**Summary of the IAEA technical meeting on plasma disruptions and their mitigation**

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Abstract

This report summarizes the contributions presented at the IAEA technical meeting on plasma disruptions and their mitigation, held virtually, 20–23 July 2020. The meeting brought together more than 120 experts from nuclear fusion research sites worldwide to discuss experimental, theoretical and modelling work in the field of plasma disruptions with special emphasis on developing a solid basis for possible mitigation strategies in ITER and next generation fusion devices. The main topics of the meeting were: (i) disruption consequences, including electromagnetic loads, heat loads, and runaway electrons; (ii) disruption prediction and avoidance, including machine learning and physics-based approaches, and control aspects; and (iii) disruption mitigation, including shattered pellet injection, alternative techniques and general aspects of disruption mitigation.

Keywords: plasma disruptions, electromagnetic and heat loads, runaway electrons, disruption prediction and avoidance, plasma control, disruption mitigation, shattered pellet injection

1. Introduction

Nuclear fusion is recognized as a long-term energy source. The IAEA plays an important role in nurturing research and development (R&D) on nuclear fusion by: (i) fostering and coordinating the exchange of scientific and technical information on nuclear fusion through conferences, meetings and projects; and (ii) establishing and maintaining internationally recommended numerical databases of fundamental atomic and molecular data for nuclear fusion.

The most advanced initiative on fusion R&D is ITER: the international tokamak reactor scale experiment being assembled in France. In tokamaks, instabilities can develop under certain operational conditions or as a consequence of a loss of plasma control. These instabilities, if not counteracted, eventually lead to the rapid loss of thermal and magnetic energy, a phenomenon known as plasma disruption.

Plasma disruptions cause thermal and mechanical loading to the tokamak components. Due to the high amounts of stored thermal and magnetic energies in ITER, the in-vessel components, such as the first wall panels and the divertor, will receive significant thermal loads. Furthermore, the in-vessel components, the vacuum vessel and the coils in the tokamak must also bear substantial mechanical loads. Therefore, ITER’s operational strategy must have a strong focus on disruption avoidance. Disruption mitigation must be the last resort but has to be also highly reliable and effective in reducing the thermomechanical loads. Only with efficient disruption management, it will be possible to follow the ITER research plan [1] and eventually achieve the goals in fusion performance.

Even though it is well recognized that disruptions are a key challenge for ITER and any future large-scale tokamak installation and have been the subject of continuous R&D, it is only relatively recently that awareness has grown of the magnitude of the problem, reflected in increased effort throughout the tokamak R&D institutes. The IAEA previously organized meetings in this area in 1987 [2], 1991 [3] and 1993 [4]. More recently, specialised events in the field took place like the workshop on Theory and Simulation of Disruptions (TSDW) [5], the workshop on Runaway Electron Modelling (REM) [6], and the ITER Disruption Mitigation Workshop [7].

The 2020 IAEA Technical Meeting on Plasma Disruptions and Their Mitigation jointly organized with the ITER Organization was held virtually during 20–23 July 2020. This event was a unique occasion to discuss experimental, theoretical and modelling work on all aspects of plasma disruptions, but with a special emphasis on developing a solid basis for possible mitigation strategies in ITER and next generation fusion devices.

The format of the meeting was adapted to address the specific issues related to videoconferences with a large number of participants connecting from many different time zones. Presentations were recorded and made available a week before the start of the meeting on the meeting’s website [8]. On this website, each topic has a dedicated webpage; and each topic-webpage is organized around three columns:

* List of contributions under that specific topic;
* Discussion threads for each contribution;
* Threads on topic-related subjects raised by the meeting participants before and during the topical sessions.

The virtual meeting agenda featured summary presentations prepared by the programme committee members followed by topical discussions addressing the material made available. The entire meeting material and all recorded presentations are openly accessible [8]. The meeting was attended by 122 experts from 17 countries (China, Czech Republic, France, Germany, India, Italy, Japan, Lithuania, Portugal, Rep. of Korea, Russia, Spain, Sweden, Switzerland, Thailand, UK, USA) and 1 international organization (ITER Organization).

2. Topics and session summaries

The meeting was organised around the following three main topics:

* + Disruption Consequences, including electromagnetic loads, heat loads and formation and impact of runaway electrons;
  + Prediction and Avoidance, including machine learning and physics approaches as well as control aspects
  + Disruption Mitigation, with special emphasis on Shattered Pellet Injection, but also including general aspects and alternative techniques.

A total of 61 contributions were accepted.17 presentations (28%) were authored or co-authored by early career researchers, indicating the growing interest and possible expansion of the community working in this field. The scientific programme and paper selection were the responsibility of an international Programme Committee (PC) composed of the following members: Michael Lehnen (Chair, ITER Organization), Indranil Bandyopadhyay (India), Amitava Bhattacharjee (United States of America), Nicholas Eidietis (United States of America), Alexander Huber (Germany), Akihiko Isayama (Japan), Jayhyun Kim (Republic of Korea), Sergey Konovalov (Russian Federation), Eric Nardon (France), Gabriella Pautasso (Germany), Cristina Rea (United States of America), Carlo Sozzi (Italy), Fabio Villone (Italy), Long Zeng (China).

Summaries of the contributions and corresponding round table discussions are presented in the following topical sections. The discussions at the meeting covered many aspects of disruptions, but also had to focus on specific areas due to the limited available time. Note that the following summaries intend to give a brief overview on the contributions and to highlight specific aspects of the discussions and resulting future directions for disruption R&D. They reflect the view of the PC members and do not claim to be complete.

3. Consequences of disruptions

This session was chaired by I. Bandyopadhyay, A. Huber, and F. Villone and a total of 13 contributions were presented, including 3 invited presentations. The topic of the session was on the negative consequences of disruption on the various structures surrounding the plasma, due to electromagnetic and thermal loads and to the formation of runaway electrons. Specifically, the presentations focused on the following aspects related to disruption consequences: damage to plasma facing components (PFC) and their protection, validation of models for electromagnetic loads during disruptions and their extrapolation to ITER, models for runaway seed formation and characterization and impact analysis of runaway electrons.

3.1 Contributions summary

3.1.1 PFC damage

An overview on the impact of metallic first walls on disruption consequences was given by S. Gerasimov (CCFE) with emphasis on observations at JET with the ITER-like wall (ILW). This paper shows that with ILW, almost 50% of the high-performance shots in JET end up in disruptions, while the average disruptivity with ILW is 16%. Most of these cases were central disruptions during plasma current ramp-down with large impurity influx. Unmitigated disruptions lead to strong melting of the upper dump plate and temperature measurements indicate asymmetric evolution during VDEs. Impact of runaway electrons on the Be tiles in JET was found during inspection after dedicated runaway experiments and shows strong and localized melting.

Heat loads on plasma facing components (PFCs) were also discussed in a presentation on DEMO given by F. Maviglia (EUROfusion). The heat load requirements and the initial design of discrete limiters to protect the breeding blanket first wall during disruptions were presented.

