A Radiation Hardened Soft X-Ray Camera
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A Radiation Hardened 
Soft X-Ray Camera

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ABSTRACT

A proposal is made to construct a radiation hardened soft X-ray camera which will be used to provide a vertical stabilisation signal immune from the interference from edge effects and also signals which can be used to study mhd effects. The system will work through the future D-T periods of operation and will consist of two heavily shielded soft X-ray cameras opposite each other on octants 4 and 8.

1. INTRODUCTION

The present proposal is motivated by the wish to carry out soft X-ray measurements throughout the future D-T phases of operation of JET. The present systems (KJ3, 4) will work only for D-D discharges and at higher neutron fluxes the signals will become excessively noisy and the detectors will eventually cease to work. It is the intention that the radiation hardened system will provide a measurement of the plasma vertical position for feedback stabilisation and determine the mhd properties of the plasma both from soft X-ray measurements and from neutron flux measurements.

1.1 Radiation Effects

It has always been recognised that it is difficult to determine the plasma X-ray emission in the presence of large fluxes of neutrons. The neutrons induce a background signal in the X-ray detector which needs to be corrected, and it produces a disproportionately large noise level because the incident radiation has much higher energy per particle compared with the energy per particle for X-radiation (1.4 x 10^2:10). Further, if Si diodes are used as detectors these will start to suffer from radiation damage at ~2000 rads (Si) and will stop working altogether at radiation levels 100 times larger. The solution to these problems is to mount the detectors in a well shielded environment to reduce the effects of neutron flux to an acceptable level.
1.2 Determination of Vertical Position

To measure the vertical position of the plasma, a camera arrangement is required so that the mean plasma position can be determined. However, a single camera viewing the plasma at one toroidal position will be sensitive to $m = n = 1$ plasma instabilities which are both large and frequently present. To overcome this limitation it is proposed to install two cameras viewing the plasma at diametrically opposite positions on the torus at octants 4 and 8. By averaging the signals from both cameras the effects of any odd $n$ modes will be eliminated.

The accuracy of the measured vertical position will be determined by the accuracy of the individual measurements of the different lines of sight and the total number of channels ($n$). In a peaked soft X-ray profile the relative error, $\sigma_h$, of the height of centre of the plasma, $h$, is given approximately by

$$\frac{\sigma_h}{h} = \frac{1}{\sqrt{n}} \frac{\sigma_I}{I}$$

where $I$ is the intensity of the central soft X-ray detector and $\sigma_I$ its error. As $\sigma_I/I \leq 1\%$ will be achieved and $n = 19$, $\sigma_h/h \leq 0.23\%$. As $h \sim 1.7m$, $\sigma_h \leq 4mm$. Generally the accuracy will be better than this.

2 Soft X-ray Measurement in High Neutron Fluxes

In the remainder of this report the performance of the proposed system in the DTE2 experiment will be considered. This will be assumed to consist of 1000 D-T shots each producing 10MW of power of which 80% will be in the form of 14MeV neutrons. In addition it will be assumed that a total X-ray power of 100kW will be observable. This represents a very cautious estimate, based on experience with the present systems, of the power level which will be encountered in high performance discharges. The use of 250μm thick Si detectors will be assumed. These have an efficiency of 1 for X-rays in the region of interest. The estimated detector efficiency, defined as the ratio of the power deposited in the detector to the incident power, is shown in table 1.
Table 1

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy</th>
<th>ε</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray neutron</td>
<td>1-20keV</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2.5MeV</td>
<td>3 x 10⁻⁵</td>
</tr>
<tr>
<td></td>
<td>14MeV</td>
<td>4 x 10⁻⁴</td>
</tr>
<tr>
<td>X-ray</td>
<td>3-10MeV</td>
<td>1.3 x 10⁻³</td>
</tr>
</tbody>
</table>

If it is assumed that the powers per unit volume for X-ray and neutron production are $S_X$ and $S_n$ then the observed currents observed directly in a Si detector are

$$I_x = \frac{\Lambda}{3.6} S_x \ell_x, \quad I_n = \frac{\Lambda}{3.6} S_n \ell_n \varepsilon_n,$$

where $\ell_x$ and $\ell_n$ are the effective chord lengths in the plasma over which emission takes place and $\Lambda = A_1 A_2 / 4\pi L^2$ where $A_1$ is the pinhole aperture, $A_2$ the detector area and $L$ their separation (Figure 1).

