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DENSEPACK: An Array of Langmuir Probes in the Limiter Shadow Plasma of the Alcator C Tokamak Fusion Experiment

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Abstract: The boundary plasma of the Alcator C tokamak exhibits poloidal asymmetries in plasma parameters. In order to investigate this phenomenon, an array of 80 closely spaced Langmuir probes has been built to directly sample this plasma region. This specially developed, densely packed probe array (DENSEPACK) is unique in that it provides a simultaneous, time-dependent, two-dimensional mapping (minor radius r, poloidal angle θ) of plasma density, electron temperature, and floating potential over nearly the full 360^0 poloidal extent of the boundary plasma in this circular cross-section tokamak. The construction and operation of the DENSEPACK probe array as well as support hardware and software systems needed to handle the large volume of data generated by this array are described in this report.

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1. Introduction

The edge plasma of the Alcator C tokamak exhibits strong asymmetries in poloidal angle through non-uniform limiter power loading[1] and enhanced edge radiation characteristic of a MARFE[2] (Fig. 1). A Langmuir probe is perhaps the simplest localized diagnostic that can be employed to study phenomena in the limiter shadow or scrape-off layer (SOL) plasma of tokamaks ($r > a$). The idea of a fixed array of densely packed Langmuir probes (DENSEPACK) grew from the need to map the poloidal variations in n and T_e over short distances in this plasma region. The DENSEPACK probe system described in this report is a poloidal array of 80 fixed length Langmuir probes that sample plasma at three minor radii in the SOL region of the Alcator C tokamak.

The DENSEPACK probe array, probe drivers, and data processing systems are designed to meet a number of constraints imposed by the Alcator C environment. The probe array itself is designed to withstand the high heat fluxes ($q \sim 1$ kW/cm^2) associated with the high density edge plasma ($n \lesssim 5 \times 10^{13}$/cm^3) found in Alcator C. This is achieved by using molybdenum probes and relying on thermal inertia with cooling between discharges (discharge time ≈ 500 msec).

The array is modular, allowing the full poloidal ring to be assembled as it is installed through the narrow keyhole access slots (~ 1 inch wide by ~ 3 inches long). This limited access constraint also led to the use of mineral insulated (MgO), stainless steel clad, copper cables to carry current in high vacuum (10^{-8} torr) to the probes.

During a typical experiment, 30 of the single Langmuir probes are operated simultaneously. Each probe is swept through a complete Langmuir characteristic in ~ 5 msec for a total of ~ 3000 probe characteristics per discharge. Consequently, automated probe data fitting algorithms and data display programs were developed to efficiently handle the large volume of data.

The DENSEPACK probe array combined with the poloidally symmetric limiter system in Alcator C provides a unique opportunity for the study of poloidal asymmetries in the SOL plasma. Since the limiters and the magnetic flux surfaces are poloidally uniform, any poloidal variations which are detected by the array can be related to poloidal asymmetries in the transport of the edge plasma.[1]

Section 2 discusses the DENSEPACK hardware including the probe design and the limiter shadow geometry of Alcator C. Details of the probe current and voltage monitor circuitry along with typical probe signals are presented in section 3. Programs developed for data processing are outlined in section 4. Typical fits to the Langmuir characteristic and an example plot of density versus time and angle are included in this section. Finally, section 5 summarizes the DENSEPACK probe diagnostic system.

2. DENSEPACK In-Vacuum Hardware

2.1 Probe Array Structure

The DENSEPACK array shown in Fig. 2 consists of three different length molybdenum probes spaced $\sim$ 1 cm poloidally and mounted on a rigid stainless steel support ring. Plasma is sampled at minor radii of 16.8, 17.2, and 17.6 cm (limiter radius, $a = 16.5$ cm) over a poloidal angular extent of 360° excluding two $\sim$ 40° segments at the top and bottom of the vacuum vessel. The stainless steel support ring is divided into six segments which are inserted through the vessel access slots and clamped into place with wedge-shaped expansion blocks. The outer radius of the support ring is designed to rest against the vacuum vessel wall, insuring that the ring structure is positioned accurately with respect to minor radius. The inner radius of the support ring is at 18.0 cm which coincides with the radial extent of nearby vacuum bellows weld guard rings.

Data acquisition electronics allow 30 probes to be operated simultaneously. The purpose was to map out any poloidal variations in plasma density and temperature. Through the use of fast digitizers (1 MHz sampling rate), this system was also designed to record fluctuation spectra and to search for large spatial scale fluctuation correlations ocurring between probes.

2.2 Detail of Probe Assembly

A close-up view of the DENSEPACK probe assembly is shown in Figs. 3 and 4. Each Langmuir probe consists of a 1 mm diameter molybdenum wire with an exposed length of ~ 1 mm. The remaining wire length is insulated from plasma by a Al_2O_3 sleeve which is thermally protected by an outer, electrically floating molybdenum sheath. A spring roll pin interlocks with a groove on the ceramic sleeve, securing it to the stainless steel support ring. A small molybdenum button is e-beam welded to the molybdenum sheath and traps the sheath on another groove on the ceramic sleeve.

Electrical connnection is made to each probe in vacuum through a single conductor mineral insulated cable. A .032 inch diameter copper conductor size was chosen to minimize the voltage drop in the cable and provide a thermal conduction path for probe cooling between shots. A 850^o C copper to molybdenum braze provides a good electrical and thermal connection between the probe wire and copper conductor. The other end of the mineral insulated cable connects to high vacuum feedthroughs at the port access flange. Instrumentation cables carry current on the air side of the feedthroughs to probe driver and data acquisition electronics in a nearby isolated rack.

2.3 Shadow Plasma Geometry

The physical configuration of both DENSEPACK and Alcator C's poloidal ring limiters are shown in Fig. 5. In this configuration, the array of probes is installed with both a complete and a partial (3/4) poloidal ring of carbon limiters located $\sim 60^\circ$ and $\sim 120^\circ$ toroidally away from DENSEPACK. This limiter configuration scrapes off the plasma on the DENSEPACK half of the torus with poloidal uniformity.

3. Probe Driver and Data Acquisition Electronics

A conceptual diagram of the DENSEPACK probe electronics system is shown in Fig. 6. Probe voltage is maintained on a common feed line by two 1400 watt TECRON 7570 audio amplifiers which are driven by two TEKTRONIX 502 function generators. The TECRON amplifiers provide up to 40 amps of total probe current in the range of ± 80 volts for frequencies less than 40 kHz. A triangular voltage waveform sweeping from –60 to +40 volts at 100 Hz is typically programmed to drive the Langmuir probes. For sweep frequencies above 5 kHz, displacement currents due to stray capacitances start to appear as probe current on the current monitors. In any case, all offset or induced current components are numerically subtracted during data processing by monitoring the probe currents before a plasma discharge.

Voltage outputs corresponding to the common bias voltage and individual probe currents are digitized and stored by two types of CAMAC modules. Two LeCroy 8212 CAMAC units are used to store a total of 32 channels of data with a sampling rate of 10 kHz for 600 msec. Sixteen of these channels are also sampled at 1 MHz by four LeCroy 8210 units with a 8 msec storage capacity. Ten pole Tchebyshev-Elipsoidal lowpass filters with a cutoff frequency of 416 kHz are inserted before the 1 MHz digitizer units to suppress digital aliasing to below –60 db for frequencies greater than 500 kHz.

The system is capable of driving 30 of the 80 Langmuir probes during a single discharge. Any combination of 30 probes can be selected via a patch panel located on the back of the electronics rack. Maximum currents drawn by the longest probes can exceed 2 amperes. Each probe driver line has a 1–2 amp fuse in series with the probe for protection against shorted probe wires or to shut down the probe should it receive too much power flux.

A switch selectable current monitor load resistor is used to maintain the optimum signal to noise ratio over a wide range of collected current. A design criteria is to have a typical voltage drop across this resistor of ~ 1 volt. Due to large radial and poloidal variations in plasma density, a switch selectable resistance range of 1–200 ohms was found necessary.

All probe driver and digital data storage electronics are grounded at a point on Alcator C's vacuum vessel. This eliminates the need for isolation amplifiers and the associated loss of frequency response. A 5 kVA isolation transformer provides power to the insulated rack and cable trays. Digital data stored in the CAMAC units is read by a VAX 11/780 computer between plasma shots via a fiber optic link.

3.1 DENSEPACK Probe Current Monitor Circuit

Two versions of probe current monitor circuits are used in the probe drive system. The first version is shown in Fig. 7. One of two drive voltages on the programmed power supplies can be selected for any probe using switch S_3. The probe draws current from this source through a load resistor determined by the position of S_1. The voltage drop across the load resistor is differentially stepped down and amplified through resistor dividers and four LF357 operational amplifiers. This arrangement of LF357s provides a common mode voltage rejection of 100 volts with optimum common mode frequency rejection up to 1MHz. Switch S_2 allows a selection of simple RC filtering at ~ 1 MHz, 100 kHz, and 10 kHz.

The output voltage is calibrated and balanced using trim resistors such that it is equal to the voltage drop across the load resistor. When switch S_1 is in position 1, only the positive leg of the differential amplifier system is used. The output of this circuit then corresponds to the floating potential of the probe.

A second version probe current monitor circuit is shown in Fig. 8. The option of monitoring the floating potential is eliminated in favor of another load resistor as well as a trim resistor for each position of switch S_1. This circuit modification was performed to improve the low current sensitivity (low plasma density). In order to balance the resistor dividers at high load resistor values, individual trim resistors for each load resistor are included.

Each circuit, combined with a CAMAC logger channel, is capable of cleanly recording from ~ 2 amps to ~ 1 milliamp of probe current for triangle bias waveforms of ± 60 volts at 100–5000 Hz. The bandwidth of the amplifier system is designed to be ≈ 1 MHz which is needed for recording high frequency fluctuations.

3.2 DENSEPACK Bias Voltage Monitor Circuit

The voltage output of each probe bias power supply is monitored by the circuit shown in Fig. 9. The circuit divides the input voltage by 20, inverts it, and sends it to a CAMAC logger channel. The operational amplifier and filter arrangement is designed to match the probe current monitor circuit.

3.3 Typical Raw Voltage and Current Traces from DENSEPACK

Each of the 30 driven DENSEPACK probes can be operated in one of three modes: 1) *sweep mode* (yielding typical Langmuir trace), 2) *ion saturation mode* (constant negative bias), and 3) *floating potential mode* (no bias). Figure 10 displays typical current and voltage traces that are recorded on the LeCroy 8212

Data Loggers for a $r = 16.8$ cm probe in sweep mode. A triangular bias voltage waveform of 100 Hz spanning +40 to −60 volts is shown. Current collected by the probe displays the usual Langmuir characteristic from the begining of the discharge at 40 ms to the end at 490 ms. With a digitizer sampling rate of 10 kHz, 50 data points are recorded during a full voltage sweep. A 1 ohm series load resistor was selected to monitor this probe current. The probe draws ion saturation current at biases below ~ -20 volts and fluctuations in plasma density appear as 'hash' on the signal. Downward 'spikes' in the current trace can be seen as the probe is biased more positively to collect electrons. On closer inspection these 'spikes' have an exponential dependence on voltage and suggest that electrons with a maxwellian velocity distribution are being collected. Electron saturation is not observed at the maximum positive potential of +40 volts. Maximum collection currents of ~ 1 amp become the limiting factor in setting the range of bias for electron collection.

Figure 11 displays a typical probe current trace versus time for a probe biased in ion saturation mode and a typical probe voltage trace versus time in floating potential mode. In ion saturation mode, the TECRON amplifier is held at −60 volts throughout the duration of the discharge. Ion saturation mode is used primarily to record density fluctuations on the 1 MHz LeCroy 8210 digitizers. The probe floating potential displayed in Fig. 11*b* is obtained by disconnecting the probe from the common voltage line and monitoring the zero current or 'floating' probe potential. Both floating potential and ion saturation modes are not used as often as sweep mode since estimates for the ion saturation current and floating potential can be made from the complete Langmuir characteristic.

4. Data Processing

Starting with the raw digital data stored in LeCroy 8212 and 8210 data loggers and producing a graphic display of density or temperature in the edge plasma in Alcator C involves the execution of a number of successive data reduction, archiving, and display programs. The multiple steps that occur in this data processing are presented chronologically in this section beginning with raw data acquisition and ending with a description of DENSEPACK database programs.

4.1 Raw Data Acquisition and Display

During an Alcator C run, data is archived and displayed as shown in Fig. 12. Diagram (*a*) depicts the flow of data during execution of a data aquisition program, 'PROBE', which is run after each plasma dishcarge. DENSEPACK data stored in CAMAC memory modules is read, combined with other diagnostics' output such as plasma current and density, and stored in a disk file. The DENSEPACK configuration and load resistor settings are read from a set-up file and saved as header information in the raw data file. A separate editor program allows information to be updated in the set-up file any time changes are made in the DENSEPACK hardware.

