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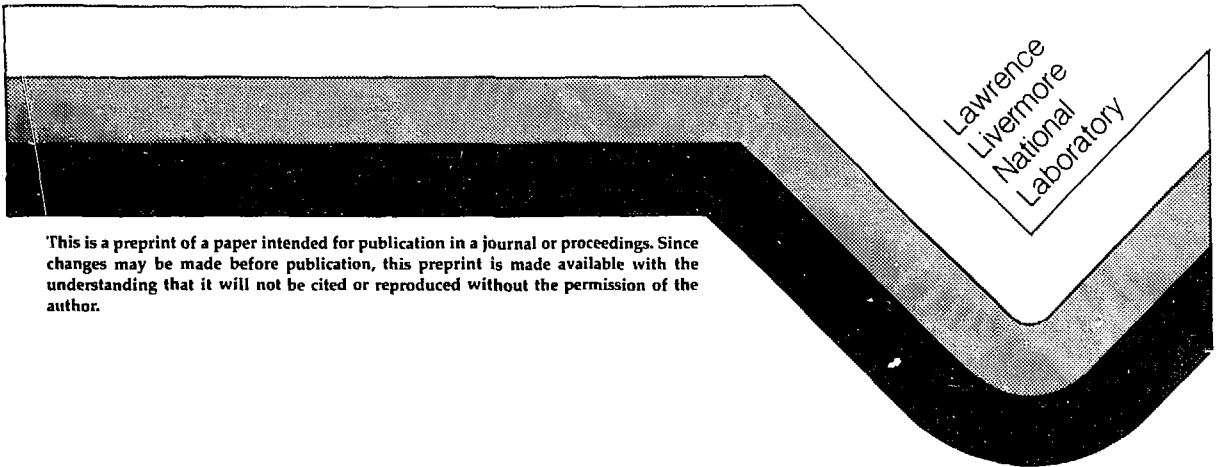
EDGE DIAGNOSTICS FOR TANDEM MIRROR MACHINES

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## EDGE DIAGNOSTICS FOR TANDEM MIRROR MACHINES

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## ABSTRACT

*The edge plasma in a tandem mirror machine shields the plasma core from cold neutral gas and impurities. A variety of diagnostics are used to measure the fueling, shielding, and confinement of the edge plasma in both the end plug and central cell regions. Fast ion gauges and residual gas analyzers measure the gas pressure and composition outside of the plasma. An array of Langmuir probes is used to measure the electron density and temperature. Extreme ultraviolet (EUV) and visible spectroscopy are used to measure both the impurity and deuterium densities and to estimate the shielding factor for the core plasma. The linear geometry of a tandem mirror also allows direct measurements of the edge plasma by sampling the ions and electrons lost out the ends of the machine. Representative data obtained by these diagnostics during operation of the Tandem Mirror Experiment (TMX) and Tandem Mirror Experiment-Upgrade (TMX-U) experiments are presented. Diagnostics that are currently being developed to diagnose the edge plasma are also discussed.*

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## INTRODUCTION

The edge plasma in a tandem mirror is very important because it is the interface between the core plasma and any external walls or surfaces of the device. The edge plasma shields the core plasma from neutral gas and impurities that are produced outside of the plasma. In addition, it must minimize plasma-wall interactions that can generate impurities, damage surfaces, and generally degrade plasma parameters. We present here a discussion of the diagnostics measurements performed on the TMX [1] and TMX-U [2] tandem mirror machines to measure the parameters at the edge of the plasma and in turn to determine the influence of the plasma boundary on the core plasma. A variety of measurement techniques are used, including optical measurements, probes, particle detectors, pressure measurements, and surface analysis. All of the data from these instruments are used to model and ultimately guide the control of the edge plasma.

The linear-geometry and open-field-line configuration inherent to a tandem mirror offers unique possibilities both for the diagnosis and the control of the edge plasma. To fully appreciate these advantages, the basic operation of a thermal-barrier tandem mirror must be understood, but a detailed explanation is outside of the scope of discussion and is presented elsewhere [3,4]. Briefly, though, a tandem mirror is composed of a central cell confinement region that is terminated on each end by a minimum-B end plug. Axial ion confinement is achieved by forming an ambipolar potential between the central cell and the end plugs. The axial profiles of magnetic field, electron density, and plasma potential for the standard and thermal-barrier tandem-mirror modes are shown in Fig. 1. In a standard tandem mirror machine like TMX, this potential is the result of creating a greater electron density in the end plugs. In a thermal-barrier tandem mirror like TMX-U, the confining

potential is established with electron-cyclotron resonant heating (ECRH), ion-cyclotron resonant heating (ICRH), and neutral-beam heating so that the central cell density (the fusion producing region in a reactor) is greater than the end cell. The depression in the potential in the thermal barrier plug region (Fig. 1), is the result of neutral-beam injected "sloshing ions" [2] and ECRH created hot electrons. Detailed measurements of the thermal barrier potential profile are presented in Refs. 4 and 5.

