



HAL
open science

Theory and modelling activities in support of the ITER disruption mitigation system

E Nardon, G Huijsmans, Y Peysson, C Reux, A Matsuyama, M Lehnen, P
Aleynikov, F J Artola, V Bandaru, M Hoelzl, et al.

► **To cite this version:**

E Nardon, G Huijsmans, Y Peysson, C Reux, A Matsuyama, et al.. Theory and modelling activities in support of the ITER disruption mitigation system. IAEA FEC 2021 - The 28th IAEA Fusion Energy Conference, May 2021, Nice (Virtual conference), France. cea-03253650

HAL Id: cea-03253650

<https://cea.hal.science/cea-03253650>

Submitted on 8 Jun 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

THEORY AND MODELLING ACTIVITIES IN SUPPORT OF THE ITER DISRUPTION MITIGATION SYSTEM

E. NARDON, G. HUIJSMANS, Y. PEYSSON, C. REUX
CEA, IRFM
F-13108 Saint-Paul-lez-Durance, France
Email: eric.nardon@cea.fr

A. MATSUYAMA
QST, Rokkasho Fusion Institute
Aomori 039-3212, Japan

M. LEHNEN
ITER Organization
13067 Saint Paul Lez Durance Cedex, France

P. ALEYNIKOV
Max Planck Institute for Plasma Physics
Greifswald, Germany

F.J. ARTOLA, V. BANDARU, M. HOELZL, G. PAPP
Max Planck Institute for Plasma Physics
Boltzmannstr. 2, 85748 Garching b. M., Germany

O. BARDSLEY, M. KONG
UKAEA-CCFE
Culham Science Centre, Abingdon, Oxon, OX14 3DB, United Kingdom

M. BEIDLER, D. DEL-CASTILLO-NEGRETE, D. SPONG
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-8071, United States of America

D. BONFIGLIO
Consorzio RFX
Corso Stati Uniti 4, 35127 Padova, Italy

A. BOOZER, C. PAZ-SOLDAN
Columbia University
New York, NY 10027, United States of America

B. BREIZMAN, D. KIRAMOV
Institute for Fusion Studies
The University of Texas, Austin, TX 78712, United States of America

D. BRENNAN, N. FERRARO, S. JARDIN, C. LIU
Princeton Plasma Physics Laboratory
Princeton, New Jersey 08543, United States of America

N. GARLAND, X. TANG
Theoretical Division, Los Alamos National Laboratory
Los Alamos, NM 87545, United States of America

J. DECKER, C. SOMMARIVA
Swiss Plasma Center
EPFL, Lausanne, 1015, Switzerland

O. EMBREUS
Department of Physics, Chalmers University of Technology
SE-41296 Göteborg, Sweden

R. HARVEY
CompX
P.O. Box 2672, Del Mar, CA 92014-5672, United States of America

D. HU
Beihang University
Beijing, China

V. IZZO
Fiat Lux
San Diego, CA 92103, United States of America

C. KIM
SLS2 Consulting
San Diego, California 92107, United States of America

S. KONOVALOV
National Research Centre «Kurchatov Institute»
Pl. Kurchatova 1, Moscow 123182, Russian Federation

L. LAO, Y. LIU, B. LYONS, J. MCCLENAGHAN, P. PARKS
General Atomics
San Diego, California 92121, United States of America

S.J. LEE
Seoul National University
Republic of Korea

J.R. MARTÍN-SOLÍS
Universidad Carlos III de Madrid
Avenida de la Universidad 30, 28911-Madrid, Spain

C. MCDEVITT
University of Florida
United States of America

R. SAMULYAK
Stony Brook University
Stony Brook, NY, United States of America

H. STRAUSS
HRS Fusion
West Orange, New Jersey 07052, United States of America

JET contributors

See the author list of ‘Overview of JET results for optimising ITER operation’ by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)’

