Summary of the Meeting of the ITPA Topical Group on MHD Stability, Lausanne, Switzerland, October 20-22, 2008

The ITPA Topical Group on MHD Stability (reconstituted from the previous ITPA Topical Group on MHD Stability) held its first meeting at Lausanne, Switzerland during October 20-22, 2008. The meeting was kindly hosted by the Centre de Recherches en Physiques des Plasmas at the Ecole Polytechnique Federal de Lausanne. There were 35 participants (2 from the ITER IO, 3 from Japan, 10 from the EU, 1 from China, 1 from India, 1 from Korea, 3 from Russia and 14 from the US). Following an agreement between the ITER-IO and the ITPA Coordinating Committee (CC) early this year, ITPA now operates under the auspices of ITER and its new role is to provide a framework for ITER coordinated research program. The restructuring of the topical groups has also been carried out to address in a more focused manner the various long term and short term needs related to preparations for ITER operation. Keeping in mind this new role of the TG the agenda of the meeting (see Annex 1) was designed to mainly cover topics related to the High Priority Research areas in MHD stability for ITER. These were principally vertical stability, disruptions (control, mitigation and loads), NTMs, Error field effects, and RWM control. The meeting also discussed progress on the IEA-ITPA Joint Experiments related to MHD high priority research areas and gathered inputs for generating a comprehensive work plan for 2009 and beyond. There was a joint session with the Integrated Operations Scenario TG and the Energetic Particles TG and in addition a small sub-group also held an in-depth discussion on the status and future plans for updating the tokamak disruption database. The TG also heard a special presentation on Magnetics Diagnostic for ITER. Finally the venues for the next meeting was discussed – the next meeting is likely to be in Daejon, S. Korea, in the spring of 2009, subject to final confirmation and approval by the ITPA CC. Viewgraphs from the meeting are available at the ITPA website (http://itpa.ipp.mpg.de) and what follows is a brief summary.

Vertical Stabilization

Following the Design Review recommendations there has been a concerted effort over the past year to make a critical assessment of the vertical stability options for ITER based on experimental data and model studies and to define suitable baseline enhancements in the design provisions. Substantial progress was reported on this topic at the meeting. It was shown that multi-machine data have helped in defining metric specifications and to also validate theoretical scaling predictions. These studies have shown that safe operation of ITER requires a maximum controllable displacement ΔZ_{MAX} of at least 5% of the minor radius. The deployment of in-vessel coils is found to be the best and the only effective solution for providing control at high li and full elongation. As a result, two sets of 3-turn coils (anti-series) connected to 1 power supply are now part of the ITER baseline design. There are still some issues related to noise determined control limits, details of expected types of disturbances in ITER, their magnitudes and time histories that need to be addressed. It was further suggested that experimental and theoretical studies of vertical stability scaling limits with other performance parameters be also carried out. The up-gradation of the VS1 and VS2 systems (as suggested in the Design Review) was also recommended as a backup provision.

Disruptions

Disruption related issues remain a major concern for ITER design and operation. A number of important aspects of this topic were discussed at the meeting. It was pointed out that uncertainties in mechanical loads due to halo currents, disruptions and VDEs on the PFC and vacuum vessel have been identified as a major concern by STAC. The largest vertical force, calculated under the condition for the maximum halo current generation is 108MN with an uncertainty of 20%. Further improvements in the halo current modeling are needed to decrease the uncertainty and to improve the estimates for both mechanical and EM loads. A critical evaluation ("deconstruction") of the existing halo current database was presented highlighting the difficulties in arriving at a proper assessment of its collective attributes and in determining its implications for ITER design specifications. The study emphasized the need for further analysis and `renormalization' of the present experimental data set to extrapolate it to ITER operation and the necessity of generating additional data in the future from controlled experiments on present day large machines.

