THE STUDY OF RUNAWAY ELECTRON CONFINEMENT TO PROBE THE ELECTROMAGNETIC TURBULENCE IN OH, L-AND H-DISCHARGES OF ASDEX

F. Wagner, G. Fussmann, G. Becker, H.S. Bosch, H. Brocken, A. Carlson,
A. Eberhagen, G. Dodel[1], H.-U. Fahrbach, O. Gehre, J. Gernhardt,
G. v.Gierke, E. Glock, O. Gruber, G. Haas, W. Herrmann, J. Hofmann,
A. Izvozchikov[2], E. Holzhauer[1], K. Hübner[3], G. Janeschitz, F. Karger,
M. Kaufmann, O. Klüber, M. Kornherr, K. Lackner, M. Lenoci, G. Lisitano,
F. Mast, H.M. Mayer, K. McCormick, D. Meisel, V. Mertens, E.R. Müller,
H. Murmann, J. Neuhauser, H. Niedermeyer, A. Pietrzyk[4], W. Poschenrieder,
H. Rapp, A. Rudy, F. Schneider, C. Setzensack, G. Siller, E. Speth,
F. Söldner, K. Steinmetz, K.-H. Steuer, N. Tsois[5], S. Ugniewski[6],
O. Vollmer, D. Zasche

Max-Planck-Institut für Plasmaphysik,
EURATOM Association, Garching, FRG

and

O.J. Kwon and P.H. Diamond, The University of Texas, Austin, USA

ABSTRACT Confinement studies of runaway electrons have been performed in order to elucidate the nature of electromagnetic turbulence and its role in ohmically and beam heated L- and H-plasmas. Under ohmic conditions, the confinement time τ_R of runaway electrons depends strongly on the choice of q_a; in the L-mode, τ_R degrades with beam power; in the H-phase, runaway electrons are again well confined. With plausible assumptions, a correlation length of the underlying microturbulence of 0.1 cm is found which requires a magnetic perturbation $\tilde{B}_r/B_0$ ~10^{-4} to be consistent with L-mode confinement.

The confinement of runaway electrons (R.E.) has been studied in ASDEX in ohmically and beam heated L- and H-mode plasmas. R.E. are produced within the first hundred ms when the loop voltage reaches values up to 10V. Thereafter, the R.E. production rate decreases sharply; at 0.3s $n_e^{-1}dn_R/dt$ ~4×10^{-4} s^{-1} and is still decreasing. In the birth phase of R.E., the plasma T_e- and n_e-profiles are still very broad probably resulting in a largely homogeneous R.E. density. During the current ramp-up phase (typically 600-800 ms), R.E. are continuously accelerated. After about 1 s (with the plasma current being in the plateau phase) the R.E. distribution reaches steady state at a mean energy of about 1 MeV and with maximal energy around 10 MeV.

R.E. are measured via the thick target hard X-ray bremsstrahlung emitted when their orbit intersects a molybdenum target placed at the plasma mid-plane a few cm outside the separatrix on the low field side. During the current ramp-up phase the hard X-ray radiation increases because the electrons become increasingly energetic though their number does not further increase. The transition of rational q-surfaces across the plasma surface destabilizes the magnetic field topology resulting in transiently

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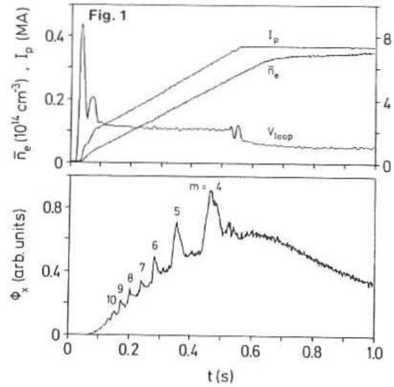
[1] University of Stuttgart; [2] Ioffe Institute; [3] University of Heidelberg;
[4] University of Washington, Seattle, USA; [5] N.R.C.N.S. "Democritos", Athens, Greece; [6] Inst. for Nuclear Research, Swierk, Poland;

