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MIRI: A MULTICHANNEL FAR-INFRARED LASER INTERFEROMETER FOR ELECTRON DENSITY MEASUREMENTS ON TFTR

By

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ABSTRACT

A ten-channel far-infrared laser interferometer which is routinely used to measure the spatial and temporal behavior of the electron density profile on the TFTR tokamak is described and representative results are presented. This system has been designed for remote operation in the very hostile environment of a fusion reactor. The possible expansion of the system to include polarimetric measurements is briefly outlined.

MASTER

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1. INTRODUCTION

A Multichannel far-InfraRed laser Interferometer (MIRI) has been developed for use on the Tokamak Fusion Test Reactor (TFTR) presently operating at the Princeton Plasma Physics Laboratory. Using the Michelson geometry, the system provides a ten-channel measurement of the spatial and temporal distribution of the plasma electron density. The system employs the 118.8 micron line of the CH_3OH laser and is similar to that described by Wolfe *et al.* [1]. However, a unique feature of this system is that it is designed to be operated and monitored remotely by computer. These capabilities will be necessary for future operation of the tokamak with deuterium and tritium (DT) plasma components. During this phase of operation, the residual levels of radioactivity in the vicinity of the tokamak will preclude the presence of maintenance personnel; hence, all diagnostic systems must be both reliable and remotely operable.

Also, with the installation of polarizing beamsplitters and additional detectors, the present system could be expanded to allow a simultaneous measurement of both the plasma density and the plasma current density via Faraday rotation. Initial attempts of that measurement have been described elsewhere [2,3].

2. VIBRATION ISOLATION

Because the electron density is measured interferometrically, vibrations must be reduced to the lowest possible level. Therefore, the entire MIRI optical system is mounted on a massive frame which encircles the tokamak and floats on three pneumatic vibration isolation mounts. The frame is constructed of stainless steel to minimize the effects of eddy currents. The structure stands approximately 12 meters tall and weighs about 30 tons. The level of vibrations present in this structure is discussed in Section 8.

As shown in Fig. 1 the upper shelf of the frame supports ten stainless steel corner cube reflectors while the interferometer, the lasers, and the collimator are supported by the lower shelf which is located below the floor of the TFTR test cell. Therefore, all essential parts of the MIRI system are located in an area which is shielded from the high levels of radioactivity which will be present in TFTR during DT operation. This feature will make future maintenance of the system more tenable and is the reason that the Michelson geometry was chosen. A partial view of the stand is shown in Fig. 2.

3. THE INTERFEROMETER

A. The Optical Housing

The interferometer optics are housed in a reinforced fiberglass box the purpose of which is to accept two collimated beams from the lasers, to divide those beams into ten scene beams which are mode matched into the TFTR vacuum vessel, to direct those beams to the corner cube reflectors above the tokamak, and to match the return beams into the antenna patterns of the detectors which are also housed in the box. To accomplish this the interferometer employs over 400 optical elements none of which are adjusted *in situ* except the mirrors located just below each of the ten bottom windows (i.e., the mirrors that direct the scene beams to the corner cube reflectors).

Because stray magnetic field levels at the interferometer can exceed one kilogauss, it is necessary that all components be nonmagnetic; hence, all optical mounts are constructed of stainless steel while the housing is constructed of fiberglass. The weight of the optical housing is approximately one ton.

The interferometer housing is actively temperature controlled and dehumidified 24 hours per day. This helps to ensure long-term optical alignment and minimizes the attenuation of the far-infrared (FIR) beam due to water vapor absorption [4,11].

B. The Optical Components

All mirrors used in the interferometer are first-surface aluminum and are used at input angles of 45 degrees (i.e., all mirrors and beamsplitters are used to make right angle beam deflections). All beamsplitters used in the interferometer employ metal mesh and for the most part are required to reflect and transmit equal fractions of the beam power. This requirement dictated that different mesh sizes be employed for different beam polarizations. It was found experimentally that for the 118.8 micron line, a copper mesh with a spacing of 400 lines per inch (400 mesh) reflected and transmitted 50% (+/- 2%) of the beam power when used at an input angle of 45 degrees in the TE mode and with the FIR beam polarization parallel with the lines of the mesh. For the TM mode in the same geometry it was found that 500 mesh reflected and transmitted equally. In both cases the beamsplitter loss is only a few percent. Hence, 400 mesh is used for all TE beamsplitters and 500 mesh is used for all TM beamsplitters.

In all cases the mesh was stretched over and epoxied onto a flat polished titanium frame. This process was carried out at 100^{o}C. The difference in expansion coefficient between copper and titanium ensured that when the beamsplitter assembly cooled to room temperature the mesh would be taut and will therefore remain flat for long periods of time. Titanium was also chosen as the frame material because its large resistivity should effectively minimize any vibrations caused by induced currents. The rectangular size of the optical components (75 mm x 110 mm) is large enough to introduce negligible diffraction losses into the collimated FIR beam. Shown in Figs. 3 and 4 are pictures of the interferometer and some of the optical components.

