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First observation of Moiré fringes in a laser driven proton beam

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ABSTRACT:

High contrast Moiré fringes have been observed when two gratings were inserted into a proton beam produced from the interaction of an 100TW laser beam with a thin solid foil. Moiré fringes with modulation close to 20% were observed in protons with energies between 4 and 7MeV. The fringes were rotated with respect to a collimated optical test beam, a finding consistent with the protons originating from a point source close to the original target surface. These important results indicate that proton Moiré can be used as a high precision diagnostic of proton beam deflections from electric and magnetic fields in plasmas.

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The generation of multi-MeV proton and ion beams in high intensity interactions of ultra-short laser pulses with solid targets is a rapidly growing research area. Distinctly collimated beams with cut-off energies up to 55MeV have been observed at high laser intensities [1-4]. The remarkable collimation, high cut-off energy and emission from the un-irradiated rear of the target distinguish these beams from less directed, lower energy protons observed in earlier work at lower laser intensity [5,6]. Recently these proton beams have been used as a probe beam to investigate electromagnetic fields in plasmas. In these experiments increases in deposited dose in particular locations on spatially resolving particle film detectors is used to infer the deflections in the proton beam. The deflection angle of the protons as they go through the plasma regions is inferred from these observations [M. Borghesi et al., Phys. Plasma 2002, M. Borghesi et al Plasma Phys. Cont. Fusion, 2001]. The use of quantitative methods for measuring proton beam deflections is very exciting for this field particularly in the measurement of deflections from small fields which would be difficult to observe using straightforward point projection imaging. Moiré Techniques may also be important for measuring stress and strain inside materials that are opaque to conventional optical probes.

This paper reports on the generation of Moiré fringes when a pair of crossed gratings were inserted into the proton beam. The experiment was performed at Lawrence Livermore National Laboratory using a Ti:Sapphire laser operating in Chirped Pulse Amplification mode (CPA) at a wavelength of 0.8 m and duration of 100 fs [11]. The pulse was focused by an f/2 off-axis parabola at a P polarized angle of incidence of 22 degrees onto the target with a focal spot size of 3-5 m, full width at half maximum (FWHM). This spot contained 30-40 % of the energy, giving a peak intensity in excess of 10^{20} W/cm^2. The laser used an ASE suppression system to attain an intensity contrast ratio of 10^{10}:1 [12]. The targets were Al foils, 3mm wide, 10mm long, with a thickness that was varied from 3 to 25 m. The preformed plasma was monitored with a sub-picosecond interferometric probe, operating at =0.4 m and with a target plane resolution of 3 m.

Radiochromic film (RCF) radiation dosimeters and CR-39 particle detectors diagnosed the proton beam. CR-39 is a polymer particle detector in which energetic ions cause damage as they transit through the sample.CR-39 is not sensitive to either electrons or x-rays and has been widely used as a high energy ion diagnostic[2,3,5]. In this experiment the CR-39 was filtered by 10 layers of RCF which stopped all slower moving high z ions so only protons were recorded. Each layer of RCF consists of an organic dye sandwiched between layers of plastic with a total thickness of 265 m [1]. The dye is sensitive to total radiation dose (x-rays, ions and electrons) and has been absolutely calibrated to give absorbed radiation dose in krads (10^{-2}J/g). The energy deposition of protons within the active RCF layer is mainly in the Bragg peak towards the end of the stopping range, so that successive sheets respond to protons in a fairly narrow band of increasing energy. As RCF also responds to electrons and x-rays, energy deposition attributed to protons has been compared to diagnostics that are sensitive only to ions, such as nuclear activation and CR-39 track detectors. In this work the CR-39 always correlated well with the signal attributed to protons on RCF whether the CR-39 was positioned towards the front (low proton energy) or at the rear (high proton energy) of the film pack. Previous work has found that the absolute dose attributed to protons on RCF also agreed quantitatively with proton energy deposition measured from nuclear activation in titanium foils [1].

