Scanning retarding field analyzer for plasma profile measurements in the boundary of the Alcator C-Mod tokamak

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A new Retarding Field Analyzer (RFA) head has been created for the outer-midplane scanning probe system on the Alcator C-Mod tokamak. The new probe head contains back-to-back retarding field analyzers aligned with the local magnetic field. One faces ‘upstream’ into the field-aligned plasma flow and the other faces ‘downstream’ away from the flow. The RFA was created primarily to benchmark ion temperature measurements of an ion sensitive probe; it may also be used to interrogate electrons. However, its construction is robust enough to be used to measure ion and electron temperatures up to the last-closed flux surface in C-Mod. An RFA probe of identical design has been attached to the side of a limiter to explore direct changes to the boundary plasma due to Lower Hybrid (LH) heating and current drive. Design of the high heat flux (>100 MW/m²) handling probe and initial results are presented.

1. Introduction

The ion temperature ($T_i$) has not been routinely measured in the boundary (or Scrape-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 an impurity temperature—not the main fuel—and they tend to be limited in spatial resolution. Langmuir probes are the most common edge diagnostic technique, but they are
only capable of measuring $T_e$. RFAs have been the most widely used diagnostic of $T_i$ in tokamaks [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22], [23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36]. They are also used in other plasma physics experiments, and thus have many design and operation considerations. However, here we focus on concerns specific, but not all unique, to magnetic fusion devices and especially to tokamaks.

The major concern for probe operation in magnetic fusion devices is surviving the intense heat flux. Measurements with RFAs, requiring thin slit plates and delicate grids, are exceedingly challenging. Alcator C-Mod has the highest power density of any current experiment; heat fluxes easily exceed 100 MW/m$^2$ on open field lines. We have created the most robust RFA ever operated in a tokamak, capable of measuring in much of the same parameter space as our current high-heat flux Langmuir probes [37]. The probe is constructed of mostly refractory metals (i.e. tungsten and molybdenum) and the slit is placed only 1.7 mm back from the front face to maximize the depth of the measurement into the SOL.

Despite such a robust design, the RFA has disadvantages. Its main surfaces must be oriented perpendicular to the magnetic field, maximizing the incident heat flux and limiting its heat flux exposure. Additionally, the space charge of the beam of ions within the probe creates its own potential. Space charge fundamentally limits probe currents to less than 1 mA, with currents typically on the order of ~10 µA. This places strong demands on reducing noise in our measurement electronics—an especially tough challenge when MWs of RF heating is injected into the tokamak.

The Ion Sensitive Probe (ISP) provides an attractive alternative to the RFA [38]. 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. 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 RFA head described in this paper and an ISP head described in a companion paper (see Ref. [39]). Comparisons of measurements from these two probe systems along with CXRS measurements will be presented in a future paper.
In addition to measuring $T_i$, the RFA can be used to explore $T_e$. Comparisons between $T_e$ measured with an RFA and a Langmuir probe are generally favorable [10]. The RFA has the advantage of its measured current being due to only electrons whereas a Langmuir probe relies on a constant ion current through its sweep below the floating potential. Thus any departure from the exponential typically used to fit experimental RFA data, Eq. 3 discussed below, is due to a non-Maxwellian electron energy distribution. With a Langmuir probe there remains the ambiguity to whether the departure from an exponential is due to a non-Maxwellian electron population or changes in the ion current collected.

Lower Hybrid Current Drive (LHCD) is currently thought to be the most viable method to extend tokamak operation to steady state [40]. Lower hybrid heating extends the tail of the electron energy distribution. Extensive studies with LHCD at C-Mod have demonstrated an anomalous drop in current drive as density is increased [41, 42]. There is evidence of large changes to the boundary plasma during LHCD. The RFA has been demonstrated to be an important tool for exploring the SOL during LH operation; demonstrating both changes to fluctuations [33] and non-Maxwellian electrons [34]. But, the outer midplane scanning probe on C-Mod doesn’t map magnetically to the LH launcher (both systems are located near the midplane of horizontal ports separated ~72° toroidally). To explore direct interactions, we have installed a RFA assembly on the side of a limiter which maps magnetically to the launcher in all plasmas (separated by ~40° toroidally). Initial results show strong changes to the boundary plasma, including large increase in $T_e$ and a transient drop in floating potential at LH turn-on.

The main auxiliary heating system on C-Mod is Ion-Cyclotron Resonance Heating (ICRH), with up to 6 MW injected, typically at 50 or 80 MHz [43]. Strong interactions between the ICRH waves and the edge plasma are common [44, 45]. A non-linear response of the plasma to the RF, ‘sheath-rectification’ sets a large DC-electric field above the plasma potential to maintain ambipolarity. The floating potential of a Langmuir probe in this plasma can rise a few 100 V and emissive probes show the plasma potential to rise over 400 V [44]. The RFA could also be a valuable tool in studying ICRH-plasma interaction physics. Operation during ICRH is challenging however. For example, we have found that RF interference can be transmitted to control electronics, affecting bias waveform programming.
This paper presents the design and initial operation of a high heat flux RFA probe operated in scanning and fixed locations on Alcator C-Mod. Basic RFA theory is presented in Section 2. The design of the RFA for the extreme environment in Alcator C-Mod is described in Section 3. Initial measurements of the RFA are discussed in Section 4.

