REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 72, NUMBER 1 JANUARY 2001

Digital-image capture system for the IR camera used in Alcator C-Mod

R. J. Maqueda and G. A. Wurden
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

J. L. Terry
Plasma Science and Fusion Center, MIT, Cambridge, Massachusetts 02139

J. Gaffke
Engineering Design Team, Inc., Beaverton, Oregon 97006

(Presented on 21 June 2000)

An infrared imaging system, based on an Amber Radiance 1 infrared camera, is used at Alcator C-Mod to measure the surface temperatures in the lower divertor region. Due to the supra-linear dependence of the thermal radiation with temperature it is important to make use of the 12-bit digitization of the focal plane array of the Amber camera and not be limited by the 8 bits inherent to the video signal. It is also necessary for the image capture device (i.e., fast computer) to be removed from the high magnetic field environment surrounding the experiment. Finally, the coupling between the digital camera output and the capture device should be nonconductive for isolation purposes (i.e., optical coupling). A digital video remote camera interface (RCI) coupled to a PCI bus fiber optic interface board is used to accomplish this task. Using this PCI-RCI system, the 60 Hz images from the Amber Radiance 1 camera, each composed of 256×256 pixels and 12 bits/pixel, are captured by a Windows NT computer. An electrical trigger signal is given directly to the RCI module to synchronize the image stream with the experiment. The RCI can be programmed from the host computer to work with a variety of digital cameras, including the Amber Radiance 1 camera. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1321008]

I. INTRODUCTION

An infrared imaging system is used at Alcator C-Mod[1] to measure the surface temperatures in the lower divertor region.[2] This system employs an Amber Radiance 1 infrared camera that is optically coupled to the torus via a reentrant, 5-m-long, ZnSe-based periscope. Due to the supra-linear dependence of the thermal radiation on temperature it is important to make use of the 12-bit digitization of the focal plane array of the Amber Radiance camera and not be limited by the 8 bits inherent to the video signal. It is also necessary for the image capture device (i.e., fast computer) to be removed from the high magnetic field environment surrounding the experiment. Finally, the coupling between the digital camera output and the capture device should be nonconductive for isolation purposes (i.e., optical coupling). This article presents one solution to this problem.

The 60 Hz images from the Amber Radiance 1 camera, each composed of 256×256 pixels and 12 bits/pixel, are captured by a Windows NT computer using a digital video remote camera interface system. This system is composed of two parts (Fig. 1), the remote camera interface (RCI) that is located close to the digital camera and a fiber optic interface board that is located on the PCI bus of the Windows NT computer. A brief description of this PCI-RCI system together with the implementation of the system in Alcator C-Mod can be seen in Sec. II. An example of data obtained in Alcator C-Mod with this new digital-image capture system is presented in Sec. III.

II. EXPERIMENTAL SETUP

A. Fiber optic camera interface

The PCI-RCI system from EDT[3] serves as the link between the Amber Radiance camera and the host computer. It consists of a PCI bus fiber optic interface board in the host plus a remote camera interface (RCI) module. These two assemblies are connected by a 1.25 gigabaud fiber optic cable. The PCI-RCI system can accommodate fiber optic cables of up to 3 km, providing both electrical isolation and unusually long range.

The RCI module has a standard AIA 68 pin connector

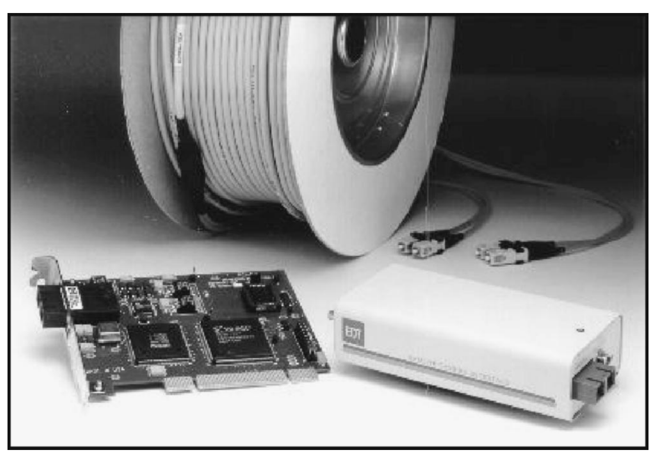

FIG. 1. PCI-RCI system components from Engineering Design Team, Inc. The PCI fiber optic interface board can be seen on the left and the remote camera interface is on the right.

through which it is connected to the camera by cable of up to 3 m in length with differential signals at RS422 or LVDS signal levels. The RCI module is powered from a 24 V dc source, a small 100-240 VAC switching power supply provided with the module. A wire pair at RS422 signal levels into the RCI module allows the user to trigger the start of data acquisition from the camera. Acquisition terminates when a user-specified frame count is attained.

