A Two-Optical-Path Laser Fluorescence Signal Extraction Method

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ABSTRACT

Resonance Fluorescence of neutral hydrogen illuminated by H_α radiation has been used as a technique for spatially and temporally resolved density measurements of neutral hydrogen in high temperature plasmas. The fluorescence signal, very weak and buried in the background of stray laser light and H_α emission, is very difficult to extract and the measurement is inaccurate. This paper discusses a Two-Optical-Path signal extraction method. One optical path carries the fluorescence signal and the background (stray laser light and H_α emission), whereas the other path carries only the background signal. Combining these two signals a clean fluorescence signal can be isolated by subtracting out the background using a differential amplifier. The measurement is obtained instantaneously in one pulse rather than the double-pulse technique. This greatly improves the accuracy of the measurement as well as the time resolution.

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I. INTRODUCTION

The neutral hydrogen density N_o is a very important parameter for a plasma system. It provides information on particle and energy balance, particle recycle and plasma-wall interaction in a high temperature plasma fusion device. It will also help with the understanding of the plasma-material interaction in a material processing device. To understand the dynamic properties of a plasma plume, the spatial neutral density profile is a very important characteristic in the exhaust of a hydrogen plasma propulsion device. Measuring the H_α laser induced resonance fluorescence scattered from plasma is a method for determining the neutral hydrogen density. This method has been applied to toroidal tokomak plasmas[1,2,3] and tandem mirror plasmas[4,5],

The laser induced fluorescence signal is usually much weaker than the H_α emission from the plasma and the laser stray light. The intensity of the fluorescence signal depends on the plasma conditions. In the plasma of temperature and low density (roughly where the electron temperature is below 100 eV, electron density below $5 \times 10^{12} cm^{-3}$ and neutral hydrogen density below $10^{11} cm^{-3}$), the signal/background ratio is on the order of 10^{-2}. Gus et. al.[5] used a double-pulse technique to isolate the fluorescence signal by subtracting out the background from two spectra taken subsequently at 2-3 S time interval. The error is large because the plasma conditions may be different when the shots are made at different time, and particularly when there are fluctuations. To improve the accuracy we have developed a two-optical-path technique,i.e., the fluorescence signal is extracted from two signals taken simultaneously with a single laser pulse during the same plasma shot thus eliminating the aforementioned uncertainty.

This method involves two optical paths: One optical path was focused on the spot in the plasma shone by the laser light, therefore it carries all signals (the H_α emission from

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plasma, laser stray light and fluorescence signal). Another path is focused on the spot inside the plasma slightly off the laser shone spot. It therefore carries only the H_α signal and stray light which will be called background signal for convenience. The optical paths are separated by a prism and then led to two photomultipliers. By subtracting the electric signals from the photomultipliers using a differential amplifier we were able to eliminate the background, and a definitively clean fluorescence light spectrum was obtained.

II. EXPERIMENTAL METHOD

This Two-Optical-Path (TOP) method experimental work was performed on a Compact Tandem Mirror Plasma Experimental device which was built at MIT for space plasma propulsion study[6-8] (Fig. 1). This is a compact linear magnetic plasma confinement device which confines a hot and dense plasma with a magnetic bottle and ambipolar electric potential. The system parameters are: the overall length is 3.2 m, the central cell length is 1.15 m, the central cell coil radius is 0.36 m. In the central cell, the plasma radius is 10 cm, magnetic field intensity B_c is 2.4 kG, and the mirror magnetic field B_m is 20 kG. The goal of this program is to achieve a plasma with a density that can be varied from $10^{10} cm^{-3}$ to $10^{16} cm^{-3}$ with ion temperature variable from 1 keV to 0.01 keV. This characteristics will give us a most desirable variable thrust and variable specific impulse propulsion profile: The exhaust can be varied from high thrust at low speed during acceleration to a high speed at low thrust during coasting of a space craft. It is now operating in the neighborhood of $2 \times 10^{10} cm^{-3}$ and 100 eV. The plasma was created by back filling the chamber with hydrogen gas which was broken down with a microwave source at frequency of 2.45 GHz and input power of 500 W. Both gas feed and microwave injection were located at the north end of the central cell. The plasma ions were subsequently heated by ICRH (Ion Cyclotron Resonance Heating) at power level of 10 kW and pulse duration of 20 ms. The system was pumped at the exhaust chamber on both ends. The laser fluorescence diagnostic system was located in the south exhaust chamber of the machine at a distance of

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25 cm from the closest mirror point of the end cell. The electron temperature and density were measured by a fast Langmuir probe [9].

