ELSEVIER

Fusion Engineering and Design 34-35 (1997) 271-275

Fusion Engineering and Design

Correlation spectroscopy diagnostics in the H-1 heliac

M.G. Shats, J. Howard

Plasma Research Laboratory, Research School of Physical Sciences and Engineering, Australian National University, Canberra, A.C.T. 0200, Australia

Abstract

A simple diagnostic arrangement is suggested for measuring density and temperature fluctuations. The diagnostic uses a cross-correlation technique to extract local frequency spectra, spatial distribution or (in the case of low mode numbers) the mode structure from the chord-average fluctuating intensities of the visible light in the H-1 heliac. For low temperature H-1 plasmas ($T_e \approx 20$ eV, $n_e \approx 2 \times 10^{12}$ cm^{-3}), the spectral line emission from neutral atoms is used. For strong turbulence, where the coherence length of the fluctuations is much shorter than the plasma radius, the amplitude of the cross-correlation between two crossed-sightline fluctuating intensities is proportional to the fluctuation amplitude in the intersection volume. The optical arrangement on the H-1 heliac uses two orthogonal views with mirrors that allow the intersection volume to be scanned over the full plasma poloidal cross-section. Under certain discharge conditions, the plasma is dominated by strong, low frequency oscillations with frequencies in the range 15–20 kHz. Although such discharges are not very suitable for implementing the main idea of the diagnostic (because, in this case, the fluctuation correlation length is of the order of the plasma diameter), the measurements allow the poloidal mode number and spatial localization of the fluctuations to be determined after comparison with numerical modelling results; these show good agreement with the Langmuir probe results. © 1997 Elsevier Science S.A.

1. Introduction

In low temperature (10–30 eV) and low density (2×10^{12} cm^{-3} or less) plasmas typical for H-1 [1] in its first stage of operation, spectral line emission is not spatially limited to the ionization shells, even for low ionization stages, because the electron temperature is of the order of the excitation potential and the T_e profile is almost flat. This allows plasma emission from a single spectral line to be used for measurements of electron temperature and density distributions. To obtain an accurate tomographic reconstruction of the plasma emissivity from the chord-average signals requires a relatively large number of angular views (6 or more [2]). A multi-view tomographic spectroscopy diagnostic is currently being designed in the Plasma Research Laboratory at ANU. In this paper, we propose using cross-correlation techniques to extract the local intensity of the fluctuations. We present initial results from fluctuation studies using a two-view optical system with scanning mirrors.

2. Spectroscopic measurements of plasma fluctuations

In the coronal approximation (valid for the described plasma parameters), the chord-average

PII S0920-3796(96)00661-8

intensity of the spectral line emission (p–q transition) is given by [3]

$$I(p,q)=\frac{1}{4\pi}\int \mathrm{d}s\, n_o n_e X \frac{A(p,q)}{\sum_{r<p} A(p,r)} = \int \mathrm{d}s\, I_0 \quad (1)$$

where

$$X=\frac{5.56 f(p,q)}{\chi(p,q)}\frac{1}{T_e^{1/2}}\exp\left(-\frac{\chi}{T_e}\right)$$

is an excitation coefficient, n_0 is the density of ions or neutrals in the ground state, n_e and T_e are the electron density and temperature, $\chi(p,q)$ is the excitation potential, $f(p,q)$ is the line oscillator strength and A is the transition probability.

If the plasma density fluctuates, $n_e=\bar{n}_e+\tilde{n}_e$, then the light intensity will also fluctuate. Thus, we have

$$I=\frac{1}{4\pi}\int \mathrm{d}s\, \bar{n}_o \bar{n}_e X \frac{A_{pq}}{\sum_{r<p} A_{pr}}\left(1+\frac{\tilde{n}_e}{\bar{n}_e}\right) = \int \mathrm{d}s\, I_0\left(1+\frac{\tilde{n}_e}{\bar{n}_e}\right)$$

If the fluctuation correlation length is short compared with the plasma characteristic dimension, then the cross-correlation between fluctuating intensities from intersecting chords gives a value proportional to the fluctuation intensity in the intersection volume, i.e.

