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A Fast Reciprocating Langmuir Probe for the DIII–D Divertor

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A new reciprocating Langmuir probe has been used to measure density and temperature profiles, ion flow, and potential fluctuation levels from the lower divertor floor up to the X–point on the DIII–D tokamak. This probe is designed to make fast (2 kHz swept, 20 kHz Mach, 500 kHz Vfloat) measurements with 2 mm spatial resolution in the region where the largest gradients on the plasma open flux tubes are found and therefore provide the best benchmarks for SOL and divertor numerical models. Profiles are constructed using the 300 ms time history of the probe measurements during the 25 cm reciprocating stroke. Both single and double null plasmas can be measured and compared with a 20 Hz divertor Thomson scattering system. The probe head is constructed of four different kinds of graphite to optimize the electrical and thermal characteristics. Electrically insulated pyrolytic graphite rings act as a heat shield to absorb the plasma heat flux on the probe shaft and are mounted on a carbon/carbon composite core for mechanical strength. The

Langmuir probe sampling tips are made of a linear carbon fiber composite. The mechanical, electrical, data acquisition and power supply systems design will be described. Initial measurements will also be presented.

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INTRODUCTION

A fast reciprocating probe has been installed in the lower divertor of the DIII–D tokamak which can provide high spatially resolved profiles of density, electron temperature, floating potential, and flow up to 25 cm above the floor, the height of a typical X–point. The divertor plasma is poloidally anisotropic (a two dimensional structure) and localized measurements are needed here to verify or extend our understanding of the important physics at work. One of the objectives of these measurements is to measure gradients on open field lines with a fixed Langmuir probe array across the divertor floor, another reciprocating probe[1] near the midplane and a divertor Thomson scattering system.[2] Additionally, the divertor reciprocating probe measurements can be used to verify measurements from a new divertor Thomson scattering system[3] along a vertical chord at the same major radius. Flows, an important parameter in modeling, and electrostatic fluctuation levels, indicative of convection and various instabilities, can also be measured by this probe and are useful in understanding the physics of divertors. By changing the magnetic configuration, the probe can sample the inside and outside legs of the divertor including the private flux region, scrape-off layer, and core plasma. The comparison of probe and Thomson scattering measurements under different conditions will be useful for verification of both systems. The detailed local measurements in the divertor will also be useful for studies of radiatively cooled zones in and around the X–point or the divertor floor occurring naturally or by deliberately raising the neutral pressure in the divertor.[4] The divertor reciprocating probe has been developed in collaboration with the University of

California, San Diego and General Atomics and was installed on DIII–D in the summer of 1995.

I. MECHANICAL DESIGN

The probe system is mounted below the tokamak vacuum vessel in order to complement the other diagnostics which are measuring in the lower divertor of DIII-D, The configuration is shown in Fig. 1. The probe mechanical support structure consists of two concentric inconel tubes supported by transformation toughened zirconia (TTZ) sleeve bearings. The larger tube (73 mm diam, 6 mm wall) provides mechanical support and electrical isolation for the fast moving 25 mm diameter tube which carries the graphite probe head into the divertor plasma. The large tube position is adjusted with a stepping motor through two coupled ACME drive rods. The stepping motor drive can be used under the machine to lower the entire assembly to the floor (no crane access). The frictional forces at the bearings, normally dominated by perpendicular loads, are very low for the vertical structure. The disadvantage of this bottom mounted orientation is that particulate matter can fall into the sleeve bearings and shields were added to prevent this. The entire assembly is supported by the torus hall floor and fixed at the top flange by a rigid side support structure attached to the large tube main bearing.

The pneumatically driven air piston pushes the rigid probe shaft upward and into the divertor plasma. A spring damper slows and reverses the motion as the piston force reverses and pulls the probe out again. The fast motion is a reproducible 25 cm stroke shown in Fig. 2. The starting position below the floor is adjusted with the stepping motor drive. The energy for the stroke is stored in a reservoir near the piston which is several times larger than the piston volume. The piston chambers are quickly pressurized or vented with a fast, high flow, solenoid valve controlled by a programmable logic controller (PLC). The PLC also controls all the system interlocks and the stepper motor. A CAMAC programmable timing pulse triggers the data acquisition system and the mechanical motion of the probe. The weight of the moving assembly (~ 10 kg) approximately compensates for the upward force of the vacuum on the probe fast flange and symmetric in and out motion was achieved with only one pressure regulator and one valve. There is also a partial balancing of the external assembly weight and the larger bellows upward vacuum force.

Because of spatial limitations on the length of the mechanical structure below the DIII–D vessel, the probe system could not be isolated from the DIII–D vacuum system. The fast stroke welded bellows has an expandable pumping cover in case a leak develops during machine operation. The entire system is baked along with the DIII–D vessel up to 350°C. The 92 mm port tube has a formed bellows at the top which flexes during machine baking. Only the smaller 25 mm tube travels past this bellows and rises above the vessel floor.

