PL-2219

DR-11037

PPPL-2219

I-21614

PERISCOPE-CAMERA SYSTEM FOR
VISIBLE AND INFRARED IMAGING DIAGNOSTICS ON TFTR

By

S.S. Medley et al.

MAY 1985

PLASMA
PHYSICS
LABORATORY

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-75-CO-3073.

DISSEMINATION OF THIS DOCUMENT IS UNLIMITED

PRF--2219

DE85 013768

PERISCOPE-CAMERA SYSTEM FOR
VISIBLE AND INFRARED IMAGING

DIAGNOSTICS ON TFTR

MASTER

S.S. MEDLEY, D.L. DIMOCK, S. HAYES,

D. LONG, J.L. LOWRANCE, V. MASTROCOLA,

G. RENDA, M. ULRICKSON,

and K.M. YOUNG

PLASMA PHYSICS LABORATORY

PRINCETON UNIVERSITY

PRINCETON, NEW JERSEY 08541

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED

22

ABSTRACT

An optical diagnostic consisting of a periscope which relays images of the torus interior to an array of cameras is used on the Tokamak Fusion Test Reactor (TFTR) to view plasma discharge phenomena and inspect vacuum vessel internal structures in both visible and near-infrared wavelength regions. Three periscopes view through 20-cm-diameter fused-silica windows which are spaced around the torus midplane to provide a viewing coverage of approximately 75% of the vacuum vessel internal surface area. The periscopes have f/8 optics and motor-driven controls for focusing, magnification selection (5°, 20°, and 60° field of view), elevation and azimuth setting, mast rotation, filter selection, iris aperture, and viewing port selection. The four viewing ports on each periscope are equipped with multiple imaging devices which include: 1) an inspection eyepiece, 2) standard (RCA TC2900) and fast (RETICON) framing rate television cameras, 3) a PtSi CCD infrared imaging camera, 4) a 35 mm Nikon F3 still camera, or 5) a 16 mm Locam II movie camera with variable framing rate up to 500 fps. Operation of the periscope-camera system is controlled either locally or remotely through a computer-CAMAC interface. A description of the equipment and examples of its application are presented.

I. INTRODUCTION

The objectives of the Tokamak Fusion Test Reactor (TFTR) to produce and study reactor-relevant plasmas, including tritium operation, required the development of several state-of-the-art, first-wall systems.¹ An isometric view of a section of the TFTR torus in Fig. 1 illustrates some of these first-wall components. A moveable limiter system was required to enable plasma size scaling and adiabatic magnetic compression experiments.² A bellows protection system was designed to shield the bellows sections, which increase the toroidal resistance of the vacuum vessel, against damage due to energy deposition from the plasma. In response to the need for density and impurity control in the presence of tritium, a surface gettering system was developed to reversibly pump hydrogen isotopes.³ A large area toroidal (bumper) limiter was designed to withstand the high input power and pulse length required for the large plasma experiments with intense neutral beam heating. In conjunction with neutral beam operation, a protective plate system shown in Fig. 2 was required to intercept that portion of the neutral beam power that passes through the plasma and impacts the vacuum vessel walls under normal and discharge fault conditions. The design of these components was realized through a detailed balancing of the physics requirements against the constraints imposed on engineering by the thermal and structural properties of materials. The need to monitor the performance of these complex first-wall systems in the harsh environment of TFTR plasma operation was a significant driver in the development of the viewing diagnostic presented in this paper.

The periscope-camera system developed for TFTR is a multipurpose diagnostic which is used to view the vacuum vessel interior in both the visible and near-infrared wavelength regions. Three periscopes located around the torus periphery view into the vacuum vessel through fused-silica, midplane

windows to provide approximately 75% viewing coverage of the vessel interior surfaces. A variety of visible and infrared television cameras as well as film cameras are used as imaging devices.

Since the start of TFTR operations on December 25, 1982 the periscope-camera system has proved to be an extremely useful diagnostic for understanding the control and macroscopic behavior of plasma discharges. Direct visualization of the plasma using this diagnostic has assisted in developing the plasma position feedback control system, understanding plasma-limiter interactions, identifying plasma impurity sources, improving plasma startup control, detecting malfunction of vacuum vessel interior components, and studying plasmas heated by magnetic compression. Other applications, including infrared imaging camera measurement of limiter heating, will be described later in this report.

II. PERISCOPE APPARATUS

The interior of the TFTR vacuum vessel is viewed through a periscope which was custom designed and fabricated by Instrument Technology, Inc., Westfield, MA 01085 to specifications provided by the Princeton Plasma Physics Laboratory (PPPL). Basically, the periscope serves a three-fold function by: 1) providing flexible viewing capability through magnification selection, field-of-view scanning in elevation and azimuth as well as other control features, 2) relaying images to a camera station which is removed from the strong magnetic field environment near TFTR and shielded against hostile neutron/gamma radiation, and 3) enabling multiple modes of operations (television, IR photometry, photography) by routing the output image onto different cameras. A mechanical schematic of the periscope is shown in

Fig. 3, and salient periscope characteristics are listed in Table I. The offset arm at the head of the periscope mast allows positioning the input optics close to the torus window for optimal field of view. The input element, a prism, is rotatable around a horizontal axis to provide a $\pm 30^\circ$ scan in elevation while the short cylindrical element is rotatable around a vertical axis to provide a $\pm 45^\circ$ scan in azimuth. Selection of the 5° , 20° , or 60° magnification is accomplished by changes in the objective lens system also housed in the upper section of the periscope mast. Note that the magnification corresponds to one-half of the full angular viewing field. Three mechanical shafts extend from motor controls in the base to the periscope head and connect to stainless steel linkage belts to control the magnification, elevation scan, and azimuth scan. A motor-driven rotary thrust bearing mounted to the 11.4-cm-diameter mast supports the periscope and allows for 360° mast rotation. At the base of the periscope are mechanisms for control of the focus, iris, 4-position filter wheel and routing of the image to one of the four viewing ports.

