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Velocity components in the highly magnetised expanding plasma jet of Pilot-psi

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1. Introduction

In support of the design of Magnum-psi**, we currently operate the Pilot-psi experiment [1] to investigate the production of a high-flux hydrogen plasma jet with a wall stabilised cascaded arc. This jet is confined by a magnetic field up to 1.6 T, which leads to plasma densities up to ~ 10^{21} m^{-3} as was confirmed by Thomson scattering. The high magnetic field is also essential for mimicking divertor conditions [2], as it influences the transport of species relevant for the erosion-redeposition cycle at the surface under plasma exposure. Obviously, detailed characterisation of the flux density is imperative as it is a prime parameter in plasma-surface interactions. In this context, the various velocity components of the jet are the missing link between the known plasma density and the flux density. Measurements of these velocity components are the main subject of this contribution.

The axial velocity component of the plasma jet was evaluated on the basis of the time correlations of plasma light fluctuations measured by two adjacent light detectors. The results demonstrate that high frequency components in the signal complicate the analysis. It is evident that alternative techniques will be required to complete the picture on axial velocities.

The perpendicular velocity component of the plasma jet is determined by high-resolution optical emission spectroscopy (HR OES). Doppler shifts $\Delta\lambda/\lambda$ = v/c up to 0.01 nm/486.1 nm in the light collected perpendicular to the magnetized plasma jet revealed its rotation. The dependence of the plasma rotation on the magnetic field strength is presented. The rotation frequency is observed to increase linearly with the magnetic field strength up to 12000 m/s in a magnetic field of 1.6 T. Possible mechanisms causing the observed rotation of the plasma jet are discussed.

Finally, we demonstrate that HR-OES is also very useful to obtain information on electron densities complementary to Thomson scattering as it is entirely flexible with respect to spatial positioning.

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* Partner in the Trilateral Euregio Cluster

** Magnum-psi (MAgnetised plasma Generator and NUmerical Modelling for Plasma-Surface Interaction studies) is an experiment under design that aims to study plasma-surface interaction under conditions relevant for detached divertor plasmas in ITER.

2. Experimental set-up

A schematical drawing of the experimental set-up is depicted in Figure 1. Hydrogen plasma is produced in a wall-stabilised cascaded arc plasma source [3, 4] and expands into a vacuum vessel of about 1 m long and 40 cm in diameter. The typical background pressure in the vessel is about 6 Pa at the typical gas flow rate of 2.5 slm (standard liters per minute).

5 oil-cooled coils produce a continuously variable steady state magnetic field up to 0.2 T, a 4 min. pulsed field of 0.4 T or a 4 sec. pulsed field of 0.8, 1.2 or 1.6 T.

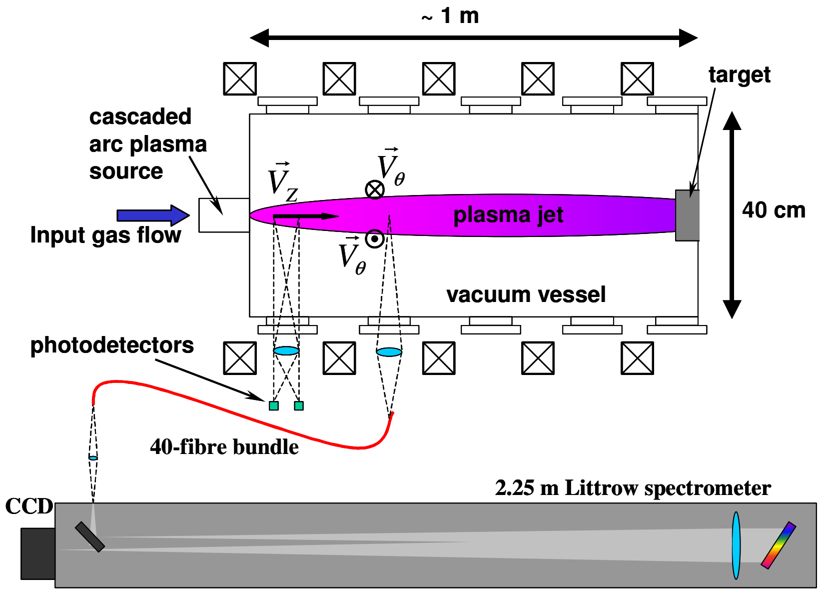

Fig. 1: Schematic drawing of the Pilot-psi linear plasma generator and the optical system for high-resolution emission spectroscopy.

