UCRL-JRNL-210529

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March 14, 2005

Physical Review Letters

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***ABSTRACT:***

Protons accelerated by a picosecond laser pulse have been used to radiograph a laser driven implosion of a 500μm diameter, 3μm wall thickness shell, imploded with 300J of laser light in 6 symmetrically incident beams of wavelength of 1.054μm with pulselength 1ns. Point projection proton backlighting was used to characterize the density gradients at discrete times through the implosion. Early time asymmetries were diagnosed, while the peak density of 3g/cc measured by this technique agreed well with complimentary x-ray radiographs. Simulations show that the technique can be used to diagnose density conditions for ignition scale implosions.

PACS numbers: 52.50.Jm, 52.40.Nk, 52.40.Mj, 52.70.Kz

The conditions leading to ignition of fuel in inertial confinement fusion capsule are extremely difficult to generate. For the conventional, isobaric ignition approach, cryogenic deuterium tritium fuel is compressed from an initial diameter of 2mm to a 100μm diameter hotspot, resulting in particle densities (ρ) ranging from 100-600g/cc around the cold fuel-hot spot interface region, with an areal density (ρR) of 0.3gcm$^{-2}$ inside the hot spot. To achieve these extremely high densities the compressed core must be very spherical symmetric, with a relatively smooth interface between the cold fuel and central hot ignition region [1]. Diagnosing density perturbations and general deformity of the core shape in these conditions is a challenge to conventional radiographic techniques. The ideal diagnostic would penetrate densities up to 600g/cc and resolve features of less than 5-10μm. Imaging of neutron emission from an igniting core is capable of providing such resolution during ignition shots, however it is not certain that a target that does not reach ignition will not produce the large number of neutrons required to image the core using this technique [2].

There is a clear need for an advanced diagnostic that can characterize hotspot symmetry in highly, compressed media. One possible method, currently under development is x-ray imaging in the range of 15-30KeV [3]. An alternative, perhaps complimentary, technique utilizes laser driven proton beams of 30-100MeV to probe density perturbations in highly dense materials. Multiple scattering arising from density structures in the probed object modulate proton beam, thus allowing micron scale structures to be imaged onto the film plane [4,5]. Proton probing experiments of electromagnetic fields in low-density laser-produced plasmas have been carried at the Rutherford Appleton laboratory [4] however the utility of proton radiography in dense laser-compressed materials typical of those that exist in laser driven implosion has yet to be studied. Protons beams with substantial particles in the 40-50MeV region been produced by a focusing a petawatt laser on a thin foil target [6]. This is just the energy required to penetrate particle densities 500-1000g/cc and so picosecond laser driven proton radiography is a potential candidate as a probe of dynamic events in extremely dense matter.

This letter reports the first proof of principle study of dynamic proton probing to diagnose density gradients in a laser driven spherical implosion. The experiment was carried out using the 100TW, 1ps Vulcan laser pulse coupled to a six-beam laser driven implosion system. The compressed core was characterized by protons and verified using x-ray radiography; the experiments were simulated by the 1 dimensional hydrocode (Hydra [7]) and a 3D Monte Carlo particle tracing code based on SRIM [8].

The experiment was performed at the Rutherford Appleton Laboratory using the Vulcan Nd:glass laser operating in the Chirped Pulse Amplification mode (CPA[9]). The 1.054 μm CPA backlighter pulse, 1 ps in duration, with an energy of about 50 J was focused by an F/3.5 off-axis parabola (OAP) at normal incidence onto the center of a 25μm thick Tungsten target. The focal spot diameter was10 μm full width at half maximum (FWHM), which contained 30-40 % of the energy, giving peak intensity of $5\text{x}10^{19}$ W/cm$^2$. The protons were obtained from the Tungsten foil in an exponential spectrum of mean temperature 3MeV and a high-energy cut-off around 15-20MeV. Models predict that these protons are accelerated in a timescale of the order of a few times the laser pulse length[3]. The implosion was driven by six laser (heater) beams of Vulcan, each 1μm wavelength, 1ns duration, focused onto a microballoon at an irradiance of $1\text{x}10^{13}$ Wcm$^{-2}$ and without phase plates. These heater beams were derived from the same oscillator as the short pulse backlighter and so there is no relative timing jitter between the implosion and backlighter beams. The targets were plastic microballoons ($C_4H_4$), 500μm in diameter and with wall thickness either 3μm or 7μm. Individual heater beam energy was in the range of 50J giving a maximum energy on target of 300J and these beams were arranged such that they illuminated the target tangentially from 6 orthogonal directions, giving the best symmetry for a six beam implosion, as shown in Fig.1. The synchronization of the 1ns heater beams to the picosecond backlighter beam was measured to within accuracy of 100ps using an optical streak camera.

