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High Energy X-ray Pinhole Imaging at the Z Facility

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Abstract: A new high photon energy (hν > 15 keV) time-integrated pinhole camera (TIPC) has become available at the Z facility for diagnostic applications. This camera employs five pinholes in a linear array for recording five images at once onto an image plate detector. Each pinhole may be independently filtered to yield five different spectral responses. The pinhole array is fabricated from a 1-cm thick tungsten block and is available with either straight pinholes or conical pinholes. Each pinhole within the array block is 250 μm in diameter. The five pinholes are splayed with respect to each other such that they point to the same location in space, and hence present the same view of the target load at the Z facility. The fielding distance is 66 cm and the nominal image magnification is 0.374. Initial experimental results are shown to illustrate the performance of the camera.

INTRODUCTION

The Z facility is a large pulsed power accelerator designed to deliver up to 26 million amps of current to a target load such as wire arrays, liner targets or gas puffs.[1,2,3,4] The ensuing z-pinch produces plasma that radiates copious amounts of x-rays as line radiation, as black body continuum or as bremsstrahlung radiation. Historically, the available spectral diagnostics have covered the energy range from about 250 eV to 20 keV.[5, 6, 7] Diagnosis of higher photon energies is important given recent efforts to develop high photon energy x-ray sources and also to assess the effects of high energy Bremsstrahlung radiation on the electronics of other diagnostic instruments fielded at the Z facility. In general, we are seeking to diagnose the spectrum, source size, radiated energy bands and time history of radiation from the z-pinch. During the early years of the Z facility, there was an effort to characterize the high energy output of the generated plasma.[8] While work has continued on developing and measuring line emission from selected target designs,[5,9,10] little effort has been made since the upgrade to the facility in 2006 to characterize either the high energy spectral output or the source size.

Delivering millions of amps of current to the target load within the experimental chamber of the Z facility produces a challenging high radiation environment in which to place diagnostic

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equipment. Diagnostic equipment housings located close to the load must be able to withstand a significant blast wave and high velocity debris. Any electronics within the diagnostic equipment must be shielded from x-ray generated electromagnetic pulses (EMP) or electromagnetic pulses generated from pulsed power components in Z, including high voltage switches. The simplest diagnostic that one might consider for this type of environment is a filtered pinhole camera with an EMP passive detector such as x-ray film or image plate. Such an instrument would record a time integrated image of the region of the target plasma that is emitting radiation above the transmission threshold of the specified filter. Fielding multiple pinhole cameras at once renders it possible to record time integrated images of various photon energies on the same shot. The new diagnostic instrument described in this manuscript is designed to characterize both the spatial size and specific energy emission region of the high energy radiation output of the Z facility above 20 keV, whether it be continuum or line radiation. This manuscript describes a single time integrated pinhole camera, employing five extended pinholes to provide five images from each Z shot, which has been designed and built for fielding in the center section of the Z facility. The prototype version of the camera proved sufficiently successful that two new housings have been built and are now part of the diagnostic suite at Z. Data from one of the new instruments is presented to illustrate the capability of this new diagnostic pinhole camera.

PROTOTYPE PINHOLE CAMERA DESIGN

Due to Z facility time requirements associated with bringing online a new diagnostic instrument, it was important to quickly demonstrate that a carefully engineered instrument would be of sound concept and work as needed. The prototype pinhole camera was designed around a number of general goals. The desired field of view was to be limited to the size of the source to be diagnosed, 1.5 to 2 cm, corresponding to the height of a typical wire array load. Sufficient resolution was required to supply multiple resolving elements within the field of view (i.e. few hundred μm resolution). Finally, the goal was to design an instrument that was easy to field and provided data that was simple to interpret (e.g. analysis not being overly dependent on the precise alignment of the instrument to the load). For this demonstration of a high energy pinhole camera, the bottom third of an existing spectrometer housing[11] consisting of 1 inch thick tungsten walls was used, see Figure 1. (To ensure adequate shielding of detectors from the radiation environment of the Z accelerator, the minimum wall thickness for a diagnostic fielded in the center section of the Z facility is 1 inch of tungsten[5], which begins to transmit radiation at about 375 keV.) The pinhole camera design consists of three parts:

1. pinhole array;
2. filter array for holding filter stacks; and
3. image plate (IP) detector.