The characterization of runaway electrons (REs) generated during disruptions and their suppression, confinement/loss mechanisms constitute another major physics issue for ITER. Its present specifications are derived from a very limited database and analyses and further improvements are urgently needed. There is still a fundamental lack of understanding of several presently observed experimental findings related to conditions for generation of REs, threshold dependencies on B_t and q, effect of plasma facing components etc. Recent experiments on C-Mod have revealed interesting new results on the confinement/loss of LHCD enhanced runaways created during gas jet triggered disruptions. The lack of avalanching during these disruptions may be due to enhanced loss of REs due to other mechanisms which might relax the need for massive gas injection for disruption mitigation. However more controlled experiments over a wider range of equilibrium parameters and detailed model simulations are necessary to identify and confirm the existence of such a mechanism. MGI experiments carried out on ASDEX-U studied the dependence of fuelling efficiency on a number of parameters including the valve-plasma distance, the gas pressure, the type of gas, the gas quantity, the plasma energy etc. and found it to be independent of the gas pressure, the gas quantity as well as the plasma energy. Higher efficiency was observed for He compared to Ne. Simulation results using the code SOLPS were also presented to shed some light on the principle mechanisms.

NTMs

Experimental data from several tokamaks (DIII-D, JET, NSTX, JT-60U) show clear evidence of the effect of plasma rotation on the threshold β_N for the onset of an NTM. The threshold decreases as the amount of rotation is decreased either through the use of counter beams or using external braking mechanisms. However the threshold continues to decrease in the counter rotation direction particularly in the low rotation region. This dependence on the sign of the rotation is a puzzle and not yet well understood. Other experimental investigations have explored the scaling with ρ^* (found to be weak), flow shear, error fields and current profiles. Flow / flow shear can influence the island dynamics either through a change of $\Delta^/$ or by altering the inner layer dynamics e.g. through a modification of the polarization current term. It can also lead to a significant deformation of the island shape. Current theoretical models do not provide an unambiguous answer regarding the stability characteristics of the islands in the presence of flow that can help explain the experimental results. More detailed analysis of the existing data base and an integrated theoretical effort including simulation efforts on major codes are being planned. Recent experimental results from JT-60U emphasize the importance of phase matching in the control of NTMs using ECCD.

RWM control

New experimental results from NSTX, JT-60U and DIII-D are providing better insights into mechanisms governing the excitation, damping and control of RWMs. JT-60 reported the observation of a new branch of RWM – an energetic particle excited wall mode (EWM) whose impact on ITER needs to be assessed. NSTX reported significant progress in global mode feedback control (maintaining a long pulse plasma over the ideal $\beta_N^{no\text{-}wall}$ limit) and in the exploration of kinetic stabilization physics and magnetic braking research. The experimental control performance is found to be consistent with theory. DIII-D has reported stable operation beyond the no-wall β_N limit at nearly zero rotation profile and also identified two other interesting phenomena – the fishbone driven RWM in the high β advanced tokamak mode and the feedback suppression of current driven RWM in the low β regime. The ITER internal coil system studies have been done and found to predict a 50% increase in β_N over RWM passive stability. Benchmark tests and validation of various RWM codes (VALEN, STARWALL, CARMA) are in progress. Important issues identified for further work include incorporation of kinetic damping effects, multimodal analysis, specification of noise, effect of blankets and assessment of power supply requirements. The CARMA code can self-consistently analyze RWMs with 3D structures that can be useful to take into account effects from port extensions and other structures in ITER.

Error Field Control

Results from experiments on DIII-D show that resonant braking determines the n=1 error field threshold in NBI heated H mode plasmas leading to a loss of torque balance. However the overall error field tolerance is determined by both resonant and non-resonant effects as determined by the plasma response. More quantitative modeling of the plasma response is necessary to predict error field tolerance in ITER at high β_N for which appropriate validation of codes are in progress and further controlled experiments are planned.

ITER Magnetics Diagnostic

Jo Lister presented some of his SOFT 2008 conference slides on the ITER magnetics diagnostic with the aim of underlining one of his primary worries while assessing the risk of the diagnostic under an EFDA-funded Task. The presence of a large amount of magnetic material relatively close to the machine certainly will require compensation of the non-axisymmetric effects of this iron when mapping from the local measurements of fields to the 2D axi-symmetric equivalent. He called for anyone with experience of such compensation methods to contact him, and raised the question whether such issues are appropriate for this ITPA group which possesses considerable experience in the magnetics diagnostic.

