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Scanning ion sensitive probe for plasma profile measurements in the boundary of the Alcator C-Mod tokamak

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A new Ion Sensitive Probe (ISP) head has been created for the outer-midplane scanning probe system on the Alcator C-Mod tokamak. The new probe head contains three elements: an ion sensitive probe to measure ion temperature and plasma potential, a Langmuir probe to measure electron temperature, density, and floating potential and a second Langmuir probe to measure ion saturation current and the density fluctuations arising from ‘blob’ events. The ion sensitive probe current is normalized to this measurement to reduced deleterious effects of the strong fluctuations. Design of the high heat flux probe (>100 MW/m²) and initial results are presented.

1. Introduction

Ion temperature ($T_i$) is not routinely measured in the boundary (or Scraper-Off Layer, SOL) of magnetic fusion devices. High spatial resolution measurements of $T_i$, along with the electron temperature ($T_e$), are crucial for understanding cross-field transport of energy in the boundary plasma. Cross-field heat transport strongly affects the divertor heat flux width and thus the peak heat flux [1]—a parameter that is at engineering limits in present experiments and will likely be larger in reactor scale devices. Additionally, $T_i$ plays an important role in the sheath heat flux, plasma potential, and sputtering.

While spectroscopic techniques, such as Charge eXchange Recombination Spectroscopy (CXRS) [2], can provide information on ion temperature, they typically measure the impurity temperature—not the main fuel—and tend to be limited in spatial resolution. Langmuir probes are the most common edge diagnostic technique, but they are only capable of measuring $T_e$. Retarding Field Analyzers (RFAs) are the most widely used diagnostic of $T_i$ in tokamaks [3] and are often used in other plasma physics experiments. Their operation is simple, relying on single-particle motion along the field, sheath physics, and the assurance that the density in the probe volume is below the space-charge limit. Yet measurements with RFAs are challenging, requiring thin slit plates and delicate grids. The operation of such probes in the boundary plasma is limited by the intense heat flux (100s MW/m²).

The Ion Sensitive Probe (ISP) provides an attractive alternative to the RFA [4]. Its construction is simple: two concentric, electrically isolated cylinders which are easily manufactured with refractory metals. The geometry is ideal for handling heat flux, with plasma-facing surfaces nearly tangent to the magnetic field and the incident heat flux. Yet the ISP has a major drawback: the physical model of how it measures $T_i$ is not as simple as the RFA and it has yet to be thoroughly benchmarked against other accepted techniques, especially in the high density plasmas ($\sim 10^{20}$ m⁻³) typical of the C-Mod SOL. To this end we have developed two probe heads to measure $T_i$ in the C-Mod boundary plasma: an ISP head, described in this paper, and an RFA head, described in a companion paper (see Ref. [5]). Comparisons of measurements from these two probe systems along with CXRS measurements will be presented in a future paper.

Section 2 provides a brief review of the use of ISP-type probes and the theory of their operation. The design of an ISP for the high-heat flux, ultra high vacuum environment of the Alcator C-Mod tokamak is described in Section 3. Initial measurements with the ISP are presented in Section 4.

2. Ion sensitive probe operation
   a. Ion Temperature
At the most basic level, an ISP uses the large difference in Larmor radii \( r_g \ll i \ll \propto \) between ions and electrons: 

\[
\frac{\rho_i}{\rho_e} = \frac{\sqrt{m_i/m_e}}{\sqrt{1 + \frac{E_i}{2k_B T_e}}/\sqrt{1 + \frac{E_e}{2k_B T_e}}} \approx 60, \text{ for } T_i = T_e \text{ in deuterium.}
\]

An ISP typically consists of two concentric cylinders with their axes normal to the magnetic field, see Figure 14. The inner cylinder (here called the Collector, in other works called the P-electrode) is recessed at least the electron Larmor radius behind the outer cylinder (here called the Guard, in other works called the Wall or G-electrode). The recess prevents line-of-sight access by the electrons along the magnetic field to the Collector. In principle the only current appearing on the Collector is that due to ions. In practice it is found that the Guard needs to be biased slightly positive with respect to the Collector [6]. Additionally, the Collector must be about an ion Larmor radius behind the Guard for proper operation.

![Figure 1](image_url)

Figure 1. Cross section of C-Mod ion sensitive probe with all parts to scale. The Collector is recessed about an ion Larmor radius behind the Guard. Because the electron Larmor radius is so much smaller than the ion, this prevents any electron from streaming directly along the magnetic field to the Collector.

Positive bias of the Collector electrostatically repels ions, much like a negatively biased Langmuir probe repels electrons (albeit in the presence of a constant ion flux for Langmuir probes). Sweeping the Collector bias samples an energy integral of the ion energy distribution perpendicular to the magnetic field. For a Maxwellian energy distribution the resulting \( I-V \) (current-voltage) relationship is an exponential,

\[
I(V) = \begin{cases} 
I_0, & V < V_0 \\
I_0 e^{-e(V-V_0)/k_BT_i}, & V \geq V_0. 
\end{cases}
\]  

(1)

Where \( V_0 \) is a reference potential. There is some discrepancy in what \( V_0 \) represents. Falabella found, through comparison with a thallium beam probe-plasma potential diagnostic, that \( V_0 \) was the plasma potential [7]. On the other hand, Ochoukov found the plasma potential to be where the current decayed to near-zero [8]. This may be because Ochoukov’s probe was space charge limited and not able to resolve the \( I-V \) response indicated by Eq. 1.

