Annual report of the ITPA Topical Group on MHD Stability

For the period July 2009 to June 2010

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The Topical Group (TG) on MHD Stability held two meetings during the reporting period – (i) at Culham Laboratories, UK during October 6-9, 2009 and (ii) at NIFS, Toki, Japan during March 8-12, 2010. The Culham meeting was held in conjunction with an IEA Workshop (W70) on "Key ITER Disruption Issues" while the Toki meeting was held in jointly with a US-Japan Workshop on "Physics of MHD Control of Toroidal Plasmas". The two TG meetings derived a great deal of scientific benefit from the presence of these specialized workshops. At the Culham meeting the IEA workshop provided an excellent opportunity to devote major time and in-depth attention to several important disruption issues such as disruption mitigation, halo currents, disruption statistics and databases, runaways and heat loads, and disruption modeling. At the Toki meeting the focus was on the importance of 3-d effects in ITER and in drawing upon the common physics base of helical systems, tokamaks and reversed field pinches and tools developed in helical system research for addressing these 3-d issues in ITER. Detailed reports on the two meetings as well as the viewgraphs presented at the two meetings are available at the ITER website for ITPA. In this report we provide the main scientific highlights and progress made by the TG in its R&D efforts towards addressing the High Priority Research issues related to MHD stability for ITER. The report also summarises the progress achieved in the joint experiments during the year and the work carried out by six internal working groups that were formed during the Culham meeting with the goal of providing timely recommendations on urgent, short-term research questions.

Disruptions

The subject of disruptions continued to receive major attention during the year through joint experiments, development and updating of the experimental database and modeling efforts. The principal issues addressed were in the areas of disruption mitigation, halo currents, runaways and heat loads, and development of better disruption modeling. Valuable new experimental data was reported during the year from AUG and C-MOD on MGI radiation asymmetries following MGI for disruption mitigation. DIII-D reported promising first results from the shotgun pellet injector. The successful avoidance of disruptions by ECRH application was reported from FTU and AUG. Halo current measurements from NSTX, JET and DIII-D have provided valuable inputs for better modeling of halo widths. Disruption modeling efforts have shown a significant rise during the year with major initiatives using the TSC, DINA, M3D and NIMROD codes. A Task Agreement has been signed between the US, Japan and India to carry out improved halo modeling and provide useful projections for ITER. A parallel effort has also begun in EU to carry out similar work. Tore Supra and DIII-D have reported promising results on runaway control using resonant magnetic perturbations. The results of the joint experiment activities devoted to this topic (namely MDC-1, 16 and 17) are detailed in a later section of the report.

RWM, NTM, Sawteeth

There has been significant progress on issues related to control of various MHD modes. Experimental results from NSTX and DIII-D have demonstrated the significance of applied 3-D magnetic fields as a useful tool for the study and control of MHD stability in tokamaks such as control of locked modes, control of plasma rotation profile, triggering/suppression of ELMS, NTM stabilization, RWM stabilization, error field control and de-confinement of runaway electrons. A dynamic error field correction scheme using I-coils and C-coils in the feedback-stabilized regime of RWMs has been demonstrated on DIII-D to be very efficiant. High beta performance can be improved and sustained by n=1 active RWM feedback control and n=3 error field correction, and further improved with beta feedback control (NSTX) or with dynamic error field correction (DIII-D). This result was reproduced in NSTX at various plasma rotation speeds. The role of kinetic effects on RWM stability has been experimentally established in DIII-D through a measured rotation dependence of the plasma response to a quasi-static external n=1 field and compares favourably with theoretical predictions of kinetic stabilization by the MISK code. A systematic and detailed analysis of various strategies for control of NTMs using EC heating and ECCD in ITER has been developed. Although ECCD can modify the global q profile within r~0.3 and thereby control q0 in the advanced scenario it is felt that NTM stabilization may not be best for attaining the highest Q value. The best strategy might be to control sawteeth and use preemptive ECCD to control the seed island. Controlling the effective sawteeth period could also be the key for attaining the Q=10 operational goal. A fully integrated dynamical RWM control simulator in RFX-mod can potentially have an application as a “flight simulator” for active MHD control in tokamaks.

