Annual report of the ITPA Topical Group on MHD Stability

For the period June 2008 to July 2009

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The reconstituted Topical Group (TG) on MHD Stability held two meetings during the reporting period – (i) at CRPP, Lausanne, from 20th-22nd October 2008, and (ii) at Daejeon from 21st -24th April 2009. The Lausanne meeting was held in conjunction with the Energetic Particles (EP) TG and the Integrated Operation Scenario (IOS) TG while the Daejeon meeting was in conjunction with the EP TG. During this year the R&D efforts of the TG were primarily focused on High Priority Research areas in MHD stability for ITER with particular attention to urgent requirements during the design/construction phase. Some of the principal topics were disruptions and disruption mitigation, vertical displacement events, runaway electrons and control of plasma position and shape, resistive wall modes, error fields, neoclassical tearing modes and sawteeth. Detailed summaries of the activities in these areas as well as the viewgraphs presented at the two meetings are available at the ITPA website. In this report we provide the main scientific highlights and progress made in these high priority areas.

Vertical Stability

During the year there has been substantial progress in making a critical assessment of the vertical stability options for ITER based on experimental data and model studies and in defining suitable baseline enhancements in the design provisions. It has been established that max(Z_0)/a > 5% is necessary for a minimal robust control of vertical instability in ITER. It has also been shown that the deployment of in-vessel coils are 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. Some other important issues related to noise determined control limits, details of expected types of disturbances in ITER, their magnitudes and time histories have been identified and are the subject of ongoing investigations. A detailed theoretical model incorporating surface currents (so called `Hiro' currents) excited by a VDE associated kink mode has been used to explain and calculate the unusually large sideways force experienced by JET and to carry out model calculations for ITER.

Disruptions

Disruption related issues received major attention during the year in view of the urgent need to address ITER concerns about the resultant forces and for designing effective means of control and mitigation. The principal issues addressed by the TG were those associated with uncertainties in mechanical loads due to halo currents, disruptions and VDEs on the PFC and vacuum vessel, the characterization of runaway electrons (REs) generated during disruptions and their suppression, confinement/loss mechanisms and the physics and technological challenges of mitigation using Massive Gas Injection (MGI) schemes. Both experimental and modeling efforts were directed towards gaining a better understanding of the above issues. Model predictions of disruption forces were found to be in the range of 15% for current and 10-15% for impulse measurements in experiments. Experimental results of DIII-D on vacuum vessel (VV) impulses arising from VDE events were shown to support the premise that 'limitcase’ vessel forces in ITER may increase as Ip^2. Hence for a 17-MA operation one would either need to provide adequate structural capability and/or adopt a cautious ‘active detection and mitigation’ strategy. Results on disruption mitigation (DM) optimization experiments carried out in DIII-D with the MEDUSA injection valve using He was seen to give moderate halo mitigation and moderate to low VV impulse reduction. Similar MGI experiments on JET using a variety of gases and gas mixtures on different target plasmas (such as ohmic or NBI discharges) found an Ar/D_2 mixture to be the most suitable for mitigation leading to fast current decay and no runaway production. NSTX experiments showed the envelope of the halo current fraction to scale as the quench rate and the toroidal peaking factor (TPF) to scale inversely as the halo current fraction. Experiments on runaway suppression by MGI and RMP were carried out on a number of machines including ASDEX, JET and C-MOD. 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 from 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. Simulation studies on some of the principal issues associated with disruptions have been initiated using codes like SOLPS, NIMROD etc. The TG also undertook a detailed review of the status of the tokamak disruption database and put in to place a plan and procedure for updating the database.

