The JET Soft X-Ray Diagnostic Systems

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ABSTRACT

A 250 channel soft X-ray detector system has been constructed for the pumped divertor phase of JET. It is based on 12 compact pinhole cameras each of which uses a 35 element PIN photodiode, providing six independent poloidal views of the plasma at one toroidal location. The cameras are housed in a secondary vacuum and view the plasma through beryllium windows 250µm thick. The front-end electronics, located up to 10m away from the detectors, sample data at 250kHz, with a 100kHz pass-band. With the diodes at zero bias voltage, the diagnostic operated successfully during the 1995 phase of JET operation with noise levels below 1nA. Some deterioration in diode performance was observed after exposure to an integrated neutron fluence of $\sim 10^{13}$ $n.cm^{-2}$. Tests have shown that operating with 3V reverse bias can offset much of the fall in performance from radiation damage. Using a similar 16 element PIN photodiode, a windowless camera has been developed for installation in the JET primary vacuum, to investigate fast XUV/X-ray events in the divertor. Finally, a radiation hardened system is being developed for D-T operation.

I. INTRODUCTION

The opportunity was taken during the long 1993/4 operational shutdown of JET tokamak, for the installation of the Mark I pumped divertor, to upgrade the original JET soft X-ray (SXR) diode array system [1]. The primary objectives of the diagnostic upgrade were to improve the spatial and temporal resolution of the SXR system and at the same time to standardise the data acquisition system using state-of-the art electronics for all fast diagnostics on JET. (For a more detailed description of the data acquisition system see [2]).

The original SXR diode camera system provided two independent orthogonal views of the plasma at one toroidal location. Although nearly 100 channels were available, with only two views, the tomographic reconstruction of the plasma was limited to the use of poloidal fourier terms up to $\cos(2\theta)$ only. This has caused some difficulty when interpreting MHD activity such as the sawtooth collapse. The new system has consequently been upgraded to provide 6 independent views.

Viewing the plasma from a number of directions at one toroidal location has required the installation of cameras around the vessel wall away from access ports. As the vessel is maintained at above 300°C and space is limited, a number of novel features were incorporated into the design.

This paper describes the system design, summarises our operational experience and outlines some changes to be implemented for the next phase of operation.

II. FEATURES OF THE SXR CAMERA ASSEMBLIES

The limitation of available space inside the JET torus has inevitably led to the choice of multichannel diode arrays on a single silicon chip. The detectors used are Centronic LD35-5 PIN photodiode arrays. Normally designed to operate in the visible, these type of detectors have been found to work well in the SXR region[3]. Each array consists of 35 elements with anodes 4.5mm by 0.96mm at 0.99mm spacing with common cathodes. In this application we use only every other channel in each array, i.e. 18 channels per array, (except in the vertical cameras where every element is used). The unused channels have their anodes shorted to the common cathode to minimise cross-talk and also because floating channels were found to affect the gain of neighbouring elements by up to 20%. Views of the plasma from six independent directions at one toroidal location - octant 2 - have been implemented using 5 separate assemblies. Figure 1 illustrates the main features of the system as it is now, with the upper horizontal camera (not shown but similar to the lower assembly) replaced by a new windowless camera (see Section V below).