3.1.2 Electro-magnetic loads

There were 5 papers discussing electro-magnetic loads. E. Matveeva (IPP Prague) presented recent measurements of current flows in the wall structure of COMPASS during asymmetric vertical displacement events (AVDE). Two divertor segments toroidally separated by 180° have been specifically designed to measure currents from the tiles to the vacuum vessel or to the adjacent tiles. These measurements aim on the validation of models that describing current flows during AVDEs. The measurements have not yet been conclusive and a new set of tiles will be installed to continue these experiments. V. Yanovskiy (IPP CAS) presented modeling for COMPASS-U with the CarMa0NL code, with specific focus on the effect of negative triangularity on the forces during disruptions. L. Zakharov presented predictions for JET vessel displacements using the Noll formula and a stiffness model of the vacuum vessel. A total of 23 plasma disruptions have been analyzed for the forces, which can be as high as 40MN. Good agreement with the experimentally observed phases and amplitudes was reported. Two papers presented predictions of the electromagnetic forces to ITER, one by H. Strauss (HRS Fusion) and the other by S.C. Jardin (PPPL) using the M3D and M3D-C1 codes. Both these papers suggest that shorter current quench time compared to the vessel resistive time would be beneficial for ITER and that the role of the (1,1) mode is critical in determining the sideways forces. There is an active collaboration ongoing between various modeling groups (both 2D and 3D) to benchmark and validate the model predictions.

3.1.3 Runaway electrons

Runaway electrons (RE) were the topic of 6 presentations. Three contributions focused on the runaway formation process. O. Embreus (Chalmers University of Technology) presented the effect of radial transport on seed formation using a reduced kinetic model. O. Linder (IPP Garching) presented the non-negligible impact of partially ionized impurities on the RE evolution through ASTRA-STRAHL simulation on ASDEX-Upgrade experiments. These simulations have to assume higher transport coefficients to mimic the propagation of the high Z impurities inside the q=2 surface. V. Plyusnin (IPFN) presented the characterization of the RE distribution in the JET experiments, where the RE generation was grouped with various parameters that may affect it, e.g., magnetic field, plasma current and current quench rates, etc., which is a very valuable database especially for theory and modelling studies.

There were three presentations on the RE analysis, characterization and impact. M. Hoppe (Chalmers University of Technology) presented the analysis of post-disruptive RE distributions using measurements of the synchrotron radiation produced by the hot tail population in ASDEX-Upgrade. C. Zhao (PPPL) presented simulations of MHD instabilities including a self-consistent RE fluid model, especially 1/1 and 2/1 modes, using the M3D-C1 code. U. Sheikh (EPFL) presented the correlation of the runaway current quench time with the quantity and species (He, Ne, Ar, Kr, Xe) of the material injected into the runaway beam created by full current conversion in the TCV tokamak. It was also confirmed that pure deuterium injection leads to purging of the background plasma from neon followed by reheating of this plasma.

3.2 Discussion and future work

3.2.1 Validation of electro-magnetic load models and extrapolation to ITER

In summary, there has been considerable progress in model development to assess electro-magnetic loads with a number of 3D models now available to model disruption and VDE scenarios. However, there is still considerable uncertainty in model predictions for ITER, as the models differ by more than an order of magnitude in the predicted forces during AVDEs in ITER. ITER is actually very difficult to model by the 3D codes due to the very long current quench and wall time (> a million Alfvén time) and hence VDE growth time. These parameters play an important role in determining the amplitude of the MHD perturbation and the resulting forces during an AVDE. More reliable predictions from the 3D codes would still take some time. Specific numerical modelling efforts should be devoted to the realistic description of three-dimensional features of the first wall and other conducting structures, on one side, and to the description of the electric current exchange and flow between the plasma and the first wall, on the other side. This is particularly important in cases where the plasma itself exhibits a non-axisymmetric behavior during the disruption. In this respect, accurate measurement of the halo currents is still a challenge also from the experimental point of view. More machines need to invest in high quality measurements to determine current flowing from the plasma halo to the first wall and in determining the halo width evolution. This is definitely a fundamental step needed both in view of a thorough understanding of the phenomenon, and for a comprehensive validation of proposed theoretical and numerical models.

3.2.3 PFC damage and protection

One of the worrying outcomes of the JET ILW data presented in this meeting is the significantly higher disruption rate compared to the earlier discharges, which can be as high as 50% in the high-performance shots with ILW. Here, it has to be taken into account that the existence of a mitigation system also led to acceptance of false-positive alarms where discharges could potentially also have been terminated without disruption. Naturally, the number of these events is difficult to quantify. It is to be noted that ITER needs to have disruption rates around 1% in the high current, high power discharges.

Melting of PFCs can occur not only during the thermal quench, but also unmitigated current quenches can cause significant heat fluxes to the first wall due to the lack of radiating impurities. The longer duration of this phase facilitates significant melt motion resulting in melt splashing as already observed in JET. Due to the high steady state heat loads during normal operation of ITER and reactor-scale devices, the possible degradation of the heat load handling capability of the PFCs affected by such melt events could lead to operational constraints. In view of DEMO requirements, it would be important to anticipate the possible location of plasma-wall impact points during disruptions, in order to allow specific countermeasures to be adopted (e.g. sacrificial limiters). This can be achieved both through models and via dedicated experimental campaigns.

3.2.4 RE formation and characterization

Regarding runaway seed formation, the critical issue is the stochastization of the magnetic field lines, energy transport along these open field lines and the inward transport of impurities. The models can at present do sensitivity studies of these scenarios or explain experimental data with model parameter variations, but they are not yet able to accurately predict for ITER or other machines. Experimental validation of the simulated processes during the thermal quench when runaway seeds are formed is required. A next step should be one-way coupling of 3D MHD codes with kinetic solvers that are 4D in phase space.

Diagnostics appropriate to study runaway electron formation and loss are essential to progress on the experimental side. Here, the possibility to receive profile information of seed REs through measurements of synchrotron radiation has been mentioned, but is regarded challenging due to the low intensity during the RE formation phase. Correlating RE events to the spectrum and amplitude of magnetic fluctuations as measured by Mirnov coils is an important ingredient to improve the understanding of RE transport driven by MHD.

4. Disruptions avoidance and prediction

The session on Disruption Avoidance and Prediction (DA&P), chaired by A. Bhattacharjee, A. Isayama, G. Pautasso, C. Rea, and C. Sozzi, hosted 10 invited and 10 oral contributions from three major areas of expertise, namely scenario development, plasma control focused on disruption avoidance and disruption prediction. These three areas of research are strongly interlinked and, although they have different foci and methods, they are all needed in the identification of disruption-plasma operation for ITER and subsequently, for DEMO and future fusion power plants (FPPs).

4.1 Contributions summary

*4.1.1 Development of the ITER Baseline Scenario (IBS)*

The work of F. Turco (Columbia University) is an exemplary case of scenario development, which relies on physics understanding and informs the Plasma Control System (PCS) on how to prevent disruptions. The IBS developed at DIII-D matches most of the target plasma parameters, e.g. ITER shape, q95 = 2.9-3.3 and H98 =1. Nevertheless, many discharges terminated in the past with the growth of a (m,n)=(2,1) classical tearing mode. The equilibrium reconstruction with motional-Stark-effect data revealed a peaked bootstrap current at the plasma edge and a current well at q=2 in all these discharges. It was observed that the steeper the well, the higher the probability of the growth of a (2,1) mode. ECCD (Electron Cyclotron Current Drive) stabilization was found to be ineffective in suppressing the island, because of the low local temperature and inefficient current drive. Further experiments with modified current and beta ramp-up (slower current ramp, later heating, lower pedestal temperature, modest gas flow) successfully led to a passively stable scenario.

