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Fusion Engineering and Design 34–35 (1997) 383–386

Fusion Engineering and Design

Plasma flow velocity measurements using a modulated Michelson interferometer

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Abstract

This paper discusses the possibility of flow velocity reconstruction using passive spectroscopic techniques. We report some preliminary measurements of the toroidal flow velocity of hydrogen atoms in the RTP tokamak using a phase modulated Michelson interferometer. © 1997 Elsevier Science S.A.

Keywords: Plasma flow velocity; Modulated Michelson interferometer

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1. Introduction

The application of tomographic techniques to the study of vector fields has been demonstrated only in the last few years. Various applications in plasma diagnostics are discussed by Howard [1]. In this paper we consider the potential for time-resolved tomographic reconstruction of particle flow velocity fields from line-integrated spectroscopic measurements.

The method relies on directly measuring the low order spectral moments of the transition radiation from a given atomic or ionic species. The zeroth moment is the spectrally integrated brightness of the chord-averaged emission. The second moment is proportional to the ionic temperature weighted by the emission intensity and integrated over the viewing chord. Both these quantities can be tomographically inverted to obtain the spatial distribution of the plasma emission-weighted temperature. The first moment (Doppler shift) is proportional to the emission-weighted component of the ion velocity in the direction of, and integrated over, the line-of-sight. From a sufficient number of measurements it is possible, using principles of vector tomography, to recover the 2-d structure of the emission weighted flow field.

The three low order moments can be simultaneously measured using a path-modulated Michelson interferometer and a single detector. In this paper we expand the idea and its relation to vector tomography, discuss the spectroscopic instrument and present some preliminary experimental results obtained for discharges in RTP.

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PII S0920-3796(96)00609-6

2. Vector tomographic spectroscopy

We assume a locally Gaussian, isotropic emission profile:

$$I(\boldsymbol{r}, \hat{l}; w) = \frac{I_0(\boldsymbol{r})}{\sqrt{2\pi}\sigma(\boldsymbol{r})} \exp\left[-\frac{(w-\beta(\boldsymbol{r}))^2}{2\sigma(\boldsymbol{r})^2} \right] \quad (1)$$

where $w = (v - v_0)/v_0$ is a normalized frequency coordinate, v_0 is the rest frame line centre frequency, $\boldsymbol{r}$ is a position in the plasma and $I_0(\boldsymbol{r})$ is the local emission intensity. The species temperature is given by $kT_s/(m_s c^2) = \sigma^2(\boldsymbol{r})$ where m_s is the atomic weight. The normalized line centre frequency is Doppler shifted by an amount $\beta(\boldsymbol{r}) = \boldsymbol{v}(\boldsymbol{r}) \cdot \hat{\boldsymbol{l}}/c$ where v is the gross flow velocity of the emitting species and $\hat{\boldsymbol{l}}$ is the emission direction. The measurement is approximated by an integral $g(p, \phi; w)$ of the emission I over the line $L(p, \phi)$ with impact parameter p and direction ϕ in a planar cross-section of the plasma (the x–y plane)

$$g(p, \phi; w) = \int_{L(p,\phi)} I(\boldsymbol{r}, \hat{l}; w)\, \mathrm{d}l \quad (2)$$

The spectral information is carried by the low order spectral moments of the line-integrated emission:

$$\mu^{(m)}(p, \phi) = \int_{-\infty}^{\infty} g(p, \phi; w)\, w^m\, \mathrm{d}w \quad (3)$$

It is straightforward to show that

$$\mu^{(0)} = \int_{L(p,\phi)} I_0(\boldsymbol{r})\, \mathrm{d}l$$
$$\mu^{(1)} = \int_{L(p,\phi)} I_0(\boldsymbol{r}) \boldsymbol{\beta}(\boldsymbol{r})\, \mathrm{d}l$$
$$\mu^{(2)} = \int_{L(p,\phi)} I_0(\boldsymbol{r})[\sigma^2(\boldsymbol{r}) + \beta^2(\boldsymbol{r})]\, \mathrm{d}l \quad (4)$$

where $\beta = \boldsymbol{\beta} \cdot \hat{l}$. For measurements sufficiently covering the space (p, ϕ), the intensity distribution can be obtained by standard tomographic methods on $\mu^{(0)}$.

The first moment $\mu^{(1)}$ is sensitive to the line integral component of the vector field $\boldsymbol{V}(\boldsymbol{r}) = I_0\boldsymbol{v}$ along the line-of-sight. From such longitudinal measurements of a 3-d vector field $\boldsymbol{V}$ it is possible to reconstruct the component of the vorticity $\nabla \times \boldsymbol{V}$ normal to the measurement x–y plane. From measurements sensitive to the transverse component of the field, can be recovered the divergence of $\boldsymbol{V}$ in the x–y plane. When the vector field components do not vary in the z (toroidal) direction it is possible to recover the solenoidal part of the vector field in the longitudinal case and the irrotational component from transverse measurements. thus, from poloidal plane measurements of $\mu^{(1)}$ it is possible to recover the solenoidal component of the field $I_0\boldsymbol{v}$. Given knowledge of $I_0(\boldsymbol{r})$ from inversion of $\mu^{(0)}$, and provided the flow is incompressible and that $\nabla I_0 \cdot \boldsymbol{v} = 0$, it is possible to derive the solenoidal part of the flow field $\boldsymbol{v}$ (see Howard [1]).