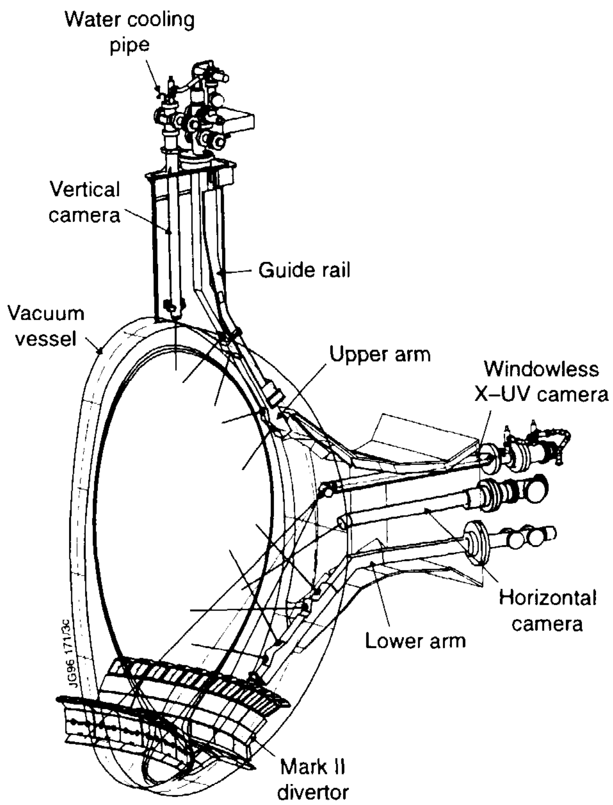

Figure 1. General view of the current layout of 5 SXR diagnostic assemblies located at octant 2. The figure includes the new windowless X-UV camera which replaces the original upper horizontal SXR assembly. The central line-of-sight of each soft X-ray camera and the outer lines-of-sight of the XUV camera are indicated.

The upper and lower arms each contain four arrays mounted in two pairs enclosed in a single water-cooled secondary vacuum assembly. Each camera-pair has ~ 90° viewing angle. The viewing aperture of each array (1mm by 6mm) is defined by a 1mm thick tungsten plate contoured for precise edge definition. The plasma is viewed through 250 μm thick Be windows to isolate the primary and secondary vacuum and to filter out X-rays below energies of 2 keV. The windows were tested to a pressure differential of over 3 bar. Each camera incorporates a shielded single element version of the diode to allow subtraction of neutron and gamma ray backgrounds during high performance discharges and a pair of infra-red emitting diodes for calibration. The horizontal and vertical cameras were housed in straight tubes, one array per tube, which allowed removal of the detector assemblies without the need for venting the torus. A further assembly, identical to the vertical camera but displaced toroidally by 3 octants has been installed to provide information on toroidal variations in SXR emissions. Detailed survey measurements of each camera during manufacture and of the final assemblies before and after installation were carried out to establish the lines of sight within the plasma.

In the design of the camera heads careful attention had to be taken to optimise heat transfer to the water cooling pipes, yet minimise radiative and convective heating from the torus. Also, the copper content (required for conductive cooling of the diodes) had to be minimised to reduce possible forces on assemblies from eddy currents during plasma disruptions. A multi-layer thermal radiation shield was included in each camera and the secondary vacuum was maintained below 10^{-5} mbar to minimise convective heat transfer to the diodes. With the JET vacuum vessel held at 250 $^{\circ}$C, the camera temperatures have been measured at 5°C above the supply water temperature. Under test conditions of no water flow, the camera temperatures rose at a rate of 0.7°C per minute which would lead to potentially damaging temperatures for the detectors (>150°C) in about 3 hours.

The front-end amplifier and ADC electronics are housed in cubicles in the torus hall. Typical signal cable lengths from the detectors to ADC cards are ~8.5m. Each amplifier/ADC card is electrically isolated from the rack and is powered by a dedicated isolated supply. Electrical ground is referenced to the torus at the detector common cathode only, to remove possible earth loops. One rack holds up to 19 ADC cards - sufficient for one camera array and neutron detector. The ADCs sample at 1MHz (12 bits) but are filtered down to 250kHz, with a 100kHz pass band. The data from up to 19 ADC cards is multiplexed together and transmitted via a single TAXI / fibre optic interface to the diagnostic area for selection and storage [2].

III. DETECTOR PERFORMANCE TESTS

The detectors were operated in photoamperic mode; that is with zero bias into low impedance amplifiers. This has the advantage of minimising noise and dark current and removing the possibility of cross-talk through a common power supply for the bias voltage. Tests carried out in the infra-red showed that for a new detector the gain was stable against small variations in bias voltage from -75mV to +100mV and that the frequency response was adequate for the 100kHz bandwidth (3db), originally specified.

