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Soft X-ray Imaging System for Measurement of Noncircular Tokamak Plasmas*

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Abstract

A soft X-ray camera and image processing system has been constructed to provide measurements of the internal shape of high temperature tokamak plasmas. The camera consists of a metallic-foil-filtered pinhole aperture and a microchannel plate image intensifier/convertor which produces a visible image for detection by a CCD TV camera. A wide-angle tangential view of the toroidal plasma allows a single compact camera to view the entire plasma cross section. With Be filters 12 to 50 μm thick, the signal from the microchannel plate is produced mostly by nickel L-line emissions which originate in the hot plasma core. The measured toroidal image is numerically inverted to produce a cross-sectional soft X-ray image of the plasma. Since the internal magnetic flux surfaces are usually isothermal and the nickel emissivity depends strongly on the local electron temperature, the X-ray emission contours reflect the shape of the magnetic surfaces in the plasma interior. Initial results from the PBX tokamak experiment show clear differences in internal plasma shapes for circular and bean-shaped discharges.

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Introduction

The ability to measure the internal shape of a magnetically confined high temperature plasma is of fundamental importance in studies of both the equilibrium properties of such a plasma and the nature of perturbations of that equilibrium. As interest in tokamak toroidal confinement devices with highly noncircular cross sections has grown due to their beneficial stability properties, the need to measure easily the internal plasma shape has become acute. Knowledge of the internal plasma shape also provides an indirect means of probing the plasma current and pressure distribution in current-driven devices such as the tokamak.

A common technique for internal high temperature plasma diagnosis has been the measurement of the spatial distribution of soft X-ray (SXR) radiation from the plasma core.¹ This radiation, in the 1 to 10 keV photon energy range, is generated by hydrogenic and impurity bremsstrahlung emissions and by line radiation from highly ionized metallic impurities in the plasma core. Since the emission rates for both of these processes depend strongly on the local plasma electron temperature, a measurement of the SXR emission contours in the plasma cross section provides a map of the electron temperature distribution, assuming of course no strong asymmetries in other parameters such as electron or impurity densities. Since the electron temperature (and the density to some extent) is constant on a magnetic flux surface, a cross-sectional map of the SXR emissions provides a map of the internal magnetic flux surfaces.

In the past, measurements of two-dimensional SXR distributions in tokamaks have mostly been accomplished by employing several discrete silicon surface barrier or PIN diode arrays to provide chordal views of the plasma from different viewing directions.¹⁻³ These observations are then combined

with tomographic inversion techniques to transform the chordal measurements to a cross-sectional (or poloidal) distribution of the SXR emissivity. Such an approach has the advantage of using well-known detector technology with high sensitivity, which allows measurements with high temporal resolution which in turn provides observations of perturbations of the plasma flux surfaces. Its disadvantage lies principally in the need for viewing the plasma from several directions simultaneously in a poloidal plane with often cumbersome detector arrays. On the other hand, using a two-dimensional SXR imaging camera to view the entire plasma cross section from a tangentially viewing perspective allows at least low time-resolution measurements of the plasma cross-sectional shape to be made with minimal access to the experimental facility. Such a system can also provide measurements of relatively low-frequency long-wavelength perturbations in the plasma interior, as has already been demonstrated on the D-III tokamak experiment.⁴

The present paper provides a description of the first generation of a two-dimensional SXR imaging system used on the PBX tokamak experiment to measure quantitatively the internal shape of the plasma. The PBX plasma is characterized by a highly noncircular cross section (usually in the shape of a kidney bean) which is predicted to provide superior stability properties at high plasma pressures.⁵ While external magnetic probes provide sufficient shape information to establish and control the discharge, they are insufficient in themselves for inferring the internal plasma shape, which is of interest from the stability viewpoint. The design features of the PBX SXR imaging system included the desire for a relatively simple and compact mechanical system, the need to employ off-the-shelf components as much as possible, and the requirements of modularity and flexibility for ease of future upgrades such as those which would provide higher time resolution or

different spectral ranges. While this paper concentrates on the applications to a tokamak plasma, this system is obviously applicable to a variety of high temperature plasma experiments.

Instrumentation

The optical field of view of the SXR camera system on PBX is indicated in Fig. 1. The camera is located in the vertical midplane of the torus and views the plasma tangentially (i.e., in the toroidal direction) with a tangency radius of 145 cm. The vacuum vessel has an outer wall radius of 220 cm and an inner wall of 80 cm. The entire camera assembly is mounted on a tangential viewport and is situated behind a large-aperture vacuum valve to allow removal without loss of torus vacuum. The field of view of the camera subtends approximately 38 degrees in the horizontal and vertical directions.