Information about the density is captured in \( I_0 \) [9, 10, 7], although a quantitative relationship is complicated by probe geometry as well as the ratio of parallel to perpendicular ion temperature \( T_{i,\|}/T_{i,\perp} \). We find that our measurements of \( I_0 \) do increase proportionally to density measured by a Langmuir probe, suggesting that possible corrections for variations in \( T_{i,\|}/T_{i,\perp} \) are likely small.

An assumption must be made on the effective ion charge, \( Z_e \) to get \( T_i \) from a fit of Eq. 1 to the data. Kinetic simulations of ion collection by an RFA have been made to investigate the impact of a \( C^{+4} \) impurity fraction ranging from 0 to 100% in an otherwise pure \( Z=1 \) plasma [11]. If \( Z \) in Eq. 1 is taken to be that of a pure plasma, a less than 20% error in \( T_i \) will occur for impurity fractions up to 50%. Although the details of particle collection are different, it is likely that similar results apply for the ISP.
Ion temperature measurements have been performed with ISPs in Q-machines [12, 13], tokamaks [14, 15, 10, 16, 17, 18, 19], mirror machines [20, 7, 21], a simple plasma device [22], a stellarator [23, 24], linear plasma devices [25, 8, 26], an electron cyclotron heated plasma [27], and even an unmagnetized processing plasma [28]. One has also been used to estimate tokamak plasma transport coefficients [29].

Measurements of ion temperature from ISPs are found to be consistent with other diagnostics, including favorable comparisons with a Faraday cup on the DIVA tokamak [14], gridded analyzer in the MIX 1 mirror machine [20], and a compact neutral particle analyzer in the GAMMA-10 mirror machine [21]. Comparison of an RFA data point (~30 eV) and an ion sensitive probe profile (~18 eV at the RFA position) showed disagreement between the measurement techniques in the WEGA tokamak [15, 30]. Comparison of an ISP with a retarding field analyzer in the TMX-U mirror machine matched with no auxiliary heating, while the ISP measured hotter ion temperature during ion cyclotron resonance heating—a strong indication that it measures the perpendicular ion energy component [7].

In practice the simple picture of magnetic shadowing of electrons by the Guard is not strictly followed. Insight into the physics of the particle collection is obtained by varying the bias between the Collector and Guard. When the Collector is biased below the Guard (typically 10 V in C-Mod) only positive current is seen on the Collector. Conversely, when the Collector is not biased below the Guard, negative current (i.e. net electrons) is seen on the Collector for part of its voltage sweep, despite the Collector being recessed many \( \rho_e \) behind the Guard.

Particle-In-Cell (PIC) simulations have reproduced the phenomenon of electron collection in both 2D [31, 32] and 3D [33]. The simulations demonstrated that electrons entered the probe volume by \( \mathbf{E} \times \mathbf{B} \) drifting along equipotential surfaces. Experiments with segmented Collectors also support this picture [6, 34]. Additionally, PIC simulations demonstrated that the collected ion current through a bias sweep was representative of the ion temperature [33]. Negative current on the Collector may also be due to ion impact induced secondary electron emission from the Guard. An ISP required an additional electrode to repel secondary electrons emitted from the Collector [21]. It was found in Ref. [12] that the surface condition of the probe mattered when ion temperature is very low (< 1 eV), and periodic heating helped to keep the surface clean. After installation of a new probe in C-Mod, it is routine to need a few scans to ‘clean up’ the probe and remove oxide layers which enhance secondary electron emission.

b. Plasma potential

The ion sensitive probe was originally developed by Katsumata to measure the plasma potential in the figure 8 torus RAHITOP III [4]. Since then, ion sensitive-type probes have also been used to measure plasma potential in a mirror machine [21], tokamaks [35, 36, 37, 38, 39], and linear plasma devices [25, 8].

To understand how an ISP is thought to measure plasma potential, first consider the floating potential of a probe in plasma. For non-magnetized plasmas and magnetized plasmas not at glancing angles, the electron saturation current is the one-way Maxwellian flux and the ion saturation current is given by the Bohm criteria such that the ions enter the sheath at the sound speed. In this case, the floating potential can be expressed as

\[
V_f = V_p - k_B T_e \ln \left( \frac{l_{sat,e}}{l_{sat,i}} \right),
\]

with \( V_f \) and \( V_p \) the floating and plasma potentials, \( l_{sat,e} \) and \( l_{sat,i} \) the electron and ion saturation currents, and \( T_e \) the electron temperature. For a deuterium plasma with \( T_i=T_e \):

\[
T_e \ln \left( \frac{l_{sat,e}}{l_{sat,i}} \right) = T_e \ln \left[ \frac{\sqrt{T_e / 2 \pi m_e}}{\sqrt{(Z T_e + T_i) / m_i}} \right] \approx 2.7 T_e.
\]

If the ratio of electron to ion saturation
currents is modified such that it is approximately unity the probe will float at the plasma potential, an idea first put forth in Ref. [35] and implemented as a Ball-Pen Probe (BPP).