A schematic model of a tandem mirror plasma is shown in Fig. 2. The core of the end cell plasma confines the ions escaping from the central cell; the edge plasma outside of the core is not as well confined. Heating of the edge plasma is accomplished by ECRH, ICRH, and neutral beams. The boundary of the plasma core is determined by the radial extent of the axial confining potential in the end plug and plasma losses in the central cell. Part of the edge plasma escapes to the end region outside of the end plug, where it is pumped or converted directly to electrical power. Our experiments show [6] that the size of the end plug plasma can be controlled; this in turn determines the size of the central-cell core plasma. In this way, plasma wall interactions in the central cell can be minimized.

The edge diagnostics on the TMX and TMX-U machines were selected with specific goals in mind: (1) measurement of confinement, fueling, and heating; (2) measurement of deuterium neutrals; and (3) measurement of impurities. The measurement of electron temperature, electron density, and confinement time are important to understand the most important sources of fueling in the edge plasma, and thereby, the most effective means of control. The shielding of neutrals and impurities by the edge plasma is important in the thermal barrier region to minimize neutralization of the potential profile (Fig. 1), and is important in the central cell to minimize energy losses.

## I. CONFIGURATION OF DIAGNOSTICS ON TMX-U

Figure 3 shows the locations of the diagnostic instruments used for study of the edge plasma. A high speed video camera views the end plug and central cell plasmas from the end of the machine. Mounted on the end wall of each end of the machine are a group of instruments used to measure the particle flux and energy of plasma escaping out of the machine: Faraday-cup arrays, end-loss analyzers, net-current-collector arrays, and net-current-collector plates. Located in each end plug and in the central cell are several diagnostics that measure the deuterium and impurity characteristics: EUV spectrometers, fast ion gauges, and residual gas analyzers (RGA). Langmuir probes are used to measure the edge density and temperature. In some cases, microwave interferometers and a beam attenuation diagnostic (BAD) [7] are also used to monitor radial profiles of the electron density. Surface probes are located at the edge of the plasma both to measure the particle flux and energy, and to determine the wall conditions.

## II. FUELING AND CONFINEMENT OF THE EDGE PLASMA

A SP-2000 high-speed video camera is used to measure general characteristics of plasma operation. It views the end plug and central cell plasma (Fig. 3) near the gas valves used for plasma fueling. Several different filters can be mounted on the camera, including 6563 Å interference filters with either a 30- or 8-Å bandpass to measure neutral deuterium emissions. The camera system has a time resolution of 0.5 ms; during each shot, the equivalent of approximately one-half million bytes of data are recorded on magnetic tape. In addition, this system interfaces to a microcomputer system so that the digital images can be processed. A single frame of data from the camera is shown in Fig. 4; the bright region at the

edge of the photo is the emission from the edge plasma, which is fueled by the gas puffed near the circular aperture (the top and right hand side of the picture are cut off because of vignetting in the optical field of view). Near the center of the circular aperture, the plasma emission is quite low, indicating the ionized core plasma.

The video camera views the plasma axially, rather than radially. Because most of the neutral deuterium emission originates near the gas injection region, this axial view enables us to make a qualitative measure of the axial-line integral of the edge-plasma-source function. We plan to perform quantitative measurements of this emission with the absolutely calibrated monochromator discussed in Sec. II. At present we are investigating methods to optimize plasma fueling, which is pre-programmed by computer before each shot, for both the end plug and the central cell. The radial extent and efficiency of the edge plasma can be estimated under each fueling condition.

The open field-line geometry of a tandem mirror also permits a somewhat unique diagnostic capability: the direct measurement of the energy and flux of particles. This is particularly useful because it is a line integral along the field line. For most useful analysis, this data does not require an inversion-like radial chord measurements. Furthermore, if a sufficient number of these measurements are made, azimuthal symmetry need not be assumed. An example of such a diagnostic is a simple Faraday-cup array to collect ion current as a function of position. These detectors have an applied negative-bias voltage of 1500 to 3000 V to repel low energy electrons. Results from a radial array of Faraday-cup ion detectors mounted on the end wall of TMX-U are shown in Fig. 5; the current density as a function of position is plotted for several times during a plasma pulse. These profiles clearly show the development of the less-well confined plasma

at the edge and the low-ion losses in the plasma core. When combined with the radial electron density profile, we can calculate the axial ion lifetime; the results of these calculations are consistent with the qualitative picture of the edge plasma presented in Fig. 2.

Additional end-loss diagnostics are mounted on the end wall: (1) moveable end-loss analyzers (ELA) [8] to measure the profile of particle energy and flux on a shot-by-shot basis; (2) unbiased current collectors that measure the net current to the end wall; and (3) large plates, which are segmented in radius and azimuth and are used primarily to control the plasma potential [9], but can also be used as a diagnostic to measure the particle flux. These plates are particularly useful in that they can measure the loss current integrated over the plasma annulus at a particular radius, and do not depend on symmetry arguments like point detectors. Because these plates are unbiased, they measure the net charged-particle current to the end wall. Under most operating conditions, the net current is a negative (electron) current; therefore, this is a measurement of nonambipolar radial transport: the ions are lost radially, and the electrons are lost axially. A complete treatment of these radial transport measurements, including the edge plasma, is included in Ref. 9.

