A novel tracer-gas injection system for scrape-off layer impurity transport and screening experiments

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Abstract

The design, operation, and initial results of a novel tracer-gas injection system is described. This system has been developed to diagnose local impurity transport and screening properties as a function of depth into the scrape-off layer (SOL) of Alcator C-Mod. A fast-scanning Langmuir-Mach probe has been outfitted with a capillary gas-feed and an inertially-activated valve. Impurity injection plumes lasting 5-10 msec can be formed at any depth into the SOL, up to the separatrix location. The local dispersion of selected charge state impurities in the SOL can be followed by camera imaging and Doppler spectroscopy. In principle, the local screening properties of the SOL can also be directly assessed by injecting gas at different depths into the SOL and observing the resultant impurity concentrations in the core.

1. Introduction

Impurity concentrations in the core plasma of a tokamak depend on the transport and screening properties of the divertor and the scrape-off layer (SOL). Parallel plasma flows in the divertor/SOL play an important role in the overall impurity transport picture. In Alcator C-Mod, reversed parallel flows are detected near the separatrix on the outer divertor leg[1], perhaps affecting the screening efficiency of the SOL. Cross-field diffusion and drifts are also important and need to be quantified.

One way to directly study impurity transport in the SOL is to inject trace amounts of gaseous impurities and follow the dispersal of the resultant impurity "plumes". In the past, this technique has been used to study plasma properties near wall, limiter, and divertor surfaces.[2,3,4,5] The gas delivery system for these experiments typically employs capillary tubes embedded into the wall structures. One limitation of this technique is that there is little external control over where the ionization takes place. In nearly all cases, the resultant impurity emission plume is either localized to very near the wall (e.g., injection from a limiter or a divertor surface) or forms in a region of the SOL that is far from the separatrix location (e.g., injection from a wall surface in the main chamber).

An obvious way to overcome these limitations is to inject gaseous impurities from the end of a fast-scanning Langmuir probe. In dense, high temperature plasmas such as that found near the magnetic separatrix, the emission plume would be localized near the gas injection nozzle, providing an accurate positioning of the impurity source. Furthermore, by using Langmuir probe elements embedded in the scanning probe head, one can directly measure the local plasma conditions, including density, temperature and an estimate of parallel plasma flow velocity. The Langmuir probe measurements also allow one to determine if the gas injection is truly a 'trace' injection by detecting any perturbations in local plasma conditions.

Based on these ideas, a scanning gas injection system has been assembled for Alcator C-Mod, built upon the existing vertical fast-scanning Langmuir probe drive. In addition, the system employs a novel 'inertial-valve' in the probe head that restricts gas injection to only a time during deepest probe insertion. In principal, this feature can be used to directly assess the impurity screening properties of the SOL by injecting gas at different depths into the SOL and observing the resultant impurity concentrations in the core.

2. Experimental Arrangement

The arrangement of the principal diagnostics associated with the gas injection system on Alcator C-Mod is shown in fig.1. A fast, vertically scanning, Langmuir-Mach probe[1] is used to record cross-field profiles of plasma density, electron temperature, and parallel flow velocities at a location which is 'upstream' from the outer divertor leg. The fast-scanning probe system has been modified to allow gaseous impurities to be injected at the tip of the probe. CCD cameras view (via fiber-optic relay systems) the toroidal and poloidal dispersion of the resultant visible-light emission plumes through selected optical interference filters. One of six possible interference filters can be selected via computer control prior to a tokamak discharge. At present, only the top CCD camera and associated fiber-optic system is operational. A six channel, toroidally-viewing optical fiber array also images visible light from the plume emission volume with a ~ 9 mm diameter spot size. The latter system provides spectral information on the plume emission which can be used to select interference filters and (in the future) to perform line-shape analysis including Doppler shift (parallel ion flow) and broadening (ion temperature).

A diagram of the fast-scanning probe head is illustrated in the top half of fig. 2. The location of the capillary gas feed tube and the embedded inertial gas valve is shown. Stainless steel capillary tubes (1 mm I.D.) connect between the gas supply (fig. 3) and the inertial valve through a short ceramic tube that provides an electrical break. Another short capillary tube connects the inertial valve (normally closed) to a 1.5 mm diameter outlet orifice located at the center of a four Langmuir probe cluster (see bottom half of fig. 2). The inertial valve consists of a stainless steel ball and seat, held closed by a stainless steel spring. The mass and spring force are chosen such that the valve opens when the de-acceleration of the probe head exceeds ~30 times gravity. The maximum de-acceleration of the probe head at the end-of-stroke is ~70 times gravity. The Langmuir probes are arranged at the vertices of a pyramidal surface so as to provide directional information about plasma flows along and across the magnetic field.

The gas supply system for the scanning probe head is illustrated in fig. 3. A critical element in this design is a flexible stainless steel capillary tube (1 mm I.D.) which connects between the moving and stationary parts of the scanning probe drive. Because the scanning probe head can not be retracted behind a gate-valve for service, this capillary tube must reliably hold vacuum for the full duration of a run campaign. Destructive, cyclical fatigue testing of prototype flexible capillaries has demonstrated that vacuum integrity can be expected for a minimum of 18,000 cycles.