The crossectional view of the vacuum chamber, the laser beam and the detection optical system is shown in Fig. 2. The laser used here is a flashlamp–pumped dye laser (Candela EDL–6) tuned by an angle–tuned 40μ air–spaced etalon. A monochromator was used to monitor the wavelength of the laser output. A photodiode, mounted directly behind the 99.9% reflecting rear cavity mirror of the laser, is used to monitor the power of each laser pulse. A telescopic system in front of the laser improves the beam convergence. The beam can be focused at various radial position in the plasma by adjusting the concave lens. In the beam entry port there were three copper knife-edge baffles which were arranged to minimize the stray light intensity. The gate valve in front of the baffles was used for vacuum isolation. The scattering system, housed in a box on top of vacuum chamber, can be moved radially. It contains a big collection lens, 7 cm in diameter and 10 cm in focal length, mounted across a $30cm \times 10cm$ observation window. Radial scan can be made from $r = 0$ to $r = 4.5$ cm. This limitation was due to the 10 cm transverse opening of the aperture, which can be increased for larger radial scan in the future. A $30cm \times 10cm$ viewing dump which was made of stacked non–magnetic razor material was placed on the bottom of the chamber opposite to the scattering system box. The beam dump at the exit port consists of two disks of absorbing OB10–type glass. The glass was set at Brewster's angle to the incident laser direction in such a way that both polarization components were attenuated.

A sketch of the scattering system, the light paths and side view of the plasma and vacuum chamber are shown in Figure 3. The laser beam is normal to the quartz window of the entry port and shines on the plasma at the spot as shown. The optical paths consist of a big lens, a filter, a prism and two small lenses. The surface of the prism is deposited with a thin coating of aluminum which gives a surface reflectivity of 95%. The prism was adjusted

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so that the image of the each optical path fell on the entrance slits of the photomultipliers, PM1 and PM2 respectively. PM1 receives the light from the laser shone plasma spot, whereas PM2 receives the light from the plasma spot at an axial position slightly off from the laser spot. To induce the fluorescence emission of H_α from the hydrogen the wavelength of the laser was tuned to 6563Å . The induced fluorescence light emitted from the plasma at the laser spot is led to PM1, whereas PM2 picks up the background signal only. When the laser light is not in tune with the H_α line no fluorescence emission was induced and both photomultipliers PM1 and PM2 receive only the background signal. The outputs from PM1 and PM2 are nearly equal and can be subtracted completely. The difference of the signals was obtained using a differential amplifier (Tektronix 502) with a gain of 10. The contribution of the background was further reduced by placing a narrow band filter, with a bandpass of 5Å and transmission coefficient of 53%, in between the big lens and the prism. The Hamamatsu R928 photomultiplier tubes are shielded magnetically with high μ material. The optical parts were also shielded both optically and magnetically. The output from the differential amplifier and the power monitoring signal were processed by 6 MHz and 100 kHz digitizers respectively.

The laser was tuned to Balmer–alpha line 6563 Å by an etalon and had a linewidth of about 0.75 Å. The laser output power was about 80 kW and 1/3 of that power was focused on the plasma. The focused spot size was $0.4 - 0.5 cm^2$. The laser power of $10 kW \mathrm{cm}^{-2} \text{Å}^{-1}$ was sufficient to saturate the $n = 2$ to $n = 3$ transition of the hydrogen atom. The fluorescence intensity does not depend on the laser power.

The laser fluorescence signal was absolutely calibrated with Rayleigh scattering[10] in nitrogen gas. The ratio of the fluorescence signal, F, to the Rayleigh scattered signal, R, is

$$\frac{F}{R} = \frac{\Delta N_3 A_{32} T_L \pi r^2}{N_L N_{N_2} \sigma_R}, \tag{1}$$

where ΔN_3 is the difference in population of hydrogen atom in the $n = 3$ state with and without laser, $A_{32} = 4.4 \times 10^7 sec^{-1}$ is the induced transition probability from $n = 3$ to $n = 2$, $\sigma_R = 2.16 \times 10^{-27} cm^2$ is the Rayleigh scattering cross section, $T_L = 5\mu s$ is the duration of the laser pulse, $r = 0.5$ cm is the radius of laser spot, $N_{N_2} = 3.54 \times 10^{16} P$ (P is the pressure of nitrogen in Torr) is the molecular number density of nitrogen in Rayleigh scattering, and $N_L = 7.9 \times 10^{17}$ is the input photon number for the Rayleigh scattering laser light of energy $E_L = 480$ mJ used in our experiment. The Rayleigh scattered signal was found to be $R = 7.8P$. Thus, $\Delta N_3 = 4.49 \times 10^4 F$, where F is fluorescence signal related to the Rayleigh scattered signal. According to the theory of the collisional–radiative model[11], the ground state population of neutral hydrogen depends on the electron temperature and plasma density. They were measured by a fast Langmuir probe located at same radial position as the laser spot.

III. RESULTS and DISCUSSION

The flat top of the ICRH pulse duration is 20 ms as is shown by the voltage signal from the triple probe in figure 4a. The triple probe is located at a fixed radial position of 5 cm (one half of the plasma radius) and was used for the purpose of monitoring the plasma pulse shape. It can be seen that there are high frequency fluctuations superimposed on the flat top of the signal. The uncertainty would be extremely large if the double pulse technique is used to extract the fluorescence signal. The laser was fired at 12 ms after the initiation of ICRH pulse and was at about the middle of flat top. Figure 4b shows the light spectrum from path PM1. The sharp line contains the laser stray light and fluorescence light, and the continuous spectrum is the H_α emission. Figure 4c shows the spectrum of the lights from the path PM2. The difference of the magnitudes of the two sharp lines is the fluorescence signal as shown in Figure 5. The magnitude of this real signal is much

smaller than the stray laser light and the H_α emission. Without the use of the two optical paths PM1 and PM2 the extraction of the signal would be very difficult and inaccurate. As is shown in figure 5 the TOP method gives a clean signal, free of noise.