![Detector - plasma geometry.]

The indirect neutron signal will be considered later. It can be shown that for 10MW of fusion power $I_n/I_x = \varepsilon_n S_n \ell_n / S_x \ell_x = 1/18$. It is therefore in principle possible to design a system with a small neutron radiation signal assuming the indirect signal can be adequately shielded.
2.1 Signal Noise

As well as the magnitude of the neutron induced signal, its effect on the overall signal to noise must also be considered. The main noise arises from fluctuations in the number of particles per unit time (N) depositing energy in the detector. In a time interval $\tau$ the current fluctuations are $\frac{\Delta I}{I} = \frac{1}{\sqrt{N\tau}}$. Each particle deposits an energy $E(eV)$ so that $I = eEN/3.6$ and hence

$$\frac{\Delta I}{I} = \sqrt{\frac{eE}{3.6I\tau}}$$

As $E_x \sim 8eV$ for X-rays and $E_n = 8\text{Mev}$ from $(n, \alpha)$, $(np)$ reactions it is clear that neutron induced signals have a disproportionately high noise level and in the DTE2 experiment the neutron induced noise will be of predominant importance as $I_xE_x \ll I_nE_n$. If the detector current is $I_d = I_n + I_x$ then

$$\frac{\Delta I_d}{I_d} = \left(\frac{eE_n}{3.6\tau} \frac{I_n}{I_d^2}\right)^{1/2}$$

Taking $I_n/I_x = 1/18$ and $\tau = 33\mu$s gives

$$\frac{\Delta I_d}{I_d} = 2.4 \times 10^{-5} \quad \text{assuming } I_d = I_x$$

Hence low noise requires high detector current. Typical values are shown in Table 2. The original soft X-ray camera system had $I_d$ in the range 1-10$\mu$A and so

<table>
<thead>
<tr>
<th>$I_d$ ((\mu A))</th>
<th>$\frac{\Delta I_d}{I_d}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>0.7</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
</tbody>
</table>
it is clear that it is possible to build a system with an acceptably low noise - say better than 1% - as long as $I_d$ is kept reasonably large - i.e. the solid angle factor $A$ must be large.

2.2 Radiation Damage

The direct neutron flux at the detector

$$F = \frac{\Lambda S_n \ell_n}{A_2 e E_n} \text{ cm}^{-2} s^{-1}$$

and the dose rate $\mathcal{D}$ is the product of the flux and the kerma

$$\mathcal{D} = FK = \frac{\Lambda S_n \ell_n K}{A_2 e E_n}.$$ 

If $I_n = I_x/18$ as assumed above $\mathcal{D} = 5 \times 10^5 I_x A_2$ rads/s.

If the detectors can withstand a maximum of 2000 rads or 1.4 rad/s for 800 DT shots of ~2, then $\frac{I_x}{A_2} < 2.8 \times 10^{-6}$ A. cm$^{-2}$. For a detector of 2 cm$^2$ $I_x < 5.6 \mu$A which corresponds with a noise level of 1.0% which can be regarded as satisfactory. It should also be noted that the effects of the gamma ray background induced by the neutrons has been ignored as this is much less important than for 14MW neutrons.

