The new infrared imaging system on Alcator C-Mod

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A new infrared imaging system has been installed on Alcator C-Mod. This system uses an Amber Radiance 1 IR video camera (filtered to the 4.2–4.4 μm band) to view a 30 cm×30 cm region of the lower divertor from above by means of a re-entrant 5-m long ZnSe based periscope. Capture of the standard 30 Hz video frames (8-bit) and camera control are performed remotely over fiber optic links by a Windows 95 PC, using a MuTech MV-1000 video grabber board. Plans are under way to directly capture the 60 Hz, 12-bit, 256×256 pixel images using a digital video camera interface with a fiber optic link from EDT (Beaverton, Oregon). Preliminary results show that during nondisruptive discharges no substantial surface temperature increase is observed on the upper sections of the divertor, with the exception of "hot spots," although occasionally, increased heating in toroidal bands is seen. Bands can also be observed after disruptions that result in a downward movement of the plasma. © *1999 American Institute of Physics*. [S0034-6748(99)53501-6]

I. INTRODUCTION

It is well known within the magnetic confinement fusion community that the overheating of plasma facing components adversely affects the plasma performance by the introduction of impurities emanating from these material walls through evaporation or other processes. This overheating can eventually lead to surface melting of plasma-facing components. This is not only recognized current day experiments but is a serious consideration in the design of future devices such as the International Thermonuclear Experimental Reactor (ITER). In this article we describe the new infrared thermography system that was installed on the Alcator C-Mod tokamak for first use during the recent Winter of the 1997–1998 experimental campaign. The goal of this system is to assist in the study of phenomena that minimize wall heating such as plasma detachment, radiative mantles, volume recombination, etc.

In a diverted tokamak, such as Alcator C-Mod,[1] the heating of plasma facing components is most severe in the divertor area and hence measuring the surface temperature of this region prevails over other regions, with the possible exception of RF heating antennas. The infrared (IR) imaging system described here is used to monitor the surface temperature of the lower divertor of this compact, high magnetic field, high energy density, ICRF auxiliary-heated tokamak. In Sec. II we present the diagnostic setup on the Alcator C-Mod experimental device. Due to the unavailability of midplane level viewports, a 5-m long periscope was designed and built to view the divertor from above while trying to keep the IR camera in a region of low magnetic field. Results obtained during the first experimental campaign are shown and discussed in Sec. III. These results show that the surface where the most intense heating occurs are not directly imaged by the present periscope configuration in which the view is limited to the upper, open sections of the divertor. Planned improvements to the diagnostic, that among other things will overcome this limitation, are presented in Sec. IV.

II. DIAGNOSTIC

The new infrared imaging system on Alcator C-Mod is mainly composed of an Amber Radiance 1 IR video camera, a 5-m long ZnSe based periscope, and a data acquisition and control station. The Amber Radiance 1 IR camera uses a 256×256 indium antimonide sensor array (i.e., a focal plane array) sensitive in the 3–5 μm range which is cooled down to 77 K by an internal closed-cycle Stirling microcooler. The progressive exposure of the array can be varied between 1 μs and 16 ms to accommodate a wide range of object temperatures. After an internal two-point nonuniform correction that compensates for variations in the sensitivities of the individual elements in the array, the 60 frame/s camera output is available in either video format (RS-170, RGBS, NTSC, and S-Video) or digitized (12-bit) through a high speed video bus.

A 2.23/7.4° dual field of view germanium–silicon lens is used attached to the camera. This lens, from Diversified Optical Products, has a motorized five-position filter wheel. We use a commercially available CO_2 bandpass filter (4.28–4.42 μm) to minimize the amount of plasma infrared radiation, mainly deuterium molecular radiation, that is detected. Full remote control of the camera and its attached lens are accomplished through an RS-232 link.

Figure 1 shows the calculated hemispherical blackbody emission in the spectral sensitive band of the filtered camera. The functional form of this emission is compared in this figure to measurements obtained with the camera/lens assembly of the thermal emission from a molybdenum tile similar to those that form part of the plasma facing components in Alcator C-Mod. The good agreement indicates that in the 40–140 °C range the tile emissivity is not a sensitive function of the temperature. This behavior is then extrapolated along the calculated, constant emissivity, curve up to the 200–300 °C range. It should be pointed out that, in addition to an appropriate scale factor, an offset due to background photons from hot elements (i.e., lens elements) has been subtracted from these measurements. These background photons represent, for instance, ~92% of the photons detected at 80 °C.

