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Comparison of heat flux measurements by IR thermography and probes in the Alcator C-Mod divertor

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Abstract

Alcator C-Mod was recently upgraded with multiple diagnostics to measure the heat flux footprint on the outer divertor: IR thermography, plasma conditions from Langmuir probes (LPs), and embedded calorimeters to measure local energy deposition. In addition to providing consistency checks of the inferred heat flux profiles, these measurements allow an assessment of the local sheath heat flux transmission coefficient (γ). We report measurements of the sheath heat-flux transmission coefficient at multiple locations in the scrape-off-layer (SOL) during an EDA H-mode discharge. The LP data are consistent with the presence of a heat flux "tail" measured by the IR system, extending into the far SOL. Measured γ are found to deviate from theoretical values by up to a factor of 3, depending on position in the SOL, pointing to some as yet unresolved physics. Calorimeter-inferred energy deposition profiles are found to be within 20% of the IR-inferred values across the footprint.

Keywords: JNM: Plasma Properties, Plasma-Materials Interaction

PSI-19: Alcator C-Mod, Calorimetry, Probes, Sheaths, Thermography

PACS: 52.40.Kh Plasma sheaths, 52.55.Rk Power exhaust; divertors, 52.70.-m Plasma diagnostic techniques and instrumentation

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1. Introduction

Exhaust of energy from the core plasma to material surfaces is one of the most challenging aspects of magnetic fusion plasmas. Engineering limits restrict peak surface heat fluxes to under ~ 10 MW/m^2, while unmitigated heat fluxes are projected to exceed ~ 40 MW/m^2 in ITER, based on current projections for the heat flux profile in the outer divertor[1]. An accurate description of the heat flow to divertor surfaces and its dependence on plasma conditions is therefore paramount to confidently designing a reactor.

Alcator C-Mod provides a unique environment among today's experiments to explore reactor-level heat fluxes in reactor-like divertor geometry. An important first step is to verify the accuracy of divertor heat flux profiles inferred from C-Mod's diagnostic set. In addition, we wish to test our understandings of the mechanisms responsible for heat deposition, namely the physics of the plasma-material sheath interface. In this paper, we report on a comparison among three independent measures of energy deposition to the C-Mod outer divertor: IR thermography, embedded Langmuir probes and embedded calorimeters. Calorimeter data are found to be consistent with the IR-inferred heat flux profile, confirming the overall shape and magnitude. Calorimeters, IR, and LPs confirm a "tail" of heat flux into the far SOL. A comparison of LP and IR data yields heat transfer coefficients that deviate substantially from the nominal value of 7.5, depending on local plasma conditions and location in the SOL. Such deviations are not explained by refinements to the sheath computation, including nonzero sheath currents, enhanced secondary electron emission yields, over-estimated T_e values and/or values of T_i much greater than T_e. These results indicate that there are physical processes at play which have not yet been identified.

2. Experiment

In preparation for coordinated experiments on boundary layer heat transport with DIII-D and NSTX (a DoE Joint Research Target for 2010), the C-Mod divertor was enhanced with multiple heat flux measuring systems[2]. A poloidal array of calorimeters was installed into a specially designed column of a 2° "ramped tiles", located in view of an IR camera camera system (see Fig. 1). Each calorimeter consists of a molybdenum body with an embedded type-K thermocouple, thermally isolated from the tiles by an Inconel spacer. Thermocouple signals are carried on type-K thermocouple wire through electrically isolated vacuum feed-throughs to custom built, ice-point compensated cPCI cards (RC-filtered to 0.006 ms) and digitized on D-tAcq ACQ196 CPCI boards. The IR camera is an FLIR Titanium SC7000 with 320x256 resolution that detects in the 3-5 μm band[3].

A poloidal array of 10 LPs is located in the outer divertor of C-Mod, displaced 90 degrees toroidally from the ramped tiles; they are not in view of the IR camera. The LPs consist of 4 mm diameter tungsten pins that present a surface 10° with respect to the magnetic field. Local plasma densities and temperatures are found by fitting I-V characteristics obtained at $\sim$ 5 ms intervals[4]. We restrict our attention in this paper to data taken from the top three LPs shown in Fig. 1. Analysis of data from the other LPs has revealed that these electrodes may be experiencing a shadowing effect along magnetic field lines due to divertor misalignments [5].

