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ITER Disruption Mitigation Workshop, ITER HQ, 8 – 10 March 2017

AUTHOR/AUTHORS
Michael Lehen
So Maruyama

AUTHOR EMAIL(S)
Michael.Lehen@iter.org
So.Maruyama@iter.org

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Acronyms

DIII-D	<i>Tokamak operated by General Atomics</i>
DINA	<i>Free-boundary equilibrium evolution code</i>
DMS	Disruption Mitigation System
DT	Deuterium-Tritium
EM	Electro-Magnetic
FTU	Frascati Tokamak Upgrade
IO	ITER Organization
ITPA	International Tokamak Physics Activity
JET	Joint European Torus
MGI	Massive Gas Injection
MHD	Magneto-Hydro-Dynamics
ORNL	Oak Ridge National Laboratory
PFPO	Pre-Fusion Power Operation
RE	Runaway Electron
RES	RE Suppression
RF	Radio Frequency
SPI	Shattered Pellet Injection
TG	Topical Group
TLM	Thermal Load Mitigation
TQ	Thermal Quench
VV	Vacuum Vessel

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Executive Report

The disruption mitigation system (DMS) is a key plant system to ensure the reliable and successful operation of ITER from the first experimental campaign (Pre-fusion power operation 1 (PFPO-1)) onwards. A fully functional and effective DMS is essential for ITER to achieve its mission. The DMS baseline concept and design is based on present knowledge on disruption mitigation, which, nevertheless, remains subject to significant gaps in understanding, especially as concerns runaway electron (RE) formation and mitigation. This workshop was therefore launched with the following aims:

- Review the present understanding of the relevant physics and identify R&D needs to address gaps;
- Discuss the current conceptual and design status of the ITER DMS and, if possible, confirm the present approach, or identify issues that need to be addressed through near term R&D;
- Discuss the approach towards possible alternative concepts, or identify possible mitigation concepts that can be applied in addition to the baseline concept.

The participants to this meeting, 24 external experts from all Members' fusion communities and several senior ITER scientists and engineers, emphatically agree that immediate decisive action must be taken to directly support research into solutions to outstanding critical issues relating to the specification and performance of the DMS. The consensus is that significant uncertainties exist, in particular, as to whether the present baseline disruption mitigation system will offer sufficient protection to ITER from relativistic electron impacts. The need for a strong action plan for the future, such as a properly resourced international task force, has been expressed by workshop participants.

The workshop discussion was organised around 'focus issues' that were circulated prior to the workshop to allow participants to provide input to the scope of the discussions through modifications or additions to the initial list of issues. Three presentations introduced the present status of the physics basis and the DMS design. Some participants expressed the view that more time would be needed beyond that allocated for this workshop to discuss critical issues of the DMS and the physics understanding of disruption mitigation, in particular aspects relating to RE prevention. However, this workshop report has been developed to serve as a starting point for defining a detailed work program to solve DMS-related issues.

The unanimous conclusion of the workshop was that the urgent need for an improved framework to strengthen the coordination of the ITER Organization (IO) needs in the field of disruption mitigation and the supporting R&D programs in the member states should be communicated to the ITER leadership. This framework would need to include

mechanisms to promote a program preparing efficient commissioning and operation of the ITER DMS and to promote R&D on alternative injection schemes or mitigation concepts for risk mitigation.

There are several outstanding scientific questions which must be addressed to be able to specify a DMS design with sufficient confidence. Answers to these questions are needed on a short timescale. It is, therefore, considered very unlikely that relying solely on existing research programs in the member states will provide the required answers, since it is unlikely that they will be able to implement R&D activities with the necessary scope on the required timescale. Many workshop participants emphasized the need for a highly focussed effort, led by the ITER project itself and implemented in the Members' fusion communities by the Domestic Agencies as the Members' representatives of the ITER project. Such an implementation framework should directly support the most urgent research needs and coordinate the efforts of the existing programs to answer the outstanding scientific questions most expeditiously. The risks associated with the execution of the ITER Research Plan imply that the baseline design must be allowed to evolve as much as practicable until a satisfactory solution for the DMS is found. In the coming years, the R&D program in support of the DMS development will need to encompass a broader scope: not only should the implementation and exploitation of the baseline concept be investigated and characterized further, but alternative concepts with the potential to improve on the performance of the baseline concept, particularly as regards RE suppression or mitigation, should be investigated in sufficient depth to allow an adequate assessment of their feasibility and efficacy in the ITER environment.

The key outstanding issues that were identified are

1. Within the baseline ITER DMS concept, avoidance or suppression of RE during disruption mitigation cannot currently be guaranteed because of the present limitations in the physics understanding of RE generation and disruption mitigation processes, and the pending demonstration of the technical feasibility to inject and assimilate sufficient quantities of material before the thermal quench (TQ).
2. A self-consistent scenario for dissipation of a fully-formed RE plateau as a second layer of defence is not yet available. The present experimental and modelling database, together with the constraints associated with the ITER environment, puts the feasibility of any scheme based on massive high-Z injection in question.

