

Energetic electron transport in the presence of magnetic perturbations in magnetically confined plasmas

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(Received ?; revised ?; accepted ?. - To be entered by editorial office)

The transport of energetic electrons is sensitive to magnetic perturbations. By using 3D numerical simulation of test particle drift orbits we show that the transport of untrapped electrons through an open region with magnetic perturbations cannot be described by a diffusive process. Based on our test particle simulations, we propose a model that leads to an exponential loss of particles.

PACS codes: 41.75.Ht, 52.25.Fi, 52.55.Fa, 52.65.-y

1. Introduction

There is an increasing interest in the effect of magnetic perturbations on transport in fusion plasmas, as it has been shown that externally generated magnetic perturbations influence many aspects, including e.g. the presence and properties of Edge Localized Modes (Evans *et al.* 2004; Suttrop *et al.* 2011), plasma rotation (Fietz *et al.* 2015), Neo-classical Tearing Modes (Koslowski *et al.* 2006) or losses of relativistic electrons (Lehnen *et al.* 2008). Electrons with relativistic velocities (runaway electrons) are the particles that are most sensitive to magnetic perturbations as they follow open field lines with $v_{\parallel} \simeq c$. The purpose of this work is to provide insights into the effects of magnetic field perturbations on the transport and loss of energetic electrons by using three-dimensional (3D) numerical modelling of the electron drift orbits.

Runaway electrons are frequently generated in tokamak disruptions and can cause damage on plasma facing components. One of the envisaged mitigation strategies is to use magnetic perturbations to lower the confinement of the runaway electrons and prevent the formation of a potentially harmful runaway electron beam. Resonant magnetic perturbations were tested with some success on various tokamaks (Lehnen *et al.* 2008; Yoshino *et al.* 1999; Commaux *et al.* 2011). Possible effects and uses of 3D magnetic field perturbations in ITER have been explored (Shimada *et al.* 2007; Papp *et al.* 2011a,b, 2012). The individual particle orbits in perturbed magnetic fields are chaotic (Papp *et al.* 2012), and for a precise calculation of the transport one needs to resort to 3D numerical simulations at large computational expense. However, for the purposes of self-consistent modelling of runaway electron dynamics, it is important to describe the transport due to

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magnetic perturbations with a reasonably simple model, so that it can be included in the modelling of the coupled dynamics of the runaway electron current and resistive diffusion of the electric field (Papp *et al.* 2013). This work aims to provide insight into how such a simple model can be constructed so that it faithfully reproduces the dynamics of particle losses due to magnetic perturbations.

2. Effect of magnetic perturbations

The transport of electrons in enclosed stochastic magnetic fields is usually described with the Rechester-Rosenbluth diffusion coefficient $D_{RR} = \pi q v_{\parallel} R (\delta B/B)^2$ (Rechester & Rosenbluth 1978). Here q is the safety factor, $v_{\parallel} \simeq c$ is the parallel velocity, R is the major radius and $\delta B/B \equiv \sqrt{\langle (\delta B/B)^2 \rangle_{\psi}}$ is the flux surface averaged normalized magnetic perturbation amplitude as a function of radius. In mixed magnetic topologies consisting of magnetic islands, intact toroidal magnetic surfaces and stochastic regions, this diffusion coefficient is not valid (Myra & Catto 1992; Mynick & Strachan 1981). In such circumstances, some fraction of the electrons will be trapped in magnetic islands and the confinement time of these particles can equal the characteristic system evolution time. Furthermore, in open chaotic systems, such as the edge region of a magnetically confined plasma in the presence of external magnetic perturbations, not only the Rechester-Rosenbluth diffusion is not applicable, but the diffusive approach itself breaks down. Unlike in the case for enclosed stochastic fields, the region of increased transport (compared to the unperturbed case) extends all the way to the wall, making it easier for particles to get lost. As was confirmed by numerical simulations described in this paper, the runaway electron flux starting from a certain radial position is not proportional to the runaway density gradient, but the local runaway density itself. If a flat runaway profile is initialized, losses occur immediately all around the simulation zone, i.e. the flux is not gradient-driven, as the initial density gradient is zero. This dynamics is due to the *open* ergodic region that is created by the RMP coils. Note, that the diffusive approach may still be applicable in closed ergodic regions. The net radial displacement of the particles is highly sensitive to the initial position and can differ by several orders of magnitude. Particles born within resonant loss regions will reach the outer edge of the plasma faster than the rest and be lost to the wall. Since the system is open at the plasma edge, there is no return flux of fast electrons, and hence the density gradient is not the governing factor in the evolution, as it would be in a diffusive picture. As we will show, this process can be approximated with a position dependent exponential loss of particles, that describes the ensemble behaviour with reasonable accuracy.