Details of the camera assembly are shown in Fig. 2. It consists of an SXR filter, a pinhole imaging aperture, a SXR-to-visible image convertor/intensifier, and relay optics to either a standard or nonstandard solid-state imaging device. While this design was chosen due to the ready availability of the particular components and is not optimal for operation in a high magnetic field environment, it is sufficient to demonstrate the range of information available from such an approach. The filters were mounted on a rotary filter wheel which allowed a change of spectral range between discharges. A total of twelve filters could be mounted at a given time. Typically, beryllium filters ranging in thickness from 12 to 100 μm were used, plus a hydrogen Lyman-alpha interference filter to provide spatial calibration of the camera's field of view in the torus. The imaging pinhole was a 200 or 400 μm diameter laser-drilled hole in a 13 μm thick stainless steel foil. A bare 25 mm diameter microchannel plate (MCP) with a 1000 $\text{\AA}$ copper iodide

overcoating was positioned 1.9 cm behind the pinhole to serve as the photocathode surface and first stage intensifier. A second MCP was mounted in a chevron configuration to provide higher gain to compensate for the gain loss due to the presence of an ambient magnetic field of 1 to 2 T. Conversion of the amplified electrons to visible radiation was accomplished by depositing a P-11 phosphor on the aluminized side of a fiber-optic image conduit which also served as a vacuum window and a 2:1 image reducer. Two high quality camera lenses were used to transmit the image to the photodetector with unity magnification. Two types of cameras were tested. The first was a commercial CCD television camera (Hitachi Model KP-120) which provided a standard RS-170 composite video signal, resulting in a time resolution of 16 msec per field without gating of the intensifier. While all of the results reported here were obtained with this camera, we note that we have also tested a 128 by 128 square photodiode array (Reticon Model MC9128) which provided a framing time down to 4 msec in a nonstandard format. Details of the operation of this camera will be reported later.

A schematic diagram of the data acquisition and control electronics for this diagnostic is given in Fig. 3. Due to the hostile electrical and radiation environment in the vicinity of the tokamak, all control and data signals are transmitted to a remote control room via fiber-optic data transmitter/receivers. Both the programmable high voltage power supplies for biasing the image intensifier and the stepper motor driver for the filter wheel were controlled by a CAMAC system driven by a general purpose PDP-11 Data Acquisition System which services the entire experimental facility. The composite video signal from the free-running TV camera was transmitted through an analog fiber-optic safety break (MERET model MDL286TV) to a receiver in the control room. The signal was then sent to a time-base label generator and

sync regenerator before being recorded on standard 1/2-in video tape for permanent storage.

Qualitative processing and quantitative analysis of a given image from the video tape is accomplished off-line from the tokamak cycle with a local image processing station consisting of several components. The heart of the system is a commercially available real time image processing system from Recognition Concepts, Inc. (RCI TRAPIX Model 55/64) which provides an 8-bit digitizer for the RS-170 signal, a phase-locked feedback loop and time-base corrector for digitizing signals from the video tape, 2 Mbyte of frame memory with a standard video frame consisting of 512 x 512 pixels, a high-speed pipeline processor, and psuedo-color output lookup tables. The RCI is connected directly to the Q-bus of a local dedicated LSI-11/73 microcomputer for control and standard image processing. Most of the image processing functions are performed using the high level Real Time Image Processing Software (RTIPS) language developed by TAU Corporation for the RCI TRAPIX system. Output from the image processor is directed to a Dunn Instruments MicroColor TV Camera in RGB format for film recording and/or passed through an RGB-to-NTSC convertor for storage on video tape or a thermal hardcopy (Mitsubishi Model P50U). Finally, the LSI-11/73 is connected in a terminal emulation mode to a VAX cluster via an RS232 line to allow transmission of subimages to a VAX 11/785 or 8600 for the detailed inversion procedures discussed below.

Image reduction and analysis

The analysis and reduction of the raw SXR image data to useful information takes place in several discrete steps. At the lowest level, a given image is processed to allow a clear elucidation of the intensity

distribution of the tangential image. This involves subtracting the zero background level from the image, rotating and translating the image so that the optical axis of the camera field of view is in the center of the digitized image, stretching the contrast of the image to use the full dynamic range of the display, interpolating the intensity patterns across the image of a magnetic flux loop wire which lies in the camera field of view, spatially smoothing the image to eliminate irrelevant high frequency noise in the image, and finally imposing a psuedo-color lookup table on the output image to allow easy intensity discrimination. All of these functions are performed locally with the LSI-11/73-RCI combination. A sample raw and processed image for a typical case is shown in Fig. 4.

