PARTICLE DENSITY PERTURBATION MEASUREMENTS WITH SCHLIEREN

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A new, fast time resolved λ=2 mm schlieren diagnostic provides experimental evidence of an m=1 particle density perturbation in the plasma interior.

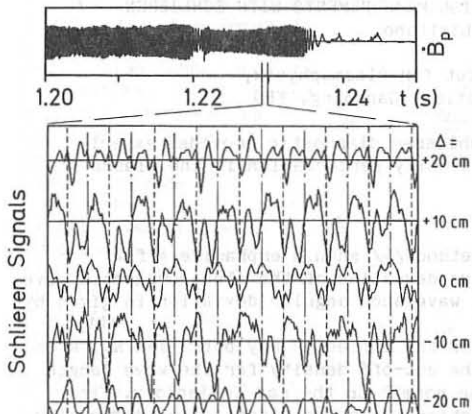
Measuring system

A brief reminder of the schlieren method /1/ should emphasize a few peculiar properties of the refractive deviation of the electromagnetic wave ray path in plasma. For an ordinary wave such angular deviation is given by

$$1/R = -(\vec{N}/2)\ [\nabla V/(1-V)] \ , \qquad (1)$$

where R is the radius of curvature of the deflected ray path, $V=N/N_c$, N is the local particle density, N_c is the cut-off density for the wave length used and $\vec{N}$ is the unit vector of the normal to the ray trajectory. From Eq. 1 it is seen that the ray deflection is in the direction of decreasing density and is directly proportional to the transversal density gradient, the deviation being also dependent on the local value of the density. The ASDEX schlieren beams have a pencil radiation pattern extending 30^o between the two radiation minima. As expressed by Eq. 1, the local refractivity of a given density distribution angularly enlarges or compresses all the rays of the exploring pencil beam like a fan. Both the intensity and the density of the rays within that small fraction of the beam which reaches the receiver antenna determine the amplitude of the schlieren signal, the detection width of the antenna being 0.5^o. Owing to the large intensity variation per unit angle of the pencil beam radiation pattern, the small angular detection width of the receiver antenna automatically identifies the exploring rays that reach the receiver. Such rays are uniquely determined by the local density distribution traversed by the exploring pencil beam. A perturbation of this distribution selectively varies the rays which reach the receiver antenna. This causes the amplitude fluctuations of the schlieren signals as shown in Fig. 1 during an almost steady state train of $\dot{B}_p$ oscillations preceding a soft disruption.

Such signals are detected by schlieren chords exploring the poloidal plane at a distance of Δ=0 cm, ±10 cm and ±20 cm from the midplane of the tokamak. The signals were recorded during an L-phase of deuterium injection into deuterium plasma dominated by the m≥1, n=1 mode /2/. The onset of the $\dot{B}$ oscillations occurs nearly at the line when β_p attains its maximum. At the time interval in Fig. 1, owing to a transition back into the L-phase, β_p decreases from its maximum value of 2.2 to 1. The injection power, plasma current and safety factor are NI=4 MW, I_p=0.32 MA and q(a) = 3.3 [$q(a) = 2\pi a^2 B_T/\mu_o R I_p$]. The mean value of the particle density increases from 3.5×10^{13} cm^{-3} at the start of injection up to 4.1×10^{13} cm^{-3} at the time of maximum β_p. It then decreases to 2.9×10^{13} cm^{-3} at the time interval in Fig. 1. Owing to their dependence on a fairly localized small region of maximum density gradient, the schlieren signals exhibit far more detailed information than the corresponding Mirnov oscillations and line-integrated



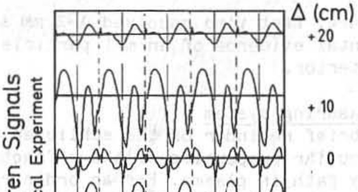


Fig. 2: Numerical simulation of cycles 1,5 and 6 of the actual schlieren signals of Fig. 1.

Fig. 1: Characteristic two-hump schlieren wave forms at $\Delta = \pm 10$ cm, indicating an m=1-like density distribution structure in the plasma interior.

measurements of density shown by, respectively, the last but one and the last trace of Fig. 1. The fluctuation amplitude of the actual and simulated schlieren signals shown in Figs. 1 and 2 is 60 % of the unperturbed amplitude of the $\Delta = \pm 10$ cm beams and 40 % of that of the other beams. Such amplitude fluctuation of the schlieren signals represents a macroscopic variation of the density distribution involving the whole column.

Density perturbation model

For quantitative evaluation of the schlieren signals all experimental facilities pertaining to the schlieren diagnostic were numerically simulated as in real space. Since the signals are directly dependent on the local gradient of density traversed by the schlieren beams, each beam is first used to determine the corresponding variations of the local gradient. A complete density distribution model for the whole plasma cross-section is then obtained from the individual gradients of density.

For each class of MHD perturbations a representative density model may then be adapted to simulate various details of the actual experiment on that class of perturbation. By this procedure, after modelling the density distribution of Fig. 3 by means of individual gradients, the actual schlieren wave forms of representative cycles 1,5 and 6 of Fig. 1 are numerically reproduced as shown in Fig. 2.

