High Resolution Bolometry on the Alcator C-Mod Tokamak

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Recent breakthroughs in silicon detector technology now permit measurement of radiated power over a wide range in photon energies. These detectors (also known as AXUV photodiodes) have a flat spectral power response from ultra-violet to X-ray energies, and with a slightly reduced efficiency all the way down to visible wavelengths. Since they can be made small, multi-channel detectors allow high spatial resolution to be combined with an intrinsic high temporal resolution, which can reach the microsecond range, depending on the application. A combination of two multichannel toroidally viewing systems has been recently installed on the Alcator C-Mod tokamak. The first array, which is composed of 16 channels, sees tangentially the outer half of the plasma at the midplane, and is used to measure the total power radiated. The second array, also located at the midplane, consists of 19 channels and views the edge of the plasma. This array has a 2 mm radial resolution, allowing, for example, the study of edge dynamics in high confinement (H-mode) plasmas. Because these detectors are largely insensitive to neutral particles (at least at particle energies of interest), it is now possible to measure the radial distribution of neutral ”radiated” power emissivity, by looking at the difference between these measurements and those obtained with standard bolometers. Examples of applications of these measurements to the study of edge H-mode dynamics, impurity injection, disruptions, and internal barrier formation, are described. Planned upgrades and new applications for Alcator C-Mod are also discussed.

I. Introduction

The precise accountability of power balance in a tokamak plasma discharge has always been important for the understanding of particle and heat transport. That understanding leads naturally to the study of power handling at the boundary between the plasma and material surfaces such as divertor plates and limiters.

Presently, only one technique for measuring total radiated power is widely used in tokamak experiments. This technique, commonly referred to as bolometry, is based on the measurement of the resistance of a small wire attached to a foil which is exposed to plasma radiation. In many experiments, silicon photodiodes have also been used, but their restricted spectral bandwidth limited their use to a narrow photon energy band. However, recent breakthroughs in silicon technology have allowed the development of a wide-band bolometric detector. This type of detector has a flat spectral response (in power) over a wide band of photon energies and, consequently, can now be used as bolometers for fusion plasmas.

In this paper we will describe the applications of such silicon photodiode detectors in the Alcator C-Mod tokamak located at MIT. The Alcator C-Mod experiment is based on a high toroidal field ($\leq$9T), compact design (major radius of 0.67 m, minor radius of 0.22 m), operating at high density (up to 1x$10^{21}m^{-3}$), with a closed divertor and molybdenum ($Z = 42$) as the plasma facing material. The source of auxiliary heating is presently composed of 4MW of Ion Cyclotron Radio Frequency (ICRF) power, with an additional 4MW to be added later in 1998. In addition to a description of the instruments, we will show many applications of such detectors, their limitations and long term stability. Finally, we will describe some future upgrades.

II. Detector

The bolometric diagnostic system is based on silicon photodiode (AXUV - absolute extreme-ultraviolet) detectors manufactured by International Radiation Detectors.[1] As shown in Fig.1, the detectors have a high quantum efficiency (even at low photon energies) which allows a nearly flat spectral response in power.[2] This has been made possible with the development of a new treatment of the exposed surface which reduces drastically the so-called dead layer. In our case, the silicon thickness has been chosen to be 30-40 μm, allowing the detection of photons between 1 eV and 4-6 keV.

The advantages of a silicon photodiode system over a foil based bolometric system are multiple. They possess a very high sensitivity (typically 0.24A/W, see Fig. 1), which allows the physical dimensions to be made small (of the order of a millimeter), which in turn permits very high spatial resolution. They are intrinsically very fast, with a nominal risetime which can be as short as a fraction of a microsecond. One additional and interesting feature is their relative insensitivity to neutral particles, (mainly hydrogenic species) contrary to normal foil bolometers which measure them as well as photons. This is true in our application, partially because most of the neutral flux power is carried by particles of $\sim$ 500 eV or less.

III. Experimental Set-Up

A variety of bolometer detectors has been installed inside the vacuum vessel of the tokamak. A single channel (model AXUV-100G) is positioned 25.6 cm above the torus midplane, on the outside periphery, at 1.1m in major radius. The 1cm by 1cm detector is located approximately 2mm behind a 100μm diameter precision pinhole. Thus, it has a global view of the plasma, with a solid angle approaching 2π, and is simply referred to as the 2π bolometer. A signal level of the order of 0.1 mA is usually obtained for a total radiated power of $\sim$1MW. The conversion from a point measurement to a global radiated power is simply done by calculating the emission collected by the detector for a ring of plasma emitting at the plasma center. Changes in the emissivity profile were found to modify the collection efficiency factor by approximately 15% at most.

At the outboard midplane, as shown in Fig.2, a 16 channel detector (model AXUV-16ELO) looks tangentially at the outer half of the plasma, from slightly inside the magnetic axis (the nominal center of the plasma) to past the edge of the plasma (separatrix), a 28 cm span (major radius of 0.64 to 0.92 m). Each channel is 2mm wide by 5mm high (vertical direction), with the array located 8.6 cm away from an aperture 1mm wide by 3mm high. In this case, signal levels of approximately 10 μA are routinely obtained for a 1MW total radiated power discharge.

Also at the outboard midplane, looking tangentially, a 20 channel detector (model AXUV-20EL) has been installed inside one of the RF protection limiters. This array is dedicated to edge plasma studies, with a spatial resolution of 2mm (spanning major radii from 0.89 to 0.93 m). Each channel is 0.75mm wide by 4 mm high, located 13.5 cm away from a 1mm by 3mm aperture. Typical signal levels vary greatly in this case, going from ∼2μA inside the edge of the plasma to less than 0.1μA on the outermost chord.

