Imaging the Burn Region of Laser Driven Implosions on OMEGA Using the Proton Core Imaging Spectroscope

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Abstract

The first measurements of the nuclear burn region of OMEGA implosions have been made with the Proton Core Imaging Spectroscopy (PCIS). Using CR-39 nuclear track detectors, PCIS applies the technique of penumbral imaging to measure the radial profile of D-D and D-\textsuperscript{3}He protons produced by implosions of D\textsubscript{2}-\textsuperscript{3}He-filled capsules. For capsules with 20 \textmu m-CH shells, images of D\textsuperscript{3}He protons resulted in Gaussian profiles with an average 1/e radius of \textasciitilde35 \textmu m. Gaussian profiles inferred from the D\textsuperscript{3}He protons and D-D protons produced by implosions of 2 \textmu m SiO\textsubscript{2}-shell capsules had average 1/e radii of 60 \textmu m and 94 \textmu m, respectively.

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# Table of Contents

1. Introduction ........................................................................................................... 7

2. Penumbral Imaging ............................................................................................... 11

3. Instrument Design .............................................................................................. 13

4. Data Processing and Analysis ............................................................................ 17
   4.1. Processing the Data .................................................................................. 17
   4.2. Analysis of PCIS Data ............................................................................. 19

5. Diagnostic Issues .................................................................................................. 25
   5.1. Issues related to experimental conditions ................................................. 26
      5.1.1. Pinhole Conditions ........................................................................... 26
      5.1.2. System Magnification ....................................................................... 29
      5.1.3. Effects of ranging Filters ................................................................. 30
      5.1.4. Treating yield issues ......................................................................... 31
   5.2. Issues related to extracting data .................................................................... 35

6. Experimental Results ........................................................................................... 37
   6.1. Results From D_2(6)^3He(12)CH[20] Capsule Implosions ...................... 37
   6.2. Results From D_2(6)^3He(12)SiO_2[2] Capsule Implosions ....................... 42

7. Conclusions and Future Work .............................................................................. 46

Appendix A: PCIS Data Summary Table .................................................................... 48

Appendix B: PCIS Shot Picture Book ......................................................................... 53

Appendix C: Test of Source Function Reconstruction with Monte Carlo Simulated
PCIS Data ......................................................................................................................... 141

Bibliography ................................................................................................................. 143
List of Figures

Figure 1.1 Gaussian burn profiles from shots 29827 and 27807................................. 9
Figure 1.2 A summary of all current burn profile measurements............................ 10
Figure 2.1 The basic concept of penumbral imaging.............................................. 11
Figure 3.1 Schematic of the PCIS design............................................................... 13
Figure 3.2 Schematic of the pinhole assembly in the nose cone............................... 14
Figure 3.3 Photographs of the PCIS hardware components..................................... 15
Figure 3.4 Schematic of the assembled PCIS hardware in the OMEGA target chamber. 16
Figure 4.1 Images taken from the scanning microscope........................................ 17
Figure 4.2 Scan image of D–3He protons from shot 27807, with and without noise thresholds.............................................................. 18
Figure 4.3 Scan image and contour plot of D–3He protons from shot 26081.............. 19
Figure 4.4 N(r) and dN/dr for D–3He protons from shot 26081................................. 20
Figure 4.5 Analytic inversion for a family of functions between parabolic and gaussian 21
Figure 4.6 Contours of total $\chi^2$ for D–3He protons from shot 26081................... 22
Figure 4.7 dN/dR from shot 26081 fit by a gaussian.............................................. 23
Figure 4.8 Angularly-averaged burn profile of D–3He protons from shot 26081........ 23
Figure 4.9 D–3He yield from several Wedge Range Filter Spectrometers for shot 26081. 24

Figure 5.1 Example images resulting from a small diameter pinhole and low magnification.............................................................. 27
Figure 5.2 Demonstration of pinhole debris' affect on imaging.............................. 28
Figure 5.3 A scan image and contour plot of D–3He protons from shot 25612........... 29
Figure 5.4 Integration of shots 26625,26,30,31,32............................................... 31
Figure 5.5 Improved integration of shots 28915,16,18........................................... 32
Figure 5.6 Demonstration of summing several pinholes from shot 27808................. 33
Figure 5.7 Track saturation on CR-39 from D-D protons of shot 26081................... 34
Figure 5.8 Scan images exhibiting banding due to focus inaccuracies..................... 36
Figure 6.1 Cartoon of a 20μm CH shell, D2–3He-filled capsule implosion............... 38
Figure 6.2 Summary of 1/e radii for all inferred D3He burn profiles of thick-shell capsules............................................................................. 39
Figure 6.3 Burn profiles from orthogonal 20μm-shell shots 30956 and 30977.......... 40
Figure 6.3 Comparison of D–3He proton yields calculated from PCIS and from WRFs.. 41
Figure 6.4 Cartoon of a 2 μm SiO2 shell, D2–3He-filled capsule implosion............... 42
Figure 6.5 Burn Profiles from shot 29827............................................................. 43
Figure 6.6 Yield ratio vs. ion temperature and inferred Ti from 29827 burn profiles..... 44
List of Tables

Table 6.1 Comparison between PCIS P and PCIS 1 for shots 30956 and 30977 ........... 41
Table 6.2 Summary of D-D results from 2μm-shell implosions .................................. 45
Table 6.3 Summary of D-3He results from 2μm-shell implosions ................................. 45
1. Introduction

Detailed measurements of the nuclear burn region are important for advancing direct drive laser fusion [1]. The Proton Core Imaging Spectroscopy (PCIS) has been designed in order to make the first direct measurements of nuclear burn regions of OMEGA implosions. Herein we describe PCIS and its first implementation at the OMEGA laser facility.

OMEGA is a neodymium-doped phosphate glass laser capable of delivering up to 30 kJ of frequency-tripled, 0.35 μm light onto a spherical target that measures less than 1 mm in diameter. This energy can be distributed into 60 beams, each individually focused with a pointing accuracy of ±10 μm and a timing jitter on target of ±10 ps. A variety of pulse shapes are possible, with widths ranging from 115 ps to a few nanoseconds. The OMEGA target chamber is a 3.3 m-diameter aluminum spherical shell with 60 beam ports and 32 diagnostic ports. The chamber is kept at a vacuum of about 10⁻⁵ Torr during experiments [2,3].

OMEGA utilizes an assortment of diagnostics to investigate the wide range of physical conditions that characterize laser-driven Inertial Confinement Fusion (ICF). These conditions involve issues of irradiation uniformity and laser imprinting; Rayleigh-Taylor instabilities; compressed core performance and shell-fuel mixing; laser-plasma interactions and their effect on target performance; and cryogenic target fabrication and handling [4].

Currently, information about the spatial distribution of the nuclear burn region of capsule implosions is minimal. Measurements of the burn region are valuable for investigating the extent of the burn, the presence of burn asymmetries, the effects of mix and thermal conduction on the burn region, and the accuracy of code predictions. Neutron and x-ray images have been produced for some OMEGA implosions, but these techniques are
limited [5,6]. X-ray images do not directly measure the nuclear burn and neutron images, though taken directly from the burn, do not yet meet resolution requirements and can only be used for imaging high yield neutron producing reactions.

PCIS is a pinhole camera that makes use of penumbral imaging to measure nuclear burn regions of OMEGA implosions. The technique of penumbral imaging and the PCIS design will be illustrated in Chapters 2 and 3, respectively. With PCIS, we have already made initial measurements of nuclear burn regions from implosions of many 18 atm D$_2$-^{3}He filled capsules. These measurements concentrate specifically on the proton burn regions from capsules with 20 $\mu$m CH shells and 2 $\mu$m SiO$_2$ shells. [For convenience, capsule types may be identified by the notation D$_2$(6)^{3}He(12)CH[20], for example, where numbers in parentheses indicate atmospheres of fuel in the capsule and the number in brackets indicates the shell thickness in microns.] Presently, we are making 1-D approximations of nuclear burn regions. The method used to estimate the size and shape of the burn will be described in Chapter 4. Currently, we are able to measure only D-^{3}He proton burn regions of thick-shell capsules. But, for thin-shell capsules we have measured both D-^{3}He proton and D-D proton burn regions. We have determined that these burn regions tend to be Gaussian or possibly slightly more peaked than Guassian, so at this stage all burn region profiles are approximated as Gaussian. As an example, Figure 1.1 shows the D-^{3}He proton burn profile and the D-D proton burn profile from shot 29827: D$_2$(6)^{3}He(12)SiO$_2$[2], and the D-^{3}He proton burn profile from shot 27807: D$_2$(6)^{3}He(12)CH[20].
Figure 1.1 Gaussian burn profiles from shots 29827 and 27807.

Shot 29827: D$_2$(6)$^3$He(12)SiO$_2$(2) resulted in D-$^3$He proton burn profile with a 1/e radius of 56 µm and a D-D profile with a 1/e radius of 82 µm. The Gaussian inferred from shot 27807: D$_2$(6)$^3$He(12)CH[20] has a 1/e radius of 36 µm. In general, radii from thick-shell capsule D-$^3$He protons are smaller than those of thin-shell capsules; and for thin-shell capsules, the D-D protons have a wider profile than the D-$^3$He protons.

An average 1/e radius of 35 µm was found for the distribution of D-$^3$He protons produced from implosions of 20 µm-thick CH shells. Implosions of 2 µm SiO$_2$ shell capsules resulted in 1/e radii of about 56 µm for the D-$^3$He proton burn region and about 83 µm for the D-D proton burn region. A summary of all nuclear burn region measurements made from PCIS thus far is shown in Figure 1.2. It includes data from orthogonal PCIS assemblies for thick-shell shots 30956 and 30977 as well as comparisons of measurements of D-$^3$He protons and D-D protons for three thin-shell shots. Simulations indicate that these measurements are reasonable. The data will be discussed further in
Chapter 6. Also, Appendices A and B catalogue information and analysis of each shot for which PCIS data were taken.

![1/e Radii of Profiles for All Shots](image)

Figure 1.2 A summary of all current burn profile measurements.
D-3He proton burn region profiles from thick-shell capsules have an average 1/e radius of 35 μm. Thin-shell capsules exhibit a higher 1/e radius of D-3He proton burn regions and an even higher radius of D-D proton burn regions.

Although we have reconstructed several source profiles with PCIS, the diagnostic is still in its developmental stages and many upgrades are anticipated. Our earliest efforts concentrated on establishing optimal set-up parameters, while more recent experiments examine ways to improve measurement accuracy. This is a long-term endeavor, with many questions remaining, and this thesis is meant to document the status of the project and the current results, and to discuss future plans for further studies with PCIS.
2. Penumbral Imaging

Nugent proposed penumbral imaging for the study of laser-produced plasma emissions in 1984 [7] and, in 1989, the method was applied to image D-D protons of a deuterated polystyrene (CD) shell capsule at the Institute of Laser Engineering, Osaka University by Chen [8]. The advantages of this technique, as opposed to previous coded aperture imaging (CAI) techniques, are that, since it requires only a large diameter hole as an aperture (much larger than the size of the source), the design is simple (and therefore inexpensive) and can be made in a thick substrate, necessary for “ranging out” very energetic particles.

The method relies on the fact that spatial information can be recovered from the penumbra generated by imaging an unknown source through a simple large circular aperture [9]. The basic concept for penumbral imaging is shown in Fig. 2.1.

