Design of an X-ray Photoconductive Device Spectrometer

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When a target is imploded by the OMEGA laser, the plasma generated emits x rays. Cryogenic targets are affected by x rays that may preheat the fuel layer and make it harder to compress the fuel. Through the use of an x-ray spectrometer these x rays can be separated into their different wavelengths and measured, providing information important for understanding the implosion dynamics. An x-ray spectrometer was designed. It consists of a modified pinhole camera, a transmission grating, a diamond photoconductive detector (PCD) array, and a beryllium filter. The pinhole camera is used as the basic holder for the grating and diodes. The transmission grating separates the x rays into their individual wavelengths. The PCD's are used to determine the intensity of the diffracted x rays. The x-ray wavelength is calculated from the location of the PCD's. The beryllium filter is used to decrease the intensity of the x rays so that the grating will not be damaged.

Introduction

The OMEGA laser at the Laboratory for Laser Energetics is attempting to obtain nuclear fusion through thermonuclear ignition of deuterium-tritium cryogenic targets. Thermonuclear ignition requires a temperature above 10 keV and density above 100 g/cm^3. When the target is shot by the laser, it is transformed into plasma. The plasma implodes and briefly reaches the temperature and density requirements for thermonuclear ignition. After 100 picoseconds at these conditions, the target rapidly expands. X rays are emitted during the entire implosion process.

A model of the expected x-ray intensities integrated over time as a function of their energies has been calculated (Fig. 1). Preheating a cryogenic deuterium-tritium target involves heating the cold fuel layer prior to the target's implosion. When a target is preheated the core is much harder to compress and less neutrons are produced when compared to a non-preheated implosion. Fig. 1 shows the x-ray spectra expected for models with and without preheat.

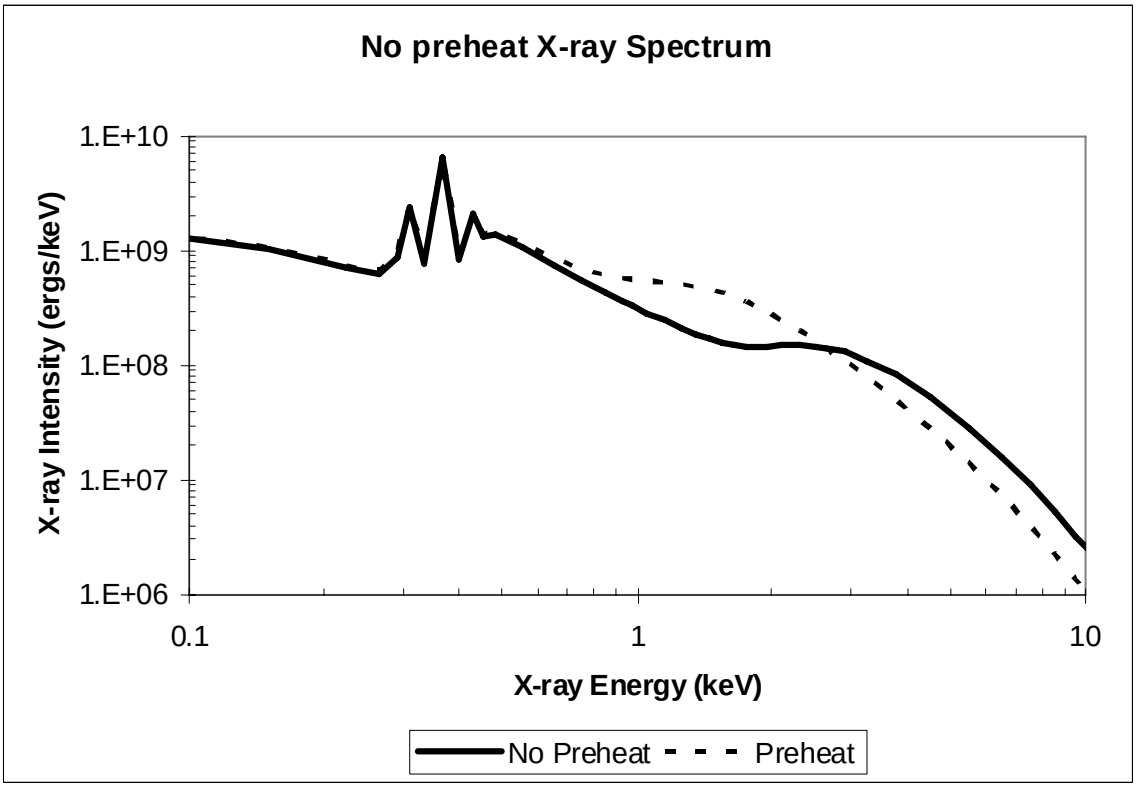

Fig. 1. The expected x-ray intensity as a function of its relative energy. The preheat and no-preheat models show a difference in intensity starting at about 0.5 keV.