The RCI system does not contain frame buffer memory. Video data is stored in the host computer memory as required by the camera and application. The software drivers and library calls provided by EDT handle the camera and deposit the images from the camera in the main memory of the host computer. Data rates of greater than 80 Mbytes/s can be sustained. Drivers are available for Windows NT/2000, Solaris 2.x, and Linux. In addition, the RCI module contains a reprogrammable gate array. This gate array can be programmed to implement a wide range of camera interface protocols by executing a program that downloads a bit pattern from a host computer file over the fiber to the RCI module. Up to four RCI modules (and thus four cameras) may be connected to a single PCI board by looping the fiber optic cable through the RCI module for each camera.

B. Implementation in Alcator C-Mod

The PCI-RCI digital-image capture system from EDT has been implemented in Alcator C-Mod between the Amber Radiance 1 camera, located in the test cell, and a Windows NT computer that resides in the control room. A 100-m-long multi-mode fiber is used to connect the PCI bus fiber optic interface in the computer to the RCI module that is located next to the IR camera within the same soft iron shield enclosure. A TTL trigger pulse, locally converted to a low voltage differential signal (LVDS) levels, is used to trigger the camera and synchronize the image stream with the experiment.

The data acquisition is controlled within the Windows NT computer by a simple console application written in C software language. This control application receives a signal from the Alcator C-Mod shot cycle to initialize the camera approximately 40 s before the shot. Once the TTL trigger has initiated the image stream, 120 images (i.e., 2 s) are written into memory. These images are then copied into the hard disk of the computer and into a VAX cluster disk for prompt analysis and, if necessary, remote display. The control program also extracts 10 selected time traces for direct storage into the MDS+ experiment tree. Since this control program is a console application that can be operated through line commands (i.e., DOS), in opposition to a graphical user interface application (i.e., windows), it can be run remotely via a simple telnet session to the host computer and does not need for a remote PC control application to be run in the host. The digital images are later archived into CD-ROMs.