2. Description of RFA
   
a. Theory of Operation

A retarding field analyzer uses a series of biased grids to interrogate the energy distribution of a desired plasma species (i.e. ions or electrons). Typically, plasma ions and/or electrons enter the analyzer volume through a narrow slit. The slit width is chosen to be on order the Debye length \( \lambda_D = \sqrt{\frac{\varepsilon_0 k_B T}{n e^2}} \), typically 5 to 50 µm in the boundary of C-Mod) to insure that no internal biases are seen by the plasma and that all particles that enter the probe have passed through a well-defined sheath potential structure. If the slit is wider than a few \( \lambda_D \) then a full sheath potential drop is not developed and the electric field in front of the probe is not uniform. Parallel ion energy is converted into perpendicular and proper operation is lost [35]. In low-energy density plasmas, a grid, thin foil, or micro-channel plate may serve as the slit plate. However, a more robust design is necessary for C-Mod plasmas.

![Ion Temperature Diagram](image1)

![Electron Temperature Diagram](image2)

Figure 1 Typical operating modes of a 2-grid retarding field analyzer. Plasma forms a sheath over the Slit plate. When measuring the ion temperature, electrons are rejected from the collector by either very negative Slit and/or Grid 2. Grid 1 is swept; only ions with enough energy to overcome the bias are incident on the Collector. When measuring the electron temperature, Grid 1 is biased very positively to reject all ions from the Collector. Grid 2 is swept; only electrons with enough energy to overcome the bias are incident on the Collector. In both scenarios, Grid 2 is always more negative than the Slit or Collector to ensure that secondary electrons formed at the Collector are recollected. Ion- or electron-induced secondary electrons from Grid 2 could also contribute to the Collector current but are...
In measuring $T_i$ (see Figure 18) the voltage of Grid 1 ($V_1$) rejects ions without sufficient energy to overcome it. Grid 2 is held at a sufficiently negative voltage ($V_2$) such that no plasma electrons may reach the Collector. It is crucial that Grid 2 be at the lowest potential in the system so secondary electrons emitted from the Collector return (as well as those released from ions rejected by Grid 1 impacting the rear of the Slit). This ensures that the only current to the Collector is due to ions with enough energy to overcome $V_1$. Secondary electrons from Grid 2 could contribute to the Collector current, but in practice their current is insignificant. Sweeping $V_1$ produces a current on the Collector that corresponds to a velocity moment of the ion distribution function for ions with energy parallel to the magnetic field above the bias potential:

$$I_C = A_{slit} e Z \int_{\sqrt{2eZV_1/m_i} \xi_{\text{total}}}^{\infty} v_y f(v_{||}) \, dv_{||},$$

(1)

where $I_C$ is the current on the Collector, $A_{slit}$ is the area of the slit, $e$ is the unit electric charge, $Z$ is the charge of the ions, $m_i$ is the ion mass, $\xi_{\text{total}}$ is the total system ion transmission factor, and $f(v_{||})$ is the ion distribution function in velocity parallel to the magnetic field. In an ideal system the distribution function may be inferred by differentiation the $I$-$V$ (current-voltage) characteristic with respect to voltage. In reality, the quality of the data is too poor to differentiate (due to both noise and the present inability to sweep faster than turbulent fluctuations). Typically a model $I$-$V$ characteristic function is fitted to the data to extract the ion temperature. For a half-Maxwellian distribution shifted by the sheath voltage ($V_s$), a functional form for the Collector current is:

$$I_C = \begin{cases} 
I_0, & V_1 < V_s \\
I_0 e^{-(V_1-V_s)/T_i}, & V_1 \geq V_s 
\end{cases},$$

(2)

where $I_0 = A_{slit} e Z \xi_{\text{total}}$. It is assumed that $\xi_{\text{total}}$ is not a function of particle velocity. A fit of Eq. 2 to the experimental data results in a value for $T_i/Z$, along with $I_0$ and $V_s$: hence an assumption must be made for the charge of the plasma species. 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 [26]. If $Z$ in Eq. 2 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%.

Care must be taken in interpreting $T_i$ measurements in flowing plasma and under conditions when the ion distribution function can be anisotropic along field lines. Measurements in Alcator C with a double-sided RFA,
Janus, noted that $T_i$ was asymmetric looking ‘upstream’ (facing into the flow) versus ‘downstream’ (facing away from the flow) along field lines [11]. The physical mechanism was unknown, but asymmetries were well documented over a wide range of plasma conditions. Since then, at least one mechanism that can cause directional asymmetries has become understood. Using the kinetic model of Chung and Hutchison [46] Valsaque et al. found that a flowing plasma would make the $T_i$ measurements appear asymmetric [47]. In the absence of the disturbing probe, $T_i$ was found to be well represented by the arithmetic average of the upstream and downstream ion temperatures. Motivated by these observations, we have gone to exceptional effort to fit two RFAs within a single probe head.

