Development of energetic runaway electrons with operation of the Dynamic Ergodic Divertor

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On TEXTOR, a method has been developed to measure highly relativistic runaway electrons (ε = 25 MeV to 30 MeV) by synchrotron radiation[1-4]. The synchrotron radiation is a continuum radiation and for this electron energy it is emitted at wavelengths $\lambda > 4$ µm; for its detection an infrared camera is used. The synchrotron radiation competes with the thermal radiation of the wall components of TEXTOR which sets the detection limit for the runaways. Complementary to the synchrotron emission, radiation from hard X-ray and neutrons are recorded; X-rays and neutrons are generated from runaway electrons hitting the vessel wall elements. Therefore the synchrotron radiation intensity is a measure of the runaway electrons inside the plasma while the X-ray and neutron signals represent the loss rate of the runaway electrons. A well reproducible scenario for runaway electron production has been set up for discharges with a line averaged electron density of typically $5*10^{18}$ m^{-3}. The runaway electrons are created and accelerated to the required energy during the first second of the discharge and subsequently can be utilized as “probes” for investigating losses and internal structures.

The Dynamic Ergodic Divertor (DED)[5-7] imposes a helical perturbation magnetic field structure in the plasma. The individual coil endings of the DED can be interconnected in different ways and allows e.g. for the generation of the “fine” m/n = 12/4 base mode or the “coarse” m/n = 3/1 base mode of the DED. The high poloidal mode number of m=12 guarantees a fast radial decay of the perturbation field away from the perturbation coils which are located at the high field side of the torus inside the vacuum. Therefore the DED field is restricted to the plasma edge in this mode of operation and resonances are excited at

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the q-surfaces 10/4 < *q=m/n* < 14/4 leading to magnetic islands and ergodized patterns of the magnetic field lines. The perturbation field of the *m/n* = 3/1 base mode penetrates deeply into the plasma and excites major islands at the *q*=2 and *q*=3 surfaces. If the DED current exceeds a threshold value, it excites tearing modes first at the *q* = *m/n* = 2/1 surface and at higher currents even at the *q* = *m/n* =3/1 surface. The threshold value is rather reproducible but depends on the heating scenario, on the plasma rotation (with respect to the DED rotation), on density etc[8].

Because of their low collissionality, the individual runaway electrons are confined in unperturbed discharges for seconds; otherwise they could not acquire their energy by the given loop voltage drop of about 1 eV/turn. The perturbation field breaks the otherwise good magnetic surfaces and leads to islands, to internal ergodized areas which are not connected with the plasma boundary, and open ergodic field lines which leave the plasma. The island formation is the weakest form of perturbation but may lead to a depletion of runaways in that region. The internal ergodization leads to an enhanced radial transport of the runaways which finally should result in additional losses[9]. The open magnetic field lines finally should lead to a rapid loss of the runaway electrons. In addition to these “field tracing considerations”, the plasma may react on the error field with the excitation of plasma modes such as the tearing modes mentioned above.

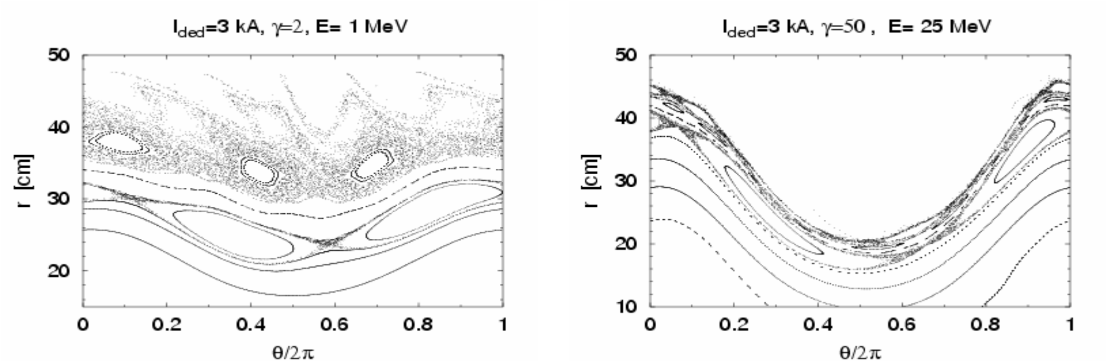

Fig.1: Poincaré plots for runaway electrons of 1 MeV (left subfigure) and 25 MeV energy for the DED base mode m/n = 3/1.

The identification of the drift orbit of the runaway electrons with the magnetic field lines is an oversimplification. Actually, the runaway electrons are displaced from “their” magnetic surface systematically to the low field side by nearly 10 cm for the highest energies observed on TEXTOR. Fig. 1 shows a Poincaré plot of the runaway orbits for the low relativistic energy ε=1MeV and for ε=25 MeV for the coarse *m/n*=3/1 base mode configuration of the DED. The horizontal axis is the unfolded poloidal angle and the ordinate is the radius where

r=46 cm corresponds to the plasma edge. The high field side in this graph corresponds to $\theta = \pi$. The orbits of the electrons with low relativistic energy (left sub-figure) corresponds practically to the magnetic field lines; one observes a broad ergodic zone at the plasma edge and islands both in the ergodic sea and in the non-chaotic area. The area inside the q=2 surface is very little disturbed. The downwards "bending" of structures corresponds the shift of the orbits by the Shafranov shift. At high runaway energy (right subfigure) one practically looses the ergodic zone and only the islands at the q=2 surface survive. The reason for the loss of the ergodic orbits is their strong displacement to the low field side which eliminates the orbits after intersecting a wall structure. The 2/1 island chain is strongly compressed as compared to the case of low energetic particles.