The periscope mast is constructed of nonmagnetic material, has an operating temperature limit of 100°C with a temperature gradient of 36°C/m . The mast section above the thrust bearing is electrically insulated to 3 kV.

The optical elements are comprised of Schott BAK 1G and F2G cerium-stabilized glass and have a total glass path length of ~ 20 cm. The output images at all four viewing ports are par focal and the image remains erect over the full scanning range in elevation and azimuth. For the 5° magnification at a typical viewing range of 4 meters ($\sim$ twice the minor diameter of the torus), the periscope will resolve details as small as 0.1 mm and the half-width of the field of view is 35 cm.

A periscope installation on TFTR is illustrated in Figs. 3-5. The upper

mast of the periscope emerges from the building floor supporting the machine and extends up through a penetration in the toroidal field coil shear compression panel to the diagnostic port cover on the vacuum vessel as shown in the insert of Fig. 3. The periscope can be rotated 360° around the axis of the main vertical shaft subject to limitations imposed by interference with neighboring equipment. Details in the region of the periscope head are shown in Fig. 4. In order to facilitate installation, the offset arm is demountable from the main vertical shaft by a keyed rotary coupling which was designed for servicing by a remote handling mechanism should removal or maintenance be required during the TFTR tritium operating phase. The offset arm allows positioning of the periscope input optics close to the 20-cm-diameter, fused-silica window through which the interior of the vacuum vessel is viewed, thereby maximizing the available field of view.

The periscope extends through a penetration in the ~ 1.8 -m-thick concrete floor beneath TFTR to a control and camera station at the base which is shown in the photograph in Fig. 5. This arrangement adequately isolates the control and camera electronics against the hostile neutron and gamma radiation as well as the stray magnetic fields produced during high power TFTR plasma discharges. The motorized rotary thrust bearing which supports the erected periscope unit is shown at the top of the photograph.

The toggle switch actuated console provides local control of the following nine periscope functions:

- Focus
- Magnification selection
- Elevation scan
- Azimuth scan
- Mast rotation

- Iris opening
- Filter selection
- Splitter insertion
- Viewing port selection

The filter wheel has four positions of which one is left open while the remainder typically contain 51 mm filters consisting of an H α blocking filter, an H α passing filter, and a pass filter for one of the dominant visible plasma impurity lines. The splitter is a half-reflecting pelicle which enables simultaneous use of two cameras at different viewing ports. The periscope base contains four viewing ports which are equipped with an eyepiece and one or more of the following imaging devices: 1) visible television cameras with either standard (60 fps) or fast (400 fps) frame rates, 2) an infrared television camera, or 3) film cameras, either 35 mm still or 16 mm movie with adjustable speed up to 500 fps. One of the viewing ports is selected by insertion of the splitter noted above. Selection of the other ports is accomplished by rotation of a 45° mirror mounted on a motor-driven vertical shaft. Further description of the cameras as well as the control and data acquisition systems is presented later in this report.

Three periscopes are installed around the torus periphery at diagnostic bays H, L, and P as shown in Fig. 6. For each periscope, an associated hatched region depicts the total viewing field in the torus equatorial plane. An angular segment of this field is accessed by choice of the periscope magnification. This segment can be "scanned" over the relevant hatched region by employing a suitable combination of periscope azimuthal scan and/or mast rotation. The three periscope configuration plus capability to scan $\pm 30^\circ$ in elevation about the equatorial plane provides a viewing coverage

in excess of 75% of the torus internal surface area.

III. VACUUM VESSEL ILLUMINATION

During experimental operations, illumination of the vacuum vessel interior is provided by the plasma discharge. To enable inspection of the vessel interior during nonoperating periods, an array of quartz halogen lamps is used. At each of several illumination points around the torus periphery, four 400 watt bulbs in reflector assemblies are mounted on a bellows-sealed shaft which is inserted into the vessel to place the lamps - 50 cm inboard of the torus outer wall. The shaft is also the conduit for AC power to the lamps, which normally are operated at 75% of rated power for extended life. The cylindrical housing for one of the illumination probes is seen at the top of the photograph in Fig. 4.

Provision exists for implementation of seven illumination probes distributed around the torus periphery at locations designated by triangular symbols in Fig. 6. Solid triangles denote presently operating probes while hatched triangles identify future installations.

To prevent unnecessary clouding of each viewing window during glow- and pulse- discharge cleaning operations used to condition the vacuum vessel internal surfaces,⁴ an in-vacuo stainless steel shutter can be rotated over the window by means of a pneumatically actuated rotary vacuum feedthrough mechanism seen immediately above the periscope head in Fig. 4.

IV. CAMERA SYSTEMS

As described in Sec. II, each of the three periscopes has four viewing ports for eyepiece or camera installation. Several camera systems are mounted on each periscope to provide visible television coverage of the plasma discharge, near-infrared photometry of the vacuum vessel wall and internal structures, and film cameras for plasma photography or for inspection documentation of first-wall components under cumulative exposure to plasma discharges and disruptions. This section describes the various imaging devices currently in use.

A. Visible Television

Two types of visible television cameras are employed: an RCA TC2900 CCD camera which provides high spatial resolution imaging at a standard framing rate and a Reticon camera which provides increased time resolution at the expense of reduced spatial resolution. Salient specifications for these imaging devices are presented in Table II.