$$\langle \tilde{I}_1\tilde{I}_2\rangle=\left\langle \int \mathrm{d}s\, I_0(s_1)\frac{\tilde{n}_e}{\bar{n}_e}\int \mathrm{d}s_2\, I_0(s_2)\frac{\tilde{n}_e}{\bar{n}_e}\right\rangle$$
$$\approx \int_{r_x-l_c}^{r_x+l_c} \mathrm{d}s_1\, I_0(s_1)\frac{\tilde{n}_e}{\bar{n}_e}\int_{r_x-l_c}^{r_x+l_c} \mathrm{d}s_2\, I_0(s_2)\frac{\tilde{n}_e}{\bar{n}_e}$$
$$\propto I_0^2(r_x)\left[\frac{\tilde{n}_e(r_x)}{\bar{n}_e}\right]^2 \quad (2)$$

where r_x is the coordinate of the intersection point of two chords and we assume that the cross-correlation is zero outside the sphere of radius $r>l_c$. If the plasma emissivity $I_0(r)$ is known (for example, from the tomographic spectroscopy diagnostic), it is possible to reconstruct the spatial distribution of the fluctuation intensity in the plasma.

In plasma with both electron temperature and electron density fluctuations ($n_e=\bar{n}_e+\tilde{n}_e$ and $T_e=\bar{T}_e+\tilde{T}_e$), variations in the excitation coefficient X will also contribute to the fluctuating part of the line intensity:

$$\tilde{I}=\int \mathrm{d}s\, I_0\left(\frac{\tilde{X}}{\bar{X}}+\frac{\tilde{n}_e}{\bar{n}_e}\right),$$

where

$$\frac{\tilde{X}}{\bar{X}}=\left[\frac{1}{(1+x)^{1/2}}\exp\left(\frac{\chi}{T}\frac{x}{x+1}\right)-1\right]$$

and $x=\tilde{T}_e/\bar{T}_e$.

It is possible, in principle, to estimate a relative contribution of $\tilde{T}_e/\bar{T}_e$ to $\tilde{I}$, by measuring $\tilde{I}$ and $I_0(r)$ for two spectral lines which have different excitation potentials. The contribution of the density fluctuations to $\tilde{I}$ remains the same, while the temperature fluctuation component increases with χ/T_e, as shown in Fig. 1.

3. Diagnostic arrangement and experimental results

Although the reconstruction of the $\tilde{n}/\bar{n}$ distribution in the poloidal cross-section using the cross-correlation technique is possible only when the fluctuation correlation length is much less

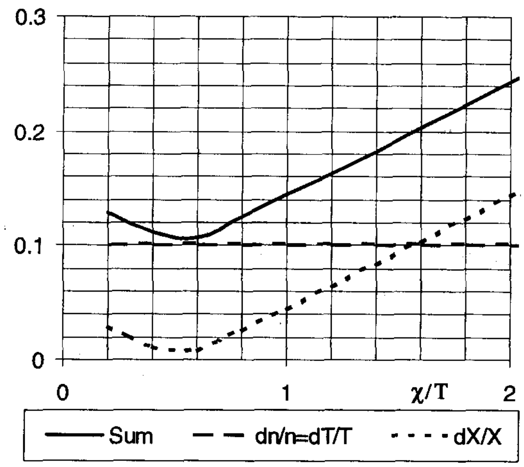

Fig. 1. Contribution of the density ($\mathrm{d}n/n$) and the electron temperature ($\mathrm{d}T/T$) fluctuations to the emission intensity fluctuations as a function of χ/T. We assume that $\tilde{n}/\bar{n}=\tilde{T}_e/\bar{T}_e=0.1$.