Standard Langmuir probe theory[6] dictates that the heat flux $\left(q \text{ W/m}^2\right)$ through a collisionless sheath is related to the electron temperature (T_e eV) and ion saturation current $\left(J_{sat} \text{ A/m}^2\right)$ by:

$$\frac{q}{T_e J_{sat}} = \gamma = 2.5\tau + \frac{2}{1-\delta_e}(1-\iota) + \ln\left[\frac{1-\delta_e}{\left[2\pi m_e/m_i\left(1+\tau\right)\right]^{1/2}(1-\iota)}\right] \tag{1}$$

where τ is the ratio of ion to electron temperature (T_i/T_e), δ_e it the secondary electron emission coefficient, and ι is the ratio of net current through the sheath (ground current) to ion saturation current (J_{gnd}/J_{sat}). ι is often left out of analysis of γ. We leave it in because ι of -1 to -2 is common in the C-Mod outer divertor[4]. The first term arises from kinetic calculations of ion transport through the sheath, the second from electrons convecting through the sheath (including secondary electron emission), and the third from the energy transferred from the electrons to the ions through the sheath potential. As is often assumed, in a deuterium plasma with $T_i/T_e = 1$, $\delta_e = 0$, and $\iota = 0$, Eq. 1 yields: $\gamma \simeq 7.5$. There are many other processes that change the value of γ (reflection of particles/energy, secondary electrons from ion impact, ion-electron recombination energy…), but these at most contribute a 20% increase to Eq. 1[7].

Data presented here are from a series of EDA H-mode plasmas. EDA is an ELM-free regime of steady H-mode operation in Alcator C-Mod[8]. Toroidal field was 5.4 T, plasma current 0.5 MA, line-averaged density 1.1×10^{20} m^{-3}, and ICRF power 3 MW.

3. Thermography-LP Comparison

Initial observations of the heat flux footprint by the IR camera showed the expected large peak at the seperatrix and nearly no heat in the private flux region. Curiously, it also showed a long tail of about 15% of the peak heat flux extending far into the SOL. Initial thoughts were it was a calibration error with the IR camera. However, comparison of the IR-inferred heat flux profile with LPs (assuming $\gamma = 7.5$) confirms the measurement to be real, see Fig. 2.

Sweeping the strike point over LPs maps the profile of T_e, J_{sat}, and other plasma parameters of interest in the SOL, see Fig. 3. A strong correlation among γ and local plasma parameters is seen, in particular an inverse relationship with T_e. In Fig. 4 we compare the measured γ to that of Eq. 1 (using ι from measurements and assuming $\tau = 1$ and $\delta_e = 0$). With these standard assumptions, Eq. 1 does not replicate the shape of γ as measured. Adding in an empirically based relation for secondary electrons[6],

$$\frac{\delta_e\left(T_e\right)}{\delta_{max}} = 2.72^2 \frac{T_e}{E_{max}} e^{-2(T_e/E_{max})^{1/2}} \tag{2}$$

where $\delta_{max} = 1.4$ and $E_{max} = 650$ eV for a tungsten LP. It should be noted that this expression is for a clean surface bombarded with monoenergetic electrons at normal incidence. Our actual situation is a tungsten surface subject to periodic boranizations, etched by plasma with a distribution of energies, and at an angle of incidence of about 10°. As shown in Fig. 4, inclusion of $\delta_e\left(T_e\right)$ does not help in matching the profiles. The positive dependence of δ_e in this range of T_e is the wrong direction for secondary electrons to explain the measured profile of γ. Thus, not even a hypothetical surface film with enhanced secondary yields above that in Eq. (2) would improve the match.

The one place where γ has an inverse dependence on T_e is in the ratio of temperatures (T_i/T_e). Yet this in an unknown quantity, as Alcator C-Mod presently lacks T_i measurements in the SOL. However there is good reason to expect T_i to be greater than T_e in the SOL, measurements of T_i in Alcator C[9] yielded T_i/T_e ratios of around 2. Assuming a flat $T_i = 50$ eV profile in the SOL and using the measured T_e we find that it improves the agreement of Eq. 1 with measurements. Although such a profile for T_i is unrealistic and it doesn't reproduce variation in the γ near the strike point. Thus we are not yet able to resolve the plasma-surface physics that accounts for the IR-inferred parallel heat fluxes.