![Diagram of penumbral imaging](image)

**Figure 2.1** The basic concept of penumbral imaging.

Spatial information about an unknown source can be recovered from the penumbra region of the image formed on a detector from an aperture much larger than the size of the source.
The image formed on the detector consists of a uniform central region of full illumination surrounded by the penumbra of partial illumination which contains information about the source. The encoded image for the source surface brightness, $I(\tilde{r})$ is given by [7,8]

$$I(\tilde{r}) = A\left(\frac{L_p}{L_p + L_d}\frac{\tilde{r}}{\tilde{r}}\right) * O\left(\frac{L_e}{L_d}\tilde{r}\right),$$

where $A(\tilde{R}_A)$ is the aperture function, $O(\tilde{R}_O)$ is the function describing the source, $L_p$ and $L_d$ are the distances from the source to aperture and from aperture to detector, respectively and $*$ is the convolution operator. If the image function, the aperture function and the distances $L_p$ and $L_d$ are known, then theoretically, the function describing the source may be deconvolved. However, the deconvolution is very sensitive to noise and a variety of methods have been developed to deal with this problem. The method currently used for PCIS will be discussed in Chapter 4.
3. Instrument Design

The Proton Core Imaging Spectroscope (PCIS) was conceived in order to make the first direct measurements of the proton burn region of OMEGA implosions, applying the technique of penumbral imaging. The concept of the diagnostic is show in Figure 3.1. It is essentially a pinhole camera, consisting of a circular pinhole aperture and a stack of CR-39 nuclear track detector sheets as the recorder. CR-39 has been used extensively for charged particle detection, and will be discussed briefly in Chapter 4. Ranging filters separate the sheets of CR-39, so that each sheet is tuned to detect a particular species of particle.

![Diagram of PCIS design](image)

**Figure 3.1 Schematic of the PCIS design.**

A stack of CR-39 sheets is used to image each species of protons separately. Filters FA and FB range down appropriate particles to within the sensitivity of their respective sheets of CR-39, DA and DB. The radius of an image on the detector plane is usually on the order of 1 cm. The distance from the capsule to the aperture, \( L_p \), may be anywhere between 3 and 33 cm, while the distance from the aperture to the detector, \( L_{ap} \), is fixed at roughly 33 cm.

Since the CR-39 is sensitive to a limited range of particle energies depending on its thickness, the filter thicknesses are chosen so that certain energetic particles are ranged

13
down to within the sensitivity of a particular piece of CR-39. For studies of \( \text{D}_2^{\text{3He}} \) capsules, two sheets of CR-39 are used to image the resulting 3.0-MeV D-D protons and 14.7-MeV D-\( ^{\text{3He}} \) protons separately. Because the D-D protons are less energetic, they are imaged onto DA, the sheet closest to the capsule, while the D-\( ^{\text{3He}} \) protons are energetic enough to pass through this sheet and then be ranged down to within the sensitivity of the second sheet, DB. DA sheets are always 1000 \( \mu \text{m} \)-thick, where as the thickness of DB sheets are less critical and range between 1000 \( \mu \text{m} \) and 1200 \( \mu \text{m} \).

The main components of PCIS (i.e. the pinholes, CR-39 and filters) are assembled with hardware borrowed from Lawrence Livermore National Laboratory and adapted for PCIS by Samuel Roberts (Laboratory for Laser Energetics, University of Rochester) and Joseph DeCiantis (MIT Plasma Science and Fusion Center). The assembly must fit into a pre-existing OMEGA diagnostic port, and therefore the design of the hardware accommodates compatibility with the port.

![Schematic of the pinhole assembly in the nose cone.](image)

The pinhole fits into a nose cone assembly to keep it properly aligned in the OMEGA target chamber. The pinhole substrate is roughly 0.5 cm in diameter and has 3 notches to fit it to the nose cone piece. The apertures of the collimator and disc spring are large enough not to interfere with the particles that pass through the pinhole.

The pinhole apertures are drilled into 500 \( \mu \text{m} \)-thick, disk-shaped tantalum substrates and have ranged in diameter from ~20 to 2000 \( \mu \text{m} \). The substrates fit into a removable nose
cone, along with a collimator and spring to ensure that the pinhole fits snugly and remains properly aligned once it is inserted into a diagnostic port. Due to concerns about the post-implosions pinhole integrity, each pinhole aperture is used only once.

The filters and CR-39 detectors are sandwiched together in a small aluminum frame (shown in Figure 3.3(c)). The nose cone (Figure 3.3(d)) and "filter pack" are connected to the narrow end of the aluminum mount shown in Figure 3.3(a) so that the pinhole sits 33cm in front of the CR-39. The wider end of the mount attaches to the target chamber by screwing into the sides of the diagnostic port. Holes are drilled into the side of the mount to reduce weight for manageability. Figure 3.3(e) shows the entire PCIS assembly with the nose cone and filter pack connected to the aluminum mount.

Figure 3.3 Photographs of the PCIS hardware components.
(a) The PCIS mount that holds the nose cone and filter pack together and fixes to the diagnostic port. (b) The end of the mount that secures the filter pack. (c) A filter pack. (d) The nose cone, which contains the pinhole and connects to the front of the mount. (e) The entire PCIS hardware assembly.
Once the complete assembly is fixed to the diagnostic port, the port is positioned to align PCIS with the capsule at the target chamber center. The distance from the capsule to the pinhole can be set between 3 and 33 cm to adjust the magnification in the image plane (from 1-11 times the source size). Figure 3.4 shows the PCIS assembly secured to a diagnostic port inside the OMEGA target chamber. On the left is the target positioner, with the capsule at the tip of the stalk.

Figure 3.4 Schematic of the assembled PCIS hardware in the OMEGA target chamber.

The PCIS mount attaches to the diagnostic port of the OMEGA target chamber. The filter pack and nose cone are attached at the end, and the diagnostic port adjusts to position the entire assembly. On the left is the target positioner, which holds the capsule at the end of a stalk.
4. Data Processing and Analysis

PCIS can be thought of as a camera, where imploding a capsule while the diagnostic is set up in the target chamber is like taking a picture. The next step is to develop the film to produce an image. The film here is our stack of CR-39 detector sheets, and the data must be processed to get the image before it is used for analysis. There are many subtleties that make this processing complicated, but first it is useful to go through a simple explanation of the technique for retrieving the data from the CR-39.

4.1. Processing the Data

CR-39 has been used extensively to detect and measure the charged reaction products from OMEGA implosions and only the basic technique used for PCIS data is described here. A paper by Fredrick Séguin discusses CR-39 spectrometry for ICF studies more thoroughly [10].

For current PCIS data, the CR-39 is etched at 80°C in 6-molarity sodium hydroxide (NaOH) for up to 6 hours (depending on the yield predicted by other diagnostics).

Figure 4.1 Images taken from the scanning microscope.

(a) Microscope image from the center of a pinhole on Detector B from shot 27806: \( \text{D}_2(6)^3\text{He}(12)\text{CH}[20] \). (b) Microscope image from the center of a pinhole on Detector B on shot 29827: \( \text{D}_2(6)^3\text{He}(12)\text{CH}[20] \) after 4 hours etch.
Once the piece is removed from the etch bath, rinsed and dried, it is inspected on an optical microscope to determine the appropriate parameters for a computer-driven scan of the data area. A CCD camera captures a digital image of each microscope frame, and image analysis is performed by software that identifies the “tracks”, which appear as dark circles on a light background. The software determines the perimeter of each track by locating image intensity drops below a specified “boundary threshold.” The software then records the diameter, optical contrast and eccentricity of the track, as well as its position.

After the “scan” is complete, a separate computer program is used to interpret the data retrieved by the computer/microscope system. The program creates a raw image of the tracks recorded by the microscope, with the density of tracks per pixel or frame proportional to intensity.

27807: $D_2(6){^3He}(12)CH[20]$

![Image](a) ![Image](b)

**Figure 4.2** Scan image of D-He protons from shot 27807, with and without noise thresholds.

(a) Raw scan image from shot 27807 before. (b) The same scan image after limits have been imposed on the eccentricity, diameter and contrast. See page 130 for further analysis of this shot.

Thresholds are identified for track contrast, eccentricity and diameter to remove false counts that may have resulted from irrelevant particles, scratches or other noise, revealing the image created by the protons. These limits are chosen based on an examination of all counts, with attention to how the track contrast and eccentricity vary with diameter.
Background noise is statistically subtracted based on an area of the scan outside of the data region, chosen by the user.

4.2. Analysis of PCIS Data

Now with the scan image optimized, the pinhole images may be used to infer the structure of the burn region. However, this can be difficult due to a high sensitivity to noise and poor statistics. As a first order approach we assume spherical symmetry and burn region profiles are inferred by angular averaging of the images. With improvements to the diagnostic, angular averaging will not be necessary and PCIS will be used for studying 2 and 3 dimensional structure of the burn region. In the mean time, angular averaging is a good first approximation since it gives the size of the nuclear burn region.

The first step in deconvolving the source profile is to determine the angularly-averaged shape of the penumbra (i.e. finding the number of particles as a function of the radius from the center of the pinhole image, \( N(r) \) [see Figure 4.3]). Identifying the center location of the image is crucial to generating an accurate burn profile since an angular average around an off-center location will smear the penumbra over a wider band of the radius than an average around the actual center would.

26081: \( \text{D}_2(6)\text{^3He}(12)\text{SiO}_2[2] \)

![Image](image.png)

(a) Scan image after noise thresholds have been identified. (b) Contour plot of the same data showing the penumbral region.
To deal with this, the analysis program has a center-finding algorithm (written by Fredrick Séguin) that varies the assumed center and determines the location that results in the narrowest penumbra.

26081: D$_2$(6)$^3$He(12)SiO$_2$[2]

![Graphs showing N(r) and dN/dr for D-3He protons from shot 26081.](image)

*Figure 4.4 N(r) and dN/dr for D-3He protons from shot 26081.*

Next, a spherically symmetric source function is calculated from N(r) [11]. In the limit where the pinhole radius is much larger than the source size, values of dN/dr in the penumbra are proportional to integrals along parallel, straight lines through the surface brightness of the source. The absolute local emissivity in the plasma is inferred from these integrals. (For the geometry used here, this is accurate to within a few percent.) If we assume a source function, $S(R)$, of the form:

$$
S(R) = 4\pi M \left( \frac{L}{r_o} \right)^2 \frac{A_d}{2} \left[ 1 - \left( \frac{R}{r_o/M} \right)^2 \right]^{n-1}
$$

in particles per unit volume, where $R$ is the radius from the center of the source, $L$ is the target to CR-39 distance, $M = L/L_p - 1$ is the magnification (with $L_p$ as the distance from...
target to pinhole), $A_d$ is an amplitude, $r_o$ is half the total penumbra width, and $n$ is a positive number, then the resulting $dN/dr$ has the form:

$$dN(r)/dr = A_d \left[1 - \left(\frac{r'}{r_o}\right)^2\right]^n,$$

where $r'$ is the distance from the centroid $r_c$ of $dN/dr$ [see Figure 4.4]. Both functions approach Gaussians as $n$ goes to infinity. For convenience, we can parameterize this family of solutions by a "peakedness" shape factor:

$$P = 1 - \frac{1}{n}.$$  

Then, $P = 0$ ($n = 1$) for a flat (uniform) source, which generates a parabolic $dN/dr$, and $P = 1$ ($n = \infty$) for a Gaussian source and a Gaussian $dN/dr$, as shown in Figure 4.5.

