ITPA Topical Physics Group on "Integrated Operation Scenarios"
Report of Activities in the period of July 2008 – July 2009

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The Steady State Operation (SSO) topical group (the TG) was reorganized to a group with a new name "Integrated Operation Scenarios (IOS)" in 2008. The general scope of the IOS TG is to contribute to establishing operational scenarios in burning plasma experiments, especially, candidate scenarios in ITER, including standard inductive operation, Hybrid operation and steady state operation.

High priority research topics in 2008 – 2009 (as approved by the ITPA-CC, July 2008)

- Joint experiments: Focus on qualifying candidates for ITER scenarios.
- The breakdown, current rise and ramp down of ITER. Joint experiments and code simulations.
- Actuator code benchmarking with the emphasis on NBCD (code benchmark + joint experiments).
- Continue the focussed modelling-benchmark activity on ITER Hybrid, current rise and steady state scenarios, using common input data.

TG Meetings

The TG had two meeting in the period:

The 1st IOS TG meeting:
CRPP, Lausanne, Switzerland, 20th – 22nd October 2008, ~30 participants

The 2nd IOS TG meeting:
JAEA, Naka, Japan, 31st April – 3rd May 2009, ~ 40 participants

In these meetings, the progress on the related research was reported and discussions on future issues and coordination were held. The 1st meeting followed the IAEA 22nd Fusion Energy Conference held at Geneva. Two sessions were shared with the MHD TG and the Energetic Particle TG respectively. At the 2nd meeting, one day was shared with the Transport & Confinement TG and common issues on the H-mode transition and the ramp-up and down were discussed.
The TG acknowledges the effort of the local organizers to hold these meetings.

Summary of the activities

Summary of the activities during the period in areas of the group's focus are summarized:

Joint experiments

The following joint experiments were proposed for 2008 by the SSO TG.

SSO-1: Document performance boundaries for steady state target q-profile.
SSO-2.1: Qualifying hybrid scenario at ITER-relevant parameters.
SSO-2.2: MHD effects on q-profile for hybrid scenarios (joint with MHD-TG).
SSO-2.3: ρ* dependence on transport and stability in hybrid scenarios (joint

with TP-TG).

SSO-3: Qualify real-time profile control methods for hybrid and steady state scenarios.

SSO-PEP-1: Documentation of the edge pedestal in advanced scenarios. This is a joint proposal with the Pedestal TG (formerly called SSO-4).

SSO-5: Simulation and validation of ITER start-up to achieve advanced scenarios.

SSO-6: Ability to obtain and predict off-axis NBCD.

In addition, the following experiments were proposed from the IOS TG for 2009.

IOS-1.1: ITER demo, at q_{95}=3, β_N=1.8, n≤0.85n_{GW}

IOS-1.2: Study seeding effects

IOS-2.1: ECRH breakdown assist at 20° toroidal angle (from SSO-5)

IOS-2.2: Ramp-down from q_{95}=3

IOS-3.1: Beta limit for AT with ITER recommended q-profile. (from SSO-1)

IOS-3.2: Define access conditions to get to SS

IOS-4.1: Access conditions for hybrid with ITER-relevant restrictions

IOS-4.2: ρ* dependence on transport and stability in hybrid scenarios (from SSO-2.3)

IOS-5.1: Ability to obtain and predict off-axis NBCD (from SSO-6)

IOS-5.2: Maintaining ICRH Coupling in expected ITER regime

IOS-6: Modulation of actuators to qualify real-time profile control methods for hybrid and steady state scenarios (from SSO-3)

Concerning SSO-1 and IOS-3.1, DIII-D demonstrated full-CD in the ITER shape and the operational boundary was studied. JT-60U reported sustainment of high β_N ~3 > $\beta_N^{no\text{-}wall}$ in a WS plasma and achievement of high β_N ~2.7 at q_{95} ~5.3 and q_{min} ~2 with high f_{BS} ~0.9 in an RS plasma. Also full CD of a WS plasma by combining LHCD+NBCD was demonstrated in JT-60U. JET low field experiments at steady-state relevant q_{95} have extended the domain at high β_N (~3) to higher confinement (H_H ~1.3/q_{min} ~1, H_H~1.2/q_{min} ~2) using an I_p overshoot technique. High performance at q_{min} ~2 has also been extended to higher field (up to 2.7T). NSTX showed extension of high β_N sustainment by improved control. In the area of SSO-2, in DIII-D good advanced inductive performance was demonstrated in the ITER shape, and ELM suppression was obtained in an advanced inductive scenario. In JET, the I_p overshoot technique was adopted also in the hybrid domain (in fact, firstly to hybrid then to steady state discharges), the technique lead a broader q profile and higher confinement and β_N. JT-60U demonstrated long sustainment (25s ~14τ_R) of $\beta_N H_H$ >2.6 in a hybrid discharge. Alcator C-Mod started exploration of a hybrid plasma using LHCD in the current ramp-up. Concerning SSO-3 (IOS-6), JT-60U data were analyzed with the same technique adopted by JET. In addition to kinetic and q profiles, the response function for