The BPP is similar to the ion sensitive probe in that it contains a Collector recessed from a Guard. But its Collector is typically conical and the Guard is an electric insulator (thus, unlike a standard ISP, the Guard cannot be biased). Using a BPP with an adjustable recess height, Adámek observed the transition from a traditional Langmuir probe (when the Collector was proud) to a BPP. When the Collector was proud it floated at the same potential as the Langmuir probe and $\ln\left(\frac{I_{\text{sat,c}}}{I_{\text{sat}}}\right) \approx 2.7$. As the surface became flush the Collector transitioned to floating at the plasma potential and $\ln\left(\frac{I_{\text{sat,c}}}{I_{\text{sat}}}\right) \approx 0$. This is consistent with observations made by Matthews in an experiment where he systematically varied the angle between Langmuir probes and the magnetic field: the ratio of ion to electron saturation currents is approximately unity for nearly flush (within $2^\circ$ of parallel to B) Langmuir probes [40].

The plasma potential measured with a BPP was compared to the plasma potential measured with an emissive probe [37]. An emissive probe is generally taken to float at the plasma potential [41]. However, analytic analysis, including space charge limits, indicates that an emissive probe should float at $V_f = V_p - k_B T_e$ [42]. It was found that the BPP floated 5 V higher than an emissive probe [37], consistent with both probes measuring the plasma potential and the emissive probe floating potential being restricted by space charge. Using the floating technique with a BPP is advantageous over sweeping an ISP because the time between measurements is not limited by the sweep rate but by the digitization rate—and thus is likely fast enough to measure turbulent fluctuations.

Ochoukov compared plasma potential measurements with an emissive probe to a swept ion sensitive probe and found good agreement both in a linear plasma device [8] and a tokamak [39]; although no correction for space charge affects were made to the emissive probe measurements. It was found that the emissive probe floating potential corresponded to the voltage at the ‘knee’ of the ISP $I$-V characteristic where the current decays to zero, independent of if the Guard was biased positive or negative with respect to the Collector.

The C-Mod ISPs were fixed to the sides of limiters and attached to the Surface Science Station [39]. As a result, measurements were restricted to positions in the far scrape-off layer with location being set between plasma shots. Based on the work of Ochoukov and others we seek to extend ISP measurements to the complete boundary profile up to the last-closed flux surface in Alcator C-Mod. This requires designing a robust probe head for a scanning probe drive that can survive the extreme heat flux.

3. Design of a Scanning ISP for Alcator C-Mod

Alcator C-Mod is one of the most challenging experiments to make plasma measurements with probes. Only a handful of materials are allowed in the ultra-high vacuum chamber due to limits on outgassing. The high plasma temperature ($\sim 100$ eV) and density ($\sim 10^{20}$ m$^{-3}$) places extreme heat flux ($>100$ MW/m$^2$) on the probe surfaces. This necessitates using materials with the best thermal performance and a design focused on optimal heat flux handling. Careful consideration must also be made for the biasing and measurement electronics: the probes need to measure $\mu$A-level currents within meters of MW-level RF antenna. The short scale-length of plasma parameters (a few mm) in conjunction with the high heat flux requires that the probe move in and out of the plasma quickly ($\sim 1$ m/s) and the bias swept quickly ($\sim 2$ kHz) to resolve the gradients. Additionally, the plasma is quite turbulent in the edge, with fluctuation amplitudes (e.g. $\bar{n}/n$) up to order unity and fluctuation frequencies up to $\sim 1$ MHz.

The horizontal scanning probe system has been on C-Mod for many years with both Langmuir probe (see Refs. [43, 44] among others) and magnetic probe heads (See Ref. [45]). Figure 15 presents a cross section of C-Mod highlighting the location of the scanning probe. Radial motion of the probe head into and out of the plasma is performed with a pneumatic cylinder. Vacuum is maintained by a set of fast-action bellows. The system allows for up to three scans to the same depth (separated by at least 0.2 seconds to allow return of the probe to its rest position
before the next scan starts) or one ‘dwell’ scan to a fixed depth for the whole shot (usually 0.5 seconds for ramp-up, 1.0 seconds of flat top, and 0.5 seconds for ramp-down). The probe may be scanned up to, and sometimes to a few millimeters inside, the Last Closed Flux Surface (LCFS) in ohmically-heated plasmas; dwell scans are limited to further out into the SOL due to the intense, steady plasma heating. Accurate targeting relies on repeatable shots with a steady boundary. The scanning probe is moved into position based on the plasma equilibrium of the previous shot.
All C-Mod probes are baked under vacuum at 150 °C (or higher if the materials allow) for a couple of days to remove water vapor and verify high-vacuum (low-outgassing) compatibility. After baking, probes are stored in a desiccant container under rough vacuum, \( \leq 0.5 \text{ atm} \) (380 torr), to prevent reabsorption of water vapor. The horizontal scanning probe drive system has its own gate valve and turbo pump. This allows us to change the probe head after a day of experiments. Back-filling dry nitrogen through the probe system while changing the probe head and storing probes in the desiccant box aids in reducing turnaround time. The system is usually pumped down overnight (to \( \approx 1 \mu\text{torr} \)) in time for the next day’s experiments.

a. **Probe construction**

The extreme heat fluxes along with operation in an ultra-high vacuum are the two most important factors in choosing materials for probe construction. Thus materials are primarily chosen on their ability to survive high heat flux and low vapor pressure. Metals used include:

