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ABSTRACT
Real time density profile measurements are essential for advanced fusion Tokamak operation and interferometry is a proven method for this task. Nevertheless, as a consequence of ELMs, pellet injections, fast density increases or disruptions, the interferometer is subject to fringe jumps, which produce loss of the signal preventing reliable use of the measured density in a real time feedback controller. An alternative method to measure the density is polarimetry based on the Cotton Mouton effect, which is proportional to the line integrated electron density. A new analysis approach has been implemented and tested to verify the reliability of the Cotton Mouton measurements for a wide range of plasma parameters and to compare the density evaluated from polarimetry with that from interferometry. The density measurements based on polarimetry are going to be integrated in the real time control system of JET since the difference with the interferometry is within one fringe for more than 90% of the cases.

1. INTRODUCTION
At JET machine the measurement of the line integrated electron plasma density is performed by interferometry, which is a proven method, since many years, to provide a profile of the plasma density. Since this diagnostic is integrated in the real time control system for many JET experiments, it is important to recover the signal when it is corrupted or even lost, resulting in a wrong reconstruction of the density profile. This failure of signal occurs mainly due to refraction of the laser beams during ELMs events, fast density increases, disruptions and pellets injection [1] which cause fringe jumps. An alternative way to measure the line-integrated electron density with the time sampling needed for the real-time control is the polarimetry. The measurements of the Cotton Mouton effect, which mainly consists of a change of the ellipticity of a FIR probing beam due to the interaction with the magnetic fields perpendicular to the beam propagation direction can be used in some conditions to extract the line integrated electron density. Given the results obtained at the stellarator W7-AS [2], also at JET the possibility of obtaining the electron density from measurements of the Cotton Mouton effect has been seriously considered. The paper presents a comparison between the line integrated plasma density from interferometry and from polarimetry by the Cotton Mouton effect, for two vertical channels of the JET FIR interferometer/polarimeter diagnostic system. A preliminary study for real-time evaluation of the line integrated plasma density profile has been performed too and the first results are presented. These results confirm that polarimetry can provide measurements of the line integrated density. Thus when fringe jumps are detected, the interferometric signal can be corrected, reading the current value of the line integrated density from polarimetry.

2. THEORY
The polarization state of an electromagnetic wave can be described by Stokes vector $s \equiv (s_1, s_2, s_3)$ [3] and its evolution in the plasma satisfies the following relation, as a function of the propagation direction z:

$$\frac{d\boldsymbol{s}(z)}{dz} = \Omega(z) \times \boldsymbol{s}(z), \tag{1}$$

where the components of the vector Ω are proportional to the line integrated plasma density and the components of the magnetic field B. In a Tokamak the toroidal magnetic field B_t is stronger than the other components and it can be considered constant for a vertical line of sight, and therefore the following relation is satisfied:

$$W_1 \equiv \int_{z_1}^{z_2} \Omega_1 (z)\mathrm{dz} = C_1 \lambda^3 B_t^2 \int_{z_1}^{z_2} n_e (z)\mathrm{dz}, \tag{2}$$

with $C_1 = 2.44\times10^{-11}$ [rad/m T²] and λ = 195.8μm, which is the FIR wavelength employed at JET. Thus, if W_1 is known, the line integrated electron plasma density can be easily derived. To this purpose, considering a particular approximate solution of equation (1) [4], it is possible to write the Stokes vector coming out from the plasma in the form:

$$s_f = M \cdot s_0 \tag{3}$$

where M is the transition matrix of the plasma and s0 is the initial polarization state of the probing beam. As described by Segre [4], for an input beam linearly polarized at 45° and for small plasma effects (for the considered data set $W_1 < 0.1$), the final Stokes vector can be written as: $s_f = (-W_3, 1, W_1)$. In this case the third component of the Stokes vector is equal to W_1 and writing s_{3f}, as a function of the ellipticity ∈ = tan χ of the polarization ellipse, the following relations are satisfied:

$$s_{3f} = \sin 2\chi = W_1 \tag{4}$$

From the ellipticity measured by polarimetry it is possible to reconstruct the line integrated plasma density using the next relation:

$$\int_{z_1}^{z_2} n_e (z)\mathrm{dz} = \frac{\sin 2\chi}{C_1 \lambda^3 B_t^2} \tag{5}$$

