in duration, was split into two beams, CPA1&CPA2.

These beams were focused to 10 μm diameter spots at 41^0 and 20^0 to the target normal by two f/4.5 off-axis parabolic mirrors from the left and right hand respectively. The targets were thin 5mm×8mm gold foils with varied thickness. Both beams were p-polarized. Up to 30 J and 20 J on the target from CPA1 and CPA2 give the peak intensity of 3×10^{19} W/cm^2. The main diagnostics used in the experiments were the multi-layered stack consisting of radiochromic films (RCF) and CR-39 particle track detectors. RCF is a type of radiation dosimeter, which contains a thin active layer on the clear polyester substrate. When exposed to any kind of ionizing radiation, the active organic dye reacts to form a blue coloured polyester. The films have been absolutely calibrated to give absorbed radiation dose in kRad (10^{-2} J/g). CR-39 nuclear track detectors are only sensitive to the energetic ions. In the experiments, the stacks were positioned on both sides of the target and aligned so that the faces of the detector were parallel to the surface of the targets. The detailed experimental arrangement is shown in Fig 1. A frequency doubled green beam, split from the uncompressed main beam, was used as a probe. The probe passed transversely across the target, both surfaces being in the field of view. The probe was used to check that the two laser focal spots were in line along the target normal. In addition, single sided illuminations were also carried out with CPA1 laser pulses.

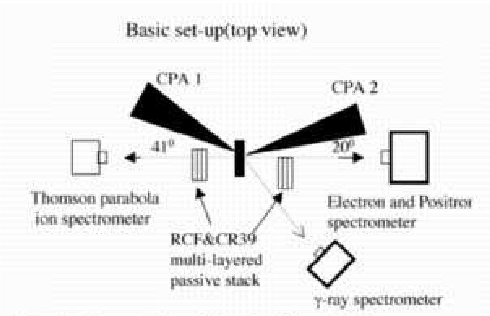

Fig.1 Schematic of the double-sided illumination experimental arrangement

3. Experimental Results Typical images of the radiochromic films are presented in Fig.2, which shows that there is the existence of the off-normal electron beam. Scanned RCF images (a) and (b) are from the same shot when the target was illuminated on both sides with two laser beams. Except for the lower energy electron and proton emissions due to the CPA2 laser produced plasma (only seen in the first two front layers of the RC film), there was the higher energy off-normal electron beam recorded on all the RC films in the stack, which is on the right side 5 cm from the targets. The evidence that the beam consists of electrons rather than ions was obtained by comparing the signals on the RC film and the subsequent CR39 pieces in the stack, which did not show any signal. The collimated off-normal off-axis intense electron beam was emitted at 20^0 from the target normal with full emission cone angle of 11^0. A distinct feature of the electron beam is that it has very fine speckle-like emission pattern, which can be seen in fig.2 (c). Image (c) is a zoom-in view of the small square region of (b). Such electron beam was also observed when the timing between CPA1 and CPA2 laser pulses was varied (by up to 2 ps). It is noted that these variations did not affect the behaviour of the electron beam. From the RCF absorbed dose, it is estimated that the beam consists of 10^{12} electrons.

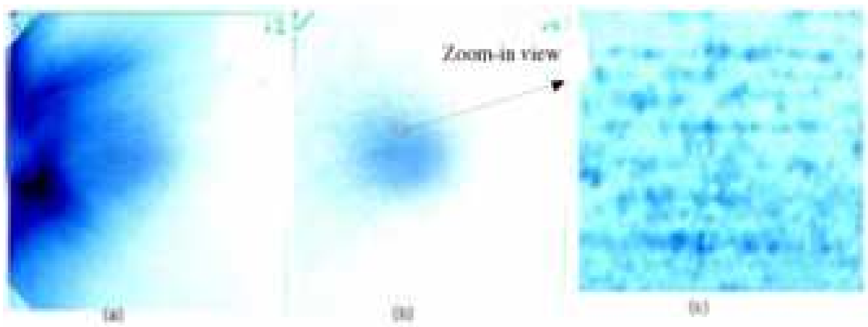

Fig.2(a)(b) are scanned RCF images showing the off-normal electron beam. (a) is the front layer and (b) is a deeper layer from the right side stack in a double-sided illumination shot. Left edge of (a) is at the target normal. (c) is a zoom of the small square in (b) showing the speckle in the beam.