There is a trade-off in deciding which recording medium to use for the pinhole camera. While older formats of x-ray film are better characterized and calibrated for photon energies below 20

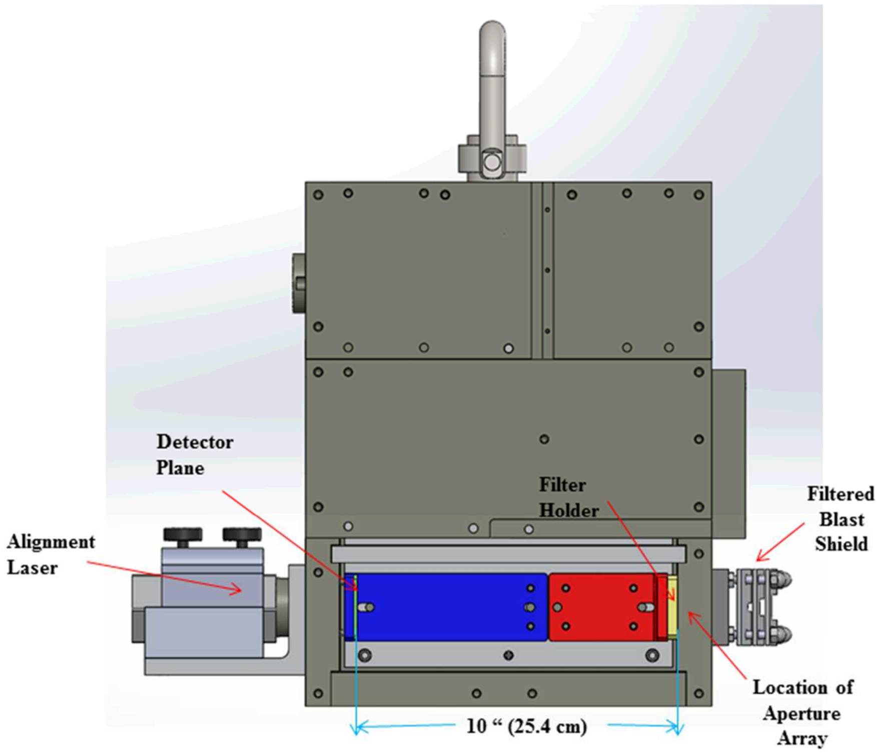

Figure 1: The lower third of an existing spectrometer housing[11] was chosen to demonstrate the concept of the filtered time integrated pinhole camera. The new instruments deployed for use at the Z facility are based upon this architecture. Source is to the right.

keV for source yield measurements, this is not the case for newer x-ray film formats for photon energies above 20 keV. Also x-ray film has a non-linear response with respect to dose. On the other hand, image plates have a linear response to dose up to near the saturation level but are not as well characterized as x-ray film. Ultimately it was decided that the linear response of image plates was critical to interpreting image data above 20 keV, and there was the hope that image plates could be calibrated in house for source yield measurements.

The fielding distance of the instrument from a target load was selected to be outside of the blast shield normally fielded around a target load, and to be sufficiently back as not to interfere with placement of other diagnostics located closer to the target load. (The spectrometer housing has a large foot print.) This distance between the target load and the front of the pinhole array was selected to be 66 cm. The distance between the back side of the pinhole array and the detector plane is dictated by the maximum available space inside the existing spectrometer housing, which is a little over 25.4 cm. Likewise, the depth of the existing housing dictated the available linear space for recording the images. Within this limited rectangular space, the scientific requirements of field of view and resolution had to be satisfied. From the physical space available, nominal magnification of the instrument would then be about 0.385. Reduced magnification was not considered an operational problem because the resolution of the image plate detector was deemed sufficient to yield high quality images once they were digitized. The pinhole array would have to be manufactured from a thick high density metal substrate, at least 0.5 cm W, to ensure good imaging of the source against background x-rays at photon energies ~1 MeV. A tradeoff between field of view and desired resolution within the image led to a pinhole diameter of 250 μm as a design goal. Once the distance between the target load and the front of the pinhole array was chosen as 66 cm, this distance together with the maximum source size anticipated, determined the number of pinholes that would be possible to position within the allowed linear depth of the spectrometer housing. The relative positions of the images at the detector plane set the requirements on the spacing of the pinholes in the pinhole array block as well as the requirements for the splayed angle at which each pinhole is machined into the array block. When the design was completed, the geometry resulted in an array of five extended pinholes in a 1 cm thick W block operating at a magnification of 0.374.

