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ABSTRACT

To meet the requirements of the scientific programme, the EFDA JET Real Time Measurement and Control Project has developed an integrated set of real-time plasma measurements, experiment control, and communication facilities.

Traditional experiments collected instrument data during the plasma pulse and calculated physics data after the pulse. The challenge for continuous tokamak operation is to calculate the physics data in real-time, keeping up with the evolution of the plasma.

In JET, many Plasma Diagnostics have been augmented with extra data acquisition and signalprocessing systems so that they can both capture instrument data for conventional post-pulse analysis and calculate calibrated, validated physics results in real-time. During the pulse, the systems send sampled data sets into a network, which distributes the data to several destinations. These may do further analysis integrating data from several measurements or may control the plasma scenario by heating or fuelling.

The simplest real-time Diagnostic systems apply scale factors to the signals, as with the Electron Cyclotron Emission Diagnostic s 96 tuned radiometer channels, giving the electron temperature profile. In various Spectroscopy Diagnostics, spectral features are least-squares-fitted to measured spectra from several lines of site, within 50 ms. Ion temperatures and rotation speed can be calculated from the line widths and shifts. For Diagnostics using modulation techniques, the systems implement digital-signal processing phase trackers, lock-in amplifiers and filters. The interferometer samples 15 channels at 400kHz for 30 s, i.e. 6 million samples/sec!

Diagnostics have specific lines of sight, spatial channels and various sampling rates. The Heating/Fuelling systems have relatively coarse spatial localisation. Analysis systems have been developed to integrate the basic physics data into smaller sets of controllable parameters on a common geometry e.g. temperature, density and safety factor profiles with values at 10 points of normalised radius.

The EFDA Real Time project is essential groundwork for future reactors such as ITER, and has successfully involved many scientific and technical staff from several institutions. The facility is now frequently used in experiments.

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INTRODUCTION

ITER relevant experiments at JET require real-time control of electron and ion temperature profiles, density and current profiles [1], using Electron Cyclotron Emission [3], Far Infrared Interferometry and Polarimetry [4], Visible, Vacuum Ultra Violet, Charge Exchange [5], Motional Stark Effect Spectroscopy as well as global parameters (plasma density and current, neutron rate). This paper presents some of the technical issues and summarises solutions designed at JET associated with data-acquisition, signal processing and physics analysis in realtime.

The individual projects followed this general methodology:

(1). Re-formulate the existing signal processing or physics analysis, adapting to real-time constraints, i.e. -

(1.1). Process the input data in time-order, possibly in time-frames. Real-time analysis can t use data before it has been acquired, whereas some conventional processing uses the whole, recorded data e.g. for baseline drift removal, symmetric filtering (zero phase delay), etc.

(1.2). Reduce the physics output to that specifically associated with the Diagnostic. Any further analysis, which depends on other data, would be deferred to an additional system, if required

(1.3). Reduce the sophistication of the numerical analysis, e.g. ensure any iterations are minimised and there is always an exit with one sample time-period. If necessary, find approximations for complex calculations, e.g. flux surfaces.

(2). Test the algorithm using recorded data, usually in Matlab or C, on a normal workstation. Check the results of the new formulation are consistent with the standard analysis over a range of plasma conditions. Check the new code copes with a range of plasma conditions, not just those for which the standard analysis works well. For example, if the data is poor, the code should exit reliably and make output values safe. Check the calculation time is feasible for the target processor and sample rate.

(3). Implement the new algorithm on the target real-time system, and integrate it with JET countdown and status monitoring systems. To provide maintainable products, we have developed a set of run-time frameworks which provide the standard interfaces, a one for VxWorks and C codes for simple ADC applications, one for VxWorks and Windows in C++ providing built-in plasma boundary (and other) calculators, and one for PC-based image acquisition cameras. Very often a new system will acquire the instrument signals in parallel with the existing system, to preserve the existing post-pulse analysis.

(4). Commission the real-time system first with synthetic or recorded data (when the code is switched to generate test input data and process it) and live data from plasma shots (when the code uses live inputs signals). Compare the real-time results with the standard analysis and resolve any inconsistency.

