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Abstract

A liquid Nitrogen cooled solid state Ge diode has been installed on the TCV tokamak to examine the X-ray spectrum from ~1→100 kev. The electronics for signal processing and data acquisition have been optimised to improve the data throughput to match the high flux 2sec time duration of a TCV plasma pulse. The plasma electron temperature has been measured both in L and H-mode type discharges and the observed count rate and spectral shape varied using externally selectable apertures and Be filters. No line radiation from intrinsic impurities has been observed in either case. The effect of pulse pile-up in such a system is analysed both experimentally and using a numerical model. The maximum count rate is shown to be limited by the analogue electronics processing but not by the signal processing.

Introduction

The plasma temperature in fusion related research is such that a considerable fraction of the radiation is emitted in the form of X-ray radiation (> 1 kev). The spectral resolution of a cooled solid state detector, as used in this paper, has historically been used to examine the X-ray emission from such a plasma where the energy of a single photon is measured, electronically recorded and the spectrum deduced by histogramming the photon energies (von Goeler). In a pulsed device, such as a Tokamak, the X-ray emission characteristics can vary over very short time periods and collection times are restricted. This type of diagnostic is thus often limited by the maximum signal rate, both in the diode itself and the electronics and acquisition systems. Furthermore, the dependence of the measured spectrum on the data rate must be understood or any measurement based on the spectral shape, such as the electron temperature, will be perturbed. In the installation on TCV (hoffman) , special care has been taken to ensure the highest count rate possible from the diode and to retain the time history of the collected information in order to examine and account for these effects.

X-ray Emission from a Tokamak Plasma

A Tokamak plasma consists of fuel gas (often deuterium) and small quantities of other (often unwanted) elements termed impurities. X-ray emission from a plasma where hν > T (plasma temperature) can be divided into three main parts (Hutchinson). Bremsstrahlung, mainly from the scattering of electrons on the slower ions gives an exponentially decaying spectrum in the X-ray region depending on the (maxwellian) electron temperature with the radiation intensity depending as Z^2 on the charge of the colliding ion. The inverse ionisation process, called Radiative Recombination, also gives an exponential X-ray tail at energies higher than the characteristic photon energy for capture into a given bound state. In a Tokamak, the combined intensity of these recombinations often dominates the Bremsstrahlung radiation even for small impurity levels. The final component is from line emission of partly ionised impurities with an intensity determined by the local plasma parameters and impurity content. Since the energy resolution of a diode detector is at best of the order of 100ev, these spectral lines are not often well resolved. If an impurity level is sufficient, the resonant spectral lines (ionised equivalents of the L and K-series) can appear as bumps on the exponential spectral tail.

The interpretation of the X-ray spectrum from the diode also be perturbed by other phenomena two of which are particularly pertinent in TCV. A non-maxwellian electron velocity distribution (often accompanying Radio Frequency heating) will result in a deformation of the exponential spectral tail. Secondly there exists a "run-away' regime in a tokamak plasma where the electron collision cross section decreases as the electron velocity increases. A class of electrons can then accelerate, unimpeded, to very high velocities and then collide with the vessel yielding photons with often several hundred kev energies. Since the semiconductor diode is not sufficiently thick to completely absorb these photons, a wide range of high energy events is observed.

The spectrum deduced obtained from PHA can thus be used to measure the plasma electron temperature, the general impurity content and the presence of specific impurities in the plasma. In particular, where a "two foil" method of electron temperature measurement is also used (as on TCV), PHA can be used to confirm the assumption of an exponential X-ray spectral tail.

TCV Implementation

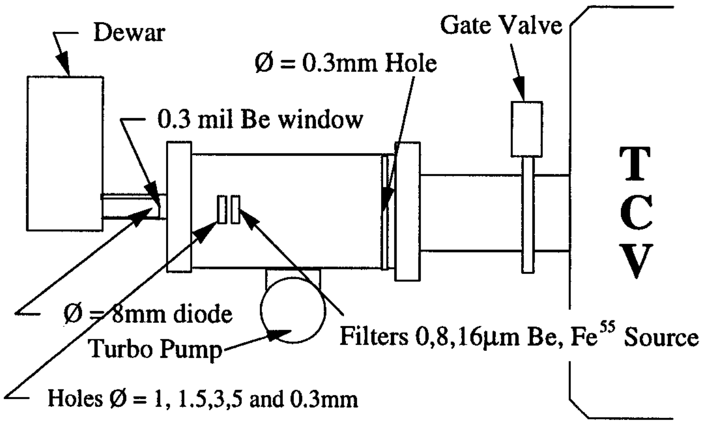

Fig 1: Schematic View of the PHA diagnostic showing the position of the filters and defining apertures.