The proton detector used in this experiment consisted of a multilayer film pack containing spatially resolving dosimetry film (RCF) and particle track detectors (CR-39). This arrangement, which has been extensively used in laser driven proton acceleration experiments, gave a diagnostic in which each layer was filtered by the preceding layer, giving a series of images on each shot each with a slightly different energy, ranging from 3 to 15MeV. The propagation of protons through the radiography objects was modeled using a Monte-Carlo simulations code based on TRIM [8]. TRIM calculates the final spatial and energy distribution of ions passing through the object, taking into account ionization energy loss by the ion into the target and energy transferred to recoil atoms. The simulation code uses TRIM to record the energy and position of each proton as it passes through the target and the RCF film pack. The program calculates the dose deposited in each RCF layer by adding up the contributions from each incident proton. This procedure provides a radiographic projection of a transverse 2D slice of the target. If the object has spherical symmetry then a three dimensional object can be obtained by superimposing a large number of profiles rotated in small angles about the center [10].

The protons used to radiograph the foil were produced by focusing the 1ps pulse onto thin tungsten (W) foils with an irradiance of $5\times10^{19}$Wcm$^{-2}$. Experimentally it was found that little or no protons were produced on shots when the back surface of the 25μm Tungsten foil was exposed to the coronal plasma that surrounded the imploding balloon. This is consistent with a scenario where the source of the proton beam is exposed to a combination of fast ions, scattered laser light and soft x-rays from the coronal plasma. This environment disrupts the proton beam by disturbing the back surface of the target as previously observed [11]. It was found that inserting a shielding foil, of Aluminum, 6μm thick, provided enough protection to the foil to preserve the fidelity of the proton beam while preserving the good spatial resolution in the proton images.

A static test of point projection proton imaging was obtained by backlighting an undriven microballoon with diameter 500 μm and wall thickness of 7 μm. The image of the balloon shown in fig 2(a) was obtained by projecting the proton beam onto the film pack with a magnification of 10.5x. A one dimensional line through the center of the shell is shown in Fig 2(b). It is clear that the balloon strongly modulates the proton beam, with the highest modulation occurring at the edges of the shell where the path length through solid density material is highest. Also shown on fig 2(b) is the output of 3D proton Monte-Carlo simulations of a point source propagating through the microballon using 7MeV protons. It can be seen that these simulations agree well with the data, reproducing the shape of the edge of the balloon confirming that multiple small angle scattering is responsible for modulating the proton beam and forming the image of the balloon. The equivalent target plane edge resolution in this image is limited by multiple scattering in the shell to 10μm.

Temporal evolution of the capsule density profile during the implosion was studied by varying the delay between the backlighter and the implosion beams. With nominally symmetrical drive conditions the capsule remains roughly spherical as the implosion proceeds as can be seen from Figure 3(a). This 7MeV proton radiograph, taken 2ns after the start peak of the heater beams, shows that the capsule has retained roughly spherical symmetry with the overall diameter of the shell reducing from 500 to 300μm and with capsule walls that are still largely intact. There is also some residual asymmetry due to the imperfect synchronization and energy balance of the 6 heater beams. From this view it can be seen that the shell has departed from its original spherical shape and is slightly elliptical with a ratio of major to minor axis of (1.2). This is consistent with reasonable beam synchronization (to within 300ps). In contrast Figure.3 (b) shows a proton image of a capsule where the drive was very asymmetrical due to significant timing difference between the drive beams. In this case the laser beams on the left hand side of the image arrived between 1 and 2ns before the laser beams on the right-hand-side. This led to the gross distortions from the sphericity. These radiographs demonstrate that due to the high spatial resolution and contrast in the early phases of the implosion, this technique gives quantitative information in the early phases of the implosion. This may be useful in ignition scale capsules for diagnosing the onset of early time instability growth such as the feed-through from imperfections in the ice surface to larger scale density perturbations in the ablation surface through the Raleigh-Taylor instability [12].

