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# Observation of divertor and core radiation in JT-60U by means of bolometric imaging

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## Abstract

An imaging bolometer has been realized for the first time on a tokamak (JT-60U). The imaging bolometer utilizes a 7 cm × 9 cm × 2.5 μm gold foil and an Omega/Micron infrared (IR) camera by Indigo/FLIR (128 × 164 pixels, 70 mK, 30 fps). The imaging bolometer has an array of 12 (toroidal) × 16 (poloidal) (192 in total) channels, a noise equivalent power density of greater than 350 $\mu W/cm^2$ and a frame rate of 30 fps. The field of view of the imaging bolometer is semi-tangential covering the divertor for more than 100° toroidally in addition to the entire poloidal cross-section. The data clearly shows examples of the radiation changing from strong divertor radiation to core dominated radiation in agreement with the resistive bolometer data.

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*Keywords:* JT60U; Divertor; Divertor diagnostic; Radiation

## 1. Introduction

Diagnosis of the radiation from both the divertor and core plasma regions is a key issue for the study of power balance and of impurities resulting from plasma-surface interaction in existing magnetic plasma confinement experiments and future fusion reactors [1,2]. An infrared imaging bolometer provides a uniquely robust diagnostic solution for a fusion reactor in that it requires no electrical feedthroughs and in that all the in-vessel, unshielded components would be neutron resistant [3]. An infrared imaging video bolometer (IRVB) [4,5] has been designed [6], fabricated and installed on the JT-60U tokamak [7]. This diagnostic utilizes an IR camera to image the temperature change of a thin foil which is exposed to plasma radiation through an aperture resulting in an image of the incident plasma radiation absorbed by the foil.

In the 2004–2005 experimental campaign initial data was taken which was limited to 8-bit analog

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video data from ohmic and hydrogen neutral beam discharges due to inadequate shielding. This preliminary data showed a strong radiation zone from the divertor that moved up into the core plasma as the discharge terminated in agreement with the data from the resistive bolometer arrays [7].

In October of 2005 the system was upgraded by improving the shielding and data acquisition system. This has enabled the triggered capture of 14-bit digital IR camera data during high magnetic field and some high-power, deuterium neutral beam heated discharges. In this paper we describe the diagnostic highlighting the recent upgrade and give examples showing the evolution of the radiation structure in comparison with resistive bolometer data.

## 2. The JT-60U IRVB

The JT-60U IRVB utilizes a 7 cm × 9 cm × 2.5 μm gold foil and an Omega/Micron infrared (IR) camera by Indigo/FLIR (128 × 164 pixels, 70 mK, 30 fps). The IR camera has a micro bolometer type sensor with sensitivity in the range 7.5–13.5 μm. The IR camera views the foil through a 30 mm lens, gold mirror and a ZnSe vacuum window. The IR camera is housed in a shield which was upgraded in October of 2005. The current shield consists of 20 mm (previously 6 mm) of soft iron against the stray magnetic field, enclosed in 15 mm (none previously) of lead to block gamma rays, which is in turn surrounded by 90 mm (previously 30 mm) of polyethylene to reduce the neutron flux. The magnetic shield has proven effective in that few problems are now observed with regard to the rise of the magnetic field or the plasma current. The new neutron/gamma shield has also proven effective in that data could be acquired for the first time during high deuterium neutral beam-powered discharges. Through this additional shielding the maximum acceptable neutron flux has been increased from a the previous value of $\sim 1 \times 10^{15}\ \mathrm{s}^{-1}$ up to $\sim 4 \times 10^{15}\ \mathrm{s}^{-1}$, which is consistent with the design value based on a model calculation [8]. The data transfer and acquisition system was also upgraded to permit the storage of 14-bit digital data from the IR camera which was triggered with the JT-60U timing system.

The IRVB has 12 (toroidal) by 16 (poloidal) channels, each of which is 5 mm × 5 mm and views the plasma through a 5 mm by 5 mm square aperture which is 56 mm in front of the foil and is offset from the center of the foil by 18 mm downward and 15 mm to the left. This provides a semi tangential, wide-angle view of the plasma from JT-60U Port P-9 covering the entire poloidal cross-section and the divertor extending over 100° toroidally. Computer aided drawings of the poloidal cross-section and the two-dimensional view are shown in Figs. 1 and 2, respectively. The spatial resolution in the divertor at the poloidal cross-section is approximately 15 cm. A calibration technique has recently been developed for the IR camera and for one point on the foil to allow absolute measurements of radiated power [9]. Using these calibration coefficients and the bit noise of the IR camera, the noise equivalent power density at the foil of the IRVB is calculated as 350 $\mu\mathrm{W/cm}^2$ from Eq. (10) of Ref. [5]. The actual noise equivalent power level is estimated to be up to 2 times higher than this due to other noise sources. This gives a range of signal to noise on the order of 10–100. In the rest of the paper radiation power density is quoted in terms of the equivalent area to account for differences in the angle between the aperture normal and the detector in order to compare among channels and between different detectors.