Since the side of the spectrometer housing has heavy interlocking tungsten plates, only one small section over the lower right in Figure 1 could be easily removed for placing components into the spectrometer housing. For ease of installing these components within the spectrometer housing, the spectrometer base plate was removed and a new base plate for the pinhole camera was mounted into the spectrometer housing. (This required removal of all the interlocking tungsten plates.) The filter stack holder and pinhole array are mounted to an L bracket (red in Figure 1) while the image plate detector is mounted to a separate L bracket (blue in Figure 1). Each of these L brackets were located onto the base plate using dowel pins and bolted into position. The remaining tungsten plate was then bolted into position. After the Z shot, only the lower right tungsten plate was removed to retrieve the image plate holder.

The active optical element of the pinhole camera, and the most difficult component to manufacture due to the large numerical aperture (NA) of 40, is the five splayed pinhole array, illustrated in Figure 2 with a schematic of the new camera assembly. The high photon energy output from the z-pinch plasma requires that the pinhole array be manufactured from a thick, high atomic number material in order to achieve good contrast within the image. It was highly desired that the pinhole array be made from a single piece of stock tungsten material in order to eliminate sources of light leaks through overlapping plates. Two types of pinhole arrays were considered: one with straight bore pinholes and one with conical pinholes. The straight bore pinholes give better overall source resolution within an image with increasing resolution across the image from image center to image edge. This changing resolution across the image results because of the extended pinhole which causes a reduced field of view by each adjacent pixel element within the image, from center of image to the edge of the image. (Think of a long pipe. As it is rotated, the effective circular aperture becomes an ellipse with decreasing major and minor axis.) While this characteristic of the straight bore pinhole benefits the determination of source size, most notably for high energy sources, for interpretation of the images it must be remembered that due to the decreasing field of view per pixel from image center to image edge, the incident flux onto the image plate is decreasing from image center to image edge per pixel. Said differently, sensitivity varies across the image and is dependent upon alignment of the

