

## “Optical” soft x-ray arrays for fluctuation diagnostics in magnetic fusion energy experiments

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We are developing large pixel count, fast ( $\geq 100$  kHz) and continuously sampling soft x-ray (SXR) array for the diagnosis of magnetohydrodynamics (MHD) and turbulent fluctuations in magnetic fusion energy plasmas. The arrays are based on efficient scintillators, high throughput multicladd fiber optics, and multichannel light amplification and integration. Compared to conventional x-ray diode arrays, such systems can provide vastly increased spatial coverage, and access to difficult locations with small neutron noise and damage. An eight-channel array has been built using columnar CsI:Tl as an SXR converter and a multianode photomultiplier tube as photoamplifier. The overall system efficiency is measured using laboratory SXR sources, while the time response and signal-to-noise performance have been evaluated by recording MHD activity from the spherical tori (ST) Current Drive Experiment-Upgrade and National Spherical Torus Experiment, both at Princeton Plasma Physics Laboratory. © 2004 American Institute of Physics. [DOI: 10.1063/1.1787902]

### I. MOTIVATION OF THE PRESENTED RESEARCH

The use of optical, scintillator-based, soft x-ray (SXR) arrays for plasma physics imaging diagnostics, could circumvent many of the problems encountered by solid state devices. These optical arrays will match the present diode-amplifier-based arrays fast time response (on the order of  $1 \mu\text{s}$ ), having at the same time a superior performance with respect to noise introduced by neutron bombardment [neutrons flux from the plasma-neutral beam (NB) interaction and fusion reactions in the case of burning plasmas] and electromagnetic pickup. Other benefits of the proposed system rely on its compactness, UHV compatibility, portability, and relatively reduced price. Its applications are of great importance and interest in confinement, magnetohydrodynamics (MHD), perturbative, and nonperturbative transport and turbulence studies, in magnetically confined plasmas.

The present article deals with the optimization of the conversion of optical data into an electrical signal and the construction, installation and characterization of an optical soft x-ray (OSXR) array for spherical tokamaks. The configuration used has a long history as part of soft x-rays and vacuum ultraviolet (VUV) diagnostics schemes.<sup>1,2</sup> Section II describes the array elements and the photomultiplier tube (PMTs) electrical characteristics and constraints. The results obtained in both the Current Drive Experiment-Upgrade (CDX-U) and National Spherical Torus Experiment (NSTX) ST are pointed out in Sec. III.

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### II. COMPONENTS OF THE OPTICAL SOFT X-RAY (OSXR) ARRAY

The in-vacuum components consist of a rectangular pinhole, a filter foil, and a SXR converter. The hard x-ray shielding is made out of a thick ( $3/4''$ ) 304 SS plate mounted on an 8 in. zero length vacuum flange adaptor attached to a pneumatic gate valve. The 5 mm beryllium foil cuts off the low VUV energy with a typical transmission coefficient of 58% for a 1 keV photons. The filter holder and rectangular ( $2 \text{ mm} \times 12 \text{ mm}$ ) pinhole determine the radial and toroidal light integration, thus defining the spatial resolution. The soft x-rays to visible light converter is made out of a thin ( $30 \mu\text{m}$ ) CsI:Tl crystal growth deposited on a numerical aperture (NA)  $\approx 1$  fiber optic face plate, as depicted in Fig. 1. The scintillator of choice has a conversion efficiency close to 70% of the well-known P45, but a time response 1000 times faster.<sup>3</sup> The converter is optically coupled to a 40 mm diameter,  $1/3$  in. thickness, NA  $\approx 1$ , UHV compatible fiber optic window (FOW) mounted on a 6 in. CF flange. Outside the vacuum, high throughput, multicladd, nonscintillating (NA  $\approx 0.7$ , 4 mm square, 1.5 m long) fiber optics are distributed radially outwards at the bottom of NSTX ST. These fibers are perpendicularly attached to the FOW with the help of fiber optic grease to enhance the optical coupling. The fibers optics extend for 1.5 m to NSTX floor where the optoelectrical converter (PMT) is located.

Among the numerous photodetectors available, the photomultiplier tube (PMT) is one of the most versatile and “efficient” devices on the market, providing extremely high sensitivity and ultra-fast response to low incident light levels. A *Hamamatsu H6568-10*,  $4 \times 4$  multianode array (metal package, 12 dynode head-on type PMT) was the detector of

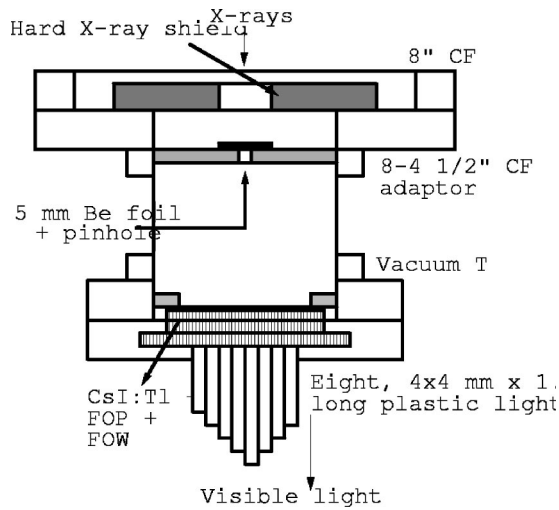


FIG. 1. Expanded view of the conversion in-vacuum system.