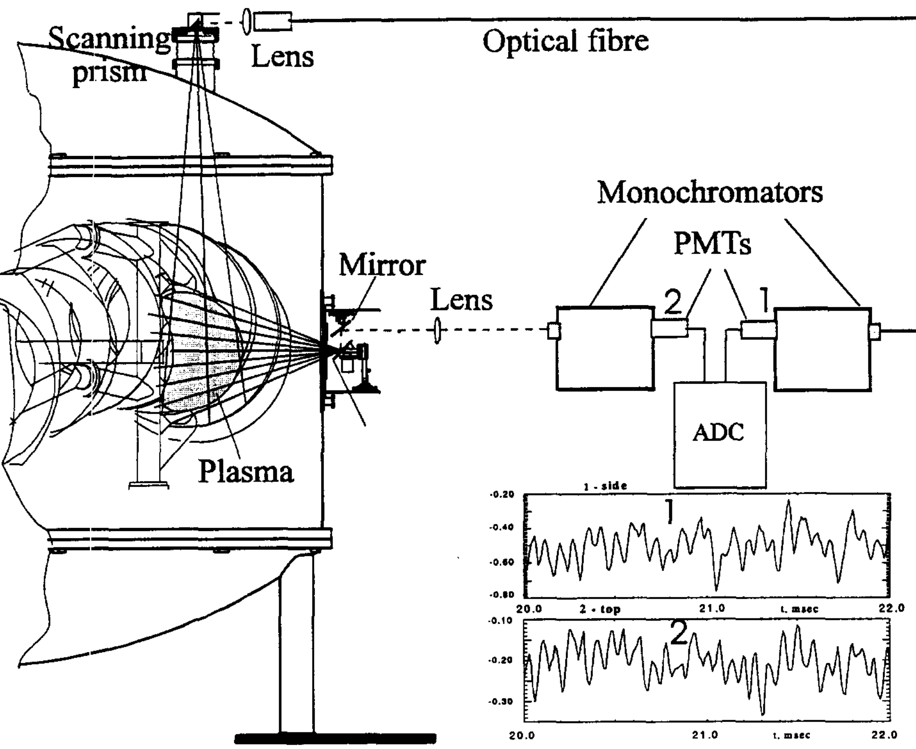

Fig. 2. Visible spectroscopy diagnostic for the H-1 heliac.

than the plasma radius, we demonstrate that a two-view optical arrangement (described below) is useful for detecting and identifying highly coherent long-wavelength fluctuations. The diagnostic layout is shown in Fig. 2. Plasma light is collected through two diagnostic ports in the same toroidal location. Vertical and radial sight-lines can be orthogonally arranged so that the intersection volume of the two chords can be moved over the plasma poloidal cross-section on a shot-to-shot basis. The input slits of two monochromators are imaged into the plasma, with the intersection of the chords having typical dimensions of 8 mm × 5 mm. The signals from two photomultipliers are digitized at a rate of 200 kHz and stored for later analysis.

Plasma is produced in the H-1 heliac using radio frequency (r.f.) power ($f = 7$ MHz, $P < 50$ kW) at very low (less than 0.2 T) magnetic fields in argon, helium and hydrogen. In this paper, we present experimental results obtained in a helium plasma, for which the electron temperature is in the range 20–30 eV for an electron density of 1×10^{18} m^{-3}. The plasma is dominated by strong coherent oscillations [4], which have been extensively studied using various Langmuir probes. The fluctuations oscillate in the frequency range 15–20 kHz and their intensity is a maximum in the region of the maximum density gradient. Fig. 3 shows the distribution of the fluctuations of the ion saturation current in the H-1 poloidal cross-section, as measured with a two-dimensional scanning Langmuir probe. These oscillations have been identified as an $m = 1$ poloidal mode propagating in the direction of the electron diamagnetic velocity.

In this experiment, we use light at a wavelength of 587.6 nm, which corresponds to the neutral helium triplet (excitation potential $\chi \approx 23$ eV). The line intensity is maximum in the plasma centre, as shown in Fig. 4(a), where the product of the time-average and chord-average intensities