Because disrupting plasmas tend to go down and often terminate on the lower divertor floor, the probe had to be designed to survive the expected conditions without catastrophic damage. This put constraints on the probe electrical and mechanical properties. The probe tip, drive shaft, and support shaft are all isolated from each other. This provides two electrical breaks so current cannot flow down the axis of the probe shaft and across the magnetic field. This greatly reduces the possible J×B force on the probe. All support shafts are insulated by G-10 (borosilicate fiberglass) high temperature shaft isolation sleeves to prevent large currents flowing around loops in the stainless steel support structure and to isolate the moving parts from the vessel potential.

II. PROBE TIP DESIGN

The probe is designed to operate at auxiliary heating power levels of 10 MW and to survive disruptions (both thermal and current quench phases), edge localized modes (ELMs), and vertical displacement events (VDEs). Estimates of the heat flux expected on the plasma facing surfaces of the probe tip were obtained from a survey of the floor grazing incidence heat flux measurements in the DIII–D boundary database and were used to calculate the thermal response of the probe tip to heat flux parallel to the magnetic field lines in both one and two dimensions. For most cases, the heat flux is intense (<260 MW/m^2) for short periods (<100 ms) and therefore the maximum surface temperature could be characterized by a one-dimensional analysis using temperature dependent properties of the materials. For normal operating conditions we restricted the surface temperature to less than 1600°C. Two-dimensional finite-element analysis was performed using PATRAN and ABAQUS and geometric effects such as stresses resulting from differential expansion were included. The disruption, ELM, and VDE heat flux scenarios were all based on DIII–D measurements. Graphite ablation rates, using the heat of vaporization of graphite[5] of 75 kJ/gm, were estimated for thermal quench disruptions and found to be an acceptable 0.3 mm of material per event.

The probe tip has only low Z materials facing the plasma: graphite (four types) and boron nitride (BN). No wires or metal components travel above the divertor floor. The probe head is modular for ease of replacement.

The probe head design, shown in Fig. 3, incorporates a stack of pyrolytic graphite washers that are coated on the inside, top, and bottom surfaces with a pyrolytic boron nitride coating to reduce the current flow along the probe tip axis and therefore reduce J×B forces on the probe tip itself. The pyrolytic graphite washer stack shields the probe shaft from the strike point heat deposition during the dwell time and provides high radial heat flow which limits the surface temperature rise. The washer stack is compressed by an inconel spring which compensates for differential axial expansion of the washer stack during baking and during plasma operation.

The collecting tips used for the measurements are made of a graphite fiber composite with all fibers aligned in one direction (a 1D composite - Thermograph 8000). The 1D carbon fiber, domed, probe tip collectors provide high axial heat flow for reduced surface temperature during operation. The domed shape is insensitive to changes in the angle of the magnetic field. The tips are joined to isotropic graphite rods to extend their length. This avoids use of metal above the divertor floor to protect the machine surfaces from contamination in case the probe is mechanically damaged while operating. The collector diameter is 2 mm and the hemispherical dome projects 1 mm into the plasma. This yields a projected area of 1.5 mm^2 for each collection direction. Two pins are recessed into a cutaway zone 1.5 mm below the uppermost surface for a directional measurement of ion flux. This configuration of the collectors allows the heat flux to be incident onto the fiber ends which takes advantage of the high conductivity properties of this material. The collectors are isolated with 1 mm wall BN sleeves which are flush with the probe tip surface. These sleeves have a 0.1 mm gap at the inner diameter which extends 3 mm down the axis to prevent electrical problems from graphite deposition on the insulators.

To add strength to the probe tip assembly, a 3D carbon fiber composite rod is used as a core for the washer stack. This 3D carbon/carbon fiber composite interior support rod has high strength, low Z, matches the PG washer radial expansion, and also has a pyrolytic BN insulating coating which limits current flow and reduces J×B forces. The probe tip is deliberately designed to be the weakest link in the load bearing structure so as to protect the fast moving mechanism and allow proper retraction. The bearings are all designed to take the J×B forces even in the case where current does flow down the probe tip axis.

III. MEASUREMENTS OF PHYSICAL PARAMETERS

There are five collectors: two tips can be used for a double probe or two single probes to get density and electron temperature measurements at 2 kHz. A floating potential (V_f) tip provides a high frequency floating potential measurement. It has a 100 kΩ vacuum compatible metal film resistor in the lower part of the tip which eliminates the low impedance capacitive losses to the coax cable ground at high frequency. Two recessed Mach probe tips measure directional ion flux. Signals connect to the feedthrough in a bakable vacuum coax composed of an alumina dielectric, aluminum tube, and OFHC copper wire. All cables are insulated and tested for electrical isolation at 5 kV. The rear cable interface uses a cube design[6] to bring out the signals with bakable SHV connectors and connect the piston drive to the fast tube.