The RCA camera provides a composite video output which is utilized for direct recording onto video cassette tape or real-time image display over the TFTR closed-circuit TV network. As discussed in Sec. V, provision exists to digitize and store the output images in a 12 Megabit fast memory catch as well. Since the digital memory size limits the number of image frames that can be captured, nonstandard camera operation modes are optionally used to reduce the number of picture elements per frame thereby increasing the number of stored frames in memory but at the expense of spatial resolution. First, a noninterlace operation is used which halves the number of picture elements to $\sim 1 \times 10^5/\text{frame}$. Second, the pixel readout is controllable to compress the frame by vertical binning. A further advantage of this option is a

concomitant increase in the framing rate by an amount comparable to the binning factor thus improving the time resolution. Finally, the digital memory is programmable to compress the image by binning horizontally but no gain in frame rate attends this option. This vertical and/or horizontal image compression feature is invoked through software control of the camera readout electronics and/or the digital memory catch, respectively.

The Reticon camera provides a digital output which can be directly recorded only by the digital memory catch. For TV network viewing and video tape recording of the Reticon images, the digital memory is scan converted to analog video format.

B. Infrared Television

Implementation of infrared photometry with the periscope viewing system is constrained by the optical transmission characteristic which is shown in Fig. 7. For example, the limited wavelength range available due to transmission cutoff at approximately 2100 nm contributed in part to selection of one-wavelength photometry as opposed to the two-wavelength technique favored during the design phase of the infrared system.⁵

For infrared diagnostics on TFTR, a custom-designed camera was constructed at PPPL based on a LN₂-cooled Schottky barrier platinum silicide CCD sensor made by RCA (see Table II). The CCD consists of a 64 x 128 array of pixels that are 120 x 60 microns in size. Within each pixel, 22% of the total area is optically active. In the operating wavelength band of 1.7 ± 0.4 microns, the effective Q_e is about 3% considering the 22% fill factor.

The CCD utilizes interline transfer where the photoelectrons are transferred from the photo sites to optically opaque vertical strips and then each horizontal line is shifted down in parallel to the output register where

each pixel is shifted out serially to an on-chip amplifier. The output amplifier transfer function is approximately 0.4 microvolts per electron and the saturation signal is about 3×10^6 electrons per pixel.

From calculations of the power deposition on the TFTR first-wall structures,⁶ a desired temperature operating range of 220-2300°C was adopted for the infrared camera which imposes a requirement for the signal dynamic range to be the order of 10^6 . Since this far exceeds the PtSi sensor capability, the dynamic range requirement was met by using a servo-controlled motor to drive a neutral density filter wheel located at the camera input optics. The wheel contains one nonfiltered position and three filters with attenuation ratios in the range of 10:1, 100:1, and 500:1. The neutral density filters were selected because of their small mass which enables insertion of a filter step in approximately 20 ms. The signal is obtained from the camera video by using a comparator technique to sense occurrence of saturated pixel output levels during the CCD readout stage. Typically, the feedback is set to increase the signal attenuation when ~ 8% of the elements in any 54 pixel line exceed 94% of maximum signal and, to avoid feedback instability, the attenuation is decreased when the peak amplitude of approximately 69% of all the pixels falls below 7% of maximum signal. For subsequent analysis requirements, the active filter position is coded in the first pixel after the synchronization signal for each frame and therefore becomes archived along with the image data.

Each infrared camera was calibrated through the viewing optics of the particular periscope to which the camera was assigned using a blackbody source located approximately 45 cm from the periscope input. The blackbody spectral energy is given by Planck's law as:

$$W_\lambda = 2\pi c^2 h \lambda^{-5} [\exp(hc/\lambda kT) - 1]^{-1} \quad (1)$$

which, using $C_1 = 2\pi c^2 h$, $C_2 = hc/k$ and for $\exp(C_2/\lambda T) \gg 1$ can be expressed as:

$$W_\lambda \approx C_1 \lambda^{-5} \exp(-C_2/\lambda T). \quad (2)$$

Putting Eq. (2) in terms of the camera signal yields

$$\Delta V = \frac{G_V C_1 \epsilon K_F \lambda^{-5} \exp(-C_2/\lambda T)}{K_C} \quad (3)$$

where ΔV represents the voltage change at the camera output and

T = Temperature $^{\circ}K$

$C_2 = 1.4388 \times 10^7 \text{ nm}^{\circ}K$

$C_1 = 3.7405 \times 10^{-12} \text{ Wcm}^2$

G_V = Electronic gain $V/V = 2$

$\lambda = 1700 \text{ nm}$

ϵ = Emissivity

K_F = Filter attenuation constant

K_C = Calibration Constant.

To calculate the temperature from the voltage change,

$$T = \frac{C_2/\lambda}{\ln \frac{G_V C_1 \epsilon K_F}{\Delta V K_C \lambda^5}} \quad (4)$$

The calibration constant, K_C , must be determined separately for each of the 5°, 20°, and 50° periscope magnifications since different optical elements are involved in realizing the various settings. An example of the calibration

results is shown in Fig. 8. The solid line represents calculated values from Eq. (3) assuming $\epsilon = 1$ and using the calibration constant $K_0 = 1.236 \times 10^{-32}$ measured at $T = 673^\circ\text{K}$. Although the agreement between the measured data points and the calculated curve is good, the problem associated with inadequately known emissivity must be addressed, particularly during application on TFTR where a variety of materials with different emissivities exists. Using Eq. (2), the fractional temperature error, T_F/T , is given by

$$\frac{T_F}{T} = \frac{1}{T \frac{\lambda}{C_2} \ln \frac{\epsilon_1}{\epsilon_2} + \frac{1}{T}} \quad (5)$$

where T_F is the "false" temperature associated with the assumed emissivity, ϵ_1 , and T , ϵ_2 are the actual temperature and emissivity. A plot of Eq. (5) for various temperatures is shown in Fig. 9. It is apparent that uncertainties in the emissivity produce minor errors in the determination low temperatures but result in significant errors with increasing temperature.

