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The line-integrated plasma density from both interferometry and polarimetry at JET

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** See the Appendix of M.L.Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA*

I. Introduction

The polarisation of an electromagnetic wave travelling through an optically active and birefringent medium such as a magnetised plasma changes due to both Faraday rotation and Cotton-Mouton effects. From the latter, in certain conditions, one can obtain information on the line-integrated plasma density, which is usually measured by the interferometer, in terms of the Cotton-Mouton phase shift [1].

The work reports the comparison of the line-integrated plasma density derived from interferometer and polarimeter diagnostics measurements with the purpose of testing different models to recover the line integrated plasma density from the measured Cotton-Mouton phase shift. A systematic analysis of the quality of the Cotton-Mouton measurements for a wide range of plasma conditions at JET (different regimes of temperature, density and toroidal magnetic field) is presented for the first time.

The purpose of the work was to identify a suitable model for the line-integrated plasma density from polarimeter. These new measurements could be used to alleviate the problem of "fringe jumps" in the interferometer, which poses serious difficulties for the plant safety and real-time control of many JET experiments. Many of the reported results will also contribute and support the design of ITER interferometer/polarimeter.

II. The models

The evolution of polarisation state of an electromagnetic wave propagating in a magnetised plasma can be described in terms of the evolution of the reduced Stokes vector [1]:

$$\vec{s} = \begin{pmatrix} s_1 \\ s_2 \\ s_3 \end{pmatrix} = \begin{pmatrix} \cos 2\chi \cos 2\psi \\ \cos 2\chi \sin 2\psi \\ \sin 2\chi \end{pmatrix} \qquad (1)$$

where ψ is the angle of the polarisation plane with respect to the reference axis and χ is related to the ellipticity $\varepsilon = \tan\chi$ of the wave. From the ellipticity the Cotton-Mouton phase shift ϕ can be derived [1]. The evolution of the Stokes vector $\vec{s}$ in the cold plasma approximation $\left(\omega_p^2, \omega_c^2 << \omega^2\right)$, where ω_p, ω_c and ω are the plasma, electron cyclotron and probing wave frequency respectively, can be written as function of the propagation direction z:

$$\frac{d\vec{s}}{dz} = \vec{\Omega}(z) \times \vec{s}(z) \qquad \text{(2a)}$$

In (2a) $\vec{\Omega}$ is a 3-element vector from which the Mueller matrix of the plasma can be computed and it is expressed by:

$$\vec{\Omega} \equiv \begin{pmatrix} \Omega_1 \\ \Omega_2 \\ \Omega_3 \end{pmatrix} \propto \begin{pmatrix} n_e B_\perp^2 \\ n_e B_r B_\perp \\ n_e B_\parallel \end{pmatrix} \qquad \text{(2b)}$$

where n_e is the electron plasma density, $B_\parallel, B_r$ and $B_\perp$ are the parallel, radial and perpendicular components of the magnetic field with respect to the wave's propagation direction. In the case of JET, for the vertical channels $B_\perp = B_{Toroidal}$. The terms (Ω_1 , Ω_2) and Ω_3 account for the Cotton-Mouton and Faraday effect respectively. As described in (2a) the Stokes vector's components are dependent on the line integrals of Ω_i :

$$W_i = \int_{z_1}^{z_2} \Omega_i \mathrm{dz} \qquad \text{where } i = 1,2,3 \qquad \text{(3)}$$

The line-integrated plasma density $\langle n_e \rangle$ can be evaluated directly from the Cotton-Mouton phase shift ϕ using $\int n_e = C\,\phi / B_{Toroidal}^2$ where n_e is the plasma density and C is a constant depending of the wavelength of the probing wave. The phase shift is provided by polarimeter or by the following possible solutions for the (2a) equation.

A. Rigorous solution

The Stokes vector of the wave after the plasma has been calculated numerically solving the propagation equation (2a) [1]. A code has been developed by using the magnetic field components given by the equilibrium code EFIT and the profile of the plasma density provided by Thomson scattering measurements.

B. Type I approximation

In plasma conditions for which $W_i << 1$ and for an initial linearly polarised radiation oriented at 45°, the Faraday rotation (ψ) and Cotton-Mouton phase shift ϕ angles can be derived by $s_1 \approx -W_3 \propto -\int nB_{\|} dz \approx 1/\tan 2\psi$, $s_3 \approx W_1 \propto \int nB_T^2 dz \approx \tan\phi$ respectively [2].

C. Type II approximation

The condition of small W_i is often too restrictive but when ($\Omega_3 > \Omega_1 >> \Omega_2$), i.e. Faraday rotation effect is much larger than the Cotton-Mouton effect and for an initial linearly polarised radiation oriented at 45°, an approximate solution [2] can be found for the equation (2a), which consists of assuming $s_1 = -\sin W_3, s_2 = \cos W_3$ and $s_3 = \int_{z_1}^{z_2} \Omega_1(z') \cos W_3(z') dz$.

