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Fast 2-D Soft X-ray Imaging Device Based on Micro Pattern Gas Detector

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An innovative fast system for X-ray imaging has been developed at ENEA Frascati (Italy) to be used as diagnostic of magnetic plasmas for thermonuclear fusion. It is based on a pinhole camera coupled to a Micro Pattern Gas Detector (MPGD) having a Gas Electron Multiplier (GEM) as amplifying stage. This detector (2.5 cm × 2.5 cm active area) is equipped with a 2-D read-out printed circuit board with 144 pixels (12 × 12), with an electronic channel for each pixel (charge conversion, shaping, discrimination and counting). Working in photon counting mode, in proportional regime, it is able to get X-ray images of the plasma in a selectable X-ray energy range, at very high photon fluxes (10^6 ph $s^{-1}mm^{-2}$ all over the detector) and high framing rate (up to 100 kHz). It has very high dynamic range, high signal to noise ratio (statistical) and large flexibility in the optical configurations (magnification and views on the plasma). The system has been tested successfully on the Frascati Tokamak Upgrade (FTU), having central electron temperature of a few keV and density of 10^{20} m^{-3}, during the summer 2001, with a one-dimensional perpendicular view of the plasma. In collaboration with ENEA, the Johns Hopkins University (JHU) and Princeton Plasma Physics (PPPL), this system has been set up and calibrated in the X-ray energy range 2–8 keV and it has been installed, with a two-dimensional tangential view, on the spherical tokamak NSTX at Princeton. Time resolved X-ray images of the NSTX plasma core have been obtained. Fast acquisitions, performed up to 50 kHz of framing rate, allow the study of the plasma evolution and its magneto-hydrodynamic instabilities, while with a slower sampling (a few kHz) the curvature of the magnetic surfaces can be measured. All these results reveal the good imaging properties of this device at high time resolution, despite of the low number of pixels, and the effectiveness of the fine controlled energy discrimination.

1. Introduction

A new system for fast, high contrast X-ray imaging is presented. It is a pinhole camera, whose detector is a Micro Pattern Gas Detector having a true 2D pixel read-out board and a Gas Electron Multiplier (GEM) as electron amplifier. Each pixel is connected to an independent electronic chain. The system has many innovative features: energy discrimination, high dynamic range, and good two-dimensional imaging capabilities and high time resolution. It has been developed for magnetic fusion plasmas and, in this context, it revealed an excellent diagnostic capability, despite the low number of pixels. Thanks to these attractive features, its applications can go far beyond the field in which it has been developed.

2. Detector and electronics

The Micro Pattern Gas Detector [1] has a "drift" region, delimited by the entrance window (cathode) and the upper face of the GEM foil, of 8 mm in order to have a good conversion efficiency in a quite broad energy range (1–8 keV), relevant for magnetic fusion plasmas. The "transfer" region, between the lower face of the GEM and the read-out printed circuit board (PCB), is 1.3 mm. The GEM foil [2] is a thin kapton foil, metal-clad on both sides and pierced by a high density of narrow holes (typically 60 μm of diameter and 90 μm of pitch). The read-out board (fig. 1), with 144 pixels (12 × 12), has been designed to have high counting rate, large gain range, good spatial resolution and moderate number of pixels, each one connected to its independent acquisition channel [3]. The size of the pixel is 2 mm × 2 mm and the

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full active area of the detector is 2.5 cm × 2.5 cm. The drift electric field is about 2.5 kV/cm and the transfer field is 4.5 kV/cm. The voltage difference applied to the faces of the GEM foil is in the range 450 – 500 V, depending on the required gain for the detector. In order to maximize the detector gain (a few thousand times), the counting rates (of the order of 10^6 ph $s^{-1}mm^{-2}$) and the efficiency in the energy range of 1-8 keV, a mixture of Ne (80%) and DME (20%) has been chosen, flowing at atmospheric pressure.