3. Initial Results

3.1 Gas delivery tests

Figure 4 demonstrates the typical operation of the gas injection system for nitrogen plume experiments. In this test, nitrogen is injected into an empty torus chamber (with turbomolecular pumps on). The quantity of nitrogen injected (minus some loss due to pumping) is recorded by the torus ionization gauge (bottom trace in fig. 4). Prior to testing, the 0.5 liter plenum is filled with 45 mtorr of nitrogen. At -0.4 seconds, the fill valve is opened, allowing the volume of the inertial valve (~ 0.3 cm^3) to fill with gas via the capillary tubing. The differential gauge records the change in plenum pressure, quantifying the number of N_2 molecules flowing through the fill valve and into the capillary tubes (third trace). The top trace shows the vertical position of the scanning probe as it scans three consecutive times. The torus ionization gauge signal shows that no significant nitrogen is injected except during the maximum insertion times of the probe, when approximately $2x10^{17}$ molecules of nitrogen is injected per scan.

The precise timing of the gas injection can be determined by injecting a large quantity of gas in a plasma discharge and detecting the resultant perturbation on one of the Langmuir probes. Figure 5 shows the current and voltage time traces for the 'south' probe during the peak insertion time of the scanning probe. In this case, the system is setup to deliver ~$8x10^{18}$ helium molecules per injection. The timing of the increased ion saturation current indicates that the inertial valve opens approximately 2.5 msec before the peak insertion time and remains open for ~ 7 msec. During this time, the scanning probe has moved a total distance of ~6 mm vertically, corresponding to a distance of ~4 mm measured perpendicular to flux surfaces.

3.2 N_2 and He plumes

A typical false-color image of NIII emission (451.5 nm) recorded by the top CCD camera is shown in fig. 6. The emission plume was formed near the separatrix location by injecting ~$2x10^{17}$ molecules of nitrogen. The camera was exposed for 16 msec, capturing the evolution of the plume over its full lifetime in time (~7 msec) and space (~4 mm movement across flux surfaces). For reference, the dashed line in fig. 6 indicates a toroidal arc projected onto the camera view. A magnetic field line passing through the centroid of the emission volume is also show in fig. 6 (solid line), which was obtained from an EFIT[6] reconstruction of the magnetic equilibrium.

The overall emission pattern is similar to that seen from wall-injected gaseous impurities[2] with emission extended along the local magnetic field lines. However, owing to the higher densities and temperatures at the injection location (leading to shorter ionization times), the extent of the plume is greatly reduced for a given charge state. Figure 7 shows emission profiles along the local magnetic field line of NII, NIV, HeI and HeII obtained from four different plumes. These profiles are the result of integrating the 2-D emission patterns in the cross-field direction. The nitrogen plumes where formed near the separatrix where the Langmuir probes measure $n \sim 10^{20}$ m^{-3} and $T_e \sim 50$ eV. The helium plumes were formed ~ 4 mm outside the separatrix with $n \sim 4 \times 10^{19}$ m^{-3} and $T_e \sim 25$ eV.

As expected, higher charge states of nitrogen and helium show a larger dispersion along the magnetic field line. By looking at successive charge states, one is effectively viewing the time and spatial evolution of a swarm of impurities as they progress from neutral, to single, and to multiply ionized impurities. Asymmetries in the emission profiles for NIII and HeII (see dashed lines in fig. 7) may be interpreted as evidence of a background plasma flow since these ions have been immersed in the plasma long enough to experience momentum transfer from the bulk plasma.

3.3 Langmuir-Mach Probe Profiles

Figure 8 shows cross-field profiles of density, electron temperature, and parallel Mach number inferred by the scanning Langmuir probes during the NIII experiment shown in figs. 6 and 7. The parallel Mach numbers are inferred from the Hutchinson model.[7] Similar to observations on many discharges (see discussion in ref. 1 and recent spectroscopic measurements in [8]), a reverse parallel flow condition (flow *away* from the divertor) is detected in this discharge over a zone extending a few millimeters from the last-closed flux surface (LCFS). Nitrogen gas injection occurs during the time when the scanning probe traverses a zone extending from 0 to 4 mm. Since the CCD camera was operating with a 16 msec exposure time, the camera image represents a combination of plume emission from plasmas with widely varying local conditions: $3 \times 10^{19} < n < 1.2 \times 10^{20}$ m^{-3}, $25 < T_e < 50$ eV, and $-0.3 < M < 0$. Nevertheless, the data indicate that the plume is formed in a zone of parallel flow reversal, consistent with the asymmetry in the observed impurity dispersal patterns.

3.4 Comparison with DIVIMP Modeling

An important goal of the trace-gas injection experiments is to unfold the magnitude of parallel and perpendicular impurity ion transport and to study relationships between impurity transport and tokamak plasma conditions. At the present time, we have used the DIVIMP[9] impurity transport code to perform some initial scoping studies to determine the spatial extent of possible impurity injection plumes. Figure 9 shows the results from a numerical simulation of a nitrogen plume injected into a uniform background plasma with $n = 5 \times 10^{19}$ m^{-3}, $T_e = 40$ eV, and $M = -0.12$. Emission profiles along the magnetic field line are computed from the 3-D distribution of impurities and displayed in a format similar to that of the experimental data in fig. 7. The background plasma conditions of this simulation are close to the conditions (spatially averaged) measured by the scanning Langmuir probes for the nitrogen plumes shown in figs. 6 and 7. However, unlike the experiment, nitrogen is introduced as a point source, perhaps explaining the highly peak emission profiles which are not see in the experiment.