C. Collimation of the FIR Beams

The FIR laser beams are matched into the main body of the interferometer by the collimator as shown in Fig. 5. The beam is allowed to expand on its way from the laser output to the collimating mirror M1. This mirror beam places a beam waist at the final focussing mirror(s) M2. Each of these ten identical mirrors matches the FIR beam into the minimum diameter Gaussian beam that can propagate over 7.5 meters, which is the distance between M2 and the corner cube reflectors. Hence the beams leave the interferometer with a diameter of 48 mm and are focussed down to a waist diameter of 34 mm on the corner cubes. Because of the symmetric nature of the optics, the beam that returns to the interferometer is in the same mode as the beam that leaves so that the forward and backward going beams are mode matched in the interferometer as well as at the detectors. This design feature eliminates the need for path length compensation. However, the physical path length of every channel is within ~ 20 cm of the mean as an added precaution.

Monitoring of the laser power and mode structure is also accomplished in the collimator. Two polyethylene beamsplitters oriented near their Brewster angle are used to direct a small fraction of the laser output power toward two pyroelectric detectors which serve as power monitors. The pyroelectric signals are then processed in a lock-in amplifier, digitized, and finally read by computer.

4. THE WINDOWS

The 63 mm diameter vacuum windows on TFTR consist of twenty Z-cut crystalline quartz etalons. To reduce absorption, the etalons were made as thin as possible consistent with their diameter, which is the minimum diameter needed to pass the Gaussian beam from the FIR laser as it enters the vacuum vessel (see Fig. 5). The thickness of these etalons (2.383+/- 0.001 mm) was adjusted to minimize their reflectivity at the 118.8 micrometer line of the CH_3OH laser. Indeed, each window has a measured reflectivity for the line in question o. less than 1.5 percent. This agrees very well with the reflection coefficient calculated using the published FIR optical constants of crystalline quartz [5]. Also, to reduce the effects of stray reflections all windows were installed with a tilt of 2 degrees.

The windows were diffusion bonded using pure aluminum to 304 stainless steel flanges by a technique developed for the Joint European Tokamak at Culham Laboratories [6]. Prior to installation each window was subjected to vacuum tests with a pressure difference of 2.5 atmospheres and thermal cycling to 250 degrees Celsius. The window seals have performed well in the rather hostile environment of the tokamak. For the last two years they have been subjected to regular vacuum openings as well as to bakeout cycles with temperature excursions from room temperature to 150 degrees Celcius. Prior to installation each window was subjected to vacuum tests with a pressure difference of 2.5 atmospheres and thermal cycling to 250 degrees Celsius.

During DT operation these windows will experience a neutron flux of about $6x10^{13}$ $cm^{-2}sec^{-1}$as well as a maximum X-ray intensity of 15 Watts cm^{-2}. It has been demonstrated that the discoloration of the quartz resulting from this level of radiation will not lead to increased FIR attenuation. In any event, it is anticipated that the discoloration could be eliminated by a bakeout *in situ* [7,8].

5. THE LASERS

The lasers employed in this system are designed to be reliable and remotely adjustable by computer–controlled motors. They are also designed to be housed in a hostile environment in that passive stabilization of the cavities is accomplished with quartz tubes rather than Invar rods. This is done to avoid problems with large flux swings as well as the high magnetic field levels present near TFTR. Indeed, the ambient magnetic field at the lasers due to the tokamak can be as high as 500 gauss. At that field level the discharge of the CO_2 laser is observed to move around on the laser electrodes and the output of the FIR laser is terminated as a result. Therefore, magnetic shielding of the CO_2 laser tube is necessary. With adequate shielding of the CO_2 laser the FIR output is unperturbed by the stray fields present during a TFTR discharge.

The construction details of the pump and the FIR lasers as well as a summary of their performance have been given elsewhere [9]. These lasers are routinely operated 24 hours per day for periods of up to two weeks at a time without the need for or possibility of maintenance. They have performed at this level of reliability for approximately two years on TFTR, and appear to be sufficiently reliable for use during the DT stage of TFTR operation. Also, at the time of this writing a CO_2 laser acousto-optic stabilization scheme has been installed and an automatic FIR beat frequency stabilization loop is being tested *in situ*. Both of these measures were undertaken in an effort to reduce the need for human interactive laser stabilization and adjustment because TFTR operates16 hours per day.

6. THE DETECTORS

The interferometer has twenty-one detector ports. Eleven of these ports accommodate interferometer detectors while the remaining ten could house polarimeter detectors. The interferometer employs quasi-optical Schottky diode detectors [10]. Each diode is contained inside a stainless steel housing which also contains a goniometer for detector positioning and manipulation, a preamplifier for local amplification of the 1 MHz beat signal, and a quarter wave plate with a polarizer for optical isolation of the FIR beams. Each detector housing contains three mirrors for turning and focussing the beams into the antenna pattern of the diode.

This type of detector was chosen because it is fast enough to respond to the 1 MHz interferometer modulation signals and sensitive enough so as not to require cryogenic cooling with all the attendant complications. Because of the modular nature of their design each detector housing can be quickly removed and replaced. A more complete description of the detector optics and housing has been given elsewhere [11].

7. THE SIGNAL PROCESSING ELECTRONICS

The 1 MHz beat signals from the interferometer are processed in circuitry which consists of both a phase comparator and a fringe counter. The phase comparator has as its heart a phase-locked loop with a tracking bandwidth of +/- 300 kHz which corresponds to a maximum measurable data rate of 0.3 fringes per microsecond. Also, this bandwidth is large enough to accommodate the 50 kHz frequency jitter environmentally induced in the beat signal by a typical TFTR discharge. The accuracy of the measurement at this stage is 1/32 of a fringe.