Calibration results indicate that the infrared camera has a temperature measurement range of 220-2300°C. In the high temperature limit, an error of approximately $\pm 20\%$ can be expected if a factor of 2 uncertainty exists in the estimated emissivity. During calibration, pixel to pixel gain variations were found not to be significant ($\leq \pm 5\%$) so that only background correction is necessary for data reduction.

C. Film

A 35 mm Nikon F3 still camera is used to photograph plasma discharges and to document the integrity of the first-wall components during inspection performed using the vacuum vessel illumination probes. Remote camera control via CICADA software is used to synchronize the shutter actuation with the

plasma discharge, set the exposure duration, and download shot number, date, and time through an RS232 serial link to the camera data-back for identification of each exposure.

A 16 mm Locam II movie camera is used for plasma discharge photography with speeds that can be locally set from still frame up to 500 frames per second. Start and stop signals synchronized with initiation of the plasma discharge are software generated through the CICADA computer system.

V. CONTROL AND DATA ACQUISITION

The periscopes can be operated locally through individual toggle switch consoles as discussed earlier and, similarly, local controls are available for the cameras, periscope shutters, and vessel illumination probes. In this section, attention is focused on the remote control and data acquisition aspects of the system.

A signal path schematic presented in Fig. 10 illustrates the control and data acquisition concept. The left side of the schematic pertains to equipment located in the vicinity of the periscope-camera apparatus while the right side addresses components situated in a special diagnostic data acquisition room removed some 150 meters from the TFTR machine. In both cases, the control path is from the central Computer Interface Control and Data Acquisition (CICADA) system through CAMAC interface modules to the individual devices to be controlled. From the Diagnostic Basement, standard CAMAC modules (such digital and analog input and output, timed gate drivers, RS232 ports and other devices) provide control and monitoring links to the periscope, cameras, and associated camera signal processing electronics. An exception is the shutter control which originates in the Data Acquisition Room.

The primary data acquisition device is the Video Data Acquisition System (VDAS) which is a microprocessor-controlled, 12-Megabit, local digital memory designed and built at PPPL. During a given plasma discharge, the VDAS memory catch can acquire data from only one of the several available television cameras. Selection of the television camera is accomplished through a DYNAIR video switch which is controlled by VDAS as well as several data stream multiplexers which are controlled via the CAMAC interface.

In addition to digital data acquisition by means of VDAS, a bank of Video Cassette Recorders (VCR's) is available for analog data acquisition. Of the available television cameras, only the RCA TC2900 "Plasma TV" can record directly onto video tape during a plasma discharge because the other cameras do not have a standard video output format. Three such direct recording VCR's are provided, one for each Plasma TV associated with each of the three periscopes.

A permanent archive of the VDAS memory is available in both analog and digital format. After each plasma discharge, the VDAS memory is automatically scan converted for analog recording on one of the video cassette recorders dedicated to this function. Alternatively, on request from the diagnostic operator the VDAS memory can be digitally archived to the main CICADA computer via a high speed block transfer fiber optic link for subsequent software processing and analysis. Digital archiving is particularly important for the infrared camera data, since the 12-bit acquisition resolution would be degraded by the low resolution (~ 8 bit) of video tape.

Besides providing a temporary memory catch with flexible capture programming capability through microprocessor control, VDAS also serves a number of additional functions.

The standard VCR functions such as recording, playback, fast forward,

fast reverse, and so forth are computer controlled via VDAS. Using timing and shot number information downloaded from the CICADA computer prior to a plasma discharge, the VDAS microprocessor starts and stops recording for all VCR's (except the one dedicated to the VDAS memory archive) and inserts leading and trailing bar codes to identify the recorded image sequence according to the discharge shot number. Provision exists for VDAS to search the VCR tapes automatically for a given shot using the inserted bar code data and digitize the image sequence into VDAS memory, thus enabling conversion of analog recorded data to digital format for software processing.

For camera images captured by the digital memory during a plasma shot, VDAS inserts data such as shot number and elapsed time after start of the discharge on each data frame. This information becomes part of the VCR analog record. Following the transfer of digital memory content to tape, VDAS automatically switches to a continuous loop playback mode to display the scan-converted memory images on a closed network cable TV system in the CFTF control room. Control of VDAS through CICADA software allows the user to advance, reverse, speed select, or still frame the image playback.

Remote operation of the periscope-camera diagnostic is accomplished through software resident on the CICADA computer system. The user interface consists of menu-driven mimic diagrams of the apparatus which are displayed on a color graphics console. By way of example, Fig. 11 shows the menu page for control and monitoring of the three periscopes, selection of the television camera for data capture by VDAS, shutter control, film camera activation, and so forth. Using a ball-driven cursor and an alphanumeric keycard, the user can enter control data into assigned fields or execute device control by placing the cursor in designated field areas and issuing a send-command action. Other menu pages exist, for example, to control VCR and VDAS playback

functions and to perform analysis of the infrared television camera data.

VI. APPLICATIONS

Since December 25, 1982, when the first plasma discharge in TFTR was documented using a Reticon television camera, both the periscope camera instrumentation resources and the scope of application have been greatly extended. At present the diagnostic consists of three periscopes, three RCA television cameras, two Reticon television cameras, two infrared television cameras, and two film cameras along with advanced software for device control and data analysis. In this section, exemplary results obtained from the various imaging devices are presented to illustrate the scope of applications encountered during ohmic, magnetically compressed, and neutral-beam-heated TFTR plasma discharges.

