Fast Ion Loss Measurement by IRTV in a Reduced Ripple Experiment with Ferritic Inserts on JFT-2M

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Abstract
In the medium size tokamak JFT-2M, ferritic steel plates (FPs) were inserted in order to reduce the toroidal field ripple, which caused fast ion losses. A 2D infrared TV (IRTV) system with time and spatial resolutions appropriate for measuring the first wall temperature increment caused by the ripple ion losses was developed. An IR thermal-imaging camera was used in the present study; this device provided a field rate of 60 fields/sec and a detectable temperature range of 0–500°C with a resolution of 0.2°C. The PtSi detector, sensitive to 3–5 μm IR radiation, was arrayed in 256 × 256 pixels. The optical system consisted of an IR-lens, a turning mirror, and a sapphire vacuum window with a distance from the camera position to the target wall of 3.5 m, resulting in spatial resolution of ~3 mm. The target wall consisted of ~9 cm × ~15 cm carbon tiles. By using this system, local hot spots due to the ripple-trapped and banana drift losses were observed when fast ions were produced by tangential NBI (36 kV, ~0.5 MW). The peak temperature increment reached ~75°C and ~150°C on the ripple-trapped and banana drift loss regions, respectively. In the optimized condition with FP insertion, the temperature increment was reduced to an almost negligible level for the ripple-trapped loss regions. The corresponding increment for the banana drift loss regions was also minimized. These IRTV data clearly demonstrate the efficacy of FPs for the reduction of fast ion losses.

Keywords:
IRTV system, first wall temperature measurement, ferritic steel plate insertion, ripple loss reduction, ripple-trapped ion loss, banana drift loss

1. Introduction
In a tokamak configuration, the toroidal field ripple significantly enlarges the radial diffusion loss of energetic particles such as alpha particles and fast ions produced by neutral beam injection (NBI). The particle bombardment and the heat flux result in serious local damage for the first wall. In the ITER, it is expected that the ripple loss of alpha particles reaches 25% during the negative magnetic shear operation and the heat flux exceeds 4 MW/m² [1]. Therefore, ripple reduction is an important issue at present.

It is already known that the application of ferromagnetic ferritic steel is the most effective and economical method of ripple reduction [2]. In the JFT-2M tokamak (major radius $R_0 = 1.31$ m, small radii $a \times b = 0.35$ m × 0.53 m), ferritic steel plates (FPs) were inserted in order to demonstrate the effect of this method of ripple reduction for the first time [3-5].

In this article, we describe a new infrared thermography system that was developed on JFT-2M in...
order to measure the first wall temperature increment caused by ripple ion losses and to evaluate the effects of FP insertion. For monitoring the surface temperature, an infrared TV (IRTV) thermal-imaging system was designed and manufactured to satisfy the following demands: 1) a wide viewing area with high spatial resolution to cover the ripple loss regions, 2) a suitable time resolution, and 3) detectable temperature range from room temperature to several hundreds of degrees.

In Sec. 2 we present the setup of this IRTV system on JFT-2M. Results of the temperature measurements are shown in Sec. 3. The ripple ion losses were detected clearly as local hot spots on the first wall. In Sec. 4, it is shown that the temperature increment due to ripple ion losses can be successfully reduced by inserting FPs. A summary is given in Sec. 5.

2. IRTV System on JFT-2M

The new IRTV system on JFT-2M consisted of a Mitsubishi IR-M300 thermal-imaging camera and an IR-T300 thermal image analyzing system for camera control and data acquisition, as shown in Fig. 1. The IR-M300 provided a field rate of 60 fields/sec which time resolution was suitable for measuring the first wall temperature increment for a one-second discharge on JFT-2M. A wide detectable temperature range was achieved by changing four step band pass filters with a resolution of 0.2°C. The 1st, 2nd, 3rd, and 4th filters covered temperature ranges of 0–60°C, 40–130°C, 100–250°C, and 220–500°C, respectively. The 256 × 256 PtSi (26 × 20 μm) Schottky barrier sensor array (i.e., the focal plane array), sensitive within the 3–5 μm range, was cooled down to −197°C by an internal Stirling cycle cooler. A 14°/9° dual field of view germanium-silicon lens was attached to the camera. The images were selectively stored in real time in 128 Kbytes/frame × 16 frames of memory (FM) or 128 Kbytes/frame × 256 frames of bulk memory (BM). Synchronization with the one-second discharge was achieved by an external trigger input to the IR-T300. After the discharge took place, the image sequence was stored on an internal hard disk (HDD) or external magnetic disk (MO; DOS format was primarily used). The IR-T300 was operated remotely from a Windows PC through an RS-232C link. Stored image data could be changed to a text format for data analysis by comma separated values (CSV) conversion software on a Windows PC.