In an axisymmetric tokamak equilibrium the magnetic topology consists of nested magnetic surfaces that provide good particle confinement. The main loss mechanism for fast electrons is due to the drift orbit shift associated with the energy gain (Papp *et al.* 2011a,b), which is determined by the electric field evolution. In the simulations presented here we use static externally-imposed magnetic fluctuations on a static equilibrium field with nested toroidal magnetic surfaces. Whenever a magnetic perturbation is present, the topology of the magnetic field is strongly modified. There appear island chains (the locations of which are correlated with the low order rational values of the rotational transform $\iota = 1/q$), together with intact, but deformed magnetic surfaces (KAM barriers Kolmogorov (1957); Arnold (1963); Moser (1962)) at irrational ι values. In between these ergodic zones are formed.

We solve the relativistic gyro-averaged equations of motion for test energetic electrons in the perturbed field with the ANTS code (Papp *et al.* 2011a). The simulations have been carried out for a specific ITER-like scenario as described in (Papp *et al.* 2011b). The

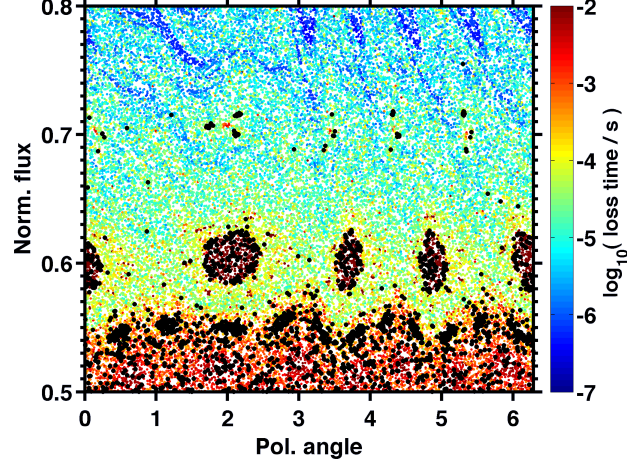


FIGURE 1. Electron loss time as function of initial coordinates in normalized flux (ψ) and poloidal angle (ϑ) at 60 kA coil current.

perturbations are externally imposed by the 9x3 quasi-rectangular perturbation coils at the outer side of the device. In the configuration we use (formerly labeled “B” (Papp *et al.* 2011b)), electrical currents flowing in these coils generate a 120° rotationally symmetric perturbation field that decays radially towards the inside of the plasma and results in the relative perturbation strength $\delta B/B > \mathcal{O}(10^{-3})$ outside the $\psi = 0.5$ flux surface (the normalized radius relates to the normalized flux as $r/a \simeq \sqrt{\psi}$, where a is the minor radius of the torus).

To determine the evolution of the particle ensemble in such a topology a direct calculation of test particle trajectories has been carried out. In each simulation a minimum of 40 000 test particles with 1 MeV energy were launched parallel to the magnetic field lines with various starting position distributions. In the simulations we use a time-dependent electric field obtained for an ITER-like disruption scenario calculated with a model of the coupled dynamics of the evolution of the radial profile of the current density (including the runaways) and the resistive diffusion of the electric field (Smith *et al.* 2009). The electric field peaks between 6-15 ms, which means that most of the acceleration happens in this time frame, as it is shown in Fig. 1a of Ref. (Papp *et al.* 2012). The electrons are gaining energy due to the electric field mainly during this time-interval. In the unperturbed scenario, the drift orbit shift associated with the energy gain dictates the particle losses, which in this ITER case happens on the $\tau \simeq 10$ ms timescale (Papp *et al.* 2011b).