The electron temperature may also be found by changing the bias arrangement of the grids (see Figure 18). A functional fit to electron collection data is analogous to Eq. 2:

$$I_c = \begin{cases} I_0 e^{(V_2 - V_0)/\tau_e}, & V_2 \leq V_0 \\ I_0, & V_2 > V_0 \end{cases}$$

(3)

Although, here $\xi_{total}$ is different for electrons versus ions. Directional asymmetries in electron temperature have also been seen in scrape-off layer plasmas. In Alcator C-Mod, electron temperature asymmetries on the high field side midplane were associated with poloidally asymmetric heat transport [48]. Due to ballooning-like transport the majority of plasma in the SOL originates at the outer mid-plane. The plasma that transports into the flux tubes on either side of the probe could be from two different sources, one side dominated by hot plasma from the core and the other side from the cold electrons rejected by the sheath voltage in the divertor and from ions created from cold, recycling neutrals. Thus a two-sided RFA could be used to study the physics of asymmetric heat transport. Although separating the effects of asymmetric heat transport and apparent asymmetries due to a flowing plasma may be challenging.

b. Single-particle motion and space-charge current

RFA operation and analysis relies on undisturbed, single-particle motion within the probe cavity such that the ion distribution function is not appreciably changed from that outside the probe. Wan, Nachtrieb, and Kocan [11, 19, 22], among others, have done extensive work demonstrating that typical slit plate and grid geometry do not significantly change the distribution function of particles within the cavity. It has been demonstrated numerically for
typical slit geometries that selective removal of ion orbits does not significantly affect fitted $T_i$ nor do misalignments to the magnetic field up to $\sim 10^\circ$ [22]. It is also important that the ions are collisionless within the probe. Following Nachtrieb [19], the mean time between collisions for deuterium ions at 50 eV and $10^{19} \text{ m}^{-3}$ is $\sim 40 \mu$s, much longer than the time for a particle to transverse the length of the analyzer, $\sim 10 \text{ ns}$; therefore ion-ion collisions and a redistribution of ion energies within the probe are highly unlikely. Unless the neutral density in the analyzer greatly exceeds the ion density, ion-neutral collisions are also unlikely. Thus the distribution of ions within the probe is that of those fallen through a sheath and Eq. 2 is a valid functional form to fit to experimental data.

Given the high ($>10^{19} \text{ m}^{-3}$) densities typical of the edge of Alcator C-Mod, space-charge limited current is the biggest challenge to proper operation of the retarding field analyzer, beyond simply surviving the heat flux. After the electrons are rejected, only ions remain between the grids. This ion beam forms its own potential structure. If the ion beam is sufficiently dense, its space-charge potential will overwhelm the bias of the grids—thus the true retarding potential is not known to the operator and the resulting data is essentially useless for determining $T_i$. Space charge limits are not a concern for electrons; for deuterium and $T_i=T_e$ the limit is higher by $\sqrt{m_i/m_e} \approx 60$. Specific design considerations for dealing with space charge limited current are given in Section 3.c.

3. Design of the RFA 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 ($\sim 100 \text{ eV}$) and density ($\sim 10^{20} \text{ m}^{-3}$) places extreme heat flux ($>100 \text{ MW/m}^2$) 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 ($\sim 1 \text{ m/s}$) and the bias swept quickly ($\sim 2 \text{ kHz}$) 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 $\sim 1 \text{ MHz}$.

The horizontal scanning probe system has been on C-Mod for many years with both Langmuir probe (see Refs. [48, 49, 50] among others) and magnetic probe heads (see Ref. [51]). Figure 19 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 depth is targeted based on the plasma equilibrium of a previous shot that must be repeated.

Figure 2 Cross section of the Alcator C-Mod tokamak with a near double-null plasma equilibrium. The red line is the last closed flux surface, the boundary between open and closed magnetic flux surfaces. Inset is a close-up view of the RFA scanning probe which scans through the plasma from behind the limiter shadow to the last closed flux surface.
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, $\lesssim 0.5$ 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 $\sim 1 \mu$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 $T_{\text{melt}} = 2896$ K and thermal conductivity $\alpha \approx 138$ W/m·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 ($T_{\text{melt}} = 3695$ K, $\alpha \approx 173$ W/m·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 ($T_{\text{melt}} \approx 1700$ K, $\alpha \approx 17$ W/m·K) but is inexpensive and easy to machine. Stainless steel is used wherever high heat flux performance is not needed.
- **Silver**—($T_{\text{melt}} \approx 1235$ K) silver plated screws are used wherever possible. The silver reduces galling in the lubrication-free environment of high vacuum.
• Beryllium Copper—used for removable electrical contacts due to good electrical conductivity and resiliency as a spring (high yield strength).

Insulators used include:

• Boron nitride—has very high thermal conductivity for an insulator (depending strongly on type, $\alpha \geq 100$ W/m·K) and sublimates at ~2000 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 ($T_{\text{max}}=2345$ K, $\alpha \approx 30$ W/m·K). It is very hard and may be precision ground to better than ±5 µm.

• Mica—silicate mineral that may easily be cleaved into sheets <25 µm thick with good thermal performance ($T_{\text{max}}=972$ K) and excellent voltage stand-off (20 V/µm). Easily laser-cut into complex patterns.