The modeled NIII emission profile in fig. 9 exhibits an asymmetry along the magnetic field line which is consistent in magnitude with that seen experimentally in fig. 7 (ignoring the excessive emission peak). However, the asymmetry is weak, indicating that NIII emission is not a sensitive measure of parallel flow velocities under these plasma conditions. On the other hand, the NIV emission profile exhibits a large asymmetry, suggesting that future experiments should look at higher charge states, if possible.

4. Summary and Future Plans

A novel system to directly diagnose the local impurity transport and screening properties as a function of depth into the SOL has been assembled for Alcator C-Mod. A fast-scanning Langmuir-Mach probe has been outfitted with a capillary gas-feed and an inertially-activated valve. This system can inject up to $\sim 10^{19}$ gas molecules over a 5-10 msec time interval corresponding to the end-of-stroke de-acceleration period of the probe. Injections are localized to a ~4 mm zone in SOL width. Deep injections (i.e., at locations up to the separatrix) are routinely achieved. This system is capable of performing three types of basic transport experiments: (1) CCD cameras with optical interference filters can be used to monitor the local cross-field and parallel dispersion "plumes" of selected charge states, (2) a fiber-optic telescope can be used to view Doppler-shifted emission from parallel flow, and (3) by injecting gas at different depths into the SOL and observing impurity concentrations in the core, the local screening properties of the SOL can be directly assessed.

Initial plume dispersal experiments with N_2 and He gas injections have been performed. Reversed parallel impurity flows near the separatrix have been detected in N^{+2} and He^{+1} distributions. Modeling with Monte-Carlo techniques (DIVIMP) indicate bulk plasma flow velocities that are consistent with Langmuir-Mach probe data. DIVIMP modeling also shows that the dispersal of longer-lived high charge states are a more sensitive measure of the flows in these high density ($\sim 10^{20}$ m^{-3}) and temperature (~60 eV) plasmas.

Future plans include: (1) detect C^{+3} dispersal patterns (CIV at 581 and 580 nm) resulting from C_2H_4 gas injection to provide a more sensitive measure of parallel flows, (2) implement a side-viewing camera/periscope system (see fig.1) to perform full 3-D tomographic reconstructions of plume emission, (3) convert to intensified, gated CCD cameras to 'freeze' the scanning probe motion and allow smaller quantities of gas injection, and (4) perform direct SOL screening experiments by injecting chlorine-containing gases

(CCl_2F_2) at different depths in the SOL an look at the resulting Cl^{+16} concentration in the core plasma (via x-ray spectroscopy).

Acknowledgments

This work is supported by U.S. Department of Energy Contract No. DE-AC02-78-ET-51013.

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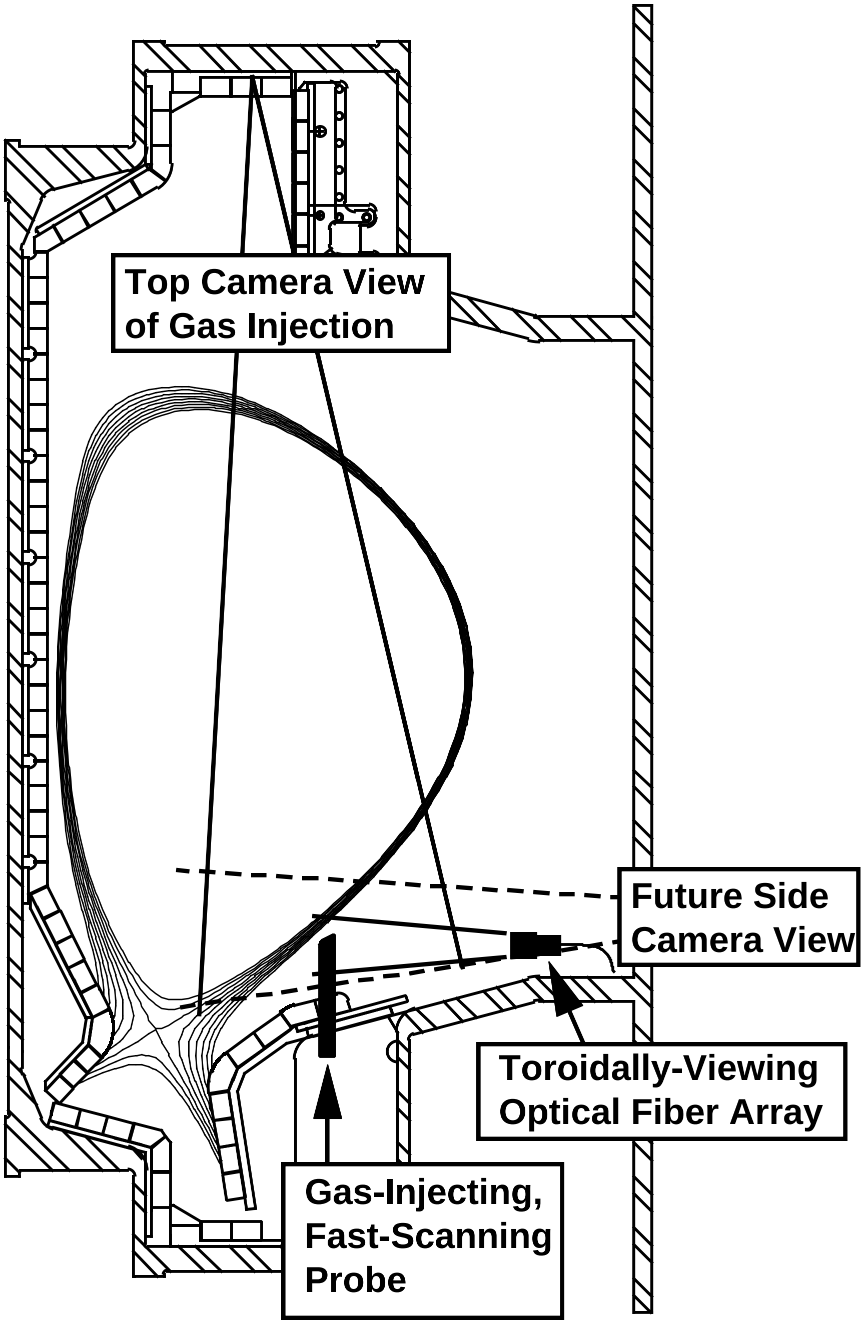