A. Plasma Operation

Direct visualization of the plasma behavior either time resolved using the visible television cameras and 16 mm movie camera or time integrated using the 35 mm still camera provided guidance to machine operations during start-up and optimization of the plasma discharge, early detection of first-wall component malfunctions, and identification of macroscopic plasma phenomena.

The schematic presented in Fig. 12 shows the view of the moveable limiter and other in-torus components observed through the Bay H periscope (see Fig. 6) with 20 $\times$ magnification. The moveable limiter is shown in the full open position used for large plasma operation with major radius $R=258$ cm, minor radius $a=83$ cm, and plasma currents in the range $I_p = 600-2000$ kA at toroidal magnetic fields of $B_T \leq 4.0$ Tesla. As the maximum plasma electron density is approached for a given plasma current, a plasma edge phenomenon

known as a MARFE⁷ is frequently observed in tokamak plasmas. This phenomena is ascribed to a thermal instability which develops at the inboard periphery of the plasma producing a localized region of low temperature and high density. Occurrence of MARFE phenomena in TFTR was first identified during plasma observation with the Reticon television camera and subsequently other diagnostic signatures were recognized, such as increases in the line integral electron density, loop voltage, radiated power, H α emission, and so forth. Plasma TV images illustrating the evolution of a typical MARFE event are presented in Fig. 13. The two oblong bright regions on the left side correspond to the contact points of the plasma with the moveable limiter shown in the insert illustrating the camera field of view. The MARFE develops at the plasma periphery in the upper inboard quadrant of the torus, evolves poloidally clockwise, and finally decays in the lower inboard quadrant as shown on the right side of the photographs which were obtained with 27-ms time resolution. Although the instability appears localized in the region of the moveable limiter, this is a field-of-view artifact and other diagnostic measurements show that the instability extends toroidally around the entire inner wall region.

Photography using a 35 mm Nikon F3 still camera has been used to record plasma discharges and to document the integrity of the vacuum vessel first-wall components. Shown in Fig. 14 is a time-integrated exposure of a magnetically compressed ohmic discharge in TFTR.² Prior to compression, an $I_p = 500$ kA, $n_e L = 2.6 \times 10^{19} \text{ m}^{-2}$ ohmic discharge equally contacts the upper and lower blades of the moveable limiter. Following compression from the initial major/minor radii of $R/a = 3.00/0.55 \text{ m}$ to the final position of $R/a = 2.10/0.45 \text{ m}$, the plasma appears as the luminous crescent against the torus bumper limiter of the right side of the photograph. Under the plasma

conditions for this discharge, heating due to magnetic compression raised the electron and ion temperatures from a precompression value of 1.3 keV to 1.8 keV after compression.

B. Vessel Inspection

Periodic inspection of the TFTR torus interior is made using the illumination system described in Sec. III. A composite inspection photograph of the moveable limiter and surrounding structures obtained viewing through the Bay H periscope (see Fig. 6) using a 20° magnification setting is presented in Fig. 15. During high power plasma operation with up to ~ 5.0 MW of injected deuterium neutral beam power, part of one tile on the lower limiter blade fractured. Documentation of the damaged area discovered during routine inspection is shown in the photograph at the top of Fig. 16 which was obtained using the 5° periscope magnification setting. Below is a photographic enlargement of the damaged region which illustrates the capability for resolving details to dimensions of ≤ 1 mm.

C. Infrared Photometry

The most extensive application of the infrared television system so far has been to investigate heating of the moveable limiter surfaces due to power deposition from ohmic and neutral-beam-heated plasma discharges. Future studies include heating of the bumper limiter (Fig. 1) and protective plate (Fig. 2) during plasma and neutral beam operations.

Following a plasma discharge, the infrared data archived by the local VDAS digital memory catch during the shot are accessed via a high speed data block transfer link for permanent archival and data analysis by the CICADA computer. Using a data frame acquired ~ 100 ms prior to the discharge for

background correction, the on-line analysis program creates a color-coded reconstruction of the plasma thermal footprint and generates temperature curves along horizontal and vertical slices through the peak temperature point. An example of the graphical output is shown in Fig. 17 for a selected data frame occurring at $t = 4.3$ seconds during a 2.5-MW deuterium neutral beam injection into a deuterium target plasma with parameters: $I_p = 1.8$ MA, $n_{eL} = 3.8 \times 10^{19} \text{ m}^{-2}$, $B_T = 4.0$ T, and $R/a = 2.58/0.82$ m. The reconstructed thermal image corresponds to an area ~ 22 -cm high by ~ 44 -cm wide centered on the plasma contact point with the upper limiter blade (see Fig. 12). The temperature profile along a horizontal line indicated by the white marker located on the ordinate of the image shows a double-peaked structure corresponding to the electron (lower temperature) and ion (higher temperature) sides of the limiter blade. The abscissa refers to horizontal pixel number in the $128K \times 64V$ CCD pixel array. Similarly, a thermal profile along a vertical line through the peak temperature point is given as well as the temperature color scale associated with the thermal image.

Further analysis of the temperature plots obtained as a function of time during the plasma discharge yields a number of important plasma measurements. The measured spatial temperature profiles across the width and along the length of the limiter blade as illustrated in Fig. 18 are used in conjunction with geometrical code modeling of the plasma-limiter interaction to deduce a typical energy scrape of thickness in the plasma boundary of $\lambda = 1.5 \pm 0.3$ cm. Heat deposition profiles derived from the infrared camera temperature data are in good agreement with the predictions from design calculations.⁶ The segmented, backside-cooled construction of the limiter allows use of a one-dimensional, finite element, heat conduction code for simulation of the limiter heating as a function of plasma power deposition.