The output of the phase comparator is then sampled by the fringe counter which stacks the individual fringes in real time. A digital-to- analog convertor then samples the output of the fringe counter at 2 kHz so that the output of this circuitry is proportional to the line density of the tokamak. This real-time signal is then used in a feedback loop for density control during machine operations.

In addition, the digital output from each fringe counter is loaded at 2 kHz into separate 16 k word by 12 bit dual port memory modules. These raw data are then read by computer and archived for post-detection analysis. A fringe counter/memory sampling rate of 100 kHz is also available to the user in two selected channels. The details of the phase measuring circuitry have been presented elsewhere [12,13].

8. RESULTS

The MIRI system has been called upon to measure a large range of plasma densities. Below are discussed two examples.

As an example of the smallest density changes which MIRI has handled, shown in Fig. 6 are density traces taken during an experiment to study the effects of a single gas puff. Early in this discharge the gas flow was turned off and the density was allowed to fall to a steady-state value supported only by recycling. At 3.0 sec a small single gas puff was introduced into the discharge and the resulting density rise was observed in all of the MIRI channels. Shown in Fig. 6a is an expansion in time of the resulting density rise as observed on opposite sides of the plasma in channels 1 and 8. Shown in Fig. 6b is the result of a simple averaging of the raw data from eight such nominally identical discharges. As can be seen, the signal-to-noise ratio of the averaged data is larger than that of the data from a single discharge. Shown in Fig. 6c is the result of a light smoothing of the averaged data. The smoothing technique simply involved the calculation of a triangular-weighted average of +/- 25 unsmoothed data points. After the averaging/smoothing process there appears on the data a coherent 28 Hz oscillation. Moreover, this oscillation was present with equal amplitude and phase in all ten MIRI channels indicating that it was due to a coherent oscillation of the vibration isolation stand. These oscillations, therefore, determine the minimum measurable density achievable using the averaging /smoothing techniques. In this example the amplitude of the stand vibrations correspond to an equivalent line density of approximately 4×10^{12} cm^{-2}. However, on a single shot basis the minimum measurable density is not determined by the vibrations present, but rather by the bit noise of the electronics employed. The equivalent line density of the bit noise shown in Fig. 6a is about $4 \times 10^{13} cm^{-2}$.

As an example of the maximum density which the MIRI system has measured, shown in Fig. 7 is a density trace taken during an experiment involving the injection of three frozen hydrogen pellets into the discharge. As shown, a large and rapid change in the density occurred as a result of the third pellet. Inversion of the data from this discharge has shown that the density profile became extremely peaked as a result of the injection (see Fig. 8). Refraction of the FIR laser beams caused by a density gradient as large as that seen in Fig. 8 is near the system design limit as determined by the size of the TFTR windows. Therefore, this example probably represents a practical limit to the density gradient which MIRI can tolerate.

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FIGURE CAPTIONS

Figure 1 The general layout of the MIRI system. Shown are the lasers and optical hardware as they are situated on the isolation stand which encircles TFTR. The bottom windows are located immediately above the interferometer housing.

Figure 2 A view of the outside two legs of the MIRI isolation stand as they are seen from the floor of the TFTR test cell. These legs extend into the basement and are supported there by pneumatic mounts. The third leg passes through the central air column of TFTR and is therefore hidden from view.

Figure 3 The lasers and interferometer housing as they appeared during assembly of the MIRI system. Seen attached to the side of the interferometer housing are some of the detector modules. The collimator is not shown in this view.

Figure 4 A close-up view of some of the optical components in which can be seen the diffractive effects of the metal mesh beamsplitters on a HeNe laser alignment beam.