The use of a spectrometer can provide valuable information about the implosion. The spectrometer provides information on how many volts each PCD emits. The voltage can be converted to intensity using a response function for each PCD. The position of the PCDs from the center can be used to calculate what wavelength range was detected. The equations will be able to provide the x-ray spectrum to determine dynamics of the implosion.

Diffraction is a property of light which makes the spectrometer possible. When light is passed through a small enough aperture, the waves will spread as if they came from the source. If many of these small openings are placed together interference occurs. Interference is when two waves of light combine either constructively or destructively. Constructive interference occurs when the two waves are in phase when combined and form anti-nodes (bright spot). Destructive interference is the opposite and instead of being in phase, the two waves are out of phase by 180º and form nodes (dark spots). A transmission grating has the same principle. Instead of many small apertures, a transmission grating is made up of a ruled light transmitting material. The grating used is

made of gold and has a period, or the distance from one slit to another, of 2000 Å. The longer wavelengths are diffracted much more than short wavelengths and therefore the spectrum is dispersed by the x-ray wavelength.

PCDs are used to detect light energy. These detectors consist of a semiconductor material, usually silicon, between two metal contacts. The PCD used for detecting x rays consists of a 1mm x 3mm x 1mm diamond semiconductor. Diamond is used because it has a higher band gap and a larger energy per electron-hole pair than silicon which makes it much less sensitive to UV energy. Electron and hole mobility, density, and resistivity help to increase the sensitivity to x ray energy.[1] When light energy is absorbed by the PCD, the valence electrons of the carbon atoms move to the conduction band. The electrons in the conduction band move to the anode and contribute to the electric current. The holes left by the electrons move to the cathode and also contribute to the current. This lowers the resistance of the diamond and the voltage increases. When too much x-ray energy is absorbed, many electrons move to the conduction band. This causes the carrier density to become too high and the resultant voltage will be less then what is predicted.[2]

The beryllium filter is used to protect the transmission grating and to prevent visible light from entering. The high intensity of the x rays will damage the grating and it may have to be replaced after every shot. The x rays are able to pass with only minor energy loss. The beryllium used for the spectrometer will be 25 μm thick and will be placed before the pinhole.

Transmission Grating and Photoconductive Detectors

The experimental configuration is shown in Fig. 2. A transmission grating is placed 600 mm from the target and 1076 mm from the PCDs. The PCDs must be at least 1.5 mm and not more than 42 mm from the image, or 0^{th} order. The image of the implosion will have a radius of 1.5 mm from the center and the diameter of where the PCDs will be placed is 85 mm, leaving a maximum distance of 42 mm. Based on this, the wavelength of the x rays can be calculated using

$$\lambda = \frac{d \sin \theta}{n} \tag{1}$$

where λ is the wavelength, d is the grating period, θ is the diffraction angle, and n is the diffraction order.[3] Using this, the maximum energy that can be viewed by this spectrometer is 4446 eV at order 1 and 824 eV at order 5.