Abstract

In 2018, an international Task Force (TF) dedicated to the ITER Disruption Mitigation System (DMS) has been formed. The present paper summarizes Theory and Modelling (T&M) activities performed within this TF. The ITER DMS is planned to rely on Shattered Pellet Injection (SPI). The most critical issue, at present, is that of Runaway Electrons (REs). Indeed, recent T&M work suggests that previously envisaged means of RE avoidance or mitigation may prove inefficient. However, RE simulations have not yet taken into account the possibly beneficial role of magnetohydrodynamic (MHD) instabilities. Furthermore, new promising schemes for RE avoidance or mitigation are being investigated. These comprise, among others: 1) a prompt plasma dilution before the disruption by means of pure H₂ SPI in order to suppress hot tail RE generation, and 2) should a RE beam form, a “cleanout” of the beam’s companion plasma, *via* (again) pure H₂ SPI into the beam, which may lead to a benign beam termination. The paper also discusses the status of 3D MHD modelling. The JOREK, M3D-C¹ and NIMROD codes have been extended in recent years to be able to simulate SPI. Good cooperation exists between

the 3 teams, which materializes for example in useful benchmarks. Code validation on present experiments is progressing hand-in-hand with physics understanding. Predictions for ITER, although still at an early stage, suggest that multiple SPI may be an efficient way to limit radiation asymmetries. Substantial 3D MHD modelling work is also ongoing in the areas of vertical displacement events, halo currents and electromagnetic loads. Finally, integrated modelling shows that material deposition from SPI will strongly depend on the target plasma, suggesting that SPI parameters may need to be adapted to the latter. SPI for disruption mitigation poses new questions in terms of detailed pellet physics, which will be outlined.

1. INTRODUCTION

The ITER Disruption Mitigation System (DMS) [1][2] will be in charge of preventing disruption-related damage in ITER, whether from thermal loads, electromagnetic forces, or Runaway Electron (RE) beam impact. The DMS is currently in its design phase. It will be based on the Shattered Pellet Injection (SPI) technique, and is presently planned to comprise 24 injectors located in 3 equatorial ports, as well as 3 injectors in 3 upper ports.

In 2018, an international DMS Task Force (DTF) has been formed under the auspices of the ITER Organization (IO) to implement a research and development plan in support of the DMS. The DTF, led by Michael Lehnen (IO) and Nick Eidietis (GA, USA), comprises 3 divisions: technology, experiments, and Theory and Modelling (T&M). The present paper summarizes the work and plans of the T&M division, which is led by Eric Nardon (CEA, France) and Akinobu Matsuyama (QST, Japan).

The general DMS strategy is, upon reception of an alarm from a disruption prediction system, to inject shattered pellets into the plasma so as to trigger a benign disruption. More precisely, the objectives of the DMS are the following (numbers below correspond to requirements for the 15 MA, 350 MJ ITER baseline scenario) [5]:

- (a) To dissipate a large fraction ($> 90\%$) of the plasma's thermal energy by radiation, with as little toroidal and poloidal peaking as possible.
- (b) To ensure a Current Quench (CQ) timescale τ_{CQ} (defined as the time of exponential decay between 80 and 20% divided by 0.6) both large enough (> 50 ms) and small enough (< 150 ms) that respectively eddy current forces in the blanket modules and halo current forces in the vacuum vessel remain tolerable.
- (c) To avoid the generation of a significant RE population.
- (d) In case a RE beam forms accidentally, to avoid a damaging impact.

The above objectives should be fulfilled by the equatorial injectors. The upper injectors would be used only as a second layer of defense, should the DMS trigger be received after the Thermal Quench (TQ). In such a case, SPI from the upper ports would be performed during the CQ in order to limit at least CQ heat and electromagnetic loads.

The injected pellets are planned to be composed of a mixture of Ne and H₂. It is clear that Ne injection will help reach objective (a) *via* line radiation. On the other hand, objective (b) places constraints on the plasma composition during the CQ, requiring the Ne amount to be within a certain range (which depends on the H₂ amount). Regarding objective (c), an *a priori* attractive strategy is to inject a large quantity of H₂ so as to densify the plasma with a limited increase in its resistivity (and therefore in the electric field). From these considerations, it appears that the DMS should be able to fulfil its mission if a Ne/H₂ mix can be found which satisfies objectives (a), (b) and (c) at the same time. As will be discussed in Section 3, recent modelling results however suggest that objective (c) cannot be reached, whatever the plasma composition, which motivates the study of other approaches.