The radial profile of the fluorescence signal is shown in Figure 6. The radial profile of the measured electron temperature, T_e, and density, N_e, are shown in Figure 7a and 7b respectively. Inferred from ΔN_3, the neutral hydrogen density spatial profile, $N_o(r)$, is obtained and presented in Figure 7c. The electron temperature T_e ranges from 40 to 50eV and is slightly peaked at the center. The density profile is nearly flat with the radial variation between $2 - 3 \times 10^9/cm^3$. The value of N_e is an order of magnitude lower than that in the center cell; this effect is due to the magnetic expansion in the exhaust where the mirror ratio is about 20. The neutral density near the center is one order of magnitude smaller than that at $r = 3.5cm$. This indicates that the plasma is nearly fully ionized at the center. There are two possible implications: (1) This indicates the puffing fueling of fusion energy systems. The neutral gas is being puffed at the plasma edge and is ionized by both the microwave and the plasma when defusing toward the center. (2) This characteristic is in fact what we would like to achieve in the exhaust of a propulsion system. The flat temperature and density implies a very desirable flat thrust and I_{sp} profiles. There is no reduction in I_{sp} after being exhausted since electron temperature is the same as that in the central cell. The high neutral density at the edge will have two effects: it insulates the material wall from the hot plasma and it may facilitate the plasma detachment from the magnetic field lines.

The TOP method will also greatly improve the time resolution. In a double pulse technique the time resolution is severely limited by the time interval needed to make sequential shots. In TOP method only one pulse is involved so that the resolution is limited only by the repetition rate of a pulsing laser device.