![Diagram showing analytic inversion for a family of functions between parabolic and Gaussian. According to the equations above, for the case $n = \infty$, the source is Gaussian and so is the associated $dN/dr$.]

Figure 4.5 Analytic inversion for a family of functions between parabolic and Gaussian. According to the equations above, for the case $n = \infty$, the source is Gaussian and so is the associated $dN/dr$. 

| 21 |
The relationship between source function and $dN/dr$ has been verified directly by using synthetic PCIS data sets generated with a Monte-Carlo program (written by Shinya Kurebayashi and Johan Frenje) and using the analysis program to recover a source function consistent with that used to generate the data [See Appendix C]. The details of these results will be published in the Review of Scientific Instruments by F. Séguin, S. Kurebayashi, J. Frenje and B. Schwartz in the future. Error in the reconstructed source function due to the assumption of a large pinhole diameter relative to the source size was seen to be small (a few percent at worst) for the actual geometry of the PCIS instrument.

![Figure 4.6 Contours of total $\chi^2$ for D-$^3$He protons from shot 26081.](image)

The interval between contours is 33. The plot indicates that the minimum is at or slightly above $P=1$, so $dN/dr$ is either Gaussian, or slightly more peaked than Gaussian. The horizontal axis is half width at 0.1 maximum, which is related to $r_o$.

The source function is inferred by performing a least-squares fit of Equation 4.2 to $dN/dr$ (calculated from the data), using $r_c$, $r_o$, $A_d$ and $P$ as free parameters. The source function is then completely defined through Equation 4.1. Figure 4.6 shows a typical variation of chi-squared with $P$ and a measure of $r_o$. In this sample data (of D-$^3$He protons from shot 26081: $D_2(6)^3He(12)SiO_2[2]$), the minimum of the total chi-squared plot is at or slightly above $P = 1$, indicating that the source is Gaussian or possibly slightly more peaked than...
Gaussian. All of the (statistically sufficient) PCIS data analyzed to date have yielded values of $P$ very close to 1, so all profiles presented here will appear Gaussian.

**Figure 4.7** $dN/dr$ from shot 26081 fitted by a gaussian.

Finally, from the analytic inversion of the fit and the system geometry, the angularly averaged burn profile is produced as a plot of Particles per Volume as a function of Radius from the target chamber center.

**Figure 4.8** Angularly-averaged burn profile of D-³He protons from shot 26081.
The proton yield of the implosion can be calculated from the inferred profile and compared to measurements made by other charged particle diagnostics (e.g. Wedge Range Filter Spectrometers (WRF’s) and Charged Particle Spectrometers (CPS) [10]. Wedge Range spectra of D-\(^3\)He protons from shot 26081 are shown in Figure 4.9. The filters were placed at various ports around the target chamber, so the average value of the D-\(^3\)He proton yield is compared to the yield calculated from PCIS to check the accuracy of the PCIS profile calculated.

![Graphs showing proton yield](image1)

![Graphs showing proton yield](image2)

**Figure 4.9** D-\(^3\)He yield from several Wedge Range Filter Spectrometers for shot 26081.

For shot 26081, the average D-\(^3\)He proton yield found from WRF’s was \(3.3 \times 10^{10}\). From PCIS, the yield was found to be \(2.9 \times 10^{10}\). In this case, PCIS shows fairly good agreement with WRF values. Typically, PCIS yields tend to be lower than WRF values by a factor of 2. This will be given further consideration in Chapter 5.
5. Diagnostic Issues

A variety of interrelated factors play into the quality of PCIS data and much attention has been given to finding an appropriate balance between these factors to get the best possible data. Over the series of implosions for which PCIS ran, many system parameters have been tested to determine the optimal conditions and to examine the diagnostic's range of applicability.

Image statistics are probably the most significant factor in producing valuable results. PCIS analysis requires the image to be created by a statistically significant number of particles so that the penumbra is clearly defined. The number of particles produced by an implosion can be controlled somewhat by tweaking implosion conditions (such as laser energy and pulse shape), but overall the statistics will be determined by the type of capsule. PCIS has mainly been used for thin glass shell and thick plastic shell D-^3^He capsules, and each of these represents an extreme associated with appropriate particle yields. Thick-shell capsule implosions typically have D-^3^He proton yields on the order of 10^9, which would result in a track density of about 50-100 tracks per frame in the image umbra with the highest PCIS magnification. While this is about the maximum number of particles that the scan system can resolve (assuming a standard etch time), the statistics are rarely high enough to determine the structure of the penumbra, and the yield is usually lower. In addition, D-D protons can only escape at shock time, so the D-D burn region is even more difficult to image. On the other hand, for thin-shell capsule implosions, both D-^3^He and D-D protons can escape during shock time and bang time. Thus, the proton yield from thin-shelled capsules is much higher than that of thick-shelled capsules, and instead of being starved for counts, there are too many for the spatial resolution of the CR-39.

Chapter 6 will concentrate on experimental results of the thin and thick shell cases, but before getting into that, it is wise to discuss issues associated with imaging each type of
implosion. First, we will discuss the issues associated with the actual experiment, and then follow with issues relating to our ability to extract and analyze the data. It is important to remember that all of these issues are closely connected; and thus the optimization of PCIS is a complicated task. The concerns presented here are merely a few of the more critical issues that influence the quality of PCIS data. Many other topics are yet to be addressed.

5.1. Issues related to experimental conditions

Before addressing the implications of excessively high or low yield implosions, the impact of the system's physical parameters should be mentioned. Since the PCIS design is relatively simple, these parameters center on the pinholes, the CR-39 filter packs, and the distances between these components.

5.1.1. Pinhole Conditions

The most obvious question regarding the pinholes is what diameter should be used for PCIS. Clearly, the diameter of the pinhole affects the size of the image produced, so in order to decide upon an appropriate pinhole diameter, we must address any constraints on the actual image size. On one hand, an image must be at least big enough to resolve the penumbral structure on the CR-39. If the pinhole is too small, the penumbral area will be too small to distinguish from the rest of the image and more sensitive to noise. The statistics are better for larger pinholes, because the circumference over which the penumbra is angularly averaged increases. On the other hand, a large image also has drawbacks. For one thing, it requires greater precision in the system alignment to ensure that the entire image fits onto the detector. Second, the area of the image affects the duration of the scan, which is not entirely trivial. Aside from inefficiency of long scan times, several difficulties arise in the scanning process, and large scan areas are typically more susceptible to these problems. But this will be discussed in the next section. At present, the pinhole diameter must be chosen to compromise between these opposing constraints. Most frequently, PCIS has run with pinholes of 600 μm-diameter or greater.
In early experiments, the diagnostic ran with smaller pinholes (e.g. 82, 162, 325 μm), but these were found to produce images too small to resolve any structure in the penumbra and 600 μm was deemed large enough to make out the shape of the penumbra, but small enough to minimize current limitations associated with having a very large image.

![Image](image0.png)

**Figure 5.1 Example images resulting from a small diameter pinhole and low magnification.**

(a) D-²He proton image and contour plot from shot 25635: D₂(6)³He(12)CH[20] with pinhole diameter 166 μm and an 8x magnification. The contour plot shows that the penumbra is not very circular. (b) D-²He proton image and contour plot from shot 25634: D₂(6)³He(12)CH[20] with pinhole diameter 1000 μm and an 8x magnification. The image was too large for the detector.

Pinhole flaws may also have an impact on the quality of the data. Imperfections in the rim of the pinhole, taper of the hole drilled, circularity and diameter of the pinhole can all affect the spatial distribution of the particles allowed to pass through the aperture, therefore impeding our ability to determine the source shape. Each pinhole is inspected under a microscope before it is installed, and the diameter is measured on both sides of the substrate. The diameters measured on each side are within 5 μm of each other, and in
the case of substrates with multiple pinholes, typically each of the pinholes is within 5
μm diameter of the others. This is well within the tolerances of our ability to resolve the
image.

Debris on the edge of the pinhole could also potentially ruin the image. The pinholes
occasionally have imperfections or dirt on the rim. Before shots, they are cleaned in an
ultrasonic acetone bath to remove as much debris as possible. The pinholes used have no
imperfections greater than \( \sim 10 \) μm wide. To test the effect of debris, Johan Frenje and
Shinya Kurebayashi (both of the MIT Plasma Science and Fusion Center) created an
algorithm that statistically simulates proton images of specified system parameters and
imperfections on the pinhole rim. Basically, it shows that imperfections on the order of
those seen on the pinholes are too small to show up in images produced from the yields
expected.

29836: \( D_2(6)He(12)CH[20] \)

(a) (b) (c)

Figure 5.2 Demonstration of pinhole debris' effect on imaging.

(a) Actual \( D_2^3He \) proton image of shot 29836, showing a flaw on the top left of the
penumbra. (b) Microscope image of the ID side of the pinhole used for this shot, pre-
shot. (c) Microscope image of the ID side of the pinhole, post-shot, showing some debris
on the top left of the rim.

Figure 5.2(a) shows the image produced from the \( D_2^3He \) burn of shot 29836, an
implosion of a \( D_2^3He \) capsule with a 20 μm CH shell. A defect can be seen on the top
left portion of the penumbra, which also appears in the corresponding D-D image, as well
as rescans of this image. Microscope pictures of the pinhole used, taken before and after
the shot, were inspected in hopes of determining the reason for this defect (Figures 5.2(b) and 5.2(c), respectively). While the pinhole looks clean pre-shot, the post-shot image shows some debris in the location of the defect and also on the left-most edge. A simulation was run with debris roughly the size of what appears on the pinhole, but the simulated image did not clearly exhibit the effects of this debris. However, because the pinhole was clean before the shot, and it is seen that the condition of the rim changed during the experiment, it is possible that the debris deposited on the rim was larger at the burn time, causing the defect in the proton image. Further studies are necessary to diagnose the reasons for these changes in pinhole condition throughout the implosions.

5.1.2. System Magnification

Due to its effect on image size, the system magnification requires consideration similar to that of pinhole size. As explained in section 5.1.1, a balance must be struck to produce an image that is large enough for good statistics and spatial resolution, but not so large as to cause alignment or scanning problems. Subsequent to tests of several possible system magnifications, and a switch to the larger of two standard sizes of CR-39, PCIS is typically run at magnification of 10 or 11 times the source size (with 11 being the maximum possible magnification with the current system geometry).

25612: D₂(6)³He(12)CH[20]

(a) (b)

Figure 5.3 A scan image and contour plot of D⁻³He protons from shot 25612. The images shown were produced with a 600 µm pinhole at 3x magnification. The contour plot shows that the image was too small to properly resolve the penumbra.
5.1.3. Effects of Ranging Filters

As mentioned in Chapter 4, the filter thicknesses in front of the detectors are chosen so that particles of a certain energy are ranged down to within the sensitivity of the CR-39. Because of this sensitivity limit, appropriate filter thicknesses are critical for detecting the entire distribution of particles. If the wrong filter thickness is chosen, some (or all) of the particles meant to be imaged may not fall within the sensitivity window, and the PCIS data will provide an inaccurate proton yield. Since the filtering affects the particles’ incident energy on the CR-39, it also affects the diameter of the tracks, playing into issues of the scan system’s ability to detect particles (see section 5.2).