Due to access constraints in the Alcator C-Mod device, a 5-m long re-entrant periscope was designed and built to view the divertor from above while keeping the magnetic field sensitive IR camera in a region of low field. A poloidal cross section of the device, with periscope and partial ray tracing added, can be seen in Fig. 2. Despite the remote location of the camera on top of C-Mod's concrete igloo, a one-fourth in.-thick soft iron shield had to be placed around the camera to reduce the ~300 G local field at full device performance to acceptable levels. With the only exception of a sapphire vacuum interface window and an Al–SiO-coated turning mirror, all periscope optics are ZnSe elements with antireflection coating for the 3–5 μm range.

The periscope is composed of three sections (lower, upper, and optical rail sections) and is located on Alcator C-Mod's Bay A. In its present configuration the periscope allows a 30 cm×30 cm section of the lower divertor and inner wall to be imaged at any time with a spatial resolution better than 1 mm. The lower section of the periscope is inserted in a 2.5 in. OD re-entrant tube and can be rotated about its axis ±45°, overnight and without vacuum break, to increase the coverage of plasma facing components. Although the re-entrant tube restriction, together with the large distance between the divertor surface and the first element of the periscope, limits the numerical aperture of the collection cone to ~0.0015, this does not impose a problem in terms of photon flux due to the high sensitivity of the Amber Radiance camera, even when the narrow bandpass filter is used.

The re-entrant, lower section of the periscope has suffered from both shock and thermal damage. Efforts are being made to avoid shock damage of the lower most five elements which in time get their edges cracked and chipped. The thermal damage on the other hand, which was severe enough to melt a Teflon holding ring, was effectively controlled by a constant flow of cool (~10 °C) nitrogen. This cool flow also helps in reducing the background photon counts.

Video image (30 Hz, RS-170) capture and camera control are performed remotely over fiber optic links by a Windows 95 PC and using a MuTech MV-1000 video grabber board. The images are stored in real time in the PC's RAM through the high speed PCI bus. Synchronization to the experiment is achieved through a TTL external gate input to the video grabber board. After the discharge has taken place the image sequence is stored on disk, generally in multiframe GIF format. Further details on this process can be seen in Ref. 2. An analog VCR record of the images is also obtained during the discharge. It should be pointed out that although the Amber Radiance camera performs a 12-bit digitization of the 60 Hz exposures, the current data acquisition implementation has only 8-bit resolution due to the RS-170 video signal. In addition, some of the information is lost by the interlacing of the 60 Hz frames into the 30 Hz video images. A new "all digital" capture of the 12-bit 60 Hz exposures is being implemented for the next run campaign and is briefly described in Sec. IV.

III. PRELIMINARY RESULTS

An infrared image of the divertor region can be seen in Fig. 3(a). This image corresponds to a 1 MA discharge in which 2 MW of ICRF power was injected into the torus for over 0.8 s, followed by a 1.2 MW phase for ~0.1 s before the image was obtained at 1.333 s. The divertor "noses," private flux region, and machine floor can be distinguished in this image, as well as the individual molybdenum tiles, nominally 1 in.×1 in. in size.

Several observations can be made with respect to this image. First, no localized heating in toroidal bands is observed, just hot spots. These hot spots correspond to either edges around depressions, like those observed on the inner divertor nose, or to slightly protruding elements such as the big hot spot on the floor at Bay A, a turning mirror for another diagnostic. The portion of edge around the depressions that is observed to be hotter is consistent with ion governed losses. [The ion flow is from right to left in Fig. 3(a).]

Second, the line of bright spots along the floor are actually recessed silver-plated bolts. These bolts apparently reflect intense IR thermal radiation from the surface below the outer-divertor nose, hidden to the camera. During typical plasma operation of Alcator C-Mod the outer divertor strike point is located below this nose, either on the vertical plate or on the floor, both hidden from the camera. (The three bolts closer to Bay A are in turn reflected on the vertical wall on the small radius side of the floor.)

Third, there are two foreign elements in the image of Fig. 3(a), both of which are useful in converting image intensities into photon counts. The dark line near the image's midplane corresponds to a lineout reading of photon counts from the InSb sensors located at the midplane of the image. This lineout is then compared to the midplane image intensities to correlate photon counts with recorded intensities. The dark spot at the Bay A end of the image midplane, is a cold (room temperature) fiducial placed in an intermediate image plane that produces a controlled drop in the lineout, and in this way increases its range and reduces the error introduced in this step of the calibration process. Subsequently, a hot fiducial was introduced on the other end (Bay K) of the image midplane, while at the same time the cold fiducial was slightly warmed. It should be emphasized that these fiducials are not used in the absolute temperature calibration of the camera but in producing controlled variations in the midplane lineout.