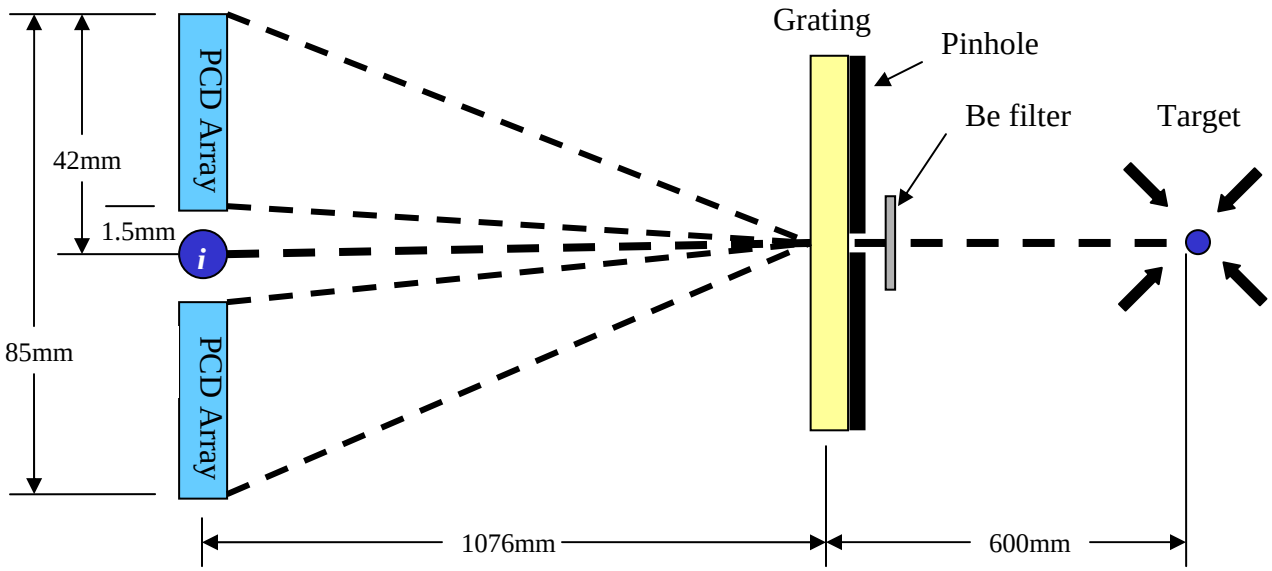

Fig. 2. Experimental configuration. The image (*i*) does not interfere with the PCD array. The image has a 1mm radius and the closest PCD is 1.5mm away from the center of the image.

When the x-ray energy passes through the beryllium filter, pinhole, grating, and PCDs, much of the energy is lost. The total intensity (E_x) reaching the detectors can be calculated by

$$E_x = E_{rad} \cdot \varepsilon_g \cdot \varepsilon_\tau \cdot \left(\frac{\pi r^2}{l^2} \right) \cdot \left(\frac{1}{4\pi} \right) \cdot \left(1 - e^{-t/\lambda_x} \right) \tag{2}$$

where E_{rad} is the initial intensity of the x rays, ε_g is the grating efficiency, ε_τ is the transmission of the beryllium, r is the radius of the pinhole, l is the length from the source to the pinhole, t is the thickness of the PCD, and λ_x is the x-ray mean free path in diamond. The x-ray efficiencies and mean free path do not have to be calculated and are available at Lawrence Berkeley National Laboratory.[4] So much energy is lost that at the distances above, order one has an intensity nearly zero at low x-ray energy. Different orders have to be used to counteract this problem. By calculating the total efficiency and

determining which order has the least energy loss at each distance, the ideal order can be used. Based on these calculations, order 1 will be used between 1.5 mm and 6.5 mm, order 3 will be used between 6.5 mm and 16 mm, and order 5 will be used between 16 mm and 42 mm (Fig. 3).

