MILLIMETER WAVE SCHLIEREN DIAGNOSTICS FOR FUSION PLASMA

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The schlieren diagnostic presented in this paper is based on a finite angular deflection of exploring electromagnetic wave beams, which, for the density of fusion plasmas of $N_e \approx 10^{14} cm^{-3}$, is encountered in the millimeter wavelength range /1/. The plasma is explored by several beams which are deflected in a small region around the intersection of the exploring mm-wave beams with a plane normal to the beams and passing through the center core of the plasma. Besides affording the possibility of calculating the density distribution, the schlieren signals present a direct view of the density gradient transverse to the beams. The amplitude of the schlieren signals is numerically calculated in this paper, from a known density distribution and a known radiation pattern of the mm-wave antenna. The opposite problem of calculating the density distribution form the measured schlieren signals has not jet been faced. It may, however, be solvėd by imposing some constraint on the numerical results in order to avoid the ambuguity resulting from asymmetric situations. In the following a numerical model for calculating the schlieren signals is applied to several density distribütions. In particular, displacement and rotation of the central core reproduces measured schlieren oscillations in the Pulsator tokamak immediately preceding a current disruption.
As well known, the schlieren calculation of a ray path deflected in a dispersive medium is derived from the Fermat law by taking the minimum of the integral $\int_s k dl$, where k is the wave number. Replacing this k with that given by the dispersion relation of an ordinary wave, the radius of curvature R of the deflected ray path is expressed by /2/:

$$\frac{1}{R} = - \frac{\vec{N}}{2} \frac{\nabla V}{1-V} \quad (1)$$

where $V = N/N_c$; N is the local density and N_c is the cut-off density for the wavelength used; $\vec{N}$ is the unit vector of the normal to the trajectory. From eq. 1) it is seen that the ray deflection is in the direction of decreasing density, is directly proportional to the density gradient and increases for an increasing density.
Assuming a pencil radiation pattern $I(\theta)$ for an exploring electromagnetic wave beam, the unperturbed signal at the receiver is $A = 2\int_0^{\mu} I(\theta)d\theta$ where μ is the angular width of the two undeflected external rays of a wave beam inpinging on the edges of the receiver antenna.

For a perturbed radiation pattern the received signal $\Delta A = \int_{\theta-}^{\theta+} I(\theta)d\theta$ depends on the ray density of the beam inside the two deflected external rays which reach the receiver edges.

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Analytically, these two rays, which are calculated from eq. 1), are identified by the two angles θ^+ and θ^- of the radiation pattern $I(\theta)$ which is approximated by the function

$$I(\theta) = \frac{1}{2}\left(e^{-a\theta^2} + e^{-b\theta^2}\right). \tag{2}$$

The amplitude of the normalized schlieren signal is then given by:

$$\Omega = \frac{\Delta A}{A} = \frac{\int_{\theta^-}^{\theta^+} I(\theta)\,d\theta}{2\int_{o}^{\mu_2} I(\theta)\,d\theta} \tag{3}$$

where the error introduced by the numerically simulated radiation pattern resulted below the uncertainty limit for the experimental data. From eq. 3) one immediately sees the advantage of the schlieren method in comparison with other diagnostics or other models for simulating MHD mode perturbations: the detected signal at the receiver antenna does not need to be integrated along the ray path like the x-ray emissivity or the phase shift of an ordinary wave. Any change in the distribution of the density $V(\xi,\eta)$ deflects the ray path as calculated by eq. 1) to 3) and the signal is that which is not deflected from the edges of the receiver antenna.

Even small variations of the density distributions at any point of the plasma are detected by a sufficient array of exploring wave beams.

In view of the asymmetrical situations that must be faced by the model all the calculations involved by eq. 1), 2) and 3) were referred to orthogonal coordinates ξ,η. Equation 1) is then expressed by:

$$\eta'' = \frac{1}{2\,[1-V(\xi,\eta)]}[1 + \eta'^2][\frac{\partial V}{\partial \xi}\,\eta' - \frac{\partial V}{\partial \eta}] \tag{4}$$

where the density distribution $V(\xi,\eta)$ is given by: (5)

$$V(\xi,\eta) = Vo\,\{1 - [\frac{(\xi-\tau\cos\Psi_2-\varrho\cos\Psi_1)^2+(\eta-\tau\sin\Psi_2-\varrho\sin\Psi_1)^2}{1+\tau^2-2\tau\cos\Psi_2(\xi-\varrho\cos\Psi_1)-2\tau\sin\Psi_2(\eta-\varrho\sin\Psi_1)}]^f\}$$

where $Vo = No/Ne$ is the maximum normalized density value; τ is the radial coordinate of Vo; $\tau\cos\psi_2$ is the vertex abcissa; ψ_2 is the angle of Vo; ψ_1 is the angle of the plasma centre and ϱ its radial coordinate; f is a profile-flattening index.

Equation 5) represents a generalized density function which, as it will be seen, allows the observed schlieren oscillations of Fig. 1 to be simulated by displacement and rotation of the central peak of the parabolic density funtion.