Since the image is chordally integrated along the tangentially viewing line of sight for each picture element, the desired poloidal emissivity distribution is not immediately apparent in this projected image. However, general characteristics of the parent poloidal distribution which gives rise to the measured tangential image can be inferred from model images derived from model poloidal emissivity source functions. For example, Fig. 5 shows the parent poloidal emissivity function and the corresponding toroidal image for a circular and an elliptical plasma shape (the center of the torus is to the right of the image). The most relevant feature for our purposes is that the central intensity contours of the tangentially projected image are increasingly oblate as the poloidal distribution becomes more circular in the plasma center. Such modelling allows one to interpret qualitatively tangential images from the plasma in order to estimate the relative degree of central plasma elongation after the initial processing described above. For example, Fig. 6 shows a comparison of three discharges in the PBX tokamak where the plasma shape was varied by adjusting the plasma size and the ratios

of external shaping coil currents. In Fig. 6(a), a small nearly circular plasma is indicated by the strongly oblate inner intensity contours, while Figs. 6(b) and (c) are examples of strongly shaped discharges. In both (b) and (c), the outer plasma edge was nominally bean-shaped while the SXR images indicate more central elongation for case (c) than (b). Such variations in internal shape can be produced by modifications to the external shaping currents and/or the plasma current profile. For constant external conditions, the plasma current profile in the interior is a sensitive function of such parameters as impurity distributions, rate of rise of plasma current, toroidal magnetic field strength, and possibly MHD activity.

To advance the analysis beyond this qualitative comparison requires two steps: 1) the determination of the relative gain of the detector across the image; and 2) the development of an inversion algorithm which will convert the measured tangential image to a poloidal emission distribution.

Since the photons strike the MCP at different angles for each area of the image, there is every reason to expect some spatial variations in the detector gain. Nonlinearities due to gain saturation of the MCP intensifier are also a possibility. Ideally, an independent measurement of the sensitivity of the detector should be done using a laboratory SXR source. We are presently in the process of constructing such a source for an in-lab calibration in the near future. In the meantime, a crude in situ calibration of the detector was possible by comparing the measured image of a symmetric near-circular plasma to that calculated using a poloidal emissivity profile measured with a standard vertically scanning X-ray diode array wave detector on PBX. Even though the energy response of these discrete surface barrier diodes differs from that of the SXR camera MCP, it is reasonable to assume that both diagnostics detect the same poloidal distribution from these PBX discharges

since, in both cases, the signal is dominated by nickel L-line emissions which are emitted in the relatively narrow 0.8 to 1.5 keV energy range.⁶ The resulting gain correction surface derived in this manner for the SXR camera shows a roughly cylindrical gain correction centered near the optic axis with a total range of about a factor of two across the detector. A constant gain is assumed in the outer regions of the detector where the comparison with the diode array data does not provide any overlap with the camera field of view.

As mentioned earlier, the measured image is a toroidal projection of the desired poloidal emissivity distribution. Assuming toroidal symmetry, the intensity of light detected by a given pixel at location (i,j) in the image is given by

$$I_{i,j} = A_{i,j} \int E(R,z) dl, \quad (1)$$

where $A_{i,j}$ is a geometric constant for the given line of sight. R is the major radius from the torus center, z is the vertical displacement from the torus midplane, E is the volume emissivity in the poloidal (i.e., R,z) plane, and the integral is along the line of sight of the given pixel. Several techniques are available for inverting the integral in Eq. (1) to derive reasonable estimates of $E(R,z)$ from the intensity measurements. Given a camera field of view which is sufficiently wide to cover the entire plasma cross section, Eq. (1) can be reformulated as a discrete matrix operation which can then be formally inverted to derive $E(R,z)$. This approach, however, tends to be ill-conditioned in that very accurate and noise-free measurements of the image are required to avoid excessive noise in the resulting emissivity profile.

A more tolerant approach has been employed in our initial attempts at deriving emissivity contours, and we refer to this inversion technique as Fourier mode modelling by minimization of the spectral radius. Here we reconstruct the measured image by building a poloidal emissivity profile, $E(R,z)$, with a sum of cartesian Fourier components in R and z . That is, a best fit to the gain-corrected measured image is obtained while minimizing the functional

$$W = \sum_i \{ \nabla E_i \}^2 / \sum_i \{ E_i \}^2 + \lambda^2 \sum_j \{ I_j - I_j^* \}^2, \quad (2)$$

where E_i is the emissivity in poloidal zone i , I_j is the calculated intensity for pixel j , I_j^* is the measured intensity for pixel j , and λ is a variational multiplier. The first term in Eq.(2) restricts the reconstructed poloidal distribution to having the lowest frequency Fourier components consistent with fitting the data, while the second term forces the model image to approximate the measured image in a least-squares sense. Limitations on the use of this inversion algorithm to date include the fact that we expand only in terms of $\sin(nR/a)\sin(mz/b)$ with n,m ranging from 1 to 17 (where a and b are constants). Also, we have not yet included all relevant geometric constraints in the code (e.g., vignetting by the vacuum flange, internal hardware, etc.). This model can usually be made to converge to a best fit of the measured image that deviates from measurements by about 5% or so across the image. This iterative convergence code operates on a 31×31 pixel image derived from the original 64×64 pixel image which was uploaded from the LSI-11/73 to the VAX cluster where these inversions are computed. The final results are then downloaded back to the RCI image processor for final display.

