Collective scattering and optical probing as turbulence diagnostics

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Collective Scattering and Optical Probing as Turbulence Diagnostics.

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Abstract.

Small scale turbulence is a very important phenomenon in magnetized plasmas. Turbulence is generally described by dividing it in sets of waves. Alternatively turbulence can be interpreted as a set of moving local density fluctuations. In a current driven plasma local electron density perturbations have a strong coupling with turbulence.

There are few diagnostics which can register electron density fluctuations inside a plasma. These diagnostics are either founded on emission or scattering of electro magnetic radiation. With respect to the emission we assume the increase of emitted radiation to be proportional to the increase in electron density. With scattering the use of heterodyne detection increases the sensitivity enormously. With small angle scattering we need to use infrared radiation to be able to resolve sub millimeter fluctuations. Both diagnostics will be discussed. We will show that separately they give only limited information but together they are a powerful tool to study plasma perturbations.

Introduction.

Plasma technology uses magnetic fields to constrict plasmas. In this way hot and dense plasmas can be made. Turbulence interferes with this aim. It causes additional transport or plasma disruptions. On the other hand externally driven turbulence can be used to heat the plasma. To improve our knowledge we set out to determine plasma perturbations in the interior of a plasma. Inspecting our toolbox we find very few suitable diagnostics. Two of them will be discussed below.

One can view turbulence either from the space-time domain or from the wave-frequency domain. Each can be converted to the other through Fourier Transform. For the ease of discussion we will continue in the space-time domain. We will consider a homogeneous plasma with a simple moving electron density perturbation. If we later integrate over all possible electron density perturbations we are back at the general case assuming linearity of our signal with the electron density perturbation.

Turbulence and Anomalous Transport in Magnetized Plasmas
D. Gresillon & M.A. Dubois, Ed. - Editions de Physique, Orsay 1987

Collective Scattering.

The theory behind collective scattering and heterodyne detection is handled by several authors. e.g. lit 1. We will discuss the experimental implications of this tool. A general setup is given in fig. 1.

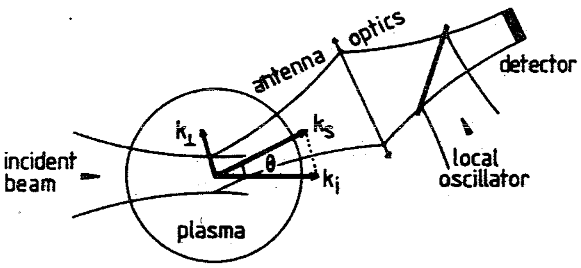

Fig. 1. Collective Scattering, General Setup.

We have focussed an incident laserbeam in the plasma. The scattered radiation is collected by the antenna optics and focussed on a detector. The detector is irradiated with a local oscillator (L.O.) beam. A local electron density perturbation moves through the detection volume which is determined by the overlap of the incident beam and the antenna optics. The intensity of the scattered radiation is proportional with the intensity of the incident beam and with the electron density of the perturbation. The frequency ω_s seen by the detector is the frequency of the incident radiation ω_o corrected with the Doppler shifts caused by the velocity $\underline{v}$ of the moving perturbation with respect to the incident beam and with respect to the antenna optics.

$$\omega_s = \omega_o + \omega_D; \; \omega_D = \underline{v}.\underline{k}_\perp; \; k_\perp = k_i \sin\theta \; ; \; k_i = \omega_o/c; \qquad \text{(form 1.)}$$

In the most simple setup the L.O. is taken from the same laser as the incident beam or from the incident beam itself after it has passed through the plasma. (fig 2.)

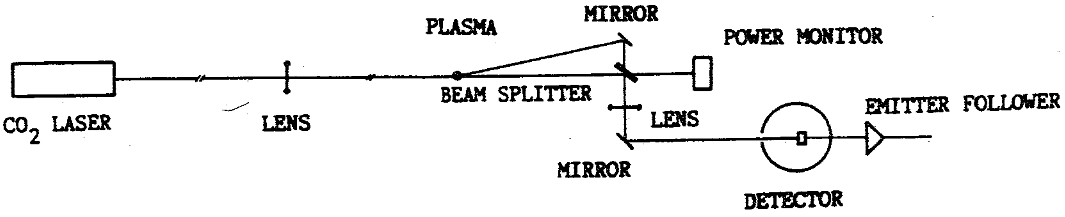

Fig. 2. Simple experimental scattering setup.

