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** See annex of F. Romanelli et al, "Overview of JET Results",*
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ABSTRACT.
The Far Infrared diagnostic provides essential internal measurements of the plasma density and magnetic field topology (q-profile via Faraday rotation angle) in real-time. The diagnostic capabilities have recently been extended in a number of key areas. Fast interferometer data, with 10μs time resolution, and a new Matlab code, have allowed improved analysis of the evolution of density profiles during fast events such as vertical plasma displacements, ELM, pellet fuelling and disruptions. Using the polarimeter measurements in realtime, a new calibration procedure has been developed, based on a propagation code using the Mueller matrix formalism. This approach leads to good estimates of the Faraday rotation (F) and Cotton-Mouton (C-M) angle in all JET plasma regimes and particularly for high performance discharges (plasma current of 4.5MA and large F and C-M angles).A further major upgrade of the system is presently underway: adding a second colour laser to the vertical channels and implementing a new phase counter based on analogue zero crossing and FPGA.

1. DESCRIPTION OF THE DIAGNOSTIC

The JET Far-Infrared (FIR) diagnostic1 is a hybrid interferometer-polarimeter laser based instrument used for measuring the plasma line-integrated density via interferometry and Faraday rotation angle and recently the Cotton-Mouton phase shift via polarimetry. This is a very large diagnostic with 80 meters optical path, heavy structures (70 tons tower) and hundreds of optical components. It employs FIR lasers with wavelengths of 195μm (Deuterated cyanide) and 118.8μm (Methanol). At these wavelengths (THz region in terms of frequency) high temperature plasmas are a transparent and not absorbent/reflecting medium. The system probes the plasma via eight channels, four vertical and four laterals. The sensitivity of this instrument is 3×10^{17} particle/m^2 for the line-integrated density and 0.2 degrees for the Faraday rotation angle measurements. There have been many developments since the first operation in early 80s in the optics, calibration, electronics and software processing to keep pace with the developments of the JET machine as a whole. For example, a schematic of the signal processing with recent and undergoing upgrades is displayed in figure 1.

2. BASIC PHYSICS CONSIDERATIONS

The principles of interferometry/polarimetry were described in detail in many references [1,2] and they rely on the plasma properties of refractive index for interferometry and optical activity and birefringence for polarimetry. If a linearly polarized electromagnetic wave is sent into a plasma three effects occur:

(1) Phase shift due to the refractive index of plasma.
(2) Faraday rotation angle of the polarization plane proportional to the density times the magnetic field component parallel to the direction of the laser beam propagation.
(3) Cotton-Mouton phase shift angle proportional to the density times the square of the magnetic field component perpendicular to the propagation direction. These effects can be described by the following equations:

$$\varphi \propto \lambda \int n_e \, dz \quad (1)$$

$$\Delta\psi \propto \lambda^2 \int n_e \, B_{//} \, dz \quad (2)$$

$$\Phi \propto \lambda^3 \int n_e \, B_{\perp}^2 \, dz \quad (3)$$

Here λ is the laser wavelength n_e is the plasma density and B_u and $B_{\perp}$ are the parallel and perpendicular components of the magnetic field respectively. In JET the two latter effects are comparable and have to be treated together [3]. There is a major advantage in the plasma density measurements derived from the Cotton-Mouton angle with respect to classical interferometry and this is the fact that the measurements are not history dependent but absolute measurements. Thus, even in the case of a temporary loss of the signal that causes the so-called “fringe jumps” to interferometry, after recovery the signal level, the density derived from polarimetry is correct. This it is of particular interest in the case of JET, particularly for protection systems, when in many high performance plasmas the interferometer fails due mainly to the refraction correlated with the Edge Localized Modes (ELMs) or pellet injection.

3. RECENT DEVELOPMENTS AND UPGRADES

3.1. FAST INTERFEROMETRY MEASUREMENTS AND MHD

During 2007-2008 the electronics hardware system of the interferometer was upgraded to a fast acquisition system of the raw unfiltered signals from the cryogenic detectors. The main driver for this addition was the prospect to use the interferometry measurements for the qualitative evaluation of the MHD via spectrograms of the interferometer detected signal. The system uses PCI–based fast transient recorders from INCAA [5].

The main parameters of these components are:

- 2MHz sampling (allows 1MHz FFT)
- 14bit resolution, 4 simultaneous channels
- 64MSamples per channel (64 sec of recording data at 1MHz).

