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ABSTRACT.

The change in the ellipticity of a laser beam that passes through plasma, due to the Cotton-Mouton effect can provide additional information on the plasma density. This approach, complementary to the more traditional interferometric methods, has been implemented recently using the JET interferometer-polarimeter with a new set-up. Routine Cotton-Mouton angle measurements are made on the vertical central chords simultaneously with the Faraday Rotation angle data. This new data is used to provide robust line-integrated density measurements in difficult plasma scenarios, with strong ELMs or pellets. These always affect interferometry, causing fringe jumps and preventing good control of the plasma density. A comparison of line-integrated density from polarimetry and interferometry measurements shows an agreement within 10%. Moreover, in JET the measurements can be performed close to a reactor relevant range of parameters, in particular at high densities and temperatures. This provides a unique opportunity to assess the quality of the Faraday rotation and Cotton-Mouton angle measurements where both effects are strong and mutual non-linear interaction between the two effects takes place.

2. DESCRIPTION OF THE DIAGNOSTIC

In any fusion machine at present one of the essential diagnostics is the interferometer for measuring one of the main parameters that is the plasma density.

At JET, the Far InfraRed (FIR) diagnostic operates as a dual interferometer/polarimeter system. This diagnostic it is the largest of its kind in the world at present (the tower is 14 metres high and weights 70 tons!) as can be noticed in figure 1.

The system probes the plasma with 4 vertical and 4 lateral laser beams which provide line-integrated measurements of the plasma density by means of interferometry and Faraday Rotation angle with the polarimetry;

After an optimisation of the hardware and implementation of a new set-up for this diagnostic it is now possible to measure routinely the Cotton-Mouton angle with the polarimetry on several channels. The experimental set-up it is as follows:

- The diagnostic involves the use of the far infrared lasers because at these wavelengths the laser radiation is not absorbed by the plasma
- Two FIR lasers (195μm Deuterated cyanide (DCN) and 119μm Methanol) modulated at two different frequencies allow vibration and plasma induced phase shifts to be measured;
- Very long optical path: 80 metres each of its 8 channels;
- Time resolution is 10μs;
- The interferometer measurements are integrated in the Plasma Fault Protection System at JET, the real-time system in charge of the machine safety.

3. BASIC PHYSICS CONSIDERATIONS

3.1. INTERFEROMETER PRINCIPLE

The velocity of a laser beam is reduced when it passes through magnetically confined plasma by an amount dependent upon the number of electrons in the plasma. The change in velocity can be measured by comparing this beam with a reference beam, which does not pass through the plasma. The line-integrated plasma density measurements provided by the interferometry are history dependent. Loss of the signal (due to refraction in particular) at any moment during a pulse can cause fringe-jumps. This means that the measurements of the plasma density can be lost for the rest of the pulse, and any real-time control schemes of the plasma based on density are compromised. The interferometry also fails during pellet experiments where the time response/sensitivity of the present interferometer is not fast enough to track the rate of change of the plasma density.

3.2. POLARIMETER PRINCIPLE

Two separate phenomena influence the polarisation of the FIR beam that passes through a magnetically confined plasma [1]:

- *Faraday Rotation effect*: the plane of linearly polarised light passing through plasma is rotated when a magnetic field is applied PARALLEL to the direction of propagation.

$$\Delta\Psi \propto \lambda^2 \int n_e B_{p||}\, dz \tag{1}$$

- *Cotton-Mouton effect*: the ellipticity acquired by a linearly polarised light passing through a plasma is dependent on the magnetic field PERPENDICULAR to the direction of propagation.

$$\Phi \propto \lambda^3 \int n_e {B^2}_t\, dz \tag{2}$$

Here λ is the laser wavelength n_e is the plasma density and $B_{p||}$ and B_t parallel and perpendicular components of the magnetic field respectively.
In JET these two effects can be comparable.

Plasma density measurements derived from Cotton-Mouton angle are absolute measurements. Thus, even in the case of a temporary loss of the signal the next value is correct and can be used in codes for real-time control of the plasma as well to correct the interferometer data.

