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First results obtained with the real-time PHA diagnostic on TCV

T.I.Madeira[1], P.Amorim[2], B.P.Duval[3], A.P.Rodrigues[1], L.Pereira[1], C.A.F.Varandas[1]

[1]Associação EURATOM-IST, Centro de Fusão Nuclear, P-1049-001 Lisboa, Portugal
[2]Universidade de Lisboa, Faculdade de Ciências, Departamento de Física and Centro de Fusão Nuclear, Portugal
[3]CRPP-EPFL, Centre de Recherches en Physique des Plasmas, Lausanne, Switzerland

Introduction

The x-ray emission intensity from a hot plasma is characterised by a set of continua with exponential fall off with photon energy where *Bremsstrahlung* and radiative recombination are dominant for Tokamak plasmas. Line radiation particular to impurity species may also be observed. Pulse Height Analysis provides a straightforward measure of this emission where the amplitude resulting from the interaction of an x-ray photon with a diode is recorded. A histogram of these values provides a measurement of the initial x-ray spectrum. In modern PHA systems, the classical analogue analysis chain is replaced by Digital Signal Processing which increases the processing speed and can provide a real-time measurement of spectra and derived plasma parameters during the plasma discharge. The vertical PHA diagnostic operational on TCV is a hybrid with a compact Silicon Drifted Detector (SDD) Peltier cooled diode, equipped with a set of three beryllium filters and a variable slit aperture, which are remotely positioned in front of the detector by two fast stepper motors. Signal conditioning and processing is performed by two independent systems: a commercial multiple-frame multichannel analyser (MCA3) with post acquisition analysis and a CFN designed VME hosted DSP card providing real-time analysis of the emission. Both may be used to feedback control the system *étendue* to regulate the high dynamic range of TCV's x-ray flux. Measurements of the central electron temperature and the presence of impurities in the plasma have been obtained for several TCV operation regimes. With the addition of other diagnostic information, other information such as the Z_{eff} parameter and the enhancement factor ζ may also be deduced. One goal of this work is to demonstrate an extremely low *étendue* x-ray spectral measurement of a hot plasma with a regulated flux permitting real-time measurements of plasma parameters for a wide range of plasma conditions.

Diagnostic description

The vertical Pulse Height Analysis diagnostic on the TCV tokamak measures the soft x-ray emission in the 700 eV to 10 keV range along a vertical line of sight, with an energy resolution that varies between 150 eV and 175 eV. A Silicon Drifted Detector (SDD) (surface area ~5 $mm^{2)}$ Peltier cooled diode featuring a thin (~ 300 μm) fully depleted silicon wafer, is sensitive to soft x-ray energies but becomes transparent above 15 keV. Preliminary tests have demonstrated a constant energy resolution up to a 100 kHz input count rate which then degrades. The detector is, however, still able to useful deliver spectroscopic information with count rates as high as 1-3 MHz [1].

The commercial MCA acquisition features 512 k channels of onboard memory and 32-bit capacity. It includes a built-in pulse height analyser ADC with 500 ns conversion time with 8 kbin conversion range with a throughput capacity exceeding 1 Mevents/s depending on the shape and duration of the input pulses. Collected raw data, triggered synchronously with the TCV plasma, is acquired and analysed after discharge termination. With a regulated input rate, a spectrum, with spectroscopic quality, may be obtained every 100 ms during a 2 s TCV discharge.

The CFN/IST VME card [2] is designed to perform the same analysis operation in real-time whilst simultaneously regulating the system *étendue* to maintain an optimal count-rate. The acquired data is parallel processed by up to 4 DSPs with: moving average, triangular and/or trapezoidal filter, custom algorithms that measure the amplitude of the pulses and eliminate pile-up events and register and evaluate the pulse-height histograms. Plasma electron temperature is obtained by searching for the start of a linear zone in the histogram and a linear regression fit. The digital errors introduced by the DSP calculation are negligible with <2 % difference with the value obtained from off-line analysis. For a statistically meaningful fit, real-time calculation of plasma electron temperature is performed in cycles of 100 ms, providing 20 spectra and 20 values of the electron temperature during a 2 s TCV discharge. Above the count rate limit of each system (N>250 kHz for the MCA3 and N>600 kHz for the DSP card) the probability of pulse pile-up is excessive necessitating a flux reduction. This is achieved in the TCV arrangement with a set of beryllium filters of 50, 100 and 150 μm to reduce the dominant lower energy x-ray photon rate and a variable aperture placed between the plasma and the detector. Both systems can be remotely positioned in front of the detector by stepper motors with a 120 degree arc range. The filter system uses discrete positions and the aperture holder allows continuous positioning between 0 and 120 degrees corresponding from fully closed to a ~2 mm opening. The aperture can be real-time varied during a single discharge: a lower limit of 20 kHz is imposed for both systems and the upper is 250 kHz for the MCA3 and 600 kHz for the DSP system. For the DSP system the count rate is feed into a subsystem with a DAC that supplies the appropriate voltage to actuate the stepper motor; for the analogue system an integrator (sensor) is employed together with a comparator that when the limits are surpassed, gives out a signal that actuates the motors and change the position of the aperture. A low power ^{55}Fe source occupies one of the filter-holder positions and can be used to diagnose and calibrate the system *in situ*.