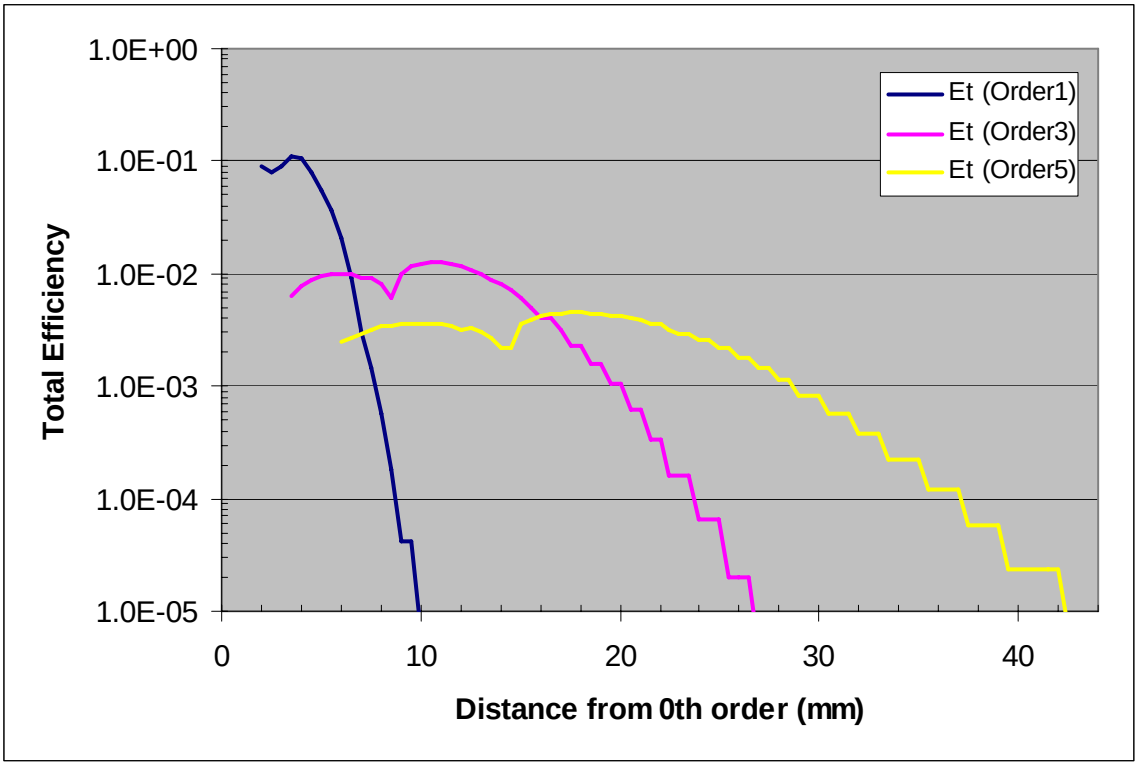

Fig. 3. The total efficiency at distances from 0^{th} order. This shows that 3 orders must be used to ensure the total 42 mm distance can be detected.

The placement of the PCDs can now be determined (Fig. 4). The PCD array used for this experiment is expected to have a 1 mm distance between the diodes and have connectors on three sides. The desired energy range for each diode is 300 eV. To achieve this, the PCDs must be placed horizontal in the first and third orders and placed vertical in fifth order.