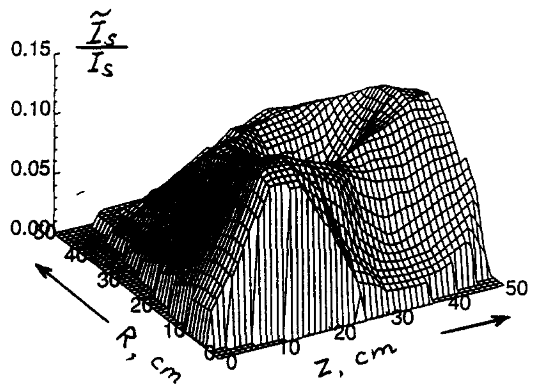

Fig. 3. Experimentally measured spatial distribution of the density fluctuations in the poloidal cross-section in the H-1 heliac (scannable Langmuir probe in the ion saturation current).

from the intersecting chords is plotted in the poloidal plane of the machine. The electron temperature measurements using a singlet-to-triplet ratio method in helium have shown almost flat T_e profiles in this plasma, so that the line intensity is proportional to the electron density in the plasma core.

The Fourier transform of the cross-correlation function between the two fluctuating signals can be computed as

$$\mathrm{Corr}(\tilde{i}_1,\tilde{i}_2) \Leftarrow \mathrm{FFT} \Rightarrow P_{12}(f) = P_1^*(f)P_2(f)$$

where P_1 and P_2 are the Fourier transforms of the signals from two chords, and * denotes a complex conjugate. If the fluctuation correlation length is short compared with the plasma scale, then the amplitude of P_{12} will be proportional to the fluctuation intensity in the intersection volume (Eq. (2)). For the long-wavelength coherent fluctuations described here, the spatial coherence gives a four-lobe structure, as shown in Fig. 4(b). These four peaks are observed in the region of the

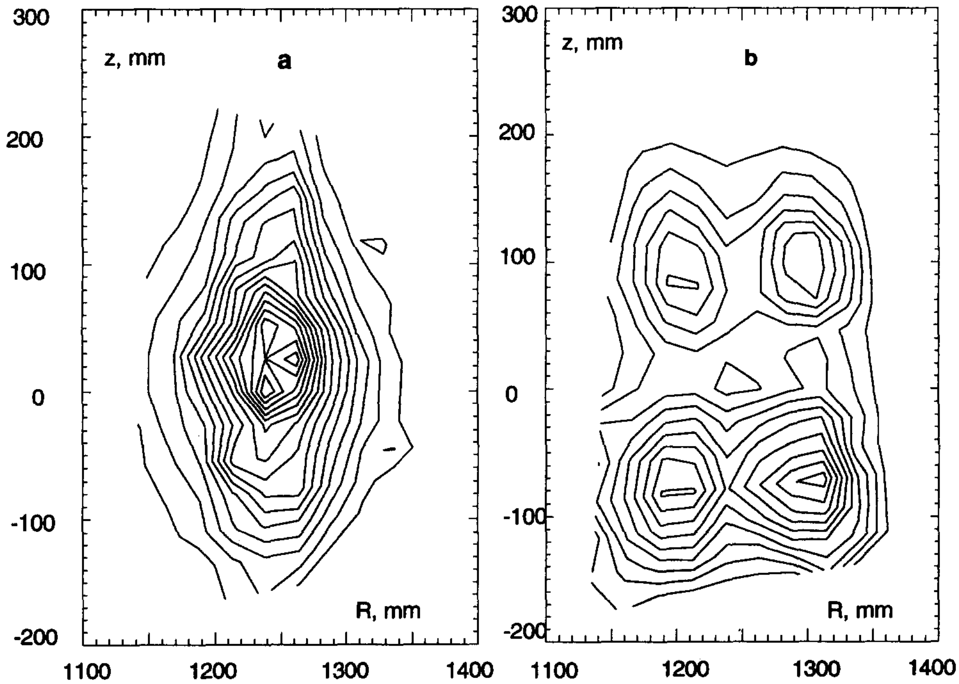

Fig. 4. Contour plots of (a) the product $I_1^*I_2$ of the chord-average intensities of the HeI 5876 spectral line and (b) the normalized amplitude of the cross-power spectrum P_{12}/I_1I_2 in the poloidal cross-section of the plasma, as measured by the visible spectroscopy diagnostic.