*4.1.2 Developing the ITER PCS*

D. Humphreys (General Atomics) reminded us that disruptions are a control and operation problem. They are the result of insufficient control capability for the given operational regime, of hardware and system faults, the consequence of operational error or intentional investigation. Improved control algorithms and team experience have shown to reduce the disruption rate on existing devices. His talk provided a clear-cut overview of the ITER PCS, which is the correct ambit for discussing DA&P. The control of tokamak plasmas involves different control goals, several of which pertain to mature control areas. In addition, the ITER PCS foresees a more mature layered approach to DA&P. This approach foresees several functional elements as

* The active continuous disruption prevention through control of proximity to controllability boundaries,
* The real time (RT) forecasting of trajectories and prediction of risk to prevent approach to boundaries,
* The asynchronous avoidance of disruptive states through high-level supervisory monitoring and action,
* The actuator management to coordinate limited resources,
* The off-normal event and system fault prediction/detection, and
* Effective exception handling responses.

*4.1.3 PCS development and disruption avoidance on existing devices*

The following contributions describe how existing devices are developing increasingly complex PCSs, often expanding on their existing expertise, and by taking advantage of their diagnostics and actuators.

A. Pau (EPFL) described the generic framework of the TCV PCS, which allows for the easy integration of new algorithms and the evolving PCS tasks related to disruption avoidance. The task-based PCS approach relies on a plasma supervisory controller and on an actuator manager to make high-level decisions on how to handle different control tasks. The developed scheme is capable of robust event handling with a limited set of actuators. Specifically, it is used on TCV for simultaneous *β* and neoclassical tearing mode (NTM) control. In addition, the modified Rutherford equation allows for RTprediction of the power needed to prevent or stabilize NTMs.

J. Barr (General Atomics) presented the work done on DIII-D to develop, test and qualify control tools for comprehensive disruption avoidance along with the concepts supporting the development of the DIII-D PCS. A novel “Proximity-to-Instability” control architecture has been implemented for RT scenario modification to maintain a stable discharge. Its goal is to rely on stability models (for vertical stability, ideal beta, density and other limits as well as new stability models based on machine learning (ML) and provide the connection between them and the available actuators, by mapping the distance to the instability to the desired changes in plasma parameter . The architecture allows control of multiple stability metrics in parallel. Asynchronous actions are essential for disruption avoidance and are taken when an instability is detected. The PCS reacts to restabilize the plasma and starts an emergency shutdown when the recovery fails. The effectiveness of emergency shutdown, which consists essentially in ramping down the plasma current, is also being investigated on DIII-D and EAST. It has been found that changing the plasma shape, from a diverted to a limited configuration, reduces dramatically the disruption risk during the current ramp-down in the presence of a locked mode.

M. Maraschek (IPP Garching) and the Eurofusion MST1 team are exploring the controllability of an H mode scenario close to the density limit. This scenario is ITER and DEMO relevant because of its high density and good confinement. Nevertheless, as the density is increased, the plasma evolution is characterized by confinement degradation and MARFE formation followed by the development of tearing modes, leading to a disruption. In present devices, a MARFE can be suppressed with auxiliary heating; in FPP devices it would probably not be suppressed because the requires auxiliary power would not be available. Therefore, control actions for disruption prevention would be required before MARFE formation. The addition of nitrogen puffing to this scenario was found to modify the plasma evolution and the controllability boundaries. Therefore, the use of impurities for divertor power load control requires alternative sensors, control setup and plasma state definition. Very similar experiments are carried on on TCV and allow for testing of extrapolability among devices.

*4.1.4 Integrated modelling of DEMO plasma scenarios*

F. Janky (IPP Garching) has been developing the code Felix for the integrated modelling of the H-mode DEMO scenario. Felix is based on the codes ASTRA (1D transport in plasma) and SPIDER (equilibrium solver) linked with the models of several plasma phenomena and all relevant plant systems. It can simulate ASDEX Upgrade (and therefore allows for validation against experiments) with magnetic and kinetic control and DEMO. In case of an unexpected event, which perturbs the plasma status, the PCS has to lead the plasma to the reference status or shut down the plasma without disruptions. Thus, Fenix has been used to simulate the dynamics of the plasma-plant system close to the relevant operational limits, which are the density and radiation limits, or subject to unexpected events like UFOs and loss of actuators.

*4.1.5 Physics based and ML approaches to DA&P*

S. Sabbagh (Columbia University) and co-workers have been developing the code DECAF for a few years. DECAF is a suite of routines for the study of the stable and pre-disruption plasma regions. The routines allow the access to data of several tokamaks (AUG, KSTAR, MAST-U, NSTX-U), the assembly and analysis of large databases, the identification of event and event chains, the evaluation of disruption forecasting and performance, MHD mode analysis, stability analysis, the use of ML tools for event analysis and prediction models. The code can provide early warning disruption forecasts on transport timescales. A RT implementation of the code in KSTAR is under development.

E. Kolemen (Princeton University) presented his portfolio-approach to RT A&P of plasma instabilities, which comprises the development of several fundamental computational and interpretation tools. The program CAKE (the automatic kinetic version of EFIT) generates quality equilibria using the RT Thomson scattering measurements, MSE and CER data to constrain the current and pressure profiles. The RT implementation of the code is functional and being tested on DIII-D. The code STRIDE is then used for the RT stability analysis of the reconstructed equilibria. It performs the calculation of δW (for ideal stability) within 200 ms, while a faster off-line version (STRIDE GPU) is being developed. A fast Δ’ calculation (< 10 ms CPU, for resistive stability) has also been developed and it is planned to be implemented in RT on DIII-D this year. ML approaches are then used to predict plasma transport and the evolution of kinetic profiles in time, and for disruption prediction. The performance of a recurrent neural network (NN), called reservoir computing network, which can process temporal information much faster and is easier to train than deep-NNs, is also being investigated within his group.

C. Rea’s (MIT) contribution was a critical discussion on the use of interpretable data-driven predictors for DA&P. Her published work made use of the so-called Random Forest method to discern between non-disruptive and disruptive samples on several devices (C-Mod, DIII-D and EAST). The work has evolved into a RT algorithm which uses peaking factors of plasma profiles, in addition to 0D input variables. It computes disruptivity and explains disruptivity drivers, by identifying the most influential variables. It is being installed in the EAST PCS and in the DIII-D proximity control architecture and can inform the PCS about plasma stability.

J.X. Zhu (MIT) trained NNs with a multi-machine database to extract a universal representation of disruption boundaries. He found that it is not sufficient to train the NN on non-disruptive samples, because the operational spaces of the different devices can differ. Disruptive examples from the devices are needed to improve the NN performance.

The following contributions illustrate methods used to identify events relevant for control actions.