Radiographs were also taken closer to the time of peak density (stagnation) point of the implosion. The proton radiograph in figure.4(a) was taken at to + 3ns which is close to stagnation for this 3μm wall thickness shell. At this time a dense core has assembled just below the center point of the original capsule. The core has formed in the lower third of the original shell, due to the higher drive levels from the upper beams. As with the earlier time the core is slightly elliptical with a minor diameter of 100μm and a major diameter of 120μm (fwhm). Again the radiograph clearly resolves this asymmetry. It is important to note that the primary goal of this experiment was not to achieve a perfect implosion but to prove the capability and effectiveness of protons as a radiography source of dynamically evolving compressed plasma.

Following Bethe's treatment of Moliere's multiple scattering theory [13], a beam of particles of momentum p (in units of MeV) and velocity v and charge z, traversing a material of, atomic number Z and atomic weight A, length t (in units of gcm$^{-2}$) will be spread into a cone with half angle given by $\gamma_o = ([0.157BZ(Z+1)\ z2L/Ap^2v^2)^{1/2}$, where B is a Z dependent constant [14]. For 7MeV protons traversing 100μm of carbon at 3g/cc, Z= 6, A=12, L~100μm*3g/cc = 0.03gcm$^{-2}$, B=10 giving , $\gamma_o \sim 1.75°$. For the 7MeV proton image, the resolution, δ in the film plane is given by the product $d = (\theta_o * d)$, where d is target to film distance. For d = 40mm, δ ~1200μm in the film plane, which is equivalent to 120μm in the object plane (at M=10), in good agreement with the resolution observed in the data and the Mote-Carlo simulation of a realistic imploded capsule density profile. For a fixed ρL product and magnification, higher resolution can be attained by using more energetic protons or by reducing the distance from the radiography object to film plane.

In order to obtain a quantitative measure of the core density profile, the Monte-Carlo simulation code was used to model the propagation of a proton beam through a spherically symmetric object assuming a Gaussian radial profile. The peak density and fwhm of the core were treated as variable parameters in the model until the best match with the data was obtained. In order to match the data the background level of simulations were scaled to match that of the data. Figure.4(b) shows a line-out across the minor diameter of the core feature, together with the output from Monte-Carlo simulations. In this particular case the peak density was fixed at 3g/cc while the fwhm of the original object was varied between 63, 83 and 126μm. It is clear that the 83μm object most closely matches the data in both modulation depth and feature size.

Simulations were also run where the peak density was varied while keeping the profile diameter constant, as shown in fig 4(c). These data show that the best fit occurs for a density profile with a peak density of 3g/cc and a fwhm = 83μm. Independent confirmation of the peak density of the imploded core was obtained was obtained with a follow on experiment using picosecond duration $K_\alpha$ radiography at 4.5 keV of identical capsules imploded using the same implosion system. This experiment measured a peak density of 4g/cc in a core with FWHM of 90mm [15].

These results were obtained using 7MeV protons. From fig 4(b) and (c) it can be seen that multiple scattering results in a blurring from the original object fwhm of 83μm to the measured fwhm of 100 μm. This blurring effectively results in a spatial resolution of 20μm. This resolution is adequate for inferring the overall shape and uniformity of the compressed core but not for investigating small-scale density perturbations. To resolve these structures requires higher proton energy and/or reducing the object to film plane distance. For the particular areal density conditions relevant for this imploded capsule, increasing the proton energy by a factor of two leads to an improvement in resolution to 10μm due to reduced small angle scattering.

The feasibility of proton radiography for diagnosing density uniformity in very dense objects such as a compressed inertial confinement fusion shell was investigated by using a Monte-Carlo model to simulate radiographs of density profile generated by a 1D Hydra simulation of a sub ignition NIF implosion. Fig 5 shows a hydra profile of a “failed” indirect drive NIF implosion, where some of the shocks used to assemble the high density fuel have been mistimed together with simulated proton radiographs at three energies. The density conditions inside this non igniting core are still extreme, with peak densities in the core of around 350g/cc. The resulting profile shows the stagnating imploded shell, with a high density shell surrounding a hollow core. In this case the core density peaks at 350g/cc at a radius of 50μm surrounding a core region with density around 50g/cc. Simulation of a point projection proton image of the object in 50 to 200MeV protons is shown in fig 5. It can be seen that the density peak at 50μm radius is clearly resolved using 120 or 200MeV protons but only marginally resolved using 50Mev protons. These simulations showed that protons between 30 and 50MeV would be able to characterize asymmetries in the stagnated core. Proton beams with these energies have already been produced by PW laser systems [6]. Good resolution of fine structure in the density profile would require proton energies above 120MeV, which would require a significant increase in the high energy cut off on the proton beam. In a real implosion other factors such as electric fields driven by pressure gradients and hot plasma effects on the proton propagation will also contribute to the proton dose observed on the detector. Electric field effects would lead to a general deflection rather than scattering shown here. In fact deflectometry techniques could be used to diagnose these fields thus providing additional information on pressure gradients in the core of an ICF target [4,16].