A simple double-tipped Langmuir probe is used to study the edge-plasma electron density and temperature. These data have been particularly important for determining the power input into the edge plasma under various operating conditions. A detailed presentation of all the experimental trends is included in Ref. 10. In summary, we determined that ECRH heating in the end plugs can provide a significant fraction of the power input into the edge plasma, which exists both in the end plugs and the central cell. This is demonstrated by the general increase in the edge electron temperature with

increasing FCRH power. We also found that by operating the ICRH systems with the proper antenna configuration and frequency, this mode can selectively heat the edge plasma. Under current operation, the fueling by neutral beams seems to be small because of the modest electron density ( $10^{12}$ - $10^{13}$ ); this heating mode will become more important for the edge plasma as the density increases.

## II. DIAGNOSTICS FOR NEUTRALS

The control of the neutral density in the plasma-edge region is important, particularly in the thermal-barrier end-plug region. This is accomplished by controlling gas sources such as the neutral beams and by conditioning the plasma wall by gettering and glow discharge cleaning. To measure the total gas pressure outside of the plasma, we placed 24 ion gauges in the various vacuum regions of TMX-U to produce the data needed to develop a time-dependent computer model of the pressure evolution [11]. These results have guided our improvements to the vacuum system [12].

Five of these gauges are magnetically shielded and have fast electronics so that they can measure the neutral pressure outside of the plasma region during a plasma shot [13]. These gauges are located in each end plug, each end fan, and the central cell. Figure 6 shows the time histories of the pressure in the end plug, and the axis ion losses before (Fig. 6a) and after (Fig. 6b) vacuum system improvements were implemented. Before the improvements, as the pressure increased, the ion end losses also increased showing a decrease in the axial ion confinement; after the improvements, the pressure in the thermal-barrier end-plug region is reduced, and the duration of the end-plugging is now determined by the turn-off of the heating systems.

The time evolution of the pressure in the end-fan region (near the Faraday-cup detectors discussed above) is also an important indicator of the



edge- and core-plasma operation. During a plasma shot, this pressure increases until the onset of end plugging and then remains constant or decreases. The initial pressure increase is due to the transport of the core and edge plasma to the end-wall region; the pressure stops rising because of the end plugging of the core plasma. The value of the pressure at the plateau is determined by the edge plasma that is transported to this region.

To determine the neutral density in the plasma, we measure the radial profile of neutral deuterium emissions at 1216 Å with an absolutely calibrated ultraviolet monochromator equipped with a spatial-imaging detector system [14]. This instrument measures 22 radial chords of the plasma simultaneously with about 0.5 to 1 ms time resolution. To measure the cold background neutrals, we obtain profiles immediately after the neutral beams are turned off. During this transition, shot-by-shot spectral scans verify that the emission line changes from a substantially doppler-broadened width of several angstroms resulting from high-energy-beam neutrals to the (1 Å) instrumental line width. The brightness profiles are Abel inverted and combined with electron density and temperature profiles to obtain the neutral-density profile. Figure 7 shows the neutral density profile obtained in the end plug during high-density sloshing-ion operation of TMX-U [2,15]. For comparison, measurements of the gas pressure at the edge of the plasma by fast-ion gauges along with a gas penetration model were also used to estimate the molecular and atomic neutral profiles. Qualitatively, the agreement is quite good, however, the inverted measurements of emission brightness and electron density are susceptible to propagated errors, particularly in the plasma core.

Currently, we are making similar emission measurements during thermal barrier operation on TMX-U. In addition, plans for laser fluorescence

measurements similar to those performed on the RFC-XX [16] machine are being considered. This is a particularly attractive technique because existing optical systems can be used (Thomson scattering) and it is a point measurement.

### III. DIAGNOSTICS FOR IMPURITIES

Impurities in the core plasma must be controlled to minimize radiated power losses and the alteration of the thermal barrier potential profile. This is accomplished by controlling impurity sources outside the plasma and by efficient impurity shielding in the edge plasma. Three time-resolving RGA's and several surface analysis probes are used to measure the external sources, and three EUV instruments are used to determine the impurity densities in the edge and core plasmas.

The location of the RGA instruments is shown in Fig. 3; note that the magnetically-shielded RGA systems are located in close proximity to the fast-ion gauges so that the gas composition in the edge plasma can be obtained. A programmable mass selector connected to the RGA system allows us to monitor the time history of six mass peaks. Two different sampling time bases are used so that we can study the 4-min gettering cycle before the plasma shot with coarse time resolution, and so that we can sample the plasma shot at a higher rate. In many cases, the largest component of the residual gas before the plasma shot is methane. In some cases, this source is large enough to explain the carbon concentrations measured in the plasma by spectroscopy. The RGA measurements performed during the warm-up of the liquid-nitrogen panels used for pumping in TMX-U indicate that methane is loosely bound to these walls. Recent results show that during initial wall cleanup, there can also be a significant partial pressure of hydrogen in the edge region during

deuterium plasma operation. This is presumably due to gettering of water by the titanium films on the wall, resulting in tightly bound oxygen and a liberation of hydrogen.