The discussion on the physics basis focussed on three main topics: *runaway electron (RE) avoidance, RE energy dissipation and thermal quench mitigation*.

- **RE avoidance** has highest priority when operating the DMS. The injections to mitigate the thermal quench and to control halo current induced forces must ensure that REs are not formed during the mitigated disruption. The present concept to

avoid RE formation is to inject an admixture of hydrogen or deuterium with highly radiating impurities such as neon or argon. This scheme is effective in JET up to 3.5 MA, but is not confirmed for high current operation in ITER. The thermal quench mechanism and runaway seed formation are not well understood. Initial 1D simplified modelling has been performed, but more work is required on:

- improving the understanding of seed mechanisms (especially the so-called ‘hot tail’ mechanism);
- the role and optimisation of deep implantation of impurities or hydrogenic species;
- the role of field line tearing and reconnection;
- and the impact of plasma parameters, plasma heating and external magnetic fields on the effectiveness of this suppression scheme.

Should the quantities predicted by simple initial modelling be confirmed, this scheme will also require massive superposition of SPI prior to the TQ, which has not yet been demonstrated as technically feasible.

- **RE energy dissipation** is a second layer of defence should a RE beam have formed due to the ineffectiveness of RE avoidance. This scheme is based on massive injection of argon into the current quench of the disruption to dissipate the runaway energy on a fast timescale before significant energy is deposited on the first wall or divertor components. Recent simulations and experimental data show that the feasibility of this scheme is unproven. The assimilation of the injected particles has to be further assessed, since several MGI experiments observe very low efficiency and initial SPI tests in DIII-D confirm this trend. More experiments are planned at DIII-D and JET to test possible improvements with SPI. DINA simulations show that the required quantities are higher than previously predicted from kinetic simulations that did not take into account the plasma dynamics during the current quench. The ITPA MHD TG is establishing a multi-machine database which might allow for extrapolation to ITER through comparison with DINA simulations. The injection quantities currently estimated to be required to allow for both RE avoidance and RE energy dissipation are, based on present knowledge, beyond the present DMS capabilities. This implies that an additional equatorial port allocation to the DMS would be required.
- **Thermal load mitigation** requires injection of neon to radiate the plasma thermal energy on a rapid timescale. Uncertainties exist on the quantities required to achieve sufficient radiation levels. Moreover the quantities required for full mitigation might be in conflict with electromagnetic load mitigation, since, if the plasma current quench time is too short, excessive eddy current loads might be generated on the blanket modules. During the workshop discussion, the operational risk associated with this issue was regarded as non-critical, since any restriction on the injected quantities would result in partially mitigated (rather than entirely unmitigated)

thermal quenches. By the time that high stored thermal energies are achieved in DT operation, the disruptivity will, of necessity, be very substantially reduced (as a result of the learning process during the PFPO phase) so as to ensure reliable operation of ITER. This should ensure that the net melt damage due to disruptions in plasmas with high thermal energies is limited to an acceptable level. The quantities required to achieve acceptable thermal load mitigation will be confirmed during DMS commissioning, for which substantial operational time has been reserved in the ITER Research Plan. However, more R&D is required to obtain greater confidence in extrapolating to ITER and to establish a detailed disruption management plan for the experimental program.

Hybrid Shattered Pellet Injection (SPI) is the baseline DMS for both thermal and EM load mitigation (TLM) and RE suppression (RES). The hybrid SPI functions not only in the SPI mode, but also provides a capability for Massive Gas Injection (MGI) without forming pellets. The DMS is in the preliminary design phase and will be installed for PFPO-1 together with Diagnostic port plugs. The main outcome of the discussion on the DMS design and concept are summarised in the following.

- Most of the workshop participants concurred that the previously planned hybrid option for the DMS (MGI and SPI), as well as the in-port plug MGI valve planned for the non-active phase of operation are not essential and could be dropped. The performance of the MGI option is expected to be low due to the long and complex delivery geometry (simulations presented by the ORNL design team). The in-port-plug valve had been proposed by IO to reduce the risk of achieving insufficient warning times at the early stage of operation to allow injection via SPI before the thermal quench. However this risk can be regarded as low, since thermal loads are not critical during the early stage of operation, the current quench can still be mitigated even with late injection, and sufficient warning times are expected through locked mode detection for the pulse types planned for this stage. No disadvantages with SPI have been identified so far in terms of mitigation efficiency in DIII-D experiments. The benefits are a static muzzle break, reducing the risk of failure inside the port plug, and fewer penetrations.
- Three upper ports are allocated for TLM and 1 equatorial port for both TLM and RES. The present capabilities do not include redundancy and do not allow both RE suppression and mitigation in the same pulse, based on present projections. Services (gas feed, cryogenic lines, etc.) would need to be available in case upgrades of the DMS are required at a later stage. The requirement for symmetric injection needs to be revisited in the R&D program in case changes in injection location are needed.
- Multiple injections will be required to achieve the envisaged injection quantities. The effectiveness of this scheme requires that all injected pellets for TLM arrive within a short time window which is possibly of the timescale of the thermal quench. JET and

DIII-D experiments will aim at quantifying this timescale and the possible implications for the requirements on jitter and pellet speed variation. Synchronisation of injection will require the development of measurement techniques to determine the timing of the pellet/shard arrival at the tube exit.