Similarly, the filters must be chosen to keep charged particles that may interfere with the image off the CR-39 altogether. For instance, one difficulty is ranging out protons that are ablated off the capsule without ranging out the D-D protons. Ablator protons usually have energies of about 1MeV, which is inconveniently close to the energy of the D-D protons (3 MeV). Also, if full laser energy (23 kJ) is used to irradiate a thin shell capsule, the fusion reaction products can be accelerated, since the laser is still on during bang time [12].

In early experiments, the filtering was such that D-D protons were ranged out before reaching the CR-39. The side of Detector A facing away from the target chamber center was scanned in attempts to make another image of the D-3He protons, but it was decided that this was too difficult and it would be more useful to use Detector A for imaging D-D protons.

There were also a few attempts at using several layers of thin CR-39 as the entire filter pack to detect a wider range of particle energies, but the thin CR-39 was too difficult to scan, and this was deemed too complicated for the current state of the project.
5.1.4. Treating Yield Issues

Two options have already been investigated to improve upon the statistics of implosions with insufficient track densities. Both options work by essentially adding images together. One option is to image more than one implosion of the same type onto a single piece of CR-39 and the other involves overlaying several pinhole images from the same implosion.

First attempts at integrating an image over several like implosions utilized the same filter pack for all implosions, but different pinhole apertures (of the same diameter). The apertures were switched (and usually used only once) because they become slightly scorched during the implosion and because of the previously discussed concerns about debris. Unfortunately, switching the apertures requires retracting and realigning the diagnostic port, which may not be exactly the same each time and the pinholes also may not line up perfectly. In a particular integration over 5 implosions where the apertures were switched between shots, the images of each shot did not overlay well, and the resulting total image exhibits a smeared penumbra and is unusable for determining a source profile.

(a)  
(b)

![Images](image_url)

Figure 5.4 Integration of shots 26625,26,30,31,32.

The images are D-\(^3\)He protons integrated over five CH/CHTi layered shell capsules (see Appendix B for specific details of these shots). The 600 \(\mu\)m pinholes were changed between each shot. The images from each shot did not overlaid properly, so the penumbra appears smeared.
In later attempts at integration, the entire PCIS assembly was kept in place for integration of only 2 or 3 shots and this resulted in a cleaner total image. Images made from 2 or 3 integrated shots have sufficiently defined penumbras and source profiles have been inferred from these integrations.

![Figure 5.5 Improved integration of shots 28915, 16, 18. Scan image and contour plot of D-3He protons integrated over three D2(6)3He(12)CH[20] implosions. There are two 600 μm pinholes and three 500 μm pinholes. For this integration, the entire PCIS set up was left in place. Pinhole images are much clearer than previous integrations.](image)

Summing several images of the same implosion avoids the problems associated with integrating implosions. To sum theoretically identical images, apertures with up to 5 pinholes in the substrate were manufactured. The analysis program was updated so that the images could be superimposed creating an image that contains all tracks from the separate images. In addition to improved statistics, another benefit to this method is that if any area of the scan is spoiled, hopefully at least one of the images will be clean. But, again, summing images in this manner requires a larger scan area with greater possibility of scan problems and this also introduces greater error related to the issue of locating the center of each image, as previously noted. Now the penumbra may be spread not only by an off-center average, but also if the superimposed images are not perfectly aligned. To account for this, each pinhole image is inspected individually. Pinholes that seem inconsistent or corrupted are rejected, and results of summed images are compared to the
results of a single image. Of course, the more clearly defined an image is (i.e. higher statistics), the greater the confidence in the summation. Typically, the variation between not summing any images, summing a few or summing all images results in source profile 1/e radii differing by ~5 μm, which is comparable to the disparity of the radii based on the uncertainty of choosing threshold parameters on the scan image.

27808: D<sub>2</sub>(6)³He(12)CH[20]

![Images of 1 to 4 pinholes with corresponding N(r) and dN/dr plots]

**Figure 5.6 Demonstration of summing several pinholes from shot 27808.**

This series of images shows the effects of summing pinhole images. The statistics of the N(r) plots improve with each added pinhole, defining the penumbral region more clearly in the dN/dr plots. These pinholes are 600μm in diameter.

For thin-shell capsules where the yield is very high, difficulty lies in the spatial resolution of the CR-39. Though an image made up of a high number of particles is desirable, if the track density is too high, the tracks will overlap on the CR-39 and the scan system will
not recognize each track. In the case of shot 26081: \( \text{D}_2(6)^3\text{He}(12)\text{SiO}_2[2] \), the D-D proton yield was \(~2 \times 10^{10}\) , resulting in a density of approximately 1600 tracks per frame in the umbra region on the detector. Figure 5.7 shows that due to this overlap many particles could not be counted by the scan system and only the less dense outer edge of the penumbra could be made out.

To accommodate this high track density, the CR-39 was etched for a shorter time than usual. Since the track diameters increase in linear proportion to the etch time, shortening the time produces smaller area tracks, meaning that more tracks fit into a given area without overlap. At present, the compromise for fitting more tracks in an area is that smaller tracks are harder to distinguish from background noise. This is because they have less contrast from the background area, and less clearly defined diameter and eccentricity. The scan system’s sensitivity to track diameter, eccentricity and contrast leads us to a discussion of the issues associated with the scanning process and our ability to correctly extract the data from the detector.

26081: \( \text{D}_2(6)^3\text{He}(12)\text{SiO}_2[2] \)

![Figure 5.7](image.png)

Figure 5.7 Track saturation on CR-39 from D-D protons of shot 26081.

For this shot, the hit density was so high that the protons tracks overlapped on the CR-39. Because the microscope system sees this as a large blotch, fewer proper circular tracks are detected in the umbra area of the pinhole. On the right is a horizontal slice of the intensity along the center of the image. There is no way to tell how wide the penumbra of this image actually is.
5.2. Issues related to extracting data

The ability to successfully image burn regions is strongly linked to scanning capability. It is not only a matter of having the appropriate particles hit the detector, but also one of extracting the information from the CR-39 detector. Since it is a spatial detector, any extraneous particles that come into contact with the surface of the CR-39 could potentially interfere with the data. The nuances of the scanning process are very closely entwined with one another, so attention must be paid to all aspects that may cause problems. For a more extensive discussion on this topic see the paper by F. H. Séguin on spectrometry of charged particles from ICF plasmas [10].

Maintaining a consistent microscope focus throughout PCIS scans is probably the greatest obstacle in extracting PCIS data. The difficulty in maintaining a focus is that the sheets of CR-39 are usually not flat. Their shape may even change over time depending on the surface they are resting on, how they have been etched or even as a result of ambient temperature changes. This means that the microscope focus constantly needs adjusting throughout the scan. With such large scan areas, the duration of the scan is too long for manual focusing to be practical. The current scan system uses a computer-based system for interpolating the appropriate focus across the scan. However, this system cannot perfectly maintain a focus on the CR-39 and frequently results in a variation of focus depending on the direction at which the CR-39 is traversed. Because contrast and borders of the tracks (with respect to the background area) are very sensitive to the focus of the microscope, if the focus varies across the scan, some particles may fall within the limits in some areas and be excluded elsewhere. The outcome is often a scan that exhibits a banding effect in the horizontal direction, rendering the scan unusable.

Of course, the contrast of the particles depends on their incident energy (referring back to the filtering issue) and also the length of the etch time. When etching less than the standard 6 hours is necessary (i.e. when the track density is high), the tracks are smaller.
Smaller tracks tend to have less contrast and less well defined eccentricity, thus affecting the microscope system’s ability to detect the particles.

![Figure 5.8 Scan images exhibiting banding due to focus inaccuracies.](image)

(a) D-\(^3\)He protons from shot 29830: \(D_2(6)^3\)He(12)SiO\(_2\)[2]. (b) D-D protons from shot 27806:D\(_2(6)^3\)He(12)CH\(_2\)[2]. Due to borderline sensitivity of small tracks, these scans have inconsistent track densities across the scan image. Because the densities are not continuous, these scans cannot be used to measure the implosion burn regions.

Additionally, scratches can render scans unusable. On occasion, the CR-39 may experience some surface damage that will appear in the scan image. If these scratches interfere with the pinhole images, they may result in false counts in the penumbra region, and distort the angularly averaged shape of the penumbra. Some correction for scratching is possible. If a scratch or other imperfection is highly localized, the data from that area of the scan can be interpolated or replaced by data from an area that should have similar track counts.

Improvements to the scanning technique will greatly advance PCIS data. Currently, tests for implementing a laser-based auto-focus scan system and a high-resolution camera are underway. Once these new systems are ready to use, there should be fewer problems with inconsistent focus and banding on PCIS scan images and smaller tracks will be made countable. Trial scans of the laser-based system have already demonstrated promise in eliminating focus problems and counting tracks more consistently, but some kinks still need to be worked out. Analysis of several shots based on auto-focus scans can be found in Appendix C (e.g shots 29830, 30956 and 30977).
6. Experimental Results

So far, PCIS data have been taken for a total of 75 OMEGA implosions, testing its applicability to a variety of capsule types. This involved extensive experiments on D$_2$-$^3$He- filled capsules, as well as a few attempts at D$_2$-filled capsules. The diversity of implosion type is due to the fact that many of these PCIS experiments were piggybacked onto other OMEGA experiments when a diagnostic port was available. The D$_2$ implosions were determined to have yields too low for sufficient image statistics and were not scanned. D$_2$-$^3$He capsules with 2 $\mu$m SiO$_2$ glass shells; 20 $\mu$m, 24 $\mu$m and 27 $\mu$m-thick CH plastic shells and CH/CHTi layered shells were tested. The capsules with layered shells and CH shells thicker than 20 $\mu$m were found to be too thick to allow enough particles out for adequate statistics, and no source profile could be deconvolved from any of these data. More information about each of the shots is given in Appendices B and C. The results presented here focus on summarizing the results of 2 $\mu$m SiO$_2$ glass-shell and the 20 $\mu$m CH-shell implosions.

6.1. Results From D$_2$(6)$^3$He(12)CH[20] Capsule Implosions

The case of thick-shelled 18 atm D$^3$He-filled capsules is interesting because these capsules can attain such high shell areal density ($\rho R$) that only the higher energy D-$^3$He protons can escape at bang time. At the time of first shock coalescence, the $\rho R$ is relatively low and both D-D and D-$^3$He protons can escape, but a few hundred picoseconds later at bang time the $\rho R$ is much higher and the lower energy D-D protons cannot escape. Because of this dependence on energy, it is interesting to compare the D-D and D-$^3$He burn regions, since the D-D image is created from particles escaping only at shock time, while the D-$^3$He image is created from particles escaping during both shock and bang.
\[ D_2(6) \!^3\text{He}(12)\text{CH}[20] \]

**Shock Time**

\[ p(3.0\text{MeV}) \]

\[ p(14.7\text{MeV}) \]

**Bang Time**

\[ p(14.7\text{MeV}) \]

\[ D + D \rightarrow T[1.0\text{ MeV}] + p[3.0\text{ MeV}] \]

\[ D + ^3\text{He} \rightarrow \alpha[3.6\text{ MeV}] + p[14.7\text{ MeV}] \]

**Figure 6.1** Cartoon of a 20\(\mu\)m CH shell, \(D_2-^3\text{He}\)-filled capsule implosion.

D-D protons and D-\(^3\text{He}\) protons both escape at shock time, but only the D-\(^3\text{He}\) protons escape at bang time. Separate images of the D-D protons at shock time and D-\(^3\text{He}\) protons at bang time would be valuable for studying capsule evolution throughout the implosion.