The interferometer detectors are liquid He cooled InSb bolometers with very low NEP (system noise equivalent power) of 10^{-11}W×Hz$^{-1/2}$. These are able to observe any perturbation in this frequency spectrum with several order of magnitudes smaller than the main modulation frequency of 100kHz. As the frequency response is 1.2MHz, this system was fully compatible with the already present electronics for fast measurements developed for other diagnostics and made possible recording of the raw data for the full length of the plasma pulse.

In parallel with the hardware development there was a software development as well in order to better synchronize the interferometer/polarimeter with other diagnostics used for MHD studies (magnetic probes, reflectometry, and fast x-ray).

Since the first day of operation the system delivered impressive results, with higher contrast spectrogram than most of other MHD diagnostics [5]. The system was able deliver high contrast spectrogram of Alfvén cascades, magnetic modes as well as to trace the third harmonic of the TAE antennae that correspond to perturbation of the magnetic fields of the order of 10^{-10} Tesla [4].

The use of the 1MHz raw data from interferometry has been extended further in 2008-2009. The interferometer beat-signal is modulated at a frequency of 100kHz via a diffraction grating wheel. This corresponds to a time resolution of the phase counter of 10μs in which the system is able to measure a variation of a phase of 360^{o} (2π). In order to accomplish that, the signal has to be sampled at a frequency of at least 400kHz in order to acquire four points of the sin-wave ($s_{1..4}$):

$$\begin{cases} x = s_1 - s_3 \\ y = s_2 - s_4 \end{cases} \overset{polar\ coord}{\Rightarrow} \begin{cases} x = 2r\cos\varphi \\ y = 2r\sin\varphi \end{cases} \Rightarrow phase\ \varphi \qquad (4)$$

A new Matlab code has been developed to reconstruct the lineintegrated density with a true time resolution of 10μs from a signal that is acquired with a frequency of 500kHz−2MHz. That made possible for the first time at JET to study the density variation during fast events such as ELMS, VDE, disruptions or pellet injection. As the standard system is delivering measurements with a time resolution integrated over 0.8ms at its best, the study of such events was very limited. With this new upgrade we can describe these transient fast events with 300+ time points. In the Figure 2 the density during a disruption is displayed. As the density trace is lost for a period of time we had to recover the density backwards from the end of the pulse when the density is assumed to reach zero. The standard line-integrated output (Pulse Processed Files(PPF) dots in the picture) has been validated only thanks to the availability of the raw data..

In the figure 3 we can notice that there is a lot of additional information on the physics of the ELM precursors that the standard measurements were not able to capture [5].

3.2. NEW POLARIMETRY SET-UP AND CALIBRATION

The polarimeter was used mainly for Faraday angle measurements and q-profile calculation since 2001 and Cotton-Mouton1 phase shift at a later stage (2005).

In preparation for the 2008-2009 experimental campaign there was a requirement to set-up the polarimeter for ITER-relevant high current plasma experiments (4.5−5MA).

As the Faraday rotation angle varies roughly with the square of the plasma current, it can be easily noticed that there is more than one order of magnitude for polarimetry measurements between 1MA plasmas and 3.5MA plasmas for example. As the original system had been designed for different plasma regimes, it was very difficulty to set-up the diagnostic for all these extreme configurations, at the same time without putting at risk the operation of the instrument as interferometer. In particular, the interferometer measurements are heavily affected by the refraction effects of the laser beams due to high densities plasmas that were the most important for JET scientific programme.

A new set-up allowed covering the full scale of the Faraday rotation angle as well as a robust operation as an interferometer but this affected the original calibration for the Cotton-Mouton angle. As this calibration procedure was a mainly an empirical one, based on fitting it required a novel approach based on the real physical layout of the optical system. This new model of calibration, based on Muller matrix treatment is under development but already very good preliminary results have been obtained [6]. As the system has many optical elements and it is impossible to evaluate the change in polarization of each of them, it has been chosen to add two retarders to account for this contribution. The main equation that governs this model can be expressed as [6]:

$$\vec{S} = M \times \vec{S_0} \tag{5}$$

where the M is the Muller matrix of the optical system and $\vec{S}_0$, $\vec{S}$ are the initial and resultant Stokes vectors. The matrix M is expressed 6 with this new model as the product of the Muller Matrices corresponding to the wire grid used as an analyzer (*wg*), the first retarder (δ_1), second retarder (δ_2) and the half-wave plate used for calibration (*hwp*):

$$M = M_{wg}\ x\ M_{\delta 1}\ x\ M_{\delta 2}\ x\ M_{hwp} \tag{6}$$

An example of the output of this calibration is displayed in the figure 4, together with the results derived from a model based on Stokes theory that uses the field profile provided by the offline magnetic reconstruction program on JET (called EFIT) and the

