Novel energy resolving x-ray pinhole camera on Alcator C-Mod\textsuperscript{a)}

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A new energy resolving x-ray pinhole camera has been recently installed on Alcator C-Mod. This diagnostic is capable of 1D or 2D imaging with a spatial resolution of $\approx 1 \text{ cm}$, an energy resolution of $\approx 1 \text{ keV}$ in the range of 3.5 to 15 keV and a maximum time resolution of 5 ms. A novel use of a Pilatus 2 hybrid-pixel x-ray detector\textsuperscript{1} is employed in which the lower energy threshold of individual pixels is adjusted, allowing regions of a single detector to be sensitive to different x-ray energy ranges. Development of this new detector calibration technique was done as a collaboration between PPPL and Dectris Ltd. The calibration procedure is described, and the energy resolution of the detector is characterized. Initial data from this installation on Alcator C-Mod is presented. This diagnostic provides line-integrated measurements of impurity emission which can be used to determine impurity concentrations as well as the electron energy distribution.

I. INTRODUCTION

In this paper we describe a new energy resolved imaging x-ray diagnostic which employs a pixelated detector in which the lower energy threshold for photon detection can be adjusted independently on each pixel of the detector. This configuration provides an unprecedented flexibility in the configuration of a multi-energy imaging x-ray detection system. The energy resolved measurements from this diagnostic can eventually be used to produce images of both impurity concentrations, from the absolute image intensity at different energy bands, and the electron energy distribution, both thermal and non-thermal, from the variation of emissivity with x-ray energy.

II. DETECTOR HARDWARE AND CALIBRATION

The energy resolved x-ray pinhole camera is based on a novel calibration of a Pilatus 100K-S pixelated x-ray detector which was developed by the Paul Scherrer Institute and is commercially produced by Dectris Ltd.\textsuperscript{2,3} The detector module is made up of a single silicon sensor which is bump-bonded to 16 individual CMOS readout chips for a total of $195 \times 487$ pixels with a pixel pitch of $172 \times 172 \mu m^2$. The readout time for the detector is 2.3 ms which provides a limit on the maximum achievable frame rate. The sensitivity of the Pilatus detector is equal to the absorption efficiency of $320 \mu m$ of Silicon and the lower energy detection threshold can be set to any level above 2.14 keV.

When a photon strikes the detector the resulting electron pulse is passed through a charge sensitive preamplifier (CSA) and an AC coupled shaper and then compared against a threshold in a comparator. When the pulse amplitude exceeds the threshold a 20-bit counter in the pixel is incremented. The threshold level is controlled with a global threshold voltage, $V_{cmp}$, which is set on a per chip level, and then refined using trimbits for each pixel using an in-pixel 6-bit digital-to-analog converter (DAC). The voltage per bit for the trimbits is controlled through a module wide voltage adjustment, $V_{trm}$. A detailed description of the chip design, readout electronics and detector performance can be found in Kraft \textit{et al.}\textsuperscript{1,4}.

![FIG. 1. Fitted S-Curves from the trimbit scan for a single pixel shown for four different incident x-ray energies. From left to right the incident x-ray energies are 6.4 keV (Fe), 8.05 keV (Cu), 9.9 keV (Ge) and 14.96 keV (Y). The energy resolution of the system is given by the width of the s-curves as highlighted for the 8.05 keV incident x-ray curve.](image)

Due to voltage variations between the pixels arising from the interconnect resistivity, a global setting of the comparator voltage ($V_{cmp}$) would result in each pixel having a slightly different energy threshold. The trimbits were added to the detector design so that all of the pixels on the detector could be set closer to the same threshold setting. For the technique described in this paper the trimbits are used to allow each pixel to be set to a different energy threshold.

Before the trimbit calibration can be started it is nec-
ecessary to choose the values of $V_{cmp}$ and $V_{trim}$ that will allow the trimbits to span the desired range of energy thresholds. The value of $V_{cmp}$ determines the lowest energy thresholds that can be reached, while the value of $V_{trim}$ determines the threshold energy range. A technique to determine a global lower energy threshold as a function of $V_{cmp}$ is described in Ref. 4, and this process is repeated to determine the value of $V_{cmp}$ needed to access the lowest desired threshold energies. Also using a similar procedure to that described in Ref. 4, the value of $V_{trim}$ can be chosen that will allow access to the highest desired threshold energies.

To determine the relation between the trimbits and the lower energy threshold for every pixel on the detector a series of trimbit scans is performed with different incident x-ray energies. For each of these scans the detector is illuminated with a nearly monochromatic x-ray source produced by fluorescent emission from various material samples excited by an x-ray tube operated at 45 keV. The response of a pixel as a function of the trimbit setting is shown for several different incident x-ray energies in Fig. 1. The shape of each of these curves can be well represented by using an s-curve with the following form.

$$n(E_{th}) = \frac{1}{2} \left[ 1 + \text{erf}\left(\frac{(x - a_1)}{\sqrt{2}}a_2\right) \right] (a_3 + a_4(x - a_1)) + a_5 + a_6(x - a_1)$$  \hspace{1cm} (1)

Here $a_1$ is the inflection point of the s-curve, and corresponds to energy threshold that matches the incident x-ray energy. The parameter $a_2$ is the width of the s-curve, and is due primarily to electronic noise. The amplitude, $a_3$, is dependent on the x-ray flux and integration time. The slope on the left hand side of the s-curves, parameterized with $a_4$, is due to charge sharing between the pixels. A linear background is added ($a_5$ and $a_6$) which accounts for any additional x-ray emission at energies higher than the fluorescence line that is being used.