The double probe tips are presently operated with four 50 V Kepco 8A programmable power supplies in series (200 V, 8A). The 1 kHz signal to drive these supplies is controlled remotely and transformer isolated. A sample I-V characteristic is shown in Fig. 4. The downstream Mach probe pin is biased at 300 V into ion saturation by a d.c. (600 V, 4A) supply. The upstream Mach pin voltage is asymmetrically swept through zero every 10 ms to suppress arcing.

IV. CONTROL AND DATA ACQUISITION

The X–point probe interlock system is controlled by a GE Fanuc programmable logic controller operated at vessel ground. Communication with the PLC is accomplished via a RS232 serial connection from the VAXStation 4000 model 90A to a fiber optic repeater, which provides high voltage isolation between the CPU ground and the vessel ground of the PLC. The fiber optic repeater communicates with the PLC via a fiber optic to RS485 line. The interface to the PLC control system is a graphical user interface programmed with Research Systems, Inc. IDL (Interactive Data Language) software.

The divertor reciprocating probe system typically acquires 64 ksamples/discharge of monitor signals to verify proper functioning of various power supplies and probe motion, and an additional 1 Msamples/probe plunge of scientific data for n_e, T_e, parallel flow, and potential fluctuation measurements. The existing data acquisition system is limited to 2 probe plunges/discharge, or 2 Msamples of data. Combined with 4 Msamples of data from the midplane reciprocating probe array,[2] the data acquisition system must handle up to 6 Msamples of data per discharge. To accommodate this data stream, we utilize a dedicated ethernet Local Area Network consisting of our CPU (a VAXStation 4000 model 90A) and three CAMAC crates. The CAMAC crates are connected to the ethernet via Hytec Mark III Ethernet Crate Controllers capable of handling large block transfers over the ethernet LAN. The VAXStation has 4 Gbytes of on-line disk storage, and a 4 mm DAT tape drive for archiving of raw probe data. Sufficient disk storage is maintained to retain all processed data (results of raw data analysis, including electron density and temperature and all fluctuation analysis) permanently on disk for ready access.

The floating potential circuit of the X–point probe was designed with the intent to measure fluctuations in the divertor plasma. The potential fluctuations system has a bandwidth of 500 kHz, limited by the 1 MHz sampling rate of the digitizers and the signal anti-aliasing filter at 500 kHz. The capability to measure potential fluctuations in the divertor floor several centimeters above the divertor target plates is a unique capability.

V. OPERATION AND RESULTS

The probe has operated reliably for 6 months and has obtained unique and interesting information about the DIII–D divertor. After 5 months of operation with the tokamak, we inspected the probe tip and found it to be in very good condition with little sign of erosion.

We monitor the probe head with an infrared camera looking down at the divertor floor and we observe the probe surface temperature rise as it penetrates the separatrix. Typical profiles of density and temperature are shown in Figure 5 for a plunge through the outer divertor leg and into the SOL and are compared with profiles from the new divertor Thomson scattering system. The spatial resolution is very good (<2 mm) and the time response of the measurements are fast enough to track density changes during an edge localized mode (ELM) as seen in Figure 6.

First fluctuation measurements have shown that in attached discharges, the divertor plasma potential fluctuation level $\tilde{\Phi}_f/T_e \approx 0.5–1$, which is generally consistent with potential fluctuation levels measured at the outboard midplane[7]. In two cases, however, the normalized fluctuation level $\tilde{\Phi}_f/T_e$ is substantially enhanced above the outboard midplane levels: during ELMs in both attached and detached conditions, and during divertor plasma detachment.

By sweeping the divertor plasma strike points, it is possible to obtain 2-D information on the divertor plasma conditions, since the probe retraces a different part of the divertor plasma. We calculate the relative position of our probe tip every few milliseconds with EFITD65Y[8,9] in order to know our location with respect to the divertor magnetic structure.

CONCLUSIONS

The probe has demonstrated the fast time response, detailed spatial profile capability, and high power handling capability that will be needed for future divertor research. It will provide useful data for divertor characterization studies and modeling efforts, and information needed for advanced divertor designs.

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FIGURE CAPTIONS

Fig. 1 X–point probe tip - schematic of entire assembly.

Fig. 2 Time history of the probe motion.

Fig. 3 Probe tip assembly including orientation of the collectors.

Fig. 4 a sample I-V probe characteristic.