Data-driven DA&P methods require large database of labeled examples. The data preparation process, e.g. human labeling, is tedious but essential. K. Montes (MIT) is using a method, called label spreading: this is a semi-supervised method for learning time-sequences, which can recognize events on the basis of few examples. The method has been successfully applied to detect the H-L transition.

M. Fontana (CCFE) found that the peaking of the temperature profile in JET is correlated with the occurrence of disruptions, since the temperature is a proxy of the current profile. Extreme cases of flat or even hollow temperature profiles and of peaked temperature profiles are often followed by the growth of tearing modes leading to disruptions.

M. Gelfusa (University of Rome Tor Vergata) could successfully predict ITER-like-wall JET disruptions using methods of adaptive learning and a training database of ASDEX Upgrade. The variables used were the internal inductance, the normalized locked mode amplitude and its standard deviations, which are known to be informative variables.

The GTM (Generative Topographic Map) has been used to 2D-map non-disruptive and pre-disruption phases of JET discharges by the UNICA (University of Cagliari) group. The evolving operational space of the device suggests updating the map often. E. Aymeric (University of Cagliari) set up an automatic procedure to continuously update the training database, by populating it with pre-disruption and stable plasma samples.

The following contributions dealt with the locked mode phase preceding the disruption.

The KSTAR tokamak is equipped with 3 ECE imaging systems which can record the 2D temperature evolution in a plasma region. M. Choi (NFRI) presented images of various disruptive events as sawtooth crash, tearing and kink modes, cold bubbles and ballooning fingers. These measurements are very valuable because they allow to view, among others, the island evolution during the locked-mode phase and could shed light into the phase dynamics (e.g. the variables determining its duration).

A. Reiman (PPPL) reminded us that studying NTM control for disruption prevention is not sufficient, since most large islands preceding disruptions arise from off-normal events. The presence of a locked large island in ITER or DEMO would call for an emergency ramp down of the plasma current and discharge termination. Whether the use of ECCD or ECRH will be successful in stabilizing the island during ramp down is unknown. The nonlinear amplification of the power deposition of RF waves, present only in large islands, and called *current condensation*, could help stabilizing the island. The effect is still awaiting experimental confirmation. R. Nies (PPPL) introduced a numerical model for the study of the current condensation effect, in which a ray-tracing code for the wave propagation and damping is coupled with a heat diffusion equation solver to obtain the temperature in the magnetic island.

After a critical introduction on the past and future use of ML tools for DA&P, A. Murari (Consorzio RFX) revisited the formula (power law) derived by P. de Vries et al. for the LM amplitude triggering the thermal quench of a disruption. Using SVM plus symbolic regression via genetic programming, he found a different expression fitting the LM amplitude preceding disruptions on JET. Nevertheless, the physics interpretation of the formula was not given.

4.2 Discussion and future work

The discussion, which followed the summary of the DA&P session contributions, was extensive and engaged more than 80 on-line participants. Two main consensual perspectives emerged from the session.

The first perspective is that disruptions are not an endemic aspect of tokamak operation but rather the result of insufficient plasma control and of the past and present use of the present tokamaks for experimental purposes. The past decades of fusion research have been focused on the exploration of the existent plasma parameter regions rather than on disruption avoidance and routine advanced plasma control. Thanks to this practice, the physics understanding has enormously improved: the tokamak plasma remains subject to instabilities, but a large operational space has been shown to exist and to be controllable. Nevertheless, the minimization of the cost of a future FPP leads to small control margins and a higher probability of loss of control. Whether a stable operational space and the plasma trajectory within can be extrapolated to an economically interesting plasma scenario is still an open question and remains the main object of fusion research.

The second point of view which has emerged is that the PCS offers the proper context (together with methods and concepts) in which the DA&P should be treated and further developed. The PCS structure must be flexible and complex enough to monitor the plasma and the plant systems and take autonomous decisions both in normal and in emergency conditions. In particular, the PCS must *know* about the plasma stability and instability regions pertaining to the operational space in which it operates. This knowledge can only be acquired through dedicated experiments, data analysis, understanding of the phenomena involved based on theoretical models and first-principles computer simulations. To be useful, such understanding should be expressed in validated formulae, which can provide RT information.

Developing a repository of well-curated pre-disruptive event data from multiple tokamaks would enable the design and qualification of stability metrics applicable to ITER scenarios. Here, IAEA could play a crucial role by sponsoring a targeted Coordinated Research Project (CRP) to support the development of such a database.

*4.2.1 Scenario development*

The search for controllable plasma scenarios, which are at the same time economically relevant and technically realizable, is fundamental for DA&P. Limiting and intensifying the development of scenarios with low disruptivity will favor the detailed understanding of the parameter region surrounding them and allow the exploration of the possible paths leading to the development of instabilities. Scenarios at high plasma current and low safety factor (IBS), high density and good confinement are known to be relevant for ITER. More attention should be dedicated to scenarios with a high fraction of radiated power, since detached divertor operation is envisaged as a possible solution for the otherwise large or even intolerable divertor power flux.

ITER and DEMO will likely exploit different scenarios. While ITER is still an experimental tokamak, DEMO will have to demonstrate the feasibility of a FPP and will have to rely on stable scenarios. DEMO is still in the design phase and the whole plant (plasma, PCS, actuators) is being designed on the basis of the best integrated plant-plasma physics models. Negative triangularity is presently being considered as a viable condition for ELM suppression and values of the edge safety factor well above 3 are believed to increase the plasma stability against disruptions.

*4.2.2 Plasma control and disruption avoidance*

Significant progress in plasma control has been made since magnetic fusion was first envisioned. Nevertheless, present PCSs have not reached yet the level of sophistication required by ITER or by a fusion reactor. Therefore, increasingly sophisticated controllers are being designed, implemented and tested on a number of devices like DIII-D, TCV and ASDEX Upgrade, and plasma control remains an active research area.

ITER (beyond the first plasma) and DEMO will require PCSs able to control automatically the tokamak discharge, while supervising the whole plant systems. The ITER PCS is expected to actively regulate the plasma state to remain as stable as possible within the given plant and actuator constrains. It will do this through the continuous axisymmetric magnetic control of the plasma (plasma position, current, shape), the control of plasma scalars (e.g. density, energy, impurity density) and, ideally, of plasma parameter profiles. The plasma trajectory will be defined in a multi-dimensional operational space and known to the PCS.

Eventual instabilities (e.g. 3D like NTMs, 2D like vertical position or high radiation leading to power unbalance) must be promptly detected and controlled. For the chosen scenario, experiments, theory and modelling of the whole plant must have provided in advance a map of the controllable regions and controllability boundaries. The events leading to unstable states must be known to the PCS and, for each potential instability, control algorithms must have been set-up.

Many concepts have been advocated during this Technical Meeting as relevant to DA&P: the prediction of the plasma trajectory, the control of the proximity to instability boundaries, the algorithms needed to restabilize the plasma, for example. They must be implemented in present PCSs and filled with the necessary physics content, tested and proven to be useful for control over a wide operational region.

*4.2.3 Disruption prediction*

This general term (i.e. disruption prediction) is used here to designate all the works aimed at describing the onset of the thermal quench of a disruption or some distance to it or the probability of its occurrence, independently of their original motivation (which can differ, as disruption avoidance or DMS trigger generation).

