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LDRD Final Report – 01-FS-004

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Introduction

This report describes the results from an experimental program to investigate the feasibility of laser produced MeV protons as a diagnostic of electric fields or shock compressed materials. The experimental campaign was very successful, and has led to substantial advances in the characterization and optimization of proton sources from ultra-intense laser-solid interaction. This is a subject of the highest scientific interest [1] and is highly relevant to developing its use as a possible NIF implosion diagnostic and other applications relevant to stockpile stewardship.

Scientific Program

The protons were produced by focusing the JanUSP laser beam (energy: 10J, pulse duration: 100 fs) onto a thin solid foil with intensity reaching 10^{20} W/cm^2. Under these conditions a burst of multi-MeV protons, with duration of the order of the laser pulse duration, is emitted from the back of the foil along the normal to its surface, within a small cone angle. The generation mechanism is presently the object of great theoretical attention [2].

Concerning the general characteristics of the beam (energy content, divergence, spectrum) our observations were consistent with other measurements previously reported. A detailed characterization study of the source size and position was carried out during these experiments. This is of extreme importance in view of any imaging application employing the proton beams. In fact the source size determines the resolution of imaging application, while the position influences the magnification onto the detector. These studies exploit a property that was discovered in a previous experimental campaign [3] namely the fact that thin objects placed in the path of the proton beam as shown in fig1.a become electrically charged ahead of the transit of the protons. As discussed in [3], the shadow cannot be due to collisional stopping of the protons, the thickness of the wires being more than an order of magnitude smaller than the stopping distance of the protons. We believe that the charging is either due to precursor electrons travelling ahead of the proton beam and causing the appearance of an electric field near the surface of the objects or small angle Coulomb scattering of the protons as they propagate through the wire material. Recent Monte-Carlo modeling has shown that scattering of the protons can explain the modulation depths that we observe experimentally and so this mechanism is currently seems the most plausible explanation of why these extremely thin meshes are visible in the proton beam.

The images of Fig.2 provide us with information concerning the size of the source (i.e. the resolution of our projection images). For example, by looking at a lineout across the shadow of the mesh on the detector (radiochromic -RC- film [4]), we can infer -from the blurring of the shadows of the wires- that the source size is smaller than 3 μm . In fact a 2.5 μm object - i.e. half of the wire- is rendered as a 5 μm shadow. We would like to stress that the source size estimated in this way is only an upper limit estimate as straggling of protons in the detector limits our resolution to 2-3 μm. Further modeling to examine the factors limiting the ultimate resolution of the proton probe. If scattering were the major mechanism for observing the images then one would expect that thicker targets would degrade the resolution. It is crucial to answer this important issue because in applications where micron scale resolution is required this diagnostic may be limited to very thin samples. This is not a problem for electric fields produced in thin samples but is much more serious limitation for large dense objects such as compressed NIF cores, in which case scattering may limit resolution to a few 10's of microns. Monte-Carlo modeling of these experiments is in progress to fully investigate this question.

Further information on the properties of the source was obtained by measuring the magnification of the mesh images obtained on the RC film. From purely geometrical considerations the magnification of the image should be determined simply by the ratio between source-to-detector and source-to-object distances. However the magnification measured experimentally was consistently lower than expected. We believe this is due to the fact that the proton source is virtual and located in front of the target (see fig. 3).

If one makes this assumption, the experimental magnification M_{exp} can be expressed in function of the geometrical magnification M_G expected if the source was real and located at the target plane, i.e.

$$M_{exp}=M_G\,(L+x)/(L+M_G x) \quad (1).$$

M_{exp} was measured for various values of d, and plotted it versus the expected M_G (fig.3). The best fit of the data with the expression (1) give us $x \sim 400\ \mu m$. From this we can infer that, since the divergence observed for 8 Mev is about 15^o, the protons are emitted from an area of diameter 100 μm at the target surface (rather than the 2-3 μm indicated by the resolution tests). This observation provides an explanation for a series of reported experimental observations relating to source brilliance and focusability [5] which are very difficult to explain if the source is μm-sized. A brief description of this work (namely the investigation of the virtual source location) has been included in a paper recently submitted to Physics of Plasmas [6].

As the grids imposes on the proton beam a periodic modulation, the transmission through two of such structures suitably rotated can originate a Moiré' pattern. This effect is widely used with optical radiation as a beam deflection [7] or surface strain diagnostic [8]. During this experiment we have demonstrated for the first time that Moiré' fringes can be obtained using proton beams, using the set-up shown in fig. 4, where an experimental Moiré' pattern is also shown. This is a particularly important and exciting result as it will allow the use of quantitative diagnostics such as Moiré deflectometry to measure the local deflections imposed by electric fields on the proton beam, and infer the value of the fields.