Progress on Joint Experiments:

MDC-1	**Disruption mitigation by massive gas injection**

Gas injection: The hypothesis that the arrival of the cooling front at the q=2 surface initiates the thermal quench is supported by most experiments.
Divertor heat loads and halo currents are reduced with noble gas (Ar, Ne) in pure form or mixed with light species such as He or D_2 (MAST, TEXTOR, JET). AUG has achieved 24% of the critical density for avalanche suppression, but with inhomogeneous density distribution. Commonly, the fuelling efficiency is found to be low for heavy gases like argon and higher for light impurities like helium. First results on injection of shattered cryogenic pellets were reported from DIII-D, with densities in the current quench comparable to those of the best gas injection cases.

Radiated power: Gas injection is shown to reduce divertor heat loads by a factor of 5 or more in AUG. However, neon injection in AUG shows still significant asymmetries during and after the thermal quench. Experiments in C-Mod, JET, and DIII-D show strong poloidal and toroidal asymmetries in radiated power at the start of gas injection, but the power symmetrizes within a few ms.

New gas valves and new diagnostics planned at many facilities.

MDC-2	**Joint experiments on resistive wall mode physics**

2.2. Resonant field amplification: Ideal MHD plasma response modeled with MARS-F and IPEC agree with magnetic and soft x-ray measurements in DIII-D up to a high fraction of the no-wall stability limit. Comparison of the measured plasma response to ideal MHD predictions is being successfully extended to *n*=3. In NSTX IPEC successfully restores the linear correlation of locking threshold with density in H-modes.

<u>2.3. Characterize RWM stability thresholds and destabilization mechanisms across machines:</u> NSTX observations of RWM onset at intermediate plasma rotation, and the measured rotation dependence of the n=1 plasma response in DIII-D, are both qualitatively consistent with MISK predictions of weaker RWM damping in the gap between precession and bounce frequencies. A recent DIII-D experiment (joint activity with JAEA) addressed the possible nonlinear relation between energetic particle-driven modes and RWM onset.

<u>Modeling:</u> The CarMa code is now capable of modeling the RWM in the presence of 3D conductors, plasma inertia, rotation and kinetic effects. CarMA modelling of RFX-mod is in good agreement with the effect of proportional gain on RWM growth rate. The convergence of multi-mode VALEN has been successfully tested against single-mode VALEN, and multi-mode VALEN can now calculate the time evolution of plasma response to time-varying external fields.

<u>Feedback stabilization:</u> RFX-mod experiments (joint JAEA/RFX-mod activity) show that RWM feedback is successful even with only partial (25%) coverage by control coils. Feedback stabilization will be considered as a topic for a possible new joint experiment.

MDC-4	**Neoclassical tearing mode physics – aspect ratio comparison**

Data is now available for the dependence of the NTM behaviour on the aspect ratio, and analysis is in progress. MDC-4 is likely to be concluded in the coming year.

<u>AUG - MAST</u>: Onset data for both the (3/2) and (2/1)-NTM have been collected and for most cases also a marginal stability threshold in H-mode is now available.
<u>DIII-D – NSTX:</u> Mainly data on the (2/1) mode has been collected. Onset beta and marginal beta values are consistent with present theories in terms of the correlation between the marginal island width and the ion banana width.

MDC-5	**Comparison of sawtooth control methods for neoclassical tearing mode suppression**

Modification of the sawtooth period has been achieved by tailoring energetic particle populations with ICRH or NBI and by driving current near q=1. Experiments and modeling show that ICRH destabilization of NBI-stabilized sawteeth in JET is a fast ion effect, not due to ion cyclotron current drive. Experiments in TORE-SUPRA, AUG and HL-2A have demonstrated ECCD destabilization of fast ion-stabilized sawteeth; the AUG experiments accomplished this with steerable ECCD. Real-time control of ECCD destabilization is being developed.

In general, it remains to demonstrate these methods at high-β_N where the NTM would be expected to be strongly unstable and in the presence of a significant population of fast ions in the plasma core.

MDC-8	**Current drive prevention/stabilization of NTMs**

<u>AUG</u>: Real-time ECRF mirror steering was demonstrated (feedforward only, so far).