We use surface probes to obtain in-situ samples of the titanium films, which are analyzed by Auger electron spectroscopy [17]. Like the RGA results, measurements also indicate a significant fraction of oxygen in the titanium films. On TMX, surface probes were exposed to the plasma and then analyzed by nuclear-reaction analysis (NRA) and secondary ion-mass spectroscopy (SIMS) to determine radial profiles of the deuterium, hydrogen, and impurity flux in the edge-plasma region [18]. For TMX conditions, the energy of the escaping edge plasma was in the range of 25 to 50 eV, in qualitative agreement with other diagnostic measurements.

Three absolutely calibrated EUV instruments measure the impurity concentrations in the edge and core plasmas of TMX: (1) a spatially-resolving monochromator (Sec. II); (2) a time-resolving normal incidence spectrograph [19] (300 to 1600 Å); and (3) a time-resolving grazing incidence spectrograph [20] (20 to 600 Å). Both the EUV spectrographs have 1024 spectral channels and operate with a 4-ms time resolution. The normal incidence spectrograph can be operated in a 1-ms time resolution mode by selecting subsets of the spectrum and has seven selectable gratings to vary the spectral resolution. Data from these instruments indicate that the principle impurities in the TMX and TMX-U plasmas are carbon, nitrogen, and oxygen, with a lesser amount of titanium.

Note that all of the major resonance lines of the relevant ionization states of carbon, nitrogen, and oxygen can be measured by the spectrographs on each shot. The microcomputers that control the spectrographs are used to calculate the light impurity concentrations in the TMX-U plasma between

shots. This allows us to observe trends resulting from changes in wall or vacuum conditions outside of the plasma. Figure 8 shows the EUV spectrum at 31 to 35 ns under two conditions: operation with the plasma walls ungettered (top) and the subsequent shot, where the plasma walls are gettered (bottom). Note the large decrease in all the impurity signals, particularly for carbon. A further decrease is often observed after several plasma shots with gettering. Under gettered conditions, calculations of the impurity concentrations indicate that the impurity levels are low: less than one-percent of carbon, nitrogen, and oxygen [21,22].

The spectrographs are also used to locate impurity sources in the plasma that do not originate from the walls. Figure 9 depicts the time histories of carbon, nitrogen, and oxygen ionization states during a plasma shot where the neutral beams are turned off. The carbon emission remains constant, whereas the oxygen and nitrogen decrease rapidly when the neutral beams are turned off. These data indicate that the neutral beams can be a source of oxygen and nitrogen in the plasma, and also illustrate the usefulness of time-resolved EUV spectra for diagnosing changing impurity conditions during the plasma shot.

The fact that a large number of emission lines are measured by the spectrographs also enables us to estimate the electron temperature as a function of time. Where possible, temperature sensitive line ratios are used; however, ratios of carbon ionization states have been used on TMX-U to make a qualitative estimate of the time evolution of the electron temperature. Estimates of the particle confinement time obtained by other diagnostics are used with rate coefficients to predict the modified coronal equilibrium-ionization-state populations. Although this method is only qualitative and must be used with extreme caution, it often agrees well with other measurements of the temperature such as Thomson scattering.

Another important characteristic of the edge plasma in a tandem mirror is impurity shielding. This natural divertor effect was measured on the TMX experiment [23] by artificially introducing impurity gases into the central-cell edge plasma. The top of Fig. 10 shows the spatial profile of the total oxygen density as a function of time; the gas was puffed at 15 ms. These data were obtained by the spatial imaging monochromator discussed in Sec. II. The radial emission profiles of the resonance lines of the five major-ionization states of oxygen in the plasma were measured. Data from shots without injection were used to subtract the ambient oxygen background. These data were Abel inverted, combined with the electron density and temperature profiles, and added together. The radial profile at 25 ms at the bottom of Fig. 10 shows that the impurity did not penetrate efficiently into the core plasma. We also observed this natural divertor action of the edge plasma with other puffed impurities such as argon.

#### IV. DISCUSSION

In summary, we use a large array of diagnostics to characterize the edge plasma in TMX-U. Some of these instruments are quite simple, but arrays are needed to obtain the required profiles and to verify azimuthal symmetry. Because the tandem mirror is also an inherently multi-region device, diagnostics must be duplicated in the end plugs, central cell, and end-fans. Experimental results indicate that there are methods to control the edge plasma and thereby minimize plasma surface interactions. Future diagnostics will be focused on more quantitative measurements of neutrals in the plasma with imaged EUV profiles and point measurements such as laser fluorescence. Active control of the edge plasma may be possible with external devices such as a halo recycler [24]. This pumped-limiter type insert will have similar diagnostics to those used for measuring the edge plasma.