For each trimbit scan the parameters in Eq. 1 are found by fitting the s-curves to the intensity response using a non-linear least square fitting technique.$^5$ The relation between trimbit and threshold energy is found from the inflection points and incident x-ray energies from each scan. A quadratic function describes this relation very well and is determined for each pixel. Once this relation is found for each pixel, it is possible to independently choose the appropriate trimbit value for each pixel that will result in the desired energy threshold.

Since nearly monochromatic x-ray line sources are used for the calibration described in this paper, the width of the s-curve ($a_2$) represents the limit on the energy resolution achievable with the Pilatus 2 detector. This resolution has been measured to be between 1.0 and 1.4 keV depending on incident x-ray energy and the value of $V_{trim}$, where the energy resolution is defined as $a_2^22\sqrt{2\ln 2}$. A characterization of the energy resolution as a function of x-ray energy is shown in Figure 7 of Ref. 4.

The overall energy resolution of the detector is further degraded by the coarseness of the adjustment possible using the 6 trimbits, which can only adjust the lower energy threshold in finite steps. When the detector is configured for multi-energy detection, the trimbits have a stronger effect on the threshold than in the standard single-threshold configuration.

III. DIAGNOSTIC CONFIGURATION

For this initial installation on C-Mod the camera is installed on a small radially viewing port. The camera views the plasma through a 50µm thick beryllium window. Immediately in front of the window is a swapable pinhole aperture made from 1/16 inch stainless steel. The camera is placed in air at an adjustable distance from the pinhole. The spatial resolution of the system is determined by the size of the pinhole, the pixel pitch and the distances between the camera, pinhole and plasma center. A schematic of the configuration is shown in Fig. 2. For the results shown in Section IV the camera is placed 15 cm away from a 2 mm diameter pinhole.

Once calibrated it is very easy to create any configuration of threshold values on the detector. There are two configurations however that are of particular interest for x-ray measurements on Alcator C-Mod. For 2d imaging the detector can be split up into 3 × 3 metapixels, where each of the pixels within the metapixel is set to a different lower energy threshold.

For viewing a toroidally symmetric plasma, such as in Alcator C-Mod, only 1d imaging is required. In this case the detector can be configured so that each column is given a different energy threshold. This configuration provides the best spatial resolution vertically, while allowing still allowing a series of thresholds to be configured. Additionally multiple columns can be assigned to the same energy threshold to improve photon statistics, with more columns assigned to the higher energy thresh-
FIG. 3. An image of a plasma on Alcator C-Mod taken with the camera in the metapixel configuration. Image was taken with an integration time of 2 ms (corresponding to a 5 ms framing rate). The raw image from the detector is shown on the left hand side. The images on the right hand side are created from the raw data by extracting the pixels with a given lower energy threshold. The horizontal and vertical lines in the data correspond to spaces between the chips that make up the detector. The outline of the port through which the plasma is viewed can be clearly seen.

olds where reduced signal is expected. In this configuration it is possible to set the comparator voltage ($V_{cmp}$) to different values on each side of the detector, which can allow a wider range of lower energy threshold values without sacrificing energy resolution.

IV. EXPERIMENTAL RESULTS

For the results shown in this section, the metapixel configuration is chosen with the lower energy thresholds of the 9 pixels within each metapixel evenly spaced between 4 kev and 12 kev. This configuration produces time-resolved 2d images of the plasma with an energy resolution of 1 kev as shown in Fig. 3. This image is taken from a single frame during a moderate density ($n_e = 1 \times 10^{20} m^{-3}$) plasma discharge with 1 MW of radio frequency heating. Due to the relatively small amount of plasma heating the x-ray emission is very weak for this discharge.

The plasma in Alcator C-Mod is toroidally symmetric, so no variation is seen in the horizontal direction on the images, as expected. Profiles of the line integrated x-ray emission above the energy thresholds, taken from vertical slices through the images, are shown in Fig. 4.

FIG. 4. Vertical profiles of the line integrated x-ray energy emission with different lower energy thresholds. The profiles are taken from a single column of the images in Fig. 3. In the upper plot profiles were taken with an integration time of 5 ms. In the lower plot 100 frames have been binned together to improve the photon statistics and highlight the scatter in the profiles due to the variation in the threshold settings.

The scatter seen in the images and the profiles (Figs. 3 and 4) is due primarily to the variation in the lower energy threshold settings caused by the finite step size of the trimbits. The actual threshold setting for each pixel is recorded as part of the detector configuration, and can be used during further analysis.

V. CONCLUSION

A new energy resolving x-ray pinhole camera diagnostic has been installed on C-Mod which employs a novel calibration technique allowing the lower energy threshold of each pixel on the detector to be independently set. This diagnostic is capable of providing two dimensional energy-resolved images of the plasma with an energy resolution of 1 keV, a time resolution of 5 ms and a spatial resolution of 1 cm. Initial results show the flexibility and effectiveness of this diagnostic technique. This diagnostic is ideally suited for 2d and 3d energy resolved tomography with multiple camera installations.

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