Because the D-D protons have low energy and a more limited escape time, the existing D-D images do not have sufficient statistics for accurately inferring a source profile. Previously, D-D profiles were inferred using a more primitive version of the analysis program, but these measurements were not reproducible once improvements to the center-finding algorithm and the addition of chi-squared fits have been made. For this reason, no D-D burn profiles for 20\(\mu\)m-shell capsules will be reported at this time. Further improvements in the analysis technique will lead to a more in depth investigation of the comparison between the burn profiles at shock and bang times.

Regardless, the high \(\rho R\) of the thick shells does not so severely restrict the more energetic D-\(^3\text{He}\) protons and these are much easier to image. Figure 6.2 shows the radius of the D-\(^3\text{He}\) burn region at 1/\(e\) of the gaussian peak value for several implosions. For integrated shots the value given represents an average source profile created from the shots.
Inferred source profiles for 20 µm CH-shell capsules had an average value of about 35 µm.

Figure 6.2 Summary of 1/e radii for all inferred D³He burn profiles of thick-shell capsules.

These measurements have an average radius of 35µm (indicated by the solid line), and a statistical sigma of roughly 3 µm (shown with dashed lines). The measurements for shots 30956 and 30977 denoted by a triangle represent a second simultaneous orthogonal image produced by an additional PCIS assembly.

In the most recent set of experiments, a second, newly fabricated PCIS assembly was installed to test simultaneous orthogonal imaging from two systems for the purpose of studying specific three dimensional structure in the burn region. While the original assembly is referred to as PCIS P (denoting the prototype), the newly designed assembly is referred to as PCIS 1. Although the two assemblies are not yet capable of deciphering angular structure, in the mean time, the two assemblies will be useful for testing the consistency of the burn. Shots 30956 and 30977 employed both PCIS assemblies and the burn region measurements are shown in Figure 6.3. The measurements of the 1/e radii from PCIS P and PCIS 1 agree within 4 µm, which is on the order of the error due to uncertainty in analysis parameters. However, it is plausible that a discrepancy of this scale is due to actual asymmetries in the burn region. A comparison of results between PCIS P and PCIS 1 is shown in Table 6.1. The proton yield as measured by PCIS is
compared to measurements made WRF spectrometers. A comparison between yield measurements is important because it gives an indication of whether PCIS has detected all of the protons. Typically, the value determined by PCIS data is roughly a factor of 2 lower than that of WRF data (Figure 6.3), which may be attributable to filtering and scanning issues. However, we have typically seen variations in WRF measurements of 15% due to angular variations in the target chamber.

![Graph 1] Shot 30956: D^3He Protons

![Graph 2] Shot 30977: D^3He Protons

Figure 6.3 Burn profiles from orthogonal 20μm-shell shots 30956 and 30977.

Profiles from the two PCIS assemblies agree to within the errors of the measurements. The 1/e radii differ by 4 μm for shot 30956 and by 2mm for shot 30977. Despite the fact that these measurements are within errors, there may actually be asymmetries in the burn regions.
Table 6.1 Comparison between PCIS P and PCIS 1 for shots 30956 and 30977.

D-^3^He protons yields measured by PCIS P and PCIS 1 are compared to the average D-^3^He proton yield of all available WRF measurements. PCIS 1 yields are lower than those from PCIS P, and both PCIS measurements are nearly a factor of 3 lower than the WRF value for shot 30977.

<table>
<thead>
<tr>
<th></th>
<th>Y_{D^3He} (WRF)</th>
<th>r(1/e) (PCIS)</th>
<th>Y_{D^3He} (PCIS)</th>
<th>r(1/e) (PCIS)</th>
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</thead>
<tbody>
<tr>
<td>30956</td>
<td>7.5 [x10^8]</td>
<td>34 [µm]</td>
<td>3.4 [x10^8]</td>
<td>30 [µm]</td>
</tr>
<tr>
<td>30977</td>
<td>15.0 [x10^8]</td>
<td>31 [µm]</td>
<td>5.8 [x10^8]</td>
<td>33 [µm]</td>
</tr>
</tbody>
</table>

Figure 6.3 Comparison of D-^3^He proton yields calculated from PCIS and from WRFs.

Typically, yields measured by PCIS are a factor of 2 lower than the values given by WRFs. This may indicate that PCIS is not detecting all protons that hit the detector. Yield measurements of integrated shots are normalized to correspond to an average yield of the shots included in the integration.
6.2. Results From $D_2(6)^3$He(12)SiO$_2[2]$ Capsule Implosions

Only a few thin shelled-capsule implosions have been imaged thus far. But assuming that the CR-39 doesn’t become saturated, the statistics are considerably better than for 20μm shelled-capsules. The penumbras are much more distinct so even the D-D burn profiles can be inferred. Also, because this type of capsule has a lower $\rho R$ than thick plastic-shelled capsules, both D-D and D-$^3$He protons break out at bang time (Figure 6.4). Separate images of the D-D and D-$^3$He burn regions at bang time are valuable, because they can be used to infer radial profiles of the ion temperature [$T_i(r)$] as well. Since the theoretical rates for these reactions vary with ion temperature, a yield-averaged fuel ion temperature can be estimated by comparing the ratio of the reaction yields to the ratio of their rates. This type of measurement has been done with CPS measurements of D-$^3$He plasmas [13].

$$D_2(6)^3$He(12)SiO$_2[2]$$

**Bang Time**

$\rho (3.0 \text{MeV})$  
$\rho (14.7 \text{MeV})$

$$D + D \rightarrow T[1.0 \text{ MeV}] + p[3.0 \text{ MeV}]$$  
$$D + ^3\text{He} \rightarrow \alpha[3.6 \text{ MeV}] + p[14.7 \text{ MeV}]$$

**Figure 6.4 Cartoon of a 2 μm SiO$_2$ shell, D-$^3$He-filled capsule implosion.**

Since D-D and D-3He protons both escape at bang time, and statistics are good, simultaneous images of these species can be used infer burn profiles. Along with information about the rates of reaction, these profiles can be used to infer a radial temperature profile of the burn region.

Shot 29827 will be used to demonstrate the method for inferring a radial profile of the ion temperature. Figure 6.5 shows the D-D and D-$^3$He burn profiles from this implosion.
The 1/e radii of these profiles are 82 μm and 56 μm, respectively. It is interesting to note that the D-^3He burn region for the thin shell capsule is wider than that of the 20 μm shell capsules (~35 μm).

Now from the two burn profiles, a ratio is taken of the D-D proton yield to the D-^3He proton yield as a function of the radius. From the relation shown in Figure 6.6(a), a profile of the ion temperature is inferred. However, since the yields measured from PCIS are typically lower than those measured from better established diagnostics (e.g. WRF’s, CPS), the PCIS burn profiles are normalized to the yields as measured by wedge range filter spectrometers (for D-^3He protons) and neutron time of flight measurements (for D-D protons).

![Figure 6.5 Burn Profiles from shot 29827.](image)

These are un-normalized profiles. The D-D proton profile has a 1/e radius of 82 μm, whereas the D-^3He profile is narrower, with a 1/e profile of 56 μm.

Once this ion temperature profile is calculated, a yield-weighted average value can be found for both particle distributions. In this case, the average D-D proton temperature was determined to be about 7 keV and the average D-^3He proton temperature was
determined to be about 8 keV. Ion temperature estimates can also be made from neutron time of flight measurements (for the D-D proton temperature) and from the Doppler width of WRF spectra (for the D-³He proton temperature) [10]. Time of flight measurements and WRF data for this shot both give ion temperatures of 7 keV.

![Graphs](image)

Figure 6.6 Yield ratio vs. ion temperature and inferred Ti from 29827 burn profiles.
(a) The ratio of D-D proton yield to D-³He proton yields as a function of ion temperature (from rate coefficients). (b) The D-D and D-³He proton burn profiles inferred from PCIS and the ion temperature profile inferred from the burn profiles and the yield ratio plot. The ion temperature plot was created by determining the yield ratio at each point along the radius and finding the ion temperature for that ratio in plot (a).

Tables 6.2 and 6.3 show the summary of data from thin-shelled capsule implosions for D-D and D-³He protons, respectively. Shot 26081 was a case of extremely high track density in the image due to a high an irradiation of full laser energy (23 kJ). It was the first attempt at imaging an implosion of a 2 µm glass-shell capsule, and as a result Detector A was not filtered properly to detect D-D protons. The larger D-³He 1/e radius may also be due to some overlap problems with this data. Subsequent thin-shelled capsules were irradiated with laser energies in the range of 5-10 kJ. Both D-D and D-³He
profiles were inferred from shots 27456, 29827 and 29828. Since shots 29827 and 29828 were sequential, the experimental conditions for these two shots were very similar, so it is encouraging that the results from these shots are also similar to each other. Additionally, the yields and average ion temperatures as calculated by PCIS data are relatively close to those calculated by other diagnostics. It should be noted that the PCIS yields expressed in Tables 6.2 and 6.3 are the values determined directly from the PCIS data before any weighting to other diagnostics.

### D-D Protons

<table>
<thead>
<tr>
<th>r(1/e) [μm]</th>
<th>Y_{DD} (PCIS) [x10^{16}]</th>
<th>Y_{DD} (NTOF) [x10^{16}]</th>
<th>&lt;T_{e}^{&gt;DD} (PCIS) [keV]</th>
<th>&lt;T_{e}^{&gt;DD} (NTOF) [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>26081</td>
<td>3.6</td>
<td>-</td>
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<td>29828</td>
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Table 6.2 Summary of D-D results from 2μm-shell implosions.

### D-3He Protons

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<th>r(1/e) [μm]</th>
<th>Y_{D3He} (PCIS) [x10^{16}]</th>
<th>Y_{D3He} (WRF) [x10^{16}]</th>
<th>&lt;T_{e}^{&gt;D3He} (PCIS) [keV]</th>
<th>&lt;T_{e}^{&gt;D3He} (WRF) [keV]</th>
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<td>0.4</td>
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Table 6.3 Summary of D-3He results from 2μm-shell implosions.
7. Conclusions and Future Work

Even in the developmental stages of the diagnostic, PCIS data is already an important contribution to the limited information that presently exists about the fusion burn region. With this new diagnostic, D-D and D-\(^3\)He proton burn regions of 18 atm D\(_2\)-\(^3\)He capsule OMEGA implosions were measured directly for the first time.

From these first measurements, it was determined that the fusion burn regions were shaped more like Gaussian distributions than like uniform distributions (or anything in between) and subsequently estimates were made for the size of these distributions where possible. For the case of 20 \(\mu\)m CH-shell capsule implosions no measurements of D-D proton burn profiles have yet been reported, but the corresponding D-\(^3\)He proton burn regions were found to have an average 1/e radius of about 35 \(\mu\)m. For the case of 2 \(\mu\)m SiO\(_2\)-shell capsule implosions, D-D and D-\(^3\)He proton profiles were determined. The data showed an average 1/e of 94 \(\mu\)m for the D-D proton burn region and 60 \(\mu\)m for the D-\(^3\)He proton burn region.

These measurements are just the initial stages of an ongoing project. Many questions still remain and further studies must be conducted to establish the ability of PCIS to diagnose OMEGA implosions.