Finally, part of the experimental work was devoted to the optimization of the homogeneity of the source. The use of highly porous materials such as Palladium (Pd), able to absorb hydrogen in high percentage was found to be particularly advantageous. The Pd was placed in an electrolytic cell, until a sufficient quantity of hydrogen was absorbed. This determined a substantial increase in proton flux and an extremely smooth profile beam profile when the Pd was laser-irradiated for proton beam production.

Conclusions

The use of protons for imaging applications is a field rapidly evolving, in which LLNL continues to play an important role, thanks to our involvement in the successful experiments [4] performed last year at the Rutherford Appleton Laboratory and more recent JanUSP experiments that are described in this report. This feasibility study has led to substantial progress in our fundamental understanding of the properties of the proton source and has already led to ways of improving them. On the strength of these results proposals for further collaborative experiments on European laser facilities (Laboratoire d'Optique Appliquee -LOA- and Laboratoire pour l'Utilisation de Laser Intense -LULI-, both located in Paris) have been submitted. An application for experimental time on Trident is also being prepared for submittal in early 2002. The feasibility study has shown that proton probing can be used to achieve micron scale resolution in thin test targets. The ultimate limitations on resolution have not yet been established and further work is ongoing to further investigate this aspect of the technique. The results from these experiments will be submitted to two or three separate journal articles in 2002. In particular the demonstration of the proton Moiré will be submitted to Science early in 2002. In summary the experimental program described in this report have shown that proton probing is a viable diagnostic technique for measuring micron scale structures and the program has maintained LLNL's position at the forefront of this fast moving research area.

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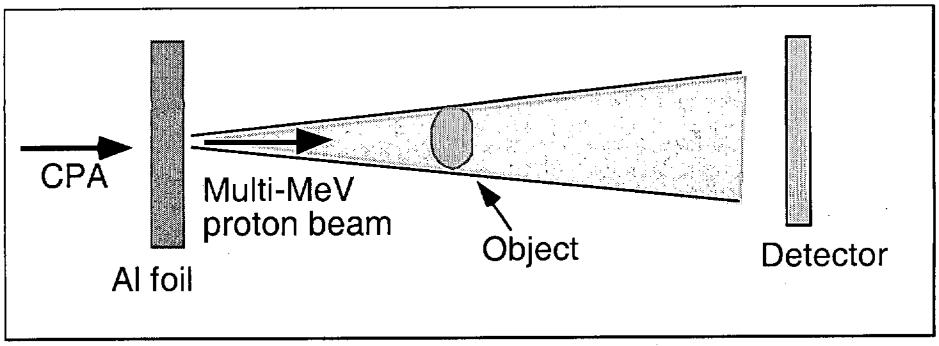

Figure 1 – Experimental set up

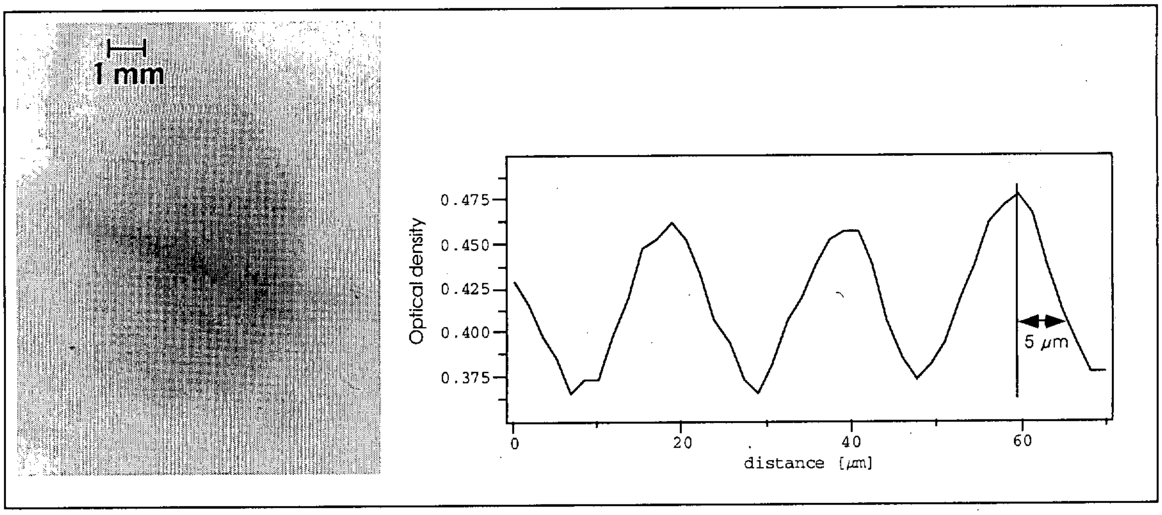

Fig.2- (left) Shadow observed on the detector (RC film) when a mesh of 5 μm wires with 20 μm spacing was placed in the path of the beam; (right) Profile of Optical Density modulation on the RC film across three elements of the shadow of the mesh of fig.2