Fig. 5 n, T_e through the outer divertor leg from below. The DTS data, taken just after the probe plunge, is shown with the probe profile acquired during the inward and outward stroke.

Fig. 6 Density rebound following an ELM demonstrates the millisecond response time of the probe measurement. The probe head was in the outer divertor SOL during the time shown.

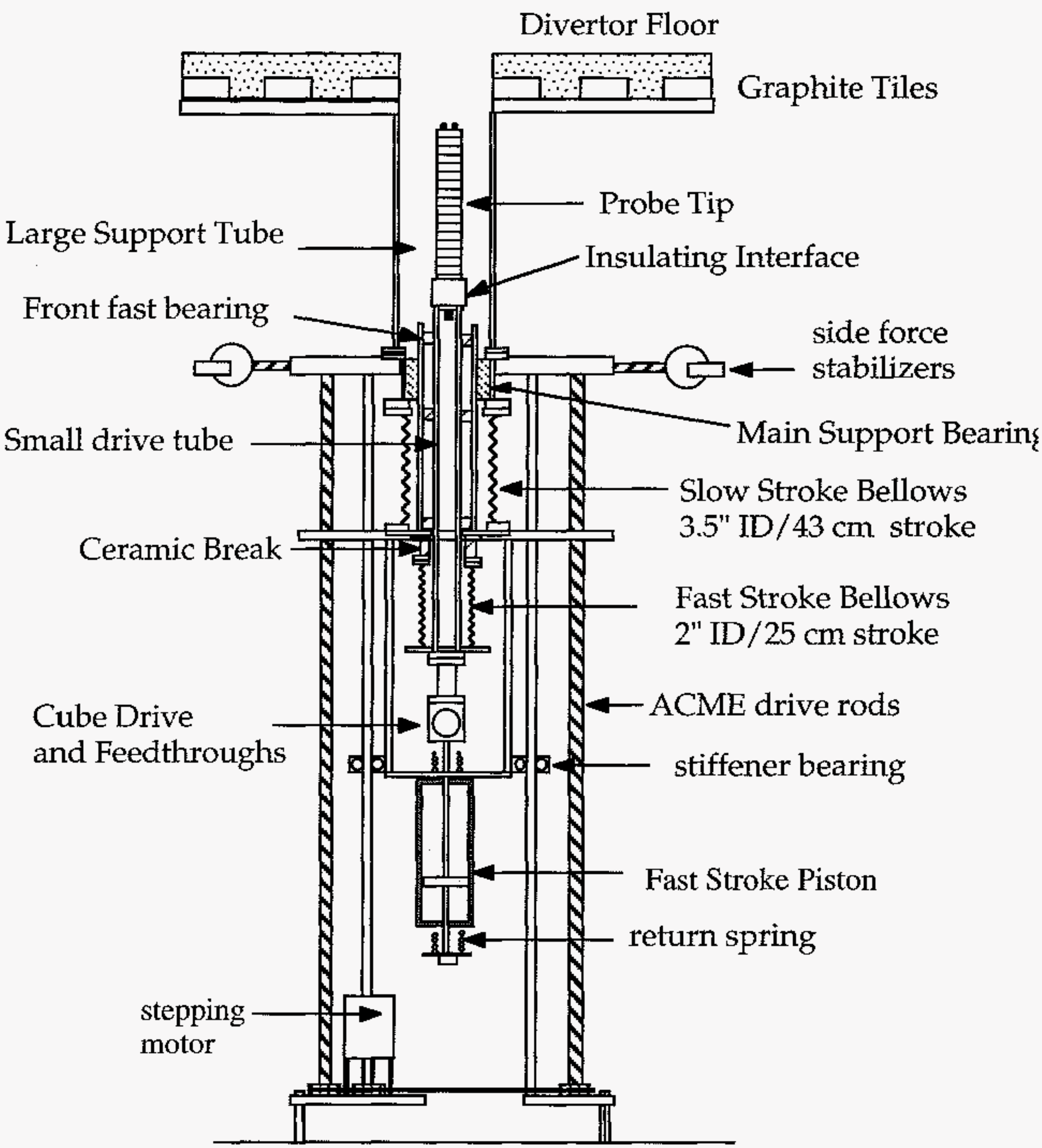

Figure 1