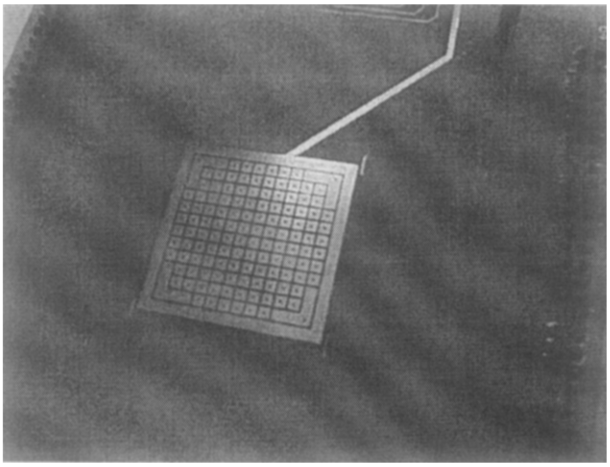

Figure 1. Printed circuit board (PCB) of the MPGD, with the read-out formed by squared pixels 2 mm × 2 mm (with the exception of the angular ones) drawn in a squared matrix 12 × 12

The electron charge, corresponding to the detected X ray photon, is collected at the pixel and processed by a fast charge pre-amplifier (LABEN 5231) and an amplifier (LABEN 5185). It has a gaussian-like shape, with 50 ns of FWHM. The peak value is proportional to the total electronic charge collected on the pixel, with a conversion factor of about 1 $\mu V/e^-$. The noise (rms) is about 5000 e^-. With a threshold of 20 mV, the electronic noise is well rejected for all the channels. Discriminators and counters for a total of 128 channels form the data acquisition system, carried out in VME standard by CAEN. The threshold of the discriminators is programmable from 5 to 255 mV.

The fast, low noise electronics coupled to the discriminators and asynchronous scalers ensure high quality data resulting in only statistical noise, with single photon counting at high rates, up to 10^7 ph/(s $*$ pixel) and high framing rates, up to 100 kHz.

The data acquisition system has been designed to allow many time intervals, in which the framing rate (from 1 kHz to 1 MHz) and the values of the thresholds of each channel can be preset. The minimum dead time between two different time intervals of acquisition is 0.25 ms.

3. Energy calibration

The energy calibration has been performed with an X-ray tube powered at 10 kV and placed at 10 cm far from the detector (fig. 2). The apparent peak at 3.5 keV is due to the progressive air absorption of the X-ray photons with energy less than 3.5 keV. The gain of the electronic amplifier of each pixel is adjusted in order to reproduce the same spectrum, with a precision of about by 2%, as shown (fig. 2) just for a few pixels. Since each channel behaves as an independent spectrometer, this fine adjustment is required to exploit the combination of imaging capability and energy discrimination, that is one of the most powerful features of this system. The energy resolution of the detector in this range, measured with line emissions (K_α), is about 20% FWHM and the electronic discrimination of the pulse amplitude can be changed dynamically during the shot, per each channel, with this uncertainty. In fig. 3 the energy calibration curves as function of peak amplitude are plotted, for three different values of the voltage applied to the GEM foil, just for one gas mixture (Ne 80% - DME 20%).

4. Results on magnetic fusion plasmas

This X-ray imaging system has been developed for magnetic fusion devices (tokamaks). These experiments produce extended (many cubic me-