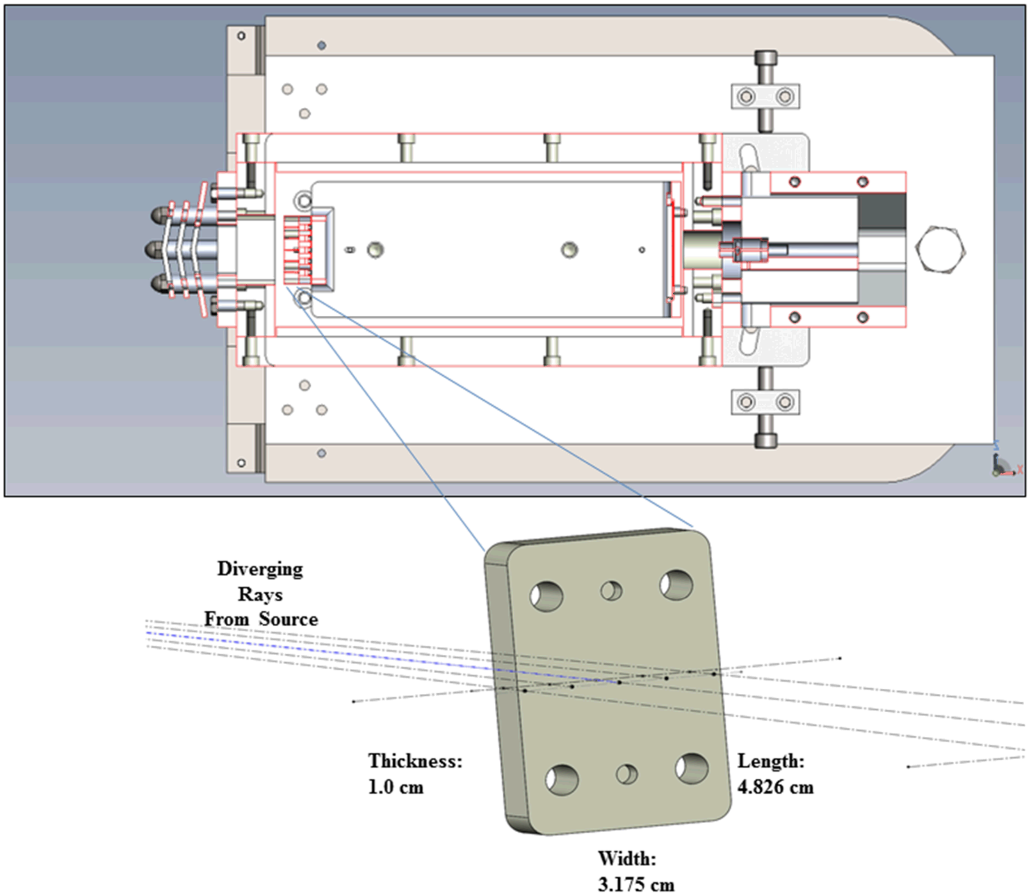

Figure 2: The active optical element of the pinhole camera is the pinhole array, made from a one centimeter thick solid tungsten plate. Each of the five pinholes is 0.0250 cm in diameter. With respect to the center pinhole, each pinhole is splayed such that all pinholes point to the same point in space located 66 cm from the front of the array.

instrument to the source. (This makes alignment an issue in conflict with one of the stated design goals.) The conical pinholes lend themselves to easier interpretation of data (and potentially to x-ray yield calculations[b]) because the field of view per pixel on the image plate, and hence the source resolution, is the same for each image plane unit area across the entire image. An additional benefit of the conical pinhole is overall increased strength of signal due to each image plane unit area viewing more of the target area than for the straight bore pinholes. In the end, it was decided to make both types of apertures.

A company employing plunge EDM manufacturing processes produced the aperture arrays. Manufacturing limits on the minimum wire size available by this company for the start hole

[b] At the time of design consideration and manufacture, it was thought that knowledge of the response of the image plate to x-rays would allow the associated x-ray yield to be calculated using published response curves.[12] To date this has proven to be problematic because of the variation of responses between image plate scanners and due to the aging electronics within any scanner. Repeated calibrations would need to be performed.

dictated the minimum diameter of the pinhole that could be made which in turn limited the maximum thickness of the material. These limitation requirements resulted in a solid tungsten array 1 cm thick, with each pinhole 250 μm in diameter at the front of the pinhole, the minimum design requirements. For the conical pinholes, the cone half-angle is 1 degree allowing rays from the full source height to pass unimpeded through the extended aperture to the image plate detector (the smallest diameter of the conical profile is 250 μm). With respect to the center pinhole, each pinhole is splayed such that they all point to a common point in space located 66 cm from the front of the tungsten pinhole plate. These pinhole arrays were manufactured by Owen Industries in Oak Creek Wisconsin.[13]

Completing the design of the camera are an alignment laser mounted at the back of the camera to align the optical axis of the pinhole camera to the target within the Z target chamber and a blast shield on the front of the camera housing designed to protect the pinhole array from shrapnel from the source region by deflecting it away from the pinhole array. This blast shield is composed of three parts:

(1) three chevron stainless steel (or tungsten, if available) plates with decreasing rectangular apertures along the optical path;
(2) a ½" thick tungsten plate with a 3/8" wide slot in front of the pinhole array; and
(3) 10 pieces of 0.5 mm kapton positioned between the chevrons and the ½" tungsten plate.

The quantity of kapton used in the blast shield begins to transmit radiation at about 9 keV.

The prototype pinhole camera was first fielded on the Z accelerator in early April 2014. For the first time on Z, images of high energy sources were produced that gave information on both source size and photon energy. It was quickly recognized that a new class of diagnostic should be made available to the experimental community for fielding inside the center section of Z.

THE NEW TIME INTEGRATED PINHOLE CAMERA (TIPC)

The success of the initial time integrated pinhole camera using the spectrometer housing led to the design and production of two new instruments. These new instruments, first fielded on Z in early February 2015, have become part of the diagnostic suite available at the Z Facility. The new instruments, called "TIPC" (Time Integrated Pinhole Camera), shown in Figure 3, are geometric copies of the prototype employing a new housing and alignment design. They may be fielded together to yield two different views of emission from the target load to check for emission anisotropy, or they may each be fitted with different filter sets to extend the range of filtering on a given shot. Both of these applications have been fielded to date. These instruments are more compact and have a smaller foot print than the original setup using the spectrometer housing. Each of these new instruments is mounted onto a dual rotation stage for alignment. On the prototype the pinhole array and the filter stack were mounted onto an L bracket and the IP detector was mounted onto a separate L bracket. With the new instruments, a U mounting platform, see Figure 3, holds the image plate mount as well as the pinhole array and the filter stack. Otherwise, the layouts for the initial camera and the new cameras are the same.