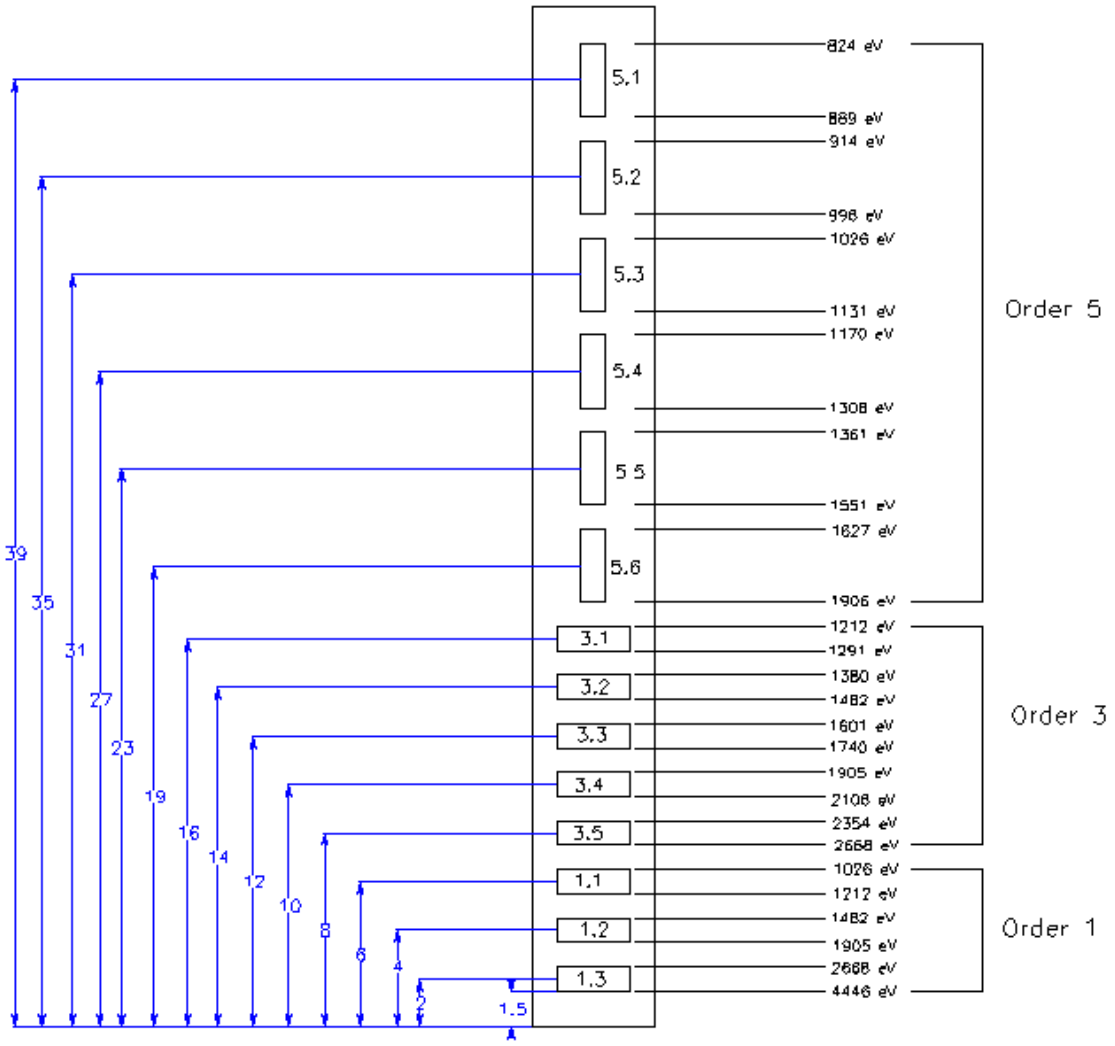

Fig. 4. The placement of the PCDs. Based on the distances the diodes are placed the energy range each diode will capture can be calculated.

Using equation 1, the energy range for each diode can be calculated. These energies can be graphed with the expected x-ray spectrum (Fig. 5). The combined coverage covers most of the x-ray energies between about 800 eV and 4500 eV. The inconsistency between the preheat and no-preheat spectrum which occurs in this region makes the placement ideal.