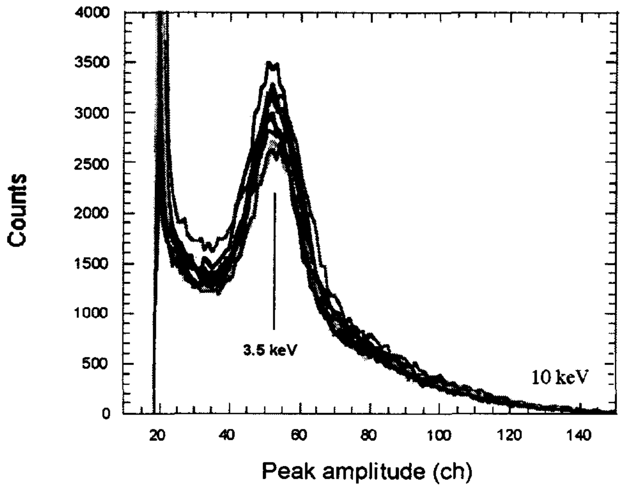

Figure 2. X-ray spectra, for a few pixels, in the range 1- 10 keV

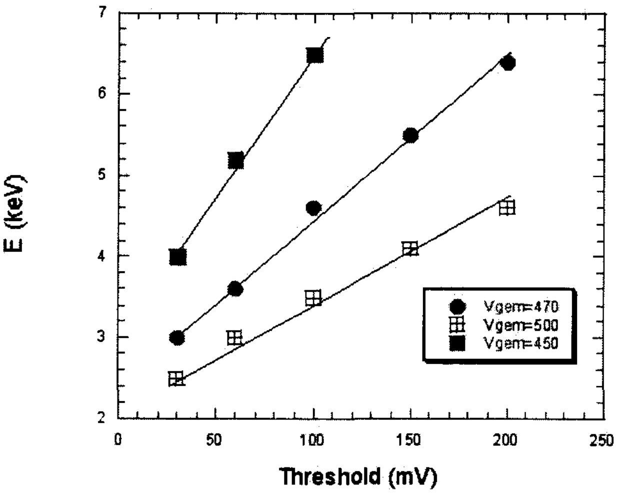

Figure 3. Energy calibration curve as function of the peak amplitude, for three different voltages applied to the GEM foil, with a gas mixture of Ne 80% and DME 20%

ters), hot (many keV) low density (10^{20} m^{-3}) plasmas, most of them living for a few seconds. They emit strongly in the X-ray domain and a 2-D fast imaging system, as the proposed one in this work, can provide tremendous information about the plasma behavior. This instrument has been carried-out in collaboration between ENEA Frascati (Italy) and INFN - Pisa (Italy). The imaging capability and the spatial resolution have been previously studied with laboratory sources [3] and then tested, for the first time (2001), on the Frascati Tokamak Upgrade (FTU) [4,5]. In 2002 it has been installed on the National Spherical Tokamak eXperiment (NSTX) [6] at Princeton (NJ, USA), whose plasma volume is about 15 m^3. A few results, obtained with these magnetic plasmas will be presented in this paragraph with the only purpose to show the performances of the proposed instrument.

Time history of a few central pixels is shown (fig. 4a) for a plasma shot, in presence of sawtooth oscillations, with a sampling rate of 1 kHz. In fig. 4b the plot of intensity (counts/pixel), at a fixed time indicated by the arrow, is shown. The plasma was measured with this instrument with a wide angle: 80 cm × 80 cm is the viewed plasma, corresponding to a demagnification 32. The core of the plasma exhibits strong oscillations (fig. 4a), while the central lines of sight of a vertical and horizontal perpendicular array of X-ray diodes (fig. 4b,c) show just weak modulations. This is mainly due to the energy discrimination capability of the MPGD system. This detector in fact is tuned on the most energetic X-ray photons (2.5-6 keV) coming from the core, whose maximum electron temperature at the center is 1.2 keV, while most of the emissions coming from the large colder plasma surrounding the core are cut off. This is not the case for the diodes, where the weaker central emissions are hidden by the prominent off core ones. This is an example showing how the fine energy discrimination enhances the contrast of the image. It is worthwhile to notice that it occurs at high counting rates up to $5\ 10^6$ ph/(s $*$ pixel) ($1.25\ 10^6$ ph $s^{-1}mm^{-2}$).

Since the only noise related to these measurements is statistic, the best condition is to use the instrument at the maximum sustainable photon flux ($\leq 2\ 10^6$ ph $s^{-1}mm^{-2}$) and set the framing rate in order to have the required statistic. As an