DIII-D: On DIII-D, preemptive use of ECCD at q=2 was used to maintain stability of ITER demonstration discharges at the ITER collisionality and at lower rotation. Suppression of a locked mode was demonstrated, with combined ECCD and magnetic perturbations. HL-2A: Suppression of a 2/1 TM was demonstrated with ECRH heating near the q=2 surface. TEXTOR: The first use of real-time mirror ECRH steering to track and stabilize a 2/1 tearing mode was demonstrated, using a line-of-sight ECE diagnostic. Further experiments are planned in several devices on 2/1 NTM stabilization with feedback-controlled mirrors.

In general, it still remains important to confirm the power requirements for ITER, and the benefits of modulated ECCD.

MDC-12	**Non-resonant magnetic braking**

Non-resonant braking results are becoming available from a wide range of machines, and validation of Neoclassical Toroidal Viscosity models for rotation damping is in progress at MAST, JET, DIII-D, and NSTX.
The results for n=3 braking are in qualitative agreement with NTV theory. In DIII-D, the NTV torque from n=3 perturbations can maintain QH mode even with zero NBI torque. The n=3 torque shows a strong peak at low plasma rotation, in good qualitative agreement with NTM theory. NSTX also shows increased n=3 braking at low rotation, which may be the same effect. Non-resonant fields as a potential source of rotation drive for ITER is also an important area requiring further study.

MDC-13	**Vertical stability physics and performance limits in tokamaks with highly elongated plasmas**

Experiments and modeling have shown that in ITER-like DIII-D discharges, controllability decreases steadily during the current rampdown, but the control limit is not reached until the current goes below an ITER-scaled value of 1.4 MA.
Initial results from benchmarking comparisons of TSC and DINA show reasonable agreement in the early phases of VDEs and major disruptions. However, differences in the models lead to significantly different predictions of maximum halo current.
MDC-13 on vertical stability physics, controllability, and performance limits has been closed, and related outstanding issues described in the original joint experimental description are being considered for inclusion in a new MDC task.

MDC-14	**Rotation effects on neoclassical tearing modes**

14.1. Rotation and 2/1 beta limit**:** Cross machine scaling (DIII-D, JT-60U, JET, NSTX) has shown a dependence of 2/1 NTM stability on rotation shear. The theory is not yet resolved.

14.2. Role of error fields: NSTX and DIII-D experiments show that error field thresholds go to zero as the NTM beta limit is approached, due to enhanced magnetic braking that either drives locked modes directly or destabilizes delta-prime further, leading to rotating NTM. A new scaling was obtained for error field tolerance in torque-free H modes. Additional multi-machine studies are needed to confirm the trends vs. beta and rotation at ITER-relevant rotation, collisionality, q_{95}, etc.

14.3. Other physics impacting thresholds:
Resistive MHD modelling of JET discharges shows that the 2/1 NTM becomes more unstable as evolution of the q profile leads to an increase of magnetic shear (and hence less curvature stabilization).

MDC-15	**Disruption database development**

The International Disruption Database has been expanded to include scalar quantities associated with halo currents and electromagnetic impulse on the vessel. Initial data from AUG, DIII-D and NSTX have been submitted. Variables related to MGI experiments are currently being defined toward the next phase of expansion. An ITPA-sponsored presentation has been accepted for the 2010 Fusion Energy Conference.

MDC-16	**Runaway electron generation, confinement, and loss**

Measurements: New diagnostics are beginning to provide information on runaway electron dynamics, including gamma ray scintillator diagnostics on TEXTOR and DIII-D, and visible synchrotron imaging on DIII-D and C-Mod.

Modeling: NIMROD modeling of runaway electron orbits now includes relevant relativistic effects (drifts, acceleration, synchrotron and bremsstrahlung radiation, slowing down. Modelling of C-Mod cases matches the timescales & dynamics of the electron acceleration & loss.

Generation: On JET, analysis suggests runaway generation to be more complex than simple production via the classical Dreicer and secondary processes.

