Measurements of runaway electrons in the TEXTOR tokamak

T. Kudyakov[1], K.H. Finken[2], O. Willi[1], M. Jakubowski[3], Y. Xu[4], S.A. Bozhenkov[23], M. Lehnen[2], and the TEXTOR team[2]

[1] *ILPP, Heinrich-Heine-Universität Düsseldorf, 40225 Düsseldorf, Germany*

[2] *Institut für Energieforschung - Plasmaphysik, Forschungszentrum Jülich GmbH, Association EURATOM-FZJ, Trilateral Euregio Cluster, 52425 Jülich, Germany*

[3] *Max-Planck-Institut für Plasmaphysik, IPP-EURATOM Association, 17491 Greifswald, Germany*

[4] *Laboratoire de Physique des Plasmas/Laboratorium voor Plasmafysica, ERM/KMS, EURATOM Association, Trilateral Euregio Cluster, 1000 Brussels, Belgium*

Introduction. Investigation of runaway electrons is of great interest for the ITER tokamak because of the possible damages to plasma facing components (PFC) [1]. A new diagnostic probe [2], was developed to provide the absolute number of runaways and their spectrum at the plasma edge. The probe consists of 9 YSO ($Y_2SiO_5 : Ce$) crystals, as shown in Fig. 1. Different thicknesses of stainless steel filters for successive channels from 1 to 9 allow to measure the spectrum of runaways with energies between 4 and 30 MeV. The runaways with the lowest energy of about 4 MeV are registered by the first crystal. The minimum energy required for an electron to be detected by a crystal grows with the crystal number. The probe was absolutely calibrated at the electron linear accelerator ELBE, Forschungszentrum Dresden-Rossendorf [2]. Additionally, measurements of the thermal load from incident runaway electrons in the material were performed by two thermocouples installed in the probe.

In this contribution the first measurements of the runaway spectrum by the probe are presented. The spectrum was measured during TEXTOR plasma disruptions.

Experimental set-up. The experiments were performed in the TEXTOR tokamak with the

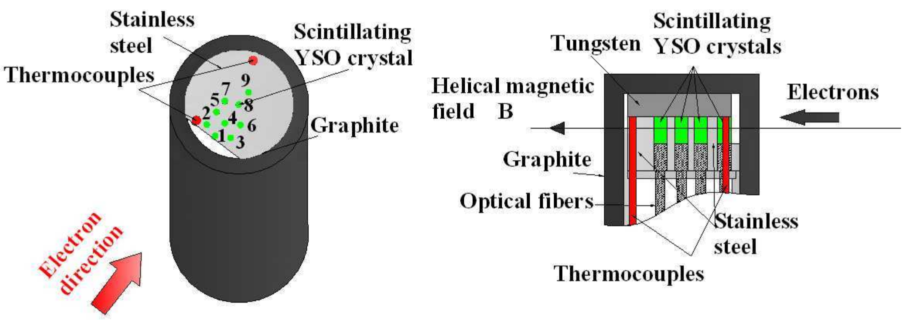

Figure 1: *The probe design and the positions of the YSO crystals inside the graphite housing are showing. The probe has 5 mm graphite mantel and depending on the crystal number the following thickness of stainless steel is used from the incidence direction of electrons: crystal 1 - 0 mm; 2 - 1 mm; 3 - 2 mm; 4 - 2.5 mm; 5 - 3.5 mm; 6 - 4.6 mm; 7 - 5.5 mm; 8 - 7 mm and 9 - 9.5 mm. The tungsten plate on the top of crystals is used as a filter to block electrons. The light produced in the crystals is transferred to photomultipliers by optical fibers. Two thermocouples measure a temperature in front and the back side of the tungsten plate.*

following plasma parameters: plasma current, $I_p = 300$ kA, toroidal magnetic field, $B_t = 2.4$ T, the averaged electron density (flat-top) $n_e = 2 \cdot 10^{19}\ m^{-3}$. The major radius of the TEXTOR tokamak is $R = 1.75$ m and the minor radius is $a = 46\ cm$ defined by the carbon limiter.

Disruptions were provoked by fast noble gas injection (Ar) to stable TEXTOR discharges. The massive gas injection is carried out by a special "disruption mitigation valve" (DMV) [3].

Measurements of runaway electrons were carried out by the scanning probe and a set of neutron detectors, which can detect runaways with energies higher than 10 MeV (defined by the photo-nuclear reaction (γ, n) threshold).

The probe provides direct measurements of runaways, which just left the plasma. During these experiments, the probe was inserted to 47 cm minor radial position (in the equatorial plane from the low field side), 0.8 s before the disruption and it was kept at this position for 200 ms after the thermal quench.