The paper is constructed as follows. In Section 2, the organization of T&M activities within the DTF is outlined. Section 3 discusses RE issues, Section 4 deals with 3D MHD modelling and Section 5 with pellet physics. Finally, Section 6 concludes.

2. ORGANIZATION

Within the T&M division of the DTF, two working groups have been formed: one focusing on REs and the other on 3D MHD and pellet physics. Each group consists of about 20 international experts from the ITER Members (some experts belonging to both groups) and meets remotely every 2 or 3 months. A non-contractual work plan for each group has been defined in 2018 and updated in 2020. In addition, the activity of some members of the groups is covered by collaboration agreements with IO. It is also important to mention that the DTF receives significant support through projects funded and coordinated within domestic programmes of some of the ITER Members such as SciDAC projects in the USA and EUROfusion projects in the EU.

3. THE ISSUE OF RUNAWAY ELECTRONS

REs [3][4] presently appear as the most critical issue in terms of disruption mitigation in ITER. Even though the physics of the RE beam impact onto the first wall is not fully understood yet, it appears likely that a single impact from a fully developed RE beam after a 15 MA plasma disruption may cause a water leak into the vacuum vessel [5][2]. Thus, it will be mandatory to avoid RE electron beams in a very reliable way (objective (c)) and to have the means to mitigate their impact as a second layer of defense (objective (d)). These two objectives will now be discussed successively.

3.1. Runaway electron avoidance

In order to design a RE avoidance scheme for ITER, experimental demonstrations in present tokamaks should be taken with much caution, for several reasons. First, the amplification factor of the RE population by the avalanche mechanism is expected to scale exponentially with the plasma current I_p [3], leading to a very large value in ITER, many orders of magnitude larger than in present tokamaks. Thus, even an extremely small seed RE population could be converted into a large, multi-MA, RE beam in ITER. Second, during the activated phase of ITER operation, RE seeds will be continuously generated by the β decay of tritium and the Compton scattering of γ rays emitted by the activated wall. In this respect, it is important to distinguish the non-active and active phases of ITER operation. Third, high performance ITER plasmas will have significantly larger electron temperatures T_e than typical present plasmas, which may lead to a much larger RE generation by the hot tail mechanism, as suggested by DIII-D experiments [6]. In consideration of these aspects, it is clear that T&M is an invaluable complement to experiments in order to establish a reliable RE avoidance strategy for ITER.

The avalanche theory, first outlined by Rosenbluth and Putvinski [7], has been refined in recent years for an accurate treatment of partly ionized plasmas [8][9], for which the avalanche growth rate may be much larger than for fully ionized plasmas with the same effective charge. This is due to the role of bound electrons as potential targets for knock-on collisions, which is only partly compensated by the extra friction that they generate on fast electrons.

Concerning RE seed generation, the Dreicer mechanism is expected to be negligible in ITER because of the relatively high electron density n_e and T_e during the CQ [10]. The β decay and Compton sources have been estimated at an order of magnitude level [10]. This may be sufficient since the final RE current scales like the logarithm of small RE seed currents [3], although a better documented estimate of the Compton source is desirable. As for the hot tail mechanism, a convincing self-consistent description exists when assuming that flux surfaces remain intact and the TQ is fully driven through radiative losses [11]. A key remaining question is the effect of electron losses associated to magnetic stochasticity during (and shortly after) the TQ. Theory [12] and 3D MHD modelling [13][14] have progressed but have not reached a conclusion on this point yet. This is related to still limited capabilities to model the MHD relaxation process, illustrated by the difficulty to quantitatively reproduce the I_p spike, although some progress has been made recently [15]. In addition to causing stochastic electron losses, one should also keep in mind that the MHD activity may generate large parallel electric fields which could play a role in RE generation [16], a topic which deserves further attention.