4. POLARIMETRY AT JET

Faraday Rotation angle is measured on all 8 channels by evaluating the two components of polarisation of a laser beam that traverses the plasma. These measurements are provided with on-line calibration before each shot (using half-wave plates) [2]. In order to measure the Cotton-Mouton angle a special set-up with initial linear polarisation of the input beam set at 45 degrees with respect to the toroidal field direction has been chosen on the vertical channels only [3].

The schematic of the polarimetry at JET is shown in figure 2. The half-wave plate at the entrance window is used to set the required direction of the *linear input polarisation* and, rotated to provide an on-line *calibration measurement* before each discharge. After traversing the plasma a linear polarised beam suffers a rotation of the polarisation plane due to Faraday Rotation and acquires ellipticity due to the Cotton-Mouton effect.

The amplitudes of the measured beat signals are proportional to the orthogonal components of the corresponding electric field vector amplitudes of the electromagnetic wave in the local co-ordinate system defined by the orientation of the wire grid in front of the detectors:

$$\begin{gathered} p'(t) \propto E_y^{(0)} \cos(\omega t\text{-}\varphi) \\ i'(t) \propto E_y^{(0)} \cos(\omega t) \end{gathered} \tag{3}$$

where ω is the modulation frequency, j is the phase shift between the two components between the two polarisation components and $E_x^{(0)}$, $E_y^{(0)}$are the components of the electrical vector. The amplified signals, are sent to a phase sensitive analog electronics module to produce four additional signals that are acquired by the data acquisition system:

$$\begin{gathered} PSD = \langle\, p(t) \times i(t) \,\rangle \quad \mathrm{RMS} = \langle\, p(t) \times i(t) \,\rangle \\ PSD = \langle\, p(t) \times i'(t) \,\rangle \quad \mathrm{RMS} = \langle\, i'(t) \times i'(t) \,\rangle \end{gathered} \tag{4}$$

where $i'(t) \propto E_x^{(0)}$ sint (ωt) is generated by phase shifting i (t).

Using software processing [2] and data from an on-line calibration the Faraday Rotation angle and Cotton Mouton angle are calculated.

At JET, for the vertical channels, Bt being largely constant along the line of sight, the previous equation for Cotton-Mouton angle can be reduced to:

$$\Phi = k\lambda^3 B^2_t \int n_e \, dz \tag{5}$$

where k is a constant .

Therefore in this case the line-integrated density $\int n_e dz$ can be directly obtained.

5. EXPERIMENTAL RESULTS

The FIR diagnostic at JET is one on the first to operate at JET and has been modified many times. Some of the modifications were the re-routing of some channels with the introduction of the divertor, replacement of the compensation laser, addition of the polarimetry in early 90's and implementation of the on-line calibration for polarimetry in 2002.

During this period the interferometer performed successfully and later the polarimeter shown to be a very good tool to evaluate the safety factor (q-profile) at JET and these measurements have been included in real-time schemes for control of the plasma.

5.1. ROUTINE MEASUREMENTS OF THE JET FIR INTERFEROMETER/ POLARIMETER

An example of the measurements with the FIR interferometer/polarimeter of the line-integrated density and Faraday Rotation on all 8 channels that are obtained routinely are shown on figures 3 and 4.

The measurements of the line-integrated density with polarimetry have been tried for many years but spurious ellipticities[2] did not allowed to obtain routine measurements.

Recently, with a new set-up of the polarimetry diagnostic the results on the plasma density tried in recent campaign at JET did shown very promising results.

One example that we consider relevant to present the potential of polarimetry as a technique to measure the line-integrated density in scenarios at JET extrapolated to ITER: high triangularity, high current, high density and high pedestal pressure. In these scenarios the interferometry may suffer fringe-jumps. In the figure 5 it can be noted that the interferometer measurements on channel 2(V2) are badly affected by the fringe jumps and make the interferometric data difficult to use. The measurements derived from polarimetry however are consistent and do not fail.