ACKNOWLEDGMENT

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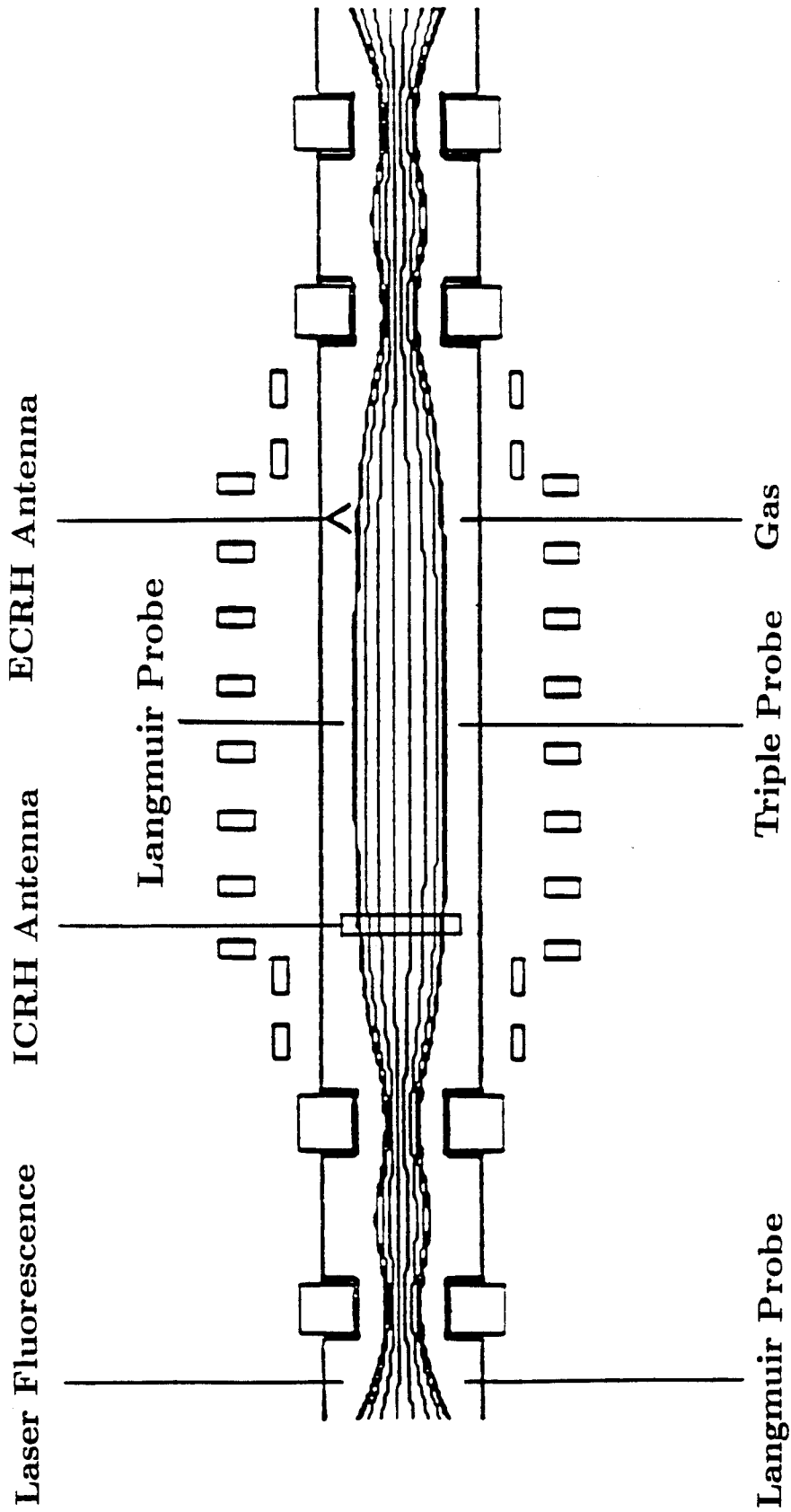
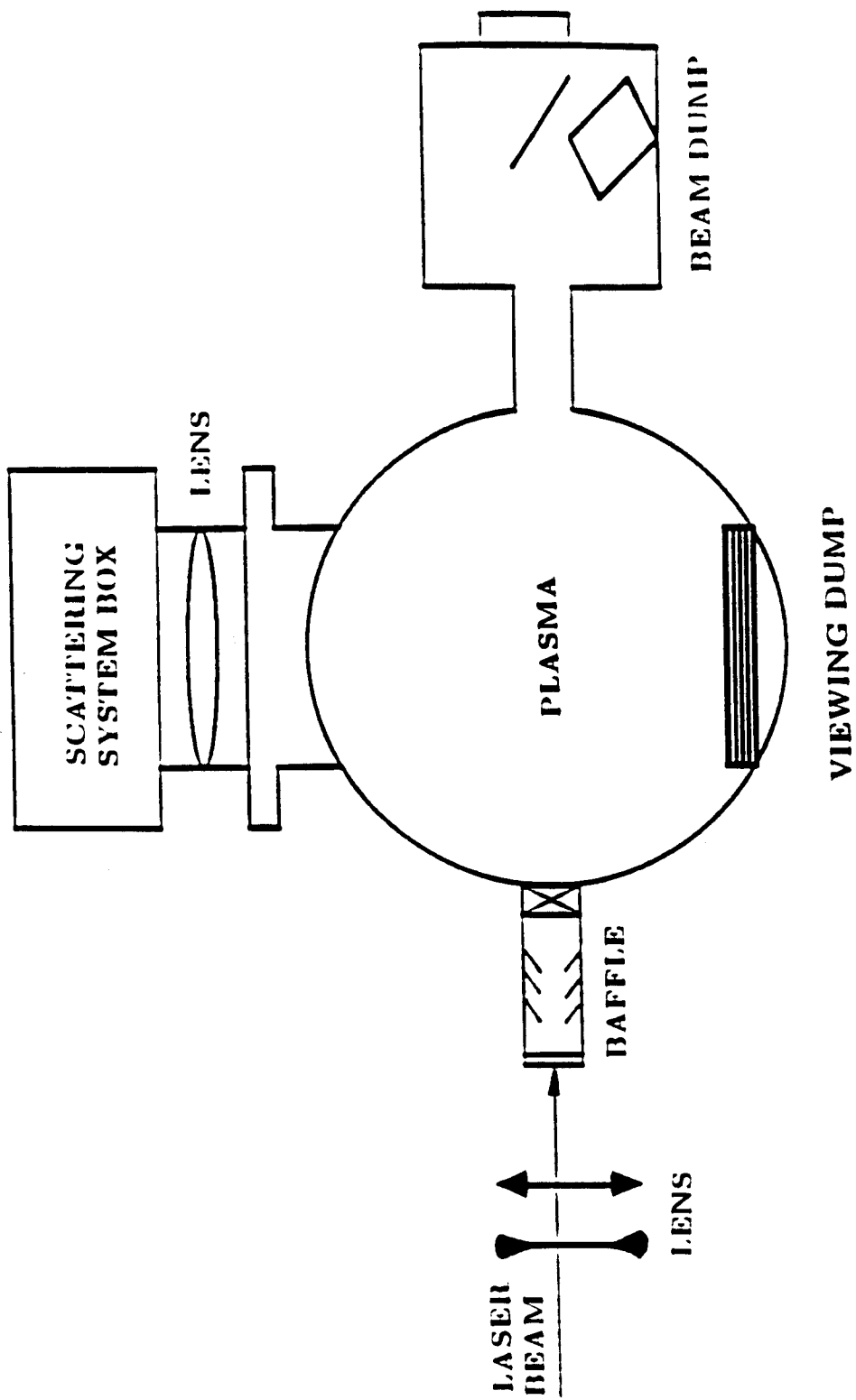Figure 1. Simplified experimental setup of the Tandem Mirror plasma propulsion facility.