The disruptive boundaries have been the subject of extensive experiments and charting of the plasma operational space in the existing tokamak devices for decades. Several operational boundaries have been empirically identified (e.g. low density, high density and beta limits, radiation collapse), and the plasma states preceding disruptions have been subject of physics investigation and modelling. Visual analysis of the plasma evolution has allowed the identification of several precursors and of recurrent chains of events preceding disruptions. The instabilities leading to the thermal quench of a disruption are mostly understood and 3D non-linear MHD codes can simulate plasma dynamics leading to the thermal quench (although these simulations cannot run in RT). In addition, data mining and mapping methods applied to existing databases have been very informative: they allow to view the information already acquired (bookkeeping), group similar discharges, identify outliers and particularly build subsets of data for specific analysis.

ML and statistical methods have been used to map the operational space and extract information on the variable importance for two decades. Supervised learning of the whole operational space has been relatively successful in discriminating between disruptive and stable samples. A false alarm rate of some % and success rate of above 90 % has been reached. The error can be attributed to missing parameters in the description of the plasma state. For example, missing details of parameter profiles or the whole time evolution could play a role. In spite of its success, the method has the disadvantage of providing only a snapshot of the known operational space, mostly pertaining to one device only. The use of dimensionless relevant parameters and the training on several devices eliminate these restrictions although the extrapolation to unknown plasma regions is expected to be incorrect.

Physics methods alone, based for example on the amplitude of the (2,1) island before the thermal quench, are also not 100 % reliable in describing the disruption onset. There is a general consensus that a disruption is caused by the growth of MHD (RWMs or/and tearing) modes causing a sudden stochastization of the magnetic field and loss of thermal confinement. The phenomenon is highly non-linear, can follow different paths and therefore is not exactly reproducible. Nonetheless, the pursuit of robust and phenomenological reduced models with lower degrees of freedom seems worthwhile.

There is not a universal accepted solution for the generation of the trigger to the DMS. An algorithm for the DMS trigger generation could take advantage from the different coexisting approaches to disruption prediction. Neither physics based nor ML algorithms have been proven 100 % reliable in predicting that a plasma state will lead or not to a disruption.

A by-product of the PCS activity is the information that a given instability is out-of-control. Controllability boundaries do not coincide with disruptive boundaries (plasma state before disruptions). There is a free-fall region between the two and the generation of the DMS trigger should be issued in this region. The larger this free-fall region is and the smaller the error bars on its boundaries are, the more correct the DMS trigger generation becomes.

No consensus has emerged during the meeting on where (at which point in the chain) the plasma control is lost along the chain of events “detachment, MARFE, tearing mode, locked mode”. This and other questions would require a dedicated survey and discussion of the already available know-how.

5. Mitigation – shattered pellet injection

This session, chaired by N. Eidietis, J. Kim and E. Nardon, received a total of 17 contributions including 11 invited presentations and was dedicated to a discussion of the state of shattered pellet injection (SPI) physics from both the experimental and modelling perspective. SPI has been chosen as the baseline ITER disruption mitigation system (DMS) technology due to its clear technical advantages over massive gas injection (MGI) in the ITER environment, but significant uncertainties exist as to its ability to successfully mitigate disruption thermal, mechanical, and runaway electron (RE) loads to the extent required for reliable ITER operation. The session aimed to assess where the state of science has resolved uncertainties in ITER SPI operation and formulate plans to retire the remaining uncertainties in the DMS final design. The timing for the session was ideal, as SPI experimental research has grown enormously in recent years from a single installation on DIII-D for a decade prior to 2019 to installations on JET, KSTAR, and J-TEXT in 2019, with additional SPI on HL-2A and ASDEX Upgrade expected later in 2020 and 2021. This experimental growth has been matched by a vastly expanded worldwide effort to model SPI mitigation physics and produce predictive modelling of ITER SPI operation.

5.1 Contributions summary

5.1.1 ITER DMS strategy and its validation

M. Lehnen (ITER Organization) introduced the design of the ITER DMS. It adopts simultaneous multi-injections of shattered pellets by using a total of 27 (=24+3) multi-barrels located in 3 equatorial ports and 3 upper ports to satisfy various aspects of disruption mitigation. The assimilated neon quantity required to achieve thermal load mitigation through radiation, and the maximum and minimum of neon quantities determined respectively by the eddy current limit and halo current limit are described. Strategies for REs are largely divided into the initial avoidance phase by low Z (hydrogen) injection and the dissipation of fully formed RE beams by high Z (neon) injection. However, it was pointed out that the improvement of the physics models and 3D MHD modelling are necessary because there are still a lot of uncertainties in the process of estimating the requirements presented. To solve these uncertainties, the ITER DMS task force is carrying out related activities. The theory & modelling group is conducting RE studies and 3D MHD modelling. The experiments group mainly supports KSTAR and ASDEX Upgrade experiments by providing appropriate SPI devices and related diagnostics. Finally, the technology group is carrying out justification and validation work for each part of the ITER DMS design.

J. Kim (KFE) presented the experimental results of dual SPIs installed in KSTAR to have a 180-degree symmetric structure in the toroidal direction to verify the effectiveness of the simultaneous multi-injection strategy adopted in ITER. As a result of measuring the current quench rate while intentionally adjusting the time difference between the two SPIs, it was confirmed that faster current quench is possible compared to single injection in dual injection synchronized to less than ~1 ms. The increase in density measured with a dispersion interferometer with a 1 μm short wavelength was also nearly twice that of single injection in dual injection. On the other hand, as expected, in the case of dual injection with n=2 structure, it was observed that the n=1 MHD mode with lower amplitude compared to single injection with n=1 structure is obtained. The amplitude of the n=1 MHD mode increases in the direction closer to single injection as the time difference between the two SPIs increases.

S. Gerasimov (CCFE) presented the current quench (CQ) and resulting EM load according to the injection of various types of shattered pellets in JET. In the JET results, the CQ rate showed a strong dependence on the neon fraction regardless of the pellet size and the neon quantity. In addition, there was only marginal dependence on pellet integrity (i.e., broken pellet). Next, the CQ rate according to the SPI was examined by changing the status of the pre-disruptive plasma. It was found that the effect of a pellet of 8.5 mm diameter was not significantly affected by the status of the pre-disruptive plasma such as plasma current or electron temperature. However, a relatively large pellet was used, and additional confirmation is required for a small pellet with a diameter of 4.5 mm. As in the case of MGI, SPI was also effective in reducing the sideway forces through the mitigation of asymmetric VDEs. Lastly, a similar effect of SPI on the CQ duration was found whether the SPI was performed before or after the thermal quench. The effectiveness of SPI for unstable plasmas other than VDEs (e.g. locked modes) remains to be addressed.

R. Sweeney (MIT) presented an overview of the radiated fraction and radiation asymmetries following SPI. It was found that simple axisymmetric assumptions of radiated power are inaccurate, and a new method for calculating a 3D radiated power fraction using distributed bolometer lines of site to constrain a helical emission distribution was developed for DIII-D and JET. The ability to control the SPI toroidal radiated power distribution with applied 3D magnetic fields remains inconclusive compared to similar attempts with MGI, with injector location exhibiting a stronger observed influence than external fields.