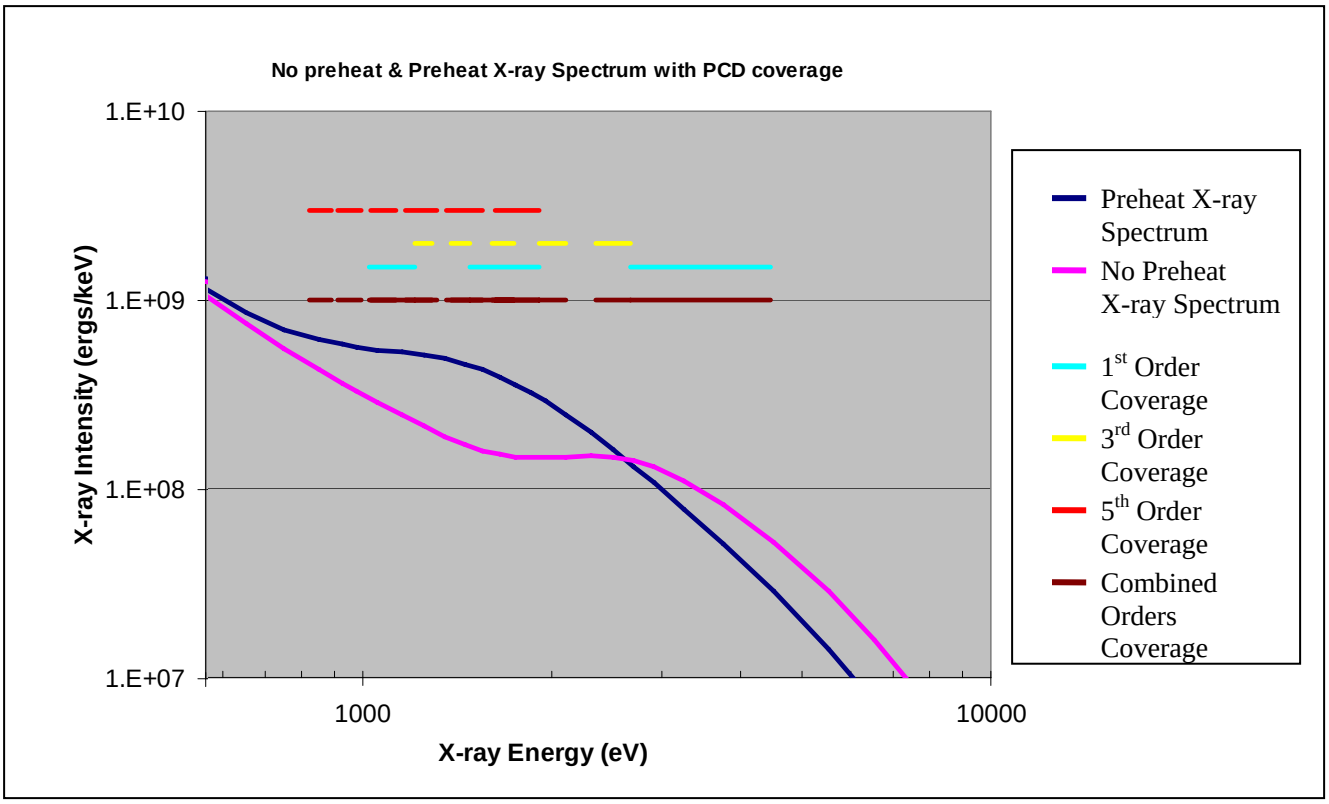

Fig. 5. PCD coverage and x-ray spectrum. The coverage by the PCDs is consistent with the difference between the preheat and no-preheat spectrum in the 800 to 4500eV range.

Expected Data

The expected voltage output of the PCDs can be calculated. This data can be compared to what the actual voltage is. The equation used for determining the voltage out (V_{out}) is

$$V_{out} = (qE)ARn_0(\mu e^{-t/\tau}) \tag{3}$$

where q is the electron charge, E is the applied field, A is the cross-sectional area, R is the impedance, n_0 is the carrier density, μ is the carrier mobility, t is time, and τ is the carrier lifetime.[5] For these calculations q is $1.6\text{x}10^{-19}$ Coulombs, E is 10^4 V cm^{-1}, A is 0.03 cm^2, R is 50 Ω, μ is 4000 cm^2 V^{-1} s^{-1}, t is 0 seconds, and τ is 180 ps.[6] To calculate n_0, two equations are used:

$$n_0 = \frac{E_x \cdot (1 - e^{-z/\lambda_x})}{\gamma \cdot A_{xy} \cdot \lambda_x} \tag{4.1}$$

$$n_0 = \frac{E_x \cdot z}{\gamma \cdot A_{xy} \cdot \lambda_x^2} \tag{4.2}$$

where E_x is the energy reaching the detector, t is time, λ_x is the x-ray attenuation length, γ is the energy per electron-hole pair, A_{xy} is the cross-sectional area, and z is the diode's thickness. For this equation t is 0 seconds, γ is 13, A_{xy} is 0.03 cm^2, and z is 0.01 cm. The value for λ_x can be found from Ref. 4. Equation 4.1 is used to calculate the peak carrier density and equation 4.2 for the average carrier density throughout the diamond.

Using equation 3 with the energy values for each PCD, the expected voltage can be calculated (Table 1). There is a direct relationship between the voltage and the x-ray intensity. The high no preheat voltage at the energy levels between 2604 eV and 4339 eV shows a high temperature implosion. Between 1142 eV and 1698 eV the preheat voltage is double the voltage of the no preheat. At the lower energies, between 804 eV and 1104 eV, the voltages with and without preheat are nearly equal.

Table 1. Expected voltages at specific distances. V_{out} calculated with equation 3 using equation 4.2 to calculate n_0 can be used to predict the voltage the PCD will release.