A film pack containing RCF and CR-39 was placed 25-60mm behind the target, and aligned so that the face of the film was parallel to the back surface of the target. Two Al filters (18 m thick) were placed in front of the RCF first layer giving a minimum detectable proton energy of 4.0MeV. The peak proton energy was measured from the depth of penetration of the proton beam through the RCF/CR-39 film pack.

The generation of Moiré fringes is shown schematically in Figure.1(a). Two gratings with pitch p are set with a rotation angle between the two gratings. Moiré fringes are observed in the regions where the two grating elements overlap to produce either a dark or light region. The pitch, P' of the Moiré fringes is determined by the angle of rotation, , between the gratings and the pitch of the original gratings, P, through P' = P/2sin (/2). When used as a deflectometer the system is set up so that one the gratings is attached to a film plane while the other is placed a distance D towards the target (as shown in fig.1(b)). Any changes in the direction of the incident beam as it passes through the target region effectively shift the image of the first grating on the second. The resulting fringes shift can be related to the angle of deflection, , of the original beam by the relation: In essence the Moiré fringes act to amplify any changes in the direction of the beam (optical or particle) by the so-called Moiré amplification factor. This technique has been widely used in optics to measure refractive index changes in materials, refractive index gradients in gases and shocked plasmas and to measure the focal length of lenses. Excellent reviews of the Moiré effect and application to these measurements can be found in the books by Kafri and Glatt [Physics of Moiré Metrology] and by Theocaris [Moiré effects and applications].

The observation of Moiré fringes in proton beams is a new application of this effect, which has great potential for accurately diagnosing proton beam deflections caused by electric and/or magnetic fields in highly transient plasmas. Fig. 2 shows Moiré fringes produced by placing two pairs of Moiré gratings before the film plane in a proton beam experiment carried out using the JanUSP laser at LLNL. As discussed above the proton beam was produced by focusing a 5J laser pulse onto a 10 m aluminum foil at an irradiance of $5x10^{19}$ Wcm^{-2}. In this case the protons are accelerated from impurity layers on the Aluminum foil into a quasi-Boltzmann spectrum with a mean energy of 2-3MeV and a high energy cut of around 15MeV [A.J.Mackinnon PRL 2002].

The Moiré fringes can clearly be seen where the two sets of gratings were placed in the proton beam as shown in the figure. It is important to note that no structure can be seen in the center of the beam where the gratings are absent. This confirmed that the observed fringes were due solely to the Moiré effect rather than structure on the proton beam. The Moiré fringes are clearly visible on the expanded image of the top grating region on the right of fig.2. These fringes have quite high contrast with modulation in this raw data of close to 20%. It is expected that the modulation will increase to close to 30% once the contribution of higher energy protons has been extracted from this image. The fine scale structure observed in the fringe pattern is due to the individual wire elements of the respective gratings. In principle the Moiré fringe modulation and the blurring of these individual wire elements can be used to infer information on the emittance of the proton beam [reference Kafri] this will be described in detail elsewhere [to be published]. Another important feature of the proton Moiré fringes is that they are rotated by around 20 degrees with respect to fringes produced by a collimated beam. Figure.3 compares the fringe orientation of the 6MeV protons with fringes produced by a collimated optical beam. This change in orientation arises because with a non-collimated beam the magnification of the image of the first grating cast onto the second is not unity.

This is shown in Fig. 4 where simulated fringes were obtained using collimated, diverging and converging sources. For a collimated source the shadow of the first grating on the second is cast with unity magnification. For a diverging source M>1 and the fringes rotate clockwise while for a converging source M<1 and the fringe rotation is clockwise. The rotation angle observed in the proton data was found to be consistent with protons diverging from a point source located within 1mm of the target surface. Future experiments are planned that will utilize larger gratings so that the source can be more accurately located (within a few tens-100's of microns). This information is of great interest to better understand the details of the acceleration mechanism.