Improvements to the scanning process are continually being made, as this pertains to CPS and WRF spectrometers as well. Efforts are being made to improve confidence that the appropriate particles are being detected. Most recently, testing has begun to institute the use of a laser auto-focus system and high-resolution digital camera for the scanning microscope to ameliorate the scan consistency and time issues that often complicate PCIS scans now.
## Appendix A: PCIS Data Summary Table

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<th>mag</th>
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In addition to scanning system developments, future experiments will include further tests of optimal PCIS set-up parameters. More imaging will be done with large pinhole apertures (e.g. 1000 µm and 2000 µm), since only a few of these have been used so far despite the fact that large pinhole data generally has better statistics. This should be a more desirable option once the scanning system is able to handle the large scan area and high number of counts associated with large pinholes.

Orthogonal imaging of implosions using the 2 PCIS assemblies will be utilized whenever possible. As the diagnostic evolves and the images become more accurate, angular averaging of penumbral regions will be phased out and the orthogonal imaging will be used to study three-dimensional structure of the burn regions. Experiments will involve imposing asymmetries in the burn region with non-uniform laser irradiation and examining the resulting structure. Algorithms will be developed to treat such asymmetries.

Also, further efforts will be made towards accurately measuring the D-D proton burn region from 20 µm CH-shell capsule implosions. Once these measurements are made, this information will be used along with the D-^3^He proton measurement to study differences in burn between shock time and bang time. This will also include a further investigation into some non-uniform D-D proton images that have been created during certain 2µm shell capsule implosions (see appendix pages 127, 139 and 141).

Finally, comparisons will be studied between PCIS results and 2-D simulations that predict the ion temperature and ion density of the implosions. Additionally, comparisons will be made to neutron and x-ray burn region images.

Obviously, a great deal of work lies ahead. However, new information will be produced with every step of the development and it is important to note the milestone of the first direct measurements of D-^3^He plasma burn regions on OMEGA.
## Appendix A: PCIS Data Summary Table

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<th>WRF Y_{DR}</th>
<th>pinhole diam (μm)</th>
<th>FA (μm)</th>
<th>DA ID</th>
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### Appendix A: PCIS Data Summary Table

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## Appendix A: PCIS Data Summary Table

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Appendix B: PCIS Shot Picture Book

This appendix is a shot by shot catalogue of all present PCIS data. It is meant to be a quick reference to the body of PCIS data. Each detector is assigned a page that includes the capsule type, pinhole diameter and CR-39 ID for that shot, as well as any notes about the shot. If no scan of the CR-39 was done, the rest of the page is left blank. Where scan have been done, the scan image and contour plot after thresholds on the contrast, eccentricity and diameter of the tracks have been set are shown. In addition, these threshold limits are listed, and contour plots of Track Contrast vs. Track Diameter and Track Eccentricity vs. Track Diameter are shown to illustrate how these limits were chosen. Where possible, inferred burn profiles are shown, along with N(r) and dN/dr plots. The inferred profile plots also include the proton yield measured by PCIS and the 1/e radius of the profile. In addition, this plot lists the shape factor, P, of the plot identifying whether it is uniform, gaussian or in between. Except in a few cases, the shape factors are 1, indicating gaussian profiles.
25599: D2(6)3He(12)CH[20]
c63_DB
Pinhole Diameter: 1000μm
Notes: None
25599: D2(6)3He(12)CH[20]
c62_DA
Pinhole Diameter: 1000μm
Notes: Image is from the backside of DA.
25600: $D_2(6)^3He(12) \, CH[20]$

**c67_CB**

Pinhole Diameter: 1000μm

Notes: Accidentally used same pinhole from shot 26599.
25600: $D_2(6)^3He(12)$ CH[20]
c68_DA
Pinhole Diameter: 1000μm
Notes: Same pinhole as from shot 25599. Scan on back side of DA.
25601,03,05: \text{D}_2(15) \text{ CH}[20]
\text{c70_DB}
Pinhole Diameter: 2000\mu m
Notes: Summed over 3 shots. Yields too low. NO SCAN.

25601,03,05: \text{D}_2(15) \text{ CH}[20]
\text{c69_DA}
Pinhole Diameter: 2000\mu m
Notes: Summed over 3 shots. Yields too low. NO SCAN.

25610: \text{D}_2(6)^3\text{He}(12) \text{ CH}[20]
* \text{Ernie}
Pinhole Diameter: 600\mu m
Notes: Tried special filter pack, which consisted of 3\mu m Al, a normal Bert and 7 thin layers of CR-39. 3x magnification. Thin pieces were too difficult to scan. NO SCAN.

25610: \text{D}_2(6)^3\text{He}(12) \text{ CH}[20]
\text{c72_DA}
Pinhole Diameter: 600\mu m
Notes: 3x magnification. Image too small. NO SCAN.
25612: $D_2(6)^3He(12)$ CH[20]
c73_DB
Pinhole Diameter: 600μm
Notes: Very small image (3x) with 184μm CR-39 3rd layer. Low Yield.

25612: $D_2(6)^3He(12)$ CH[20]
c74_DA
Pinhole Diameter: 600μm
Notes: Low Yield and very small image (3x). NO SCAN.
25614: $D_2(6)^3He(12)\ CH[24]$

$c78\_DB$
Pinhole Diameter: 1000\(\mu m\)
Notes: 3x magnification. Yield too low because of 24\(\mu m\) CH shell. NO SCAN.

25614: $D_2(6)^3He(12)\ CH[20]$

$c80\_DA$
Pinhole Diameter: 1000\(\mu m\)
Notes: 3x magnification. Yield too low because of 24\(\mu m\) CH shell. NO SCAN.
25634: D$_2$(6)$^3$He(12) CH[20]
c81_DB
Pinhole Diameter: 1000µm
Notes: Misaligned. Image goes off the CR-39.

\[ 0.00 \leq c \leq 60.00 \]
\[ 0.00 \leq e \leq 50.00 \]
\[ 0.17 \leq d \leq 21.00 \]

25634: D$_2$(6)$^3$He(12) CH[20]
c82_DA
Pinhole Diameter: 1000µm
Notes: Misaligned. Image goes off the CR-39. NO SCAN.
25635: $D_2(6)^3He(12) \text{CH}[20]$

c61_DB

Pinhole Diameter: 166µm

Notes: 8x magnification and 166µm result in very small image. Can’t determine burn profile. [Several rescans done to test focus consistency, not shown here.]

\[
\begin{align*}
0.00 & \leq c & \leq 45.00 \\
0.00 & \leq e & \leq 40.00 \\
0.17 & \leq d & \leq 20.00
\end{align*}
\]

25635: $D_2(6)^3He(12) \text{CH}[20]$

c64_DA

Pinhole Diameter: 166µm

Notes: Image too small because of small pinhole diameter. NO SCAN.
25636: D₂(6)³He(12) CH[24]
c86_DB
Pinhole Diameter: 1000μm
Notes: 8x magnification and 24μm CH shell. Banding in the image. Can’t determine burn region.

25636: D₂(6)³He(12) CH[24]
c88_DA
Pinhole Diameter: 1000μm
Notes: Image too small because of small pinhole diameter. NO SCAN.
25637: $\text{D}_2(6)^3\text{He}(12) \text{ CH}[24]$

c90_DB
Pinhole Diameter: 2000\,\mu m
Notes: Yield too low for 24\,\mu m CH shell. NO SCAN.

25637: $\text{D}_2(6)^3\text{He}(12) \text{ CH}[24]$

c91_DA
Pinhole Diameter: 2000\,\mu m
Notes: Yield too low for 24\,\mu m CH shell. NO SCAN.
25664: D$_2$(6)$^3$He(12) CH[20]
c95_DB
Pinhole Diameter: 600µm
Notes: Penumbra not clear enough to fit burn profile. CR-39 may have moved during the scan.
25664: $D_2(6)\textsuperscript{3}He(12)\text{ CH[20]}$

c94_DA

Pinhole Diameter: 600\text{\,\mu m}

Notes: Penumbra not clearly defined. Can’t fit burn profile.
25665: D$_2$(6)$^3$He(12) CH[20]

**c96_DB**

Pinhole Diameter: 82$\mu$m

Notes: Pinhole too small to see structure in image.

---

25665: D$_2$(6)$^3$He(12) CH[20]

**c97_DA**

Pinhole Diameter: 82$\mu$m

Notes: Pinhole too small to see structure in image.
25686: $D_2(8)^3He(16) \text{ CH}[27]$

**c99_DB**

Pinhole Diameter: 1000$\mu$m
Notes: Yield too low. NO SCAN.

25686: $D_2(8)^3He(16) \text{ CH}[27]$

**c100_DA**

Pinhole Diameter: 1000$\mu$m
Notes: Yield too low. NO SCAN.

25687: $D_2(8)^3He(16) \text{ CH}[27]$

**c98_DB**

Pinhole Diameter: 1000$\mu$m
Notes: Yield too low. NO SCAN.

25687: $D_2(8)^3He(16) \text{ CH}[27]$

**c101_DA**

Pinhole Diameter: 1000$\mu$m
Notes: Yield too low. NO SCAN.
25688: $D_2(8)^3He(16) \text{ CH}[27]$
c103_DB
Pinhole Diameter: 1000µm
Notes: Yield too low. No image visible.

25688: $D_2(8)^3He(16) \text{ CH}[27]$
c104_DA
Pinhole Diameter: 1000µm
Notes: Yield too low. NO SCAN.
25697: $D_2(6)^3He(12) \text{ CH}[20]$

c105_DB
Pinhole Diameter: 22μm
Notes: Pinhole too small. NO SCAN.

25697: $D_2(6)^3He(12) \text{ CH}[20]$

c106_DA
Pinhole Diameter: 22μm
Notes: Pinhole too small. NO SCAN.

25698: $D_2(6)^3He(12) \text{ CH}[20]$

c107_DB
Pinhole Diameter: 82μm
Notes: Pinhole too small. NO SCAN.

25698: $D_2(6)^3He(12) \text{ CH}[20]$

c108_DA
Pinhole Diameter: 82μm
Notes: Pinhole too small. NO SCAN.
25708: $D_2(6)\,^3\text{He}(12)\,\text{CH}[20]$

c110_DB
Pinhole Diameter: 163\,\mu m
Notes: Pinhole too small. NO SCAN.

25708: $D_2(6)\,^3\text{He}(12)\,\text{CH}[20]$

c109_DA
Pinhole Diameter: 163\,\mu m
Notes: Pinhole too small. NO SCAN.

25709: $D_2(6)\,^3\text{He}(12)\,\text{CH}[20]$

c112_DB
Pinhole Diameter: 300\,\mu m
Notes: Pinhole too small. NO SCAN.

25709: $D_2(6)\,^3\text{He}(12)\,\text{CH}[20]$

c111_DA
Pinhole Diameter: 300\,\mu m
Notes: Pinhole too small. NO SCAN.
26081: D$_2$(6)$^3$He(12) SiO$_2$[2]

**c134_DB**

Pinhole Diameter: 600µm

Notes: Very high track density.

- $0.00 \leq c \leq 100.00$
- $0.00 \leq e \leq 80.00$
- $0.16 \leq d \leq 6.00$
26081: $\text{D}_2(6)^3\text{He}(12) \text{CH}[20]$

c62_DA

Pinhole Diameter: 1000$\mu$m

Notes: Piece is heavily saturated.
26105: $D_2(6)^3He(12)\ SiO_2[2]$

c195_DB
Pinhole Diameter: 25\(\mu\)m
Notes: Misaligned. NO SCAN.