In the following sections, a few systems are described to illustrate the range of data acquisition, signal processing and physics analysis now available.

ELECTRON CYCLOTRON EMISSION AND ELECTRON TEMPERATURE, T_e

The key source of calibrated electron temperature T_e profiles is from the measurements of the full ECE spectrum made by a Fourier Transform Spectrometer (FTS) [2]. It is absolutely calibrated by using a calibration source inside the vacuum vessel. High spatial and temporal resolution ECE T_e profiles are obtained using a 96 channel heterodyne instrument (80 to 139GHz) which is cross calibrated on each JET pulse against the data from the FTS system.

The cyclotron frequency $\omega = n \frac{e}{m} B = n \frac{e}{m} \frac{B_0 R_0}{R}$ depends on the local magnetic field B, which varies along the radial line-of-sight in a tokamak, (B_0 is the toriodal field on poloidal axis). According to the Rayleigh Jeans law, the signal strength depends on temperature and frequency, $I = \frac{kT_e\omega^2}{8\pi^3 c^2}$ . . Thus an electron temperature profile Te(R) can be determined from ECE intensities I(**w**)

The real-time system [3, then 48 channels] now uses three 32 channel ADCs (Pentland MPV956B), a PowerPC (Motorola MVME5100), VxWorks, and our own software, which integrates with JET countdown / status monitoring. Before plasma, the code accumulates a baseline. During plasma, the code reads the ADC channels every 10 ms, subtracts the baseline, scales to temperature using calibrations from a reference JET pulse, and sorts the channels into radial position order, using radial positions from the reference. It also calculates the electron ITB parameter **r***$_{\mathrm{Te}}$, **r***$_{Te}$ = **r** $/ L_T$ where **r** is the proton Larmor radius and $L_T = T \frac{dT}{/\,dR}$ is the temperature scale length.

In practice, the temperature profile is filtered to minimise the noise amplified by the differentiation. Ongoing, the signal filtering is being improved.

FIR INTERFEROMETRY AND POLARIMETERY

The FIR Diagnostic sends amplitude modulated laser beams across the plasma (4 vertical, 4 lateral) and mixes the beams with a reference beam. Measurement of the phase of each modulation cycle gives the difference in optical path length, which depends on plasma density. The lateral lines of sight also suffer significant vibration, so two lasers with different wavelengths (DCN**l** = 195um, mod n 100kHz, and Alcohol **l** = 118.8um, mod n 5kHz) are used to allow mutually consistent phase changes to be calculated, and effects of machine vibration to be excluded.

The real-time system uses one 16 channel ADC (ICS 130) feeding two PowerPCs (Motorola MVME5100) through Front Panel Data Port at 400ks/s in 1ms frames. Each PowerPC addresses a different set of channels. For each channel, the code calculates the phase of each modulation cycle from 4 samples/cycle, tracks phase changes from cycle to cycle, and accumulates the total phase change since the plasma formed. Using the phase changes **y** on each line of sight, the code calculates the line-integrated density every ms.

Line Integrated Density $\int n.dl = \frac{1}{K} \frac{\lambda_1\psi_1 - \lambda_2\psi_2}{\lambda_1 - \lambda_2}$, for lateral channels, which have the two lasers, *K* is a constant [4]

VUV

The VUV impurity survey spectrometer records VUV spectra (110-1100Å) every 11ms (or longer) on a Princeton Instruments Photo Diode Array (PDA) coupled to a McPherson grazing incidence VUV spectrometer, type 251. The light is collected from a single line of sight passing though the vessel midplane in the JET plasma. Successive spectra are triggered by a CODAS timer, and read-out by a PC running Windows 2000 and our own software which integrates with the JET countdown and status monitoring.

In real-time, segments of each spectra covering specific emission lines are simply backgroundsubtracted and integrated.

$$I_{impurity} = \frac{I}{\Delta t} \sum_{i=i1}^{i2} I_{Plasma}(i) - I_{Dark}(i) \text{ counts/s}$$

where I_{Plasma} and I_{Dark} are the PDA pixel values in plasma and before plasma (dark) respectively, i1, i2 are the pixel boundaries of the line of interest, and Δt is the exposure time (see table 1).