The viewing chord location of both arrays has been verified by scanning the location of a point light source (a 4W halogen lamp) inside the vacuum vessel. Leads from the detectors are brought outside the vacuum vessel through standard feedthroughs, to current to voltage amplifiers (with respective gains of 5000, 10000 and 500,000V/A). No bias is applied to any of the detectors. These complement our standard bolometer array (also shown in Fig. 2) which is composed of 16 channels for the main chamber, (20 additional channels are available in the divertor area), looking tangentially at the outer half of the plasma, from slightly inside the magnetic axis to the edge of the plasma.[3,4]

IV. Temporal Resolution

A dramatic improvement brought by these instruments is the increase in temporal resolution. Nominally capable of reaching a time response better than 1μsec, these detectors surpass normal foil bolometers which are normally limited to ∼20 msec in time response. However, due to present digitizer limitations, our data are acquired at 10kHz only. Nevertheless, many phenomena related to magneto-hydrodynamic (MHD) events are visible also on the radiated power emissivity.

Comparison of the total radiated power between the photodiode arrays and standard bolometers is made possible by injecting trace impurities into the discharge. Shown in Fig. 3 is the injection of niobium at 0.65 second. A very good agreement is obtained between the global view detector (2π bolometer) and the photodiode arrays. We also obtained a good agreement between them and the standard bolometric measurement. Note that the standard bolometers have a 20 msec built-in acausal smoothing, which would cause the apparent radiated power to rise before the actual injection.

For the same injection, we can also follow the radiated emissivity profile as a function of time. Shown in Fig. 4 are the emissivity contours following the injection as a function of time and major radius. The measurement will be used in conjunction with modeling (such as in the MIST code[5]) to validate cooling curves for various elements, and diffusion coefficients (including convection) for various confinement regimes.

Shown in Fig. 5 are the radiated power emissivity contours for a m=1, n=1 coherent mode located at the center of the discharge (R=0.675 m). The mode exists for approximately ~70 milliseconds, but only 15 are shown. The mode clearly slows down and reverses direction at 1.12 second. The direction reversal is also observed to occur at the same time on the toroidal rotation measurement.

Finally, the time resolution of the instrument can be used to study the temporal evolution of the radiated power profiles following a disruption. Power dissipation of the thermal and magnetic energies during a disruption is crucial for the development of a reliable fusion reactor. While the details of a disruption are not fully available due partly do the present digitization rate, radiated power emissivity has been observed to be in excess of 20 MW/m^3 in the fastest disruptions. However, one must take care to avoid the spurious signal that can be recorded from a electron run-away population that can impact the detector housing.

V. Spatial Resolution

Since the detectors can be made very small and compact, multi-channel systems allow high spatial resolution. Such high resolution is very critical since energy and particle transport barriers observed in many discharges can lead to very steep gradients. Typical scale length have been observed to be as short as a few millimeters in the Alcator C-Mod H-mode edge plasma. Shown in Fig. 6 is the formation of the edge barrier visible on the radiated power emissivity profile, during the evolution of the discharge from a low confinement (L-mode) to a high confinement (H-mode) regime. We observe that the emissivity increases inside the separatrix (last closed magnetic flux surface) while it is decreasing outside. In this case, the emissivity scale-length, defined as $\mathrm{L}_E = EdR/dE$, where E is the local emissivity and R is the radius, decreases from $\sim 2-3cm$ to as low as $\sim 4-5mm$, close to the instrumental resolution. The scale-length as measured at the plasma separatrix has been found to vary with plasma current during high confinement periods while no change has been recorded during a toroidal field scan. Such information can lead to a better understanding of the formation of the edge barrier. Similar observations have been made while studying internal barrier formation, such as during Pellet Enhanced Performance Mode (PEP-mode).[6]

The scalelength in radiated power emissivity decreases also, but, in this case, near the center of the plasma ($r/a \sim 0.1 - 0.2$).

VI. Power carried by neutrals

As mentioned above, another important feature of the photodiodes is their insensitivity to neutrals. The neutrals, especially in high density discharges, such as those obtained in the Alcator C-Mod tokamak, have the potential of carrying a significant amount of power away from the confined discharge through the charge-exchange process. The high plasma density also means that low energy neutrals ($\lesssim 500$ eV), are found only in the first few centimeters of the plasma edge, due to their short mean free path for ionization. Note, that Alcator C-Mod does not utilize neutral beam heating, and consequently, no source of fast neutrals exists in the experiment at the moment.

Therefore, it is possible to quantify the amount of power carried by neutrals, by simply looking at the difference in brightness (chord integrated measurement) between normal foil bolometers and photodiodes. The difference can then be Abel-inverted, which would give the neutral power emissivity profile. The observed difference can not be attributed to a difference in sensitivity at lower photon energy (e.g. in visible), as the measured emissivity (e.g. H_α) at those wavelengths is too low by 3 orders of magnitude to explain the difference. In this case, the result would be the net emissivity, which would include any ionization along the chord. However, in the presence of absorption, the Abel inversion is technically invalid, since one has to take into account the non-axisymmetry of the problem. The issue can be resolved by including the attenuation of the signal, mainly through ionization, along the path, which requires some knowledge of electron temperature and density (electron impact ionization dominates by far over ion impact ionization at those energies).

Shown in Fig. 7 is the neutral emissivity profile as inferred from the two measurements. In this case no correction has been made for attenuation. As expected, most of the power originates from the edge of the plasma. It is noteworthy that the neutral power emissivity is comparable to photon power emissivity, at least in the region of interest. Shown also is the calculated neutral emissivity based on a simple 1-D neutral Monte-Carlo simulation. These calculations take in account the plasma density and temperature profile, and a measurement of the neutral pressure outside the plasma. The agreement is very good, increasing our confidence for this interpretation. Note that in this model, a negative emissivity is possible since neutrals can be "absorbed" though ionization. To further verify this effect we produced pure helium discharges (less than 10% percent deuterium), in which the charge-exchange process is absent (i.e. down, at least, by a factor of 10) at the energies of interest. Shown in Fig. 8 are the profiles obtained during an H-mode in a helium plasma, with the bolometer and photodiode arrays. The agreement between the two bolometric techniques is most striking in this case, and gives us additional confidence that the difference seen in deuterium discharges is not due to any difference in spectral sensitivity.