Fig. 1. Cross-section of the Alcator C-Mod vacuum chamber with a typical diverted plasma equilibrium. Gas is injected at the end of stroke of a vertically-scanning probe. Impurity emission "plumes" are presently viewed by the top camera. Future experiments will employ a toroidally-viewing fiber array (Doppler flow), and a side-viewing camera (tomography).

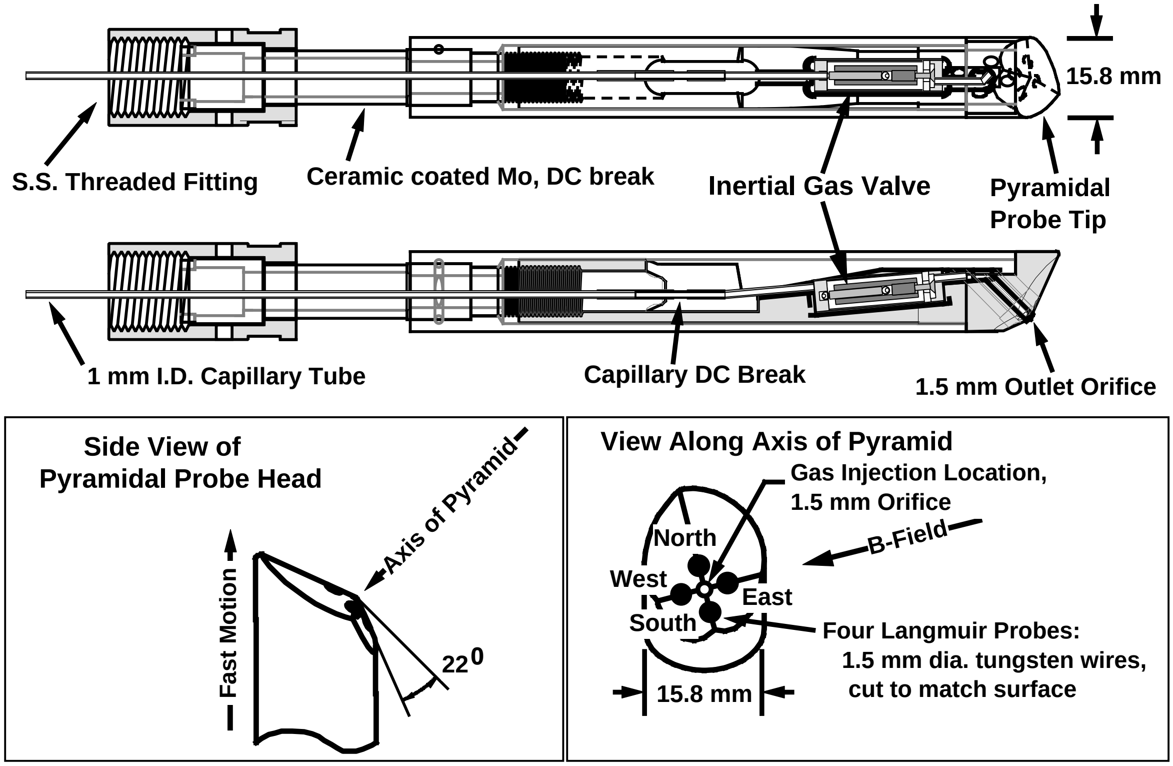

Fig. 2. (Top) Transparent view of fast-scanning probe head assembly showing gas feed and inertial valve location. (Bottom) Close-up views of pyramidal probe tip (actual scale). The materials are: molybdenum ~ body of the probe head, stainless steel ~ capillary tubes and inertial valve, tungsten ~ Langmuir probes, alumina and alumina coating ~ electrical insulation.