• Teflon—fluoropolymer used mainly as a wire insulator, softens as it approaches its melting temperature, $T_{\text{melt}}=600$ K.

• PEEK—thermoplastic that retains structural integrity to near its melting temperature, $T_{\text{melt}}=616$ K.

![Figure 3](image_url) Line drawing of the retarding field analyzer probe. The "West" side is exploded while the "East" side remains assembled. Pictured is the stack assembly of electrodes and insulators which is held in the molybdenum probe head with a screw. The tungsten guard plate, held on with molybdenum nuts and bolts, protects the internal components. The electrodes are attached with wires (not pictured) to the beryllium copper plugs. The scanning probe system allows for only 4 independent electrodes, whereas the retarding field analyzer probe head has two distinct analyzers (each with 4 electrodes); the plugs allow for flexible operation of which electrodes are connected. The boron nitride sleeve is removed for clarity.
An exploded view of the RFA head design is shown in Figure 20; pictures of the head are shown in Figure 21, and Figure 22. The probe was constructed out of a 22.2 mm outside diameter (OD) TZM cylinder, 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 the slit is aligned to the typical flux surfaces 111 mm above the outer-midplane—the location of the scanning probe drive. The probe faces are angled 8.5° in the Z-φ plane so the surface normal of the slit is parallel to the magnetic pitch angle of the standard 5.4 T, 0.8 MA plasma equilibrium. The pitch angle changes less than 0.5° over the course of a typical spatial scan and less than ±5° among extremes in equilibria. Misalignments caused by these changes are unlikely to affect probe operation [21].

The probe is composed of layers, each playing a specific role. The two TZM head halves provide machinable, high heat flux bases. Attached to each head half is a 1.5 mm thick tungsten Guard plate used to protect the Slit plate from high heat flux. Guard plates are held to the head with molybdenum screws and nuts from Thermoshield [52]. Split lock washers are used to keep the molybdenum screw in tension through thermal expansion; although a Belleville washer is preferred, it could not be used due to space restrictions. A wedge-shaped aperture 2 mm by 0.41 mm, formed by plunge EDM [53], exposes the Slit plate through the Guard plate. The wedge-aperture is stopped 0.2 mm before going through, to avoid a thin corner which would easily melt. The Guard plate reduces the total energy deposited on the Slit, reducing the peak heat flux on this delicate component.
The Slit plate, Figure 23, provides an aperture into the cavity yet maintains a sheath over the aperture. It is a 1 mm thick tungsten plate with a 45° wedge plunge EDM eroded from the back to within 25 µm of the plasma-facing side. The wedge-relief provides space for ion transmission yet leaves sufficient material, compared to a foil with a slit, to drain the energy and prevent melting the slit. At the bottom of the wedge is a laser-cut aperture—which starts at ~25 µm wide and narrows to 16 µm at the face. This is a natural result of the laser-cutting process and an improvement over the design of a straight aperture; the ions are less selectively lost [21]. The Slit plate is electrically isolated from the probe head and the Guard plate by a 400 µm thick layer of laser cut mica. The slit is aligned with the local magnetic flux surface (26° in the R-Z plane).

To reduce the plasma flux into the cavity such that it does not exceed the space-charge limit there is a low-transmission grid placed directly behind the Slit plate, Figure 24. The grid is a laser-cut [54][54] 25 µm thick tungsten foil. Three 20 µm wide slits are cut orthogonal to the slit to ensure that some particles have at least an optical path from the plasma through the Slit and low-transmission grid into the cavity. The slits are spaced 0.5 µm (≈2ρi) to minimize overlap of the transmitted ion beams. This grid reduces transmission of plasma into the probe cavity by 95%.
The high transmission grids, Figure 24, supply the potentials to retard charged particles yet must be transparent enough to not attenuate the flux. The high transmission grids are also laser-cut from 25 µm thick tungsten foil. The spacing of the grid wires is picked such that no matter the misalignment, at least one of the apertures has an optical path from the low-transmission grid to the Collector. The high-transmission grid is composed of 25 µm wires with 200 µm by 40 µm spaces, for an optical transparency of 54% and total exposed area of 2.25 mm². The grids are electrically isolated by 400 µm thick layers of laser-cut mica. Since it is challenging to solder to tungsten, each grid is pressed against a 200 µm thick stainless steel ‘solder’ plate. The stainless steel plates contain a tab with a hole to which a Teflon-coated copper wire is soldered, Figure 22. The Collector is also a stainless steel plate. The tabs for each of the stainless steel plates are offset from each other to avoid interference among the wires. The total distance from the front of the Slit to the front of the Collector is 2.875 mm and the distance between the grids is 0.6 mm. It is advantageous to keep the grid spacing to a minimum: the allowed space charge current decreases with the inverse square of the spacing [55].