Discussion

Substantial differences in internal plasma shape are readily apparent in comparisons between discharges of different external shape even with the relatively crude intensity calibration obtained to date. Figure 7 shows the inverted poloidal distributions for near-circular and bean-shaped plasmas. The expected nested circular flux surfaces are evident in the first case, where the inverted image gives a reasonably good representation of a circular cross section. Meanwhile, the discharges in Figs. 7(b) and (c) which are bean-shaped on their outermost flux surfaces show strong internal shaping. The inferred flux surfaces for the indented, or bean-shaped plasmas are elongated in the plasma interior, as expected. The more strongly shaped discharge in Fig. 7(c) also shows some evidence of triangularity as one goes away from the plasma center. While the inversion of the bean-shaped plasma is well-behaved in that the image appears to be reasonably symmetric around the plasma center, the apparent plasma center itself is 5 to 10 cm further out than measured magnetically for these discharges. This presumably reflects some standard error in the inversion which may be due to an uncertain intensity calibration and/or a positional error. Some of the detailed structure in the inverted images is due to the finite spectral radius (i.e., number of Fourier modes used) in the inversion. The outermost surfaces display more of a dee shape than the bean shape, which would be expected from external magnetics and visible edge plasma observations. However, these outermost regions are regions of low electron temperature and hence low SXR emissivity. This low emissivity, the approximate nature of the intensity calibration at wide angular fields, and the fact that the inversion code does not yet include the effects of vignetting surfaces can all contribute to a low confidence in the exact shape of the plasma well off the midplane.

Nonetheless, relative changes in the internal plasma geometry can clearly be seen using the present analysis methods.

Building on the success of these first tests, future efforts in this diagnostic development will include refinements on several fronts. A laboratory SXR source, which is in development, will allow direct calibration of the present and future detector systems. An improved detector design is under development for the PBX-M tokamak experiment, which is a modified form of the PBX experiment. This detector will consist of a local SXR scintillator to convert the SXR photons to visible light, followed by a long fiber-optic image conduit to transmit the visible image to a sealed high gain image intensifier which can be located well outside the magnetic field. Higher time resolution will be obtained by gating the intensifier photocathode. Efforts are also underway to produce a sufficiently simple inversion code which will allow image inversions to be performed on the local LSI-11/73 microcomputer in the time between plasma discharges.

In summary, a simple tangentially viewing SXR camera has been shown to be an effective means of monitoring the internal shape of magnetically confined toroidal plasmas. The compact mechanical design and moderate needs for physical access to the plasma vacuum chamber make this a relatively easy diagnostic to implement. An inversion technique which assumes only toroidal symmetry allows the cross-sectional emissivity distribution to be derived from the measured image. Further refinements on detector design, filter selection, automation, and real-time analysis are all under active consideration for future experiments.

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Figure Captions

Figure 1. Location and field of view of the soft X-ray camera system on the PBX tokamak. The camera lies in the vertical midplane of the device.

Figure 2. Schematic diagram of the soft X-ray camera on PBX.

Figure 3. Major electronics components for control, acquisition, and analysis of data from the SXR camera.

Figure 4. Example of reduction of raw image data to first level processed image: (a) Raw image from video tape; b) Same image as in (a) after background subtraction, alignment, smoothing, contrast stretching, removal of the image of a wire in the camera field of view, and imposition of contoured intensity scale. The intensity scale is indicated by the vertical bar code on the right.

Figure 5. Distortion of image due to toroidal projection of tangentially viewed source. (a) Model source distribution in poloidal plane for a circular plasma. (b) Model source for an elliptical plasma with a vertical elongation of 1.3. (c) Calculated camera image of the circular case (a) viewed tangentially. (d) Calculated camera image of the elliptical case (b).

Figure 6. Processed camera images of PBX plasmas for: (a) small circular plasma; (b) a bean-shaped discharge with mildly elongated inner flux surfaces; and (c) a bean-shaped discharge with stronger internal shaping than (b).

Figure 7. Inverted poloidal distribution for the three cases of Fig. 6: (a) near-circular small plasma; (b) indented plasma with moderate internal elongation; and (c) indented plasma with stronger central shaping than (b).

Figure 1

Figure 2

Figure 3

(a)

(b)

Figure 4

(a)

(b)

(c)

(d)

Figure 5

Figure 6

Figure 7

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