Figure 2 shows the isodensity lines and the labelling of the density distribution parameters of eq. 5. The geometrical arrangement of the exploring millimeter wave beams of the Pulsator tokamak is also sketched in Fig. 2. For a symmetric and centred density distribution, viz. $\varrho = o$ and $\tau = o$ in Fig. 2, the results of the numerical model were compared with the Shmoys model /3/ valid for a centred and parabolic radial density distribution only. The result of both models deviated less than 1%. A detailed discription of the numerical programm /4/ of the model will be reported elsewhere, the aim of this work being to show that the schlieren method can give insight

into localized MHD phenomena inside the plasma, as shown in the following application of the model.
Although the numerical method allows the calculation of schlieren effects relating to any radial distribution of density, the following density distributions were chosen in order to simulate some possible physical processes underlying the observed oscillations of schlieren signals. In this contest particular interest is shown in a central density peak radially displaced from the geometrical centre of the discharge tube. The rotation of such a peak density simulates schlieren signals relating to observed MHD perturbations.

The various examples of individual situations are aimed at affording the possibility of combining them in order to get a possible physical understanding of the observed signal.

Figure 3 shows the "kink" effect of the schlieren signals obtained by programming the peak density for: 1) $\varsigma = 0.15$ (asymmetry to the centre); 2) radial displacement $\tau = 0$; 0.25; 0.50; 3) Vo = 0.5; 0.8 and 4) f = 4, corresponding to a large flattening of the radial density distribution.

Rotation of the angle ψ_1 produces the oscillations variety of the schlieren signals in Fig. 3. Some of these oscillations are similar to those detected immediately before a current disruption, shown in Fig. 1.
The $\dot{B}(\phi)$ pick-up coil oscillations of growing amplitude, which are correlated with the observed schlieren oscillation of the millimeter-wave beam, are also shown in Fig. 1. Such oscillations, but of much lower amplitude, are also observed with soft x-rays (not shown in Fig.1). These oscillations have been ascribed to growing magnetic islands external to the hot centre /5,6/. Contrary to the line-integrated soft x-ray signals and the $\dot{B}(\phi)$ oscillations, the local spatial dependence of the schlieren signals describes the evolution of the density center core instant by instant.
This affords the interpretation given in this paper of the rotation of the centre core immediately before the onset of the current disruption, as deduced by comparing the time evolution of the observed schlieren signals with the various individual situations numerically simulated with the model of centre core displacement.
Quantitative details of the radial displacement may be obtained by performing schlieren measurements in several adjacent channels with frequencies optimized for maximum sensitivity of the schlieren signals. Besides the qualitative interpretation of the evolution of the centre core, the oscillations of the schlieren signals presented for the first time in this paper are, however, very promising for studying MHD perturbations of the density centre core of fusion plasmas.

References

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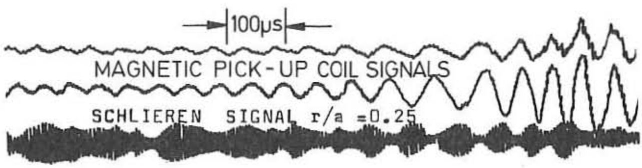

Fig. 1: Observed schlieren signal at $r/a = 0.25$ and $m = 2$ oscillations of the $\dot{B}(\phi)$ pick-up coil of a Pulsator tokamak discharge.

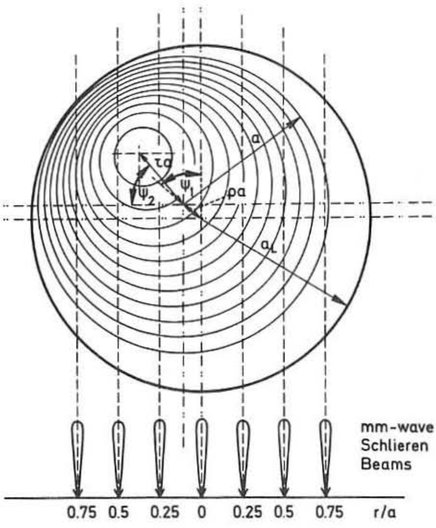

Fig. 2: Isodensity lines of the general density distribution of eq. 5).

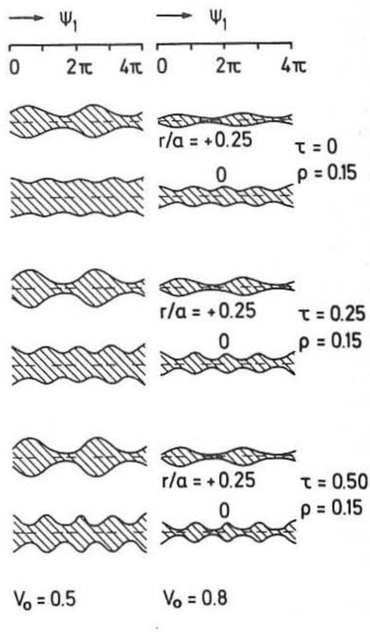

Fig. 3: Simulated "kink" effects of the schlieren signals for a very flat ($f = 4$) radial density distribution.