Synchrotron radiation pattern of the runaway beam during induced disruptions in TEXTOR

K. Wongarch[1], K.H. Finken[1,2], R. Koslowski[2], S.S. Abdullaev[2], O. Willi[1] and L. Zeng[2,3]

[1]*Institut für Laser- und Plasmaphysik, Heinrich-Heine Universität Düsseldorf, Germany*

[2]*Institut für Energie- und Klimaforschung, Forschungszentrum Jülich GmbH, EURATOM Association, Jülich, Germany*

[3]*Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China*

Introduction

Tokamak plasmas are prone to disruptions, an abrupt termination of the discharge. During a disruption upto 80% of the initial plasma current is carried by runaway electrons [1]. The runaways can gain energies as high as tens of MeV. When the high-energy electrons are lost, they can penetrate deep inside the materials and cause a severe damage to the plasma facing components (PCFs). Most of techniques employed to diagnose the runaway electrons provide an indirect measurement. These methods are based on detecting X-ray, gamma ray or neutrons, which are generated by runaway-wall interactions. One of the most promising runaway diagnostic methods is the measurement of synchrotron radiation. Since the high-energy electrons emit synchrotron radiation highly collimated in the direction of flight [2], this technique enables an observation of the shape of the high-energy runaway beam, its location and dynamics.

Experimental Setup

In the circular cross-section limiter tokamak TEXTOR (R_0 = 1.75 m, a = 0.46 m), the synchrotron radiation emitted by runaway electrons is observed by an infrared (IR) camera, which is located at the equatorial plan of the tokamak. The camera views the plasma tangentially in the electron approach direction. Its viewing area covers the plasma at the low-field side (LFS) of the torus, whereas the high-field side (HFS) is vignetted. The operational wavelength range of the camera is 3-5 μm. The camera is, therefore, sensitive not only to the synchrotron radiation emitted by runaway electrons but also the IR radiation emitted from other sources such as thermal radiation. However, the characteristic features of each source enables to differentiate between the synchrotron radiation and IR radiation from other sources.

The TEXTOR plasma position are controlled by 3 different magnetic coil systems. The vertical field coils and the radial position control coils generate the vertical fields which is responsible for the plasma horizontal position. The vertical position is controlled by the plasma vertical position control coil system. Each coil has own power supply and can be operated independently