4. Thermography-Calorimeter Comparision

Calorimeter energy deposition measurements rely on the ability to measure the thermal rise of the calorimeter body before energy is lost to the surrounding environment. To accurately measure transient temperatures, the material of the thermocouple should have a thermal diffusivity (α) an order of magnitude higher than the material being measured[10]. Our thermocouples are tipped with 3 mm of stainless steel $\left(\alpha \simeq 4 \times 10^{-6}\ \mathrm{m}^2/\mathrm{s}\right)$ and are measuring transient temperatures in molybdenum $\left(\alpha \simeq 5 \times 10^{-5}\ \mathrm{m}^2/\mathrm{s}\right)$. Because of this discrepancy in thermal conductivity, the response time of the thermocouple is not adequate to directly measure the thermal rise of the calorimeter. Thus necessitating use of a numerical 1-D heat transfer algorithm with temperature dependent thermal properties to calculate the deposited energy.

We start by estimating the energy that accounts for the measured delayed temperature rise. Coarsely replicating a typical C-Mod discharge, this energy is placed in a one second pulse on the surface of a 1-D calorimeter body. From this calorimeter simulation the temperature evolution at the tip of the thermocouple is found and applied as the front boundary condition on a 1-D model of the stainless steel thermocouple body. The algorithm searches through two parameters to look for a match between the modeled and measured temperature signals: energy deposited on the surface of the calorimeter and depth into the stainless steel thermocouple body (replicating the stainless steel tip). The least-square error between the simulated profile and the measured is minimized. Figure 5 displays a typical fit. In order to bound possible systematic errors in the 1-D model, we varied the time interval over which the modeled and measured temperature signals are compared. The inferred deposited energies were found to vary by less than 10%.

Figure 6 shows IR camera and calorimeter measurements of the energy deposited on the ramped tiles. It must be pointed out that the IR-inferred energy deposition measurements are toroidally centered on the ramped tiles. Yet, not all calorimeters are located in the middle of the ramped tiles. Due to field line shadowing effects, the IR inferred temperatures are found to be $\sim 10\%$ lower near the leading edges and $\sim 10\%$ higher near the trailing edges. Thus we expect a +/- 10% variation in energy deposition across the ramped tiles compared to that reported by the IR system. Calorimeters below the nose region (see Fig. 1) are located in the middle of the ramped tile; these sensors display excellent agreement with the IR, to within 5%. For calorimeters above the nose there are systematic deviations from the IR inferred energy depositions: calorimeters near the leading edges report less energy than the IR heat flux; calorimeters near the trailing edges report more. These data are all consistent and give us confidence that the IR-inferred energy depositions agree with the calorimeter data to within about 20%.

5. Conclusions

The new suite of IR, Langmuir probe, and calorimeter diagnostics have greatly expanded C-Mod's capabilities for divertor heat flux experiments. These redundant systems provide important cross-checks for data validation, which is especially important in C-Mod's challenging IR measurement environment. Energy deposition profiles from calorimeter sensors are found to agree with IR-inferred heat depositions within 20%. In comparing the IR camera and LP data, tests of the plasma-sheath heat flux transmission theory are performed, including the effects of a measured finite sheath current. It is found that the standard assumptions of $T_i = T_e$ and $\delta_e = 0$ can not explain the measured values of γ at the divertor surface, being a factor of 3 off in some cases. Secondary electron emission effects can not account for the discrepancy; this effect has the wrong dependence on T_e relative to the trends seen in the data. Postulating a constant T_i profile of $T_i = 50$ eV pushes theoretical values closer to measured values, although this scenario is rather extreme and significant deviations still exist. In any case, there are no measurements of T_i to support such a possibility at this time.

Motivated in part by these observations, significant improvements to C-Mod's heat flux diagnostic set are planned for the next run campaign, including LPs located in direct view of the IR camera, fast-response thermocouples in the calorimeters, and surface thermocouples to calibrate the IR system at high temperatures.