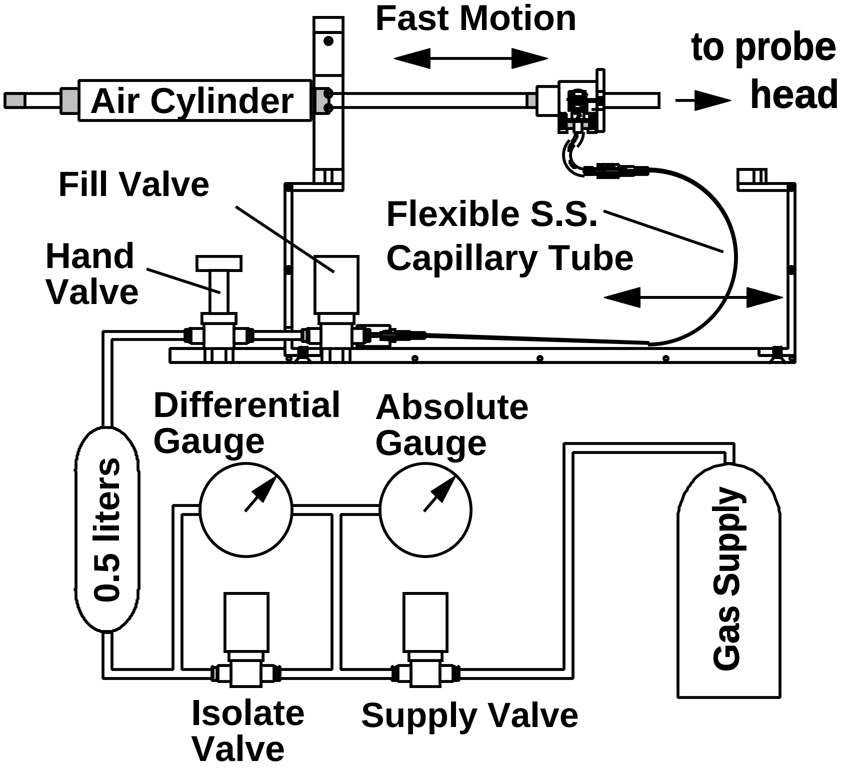

Fig. 3. Gas supply system for scanning probe head. A low-mass, flexible capillary tube connects the gas supply with the fast-moving probe head.

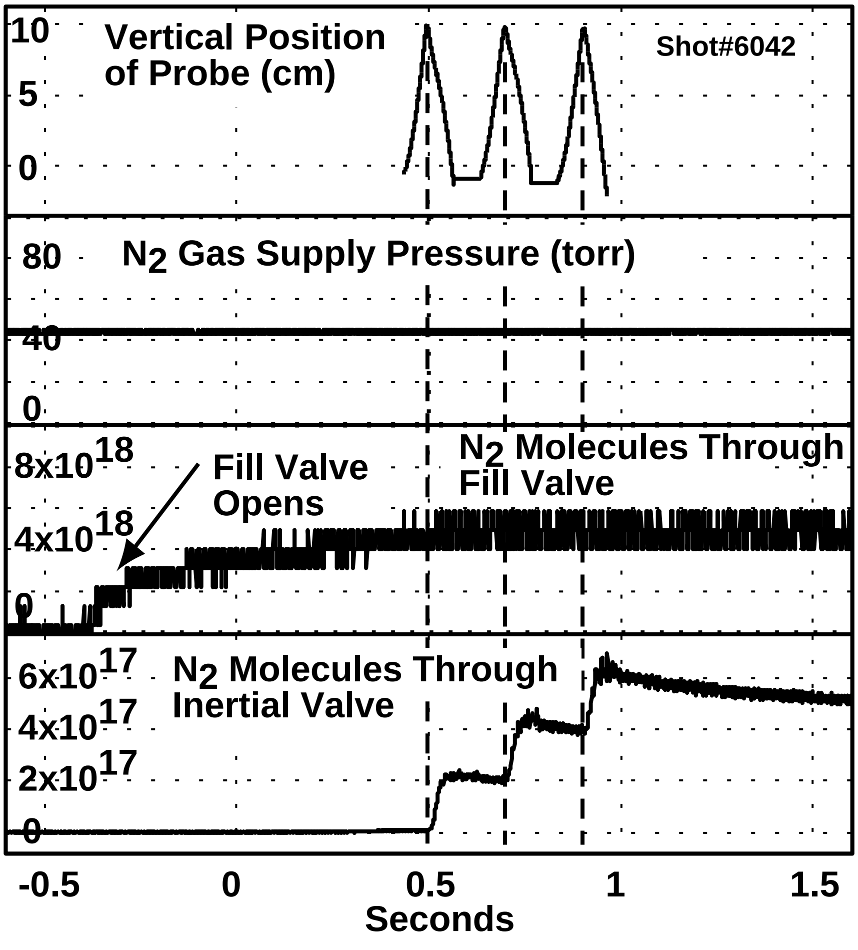

Fig. 4. Test of N_2 gas injection into an empty torus, showing a typical setup for nitrogen plume studies. Approximately $\sim 2\mathrm{x}10^{17}$ N_2 molecules are injected into the torus (bottom) during each maximum insertion time of the scanning probe (top) when the inertial valve is opened.