G. Papp (IPP Garching) introduced SPI with three different bend angles (0, 12.5, 25 deg) planned by AUG. AUG, which focuses on the effect of shard distribution according to different bend angles, is preparing a 3D imaging system using 3+1 cameras in addition to the existing diagnostic devices such as bolometers for this study.

D. Hu (Beihang University) summarized the status and plans regarding 3D non-linear MHD simulations of disruption mitigation with SPI in ITER. JOREK simulations already show how radiation asymmetries can be reduced by using dual SPI from toroidally opposite locations instead of single SPI. Efforts with JOREK, M3D-C1 and NIMROD will strongly intensify in the coming few years.

B. Lyons (USA) summarized verification and validation work related to SPI simulations with M3D-C1, NIMROD and JOREK. A benchmark of impurity models found good agreement between M3D-C1 and NIMROD. JOREK results differ, likely due to an as yet simpler impurity model. Simulations of disruptions triggered by pellet injection in DIII-D with NIMROD (resp. M3D-C1) have found quantitative (resp. qualitative) agreement. Simulations of SPI in JET and KSTAR are underway or part of near-term plans with all 3 codes.

5.1.2 Injection schemes to accommodate RE mitigation

C. Paz-Soldan (GA) presented new RE beam termination by strong MHD mode of 1 kG level that occurs in low q (=2) disruption following deuterium injection [Paz-Soldan\_2019]. The same termination effect is verified by increasing Ip, or cross-section shrinkage through VDE or inward push. The common precondition was high purity state through D2 injection.

C. Reux (CEA) presented upon the m[itigation of RE heat loads through a combination of deuterium (D2) SPI injection into the runaway plateau and kink activit](https://conferences.iaea.org/event/217/contributions/16703/)y based upon experimental observations in DIII-D and JET. The addition of [D2](https://conferences.iaea.org/event/217/contributions/16703/) to the runaway beam reduces the resistivity of the beam, allowing it to be ramped up to high current and eventually terminate by an MHD instability. Counterintuitively, it is observed in JET that these high current runaway terminations are benign, resulting in negligible wall heating compared to runaway termination at much lower currents. It is postulated that this benign termination results from a combination of kink activity spatially distributing the prompt runaway losses at termination and low resistivity suppressing the subsequent conversion of plasma magnetic energy into runaway kinetic energy.

V. K. Bandaru (IPP, Garching) presented JOREK MHD simulation results for benign MHD termination through D2 injection observed in JET. Through JOREK simulation, it was confirmed that field line stochastization caused by strong MHD mode induces fast RE loss, which is in good agreement with the experimental results.

E. Nardon (CEA) discussed two SPI schemes which may be useful to avoid the formation of RE beams in ITER. The first one, supported by JOREK simulations, consists in promptly diluting the plasma via pure D2 or H2 SPI before injecting impurities, one possible benefit being a drastic reduction of hot tail RE generation. The second scheme consists in repeated SPI during the CQ in order to deplete small RE seeds before they avalanche. This appears challenging with the present ITER DMS design but could be considered for a future DMS upgrade.

S. Sridhar (CEA) reported on an analysis of the RE beam companion plasma, an important factor in RE mitigation, for various SPI parameters. The density of the companion plasma after Ar SPI had no dependence on the initial electron temperature, but showed a tendency to increase with increasing initial electron density. In addition, when D2 was injected on the Ar background plasma, it was found that the Ar line radiation decreases, which could be accurately predicted through a diffusion model.

5.1.3 Pellet/Fragment dynamics: shattering, ablation, assimilation

T. Gebhart (ORNL) presented the results of lab tests for various types of bent tubes that determine shards distribution and plume dynamics. As a result of excluding the propellant gas effect, which was a problem in the previous lab tests, the actual dynamics of the front and rear plumes could be better observed. Gas generated in the shattering process may cause acceleration and deceleration of the front and rear plumes, which could cause large spread of plumes.

R. Samulyak (Stonybrook University) presented two codes: FronTier and the Lagrangian Particle (LP) code, which simulate the ablation of pellets and SPI fragments using near-field models. These codes have been successfully benchmarked with each other and with analytical models. The 3D LP code has been used to study and tabulate the dependency of the ablation rate on the magnetic field B. A larger B reduces the ablation rate by channelling the flow of the ablation cloud, leading to a larger screening of the incoming electron heat flux, but this effect is limited by the gradB drift of the ablation cloud. The coupling of the LP code with the 3D non-linear MHD codes M3D-C1 and NIMROD is underway.

D. Shiraki (ORNL) presented a summary of particle assimilation during SPI, including data from DIII-D, JET and KSTAR. A regression scaling for the particle assimilation of SPI on DIII-D was presented incorporating the pre-disruptive electron temperature, density, and thermal energy. 0D modeling of SPI shutdown using the KPRAD code was shown to reproduce the observed particle assimilation on DIII-D over a wide variety of plasma conditions. Similar 0D analysis applied to SPI-induced CQs on all three machines exhibited good agreement with observed CQ durations.

D. I. Kiramov (Kurchatov Institute) reported on pellet sublimation and expansion by RE current. Since the RE current density expected in ITER is much larger than the threshold for pellet sublimation, the pellet is sublimated immediately after injection. These sublimated neutrals showed a result of rapidly expanding due to heating by REs, which is consistent with the recent DIII-D experiment [Shiraki\_2018].

5.2 Discussion and future work

The discussion was structured along seven main topics, particle assimilation, radiation asymmetries, effect of SPI on MHD activity, electromagnetic load mitigation, runaway electron avoidance and mitigation, and SPI technical requirements.

*5.2.1 Particle Assimilation*

Various aspect in relation to the assimilation efficiency were mentioned during the discussion such as

* the characteristics of the fragment plume (e.g. fragment sizes, velocity dispersion);
* the physics determining the thermal quench onset (e.g. cold front penetration, 3D effects such as helical structures);
* effects that impact on the ablation rate such as non-Maxwellian distributions arising during the cooling process or generated by plasma heating systems;
* the role of the gas generated during the shattering process through evaporation.

Extrapolability to ITER may be affected by the fact that pellet sizes in present experiments are large in relation to the particle or energy content compared to the situation in ITER. The predictive capabilities of models have to be assessed in view of missing physics. 0-D models presented at this meeting are widely self-consistent and show good agreement with present experiments in terms of assimilation, but also indicate missing physics that needs to be identified in experiments and more advanced modelling possibly with 3D codes. Plans were reported to integrate more advanced ablation models into 3D MHD codes.

Particle assimilation is expected to depend on the parameters of the plasma into which the pellets are injected. The question was raised, which energies, temperatures and stability levels can be expected for ITER plasmas that are about to disrupt. In addition, the conditions for injections into runaway beams were mentioned, especially the vertical displacement of the runaway beam that may require aiming the fragment plume towards the shifted RE beam.