- The injection angle in the upper port plugs in the present design does not allow the pellet shards to be directed towards the plasma centre, which can be critical for RE suppression or thermal load mitigation. Near-term R&D, including DIII-D experiments, will address the requirement for the injection angle.
- Flexibility in species composition for each injector is currently limited, since all three barrels in each injector are connected during the freezing process. Participants agreed on the need for higher flexibility to reduce the risks in achieving mitigation goals. Consequences on pellet composition for different sizes are to be assessed in the near-term.
- The present shattering concept results in a high fraction of gas and liquid that is co-injected with the pellet shards. Physics and engineering R&D is required to draw conclusions on the optimum gas/shard composition and to optimise the shattering process towards this optimum.
- When operating the DMS, diagnostics to detect that the pellet has been released on time and intact must be available to support post-injection analysis and possibly even correct for injection failure by modifying the injection sequence.
- The DMS design has to ensure the avoidance of gas penetrating the VV before the pellet fragments to prevent premature plasma cooling.
- A mechanical punch is required for pure Ne and pure Ar pellets, if all injection options are to be retained. D₂-coated Ne and, possibly, Ar/D₂ sandwich pellets would not require a punch. The punch reduces both the upper and lower velocity limits of the pellets and this could result in advantages with respect to the shattering process, but will probably also reduce the overall reliability. Retrofitting is, however, possible.
- Limited space, close proximity to diagnostic components and possible clashes with diagnostics inside of the port plugs and port interspaces pose multiple integration issues which will make future modifications to the DMS in response to operational experience difficult.
- Since the injection path of the upper port DMS is not straight and is likely to shatter pellets prematurely, spreading pellet shards in time and reducing the effectiveness of the DMS, pellet speeds may need to be limited to avoid premature fracture.
- The need for sufficient RE diagnostic capabilities in all phases of ITER operation required for testing and commissioning the DMS has been expressed during the preparation of the workshop, but was not followed up at the workshop itself due to time limitations.

In parallel to the implementation of the baseline DMS, medium-term R&D will have to focus on preparing effective operation of the ITER DMS and developing alternative injection schemes or mitigation concepts to be available should the DMS capabilities prove to be insufficient to achieve ITER's objectives. The concepts that were raised at the workshop are listed below. Their possible implementation in ITER requires the development of the design in close collaboration with the ITER Organization to a sufficient maturity, ensuring the compatibility of the design with the ITER environment.

- Alternative injection techniques should be explored: a) to improve penetration and the DMS response time; b) to improve assimilation; and c) to provide flexibility in species (including low Z). Possible candidate systems include compound pellets (cryogenic mixed with grains/powder), shell pellets, rail gun systems.
- The possibility of using sacrificial in-vessel structures to protect the first wall and in-vessel components from RE impact has been considered for many years. However such structures would necessarily have a substantial mass and, in the ITER environment, would need to be actively cooled. This requirement for achieving adequate cooling while avoiding the possibility that the structures would, themselves, be subject to water leaks then becomes the major challenge in demonstrating the feasibility of such an approach in ITER. On the physics side, further experimental and modelling studies on the RE energy deposition pattern would be a prerequisite for informing the detailed design and location of such passive protection structures,
- Other potential techniques mentioned by workshop participants for RE mitigation or avoidance are wave-particle interactions to actively slow down REs, enhancement of natural instabilities to increase scattering and radiation, and RF current drive. Position and current (ramp-down) control of disruption-generated RE beams has been successfully demonstrated in present tokamaks (e.g. DIII-D, Tore-Supra and FTU). However, the use of the in-vessel coils in ITER for increasing RE loss or controlling the RE beam position is not considered possible by the IO with a technically feasible design of these coils (due to previous analysis addressing such possibilities). IO also considers the required radial position control as too slow for these events due to the long vacuum vessel time constant.

Disclaimer

This report has been written with contributions from workshop participants to summarise the workshop outcome and to reflect the opinions of the participants on the disruption mitigation issue. The views and opinions expressed here do not necessarily reflect those of the ITER Organization. This publication is provided for scientific purposes only. Its contents should not be considered as commitments from the ITER Organization as a nuclear operator in the frame of the licensing process.