the toroidal rotation profile was also investigated. SSO-5 is tightly related to one of the high priority research topics of the group in 2008 – 2009. DIII-D demonstrated access to the hybrid scenario at high performance with the new ITER start-up scenario. Experimental results were compiled and presented at the 22nd IAEA Fusion Energy Conference at Geneva. A large effort was focused on modelling the ramp-up phase, which will be presented in a later section. Some of the issues concerning the plasma break-down with ECRF were raised in IOS proposal IOS-2.1. Some results have already been obtained and presented at the 2nd meeting. Several machines, DIII-D, QUEST and KSTAR, showed that an optimal magnetic geometry prior to breakdown with ECRF could be different from an ideal null-point configuration. Significant progress was obtained under SSO-6 (IOS-5.1). This will be presented in a later section.
Some of the IOS proposals for 2009 are new proposals, and have already produced results. Concerning IOS-1.1, DIII-D demonstrated standard scenario with ITER shape at β_N =1.8 and I/aB=1.42. A concern on 2/1 tearing mode for the demonstration discharges was raised. This should be investigated further in the joint experiments. JET has also started to work for this proposal. In the area of IOS-1.2, ASDEX-Upgrade, a fully tungsten coated tokamak, reported successful operation (though in a hybrid) using continuos deuterium fuelling, nitrogen seeding for radiation control. JET reported benefit of Nitrogen seeding in reducing heat load at the outer hit point in comparison with Neon seeding. DIII-D reported importance of ExB drift direction in the divertor/SOL. On IOS-2.2, DIII-D demonstrated successful replication of ITER ramp-down scenario and excellent shape control at ramp-down. JET investigated "controlled" and "emergency" ramp-down. On IOS-3.2 and 4.1, discussion to detail conditions and assessment accordingly are underway with JET and DIII-D for the time being, data will be joined from other machines. Concerning IOS-4.2, data have started being collected in JET. For IOS-5.2, in addition to the existing data from Alcator C-Mod, ASDEX-Upgrade, DIII-D, NSTX, ToreSupra and JT-60U, new data from the JET ITER-like antenna will be added to complete the proposal.

Actuators (heating and current drive), modelling and benchmark

Since the SSO TG era, assessment of capabilities of the actuators (NB, ECRF, ICRF and LHRF) has been intensively carried out by the topical group, in both experiment and modelling. Validation of NBCD, especially off-axis, is closely related to one of the high priority research topics of the group in 2008 – 2009 and was nominated as one of Joint Experiments not only for the SSO TG but also for the IOS TG (SSO-6 & IOS-5.1). This has been investigated since the SSO era, and progressed also in the period of this report. A systematic study of off-axis NBCD was carried out in DIII-D. The experimental results were found to agree well with the NUBEAM calculation and off-axis NBCD did not seem more prone to anomalous fast ion transport than on-axis NBCD. JT-60U also reported that the peak of the NB driven current almost agreed between the experiments and the simulation (ACCOME, OFMC). Concerning EC, it could be said that code benchmark activity was almost closed. Application of the EC codes has shifted to scenario development. In the area of ICRF, results of the ICRF simulations on

ITER and current devices (Alcator C-Mod, DIII-D, NSTX, JT-60U and so on by AORSA, PSTELLION, TASK) were presented at the meetings. The 3-D full wave approach has made progress. Since it is important to assess ICRF for ITER, it was agreed to launch the IC code benchmark activity. For LHCD, comparison with some codes, CQL3D and LSC, was carried out. An assessment of actuators, alone and in combination, has been increasingly required. An assessment of NBCD and LHCD on Scenario 4 using the ACCOME code was presented. It was shown that even with NBCD only, q_{min} can be maintained above 2, and LHCD is effective in controlling the shear reversal point.
At both meetings, "counter ECCD on ITER" was discussed. Prior to the second meeting, the pros and cons for installing counter ECCD on ITER were collected. Although some objections and concerns were raised at both meetings, no strong supporting agreement for or against counter ECCD was reached by the group.