Figure 1 shows the loss time of electrons launched with ($\psi \in [0.5, 0.8]$, $\vartheta \in [0, 2\pi]$, $\phi = 0$) as a function of initial coordinates in the $\phi = 0$ poloidal cross section. The simulation was performed for 100 ms. The particles corresponding to the black dots have not been lost during this time, as these were trapped in the remnant O points of island chains formed around low-order rational surfaces. Figure 1 clearly reveals the chaotic nature of the process and highlights the extreme sensitivity of the individual particle loss times to the initial position.

Despite this complexity, the ensemble behaviour is smooth. Figure 2a shows the fraction of lost particles as a function of time for particles launched at individual flux surfaces. All these curves show an exponential decay of the confined particles up to the saturation value, determined by the fraction of particles trapped in remnant O-points of an island chain intersecting the starting surface. Dashed lines show exponential fits and the characteristic loss times are indicated above the curves.

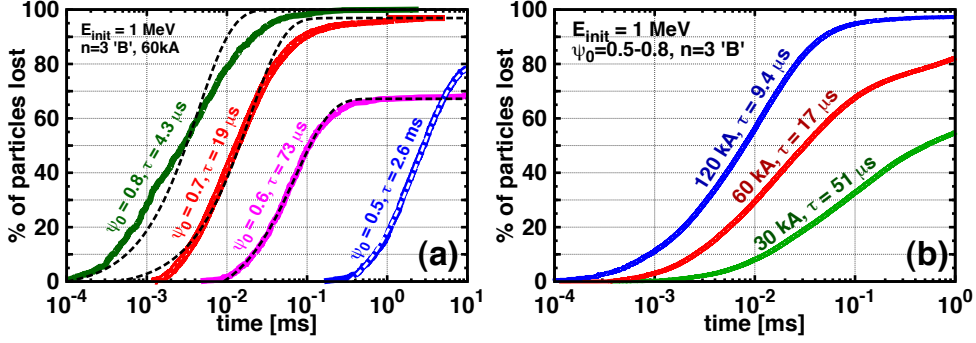


FIGURE 2. (a) Fraction of lost particles for different starting radii as a function of time. Dashed lines show $N_{\text{lost}}(t) = N_0(1 - \exp\{-t/\tau\})$ fits. (b) Fraction of lost particles within $\psi \in [0.5, 0.8]$ for different perturbation currents as a function of time.

The magnetic perturbation enhanced net radial transport leads to particle losses on the sub-millisecond timescale. Our energy scans confirmed that on this short timescale the behaviour is similar regardless of the energy of the particles if $E > 1$ MeV, as the particles mainly follow the open magnetic field lines with the speed $v_{\parallel} \simeq c$. The long-term (> 10 ms) behaviour is determined by the remnant island structures. Particles starting in specific spatial positions can be trapped in the remnant O-points and confined even at energies of 100 MeV.

If the magnetic perturbation strength is increased (by increasing the current in the coils) the island structure will change non-linearly. Therefore the relationship between the time-evolution of the losses and the magnetic perturbation magnitude is not trivial. Figure 2b illustrates the fraction of lost particles as a function of time for three different values of the perturbation current. To highlight the effect of the magnetic perturbation magnitude, in these simulations the electric field has been set to zero (the electrons are not accelerated as they were in the other simulations).