The IRTV camera provided a view of the area around No.3–4 ports (P3–P4) through a sapphire vacuum window on a P8 midplane port using a turning mirror, as shown in Fig. 2. The camera, without any magnetic shield, was placed just outside of the toroidal field coil, where the field magnitude was −0.05 T at the central toroidal field of 1.3 T. Thus, the distance from the camera position to the target wall could be as short as 3.5 m and a spatial resolution of ~3 mm was obtained with a viewing area of −50 cm × −65 cm. Compared with other IRTV systems [6,7], the present spatial resolution and the viewing area were more appropriate for a ripple loss measurement on the medium size tokamak, the JFT-2M. Eighty-two high-purity carbon (IG-430U) tiles (−9 cm × −15 cm × 3 cm each) were used as the target material for the IRTV in order to avoid reflections (thermal radiation coefficient, ε=0.97). The tiles covered regions in the toroidal direction from about half of P3 to all of P4, except for an open port area, and a poloidal angle of ±84° from the vacuum vessel (VV) center (R=1.31 m, Z=0.0 m) was achieved. Fine grooves were carved on the surface of the carbon tiles likely as meshes of a net below 1 mm to avoid further reflections. Gaps between adjacent tiles were limited to within ±0.5 mm, and some of the tiles had no bolt holes in order to avoid shadow effects. A thermocouple was mounted in a carbon tile at 15 mm depth on the facing IRTV surface for the measurement calibration, which was performed for a steady state during 120°C baking of a vacuum vessel, such that the IRTV temperature was corrected by ε=0.97. The distance between the vacuum vessel wall and tile surface was 7 cm for the upper five tiles, and 10 cm for the lower six tiles, respectively, as shown in the poloidal

Fig. 1. Setup of the novel IRTV system on JFT-2M. This system consisted of a Mitsubishi IR-M300 thermal-imaging camera and an IR-T300 thermal image analyzing system for camera control and data acquisition.
3. Measurement of First Wall Temperature with Respect to Ripple Ion Losses

Fast ion losses due to toroidal field ripple were caused by ripple well trapping (ripple-trapped loss) or enhancement of radial drift due to a change in banana tips (banana drift loss). In this section, we show that local temperature increments on the first wall due to both the ripple-trapped and banana drift losses were clearly seen using the new IRTV system. The experiments were performed using plasma current \( I_p = 200 \text{ kA} \), a central toroidal field of \( B_t = 1.3 \text{ T} \), a line averaged electron density of \( n_e \approx 2 \times 10^{19} \text{ m}^{-3} \), and limiter D-shaped configuration. When the ion grad \( B \) direction was downward (the \( B_t \) direction was clockwise (CW)), the ripple well calculation predicted that the ripple-trapped loss regions was located on the lower-shoulder portion between adjacent toroidal field coils (TFCs), as shown in Fig. 3(a). The banana drift loss region was located around the outer midplane in the D-shaped plasmas. An infrared image on the P3-P4 first wall during tangential co-NBI (36 kV, -0.5 MW) was shown in Fig. 3(b), where the 2nd filter was in use (40°C to 130°C range). As expected, hot spots were observed at the shoulder portion just under the P4 port corresponding to the ripple-trapped loss region and at the midplane near the P3 port edge between P3 and P4 in the case of the banana drift loss region. Since the temperature increment under P4 disappeared when the ion grad \( B \) direction was reversed (the \( B_t \) direction was reversed), the ripple well loss regions were clearly visible.
counter clockwise (CCW)), it was confirmed that the hot spot at the shoulder portion was due to the ripple-trapped ion losses. In addition, the energy of the lost fast ions was estimated to be approximately 25 keV by the lost ion probe [8] installed in JFT-2M.

Figures 4(a) and (b) show the time evolution of the surface temperature ($T_s$) at the highest points in the ripple-trapped and banana drift loss regions, respectively. Measurement with the 3rd filter (100°C to 250°C range) was undertaken because the signal level was saturated at 130°C with the 2nd filter, which can be seen in the image data. The data obtained using the 2nd filter is shown by open circles for the same shot as that shown in Fig. 3(b), and the data obtained using the 3rd filter is also shown by closed circles at a similar subsequent shot. The NBI was pulsed from 0.6 sec to 0.7 sec. It can be seen that the temperature increment due to ripple-trapped losses began with room temperature (~30°C) after the NBI was turned on and gradually reached ~120°C after ~0.08 sec. The temperature increment due to the banana drift losses began at ~60°C and quickly reached ~190°C after ~0.05 sec. (In this case, the temperature before NBI was greater than the room temperature, because the tiles around the midplane were receiving the heat flux from the ohmic heating phase for the D-shaped configuration.) The results suggest that the difference in the time evolution of the temperature between the two regions probably was a result of the time lag until the fast ions fell into each trapping region in velocity space.