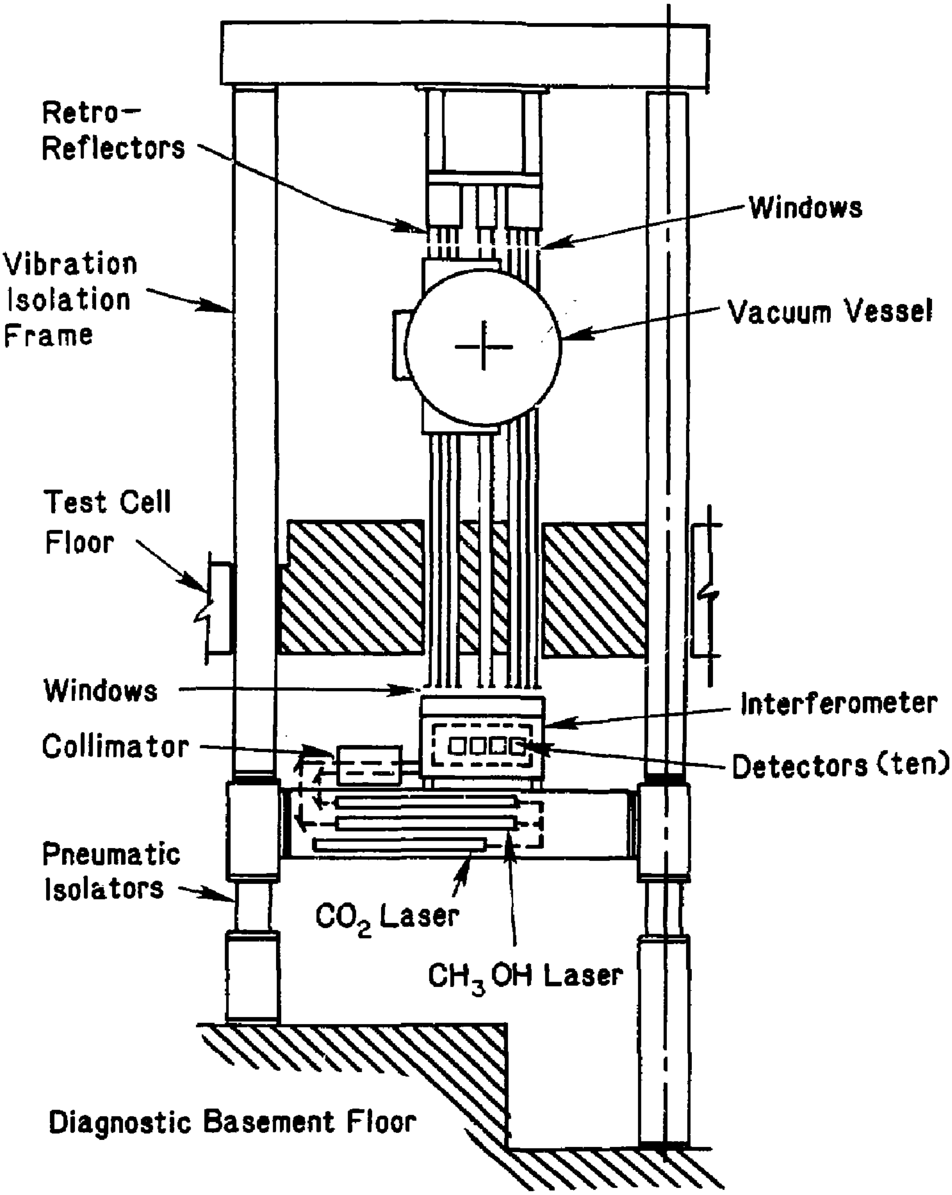
Figure 5 Shown above is a schematic view of the Gaussian beams from the FIR laser as they progress through the interferometer. It should be noted that the beams are allowed to propagate in a free space mode throughout the entire optical system even though the round trip distance is about 25 meters.

Figure 6 Shown in this figure are density traces from channels 1 and 8 taken during a discharge into which a small gas puff was introduced at 3.0 sec. In (a) one notes that bit noise determines the minimum measurable line integral density which in this case is about 4×10^{13} cm^{-2}. In (b) is shown the average of data from eight nominally identical discharges. Because of the averaging a substantial decrease in the noise is seen. In (c) is shown the result of a smoothing process applied to the averaged data seen in (b). Apparent in the smoothed data is a coherent 28 Hz oscillation. Because this oscillation appears on all ten channels with equal amplitude and phase, it is attributed to vibrations in the isolation stand. With the use of the averaging/smoothing techniques the minimum measurable line density is determined by these vibrations and is about 4×10^{12} cm^{-2}.

Figure 7 Seen here is an inverted central density trace taken from a discharge in which three pellets were injected into TFTR. The third pellet causes a very large increase in the plasma density. This discharge attained the highest density as yet observed in TFTR.

Figure 8 The inverted density profile from the discharge discussed in Fig. 7. The density gradient produced by such a peaking of the density profile is about as large as the MIRI system can tolerate because of the finite size of the windows employed. A larger gradient than this would lead to an unacceptable loss at the window aperture due to plasma refraction.