- **Molybdenum**—has superior thermal properties (melting temperature \( T_{\text{melt}} = 2896 \text{ K} \) and thermal conductivity \( \alpha \approx 138 \text{ W/m}\cdot\text{K} \)) yet still machinable with standard carbide tooling. In practice TZM (99% molybdenum, 0.5% titanium, and 0.08% zirconium) is used in place of pure molybdenum. It has similar thermal and improved structural properties. Due to its machinability, TZM is used for the majority of plasma-exposed parts.
- **Tungsten**—has the highest melting temperature of any element (\( T_{\text{melt}} = 3695 \text{ K} \), \( \alpha \approx 173 \text{ W/m}\cdot\text{K} \)) yet is challenging to machine. It is very brittle at room temperature and electro-discharge machining (EDM, also called spark-erosion) or laser-cutting typically need to be employed. EDM is more expensive than standard machining, thus tungsten parts are kept simple and limited to those experiencing the most extreme heat flux.
- **Stainless Steel**—has poor thermal properties (\( T_{\text{melt}} \approx 1700 \text{ K} \), \( \alpha \approx 17 \text{ W/m}\cdot\text{K} \)) but is inexpensive and easy to machine. Stainless steel is used wherever high heat flux performance is not needed.
- **Silver**—(\( T_{\text{melt}} \approx 1235 \text{ K} \)) silver plated screws are used wherever possible. The silver reduces galling in the lubrication-free environment of high vacuum.

Insulators used include:

- **Boron Nitride**—has very high thermal conductivity for an insulator (depending strongly on type, \( \alpha \gtrsim 100 \text{ W/m}\cdot\text{K} \)) and sublimates at \( \approx 2000 \text{ K} \) in vacuum. It has a very low thermal expansion coefficient. Boron nitride is very soft, so it is easily machined, but not to high precision.
- **Alumina**—aluminum oxide, has good thermal performance for an electric insulator (\( T_{\text{max}} = 2345 \text{ K} \), \( \alpha \approx 30 \text{ W/m}\cdot\text{K} \)). It is very hard and may be precision ground to better than \( \pm 5 \mu\text{m} \). It may be flame-sprayed onto metal parts (including tungsten and molybdenum).
- **Mica**—silicate mineral that may easily be cleaved into sheets \( \leq 25 \mu\text{m} \) thick with good thermal performance (\( T_{\text{max}} = 972 \text{ K} \)) and excellent voltage stand-off (20 V/\( \mu\text{m} \)). Easily laser-cut into complex patterns.

The ISP was constructed out of a 22.2 mm outside diameter (OD) TZM cylinder (Figure 16), limited to this size by the 25.4 mm inside diameter (ID) scanning probe guide tube. The probe face is angled to 26° in the \( R-Z \) plane such that it is tangent to the typical flux surfaces 111 mm above the outer-midplane—the location of the scanning probe. The cylindrical symmetry of the ion sensitive and Langmuir probes makes alignment to the pitch of the magnetic field unnecessary.

The Langmuir probe is a 3 mm OD cylinder 0.69 mm proud of the probe head, presenting a domed surface to the plasma. The Langmuir probe was made with tungsten because it is easily created by EDM (due to simple cylindrical geometry) and it receives the highest heat flux. The other parts: Base, Guard, and Collector, were all made of TZM due to their complicated geometry. All parts are electrically isolated from each other with precision ground (\( \pm 15 \mu\text{m} \) diameter) alumina cylinders. The Collector is a 3 mm OD cylinder, its height with respect to the Guard is set to \( \pm 5 \mu\text{m} \).
µm by filing the alumina cylinder to length. The Guard is a 3.8 mm ID, 5.6 mm OD cylinder with the tip chamfered to spread the heat flux to a larger surface area. The Guard may be adjusted to any height relative to the probe Base; it is typically kept flush to minimize the electron current collected at strong positive bias. Figure 17 shows the electrodes assembled from the rear and Figure 18 shows an assembled head.

This recess height of the Collector is typically set to the ion Larmor radius. However, at a depth of 100 µm electron current on the Collector was measured despite it being held at a bias less than the Guard, possibly due to slight misalignments in the probe system. At a depth of 200 µm there was no electron current detected on the Collector. Given the probe dimensions, the Collector should be magnetically shadowed for misalignments of up to 2°. The change in angle over the typical scan is ~0.5° with respect to the Collector surface normal. Although the pitch angle can change ±5° over the full range of magnetic configurations possible in C-Mod, it changes less than 2° with respect to the Collector surface normal.

The Langmuir probe and ion sensitive probes are contained within a Base that is electrically isolated from the head and connected (in the first version) to one of the four scanning probe electrodes. The relative location of parts within the head is maintained by having lips on the parts such that a retaining ring screwed in from the back presses and locks them in place. Electrical isolation of the Base from the head is maintained with domed, alumina buttons on the four sides and laser-cut mica on the face and back of the Base. An additional laser cut stainless steel “washer” that matched the pattern of the mica allows the retaining nut to be tightened down without ruining the mica sheet.

With this setup, it was envisioned that the Langmuir and ion sensitive probes could be biased with respect to the Base, allowing them to float on top of the plasma floating potential fluctuations. Through initial operations it was found that the density fluctuations due to the arrival of plasma blobs during an I-V sweep was a greater challenge, causing difficulties in fitting Eq. 1 to the I-V data.
Modifications were made to address the density fluctuations. An additional hole was drilled through the Base, placed 4.75 mm (center-to-center) along a field line connected between the outer-midplane and the center of the ion sensitive probe Collector. The Base wire was replaced with an alumina-coated 1.75 mm OD tungsten wire (same as that used for older Langmuir probe heads) that went through the new hole. The wire was filed flush with the surface of the Base, presenting a surface angled ~30° into the magnetic field. This new Langmuir probe is kept in ion saturation, such that the Collector current can be normalized to it to reduce the deleterious effects of density fluctuations. A similar Langmuir probe was used in Ref. [26], but that one was used to detect blobs and statistically bin the ISP measurements into those taken during blobs and those taken not during blobs.