3. THE INTERFEROMETER/POLARIMETER DIAGNOSTIC AT JET

At JET, the Far Infrared (FIR) diagnostic operates as a dual interferometer/polarimeter system, widely described in [5]. The radiation source is a DCN laser at λ = 195μm and the reference beam is modulated at 100 kHz by means of a rotating grating. The system probes the plasma with 4 vertical and 4 lateral (see Figure 1) laser beams which provide measurements of the lineintegrated plasma density by means of interferometry and measurements of Faraday angles and Cotton Mouton effect by means of polarimetry [6]. The total path between laser and detectors is ~80*m* for each of eight channels. The interferometer has an operating range for line density from 10^{18} to 4×10^{22} m^{-2}, with an accuracy of 3×10^{17} m^{-2} and the polarimeter can measure Faraday rotation angles up to 70%æ, with an accuracy of about 0.2%°.

The interferometric measurements are integrated into the real-time plasma control, and are used for machine protection against disruptions. Actually the method to correct finge jumps is the comparison between vertical and lateral channels (ch2-ch7, ch3-ch8 and ch4-ch5), assuming that the latter are already corrected. The detection depends on the difference between channels using an appropriate coefficient from one sample to the next. If the difference increases over an imposed limit the correction is applied. Starting with the current experimental campaign (C-20), the measurements of the Cotton-Mouton effect were made available in the real-time system as well as the measurements of the Faraday rotation angle, that has been successfully implemented and used since 2002 for real time q-profile experiments [6].

4. EXPERIMENTAL RESULTS

The results presented in this paper come from a wide investigation of reliability of the line integrated plasma density measured by polarimetry for various JET campaigns (years 2006 and 2007). Recently a statistics, covering different plasma conditions, has been produced to compare the line integrated density obtained by polarimetry with the one measured by the interferometer. This first analysis has been performed for channels 2 and 3 on interferometer/polarimeter system. For channel 2 the available shots are less than for channel 3 because of many fringe jumps on the interferometric signal due to the beam passing through the divertor and crossing the magnetic xpoint. Figure 2a and 2b show the difference between the density obtained by polarimetric data and the density from interferometry expressed in terms of fringes (one fringe = 1.143×10^{20} m^{-2}) as a function of the line integrated plasma density from interferometry for channels 2 and 3 respectively. The agreement is within one fringe, which represents the interferometric error, for the whole considered line integrated density range (from 10^{18} to 3×10^{20} m^{-2}). In particular for high electron density values all (99%) points plotted are within the dotted lines representing the thresholds of plus/minus one fringe. These results have confirmed that the interferometric data, after fringe jumps, can be recovered using density values provided by polarimetric measurements and thus, during the discharge, the control on the plasma density is secure.

To this purpose a preliminary study has been performed on the reliability of the real time measurements of the density by polarimetry. Figure 3 shows the time evolution of the line integrated electron density measured by both interferometry (solid line) and polarimetry (dotted line) for the vertical channels 2, 3 and 4, during an entire high density discharge. It can be noticed the good agreement (within one fringe) between the two curves for channels 2, 3 and 4, for almost the whole time range (0-35s). For channel 4, the real time signal (dotted line) is not stable for low density values ($< 3\times10^{19}$ m^{-2}) because this chord is close to LCF and the magnetic field configuration isn't stable, as well, during the ramp up of the pulse. Moreover, it has to be emphasized that the interferometry density in channel 2 had more than hundred fringe jumps, which have been manually corrected off line. These results show that it will be easy to integrate a new algorithm to correct on-line the interferometric data, reading real-time values of the line integrated density from polarimetry.

It is then possible to conclude that the polarimetry could be safely used to recover the interferometry density when a fringe jump occurs, which otherwise could result in serious difficulties for the real-time control of many JET experiments. These results may have implications on the design of ITER interferometer and polarimeter systems.