Plasma light fluctuations were imposed by sinusoidally varying the plasma source current at 20 Hz between 60 and 72 A. These fluctuations were measured by two adjacent photodiodes and stored in a PC with a 100 MHz National Instruments oscilloscope-card. The detection volumes of the photodiodes were approximately 70 mm separated (which followed from the factor 2 magnification of the optical system and 35 mm distance between the diodes).

A 2.25 m focal length spectrometer in Littrow arrangement is used for high-resolution optical emission spectroscopy ($\lambda/\Delta\lambda \approx 20000$). Plasma light is collected perpendicular to the magnetized plasma jet and transferred to this spectrometer with a fibre bundle consisting of 40 fibres of 0.4 mm diameter stacked into a linear array. The spectrally as well as spatially resolved light is recorded by a 1152 x 298 pixels CCD matrix. The instrumental function of the spectrometer was determined from the 632.8 nm line of He-Ne laser and was found to be Gaussian with a width of less than 0.003 nm (corresponding to one pixel of the CCD).

3. Experimental results

3.1 Time correlation of light fluctuations.

Figure 2 shows the signal of the two adjacent photodiodes collecting light at 60 mm and 130 mm downstream from the source for a hydrogen plasma jet at 0.2 T. It is clearly seen that interpretation is not

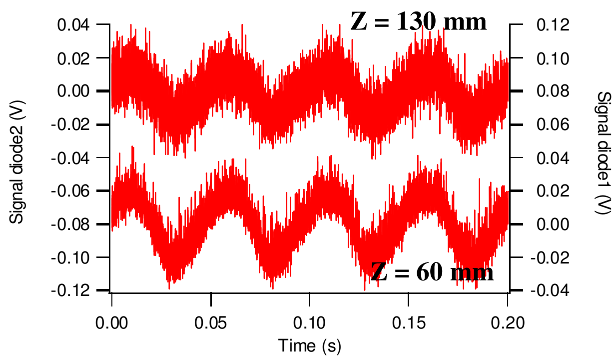

Fig. 2: The signal of two adjacent photodiodes.

straightforward due to high frequency fluctuations in the plasma light of which the origin is still unknown. Moreover, closer inspection of the signals indicates that the rising slopes seem to be more shifted than the falling slopes. This could be explained by a dependence of the jet velocity on the variation of the arc current. Cross correlation of the two signals yields a time separation of 310 μs, which would correspond to 230 m/s.

3.2 Rotation of the plasma jet in a magnetic field.

Figure 3 shows the 2D high-resolution spectrum of the H_β-line emitted by the plasma jet. The jet rotation is clearly recognised from the Doppler shifts: red shifts in the upper part of the plasma jet and blue shifts in the lower part. The rotation velocity grows with magnetic field and its maximum approaches the thermal velocity (~12000 m/s; data not shown) at 1.6 T.

The profile of the Doppler shifted H_β-lines has a clear asymmetric nature (Fig. 4). It is shown that the asymmetry is well described by the sum of a Doppler-shifted and an unshifted Voigt profile, which indicates that the H_β-line radiation is produced via two pathways. The simple explanation is that the shifted line is radiated by particles that constitute the rotating jet whereas the unshifted line is radiated after dissociative recombination of a hydrogen molecular ion that was produced by charge exchange of an ion with a background gas molecule.