The smooth ensemble behaviour is also reflected in the evolution of the electron density as a function of radial position (ψ) and time, as is shown in Fig. 3a. The continuous radial loss picture is only distorted by the enhanced confinement of the remnant island chains at $\psi = 0.5, 0.6$ and 0.7 . For comparison, Fig. 3b shows the evolution of density due to the Rechester-Rosenbluth diffusion for the same initial conditions. The evolution of the density $n(\psi, t)$ is largely different: the diffusive model predicts better confinement at the edge but worse confinement in the core, by orders of magnitudes. The generation of runaway electrons is exponentially sensitive to the existing amount of runaways through the avalanche process. If instead of a test particle scenario the runaway electron generation is included in the calculation, the differences between the two cases are increased even further, as will be shown later in this paper.

Following the observations illustrated in figures 2a-b and 3a, we approximated the particle losses with an $N_{\text{lost}}(t) \propto 1 - \exp\{-t/\tau(\psi)\}$ trend, where $\tau(\psi)$ is the characteristic loss time associated with a certain initial ψ position for the particles. We have performed fits of $\tau(\psi)$ to the evolution of fast electron density obtained by the 3D test particle simulations for various cases, such as the ones illustrated in figures 2a-b and 3a. The fitted values of $\tau(\psi)$ are shown in figure 4b for three different perturbation magnitudes. We note that the dependence of $\tau(\psi)$ on the radial coordinate is relatively smooth and is well approximated by an exponential dependence $\tau(\psi) \propto \exp\{-\psi/\psi_0\}$ (dashed lines), where $\psi_0 \propto \delta B/B$. Local maxima in $\tau(\psi)$ correspond to remnant islands and KAM zones in the perturbed magnetic topology.

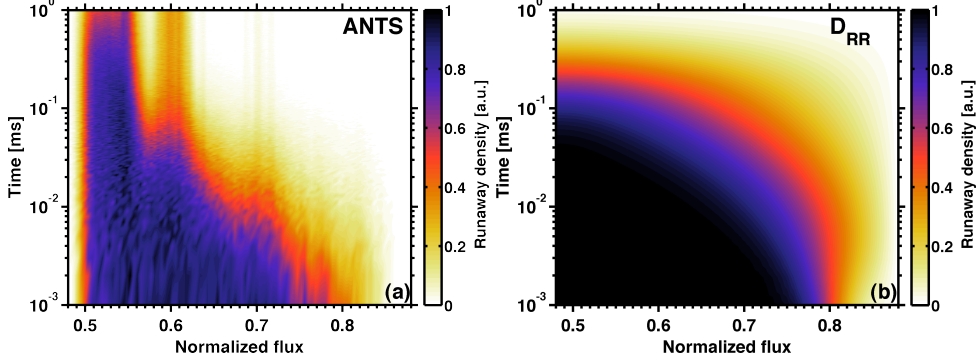


FIGURE 3. (a) Evolution of fast electron density $n(\psi, t)$ as calculated by the ANTS code. (b) Evolution of the density due to Rechester-Rosenbluth diffusion. Both figures are calculated for 60 kA coil current.

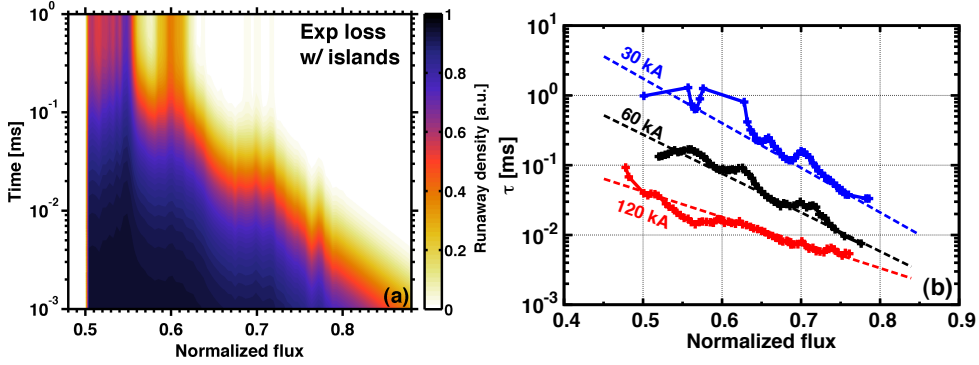


FIGURE 4. (a) Evolution of electron density using the fitted $\tau(\psi)$ values for the 60 kA configuration, including particles confined in the remnant islands (n_c). (b) Fitted values of τ as a function of normalized flux for 3 different perturbation amplitudes.