The TCV plasma pulse duration is limited to ~2s, so it was chosen to record each incident event separately and histogram the information after data collection into the analysis computer. Following pre-amplification, the signal from the Canberra model GUL0055P diode was shaped by an ORTEC model 673 gated integrator. The amplitude of the resulting pulse was recorded by an INCAA model TRCH CAMAC module which has 12bit signal amplitude resolution 1M samples of on-board memory and a 1µs cycle time. A dedicated electronics module (Sousa) was integrated into the TCV timing system such that every 1-50ms (user selected) a time "tag" was recorded into the acquisition memory, permitting the post-reconstruction of the arrival time of groups of events. Two photons arriving in the detector within a short enough space of time will not be distinguished and cause a pulse pile-up event in the electronics processing resulting in an erroneously high pulse amplitude. Such events, if detected by the ORTEC module, are also processed by the dedicated electronics module and a pulse pile-up "tag" recorded into the acquisition memory. In summary, following a TCV discharge, a single trace is acquired containing the processed X-ray photon pulse heights, their arrival time within the discharge and any detected pulse pile-up events.

The diode cryostat forced a horizontal mounting on TCV (Fig 1). In the inherently "noisy" electrical environment surrounding a Tokamak, the diode, vacuum pumps and Tokamak were all

separately earthed, and the electrical signal and power cables bundled together to minimise the effect of fluctuating magnetic fields. The diode was mechanically coupled via a high vacuum flight line (< 10^{-7} torr) to TCV which included the possibility of externally changing the viewing aperture and introducing Be filters into the flight line. For calibration purposes, it was also possible to place an Fe^{55} 5.9 kev radioactive source in one of the filter positions.
A pair of apertures of 0.3mm diameter at each end of the flight tube limited the etendue of the detector to the plasma to 1.2 x 10^{-6} Str m^2 in order to set a maximum observed count rate of ~100 khz in L-mode discharges.

Spectral resolution and saturation characteristics

As described above, the acquisition chain is able to process an event in 1μs. To investigate the system performance with high count rates the radioactive source was place at varying distances from the detector and a 10'000 - 100'000 event acquisition performed. With a 10μs shaping time, a spectral resolution of ~180ev at an average count rate of 30 khz were obtained before pulse pile-up became significant. With a 0.5μs shaping constant, count rates in exceeding 100 khz were available at the expense of a ~250ev spectral resolution, albeit with a considerable pile-up fraction. This was to a great degree determined by limitations in the ORTEC 673 amplifier rather than the charge collection time in the diode itself.
During a TCV plasma discharge, residual electrical pickup resulted in a degradation of the highest spectral resolution from 180ev to ~250ev and a 1μs shaping time was chosen for the results reported in this paper as a compromise between high count rate and good spectral resolution. As previously described, pulse pile-up has the effect of distorting the observed spectrum towards higher energies. This is demonstrated in Fig 2 where the spectrum obtained with a close coupled Fe^{55} radioactive source is shown. This source suffers electron capture into the nucleus resulting in two strong spectral features at 5.9 and 6.4 kev with an intensity ratio of ~5:1. In the energy range shown pulse pile-up events are observed at energies greater than 11.8 kev, the energy of two 5.9 kev photons. (The signal at energies < 1 kev is due to the proximity of the radioactive source to the diode).

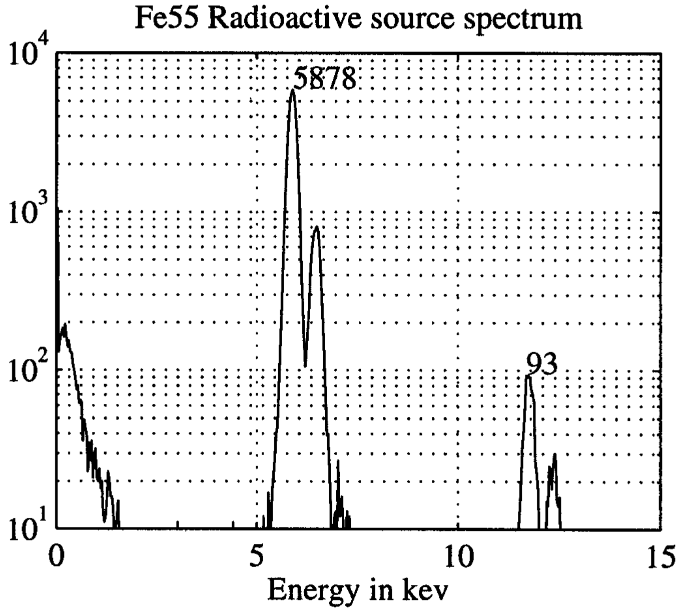

Fig 2: Spectrum measured by the PHA of a high flux Fe55 radioactive source showing pulse pile-up events at ~11 kev.