26105: $D_2(6)^3He(12)\ SiO_2[2]$

c6_DA
Pinhole Diameter: 25\(\mu\)m
Notes: Misaligned. NO SCAN.

26106: $D_2(6)^3He(12)\ SiO_2[2]$

c198_DB
Pinhole Diameter: 25\(\mu\)m
Notes: Misaligned. NO SCAN.

26106: $D_2(6)^3He(12)\ SiO_2[2]$

c13_DA
Pinhole Diameter: 25\(\mu\)m
Notes: Misaligned. NO SCAN.
26157: $D_2(6)^3He(12)\ CH[20]$

**c199_DB**
Pinhole Diameter: 600μm
Notes: Piece was scanned, but the file is corrupted and can't be opened. Not worth rescanning.

26157: $D_2(6)^3He(12)\ CH[20]$

**c17_DA**
Pinhole Diameter: 600μm
Notes: NO SCAN.
26158: D$_2$(6)$^3$He(12) CH[4.8]CHTi[0.4]CH[14.2] c200_DB
Pinhole Diameter: 1000µm
Notes: Scratches and banding problems prevent fitting a burn profile. Track density is too low for a rescan to be worth while.

26158: D$_2$(6)$^3$He(12) CH[4.8]CHTi[0.4]CH[14.2] c22_DA
Pinhole Diameter: 1000µm
Notes: NO SCAN.
26161: \(D_2(6)^3\text{He}(12)\) CH\([5.7]\)CHTi\([0.4]\)CH\([13.3]\)

**c204_DB**

Pinhole Diameter: 4\(\times\)600\(\mu\)m

Notes: First attempt at a pinhole array. Only one pinhole scanned. Low hit density

---

**26161: D_2(6)^3\text{He}(12) CH[5.7]CHTi[0.4]CH[13.3]**

**c31_DA**

Pinhole Diameter: 4\(\times\)600\(\mu\)m

Notes: NO SCAN.
26162: $D_2(6)^3He(12)$ CH[6.6]CHTi[0.4]CH[12.5]  
c205_DB  
Pinhole Diameter: 4×325μm  
Notes: Yield too low with this type of shell. NO SCAN.

26162: $D_2(6)^3He(12)$ CH[6.6]CHTi[0.4]CH[12.5]  
c52_DA  
Pinhole Diameter: 4×325μm  
Notes: Yield too low with this type of shell. NO SCAN.

26167: $D_2(6)^3He(12)$ CH[20]  
c206_DB  
Pinhole Diameter: 4×600μm  
Notes: 5x magnification and low yield. NO SCAN.

26167: $D_2(6)^3He(12)$ CH[20]  
c58_DA  
Pinhole Diameter: 4×600μm  
Notes: 5x magnification and low yield. NO SCAN.
26168: $D_2(6)^3He(12)\ CH[20]$
c210_DB
Pinhole Diameter: 600\mu m
Notes: 5x magnification and low yield. NO SCAN.

26168: $D_2(6)^3He(12)\ CH[20]$
c143_DA
Pinhole Diameter: 600\mu m
Notes: 5x magnification and low yield. NO SCAN.

26624: $D_2(6)^3He(12)\ CH[20]$
b900_DB
Pinhole Diameter: 600\mu m
Notes: Dud Implosion. NO SCAN.

26624: $D_2(6)^3He(12)\ CH[20]$
c144_DA
Pinhole Diameter: 600\mu m
Notes: Dud Implosion. NO SCAN.
26625,26,30,31,32: $D_2(6)^3He(12)\,CH[0.9]CHTi[1]CH[18.3]$  

b905_DB  

Pinhole Diameter: 600$\mu$m  
Notes: Summed over 5 shots. Image looks smeared as if PCIS moved from shot to shot.
26625,26,30,31,32: D$_2$(6$^3$He(12) CH[0.9]CHTi[1]CH[18.3]

**c145_DA**

Pinhole Diameter: 600µm

Notes: Summed over 5 shots. Image looks smeared as if PCIS moved from shot to shot. Focus problems on the bottom of the scan.

\[
\begin{align*}
0.00 &\leq c \leq 100.00 \\
0.00 &\leq e \leq 50.00 \\
0.17 &\leq d \leq 21.00
\end{align*}
\]
**26633: \( \text{D}_2(6)^3\text{He}(12) \text{ CH}[20] \)**

b910_DB

Pinhole Diameter: 4×600μm

Notes: Only one pinhole scanned. Banding and scratches. Image seems misshapen.

\[
\begin{align*}
0.00 \leq c & \leq 100.00 \\
0.00 \leq e & \leq 90.00 \\
0.17 \leq d & \leq 16.00
\end{align*}
\]
26633: D$_2$(6)$^3$He(12) CH[20]
c146_DA
Pinhole Diameter: 4 x 600μm
Notes: Poor statistics.

$0.00 \leq c \leq 100.00$
$0.00 \leq e \leq 50.00$
$0.16 \leq d \leq 15.00$
26634,35,36 $D_2(6)^3He(12)$ CH[4.8]CHTi[0.4]CH[14.3] b914_DB
Pinhole Diameter: 1000μm
Notes: Switched pinhole for each shot.
26634.35.36 D_2(6)^3He(12) CH[4.8]CHTi[0.4]CH[14.3]
c153_DA
Pinhole Diameter: 1000\mu m
Notes: Able to make a rough fit to the profile, with a uniform source shape.
26647: D$_2$(6)$^3$He(12) CH[4.8]CHTi[0.4]CH[13.9]
b915_DB
Pinhole Diameter: 600μm
Notes: None
26647: $D_2(6)^3He(12) \ CH(4.8)|CH\ Ti(0.4)\ CH(13.9)$
c154 DA
Pinhole Diameter: 600µm
Notes: Scratch and banding prevent fitting the burn profile.
26648: D₂(6³He(12) CH[5.7]CHTi[0.4]CH[13.5]

b916_DB

Pinhole Diameter: 4x300μm

Notes: Small pinholes and poor statistics.
26648: $D_2(6)^3He(12)\ CH[5.7]CHTi[0.4]CH[13.5]$ c155_DA
Pinhole Diameter: $4\times300\mu m$
Notes: Scan of backside of DA. Unusual parallel scratches.

\[
0.00 \leq c \leq 100.00
\]
\[
0.00 \leq e \leq 70.00
\]
\[
0.17 \leq d \leq 20.00
\]
26649: $D_2(6)^3He(12)\ CH[6.6]CHTi[0.4]CH[12.4]$ b917_DB
Pinhole Diameter: 4×600μm
Notes: Only one complete pinhole. Unsatisfactory statistics.

\[
0.00 \leq c \leq 40.00 \\
0.00 \leq e \leq 40.00 \\
0.17 \leq d \leq 20.00
\]
26649: $D_2(6)^3He(12) \text{CH}[6.6]\text{CHTi}[0.4]\text{CH}[12.4]$

c156_DA

Pinhole Diameter: $4 \times 600 \mu m$

Notes: Only one complete pinhole. Unsatisfactory statistics.
27456: D₂(6)³He(12) SiO₂[1.8]
bb484_DB
Pinhole Diameter: 4×600µm
Notes:

\[ 0.00 \leq c \leq 100.00 \]
\[ 0.00 \leq e \leq 40.00 \]
\[ 0.08 \leq d \leq 5.00 \]
27456: $D_2(6)^3He(12)SiO_2[1.8]$

**bb485_DA**

Pinhole Diameter: 4x600μm

Notes: Scanned only two pinholes. Rescan of all 4 pinholes was unusable
27488: D_{2}(6)^3He(12) SiO2[2.3]

bb486_DB

Pinhole Diameter: 4x600μm

Notes:

0.00 ≤ c ≤ 20.00
0.00 ≤ e ≤ 37.00
0.17 ≤ d ≤ 17.00
27488: D$_2$(6)$^3$He(12) SiO2[2.3]

bb490_DA

Pinhole Diameter: 4×600μm

Notes: Rings! This indicates some issues with diameter.

\[0.00 \leq c \leq 100.00\]
\[0.00 \leq e \leq 36.00\]
\[0.16 \leq d \leq 21.00\]
27806: $D_2(6)^3He(12)\ CH[20]$

**bb611_DB**

Pinhole Diameter: 500μm +4x600μm

Notes:

\[
0.00 \leq c \leq 100.00 \\
0.00 \leq e \leq 35.00 \\
0.17 \leq d \leq 22.00
\]
27806: $D_2(6)\,^3\text{He}(12)\,\text{CH}[20]$

**bb613_DA**

Pinhole Diameter: 500µm +4×600µm

Notes:

\[
\begin{align*}
0.00 & \leq c \leq 100.00 \\
0.00 & \leq e \leq 35.00 \\
0.16 & \leq d \leq 17.00
\end{align*}
\]
27807: \( \text{D}_2(6)^3\text{He}(12) \text{ CH}[20] \)

**bb618_DB**

Pinhole Diameter: 500\(\mu\)m +4x600\(\mu\)m

Notes:

\[
0.00 \leq c \leq 40.00 \\
0.00 \leq e \leq 40.00 \\
0.17 \leq d \leq 21.00
\]
**27807: D₂(6)³He(12) CH[20]**

**bb644_DA**

Pinhole Diameter: 500μm + 4x600μm

Notes:

\[
0.00 \leq c \leq 45.00 \\
0.00 \leq e \leq 50.00 \\
0.16 \leq d \leq 20.00
\]
27808: D_2(6)^3He(12) CH[20]
bbe621_DB
Pinhole Diameter: 500µm +4x600µm
Notes:

0.00 ≤ c ≤ 65.00
0.00 ≤ e ≤ 50.00
0.16 ≤ d ≤ 21.00
27808: $D_2(6)^3He(12)\ CH[20]$

bb647_DA

Pinhole Diameter: 500$\mu$m +4×600$\mu$m

Notes:

\[
0.00 \leq c \leq 25.00 \\
0.00 \leq e \leq 70.00 \\
0.16 \leq d \leq 18.00
\]
27810: D$_2$(6$^3$He(12) CH[20]

bb624_DB

Pinhole Diameter: 500µm +4×600µm

Notes:

0.00 ≤ c ≤ 25.00

0.00 ≤ e ≤ 40.00

0.17 ≤ d ≤ 20.50
27810: $D_2(6)^3He(12)$ CH[20]

bb649_DA

Pinhole Diameter: 500μm +4×600μm

Notes:

$0.00 \leq c \leq 60.00$

$0.00 \leq e \leq 50.00$

$0.16 \leq d \leq 17.00$
27811,12: $D_2(6)^3He(12)$ CH[20]

bb631_DB

Pinhole Diameter: 500µm +4×600µm

Notes:

\[ 0.00 \leq c \leq 70.00 \]
\[ 0.00 \leq e \leq 40.00 \]
\[ 0.16 \leq d \leq 20.00 \]
27811,12: D$_2$(6)$^{3}$He(12) CH[20]

bb652_DA

Pinhole Diameter: 500μm +4×600μm

Notes:

$$0.00 \leq c \leq 25.00$$
$$0.00 \leq e \leq 30.00$$
$$0.16 \leq d \leq 20.00$$
27814: $D_2(6)^3He(12) SiO_2[2]$

**bb638_DB**

Pinhole Diameter: 500μm +4×600μm

Notes: NO SCAN

---

27814: $D_2(6)^3He(12) SiO_2[2]$

**bb615_DA**

Pinhole Diameter: 500μm +4×600μm

Notes:

\[
0.00 \leq c \leq 70.00 \\
0.00 \leq e \leq 50.00 \\
1.00 \leq d \leq 13.00
\]

---

27814_BB615_bcr1_CPSA (x=0.97, y=0.84) (1000 levels, n=2 smoothing)

27814_BB615_bcr1_CPSA (x=0.97, y=0.84) (1000 levels, n=3 smoothing)
27815: $D_2(6)^3He(12) SiO_2[2]$

bb682_DB
Pinhole Diameter: 500µm +4×600µm
Notes: NO SCAN

27815: $D_2(6)^3He(12) SiO_2[2]$

bb673_DA
Pinhole Diameter: 500µm +4×600µm
Notes:

\[
\begin{align*}
0.00 & \leq c \leq 80.00 \\
0.00 & \leq e \leq 90.00 \\
0.16 & \leq d \leq 15.00
\end{align*}
\]

107
27817: D$_2$(15) SiO$_2$[2]
bb697_DB
Pinhole Diameter: 500µm +4×600µm
Notes: Yield too low. NO SCAN.