6. Acknowledgments

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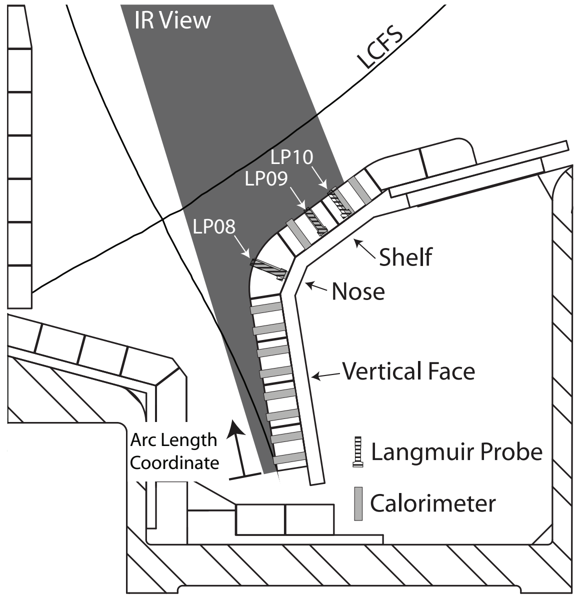

Figure 1: Cross section of the Alcator C-Mod lower divertor showing the IR camera view and locations of calorimeters and Langmuir probes (displace 90° from the IR view).

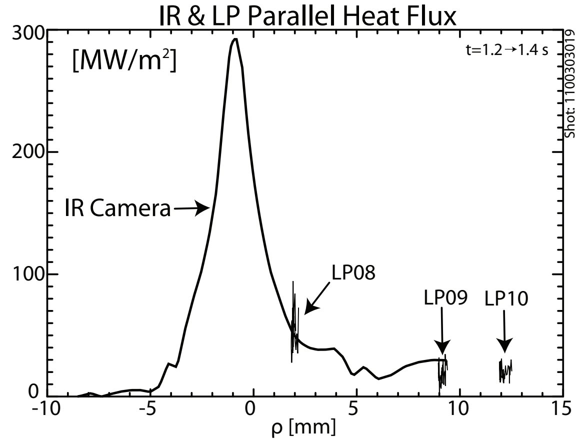

Figure 2: Heat flux profile parallel to the magnetic field measured by the IR camera along with three LPs (assuming $\gamma = 7.5$) mapped to ρ, magnetic flux surface coordinates at the outer-midplane. The LPs confirm the long tail of heat flux into the SOL.

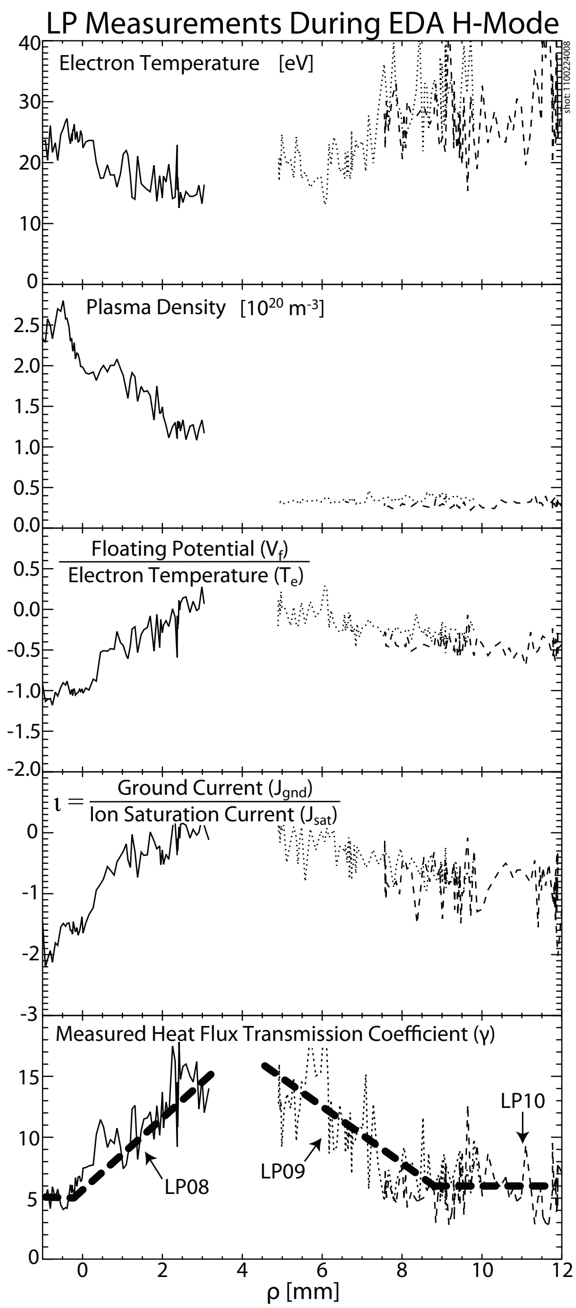

Figure 3: Strike point sweep over three probes mapping out LP measurements. The heat flux transmission coefficient has a strong inverse correlation with electron temperature. The thick, dashed line indicates the overall trend in the measured γ profile and is used for comparison in Fig. 4. The gap at $\sim \rho = 4$ is due to the inability for a full sweep of the strike point over these LPs.