This system was modelled numerically where a random number generator determined the arrival time of each event at the diode and the spectral emission profile of the generated pulse heights was arranged to be the same as that from the radioactive source. Two kinds of pulse pile-up events can be distinguished: those due to more than one photon arriving in the diode in a very short time (< 0.1μs) and those arriving in a longer space of time (0.1 < 15μs). The first kind corresponds to the finite charge collection time in the diode itself and the second ought to be at least partially detected by the pulse pile-up detection circuits in the ORTEC 673 module. Although the preamplified signal was processed in 1μs, a mean simulated pulse pile-up time above ~3μs was required in order to obtain the experimentally measured number of pulse pile-up events. Unfortunately, many of these events remained undetected by the ORTEC 673 module. Thus, not only does the electronic module limit the synchronous signal processing rate to ~200 khz, but most of the resulting pulse pile-up events are not discerned.

The numerical model was modified to the spectral profile expected from a Tokamak plasma. Pulse pile-up was found to result in a pulse height spectrum also showing an exponential spectral shape, but extended to higher energies, which would be interpreted as a higher electron temperature (This is described in greater detail in the interpretation of TCV data). From the observations of the radioactive source, we would expect significant pulse pile-up generated errors in the deduced electron temperature at non-synchronous count rates above 50 khz.

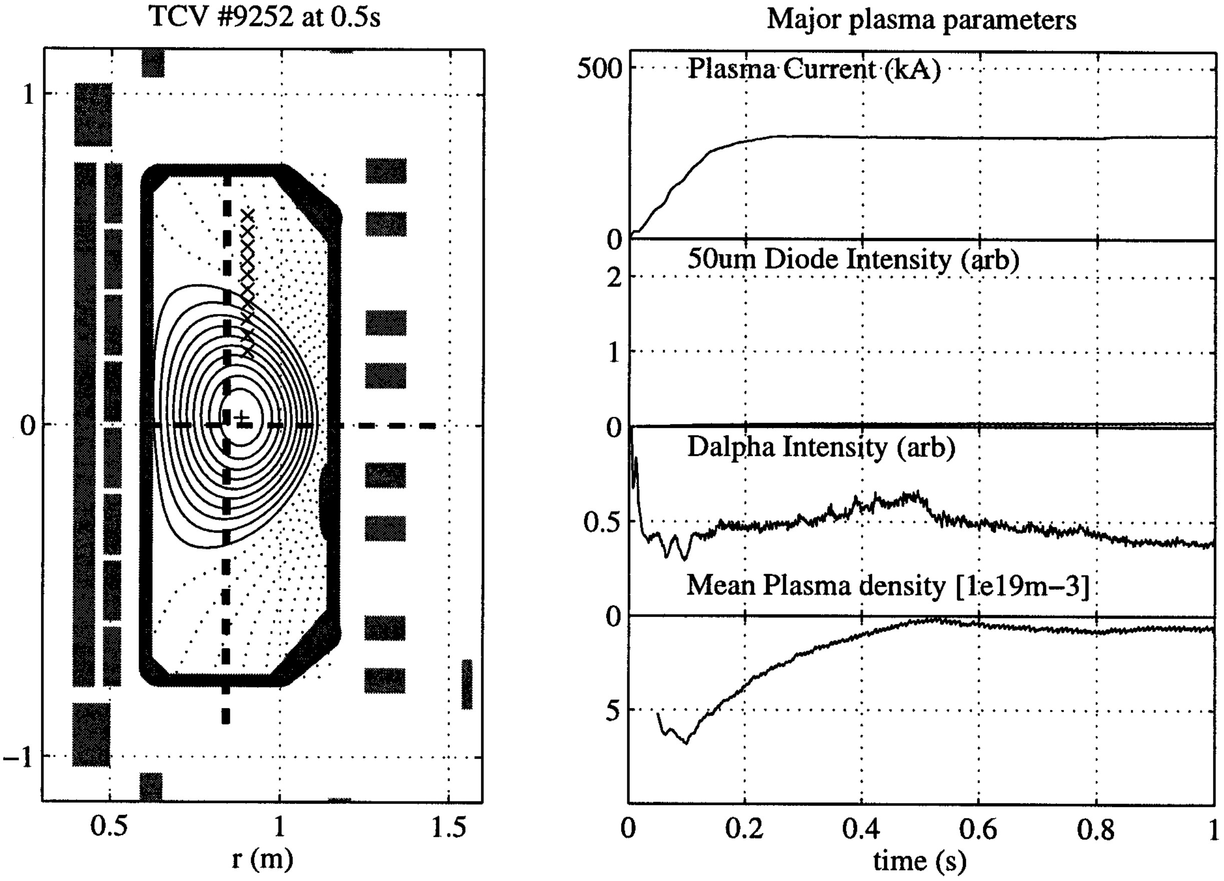

Fig 3: General view of the reconstructed magnetic surfaces of #9252 which is centred in the TCV vessel. The horizontal line indicates the viewing axis of the PHA and the vertical line the viewing axis of the 2 filtered diodes. The x points indicate the acquisition positions of the Thomson scattering system. The main plasma parameters for this sequence of reproducible discharges is also shown.