The scanning probe heads on C-Mod are currently limited to 4 coaxial electric connections. Each electrical element of the ISP head has a 1.60 mm ID hole, into which plug 1.75 mm OD diameter wires with cross patterns un their cut to allow them to be press-fit into the larger hole. The wires are coated in flame-sprayed alumina (save for the ends) to maintain electrical isolation.

The rear of the probe body is of the same construction as all other scanning probes. The probe head is held to a stainless steel core tube with two ceramic pins. Full electrical isolation is insured with mica sheets. Due to the large currents in the SOL and subsequent $J \times B$ forces during off-normal events, e.g. disruptions, it is important that the probe head remain floating. The core tube is isolated from plasma contact with a boron nitride tube, necessary because the core tube is grounded through the probe drive. The boron nitride tube also captures the ceramic pins in place. Differential thermal expansion between the stainless steel core tube and boron nitride tube is accommodated with wave washers pre-loaded to 20 lbs. Total probe alignment is ensured through asymmetric-matching keys and pins in the core tube and probe drive.

\begin{itemize}
  \item \textit{Heat flux handling}
\end{itemize}
Alcator C-Mod presents a particularly challenging environment to make probe measurements: the heat flux parallel to the magnetic field can exceed 0.5 GW/m² and has an exponential fall-off to the wall with an e-folding length of only a few millimeters. There is a fine line between making a good measurement and ruining the probe. It is desirable that the probe be able to scan as deep into the plasma as possible without melting. It has been shown that the physics that sets critical gradients near the LCFS is crucial to understanding the edge plasma [43, 44]. A probe that can operate within this space is much more useful than one that cannot.

The probe geometry was optimized for heat flux handling using the finite element code COMSOL [46]. 3D geometry was imported directly from the CAD program Solid Edge [47]. Coupling of these two powerful programs allowed for quick optimization of geometry; iterations could be performed in less than 15 minutes. To approximate the time variation of surface heat flux of the probe plunging through the exponential profile, the heat flux function in COMSOL was defined as:

$$q_{\parallel}(t, x, y, z) = q_{\text{max}} \text{tr}(t) e^{-x/\lambda},$$

(3)
where \( q_{\text{max}} \) is the peak heat flux, \( \lambda \) is the heat flux e-folding length, and \( \text{tri}(t) \) is a triangle function with a duration of the scan time. For the ion sensitive probe simulations these values were set to 0.7 GW/m\(^2\), 4 mm, and 40 ms, respectively. The probe was orientated such that coordinates \( x \) and \( y \) correspond to coordinates \( \rho \) and \( B \). To simulate the heat flux arriving parallel to the magnetic field, \( q_{\parallel} \) was multiplied on each plasma-exposed surface by the magnitude of the unit surface normal of the probe in the direction parallel to the magnetic field, \( |\hat{\mathbf{r}}_{\parallel}| \). Temperature dependent material properties were used, which is an important detail: over the temperature range of interest (room to melting) the thermal conductivities and heat capacities of tungsten and molybdenum change by at least a factor of 2. These simulations neglected heat flux perpendicular to the magnetic field as well as radiation.

The simulations readily showed the regions that needed improvement. Most of the optimization was in trade-offs between making surfaces nearly tangent to the magnetic field to reduce the normal heat flux and keeping material thick enough such that there was enough thermal mass to drain the energy. Given the short time scale, 40 ms, bodies thicker than \( \sim 2 \) mm were essentially semi-infinite. Making the parts any thicker would not reduce the peak surface temperature. The simulation results of the final probe design are shown in Fig. 6. Performance could be increase by substituting tungsten for the TZM parts, an unlikely change because manufacturing the tungsten parts would likely increase costs an order of magnitude.

For benchmarking, the current ‘high heat flux’ Mach Langmuir probe head [48] was simulated with the same parameters. Peak surface temperatures were nearly identical—great news because the ‘high heat flux’ Langmuir probe head operates to the last closed flux surface in all ohmic plasmas.

![Grid Card Circuit Diagram](image)

**Figure 7.** Diagram of the new Grid Card circuit. A high voltage ground plane is driven by a PA94 op-amp. This voltage sets the voltage on ‘grid’ and ‘mirror grid’. It also can be used to bias the coaxial shields of the cables. The PA94 responds to the difference between a programed voltage and a reference voltage (which can be another probe bias, a floating probe, or ground) at its inputs. Variable gain transimpedance amplifiers measure the grid current. A ‘mirror’ grid can be implemented to negate the displacement current due to the probe capacitance. The card outputs measurements of the high voltage (divided by 40) as well as the probe current (at both 1 and 40 times, for a larger dynamic range).

### c. Electronics and data processing

New custom electronics (Grid Bias cards) were developed to control the ion sensitive probe and retarding field analyzer, see Figure 20. The new electronics provide a low-current (100’s nA to 100 mA) capability that complements the high-current (1’s mA to 1’s A) Langmuir probe cards already employed at C-Mod. It uses a PA94 high voltage (±400 V) op-amp, limited to between 30 mA and 100 mA, depending on the configuration. Each Grid
Bias card allows for a programmed voltage waveform to be outputted with respect to an input reference voltage. The reference voltage can be from the floating potential of another probe, the bias being applied to another probe, or ground. This feature is extremely useful because it allows for the Collector to be held at a constant bias with respect to the Guard; even through fluctuating power supply voltages.