The U mounting platform is removable for alignment of the instrument to the target using an alignment laser. The alignment laser, Cole-Palmer Model EW 41935-22, comes mounted into a three point rotation gimbal. This rotation gimbal is mounted into a metal block that can be inserted into a holder mounted to the back of the pinhole camera body. Initial alignment of the laser to the optical axis of the instrument is performed on an optics table. The laser is set to pass a beam through the center pinhole of a twin pinhole array that is mounted to a dummy U mounting plate. Once the laser is aligned through the center pinhole of the array, it is locked down within the metal block. The dummy U mounting plate with the twin pinhole array is now removed and the instrument is ready to be transported to the Z center section. The alignment of the laser to the TIPC optical axis is performed for each shot series, but not each shot. Movement of the laser within the mount during a shot series has been found to be negligible if handled carefully.

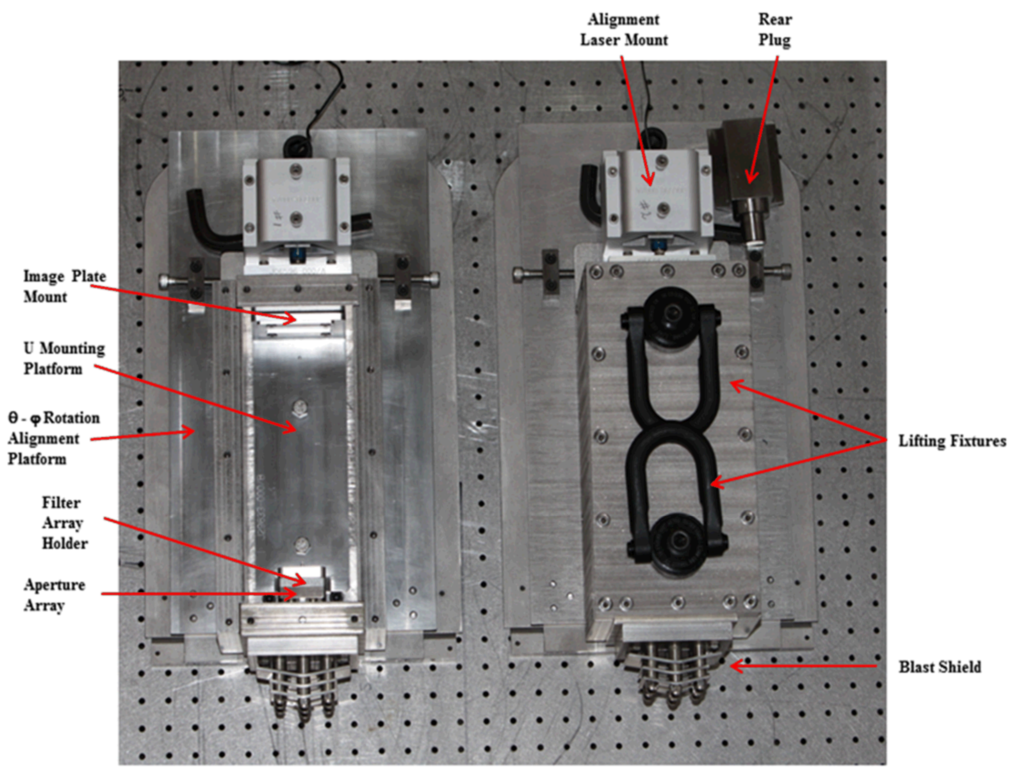

Figure 3: The two new TIPC instruments may be fielded separately or together for greater differentiation in the band pass or to check for homogeneity of the x-ray emission.

On installation of the instrument into the center section of Z the laser is aligned to the target load by adjusting the dual rotation stage. Once the instrument is aligned to the target load, the U mounting plate with the pinhole array, filter stack and image plate is then installed into the instrument. This U mounting platform is different from the one used to align the laser to the

TIPC optical axis. The optical filters have already been placed within the filter holder for each pinhole and the image plate is already installed on this U mounting plate. The laser alignment mount is then removed from the back of the instrument and replaced with a plug filling the back wall hole. Finally, the kapton sheets are placed between the blast shield plates.

In Figure 3 one can see the structure of the chevron blast shield used to protect the pinhole array. Kapton plates can be slid between these chevron plates to provide additional shielding from high velocity shrapnel from the target load. Typically 10 pieces of 0.5 mm kapton, transmission beginning at about 9 keV, are used for this additional shielding. Since these new instruments were fielded for the first time in early February 2015, shrapnel has penetrated at most 6 pieces of the kapton during a shot, but usually only three are damaged. All ten pieces are replaced for each new shot because of soot and metal deposited on the filters during and after the Z shot.