Monte-Carlo simulations using SRIM have been carried out in order to aid interpretation of the data and to evaluate the limits of this technique due to scattering of the protons in the gratings and film detectors. 6MeV Protons from a point source with finite extent were traced through a system consisting of two gratings similar to those used in the experiment. The protons were then modeled as they traveled through a radiochromic film pack. Fig. 5 (a) and (b) shows the Monte-Carlo generated Moiré fringes obtained at the film plane produced by propagating

6MeV protons through two identical gratings with elements 10microns wide (rectangular), with a 40 mm pitch. The grating rotation angle was 10 degrees. The gratings were 3mm in diameter and separated by 5mm. The run was generated for a total of 10^7 particles. In fig (a) the proton source is effectively located at infinity (z = 250mm) while in Fig. 5(b) the source is only 25mm from the first grating. The fringe orientation between the almost collimated case (a) and the diverging case (b) is clearly discernible in this simulation – confirming the interpretation of the experimental data. The modulation observed in the simulation is close to 100%. This is somewhat surprising considering that the stopping range of 6MeV protons is more than 200microns in 10micron copper. The reason that such strong modulation is observed is due to multiple small angle scattering of the protons as they go through the wire elements. The scattered protons add to the background signal without significantly reducing the resolution of the wires. This is one reason why proton imaging in this regime yields such high contrast images (the other factor is the extremely good emittance of the proton beam). Further work is underway to completely understand the implications of multiple scattering on resolution of straightforward imaging as well as Moiré deflectometry with protons. The code is also now being further developed so that deflecting elements such as electric or magnetic fields can be simulated in a variety of simple and more complicated geometry.

In summary high contrast Moiré fringes in 6Mev protons have been observed using a sub picosecond laser driven proton beam. The fringe orientation was used to locate the proton source within 1mm of the target surface. Monte Carlo simulations agree qualitatively well with the experimental data – more realistic simulations are underway to obtain quantitative agreement. This technique shows great potential as a precise diagnostic of transient field deflections in plasmas produced by ultrashort laser pulses.

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Figures:

1. Schematic of Moiré effect showing how Moiré fringe pitch is related to grating pitch and angle of rotation between the two gratings
2. Image of Proton beam after passing through a pair of Moiré gratings. The blown up region shows the details of the Moiré Fringes. The Moiré fringes are clearly visible, as are the individual wire elements of each grating.
3. Comparison of proton Moiré fringes with those obtained from a collimated optical beam. The proton Moiré fringes are clearly rotated (by around 20 degrees). This rotation angle was consistent with a point source of protons located close to the target surface.
4. Schematic of the effect of source location/collimation on the Moiré fringe rotation. Collimated source gives vertical fringes; a diverging source rotates fringes clockwise while a converging source rotates counterclockwise.
5. Monte-Carlo model of proton transport through two Moiré gratings with a set up similar to the experimental arrangement. Here a collimated source is modeled by placing a point source at infinity (250mm). The fringes clearly rotate by around 10 degrees when the source is placed close to the gratings (25mm) as is observed experimentally

