Paper No. OIV.8

13th International Stellarator Workshop

IMAGING SYSTEMS FOR THE H-1NF HELIAC

Howard, J., Michael, C., Glass, F., Collis, S., Warr, G. and Wang, A.
Plasma Research Laboratory,
Research School of Physical Sciences and Engineering
Australian National University, Canberra, A.C.T., 0200 Australia

Abstract

We describe multi-channel active and passive, non-perturbing diagnostic systems spanning the spectrum from the far-infrared to visible. System design principles and new technologies are described. The systems are combined to allow spatially and temporally resolved assessment of particle transport and force balance. To illustrate the performance of these systems, we present results for low field discharges in argon, and for electron and ion-cyclotron heated discharges in H/He at 0.5T.

Among the systems to be described are the scanning far-infrared interferometer and the MOSS imaging spectrometers. We also describe a novel imaging approach to spectroscopic line ratio measurements not reported previously. All of these systems have in common the use of time and frequency multiplex methods for encoding spatially or spectrally distinct information.

1 Electron density imaging

The H-1 tomographic imaging interferometer is capable of providing high-spatial resolution cross-sectional images of the plasma density profile [1, 2, 3, 4]. It uses a rotating diffraction grating to rapidly fan a probing far-infrared (743 μm) laser beam, in lighthouse fashion, across the plasma. This is achieved by scribing the circumference of the rotating wheel ($\sim$ 350 mm diameter) with a grating pattern whose groove spacing d varies with wheel rotation angle either continuously or in small discrete steps. At present, we use a grating rotated at 6000 rpm that generates six plasma sweeps per rotation for a minimum plasma sweep time of $\sim$ 2ms. By illuminating the wheel from different directions, and using both laser polarization states, it is possible to probe the plasma at multiple view angles as seen in Fig. 1.

1.1 Plasma formation studies at 0.5T

H-1 is now routinely operated at 0.5T using 7MHz resonant heating of H/He gas mixtures [5]. The interferometer has been used to study plasma formation across the wide range of magnetic configurations accessible by the flexible heliac. From the raw projection data only, it is possible to study configurational effects on total electron number, plasma centre-of-mass and profile width. Figure 2(a)

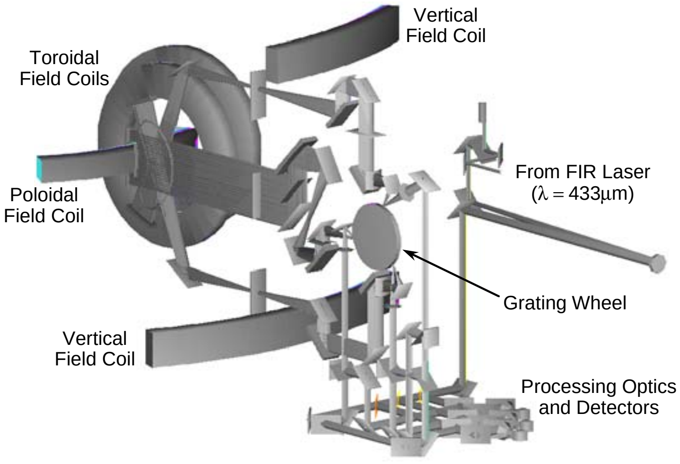


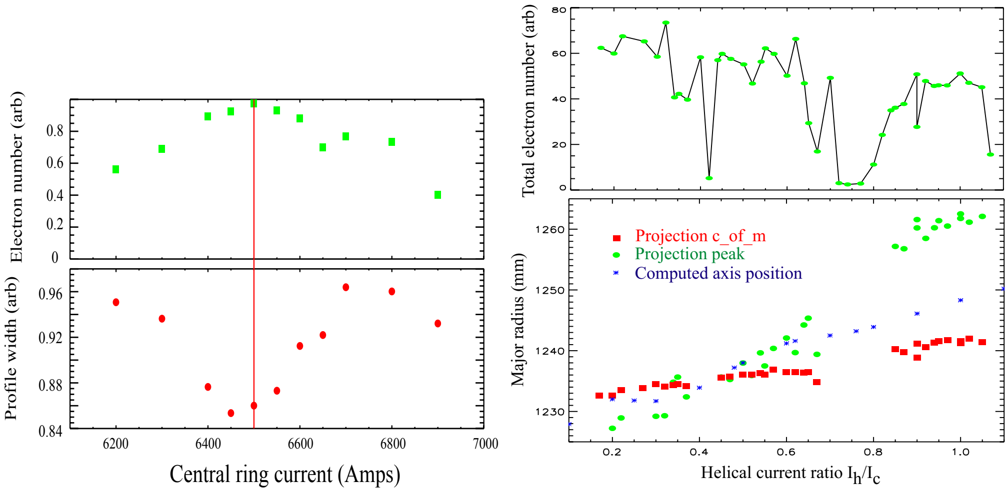
Figure 1: A 3-d Gaussian beam ray trace model of the H-1 scanning interfereometer optical system. Laser radiation incident on the rotating grating is sequentially diffracted over a fan of angles. The beam is collected by monolithic optics, directed into the plasma and returned back along the incident path to processing optics mounted on a horizontal optical table. The grating is illuminated at three positions to allow plasma probing in three directions, two diagonal and one horizontal.