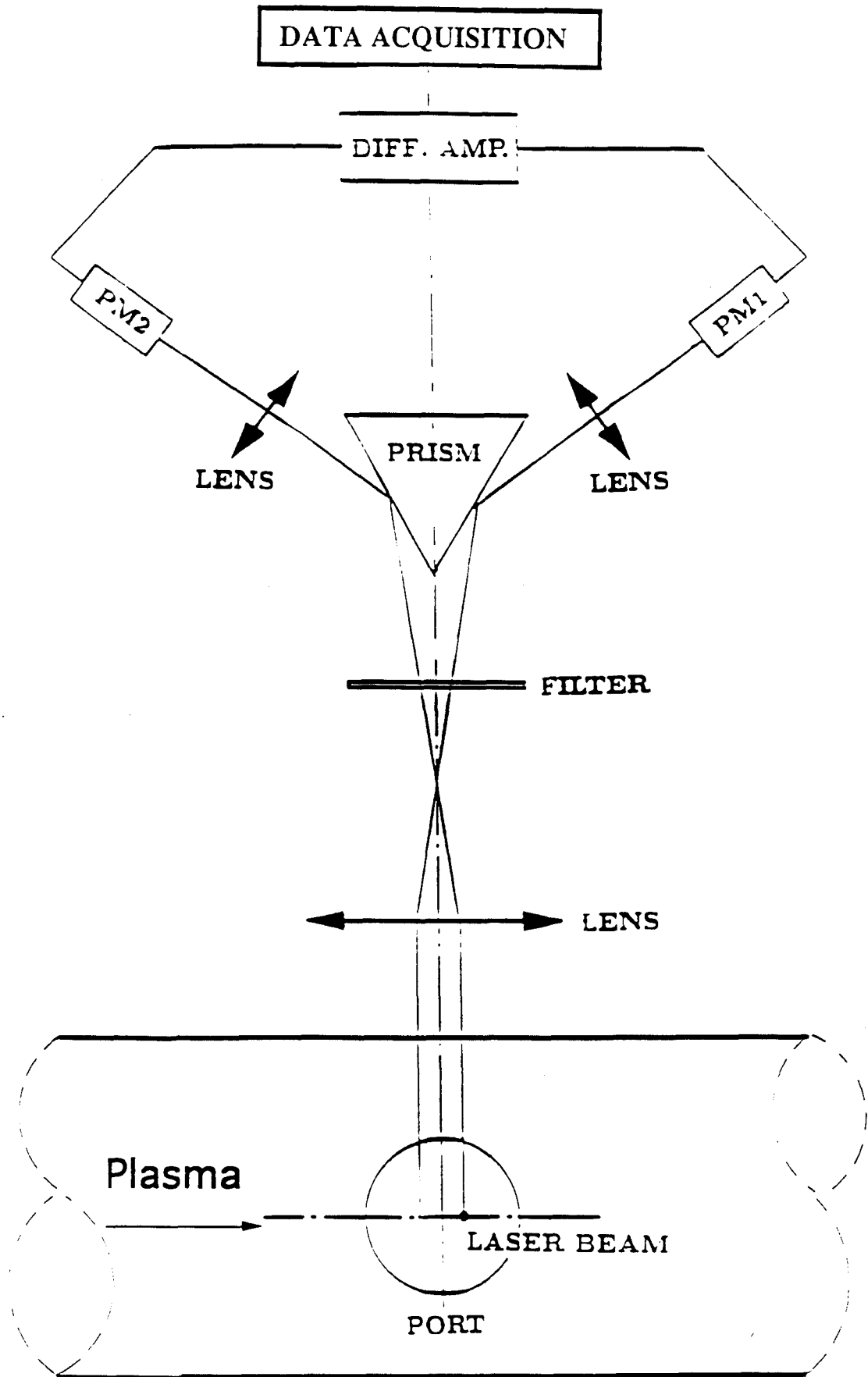Figure 2. Crossectional view of the vacuum chamber, the laser beam and the detection optical system.