Filter setups are specific to the aims of an individual experiment, typically with each pinhole filtered differently. They are selected based upon the transmission properties of the elements published by NIST and the image plate response to different photon energy as published by Meadowcroft.[12, 14] Filters were purchased from Goodfellow Corporation; the filter thickness is specified to be accurate to about 10%. At present we have a range of filters available to field in the instrument, ranging from Ti (Z=22, K-edge at 4.9 keV) to U (Z=92, K-edge at 115.6 keV).

EXPERIMENTAL RESULTS

To demonstrate the capabilities of the new TIPC, we look at data from a Z shot (shot 2775). This experiment was a Mo wire array aiming to produce Mo Kα emission at 17.5 keV (data from a crystal spectrometer for this shot confirmed the presence of this line). For this experimental test of the instrument we used the filters shown in Table 1 to investigate the emission in a narrow band and demonstrate reproducibility of the images.

Table 1: Filter configuration for shot z2775. Filter 1 provides a high energy window. Other filters make up a Ross pair, and have redundancy to demonstrate reliability of the instrument.

Material	Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
Kapton	5500 μm	5500 μm	5500 μm	5500 μm	5500 μm
Yttrium		500 μm			500 μm
Molybdenum		25 μm	200 μm	200 μm	25 μm
Tantalum	280 μm				

A differential filter pair (a *Ross Pair*[15]) was used; subtraction of two images will then provide an image from a narrow spectral band. For this experiment a combination of Y and Mo filters was used to provide a band pass between the Y K-edge (17.0 keV) and the Mo K-edge (20.0 keV), as shown in Figure 4. 25 μm of Mo is included in the Y filter in order to better match transmission in all regions other than the desired 17-20 keV band (as demonstrated by the log-scale plot).

As a test of the validity of image subtraction with this instrument, each filter of the Ross pair was duplicated to allow for a null test of the image subtraction technique. Additionally, a Ta-filtered channel was fielded to demonstrate the higher photon energy capability of the instrument.

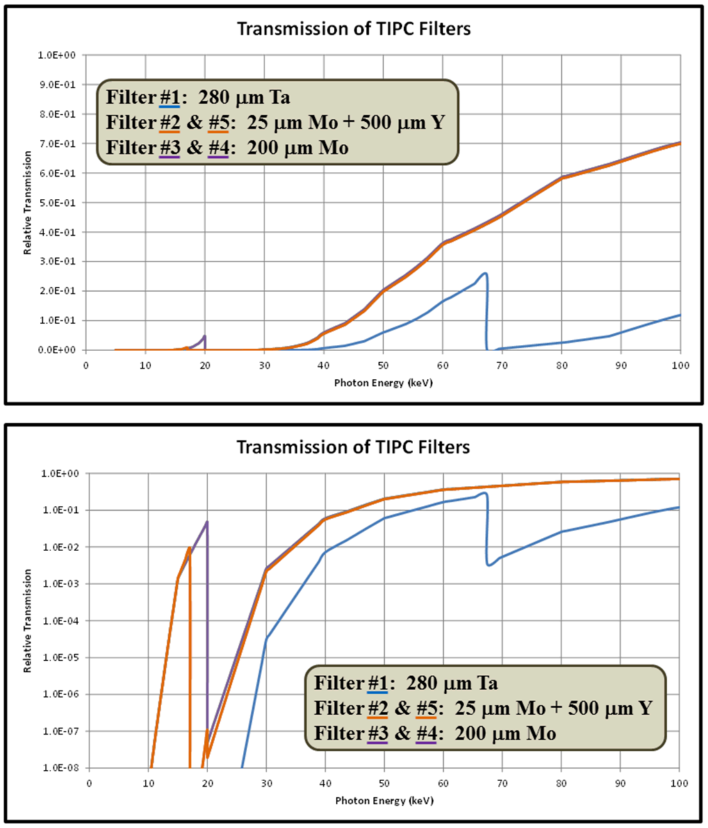

Figure 4: Filter stack used for shot z2775. Filter #1 opens a window from 42 – 67 keV and produced the weakest observed image. Filters #3 and #4 are the same and open a window from 17 – 20 keV. Filters #2 and #5 are the same and are used to subtract the <17 keV and >20 keV emission from filters #3 and #4. Each filter set also includes 5.5 mm of Kapton to prevent debris entering the instrument.