CONCLUSIONS

The recent upgrades of JET interferometer/polarimeter have increased significantly the range of measurements and the quality of the information provided by the diagnostic as well as the reliability of the instrument. Moreover, some of the modifications are ITER relevant and can provide a significant contribution of the design of this type of diagnostics in the next generation of Tokamak devices. Addition of the second color laser on the vertical system and a novel phase counter based on 20MHz analog zero crossing and FPGA phase calculation designed by CEA7 is presently ongoing (see figure 3). This is believed to have a major impact to the JET protection systems.

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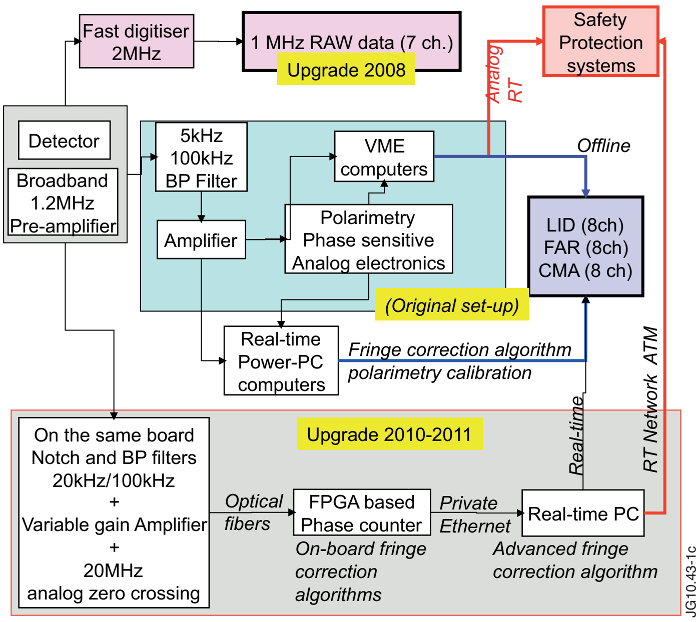

Figure 1: Schematic of the JET FIR Interferometer/Polarimeter signal processing.

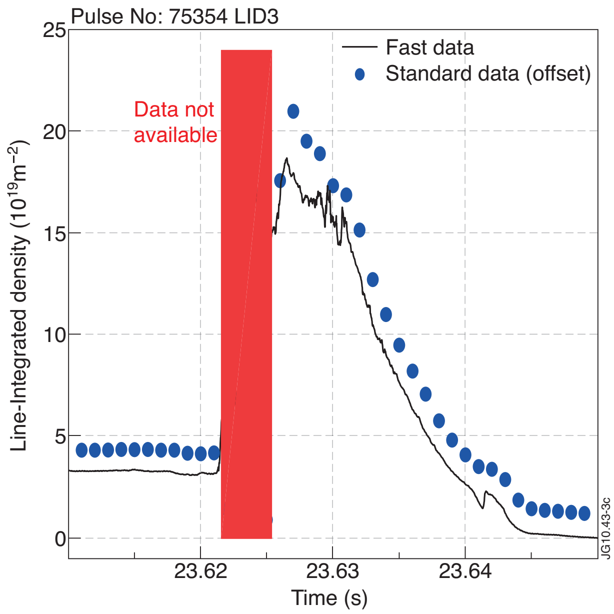

Figure 2: The reconstructed LID for the core channel during a disruption (standard data is offset in this plot for better visibility).

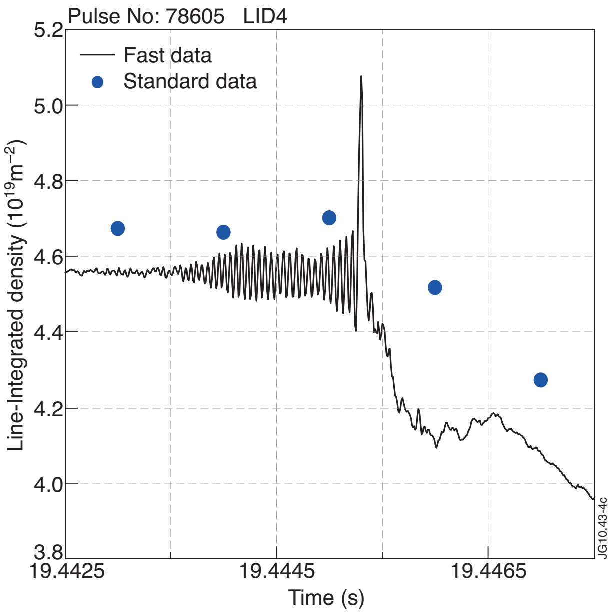

Figure 3: Line-integrated density (LID) on the edge channel of the JET interferometer during one ELM (standard data is offset in this plot for better visibility)