Scenario modelling and benchmark

In addition to the actuator activity, modelling and simulation of operation scenarios for ITER continues to be an important area and has been intensively carried out since the SSO TG era.
In this period, modelling of the ramp-up was one of the most important issues. Various codes joined the activity (TSC, CORSICA, TASK, ASTRA, DINA, TRANSP, etc.). A large effort was given to comparison of the modeling with the results of the existing experiments, especially those of ITER ramp-up experiments. Though comparisons between the experiments and modelling have shown agreement to some extent, tuning of the assumptions of the models were often required. A more versatile validated model for the ramp-up applicable to ITER is required. Concerning the importance of the ramp-up modelling, a joint session between the T&C group was held at the 2nd meeting at Naka. Many contributions were made from both groups and vital discussions were held. Even with the T&C group, more effort for achieving a robust model was recognized.
Though, a common model was not established, the effort to simulate ITER scenarios has made progress, eg. validation of operation in terms of constraints on the poloidal coils and their power supplies. Concerning the ramp-up, effects of heating and current drive were also investigated. The largest contribution of auxiliary power to save poloidal flux in the ramp-up is electron heating.
Simulations of a whole discharge have also been carried out (PTRANSP, TSC, DINA, TASK, ASTRA etc.). These simulations also contributed to clarifying the engineering limitations of the operational space . The impact of a change in impurity transport, edge temperature etc. on the ITER baseline scenario was assessed. Assessment of different heating mixes on the ITER scenarios was raised as a new and important issue. Simulations for the ITER baseline scenario did not find a big impact of the heating mix.
A benchmark of the Steady-State scenario modelling is still ongoing. For the time being, CRONOS, TASK, TOPICS, ONETWO and ASTRA are joining. Enhancement of commonality of assumptions/inputs including equilibrium would be required. In this area, more codes, and projects like SWIM (Simulation of wave

Interactions with MHD) are ready to join.

Collaboration with other TGs

Energetic Particle TG:
At the 1st meeting, one session was shared with the EP TG. NBCD issues and current drive by the alpha particles were discussed. For future collaboration, the IOS TG asked for some input from the EP TG concerning the limitations related to the high energy ions which were important in scenario development. J. Stöber was chosen as a contact person from the IOS TG.

MHD Stability TG:
At the 1st meeting, one session was shared with the MHD TG. At the joint session with the MHD TG, simulations on breakdown and baseline full scenario modeling by DINA and TRANSMAK were presented. Issues related to MHD in scenario development were discussed, such as the l_i limitation for the vertical instability and beta limit in the SS scenario. Issues which require inputs from the MHD TG were listed. T. Luce was chosen as a contact person from the IOS TG.

T&C TG:
As described above, the first day of the 2nd meeting was shared with the T&C TG for discussions on the L-H transition and ramp-up/down issues. Requested inputs from the T&C TG to the IOS TG were presented at the meeting.

The IOS TG greatly appreciate valuable discussions at the joint sessions and effort and discussions dedicated to our requests afterwards by those TGs.

Presentations and publications

The 22nd IAEA Fusion Energy Conference:
"Experimental Studies of ITER Demonstration Discharges", A.C.C. Sips, et.al., IT/2-2
"Development of ITER 15 MA ELMy H-mode Inductive Scenario", C. Kessel, et.al., IT/2-3
"Integrated modeling of steady-state scenarios for ITER: physics and computational challenges", G. Giruzzi, et.al., IT/P6-4
"Benchmarking of Neutral Beam Current Drive Codes as a Basis for the Integrated Modeling for ITER", T. Oikawa,et.al., IT/P6-5

Journals:
"Experimental Studies of ITER Demonstration Discharges", A.C.C. Sips, et.al., to appear in NF.
"Development of ITER 15 MA ELMy H-mode Inductive Scenario", C. Kessel, et.al., to appear in NF.
"Benchmarking of Neutral Beam Current Drive Codes as a Basis for the Integrated Modeling for ITER", T. Oikawa,et.al., to appear in NF.

High priority research items for 2009 – 2010

For 2009 – 2010, the IOS-TG has contributions to the following for the high priority research items for the TG, including response to ITER's research needs.

1. Joint experiments: mainly focus on,
   - Demonstration of the ITER standard scenario.
   - Assessment of the ITER ramp-down scenario.
   - Assessment of the access conditions for advanced scenarios.
   - Requirements for plasma/scenario control.
2. Actuators (heating and current drive):
   - Assessment of actuators and heating mix, both experiments and modelling.
3. Scenario modelling:
   - Modelling of experimental data, ramp-up/down and demo discharges.
   - Modelling benchmark, especially hybrid and steady-state scenarios.
4. Scenario development:
   - Stable/routine operation of the ITER standard scenario.
   - Hybrid scenario: Develop and compare the results obtained in many devices.
   - Continue the assessment of candidates for ITER SS operation with q-min close to 2.
   - To detail and add ITER scenarios, in addition to the main scenarios.

The 3rd meeting of the TG will be held at Frascati, Italy hosted by ENEA, 20th – 23rd October.