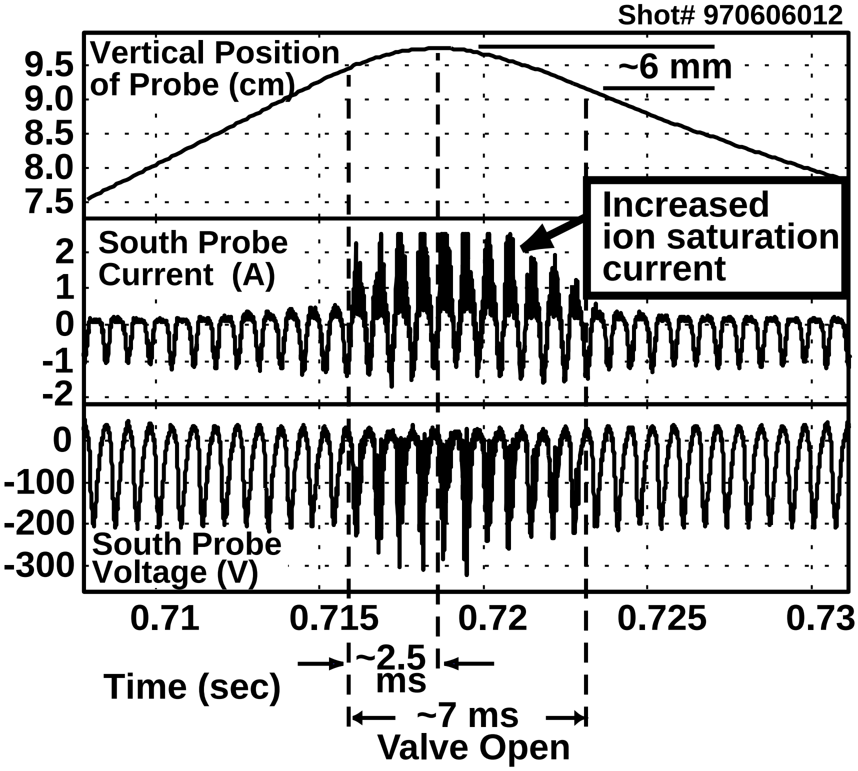

Fig. 5. Test of inertial valve time response. A large gas injection can perturb the local plasma conditions, as detected by the ion saturation current on the "south" Langmuir probe. The timing of the perturbation establishes when the inertial valve is open.

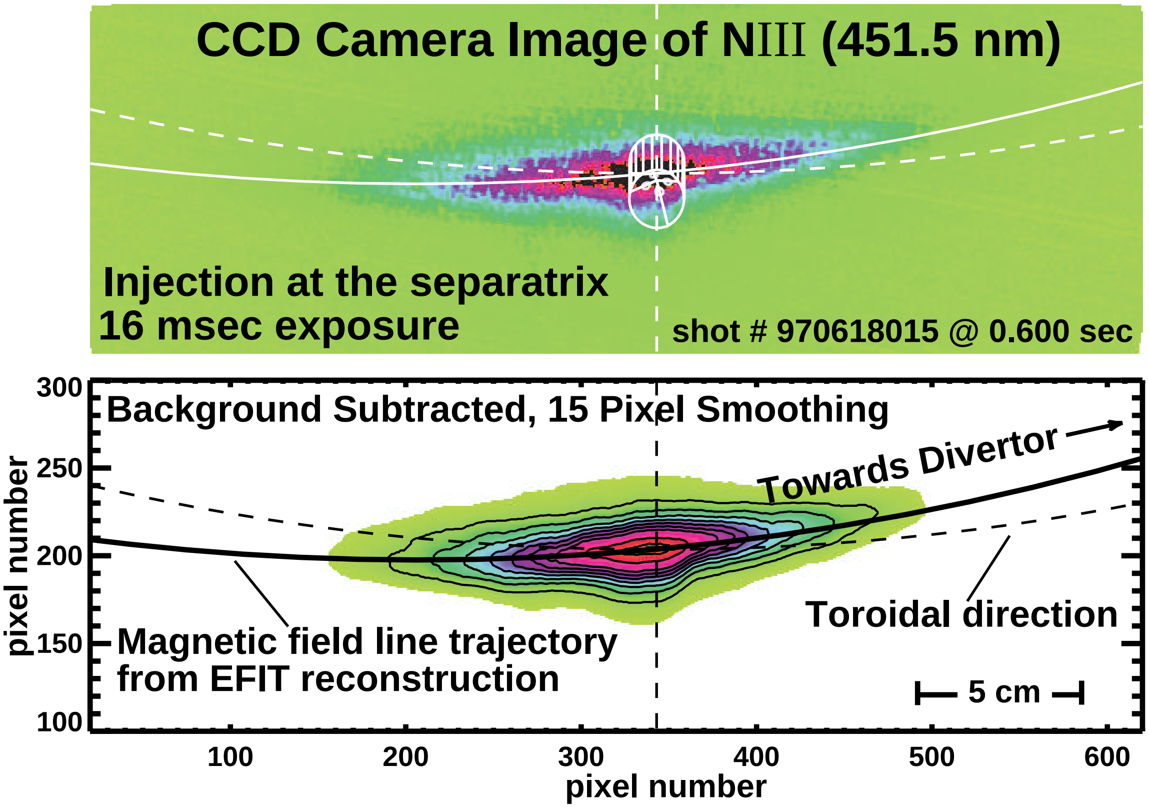

Fig. 6. (Top) False color image of a NIII emission plume recorded by the top camera (see fig.1). A 3-D wire-frame rendering of the probe head at the maximum insertion depth is overlaid. (Bottom) Processed image and emission contours. The dashed line corresponds to a toroidal arc projected onto the camera view. The solid line is a projection of a magnetic field line (inferred from EFIT) passing through the centroid of the emission.