Between plasma discharges, raw data stored in the disk files can be displayed in graphical form on the terminal (*b*). A number of programs are available to display all 8212 channels, all 8210 channels, or all other diagnostic channels that are recorded for a quick check of the system operation. Alternatively, any one channel can be displayed in detail.

4.2 Data Reduction and Archiving

Figure 13 diagrams procedures used after a run to summarize, reduce, and archive data for later reference. A more tangible record of the raw data accumulated during the day is first produced using hardcopy programs, (*a*), which plotted all data channels on a three page summary for each shot.

The task of reducing raw probe data into plasma parameters such as density and temperature is then handled by the program 'DPACK' in Fig. 13*b*. The raw data files are read in, fitted, and a reduced data file is generated. Optimized fitting parameters and program control parameters are stored in a menu file. This allows the program to be easily executed as a batch job to process data from many plasma shots.

Once the probe data for a particular day is reduced, it is copied along with the raw data to magnetic tape for permanent storage, (*c*). A log file records the file names archived on a given tape volume for later reference. Data files on the disk drive are cleared to allow space for new data.

A. Fitting to the Langmuir Characteristic

A significant amount of effort went into developing the Langmuir probe characteristic model used in the program 'DPACK'. This section outlines the data fitting section of that program. More details of this fitting procedure can be found in Ref. [1].

Figure 14 displays a typical Langmuir characteristic from a probe on the DENSEPACK array during the steady state portion of a plasma discharge. The trace was obtained by monitoring current to the probe over a 10 msec period when the voltage was swept from -65 to $+40$ volts and back. The 8212 10 kHz digitizers recorded ≈ 100 data points at this time. The current-voltage data pairs are ordered according to voltage and displayed in Fig. 14 with straight lines connecting the points.

The ion saturation portion of the probe characteristic is clearly visible for probe voltages less than ~ -15 volts. In the range -15 to $+20$ volts, the curve displays the electron transition regime and is approximated by an exponential function. At biases above +20 volts, the trace deviates from a simple exponential and tends to flatten out. This suggests that electron saturation is being approached.

Program 'DPACK' is capable of determining plasma density, electron temperature, and floating potential using two probe characteristic models. The first of these models is the simplest, approximating the total probe current as a constant ion contribution plus an electron contribution which depends exponentially on the probe voltage.

For a plane probe collection area, A_p, this first order approximation for the probe characteristic is simply[1,3-5]

$$\frac{I(V_p)}{q\ A_p\ n_0} \approx \frac{1}{2}\ C_s\ -\ \frac{1}{4}\ \overline{C}_e\ e^{(V_p-V_s)/T_e} \quad ; \text{ for } \ V_p < V_s \tag{1}$$

$$\frac{I(V_p)}{q\ A_p\ n_0} \approx -\frac{1}{4}\ \overline{C}_e \quad ; \text{ for } \ V_p \geq V_s \tag{2}$$

where $I(V_p)$ is the current collected by the probe at bias potential V_p and plasma (or space) potential, V_s. n_0 is the unperturbed electron density at a distance far from the probe, C_s is the sound speed ($= \sqrt{\kappa(T_e + T_i)/m_e}$), and $\overline{C}_e$ is the average electron thermal speed ($= \sqrt{8\ \kappa\ T_e/\pi m_e}$). Since near electron saturation ($V_p \approx V_s$) the measured probe characteristic deviates from this simple model, Eq. (2) is not used in the fitting procedure. Instead, only Eq. (1) is used over the range of the probe characteristic that exhibits an exponential shape. A cut-off probe voltage, V_{knee}, is determined below which the characteristic obeys Eq. (1) and above which the characteristic departs from exponential. With some assumption about T_i (typically $T_i \approx 2 \times T_e$), T_e and n_0 are then obtained from a fit to Eq. (1) in the voltage range $V_p \lesssim V_{knee}$. The floating potential is separately determined by interpolating to the voltage at which the probe draws zero current.

The second probe characteristic model that program 'DPACK' uses is based on the work of Stangeby.[6] This model attempts to deal with the electron saturation portion of the probe characteristic and includes the effect of cross field diffusion into the flux tube intercepted by the probe. The total current collected by the probe can be approximated by this model as[1]

$$I(\eta_p) \;=\; I_{sat}\left(e^{-\eta_h/\tau} \;-\; \frac{1}{\beta}\left[\frac{r}{1+r\ e^{\eta_h-\eta_p}}\right]\right) \tag{3}$$

when $\eta_p \leq \tau\ ln\left[\frac{1+r}{r}\right]$, and

$$I(\eta_p) \;=\; I_{sat}\left(e^{-\eta_h/\tau} \;-\; \frac{1}{\beta}\left[\frac{r}{1+r}\right]\right) \tag{4}$$

when $\eta_p > \tau\ ln\left[\frac{1+r}{r}\right]$. β is defined as

$$\beta \;=\; 4\ f(\tau)\ \sqrt{\frac{Z_i\ (1+\tau)\ \pi\ m_e}{8\ m_i}} \tag{5}$$

and η_p and η_h satisfy

$$\eta_p \;=\; \frac{V_p}{T_e}\ ; \tag{6}$$

$$\eta_h \;=\; \tau\ ln\Big[r^{-1}\ e^{\eta_p-\eta_h}+1\Big]\ . \tag{7}$$

Here, I_{sat} is the ion saturation current and r is the electron saturation reduction factor which is related to the rates of parallel and perpendicular transport along the collection flux tube.

For an assumed value of τ ($= T_i/T_e Z_i$), an optimum combination of the parameters I_{sat}, T_e, and r can be fit to probe data using Eqs. (3)–(7). This problem is complicated by the fact that $I(\eta_p)$ depends non-linearly on T_e and r with a transcendental relationship for the intermediate quantity, η_h. Also, the model equation changes form at $\eta_p = \tau \; ln\left[\frac{1+r}{r}\right]$. Nevertheless, systematic methods for arriving at optimum I_{sat}, T_e, and r values were developed and are included in program 'DPACK'.

Figure 15 displays the result of these two fitting procedures using the probe data previously shown in Fig. 14. The inferred value for the electron temperature using the Stangeby model (*b*) is notably different than that obtained from the exponential model (*a*). From the Stangeby model, T_e is $\approx$ 8 eV while for the same data fit by an exponential, T_e is found to be $\approx$ 13 eV. It appears that the electron temperature inferred by the Stangeby model is lower because, in including the r parameter, the fitting function rolls over more gently for the same T_e. This implies that it may be necessary to incorporate such effects as a collecting flux tube into the probe data analysis. In any case, it demonstrates that the electron temperature inferred by a magnetized Langmuir probe can be model-dependent.

More recently, simultaneous measurements of T_e in Alcator C using a gridded energy analyzer and a Langmuir probe show that electron temperatures obtained by the simple exponential model agree with the energy analyzer electron temperatures.[7] Consequently, the lower temperatures fitted by the Stangeby model may be in error. In any case, both algorithms are made available in the data analysis programs to fit the DENSEPACK probe data.

4.3 Reduced Data Display Programs

The benefit of reducing all the probe data before storage in the program 'DPACK' comes when data must be reviewed with fast, easy access and plotted in a number of different formats. Figure 16 shows a single channel display program (a) and a more complex multiple probe, three-dimensional display program (b). The multiple probe data display program, 'DPKPLOT', can plot directly-inferred plasma parameters such as density, electron temperature, and floating potential as a function of time, radius, or poloidal angle. Three dimensional surfaces or contour plots representing the data can be displayed.

The program also has the capability of plotting, in the same 3-D or contour plot format, quantities which are calculated from the reduced probe data such as ∇n and ∇T_e. This feature is included to allow the study of particle and energy balance in the limiter shadow region. Terms in the continuity and energy equations can be computed directly from probe data and displayed versus spatial position.

The 'DPKPLOT' program is controlled via a menu file and all output can be directed to the terminal or sent to a graphics line printer. Most of the graphics is based on a software package obtained from NCAR.[8]

A. Example Plot of Edge Density versus Angle and Time

Figure 17 displays examples of plots generated by the program 'DPKPLOT'. Density at a minor radius of 16.8 cm is shown versus poloidal angle and time as a 3-D surface. A single poloidal profile at 250 msec is also plotted. Central parameters were $\overline{n}_e \approx 2 \times 10^{14}/\text{cm}^3$, $I_p \approx 350$ kA, $B_t \approx 8$ tesla, in a deuterium plasma. Each data point was generated from a fit of two 5 msec Langmuir sweeps folded together. No poloidal or temporal smoothing was performed for these plots.

The most striking feature in this data and other data collected by the DENSEPACK array is the variation in poloidal angle. As shown here, density maxima appeared on the top and bottom of the poloidal cross-section while minima appear on the inside and outside (see Fig. 2 for angle definitions). The lowest densities for a given radius always appear on the inside midplane. In fact, some probes along the inside wall were not used on this day because the collection current was found to be too low there.

There is no obvious reason why density or other edge parameters exhibited such a poloidal asymmetry. For this data, the limiter configuration was as is shown in Fig. 5. One would expect that the edge plasma be scraped off with poloidal uniformity given that the limiters are poloidally symmetric. Nevertheless, it was found that the edge plasma displays strong poloidal asymmetries. The analysis of DENSEPACK data reported in Ref. [1] centers around mechanisms which might explain this poloidally asymmetric structure of the Alcator C edge plasma.

4.4 DENSEPACK Database Programs

Typically, one or two days of DENSEPACK data completely fill a magnetic tape reel. In order to correlate edge plasma parameters with central plasma parameters in a systematic way, a database generating program, 'DPKBASE', was written. 'DPKBASE' summarizes DENSEPACK and central plasma parameter data from each discharge and writes it in a common database file. Figure 18 shows the operation of 'DPKBASE' and a corresponding database display program, 'DBPLOT'.

The database file contains central and edge plasma parameters at four specifiable times during each plasma shot. The display program allows the user to choose any quantity in the database as the independent and dependent variable for a graph. Data before or after an event such as a pellet injection can be selected. Maximum and minimum value restrictions can be applied to any or all variables to 'window-in' on a particular subset of data. This feature allows the selection and plotting of shots with only certain plasma currents, densities, or horizontal position, for example. The program utilizes an advanced graphics package developed by McCool[9] which handles multiple labled axes and includes an extensive library of interactive features.

Reference [1] uses programs 'DPKBASE' and 'DBPLOT' to catalogue edge parameters for a variety of central plasma conditions including frozen hydrogen pellet injection and lower hybrid radio frequency heating experiments. More detailed information about the organization of the DENSEPACK database is also included in this report. In addition, edge versus central plasma parameter scaling laws have been obtained by using regression analysis techniques with this database.

5. Summary

An edge plasma diagnostic system featuring a poloidal array of 80 fixed-length molybdenum Langmuir probes is described. The probe array samples plasma in the limiter shadow region at three different minor radii over the full poloidal extent (360^0) excluding two $\sim 40^0$ segments at the top and bottom of the vacuum vessel. The poloidally symmetric limiter shadow geometry in Alcator C enables this diagnostic to record poloidal asymmetries in edge plasma parameters.

Probe driver and data acquisition electronics allow any 30 of the 80 probes to be operated simultaneously. Edge density, temperature, and floating potential as a function of time, minor radius, and poloidal angle in the scrape-off layer of Alcator C are thereby obtained. Numerical fitting algorithms facilitate the efficient processing of large batches of Langmuir probe data. Database and data display programs aid in viewing multi-dimensional density and temperature profiles and in correlating edge plasma parameters with central plasma parameters.

Acknowledgements

The authors gratefully acknowledge the Alcator C electronics and vacuum systems support groups in their assistance in the construction and installation of the DENSEPACK diagnostic system. Special thanks are extended to Joe Bosco, Tom Fredian, Marty Hughes, Bruce Oliver, and Eric Woodworth for their invaluable contributions in debugging and programming the CAMAC archiving systems and in building the probe monitor circuitry.

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[9] special graphics programs developed by S. McCool at the M.I.T. Plasma Fusion Center.