The stack is held to the probe head with a silver-coated screw electrically isolated from the stack with an alumina cylinder, Figure 22. A Belleville washer ensures the screw stays tensioned through the larger thermal excursions experienced by the probe. A stack of mica grid insulators is used to electrically isolate the Belleville washer from
the Collector. Large clearances among the stack of components and the alumina cylinder allows the stack to be adjusted within the probe head to ensure proper alignment of the Slit plate behind the Guard plate. The mica around the 3 sides of the front of the stack allows for fine positioning of the stack (mica is easily cleaved into sheets ~25 µm thick). It is crucial that the mica overlap around corners and completely surround the stack. When assembled with only butt joints in the corners there was severe arcing among grid components and the molybdenum head. In places where the stack is not pressed against mica, such as the area around the tabs, it was necessary to extend the mica in between the grids out past the ends of the solder plates to prevent arcing there.

Having such a tightly closed stack, there was concern about trapping of neutral gas within the probe cavity. This issue has been considered in other RFA designs [17, 56]. Anomalous current was thought to be caused by electron impact ionization of trapped neutral gas. The JET RFA contains holes specifically for exhausting neutral gas [17]. Despite operating in dense plasma (~10^{20} m^{-3}), no sign of breakdown due to neutral gas ionization is observed. This may be due to the pre-baking (mentioned above) of the RFA head before installation.

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. Alignment between the two head halves is maintained with press fit pins. Total probe alignment is ensured through asymmetric-matching keys and pins in the core tube and probe drive.

The RFA scanning probe head had to be fully compatible with the present probe drive system. This limits it to 4 independently biased electrodes due to space and vacuum feedthrough limitations within the scanning tube. This means that either one side may be biased and diagnosed completely or, to run double-sided, some electrodes must be biased in parallel and their currents recorded together. To accommodate the need for different bias arrangements the RFA was built to be flexible. Each electrical element in the stack is connected by a 22 AWG Teflon coated wire to a beryllium copper plug. The beryllium copper plugs may be attached in multiple configurations to the 4 stainless
steel wires within the core tube, limited to two plugs per wire due to space constraints. This allows multiple electrodes to be biased together (e.g. Grid 1 on both sides shares the same voltage) and configurations may easily be changed with only minor disassembly of the probe. The wires and plugs within the core tube were originally electrically isolated from each other and the tube with fiberglass sock. This material was found to be unreliable and later replaced with Teflon heat-shrink tubing.

The retarding field analyzer fixed to the side of a limiter has identical internal components to the scanning probe head, Figure 25. It is held in a TZM and stainless steel box. The tip of the probe is flush with the limiter surface, placing the slit 1.7 mm behind the limiter. Given that the limiter tiles here never melt, we were confident that the RFA would be safe from melting. Signals are carried out on 50 Ω coaxial cable. To reduce displacement currents induced by the cable capacitance, the shields are biased at the same voltage as the center conductor. To facilitate this, the 4 cables are wrapped in fiberglass sock and then encased in a flexible stainless steel tube. They attach to the probe box with SMA connectors. The SMA connectors are attached to the probe body with a PEEK block to electrically isolate the shield from ground (which allows the shield to be biased). Teflon wires join the stainless steel plates in the stack to the center pin of the SMA connectors.

Figure 8 Retarding field analyzer mounted on the side of a limiter. Components are identical to that of the scanning retarding field analyzer, except that it is one-sided. The tip of the analyzer is flush with the limiter surface and the slit is 1.7 mm behind. The analyzer was placed here to explore lower-hybrid interactions with the boundary plasma (the scanning analyzer is not magnetically connected to the lower-hybrid antenna). The entrance slit is aligned with the local flux surface.
### Heat flux handling

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/m$^2$ on the open field lines of the boundary 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. Melting not only destroys the probe, ruining the known collection area and possibly shorting out electrodes, it injects impurities into the plasma, changing the very plasma trying to be measured. The physics that sets critical gradients near the LCFS is crucial to understanding the edge plasma [49, 50]. 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 [57]. 3D geometry was imported directly from the CAD program Solid Edge [58]. 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:

$$q(t, x, y, z) = q_{\text{max}} \cdot \text{tri}(t) e^{-x/\lambda},$$  \hspace{1cm} (4)

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 retarding field analyzer simulations these values were set to 0.4 GW/m$^2$, 4 mm, and 40 ms, respectively. The probe was orientated such that coordinates $x$ and $y$ correspond to coordinates $\rho$ and $B$, shown in Figure 26. 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, $|\vec{n}_{y}|$. 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—both from the plasma and the probe. Plasma radiation is much lower than the plasma heat flux. With external heating it is typically \( \lesssim 0.5 \text{ MW/m}^2 \); however the RFA probe will mostly be operated in ohmically heated plasmas where plasma radiation is \( \sim 0.02 \text{ MW/m}^2 \). Thermal radiation from the probe is also relatively low. At tungsten’s melting temperature (3695 K) its black body emitted power (with emissivity 0.04) is 4.2 MW/m\(^2\).
Two design features were optimized: (1) Peak heat flux handled without melting, especially the slit—this would allow the probe to operate deeper into the plasma. (2) Distance of the slit to the front of the probe—it is advantageous to keep the slit as close to the front of the probe as possible. Simulation results are shown in Figure 26 and Figure 27 for the optimized probe geometry. The peak heat flux of 0.4 GW/m$^2$ is essentially the limit at which this probe can be operated (unless one can demonstrate proper operation is maintained with a Slit plate not normal to the magnetic field—a likely possibility given that the sheath is still developed).