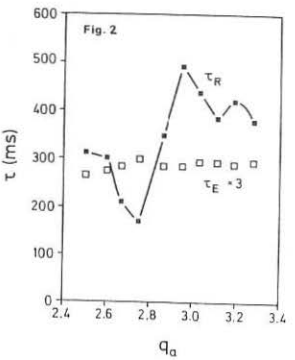
enhanced R.E. losses. Fig. 1a shows the initial discharge phase when current and density are ramped up and Fig. 1b displays the hard X-ray radiation indicating the sequence of rational q-surfaces moving from the interior across the separatrix. It is interesting to note that despite the anomaly of the magnetic field topology at the plasma surface of the magnetic limiter configuration (with q equal to infinity at the separatrix and a narrowly spaced sequence of rational q-surfaces at the plasma edge), the transit of a rational q_a-surface (q_a corresponding to the cyclindrical one ignoring the anomaly) still affects the quality of the magnetic field topology. During the subsequent plateau phase, R.E. are continuously lost; from the exponential decrease of the hard X-ray radiation a characteristic time is inferred which is interpreted as the confinement time of R.E. since the population and energy distribution of the R.E. is invariant during this period. Figure 2 plots the R.E. confinement time τ_R versus q_a in an ohmic B_0-scan. τ_R is generally a few 100 ms; for comparison, the global energy confinement time is between 80 and 90 ms. τ_R is clearly correlated with q_a and has a sharp minimum at $q_a \simeq 3$ (the actual MHD q-value is only slightly larger because of the low β_p-values of the ohmic plasma). The confinement of R.E. is sensitively correlated with the quality of the magnetic field configuration. Away from $q_a=3$, τ_R has improved by at least a factor of 2. At the unfavourable case of $q_a \simeq 3$, the hard X-ray radiation is strongly modulated by the sawteeth occurring in the plasma center /1/. Away from $q_a=3$, no distinct modulation is observed both at lower and higher q_a-values. This observation indicates the possibility that the resonant condition $q_a \simeq 3$ at the edge destabilizes the plasma further in (probably at rational q-surfaces with smaller q-values) leading to enhanced transport of R.E. from the center through the edge.

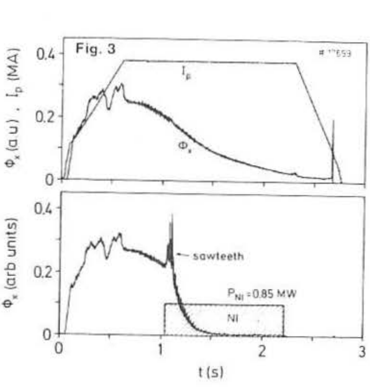
The traces of Fig. 2 clearly demonstrate that the magnetic field configuration is disturbed throughout the plasma by a rational edge q_a-value. Although the R.E. respond to this degradation sensitively, the bulk plasma properties are not affected at all as shown in Figure 2 for the global energy confinement time τ_E. There is no other known global quantity of the main or the divertor plasma (which are known to sensitively respond to confinement changes of the main plasma, such as shown in Fig. 5) which is affected by the degraded field topology.

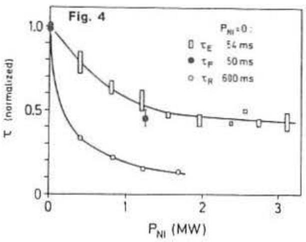
Figure 3 shows the variation of the hard X-ray radiation during a neutral injection pulse into the ohmic plateau phase. τ_R is sharply reduced and R.E. are quickly lost. (A second beam pulse later in the discharge does hardly show any increased radiation confirming the expectation that no R.E. are produced in the plateau phase). With NI, there is a simultaneous degradation of the confinement of R.E. along with the one for energy and particles (see Fig. 4). The sensitivity of the R.E. confinement on the quality of the magnetic field topology clearly indicates a substantial degradation already at low beam power causing a sharp drop in τ_R. Furthermore, sawteeth strongly modulate the hard X-ray radiation in the beam phase for all q_a-values (see Fig. 3) in a way it was only observed for rational q_a-surfaces at the edge in the OH-phase.