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## FIGURE CAPTIONS

Fig. 1. The axial profiles of magnetic field, electron density, and plasma potential for the TMX standard tandem and the TMX-U thermal barrier. The formula for the axial ion-confining potential is given for each case. Note the dip in the potential for the thermal barrier mode. The terms  $n_c$  and  $n_p$  are the end plug and central cell densities, respectively,  $T_{ec}$  is the central-cell electron temperature.

Fig. 2. A schematic model of the edge plasma in a tandem mirror. The core plasma is well confined axially by the potential in the end plugs. The edge plasma shields the core from neutrals and impurities.

Fig. 3. Overview of the diagnostics used on TMX-U to diagnose the edge plasma.

Fig. 4. Results from the high-speed video camera viewing along the plasma axis. The camera is equipped with a deuterium-emission filter. The bright circular region is the edge plasma near the gas box used to fuel the plasma. The top and right half of the view are cut off by structures in the field of view.

Fig. 5. The ion end-loss profiles as a function of time are measured by an array of Faraday cups on the end wall.

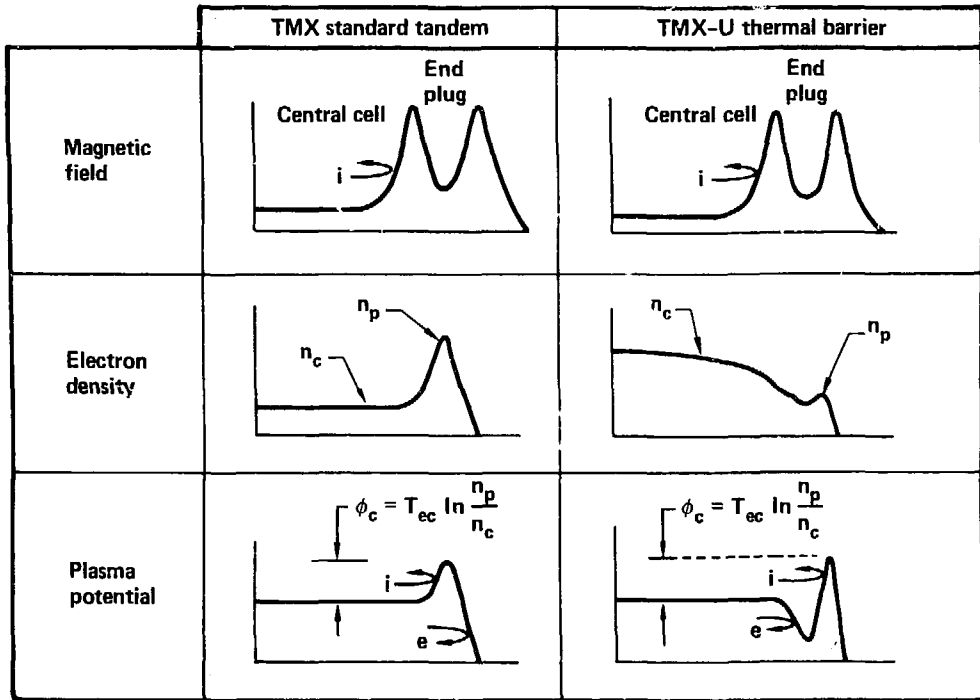
Fig. 6. The end plug pressure and axial ion loss (a) before (left) and (b) after (right) vacuum improvements were carried out on TMX-U. Note the duration of axial plugging is longer in case (b).

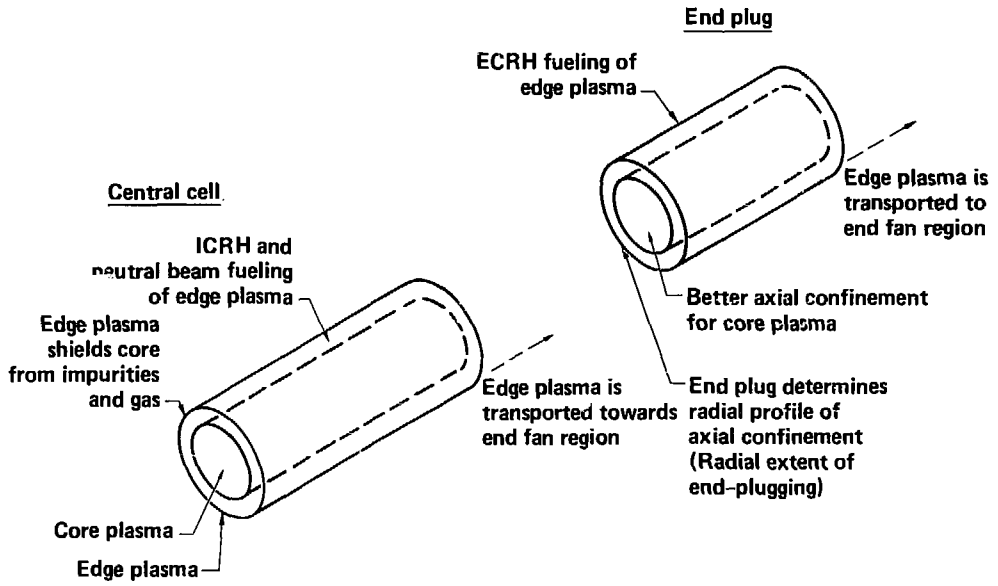
Fig. 7. The radial profile of neutral density obtained by radial profiles of EUV emissions. Code predictions using the measured pressure at the edge of the plasma and the electron density and temperature profiles are shown for comparison.