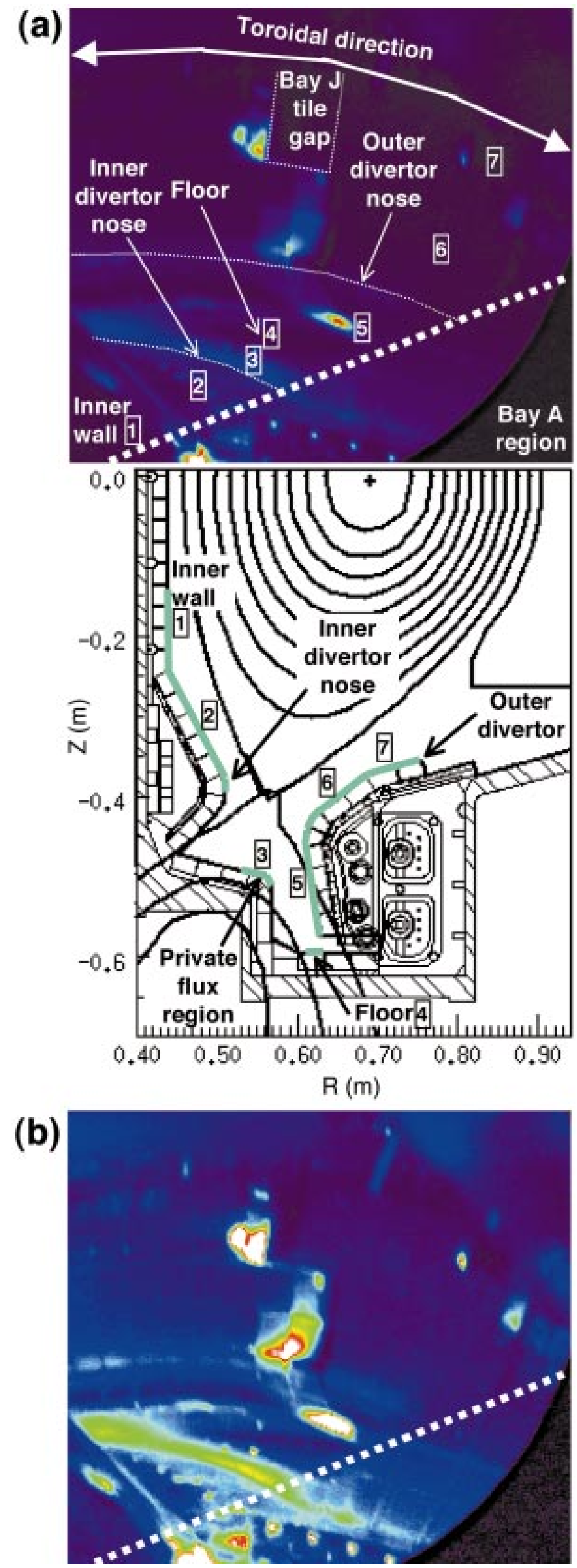

FIG. 2. (Color) Digital images of the lower divertor region of Alcator C-Mod obtained with a 4.28–4.42 μm bandpass filter and 1.04 ms exposure. (a) Raw image and poloidal cross section of Alcator C-Mod with magnetic field reconstruction. The sections of the wall viewed by the imaging system are indicated with colored (thick) lines and the numbers can be used to reference portions of the IR image to the cross section. (b) Lower 8 bits of the image shown in (a). In both cases the color scale is rainbow-like, white/red indicating bright (i.e., hot) surfaces and black/violet dark (i.e., cold) surfaces (discharge 1000615010 at 1.185 s).

III. RESULTS

In addition to the new digital-image capture system, the view of the divertor region has been modified from that in Ref. 2 to allow the measurement of the surface temperatures below the outer divertor nose where the outer strike point is typically located. Figure 2(a) shows a (raw) image obtained during a 800 kA, ICRF heated discharge. Two sections of the lower divertor of Alcator C-Mod can be seen in this image, separated by the white dotted line. On the bottom right corner, where the optic path misses the turning mirror, the Bay A region is seen. This corresponds to the section of the divertor directly below the reentrant periscope. Above the dotted line is the Bay J section of the divertor, and a small portion of the inner wall. From the bottom left corner, and moving towards the top right corner (above the dotted line), the image displays the inner wall, the inner divertor above the inner nose, a small section of the private flux region, the floor (darkest, i.e., coldest region), the outer divertor below the outer nose, and the outer divertor above its nose. These can be referenced, using the numbers in the small squares, to the sections of the first wall highlighted in the poloidal cross section of Alcator C-Mod.

The outer divertor region of Alcator C-Mod is dominated by hot spots as seen in Fig. 2(a). Toroidal bands of surface heating are also generally seen but these bands have discontinuities that follow some of these hot spots. These discontinuities are generally due to small misalignments between the different section of the divertor. Most notable is the hot spot seen below the outer divertor nose (indicated by the number 5). The poloidal position of this spot generally matches the outer strike point position determined by EFIT as shown in Fig. 2(a).[4] In certain occasions the tile gap at Bay J gives rises to hot spots on either side of the gap. In Fig. 2(a) this hot spot is seen on the left (upstream respect to ion flow) with respect to the tile gap. The ''luminous'' band just along the inner divertor nose in this figure does not correspond to surface thermal radiation but to infrared radiation from cold divertor plasma. The features seen in the Bay A region of Fig. 2(a) have been described in Ref. 2.

In Fig. 2(b) the lower 8 bits of the image displayed in Fig. 2(a) are shown. This figure is similar to what one would obtain by capturing the analog video signal with the contrast and brightness settings of the IR camera set to have the cooler areas within range. It is clear that the 12-bit dynamic range of the Amber Radiance camera is useful to resolve differences in the cooler areas, while still maintaining the hot spots within range.