shows the variation of the total electron number n_{e0} (integrated over impact parameter and time) for one of the interferometer projections versus central ring current I_c for resonantly heated discharges (7MHz) in H-He gas mixtures. The profile "width" obtained by taking the ratio of n_{e0} to the central line-average density (from a chirp frequency single channel 2mm interferometer) shows a broadening of the profile as the resonant layer moves away from the plasma axis. Strong magnetic configurational effects are revealed by monitoring the total electron number and projection centre-of-mass. The variation of these quantites with helical current ratio $\kappa_h = I_h/I_c$ (Fig. 2(b)) reveals the pronounced effects of magnetic resonances on plasma confinement.

1.2 Electronic wavelength sweep

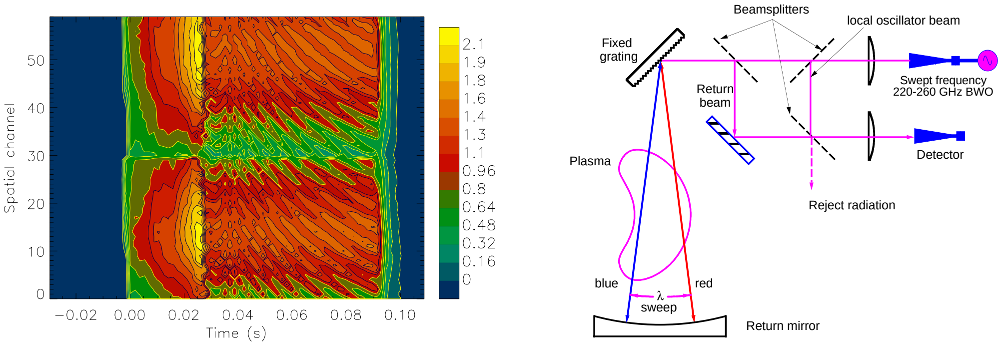
Under some plasma conditions, the wheel scan rate is insufficient to temporally resolve fast density changes. Figure 3(a) shows juxtaposed projections from the two diagonal views for a low-field discharge in argon that collapses to a strong oscillating global instability. Moiré fringe patterns result from the temporal undersampling.

We plan to alleviate this problem with the installation of a high power (100 mW), voltage tunable 260 GHz ($\lambda = 1.15$mm) microwave source. The BWO can be rapidly ($\sim 10-100\,\mu$s) voltage tuned over a wide frequency range. By illuminating a fixed grating and sweeping the frequency rapidly (< 100 μs) from 213-260 GHz it is possible to generate the identical range of diffraction angles $\Delta\beta$ as currently produced by the rotating scanning grating. With an appropriate path difference between the probing and local oscillator beams, the frequency sweep results in an intermediate frequency carrier signal at the mixer detector (Fig. 3(b)).



(a) (b)

Figure 2: (a) Variation of total electron number and plasma "width" versus central ring current. A current of 6500A produces a field of approximately 0.5T on magnetic axis. (b) Top: variation of total electron number determined by the time-integrated interferometer projection versus helical current ratio. Note the effects on plasma formation of the proximity of rotational transform resonances obtained at various helical curent ratios. Below: The shift of the projection centre-of-mass, projection peak position and the computed axis position as a function of helical current ratio.



(a) (b)

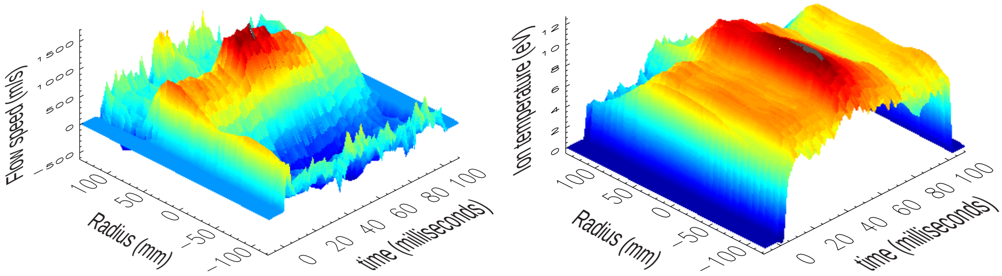
Figure 3: (a) Raw interferometer projection data. Each image shows the temporal evolution (horizontal axis) of the phase shift (radians) for the two diagonal sweeps of the plasma (vertically juxtaposed). In this case the plasma collapses to a strong global instability about 30 ms into the discharge. (b) By rapidly sweeping the output frequency of a BWO tube it is possible to effect a spatial scan of the plasma. The geometry is arranged so that the longer wavelength beams visit the less dense plasma regions.

The spatial sweep will be arranged such that the probe wavelength decreases (sensitivity to plasma density increases) as the scan moves from plasma centre to edge. Using a grating blazed for second (or higher) orders will halve the required wavelength sweep range thereby reducing the sweep time and the effects of output power modulation.