To cover the wide range of edge densities on C-Mod the Grid Bias cards have adjustable gain transimpedance amplifiers (from 0.5 to 800 V/mA). To further increase the dynamic range, Grid Bias cards output current measurements channels at both I×1 and I×40.

The Grid Bias cards apply identical bias to their ‘grid’ and ‘mirror grid’ inputs while reporting only the difference in currents from each. The ‘mirror grid’ is connected to a ‘dummy’ probe circuit. It applies the bias voltage to the same electronics as the probe. But instead of being connected to the probe, this circuit is connected to a variable capacitor, which is adjusted to match the capacitance of the probe system (~150 pF for the Collector). Uncompensated, this capacitance would generate 0.36 mA from the fast voltage sweeps (typically ± 300 V triangle sweep at 2 kHz).

A diagram of the whole ISP probe and electronics system is shown in Figure 21. Waveforms are outputted by a D-tAcq AO32 analog output unit [49] to the individual Grid Bias cards and sweep power supplies. Each of our sweep power supplies are typically ±200 V and ±1 A and may bias multiple Langmuir probe cards. Each Langmuir probe card can be biased by one of three sweep supplies. The Collector is on a Grid Bias card; all other elements, due to
their larger currents, are on Langmuir probe cards. The cable shields are biased at the same voltage as the center conductor up until the vacuum feedthrough of the scanning probe drive (~7 m) to minimize capacitive currents. Within the probe drive the cable shields are grounded (~2 m).

Current and voltage signals are digitized on D-tAcq ACQ196 (0.4 MHz) and ACQ216 (5.0 MHz) units [49]. The slower digitizer is used for quick analysis of the data after the plasma pulse and the faster digitizer is used for final processing of the data. All of the ISP probe signals are digitized at 0.4 MHz. Due to channel limitations, all but the I×40 signals are digitized at 5.0 MHz.

After digitization, residual displacement currents from uncompensated cable capacitance are subtracted through software analysis, Figure 22. The probe is biased with its programmed waveform and the current and voltage signals are digitized for ~0.5 seconds before the plasma pulse. From this data a fast Fourier transform is applied to the current and voltage (without plasma) to estimate the complex circuit impedance for frequencies less than 100 kHz. Then the Fourier transform of the voltage is taken for the whole plasma pulse. This, combined with the circuit impedance, determines the current due to the circuit alone for the whole shot. Subtracting this current from the total current leaves only that due to the plasma. DC-offssets are also removed as a result of this digital processing. Finally, the ISP current and voltage signals are split into individual sweeps and Eq. 1 is fit to each sweep.

Figure 9. Removal of the residual displacement current from current measurement. Applied voltage and Collector current before the plasma is shown in the top panels. A fast Fourier transform is taken from the signals to get the complex circuit impedance. This impedance is then applied to the during-plasma voltage to get the circuit current. The circuit current is then subtracted from the total current to get that due to the plasma alone. Although this process is not important near the separatrix, where plasma current dominates, it is important in the far scrape-off layer where the signal is low and the circuit response distorts the measurement signal.

4. First measurements with the ISP

Data from a typical good spatial scan of the ISP is shown in Figure 23. Currents and voltages for the Langmuir probe, Guard, and Collector are shown along with the probe position. The probe moves at ~1 m/s and the voltages are swept at 2 kHz, giving a measurement every ~0.25 mm. Since the typical spatial scale length in the C-Mod boundary is a few millimeters, the fast sweeping (2 kHz) of the I-V characteristic is required to resolve plasma profiles. Except where noted, the Collector was biased 10→15 V below the Guard to suppress electrons collection.

The biggest challenge to proper operation of the ISP has been in accommodating large Guard and Collector currents with external power supplies. Given its recessed geometry, it was thought that the Collector signal might be low. Thus the Collector was made as large as could fit in the probe head with the other parts. Yet, at high densities and at
Figure 10. Typical voltage and current measurement during a spatial scan of the ion sensitive probe. Sign convention: positive current is ions collected, negative current is electrons collected. As the probe scans into the plasma the Langmuir probe and Collector $I$-$V$ characteristics exhibit broader knees—indicating increasing temperature. With the Collector voltage negative with respect to the Guard voltage (in this case $V_C = V_G - 10$ V) only positive current is found on the Collector.
peak probe insertion, the ion flux to the Collector exceeds 100 mA, the limit of the Grid Bias Card. This does not affect measurement of ion temperature because the probe is still able to sweep through the exponential decay in ion collection at positive bias. When the Guard is swept (at an offset voltage) with the Collector, it receives a large electron current when the Collector is biased to fully reject ions. At high densities the electron current collected by the Guard can exceed the power supply limits (~2 A). The power supply voltage drops from the programmed voltage such that it does not exceed its current limit. This is highly undesirable because the useable voltage bias range becomes restricted such that the probe is no longer able to reject ions, rendering the measurements useless. Future modifications of the probe will likely include smaller electrode collection areas so as to not exceed power supply current limits.

a. Ion Temperature

A typical I-V characteristic from the ISP Collector is shown in Figure 24 b. Collector current is plotted versus Guard voltage because the recent work in C-Mod demonstrated that the plasma potential measurement depended on the Guard voltage [8]. Since the Collector and Guard voltages have a fixed offset, it does not change the $T_i$ from the fitting procedure.