Figure 3. Sketch of the scattering system, light paths and side view of the plasma and vacuum chamber. The laser beam is normal to the window of the entry port.
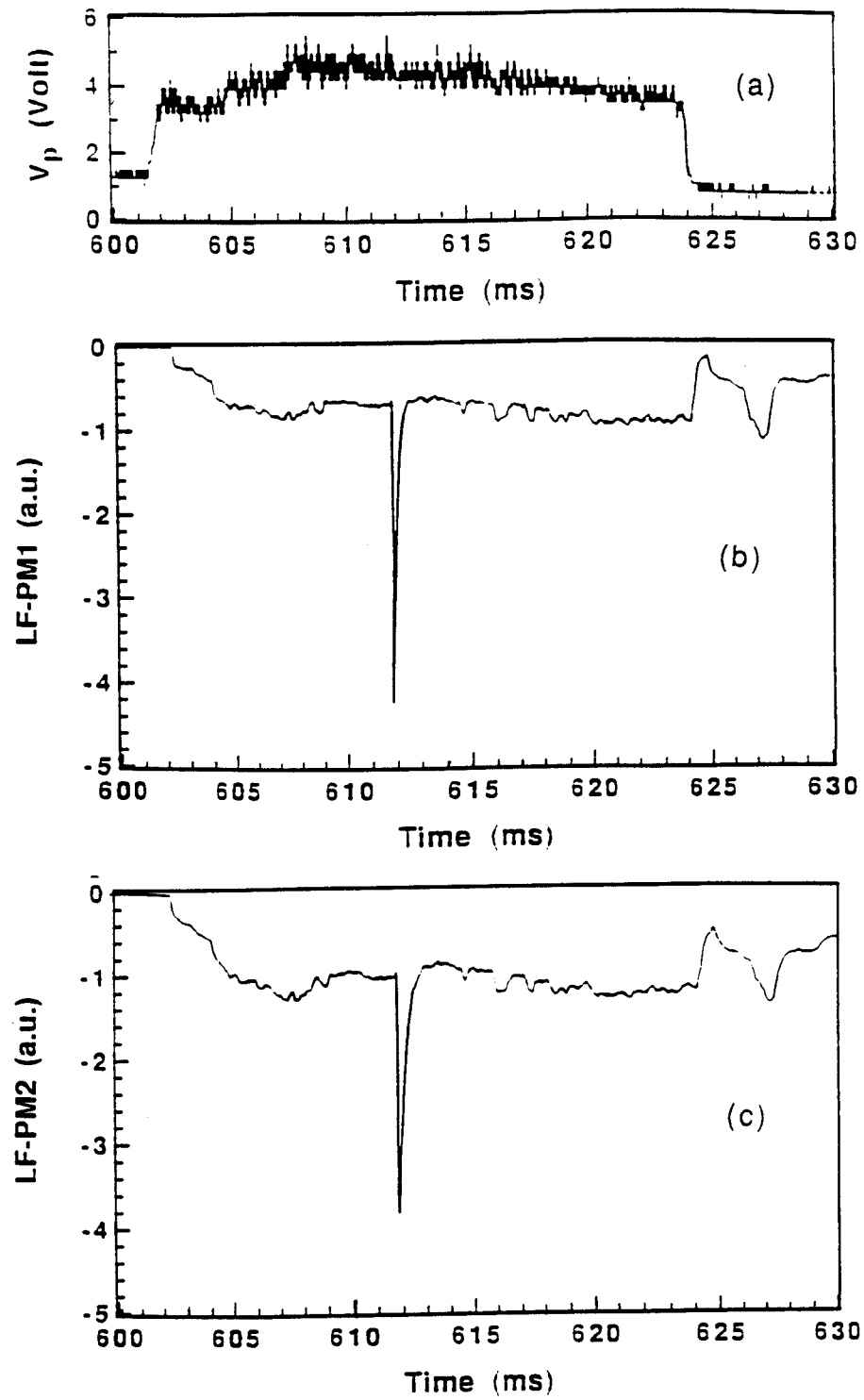
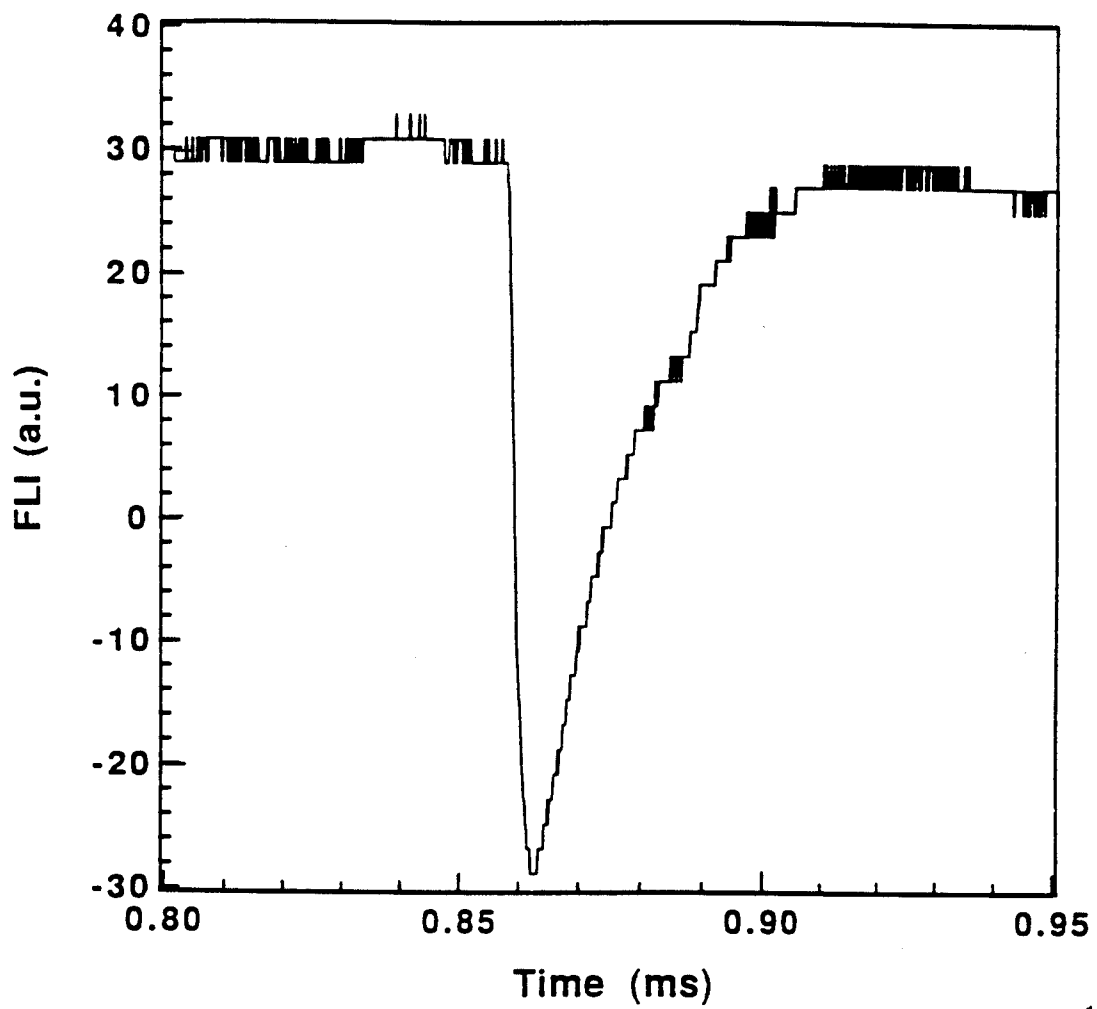Figure 4. Plots of plasma pulse, light intensity from PM1 and light intensity from PM2. The sharp lines are due to the laser pulse.