Figure 1 - **Tokamak Toroidal Geometry** Plasma is confined to a toroidal shape by strong magnetic fields (1-10 tesla). A toroidal coordinate system is defined as shown. Angle ϕ measures the *toroidal* direction while angle θ measures the *poloidal* direction. Tokamak plasmas exhibit poloidal asymmetries near the plasma boundary ($r \approx a$) as evidenced by radiation from MARFE phenomena,[2] located on the small major radius edge of the plasma. Poloidal ring limiters define the common edge of the main plasma and the *limiter shadow plasma.*

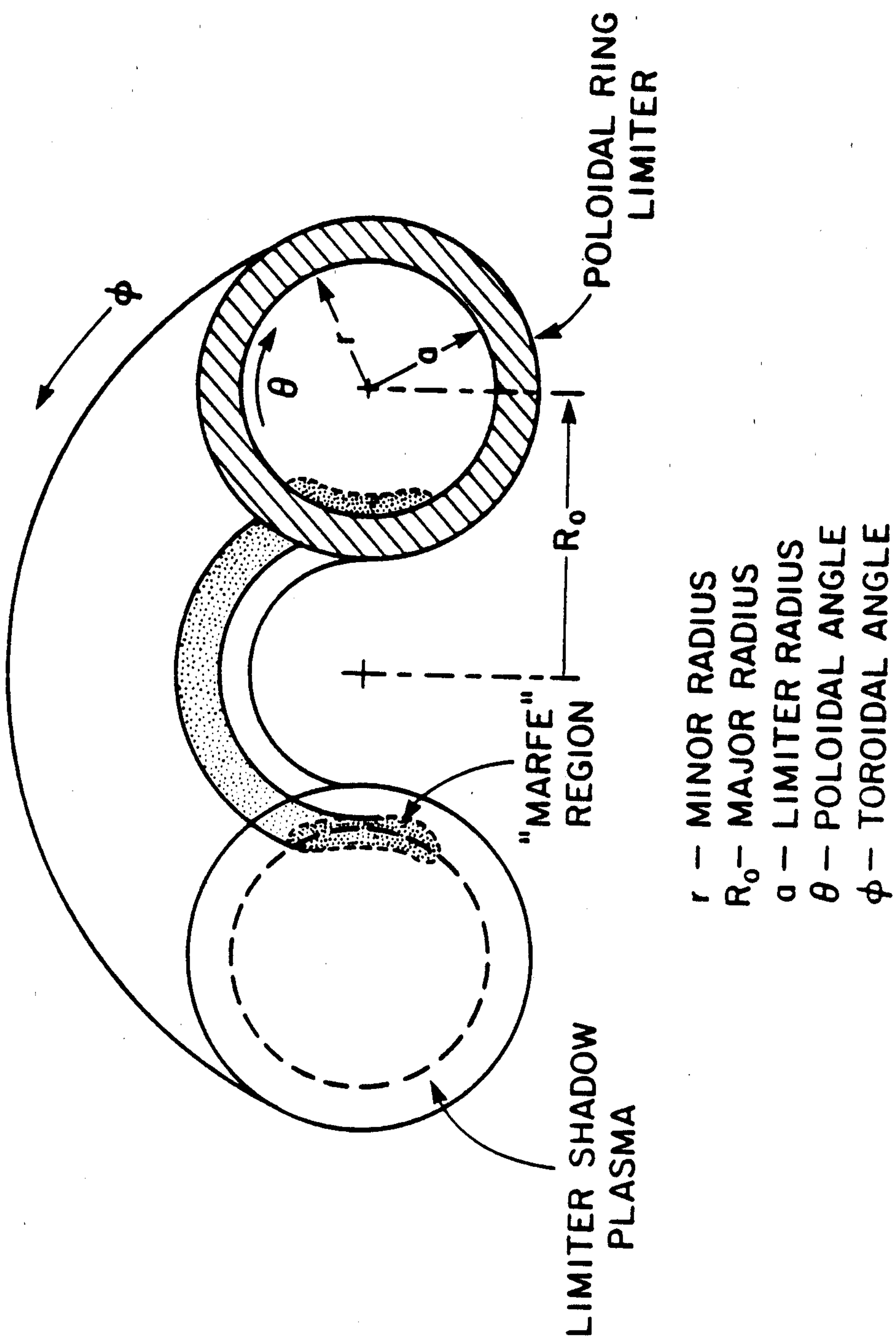
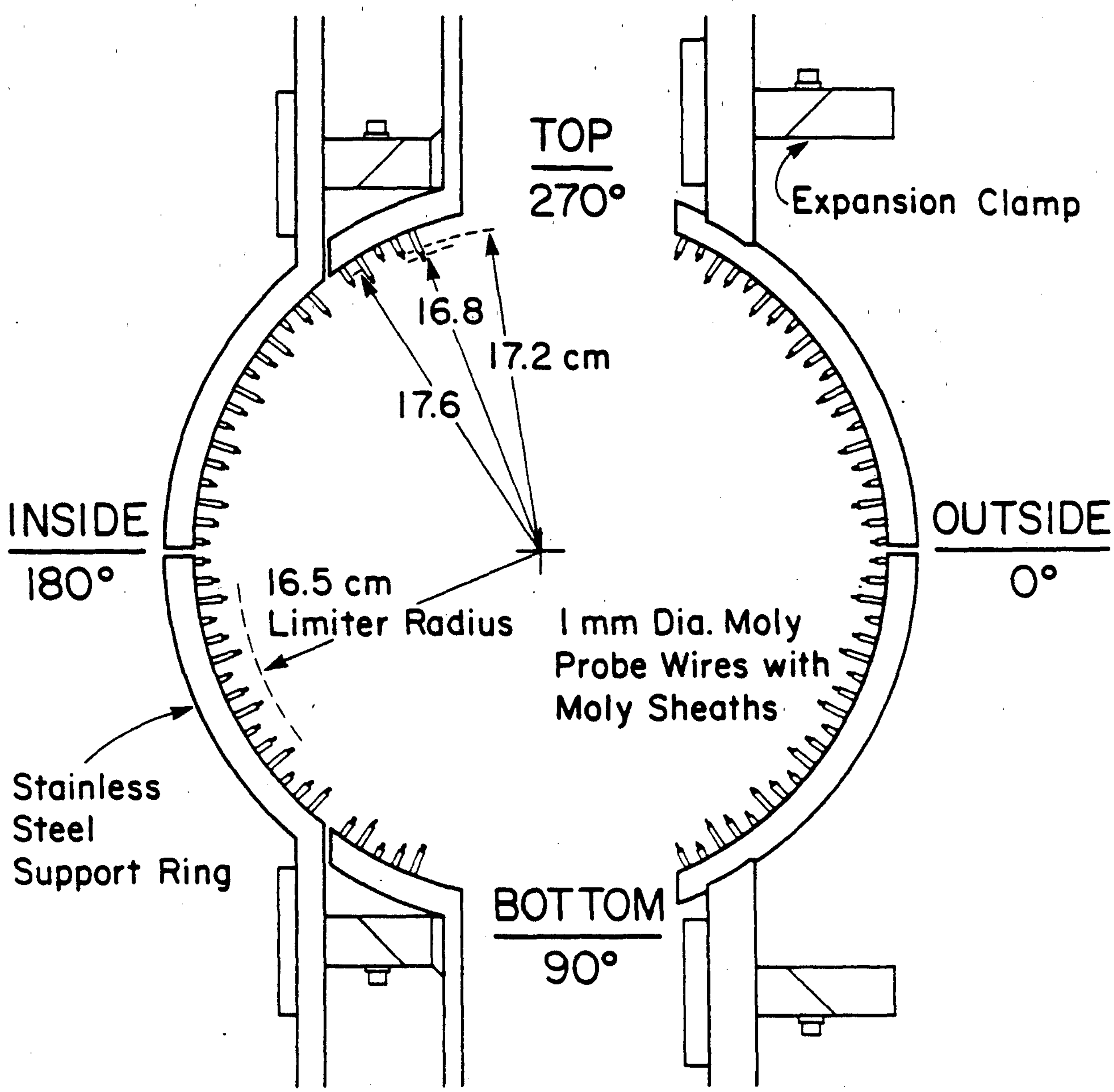

POLOIDAL RING LIMITER
"MARFE" REGION
LIMITER SHADOW PLASMA
ϕ
θ
r
a
R_o
r — MINOR RADIUS
R_o— MAJOR RADIUS
a — LIMITER RADIUS
θ — POLOIDAL ANGLE
ϕ — TOROIDAL ANGLE

Figure 1

Figure 2 - Schematic of DENSEPACK Probe Array An array of 80 Langmuir probes is built to simultaneously sample the limiter shadow plasma at various (r, θ) locations for a fixed toroidal location. The goal is to map poloidal asymmetries in plasma density and temperature in Alcator C edge plasma.



8103/19 .C

Figure 2

Figure 3 - Upper-Inside Segment of DENSEPACK The DENSEPACK support structure is designed to rest against Alcator C's vacuum vessel wall. This cross-sectional view shows the mineral insulated, stainless steel sheathed cables running inside the support ring.

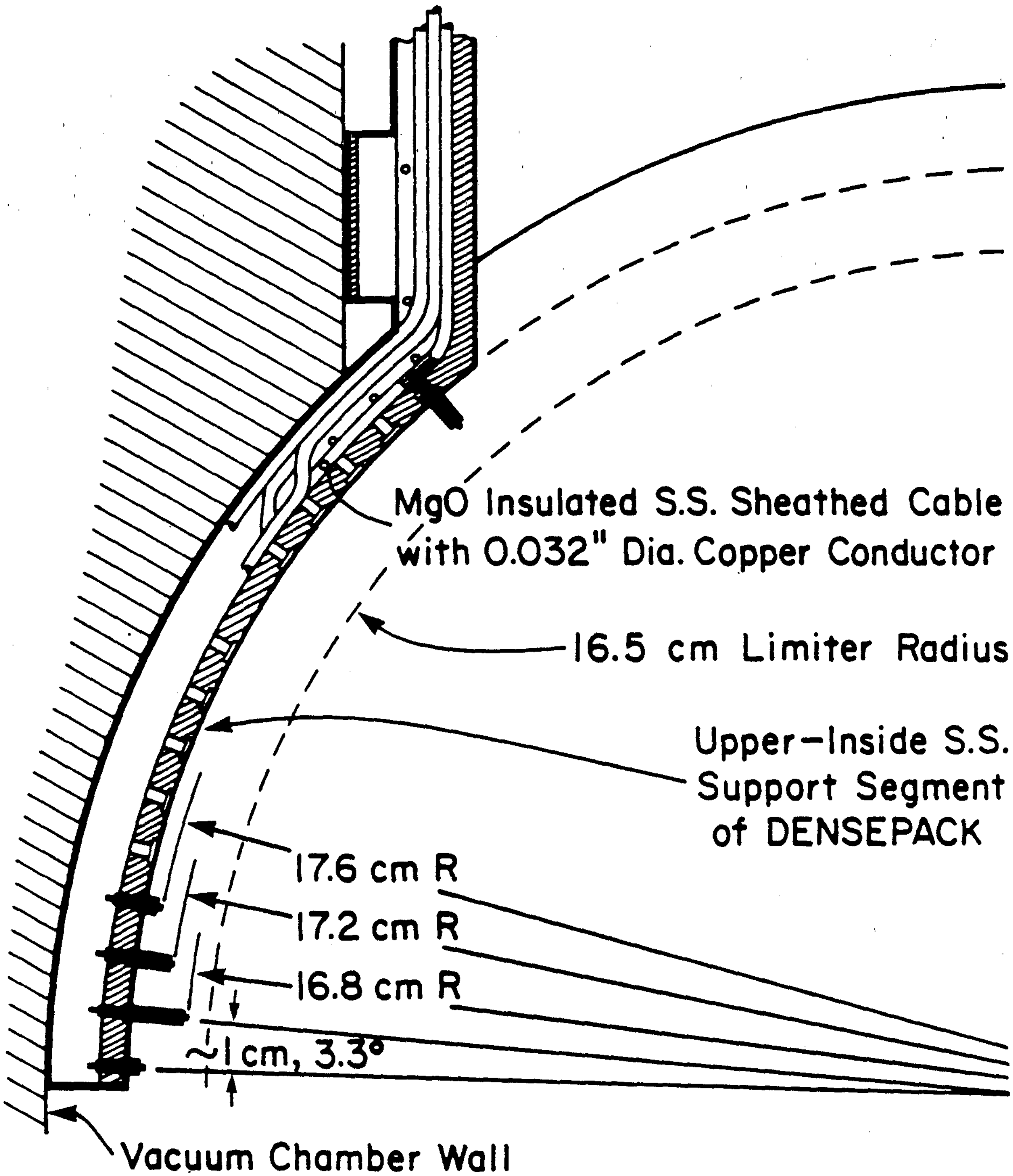


Figure 3

8075.8.7

Figure 4 - Detail of DENSEPACK Probe Assembly The assembly of one DENSEPACK probe is shown. Each probe consists of a ~ 1 mm diameter molybdenum wire with ~ 1 mm exposed length.