5.2 PELLET EXPERIMENTS AT JET

One class of experiments were the line-integrated density derived from polarimetry may became essential are the pellet experiments, especially with the upcoming high repetitive-rate injector. During these plasma pulses, because the rate of density variation is larger than the time response of the interferometry (more than 1 fringe ($\sim 10^{19}$) in 10μs), the phase shift within the sampling period of the interferometer exceed 360 degrees making the measurements uncertain.

This was always a problem with interferometer data that needs manual correction with a very difficult procedure in order to get the measurement.

In the figure 6(a) comparison between the line-integrated density for central channel 3(V3) during one JET pulse with pellet experiments with both interferometer/polarimetry is shown and the matching is excellent.

CONCLUSIONS AND ITER APPLICATIONS

At JET we it is now possible to measure routinely to measure the Faraday Rotation Angle and Cotton-Mouton angle simultaneously on two vertical channels.

The differences between the line-integrated density measurements delivered by interferometry and polarimetry are below 10% and are due to some additional effects [3] still to be studied.

The future applications of the Cotton-Mouton angle measurements at JET are for:

- Real-time plasma density measurements during ELM's and Pellets experiments where interferometry is affected by fringe-jumps
- Feedback control for automatic fringe correction of interferometry
- Integration of the plasma density in the codes for real-time control of the plasma at JET

The good performance of the JET FIR polarimeter is encouraging for the design of the ITER polarimeter that will have parameters such as dimensions, laser wavelength and channel distributions comparable with the JET one.

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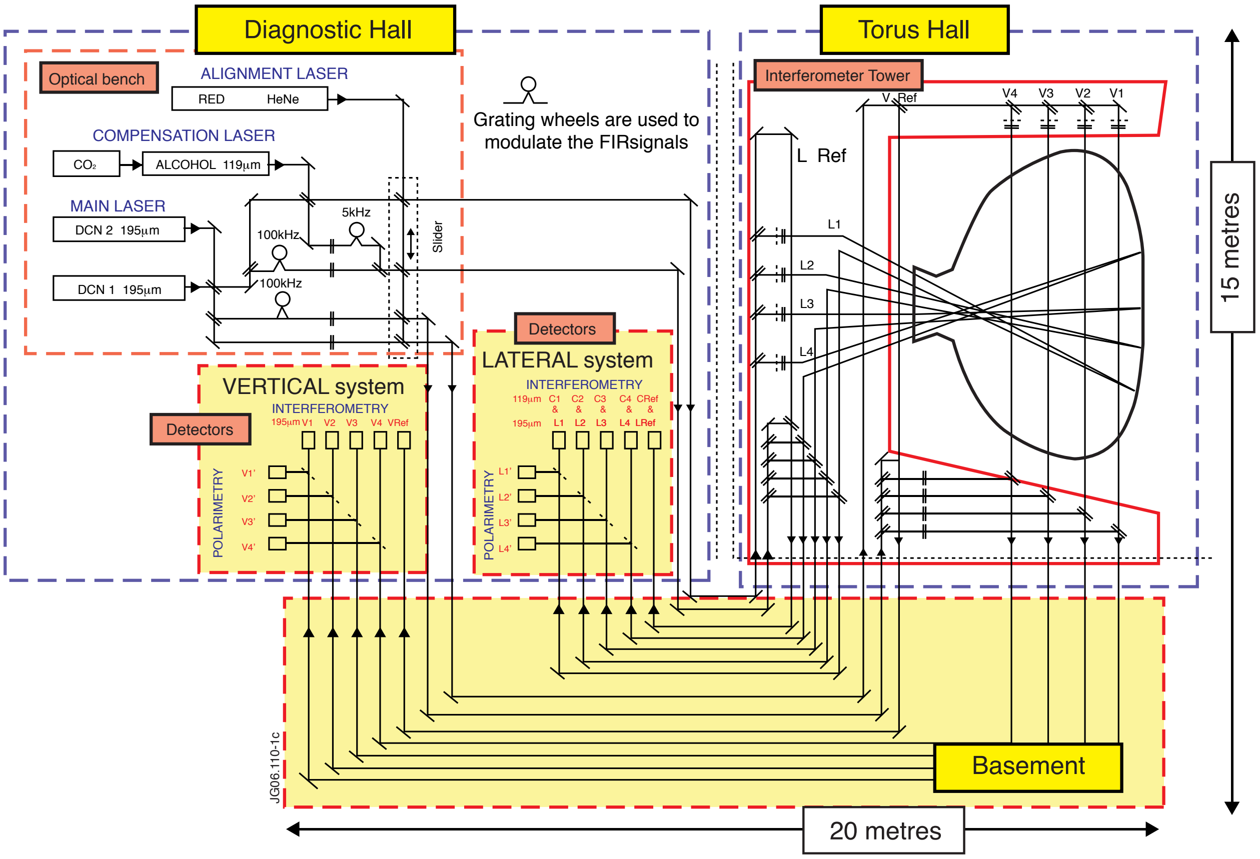