CXS

The Charge Exchange Diagnostic measures the visible light emitted when a deuterium neutral beam is injected into the plasma and electrons from some deuterons transfer to ions. E.g. C^{6+} becomes C^{5+} and emits a photon, **I** = 529A The spectral lines e.g of C^{5+} broaden and shift depending on ion temperature and drift speed due to plasma rotation.

The spectra are collected by a Jonathon Wright CCD camera system, controlled by PC running Windows 2000 and our own code. During the pulse, external hardware pulse generator triggers the readout, the code captures each spectrum (14 tracks, 8kB total, every 50ms) for post-pulse collection and sends them to an associate PC system over dedicated ethernet named pipe. The analysis code fits a flat baseline, a C^{2+} scrape off layer line (gaussian), a Be^{+} scrape off layer line (gaussian), a cold C^{5+} edge (gaussian), and a hot C^{5+} core (gaussian). That is 13 free parameters on each of 14 tracks. The ion temperature and rotation of the plasma can be determined from the width and position of the hot C^{5+}. The analysis uses the Levenberg Marquadt algorithm and takes less than 20ms for all tracks [5].

LIDAR

The LIDAR system sends a pulse of laser light radially into the plasma and measures the backscattered light in six wavelength bands. The time resolved echo represents the range-resolved scattering, which depends on electron density. The scattering at the different wavelengths depends on temperature.

The PC-based system uses Tektronix TVS645 5GHz digitizers, National Instruments PCI-6503 digital I/O, and PCI-6013 analogue input card, Windows 2000, NI libraries and our own acquisition and processing software.

For each laser pulse, the code read out the return signals from the fast transient recorders and the laser power from the slow ADC. In each return echo, the code locates timing markers, removes stray light, and then re-samples the signal. At the 50 new samples, the code fits calibrated value to find electron density and temperature vs range and the error (figure 3). The result is delivered within 10ms.

CONCLUSIONS

The EFDA JET project has solved many of the technical problems associated with real-time signal processing and physics analysis, and provides an experiment control facility essential for the development of ITER-relevant Advanced Tokamak scenarios at JET. The equipment is commercially available and should have a reasonable operational life, appropriate to JET s future programme.

The main limitations are fundamental to the diagnostic, arising from the restricted access to the plasma, e.g. limited lines-of sight, in-situ and cross-calibrations, and the complications due to necessary electrical, mechanical and radiological isolation.

Work continues to improve the above-mentioned systems and on new systems e.g. the JET EP Bolometer for bulk and divertor radiation [6], X-ray crystal spectroscopy for core Ti, and Visible Spectroscopy for H:D:T composition.

REFERENCES

[1]. E. Joffrin, et al Integrated Scenario in JET Using Real Time Profile Control Plasma Phys. Control. Fusion **45** No 12A (December 2003) A367-A383

[2]. De La Luna, E. et al Electron cyclotron emission radiometer upgrade on the JET tokamak Topical Conference on High Temperature Plasma Diagnostics, San Diego California USA. 2004

[3]. M.Riva et al Towards real time control of the internal transport barriers on JET 19th IEEE/NPSS Symp on Fusion Engineering, Atlantic City, USA, 2002

[4]. L.Zabeo et al Comparison of different approaches to the real time correction of fringe jumps at JET 30 th EPS Conference on Controlled Fusion and Plasma Physics, St. Petersburg, Russia, 2003 also Submitted to Rev. Sci. Instr.