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Figure 5. The laser induced fluorescence signal extracted by taking the difference of the signals from PM1 and PM2.
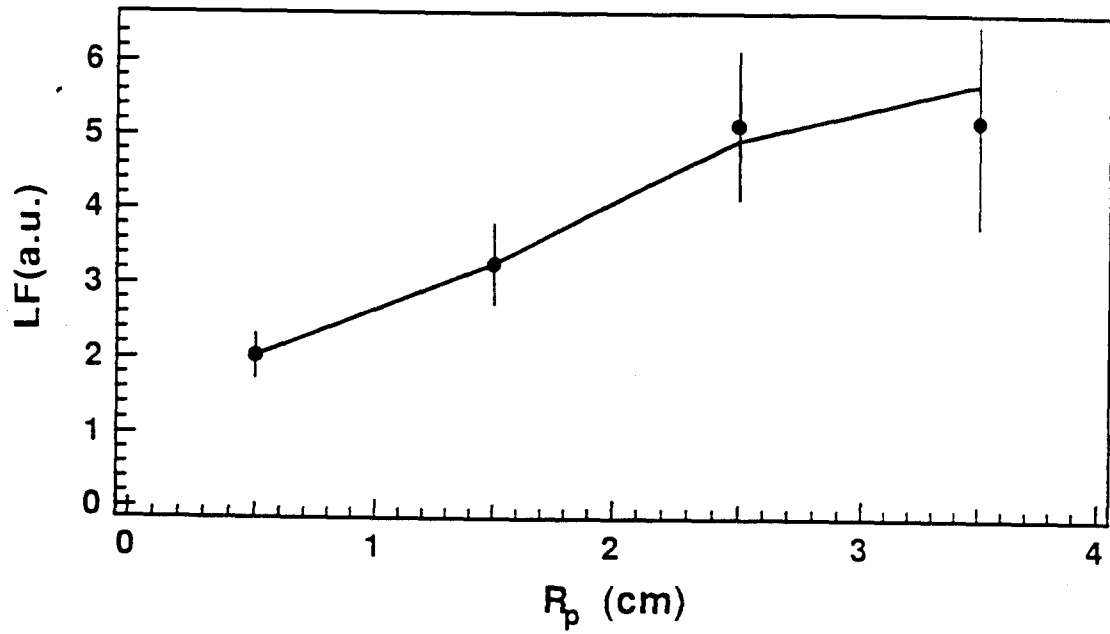