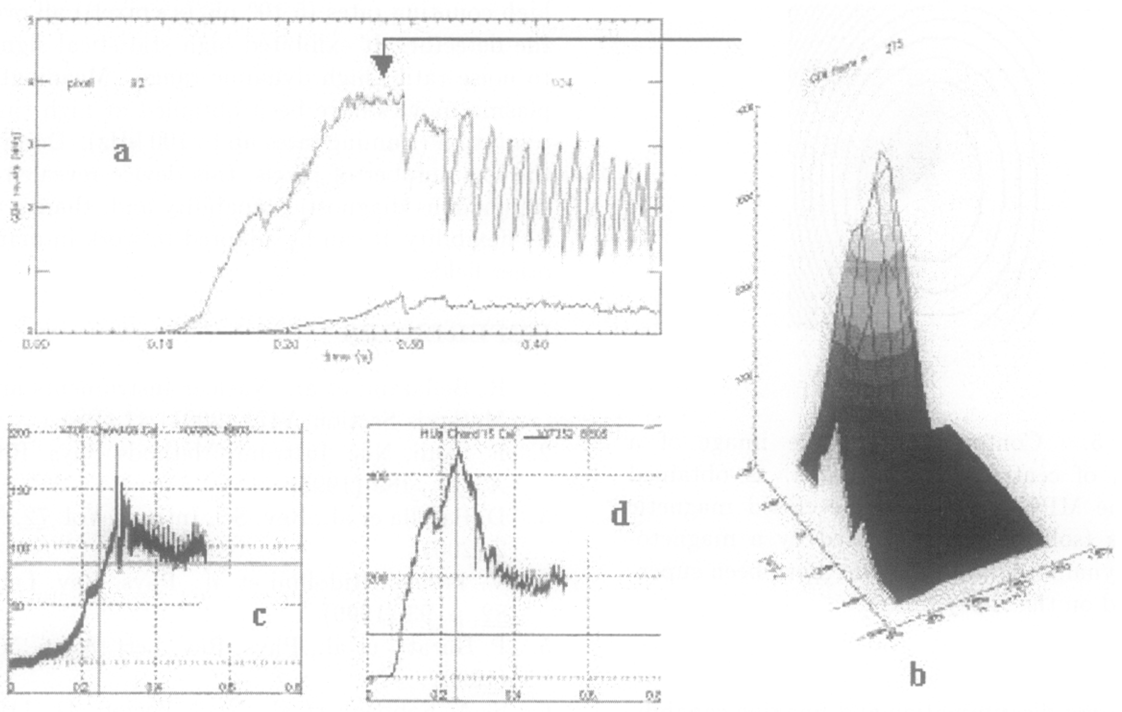

Figure 4. NSTX shot 107352 a) Time history, with sampling at 1 kHz, of two central pixels and one peripheral, showing strong central "sawtooth" oscillations. b) plot 3-D of counts as function of the pixel 2-D array, for a fixed time, indicated by the arrow, before the onset of the instability. c) d) central lines of sight of the soft-X ray tomographic diode arrays, vertical (c) and horizontal (d)

example, with framing rate of 1 kHz, we have a signal to noise ratio of $\sim$ 1000 at the maximum intensity (having just a few counts/pixel as spurious counts before the plasma). We can define also the dynamic range as the interval between the minimum counts/pixel required recognizing the structure of the plasma and the maximum counts/pixel, beyond which saturation occurs. In plasma shots with framing rates of 1 kHz, this dynamic range is about 200.

A zoom on the core is shown in fig. 5, obtained with a lower demagnification (16) and with the optical axis off the core (center of the plasma on the left bottom corner of the picture). The image, whose colors represent the counts, is superimposed on the reconstruction of the closed magnetic surface, computed by a simulation code.

Finally plasma movies, at high time resolution, have been produced. Acquisitions with framing rates up to 100 kHz have enough statistics to exhibit the core plasma dynamic, rich of perturbations and instabilities.

5. Conclusion

The major features of a new X-ray imaging system, based on Micro Pattern Gas Detector, have been discussed. This system, having a GEM foil as electron amplifier and a 2-D pixel readout equipped with independent electronic channels both for analog and acquisition phase, com-

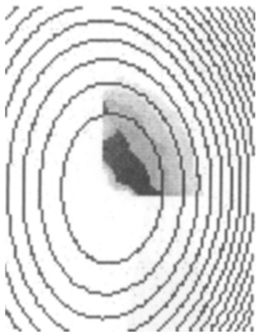

Figure 5. Contour plot of the image of a portion of central NSTX plasma, as obtained with the MPGD system. The closed magnetic surfaces (solid lines), computed by a magneto-hydrodynamic simulation code, have been superimposed on the X-ray image

bine energy discrimination and imaging capability. The instrument has been tested on magnetic fusion plasmas in the energy range of 2-8 keV, at high counting rates (5 10^6 ph/(s $*$ pixel)) all over the detector. It exhibited high statistical signal to noise ratio, high dynamic range. Meaningful plasma movies have been obtained at high time resolution (framing rates up to 100 kHz). Despite the low number of pixels, this device revealed a tremendous diagnostic capability and, thanks to its flexibility, it can be adapted to work in many other fields.

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