Let us now discuss the RE avoidance strategy for ITER. An obvious idea is to raise n_e in order to increase the drag on fast electrons. The so-called ‘‘Rosenbluth density’’ n_R above which no REs can be generated, however appears out of reach (it is estimated to $4.2 \times 10^{22} \text{ m}^{-3}$ in [17]). It is more likely that $n_e \ll n_R$ will apply, at least early in the CQ; in such a regime theory expects the avalanche gain to be independent of n_e and τ_{CQ} [18]. However, in the late phase of the CQ, the electric field may be smaller, such that n_e may approach n_R . In this case, the avalanche gain would be reduced to a certain extent. Raising n_e may also reduce RE seeds, except for Compton scattering seeds which are expected to be independent of n_e [18]. Altogether, modelling by Martın-Solis et al. had predicted in 2017 that RE beams may be avoided in ITER if the plasma could assimilate a large enough quantity of D_2 (admixed to a small quantity of Ne for thermal and electromagnetic loads mitigation) so as to raise n_e to $\sim 2\text{--}4 \times 10^{21} \text{ m}^{-3}$ [10]. Further studies by Vallhagen et al. using the GO code (which has more precise RE generation rates and atomic physics model) however resulted in a more pessimistic outlook, at least for the DT phase of ITER operation [19].

During this phase, GO simulations predict that a multi-MA beam will be generated, whatever the plasma composition. The key issue appears to be that plasma recombination occurs at low T_e , which leads to a promotion of the avalanche because of the above-mentioned role of bound electrons.

An important point to note, however, is that the possible effect of 3D MHD instabilities during the CQ (which may be beneficial if they deconfine REs before a significant beam has formed) has not been taken into account yet. JOREK simulations including a fluid model for REs similar to the model in GO [20] are planned to address this topic.

A possible strategy against hot tail RE generation may be a 2 step injection, with a pure H₂ SPI first, followed by a Ne SPI a few ms later [21][22]. The idea is that the H₂ SPI may cool the plasma by dilution down to a few hundreds of eV without immediately causing a radiative collapse. JOREK simulations suggest that in such a case, little MHD activity would be triggered [21]. Enough time may then be available before the TQ for hot electrons to be thermalized, probably suppressing any risk of subsequent hot tail generation. This appears as a promising RE avoidance strategy for the non-active phase of ITER operation. Work is ongoing with JOREK to simulate JET and KSTAR D₂ SPI experiments for validation purposes, as well as to study the effect of pre-existing islands. Further ITER simulations will be needed to assess whether the strategy may be compromised by background impurities and whether it is compatible with heat and electromagnetic loads mitigation.

In the active phase of ITER operation, avoiding hot tail seeds is unfortunately not expected to suffice because of the tritium decay and Compton scattering seeds. However, it might be possible to exploit the smallness of these seeds, which leaves a time window for action before the avalanche has turned them into a substantial RE population. One idea is to inject shattered pellets in a repeated way during the CQ, counting on the stopping power of the solid material to deplete the RE population [23]. The difficulty here is to inject material with sufficient stopping power while not accelerating the CQ beyond what is tolerable. Injecting grains containing a core of high Z material coated with low Z material is an option to consider for a possible DMS upgrade as ITER will approach its active phase.

Other ideas for alternative RE avoidance schemes involve waves and kinetic instabilities [24]. The observation and understanding of such phenomena has progressed in recent years, especially in the context of quiescent (non-disruptive) plasmas, where kinetic instabilities associated to whistler waves have been identified and shown to elevate the critical electric field for RE generation [25][26]. In the context of disruptions, experimental observations also suggest the presence of kinetic instabilities associated to REs [27][28] and theory is in progress. Whether such phenomena can be exploited to avoid REs in ITER is an important area for future studies.

Finally, in parallel to seeking RE avoidance strategies for ITER, validating RE generation codes (in particular the new generation of kinetic codes like RAMc [29], KORC [30] or DREAM) is also essential. Progress is being made in this area [31][32] but the scarcity of experimental measurements during disruptions makes it difficult to really test the models. Synthetic diagnostics may help in this respect [33].