VII. Long term stability

Due to their location inside the vacuum vessel, access to these detectors is usually limited, so long term stability of these detectors is an important factor. The manufacturer reports[7] that the first generation of detectors will suffer a degradation in sensitivity of approximately 9% for every $10^{15}/cm^2$ 10 eV photons (i.e. Lyman α photon). Fortunately, that represents a large number of C-Mod plasma discharges, of the order of a thousand. However, electron cyclotron discharge cleaning (ECDC)[8] is used to prepare the tokamak for operation, and is usually done during off-hours for periods reaching hours at a time. These discharges, while cold and tenuous, produce a smaller flux of photons and consequently we estimate that 100 hours of cleaning would produce the same decrease in sensitivity. In fact, after the last experimental campaign, the detectors were tested, using a mercury lamp and a 30-40% drop was observed, roughly consistent with the total exposure to low energy photons. Fortunately, a second generation of detectors is now available which are 20-100 times more resistant (G-series) and a third generation (series SXUV) promises to be more resistant still. These detectors should then be limited by standard neutron-induced damage, a limitation that may be avoided by annealing.[9]

VIII. Future Plans

In view of the success obtained in the use of these new detectors, we plan to increase the coverage of the plasma. First, we are planning to add 2 arrays in the divertor using the 10 element detector (model AXUV-10EL), which is very compact and easy to mount. One of them would be looking down from the divertor outer ledge, and one will be looking up from the floor of the machine. Local inversion will be then possible and will direct us towards a more fully tomographic system for the divertor.

In the main chamber we plan to add a poloidal view looking at the expanded flux surfaces located at the top of the plasma, increasing the effective radial resolution for edge studies. We plan to locate this array (with the AXUV-20EL) behind a filter wheel (8 positions are planned), which should give us valuable information on the composition of the edge radiation at different wavelengths.

IX. Summary

The recent commercial development of a silicon-based wideband bolometer has allowed many improvements in measurements of radiated power. Although they may not replace standard foil-based bolometers in all applications, they have several advantages, including high sensitivity, large dynamic range, high time response, high spatial resolution, small size, ease of installation and finally, cost. They were found to be in good agreement with standard bolometers in tokamak discharges without significant neutral particles.

X. Acknowledgments

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Figures

FIG. 1. Spectral response of the AXUV detector, ranging from visible to soft X-ray region. Note the logarithmic x axis.

FIG. 2. Top view of the Alcator C-Mod tokamak with set-up of detector views. Shown are the central array (16 channels), the edge array (20 channels) located inside the RF protection limiter, and the central bolometer array (16 channels).

FIG. 3. Comparison of the measurements of the total radiated power, following the injection of a trace impurity (Niobium). The different techniques agree well overall, considering the built-in slow time response (with acausal smoothing) of the bolometers. The result from the standard bolometer array is shown with a dash line, and with a straight line for the AXUV array. On this scale, the global AXUV (2π) view detector measurement is undistinshguishable from the AXUV array, and, consequently not shown.

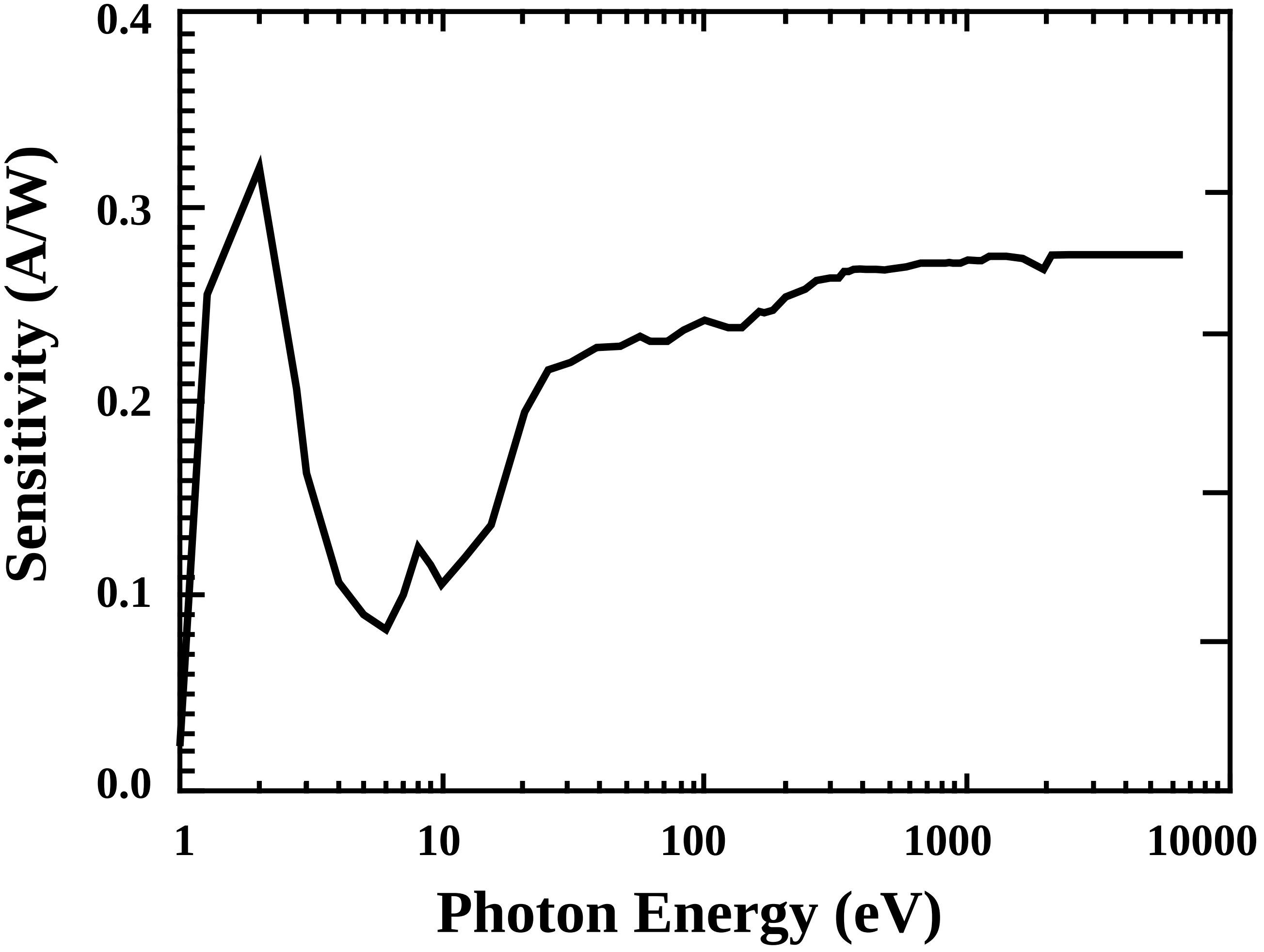
FIG. 4. Constant emissivity contours following a trace impurity injection (in this case niobium). Note also the effects of sawteeth on the transport of impurities near the center of the discharge.