L-mode TCV discharges

The variety of plasma equilibria which can be created in TCV made the horizontal diode mounting problematic since the plasma core was not always placed on the horizontal axis, and was thus not always seen by the diode. Fig 3 shows the flux contours of a plasma equilibrium, the viewing chord of the diode and the temporal evolution of the major plasma parameters for a discharge where the plasma centre has been specially positioned on the horizontal mid-plane. This configuration is not commonly used on TCV since it does not benefit from the passive vertical position wall stabilisation. The measured X-ray spectrum from a sequence of reproducible discharges of this type is shown in Fig 4a. Data was selected during the period of the plasma current flat-top where the plasma parameters are stable and the intermediate Be filter was set to 0, 8 and 16μm (above the 7.6μm Be vacuum window on the diode itself). Fig 5 plots the spectral transmission of these filters on linear and logarithmic scales showing that they have

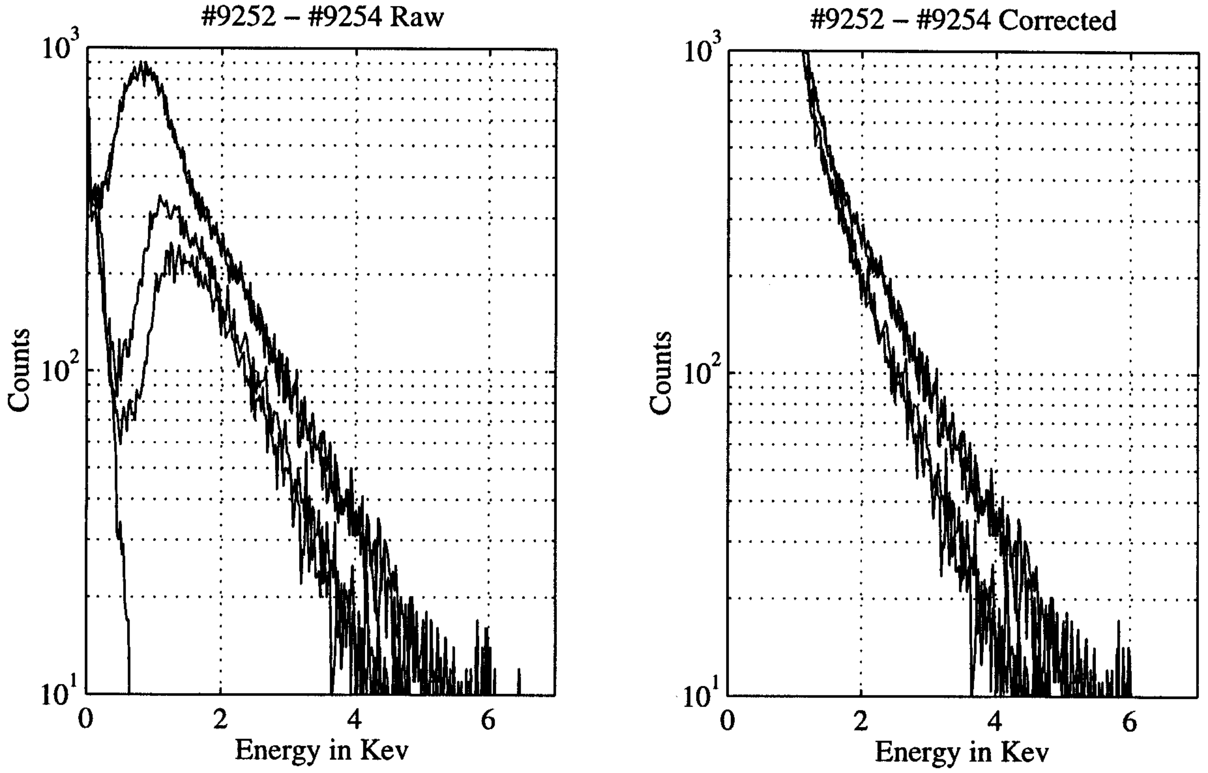

Fig 4: a) Raw signals from #9252 - #9254 where only the inline filter took values of 0, 8 and 16µm. The line terminating ~1 kev is taken from a similar discharge in which the gate valve remained closed.

b) The same data as in Fig 4A but corrected for the different filter transmissions. Clearly the spectra taken without the filter are biased towards higher energies.

no discontinuities in this spectral range.