Figure 11. I-V characteristics demonstrating aid of normalizing to density fluctuations. A Langmuir probe very close to the ion sensitive probe is kept in ion saturation to measure the density fluctuations (panel a). A large density fluctuation (blob) hits the probe as the ISP is going through the exponential part of its sweep. The minimum error fit to the raw Collector current is dominated by this density fluctuation. Normalizing the Collector current to the density fluctuations improves the fit (panel c).
Fitting Eq. 1 to the Collector current verses the Guard voltage can be troublesome during blob events; the large (order background or greater) density fluctuations with a decaying tail sometimes provide a better (lower RMS error), albeit incorrect, fit (see Figure 24 b). Here we adopt a technique following [50, 51] of using the slit plate of an RFA in ion saturation to continuously measure the density fluctuations. Normalizing the collector current to the ion saturation current reduces the effect of density fluctuations. For the ISP, a Langmuir probe provides the ion saturation current signal. The Langmuir probe is 4.75 mm (center-to-center) along the field line connecting the outer-midplane (source of blobs) to the ion sensitive probe.

Figure 24 c shows the utility of this technique. During this sweep a large blob hits the probe. Without the normalization (Figure 24 b), the software finds the e-folding temperature (12.3 eV) to be associated with the blob decay. This is significantly cooler than the local electron temperature (~20 eV) as well as the preceding and following ion temperatures points (~50 eV). Despite the model being a good fit to the data, it is clearly not representative of the plasma conditions. Normalizing the Collector current to the Blob Langmuir probe current (Figure 24 c) improves the fit. Examining over the entire SOL profile (see Figure 25), it is clear that the technique of normalizing the \( I-V \) characteristic reduces the scatter of fitted \( T_i \) values.

Although neglected here and outside the scope of this work, plasma potential and temperature fluctuations are likely as important as density fluctuations in effecting the quality of the \( I-V \) fits. Depending on the nature of the fluctuations, they can either increase or decrease the inferred temperature compared to the actual temperature [52]. Using plasma fluctuation data generated from a gyrofluid code it was found that RFA measurements must either be swept as fast as the fluctuations or the sweeps must be conditionally binned to accurately reflect the plasma temperature [53]—two techniques not possible with the current system. An ideal system would switch the probe bias faster than the fluctuations, like the Mirror Langmuir probe [54]. Magnetic fluctuations are small (\( \vec{B}/B \ll 1\% \)) and thus of no concern to measurements [45].

The Blob Langmuir probe was set to a floating condition to see if the ISP, drawing ~1 A of current from the plasma, affected the plasma potential. It would be unfortunate if it did; the bias voltage would not truly represent the repelling voltage experienced by ions. It was found that the floating voltage of the Blob Langmuir probe oscillated...
<5 V, synchronized with the bias of the ISP, mostly due to capacitive coupling between the probe electrodes. Given the ISP was biased through a ±300 V sweep, we are confident that the ISP bias is not significantly disturbing the surrounding plasma.

Initial profiles on $T_i$ and $T_e$ are shown in Figure 25. It is expected that upstream ion temperature should be greater than electron temperature in the SOL [3]. Parallel to the magnetic field, electron thermal conductivity is $\sim 30 \times$ the ion thermal conductivity when $T_i = T_e$. Assuming equal power exiting the LCFS through the electrons and ions, it is expected that upstream $T_i = 3 \times T_e$ [1], consistent with these measurements.

Some of the $I$-$V$ sweeps with the ISP, especially those at high density, do not show saturation. Instead, a linear increase in current with negative bias is seen. This may be indicative of a space charge limited current. In the 1D cold-plasma limit, the Child-Langmuir Law provides the scaling $I \propto V^{3/2}$ [55, 56], which is consistent with our measurements. This result is not entirely surprising as the volume in front of the Collector is ion-rich. However, the precise potential structure within the probe is unknown. We are presently examining probe $I$-$V$ sweeps more closely and undertaking modeling efforts to more fully characterize conditions in which the current collected by an ISP may be affected by space charge limitations.

b. Plasma Potential

As stated in Section 2, the determination of the plasma potential from an ISP $I$-$V$ characteristic comes with significant uncertainty. In an ISP that wasn’t subject to space charge limits [7], the plasma potential was found to correspond to the break in slope from saturated current to the exponential decay in excellent agreement with a thallium beam probe. On the other hand, in a probe that was orders of magnitude above the 1D Child-Langmuir space charge limit [8], the plasma potential was found to correspond to the voltage where the Collector current decayed to zero, whether the Collector was biased above or below the Guard. This measurement agreed with the plasma potential inferred from an emissive probe—although space charge effects were not included in the emissive probe analysis.

Presently, there are two measures of plasma potential to which we can compare with an ISP in C-Mod: Langmuir and emissive probes. A scanning probe head with an emissive filament and two Langmuir probes has been operated in similar ohmic plasmas to those studied here with the ISP (see Fig. 6 in Ref. [57]). Due to the delicate filament, the emissive probe was only operated behind the main plasma limiters. Here the emissive probe floated at $\sim 5$ V; inclusion of a local electron temperature correction as measured with a swept Langmuir probe ($\sim 20$ eV) results in a plasma potential of $\sim 25$ V.

