

ITPA Topical Physics Group on “Integrated Operation Scenarios”  
Report of Activities in the period of July 2009 – July 2010

*S. Ide, G. Sips and J. Snipes, August 2010*

The general scope of the “Integrated Operation Scenarios (IOS)” topical group (the 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**

1. Joint experiments: main focuses 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 on 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.

**TG Meetings**

The TG had two meetings in the period:

The 3<sup>rd</sup> IOS TG meeting:

ENEA, Frascati, Italy, 20<sup>th</sup> – 23<sup>rd</sup> October 2009, ~40 participants

The 4<sup>th</sup> IOS TG meeting:

PPPL, Princeton, USA, 20<sup>th</sup> – 23<sup>rd</sup> April 2010, ~ 35 participants

In these meetings, the progress on the related research was reported and discussions on future issues and coordination were held. Also, ITER research needs and its status, status and progress in ITER program (especially hardware design) were reported from the IO.

It is noted that at the 4<sup>th</sup> meeting most of the EU participants were not able to join due to the flight limitation caused by a volcanic eruption in Iceland.

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 experiments were proposed from the IOS TG for 2009.

- IOS-1.1: ITER demo, at  $q_{95}=3$ ,  $\beta_N=1.8$ ,  $n \leq 0.85 n_{GW}$
- IOS-1.2: Study seeding effects
- IOS-2.1: ECRH breakdown assist at 20° toroidal angle
- IOS-2.2: Ramp-down from  $q_{95}=3$
- IOS-3.1: Beta limit for AT with ITER recommended q-profile.
- IOS-3.2: Define access conditions to get to SS
- IOS-4.1: Access conditions for hybrid with ITER-relevant restrictions
- IOS-4.2:  $\rho^*$  dependence on transport and stability in hybrid scenarios
- IOS-5.1: Ability to obtain and predict off-axis NBCD
- IOS-5.2: Maintaining ICRH Coupling in expected ITER regime
- IOS-6.1: Modulation of actuators to qualify real-time profile control methods for hybrid and steady state scenarios

In addition, followings were proposed for 2010

- IOS-5.3: Assessment of lower hybrid current drive at high density for extrapolation to ITER advanced scenarios
- IOS-6.2: li controller ( $I_p$  ramp) with primary voltage / additional heating
- IOS-6.3: Control of experimentally simulated burning state

And these two proposal were closed in 2009

- IOS-2.1: ECRH breakdown assist at 20° toroidal angle
- IOS-5.1: Ability to obtain and predict off-axis NBCD

Concerning IOS-1.1, following the results of the past years efforts to establish and/or improve demonstration discharges were continued in machines (Alcator C-Mod, ASDEX-U, DIII-D, JET). Alcator C-Mod continues to optimize the ITER standard scenario demonstration discharge. A standard scenario demonstration discharge was obtained with the 3<sup>rd</sup> harmonics X-mode EC heating in ASDEX. DIII-D obtained a 17 MA equivalent demonstration discharge. JET extended the standard scenario demonstration up to 4.5 MA. Operational margin, plasma characteristics were also investigated.

For IOS-1.2, changes in confinement characteristics depending on radiation fraction and/or seeding species, effect on ELM and compatibility with the RMP coil were reported from machines (Alcator C-Mod, ASDEX-U, DIII-D, JET).

On IOS-2.1, data from several machines both new and past experiments and not only from tokamaks but also stellarator were investigated (ASDEX-U, DIII-D, FTU, JT-60U, KSTAR, TJ-II, Tore Supra). Most of the data indicate that oblique injection would not have serious problem for plasma breakdown.

Concerning IOS-2.2, many intensive efforts have been carried out in many machines (ASDEX-U, Alcator C-Mod, DIII-D, JET) and ramp-down

demonstration discharges were obtained successfully. Ramp-down rate, heating off timing, plasma cross section and so on were scanned to identify operational limitation and issues. Proposed ramp-down scenario for ITER was found to be appropriate.

On IOS-3.1, analysis of the past data (ASDEX-U, DII-D, JET, JT-60U) has been continued and will be finalized soon.

Both IOS-3.2 and 4.1 are newly proposed for 2009. A set of variables has been agreed as the starting point for a private database and discussions with data providers have begun.

Concerning IOS-4.2, identity experiments between DIII-D and JET were performed successfully.

For IOS-5.1, data from machine (ASDEX-U, DIII-D, JT-60U, MAST) had been analyzed. When injected power is relatively low and a target plasma is quiescent, NBCD profile (either on-axis and off-axis) can be explained by cod simulation.