[5]. P.Heesterman et al Real-time analysis of charge-exchange spectroscopy data at JET Rev. Sci. Instrum. **74**, 1783 (2003)

[6]. McCormick, K New Bolometry Cameras for the JET Enhanced Performance Phase 23rd Symposium on Fusion Technology, Venice, Italy, 2004

Ion	Emission	Wavelength	CCD camera
		(Å)	Pixel Range
Fe	XXIII	132.92	1948-1958
Ni	XXV	118.00	1984-1994
C	III	977.02	242-252
O	OV	629.73	914-924
N	NIV	765.15	647-657
Ne	VII	465.22	1241-1251
Ar	XVI	353.92	1476-1486
He	II	303.78	1583-1593

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Table 1: VUV emission lines

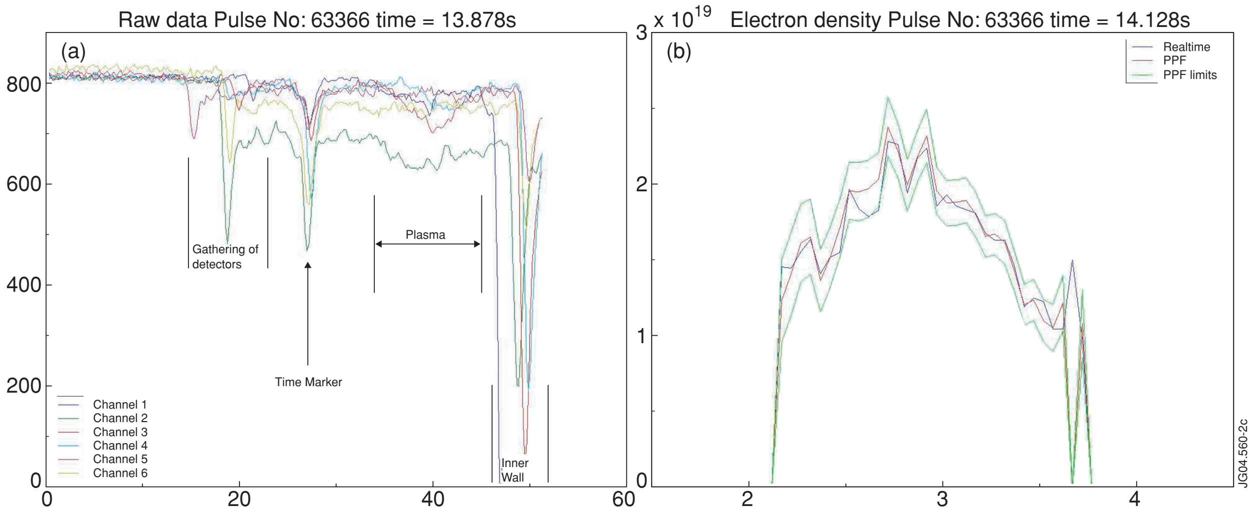

Figure 1: LIDAR data (a) return signals (b) density profile

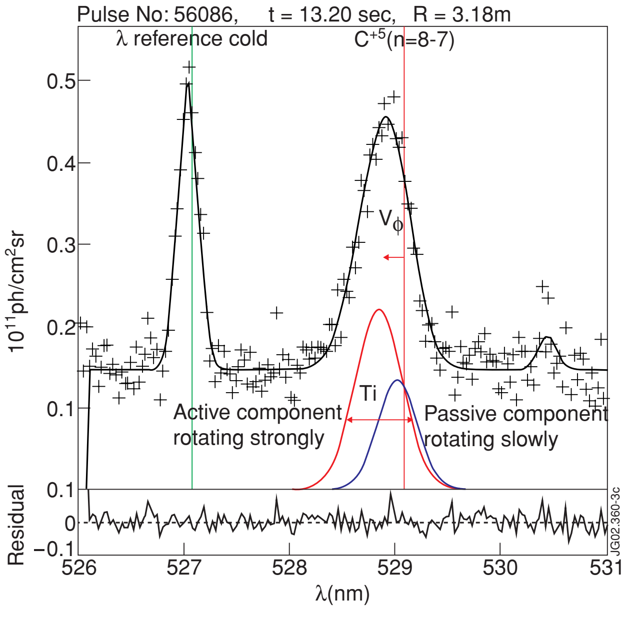

Figure 2: CXS fitting broadened and shifted lines to estimate ion temperature and plasma rotation.