Temperature estimates for the surfaces observed in Fig. 3(a) can be seen in Fig. 3(b). The temperature of the open section of the divertor reaches the 250 °C level after nearly 1 s of substantial RF heating; a very modest temperature. The first step in the calibration process involves converting image intensities into photon counts as described above. This step also relies on the two-point nonuniform pixel correction capability of the Amber camera. The photon counts are then corrected for photon losses (absorption and reflection) in the periscope and difference in collection angle between the measurement and the camera calibration with the molybdenum tile. A curve such as that in Fig. 1 is used for each of the pixels in the image to finally turn corrected photon counts into temperatures. The error in this temperature estimate is of the order of 40 °C, mainly due to the small relative amount of surface temperature photons with respect to background (hot element) photons and uncertainties in the periscope transmission.

On occasion, heating in toroidal bands is seen. Two examples are shown in Fig. 4. Figure 4(a) shows an image obtained during a 1 MA ICRF heated discharge in helium. Although in this discharge the EFIT equilibrium reconstruction indicates that the outer divertor strike point is located below the divertor's nose, substantial heating is observed above this nose. This toroidal band of increased heating is not observed on typical discharges and has to be attributed to a broader scrape off layer.

In Fig. 4(b), an image obtained soon after a disruption is shown. This 0.8 MA disruption which resulted in a downward movement of the plasma produced a toroidal band of heating located approximately 6 cm away from the outer divertor's nose. An intense, short (~1 ms) nonthermal burst of infrared plasma radiation can be observed in this image above its midplane. This burst was registered as the progressive exposure moved vertically across the sensor array.

Unfortunately, the images in Fig. 4 are saturated along these hotter toroidal bands, the surface temperature being above 320 °C. This saturation is caused by the image generation algorithm within the Amber

Radiance camera that, although producing nice looking images, gives little weight to small portions of the image and thus becomes susceptible to saturation. The new “all digital” data acquisition system, described below, circumvents the use of this algorithm and so the saturation problem will be much reduced.

IV. PLANNED IMPROVEMENTS

Although during standard discharges no substantial heating is observed, reflections noted in the images of Figs. 3 and 4 suggest that there is considerable heating below the outer divertor’s nose. It is then proposed to change the periscope’s view to image this region. A sketch of the resulting image can be seen in Fig. 5. Although this reduces the overall surface coverage of the periscope by making it nonrotatable, it allows imaging of what is believed to be a more relevant section of the divertor compared to the open sections of the divertor observed with the present periscope configuration.

A second improvement involves a new all digital data acquisition system. This will not only improve the time resolution from 30 to 60 Hz but also increase the dynamic range from 8-bit standard video images to 12-bit images. The new data acquisition system uses a PCI–RCI digital video Remote Camera Interface with a 1.25 GBd fiber optic link.[3] In this way photon counts are directly recorded without the need to deconvolute these counts from image intensities.

Finally, the error in the temperature measurements will be reduced to below the 10 °C level (at ~250 °C). This will be possible, first, by reducing the hot-element background counts with the addition of an external water chiller on the Amber Radiance camera lens; and second, by monitoring the transmission of the periscope with the use of (slow) thermocouples located below the divertor tiles.

ACKNOWLEDGMENTS

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REFERENCES

[1] I. H. Hutchinson, *et al.*, in *Proceedings of the 16th International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Montreal, Canada, 1996* (International Atomic Energy Agency, Vienna, 1997), Vol. 1, p. 155.

[2] A. J. Allen, J. L. Terry, D. Garnier, J. A. Stillerman, and G. A. Wurden, Rev. Sci. Instrum. **68**, 947 (1997).

[3] Engineering Design Team, Inc., Beaverton, OR.

FIGURE CAPTIONS

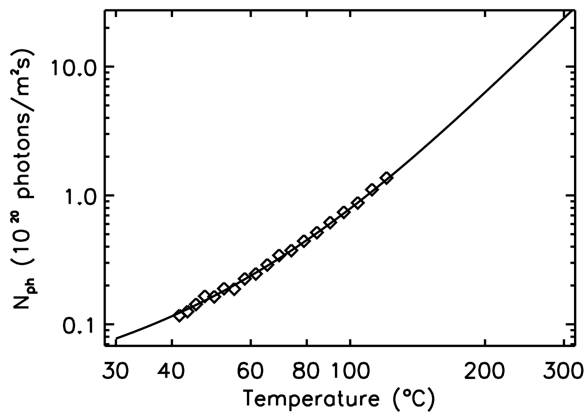
FIG. 1. Calculated hemispherical blackbody emission in the 4.24–4.42 μm band. The diamonds indicate measurements obtained with a molybdenum tile using appropriate scaling and hot element offset.