IOS-5.1 is agreed to be closed at this stage. Further investigation will be important for higher power or higher bulk plasma and/or energetic particle pressure cases. A new proposal will be submitted either from the IOS TG or other TGs when it will be required.

Concerning IOS-5.2, conditions to improve ICRF coupling mainly in view of gas puffing have been investigated using data from machines (Alcator C-Mod, ASDEX-U, DIII-D, JET, JT-60U, NSTX, Tore Supra).

IOS-5.3 was newly proposed for 2010, which was motivated by the experimental results of Alcator C-Mod, JET and FTU. IN addition to the new proposal for experiments, analysis of the above mentioned experiments by a code with new mechanisms (GENRAY-CQL3D) are on-going.

IOS-6.1 has shown constant progress since the Steady State Operation (SSO) TG era. Control-oriented magneto-kinetic system identification routines have been gradually implemented and validated (JET, JT-60U). New data were collected from specific DIII-D experiments in November 2009 with 5 actuators driven by the Plasma Control System, thus preparing for closed-loop operation. A satisfactory model has been obtained for magnetic profile control, and magneto-kinetic models are being validated.

Both IOS-6.2 and 6.3 were newly proposed for 2010. Approaches have been examined based on the related experiments performed previously.

As He H-mode in ITER is of great interest, results of He experiments were reported from machines (Alcator C-Mod, DIII-D, JET, NSTX) in relation with IOS-1.1 and 2.2 at the 3<sup>rd</sup> meeting.

### ***Actuators (heating and current drive), modelling and benchmark***

ICRF heating scenarios in ITER has been intensively investigated with many modeling codes (PTRANSP-(old)TORIC, MIT-TORIC, Garching-TORIC, AORSA, EVE, PSTELION, CYRANO, TASK) not only for DT phase but also for pre-DT phase. ICRF heating in the DT phase at full current (15 MA) and full magnetic field (5.3 T) is uncontroversial owing to enough one-pass absorption, good agreement was obtained between codes (TORIC, AORSA, EVE, PSTELION). However, in a H plasma with He<sup>3</sup> minority at half current (7.5 MA) and half

magnetic field (2.65 T), results from codes varied due to poor one-pass absorption. On the other hand, in a He plasma with H minority at half current (7.5 MA) and half magnetic field (2.65 T), it was found that good absorption can be expected with lower frequency. ICRF experimental results were reported from JET and LHD.

Status of NBCD code benchmark was shown. OFMC, ACCOME, NEMO/SPOT, ASTRA, ONETWO, TRANSP ASCOT and DRIFT were compared using ITER scenario 4 as the target. Good agreement was found in fast ion birth profiles, except for ASCOT (need to check NBI geometry/parametrisation used). OFMC is a bit optimistic in fast ion density giving largest NBCD. Power to electrons and ions seems to be well matched for the codes.

Assessment of current profile by NB and/or LHRF actuators for ITER steady-state scenario using ACCOME, GENRAY/CQL3D and C3PO/LUKE had been performed.

### ***Scenario modelling and benchmark***

Modeling of ramp-up discharges in various machines (Alcator C-Mode, ASDEX-U, DIII-D, JET Tore Supra) has been intensively continued in collaboration with the Transport and Confinement TG. Benchmark of various models (Coppi-Tang, empirical Bohm/gyro-Bohm, Current Diffusive Ballooning (CDBM), GLF23, MMM08, scaling based models) in codes (CRONOS, JETTO, TASC, TRANSP, TSC) with the demonstration discharges had been carried out. Though temporal evolution of  $l_i$  could be coarsely reproduced, reproducibility of the electron temperature profile is yet poor and differs among codes. Some codes would require empirical tuning of (a few) parameter(s). Modeling of ITER ramp-up using various models as mentioned above was also reported.

Modeling of the ramp-down phase has been also carried out with various codes (ASTRA, CRONOS, DINA, JETTO, TSC). Importance of shape and hit points control, heating and density control were addressed.

Optimization of ITER hybrid scenario performance with CRONOS+GLF23 was reported. As a transport model like GLF23 is sensitive to  $q$  and  $s$  profiles, the hybrid scenario performance is not highly sensitive to heating mix, but rather the current drive mix. In the pedestal temperature scan with combination of NB and EC current drives, it was shown that  $T_{ped} = 4$  keV is seen to be sufficient for  $q > 1$  for  $> 1000$ sec.  $T_{ped} = 5$  keV gives better performance, while  $T_{ped} = 3$  keV is not sufficient for any hybrid mode. Test of either LHCD or ICRF did not give benefit in view of hybrid scenario.