Experiments with only CPA1 laser beam single sided illumination were carried out with similar laser energy as that in the double-sided shots. Fig.3 presents the raw scanned images of the RCF of the stack, which was positioned behind the target. In this shot the centre of the detector was at the target normal. Two separate signals are clearly visible. The significant emission along target normal is mainly due to energetic protons, which was confirmed by the CR39 proton data. The off-normal off-axis signals are due to electrons, which is at the same direction as the off-normal electron beams observed in the double illumination cases. The beam was formed by dozens of separated large speckle-like electron jets. The biggest speckle has a radius of approximately 500 μm and is seen almost in the centre of the off-normal beamlets surrounded by relatively smaller speckles with diameters of the order of 250 μm. In the deeper RCF layers of the stack, only a couple of large speckles exist. The

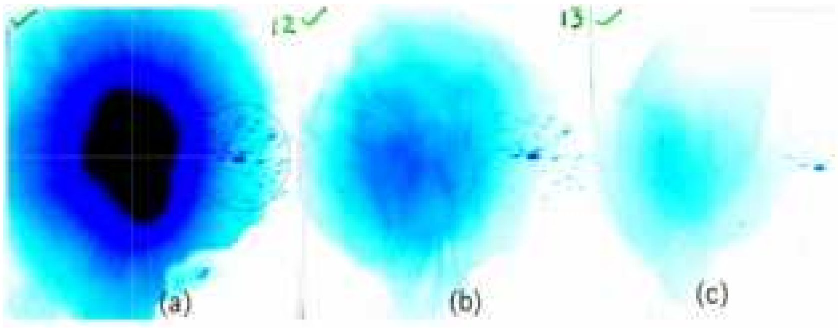

Fig.3 The raw scanned RCF images showing two separate emissions in th e single sided illumination. The detector stack was about 5 cm behind the 20 μm thick gold foil. (a) is the front layer, (b) and (c) are in the deeper layers. The off-normal beamlets are clearly visible.

angular spread of the off-normal electron beam produced in the single sided illumination is similar to those produced by the double-sided illuminations. The only significant difference is the speckle size. Therefore, it is reasonable to assume that all the off-normal electron beams were produced by the CPA1 laser pulse and then propagated through the solid density plasma the detectors on the other side. The different emission structures in the double and single sided illuminations are very likely due to the significant changes of the conditions for fast electron transport inside the solid density plasma in the two different schemes.

4. Discussion and Summary These observations are consistent with the fast electron beam breaking into filaments due to the Weibel instability as they propagate in the overdense plasma. Linear analysis of the Weibel instability including electron kinetic effects and resistivity and 2-D PIC simulations done by Sentoku et al [4], which include relativistic binary collisions, suggest that the growth rates of shorter wavelengths are significantly reduced when the initial plasma temperature is high. In a collisional plasma, the growth rate of the fast modes are suppressed due to the plasma kinetic effects and the spectral peak of the growth rate shifts to long wavelength modes in the later stage due to the coalescence of the quasistatic magnetic channels. Comparing with our experiments, in the single illumination case, the background plasma can be assumed to be cold. Consequently, plasma kinetic effects are very important in the evolution of the Weibel instability. The much larger electron beamlets seem to agree well with the simulation results qualitatively. On the other hand, the fast electron propagation in the overdense plasma in the double sided scheme can be compensated at least partially by the counter propagating hot electron beam produced on the other side.The plasmas in such case are much hotter than that in single sided scheme. Therefore, the filament sizes are much smaller. From this point of view, our experimental data agree very well with the simulation predictions.

More experiments to systematically study the off-normal electron beam (the directions, speckle size, energy spectra) as the function of laser energy, target thickness and target material have already been scheduled on the Vulcan laser.

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References 1. M. Tabak *et al.*, Phys. Plasmas. 1, 1626 (1994)

2. E.S.Weibel, Phys. Rev. Lett. **2**, 83 (1959)

3. F. Pegoraro *et al.*, Phys. Rev. E **56**, 963 (1997); F. Califano *et al.*, Phys. Rev. E. **57**, 7048 (1998)

4. Y. Sentoku *et al.*, Phys. Plasmas. **7**, 689 (2000);Y. Sentoku *et al.*, Phys. Rev. E. **65**, 046408 (2002)

5. M. Honda *et al.*, Phys. Plasma. **7**, 1302 (200); Pukhov and J.Meyer-ter-Vehn, Phys. Rev. Lett. **79**, 2686 (1997); B. F. Lasinski *et al.*, Phys. Plasmas. **6**, 2041 (1999)

6. L. Gremillet *et al.*, Phys. Plasmas. **9**, 941 (2002)

7. M. Tatarakis *et al.*, Phys. Rev. Lett. **81**, 999 (1998); M. Borghesi *et al.*, Phys. Rev. Lett. **83**, 4309 (1999); L. Gremillet *et al.*, Phys. Rev. Lett. **83**, 5015 (1999)