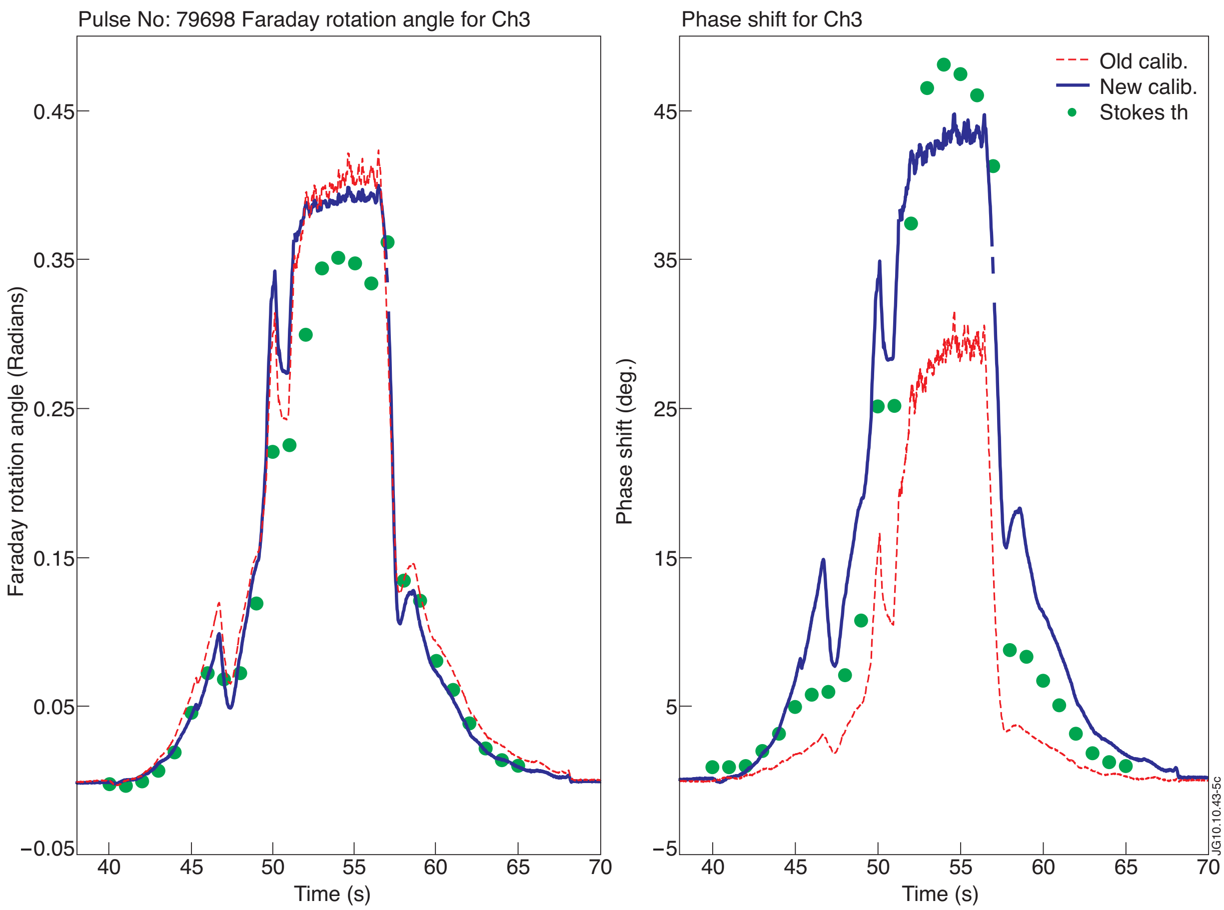

Figure 4: Preliminary results of the Faraday angle and polarimetry phase shift evaluated from the original and new calibration as well as a comparison with the output of a theory model using Stokes theory8.