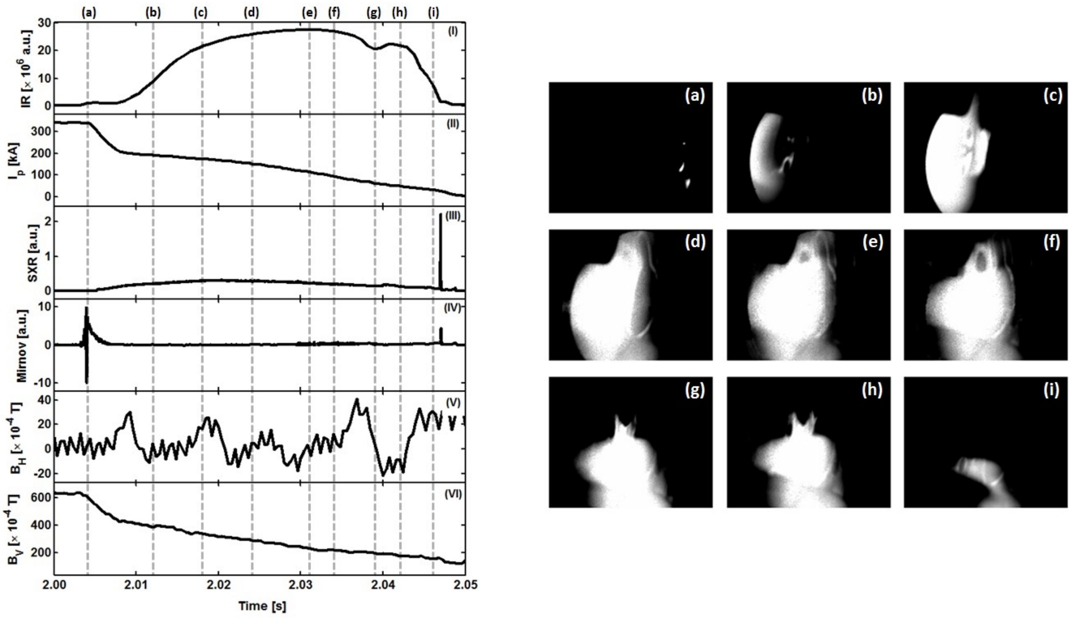

Figure 1: *left* - time traces of the discharge 117434: (top to bottom) the IR radiation intensity summed over all the camera viewing area, the plasma current, the soft X-ray emission, the Mirnov signal, the horizontal field and the total vertical field during an induced disruption. *Right* - temporal evolution of IR radiation pattern observed by the camera.

in the feed-forward mode [3].

Observation of the Synchrotron radiation pattern during disruptions

In the experimental campaign, disruptions are initiated by Ar injection performed by a fast valve [4]. In the discharge 117434, the current of the radial position control coils is switched to its limiting value of -3.5 kA and the current of the vertical position control coils is set to +1 kA shortly after the initiation of the disruption. The temporal evolution of the IR radiation, the plasma current, the soft X-ray signal, the Mirnov signal, the horizontal field and the vertical field during disruption of the discharge 117434 are shown in figure 1. The energy quench takes place at 3 ms after the gas injection. A strong Mirnov spike is present. The plasma thermal energy is lost to the PFCs. The heated components are seen by the IR camera as shown in figure 1 (a). About 10 ms after the thermal quench the runaway electrons gain high enough energies to become visible at the left side of figure 1 (b). The runaway beam develops and moves toward LFS until it reach its maximum intensity at t = 2.031 s (see figure 1 (e)). The negative field generated by the radial position control coils leads to the movement toward LFS of the beam. Figure 1 (e) - (i) shows that the runaway beam shrinks and its intensity decreases with increasing time. At the end of the discharge a sharp SXR spike and the Mirnov signal spike are present. The runaways are completely lost to the wall within less than 1 ms. A structure present in the

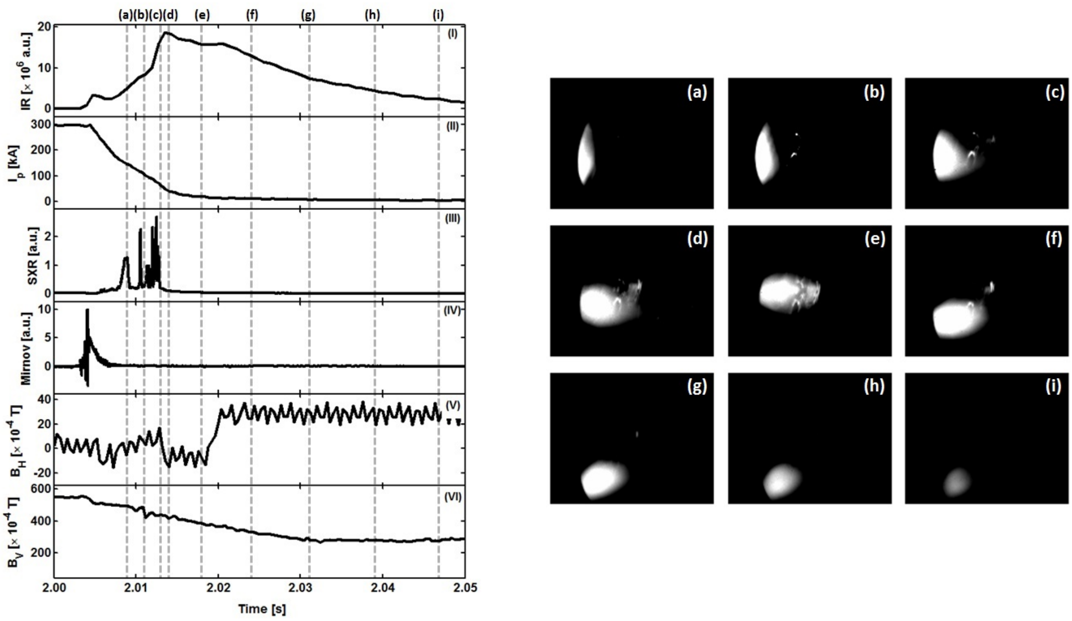

Figure 2: *left* - time traces of the discharge 117828: (top to bottom) the IR radiation intensity summed over all the camera viewing area, the plasma current, the soft X-ray emission, the Mirnov signal, the horizontal field and the total vertical field during an induced disruption. *Right* - temporal evolution of IR radiation pattern observed by the camera.