3.2. Runaway electron mitigation

In case a RE beam forms, it will have to be ensured that it does not cause excessive impact damage. A massive injection of high Z material has been shown to reduce the beam current in present devices, and modelling capabilities have progressed in this area [30][34]. However, the possibility of reducing the beam current before it impacts the wall is very limited in ITER. This is because the highly conducting wall imposes a relation between the vertical position of the plasma (or RE beam) and its current when the current decays fast [35]. Accelerating the RE current decay rate would also accelerate the vertical motion, such that the impact would still happen at the same current. DINA simulations have indeed shown that RE beam mitigation by high Z injection is very challenging in ITER [36].

Recent experiments suggest that another strategy, based on pure D₂ (or H₂) SPI into the beam, may be possible [37]. This has indeed been observed to lead to benign impacts, albeit at large RE currents (several hundreds of

kA), in DIII-D and JET. The present understanding is that the D₂ SPI cleans out the beam's companion plasma from its impurities and leads to its recombination. This allows a large, fast growing, MHD instability to occur at some later point of the beam's evolution, which deconfines REs and distributes them over a large area of the wall (which is supported by modelling works [39][40]). A clean plasma is reformed after this loss event, preventing further RE generation. The modelling effort should intensify in order to better understand the processes at play and assess the applicability of this method to ITER.

4. 3D MAGNETOHYDRODYNAMICS

3D MHD activities within the DTF mainly involve 3 codes: JOREK, M3D-C1 and NIMROD. This allows very useful benchmarks, in particular concerning the treatment of impurities, for which M3D-C1 and NIMROD have been found to match well [41]. JOREK used to give different results because of its assumption of coronal equilibrium, but this has been relaxed thanks to the recent implementation of a collisional-radiative impurity model, improving significantly the agreement with M3D-C1 and NIMROD.

JOREK, M3D-C1 and NIMROD have been used to study disruptions triggered by massive material injection (whether in the form of gas or shattered pellets) and have been validated against experimental data, mainly from DIII-D and JET, to a certain degree [15][42][43][44][45][47]. Simulations have shown that the $m=2/n=1$ tearing mode (where m and n are the poloidal and toroidal mode numbers) plays a central role in the disruption dynamics. This mode is destabilized by the penetration of a cold front leading to a very unstable current profile, as well as by helical cooling inside the 2/1 island. If the radius of the $q=1$ surface is large enough, the 1/1 mode may also have a decisive role [42][41]. Flux surfaces are typically fully destroyed during the TQ. A concern is that the I_p spike is generally much smaller in simulations than what is measured, casting doubts on the capability of the codes to simulate the violent MHD relaxation which is characteristic of disruptions. Progress at reproducing the I_p spike has been made recently [15]. However, it is clear that simulating the MHD relaxation with realistic parameters (e.g. dissipation coefficients) is presently out of reach from a computational point of view. The consequences of using non-realistic parameters should be clarified, and the best approach to simulate ITER disruptions should be defined.

Predictions from 3D MHD codes regarding SPI in ITER are still at an early stage but already give useful indications. In particular, in addition to the already mentioned results on D₂ SPI [21], it has been found with JOREK and NIMROD that radiation asymmetries may be strongly reduced by using dual or triple SPI from several toroidal locations, as compared to single SPI [42][47]. This result seems to contrast qualitatively with earlier findings with NIMROD [46]. The key factor explaining the difference seems to be the way impurities distribute relative to the path along which heat flows from the core to the edge. Further studies and experimental validation are needed to confirm these findings. Scans in the D₂ content in mixed Ne+D₂ SPI with NIMROD show a more benign TQ in terms of conducted heat loads when more D₂ is injected, due to enhanced dilution cooling and Ne mixing [47].

Although not directly coordinated or discussed within the DTF so far, considerable work is also being done with 3D MHD codes regarding plasma vertical motion during or before the CQ, halo and eddy currents, and electromagnetic forces, see e.g. [48]. This work will be extremely useful in order to establish an integrated disruption mitigation scheme for ITER.