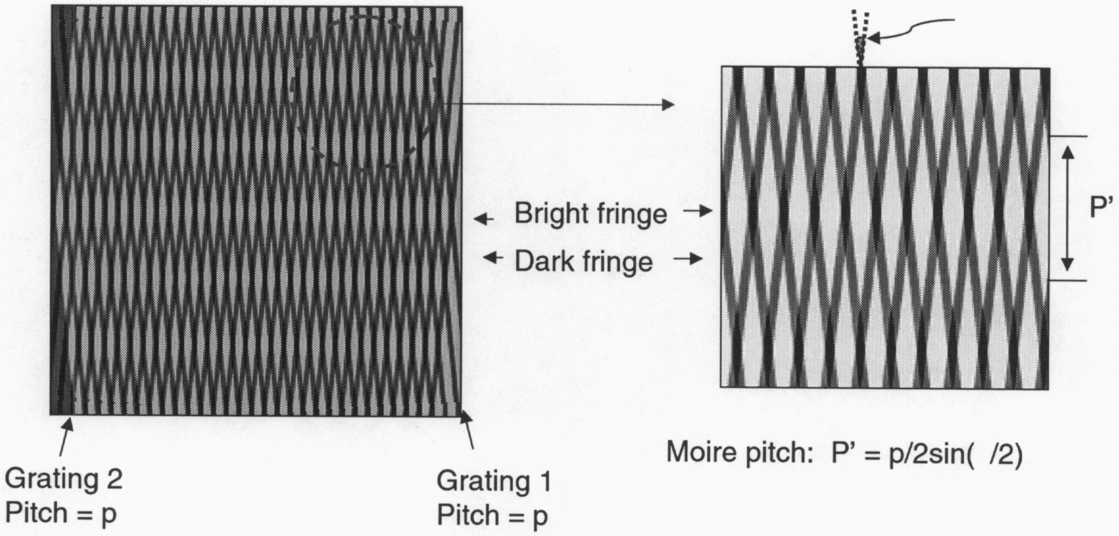
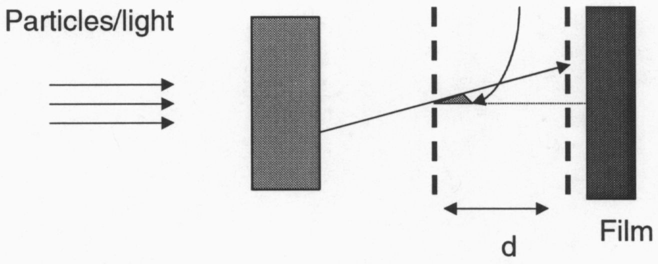

Bright fringe
Dark fringe
P'
Moire pitch: P' = p/2sin(/2)
Grating 2
Pitch = p
Grating 1
Pitch = p

Fig.1(a)



Fringe shift
x =d /
x d
P'/p so the original deflection is amplified by the ratio of the Moire fringe pitch to the original grating pitch (typically factor 10)

Fig.1(b)

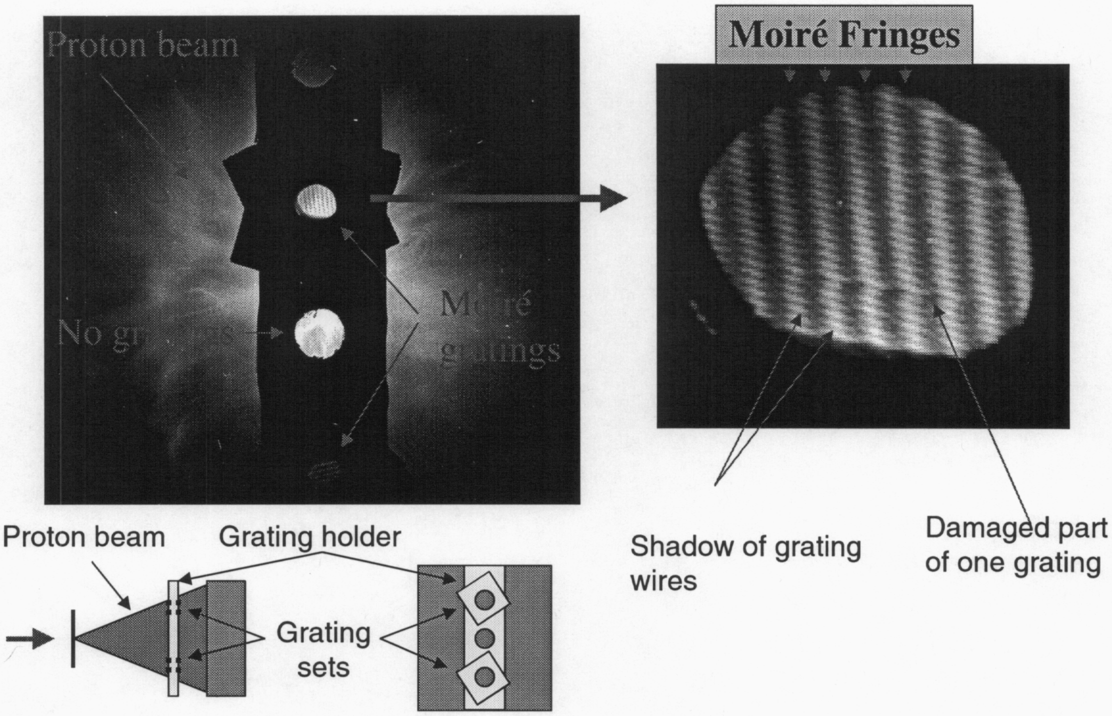
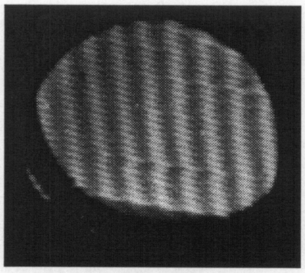
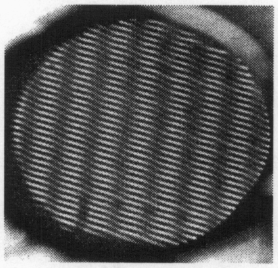