Replacing the diffusive transport in a numerical calculation with the exponential loss model, we can calculate the evolution of fast particle density using the fitted $\tau(\psi)$ values. A pure exponential loss description cannot reproduce the confined fraction. However, if we split the particle density into a confined and non-confined fraction $n(\psi, t) = n_c(\psi) + n_{nc}(\psi, t)$, where the confined part is constant at a given radial position (extracted from the ANTS simulations) and the non-confined part follows the exponential loss $n_{nc}(t, \psi) \propto 1 - \exp\{-t/\tau(\psi)\}$, we can reproduce the results of the 3D simulation. Figure 4a shows a calculation based on the exponential losses for the 60 kA case, including the $n_c(\psi)$ particles confined in the remnant islands. It clearly resembles the particle evolution calculated by ANTS (figure 3a - the figures are placed next to each other for easier comparison).

3. Self-consistent calculations

To illustrate the differences between the implications of the diffusive and exponential-loss models, we have implemented both loss models in a self-consistent simulation of the runaway current and electric field evolution (Papp *et al.* 2013). Figure 5 shows a disruption simulation for the same ITER scenario that was used for the 3D simulations. The thermal quench time is set to 0.2 ms and the effective charge $Z_{\text{eff}} = 2$ to mimic the parameter evolution of massive gas injection simulations (Hollmann *et al.* 2015; Papp

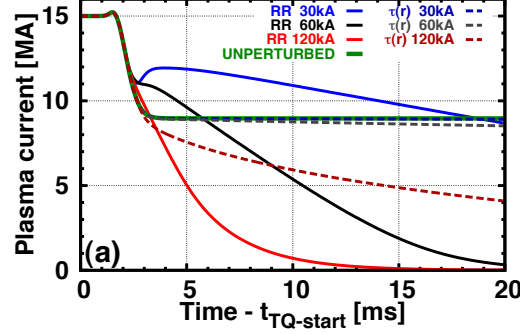


FIGURE 5. Effect of diffusive (solid lines) vs exponential (dashed lines) losses on plasma (RE) current evolution for ITER in a self-consistent calculation for different perturbation strengths.

et al. 2013). As a general conclusion for all cases, following the thermal collapse, at ~ 3 ms virtually all of the Ohmic current is replaced by runaways, and the runaway current consists of $\sim 10\%$ seed and $\sim 90\%$ avalanche current. Without losses a runaway beam of ~ 9 MA would form. Using the Rechester-Rosenbluth diffusion model and the $\delta B/B$ profile caused by the perturbation coils we get suppression of the runaways after 20 ms at $I_{\text{RMP}} = 60$ kA and after 10 ms if $I_{\text{RMP}} = 120$ kA. $I_{\text{RMP}} = 30$ kA not only does not lead to suppression, but through the redistribution of the primary seed current leads to temporary stronger avalanching, increasing the overall runaway current. However, as we argue in this paper, with the support of the 3D test particle calculations, the losses in these systems are not well described by diffusion. Also, the simulations show that although the perturbation penetrates to the core, the transport is essentially untouched inside the radius $r/a = 0.7$ for $I_{\text{RMP}} = 60$ kA. Therefore, even if the transport is largely increased towards the edge region in the exponential loss description, this does not contribute much to runaway suppression. The reason is that most of the runaways are formed in the plasma core, where there is good runaway confinement according to the test particle simulations. As the dashed lines in figure 5 clearly illustrate, *virtually no runaway suppression is achieved* even at $I_{\text{RMP}} = 60$ kA with the exponential loss model. At $I_{\text{RMP}} = 120$ kA we see a slow drop of the runaway current, however, $I_{\text{RMP}} > 75$ kA will not be accessible in ITER due to hardware limitations.