5. PELLETS PHYSICS

Accurate SPI modelling requires a good shroud ablation model. In the past, simulations for fueling pellets have been successful using ablation rates based on the Neutral Gas Shielding (NGS) theory (or extensions of it) [49]. Detailed pellet ablation models have been developed recently (Frontier [50] and the Lagrangian particle model [51]) that confirm analytic pellet ablation scaling laws for the spherically symmetric approximation but modify (reduce) pellet ablation rates in magnetic fields. In particular, the 3D Lagrangian particle model [51] quantifies the influence of magnetic field and grad-B drift on pellet ablation rates. Quite logically, most SPI modelling up to now, e.g. with 3D MHD codes, has been performed using NGS-like ablation rates. However, these rates have

been calculated based on the local n_e and T_e at the position of each shard. This may not be appropriate since SPI may generate substantial parallel gradients (according to the NGS theory, the ablation rate is determined by the flux of hot electrons coming from “far away” along field lines). Another point is that, in contrast to fueling pellets, the ablation rate for neon has not been extensively validated experimentally. These topics will be investigated soon. A reassuring fact is that 0D modelling based on NGS-like ablation rates matches experimental data well for different machines and target plasmas [52].

An important remark is that, due to the strong scaling of the ablation rate with T_e , ablation dynamics will strongly depend on the target plasma [22][47]. This may require adapting the injection to the target plasma, for example by injecting slower and/or more finely shattered pellets for lower thermal energy plasmas.

Finally, NGS ablation rates are not valid at low T_e . An extension of the theory may be required to predict ablation e.g. in dilution cooled plasmas or during the CQ.

6. CONCLUSIONS

A wealth of T&M activities are being performed within the DTF, addressing all the important topics, and the overall capability to evaluate and optimize disruption mitigation strategies for ITER is progressing at a fast rate. RE avoidance poses a significant challenge for the ITER disruption mitigation strategy, but new approaches are being developed. For the non-active phase of ITER operation, a 2 step SPI (H_2 first, then Ne) seems to be a promising RE avoidance scheme. The possibility of mitigating RE beams also appears uncertain but recent experimental findings of benign RE beam termination after D_2 SPI into the beam might lead to a solution. The present situation appears more critical regarding RE avoidance during the active phase of ITER operation: recent GO simulations suggest that, whatever plasma composition may be established *via* SPI, a multi-MA RE beam would form at 15 MA operation. This calls for more refined modelling (e.g. taking 3D MHD effects into account) and also motivates the exploration of alternative RE avoidance strategies based e.g. on waves or post-TQ solid material injection. Heat load mitigation is a generally less critical issue, but is difficult to quantify in experiments. Here, 3D MHD simulations will be essential to find optimised SPI parameters that are also compatible with the electromagnetic load requirements that will need to be addressed as well in the DTF when defining the integrated disruption mitigation scheme for ITER.

ACKNOWLEDGEMENTS

ITER is the Nuclear Facility INB no. 174. This paper explores physics processes during the plasma operation of the tokamak when disruptions take place; nevertheless the nuclear operator is not constrained by the results presented here. The views and opinions expressed herein do not necessarily reflect those of the ITER organization. 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 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

- [1] LUCE, T., “Progress on the ITER DMS design and integration”, this conference.
- [2] LEHNEN, M., et al., “R&D for reliable disruption mitigation in ITER”, Proceedings of the 27th IAEA FEC (Gandhinagar, 2018).
- [3] BREIZMAN, B., et al., “Physics of runaway electrons in tokamaks”, Nucl. Fusion **59** (2019) 083001.
- [4] BOOZER, A., “Theory of runaway electrons in ITER: Equations, important parameters, and implications for mitigation”, Phys. Plasmas **22** (2015) 032504.
- [5] LEHNEN, M., et al., “Disruptions in ITER and strategies for their control and mitigation”, J. Nucl. Mater. **463** (2015) 39.
- [6] PAZ-SOLDAN, C., et al., “Runaway electron seed formation at reactor-relevant temperature”, Nucl. Fusion **60** (2020) 056020.
- [7] ROSENBLUTH, M., PUTVINSKI, S., “Theory for avalanche of runaway electrons in tokamaks”, Nucl. Fusion **37** (1997) 1355.