Typical analysis results are shown in Fig. 19 where the data points correspond to infrared camera temperature measurements of the limiter while the solid curve is the code simulation of the temperature history obtained by step-wise adjusting the heat flux input to the code through the ohmic, neutral-beam-heated, and post-discharge phases of the plasma pulse. Finally, geometrical data obtained using the measured scrape of thickness is combined with the code-generated heat flux to obtain the total power to the top and bottom limiter blades, which for this example was 2.4 MW or 60% of the 4.0 MW total ohmic and injected neutral beam power. Excellent accountability for the plasma input power (the subject of a separate report) is obtained through combined measurements of the power deposition on the limiters using the infrared camera diagnostic and radiated power measurements obtained with the TFTR bolometer diagnostic.⁸

ACKNOWLEDGMENTS

The development and application of the periscope-camera diagnostic was aided by contributive work from many individuals among whom special gratitude is extended to B. Bergin for construction of the CAMAC control and monitoring interface, W. Journey for programming of the CICADA software for remote device control and infrared camera data analysis, V. Corso for design of the vessel illumination probes, A. Ramsey and B. McCormack for the periscope shutter installation, and G. Lemunyan, B. Hoch, and W. Harter for maintenance of the equipment. It is our pleasure to acknowledge the dedicated and capable support of the TFTR machine operators, computer operators, and technicians who have contributed to this research work. We also thank H.P. Furth, P.H. Rutherford, J.R. Thompson, and D. Meade for their support. This work was supported by U.S. Department of Energy Contract No. DE-ACC2-75-CH03073.

REFERENCES

- ¹J.L. Cecchi et al., J. Nucl. Mater. 128-129, 1 (1984).
- ²R.J. Hawryluk et al., Proc. 4th Intern. Symp. on Heating in Toroidal Plasmas, Rome, Italy, 1984 (International School of Plasma Physics, Varenna, Italy, 1984) p. 1012.
- ³J.L. Cecchi, J. Nucl. Mater. 93-94, 28 (1980).
- ⁴H.F. Dylla, W.R. Blanchard, R.B. Krawchuk, R.J. Hawryluk, and D.K. Owens, J. Vac. Sci. Technol. A2(2), 1188 (1984).
- ⁵S.S. Medley, J.L. Lowrance, and G. Renda, Princeton Plasma Physics Laboratory Technical Memo TFTR-TM-14, (1981).
- ⁶D.W. Doll et al., Proc. 9th Symp. on Engineering Problems in Fusion Research, ed: C.K. Choi, (IEEE, New York, 1981) p. 1654.
- ⁷B. Lipschultz, B. LaBombard, E.S. Marmor, M.M. Pickrell, J.L. Terry, R. Watterson, and S.M. Wolfe, Nucl. Fusion 24, 977 (1984).
- ⁸J. Schivell, G. Renda, J. Lowrance, and H. Hsuan, Rev. Sci. Instrum. 53, 1527 (1982).

TABLE I
PERISCOPE OPTICAL CHARACTERISTICS

Magnification (Angular)	Field of View	Focus Range	Resolution (Arc Seconds)	Distortion (Percent)	Depth of Focus (9.3m)
0.5x	60° 0.1m-∞	180	≤15	0.2m → ∞	
1.5x	20° 0.1m-∞	25	≤1.5	-0.2m → + 7.6m	
6.0x	5° 0.1m-∞	5	≤1.5	-0.6m → + 1.0m	

F-Number : F/8 for 25 mm image diameter

Transmission : 40% ± 10% at 500-1100 nanometers.

Optics : Schott cerium-stabilized glass resistant to radiation
browning at 10^8 Rad(SI).

TABLE II
TELEVISION CAMERA SPECIFICATIONS

Camera Type	Imager Sensitivity (Microns)	Spectral Range	Dynamic	Pixel Format	Speed fps(ms)	Maximum Spatial Resolution (mm)*
Reticon	1.0 cm CCD	0.42-1.10	$\leq 10^3$	100H x 100V	400	(2.5) 3.50H x 3.50V
RCA TC2900	1.27 cm CCD RCA SID52501	0.42-1.10		10^3	403H x 12V	60 (16.7) 0.87H x 0.14V
Infrared	0.2cm x 0.4cm RCA PtSi CCD	1.25-2.10		-4×10^3	64H x 128V	51 (19.6) 0.55H x 0.27V

*For an object at 4.0 meters with a 5° periscope magnification.

FIGURE CAPTIONS

1. Isometric view of a section of the Tokamak Fusion Test Reactor vacuum vessel illustrating the moveable limiter, axisymmetric bumper limiter, bellows cover plates, and ZrAl getter pump first-wall components.
2. Photograph of an interior segment of the TFTR vacuum vessel showing the bellows cover plates, interim bumper limiter, and beam protective plates. The latter is a mosaic armor of TiC clad Poco graphite tiles which serve to intercept that portion of the neutral beam power that passes through the plasma and impacts the vessel interior wall under normal and fault plasma discharge conditions.
3. Schematic of the periscope including the camera station and local control console situated at the base of the mast. The insert is a photograph of the upper mast section of the periscope at Bay P on the TFTR torus. Items labeled are: A) periscope mast extending through a penetration in the toroidal field coil shear compression panel, B) periscope offset arm, and C) the 20-cm-diameter midplane viewing window installed on the torus port cover plate.
4. Photograph of the periscope head showing detail of: A) offset arm, B) rotary coupling for demounting of the offset arm from the mast, C) 20-cm-diameter, fused-silica viewing window, D) rotary vacuum feedthrough actuator for the window shutter, and E) illumination lamp housing.