Operating with zero bias means that the diodes are not in a fully depleted mode. Studies by Cho[4] indicate that electron-hole pairs created in a diffusion region of typically 50-120μm depth can diffuse into the depletion region (~10μm with zero bias) and contribute towards the signal current. For 8 keV X-rays this would lead to a collection efficiency in the range 55% to 85%. The relative calibration of all diode elements for 8 keV X-rays was carried out at MIT. The performance of two arrays, the best and worst tested, is shown in Figure 2. A variation in efficiency comparable to that mentioned above was found.

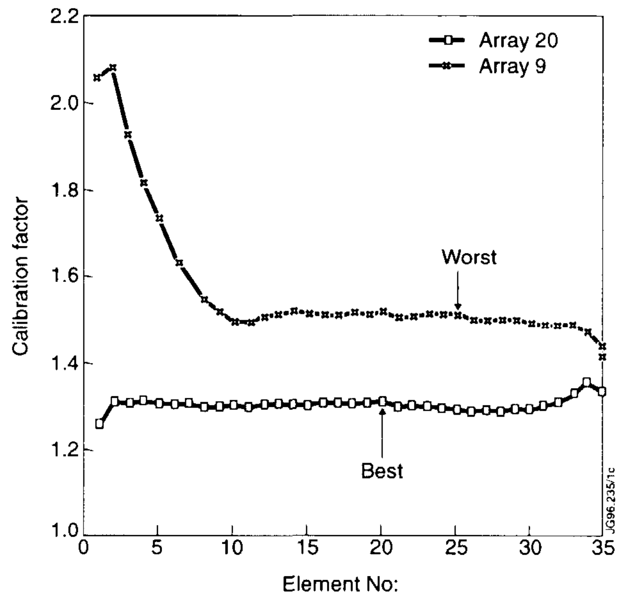

Figure 2. Relative efficiency of all 35 elements in two camera arrays, the best and worst tested, measured with an 8 keV X-ray source. The calibration factor is inversely proportional to diode efficiency. A selection was made of the 12 best arrays out of a total of 28 tested, leading to a variation in efficiency of only ± 3% for all central channels and ± 4% for all edge channels

IV. OPERATIONAL EXPERIENCE AND RADIATION DAMAGE

The system totalling 250 channels operated successfully over the 1994/5 run period. Cross-talk between channels was estimated at below 1%. The rms electronic noise during operation was ~0.8nA. For our geometry, bandwidth and filters, this implied that photon statistics would dominate over instrumental noise when the plasma brightness exceeded $80W/m^2$ which corresponds to ~5% of the typical brightness found in the centre of JET heated plasmas. Evidence from the shielded channels showed that n/γ backgrounds were negligible.

An example of tomographic reconstruction during a sawtooth on JET is shown in Figure 3, where poloidal harmonics up to 5 have been used.

The JET integrated neutron emission over this period was 2.41 10^{19} neutrons. This corresponds to a fluence through the detectors ranging from ~1-2 10^{13} $n.cm^{-2}$. Problems are expected to occur at these fluences where effective doping concentrations can invert n-type to p-type. Our first indication of damage was detected by an increase in the forward voltage required to put an element into conduction. This increased over the period from 0.51V for a new diode to over 2V, with the highest values measured for the cameras in the upper arm which were closest to plasma. With zero-bias operation, any increase in leakage current or detector noise was negligible but efficiencies for cameras in the upper arm were about 25% lower than the others at the end of the run period. Some of the damaging effects of radiation have, we believe, been offset by some self-annealing of the detectors due to the extended period of irradiance (14 months) involved.

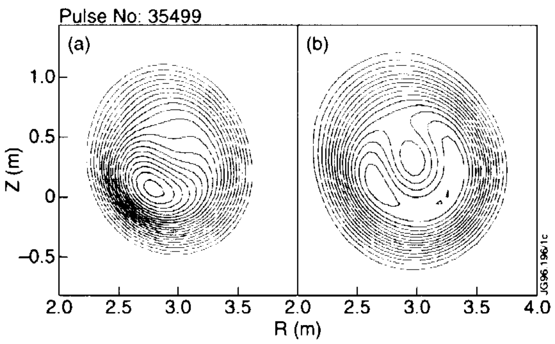

Figure 3. Tomographic reconstruction of SXR emission for two time slices separated by 24µs during a monster sawtooth collapse. Poloidal harmonics up to m=5 have been used in the reconstruction.