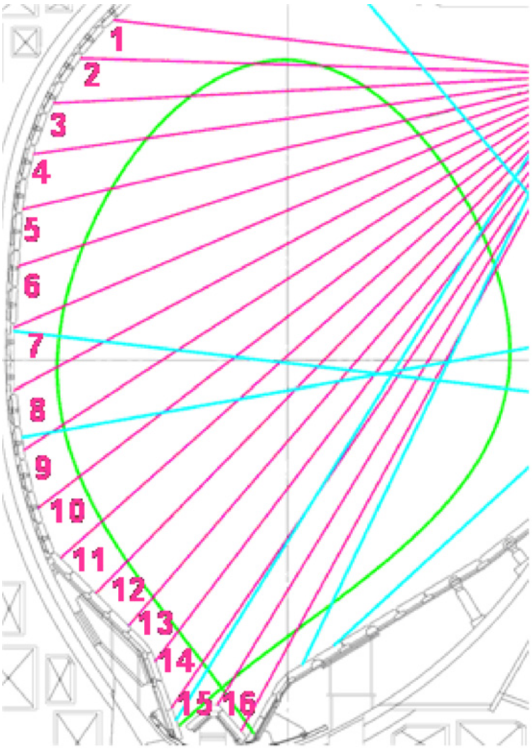

Fig. 1. Numbered sightlines of IRVB in JT-60U at poloidal cross-section.

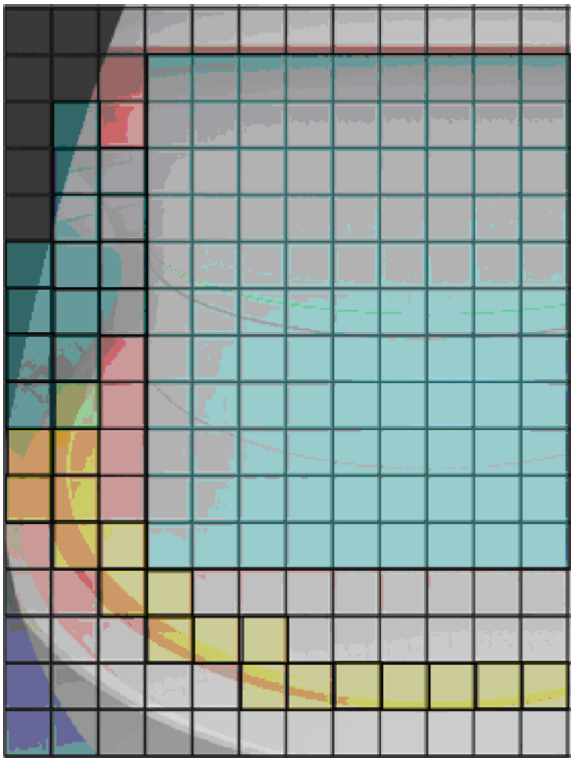

Fig. 2. CAD image of JT-60U IRVB field of view.

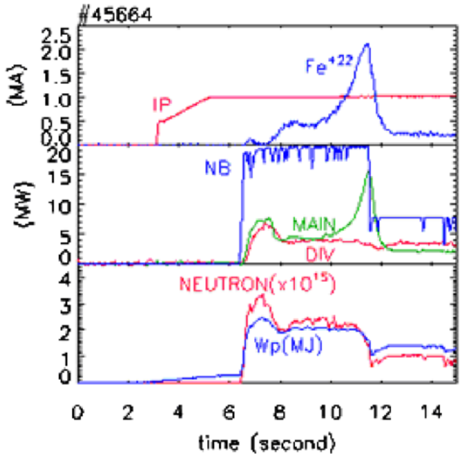

Fig. 3. Summary of JT-60U shot 45664.

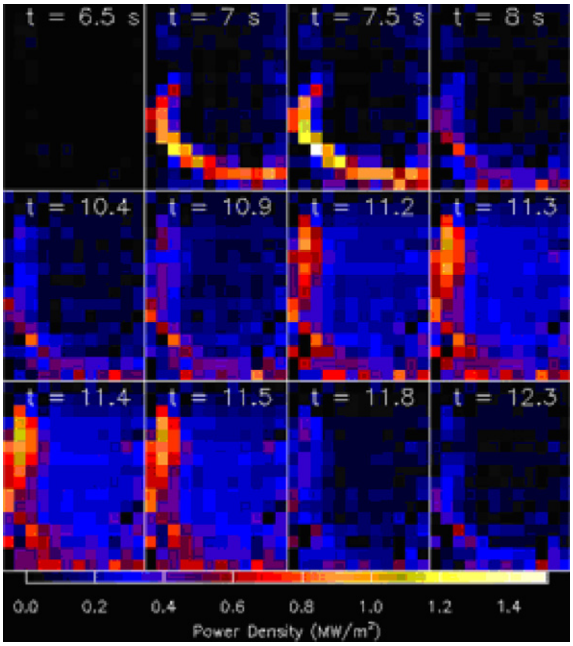

Fig. 4. IRVB images from JT-60U shot 45664.