5. Photograph of the periscope base located in the diagnostic basement beneath the TFTR machine showing: A) mast support thrust bearing, B) local periscope control console, C) motor housing for periscope control, D) viewing eyepiece, E) Reticon visible television camera, and F) infrared television camera. The fourth viewing port is located diametrically across the motor housing from the eyepiece.
6. Schematic showing the field of view of the periscope system in the equatorial plane of the TFTR vacuum vessel. Locations of the vacuum vessel illumination lamps are shown by the triangles (solid:operating, hatched:planned).
7. Transmission characteristic for the periscope optics measured in the near-infrared wavelength region. The operational band pass for the infrared camera is between 1250 and 2100 nanometers.
8. Typical calibration results for the infrared television camera showing output voltage as a function of the test source blackbody temperature. The calibration constant, K_0 , was determined at $T = 673^\circ\text{K}$ and the arrows indicate insertion points for the servo-driven neutral density attenuation filters. The solid curve shows the agreement between data points and Planck's law for a blackbody source.
9. Plot of the fractional temperature error arising from uncertainty in the assumed (ϵ_2) to actual (ϵ_2) surface emissivity. In the 2000°K

temperature range, a two-fold uncertainty in emissivity yields - 20% error in the measured temperature.

10. Representative signal path schematic between one periscope-camera system (left), the digital and analog data acquisition devices (right), and the CAMAC interface to the main CICADA computer (top).
11. Representative mimic diagram page for remote device control and monitoring of the periscope-camera apparatus. On the left are three, identical, vertically disposed areas for control of nine periscope functions and four camera stations (35 mm, Plasma TV, Reticon camera, and ITR) associated with each of the three periscope installations. On the right are control fields for the VDAS digital memory and Video Cassette Recorder (VCR) data acquisition devices. By means of a track-ball-controlled cursor and an alphanumeric keyboard, control parameters can be entered into assigned fields or control functions can be activated by placing the cursor in designated fields and issuing an execute command.
12. Schematic showing the periscope-camera view inside the TFTR vacuum vessel from the Bay H diagnostic port using the 20° periscope magnification setting.
13. Reticon camera image sequence showing the time evolution of a MAFR edge thermal instability in a high density TFTR plasma discharge. The camera field of view is shown in the insert schematic. The two oblong bright regions on the left side of the photographs correspond

to plasma contract points on the moveable limiter blades while the poloidally moving bright area on the right is the MARFE event near the torus inner wall.

14. View of the TFTR moveable limiter illuminated by a 500-kA precompression plasma (upper and lower bright areas on the left). After fast magnetic compression ($\Delta t \sim 14$ ms), the 680-kA plasma produces a crescent of light at the contact surface with the inner wall bumper limiter (right side of the photograph).
15. Inspection photograph of the moveable limiter environs inside the TFTR torus obtained using the vessel illumination probes and the 20° periscope magnification setting. The periscope elevation scan feature was employed to produce three images assembled to form the composite photograph.
16. Documentation of a moveable limiter tile fracture obtained using a 35 mm photograph with a periscope 5° magnification setting (top). A photographic enlargement of the damaged area is shown at the bottom and illustrates capability to resolve details of dimension ≤ 1 mm.
17. Illustration of the infrared television camera data analysis graphics. Shown is the reconstructed thermal footprint of the plasma contact area with the upper limiter blade (top right), the temperature scale color code (bottom left), and line scans of the temperature profile in the horizontal (bottom right) and vertical (top left) directions through the peak temperature point of the thermal image.

18. Line profiles of the surface temperature across the width of the moveable limiter blade (left) and lengthwise along the ion-side of the blade (right) obtained from analysis of the infrared camera thermal images.
19. Plot of the time evolution of the limiter temperature obtained from infrared camera measurements (data points) and the one-dimensional heat code simulation (curve following data points) generated by step-wise adjusting the input heat flux to the code. The upper and lower plots correspond to the ion and electron sides of the limiter, respectively.

FIG. 1

FIG. 2

#85X0410

FIG. 3

#85X0421

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

84-84/85
22 06:30

PERISCOPE CONTROL/CAMERA ASSIGNMENTS

VIEW_1_TITLE
FILE 114430
ACTUAL
(VOLTS)

* FOCUS
* F O VIEW
* ELEVATION
* AZIMUTH
* MAST ROT
* IRIS
* FILTERS
* SPLITTER
* PORT #

VIEW_2_TITLE
ACTUAL
(VOLTS)

* FOCUS
* F O VIEW
* ELEVATION
* AZIMUTH
* MAST ROT
* IRIS
* FILTERS
* SPLITTER
* PORT #

VIEW_3_TITLE
ACTUAL
(VOLTS)

* FOCUS
* F O VIEW
* ELEVATION
* AZIMUTH
* MAST ROT
* IRIS
* FILTERS
* SPLITTER
* PORT #

DELTA
(VOLTS)

ENG
UNITS

PORT

1
2
3
4

DELTA
(VOLTS)

ENG
UNITS

PORT

1
2
3
4

DELTA
(VOLTS)

ENG
UNITS

PORT

1
2
3
4

11-11

Fig. 11

#85X0119

TV VIEW INSIDE TFTR

FIG. 12

B530409

1.964 sec

2.076 sec

2.176 sec

1.937 sec

2.043 sec

2.150 sec

Time → 1.910 sec

2.017 sec

2.123 sec

1.990 sec

2.097 sec

FIG. 13

FIG. 14

FIG. 15

#85X0420

FIG. 16

SHOT# 12545 - FRAME 002
 SHOT DATE 01/23/89
 SHOT TIME 13:03:09

INFRARED DATA ANALYSIS
 ANALYSIS DATE 03/18/89 TIME 15:28:50
 ELAPSED TIME 02:9971
 MAX TEMP 1737 °C X= 36 Y= 39

ELAPSED TIME 00:00:00
 698 1019
 1019 1159
 1159 1289
 1289 1419
 1419 1549
 1549 1679
 1679 2664

ADJUSTED DATA

C1=0 374E-11 G= 2
 C2=0 1438E+6 FS= 51.3
 KC=0 986E-33 Lambda=1700
 Emission=0.7% A=0.0000