27817: D$_2$(15) SiO$_2$[2]
bb523_DA
Pinhole Diameter: 500µm +4×600µm
Notes: Yield too low. NO SCAN.

27819: D$_2$(15) SiO$_2$[2]
bb687_DB
Pinhole Diameter: 500µm +4×600µm
Notes: Yield too low. NO SCAN.

27819: D$_2$(15) SiO$_2$[2]
bb677_DA
Pinhole Diameter: 500µm +4×600µm
Notes: Yield too low. NO SCAN.
27820.21: $D_2(6)^3He(12)\!$ CH[20]

**bb653_DB**

Pinhole Diameter: 500$\mu$m +4×600$\mu$m

Notes:

\begin{align*}
0.00 & \leq c \leq 35.00 \\
0.00 & \leq e \leq 50.00 \\
0.17 & \leq d \leq 21.00 \\
\end{align*}
27820,21: $D_2(6)^3He(12) CH[20]$

bb532_DA

Pinhole Diameter: 500μm +4×600μm

Notes:

$0.00 \leq c \leq 30.00$

$0.00 \leq e \leq 40.00$

$0.16 \leq d \leq 15.00$
28915,16,18: D$_2$(6)$^3$He(12) CH[20]

bb727_DB

Pinhole Diameter: 2×600μm + 3×500μm

Notes:

0.00 ≤ c ≤ 45.00
0.00 ≤ e ≤ 50.00
0.17 ≤ d ≤ 20.00
28915,16,18: $\text{D}_2(6)^3\text{He}(12)\text{CH}[20]$

bb522_DA

Pinhole Diameter: 2×600μm + 3×500μm

Notes:

\[ 0.00 \leq c \leq 100.00 \]
\[ 0.00 \leq e \leq 70.00 \]
\[ 0.16 \leq d \leq 20.00 \]
28925,29,31: D$_2$(6)$^3$He(12) CH[20]

bb728_DB

Pinhole Diameter: 500µm +4×600µm

Notes: alpha501 pulse shape.
28925,29,31: \( \text{D}_2(6)^3\text{He}(12) \text{ CH}[20] \)

**bb524_DA**

Pinhole Diameter: 500\(\mu\)m +4×600\(\mu\)m

Notes: Bert indicates 2 distributions of particles.

\[
\begin{align*}
0.00 & \leq c & \leq 100.00 \\
0.00 & \leq e & \leq 70.00 \\
0.16 & \leq d & \leq 20.00
\end{align*}
\]
28935,36: $D_2(6)\ ^3He(12)\ CH[20]$

bb733_DB

Pinhole Diameter: 500µm + 4x600µm

Notes:

\[
0.00 \leq c \leq 60.00 \\
0.00 \leq e \leq 90.00 \\
0.16 \leq d \leq 16.25
\]

28935,36: $D_2(6)\ ^3He(12)\ CH[20]$

bb531_DA

Pinhole Diameter: 500µm + 4x600µm

Notes: NO SCAN
29827: $D_2(6)^3He(12)$ SiO2 [2.7]

bb772_DB

Pinhole Diameter: 5×600μm

Notes:

\begin{align*}
0.00 \leq c \leq 45.00 \\
0.00 \leq e \leq 60.00 \\
0.05 \leq d \leq 6.00
\end{align*}
29827: $D_2(6)^3He(12)\ SiO_2$ [2.7]

c62_DA

Pinhole Diameter: 5x600µm

Notes:

0.00 ≤ c ≤ 100.00
0.00 ≤ e ≤ 35.00
0.16 ≤ d ≤ 10.00
29828: $D_2(6)^3He(12)$ SiO2 [2.6]

bb773 DB

Pinhole Diameter: 5×600μm

Notes:

\[0.00 \leq c \leq 50.00\]
\[0.00 \leq e \leq 70.00\]
\[0.17 \leq d \leq 4.00\]
29828: D$_2$(6)$^3$He(12) SiO2 [2.6]  
bb544_DA  
Pinhole Diameter: 5×600μm  
Notes: Rings appear when contrast is cut down to 80.

$0.00 \leq c \leq 100.00$  
$0.00 \leq e \leq 40.00$  
$0.16 \leq d \leq 6.00$
29830: $D_2(6)^3He(12)\ SiO2$ [2.7]

**bb786_DB**

Pinhole Diameter: 2000\(\mu\)m

Notes:

\[
0.00 \leq c \leq 100.00 \\
0.00 \leq e \leq 40.00 \\
0.16 \leq d \leq 7.00
\]
29830: $D_2(6)^3He(12)$ SiO2 [2.7]

bb549_DA

Pinhole Diameter: 2000μm

Notes:

$0.00 \leq c \leq 100.00$

$0.00 \leq e \leq 40.00$

$0.16 \leq d \leq 6.00$
29834: \( \text{D}_2(6)^3\text{He}(12) \text{ CH}[20] \)

**bb791_DB**

Pinhole Diameter: 5×600\(\mu\)m

Notes:

\[
0.00 \leq c \leq 15.00
\]

\[
0.00 \leq e \leq 40.00
\]

\[
0.17 \leq d \leq 22.00
\]
29834: D$_2$(6)$^3$He(12) CH[20]
bb571_DA
Pinhole Diameter: 5×600µm
Notes:
29835: D$_2$(6)$^3$He(12) CH[20]

bb796_DB

Pinhole Diameter: 5×600μm

Notes:

0.00 ≤ c ≤ 20.00
0.00 ≤ e ≤ 35.00
0.17 ≤ d ≤ 22.30
29835: $D_2(6)^3He(12)\ CH[20]$  
bb580_DA  

Pinhole Diameter: $5\times600\mu m$  

Notes:

\[
0.00 \leq c \leq 43.00 \\
0.00 \leq e \leq 35.00 \\
0.16 \leq d \leq 22.00
\]
29836: $\text{D}_{2}(6)^3\text{He}(12)\text{ CH}[20]$

**bb560_DA**

Pinhole Diameter: 2000\(\mu\)m

Notes:

\[0.00 \leq c \leq 40.00\]

\[0.00 \leq e \leq 25.00\]

\[5.00 \leq d \leq 14.50\]
29954: \( \text{D}_2(6)^3\text{He}(12) \text{ CH}[20] \)
bb805_DB
Pinhole Diameter: 5×600\( \mu \)m
Notes:

\[
0.00 \leq c \leq 40.00 \\
0.00 \leq e \leq 35.00 \\
0.17 \leq d \leq 20.00
\]
29954: $D_2(6)^3He(12)\ CH[20]$

bb552_DA

Pinhole Diameter: 5\times600\mu m

Notes:

\[
\begin{align*}
0.00 &\leq c \leq 50.00 \\
0.00 &\leq e \leq 35.00 \\
0.17 &\leq d \leq 20.00
\end{align*}
\]
29957: $D_2(6)^3He(12)\ CH[20]$

Pinhole Diameter: 5×600μm

Notes:

\[0.00 \leq c \leq 40.00\]
\[0.00 \leq e \leq 35.00\]
\[0.17 \leq d \leq 20.00\]
29957: $D_2(6)^3He(12)\ CH[20]$

bb561_DA

Pinhole Diameter: $5 \times 600 \mu m$

Notes:

$0.00 \leq c \leq 50.00$

$0.00 \leq e \leq 35.00$

$0.17 \leq d \leq 20.00$
30956: D_2(6)_3He(12) CH[20]

bb850_DB (PCIS 1)

Pinhole Diameter: 5×600μm

Notes:
30956: \(D_2(6)^3He(12) \text{CH}[20]\)

**bb548_DA (PCIS 1)**

Pinhole Diameter: 5×600\(\mu\)m

Notes: No image visible on the scan.
30956: \( D_2(6)^3He(12) \) CH[20]

bb862_DB (PCIS P)

Pinhole Diameter: 5×600μm

Notes:

\[
0.00 \leq c \leq 35.00 \\
0.00 \leq e \leq 50.00 \\
0.70 \leq d \leq 16.00
\]
30956: $D_2(6)^3He(12) \text{ CH}[20]$

bb554_Bert (PCIS P)

Pinhole Diameter: 5×600μm

Notes:

$0.00 \leq \epsilon \leq 45.00$

$0.00 \leq \epsilon \leq 75.00$

$6.00 \leq \delta \leq 20.00$
30977: D$_2$(6$^3$He(12) CH[20]

bb869_DB (PCIS P)

Pinhole Diameter: 5×600μm

Notes:

0.00 ≤ c ≤ 45.00

0.00 ≤ e ≤ 85.00

0.05 ≤ d ≤ 17.00
30977: $D_2(6)^3He(12)\ CH[20]$

bb871_DA (PCIS P)

Pinhole Diameter: 5×600μm

Notes:

$0.00 \leq c \leq 100.00$

$0.00 \leq e \leq 36.00$

$0.16 \leq d \leq 21.00$
30977: D₂(6)³He(12) CH[20]
bb868_DB (PCIS 1)
Pinhole Diameter: 5×600μm
Notes:

\[
\begin{align*}
0.00 & \leq c & \leq 45.00 \\
0.00 & \leq e & \leq 85.00 \\
0.05 & \leq d & \leq 17.00 
\end{align*}
\]
30977: D$_2$(6)$^3$He(12) CH[20]
bb865_DA (PCIS 1)
Pinhole Diameter: 5×600μm
Notes: Scan looks very bad. Can make out image.
Appendix C: Test of Source Function Reconstruction with Monte Carlo Simulated PCIS Data

Model:
Uniform Source
Radius = 150μm
Y = 10^{10}
Magnification = 10

Inferred Profile:
Shape Factor, P = 0
Radius (1/e) = 151.5μm
Y = 9.98x10^9
Reduced χ^2 = 0.84
Appendix C: Test of Source Function Reconstruction with Monte Carlo Simulated PCIS Data

Model:
Gaussian Source
Radius (1/e) = 42.4µm
$Y = 10^{10}$
Magnification = 10

Inferred Profile:
Shape Factor, $P = 0.98$
Radius (1/e) = 43.0µm
$Y = 9.98 \times 10^9$
Reduced $\chi^2 = 1.23$
Bibliography