In conclusion proton radiography of a laser driven implosion with picosecond resolution have been demonstrated for the first time. Proton radiography exhibits high temporal, spatial resolution throughout all stages of the implosion. Monte Carlo simulations through a core with a Gaussian density profile agreed well with the experimental data. Scaling of the technique to 50-100MeV proton energy shows that this diagnostic is capable of resolving core symmetry in highly dense plasmas such as those predicted for ignition scale inertial confinement fusion plasmas.

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENF-48 and EPSRC grants. AJM acknowledges partial support from an IRCEP advanced fellowship from Queens University, Belfast.

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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**Figures:**

1. Geometry for proton radiography of the 6 beam implosion.
2. (a) 7MeV Proton radiograph of undriven 500μm diameter, 7um wall thickness shell.

   (b) Line out through data and Monte–Carlo simulation of proton propagation through shell and RCF film pack.
3. (a) Proton radiograph (7MeV protons) of quasi-symmetric implosion, taken 2ns after the peak of the heater beams (7μm wall). The shell walls are still clearly visible and the implosion is relatively spherical

   (b) Proton radiograph taken of highly asymmetric implosion, caused by mistimed heater beams. Beams from lower left side of figure are 1-2ns earlier than beams from upper right.
4. (a) Proton radiograph, in 7MeV protons, of a 500μm diameter microballoon with a 3μm wall at a time close to stagnation (To+3ns). The core is slightly elliptical and has assembled below the center point of the shell.

   (b) Radial line-out taken through center of proton radiograph data and Monte-Carlo simulation output for fixed peak density and varying core size (fwhm).

   (c) Radial lineout from data plus Monte-Carlo simulations with fixed core size and varying peak density. Best fit for all simulations was obtained for a core size of 83μm with a peak density of 3g/cc.
5. Density profile of a mistimed NIF implosion obtained from a1-Dimensional Hydra simulation (blue line) together with a simulated dose profile of a radiograph taken with 50,120 and 200MeV protons. Protons at 50MeV can resolve the overall shape of the core but >120MeV protons are required to resolve the location of the density peak within the core.

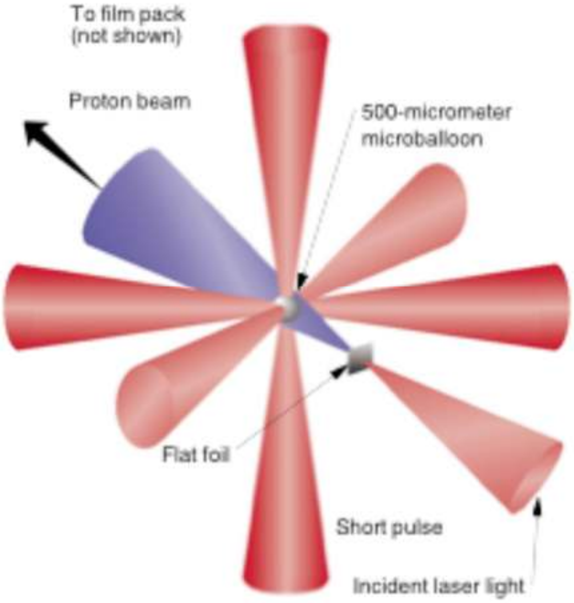

To film pack
(not shown)
Proton beam
500-micrometer
microballoon
Flat foil
Short pulse
Incident laser light