Confinement: On Tore Supra, DIII-D, and JET, active position control can hold the runaway electron beam in the chamber after the thermal quench. In JET, toroidal field ripple and applied n=1 and n=2 magnetic perturbations were ineffective at removing runaway electrons. However, argon changes runaway electron behaviour, suggesting the possibility of collisional removal.

Loss: NIMROD simulations of runaway electron confinement and loss are in progress for MGI disruptions in C-Mod and DIII-D. Previously TEXTOR and JT-60U have shown evidence for enhanced runaway loss with applied magnetic perturbations; a recent DIII-D experiment with the RMP coils is promising but needs better statistics.
Future experiments are planned to test removal or mitigation of a confined runaway beam using RMP, collisions (argon injection), and inductive electric fields.

MDC-17	**Active disruption avoidance**

At AUG and FTU, disruption delay or avoidance has been established with feedback controlled local ECRH at the resonant surface of the dominant MHD mode. HL-2A reported NTM stabilization using off-axis ECH near the q=2 surface. ECH near q=2 for improved stability is also used in DIII-D experiments for advanced scenario development. New DIII-D results show that locked mode islands can be stabilized by combined use of ECCD and magnetic perturbations. NSTX has made progress with real time beta and n=1 feedback control, which assist with disruption avoidance. A joint multi-machine scaling is in progress to provide data for predictions for the required

ECRH power at ITER.

The topical group will keep the scope of this joint experiment narrowly focused on the use of ECH and ECCD. Identification of further research needs could lead to additional joint research in related topics such as reliable early detection of disruptions and improved shutdown scenarios.

Progress on Working Groups:

Several new working groups were formed at the October 2009 TG meeting, with the goal of providing timely recommendations on urgent, short-term research questions. Since then, the groups have conferred by e-mail and videoconference. A significant amount of time at the March 2010 TG meeting was devoted to discussing the work of these groups. Progress to date is summarized below.

WG-1	**Waveforms of current in error field correction coils**
Hypothetical waveforms were developed that represent the extreme limit of what the error field correction coils might be asked to do with feedback-driven "dynamic error field correction." If evaluation by the ITER magnet group of these preliminary results shows that the resulting AC losses would be unacceptable, more realistic waveforms will be developed for further evaluation.	
WG-2	**Guideline for optimization of distribution of ferritic inserts**
The possible effects of resonant and non-resonant field errors that could arise from irregular ferritic inserts in some sectors were evaluated in the light of the recent test blanket module mockup experiment in DIII-D. A preliminary recommendation will be written.	
WG-3	**Power requirements for ECRH and ICRF control of sawteeth**
Nine subtasks were identified and begun. A multi-machine database has been established for the dependence of NTM beta limit vs. sawtooth period. Modeling of the fast ion distribution in ITER and its effect on the sawtooth period is in progress. Modeling of ECCD effects on the sawtooth period has begun, and current experimental results on modification of fast ion-stabilized sawteeth by ECCD and ICRF are being assessed. These activities are expected to be completed by Spring, 2011.	
WG-4	**Diagnostic requirements for MHD stability control**
It was agreed that the scope of this working group will be requirements for the physical quantities that should be measured, and not specific recommendations on the type, quantity, or location of the sensors. Leaders and potential contributors have been identified for subgroups on diagnostic requirements for various instabilities. Tables of requirements are now being circulated in draft form among the WG. This activity is expected to be completed by November 2010.	

WG-5	**Halo currents caused by disruptions**
Recent experimental data for halo current fraction and toroidal peaking factor is being evaluated, including frequency of occurrence, upper bounds, and discussion of one exceptional case. The ITPA disruption database (MDC-15) is expected to provide further data in the near future. A preliminary report is expected in June 2010. Comparison of experimentally measured halo current width and modeling predictions has begun. The issue of rotation of asymmetric halo currents was transferred to WG-6.	
WG-6	**Sideway forces on vacuum vessel and magnets caused by disruptions**
Experimental data (primarily from JET) have been developed toward a recommendation on the envelope for asymmetric halo current in the worst cases and the least bad 94% of cases. A recommendation on scaling of the time dependence from present machines to ITER was also discussed. After some further analysis of existing experimental data, a preliminary report is expected in the near future.	