Five high energy x-ray images, illustrated in Figure 5, were obtained from this molybdenum wire array shot using one of the new imaging camera with the conical pinhole array and TR image plate.[16, 17] The image plate was scanned at 25 µm x 25 µm pixel resolution using a FUJIFILM BAS-5000 image plate scanner. The images are shown as recorded onto the image plate and as read out by the scanner, with the top of the source being at the bottom of the image and the bottom of the source being at the top of the image. Likewise, left and right of the source are reversed in each image. An orientation fiducial (not shown in Figure 5) is included at the top left of the image plate to aid in establishing the orientation of the data.

The primary success of the pinhole camera has been to determine the spatial structure of the emission from the z pinch, explicitly the overall size and uniformity of the emission. The lineout, illustrated in Figure 5, vertically averaged over 224 pixels, illustrates a FWHM width of the source of about 3 mm for each of the energy bands associated with the Ross filter pair. As indicated on the images in Figure 5, the recorded source height is about 150 pixels corresponding to 10 mm, the maximum observable height for this target load. The amplitudes illustrated in the lineout indicate these three comparisons: (1) the emissions are in the correct order as expected from the transmissions of the filters indicated in Figure 4; (2) the two images (#5 and #2) representing identical filters for the Notch filter subtraction have nearly the same average amplitude and the two images (#3 and #4) representing the Notch transmission have slightly different amplitudes; and (3) there is a slight bias in the background of the images from left to right in the image. These variations are within the stated uncertainty of the filter thickness provided by the manufacturer. Likewise, comparison of the radiating zones (brightest spots) is in agreement with results from imaging x-ray spectrometers fielded on the same shot.[18]

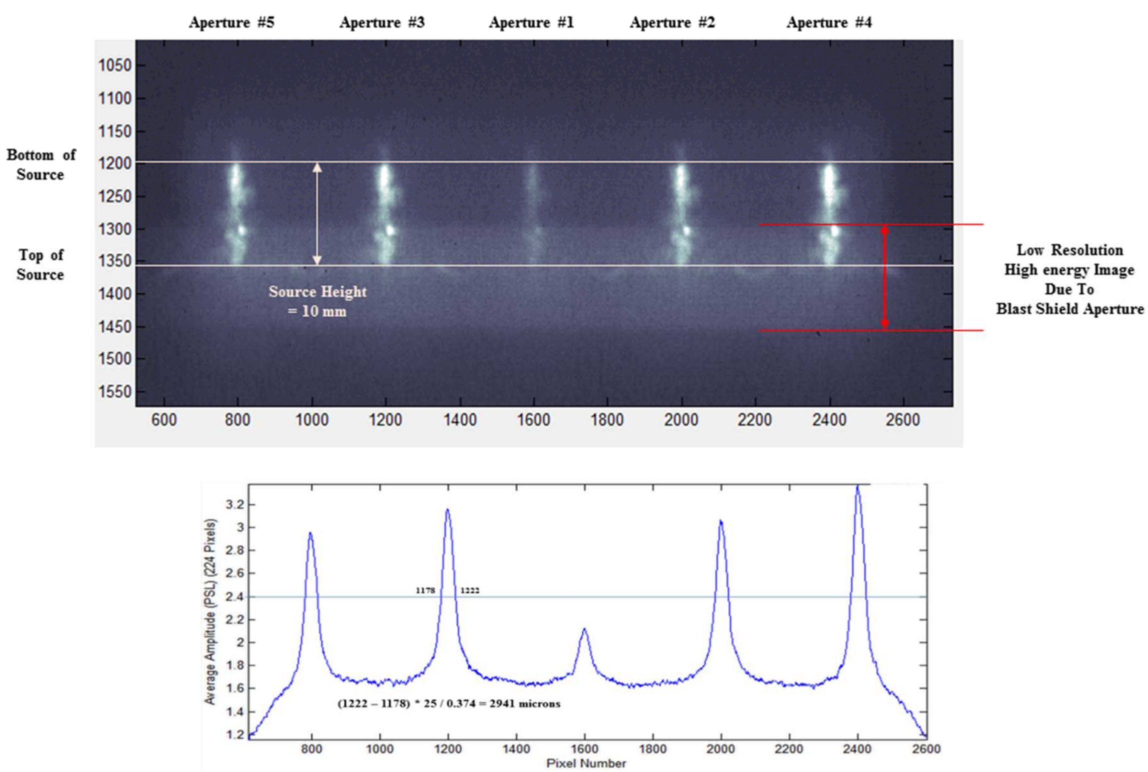

Figure 5: Example of the five time-integrated images recorded using the new diagnostic camera. Axes are labeled in pixel coordinates. Each image was individually filtered according to the specified filter stack listed in Table 1. From the horizontal lineout, the FWHM source width is about 3 mm. The observed source height agrees with the maximum hardware limit of 10 mm.