- [8] HESSLOW, L., et al., “Generalized collision operator for fast electrons interacting with partially ionized impurities”, *J. Plasma Phys.* **84** (2018) 905840605.
- [9] MCDEVITT, C., et al., “Avalanche mechanism for runaway electron amplification in a tokamak plasma”, *Plasma Phys. Control. Fusion* **61** (2019) 054008.
- [10] MARTÍN-SOLÍS, J.R., et al., “Formation and termination of runaway beams in ITER disruptions”, *Nucl. Fusion* **57** (2017) 066025.
- [11] ALEYNIKOV, P., BREIZMAN, B., “Generation of runaway electrons during the thermal quench in tokamaks”, *Nucl. Fusion* **57** (2017) 046009.
- [12] BOOZER, A., “Magnetic surface loss and electron runaway”, *Plasma Phys. Control. Fusion* **61** (2019) 024002.
- [13] IZZO, V., et al., “Runaway electron confinement modelling for rapid shutdown scenarios in DIII-D, Alcator C-Mod and ITER”, *Nucl. Fusion* **51** (2011) 063032.
- [14] SOMMARIVA, C., et al., “Test particles dynamics in the JOREK 3D non-linear MHD code and application to electron transport in a disruption simulation”, *Nucl. Fusion* **58** (2018) 016043.
- [15] NARDON, E., et al., “Thermal quench and current profile relaxation dynamics in massive-material-injection-triggered tokamak disruptions”, to be submitted to *Nucl. Fusion*.
- [16] SOMMARIVA, C., et al., “Electron acceleration in a JET disruption simulation”, *Nucl. Fusion* **58** (2018) 106022.
- [17] HENDER, T., et al., “Progress in the ITER Physics Basis. Chapter 3: MHD stability, operational limits and disruptions”, *Nucl. Fusion* **47** (2007) S128.
- [18] BOOZER, A., “Pivotal issues on relativistic electrons in ITER”, *Nucl. Fusion* **58** (2018) 036006.
- [19] VALLHAGEN, O., et al., “Runaway dynamics in the DT phase of ITER operations in the presence of massive material injection”, *J. Plasma Phys.* **86** (2020) 475860401.
- [20] BANDARU, V., et al., “Simulating the nonlinear interaction of relativistic electrons and tokamak plasma instabilities: Implementation and validation of a fluid model”, *Phys. Rev. E* **99** (2019) 063317.
- [21] NARDON, E., et al., “Fast plasma dilution in ITER with pure deuterium shattered pellet injection”, *Nucl. Fusion* **60** (2020) 126040.
- [22] MATSUYAMA, A., et al., “Requirements for Runaway Electron Avoidance in ITER Disruption Mitigation Scenario by Shattered Pellet Injection”, this conference.
- [23] NARDON, E., et al., “Post-Thermal Quench Shattered Pellet Injection for small Runaway Electron seed depletion in ITER”, <https://arxiv.org/abs/2007.01567>.
- [24] ALEYNIKOV, P., BREIZMAN, B., “Stability analysis of runaway-driven waves in a tokamak”, *Nucl. Fusion* **55** (2015) 043014.
- [25] SPONG, D., et al., “First Direct Observation of Runaway-Electron-Driven Whistler Waves in Tokamaks”, *Phys. Rev. Lett.* **120** (2018) 155002.
- [26] LIU, C., et al., “Role of Kinetic Instability in Runaway-Electron Avalanches and Elevated Critical Electric Fields”, *Phys. Rev. Lett.* **120** (2018) 265001.
- [27] LVOVSKIY, A., et al., “The role of kinetic instabilities in formation of the runaway electron current after argon injection in DIII-D”, *Plasma Phys. Control. Fusion* **60** (2018) 124003.
- [28] LVOVSKIY, A., et al., “Observation of rapid frequency chirping instabilities driven by runaway electrons in a tokamak”, *Nucl. Fusion* **59** (2019) 124004.
- [29] MCDEVITT, C., et al., “Avalanche mechanism for runaway electron amplification in a tokamak plasma”, *Plasma Phys. Control. Fusion* **61** (2019) 054008.
- [30] DEL-CASTILLO-NEGRETE, et al., “Generation and mitigation of runaway electrons: spatio-temporal effects in dynamic scenarios”, this conference.
- [31] LINDER, O., et al., “Self-consistent modeling of runaway electron generation in massive gas injection scenarios in ASDEX Upgrade”, *Nucl. Fusion* **60** (2020) 096031.
- [32] INSULANDER BJÖRK, K., et al., “Kinetic modelling of runaway electron generation in argon-induced disruptions in ASDEX Upgrade”, *J. Plasma Phys.* **86** (2020) 855860401.
- [33] HOPPE, M., et al., “Polarized synchrotron radiation as a tool for studying runaway electrons”, this conference.
- [34] BEIDLER, M., et al., “Spatially Dependent Simulations and Model Validation of Runaway Electron Dissipation Via Impurity Injection in DIII-D and JET Using KORC”, this conference.
- [35] KIRAMOV, D., BREIZMAN, B., “Model of vertical plasma motion during the current quench”, *Phys. Plasmas* **24** (2017) 100702.