Joint Experiments

Number	Description	Results presented at ITPA meeting
MDC-1	Disruption mitigation by massive gas injection	**Gas injection:** High fueling efficiencies during massive gas injection were achieved with an in-vessel valve in ASDEX-Upgrade and a multi-valve system farther from the plasma in DIII-D. With helium injection, Rosenbluth density fractions of 10% have been reached with helium (DIII-D) and neon (ASDEX-Upgrade). **Runaway electrons:** In C-Mod, suprathermal electrons generated by lower hybrid are lost without a runaway electron avalanche during the current quench of most disruptions; stochastic magnetic fields due to MHD activity are suggested as a possible explanation. **Halo currents:** In NSTX, halo currents during VDEs scale as Ip/q95, with a toroidal peaking factor well below the maximum scaling assumed for ITER. Re-analysis of the halo current database from *Progress in the ITER Physics Basis* shows significant variation in the quantity and range of data from different devices, indicating a need for caution in extrapolation from these data.
MDC-2	Joint experiments on resistive wall mode physics	**2.1. Critical velocity for RWM stabilization:** Results from DIII-D and NSTX indicate a strong contribution by kinetic effects to RWM stability at low rotation; the simple picture of a single critical velocity above which the RWM is stable may not be adequate. In JT-60U and DIII-D, transient MHD events (ELMs and fishbones) are observed to trigger RWMs in otherwise stable plasmas, in some cases leading to beta collapse. **2.2. Resonant field amplification:** Experiments in JET, NSTX, and DIII-D show increasing resonant

		field amplification above the no-wall stability limit, but differences in the threshold for a strong increase remain to be resolved.
MDC-4	Neoclassical tearing mode physics – aspect ratio comparison	No progress on this topic was reported at the meeting.
MDC-5	Comparison of sawtooth control methods for neoclassical tearing mode suppression	No progress on this topic was reported at the meeting.
MDC-8	Current drive prevention/stabilization of NTMs	JT-60U studies show that modulated ECCD is more efficient than cw (by a factor of two in these experiments) in stabilizing 2/1 NTMs. The expected strong dependence on the relative phase of the modulation was also measured.
MDC-10	Damping rate of intermediate-n Alfven eigenmodes	Transferred to energetic particles group.
MDC-11	Fast ion losses and redistribution from localized AEs	Transferred to energetic particles group.
MDC-12	Non-resonant magnetic braking	Non-resonant braking by an applied n=2 field was observed in NSTX; the braking increases with Ti as expected from NTV theory. DIII-D results with n=1 fields show strongest braking when the applied field matches the structure of the stable kink mode; non-resonant braking dominates at high rotation, and resonant braking at low rotation. Such braking decreases the tolerance to error fields.
MDC-13	Vertical stability physics and performance limits in tokamaks with highly elongated plasmas	C-Mod and DIII-D experiments show that safe operation requires the control system to recover from vertical displacements up to at least 5% of the minor radius. Data from C-Mod, DIII-D, JET, and NSTX, show typical noise levels in the control systems are equivalent to delta-Z/a~0.5-1%, while noise-abatement efforts have achieved lower levels in TCV. However, plasma disturbance such as ELMs can create larger perturbations (3% in DIII-D).
MDC-14	Rotation effects on neoclassical tearing modes	**<u>Rotation effects:</u>** Analysis of data from DIII-D, JET, JT-60U, and NSTX shows that the threshold for onset of NTMs decreases with decreasing toroidal rotation. The downward trend appears to continue as rotation passes through zero and becomes negative. The experimental results are most consistent with a modification of stability by the decreasing flow shear. DIII-D experiments indicate that the tolerance to error fields decreases

		as the NTM threshold is approached, by varying either beta or rotation. **<u>Critical beta for 2/1 NTM:</u>** Data from ASDEX-Upgrade, DIII-D, JET, JT-60U, and NSTX show that the underlying metastability threshold scales as rho*, and the marginal island width scales with the ion banana width. However, the rho* scaling appears not to apply to the onset of the 2/1 NTM, a potentially favorable result for ITER.