IR images in figure 1 is a reflection from one of the big opening ports of TEXTOR.

In the discharge 117828, the current of the vertical position control coils is also switched to +1 kA but the current of the radial position control coils is set to +3.5 kA. The runaway beam, similar to the previous case, develops at the left side of the image. However, the beam remain at the HFS until the end of the current plateau due to the positive field generated by the radial position control coils (see figure 2 (a) - (c)). During this phase SXR spikes which indicate the runaway loss are observed. After the plateau phase the plasma current drops rapidly. The poloidal field, therefore, decreases immediately. This results in a charge separation. The $E \times B$ force leads to the drift of the runaway beam toward LFS as seen in figure 2 (d). In figure 2 (d) - (i), the runaway beam moves upward and downward under the influence of the negative and the positive horizontal fields, respectively (see also figure 2 (V)). Although the plasma current drops to almost zero after the plateau termination, part of the runaway beam persists over a few tens of milliseconds. The beam decays gradually until it completely disappears at $t \approx 2.57$ s. Neither a SXR spike nor a Mirnov oscillation are observed during this phase.

Runaway parameters and critical plasma current

The runaway parameters, i.e., the pitch angle (θ) and the radius of the runaway beam (r_{beam}) can be deduced from the synchrotron radiation image [5]. From the analysis of figure 1 (e) we obtain r_{beam} = 283 mm and θ = 52 mrad. The maximum number of the runaway electron observed by the IR camera is 1.6 $\times 10^{16}$. The number of the high energy runaways is affected with an error margin of about 20%. The total number of runaway electrons estimated from the runaway current in figure 1 (II) is N_{tot} = 2.82 $\times 10^{16}$.

As can be seen from the synchrotron radiation in the second example, a significant amount of the high-energy runaway electrons are still confined after the current drop. The maximum number of the runaway electron observed by the IR camera after the current drop is 6.4 $\times 10^{15}$. Our numerical calculation shows that the minimum current required to sustain the runaway electron beam is proportional to the square of the runaway energy. The runaway electrons with energies of 25 MeV can survive the plateau termination at the low plasma current of about 20 kA.

Conclusion

The synchrotron radiation measuring system on the TEXTOR tokamak serves as an important runaway diagnostic method. This technique provides information on beam position and profile of the high-energy runaways. We have found that the magnetic fields generated by position control coils have a significant influence on the dynamics of the runaway beam even after the current decay. Generally, it has been supposed that runaway electrons are completely lost to the wall at the time the plasma current drops rapidly to almost zero [6]. However, the detection of the synchrotron radiation shows that a substantial number of high-energy runaway electrons survives the current plateau termination. Additionally, the pitch angle and the radius of the runaway beam are obtained from the IR image analysis.

Acknowledgement

This work was supported by the Royal Thai Government, an R&D contract and the Trilateral Euregio Cluster (TEC). The authors thank O. Schmitz and the TEXTOR team for their support.

References

[1] J.R. Martin-Solis, B. Esposito, et al.,Phys. Rev. Lett. **97**, 165002 (2006).
[2] K.H. Finken, S.S. Abdullaev, M.W. Jakubowski, et al., Nucl. Fusion **47**, 91 (2007).
[3] O. Neubauer, G. Czymek, B. Giesen, et al., Fusion Sci. and Tech **47**,76 (2005).
[4] A. Savtchkov, K.H. Finken and G. Mank, Rev. of Sci. Instrum **70**, 3490 (2002).
[5] K.H. Finken, J.G. Watkins, D. Rusbüldt, et al., Nucl. Fusion **30**, 859 (1990).
[6] N. W. Eidietis, N. Commaux, E.M. Hollmann, et al., Phys. of plasma **19**, 056109 (2012).