One important question when it comes to the ITER SPI system is whether superposition of several injections is effective in raising the plasma density. Here, two aspects were discussed, the impact of the injection location and the fast cooling of the plasma when injecting pellets with Ne/H mixtures. It was pointed out that in addition to dedicated experiments with dual injection, data with broken pellets as observed frequently in JET for example could also provide information about the effectiveness of multiple injection. The possibility for a two-stage injection with initial H injection, followed by Ne/H injection was discussed. Pure H pellets may avoid developing a pronounced cold front and therefore delay destabilisation of the plasma and onset of the thermal quench. Their superposition could therefore be more efficient compared to neon-doped pellets that lead to a cold front expected to be the cause for the fast onset of the thermal quench. However, it was also mentioned that instabilities already present in plasmas that require mitigation could neutralise this advantage.

*5.2.2 Radiation Asymmetries*

The 3D structure of the radiated power during the thermal quench is on one hand an obstacle for constraining the overall radiated energy fractions and on the other hand also a source for heat loads on the first wall that could lead to melting of the beryllium first wall or the stainless steel diagnostic wall in ITER.

It was acknowledged that the distribution of the radiated power is driven by the impurity density (that in turns is determined by how fast impurities can spread inside the helical structures) and by the MHD activity during the thermal quench. DIII-D data, showing that first wall heating is centred around the injection location and that external perturbation fields have less impact as compared to MGI, indicates that the impurity distribution is the main driver for radiation asymmetries. While toroidal peaking factors of around 2 are reported from experiments, the poloidal peaking is still to be determined. It was also pointed out that estimating the overall peaking would require knowledge about the variation of the poloidal peaking along the toroidal direction. Ideally, direct measurements of the overall peaking of the radiation-driven heat flux on the wall would be required, but is experimentally not available. 3D MHD simulations are in preparation to give more insight. Experimentally, higher toroidal resolution bolometry measurements in upcoming ASDEX Upgrade and KSTAR SPI experiments, in addition to accounting for helical radiation structure, should provide better estimates for the radiation distribution and reduce the uncertainty in the radiated energy fractions.

*5.2.3 Effect on MHD activity*

The discussion was focusing on the qualitative understanding of how SPI destabilises MHD and causes the thermal quench onset and how this is affected by multiple injection. It was reported from DIII-D that the arrival of the cold front at the q=2 surface leads to destabilisation (for neon-doped pellets) and that there are indications that the n=1 o-point is seeded at the injection location whereas the heat flux is highest at the x-point. Initial experiments at KSTAR indicate that although initially n=2 modes are dominant during synchronised injection from two toroidally opposite locations, n=1 modes become stronger in the later phase of the thermal quench process. Modelling confirms the suppression of n=1 for dual injections, but in contrast to experiments, the simulations have perfectly synchronised and identical injections from the two locations.

*5.2.4 Electromagnetic load mitigation*

The effectiveness of SPI for electromagnetic load mitigation as reported from DIII-D and JET appears similar to previous results from MGI and shows effective mitigation of these loads. However, the compatibility of EM load mitigation with other mitigation objectives like runaway electron avoidance is not yet confirmed. Extrapolation from present devices also needs to take into account differences between ITER and current devices such as the location and the resistive time of passive conductors, especially that of the vacuum vessel. Reliable predictions from 2D and 3D codes would require self-consistent description of the halo region including appropriate boundary conditions.

*5.2.5 Runaway electron avoidance*

The efficacy of the ITER baseline runaway avoidance scheme to utilize SPI to inject massive amounts of hydrogen prior to the TQ remains uncertain, both from the point of view of SPI particle assimilation and RE seed generation and suppression physics.

Different injection schemes to achieve the goal of suppressing the formation of large runaway currents were discussed. The benefits of pure H injection compared to the baseline scheme of injecting Ne/H mixtures were again pointed out. Especially, the question whether dilution cooling can reliably suppress the hot tail formation mechanism. This is mainly related to the available time for cooling down before the onset of the thermal quench (see also 5.2.1). Another scheme that was discussed is based on successive injection of pellets into the early post-TQ plasma to suppress seeds before they can avalanche. Such a scheme would need injection of material with high stopping power, which may require injection schemes other than SPI. Experimental requirements to test such a scheme are seen challenging.

The role of reconnection on runaway formation was discussed with respect to the efficiency of de-confining seed runaways. It was questioned whether the seed population can be reduced enough that unmitigated avalanche would not result in a significant runaway current.

In general, experimental efforts are limited in this area due to diagnostic limitations for detecting the runaways in the early phase and for resolving the plasma parameters during the thermal quench. Interpretation and extrapolation will rely on 3D MHD simulations. The question was raised if the resolution of such codes is sufficient for addressing the runaway electron issue. In this respect, the role of current sheets and kinetic phenomena for runaway formation was mentioned.

*5.2.6 Runaway electron mitigation*

The combination of H2 or D2 SPI injection and kink activity presents a promising path for benign mitigation of an existing RE beam in ITER, but numerous questions remain. In particular, would the clean out of high-Z impurities occur faster than the ITER vertical instability timescale, and how does the degree of cleanout depend upon the initial high-Z content of the RE beam? Also, what purity is required to avoid magnetic-to-kinetic energy conversion after a large kink event and what will determine the purity after this event. Could multiple RE kink events be required as the RE current is lost and subsequently regenerated during the final loss?

*5.2.7 Technical Requirements*

It is essential for successful disruption mitigation in ITER that the experimental and modelling efforts on understanding and optimising the mitigation process with SPI result in technical requirements for the ITER DMS. The required information to design components such as the shattering unit or the pellet launching unit and to validate decisions on the number of pellets, on the injection locations and on the pellet parameters was briefly discussed. Amongst others, these are the main key questions:

* What is the optimum fragment size, velocity and velocity dispersion for maximum assimilation?
* What is the required pellet size, velocity, and jitter in arrival time?
* How many pellets can be efficiently superimposed?
* What is the peaking of the radiative heat flux?
* Can argon be replaced by neon for runaway electron mitigation?
* What are the needs on integrity, reliability and reproducibility?
* How much gas can be tolerated to enter the plasma before or together with the fragments?
* What are the optimal pellet parameters for post-thermal quench injection?

6. Mitigation – general

This session (chaired by N. Eidietis, S. Konovalov, and L. Zeng) with 5 invited and 5 contributed presentations was dedicated to disruption mitigation issues not specifically associated with SPI from the previous session. Two major topics were covered. The first, overlapping with the “Mitigation - SPI” session, was runaway electron physics, and in particular assessing how or if massive impurity injection could successfully avoid the production of runaway electrons. The second was alternative mitigation techniques to SPI, including electromagnetic mitigation of RE and novel impurity injection technologies.

6.1 Contributions summary

*6.1.1 Runaway electron formation and mitigation*

X. Tang (LANL) described progress in understanding RE energy control via wave-particle interaction (WPI). WPI can produce effective pitch-angle scattering for electrons under runaway acceleration by the parallel inductive electric field, impacting RE energy through resonant pitch angle scattering in momentum space and enhancement of spatial transport. External injection of specially designed fast electromagnetic waves (~500 MHz) can target RE at energies of 1 MeV or below because the damping of the wave is through the normal Doppler-shifted cyclotron resonance.