4. Conclusions

The most important conclusion of the present work is that the transport of the untrapped electrons in open chaotic fields cannot be described by a diffusive model. Instead there is an exponential decay of confined particles, where the characteristic loss time is an exponential function of radius and the perturbation strength. This difference has a decisive effect on the runaway current and the associated electric field evolution in a self-consistent calculation. While diffusive losses would suggest that runaway avalanches can be avoided by using strong enough externally applied magnetic perturbations, the exponential loss model shows that this does not have to be the case. Although it is difficult to predict exactly the magnitude of the loss-time and its radial dependence in a specific scenario without 3D numerical simulations, the exponential dependence and non-diffusive nature of the transport is robust. Therefore implementation of such a model in self-consistent fluid simulations should give important insights into runaway electron dynamics and the prospects of RE mitigation in the presence of magnetic perturbations.

Acknowledgments The authors are grateful for I. Pusztai and P. Helander for fruitful discussions. This research was partially funded by the Max-Planck/Princeton Center for Plasma Physics. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

- ARNOLD, V. I. 1963 Small denominators II: Proof of a theorem by A.N. Kolmogorov on the preservation of conditionally-periodic motion under small perturbation of the Hamiltonian. *Russ. Math. Surveys* **18** (9).
- COMMAUX, N., BAYLOR, L.R., COMBS, S.K., EIDIETIS, N.W., EVANS, T.E., FOUST, C.R., HOLLMANN, E.M., HUMPHREYS, D.A., IZZO, V.A., JAMES, A.N., JERNIGAN, T.C., MEITNER, S.J., PARKS, P.B., WESLEY, J.C. & YU, J.H. 2011 Novel rapid shutdown strategies for runaway electron suppression in DIII-D. *Nuclear Fusion* **51** (10), 103001.
- EVANS, T. E., MOYER, R. A., THOMAS, P. R., WATKINS, J. G., OSBORNE, T. H., BOEDO, J. A., DOYLE, E. J., FENSTERMACHER, M. E., FINKEN, K. H., GROEBNER, R. J., GROTH, M., HARRIS, J. H., LA HAYE, R. J., LASNIER, C. J., MASUZAKI, S., OHYABU, N., PRETTY, D. G., RHODES, T. L., REIMERDES, H., RUDAKOV, D. L., SCHAFER, M. J., WANG, G. & ZENG, L. 2004 Suppression of large edge-localized modes in high-confinement diii-d plasmas with a stochastic magnetic boundary. *Phys. Rev. Lett.* **92**, 235003.
- FIETZ, S., BERGMANN, A., CLASSEN, I., MARASCHEK, M., GARCIA-MUNOZ, M., SUTTROP, W., ZOHN, H. & THE ASDEX UPGRADE TEAM 2015 Influence of externally applied magnetic perturbations on neoclassical tearing modes at ASDEX Upgrade. *Nuclear Fusion* **55** (1), 013018.
- HOLLMANN, E. M., ALEYNIKOV, P. B., FÜLÖP, T., HUMPHREYS, D. A., IZZO, V. A., LEHNEN, M., LUKASH, V. E., PAPP, G., PAUTASSO, G., SAINT-LAURENT, F. & SNIPES, J. A. 2015 Status of research toward the ITER disruption mitigation system. *Physics of Plasmas* (1994-present) **22** (2), 021802.
- KOLMOGOROV, A. N. 1957 General theory of dynamical systems in classical mechanics. In *Proceedings of the 1954 International Congress of Mathematics*, , vol. 1, pp. 315–333. Amsterdam: North Holland.
- KOSLOWSKI, H.R., LIANG, Y., KRÄMER-FLECKEN, A., LÖWENBRÜCK, K., VON HELLERMANN, M., WESTERHOF, E., WOLF, R. C., ZIMMERMANN, O. & THE TEXTOR TEAM 2006 Dependence of the threshold for perturbation field generated $m/n = 2/1$ tearing modes on the plasma fluid rotation. *Nuclear Fusion* **46** (8), L1.
- LEHNEN, M., BOZHENKOV, S. A., ABDULLAEV, S. S. & JAKUBOWSKI, M. W. 2008 Suppression of runaway electrons by resonant magnetic perturbations in TEXTOR disruptions. *Phys. Rev. Lett.* **100**, 255003.
- MOSER, J. 1962 On invariant curves of area preserving mappings of an annulus. *Nachr. Akad. Wiss. Göttingen II Math. Phys.* **1** (1), 1–20.
- MYNICK, H. E. & STRACHAN, J. D. 1981 Transport of runaway and thermal electrons due to magnetic microturbulence. *Phys. of Fluids* **24** (4), 695–702.
- MYRA, J. R. & CATTO, PETER J. 1992 Effect of drifts on the diffusion of runaway electrons in tokamak stochastic magnetic fields. *Phys. of Fluids B* **4** (1), 176–186.
- PAPP, G., DREVLAK, M., FÜLÖP, T. & HELANDER, P. 2011a Runaway electron drift orbits in magnetostatic perturbed fields. *Nuclear Fusion* **51** (4), 043004.
- PAPP, G., DREVLAK, M., FÜLÖP, T., HELANDER, P. & POKOL, G. I. 2011b Runaway electron losses caused by resonant magnetic perturbations in ITER. *PPCF* **53** (9), 095004.
- PAPP, G., DREVLAK, M., FÜLÖP, T. & POKOL, G. I. 2012 The effect of resonant magnetic perturbations on runaway electron transport in ITER. *PPCF* **54** (12), 125008.
- PAPP, G., FÜLÖP, T., FEHÉR, T., DE VRIES, P.C., RICCARDO, V., REUX, C., LEHNEN, M., KIPTILY, V., PLYUSNIN, V.V., ALPER, B. & CONTRIBUTORS, JET EFDA 2013 The effect of ITER-like wall on runaway electron generation in JET. *Nuclear Fusion* **53** (12), 123017.