In going from 0, (none) to 8 to 16µm intermediate filters, there is a clear reduction in the photon flux from 0 → 2 kev. The effect of pulse pile-up already visible with no intermediate filter (0µm). The increased number of photons entering the system causes an apparent increase in the high energy photon flux, together with the expected increase in the low energy photon flux. The reproducibility of the measurement is also demonstrated in Fig 4a where two discharges with no intermediate filter superimpose almost perfectly.

For all the traces, the spectrum at low energies (< 1 kev) is a second exponential shown in Fig4a from a discharge during which the gate valve to TCV remained closed. This is the complete noise spectrum of the diagnostic for the conditions of these discharges and corresponds to an effective electron temperature of ~150ev. The effective temperature of this part of the spectrum can be decreased by improving the electrical shielding but in this case does not affect the measurement apart from increasing the probability of pulse pile-up in the signal processing electronics.

When corrected for the effect of the complete filter, Fig4b, the effect of pulse pile-up becomes more apparent. With no intermediate filter, corresponding to the highest count rate, the slope of the exponential tail is decreased, equivalent to a higher deduced electron temperature. The measurements from the 8 and 16µm filters are now very similar showing that in both cases, pulse pile-up effects were strongly reduced. From the time base reconstruction, Fig 6 plots the measured electron temperature as a function of average count rate during the period where the plasma parameters were stable. These values can be compared to two other electron temperature measurements on TCV.

The TCV Thomson scattering system (Behn) uses repeated pulse YAG lasers and filtered spectrometers to measure the electron velocity distribution from the spectral profile of the scattered light. This system was only equipped with 10 spectrometers during these experiments at positions indicated in Fig3. Since none of the chords are on the axis of the PHA system a comparison with the PHA is described later.

The electron temperature is also derived from a pair of Si diodes equipped with 50 and 250µm thick Be filters whose transmission is also shown in Fig 5. This system views the plasma along a vertical chord passing close to the plasma centre (Fig 3). Since no line radiation is observed from the PHA diagnostic and the X-ray plasma radiation is strongly determined by the region of highest plasma density and temperature, the average value of 650ev obtained, Fig 2, can be used as a measurement of the true electron temperature. The effect of count rate on the deduced electron temperature was modelled numerically as described above but with a source spectrum characterised by a 700ev electron temperature and electrical noise of the intensity observed experimentally. The results are shown in Fig 7 where the deduced electron temperature is shown as a function of signal rate for a range of signal processing times. Each point in the figure corresponds to a separate simulation of 1s of pulses and a second order polynomial fit is shown for each simulated pulse processing time to guide the eye. The simulation was used to calculate the true count rate of the data from Fig 6 and is also plotted in Fig 7. Comparison of the model to Fig 6 implies that the effective pulse processing time is ~4 -5 µs. Extrapolation of the electron temperature to low count levels implies a true electron temperature of 680ev ie. ~5% higher than measured by the filtered diode pair, whose viewing chord does not pass exactly through the centre of the plasma.

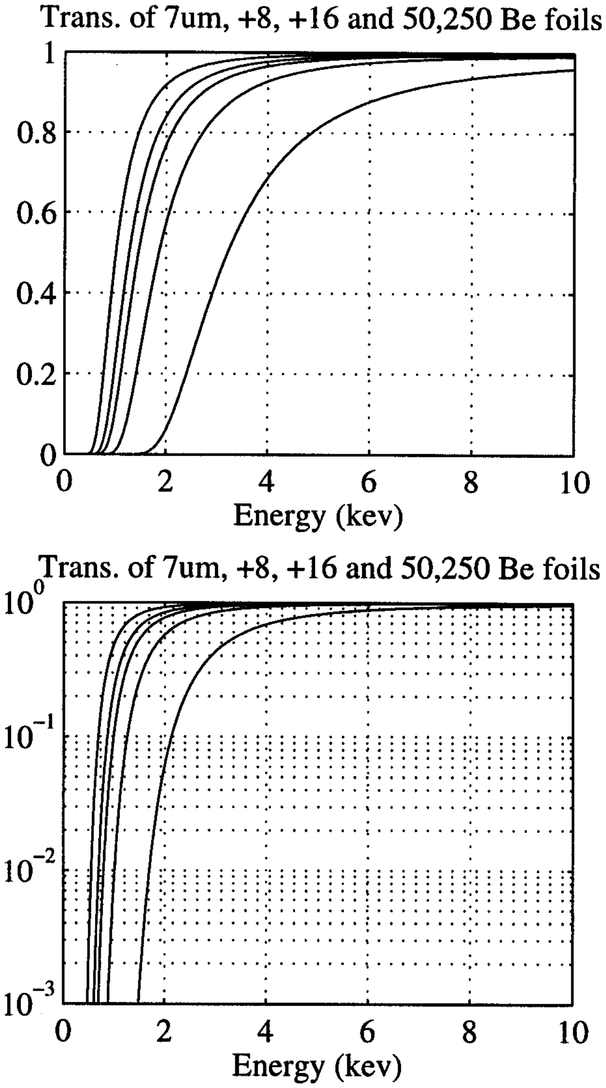

Fig 5: Filter transmissions of all the Beryllium foils described in this paper on a linear and logarithmic scale.