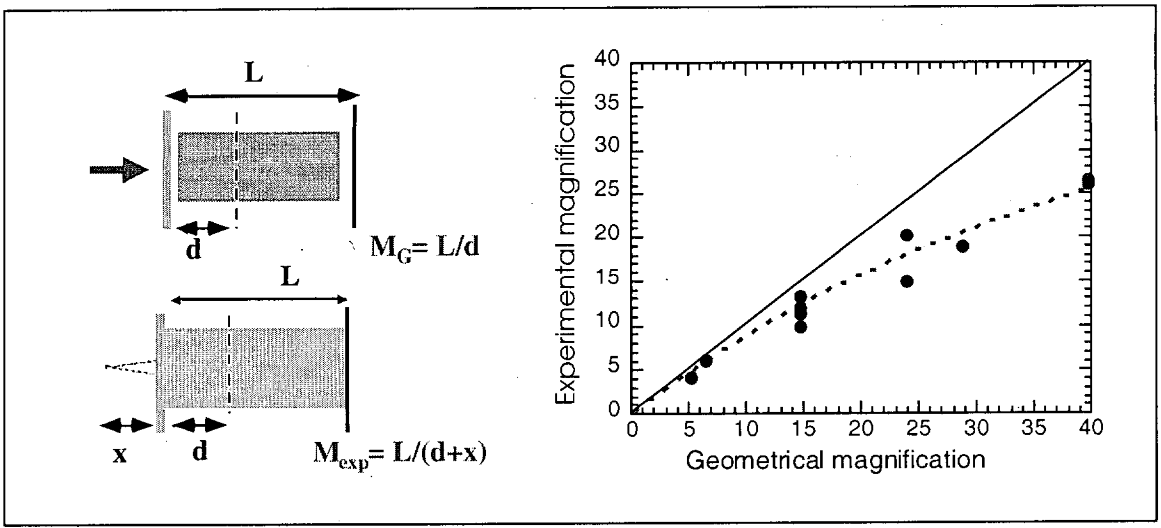

Fig.3 - (left) Schematic of set-up and magnification obtained in the two cases of: (a) real source located on target surface (above); (b) virtual source located in front of the target (below); (right) plot of Experimental magnification versus geometrical magnification obtained by varying d. The data is fitted using the expression (1).

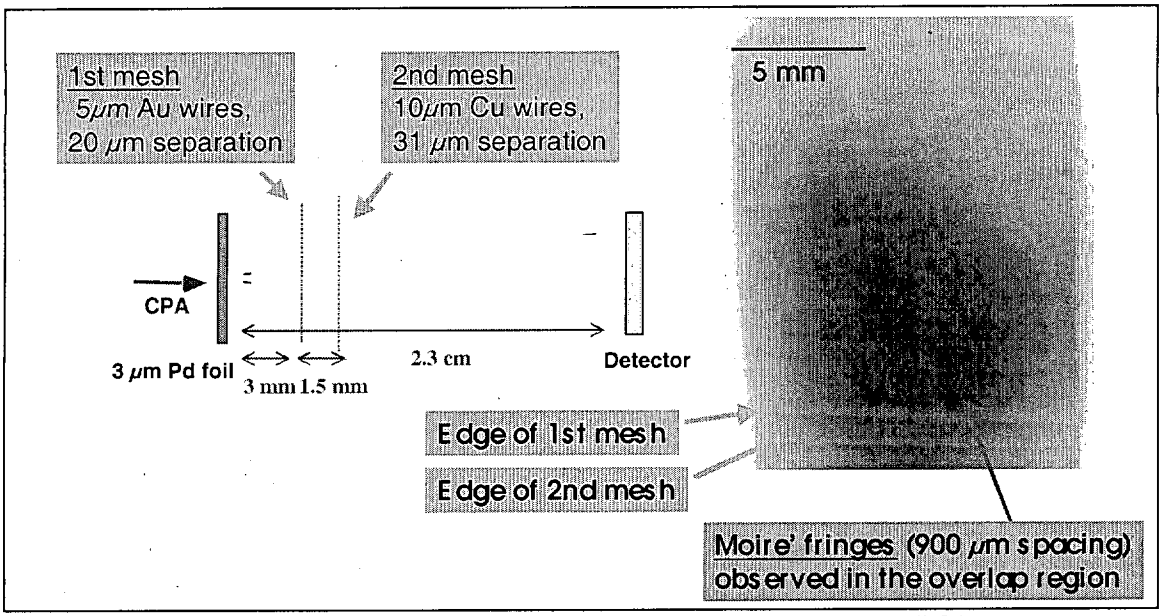

Fig.4- (left) schematic of set-up for Moiré' fringe production. (b) Moiré' fringe pattern observed on detector (Radiochromic film)