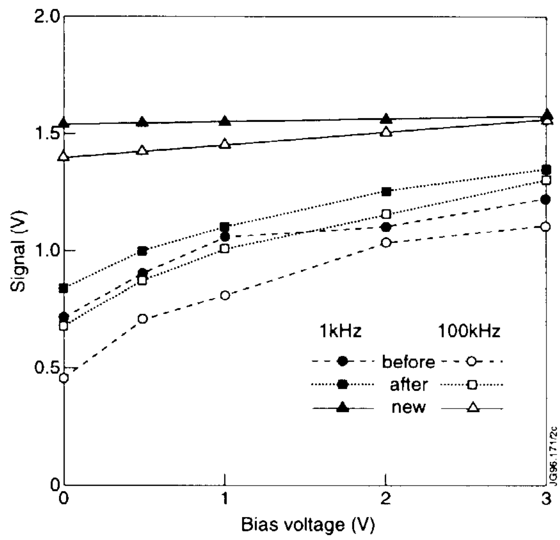

Figure 4 A comparison of the dependence of signal amplitude at 1kHz and 100kHz on bias voltage for diodes with different neutron irradiance histories. The 'before' curve corresponds to a diode exposed to a neutron fluence of ~1.5 10^{13} $n.cm^{-2}$, the 'after' curve to the same diode after annealing at 150°C for 24 hours and the 'new' curve to an unexposed diode.

At the end of this operating period diodes in the horizontal and vertical cameras were replaced by new ones. Laboratory tests on the irradiated diodes in the infra-red region are summarised in figure 4. Compared with new diodes, three significant changes have occurred. Firstly, the overall gain at zero bias has fallen by more than a factor of 2; secondly, the bandwidth has fallen somewhat and thirdly the diode voltage characteristics have changed.

Applying 3 volts reverse bias reduces the fall in efficiency to below 20% and improves the bandwidth. As a consequence of these results, 3V reverse bias has been applied to all SXR diodes in the coming operation by use of a lithium battery button cell (220mAh) at the input to each preamplifier. This method preserves the electrical isolation of each channel and with measured leakage currents below 150nA, the battery lifetime should be many years. As also seen in the figure, partial benefit can also be achieved by high temperature annealing at 150°C for 24 hours, although at these temperatures some flow of epoxy over the detector surface was observed.

V. NEW ASSEMBLIES

As already mentioned, a windowless system has now replaced the upper horizontal camera which incorporates an X-UV sensitive 16 element array, manufactured by IRD (type AXUV-16EL0 with a common anode). This camera has a longer focal length to provide better spacial resolution, at lower energies, of the divertor region and the outer edge of the plasma. The outer viewing limits are shown in Figure 1. It is hoped valuable information on the onset of ELMs (Edge Localised Modes) , in particular, as well as fast divertor instabilities will be forthcoming from this diagnostic.

During the forthcoming tritium phase on JET - DTE1 - the integrated neutron fluence is expected to be one order of magnitude higher, providing some prospect of survival for the detectors. The detectors will not survive the final tritium phase -DTE2 - where a further order of magnitude increase in neutron fluence is anticipated. For these phases a radiation hardened system consisting of two arrays of 17 individual detectors shielded from the plasma by ~1m of concrete is being developed. Each individual assembly will hold three identical detectors. The front diode will measure X-ray emission; behind it a similar diode measures gamma ray and neutron backgrounds and behind these a third diode is placed at the end of a 20cm long scintillator. This is intended to measure MHD-dependent variations in neutron emission during very high yield plasmas. The combination of the new and existing systems should provide a set of SXR diagnostics for the foreseeable future.

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