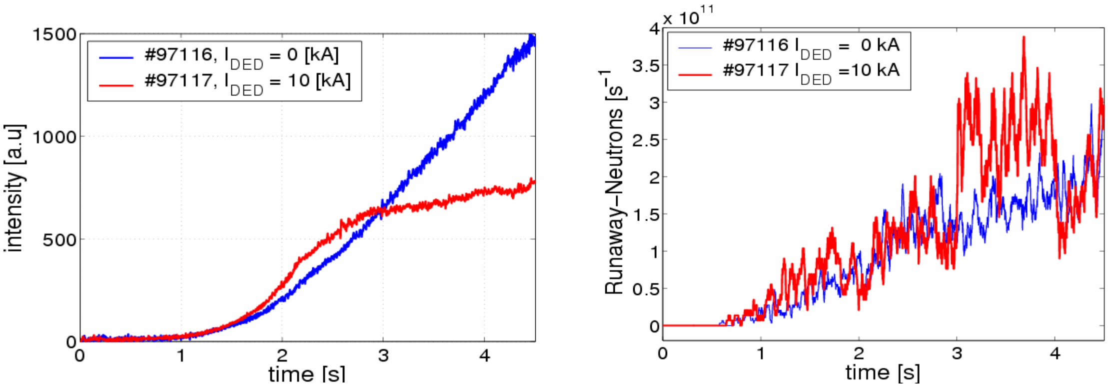

Fig. 2: Development of two runaway discharges, the blue curves show the reference case without DED and the red ones with DED (3 s to 4 s) in the m/n = 12/4 base mode. Synchrotron radiation intensity (left subfigure) represents the runaways in the discharge and the neutron signal (right) the runaway loss rate.

In order to show the runaway development for the "fine" m/n =12/4 base mode of the DED two discharges are compared in Figure 2. Both discharges are Ohmic discharges at a density of about $6 \cdot 10^{18}$ m^{-3}. The left sub-figure shows the development of the synchrotron radiation and the right one the neutron signal from the runaway electrons. The first discharge is a reference discharge (blue) without DED and the other one with DED (red) which is activated between 3 s and 4 s. The runaway development of the two discharges starts nearly in the same way and during the phase of the DED, we observe a drop of the number of runaway electrons (synchrotron radiation) and an enhanced loss rate (neutron signal). The loss rate is about a factor of two higher than during the ohmic phase. In earlier investigations we have found that the runaway loss cannot be explained by binary collisions and we have attributed them to magnetic turbulence[4]. The required perturbation field was estimated to

$\langle B_r \rangle /B=2*10^{-5}$; to explain the losses due to the DED, one has to require an additional volume averaged perturbation field of similar size. With respect to the order of magnitude, the required field is not unreasonable because the DED adds a perturbation field of 10^{-2} to 10^{-3} at the plasma boundary; however, field decays rapidly in radial direction and it is not clear whether the spectrum fits to a fine structured turbulence. Another explanation of the runaway loss is the reduction of the effective confinement zone due to ergodization and laminar zone. A transfer of the confined zone by 30 % to the open laminar / ergodic zones explains the enhanced diffusion as well.

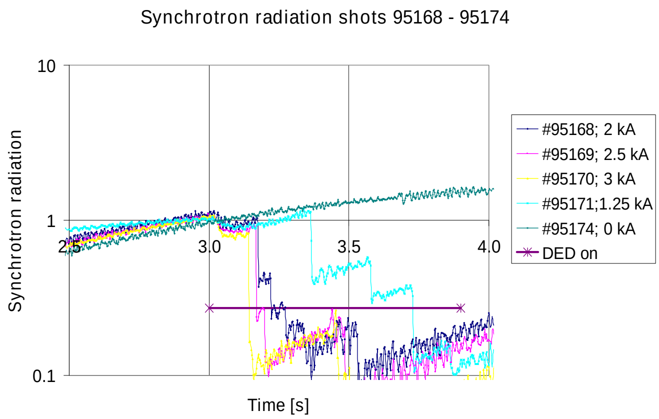

Fig. 3: Development of the synchrotron radiation for the m/n=3/1 base mode of the DED.

The interaction of the m/n=3/1 base mode of the DED leads to an unexpected and non – diffusive type of runaway loss as is indicated in the synchrotron intensity of Fig. 3. Plotted are discharges with different DED amplitudes. In contrast to Fig.2, one finds after an initial smooth loss at the onset of the DED abrupt losses. The origin of these losses is still unclear. Since however, the perturbation field penetrates for the m/n=3/1 base mode deeply into the plasma, it may be possible that internal modes are excited similar as has been observed for tearing modes at standard plasma conditions. Other candidates are fast field line reconnection processes. To reveal finally the underlying physics, imaging techniques for runaway islands have to be applied.

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