Figure 1

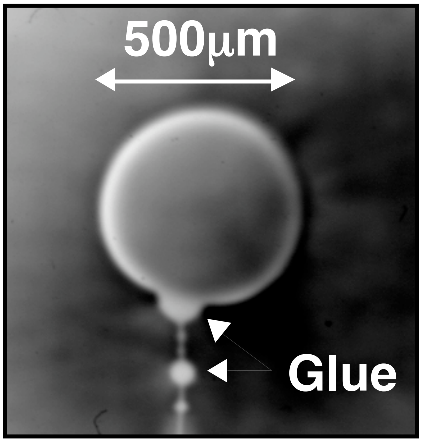


Figure.2(a)

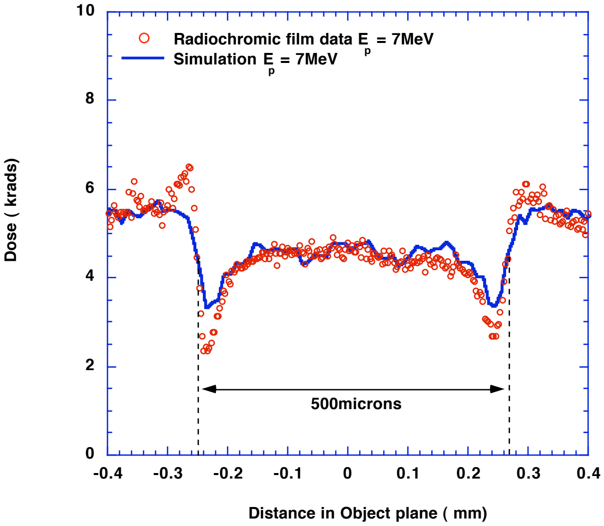


Figure.2(b)

Figure 3 (a)

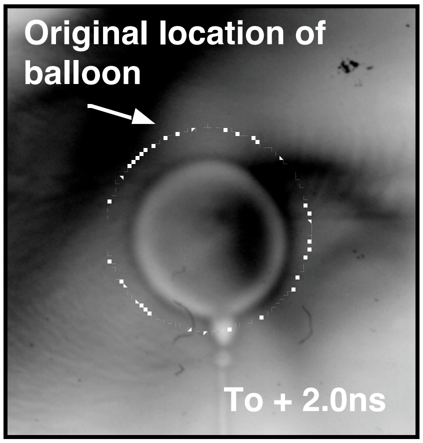


Figure 3 (b)

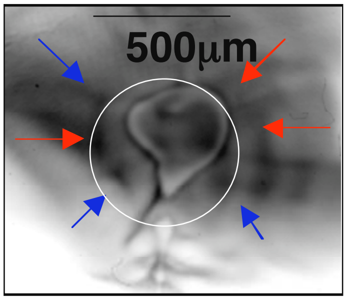


Fig. 4(a)

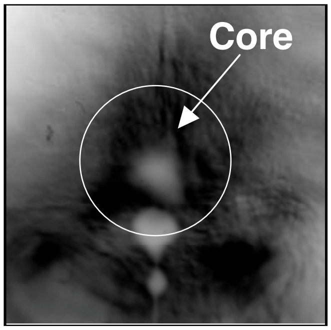


Fig. 4 (b)