Fig. 17

FIG. 18

FIG. 19

EXTERNAL DISTRIBUTION IN ADDITION TO UC-20

Plasma Res Lab, Austra Nat'l Univ, AUSTRALIA
 Dr. Frank J. Paoloni, Univ of Wollongong, AUSTRALIA
 Prof. I.R. Jones, Flinders Univ., AUSTRALIA
 Prof. M.H. Brennan, Univ Sydney, AUSTRALIA
 Prof. F. Cap, Inst Theo Phys, AUSTRIA
 Prof. Frank Verheest, Inst theoretische, BELGIUM
 Dr. D. Palumbo, Dg XII Fusion Prog, BELGIUM
 Ecole Royale Militaire, Lab de Phys Plasmas, BELGIUM
 Dr. P.M. Sakanaka, Univ Estadual, BRAZIL
 Dr. C.R. James, Univ of Alberta, CANADA
 Prof. J. Teichmann, Univ of Montreal, CANADA
 Dr. H.M. Skarsgard, Univ of Saskatchewan, CANADA
 Prof. S.R. Sreenivasan, University of Calgary, CANADA
 Prof. Tudor W. Johnston, INRS-Energie, CANADA
 Dr. Hannes Barnard, Univ British Columbia, CANADA
 Dr. M.P. Bachynski, MFB Technologies, Inc., CANADA
 Chalk River, Nucl Lab, CANADA
 Zhenggu Li, SW Inst Physics, CHINA
 Library, Tsing Hua University, CHINA
 Librarian, Institute of Physics, CHINA
 Inst Plasma Phys, Academia Sinica, CHINA
 Dr. Peter Lukac, Komenskeho Univ, CZECHOSLOVAKIA
 The Librarian, Culham Laboratory, ENGLAND
 Prof. Schatzman, Observatoire de Nice, FRANCE
 J. Radet, CEN-SP6, FRANCE
 AM Dupes Library, AM Dupes Library, FRANCE
 Dr. Tom Mui, Academy Bibliographic, HONG KONG
 Preprint Library, Cent Res Inst Phys, HUNGARY
 Dr. S.K. Tishan, Panjab University, INDIA
 Dr. Indra Mohan Lal Das, Banaras Hindu Univ, INDIA
 Dr. L.K. Chauda, South Gujarat Univ, INDIA
 Dr. R.K. Chhajlani, Vikram Univ, INDIA
 Dr. B. Dasgupta, Saha Inst, INDIA
 Dr. P. Kaw, Physical Research Lab, INDIA
 Dr. Phillip Rosenau, Israel Inst Tech, ISRAEL
 Prof. S. Cuperman, Tel Aviv University, ISRAEL
 Prof. G. Rostagni, Univ Di Padova, ITALY
 Librarian, Int'l Ctr Theo Phys, ITALY
 Miss Clelia De Palo, Assoc EURATOM-ENEA, ITALY
 Biblioteca, del CNR EURATOM, ITALY
 Dr. H. Yamato, Toshiba Res & Dev, JAPAN
 Direc. Dept. Ig. Tokamak Dev. JAERI, JAPAN
 Prof. Motoyuki Inoue, University of Tokyo, JAPAN
 Research Info Center, Nagoya University, JAPAN
 Prof. Kyoji Nishikawa, Univ of Hiroshima, JAPAN
 Prof. Sigenu Mori, JAERI, JAPAN
 Library, Kyoto University, JAPAN
 Prof. Ichiro Kawakami, Nihon Univ, JAPAN
 Prof. Satoshi Itoh, Kyushu University, JAPAN
 Dr. D.I. Choi, Adv. Inst Sci & Tech, KOREA
 Tech Info Division, KAERI, KOREA
 Bibliotheek, Rm-Inst Voor Plasma, NETHERLANDS
 Prof. B.S. Liley, University of Waikato, NEW ZEALAND
 Prof. J.A.C. Cabral, Inst Superior Tecn, PORTUGAL
 Dr. Octavian Petrus, ALI CUZA University, ROMANIA
 Prof. M.A. Hellberg, University of Natal, SO AFRICA
 Dr. Johan de Villiers, Plasma Physics, Nucor, SO AFRICA
 Fusion Div. Library, JEN, SPAIN
 Prof. Hans Wilhelmson, Chalmers Univ Tech, SWEDEN
 Dr. Lennart Stenflo, University of UMEA, SWEDEN
 Library, Royal Inst Tech, SWEDEN
 Centre de Recherches, Ecole Polytech Fed, SWITZERLAND
 Dr. V.T. Tolk, Kharkov Phys Tech Ins, USSR
 Dr. D.D. Ryutov, Siberian Acad Sci, USSR
 Dr. G.A. Eliseev, Kurchatov Institute, USSR
 Dr. V.A. Glukhikh, Inst Electro-Physical, USSR
 Institute Gen. Physics, USSR
 Prof. T.J.M. Boyd, Univ College N Wales, WALES
 Dr. K. Schindler, Ruhr Universitat, W. GERMANY
 Nuclear Res Estab, Julich Ltd, W. GERMANY
 Librarian, Max-Planck Institut, W. GERMANY
 Bibliothek, Inst Plasmaforschung, W. GERMANY
 Prof. R.K. Janev, Inst Phys, YUGOSLAVIA