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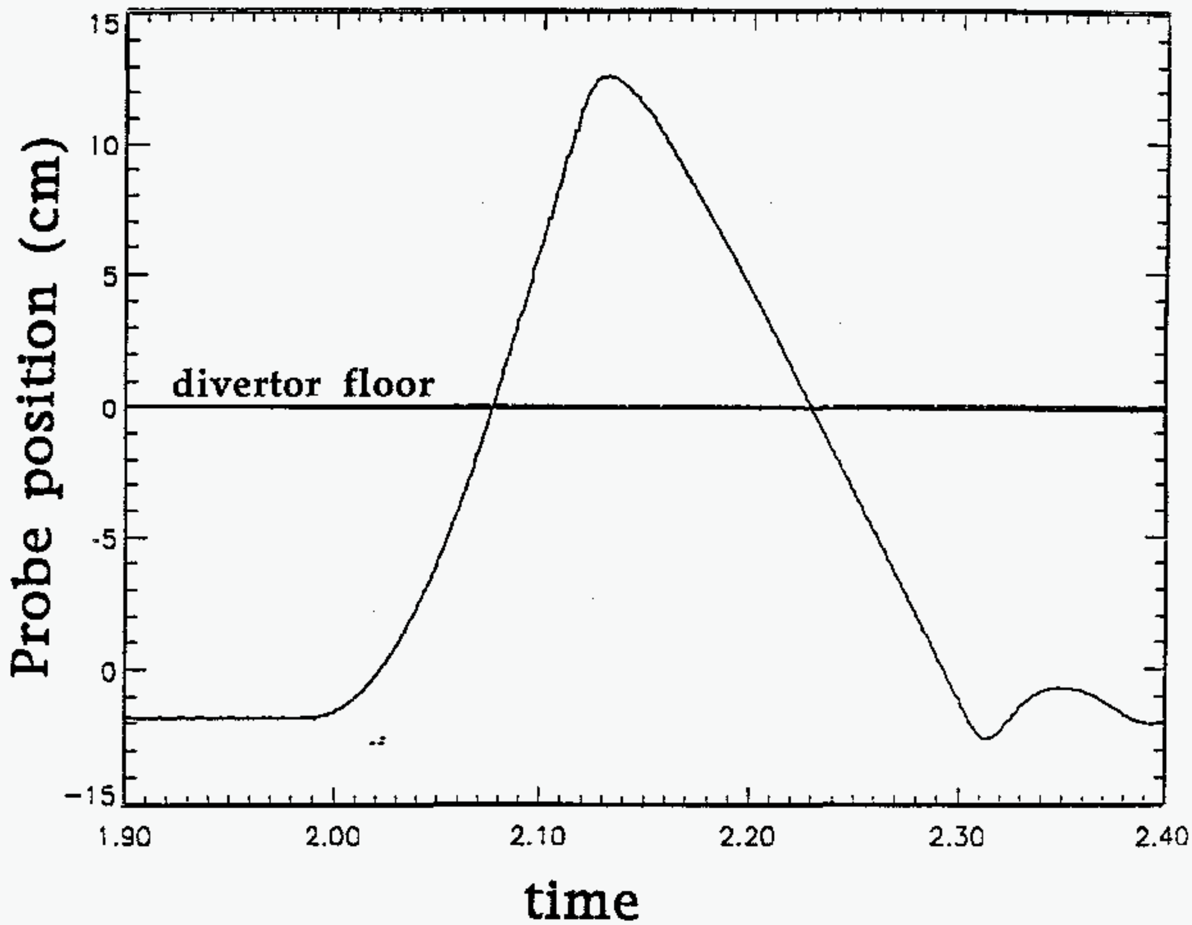
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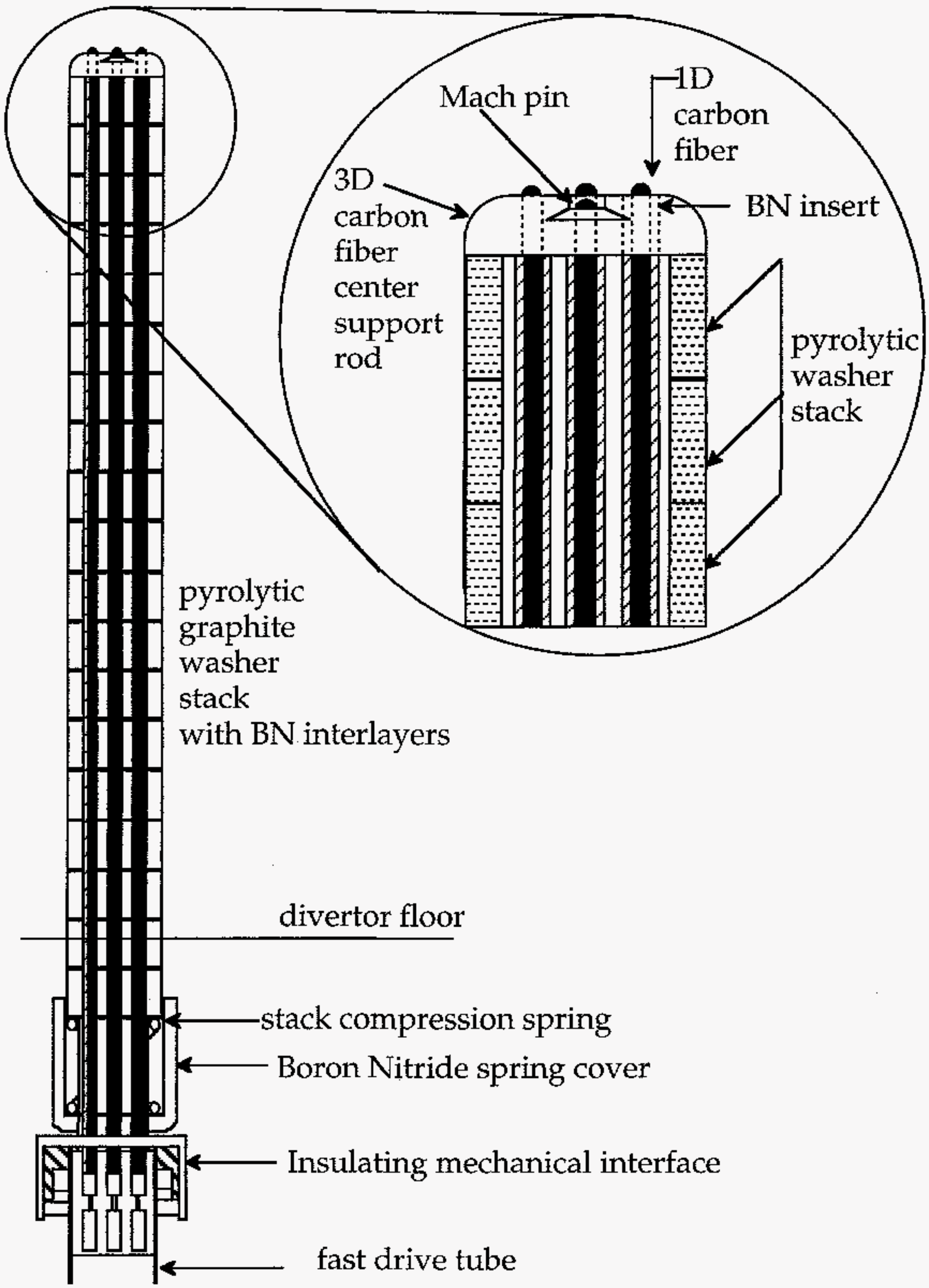