Method of analysis

The x-ray spectrum from a Maxwellian electron distribution colliding with stationary ions of charge Z_i and density n_i , including recombination radiation can be expressed mathematically by,

$$I(h\nu) = 2.60\times 10^{-14}\, n_e \sum_i n_i Z_i^2 \left(\bar{g}_i + f_i\right)\times\left[\frac{13.59\ eV}{T_e}\right]^{1/2} exp(-h\nu/T_e) \qquad (1)$$

$[I(h\nu)]=$ units of energy/units of energy cm^3 sec., which may be written, following von Goeler [3],

$$I(h\nu) = 2.60\times 10^{-14}\, n_e^2 \bar{g}\times\left[\frac{13.59\ eV}{T_e}\right]^{1/2} exp(-h\nu/T_e)\,\zeta \qquad (2)$$

where, $\zeta \equiv \sum_i \frac{n_i Z_i^2}{n_e} \frac{\bar{g}_i + f_i}{\bar{g}}$ is the x-ray enhancement factor caused by impurity ions, a measure of the contribution to the spectrum from the impurities. Assuming $\zeta = 1$ and the gaunt factor approximation $\bar{g} = (T_e / h\nu)^{1/3}$, a least square fit to the continuum together with equation (2) yields, for each time slice, the evolution of the electron temperature. Although rare in TCV, for the energy range 700 eV – 10 KeV, emission lines particular to impurity ions in the plasma, may be observed and identified. Though, to date, the acquired statistics are not sufficient to provide an accurate impurity concentration, this could be improved by additional Be filters to reduce the contribution of the lower energy X-ray photons. The following sequence shows examples of the logarithm of the intensity versus energy at different instants in time for two operational TCV regimes:

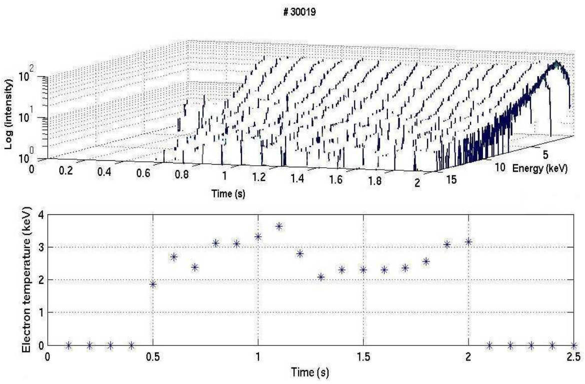

Fig.1a): Standard discharge
Ohmic heating

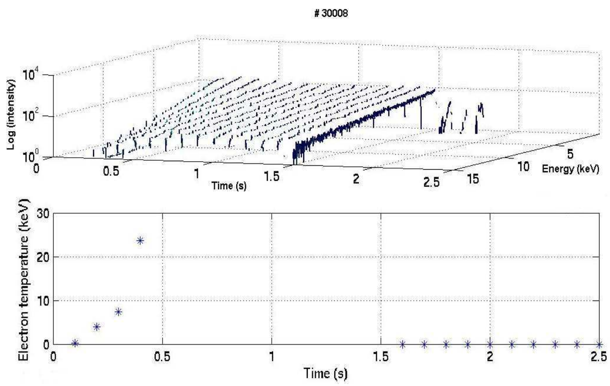

Fig.1b): ECRH+ECCD

Further improvements are already being envisaged for the near future; for shorter time intervals there are two scenarios : “zoning” the spectrum, whilst maintaining the high energy resolution with the original histogram/fit algorithm or/and the application of the concept of McDrift (Multichannel Drift Detector) which is a continuous, gapless arrangement of 10 SDDs with individual readout and common voltage supply and cooler that combines a larger sensitive area with the properties of the 5 mm^2 with an integrated FET; for improved algorithm speed the use of the DSPs in conjunction with modern FPGAs will also imply changing the board layout.

Conclusion

A modern upgrade of the “classical” PHA diagnostic has been installed and operated on TCV providing the time evolution of the soft x-ray emissivity and effective electron temperature, with an average throughput of 400 kHz. This decreases the statistical uncertainties associated with such measurements and real-time pulse-processing permits real-time diagnostic feed-back control. The results obtained are very encouraging. A “modern” PHA system with a Peltier cooled diode and DSP signal treatment can provide a diagnostic that is suitable for routine observation and real-time analysis of a plasma both in present day machines and/or as part of the control of long-pulse/continuous machines such as ITER. Solid state PHA systems are low cost, robust and mechanically simple, allowing easy replacement. Their stability and reliability permits data to be analysed into straightforward plasma parameters with clear error estimations. They feature high quantum efficiency thus only a low *étendue* is required from a high intensity source. The use of multilayer mirrors, which can offer the advantage of large collection area combined with higher source intensity and strong background, or transmission-diffraction optics, such as Fresnel zone plates, in order to deflect a usable portion of the incident light out of the direct plasma view into a particle and radiation shield measurement region makes possible this diagnostic to be in routine operation in a hostile radiation environment. Application of modern technology to this well-known diagnostic has resulted in a system that presents new possibilities with room for future improvements.

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References

[1] T.I.Madeira et al., *Real-time signal analysis on the TCV PHA diagnostic*, Rev.Sci.Inst. **74** (2003) 2004

[2] A.P.Rodrigues et al., *Multiple DSP system for real-time parallel processing and feedback control on fusion experiments*, Fus.Eng.Des. **43** (1999) 401

[3] John E. Rice and Kim Molvig, *Continuum x-ray emission from the Alcator A tokamak*, Phys.Rev.A **25** (1982) 1645