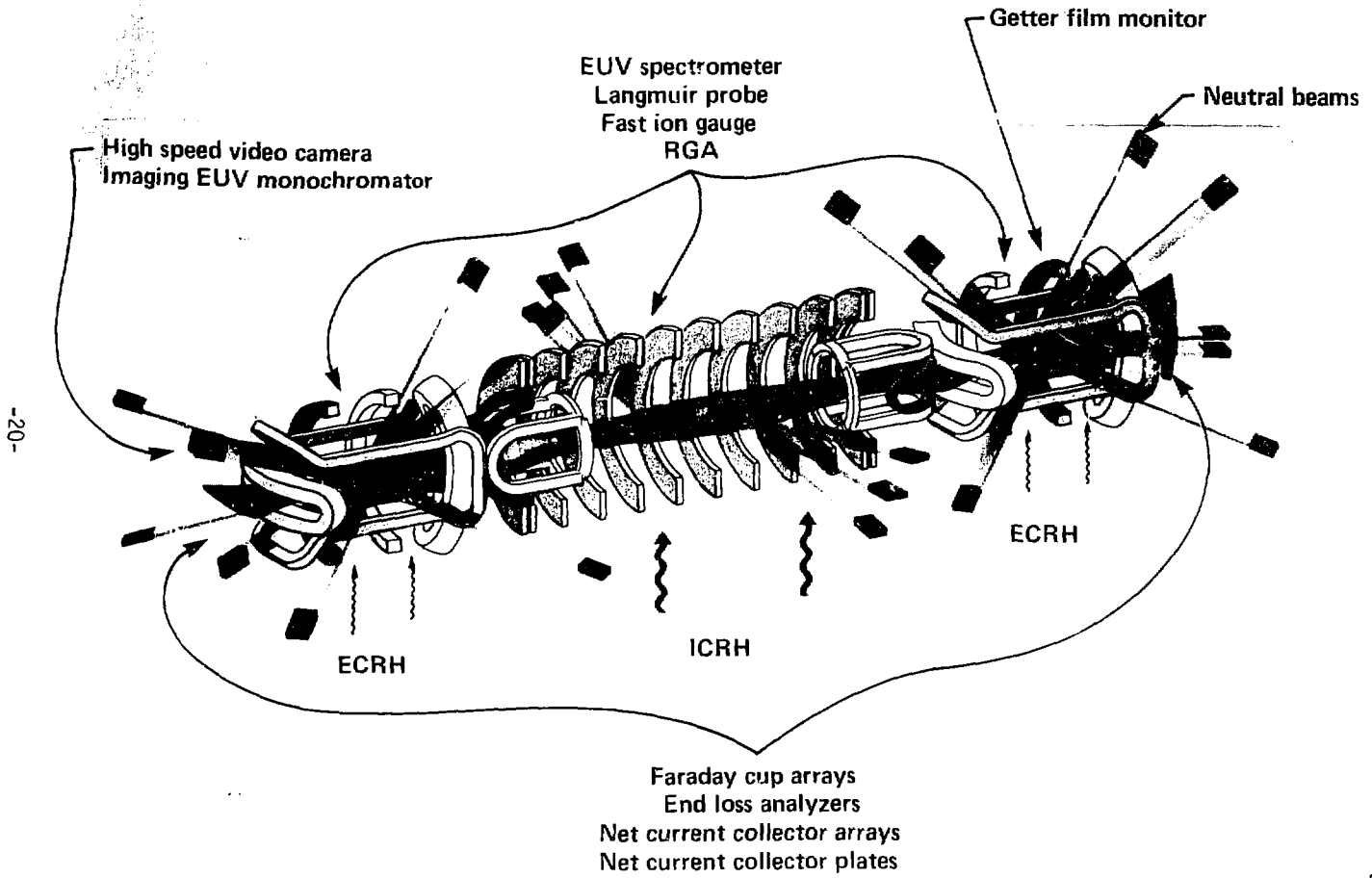
Fig. 8. EUV spectra measured from 31 to 35 ms with the plasma walls ungettered (top), and the next plasma shot with the walls gettered (bottom). Note the decrease in the impurity emissions after gettering.