FIG. 2. Poloidal cross section of the Alcator C-Mod device with periscope and partial ray tracing.

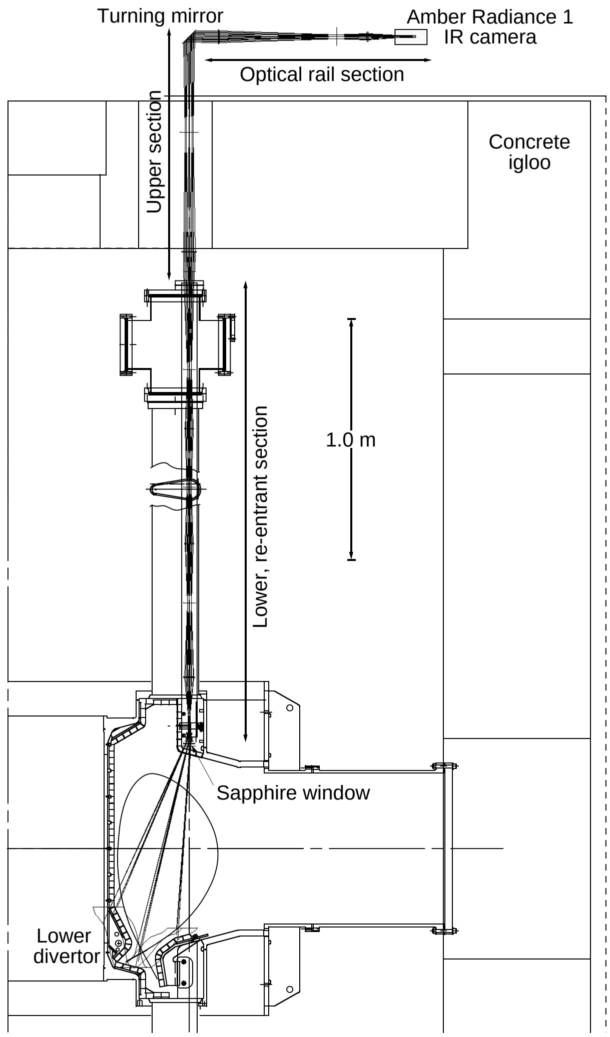
FIG. 3. Divertor image in a typical ICRF heated discharge. (a) Image obtained with Amber Radiance 1 IR camera using the 4.28–4.42 μm bandpass filter and 1.04 ms exposure. (b) Temperature estimates, the divertor region heats up to the 250 °C range.

FIG. 4. Heating in toroidal bands is occasionally observed. (a) Image during a helium discharge. (b) Image soon after a disruption in a 0.8 MA ohmically heated D_2 discharge. The 4.28–4.42 μm bandpass filter was used during both of these discharges and the exposures were 1.30 and 0.78 ms, respectively.

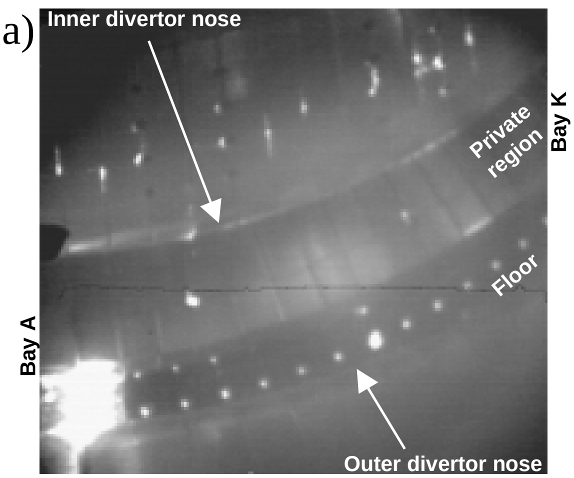
FIG. 5. Proposed modified view that will allow the surface below the outer divertor's nose to be observed. The shaded areas indicate obscured areas due to gussets or mirror edges. By (remotely) changing the focal length of the dual field of view lens on the Amber Radiance camera from 75 to 250 mm, the section within the central square can be magnified. The periscope is located on Bay A.



