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Radiated Power Profile Observed by a Tangentially Viewing IR Imaging Bolometer in JT-60U Tokamak

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1. Introduction

Reconstruction of the emissivity from line-integrated data normally requires significant numbers of measurements even under a priori assumptions such as poloidal symmetry of the core plasma. An infrared (IR) imaging video bolometer (IRVB) can provide a wide-angle view equivalent to hundreds of resistive bolometers. Radiation from the plasma is received by a metal foil absorber and the foil temperature is measured by an IR camera outside the vessel. Radiated power can be obtained by solving the two dimensional (2D) heat diffusion equation numerically at each point in the foil. Recent progress in IR technology enables the sensitivity of the imaging bolometer to approach to that of the conventional resistive bolometer, as has been successfully demonstrated in the Large Helical Device [1, 2]. A feasibility study of the imaging bolometer under a tokamak environment was initiated in the JT-60U [3]. The 2D distribution of the diverted tokamak radiation was observed for the first time by a tangentially viewing IRVB.

2. JT-60U IR Imaging Bolometer and initial operation

A close up view of the IRVB is illustrated schematically in Fig. 1, together with the field of views (FOV) on a poloidal cross-section of the JT-60U tokamak. The poloidal FOV was designed to give a similar view with that of the existing resistive bolometer arrays A, B and C [4], enabling a simple comparison between the two diagnostics. An absorber foil receives the radiated power through a pinhole. A graphite coated gold foil of 2.5 microns thickness with an effective area of 9 cm x 7 cm was used as the absorber. Photon energies up to 8 keV can be absorbed. The temperature distribution of the foil is measured by a small IR camera via a Zn-Se vacuum window and a mirror. The IR camera, consists of a 2D micro-bolometer array with 128x164 pixels and 30 Hz frame rate, and is sensitive to the radiation at wavelength from 7.5 to 13.5 microns. Taking advantage of the wide-angle view of the imaging bolometer, the toroidal FOV was determined so as to allow a semi-tangential view of the JT-60U plasma by shifting the pinhole 15 mm

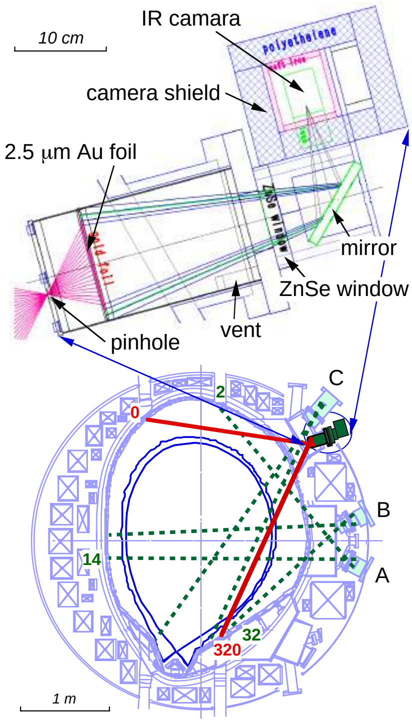


Fig. 1 IR imaging bolometer (top) and FOV in JT-60U (bottom thick lines), and resistive bolometer arrays, A-C (FOV, broken lines).

horizontally. A CAD image of the 2D field of view of the present design is displayed in Fig. 2. The IRVB views an area enclosed by the large rectangle representing the absorber foil, while the small rectangles are areas covered by the existing resistive bolometers. The expected signal to noise ratio (S/N) of the IRVB was estimated based upon previous result [4] and the noise equivalent power of the IRVB as defined in ref. [2]. The resulting S/N is relatively small, on the order of one for the core radiation and ten for the divertor radiation under typical high density discharges of JT-60U with high power heating. By upgrading to a state-of-art IR camera, the S/N should be improved by at least 20 times. The effect of nuclear heating on the foil temperature due to neutron irradiation is expected to be smaller than that of the camera noise level, inferred simply from ITER design value [5]. The magnetic field at the camera location is approximately 0.1 ~ 0.2 T. The IR camera is shielded by a 6 mm thickness of soft iron and 3 cm of polyethylene, determined primarily by the weight limit on the flange, in the present experiment. The magnetic field and the neutrons are thought to be reduced by half.

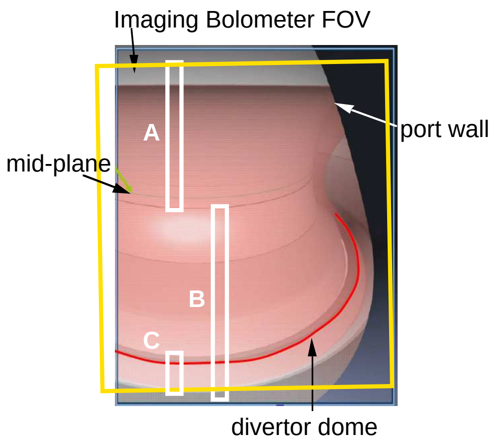
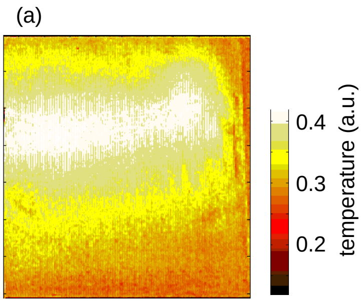


Fig. 2 3D FOV by a computer. A large rectangle is imaging bolometer view (brown), white rectangles are views of resistive bolometers A, B and C. JT-60U plasma is colored pink.