Resistive Wall Modes and their Control

Significant progress was reported in the understanding of mechanisms governing the excitation, damping and control of RWMs from experimental results obtained on NSTX, JT-60U and DIII-D and from various codes like VALEN, STARWALL and CARMA. 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 $\beta_N^{\text{no-wall}}$ limit) and in the exploration of kinetic stabilization physics and magnetic braking research. DIII-D 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. Detailed simulation studies of the sensitivity of RWM growth rates to modeling features of the ITER vacuum vessel as well as to the plasma q profiles were carried out. The role of kinetic effects and plasma rotation on the RWM growth rates was theoretically explored with the MISK code and the results compared to experimental findings on the NSTX. Fast particles were seen to have a stabilizing effect on RWMs whereas relatively high levels of plasma rotation could make them unstable. The study emphasized the need to gain a better understanding of the physics of global mode stabilization in order to obtain a realistic prediction for ITER scenarios. The VALEN-3D code was used to explore the role of sensor noise on the power requirements and the importance of early detection and control of the RWM was pointed out. Experimental studies also showed that current driven RWMs are more reproducible and are a good substitute for pressure driven RWMs for carrying out controlled feedback studies. RWM stability studies were further advanced through the study of a stable driven kink mode in DIII-D. External and internal measurements of the plasma response to externally applied n=1 fields were obtained over a wide range of normalized plasma beta and current and compared to model predictions of the MARS-F code. It was found that ideal MHD alone can describe the perturbed magnetic field measurements for values of β_N up to approximately 70% of the n=1 no-wall limit. The plasma response depends strongly on the match of the applied field structure to the kink mode and at and above the no-wall limit, it is strongly modified by non- ideal effects (e.g. kinetic effects).

Error Field Control

Experimental and modeling results indicate that both resonant and non-resonant effects as determined by the plasma response determine the overall error field tolerance. 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. A new theoretical model for the calculation of error field induced electromagnetic torque on a toroidal plasma showed that the torque maximizes at the resistive wall stability limit rather than at the no-wall stability limit. Further there was no rotation barrier at $\beta << \beta_{RWM}$ and it peaked for $\beta \rightarrow \beta_{RWM}$.

Neoclassical Tearing Modes

An important topic of discussion in this area was the influence of rotation and rotation shear on the stability of 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. Detailed analysis of the existing database and an integrated theoretical effort including simulation efforts on major codes are being planned to elucidate these issues. There have also been on-going efforts to devise optimal ECCD deposition and control schemes for NTM suppression and obtain more accurate power estimates for ITER. Experimental results from JT-60U also emphasized the importance of phase matching in the control of NTMs using ECCD.

Joint Experiments

A summary of the status (ongoing, new, closed), primary objective and participating machines is given below. For more details on the results please refer to the detailed reports on the meetings at Lausanne and Daejeon on the ITPA website.

- MDC-1 - Disruption mitigation by MGI
  - Gas injection (DIII-D, JT-60U, JET, Tore Supra, TCV)
  - Radiated Power (DIII-D, JET, C-Mod)
  - Runaway electrons (C-Mod, Textor)
- MDC-2 - Joint Experiments on RWM
  - 2.1 Critical velocity for RWM stabilization (closed)
  - 2.2 Resonant Field Amplification (JET, DIII-D)
  - 2.3 Characterize RWM stability thresholds and destabilization mechanisms across machines (New activity): (Modeling using MISK, MARS-K, CARMA, VALEN etc.)
- MDC-4 - Neoclassical Tearing Mode physics – aspect ratio comparison (MAST & ASDEX; NSTX & DIII-D)
- MDC-5 - Comparison of sawtooth control methods for neoclassical tearing mode

Suppression (ASDEX-U, JET, TCV)

- MDC-8 - Current drive prevention/stabilization of NTMs
  (DIII-D, Textor, ASDEX-U, JT60-U)
- MDC-12 - Non-resonant magnetic braking (NSTX, DIII-D, JET)
- MDC-13 - Vertical stability physics and performance limits in tokamaks with highly elongated plasmas (DIII-D)
- MDC-14 - Rotation effects on neoclassical tearing modes (DIII-D, JET)
- MDC-15 - Disruption database development (New task)
- MDC-16 - Runaway electron generation, confinement, and loss (New task) (TEXTOR, JET)
- MDC-17 - Active disruption avoidance (New task) (FTU, ASDEX, JET)

Future Meetings

The next meeting of the TG is proposed to be held in Fall'09 at the Culham Science Centre, Culham, UK.