2.3 Radiation Shield Requirements

The calculations of Avery provide radiological data at the horizontal port for the $5 \times 10^{21}$ neutrons produced in the plasma by 800 pulses in DTE2. These produce a total dose in Si of $6 \times 10^4$ rads. In any camera design this overall dose will have to be reduced by means of a shield to a level which is less than the direct dose i.e. it would be useful to aim for 10 times less than the direct dose which is 200 rads. A shield is therefore required to reduce the dose by a factor of 300. To be conservative a reduction factor of 1000 should be a design requirement and this can be achieved with 75cm of barytes concrete (high Ba concrete). This also makes an effective $\gamma$-ray shield.
The thickness of the shield at the sides and back can be considerably less, and 1/2 of 75cm would seem to be a conservative estimate. Hence the detectors should be surrounded by a shield 75cm thick in the plasma direction and 37cm thick in all other directions.

3. DETAILS OF DETECTORS AND THEIR COLLIMATOR

The X-ray and neutrons must be well collimated by a tube which is an integral part of the shield. The tube has a cross-sectional area of 2cm² and it is proposed to manufacture it by milling a slot in a metal plate. The detector assembly will consist of a Si X-ray detector, an identical neutron background monitor and a plastic scintilllator to provide a low noise neutron signal (Figure 2).

If the soft X-ray detector current is 5.6μA as determined from radiation damage consideration then the solid angle factor may be found and is 4.2 × 10⁻⁵ cm and this would give the detector area as 1.7cm² for L = 75cm. It is proposed to increase the detector area to 2cm² (i.e. 14mm square) as these seem readily available. The corresponding calculated number of neutron through the 2cm² detectors (with solid angle 5.6 × 10⁻⁵) is 1.6 × 10⁹ s⁻¹ which gives a radiation induced signal of 0.4μA. The X-ray signal will be 7μA and δIₓ = 0.009μA, δIₙ = 0.061μA. Hence, as expected, the noise is due entirely to the neutrons and δIₙ/Iₓ = 0.009 which is better that the 1% required. The level of neutron emission will be very poorly determined by the Si background monitor as δIₙ/Iₙ = 0.16 and this is the reason for the scintillator detector which will produce a signal with a lower noise figure.
3.1 Scintillator Detector

A length of BC430 scintillator has an attenuation length for 13MeV neutrons of 9.6ms. A 10cm length will interact with 65% of the incident neutrons, 30% in interactions with H atoms and the remainder with C atoms. Due to momentum conservation the energy will be deposited in the scintillator mainly via the H atoms and it will be assumed that the mean energy deposited per interaction will be 7MeV. The signal in a (blue sensitive) pin diode used as a light detector will be

\[ I_N = N_n \times 9.8 \times 10^{-2} \times N_p \times (eE_x) \times C \times S \]

with

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_n )</td>
<td>No of incident neutrons/s</td>
<td></td>
</tr>
<tr>
<td>( N_p )</td>
<td>No. of photons produced by one 7 MeV proton</td>
<td>4.6 \times 10^4</td>
</tr>
<tr>
<td>( E_x )</td>
<td>Energy of BC430 photons</td>
<td>2.14eV</td>
</tr>
<tr>
<td>( S )</td>
<td>Diode sensitivity</td>
<td>0.3A/W</td>
</tr>
<tr>
<td>( C )</td>
<td>Collection efficiency of diode</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Typical Values**

Of these factors the diode collection efficiency is the most uncertain and it is intended to experiment with different arrangements in order to optimise this quantity. Taking \( N_n = 1.6 \times 10^9 \) gives \( I_N = 0.5\mu A \). The noise in \( I_N \) will be determined by the statistical fluctuations in the incident number of neutrons in time \( \tau = 33\mu s \) so that \( \delta I_N = 4.3nA \) and the overall noise level is 0.86% which is satisfactory. A possible problem is that of noise in the pin diode due to indirect radiation transmitted through the shield. The dose unshielded per shot is 75 rads at the port which is 37 rads/s. Attenuated by the radiation shield, the dose/s at the detector is 0.04 rads/sec which corresponds to a detector current of 14nA corresponding to a noise of \( \delta I/I = 0.8 \) i.e. about 11nA and larger than the noise of 4.3nA of the direct signal. This is something of a problem area and efforts must be made to increase the light output of the scintillator by careful coupling to the diode. It should also be remarked that the indirect dose calculation is probably pessimistic as the dose value at the port has been used whereas the detectors will probably be situated 2m from the port where the dose will be lower.
4. **PROPOSED CAMERA ARRANGEMENT**