The major concern of the IRVB was the durability of the foil absorber during tokamak operations. The foil must withstand electromagnetic forces, vibrations and rapid changes of the vessel pressure associated with disruptions. The vacuum components including the absorber foil were installed earlier in 2003. Over two years of operation during 1800 discharges including disruptions, the 2.5 microns of gold foil has demonstrated its durability. Pumping mechanisms both from the pinhole and the vent, in addition to wormholes in the foil frame, are thought to have played key roles in eliminating pressure gradient across the foil. With the installation of the IR camera, preliminary testing was started in late 2004 by monitoring analog video signals. However, the IR camera could not be operated properly during high power neutral beam heating (NBI) in deuterium discharges when the neutron yield exceeded 10^{15} 1/s. In addition to the control system upgrade, both the magnetic shield and the neutron shield are to be enhanced in the near future.

3. Radiated power profiles viewed by tangential IR imaging bolometer

Some interesting images characterizing the divertor tokamak were obtained during ohmic and hydrogen operations. A radiating toroidal ring has been projected and recorded onto the foil as a clear high temperature zone during disruptions. An example of a 2D-temperature distribution on the absorber foil right at the disruption is shown in Fig. 3(a). An ohmic discharge of 1.3 MA is terminated during plasma current ramp-down at a safety factor of around 4 with enormous radiation from the core plasma (Fig.3(b)). The radiated power profile of the core plasma measured with resistive bolometers has a large centrally peaked profile just before the disruption consistent with the equilibrium calculation, Fig. 3(c), whereas the highest temperature zone is recorded slightly above the mid-plane in the foil. The discrepancy between the two measurements appears to be associated with a rapid vertical displacement of the plasma during a disruption, which will be clarified after completion of the diagnostic including the timing system.



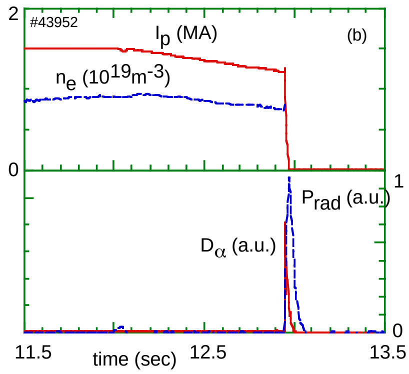
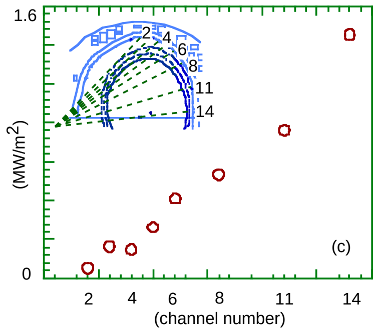
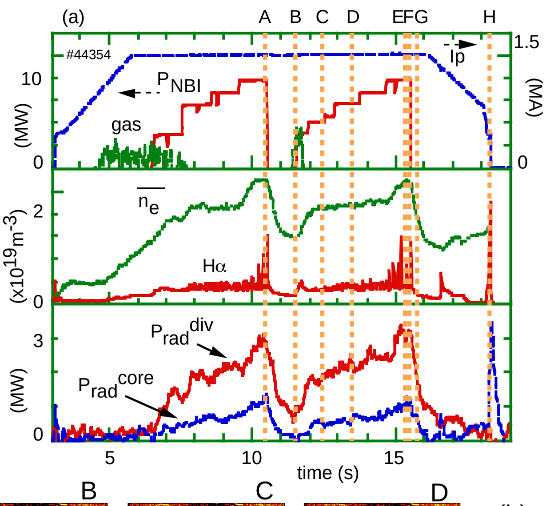


Fig.3 Foil temperature(a), plasma current Ip, density ne, Dα, bolometer signals (b), and radiated power profile (c) during a disruption



The high temperature image of the foil decays within a few frames due to heat dissipation through diffusion and black body radiation.