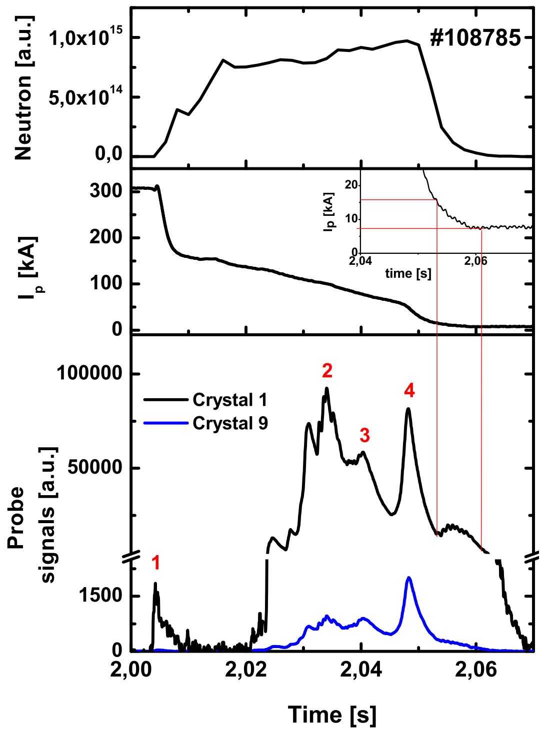

Figure 2: *The disruption is provoked by the Ar gas injection with a working pressure of 1 bar at 2 s. From the top to the bottom of the figure neutron signal, plasma current and probe signals from crystal 1 and crystal 9 during the current and thermal quenches are shown. During the current quench electron are coming from the plasma as a set of bursts (e.g. peaks 2, 3 and 4).*

Thermal and current quench phases. Fig. 2 displays characteristic signals during the disruption (Ar gas). From the top to bottom are the time traces of the neutron signal, the plasma current and the probe crystals 1 and 9 (which can detect electrons with energies higher than 4 and 20 MeV respectively) are shown. At $t = 2$ s, argon gas was injected into the plasma by the DMV operating at 1 bar. After a few milliseconds the disruption starts with a strong MHD-activity, sudden drop of the electron temperature, and the first runaway spike. Afterwards due to the low electron temperature, the plasma current decays in the resistive ways and runaways are generated. The first runaway spike is attributed to the runaways born in the high loop voltage phase at the start of the discharge which are lost when the plasma becomes ergodic during the thermal quench.

Higher probe signals are observed late in current quench (from about 2.02 s in Fig. 2). In disruptions with runaway generation one observes typically a plateau in the current. This is the time when the whole current is carried by the runaway electrons. During the current quench runaway electrons are coming from the plasma as a set of bursts as shown in Fig. 2 and Fig. 4 a). From the comparison of the signal ratios of crystal 1 and 9 follows that the relative number of high energy runaways grows for the electron bursts later in time.

A comparison of Geant4 [4] simulations performed for a series of model energy spectra with

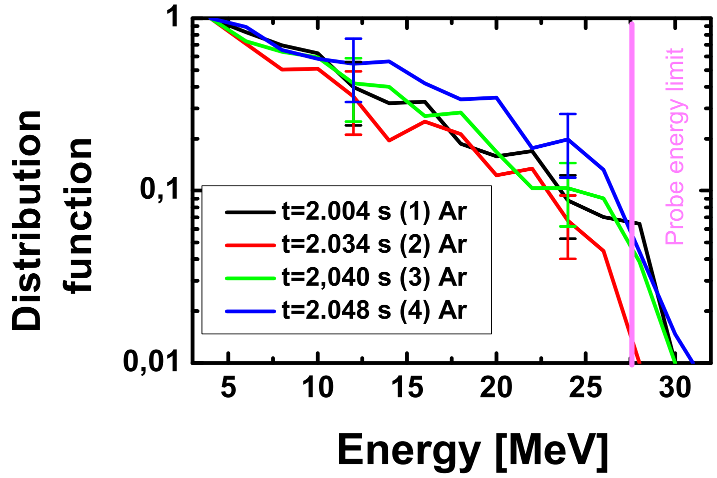

Figure 3: *Analysis of runaway spectra is performed for disruptions provoked by the argon gas injection. Runaway spectra are analyzed for 3 electron bursts during the current quench. The first peak is produced due the loss of runaways during the time of the thermal quench. These electrons are mainly produced in the plasma before the gas injection occurs.*

probe signals makes it possible to find the runaway spectrum. The time development of the runaway spectrum for the discharge in Fig. 2 is shown in Fig. 3. The spectra were calculated for bursts in thermal quench (peak 1) and current quench (peaks 2-4). The runaways detected by the probe have a decreasing distribution function. It is to be noted that the runaway spectra resemble the exponential decay with e-folding energy of about 15 MeV. However, a more careful analysis including treatment of the loss mechanism is necessary and will be reported later.