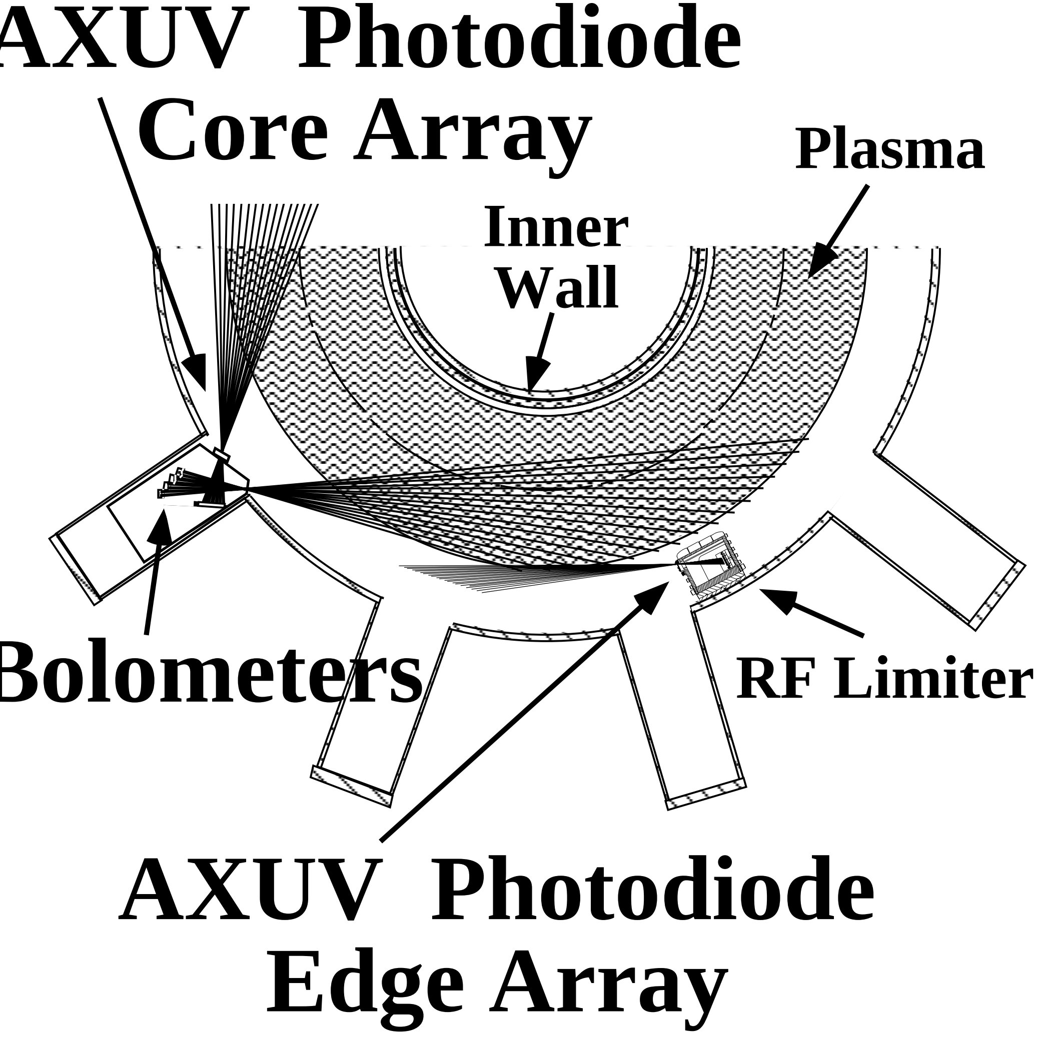
FIG. 5. Effects of a m=1, n=1 mode on the emissivity profile. The MHD activity follows a High to Low confinement (H to L) transition. At 1.12 second the mode stops and reverses direction.