## 3. Comparison with resistive bolometers

To demonstrate the two-dimensional capabilities of the IRVB we examine JT-60U shot number 45664. One notes from the summary in Fig. 3, that in the initial phase the radiation peaks at 7.5 s and is divided between the core and divertor. Then in the later phase as the inboard strike point moves down into the inner divertor, iron emission increases and the core radiation rises, peaking at 11.3 s and then decaying to a level below the divertor radiation. Presumably the rapid increase in radiation from the core plasma was due to sputtering of iron which was deposited on the divertor tiles during the year of operation after the installation of the ferrite tiles. These ferrite tiles were installed in the non divertor portions of the outer wall in order to reduce losses due to the toroidal magnetic field ripple. The corresponding evolution of the bolometric image in Fig. 4 shows the radiation coming predominantly from the divertor region whose intensity peaks at 7.5 s and then weakens and shifts outward as the core radiation builds in both the tangential region and nearer the symmetry plane (poloidal cross-section). This outward shift in the divertor radiation can be seen also in Fig. 5 in the resistive bolometers viewing the divertor. The signal levels of the IRVB and the resistive bolometers are also in the same range. In Fig. 6 the resistive bolometer estimate of the total radiated power coming from the core and divertor regions are shown and compared with the sum of signals form IRVB channels that view the core (shaded blue[1] in Fig. 2) and divertor (shaded yellow in Fig. 2) regions. This is not meant to be a

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[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

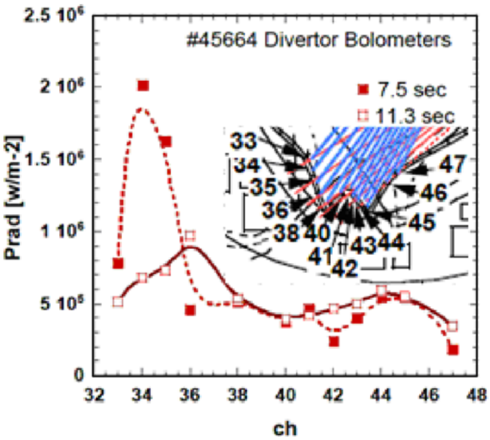

Fig. 5. Resistive bolometer brightness profiles in the divertor region during JT-60U shot 45664.

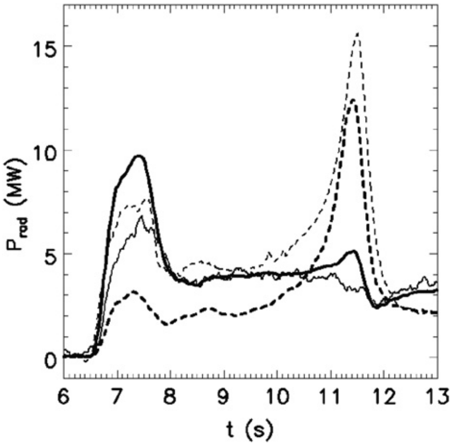

Fig. 6. Divertor (solid) and core (broken) radiated power estimates from resistive (thin) and imaging (thick, a.u.) bolometers on JT-60U during shot 45664.

quantitative comparison, but qualitatively the agreement is good showing the decrease in the divertor signals and the increase in the core radiation as the shot progresses.

## 4. Discussion and conclusion

An imaging bolometer has been successfully deployed for the first time in a tokamak showing the variation of the radiation signals which is consistent with those from resistive bolometers. The completion of foil calibration work [9] is necessary also to proceed to the next step in its development which is to demonstrate the viability of using an IRVB in conjunction with (or without) resistive bolometers to perform two dimensional computed tomography of the radiated power density from the poloidal cross-section.

Two problems became evident in the data analysis, which have not been mentioned yet. The first of these are nonthermal signal spikes which appear in the IR camera data during the discharge. It is thought that these may be due to X-rays generated in the foil by energetic neutrals or neutrons coming through the aperture from the plasma. These have been removed through a data processing program, and therefore do not present a serious problem. A second issue is the motion of the foil which has been observed during gas puffing and other events. We have corrected this by subtracting off a background prior to the beginning of the main discharge. This problem could be mitigated in the future by using a thicker foil, which will be necessary in a reactor due to the higher photon energies, or a foil material which has a stronger tensile strength. Some good candidates in this respect are Tungsten for thicker foils and Tantalum for thinner foils.

Finally it should be mentioned that the IR camera used in these experiments has rather low performance in terms of sensitivity, number of pixels and frame speed. The sensitivity of the IRVB could be increased by a factor of at least 25 with the use of a state-of-the-art IR camera. This improved sensitivity could be traded off for improved spatial resolution or for improved time resolution in a camera with a faster frame rate. It has been demonstrated that an IRVB can be operated in a reactor relevant environment and provide reasonable images of the plasma radiation. Therefore an IRVB could play an important role in the diagnosis of divertor and core radiation from a future fusion reactor.

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