3. Michelson interferometer

The three low order spectral moments can be measured experimentally by exploiting the frequency response of the dispersing instrument. One means to control and/or increase the sensitivity to the first moment is to use a Michelson interferometer. An interferometer offers high optical throughout (the Jacquinot advantage) and can be adapted easily for multiple spatial channels. Moreover, because the line is not spectrally resolved, time resolution is not compromised by having to flush a multi-element CCD array. The intensity at the output is proportional to

$$S_{\pm} = \int_0^{\infty} g(p, \phi; (v - v_0)/v_0) \times [1 \pm \zeta \cos(2\pi v \Delta/c)]\, \mathrm{d}v \quad (5)$$

where Δ is the path length difference and $\zeta \leq 1$ is the fringe contrast. By sinusoidally modulating $\varphi = 2\pi v \Delta/c$, the kernel non-linearity gives rise to harmonic components whose amplitudes convey the spectral moment information. This can be achieved by oscillating one of the mirrors with small amplitude φ_1 about the dc position $\varphi_0 = 2\pi v_0 \Delta_0/c \gg \varphi_1$ to give an instantaneous phase delay $\varphi = \varphi_0 + \varphi_1 \sin \Omega t$. From Eq. (1) and Eq. (2) the resulting signal is

$$S_{\pm} = \mu^{(0)} \pm \zeta \int_{L(p,\phi)} I_0(\boldsymbol{r}) K(\boldsymbol{r})\, \mathrm{d}l \quad (6)$$

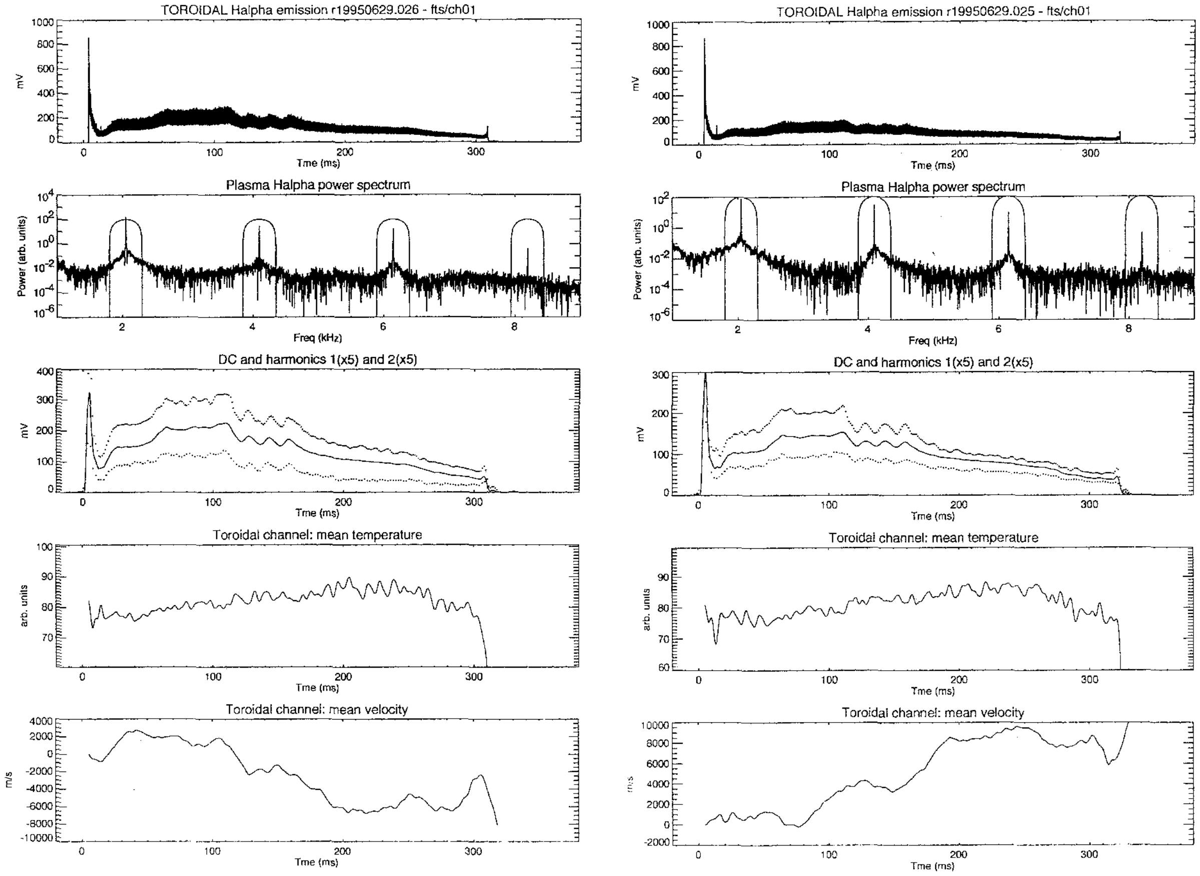

Fig. 1. Raw and processed Michelson interferometer signals for two similar ohmic discharges in RTP. See text for discussion.