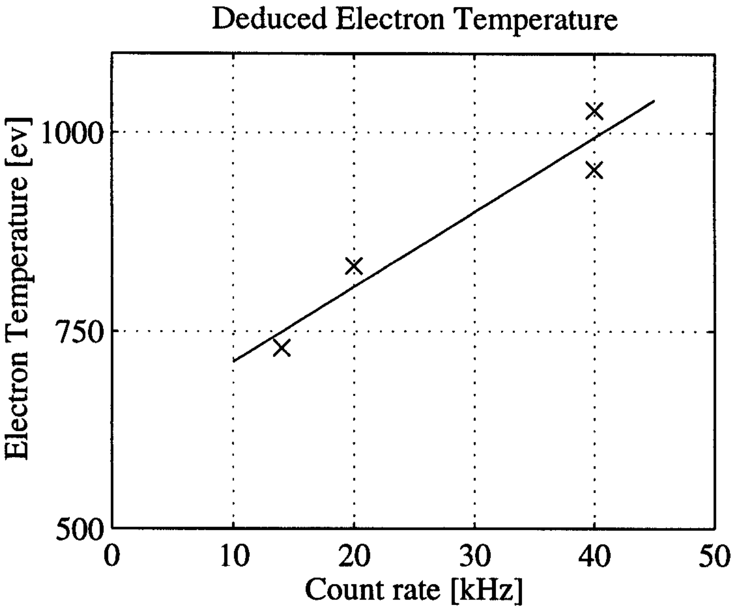

Fig 6: Effective Electron temperature as a function of measured count rate for the data in Fig 4.

Fig 8 shows a discharge in which the PHA temperature was compared to the Thomson scattering value. The electron density and temperature profiles, measured at the points indicated, are mapped onto the PHA line of sight by assuming them to be constant on a magnetic surface. The value of ~400ev obtained from the PHA compares well with the peak values of the remapped Thomson profile. This is agreement with a general observation on TCV where the filtered diode measurement of the electron temperature can be ~10% lower than that measured by Thomson scattering. That all these values agree to within this margin shows that the electron temperature on TCV is well known and corresponds to a plasma with a relatively low impurity content.

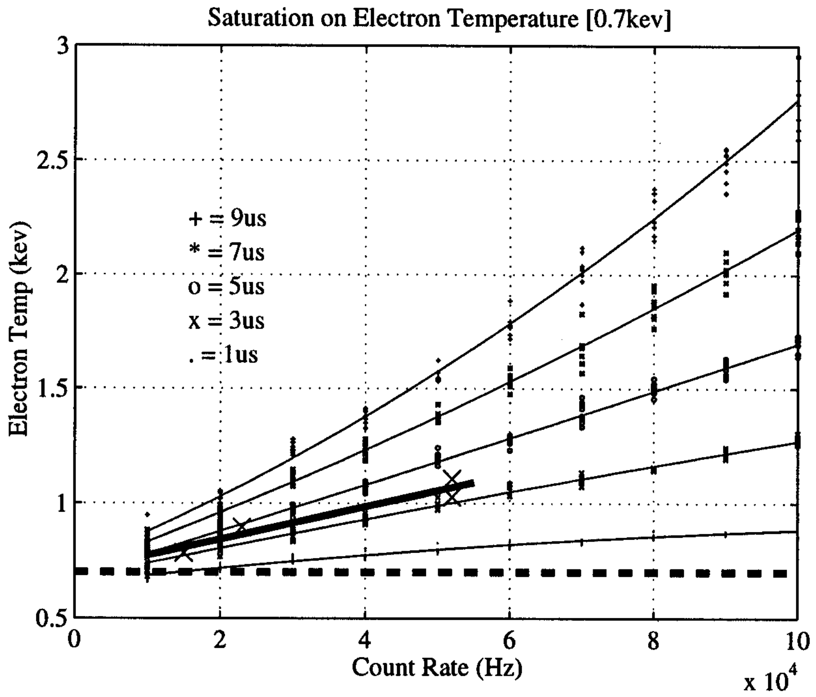

Fig 7: The effect of pulse pile-up on the determined electron temperature as a function of real incident count rate and analogue electronics processing time. Also shown are the data from Fig 6 where the measured count rate has been corrected for pulse pile-up.

