Spectral and Radial Distributions of Runaway Electrons in a Disruption at TEXTOR

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In order to study the energy spectrum and the radial decay of runaway electrons in a disruption a new heat load probe was developed. A schematic cross section of the probe design can be seen in Fig. 1. The probe has a cylindrical geometry, the outer part being a housing made of 5 mm thick graphite which shields the internal part against plasma ions and electrons with energies below 4 MeV as shown by simulations (see below). Electrons with higher energies can propagate into the core of the probe which is the actual detector. It consists of spherical copper particles in a matrix of an epoxy resin withstanding high temperatures up to about 300° C. The probe head can be plunged radially into the TEXTOR tokamak on a ms timescale. As the electrons move toroidally, they strike the probe head from one side in the electron drift direction. Only the high energetic runaways enter the core of the probe. Copper has a high stopping power for electrons [1] and hence the runaways deposit their energy mainly in those particles which consequently get heated. As the copper particles are separated from each other in the epoxy resin, the latter obtains high temperatures in the surrounding of heated copper particles only. Those temperatures should be locally above 300° C and hence the resin suffers visible damages by melting or evaporation. After the impact those damages can be evaluated as a signature of the runaways and conclusions about the energy of the runaways can be drawn. By the evaluation of the spatial extent of the damaged area information about the radial decay length of runaways can be extracted. This way a single shot disruption evaluation is possible. The TEXTOR disruption ($B_t = 2.4\,\mathrm{T}$, $I_p = 350\,\mathrm{kA}$, $n = 1.5 \cdot 10^{19}\,\mathrm{m}^{-3}$) characterized here was induced by argon injection with the TEXTOR disruption mitigation valve. The

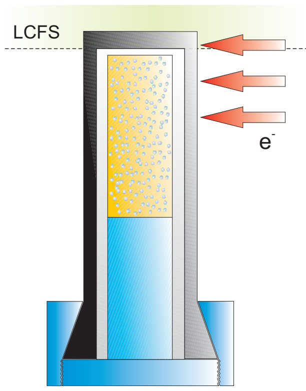

Figure 1: Schematic cross section of the heat load probe and the position of the last closed flux surface (LCFS) in the experiment

[1] database: http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

proper radial position of the runaway beam was controlled actively during the disruption by the vertical magnetic field. The runaway content of the disruption is verified by neutron detectors outside the machine, the γ-dose outside of the TEXTOR hall and the time evolution of the plasma current showing the typical runaway plateau. From the latter the number of runaways was calculated to be $2.3 \cdot 10^{16}$. The heat load probe was inserted 5 mm into the plasma for about 200 ms from 0.1 s before the argon injection. The position of the last closed flux surface (LCFS) with respect to the probe during the experiment is indicated in Fig. 1. Due to their high energy, the orbits of runaway electrons are shifted radially outwards from the flux surfaces.

Fig.2 shows the core of the probe after dismantling the housing. The damage to the copper-epoxy material is located exclusively at the electron side. As the housing shields against low energy electrons, runaway electrons must be the cause for the damage. It has to be mentioned that the graphite housing also was damaged and the top part was destroyed most likely due to the build up of a gas pressure by the evaporation of a part of the resin. This means, that the graphite broke after the runaway impact, but during the disruption the core was shielded at all times. The damage to the core showing no discontinuity at the radial position of the breakage of the graphite and going clearly deeper than this edge seems to strengthen this scenario. By scanning electron microscopy it could be checked that there is no melting of the copper particles which remain in the resin, but there are empty positions, where copper particles obviously fell out of the locally destabilized epoxy resin. To be able to quantify our analysis, metallographical studies were carried out. Properly prepared, the core cylinder was cut in longitudinal direction right through the damaged area by wire erosion. The cutting and subsequent polishing delivered a cross section which was examined with an optical microscope. Fig. 3 shows an overview over the damaged area. The dashed line indicates the radial position of the graphite edge after it broke. The larger, damaged piece on the left side was held in place behind the graphite housing during the discharge and thus should not be interpreted as a discontinuity in the damage. The damages in form of cracks and dark spots appear to be the signature of runaway energy deposition. For Fig. 3, two curves outlining nearly all visible runaway damages were placed on top of the microscope picture. To allow a comparison of the experimental picture with simulations, it had to be found out how much energy per unit volume is necessary to cause the damages to the probe material. An unused sample of the material mixture was heated in a Perkin Elmer STA 6000 simultaneous thermal analyzer which mea-

Figure 2: Probe core with runaway signature

sured the mass of the sample and the heat flow into it. Integration of the endothermic part of the heat flow curve delivers the minimum energy necessary to evoke the damages in the material. As the temperature T_0 of the probe before the runaway impact is unknown, only unlikely high temperatures can be excluded. Therefore, T_0 is a variable for the comparison of experiment and simulation. Simulations of the runaway impact onto the probe were done with the help of the Geant4 toolkit [2] from CERN. Our program includes the 3D probe geometry, the appropriate materials as well as a toroidal magnetic field. The radial distribution and the energy spectrum of the electron beam incident onto the probe are calculated using random numbers. All common electromagnetic effects are part of the program. As input for the simulations, an energy spectrum $n(E)$ and a radial distribution $n(r)$ of the electron beam have to be fixed. In the poloidal direction, the beam is chosen to be uniformly distributed over the extension of the probe. The number of simulated primary electron beam particles is scaled up to the number of runaways calculated from the runaway current. The output of the simulation is a two dimensional matrix of the absolute values of deposited electron energy per unit volume in the core of the probe.