choice. It is a metal channel-type detector with the ability to deliver a high-speed response (of the order of 0.5 ns). Its time scale satisfies the requirements of the “optical” SXR array since the diagnostic’s time resolution is limited by the scintillators time decay. The alkali photocathode has a favorable blue-green sensitivity for scintillator flashes from CsI. With a peak emission of CsI:Tl around 555 nm and a PMT high voltage between 350 and 400 V, the PMTs gain and anode sensitivity ranges from 600 to 1200 and 20 to 50 A/W, respectively. Since the PMT can experience variation of gain in the presence of an external magnetic field, a 0.05 in. thick  $\mu$ -metal cylinder has been used to provide a first layer of shielding from the toroidal and equilibrium magnetic field coils. The second and stronger shielding is provided by a 1/4 in. cast iron core surrounding the  $\mu$ -metal, in order to avoid its saturation. In the case of the 16 channels H6568-10, we have a normalized anode uniformity of (minimum) 57% and a maximum anode cross talk of 0.5%. In order to obtain signals that can be digitized, we have used *Femto*, low-noise, stable, current transimpedance amplifiers, with a set gain of  $10^7$  V/A and a 400 kHz bandwidth.

### III. RESULTS FROM CDX-U AND NSTX PLASMAS

Even though CDX-U and NSTX plasmas have intrinsically the same order in plasma density there are substantial differences with respect to their plasma current (20–60 kA versus 0.8–1 MA), flattop timescales (1–20 ms versus 0.2–0.6 s) and electron temperatures (50–300 eV versus 0.8–1.5 keV).<sup>4,5</sup> In CDX-U we have used the interaction between the plasma and a Mach 7 supersonic gas injector. Recording data at a rate of 250 kHz, we compared MHD plasma oscillations using the “optical” array and a toroidally displaced 64-channel diode based array. The comparison between channels gave an approximate time decay for low energy soft x-ray photons of less than 8  $\mu$ s. A similar comparison was made for NSTX plasmas, using the “optical” array and a 90° toroidally displaced 16-channel (absolute XUV) diode array. A first assessment of  $\tau_{\text{CsI:Tl}}$  was made using a fast, poloidally traveling, edge localize mode. A second evaluation of  $\tau_{\text{CsI:Tl}}$  was also addressed by comparing the

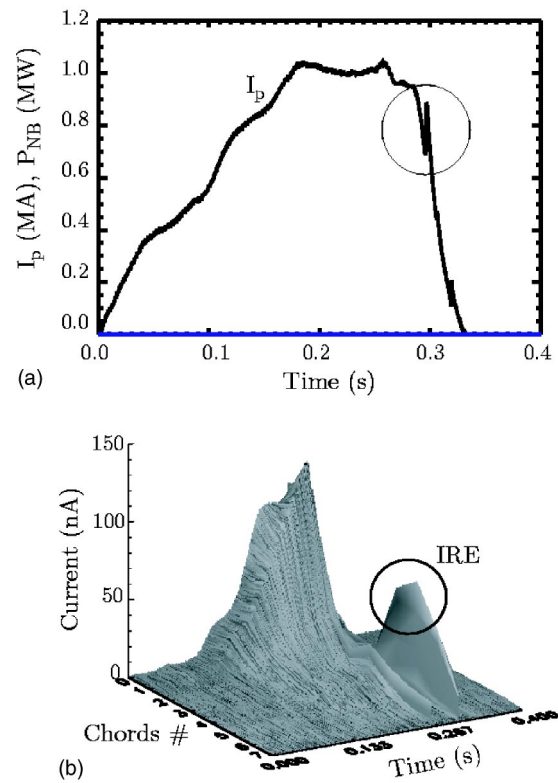


FIG. 2. Plasma current (a) and “optical” SXR chord profile (b) time histories for an ohmic shot ( $P_{\text{NB}}=0$ , NSTX 112069).

MHD frequency spectrum obtained by both arrays. From all these results we can infer that CsI:Tl time response for approximately 1 keV photons, is comparable to that of the AXUV photodiode (2–3  $\mu$ s). We can conclude therefore, that the time response for the scintillator of choice is quite appropriate for systems at which the sampling rate is in the order of 200–400 kHz.