- [36] KONOVALOV, S., et al., “Assessment of the Runaway Electron Energy Dissipation in ITER”, Proceedings of the 26th IAEA FEC (Kyoto, 2016).
- [37] PAZ-SOLDAN, C., et al., “A novel path to runaway electron mitigation via deuterium injection and current-driven kink instability”, this conference.
- [38] REUX, C. et al., “Runaway electron beam suppression using impurity flushing and large magnetohydrodynamic instabilities”, accepted for publication in Phys. Rev. Lett.
- [39] LIU, Y., et al., “MARS-F modeling of post-disruption runaway beam loss by magnetohydrodynamic instabilities in DIII-D”, Nucl. Fusion **59** (2019) 126021.
- [40] BANDARU, V., et al., “Magnetohydrodynamic simulations of runaway electron beam termination in JET”, Plasma Phys. Control. Fusion **63** (2021) 035024.
- [41] LYONS, B., et al., “Axisymmetric benchmarks of impurity dynamics in extended-magnetohydrodynamic simulations”, Plasma Phys. Control. Fusion **61** (2019) 064001.
- [42] HU, D., et al., “Radiation asymmetry and MHD destabilization during the thermal quench after impurity shattered pellet injection”, Nucl. Fusion **61** (2021) 026015.
- [43] KIM, C., et al., “Shattered pellet injection simulations with NIMROD”, Phys. Plasmas **26** (2019) 042510.
- [44] IZZO, V., et al., “Magnetohydrodynamic simulations of massive gas injection into Alcator C-Mod and DIII-D plasmas”, Physics of Plasmas **15** (2008) 056109 (2008).
- [45] FERRARO, N., et al., “3D two-temperature magnetohydrodynamic modeling of fast thermal quenches due to injected impurities in tokamaks”, Nucl. Fusion **59** (2018) 016001.
- [46] IZZO, V., “Impurity mixing and radiation asymmetry in massive gas injection simulations of DIII-D”, Phys. Plasmas **20** (2013) 056107.
- [47] KIM, C., et al., “Simulations and Validation of Disruption Mitigation and Projections to ITER’s Disruption Mitigation System”, this conference.
- [48] JARDIN, S., et al., “Vessel Forces from a Vertical Displacement Event in ITER”, this conference.
- [49] PEGOURIE, B., “Review: Pellet injection experiments and modelling”, Plasma Phys. Control. Fusion **49** (2007) R87.
- [50] BOSVIEL, N., et al., “Near-field models and simulations of pellet ablation in tokamaks”, Phys. Plasmas **28** (2021) 012506.
- [51] SAMULYAK, R., et al., “Lagrangian particle model for 3D simulation of pellets and SPI fragments in tokamaks”, Nucl. Fusion **61** (2021) 046007.
- [52] SHIRAKI, D., et al., “DIII-D and International Research Towards Extrapolating Shattered Pellet Injection Performance to ITER”, this conference.