An example of a simulation, that shows good agreement with the experiment, can be seen in Fig. 4. The figure shows a contour plot of the deposited electron energy per unit volume. The axes, r for the radial direction and d for the toroidal direction or depth in the material, refer only to the probe core without the housing. For comparison with the experimental oberservation, the two curves taken from Fig. 3 were placed on top. Here the energy spectrum and the radial electron beam distribution were chosen to be exponential respectively; $n(E) = 0.21\,\mathrm{MeV}^{-1} \cdot \exp(-0.21\,\mathrm{MeV}^{-1} \cdot E)$, $n(r) = 0.14\,\mathrm{mm}^{-1} \cdot \exp(-0.14\,\mathrm{mm}^{-1} \cdot r)$. The energy threshold for the material damages to occur and to give a good correlation of the curves in this example is $0.09\,\mathrm{J}/0.25\,\mathrm{mm}^3$. The corresponding temperature of the probe before the impact is $T_0 = 64^\circ\,\mathrm{C}$. The input parameters of this example are not exclusively giving a good agreement, rather there is a range of reasonable parameters: $\lambda_E = \{0.11..0.27\}\,\mathrm{MeV}^{-1}$ and $\lambda_r = \{0.08..0.18\}\,\mathrm{mm}^{-1}$. The corresponding e-folding

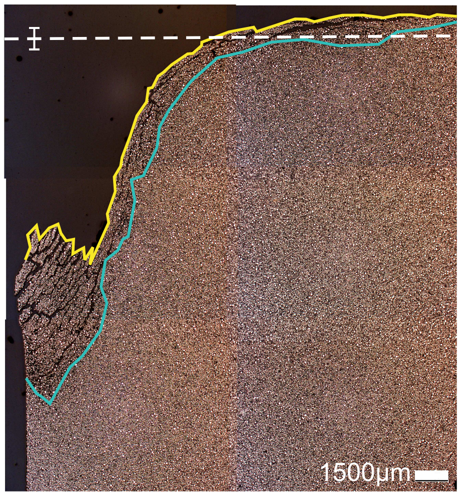

Figure 3: Cross section of the core of the probe with two added curves outlining the runaway damages and a dashed line indicating the approximate position of the graphite edge after breaking

[2]http://geant4.cern.ch/

values are $\lambda_E^{-1} = \{9.1..3.7\}$ MeV and $\lambda_r^{-1} = \{12.5..5.6\}$ mm. Here the lowest T_0 is 34° C and results giving $T_0 > 75°$ C are considered as unlikely and are not taken into account. Consquently, the comparison of simulations and experiment delivers an upper limit for the choice of the spectrum and hence also for the radial distribution. Going to a lower energy spectrum the agreement becomes better, but T_0 has to increase and too high values have to be left out of consideration.

A good agreement between simulation and experiment can also be achieved by choosing an exponential spectrum and a linear radial electron distribution. Again there is a parameter range giving reasonable results: $\lambda_E = \{0.16..0.31\}\,\mathrm{MeV}^{-1}$ and $r_0 = \{25..21\}$ mm. Here the lowest T_0 is 40° C and again results above 75° C are not considered.

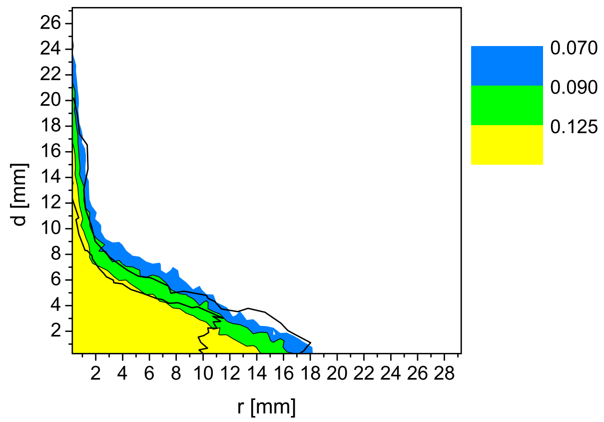

Figure 4: Comparison of the experimental curves, outlining the runaway damages, and the simulation with $n(E) = 0.21\,\mathrm{MeV}^{-1} \cdot \exp(-0.21\,\mathrm{MeV}^{-1} \cdot \mathrm{E})$ and $n(r) = 0.14\,\mathrm{mm}^{-1} \cdot \exp(-0.14\,\mathrm{mm}^{-1} \cdot r)$

Using a prototype of a probe at the tokamak plasma edge, it has been shown that in a single shot disruption measurement sufficient runaway electron damages can be obtained to allow the deduction of the energy spectrum and the radial decay of the runaways. Details of the experiment can be found in [1]. It has to be remarked that the spectral and radial distributions are attained by measurement only in the probe core. The experiment does not describe the radial distribution of the runaways in the first 6 mm of the probe housing which faces the plasma. Therefore, we cannot exclude that the runaways have a second decay distribution in these first millimeters. In future versions of the probe different materials will be used. It is planned to do several single shot measurements with a set of the probe's final version to be able to analyze different disruptions.

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References

[1] M. Forster, K.H. Finken, M. Lehnen, J. Linke, B. Schweer, C. Thomser, O. Willi, Y. Xu and the TEXTOR team, Nucl. Fusion **51**, 043003 (2011)