Figure 1: Schematic of the JET FIR Interferometer/Polarimeter

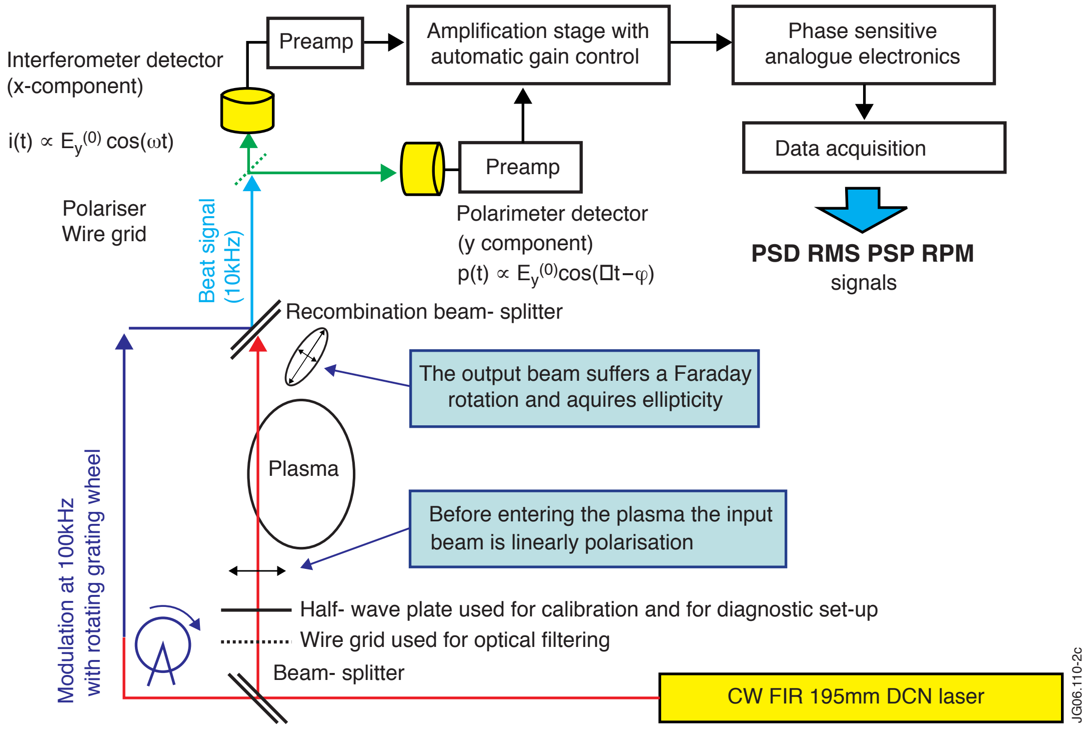

Figure2: Schematic of the polarimetry side at EFDA-JET