4. Ripple Loss Reduction by Ferritic Steel Plate Insertion

To demonstrate the ripple loss reduction, ferritic steel plates were installed between the vacuum vessel and the toroidal field coil in all (16) toroidal sections of the JFT-2M, as shown in Fig. 5. They cover a poloidal angle of ±65° with respect to the equatorial plane on the outboard side. Thickness, width, and position of the FPs were factors that reduced the fundamental mode ripple (toroidal mode number, $n=16$) which, in turn, minimized the diffusion coefficient of ripple banana.

![Diagram](image-url)

**Fig. 4.** Time evolution for the points of highest surface temperature ($T_s$) on (a) ripple-trapped and (b) banana drift loss regions. The data obtained using the 2nd filter (40°C~130°C) is depicted by open circles in the same shot as that given in Fig. 3(b), and the data obtained using the 3rd filters (100°C~250°C) are also shown by closed circles at a similar subsequent shot.

![Diagram](image-url)

**Fig. 5.** Illustration of ferritic steel plate (FP) insertion into JFT-2M. FPs were installed between the vacuum vessel (VV) and the toroidal field coils (TFC) in all (16) toroidal sections. 67 mm-thick FPs were used.
drift ions at the shoulder portion. It is estimated that the 67 mm thick FPs reduced the ripple magnitude at the shoulder portion \((R = 1.5 \, \text{m}, \, Z = \pm 0.25 \, \text{m})\) from 1.53\% to 0.07\% at \(B_t = 1.3 \, \text{T} \) and 1.0 T, respectively.

The temperature increment due to ripple ion losses was compared between a configuration using FPs and a configuration without FPs. Figure 6 shows the profiles of temperature increment \(\Delta T_s\) due to the ripple-trapped and banana drift losses. These results were processed by using CSV-converted text data. For the ripple-trapped loss images at the lower-shoulder portion, \(\Delta T_s\) was defined as \(\Delta T_s = (T_{\text{SRH}} - T_{\text{OH}})_{\text{CW}} - (T_{\text{SRH}} - T_{\text{OH}})_{\text{CCW}}\), since the wall temperature increased with NBI heating in either \(B_t\) direction. Here, the first and second parentheses give temperature differences between the ohmic and NBI heating phases in the CW and CCW \(B_t\) directions, respectively. In the case of CW, both the ripple-trapped ion loss and the uniform loss (such as radiation loss) come to the region. In the case of CCW, the ripple-trapped loss region moved to the upper-shoulder portion and only the uniform loss approached this lower-shoulder portion as mentioned in Sec. 3. Hence, the difference between the first and second parentheses is due to the intrinsic ripple-trapped losses. On the other hand, \(\Delta T_b\) for banana drift losses were calculated as the temperature increment from that of the ohmic heating, since the banana drift loss region around the outer midplane did not change in both the CW and CCW \(B_t\) directions. Furthermore, radiation loss was not considered in this case, because the portion of this surface temperature increment due to the radiation loss estimated from the bolometer measurement was relatively small, i.e., below 10\(^\circ\)C. In the optimized condition with FP insertion, the hot spot regions due to ripple-trapped losses almost disappeared and the peak temperature increment \((\Delta T_{s,\text{max}})\) decreased from \(-75\,^\circ\text{C}\) to \(< 10\,^\circ\text{C}\). \(\Delta T_{s,\text{max}}\) for banana drift losses around the midplane also decreased from \(-150\,^\circ\text{C}\) to \(-70\,^\circ\text{C}\) with FP insertion.

These temperature reductions can be attributed to ripple reduction. In particular, by inserting FPs, the lost power at the ripple-trapped loss regions could be successfully reduced to a negligible level.

5. Summary

An IRTV system on JFT-2M was developed in order to measure the first wall temperature increment caused by ripple ion losses. The effect of ferritic steel plate (FP) insertion as a method for ripple loss reduction was demonstrated by the present measurements.

The system used here possessed a 256 \(\times\) 256 PtSi focal plane array with appropriate resolutions in time (60 fields/s) and space (\(< 3 \, \text{mm}\)), and as expected, local temperature increments on the first wall due to ripple-trapped and banana drift ion losses were detected. The temperatures of each corresponding hot spot reached over 120\(^\circ\)C during tangential co-NBI (36 kV, \(< 0.5 \, \text{MW}\)). After 67 mm-thick FPs were installed in JFT-2M, ripple loss reduction was confirmed by a drastic decrease in the observed surface temperatures. The \(\Delta T_{s,\text{max}}\) decreased from \(-75\,^\circ\text{C}\) to \(< 10\,^\circ\text{C}\) in the ripple-
trapped loss regions and from \(-150^\circ C\) to \(-70^\circ C\) in the banana drift loss regions. Quite small temperature increments at the ripple-trapped loss regions indicated that the heat load was reduced to a negligible level with the insertion of FPs.

Thus, the present IRTV system proved to be a very useful tool for simultaneously measuring the temperature increments of both ripple-trapped and banana drift ion loss regions at medium size tokamaks such as the JFT-2M. In particular, a ripple reduction effect achieved by FP insertion was demonstrated for the first time using the IRTV data.

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References