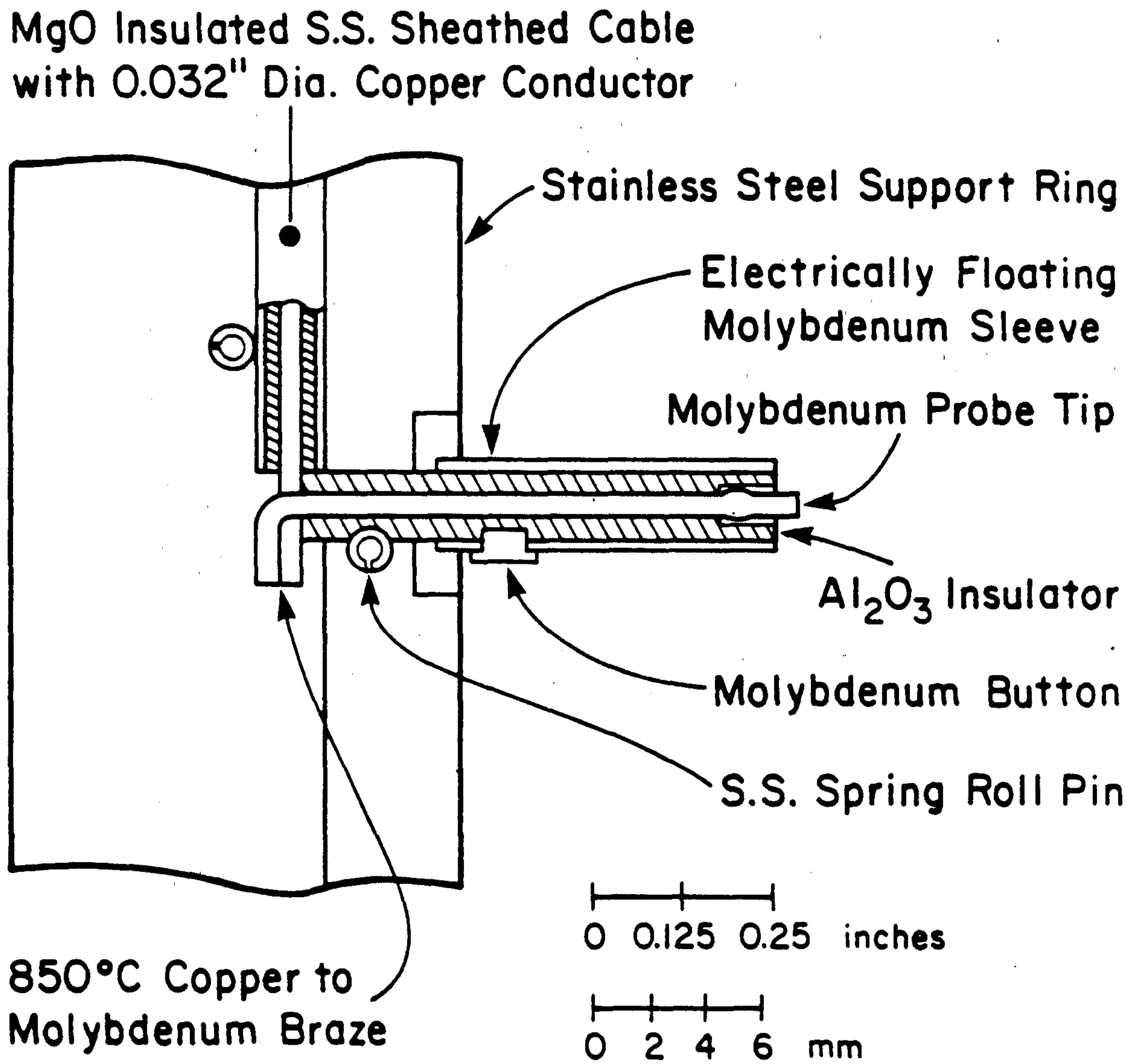


Figure 4

8075 8 6

Figure 5 - DENSEPACK and Limiter Configuration There are six toroidal locations for diagnostic and limiter access in Alcator C labelled A through F. Full poloidal limiters in B and E ports define a poloidally symmetric shadow plasma boundary, diagnosed by DENSEPACK in C port.

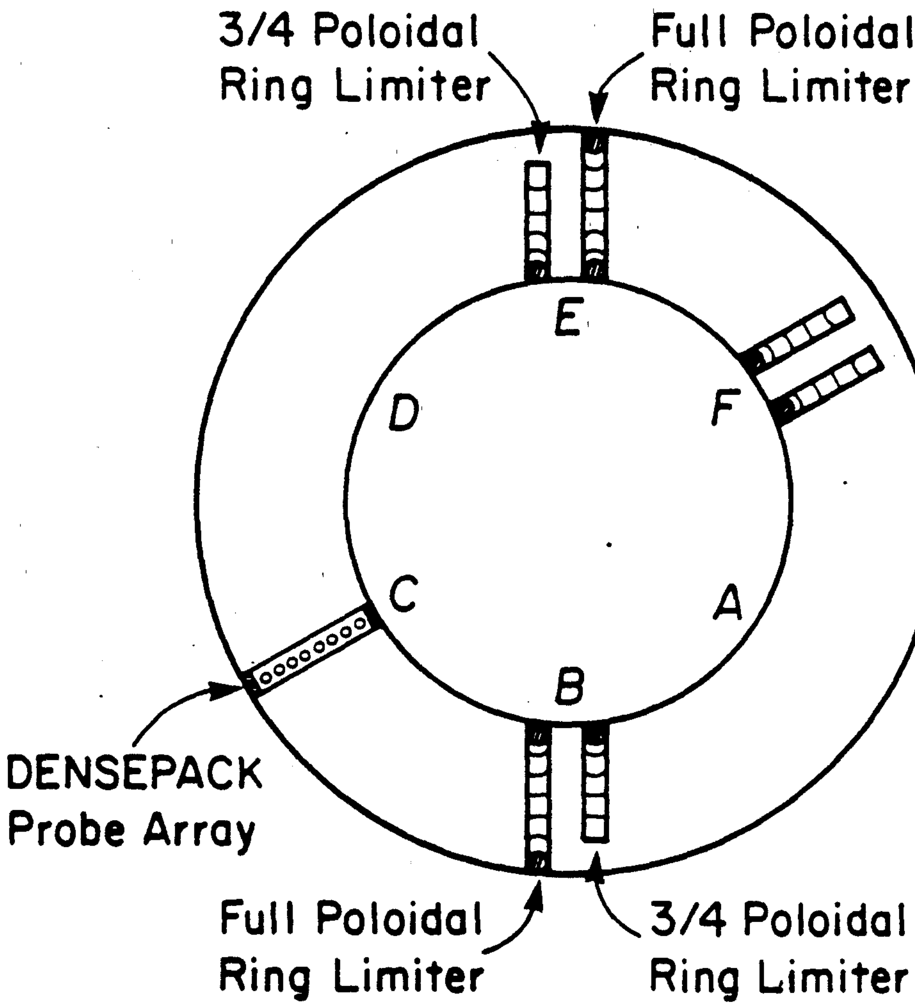


Figure 5

8075.8.5

Figure 6 - Probe Driver and Data Acquisition Electronics The multiple probe biasing and data acquisition arrangement is shown. All data acquisition electronics is grounded to the Alcator C vacuum vessel. Probe data stored in digital form is send via fiber optic link to Alcator C's VAX computer system between plasma discharges.

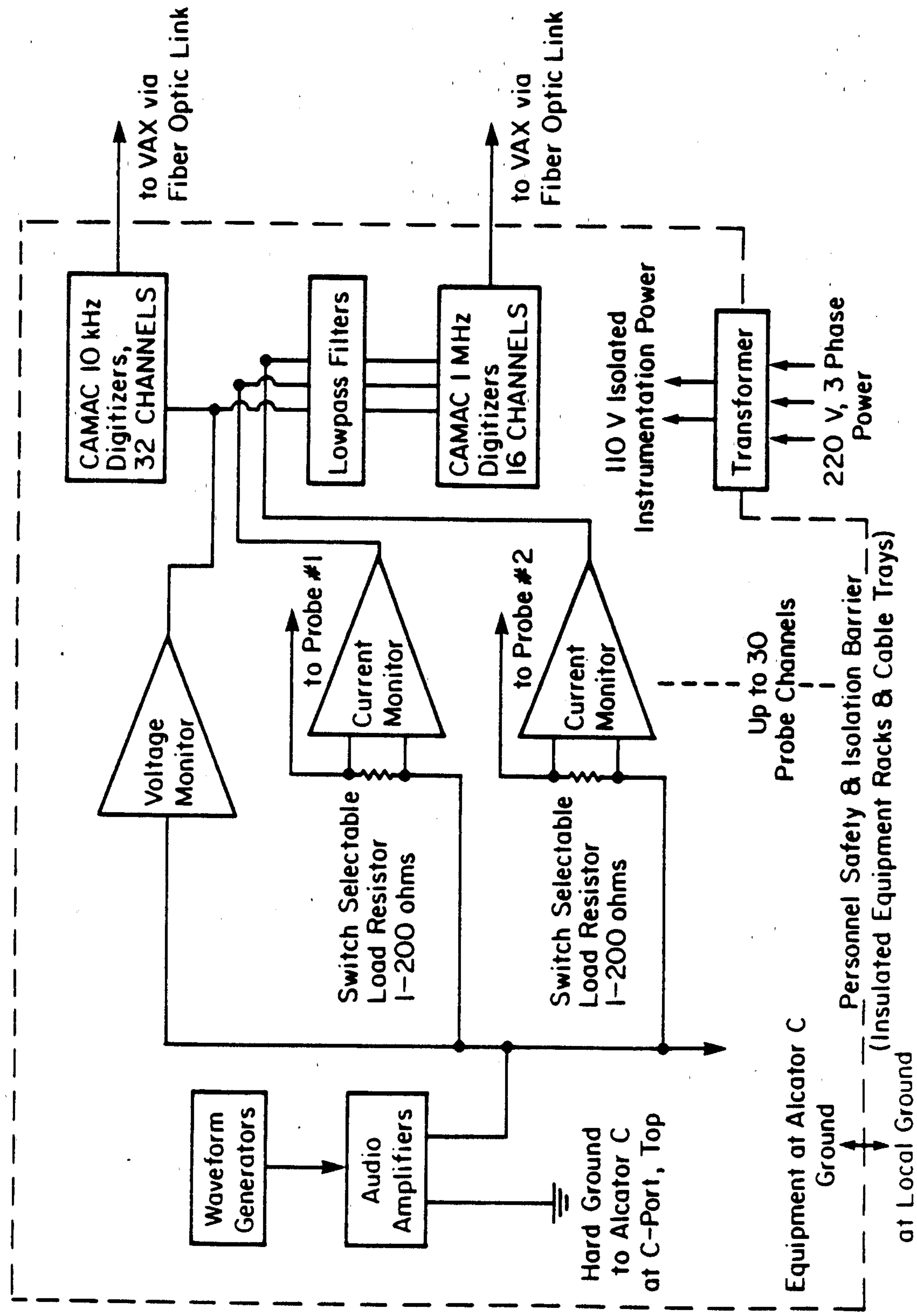

to VAX via Fiber Optic Link
CAMAC 10 kHz Digitizers, 32 CHANNELS
to VAX via Fiber Optic Link
Lowpass Filters
CAMAC 1 MHz Digitizers 16 CHANNELS
110 V Isolated Instrumentation Power
Transformer
220 V, 3 Phase Power
Voltage Monitor
to Probe #1
Current Monitor
to Probe #2
Current Monitor
Up to 30 Probe Channels
Switch Selectable Load Resistor 1–200 ohms
Switch Selectable Load Resistor 1–200 ohms
Personnel Safety & Isolation Barrier
(Insulated Equipment Racks & Cable Trays)
Waveform Generators
Audio Amplifiers
Hard Ground to Alcator C at C-Port, Top
Equipment at Alcator C Ground
at Local Ground

Figure 6

Figure 7 - **Current Monitor Circuit Diagram (First Version)** Each 'Current Monitor' shown in Fig. 6 consists of the above circuit and components. Switch S_1 allows one of four load resistors (0.5–10 ohms) to be selected for current monitoring or allows the probe floating potential to be continuously monitored. The circuit has a common input voltage rejection of 100 volts and a 0–1 MHz bandwidth.