with

$$K(r) = \sum_{n=0}^{\infty}{}' 2J_{2n}(\varphi_1)\exp[-\gamma(r)]\cos[\varphi_0(1+\beta(r))] \times \cos(2n\Omega t) - \sum_{n=0}^{\infty} 2J_{2n+1}(\varphi_1)\exp[-\gamma(r)] \times \sin[\varphi_0(1+\beta(r))]\sin[(2n+1)\Omega t] \qquad (7)$$

where the primed sum means that the $n=0$ terms are to be halved, $\gamma=\sigma^2(r)\,\varphi_0^2/2$ and terms of order φ_1/φ_0 have been ignored. This can be simplified further when $\gamma^2 \ll 1$, and setting $\varphi_0=(2m+1)\,\pi/2$ to allow the low order moments to be directly extracted:

$$\tilde{S} = \mu^{(0)} + \zeta J_0(\varphi_1)(\mu^{(0)} - \varphi_0^2\mu^{(2)}) + 2\zeta J_1(\varphi_1)(\mu^{(0)} - \varphi_0^2\mu^{(2)})\sin\Omega t - 2\zeta J_2(\varphi_1)\varphi_0\mu^{(1)}\cos 2\Omega t \qquad (8)$$

The modulation amplitude is adjusted so that $J_0(\varphi_1)=0$ (e.g. $\varphi_1=2.40$) and the dc term is sensitive only to the zeroth moment.

We have constructed a proof-of-principle dual-channel Michelson interferometer to test these ideas for Hα emission in the RTP tokamak. Two lens-coupled optical fibres are installed, one viewing in the poloidal plane, and the other viewing toroidally at the horizontal midplane. The fibres conduct the light to a remote station where it is transmitted by an interference filter before being processed by the interferometer. The Michelson has the capacity to handle up to 12 channels simultaneously, this being limited by the number of readily available photomultiplier tubes (EMI-XP1117). A mirror driven by a loudspeaker at 2 kHz generates the path length modulation. The photomultiplier signals are low pass filtered (10 kHz) prior to digitization at 25 kHz. Light from a hydrogen lamp and He–Ne laser are simultaneously analyzed, the former (or a white light source) can be used to estimate the position at which $\Delta = 0$ while the latter is used to monitor fringe visibility and time variations int he dc phase φ_0.

In these experiments, we compare the amplitudes of the odd and even harmonics (normalized to dc) to obtain intensity weighted estimates of β and $\exp(-\gamma)$. The modulation depth can be independently obtained from the relative amplitudes of the even (or odd) harmonics. The sensitivity to β is governed by the level of background phase noise or the statistical shot noise, whichever is greater. Since the offset position φ_0 for maximum sensitivity to β is obtained for $\gamma = 0.5$, the minimum measureable weighted average flow velocity is limited to $\bar{v}/v_{\mathrm{th}} \gtrsim \rho/\zeta$ where ρ is the minimum detectable variation in the ratio of the second harmonic and dc amplitudes (as determined by the noise level). Taking hydrogen at $T_s = 10$ eV, $\zeta = 0.5$ and $\rho = 0.01$ gives $\bar{v} \gtrsim 600$ m s^{-1}. The fundamental resolution of the method thus looks promising.

Fig. 1 shows the processed information for two similar ohmic discharges in RTP. In each figure, (a) shows the modulated emission for $\Delta \approx 0.5$ mm. The corresponding power spectra in (b) show carriers at harmonics of the modulation frequency and the isolating bandpass filters used for the calculations. The dc and two lowest harmonics are shown in (c), while (d) and (e) show the inferred temperatures and flow velocities. In these preliminary experiments, the phase noise was unfortunately dominated by acoustic hum from a nearby cooling system at 50 Hz (and its harmonics) at a level $\rho \lesssim 1$. Small alignment inaccuracies caused this to be not completely compensated by the He–Ne laser signal so that the computed drift velocities presented below were required to be low-pass filtered at 50 Hz. These uncertainties, also resulted in some degree of error in estimation of the fringe visibility (which varies with Δ) so that the atom temperatures are not calibrated. Nevertheless, note that the changes in measured toroidal velocities agree approximately (within a sign change) and that the temperature behaviour is reproducible. These variations disappear when $\Delta = 0$. Measurement of the absolute velocity (absolute phase change) requires a measurement of φ_0 using an atomic lamp source just prior to the discharge. It is hoped in future to build a more robust solid-state polarizing interferometer that uses birefringence modulation methods, in order to eliminate some of the difficulties encountered in this prototype instrument.

Acknowledgements

John Howard is grateful to the Australian Research Council and NWO in the Netherlands for financial support during this research.

Reference

[1] J. Howard, Plasma Phys. Control Fusion, 38 (1996) 489–503.