The probe provides reliable information about the spectrum of runaways up to the energy of about 30 MeV. This energy limit is determined by the thickness of the stainless steel filter in front of the last crystal.

The spectra were calculated for bursts in thermal quench (peak 1) and current quench (peaks 2-4). The high energy part of the spectrum grows in time during the current quench.

Thermal load. Measurements of the temperature at the front and back side of the probe are shown in Fig. 4. The temperature measured by the thermocouple at the front side grows as soon as the electrons pass through the probe. The second one demonstrates an increase of the temperature with some time delay. This delay is defined by the time which is necessary that the thermal front can reach the back side of the probe. The temperature trends from both thermocouples, in Fig. 4 b), demonstrate that the sudden increase of the temperature observed by the front thermocouple occurs mainly due to the hot electrons.

The total number of runaway electrons detected by the first crystal of the probe is about $2 \cdot 10^{11}$ $[\frac{electrons}{mm^2}]$ as shown in Fig. 4 a). The tungsten plate (6 mm) was above the crystals (in the direction to the plasma center), therefore the flux of electrons incident on the plate is not less

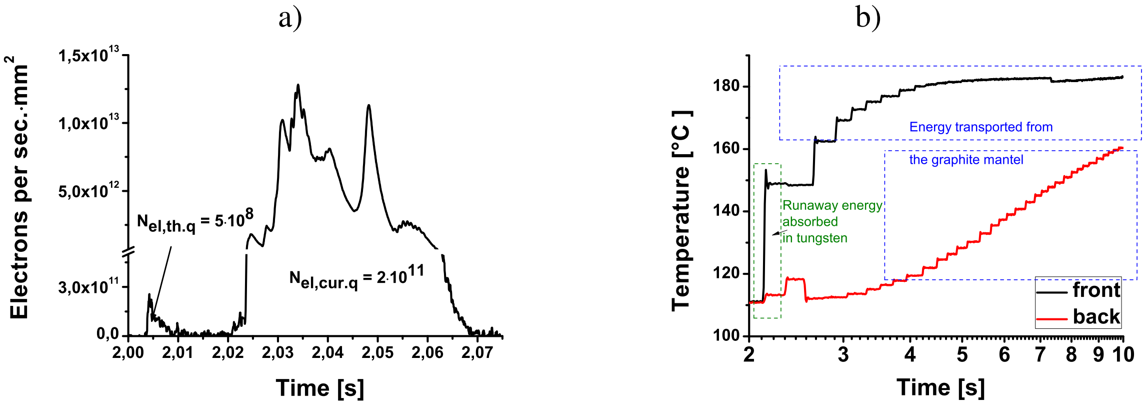

Figure 4: *Temperature measurements are performed for disruptions provoked by Ar gas injection (1 bar). a) Normalized electron numbers per second and mm*^{2} *are shown during the thermal and current quench time interval. Electrons with energies higher than 4 MeV are measured by the first crystal. b) The temperature is measured in front and the back side of the probe.*

than on the first crystal. The cross section of the tungsten is $S_W = 168\ mm^2$ (from the electron incident direction). Hence, the total number of electrons with energies between 4 and 30 MeV incident on the tungsten filter is $N_W = 3.4 \cdot 10^{13}$.
Estimations performed by means of the Geant4 code [4] for the spectrum in Fig. 3 show that these electrons can penetrate about 4 mm of tungsten. If radiation losses of runaway electrons in the material are neglected, the thermal load of these electrons in the tungsten equals their total kinetic energy $Q_{kin} \approx 80$ J. The front part of the tungsten, where almost all runaways lose their energy has a mass of $m_{fr,W} \approx 17$ g. Consequently, the temperature increase at the front of tungsten equals $\triangle T = Q_{kin}/m_{fr,W} \cdot c_W \approx 35°$C, where c_W is the heat capacity of tungsten. This value fits the measured one of about 37°C.

Acknowledgements. The authors acknowledge the assistance of the staff at TEXTOR and A. Hiller. Funding of this work by GRK1203 is acknowledged.

References

[1] S. Putvinski, P. Barabaschi, N. Fujisawa, N. Putvinskaya, M. N. Rosenbluth and J. Wesley, Plasma Phys. Control. Fusion **39**, B157 (1997)

[2] T. Kudyakov, A. Jochmann, K. Zeil, S. Kraft, K.H. Finken, U. Schramm and O. Willi, Rev. Scient. Instrum. (2009)

[3] S.A. Bozhenkov, M. Lehnen, K.H. Finken, M.W. Jakubowski, et.al., Plasma Phys. Control. Fusion **50**, 105007 (2008)

[4] Geant4 software developed by Members of the Geant4 Collaboration ($http://cern.ch/geant4$).