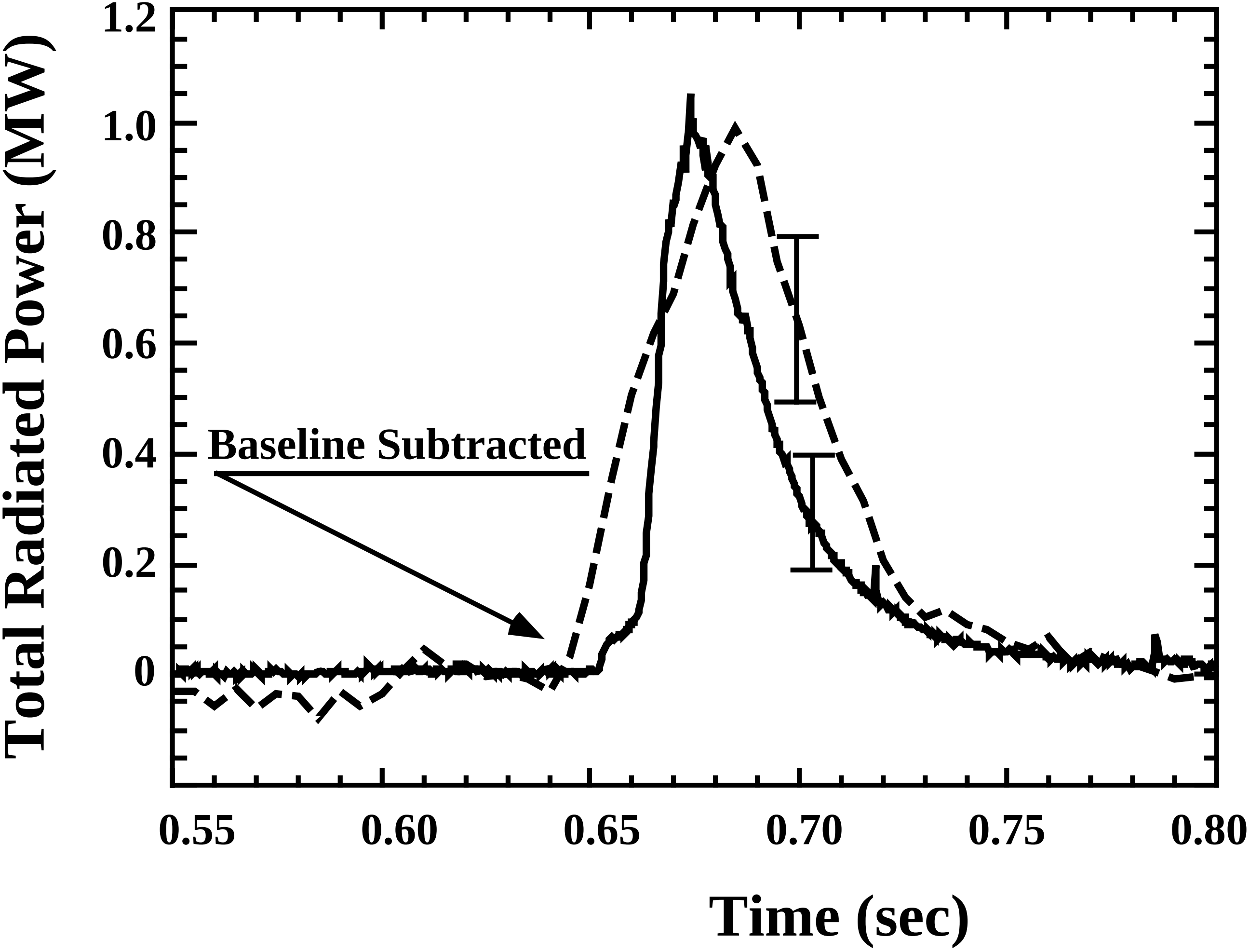
FIG. 6. Radiated power emissivity profile at the edge of the plasma for 2 different time slices, one during low confinement (L-mode) and one during high confinement (H-mode). Also shown is the separatrix location.

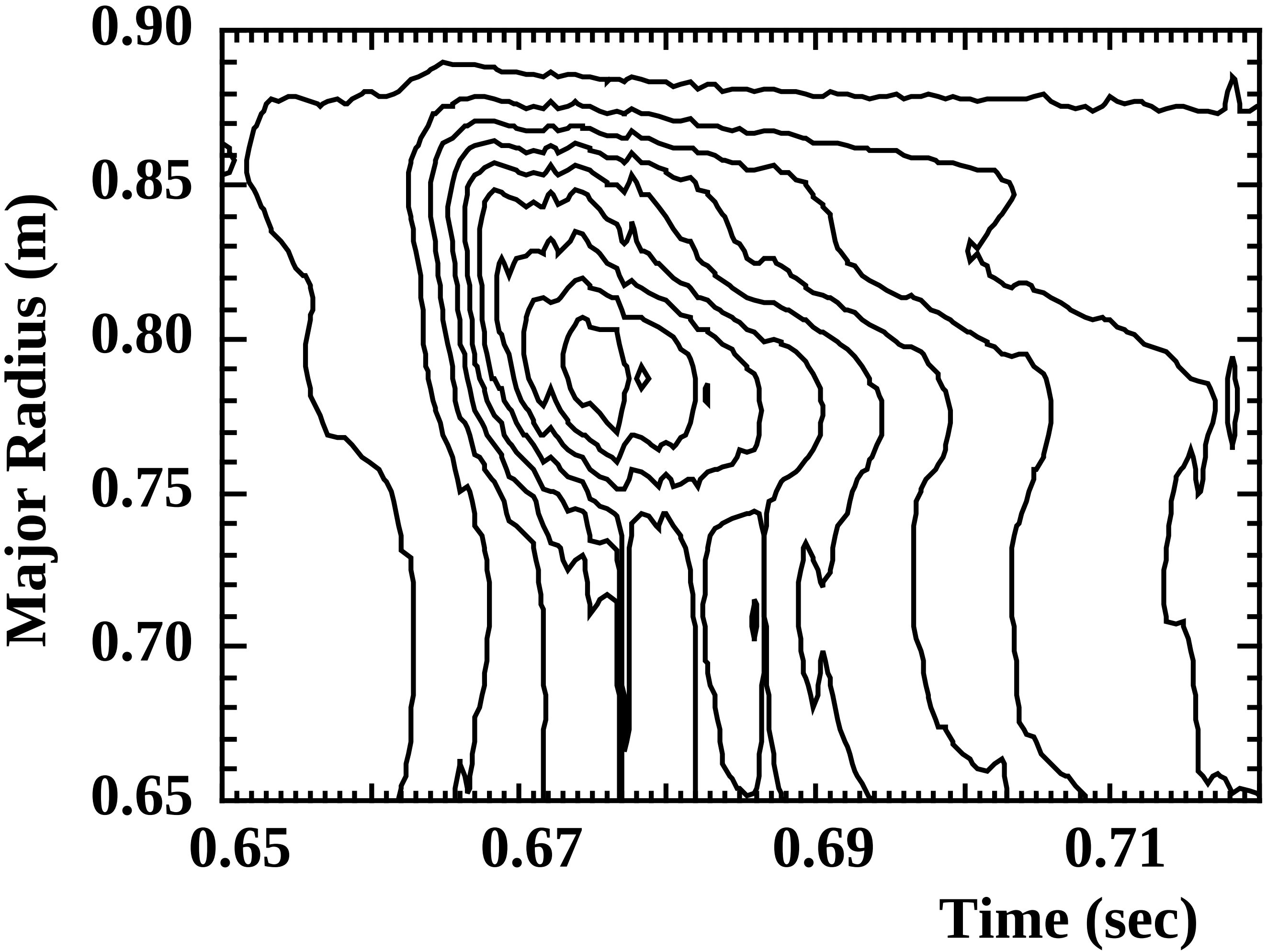
FIG. 7. Power radiated emissivity profile for neutrals and photons as inferred from the photodiodes and standard bolometers. The dashed line corresponds to the photon radiation only, the solid line for the inferred neutral component while the dot-dash is the calculated neutral emissivity for this discharge.