#87X0109



MIRI General Arrangement

Fig. 1

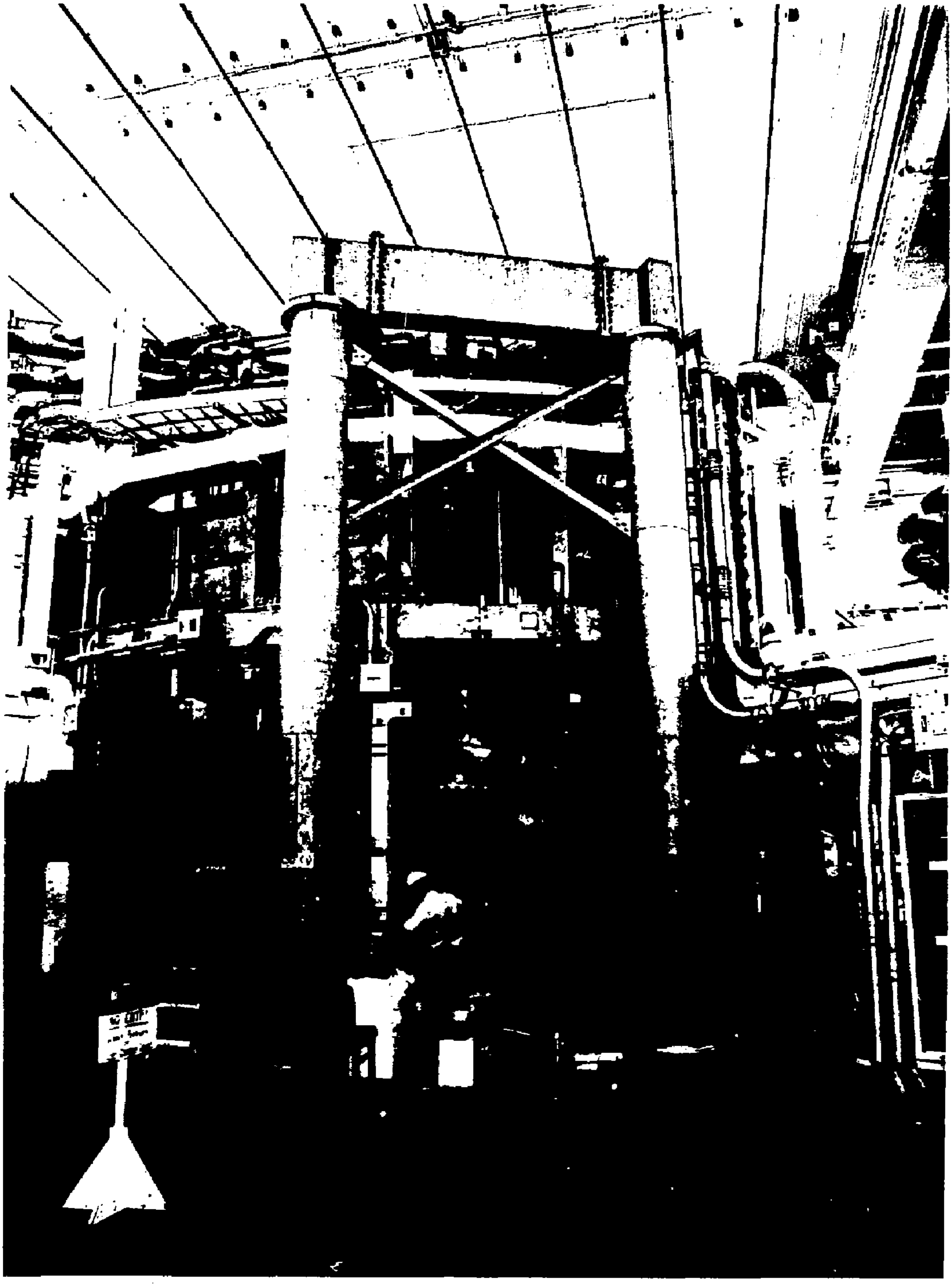