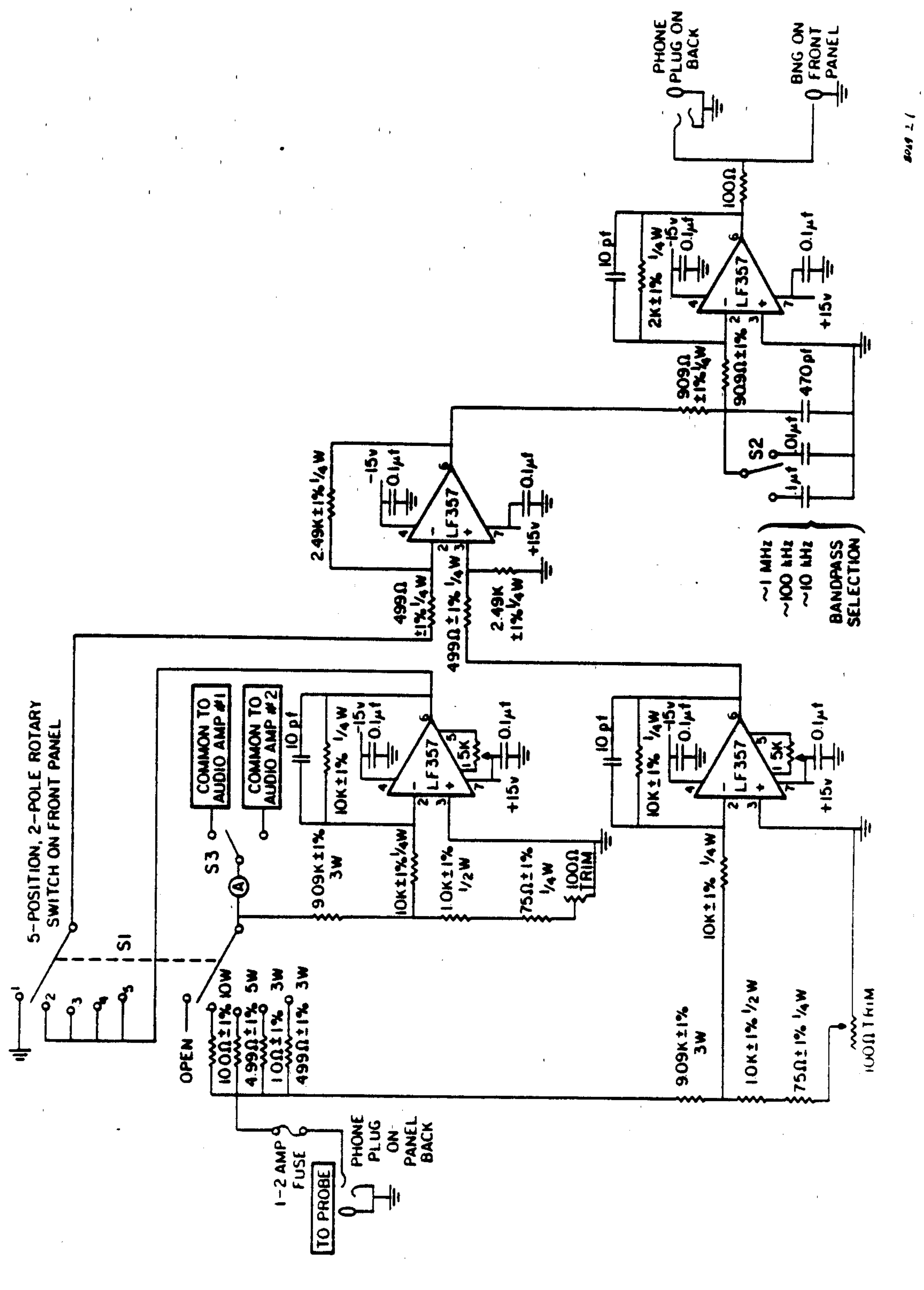

5-POSITION, 2-POLE ROTARY SWITCH ON FRONT PANEL
S1
S3
S2
COMMON TO AUDIO AMP #1
COMMON TO AUDIO AMP #2
OPEN
10.0Ω±1% 10W
4.99Ω±1% 5W
1.0Ω±1% 3W
.499Ω±1% 3W
1-2 AMP FUSE
TO PROBE
PHONE PLUG ON PANEL BACK
9.09K±1% 3W
10K±1% 1/4W
10K±1% 1/2W
75Ω±1% 1/4W
100Ω TRIM
10K±1% 1/4W
10 pf
LF357
1.5K
0.1μf
+15v
-15v
499Ω ±1% 1/4W
2.49K±1% 1/4W
2.49K ±1% 1/4W
909Ω ±1% 1/4W
909Ω±1%
2K±1% 1/4W
470pf
.1μf
.01μf
100Ω
~1 MHz
~100 kHz
~10 kHz
BANDPASS SELECTION
PHONE PLUG ON BACK
BNC ON FRONT PANEL

Figure 7

Figure 8 - **Current Monitor Circuit Diagram (Second Version)** Same as Fig. 7 with a slight modification to improve low probe current sensitivity. Switch S_1 now selects between five load resistors (1.0-200 ohms) and the floating potential option is eliminated in favor of having a trim resistor for each switch position.

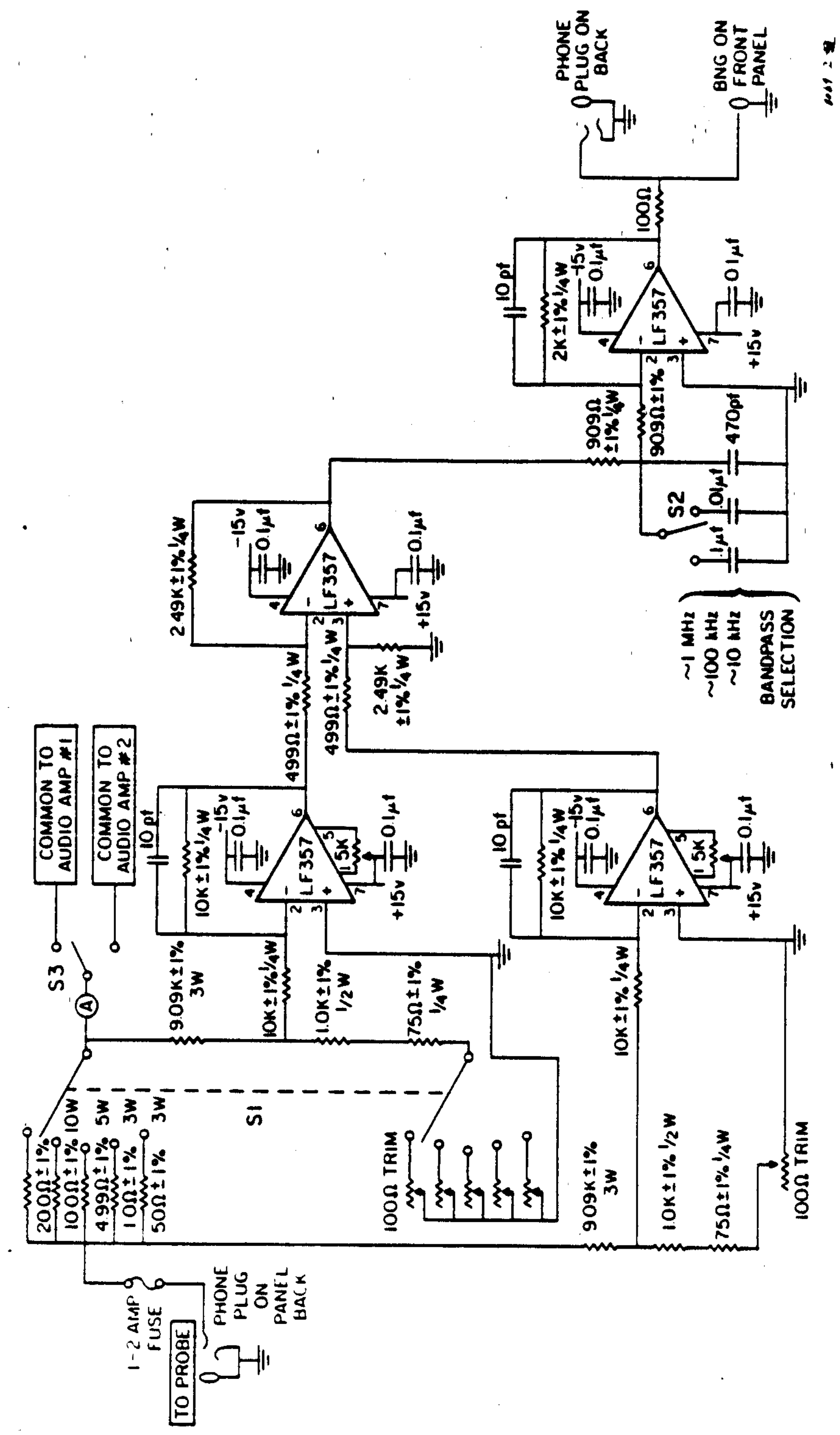

PHONE PLUG ON BACK
BNG ON FRONT PANEL
COMMON TO AUDIO AMP #1
COMMON TO AUDIO AMP #2
LF357
S1
S2
S3
100Ω TRIM
~1 MHz
~100 kHz
~10 kHz
BANDPASS SELECTION
1-2 AMP FUSE
TO PROBE
PHONE PLUG ON PANEL BACK

Figure 8

Figure 9 - Voltage Monitor Circuit Diagram The 'Voltage Monitor' in Fig. 6 consists of the above circuit. The common probe bias voltage is divided by 20 and inverted. The frequency response of this circuit is designed to match the current monitor circuits.

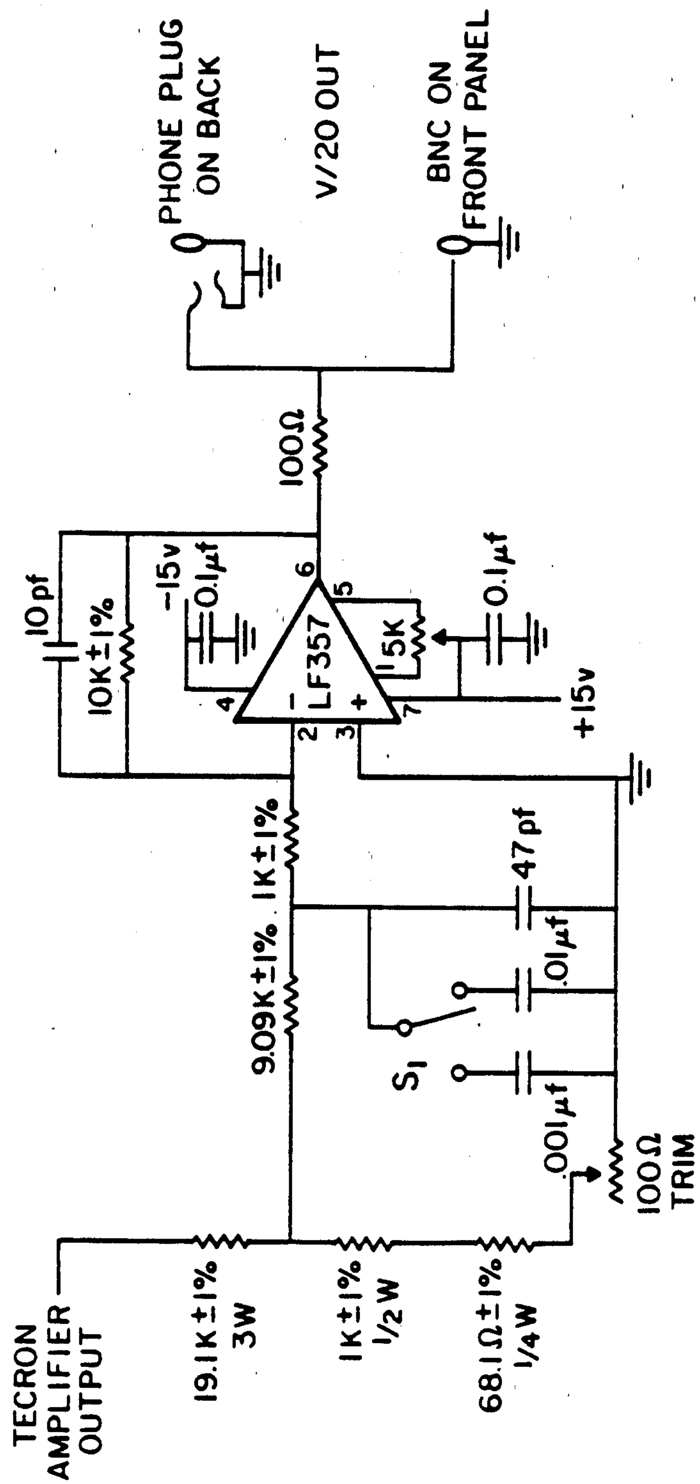

PHONE PLUG ON BACK
V/20 OUT
BNC ON FRONT PANEL
100Ω
10pf
10K±1%
−15v
0.1µf
6
5
4
2
3
7
LF357
1.5K
0.1µf
+15v
9.09K±1%
1K±1%
47pf
.01µf
S1
.001µf
100Ω TRIM
TECRON AMPLIFIER OUTPUT
19.1K±1% 3W
1K±1% 1/2W
68.1Ω±1% 1/4W

Figure 9

Figure 10 - Raw Voltage and Current Traces from DENSEPACK A typical output of probe current and voltage from DENSEPACK is shown. A 100 Hz triangular sweep is typically used to obtained a full Langmuir characteristic every 5 msec.