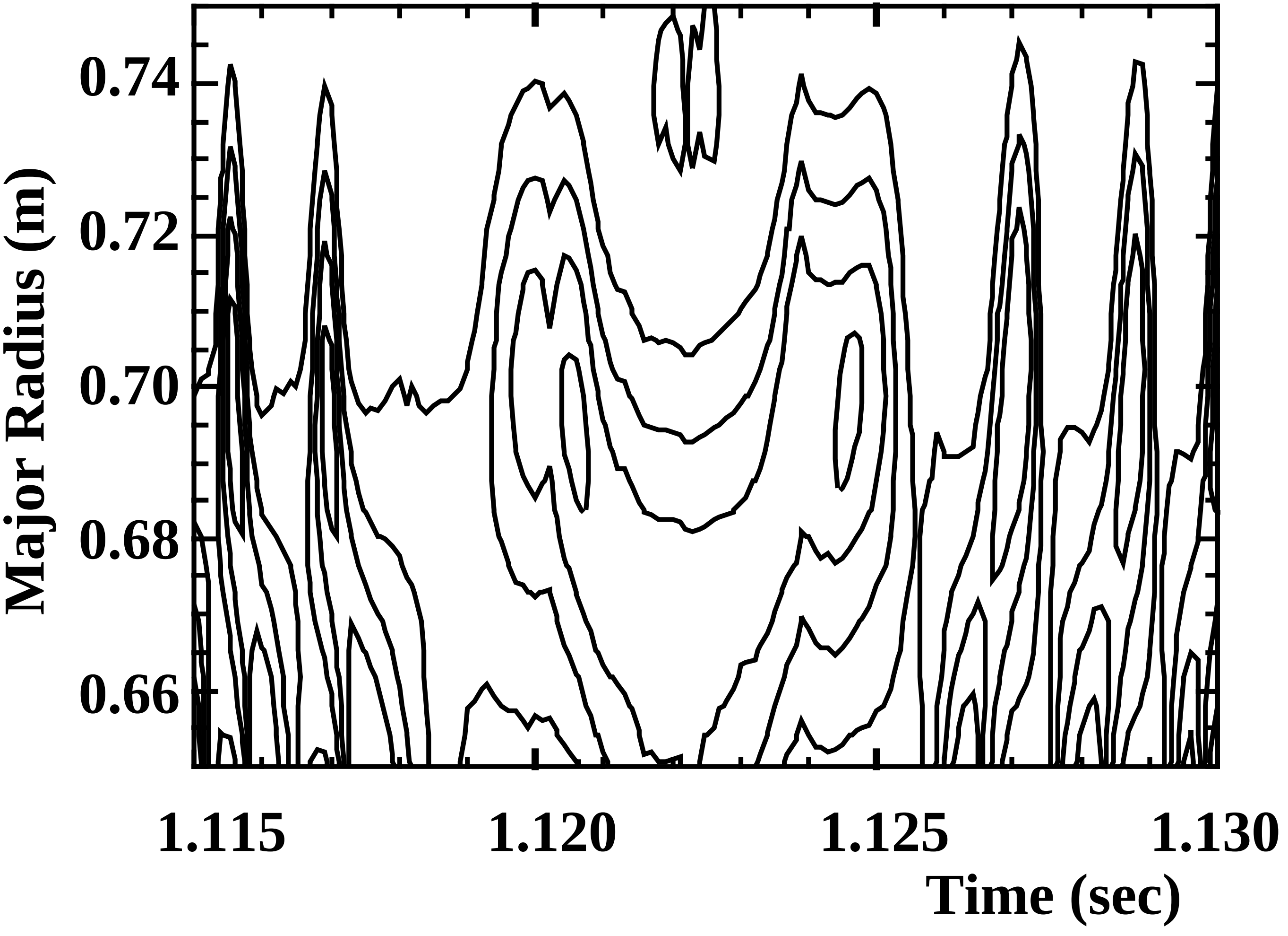
FIG. 8. Radiated power emissivity profiles from photodiodes and bolometers in pure Helium plasmas indicating the absence of neutrals in the radiated power.