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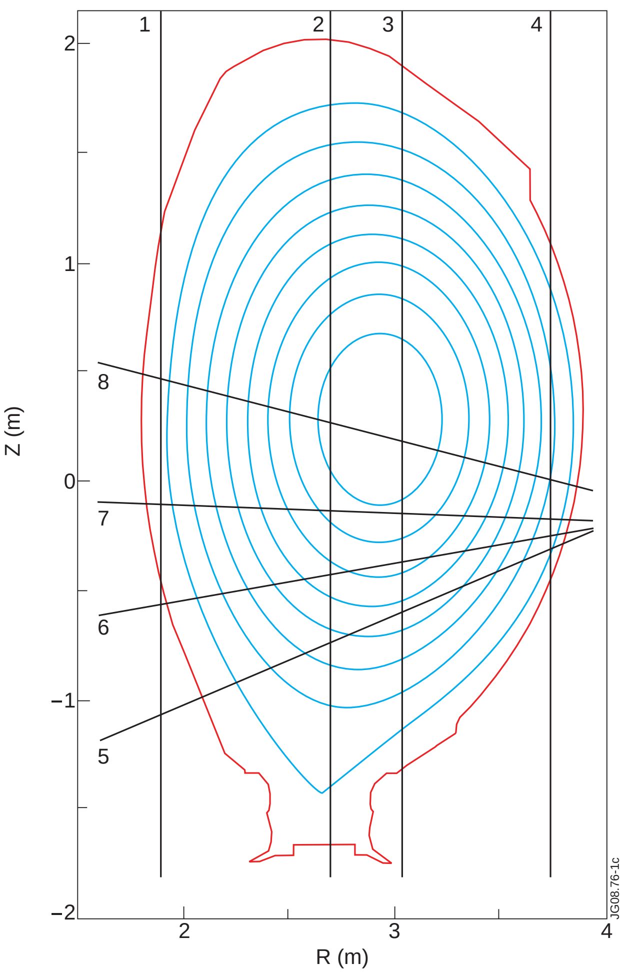