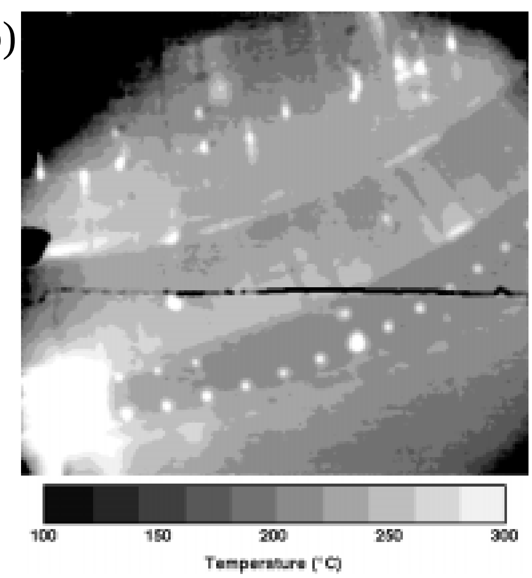
N_{ph} (10^{20} photons/m^{2}s)
10.0
1.0
0.1
30
40
60
80
100
200
300
Temperature (°C)


Turning mirror
Amber Radiance 1
IR camera
Optical rail section
Upper section
Concrete
igloo
1.0 m
Lower, re-entrant section
Sapphire window
Lower
divertor

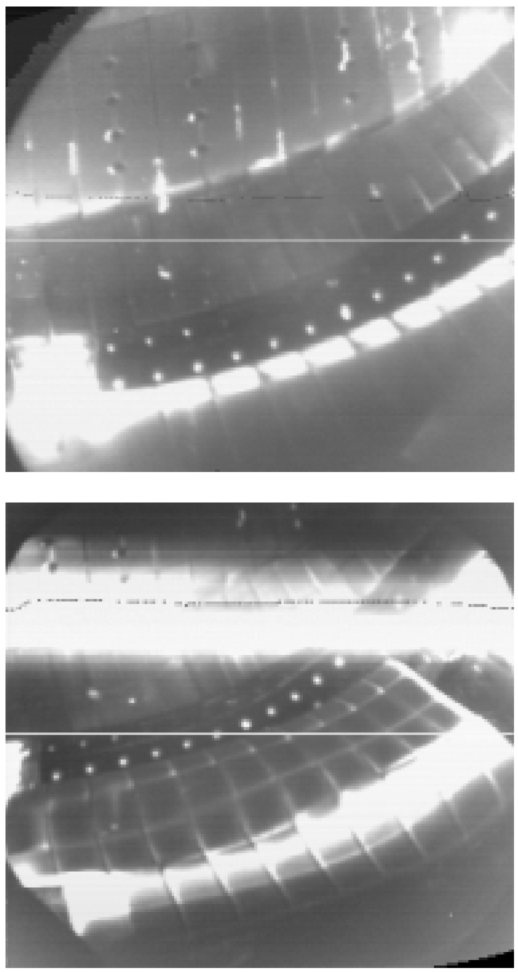
a)

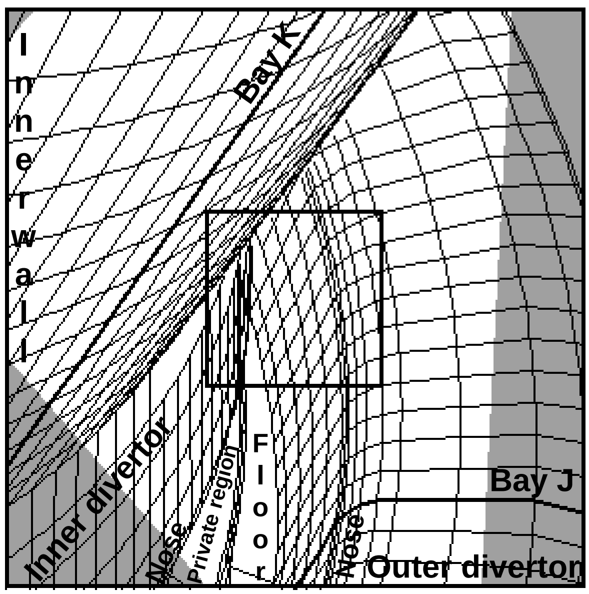

Inner divertor nose
Private region
Bay K
Floor
Bay A
Outer divertor nose

b)


100
150
200
250
300
Temperature (°C)

a) b)





Inner wall
Bay K
Inner divertor
Nose
Private region
Floor
Nose
Bay J
Outer divertor