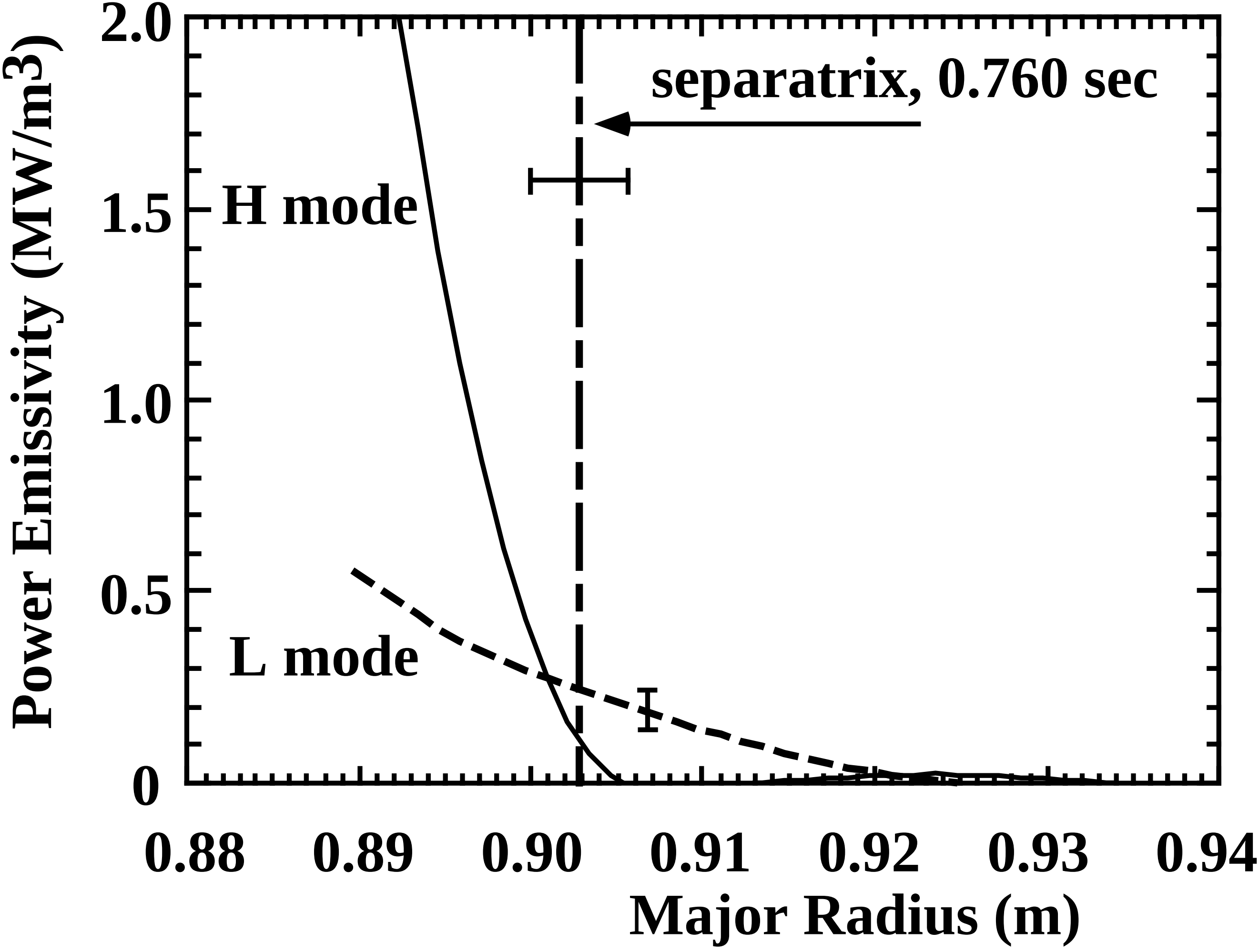

0.4
0.3
0.2
0.1
0.0
Sensitivity (A/W)
1
10
100
1000
10000
Photon Energy (eV)