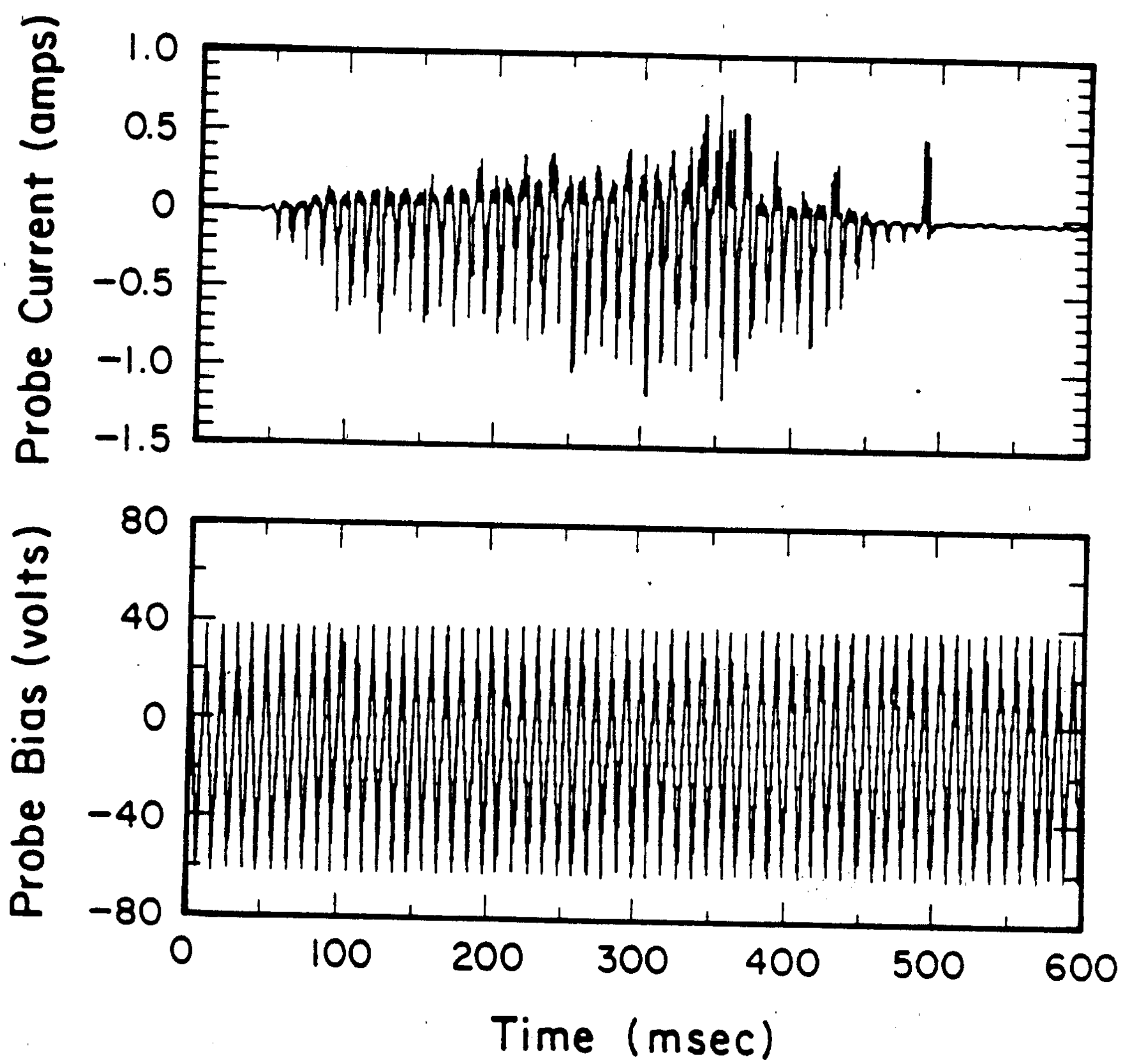


Figure 10

8075.8.3

Figure 11 - Ion Saturation Mode and Floating Potential Mode Ion saturation currents are obtained continuously by holding the common probe bias at −60 volts. Floating potential is obtained continuously for any probe with selector switch S_1 in position 1 (Fig. 7).

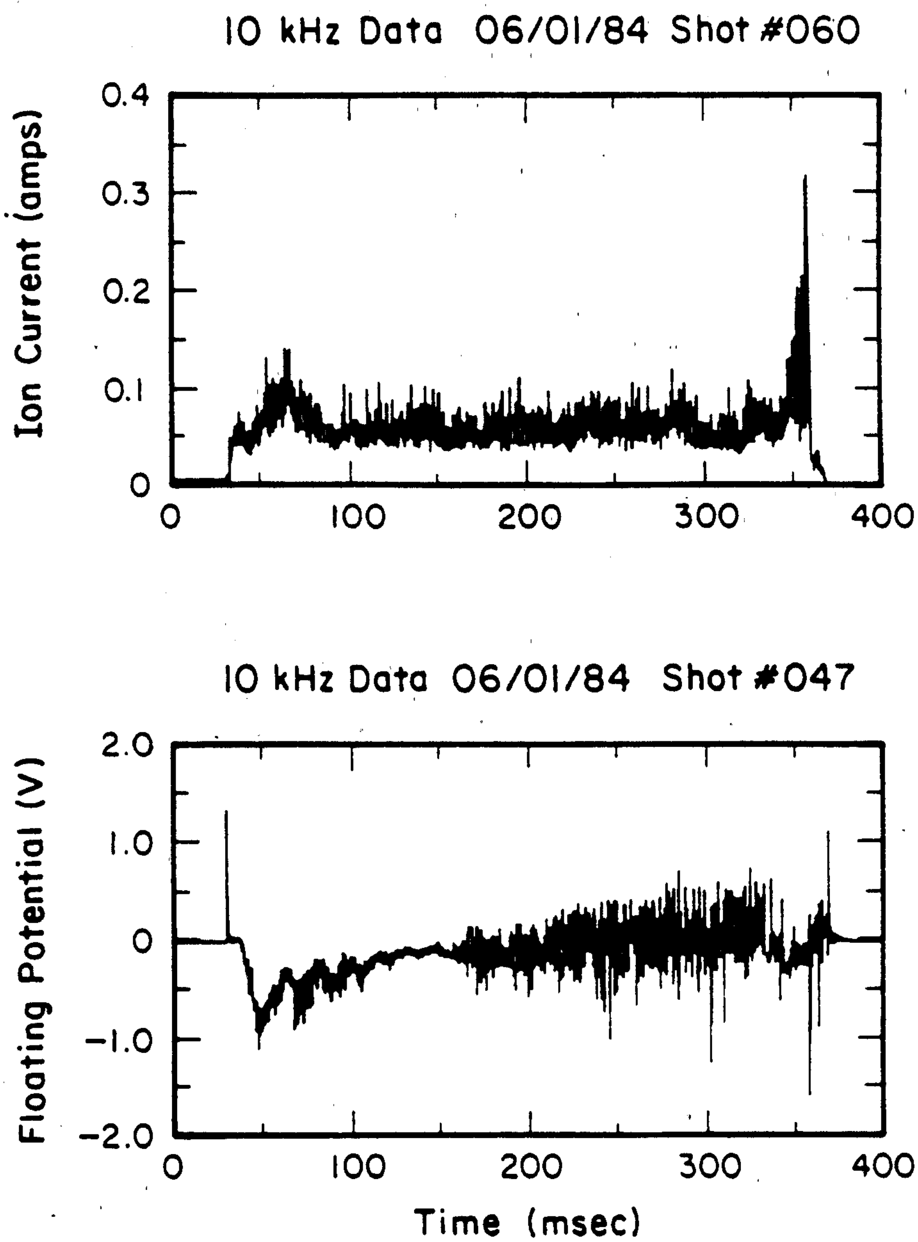
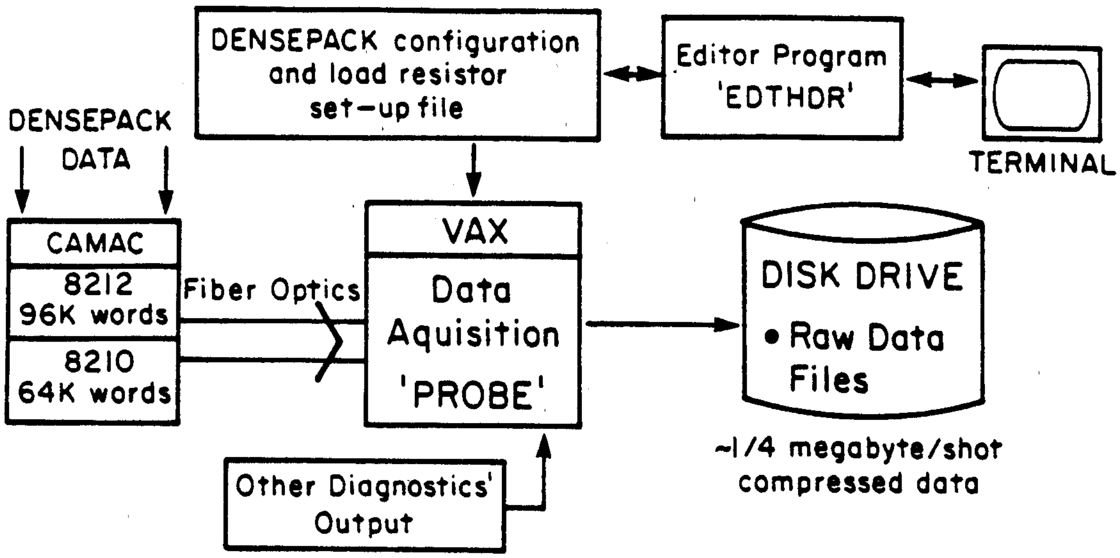


Figure 11

8075·8·4

Figure 12 - Data Acquisition and Display During An Alcator C Run Data recorded by DENSEPACK is read, compressed and stored between discharges. Information about the probe configuration is also recorded along with other tokamak diagnostics' output (central density, current, etc.). Raw data from any or all of the DENSEPACK probes can be reviewed to check the system's operation.

a) Data Aquisition Between Shots



b) Raw Data Display Between Shots

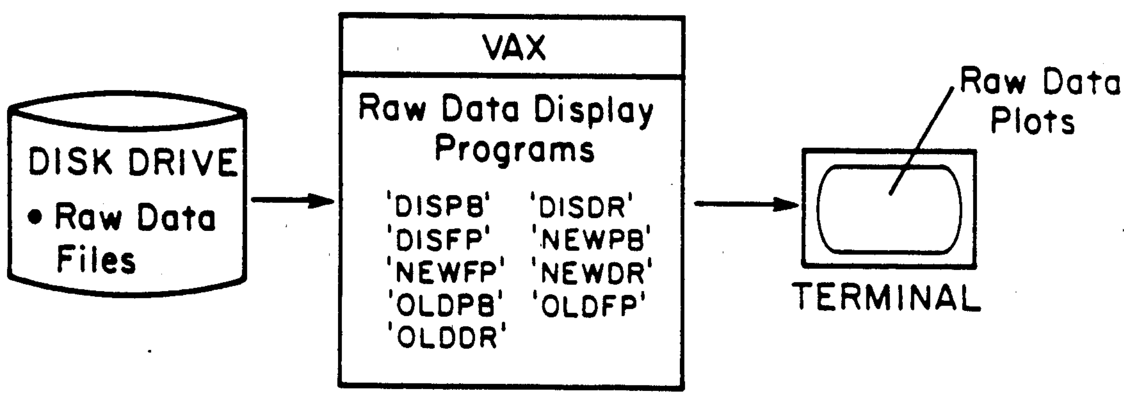


Figure 12

Figure 13 - Data Reduction and Archiving Raw probe data and central tokamak diagnostics' data is outputted in a three page summary for each shot. Langmuir probe characteristics are fitted and edge plasma parameters such as density and electron temperature are estimated and recorded in a reduced data file. Both raw data and reduced data are copied to magnetic tape for later reference.