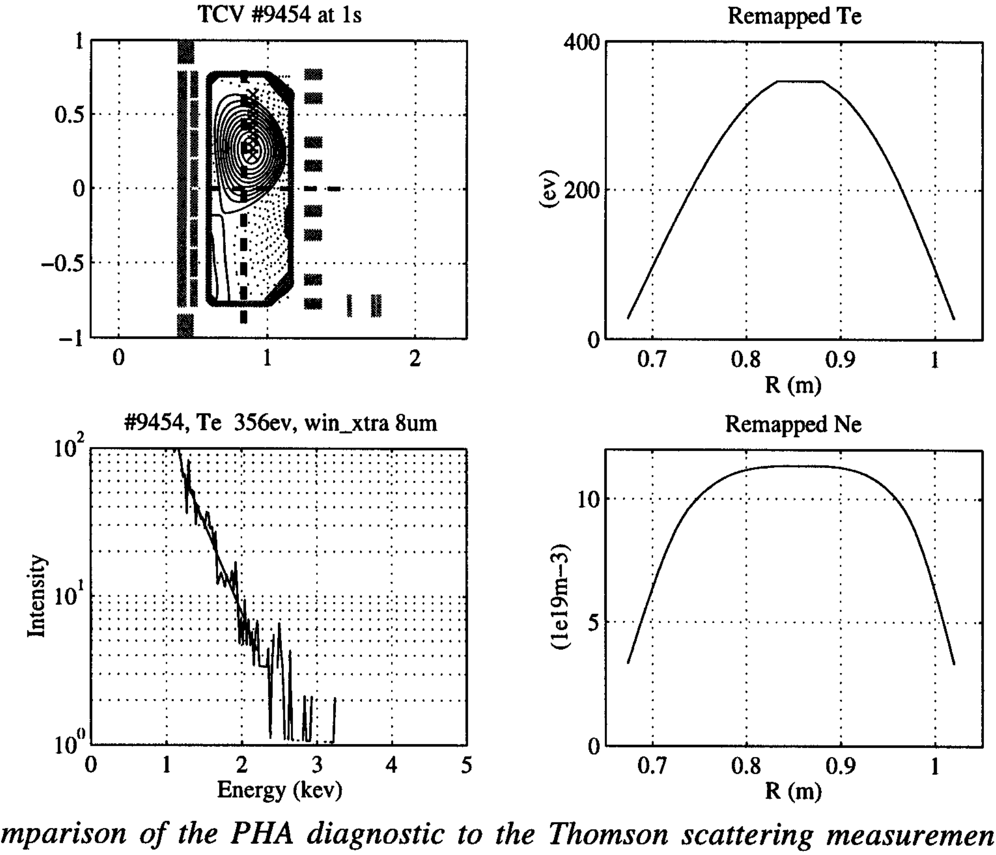

Fig 8: Comparison of the PHA diagnostic to the Thomson scattering measurement. The plasma parameters mapped from measured positions (indicated by the x in 8a) are mapped onto the axis of the PHA spectrometer, Fig 4b, 4c. The spectrum from the PHA is shown together with the deduced electron temperature.

H-mode TCV discharges

Ohmic H-mode can been obtained in TCV with sufficient plasma current and good wall conditioning (Weisen). After the transition from L to H-mode, the plasma density rises roughly linearly with time in a largely uncontrolled manner, Fig 9, until either a sequence of ELMs stabilises the density or a major plasma current disruption occurs. The improved particle confinement in H-mode has previously been associated with impurity accumulation in the plasma core which increases the radiated power and speeds up the termination of H-mode [ASDEX].

From Fig 9, the X-ray emission intensity, measured by the filtered diodes, increases by over an order of magnitude as the density rises implying the possible presence of high atomic number plasma impurities. The electron temperature is shown for a period early in the discharge when the count rate is low and during H-mode. Although the PHA system clearly suffers pulse pile-up saturation at the higher X-ray fluxes, there is no observed spectral peak due to line radiation during the discharge. The absence of any observed line radiation implies that in these conditions the contribution to the X-ray emission from heavier impurities may be neglected giving more confidence in the filtered diode measurement. It should be noted that an electron temperature of < 1 kev is would result in strong K-type emission from Fe (~6 kev). It remains to seen if the increased electron temperatures associated with additional plasma heating results in plasmas with stronger charactersitic line emission.