The 2D, toroidal and poloidal, distribution of the tokamak divertor radiation was observed successfully with the imaging bolometer. Figure 4(a) shows that a 1.5 MA hydrogen discharge with a line average density of ~ 2 x 10^{19} m^{-3} was heated by a stepwise application of hydrogen NBI from 3 MW to 10 MW. The neutron yield during the discharge, due to residual deuterons in the walls, was less than 2 x 10^{12} 1/s. The radiated power from the divertor measured by resistive bolometers increases from 1 MW to 3 MW responding to the heating power and the density increase. The core radiation increases as well but remains small, within 1 MW, except at the termination. Analog images of the foil temperature were obtained throughout the discharge as shown in Fig. 4(b) for a few time slices labeled A to H in (a). The figures show a thick curved line of higher temperature near the bottom of the foil extending to a quarter of the torus. The line is most noticeable at the highest radiation phases A, E and F, and becomes obscure during the decay phase G and even disappears in B when NBI is turned off and a large gas puff is applied. The location and



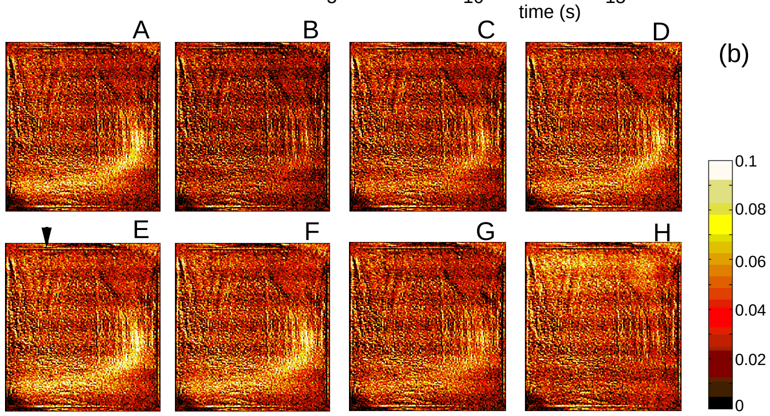


Fig. 4 (a) Time traces of a discharge and (b) 2D foil temperature images at A~H. Periodic horizontal lines in (b) are video signal aliasing artifacts.

the curvature of this line is obviously identical to that of the divertor along the JT-60U vacuum vessel, as the dome shown by the red line in Fig. 2. In the termination phase H, a temperature rise is visible only at the top of the foil, consistent with the resistive bolometer signal in (a), which is similar to the previous example shown in Fig. 3. Figure 5 (b) shows a temperature profile as a function of poloidal location mapped vertically along the foil from the top of the plasma down to the divertor area, obtained from the video image at the arrow in E of Fig. 4(b). A poloidal distribution of the resistive bolometer signals at the same timing is shown in Fig. 5(a). Normally the divertor radiation has peaks at the strike point of the separatrix intersecting with the tiles, at the inboard ψs^{i} and the outboard ψs^{o}. The typical width at the strike point is around 3-5 cm with larger radiation at the inboard. In other areas including the dome, the radiated power is small in low-density discharges below the detachment threshold as in this case [4]. Another characteristic point is the edge radiation at ψs^{u}. Since the frame of the foil could not be recorded in the images, the magnification factor, therefore the exact location relative to the tokamak geometry, can not be specified for this particular case. If an envelop of the scattered data above the background is taken in (b), the two profiles appear similar in shape having some variations near the divertor which is not evident in Fig. 4 (b). However, in addition to the relatively low sensitivity of the IRVB described above, spatial resolution is also limited due to the finite size of the pinhole. The minimum size of an object detectable in the foil image and located at 3 m is about 14 cm, which is much larger than the resolution of the resistive bolometers of 3 cm. The scatter in the data in Fig. 5(b) can be reduced at the expense of spatial resolution in the future by averaging over a many IR camera pixels to give one bolometer pixel [2]. Asymmetry in the toroidal distribution such as that caused possibly by a local nature of the neutral particles would be assessed in a future study. The IRVB may be useful also as a real-time plasma radiation monitor during tokamak operations.

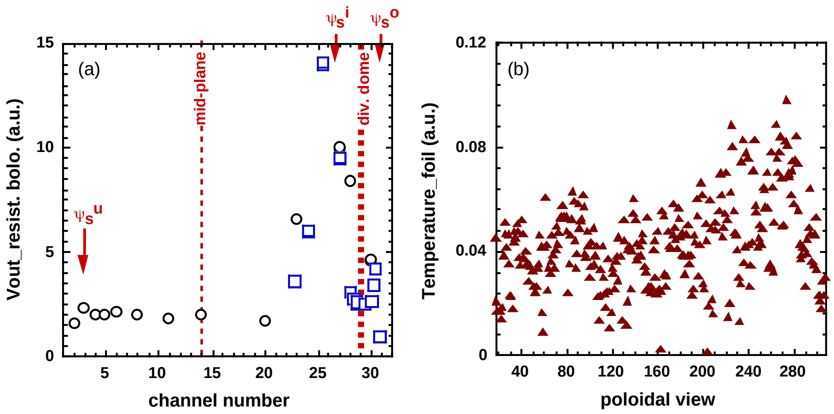


Fig. 5 Comparison of profiles by resistive bolometers, circles by A and B and squares by C arrays (a), and by imaging bolometer (b) at 15.5 sec. Channel numbers and picture pixels are shown in Fig. 1

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