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3D carbon fiber center support rod
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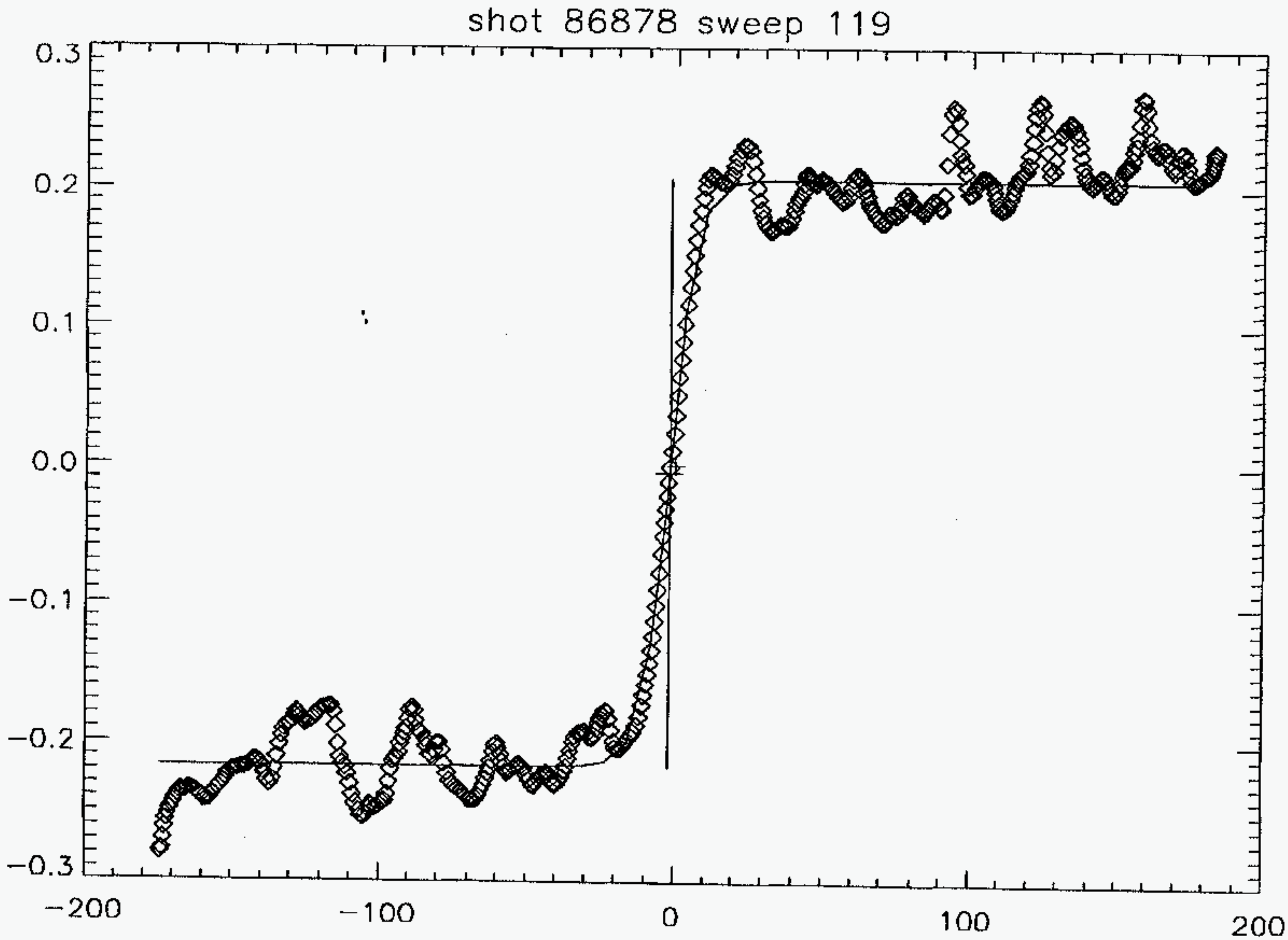
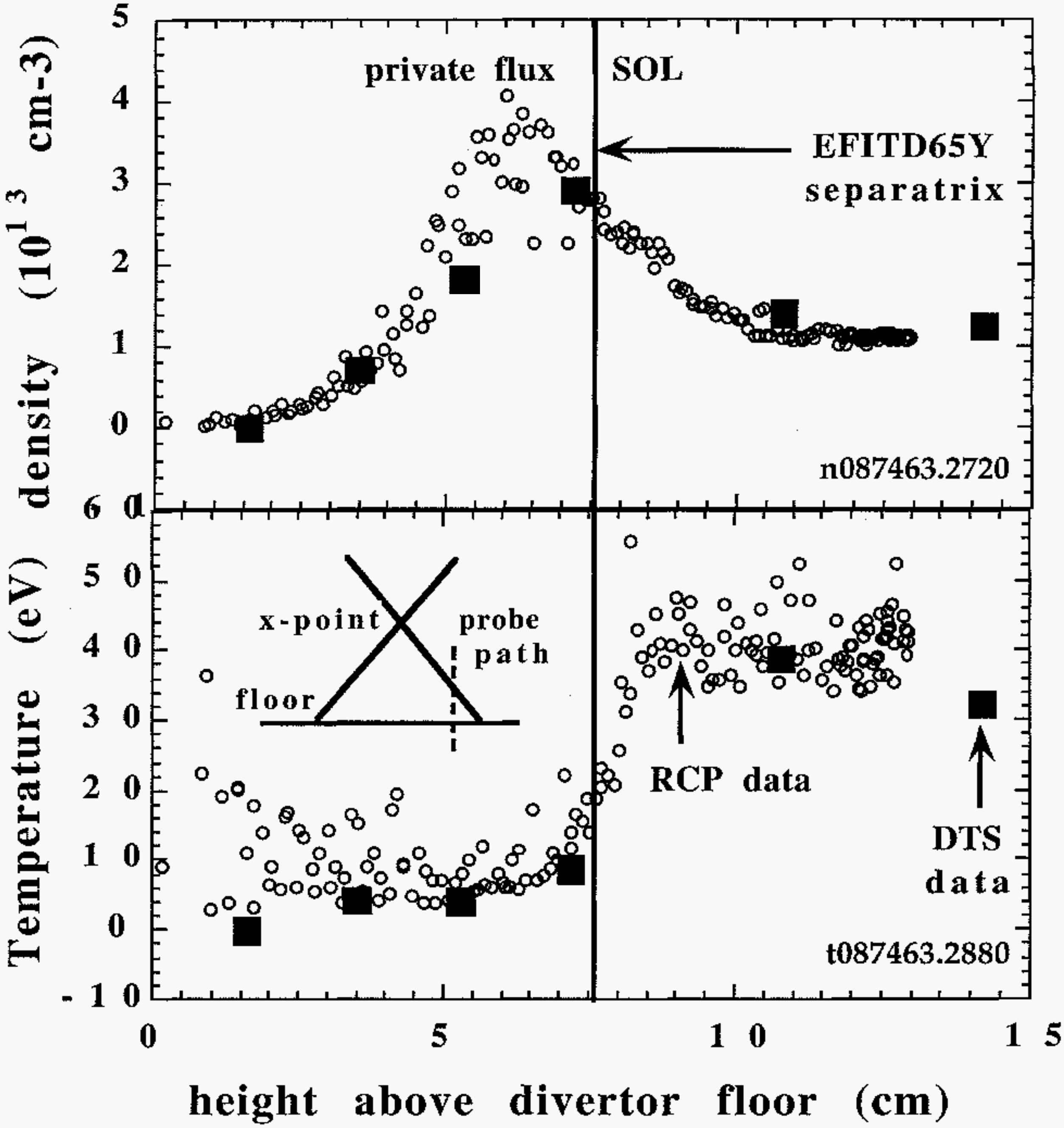