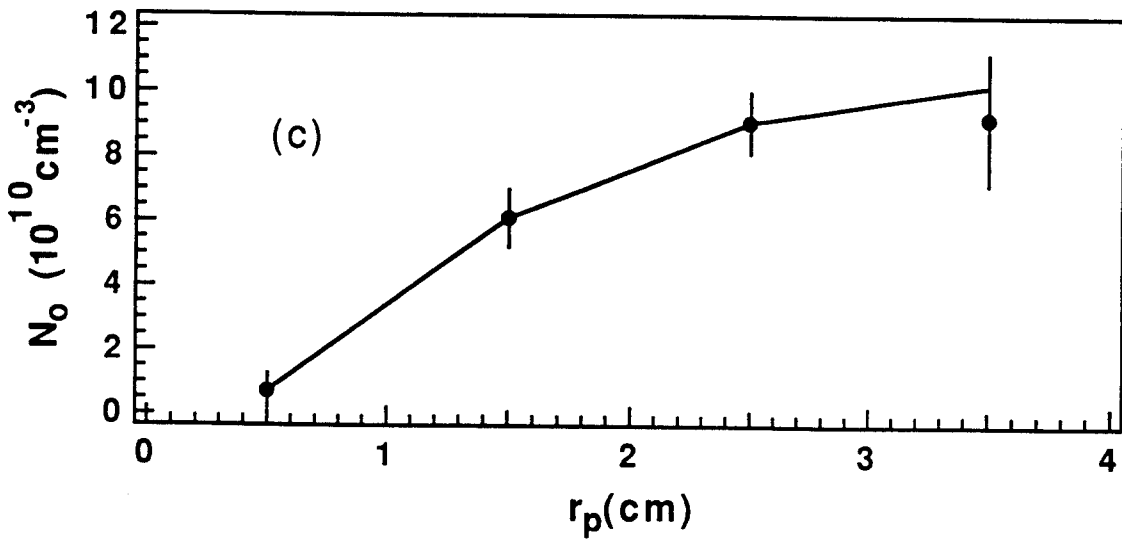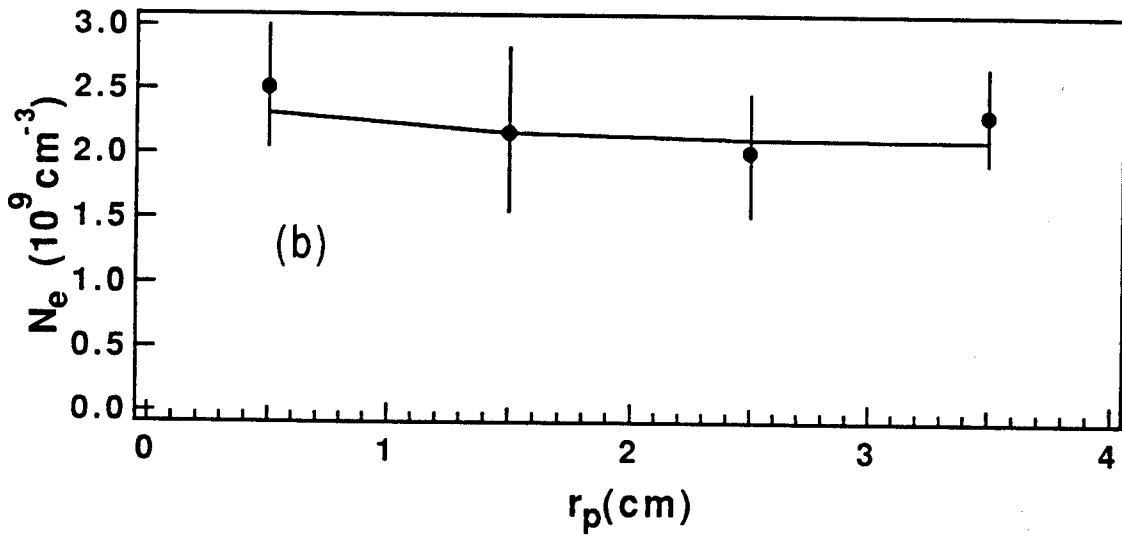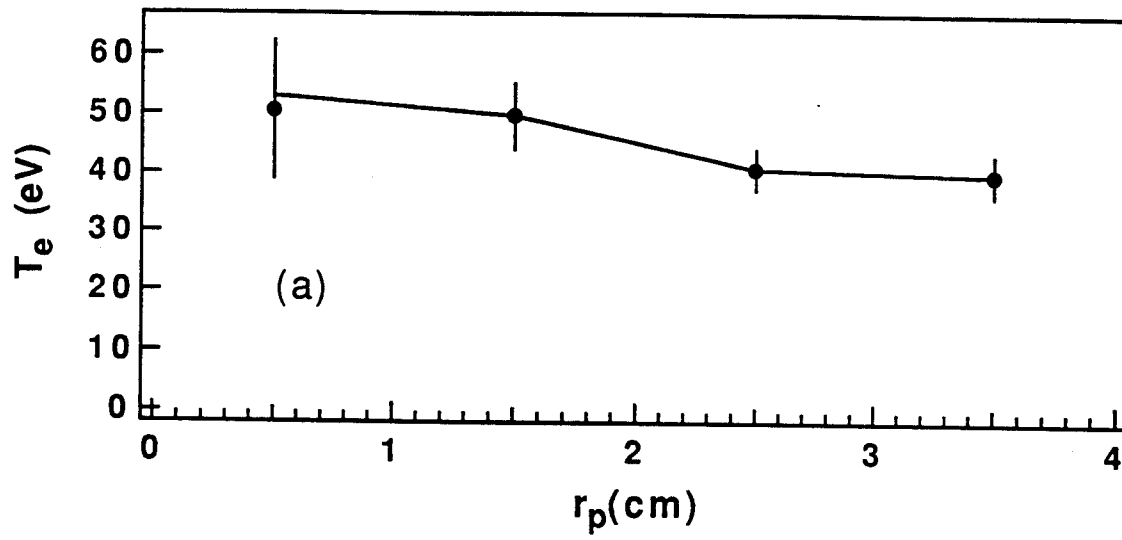Figure 6. Radial profile of the extracted fluorescence signal.

Figure 7. Plots of the radial profiles of T_e , N_e . and N_o .