D. Empirical model

It considers a mutual interference between the Faraday and Cotton-Mouton effects [3] as given by the differential equation $d\phi = d\phi_{CM} - (\sin 2\phi / \tan 2\psi)\, d\alpha$, where α and ϕ_{CM} are the measured Faraday rotation angle and phase shift and ϕ is the pure Cotton-Mouton angle.

III. Results

A large number of JET pulses have been selected covering different plasma conditions: plasma current up to 3MA, additional power up to 30MW, toroidal fields up to 3T and temperature up to 12keV. Then, the line-integrated plasma density has been evaluated using the polarimetric data and the models mentioned in the previous section and compared with the experimental measurements provided by the interferometer $\langle n_e^i \rangle$.

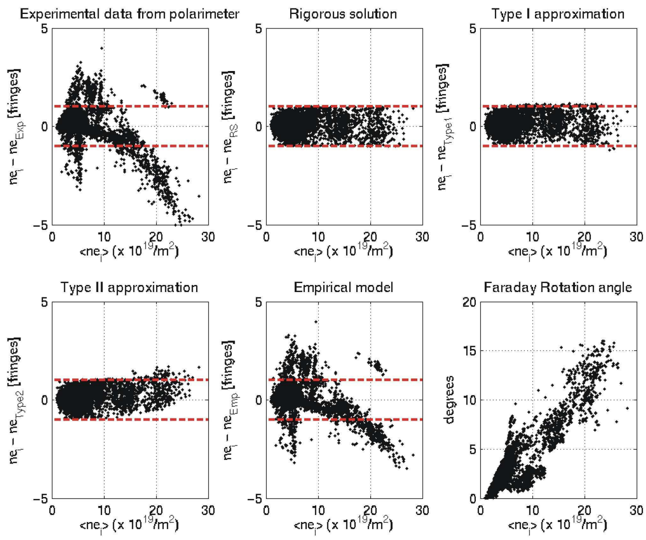

Figure 1: Density variation for polarimetric data and for different models with respect to the interferometer line density (the dotted red lines are the threshold reference of one fringe)

In Figure 1 are shown the differences in terms of fringes (1 fringe=1.143x10^{19}/m^2) only for those points where the line-integral density from the rigorous solution differs within one fringe with respect to the $\langle n_e^i \rangle$. In order to evaluate the quality of different models a merit function histogram-based similar with figure 1 have been generated but this time for various time intervals and density range as depicted in Figure 2:

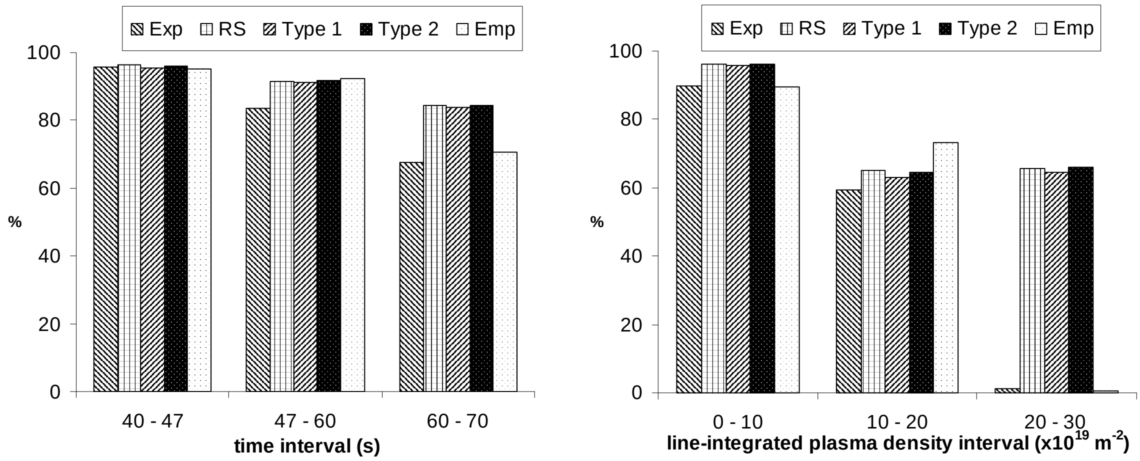

Figure 2: Histograms of agreement between different models and polarimeter with respect to the interferometer in function of the time and density ranges

IV. Conclusions

The agreement between the rigorous solution and Type I/II approximations with $\langle n_e^i \rangle$ is valid in about 90% of the cases. The differences may be caused by the errors in evaluating the EFIT or density profile from Thomson Scattering.

The density derived directly from the polarimeter is in agreement with $\langle n_e^i \rangle$ up to densities about 15*10^{19} [m^{-2}]. The empirical approximation $\langle n_e^{Emp} \rangle$ is making the agreement better but not enough for high densities. The strong dependence of the Cotton-Mouton phase shift on the Faraday rotation angle, when both are high, may indicate that an additional correction term based on the optical properties of the optical components of the diagnostic is necessary in the empirical model. This work will be performed in the future.

Acknowledgments

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