Proton beam
No gratings
Moiré gratings
Moiré Fringes
Shadow of grating wires
Damaged part of one grating
Proton beam
Grating holder
Grating sets

Fig.2



Proton Moiré



Optical Moiré (collimated beam)

Fig.3

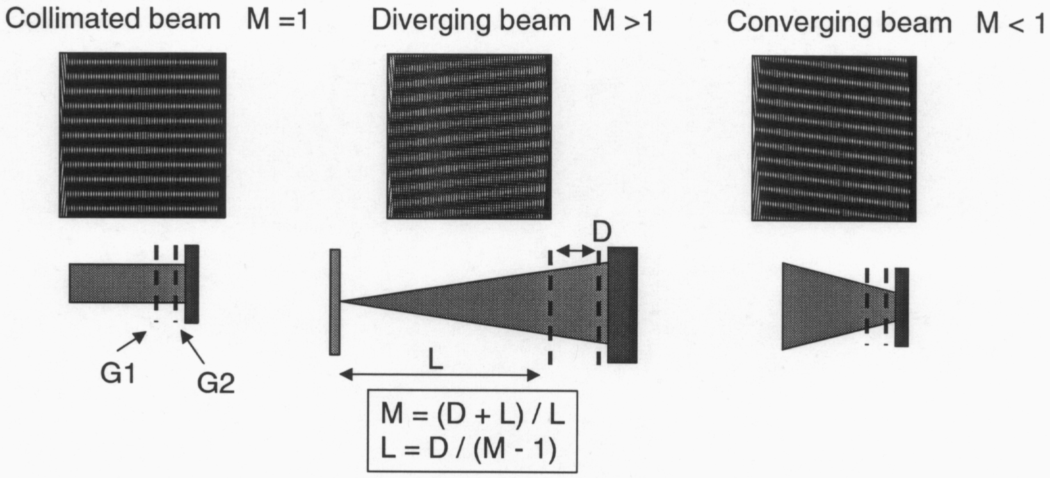
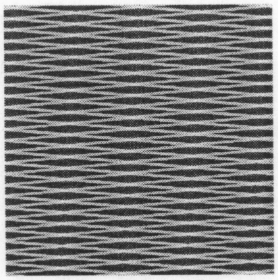
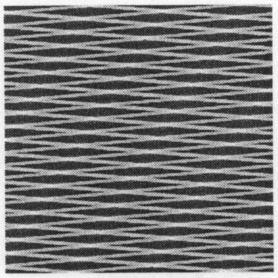

Collimated beam M =1
Diverging beam M >1
Converging beam M < 1
D
G1
G2
L
M = (D + L) / L
L = D / (M - 1)

Fig.4



Point source 250mm from gratings (quasi-collimated source)



Point source 25mm from gratings

Fig.5