2 Spectroscopic systems

Impurity and instrinsic ion spectroscopic imaging systems based on an electrooptically modulated polarization interferometer (the MOSS spectrometer) have been developed for tomographic imaging of the ion temperature and plasma flow fields [6, 7, 8]. For Doppler tomographic applications, it can be shown that time-domain instruments have certain fundamental advantages, not least of which is a simple relationship between fringe visibility and the line-integral of the intensity weighted velocity distribution function.

A wide field-of-view, high etendue 32 channel camera images a plasma poloidal cross-section via a vacuum window and internal mirror arrangement [7]. The instrument has been used to study plasma radial force balance in low field argon discharges that exhibit spontaneous confinement transitions. Some representative data are shown in Fig. 4.



(a) (b)

Figure 4: (a) Temporal evolution of the ion flow profile for low-temperature discharges in argon. In these experiments, the rf power to the plasma is ramped in triangular fashion in order to study the dynamics and hysteresis of transitions between low and high confinement modes. Note the plasma acceleration at the onset of the transition ($t \sim$ 30ms). (b) The associated ion temperature profile shows a modest increase in ion temperature to $\sim$ 12 eV after the transition.

To observe higher order spatial ion temperature and flow vorticity structures related to magnetic islands and large scale plasma instabilities [9], we have mounted an array of lens-coupled fibres on a rotatable apparatus that encircles the plasma. The wheel hosts 11 parallel viewing channels in each of five angularly equispaced modules arrayed about the plasma (see Fig. 5. The wheel can be rotated to view a number of fixed light sources for relative intensity calibration and, when not in use, can be parked so as to shield the lenses from the plasma. The tomographic instrument response has been measured in readiness for first plasma measurements.

More recently we have developed an imaging MOSS system for interferometrically determining the intensity ratio of spectral line pairs. The system, which shares the same viewing sightlines as the MOSS camera, monitors the phase and contrast of the beat pattern produced by the superposition of independent interferograms. These quantities relate in a simple way to the relative line intensity ratio from which we can image the electron temperature (for ap-

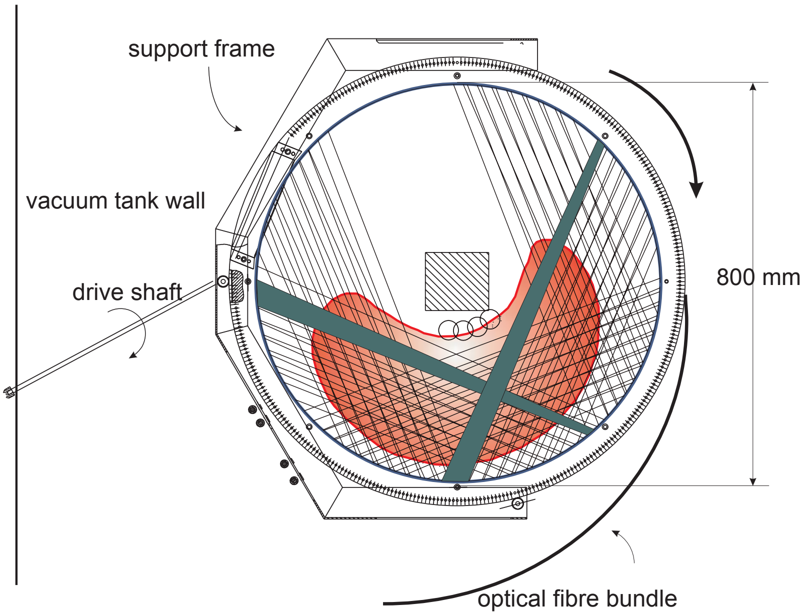


Figure 5: Schematic of the rotatable viewing platform showing the viewing chords and angles.

propriately chosen atomic helium spectral lines) or the relative abundance of hydrogen and deuterium isotopes (from H_α and D_α intensities) during plasma fuelling experiments. The experimental details are given elsewhere [10].

References

[1] J. Howard, Rev. Sci. Instrum. **61**, 1086 (1990).

[2] J. Howard, P. Dodds, and G. Warr, Rev. Sci. Instrum. **63**, 4965 (1992).

[3] G. Warr, B. D. Blackwell, J. Wach, and J. Howard, Fusion Eng. And Design **34-35**, 387 (1997).

[4] G. Warr, Phd. thesis, Research School of Physical Sciences and Engineering, Australian National University, Canberra 0200, AUSTRALIA., 1998.

[5] B. D. Blackwell, Physics of Plasma **8**, 2238 (2001).

[6] J. Howard, C. Michael, F. Glass, and A. Cheetham, Rev. Sci. Instrum. **72**, 888 (2001).

[7] C. Michael, J. Howard, and B. D. Blackwell, Rev. Sci. Instrum. **72**, 1034 (2001).

[8] J. Howard, Appl. Opt. **41**, 197 (2002).

[9] J. Howard, Plasma Phys. Control Fusion **38**, 489 (1996).

[10] J. Howard, C. Michael, and A. Wang, Applied Spectroscopy **In preparation**, (2002).