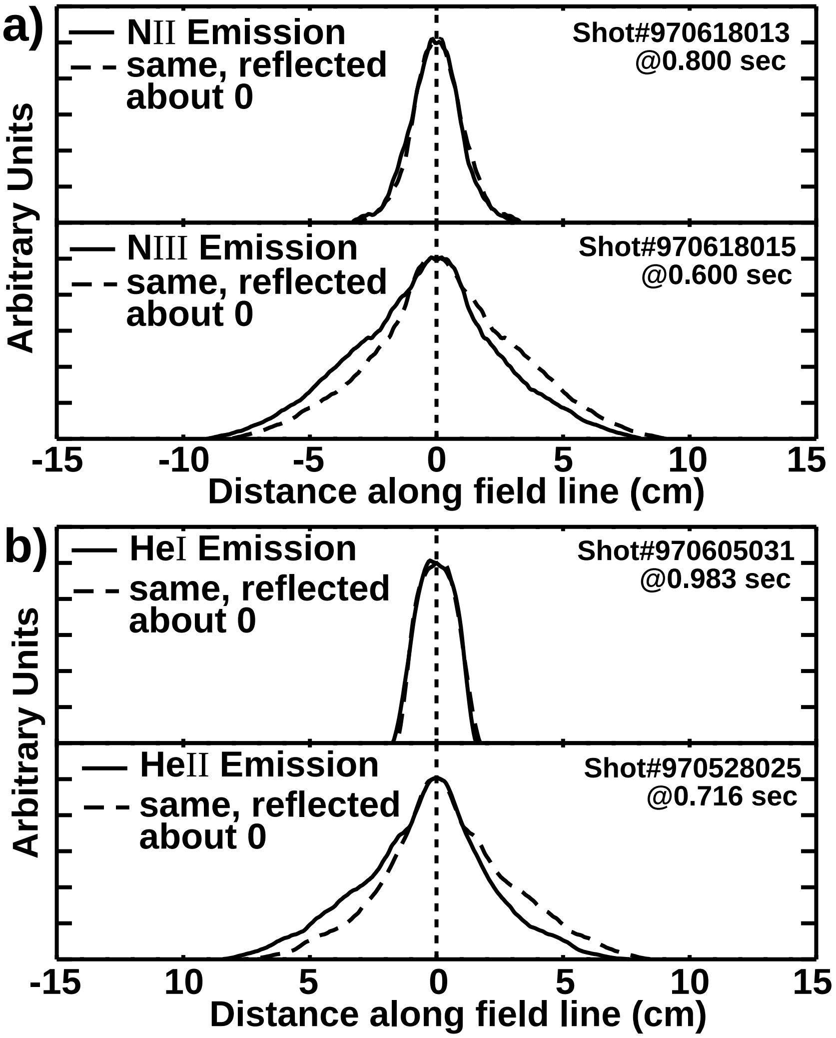

Fig. 7. (a) NII (463.0 nm) and NIII (451.5 nm) emission profiles along the magnetic field (solid lines). The dashed lines are the emission profiles reflected about zero.
(b) Similar plots for HeI (587.6 nm) and HeII (468.6 nm). In both cases, a background plasma flow towards negative values (away from the divertor) is evident.