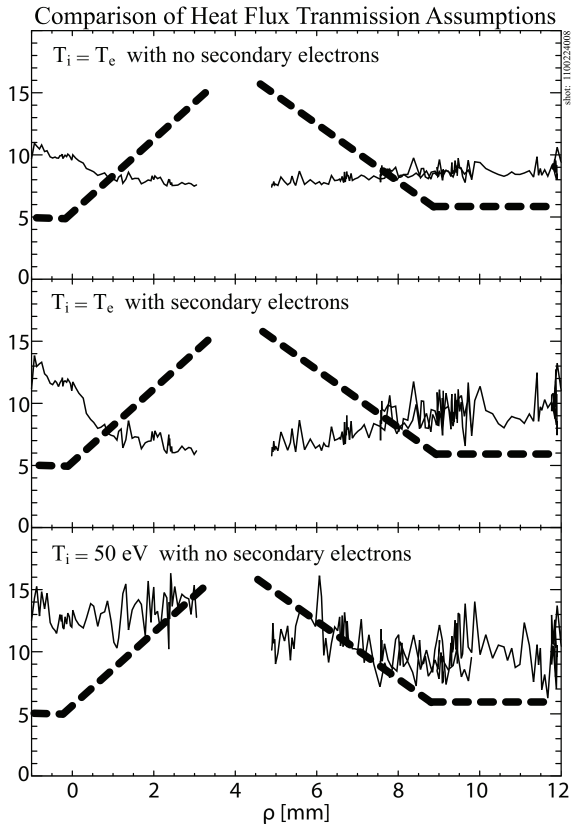

Figure 4: Comparison of the measured γ (thick, dashed line) and Eq. 1 with different assumptions. No secondary electrons and $T_i = T_e$ doesn't match the measured profile. Including secondary electrons forces the trend in the wrong direction. Postulating a constant $T_i = 50$ eV in Eq. 1 trends in the right direction but does not solely explain the measured profile.

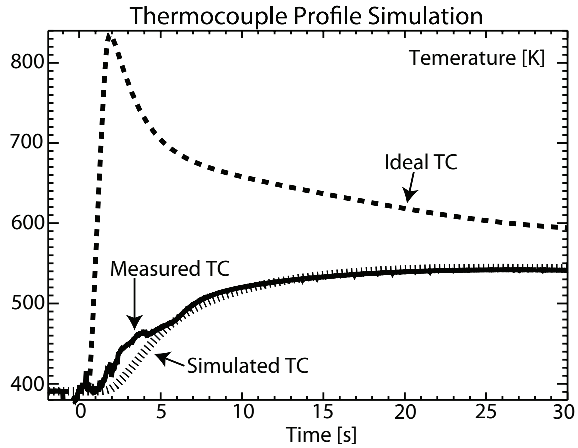

Figure 5: An example of the calorimeter-thermocouple simulation to find the deposited energy (337 J in this instance). Note the deadening effect of the stainless steel tip on the response of the thermocouple to the one second heat pulse at 0.5 to 1.5 s. The fit is not preformed on data before 5 s to avoid magnetic pickup.

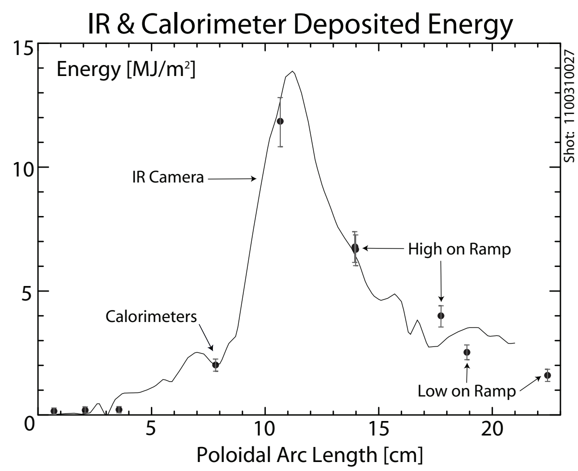

Figure 6: Local energy deposited as measured by the IR camera and calorimeters. The IR agrees with the calorimeters within the 20% variation seen across the ramped tiles.