Benchmark of ITER hybrid scenario between TOPICS-IB and CRONOS showed almost perfect match of the ECCD.

Modeling of neutrals for H $\leftrightarrow$ L transitions analysis was reported. Preliminary study using two points model for SOL and a simplified model for ionization in SOL was shown. Simulations with JT-60U like parameters at low edge density with/without neutral density model for SOL compared at various different levels of divertor compression. With neutral model SOL absorb particle flux from main plasma at the H-L back-transition.

ITER steady-state scenario modeling using DIII-D ITER discharges was

presented. Core transport was solved with GLF23, while the edge conditions were extrapolated from the DIII-D experiments. Baseline heating mix at 9 MA gives 90% non-inductive currents at  $Q = 4.5-5$ . Thirty different steady state scenarios calculated with different heating mix. ECH or ECH+ICH give at best 75% non-inductive current and  $Q \sim 4.4$ , NBCD is really needed for full CD at 9 MA at  $Q = 5$ . At 8 MA, easier to achieve 100% non-inductive current, but  $Q = 3.4-4$ . Again at 8 MA difficult to obtain 100% non-inductive current drive without NBCD, one would need 93 MW ECCD/ECH to get full current drive but then at  $Q \sim 2$ . For NBI, at fixed power the voltage used is not that sensitive, as one could still use 850 kV injection at a penalty of  $\sim 5\%$  NBCD. More optimization required for ICRH, using  $^3\text{He}$  minority current drive, which could reach 95% non-inductive current drive at  $Q \sim 4.5$ .

Modeling of the ITER steady-state and hybrid plasmas with TSC was reported. For the SS scenario development, optimization of H/CD at the ramp-up to prevent inductive current to accumulate in the core, effect of shifting the NB beam line, the ICRF frequency and advancing the pre-magnetization to accommodate with the PF coil limits, were presented. For the hybrid scenario development, advancing the pre-magnetization by 30 Wb seemed to be the optimum in terms of the coil limits and the flat-top length.

The state of ITER simulation with the SWIM framework was reported. The near term goal is to perform some integrated scenario simulations using TSC, AORSA+TORIC (for RF) and NUBEAM (for NBI and alphas) with data imports from TRANSP and the option to calculate linear plasma stability. Transport model used is GLF23.

### **Presentations and publications**

Seven papers were proposed from the TG via the IO for the 23<sup>rd</sup> IAEA Fusion Energy Conference, and all of the were accepted:

“Benchmarking ICRF simulations for ITER”

R. Budny, et.al.

“Current ramps in tokamaks : from present experiments to ITER scenarios”

F. Imbeaux, et.al.

“Development of Advanced Inductive Scenarios for ITER”

T. Luce, et.al.

“On Maximizing the ICRF Antenna Loading for ITER plasmas “

M.-L. Mayoral, et.al.

“Integrated Modeling of Steady-state Scenarios and Heating and Current Drive Mixes for ITER”

M. Murakami, et.al.

“ECRH assisted plasma start-up with toroidally inclined launch: multi- machine comparison and perspectives for ITER”

J. Stober, et.al.

“Experimental Investigation And Validation of Neutral Beam Current Drive for ITER through ITPA Joint Experiments”

T. Suzuki, et.al.

Also following two papers accepted for the FEC are closely related to the group

activity:

“Development of ITER Advanced Hybrid and Steady State Scenarios”

C. E. Kessel, et.al.

“Plasma Models for Real-Time Control of Advanced Tokamak Scenarios”

D. Moreau, et.al.

### **High priority research items for 2010 – 2011**

For 2010 – 2011, the IOS-TG has contributions to the following for the high priority research items for the TG, including response to ITER’s research needs.

- Joint experiments: Focus on qualifying candidates for ITER scenarios.
- The breakdown, current rise and ramp down of ITER. Joint experiments to be closed. Continue modeling especially on ramp-down.
- Qualify access conditions for advanced inductive and steady-state in joint experiments. Modeling to incorporate the experiment.
- Code benchmark and scenario development of ICRF especially for pre-DT phase.
- Qualify requirement and strategy on integrated control.
- Continue the focused modeling-benchmark activity on ITER Hybrid, current rise and steady state scenarios, using common input data.
- 

The 5<sup>th</sup> meeting of the TG will be held at Seoul, Korea hosted by SNU, 18<sup>th</sup> – 21<sup>st</sup> October 2010.