Preventing the Slit from melting was relatively easy; placement of a sacrificial tungsten Guard plate in front of the Slit with an aperture limits the total energy on the Slit. This allows the plasma energy deposited on the Slit to diffuse away from the Slit to areas not exposed, rather than build up around the wedge relief. Design feature 2 was more challenging, fundamentally limited by the fact that this was the region of largest heat flux. The best that could be done was make the Guard plate thick enough that it was nearly semi-infinite on the time scale of the scan (1.5 mm, also limited in thickness by space constraints) and to ensure that there were no sharp corners, which are ‘bottlenecks’ to heat conduction.

For comparison, the current ‘high-heat flux’ Mach Langmuir probe [37] and new ion sensitive probe [39] heads can survive a simulated peak heat flux of ~0.7 GW/m$^2$. Although the RFA can remain operational past a peak heat flux of 0.4 GW/m$^2$, despite melting; any molten tungsten on the Guard plate will drip down away from the Slit. On the other hand, the Langmuir probe and ISP must be operated below their peak heat flux; melting will ruin the known areas of the probe and may electrically short out elements.

c. Space charge limited current

As stated earlier, the space charge potential of the ions within the RFA may prevent proper operation. To estimate where space charge would be an issue for measurements Nachtrieb calculated the potential for an arbitrary rectangular beam in an arbitrary conducting cavity [19]. Taking a representative case of a deuterium plasma with $T_i = 100$ eV, $T_e = 50$ eV, and $n = 10^{20}$ m$^{-3}$ the current through the slit is $I_{slit} \approx 16$ mA. Using dimensions for our new RFA: grid spacing of 0.61 mm, cavity size of 1.5 mm by 1.5 mm, and assuming the ions stay in a beam with the dimensions of the slit (1.5 mm by 0.016 mm), the space-charge current limit by Nachtrieb’s model is $I_{s-c} \approx 0.84$ mA. The grid spacing is chosen to be so small (0.61 mm) because $I_{s-c}$ is inversely proportional to the square of the
distance between the grids. Yet, the expected current through the slit exceeds the space charge limit by nearly a factor of 20.

A more optimistic assumption is that the beam spreads out to about its Larmor radius, ~0.3 mm for this case. Given that the ion Larmor radius is larger than the slit width and the electron Larmor radius is of order the slit width or smaller, it is likely that the electrons stay collimated as they pass through the analyzer whereas the ions spread out to a column ~2\( \rho_i \) wide. These ideas are supported by two observations from initial operation of our RFA probe: 1) Post-mortem analysis of a low-transmission grid placed behind the Slit plate displayed discoloration over the entire exposed surface—indicating that the plasma spread to fill the entire probe volume behind the slit. 2) The Slit plate, together with the low-transmission grid, creates three beams of electrons. As the plasma current is ramped up, the pitch angle changes, and the electron beam current can be seen to scan across Grid 2. When it hits a wire on Grid 2 it is blocked from the Collector and when it passes through Grid 2 it is seen on the Collector.

The space-charge current limit, assuming the ions spread out to cover an area 2\( \rho_i \), is now \( I_{sc} \approx 1.9 \) mA. The expected current through the Slit is still over 8 times too high. To attenuate the current below the space-charge limit we placed a low transmission grid—essentially three slits—behind the Slit plate. Details of the low transmission grid were given in Section 3.a.

An additional technique for mitigating the effects of the space charge potential is to enforce a greater bias between the grids [59]. This is typically done by keeping the Slit at a very negative potential (often in ion saturation at a -100 to -300 V) while sweeping Grid 1. As opposed to keeping the Slit floating or grounded, this increased negative bias can reduce the relative maximum of the space charge potential between the grids to below the ion retarding grid potential. A simple estimate of the necessary voltage for a given current density and grid spacing can be found with the Child-Langmuir Law [55]. This technique was not necessary on the C-Mod RFAs.

d. Probe electronics and data processing

New custom electronics (Grid Bias cards) were developed to control the ion sensitive probe and retarding field analyzer, see Figure 28. The new electronics provide a low-current (100’s nA to 100 mA) measurement 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 30-100 mA, depending on the configuration. Although not necessary to measure $T_i$ or $T_e$, it is important to have current and voltage measurements for each electrode to facilitate diagnosis of probe conditions. 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.

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 $I \times 1$ and $I \times 40$.

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 network of capacitors (Figure 29) tuned to mirror the capacitances of the probe. For the fast voltage sweeps used (typically ±300 V triangle sweep at 2 kHz), ~1 mA of displacement current is generated for every 400 pF of uncompensated capacitance.

A diagram of the whole RFA probe & electronics system is shown in Figure 29. Waveforms are outputted by a D-tAcq AO32 analog output unit [60] 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 to the vacuum feedthrough on the scanning probe drive (~7 m) to reduce capacitive currents. Within the probe drive the cable shields are grounded (~2 m). The limiter RFA cable shields are biased at the same voltage as the center conductor all the way to the RFA.