Distance from 0 Order	X-ray energy (eV)	No Preheat Voltage	Preheat Voltage
1.5 – 2.5 mm	4339 – 2604	$1.7x10^{0}$	$2.2x10^{-1}$
3.5 – 4.5 mm	1860 – 1447	$8.8x10^{-1}$	$1.1x10^{0}$
5.5 – 6.5 mm	1184 – 1001	$1.4x10^{-1}$	$1.4x10^{-1}$
7.5 – 8.5 mm	2604 – 2297	$4.8x10^{-2}$	$3.8x10^{-2}$
9.5 – 10.5 mm	2056 – 1860	$4.7x10^{-2}$	$6.4x10^{-2}$
11.5 – 12.5 mm	1698 – 1562	$3.2x10^{-2}$	$6.7x10^{-2}$
13.5 – 14.5 mm	1447 – 1347	$1.9x10^{-2}$	$2.8x10^{-2}$
15.5 – 16.5 mm	1260 – 1184	$1.0x10^{-2}$	$2.8x10^{-2}$
17.5 – 20.5 mm	1860 – 1588	$3.2x10^{-2}$	$4.8x10^{-2}$
21.5 – 24.5 mm	1514 – 1329	$1.3x10^{-2}$	$1.7x10^{-2}$
25.5 – 28.5 mm	1277 – 1142	$6.3x10^{-3}$	$1.0x10^{-2}$
29.5 – 32.5 mm	1104 – 1002	$2.4x10^{-3}$	$2.3x10^{-3}$
33.5 – 36.5 mm	972 – 892	$7.3x10^{-4}$	$1.0x10^{-3}$
37.5 – 40.5 mm	868 – 804	$3.4x10^{-4}$	$2.3x10^{-4}$

The Design

The x-ray spectrometer is based on a pinhole camera body (Fig. 6). Custom parts are created and added to the body to create the specific distances necessary. The transmission grating is placed between two parts in a 0.1” gap. The two parts are fastened together and then fastened to the camera body. The pinhole part is also attached to these parts. The pinhole part is tantalum with an outer diameter of 0.5” and a thickness of 0.01”. The pinhole assembly also contains a place for the 25 μm beryllium filter. The back of the camera contains the PCD array. The back plate contains the array which will be adjustable.

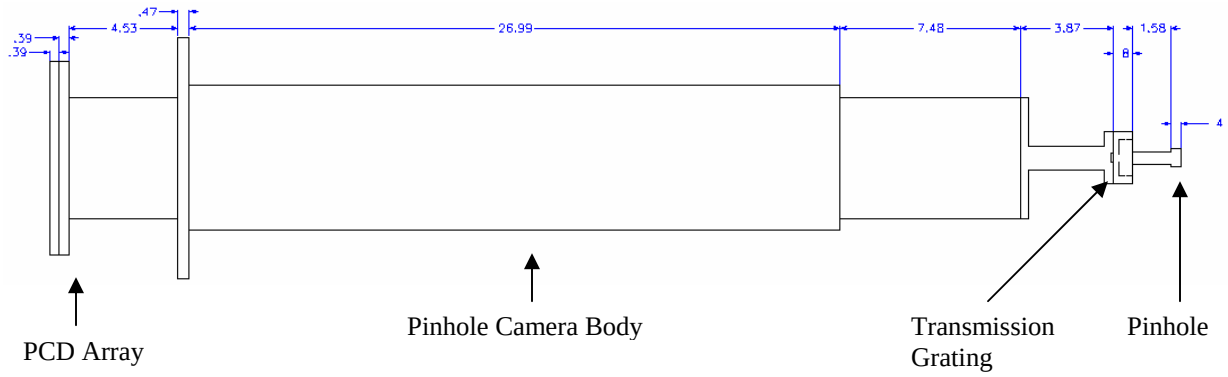

Fig. 6. The X-ray spectrometer design. The spectrometer uses a pinhole camera body with some custom parts. The pinhole is 525 mm from the center of the target chamber, the transmission grating is 600 mm from the target, and the PCD array is 1814 mm away from the target.

The camera must also be able to be centered. The exact way still has to be determined. One possible solution is to use the array and adjust it so one of the detectors is in the center. The spectrometer can be adjusted until the detector detects the image. Another solution is to use film and adjust the camera based on where the image appears on the film. The disadvantage of using film is that the vacuum will have to be broken to develop the film. The ideal solution is to move the detectors but accomplishing this may prove to be difficult.

Conclusion

The x-ray spectrometer design will be able to detect the region where the preheat and no-preheat spectra models differ. The intensities found with the spectrometer can be used to determine the dynamics of the implosion. Based on the voltage output of the

PCDs, the intensity of the x rays can be calculated. The energy of the x rays can also be calculated based on how far the PCDs are away from the center of the image. The x-ray energies and intensities can be combined to produce a chart which can be compared to the expected data for the preheat and no preheat models. This design of an x-ray spectrometer will be very useful in the effort to obtain thermonuclear ignition.

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