Fig. 2

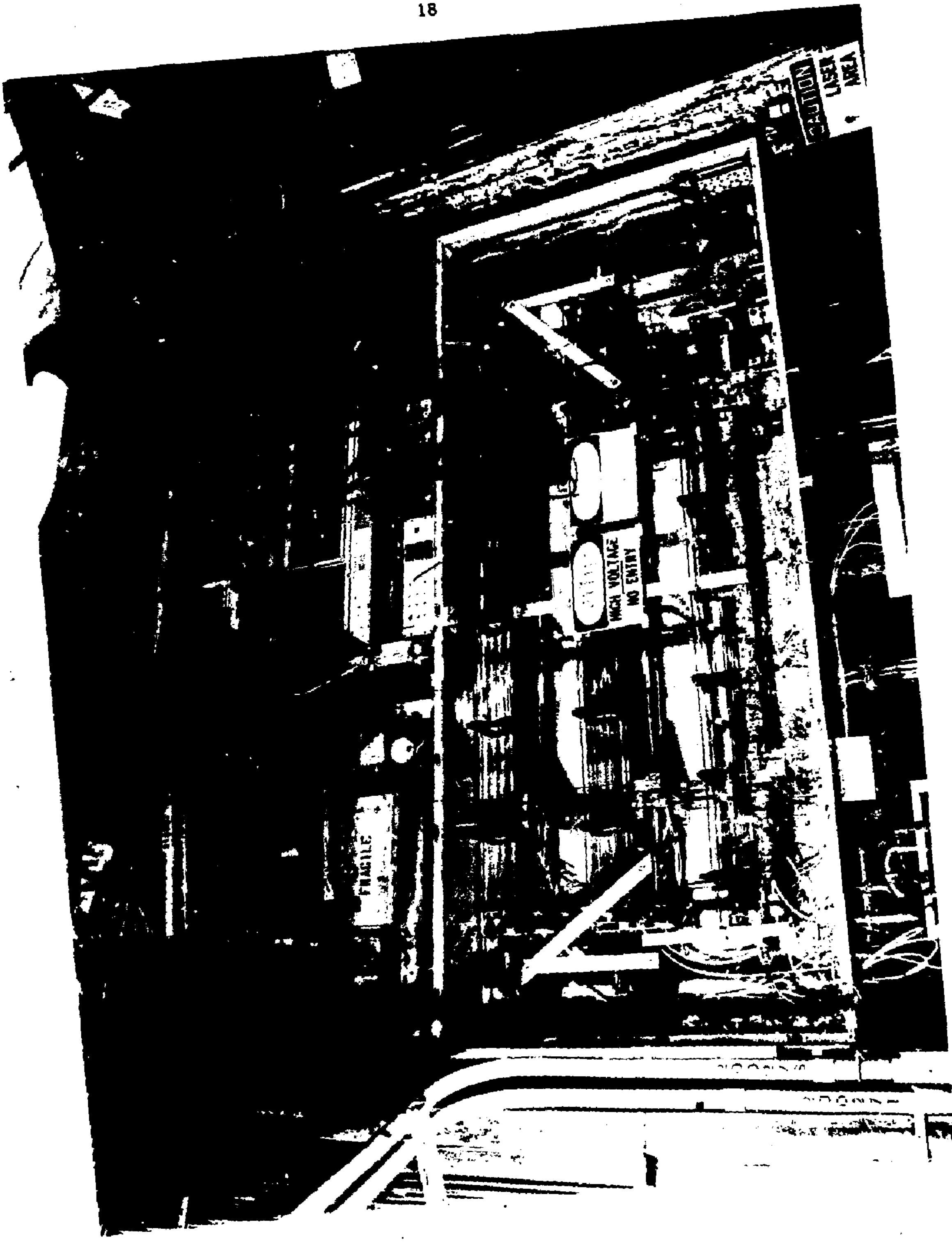


Fig. 3

Fig. 4

#87X0200