The evolution of some plasma parameters for the discharge shown in Fig. 2 together with that of two surface temperature measurements obtained below the outer divertor nose are shown in Fig. 3. This discharge is characterized by two long periods of enhanced D_α confinement (or EDA)[5] at an auxiliary heating level of just over 2 MW. In Fig. 3(e) the evolution of the hot spot present below the nose is shown with a solid line and that at a similar vertical position over the divertor target plate, but ~6 cm upstream respect to the ion flow, is displayed with a dashed line. While the hot spot reaches the 800 °C level by the time the auxiliary heating ends, the surface temperature away from the hot spot remains at a 200 °C level with only small temperature rises due to the auxiliary heating.

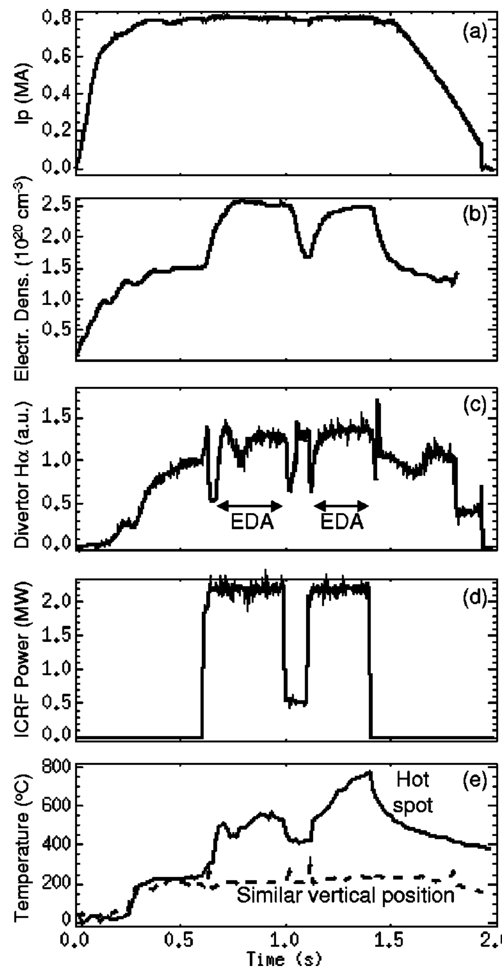

FIG. 3. Evolution of plasma parameters and divertor surface temperatures: (a) plasma current, (b) average electron density, (c) divertor D_α emission, (d) net ICRF power, and (e) surface temperatures. The solid line corresponds to the hot spot seen below the outer nose in Fig. 2 and the dashed line corresponds to a position at a similar poloidal location as the hot spot but about 6 cm upstream with respect to the ion flow (discharge 1000615010).

IV. CONCLUSIONS

A new digital-image capture system was implemented for the infrared imaging system of Alcator C-Mod. This allows an improvement from the 30 Hz, 8-bit images captured from the video signal produced by the Amber Radiance 1 infrared camera (as in Ref. 2) to a 60 Hz, 12-bit image stream being captured from the digitization of the focal plane array of the IR camera. The characteristics of the PCI-RCI system used makes it suitable for magnetic confinement fusion experiments where the image capture devices (i.e., computer) needs to be removed from the high magnetic field surrounding the experiment and a nonconductive link (i.e., optical link) is required between the camera and the capture device. The programmability of the RCI module from the host computer allows the PCI-RCI system to be used with a variety of digital cameras, such as the Amber Radiance 1.

ACKNOWLEDGMENTS

One of the authors (R.J.M.) wishes to thank J. Stillerman for his assistance with the MDS+ library calls from the PC control program. This work was supported by the U.S. Department of Energy under Contract Nos. W-7405-ENG-36 and DE-FC02-99ER54512.

[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] R. J. Maqueda, G. A. Wurden, J. L. Terry, and J. A. Stillerman, Rev. Sci. Instrum. **70**, 734 (1999).

[3] Engineering Design Team, Inc. (www.edt.com), Beaverton, Oregon.

[4] R. J. Maqueda, G. A. Wurden, and J. L. Terry, Bull. Am. Phys. Soc. **44**, 207 (1999).

[5] M. Greenwald *et al.*, Plasma Phys. Controlled Fusion **42**, A263 (2000).