Figure 12 (color online) Diagram of the RFA electronic system. An analog output sends waveforms to the Grid card and sweep power supplies. Grid 1 and Grid 2 on each side of the probe were biased and measured together. The Collectors on each side were independently biased and measured. The shields of the coaxial cables connected to the Grid Cards were biased with the center conductor to reduce displacement currents. A network of variable capacitors were connected to the mirror terminals of the Grid Cards. The network was tuned to balance out the capacitive coupling among the probe electrodes.

Current and voltage signals are digitized on D-tAcq ACQ196 (0.4 MHz) and ACQ216 (5.0 MHz) units [60]. The slower digitizer is used for analysis of the data immediately after the plasma pulse and the faster digitizer is used for final processing of the data. All of the RFA probe signals are digitized at 0.4 MHz. Due to channel limitations, only the scanning RFA V and I×1 signals are digitized at 5.0 MHz.
After digitization, residual displacement currents from uncompensated cable capacitance are subtracted through software analysis. 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-offsets are also removed as a result of this digital processing. Finally, the RFA current and voltage signals are split into individual sweeps and, depending on the mode, Eq. 2 or 3 is fit to each sweep.

4. First measurements with the RFAs

Initial measurements with the scanning RFA were made with only one side (the ‘West’ side facing towards the outer midplane and outer divertor for lower-single null plasma, see Figure 19) fully connected. This allowed for following the voltage and current of each element and simplified debugging of the system. The probe was also operated ‘double-sided’ with individual RFA stacks looking both upstream into the plasma flow and downstream away from the plasma flow. For this, the Slits were left floating, unconnected and electrically isolated from the rest of the probe head. Grid 1 on each side were wired and biased together as were Grid 2 on each side, see Figure 29. The Collectors each had their own dedicated connections so their currents could be measured separately. The probe moves spatially 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 SOL is of a few millimeters, fast sweeping (2 kHz) of the $I-V$ characteristic is required to resolve profiles.

The software and electronics have been setup such that arbitrary bias waveforms may be programmed on the RFA electrode. This is to allow for alternating between ion and electron temperature modes, among others, in a single scan. This method was done successfully. However we still favor operating in only one mode per shot. This has two main advantages: 1) Less time (and because the probe is moving, space) between data points, allowing for a finer profile. 2) Constant bias on the Collector(s) eliminates glitches in current from the fast switching of voltages between bias modes.
The RFA operates as designed within the extreme environment of Alcator C-Mod. Only occasional arcs between the grids were seen with the proper insulation (overlapping mica in the corners, mica extending over the edges, and Teflon within the core tube). When properly aligned, the Slit plate and Grids remain intact and operational with no signs of melting, despite being scanned to the separatrix where $T_e > 50$ eV and $T_i > 150$ eV (where the tip of the Guard plate melts, Figure 26).

Figure 13 Collector currents of double-sided RFA from repeated scans, once in $T_e$-mode and once in $T_i$-mode. Bottom panel is the probe trajectory in major radius during the scan.
a. Ion temperature mode

In ion temperature mode the RFA performed as expected (see Figure 30 and Figure 31). At negative bias of the ion repelling grid the current to the Collector followed the density fluctuations of the Slit in ion saturation (fluctuations may be seen as the departure from the horizontal line of the fit of Eq. 2 in Figure 31). As the grid was biased positive the Collector current decayed exponentially. No negative currents were seen at any bias during proper operation. Preliminary comparison with ISP and CXRS ion temperature measurements show good agreement, which will be presented in a separate paper.

The magnitude of the current in the probe volume was much lower than expected given simple transmission through the Slit. This may be due to the Slit not being constructed precisely as designed. If the plunge EDM wedge relief did not go as deep as specified then the slit would be thicker than designed. The ion flux in a slit much deeper than it is narrow more strongly attenuates the plasma flux [22]. Additionally, exposed linear dimensions of the grids are only a factor of few greater than the ion Larmor radius. It is possible that the ions with high perpendicular energy are attenuated on the interior of the probe [61]. Since the ion current was found to be more than a factor of 10 below the space charge limit, the low transmission grid was not used for any of the data presented in this paper.

Figure 14 RFA ion temperature and fit of Eq. 2, assuming $Z=1$ (deuterium plasma).
b. Electron temperature mode

The RFA in electron temperature mode performed as expected (see Figure 30 and Figure 32). At positive bias of the electron repelling grid the Collector current displayed density fluctuations associated with ‘blob’ events in the SOL. Again, the density fluctuations are most evident when the electron current is saturated. As the grid was biased negative the Collector current decayed exponentially. No positive currents were seen at any bias during proper operation. Preliminary comparisons to the electron temperature measurements by the Langmuir probe on the ISP head are favorable and will be discussed in a future paper.