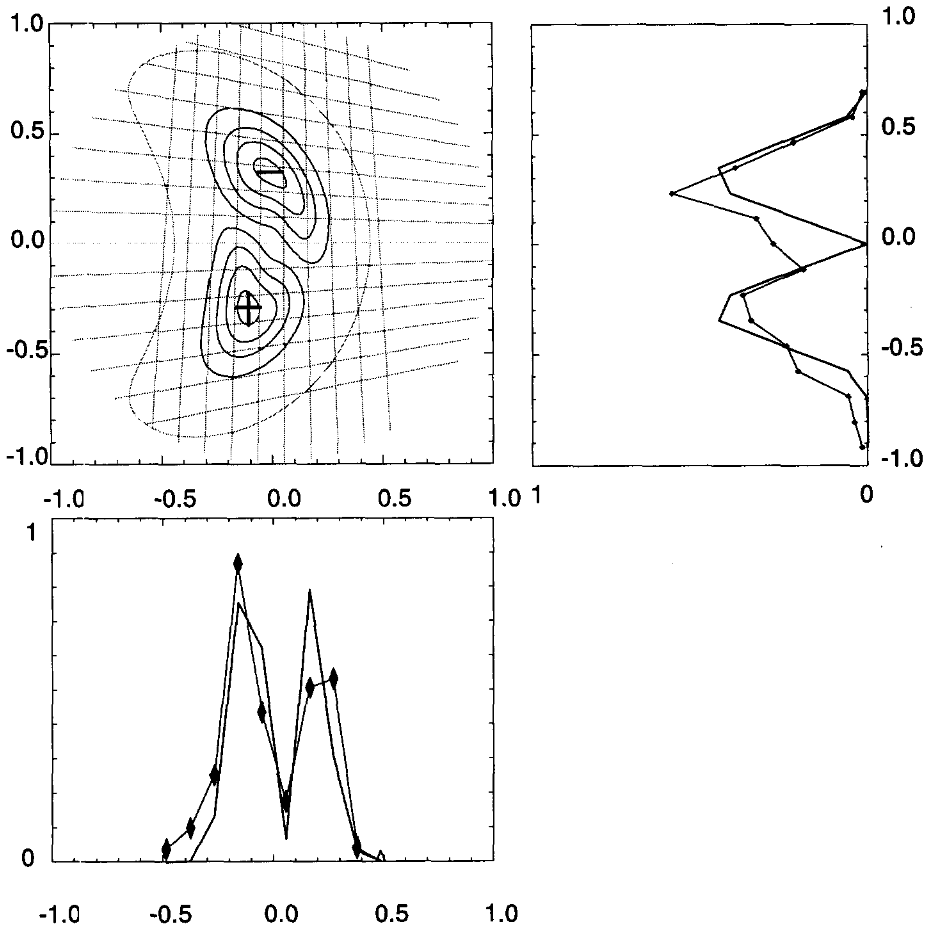

Fig. 5. An $m = 1$ mode propagating poloidally in the plasma produces a four-peak structure in the correlogram of the line-integral intensity. Model data are indicated by the solid line; experimental data are indicated by squares.

maximum density gradient—similarly to the Langmuir probe results (Fig. 3). The four separate lobes result from the projection of the $m = 1$ mode structure.

The light emission in the H-1 magnetic flux coordinates in the presence of an $m = 1$ mode localized in the maximum density gradient has been modelled numerically for the experimental geometry. The line-integral fluctuation intensity distribution obtained from the model shows the same four-lobe structure as is seen in the experiment. Fig. 5 shows a comparison of the experimental and modelled fluctuating intensity distribution as seen with the two scanning mirrors.

References

[1] S.M. Hamberger et al., H-1 design and construction, Fusion Technol. 17 (1990) 123–130.

[2] J. Howard, Novel scanning interferometer for two-dimensional plasma density measurements, Rev. Sci. Instrum. 61 (1990) 1086–1094.

[3] R.H. Huddlestone and S.L. Leonard (eds.), Plasma Diagnostic Techniques, Academic Press, New York, 1965.

[4] M. Shats et al., Magnetic configuration scans in H-1 heliac, Trans. Fusion Technol. 27 (1995) 286–289.