In addition, three new joint experiments related to disruptions were discussed and will be proposed to the CC. These are outlined below. (A fourth joint experiment on TBM effects in ITER was discussed but was ultimately rejected as being premature, since the capability to simulate the TBM in existing devices is limited.)

Number	Description	Proposed new experiment
MDC-15	Disruption database development	The goals are to use cross-machine data to: • Develop disruption science – Develop empirical scalings for disruption parameters – Validate disruption models over a range of machine sizes and operating regimes • Extrapolate disruption parameters to ITER – Provide confidence in design limits (EM forces, heat deposition) – Identify range of outcomes, worst-case limits – Provide input to detection & mitigation scenarios For 2009, the proposed work will focus on extending the database to include halo currents and related quantities, including halo current amplitude, toroidal peaking factor, vertical displacement of the plasma, and electromagnetic forces on the vacuum vessel.
MDC-16	Runaway electron generation, confinement, and loss	The goals are to use cross-machine data to: • Characterize runaway electron generation and confinement: energy spectrum, time scale, seed generation mechanisms, conditions for generation. • Test the hypothesis that the runaway level is related to discharge shaping. – NIMROD runs using a C-Mod low-κ discharge – Low elongation equilibria with LH-driven RE's • Provide the physics basis for approaches to runaway suppression and mitigation – gas injection – magnetic perturbations – position control of runaway electron plasma This topic may require collaboration with the Topical Group on Energetic Particles, e.g. for modelling of

		runaway electron orbits in a perturbed magnetic field.
MDC-17	Active disruption avoidance	This experiment builds on recent ECH results from FTU and ASDEX-Upgrade: • Quantify the requirements for postponement of disruptions with ECRH. – Effect of heating and torque from tangential NBI on the stabilization of disruption precursors. – Extend to H-mode plasmas, and conditions of an H-L transition induced by disruption precursors. – Develop criteria to determine the applicability of the technique, and boundaries between the use of disruption avoidance and disruption mitigation. • Explore other means of disruption avoidance, such as feedback stabilization or forced rotation of disruption precursors with nonaxisymmetric coils. • Investigate the combination of mode stabilization and fast current ramp-down.

Annexure 1

Agenda

1st Meeting of the ITPA MHD Stability Topical Group
CRPP, Lausanne, Switzerland

October 20-22, 2008

October 20 (Monday)

9:00	**Inaugural Session for all TGs at the Polydome**	
	- Welcome Address	A. Fasoli
9:30	Opening Remarks	A.Sen
9:40	Urgent needs for ITER	Yuri Gribov

(Coffee Break) 10:15 – 10:30

10:30	**Disruptions and Disruption Mitigation (Chair: Y. Gribov)**	
10:30	-Disruption runaway research in C-Mod	R. Granetz
10:50	-The ITER Halo Current Database Deconstructed	J. Wesley
11:10	-Massive gas injection on ASDEX Upgrade	G. Pautasso
11:40	- Current quench rates and halo current characteristics during disruptions in NSTX	S. Sabbagh

(Lunch Break) 12:00 – 13:00

13:00	**Disruptions and Disruption Mitigation (contd)**	
13:00	- ITER Issues and Modeling Needs for Disruptions and VDEs with emphasis on blanket and vacuum vessel loading conditions (STAC Issues)	M. Sugihara
13:20	- Kink mode model for calculation of disruption forces on vacuum vessel	L. Zakharov
13:40	- ITER Runaway Electron Workshop – outcome, issues, R&D and further works needs	M. Sugihara

14:00	**Common session with Energetic particles –TG (Chair: E. Fredrickson)**	
14:00	- Influence on sawtooth behaviour by NBI	S. Pinches
14:20	- Fast ion redistribution by MHD modes– ASDEX Upgrade experimental and modeling results	S. Günter