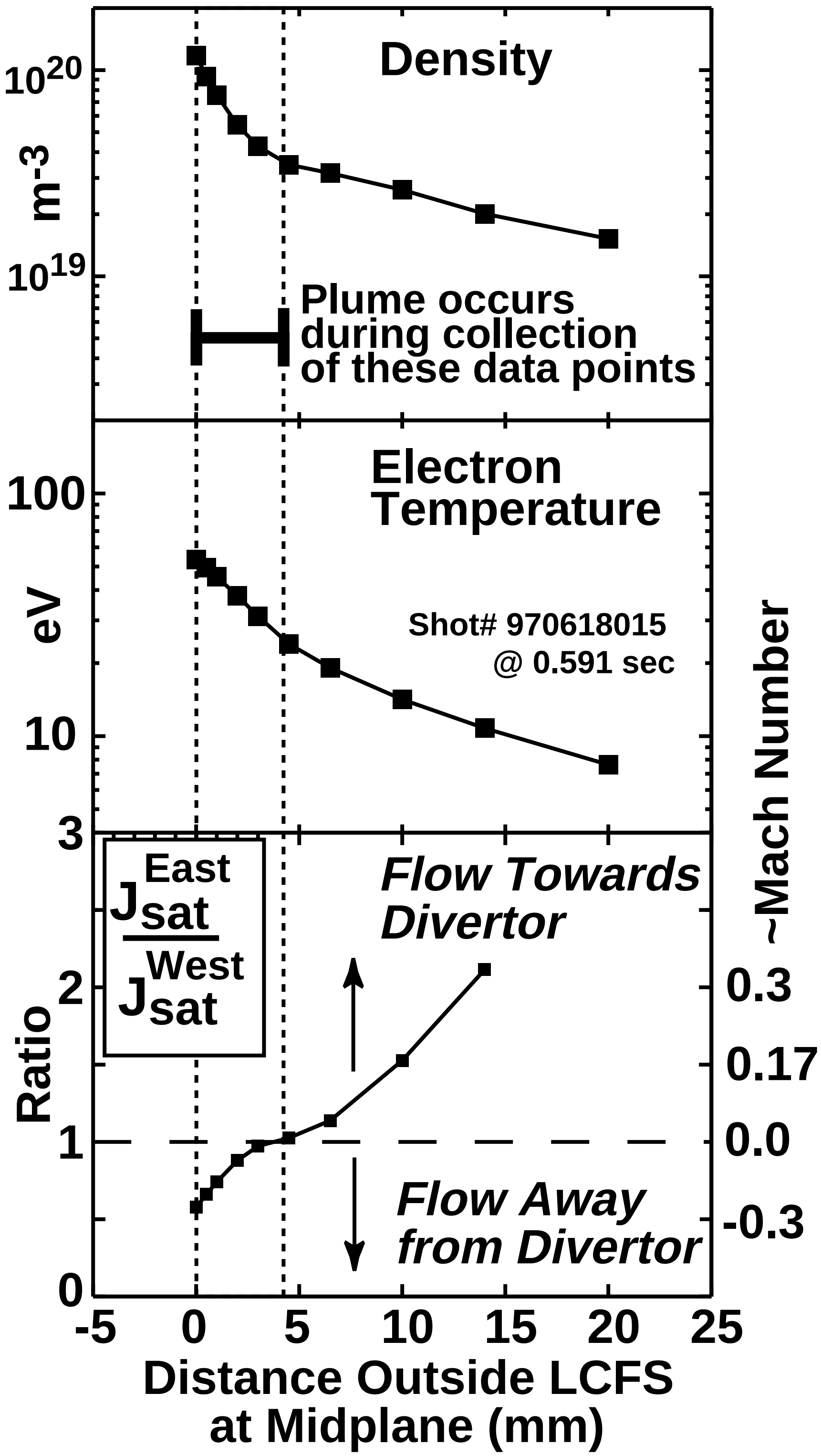

Fig. 8. Density, electron temperature and Mach number profiles inferred from the four Langmuir probes in the probe head. These data were recorded during the NIII plume shown in Fig. 6.

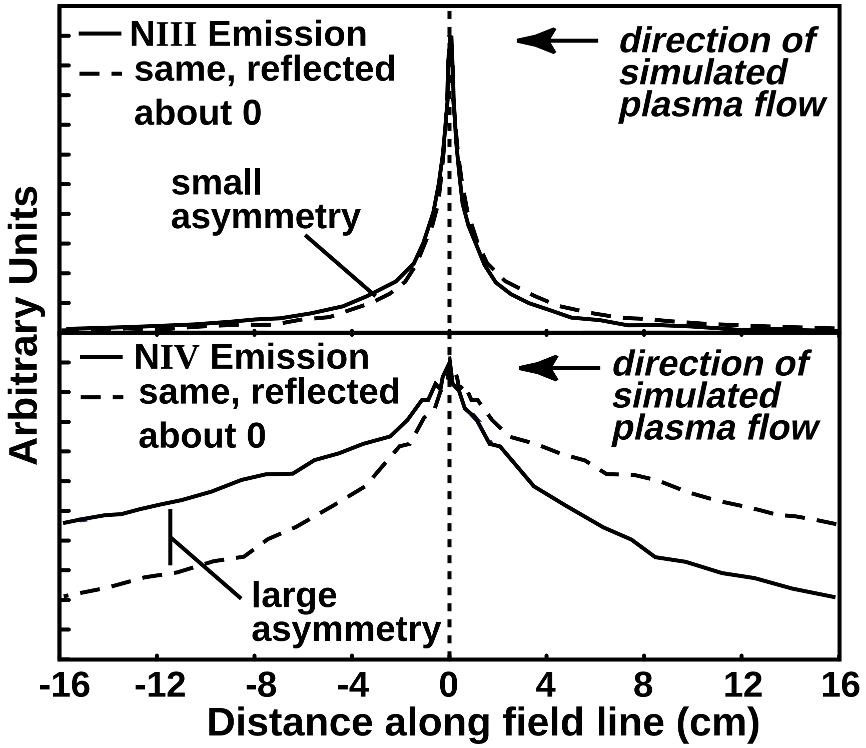

Fig. 9. Results from DIVIMP modeling of NIII and NIV emission profiles. Nitrogen is introduced as a point source into a plasma with $n = 5 \times 10^{19}$ m^{-3}, $T_e = 40$ eV and Mach number = -0.12.