As part of the diagnostic benchmarking, we have clearly identified plasma discharges where MHD phenomena, from ohmic to neutral beam and high harmonic fast wave heated plasmas, can be easily measured. Figure 2 presents the time history of the XUV distribution in a 1 MA Ohmic discharge. One can see that the SXR profile is affected by an internal reconnection event, which took place during the plasma current ramp-down. A more detailed picture (chord by chord time histories), is presented in Fig. 3: Data from the AXUV diode array Fig. 3(a) and the “optical counterpart” Fig. 3(b) have the same time histories for all channels, from views through the core to those recording the plasma outboard edge. A 2 ms time frame history of the same 1 MA, 4.5 MW NB heated H-mode plasma is shown in Fig. 4. One can clearly observe that the MHD 2.25 kHz perturbation suffers an inversion at outer radii, probably as a result of a magnetic reconnection event.

As part of the same benchmarking experiments, a noise evaluation was also performed in H-mode discharges where the plasma current was 1 MA and three 2 MW NB sources were used. Before the hot plasma formation, the AXUV diode signal is greatly affected by neutron bombarding and electromagnetic pickup noise from the current ramp up, while the “optical” array seems less sensitive to it. From a

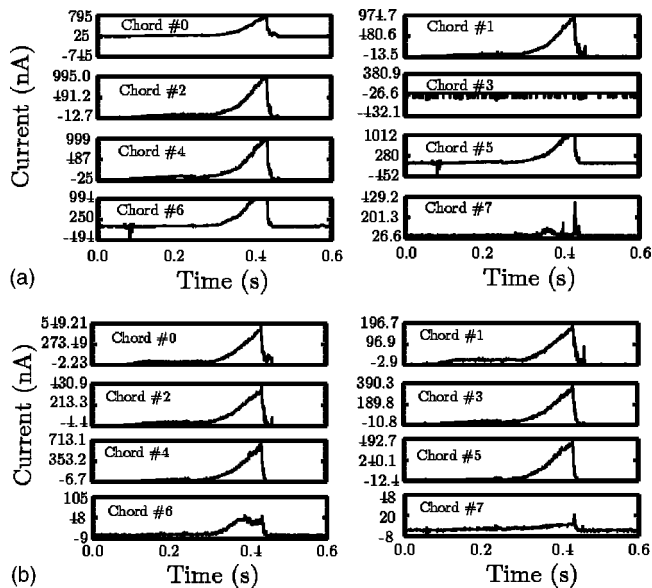


FIG. 3. Time history from AXUV diode (a) and “optical” arrays (b) (NSTX 112036).

more detailed analysis—15 ms time frame window—the noise generated on the diode array by 6 MW NB heating power is found to be higher than that of the optical array by a factor of 5.

In summary, the signals obtained in ohmic and NB heated plasma discharges on NSTX and CDX-U tokamaks indicate that the optical SXR array tested in the present work, can be easily used for MHD and perturbative transport studies. The time response for the scintillator of choice (CsI:Tl) is appropriate for systems requiring sampling rates of the order of 200–400 kHz. The “optical” arrays can be used in a mono- and/or multi-color modes as well as in a tangential imaging setup for current profile reconstructions.<sup>6</sup> A big advantage of the “optical” array over the classical x-ray diode arrays is its transparency to the neutron bombardment from NB heated plasmas. These arrays under study, can also be used in less harsh environments such as that of ion heating studies in magnetic reconnection current sheets.<sup>7</sup>

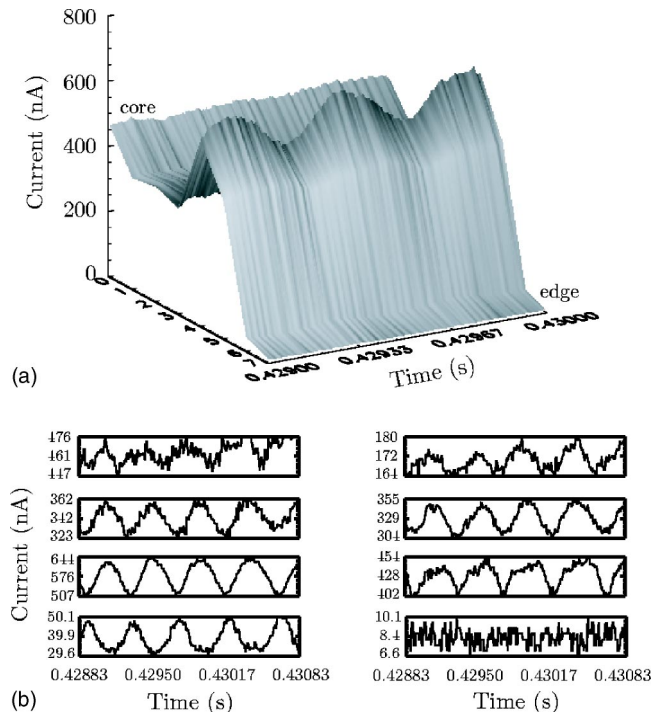


FIG. 4. Chord profile (a) and time history (b). The inversion occurs in chord 6 (NSTX 112036).

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