Fig. 9. The time histories of carbon, nitrogen, and oxygen ionization states as a function of time as measured by the EUV spectrograph system. The nitrogen and oxygen emissions decrease when the neutral beams are turned off, indicating that the beams are a source of these impurities. These data were obtained on a single plasma shot.

Fig. 10. The time-resolved radial profiles of the total oxygen emission during impurity puffing (top) and the radial profile at 25 ms (bottom). These data were measured by the spatial imaging EUV monochromator.

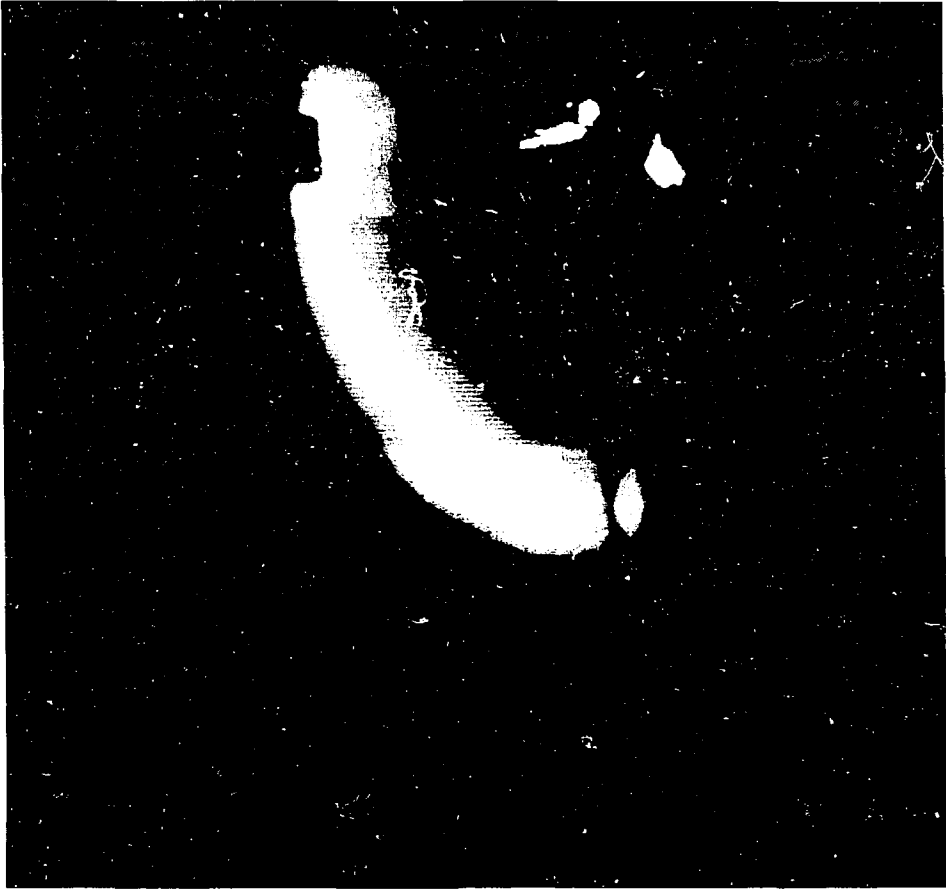


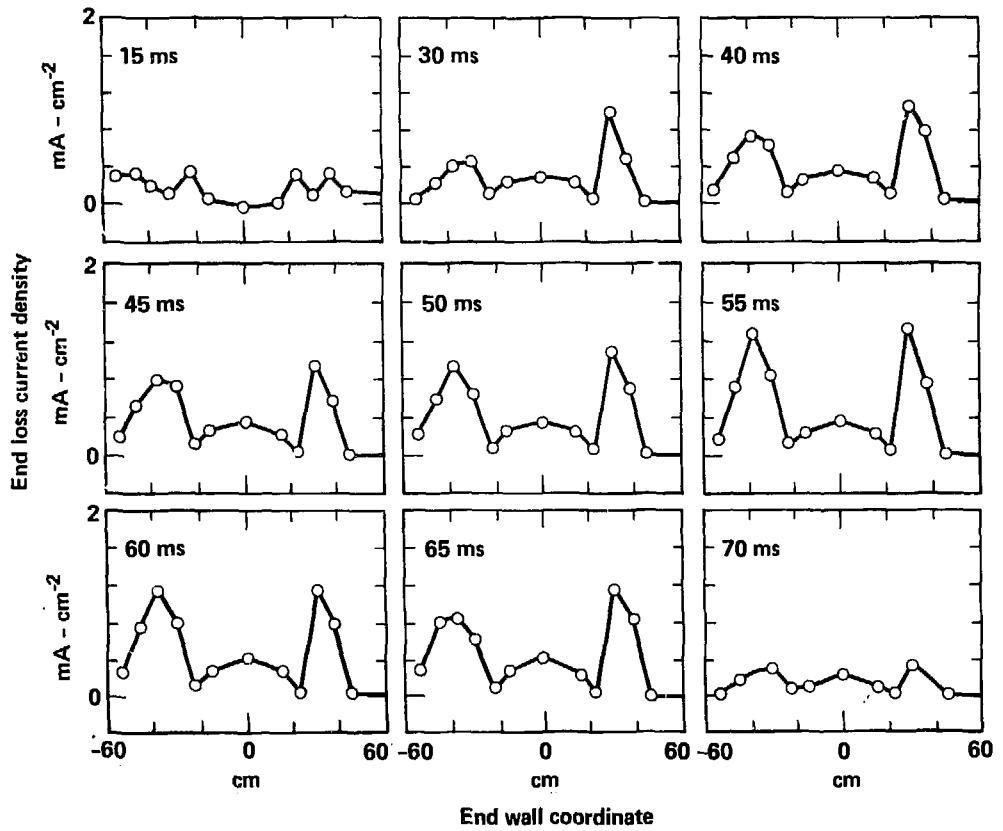


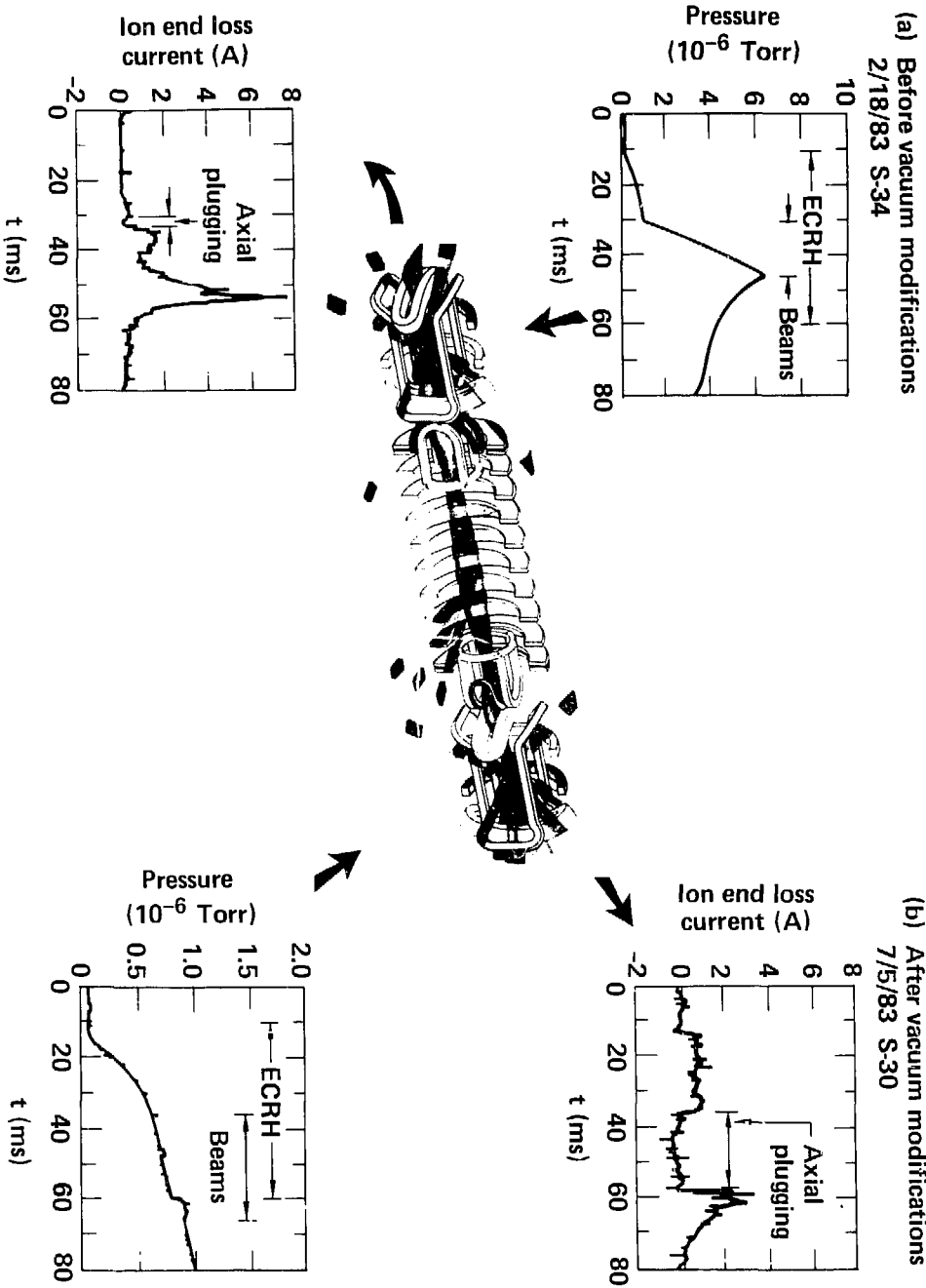


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S. L. Allen et al. - Fig. 3







S. L. Allen et al. - Fig. 6