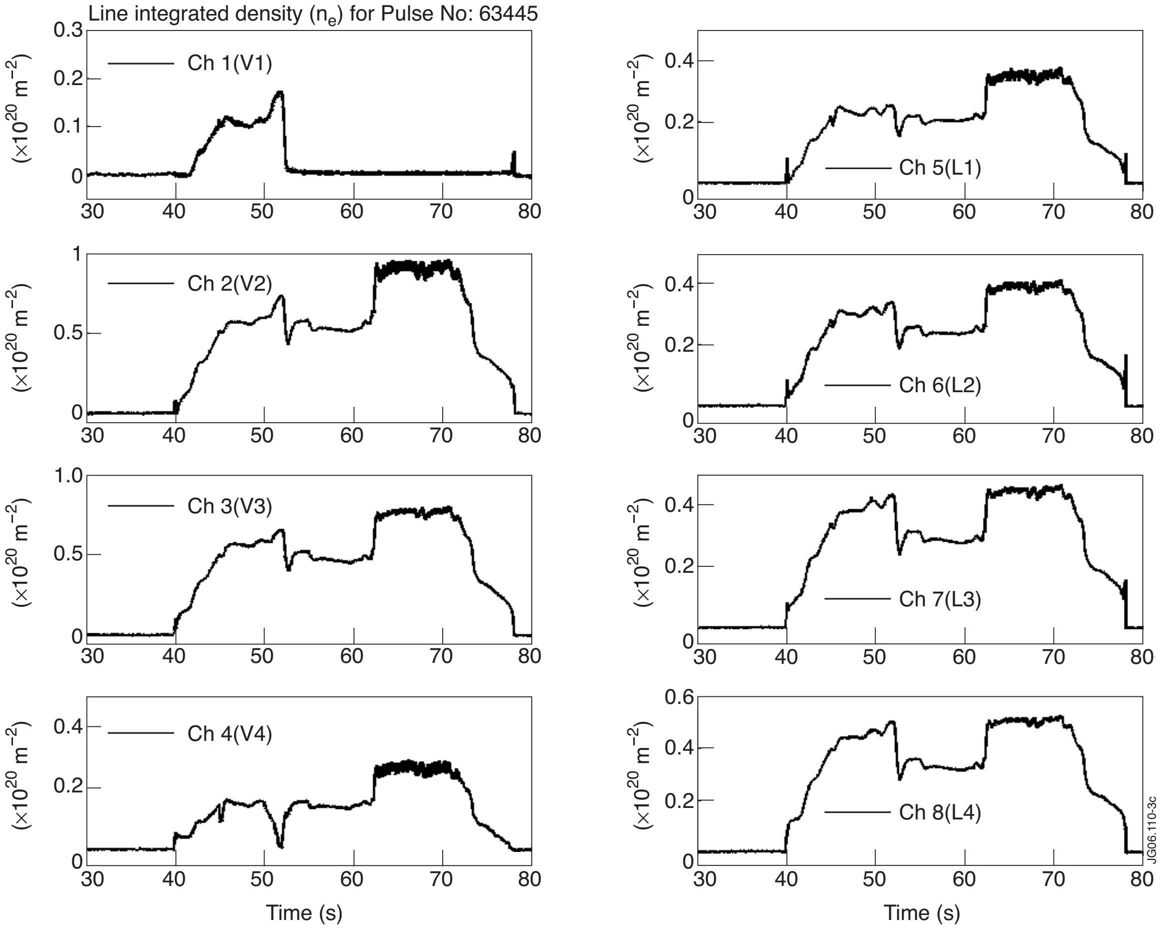

Figure 3: Example of line-integrated plasma density with interferometry measurements