Figure 6 illustrates the ability to identify the location of specific emission within the source. In Figure 6a the radiation from the Notch filter transmission region of 17 – 20 keV is obtained when the image from Pinhole #2 is subtracted from the image from Pinhole #4. There is a general trend from left to right that is not subtracted from the image. Never the less, one sees that there is uniform emission with two hot spots, one located towards the bottom of the load and one just above the center of the emission zone.

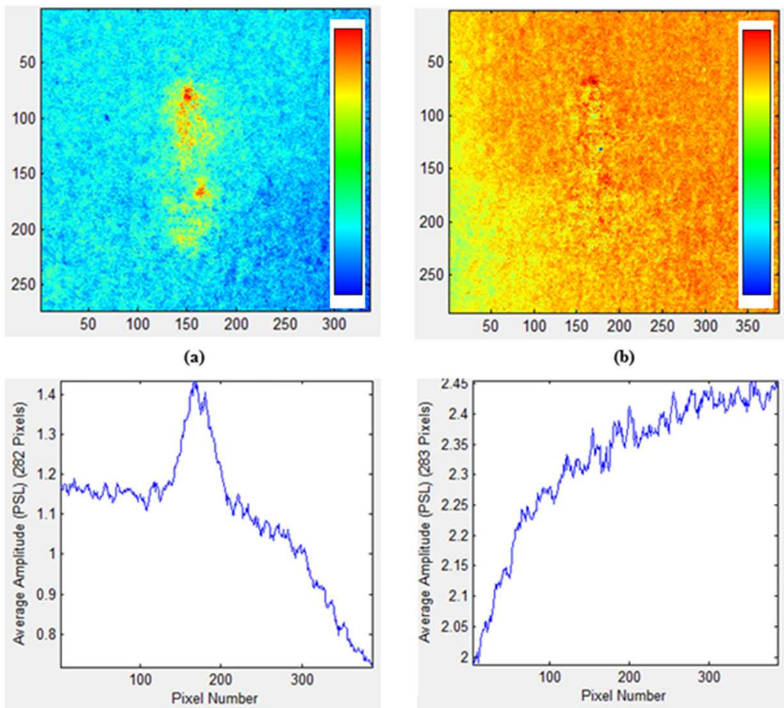

Figure 6: (a) Images created using a notch filter pair may be subtracted from each other to generate an image due to the notch energy band, such as this image due to 17 – 20 keV radiation. This technique works best if the difference in image plate response between the two filters is large and the image plate responses outside of the notch region are the same. (b) The random noise produced by subtracting images that have the same filter illustrates that the pinholes have the same view of the source. Misalignment of the images by only one pixel will result in a phantom image. The color bars represent pixel counts from low (blue) to high (red). The absolute scales are not the same in the two images.

To test the validity of the subtraction technique, the images representing pinholes #5 and #2 were subtracted from each other. Again there is a background trend from left to right that is not subtracted. Figure 6b illustrates the image of the random noise and its lineout averaged over the entire image resulting from subtracting the two background filters from each other. No source image is identifiable in the subtracted image or in the lineout from the image. It should be noted that during subtraction of these two images, misalignment of these two images by only 1 pixel was sufficient to leave a residual false image and a subsequent false image lineout. The need for such alignment precision puts a strict requirement on aligning the images to correctly interpret future images.

CONCLUSION

A new multi-pinhole high x-ray energy pinhole camera has been built and deployed at the Z facility. For the first time at the Z facility it has become possible to obtain source size information as well as energy band emission information for high energy x-ray sources on the same shot with the same instrument. This instrument will enhance the understanding of the performance of various load configurations as they become available on Z. Characterization of the high energy output of the Z Facility, up to about 100 keV from both spectral line and continuum sources will be possible. Already there is demand that the instrument be used to image sources at lower energy, with the lower energy limit being about 6 – 8 keV. A new disposable five pinhole array has been made for this purpose. Finally, efforts are ongoing to explore methods that will allow the x-ray images to be converted to yield measurements.

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