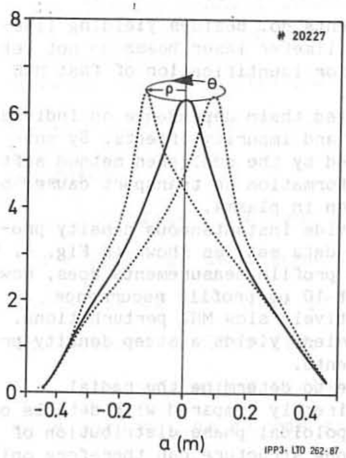


Fig. 3: Radial density profile and schlieren perturbation model used to obtain the simulated signals of Fig. 2.

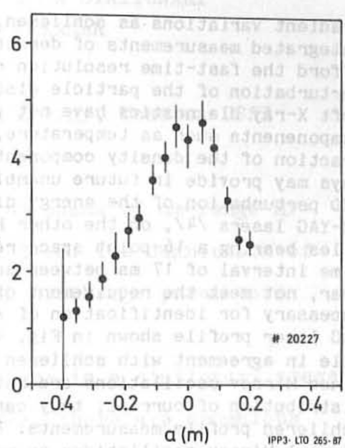


Fig. 4: Instantaneous radial density profile measured with Nd:YAG Laser affords supporting evidence for the steep density model of schlieren (Courtesy of H. Murmann)

Note in Figs. 1 and 2 that each negative hump indicates passage of a steep density gradient through the schlieren probing chords. Cycles 1, 5 and 6 of the actual signals in Fig. 1 and the simulated signals of Fig. 2 exhibit the two-hump wave forms on opposite schlieren channels. Opposite schlieren channels exhibit opposite phase relationships of their signals. The four passages on two opposite chords during a cycle are determined by a projected toroidal rotation of the density peak on the poloidal plane. The schlieren wave forms therefore establish at every instant the position of the density peak. The latter crosses the midplane of the machine, at $\theta=0$, between the last negative hump of the lower chord, $\Delta = -10$ cm, and the first one of the upper chord at $\Delta=+10$ cm. A peaked density profile as is derived from the schlieren analysis and as is observed from the Thomson scattering measurements (see Fig.4) is typical for the L-phase causing the sharp decrease of β. Such peaked profile may be due to an external resistive constraint of the particle density during the L-phase. As the peaked profile is also observed for T_e, the resistive constraint of the particle density and current reduces the safety factor value to $q=rB_T/RB_p<1$ in the plasma interior. This is conducive to the model of the helically perturbed centre core established by the schlieren measurements.

Simultaneous data from other diagnostics

Besides schlieren no other diagnostic can so far furnish reliable profile details on density during the instability. Line-integrated measurements of the particle density distribution with millimeter and submillimeter wave-interferometry cannot, in fact, distinguish such fine details of density

gradient variations as schlieren measurements do. Besides yielding line-integrated measurements of density, submillimeter laser beams do not yet afford the fast-time resolution required for identification of fast MHD perturbation of the particle distribution.
Soft X-ray diagnostics have not yet resolved their dependence on individual componenents such as temperature, density and impurity effects. By subtraction of the density component delivered by the schlieren method soft X-rays may provide in future unambiguous information on transport caused by MHD perturbation of the energy distribution in plasma.
Nd-YAG lasers /4/, on the other hand, provide instantaneous density profiles bearing a 16-point space resolution data set, as shown in Fig. 4. The time interval of 17 ms between successive profile measurements does, however, not meet the requirement of at least 10 µs profile recurrence necessary for identification of even relatively slow MHD perturbations. The YAG laser profile shown in Fig. 4 nevertheless yields a steep density profile in agreement with schlieren measurements.
Since Mirnov oscillations are not adequate to determine the radial distribution of current, they cannot be directly compared with details of schlieren profile measurements. From the poloidal phase distribution of several Mirnov oscillations an m=2, n=1 mode structure can therefore only be assumed to exist in the plasma interior without it being possible to give an experimental contour to such a structure. It should be noted, however, that a kink-like perturbation of the current centre core similar to that of Fig. 3 may not be directly detected by the Mirnov coils. The poloidal field outside the plasma is, in fact, up to a scale factor independent of the radial distribution of the current.
Supporting evidence for the schlieren perturbation model of Fig. 3 can, however, be derived by the m=2 Mirnov oscillations by assuming identical current and particle density distributions. In the presence of Shafranov pressure effect the poloidal field outside the plasma would then exhibit the m=2 variation /2/ inside and outside the location of the Mirnov coils. It should be noted that the density distributions of Figs. 3 and 4 are radial profiles perpendicular to the machine midplane. They therefore do not exhibit details of the Shafranov displacement towards the outer wall. Future work on this and on other varieties of MHD instabilities may also benefit from supplementary details of mutually supporting evidence yielded by different diagnostics, such as Mirnov, Thomson scattering, soft X-ray and schlieren.

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