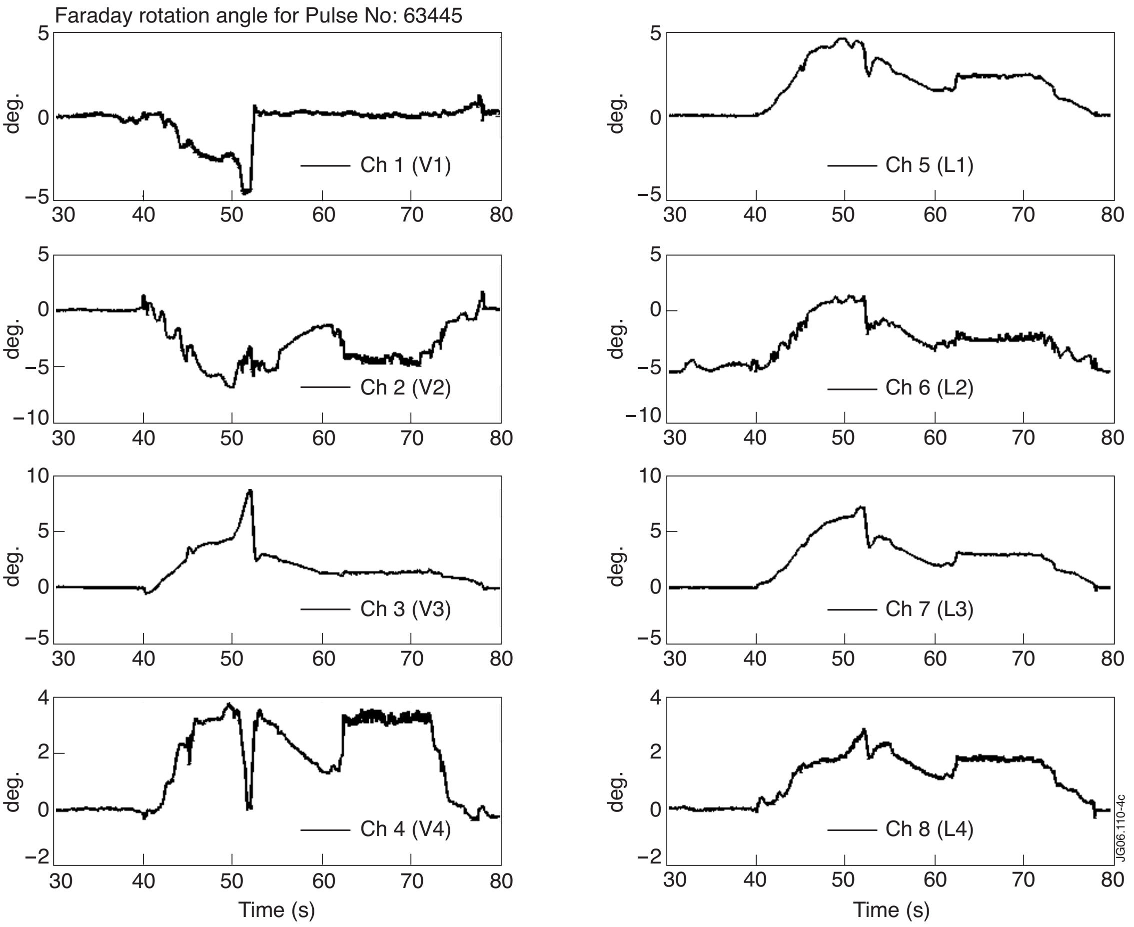

Figure 4: Example of Faraday Rotation angle measurements

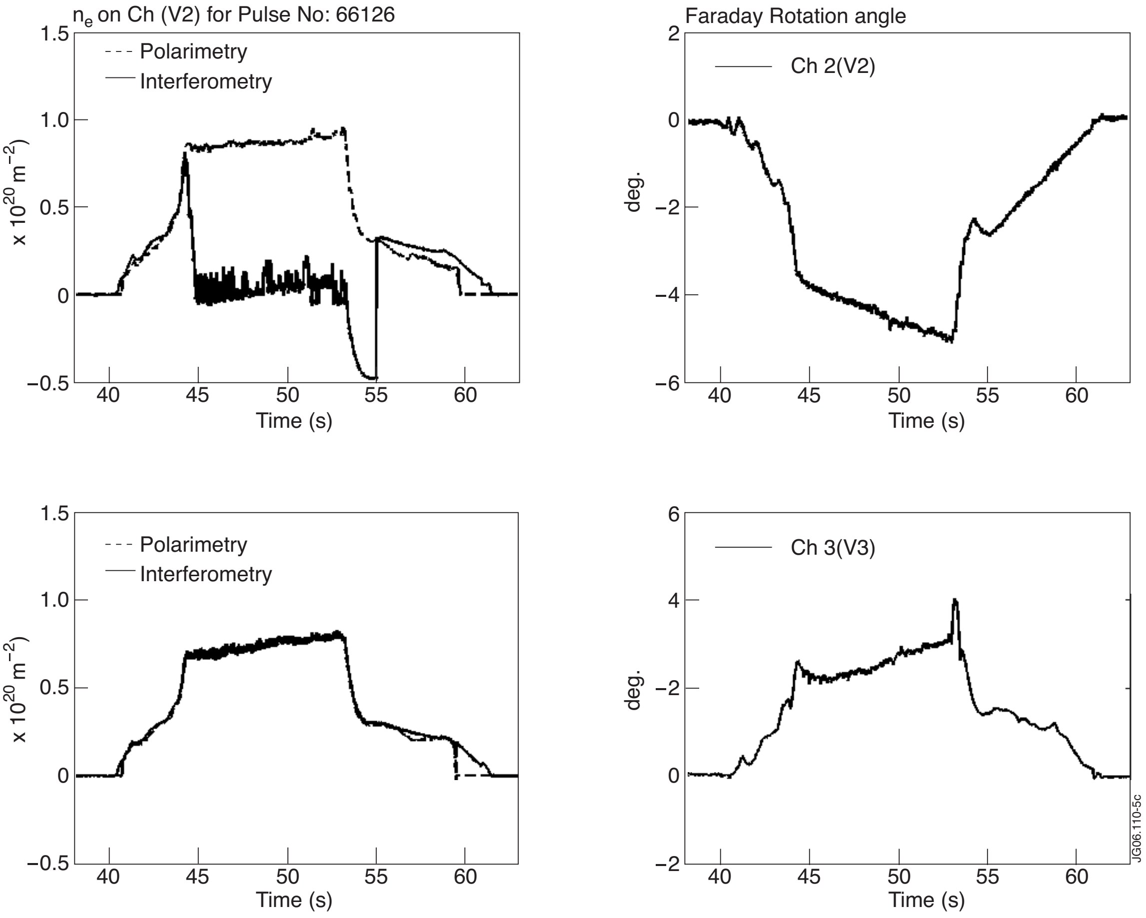

Figure 5: Measurements of the line-integrated density with both interferometer and polarimeter for ITER-like configuration pulses at JET (high triangularity, high current, high density and high pedestal pressure)

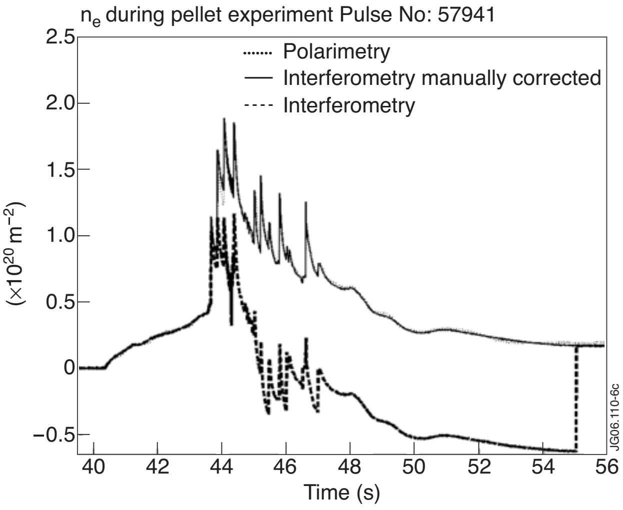

Figure 6: Line-integrated plasma density measurements during a pellet experiment pulse at JET (The strikes are pellets)