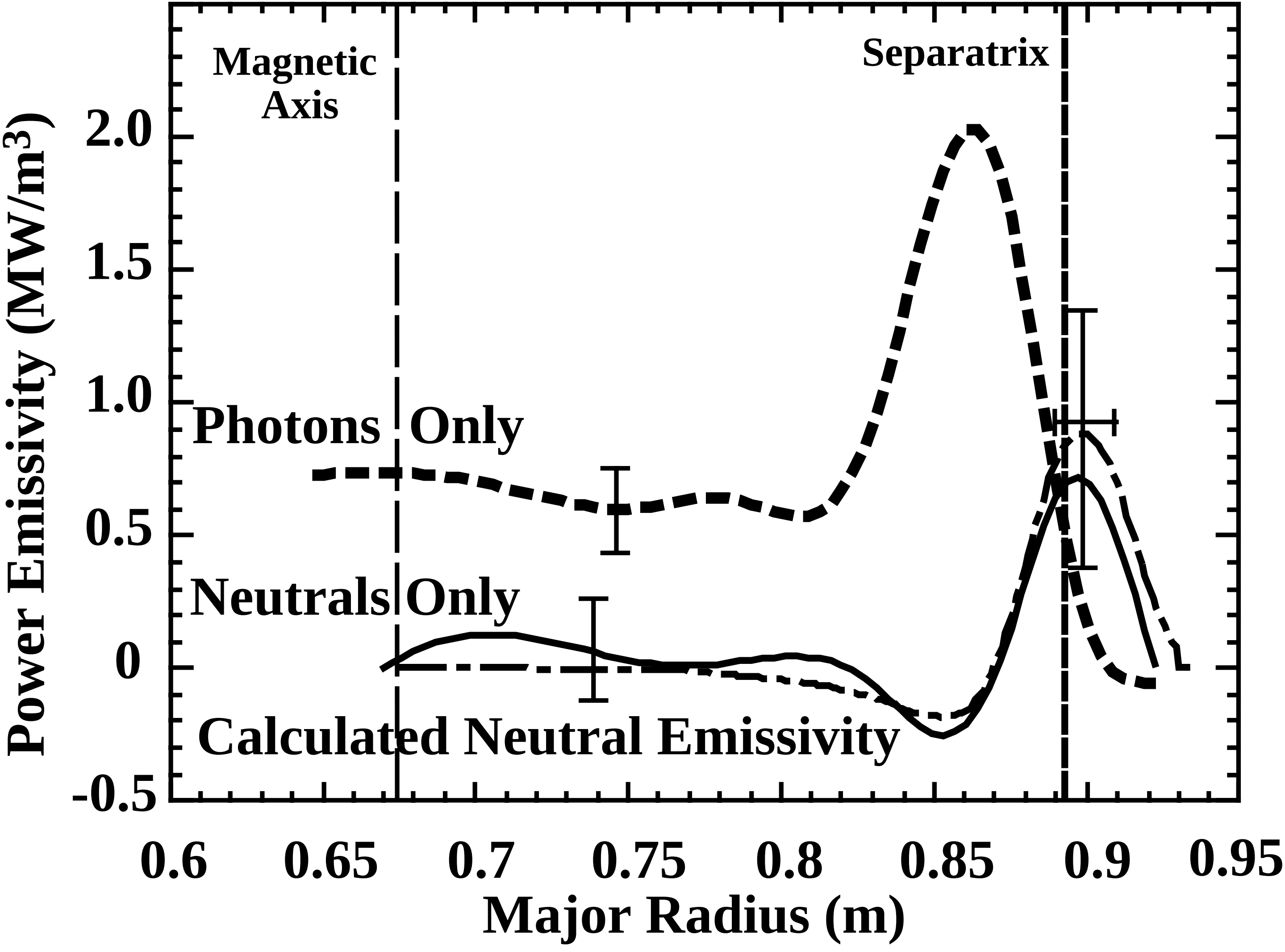

AXUV Photodiode
Core Array
Plasma
Inner
Wall
Bolometers
RF Limiter
AXUV Photodiode
Edge Array

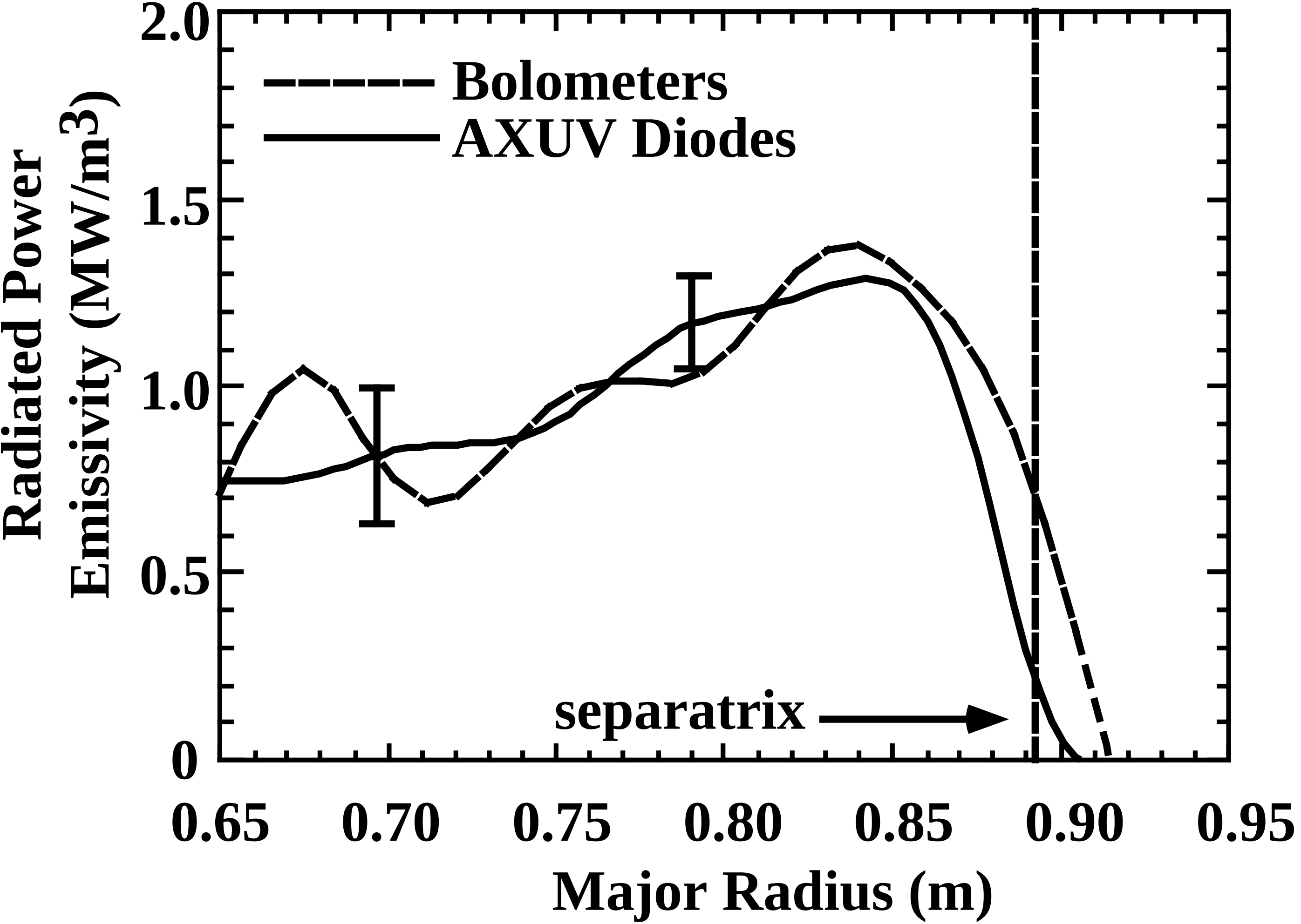

Total Radiated Power (MW)
1.2
1.0
0.8
0.6
0.4
0.2
0
Baseline Subtracted
0.55
0.60
0.65
0.70
0.75
0.80
Time (sec)


0.90
0.85
0.80
0.75
0.70
0.65
Major Radius (m)
0.65
0.67
0.69
0.71
Time (sec)


Major Radius (m)
0.74
0.72
0.70
0.68
0.66
1.115
1.120
1.125
1.130
Time (sec)


separatrix, 0.760 sec
H mode
L mode
Power Emissivity (MW/m3)
2.0
1.5
1.0
0.5
0
0.88
0.89
0.90
0.91
0.92
0.93
0.94
Major Radius (m)


Magnetic Axis
Separatrix
Photons Only
Neutrals Only
Calculated Neutral Emissivity
Power Emissivity (MW/m3)
2.0
1.5
1.0
0.5
0
-0.5
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
Major Radius (m)


Bolometers
AXUV Diodes
Radiated Power Emissivity (MW/m³)
2.0
1.5
1.0
0.5
0
separatrix
0.65
0.70
0.75
0.80
0.85
0.90
0.95
Major Radius (m)