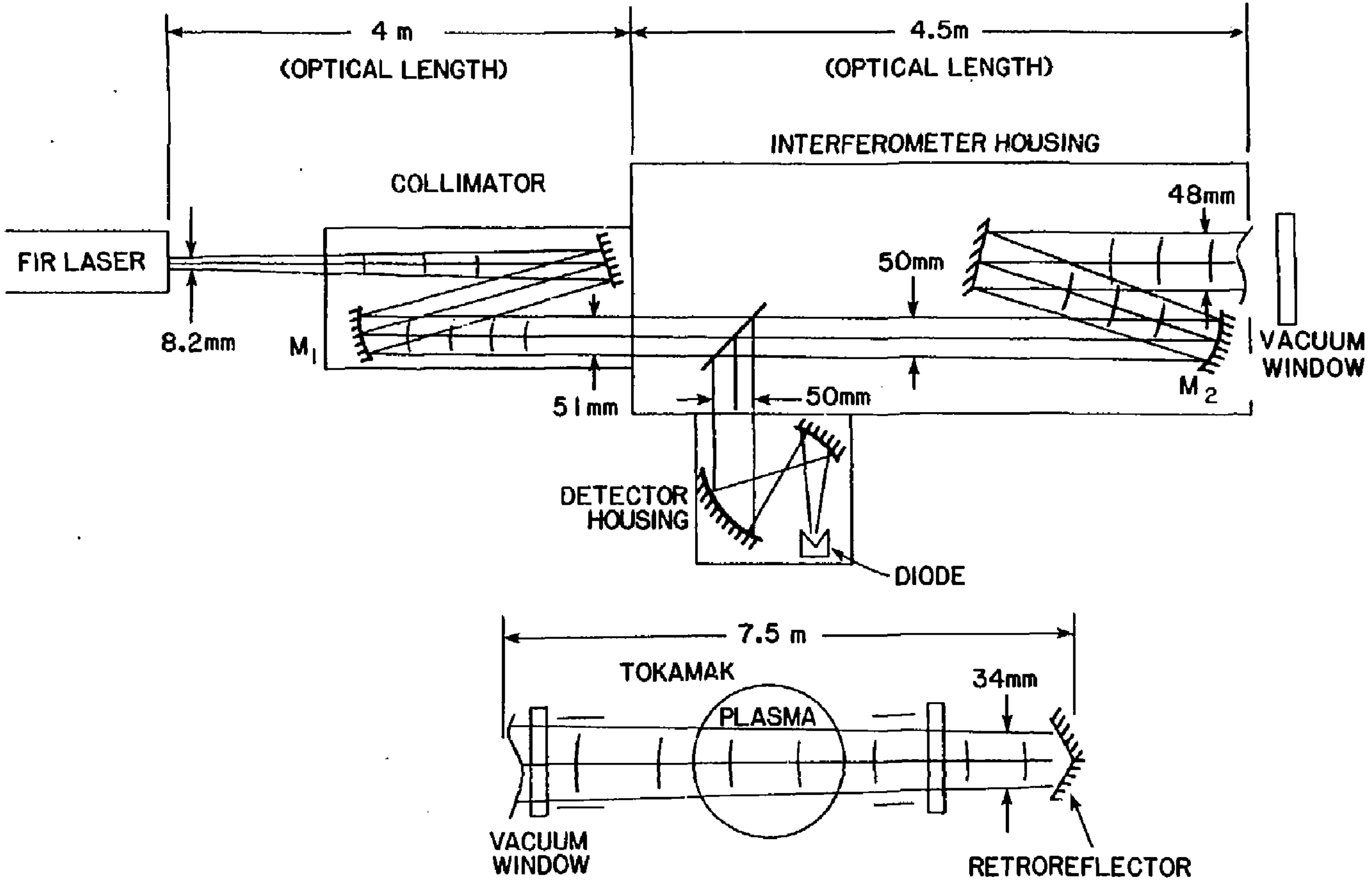
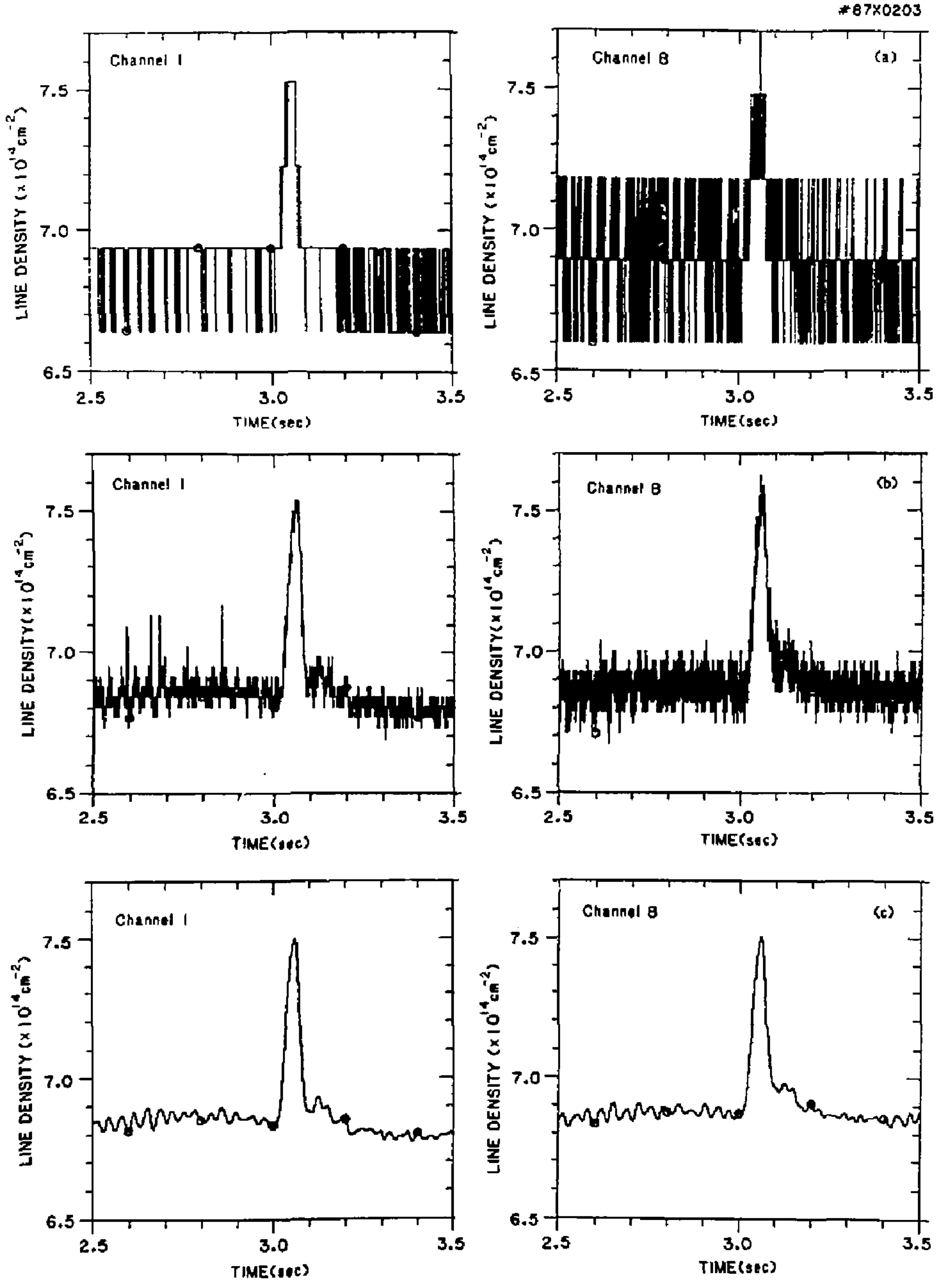