14:45	- Visible imaging of internal MHD and the fast ion profile in DIII-D	M. van Zeeland
15:10	– Discussion on tasks for the two TGs	

(Coffee Break) 15:30 – 16:00

16:00 Plasma Control Requirements (Chair: R. Granetz)

16:00	- Stabilization of plasma vertical displacements by in-vessel coils	Y. Gribov
16:25	- ITPA Joint Experimental Vertical Stability Studies for ITER Performance and Design Guidance	D. Humphreys
16:50	- ITER plasma vertical stabilization	A. Portone
17:15	- Active control results from RFX-mod	P. Martin
17:40	- Discussions	

18:00 Adjourn

October 21 (Tuesday)

9:00 Flow Shear Effects and NTMs (Chair: J. Wesley)

9:00	- Flow Shear and Islands in DIII-D	Rob LaHaye
9:25	- Studies of 2/1 NTM onset threshold vs. rotation and rotation shear in NSTX	S. Sabbagh
9:50	- Experimental observations of NTM rotation and error field dependencies and possible interpretations	R. Buttery

(Coffee Break) 10:20 – 10:50

10:50 Flow Shear Effects and NTMs (contd)

10:50	- m/n=2/1 marginal condition experiments in NSTX, DIII-D and JET	Rob LaHaye
11:10	- NTM stabilization experiments in JT-60U	A. Isayama
11:30	- ECCD efficiency for NTM control in sheared flow	S. Nowak
11:50	- Tearing mode stability in plasmas with sheared rotation	M. Furukawa
12:10	- Effect of Local Flow Shear on the Stability of Magnetic Islands in Tokamak Plasmas	F. Waelbroeck
12:30	- Discussion	

(Lunch Break) 13:00 – 14:00

14:00 Joint session with Integrated Operation Scenario group (Chair:)

- - Limits imposed on ITER plasma equilibrium - Baseline 2008 — Y. Gribov
- - Study of plasma initiation with TRANSMAK code — Y. Gribov
- - Simulation of 15MA and 17MA scenarios with DINA code — Y. Gribov

- - Preliminary study of early phase of plasma current ramp-up with DINA code — V. Lukash
- -Discussions

(Coffee Break) 16:00 – 16:30

16:30 Error Field Control & Locked Modes (Chair: V. Pustovitov)

16:30 -Stability and Error Field calculations with M3D-C1 — S. Jardin
16:50 - Magnetic braking and error field tolerance in high beta DIII-D plasmas — H. Reimerdes
17:10 - Statistical Analysis of Disruptions at JET — R. Buttery
17:30 - Discussions

18:00 Adjourn

October 22 (Wednesday)

8:30 RWM Control (Chair: A. Isayama)

8:30 - Multi mode VALEN results — G. Navratil
8:50 - Issues of RWM Stabilization in the DIII-D — M. Okabayashi
9:10 - Recent RWM control, stabilization physics, and non-resonant magnetic braking results in NSTX — S. Sabbagh
9:30 -High-beta MHD study in JT-60U — Go Matsunaga
10:10 - General formulation of the resistive wall mode coupling equations — V.D. Pustovitov
10:30 - RWM Modeling — F. Villone
10:50 - Discussions

(Coffee Break) 11:10 – 11:30

11:30 – 12:30 Joint Experiments (Chair: T. Strait)

MDC-1	Pressure and size scaling of gas jet penetration for disruption mitigation
MDC-2	Joint experiments on resistive wall mode physics
MDC-4	Neoclassical tearing mode physics - aspect ratio comparison
MDC-5	Comparison of sawtooth control methods for neoclassical tearing mode suppression
MDC-8	Current drive prevention/stabilization of NTMs
MDC-12	Non-resonant Magnetic Braking
MDC-13	Vertical Stability Physics and Performance Limits in Tokamaks with Highly Elongated Plasmas

MDC-14 Rotation effects on neoclassical tearing modes

(Lunch Break) 12:30 – 13:30

13:30 - 14:30 **Discussion on High Priority Research Topics for MHD Stability Group (Chair: A. Sen)**

14:30 **Concluding Session (Chair: A. Sen)**