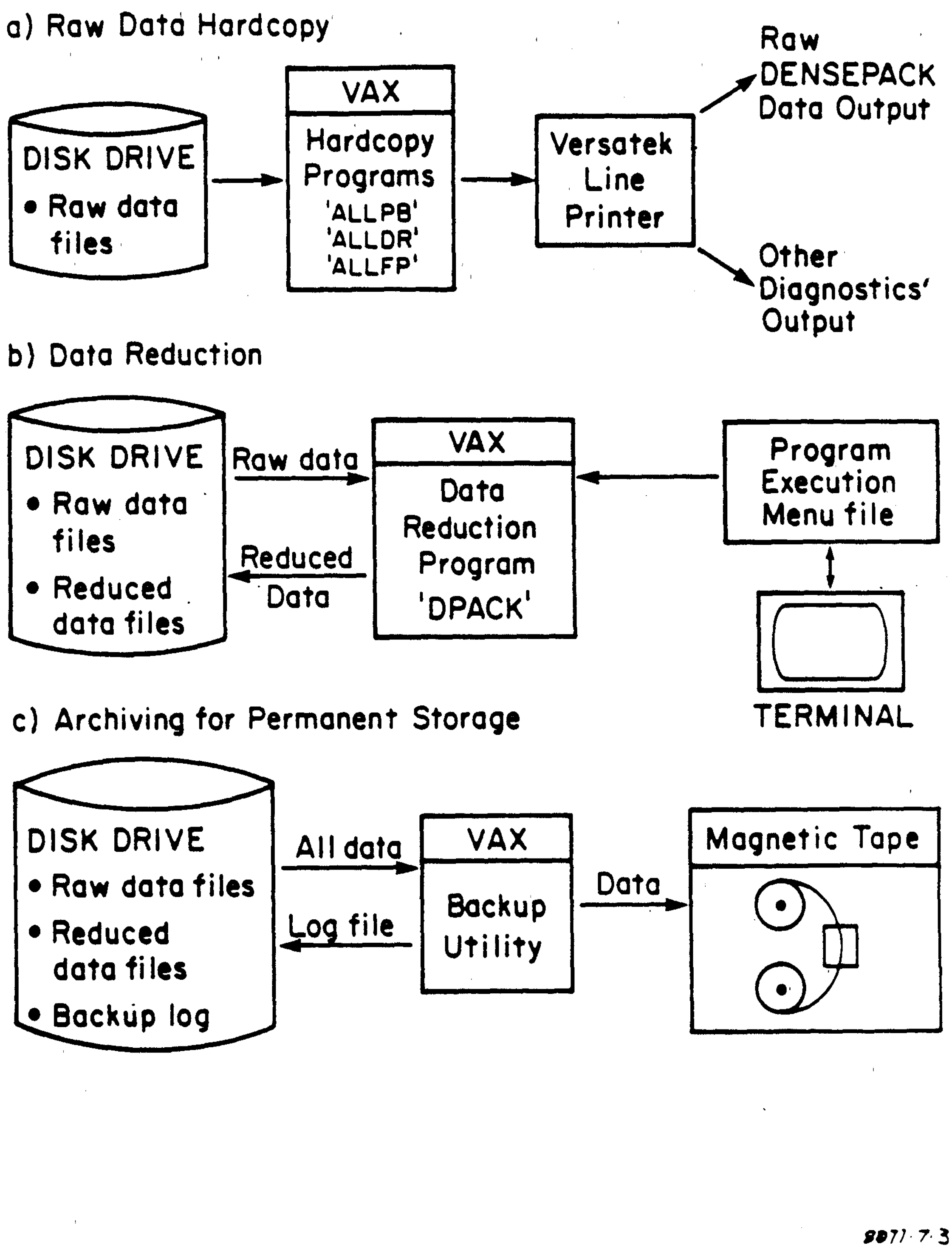

a) Raw Data Hardcopy
DISK DRIVE
• Raw data files
VAX
Hardcopy Programs
'ALLPB'
'ALLDR'
'ALLFP'
Versatek Line Printer
Raw DENSEPACK Data Output
Other Diagnostics' Output
b) Data Reduction
DISK DRIVE
• Raw data files
• Reduced data files
Raw data
Reduced Data
VAX
Data Reduction Program
'DPACK'
Program Execution Menu file
TERMINAL
c) Archiving for Permanent Storage
DISK DRIVE
• Raw data files
• Reduced data files
• Backup log
All data
Log file
VAX
Backup Utility
Data
Magnetic Tape
8871-7-3

Figure 13

Figure 14 - Typical DENSEPACK Langmuir Probe Characteristic A Langmuir characteristic from DENSEPACK displays a flat ion saturation regime ($V \lesssim -17$ volts) and an exponential electron transition regime ($-17 \lesssim V \lesssim +17$ volts). Electron saturation is not achieved but rather a gradual departure from exponential behavior is seen ($V \gtrsim +20$ volts).

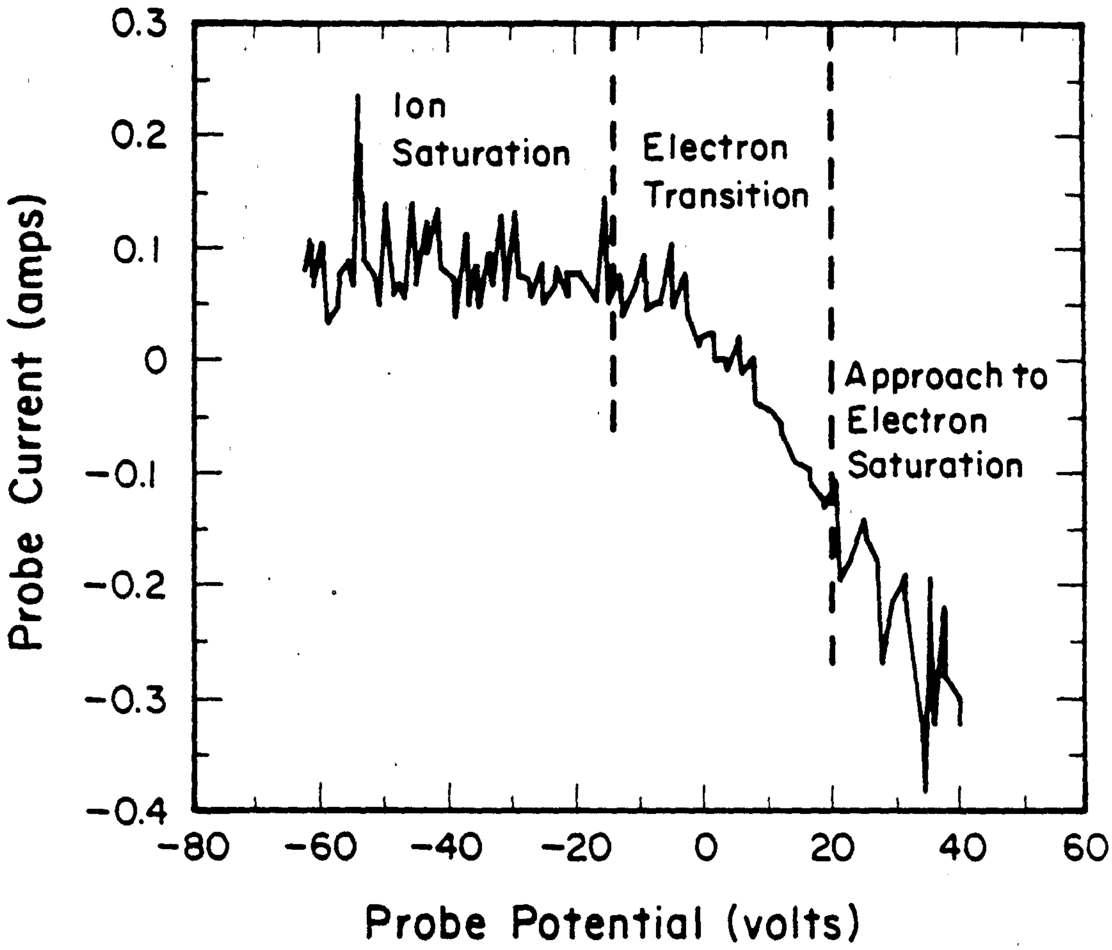


Figure 14

8075 4.2

Figure 15 - Functions Fitted to the Langmuir Characteristic Both an exponetial function (a) and a more complicated function based on the work of Stangeby[6] (b) is fitted to DENSEPACK data by the program 'DPACK'. Electron temperatures obtained by these two models can show a discrepancy.

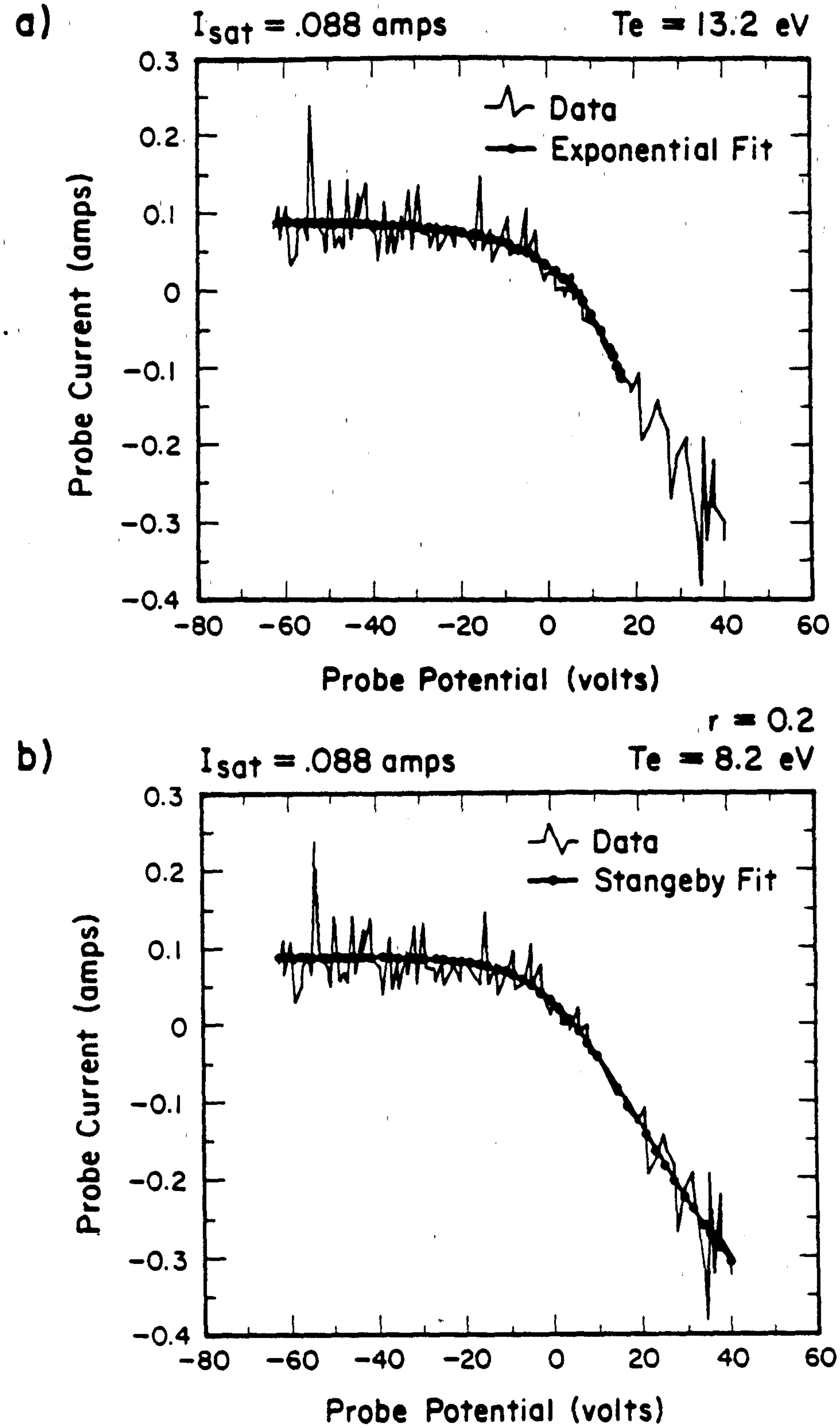

a)
Isat = .088 amps
Te = 13.2 eV
Data
Exponential Fit
Probe Current (amps)
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−80
−60
−40
−20
0
20
40
60
Probe Potential (volts)
b)
Isat = .088 amps
r = 0.2
Te = 8.2 eV
Data
Stangeby Fit
Probe Current (amps)
Probe Potential (volts)

Figure 15

Figure 16 - Reduced Data Display Programs Once the DENSEPACK data is reduced, it can be displayed in a number of formats (vs. time, radius, angle, or in a 3-D format) by programs 'DISDR' and 'DPKPLOT'.