- RECHESTER, A. B. & ROSENBLUTH, M. N. 1978 Electron heat transport in a tokamak with destroyed magnetic surfaces. *Phys. Rev. Lett.* **40** (1), 38–41.
- SHIMADA, M., CAMPBELL, D.J., MUKHOVATOV, V., FUJIWARA, M., KIRNEVA, N., LACKNER, K., NAGAMI, M., PUSTOVITOV, V.D., UCKAN, N., WESLEY, J., ASAKURA, N., COSTLEY, A.E., DONNE, A.J.H., DOYLE, E.J., FASOLI, A., GORMEZANO, C., GRIBOV, Y., GRUBER, O., HENDER, T.C., HOULBERG, W., IDE, S., KAMADA, Y., LEONARD, A., LIPSCHULTZ, B., LOARTE, A., MIYAMOTO, K., MUKHOVATOV, V., OSBORNE, T.H., POLEVOI, A. & SIPS, A.C.C. 2007 Progress in the ITER physics basis chapter 1: Overview and summary. *Nuclear Fusion* **47** (6), S1.
- SMITH, H. M., FEHÉR, T., FÜLÖP, T., GÁL, K. & VERWICHTE, E. 2009 Runaway electron generation in tokamak disruptions. *PPCF* **51** (12), 124008.
- SUTTROP, W., EICH, T., FUCHS, J. C., GÜNTHER, S., JANZER, A., HERRMANN, A., KALLENBACH, A., LANG, P. T., LUNT, T., MARASCHEK, M., McDERMOTT, R. M., MLYNEK, A., PÜTTERICH, T., ROTT, M., VIERLE, T., WOLFRUM, E., YU, Q., ZAMMUTO, I. & ZOHN, H. 2011 First observation of edge localized modes mitigation with resonant and nonresonant magnetic perturbations in ASDEX Upgrade. *Phys. Rev. Lett.* **106**, 225004.
- YOSHINO, R., TOKUDA, S. & KAWANO, Y. 1999 Generation and termination of runaway electrons at major disruptions in JT-60U. *Nuclear Fusion* **39** (2), 151.