Figure 1: Lines of sight for interferometry and polarimetry at JET

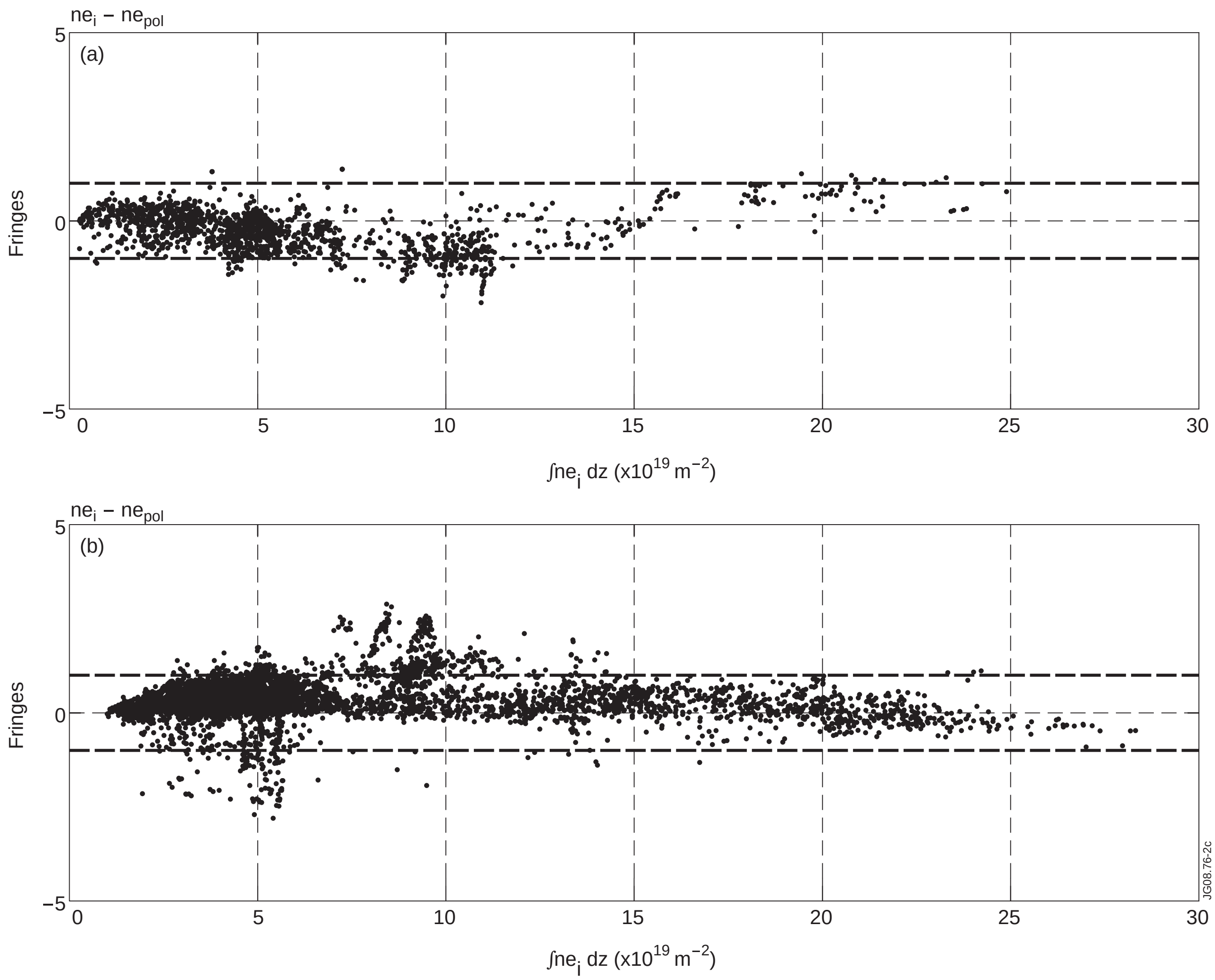

Figure 2: Difference between the line integrated density from polarimetric data and the interferometer line density in terms of fringes (one fringe = $1.143\times10^{19}m^{-2}$) for channel 2 (a) and channel 3 (b). The dotted lines are the threshold reference of one fringe.

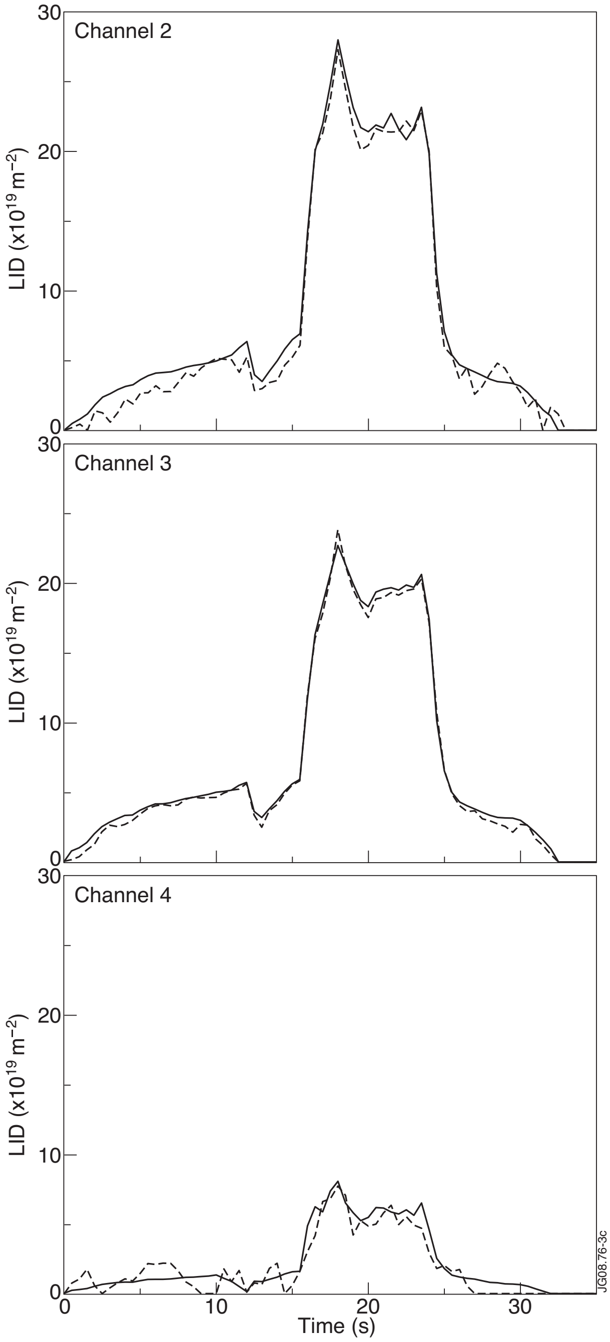

Figure 3: Comparison between the line integrated density evaluated by the interferometer (solid line) and the polarimetric real time measurements (dotted line) for the channels 2, 3 and 4 of polarimeter/interferometer at JET.