a) Single Probe Reduced Data Display

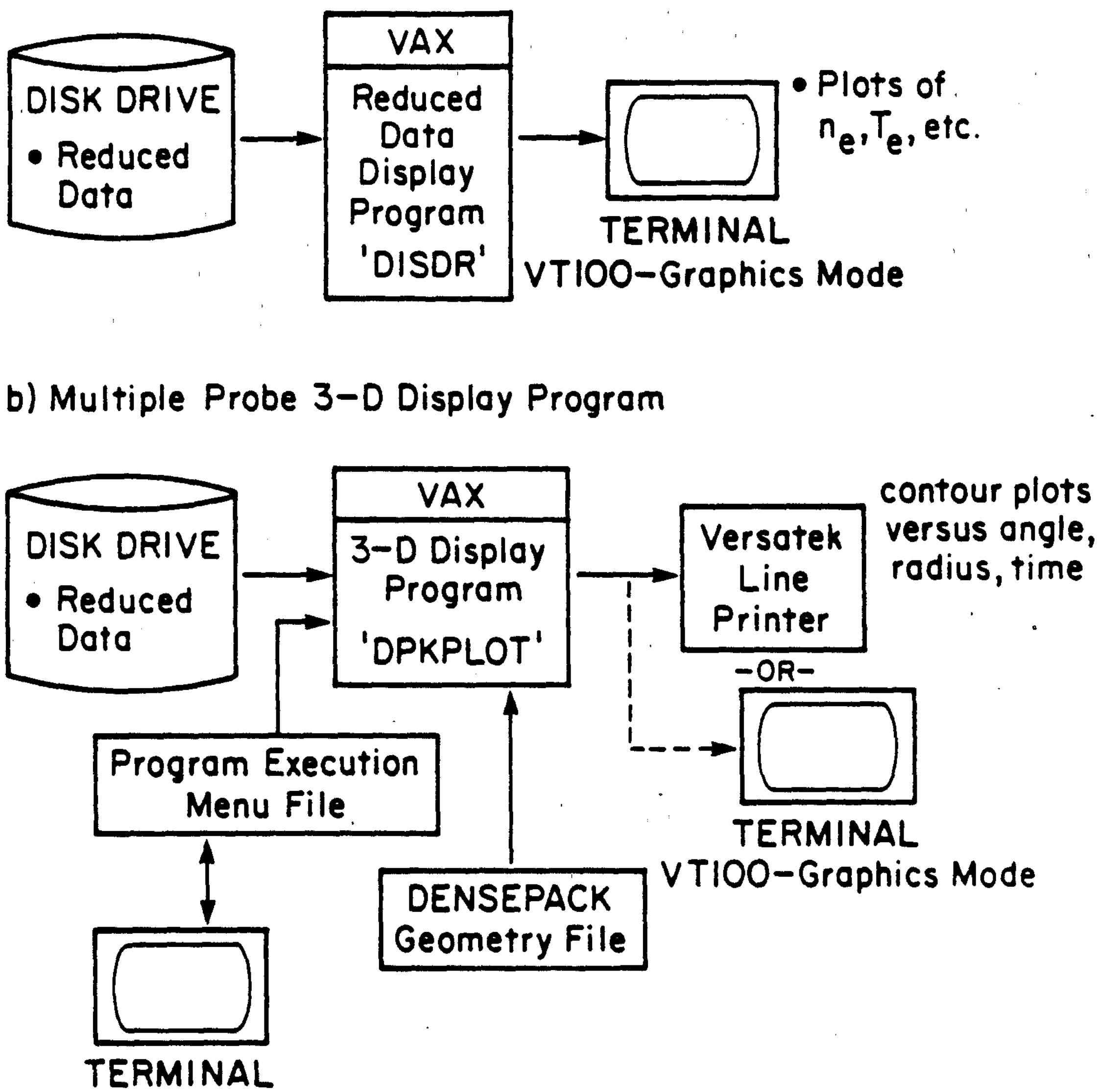


Figure 16

Figure 17 - Example plot of Edge Density versus Time and Angle One important result obtained by the DENSEPACK probe array is that density and temperature in the limiter shaodw plasma are non-uniform in poloidal angle. Here density at r = 16.8 cm is plotted showing density maxima near the top and bottom locations of the tokamak while minima occur near the inside and outside locations. (See Fig. 2 for angle definitions.)

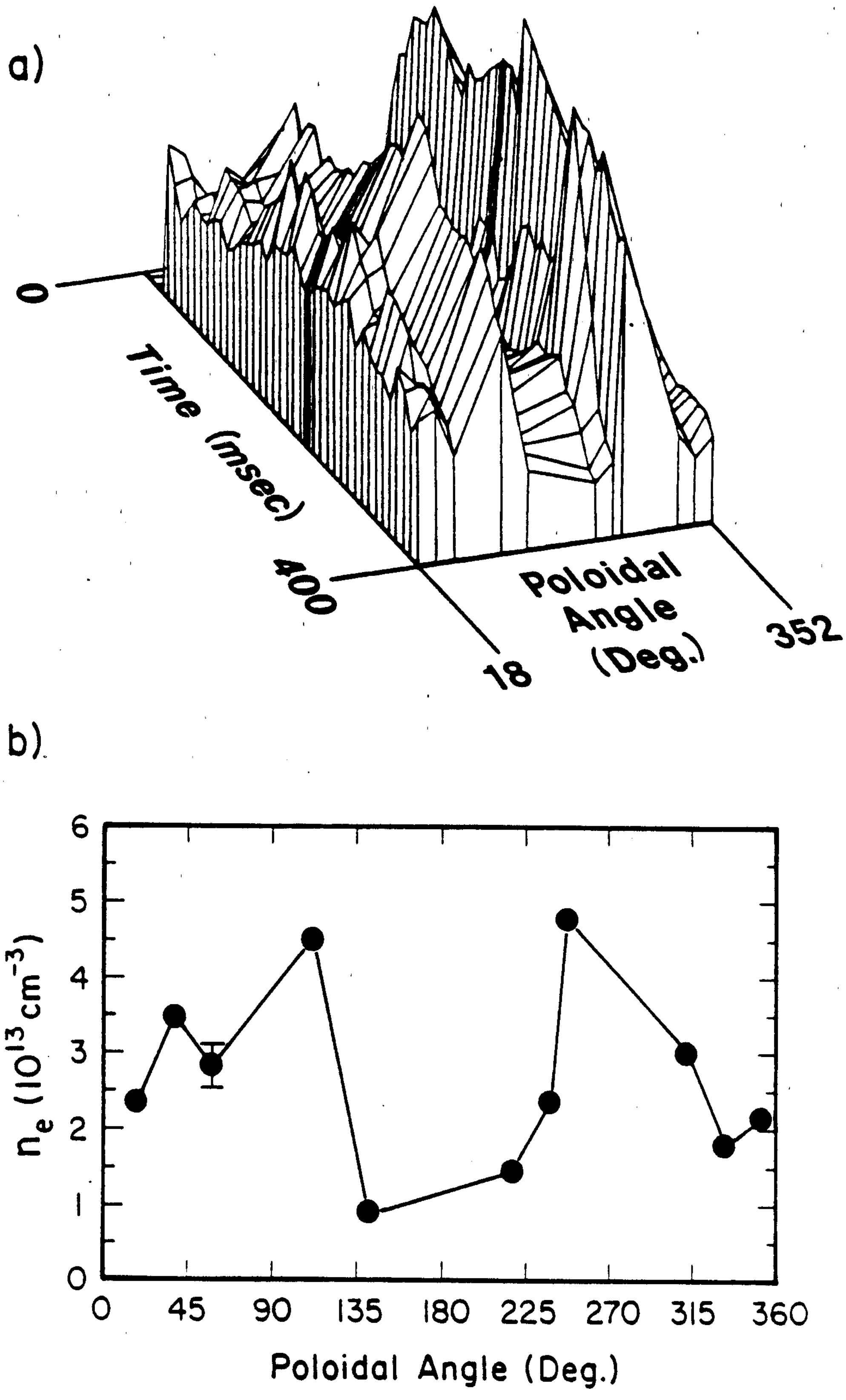

a)
0
Time (msec)
400
18
Poloidal
Angle
(Deg.)
352
b)
6
5
4
3
2
1
0
n_e (10^{13} cm^{-3})
0
45
90
135
180
225
270
315
360
Poloidal Angle (Deg.)

Figure 17

Figure 18 - Database Programs A database generation program, 'DPKBASE', scans reduced probe data files and summaries edge plasma parameters for various central plasma parameters. A database display program, 'DBPLOT', allows the user to examine edge versus central plasma dependencies by plotting any edge parameter against any central plasma parameter.

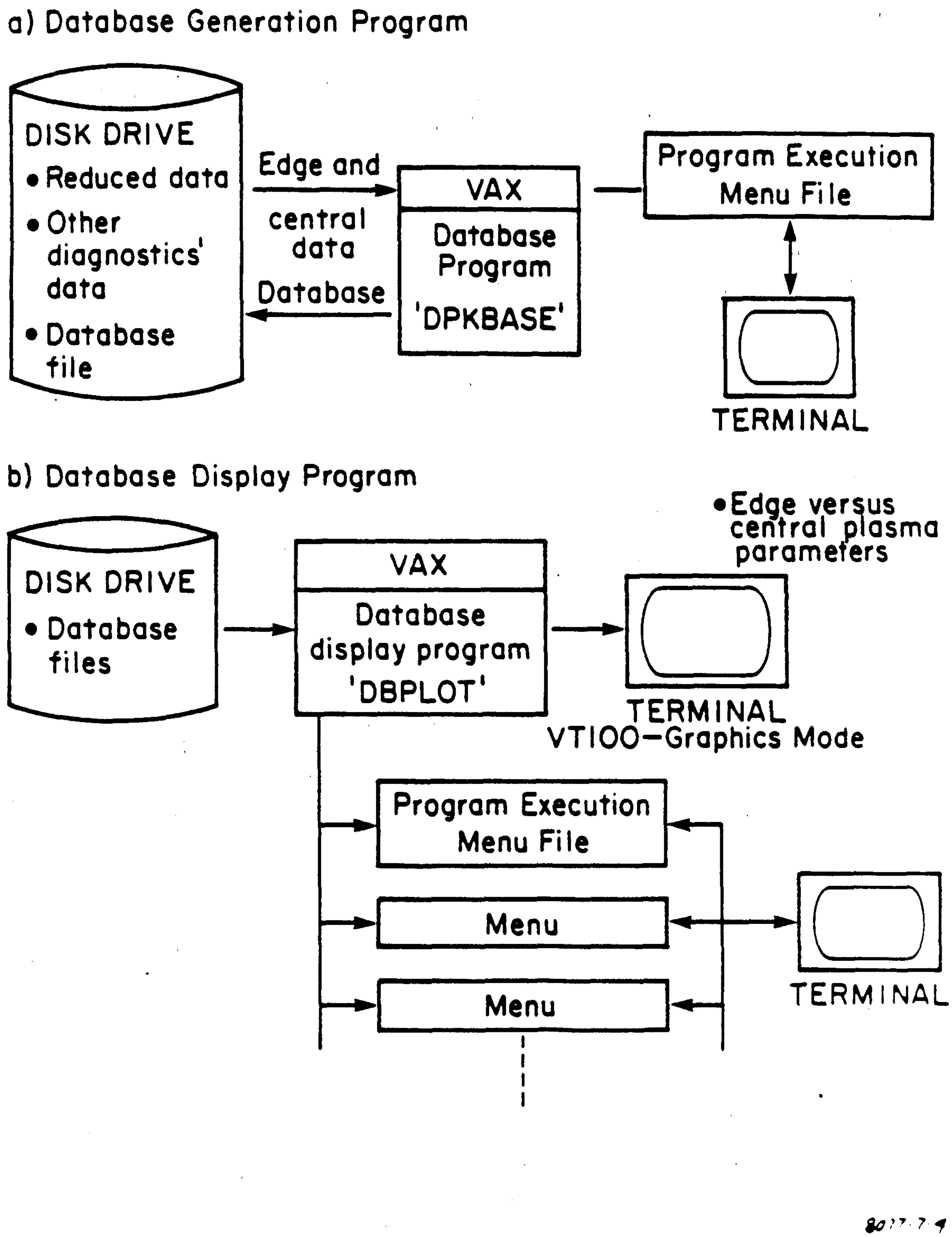

a) Database Generation Program
DISK DRIVE
• Reduced data
• Other diagnostics' data
• Database file
Edge and central data
Database
VAX
Database Program
'DPKBASE'
Program Execution Menu File
TERMINAL
b) Database Display Program
DISK DRIVE
• Database files
VAX
Database display program
'DBPLOT'
• Edge versus central plasma parameters
TERMINAL
VT100—Graphics Mode
Program Execution Menu File
Menu
Menu
TERMINAL

Figure 18