The proposed layout and the lines of sight of the camera elements are shown in Figures 3 and 4. The large size of these systems is determined mainly by the shielding requirements. The central hole through the shield on the median plane is undesirable but essential to allow a line of sight of the KM9 and KX1 diagnostics (neutrons and high resolution X-rays). The design includes the following features.

1) Separation of the diagnostic from the main plasma vacuum by a 250μm Be window capable of withstanding atmospheric pressure of 2atm from either side.

2) A secondary vacuum at roughing pressure only (10^{-2}Torr)

3) Electronic cubicles mounted on the torus limbs for ease of access and for shielding. All signal connections are by optical fibres.

4) Rear access to the electrical connections to the detector is available at the Octant 8 assembly. This assembly would be installed in one unit but would need the breaking of the vacuum flight line of KX1.

5) The rear access to the Octant 8 assembly is poor to non-existent. This assembly would be installed as one unit but would not interfere with other diagnostics.

6) A careful alignment procedure will be developed which will take account of the movement due to baking of the port. The assemblies will be installed with their front faces at a measured position from the port in the correct vertical plane and at a premeasured toroidal angle. The Be window will be large enough to allow for alignment errors and the thermal movement.

5. **ELECTRONICS AND DATA COLLECTION**

It is intended to use a slightly modified version of the data collection electronics developed for the existing soft X-ray camera system (KJ3/4). The details of this are shown schematically in Figure 5.
The ADC card can allow for diverse plasma operating levels by amplifying the signal with a gain that is adjustable from 1 to 8,000. The DC offset is also corrected. An 8-pole linear phase analogue filter prevents aliasing of out-of-band signals, or noise, that could be present above the Nyquist sampling frequency. The ADC samples at 1 MHz. The 12-bit ADC output is fed through a digital filter chain which lowers the sampling frequency to 250kHz/16-bit and the pass-band to 100kHz, with a stop band of 125kHz. The control card acquires data from up to 19ADC cards in a read cycle. This data is multiplexed together and transmitted via a TAXI fibre optic interface. The back-end is shown in more detail in Figure 6. The system consists of a network of 40 MHz Texas Instruments TMS320C40 digital signal processors running the HELIOS operating system.

However, the front end ADC electronics will need modification as there is a delay of 99 micro-seconds going through two digital filters which reduce the initial sampling rate from 1MHz to 250kHz. These will have to be removed and the analogue filter modified to ensure a suitable frequency response with minimum high frequency noise. Other more minor modifications will also be required.

6. DATA PROCESSING

The back-end Texas Instruments C40 (TI C40) system will be fully integrated into the JET Diagnostic Central Acquisition and Trigger system. This will allow up to 3 seconds of data for each channel to be recorded for JET pulses.

In addition the TI C40's provide an ideal platform for real time data processing, a single TI C40 being able to record and process data from one camera. It is intended to calculate the vertical centroid of the soft X-ray profile from each camera as a measure of the vertical position of the plasma. This calculation can be performed for each data packet sampled at 250 KHz. This results in a delay of less than 4 microseconds being introduced with the TI C40 system. The calculated vertical centroid, together with the moment of the distribution which can be used as a "quality factor" for the measurement, will then be transmitted to PPCC via optical fibre.
CONCLUSION

A design of a soft X-ray camera system has been presented which will provide a high quality measurement of the vertical plasma position and also provide measurements of the plasma mhd. The system will work throughout the future D-T phases of operation.
Possible DTE1 soft X-ray camera layout.

3. Possible layout for the radiation hardened soft X-ray systems.
4. Engineering sketch of possible mechanical assembly.
5. Front end electronics.

6. Back end data collection based on C40 system.