![Figure 15 RFA electron temperature and fit of Eq. 3.](image)

![Graph](image)

\[ T_{e,\text{fit}} = 24.0 \text{ eV} \]

\[ \text{Grid 2 Voltage [V]} \]

\[ \text{Collector Current [\mu A]} \]


c. LH-mapped limiter RFA

The RFA mounted to the side of a limiter such that it is mapped magnetically to the lower hybrid launcher performed much like the scanning RFA, capable of both ion and electron temperature measurements. However, given that it was fixed inside the vessel and could not be repaired or improved as easily as the scanning RFA could, its reliability was low. Initially shorts between the cable shields and ground developed due to the low durability of the insulating fiberglass sock. Future installments will likely be done with tri-axial cable in place of the coaxial cable. This will allow biasing of the center and second conductor to reduce displacements currents and will not need fiberglass sock to insulate the biased conductors from the vacuum vessel.
Much like early iterations with the scanning RFA, over time the limiter RFA developed shorts inside the head. This would likely be solved by implementing the coverage of mica throughout as in the scanning RFA. Yet, despite being mounted with the front face flush to an outer protection limiter the Guard, Slit, and Grids survived with no visible damage through 38 run days (total of approximately 38 minutes of plasma exposure).

The limiter RFA and lower hybrid system were jointly operational on only one day. Yet within this limited dataset a few interesting observations were made. When the limiter RFA was magnetically mapped to a row of LH waveguides there was a -0.3 kV, 0.3 ms transient drop in the Slit plate floating potential with ~150 kHz oscillations (see Figure 33). When the plasma current was changed such that the limiter RFA was mapped to a location between rows of wave guides, the transient disappeared. It is not clear why this transient happens. The large drop in floating potential suggests a response needed to repel non-thermal electrons. After the transient dip, the floating potential when mapped to the waveguide row goes slightly positive (∼7 V), but is slightly negative (∼-3 V) when mapped between waveguides. This may be a sign of $E \times B$ convection cells that develop between the waveguides of LH launchers due to the difference in electron temperature in adjacent flux tubes [62, 63].

The LH also increases the electron temperature in the SOL (see Figure 34). Before LH turns on the electrons in the shadow of the limiter are cool, ∼8 eV. During the steady portion of the LH pulse, $T_e$ increases to >40 eV.

Comparable increases in electron temperature have been measured with Langmuir probes mounted between the LH
waveguide rows. The factor of 5 increase has strong implications for SOL physics: electron impact ionization increase by $\sim 10\times$ and electron heat conduction increases $\geq 300\times$, depending on the change in temperature gradient. During the steady portion the electron distributions remain Maxwellian up to the noise floor of the electronics (bias of $-110$ V). The large spikes of electron temperature in the early phase of the LH pulse correspond to the transient drop of floating potential. The 80 Hz sweep during the shot was too slow to resolve the transient oscillations and it is likely fits performed during this part are erroneous.

Ion saturation fluctuations on the Slit plate are seen to decrease strongly when LH turns on. This is consistent with measurements of density fluctuations given by Gas Puff Imaging (GPI) and reflectometry [64]. LH interactions with the SOL present a rich set of physics and understanding it will be important. LH is currently the most viable method to allow steady state operation of tokamaks. Given its wide range of measurements, RFAs may be one of the most capable tools of studying LH SOL interactions.

\subsection*{d. Operation during ICRH heating}

The ICRH interactions with the plasma make RFA measurements challenging. Additionally, RF noise can couple into the bias electronics, confusing the feedback circuitry and ruining the voltage program. Finding the proper way to operate the RFA in ICRH was challenging. But on its last day of operation the solution was found. The only opportunity to try this technique was with the double-sided RFA with the Slits disconnected from the electronics and electrically isolated. Grounding Grid 1 proved to be the critical step—perhaps isolating the internal electrodes from
RF pickup. The Collectors were negatively biased to reject electrons and Grid 2 was swept to selectively reject ions. In this configuration the Collector current was modulated as expected (albeit including the secondary electron current).

This provides hope that the RFA could be used to study plasma dynamics during ICRH heating in C-Mod. The enhanced potentials are thought to increase sputtering of the molybdenum tiles covering the interior of C-Mod. The potentials are also suspected to increased transport of the sputtered molybdenum into the core plasma. The core plasma is only hot enough to partially ionize molybdenum, resulting in enhanced line radiation out of the plasma, partially negating the ICRH heating power. With a grounded Slit the RFA could provide information on the ion energies impacting surfaces, whether or not they are energetic enough to sputter. Limited results from the RFA on the OMEGATRON in C-Mod indicated that ion and electron energies in the far SOL increased during ICRH [19].

5. Conclusions

We have created a new retarding field analyzer for the scanning probe system on Alcator C-Mod. Geometry and materials were optimized using 3D finite element simulations for the intense heat flux in the C-Mod SOL. The probe is compact: the entrance slit is only 1.7 mm from the front face and a 0.6 mm grid spacing is used to minimize the effects of space charge limiting current. It is double-sided to allow for both upstream and downstream measurements along a magnetic field line.

Initial operation of the probe was demonstrated. The RFA remained operational, even when pushed to the point of melting the Guard plate. The probe preforms as expected in measuring both ion and electron temperatures. Ion current in the probe is lower than expected; this may be due to selective attenuation of ions with large perpendicular energy within the probe.

An RFA was also placed on the side of a limiter, mapped magnetically to a LH launcher. Initial measurements display a rich variety of physical phenomena: 5x increase in the local electron temperature, transient decrease in the floating potential to -0.3 kV, and strong reduction in density fluctuations. The RFA will be a useful tool in exploring LH interactions in the SOL plasma.
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6. References