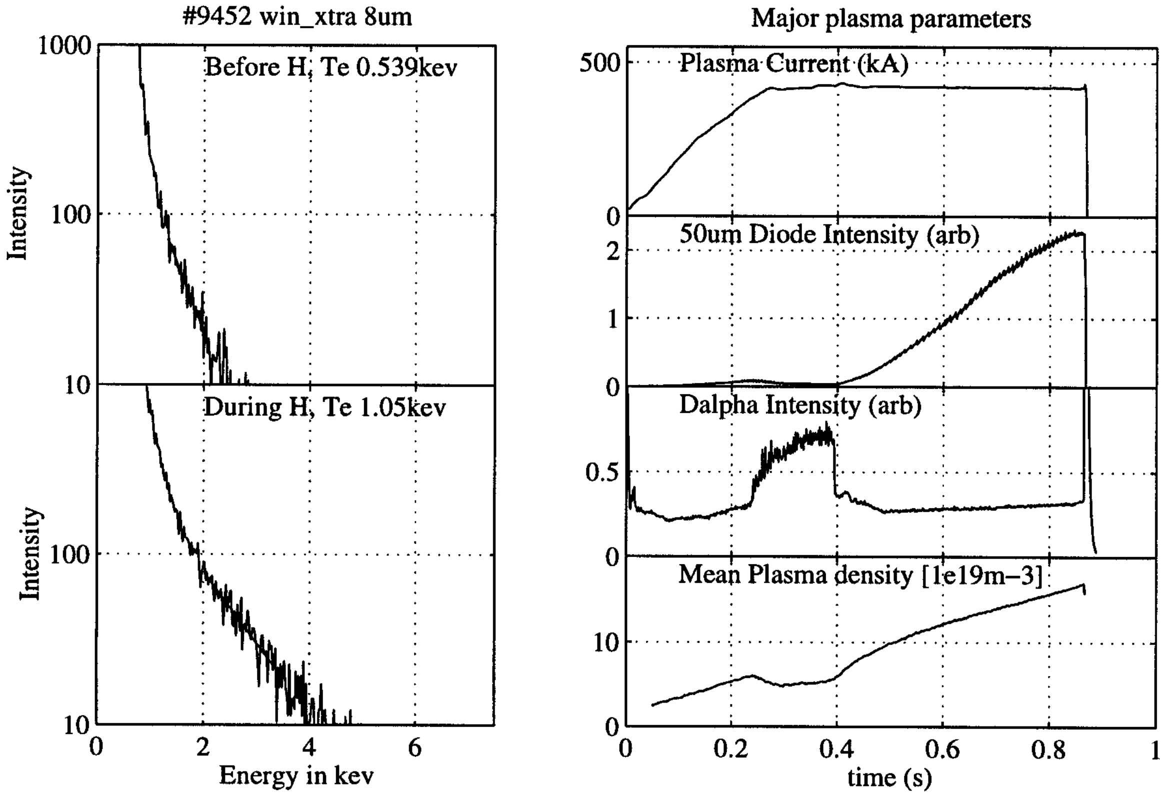

Fig 9: An Example of an H-mode discharge is shown. 9a and 9b show the measured PHA spectrum before and during the H-mode. In Fig 9c the main plasma parameters are plotted and the X-ray intensity is seen to rise strongly during the H-mode period (> 0.4 s). Although the PHA system suffers pulse pile-up saturation, resulting in an over estimated electron temperature, no line radiation is seen.

Conclusion and Future enhancements

A PHA system has been successfully mounted on TCV and used to measure the X-ray emission from a variety of plasma configurations. The system has been shown to be limited by pulse pile-up problems in the analogue signal treatment but a 1µs digital cycle time has been demonstrated. The electron temperature deduced from PHA agrees well with a filtered diode system and a Thomson scattering system which does not use the X-ray radiation. When the count rate permitted confidence in the PHA electron temperature, the value obtained was closer to the Thomson measurement ie ~10% higher than the filtered diodes, but all measurements agreed to within the error margins.

No line radiation was observed, even during H-mode where such radiation is more likely, and none of the measured spectra indicate any deviations from a maxwellian velocity distribution. Together, these observations justify the use of the filtered diode method of measuring the electron temperature in the current TCV plasma conditions.

A numerical model for pulse pile-up has been constructed and compared to the experimental pile-up observations. The perturbation of the deduced electron temperature by pulse pile-up can be explained by a processing time of ~5µs in the analogue electronics, well above the 1µs acquisition processing time. If the analogue processing rate can also be reduced to ~1µs, the PHA system is predicted to show only a 10% increase in the measured electron temperature for count rates up to ~80 khz. To further improve the system, it is planned to supplement the existing diode with a vertically mounted system which would view the plasma centre in all TCV configurations. The system may consist of multiple diodes with different Be filters to cover a large range of X-ray intensities. Clearly there is most room for improvement in the current analogue electronics which performs poorly in the electrically noisy TCV environment.

With the arrival of ECRH heating leading to non maxwellian electron velocity distributions and higher electron temperatures possibly leading to larger high Z impurity contents, the PHA of X-ray emission from TCV will become an increasingly important plasma diagnostic.

Acknowledgements

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