On the detector antenna beam and L.O. mix, if their polarisation is the same. The resulting signal is the Doppler shifted frequency ω_D enveloped by the effect of the Gaussian form of the incident beam. The centre frequency and the scattering angle yield the velocity of the perturbation in the direction k_I. If the spatial size of the perturbation is in the same order as $2\pi / k_\perp$ then the signal from the front and the end of the perturbation are out of phase so the total signal decreases. Thus varying $k_\perp$ by changing the scattering angle and observing the signal strength gives an estimate for the size of the perturbation. The antenna signal is very weak, due to the very small scattering cross section. The signal can be amplified by increasing the intensity of the incident beam or the intensity of the L.O.. The latter however can be only as high as the detector type permits. If the total noise of the detection system is governed by the shot noise of the L.O. on the detector, increasing the L.O. does not improve the SNR. If the L.O. beam goes through the plasma it makes an additional noise source which is generally forgotten. The amount of energy scattered out of the L.O. beam over the entire solid angle can be much greater than the power scattered into the small opening angle of the antenna beam. This results in additional noise at low frequencies.

Optical Probing.

If we want to study electron density perturbation by the emission of E.M. radiation there are a few conditions to be fulfilled. The plasma must be optically thin for the radiation concerned, and the signal must be proportional with the electron density perturbation. The first condition can probably be met by selecting the proper type of radiation. The second condition is obvious for free-free and free-bound radiation. For line radiation this is only the case if the turbulence time scale is long with respect to the lifetimes of the levels concerned.

Ideally we would like to make a stereoscopic picture of the plasma, with a time and space resolution suitable for the turbulence we would like to see. (fig 3.) This requires an enormous effort, both on the detector and on the data collection. E.g. a detector with 1000*1000 elements and a bandwidth of 1 MHz gives 1000 GBytes per second, with 8 bit resolution. We will therefore try to see how we can minimize the effort, and what information we lose accordingly.

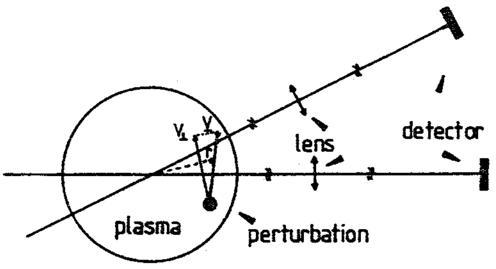

Fig. 3. Setup with two Optical Probes.

Let us assume a toroidal or cylindrical plasma. If we limit ourselves to turbulence propagating perpendicular to an axial magnetic field we can reduce one dimension. We can suffice with two lineair array detectors to get information from a planar cross section of the plasma. Detector size, pitch and bandwidth determine the resolution. If we still want to reduce effort we need a model for the behaviour of the perturbation. We can then reduce the number of detectors in an array. The simpler the model, the less detectors are needed to check its validity. A very simple setup is with only two single detectors. If again we assume a simple moving perturbation as scetched in fig 3. the cross correlation of the two signals gives the time delay between the crossing of the two probes. If we take the velocity determined with collective scattering we can determine the radial position where the crossing has taken place. From the sign of the time delay we can determine the direction of angular motion.

Experimental example.

We have used both simple setups to study turbulence in a magnetized hollow cathode argon arc plasma. (plasma diameter: 1-2 cm, n_e: 10^{20} m^{-3}, T_e: 4 eV, T_i: 2 eV, T_o: .2 eV, B: .2 T)

In the cathode region we found that the turbulence was dominated by a moving electron density perturbation, probably caused by a moving filament shaped current carrying channel in the plasma. The size of the perturbation was determined using angle varied collective scattering. The channel radius is .2 mm. For various plasma parameters $v_\perp$ was determined also using collective scattering. For the same conditions the crossing time between two simple optical probes as in fig 3. was determined. This was done by cross correlating the signals from both probes. We found the perturbation to be moving clockwise with the axial magnetic field. From the cossing time $T_{1,2}$, the velocity $v_\perp$ and the angle between the probes θ, the mean distance to the crossing point of the probes is calculated.

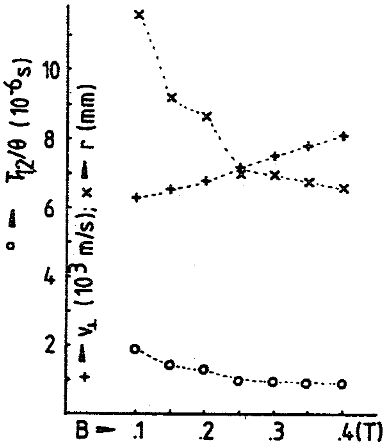

Fig. 4. Experimental Results, Radii calculated from both diagnostics.

Results as a function of the axial magnetic field are given in fig 4.

Conclusions.

Collective scattering and optical probing are powerful diagnostics to study plasma perturbations. A large number of detectors give unambiguous information about the turbulence processes. Even with simple setups one can achieve valuable information about turbulent behaviour.

1: R.E. Slusher and C.M. Surko, Phys. Fluids 23, 472 (1980)