It is interesting to note that τ_R in the degraded L-regime of a NI-heated plasma does not depend on q_a like in the OH-phase. With NI, τ_R is sharply reduced but increases monotonously with B_0 without a notch at $q_a=3$. Evidently, NI degrades the quality of the magnetic field structure to such









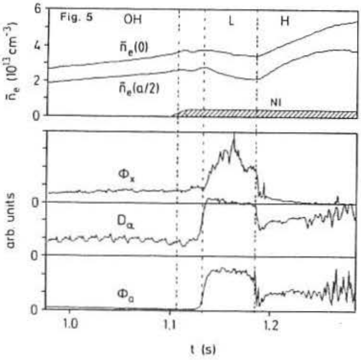


Fig.1: Current, density $\bar{n}_e$, loop voltage and hard X-ray radiation ϕ_X during current ramp-up.

Fig.2: Global energy (τ_E) and runaway electron (τ_R) confinement time in an ohmic B_T-scan.

Fig.3: Comparison of ϕ_X in an OH- and NI-discharge; the sawtooth modulation of ϕ_X is indicated.

Fig.4: τ_E, τ_R and particle confinement time τ_p versus NI-power normalized to the OH-values (as given).

Fig.5: Time dependence of 2 $\bar{n}_e$-traces, ϕ_X, H_α-radiation and particle flux ϕ_a in the divertor chamber for OH→L and L→H transition.

an extent that the additional geometrical disturbance is negligible. The uncorrelated q_a-dependence of τ_R and τ_E in the OH-phase raises doubts whether the OH confinement of the bulk plasma is indeed caused by the magnetic turbulence which is evidently responsible for the confinement of R.E. The question remains whether under beam heating conditions magnetic turbulence primarily determines transport or whether it accompanies dominant drift-like fluctuations simply because of rising β_p. In this context it is important to note that the confinement of R.E. sharply improves at the H-transition though β_p further increases due to improved global confinement. Both in the L- and H-phases we observe a clear correlation in the confinement properties of the bulk plasma and R.E.
Fig. 5 plots the time dependence of the hard X-ray flux together with the H_α-radiation in the divertor chamber (a measure of the energy flux into the divertor) and the flux ϕ_D of particles backscattered from the target plates (a measure of the particle flux). The simultaneous OH→L and L→H-transition is shown in the three signals all governed by different confinement properties. The sharp onset of the L-phase a few ms after beam initiation also indicates that the magnetic turbulence is obviously not due to rising β_p.

With the hypothesis that unlike the ohmic confinement, the degradation in the L-phase is predominantly due to magnetic turbulence, we can characterize the structure of the underlying mode from the ratio τ_E/τ_R. It is known that the ratio of τ_E/τ_R is not given by the inverse ratio of the electron velocities since the coupling of the R.E. to the mode is reduced by the shift of the $\vec{k}\cdot\vec{B}$ resonance due to magnetic drift effects /2/. These effects can be considered by a radial structure function S such that

$\tau_E/\tau_R = V^R/V^{th}\cdot S$ (V^R, V_R^{th} are the R.E. and thermal velocities, respectively). S depends on $L_s V_D/\delta X V^R$ (L_s= shear length, V_D^R = R.E. drift velocity, δX = radial correlation length) and can be approximated by $\exp-(L_s V_D^R/\delta X\ V^R)^2$ /3/. With the ratio of τ_E and τ_R at high beam power (see Fig. 4), $\delta X \simeq 0.1$ cm is calculated. This value is used to estimate the relative amplitude of the fluctuation

$\tilde{B}_r/B_o = (\chi_e^{th}\tilde{k}_\theta\,\delta X/\pi\ V^{th}L_s)^{1/2}$ (χ_e^{th} = thermal heat diffusivity, $\tilde{k}_\theta$ =

average poloidal wave number) necessary to fully explain the level of thermal heat transport. Assuming poloidal mode number m=8 (Ref. /4/), the result $\tilde{B}_r/B_o \sim 10^{-4}$ is in agreement with the level of magnetic field fluctuations at the plasma edge deduced from measurements outside the separatrix (Ref. /4/). Scaling studies indicate that $\delta X\ \alpha\ n^{0.2}B_0^{-1.3}P^{0.1}$ and $\tilde{B}_r/B_o\ \alpha\ n^{-0.1}B_0^{-0.1}P^{0.6}$. Thus c/ω_{pe}-turbulence /5/ is an unlikely candidate while a model along the line of resistive pressure driven modes offers more promise.

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