The plasma potential, from Eq. 2, for a proud Langmuir probe is $V_p = V_f + 2.7k_BT_e$. However, Eq. 2 does not take into account secondary electron emission, which is likely important for the domed Langmuir probe on the ISP head. Secondary electron emission changes the probe floating potential relative to the plasma potential. Modifying Eq. 2 to include secondary electron emission:

$$V_p = V_f + k_BT_e \ln \left( \frac{1 - \delta_e}{\sqrt[2.7]{m_e(z^2 + 1)}} \right) .$$

(4)
The secondary electron emission coefficient ($\delta_e$) may be estimated by an empirical formula \[58\]. For the tungsten probe and $T_e$=20 eV we calculate $\delta_e=0.22$. With the Langmuir probe floating potential of -8V and the ISP-measured ion temperature of 70 eV, the plasma potential at the location of the limiter from Eq. 4 is 36 V. The secondary electron emission coefficient would need to be ~0.5 to bring the Langmuir probe plasma potential measurement to match the emissive probe.

We now consider plasma potentials inferred from the ISP. The voltage bias programming for the ISP is flexible, allowing two different techniques to be compared. We can alternate between biasing the Collector above and below the Guard within the same spatial scan. Figure 26 presents consecutive voltage sweeps with the ISP where the Collector was modulated with a square-wave ($\pm 10$ V) with respect to the Guard. The probe was just behind the main limiter—the same location as the emissive probe measurements. The transition of the ISP $I$-$V$ to an exponential decay is about -30 V, much lower than the plasma potential measurements given by either the emissive or Langmuir probes.

With the Collector biased negative we find the standard $T_i$ ISP curve. Although, the knee where the ion current goes to zero is poorly defined. This is an unfortunate result of the combination of a broad decay length due to the large $T_i$ and plasma fluctuations increasing the uncertainty of its location. On the other hand, biasing the Collector positive

![Comparison of Plasma Potential Measurements](image)

Figure 13. Comparison of different methods of determining the plasma potential from ISP measurements. Middle and bottom panels are from consecutive voltage sweeps within the same probe scan. Top panel is from the same sweep as the bottom. Top panel is the Guard current. Middle panel is with the Collector biased negative with respect to the Guard. Bottom panel is the Collector biased positive with respect to the Guard, allowing electrons to $E \times B$ drift onto the Collector. Neither ISP measurements of plasma potential (start of the exponential decay and the knee where the current decays to zero) are near the plasma potential calculated from the domed Langmuir probe ($V_p = V_f + 2.7T_e$). Note that the floating potential of the Guard is a good indicator of the knee, especially when the Collector is biased above the Guard and collecting net electrons.
with respect to the Guard allows the possibility for an equipotential surface from the plasma outside of the probe to connect to the Collector. Electrons may \( E \times B \) drift onto the Collector in this case; see Fig. 4 in Ref. [31] for the results of a PIC simulation showing this. More electrons than ions are collected for part of the bias range. This method usually provides a much better defined ‘knee’: although any information on the ion energy is lost with electron collection. This knee, at about 8 V, is still lower than the Langmuir and emissive probe measurements.

Despite the challenges in matching different measurements, we have found another feature in the ISP \( I-V \) characteristic that matches the knee: the Guard floating potential. We generally find that the floating potential of the Guard matches the Collector knee, see Figure 26; especially the well-defined knee when the Collector is biased above the Guard and collecting net electrons. This method has the advantage over the two sweeping methods in that it provides a well-defined voltage along with a sweep to measure \( T_i \).

Our measurements here are by no means exhaustive, more detailed investigation needs to be done to sort out these differences. Discrepancies in comparing measurements of plasma potential to other techniques are not new. Reference [59] has an extensive discussion of the factors which may cause discrepancies in comparing hot (emissive) and cold (Langmuir) probe measurements of plasma potential, including secondary electron emission.

c. Electron Temperature

The Guard of ISPs is often used to measure the electron temperature. This is a convenient technique, because it does not require a separate Langmuir probe. Comparison of measurements between our ISP Guard and the domed Langmuir probe demonstrate that this may result in erroneous electron temperature measurements. The Guard always reports electron temperatures 1-2 times higher than the domed Langmuir probe. Given that the Guard surface is nearly flush to the probe head, this is no surprise. As shown by Matthews, the fitted electron temperature for a Langmuir probe with its surface tangent to the magnetic field is \( \sim 2 \) times that for a probe not tangent [40]. Thus \( T_e \) measurements with a flush ISP Guard should be treated with caution, especially if they have not been benchmarked by another measurement.

5. Conclusions

We have developed a new probe head containing a Langmuir probe and an ion sensitive probe to simultaneously measure profiles of electron temperature, ion temperature, plasma density, and plasma potential. Probe geometry was optimized for handling the extreme heat flux (100’s MW/m\(^2\)) in the boundary of Alcator C-Mod. First measurements of ion temperature were made. Current-voltage characteristics displayed an exponential falloff, indicative of a Maxwellian distribution. Ion temperatures were \( \sim 3 \times \) electron temperatures, consistent with their poorer parallel thermal conductivity. Initial comparisons with a retarding field analyzer and charge exchange are favorable and will be reported in a separate paper. We have found that the floating potential of the flush Guard matches the plasma potential found by sweeping the ISP Collector. Work to characterize the effects of space charge on the ISP current collection is ongoing.

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6. References