T. Fülöp (Chalmers University of Technology) presented an examination of the prospects for runaway electron avoidance with massive material injection in tokamak disruptions. Simulations indicate that, if losses due to magnetic perturbations are not taken into account, impurity injection leads to high runaway currents in ITER, even if it is combined with deuterium injection. The reason is that the cooling associated with the injected material leads to higher electric fields, which, in combination with the recombination associated with the low temperatures, leads to a large avalanche generation.

K. Särkimäki (Chalmers University of Technology) studied the transport in perturbed magnetic fields using an orbit-following Monte Carlo method to calculate the energy-dependent transport coefficients. The finite orbit width (FOW) effects were dominated by other effects arising from the non-uniform structure of the perturbation.

J.R. Martín-Solís (Universidad Carlos III de Madrid) presented a simple 0-D model, which mimics the plasma surrounded by the conducting structures, including the vertical plasma motion and the generation of runaways, which has been used for an evaluation of the runaway current dynamics during the disruption.

D. del-Castillo-Negrete (ORNL) introduced modelling and simulation of runaway’s spatiotemporal effects in dynamic scenarios, including comparative full orbit and guiding centre study of RE orbits in toroidal geometry, and comparative modelling and simulation study of RE dissipation by impurity injection.

*6.1.2 Alternative mitigation techniques*

R. Raman (University of Washington) provided an overview of alternate disruption mitigation methods for fast time response & core impurity deposition. These methods are intended to improve upon SPI by providing deep core impurity deposition, which modelling indicates may be superior to “outside-in” SPI mitigation, and faster response time to reduce the burden on disruption prediction algorithms. Technologies described included electromagnetic particle injection, two stage light gas guns, and shell pellet injection.

B. Kuteev (Kurchatov Institute) described a novel method for runaway avoidance in a tokamak reactor via reducing the seed electrons of avalanche. The concept envisions the rapid injection (via railgun) of an extended tungsten rod tangentially across a post-TQ plasma into a waiting collector. The extremely high stopping power of tungsten would suppress RE seed formation, with the long rod geometry providing both extended spatial and temporal regions of suppression. Modelling was presented to provide a conceptual design of the system and assess its efficacy.

Z. Chen (HUST) presented experimental results from J-TEXT on the effects of external magnetic perturbation on runaway transport. By application of RMPs, runaway suppression has been achieved by mode locking / mode penetration. Besides, runaway avoidance has been observed on DIII-D during plasma recovery from CQ by generating large core magnetic islands via 3D fields. An additional passive helical coil is designed in DIII-D and MHD modelling shows that it is effective at deconfining runaways.

V. Izzo (Fiat Lux) showed MHD modelling of dispersive shell pellet injection for disruption mitigation in DIII-D. An inside-out TQ has been simulated, consistent with the experimental results.

C. Clauser (PPPL) used M3D-C1 to study single C-pellet injection in NSTX-U to support electromagnetic particle injector (EPI) proposal.

6.2 Discussion and future work

The discussion mainly focussed on runaway electron related topics, but also touched on the possible benefits of injection methods others than SPI.

*6.2.1* *Runaway formation process*

Various aspects of the runaway formation process have been discussed and a centre point of the discussion was if runaway formation could be excluded for unmitigated disruptions in ITER. Although this is common observation for most devices, especially those with metal wall, there are various aspects that are different in ITER, including the many orders of magnitude higher avalanche multiplication, additional seed mechanisms during the active phase of operation (beta decay and Compton scattering), and possibly better confinement due to its size. Significant differences were found in DINA simulations in the required seed quantities to form a several MA runaway beam in ITER compared to other modelling activities. Here, it will be important to assess the impact of the equilibrium evolution during the avalanching phase and the currents induced in conducting structures that would reduce the flux available to drive the avalanche.

With respect to the ITER baseline scheme of massive pre-TQ hydrogen injection, the modelling of Fülöp et al. raises severe doubts as to the efficacy for RE avoidance, motivating further model refinements and perhaps requiring a focus on handling of an existing RE beam or alternate avoidance methods (e.g. from Kuteev’s or Raman’s talks described above).

Losses through reconnection are an important aspect of runaway beam formation. In this respect, the need to consider finite-orbit effects was discussed. The work of del-Castillo-Negrete et al. shows that orbits are more robust against stochasticity when compared to the guiding centre approximation. It was mentioned that a quantitative assessment of runaway de-confinement is difficult since the perturbation spectrum is in most cases poorly known.

With respect to MHD stability of the RE beam, it was noted that this is likely to depend on the initial seed profile shape. Knowledge on the radial runaway seed distribution is therefore required to predict the macroscopic behaviour of a fully developed RE beam.

*6.2.2* *Wave-Particle interactions (WPI)*

The self-excitation of waves has been looked at in the past and required plasma temperatures above those expected in mitigated current quenches. Active WPI was discussed as a possibility for runaway energy dissipation either in the avalanche phase or during the runaway beam phase. Application during the avalanche phase would reduce or suppress the avalanche through pitch angle scattering, but would require high wave amplitudes due to the large electric fields during this phase. In both phases, WPI is facing strong damping due to unfavourable plasma parameters. It was noted that wave accessibility and collisional damping are the main challenges for active WPI. Possibilities to overcome these such as wave burn-through making use of plasma heating associated with wave damping or impurity flushing during the RE beam phase to increase the temperature of the companion plasma were mentioned.

Experimental verification of active WPI in RE is highly desirable. New hardware, e.g. the helicon antenna on DIII-D, may allow such tests.

*6.2.1* *Resonant magnetic perturbation*

MHD, either induced by the plasma or imposed by external coils, has shown beneficial effects for suppressing runaway electron formation. It was mentioned that externally driven magnetic perturbations causing mode locking before the thermal quench can suppress runaways and could be adapted to maximise runaway electron losses. Further work would be needed to understand the difference between natural mode locking and that induced by external perturbations. In this context, revisiting the required perturbation amplitudes in ITER should be considered, especially also since previous work was focused on toroidal mode numbers larger than one when considering the use of the in-vessel ELM mitigation coils. With respect to reactor-scale devices beyond ITER, the possibility of conductive structures for the passive generation of helical currents to facilitate field line reconnection requires consideration.

*6.2.1* *Alternative injection methods*

Injection methods other than SPI and MGI have been rarely explored in experiments and their advantages for disruption mitigation could not be assessed in detail. Initial modelling has been performed (see Izzo’s talk), but more efforts with 3D resistive MHD simulations to assess the benefits of the inside-out cooling scheme for the various mitigation goals (including RE suppression) and to narrow down the required injection speeds and payload types. Simpler modelling with appropriate ablation physics could be thought of to identify how dominant core material deposition could be achieved. It was noted that uniform impurity deposition would still cause the edge to cool first due to the temperature sensitivity of the cooling power.

From the operational standpoint, it was mentioned that frequent injection of material that is not assimilated by the plasma could, depending on the required injection quantities, lead to machine deconditioning and excessive dust accumulation.

On the technology side, it was briefly mentioned that adaptation of the injection velocity might be required to account for varying plasma energies during a pulse. High-speed injection in a reactor environment will require specification and development of reliable containment mechanisms.

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