Fig. 5



#87X0203
Channel I
Channel 8
(a)
(b)
(c)
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TIME(sec)
7.5
7.0
6.5
2.5
3.0
3.5

Fig. 6

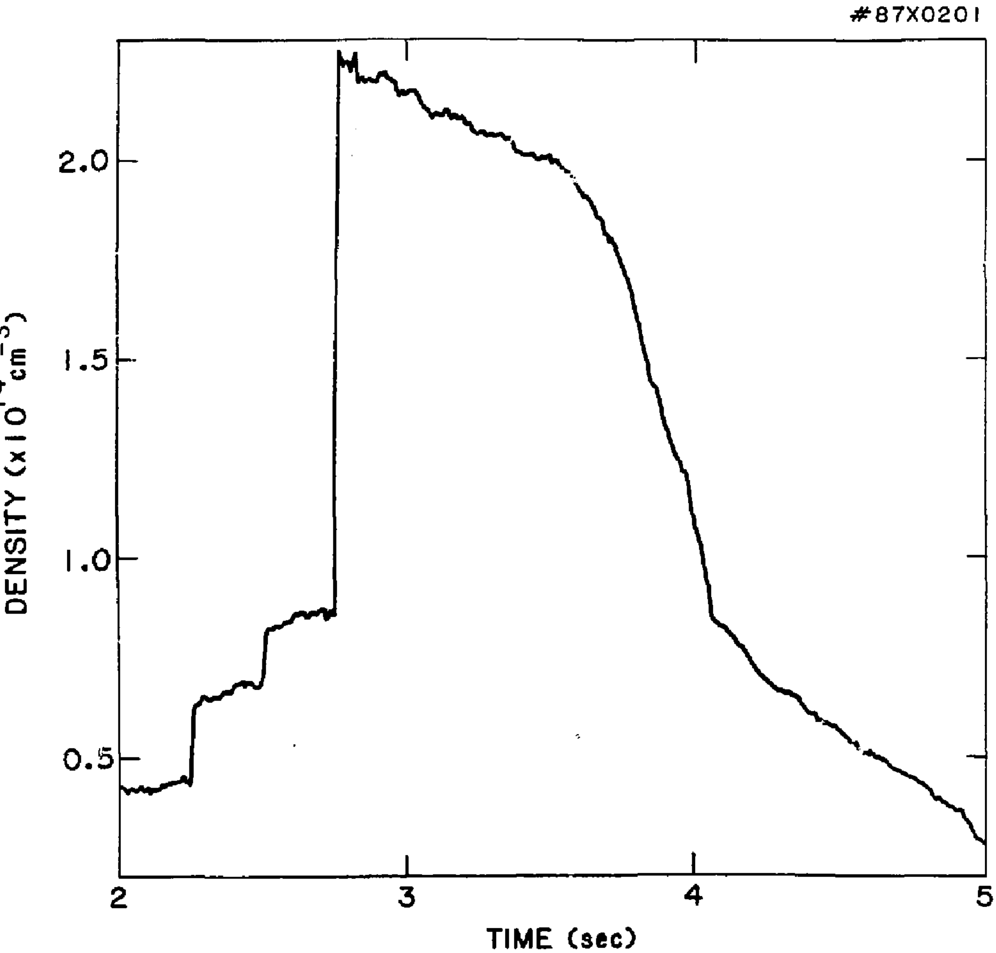

Fig. 7

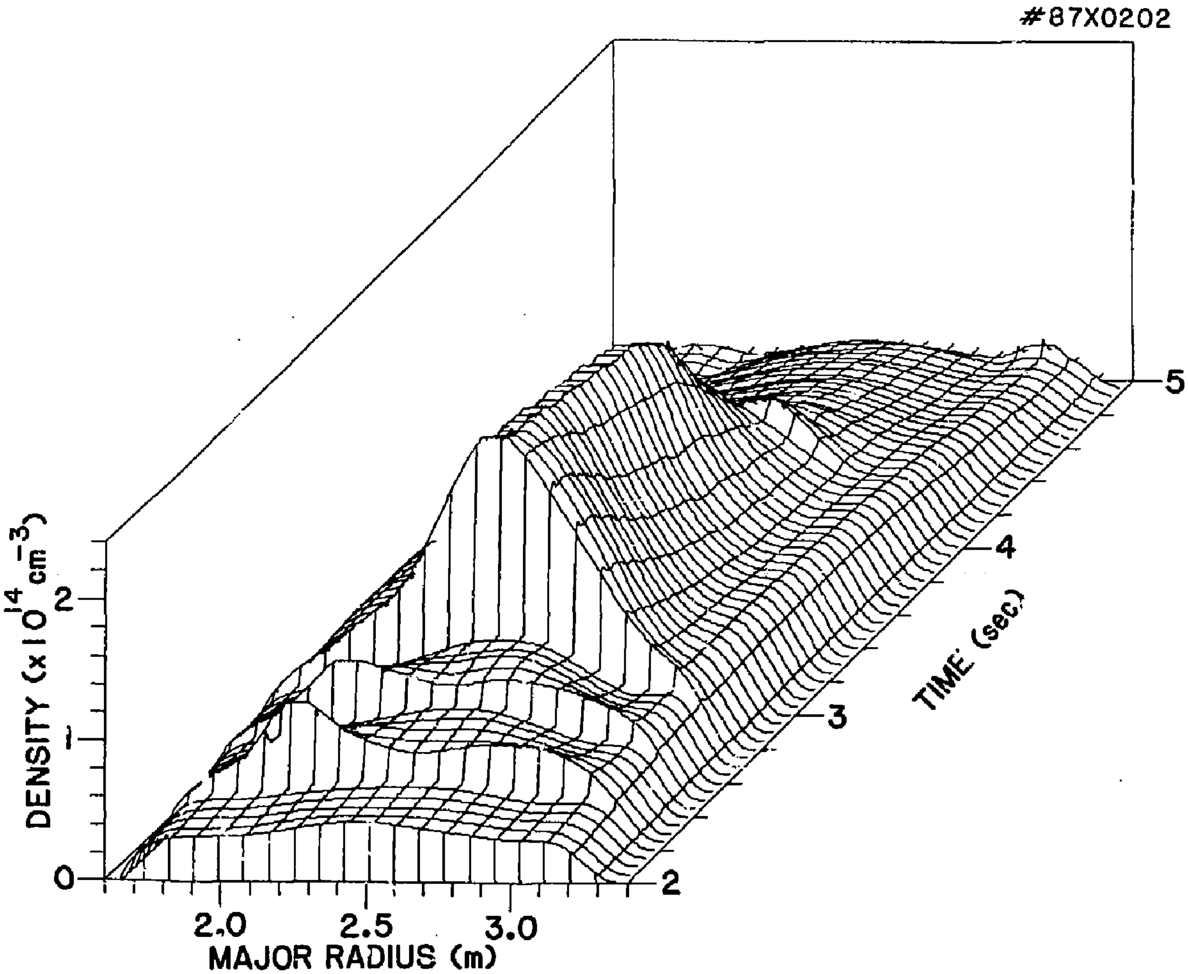
#87X0202
DENSITY (x10^{14} cm^{-3})
0
1
2
2.0
2.5
3.0
MAJOR RADIUS (m)
2
3
4
5
TIME (sec)

Fig. 8

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