Fig 4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Temperature (eV)
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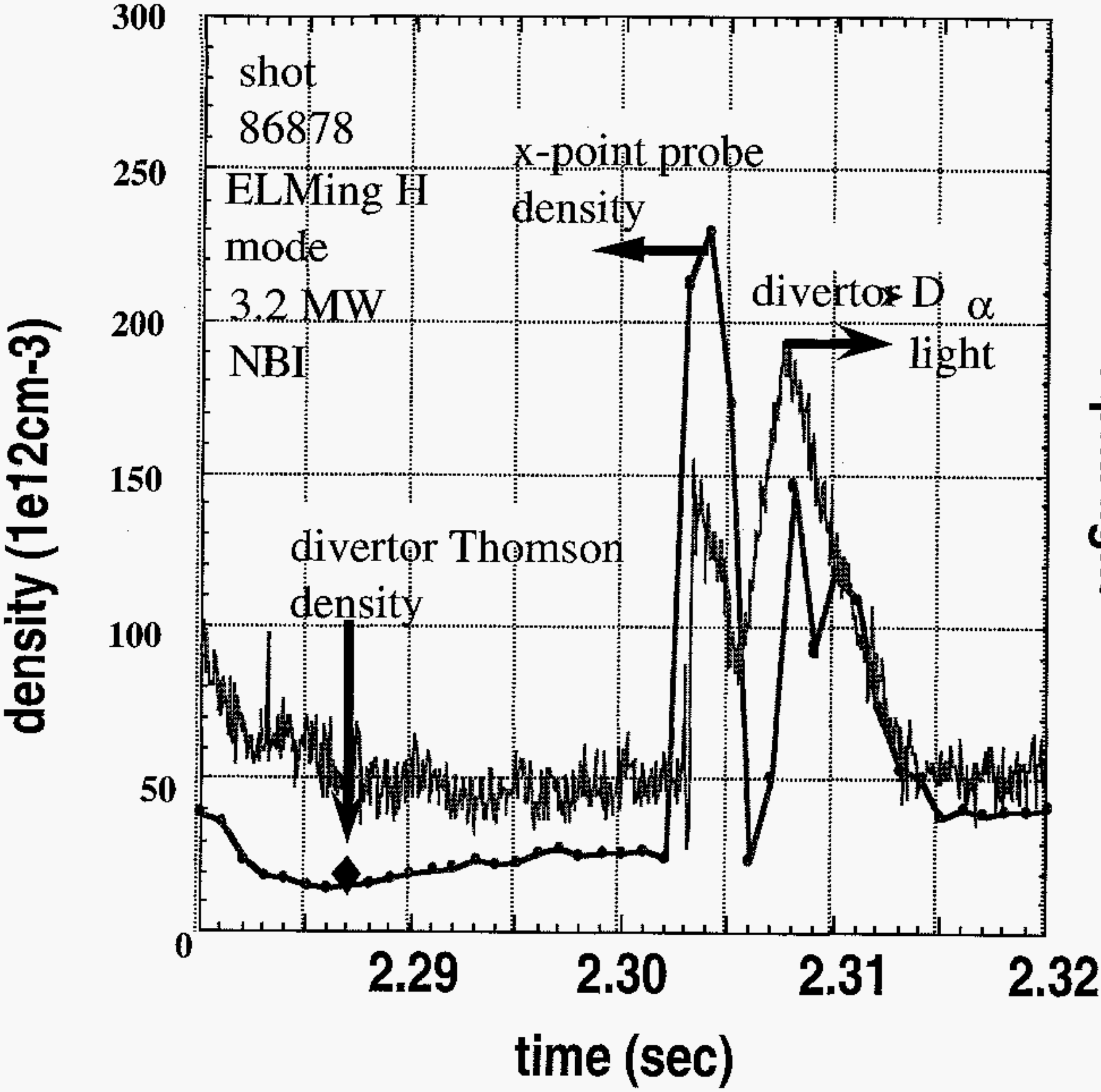

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