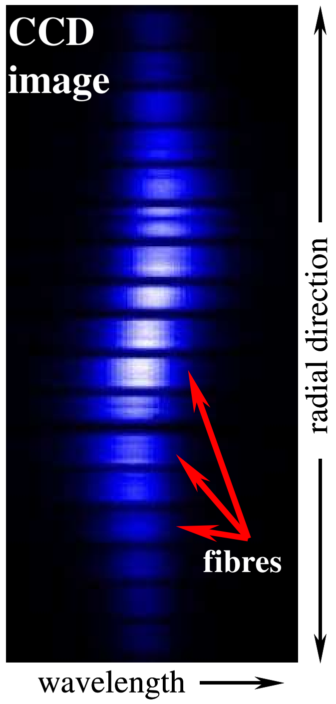

Fig. 3: H_β-line emitted across the plasma jet. The light from separate fibres is

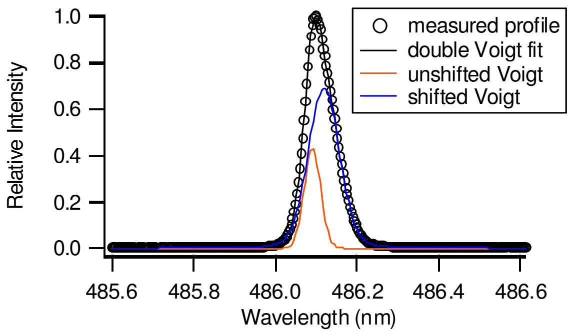

Fig. 4: Asymmetric profile of H_β-line and two Voigt components of the fit.

3.3 Electron densities

Electron densities n_e are calculated from the width $\Delta\lambda$ of the Lorentzian component (associated with Stark-broadening) of the measured Voigt profiles of the Balmer H_β-line using a simple approximation of Holtsmark field strength [5]:

$$n_e = \frac{3\cdot\pi^2}{4\cdot\lambda^3}\cdot\left(\frac{8\cdot m_e\cdot c}{3\cdot n\cdot h}\cdot\Delta\lambda\right)^{3/2},$$

where λ is the wavelength, m_e the electron mass, c is the speed of light, n is the principal quantum number of the upper shell, and h is Plank's constant. The axial variation of

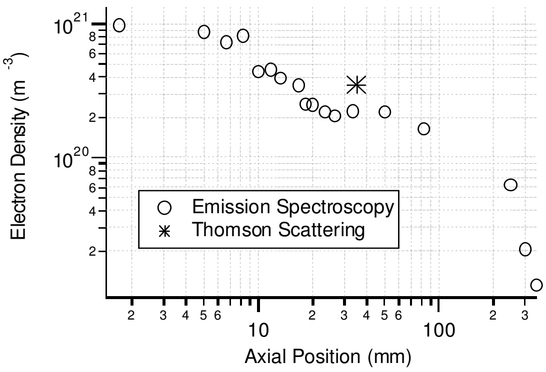

Fig. 5: The axial variation of electron density on a double logarithmic scale as measured with HR OES at 0.4 T.

electron density is presented in Figure 5. The electron density decreases before the stationary shock front (which is located around 30 mm) because of the supersonic expansion and after the shock front because of high recombination rate of hydrogen plasma. The density of the hydrogen plasma at the source exit ranges from 10^{21} m^{-3} up to 10^{22} m^{-3} in magnetic fields of 0.4 T up to 1.6 T, respectively (data not shown).

5. Discussion and conclusions

The axial velocity component as was determined from the time correlation of light fluctuations is found to be roughly 5 times less than expected for an unmagnetised free plasma expansion. As the measurements were clearly complicated by high frequency components as well as the different behaviour for increasing or decreasing source current, it is evident that alternative techniques are required to give a definitive picture on the jet propagation speed.

The plasma jet rotation is observed to increase with increasing magnetic field. This is counterintuitive as an $\mathbf{ExB}/B^2$ drift is generally accepted to drive this rotation (which would suggest an 1/B dependence). A satisfactory explanation can be found in [6] where the rotation is described to be self-limiting as it cannot exceed the thermal velocity and where it is deduced that the maximum rotation velocity is connected to the thermal velocity via the inverse of the gyro radius.

The asymmetry of the H_β-line profile is well explained by the sum of two Voigt profiles representing the radiation of particles originating from the plasma jet and the background.

Electron densities determined from HR OES measurements were found to be in agreement within 40% with Thomson scattering results. The difference could be explained by the fact that Thomson scattering measurements are local while HR OES averages data along the line of sight. The measurements were used to assess the axial variation of the density.

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