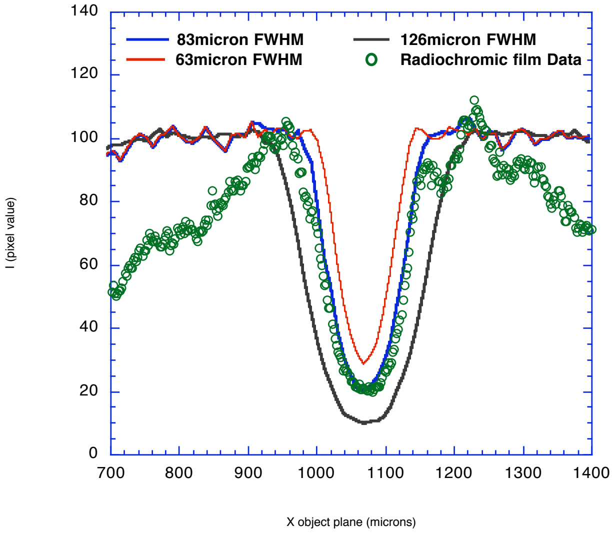
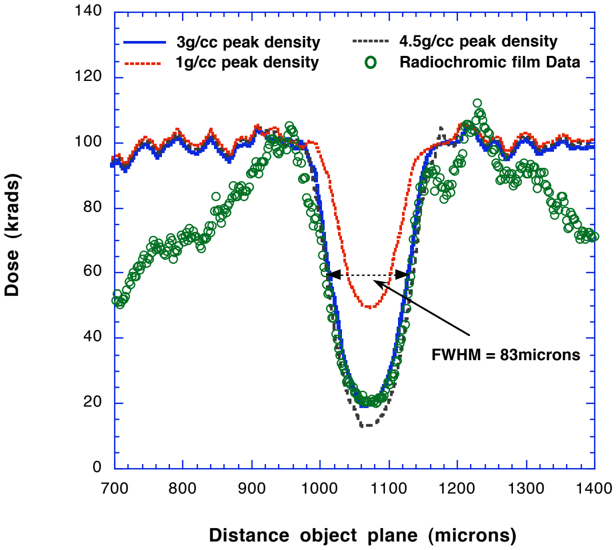
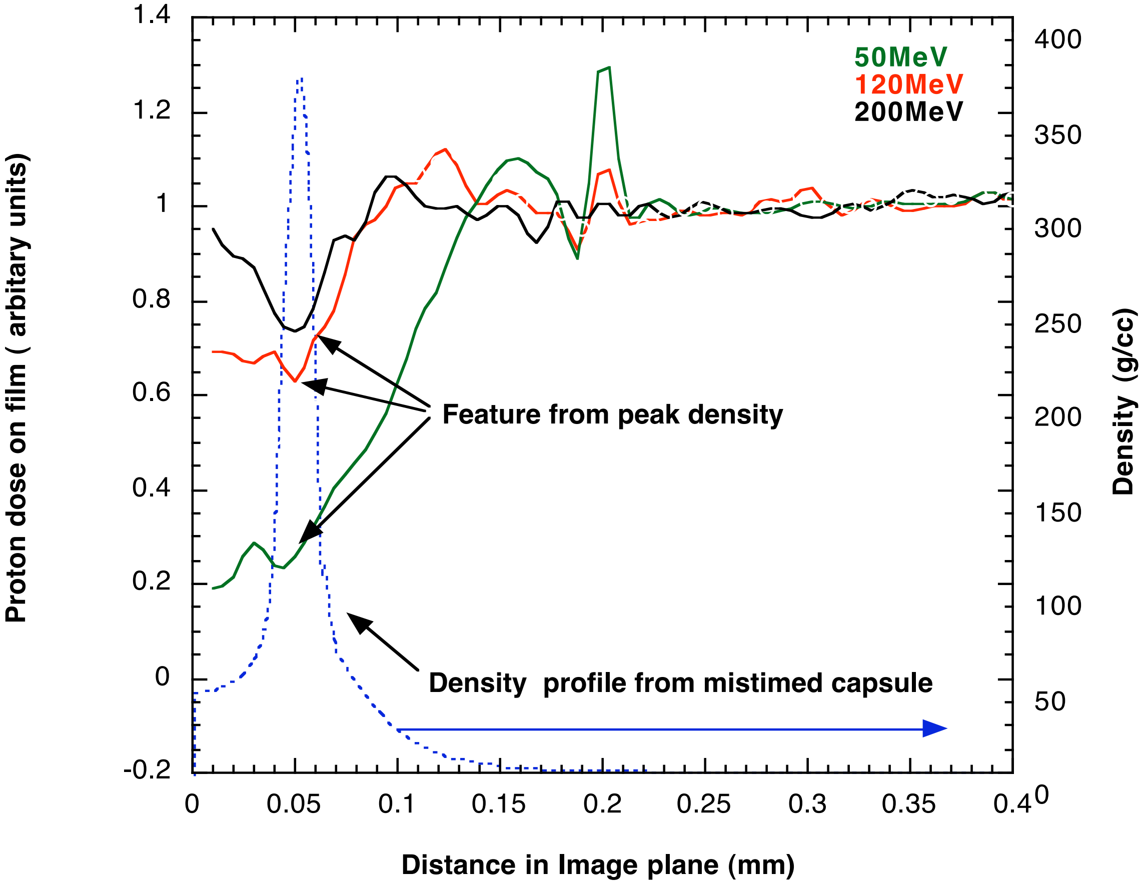


Fig. 4(c)





50MeV
120MeV
200MeV
Feature from peak density
Density profile from mistimed capsule
Proton dose on film ( arbitary units)
Density (g/cc)
Distance in Image plane (mm)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
400
350
300
250
200
150
100
50
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

Figure.5