Integrated Operation Scenarios (IOS)
Report of activities in 2012

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<u>Summary of the2 meetings held in 2012</u>

- IOS-TG meeting, 16-19 April 2012, CIEMAT, Madrid, Spain
- IOS-TG Meeting, 15-18 October 2012, La Jolla, USA

IOS-TG meeting, 16-19 April 2012, CIEMAT, Madrid, Spain

Meeting date and Venue:
The first IOS –TG meeting in 2012 was held from 16 April to 19 April 2012 in CIEMAT, Madrid, Spain. A total number of 30 people attended the meeting. The Chairs thank the hosts, and in particular E, Ascasibar and CIEMAT for the good organisation and their hospitality.

Machine status reports:
Machine status reports were given for JET, AUG, DIII-D, C-Mod, KSTAR, FTU and JT-60SA to highlight the work of the IOS-TG at these experiments. JET has continued to the new ITER-like Wall with NBI power up to 24 MW for standard H-modes and hybrid scenarios at betaN~3 and H98~1.2. AUG has used new internal coils, boron coated RF protection tiles on 2 out of 4 antennas and diagnostics upgrades. In DIII-D, steady state scenarios at betaN ~3.5 and G~0.3 that are nearly full inductive have been extended to 3s (2 tauR); off axis NBI broadens the current and pressure profile. In C-Mod, new hardware being used in 2012 include a new 4-strap antenna, divertor gas feeds, multiple location of MGI and some modifications to the LH launcher. KSTAR has not performed new experiments since the last meeting. Discharges of 1MA, 10s achieved routine H-mode operation. FTU was unable to operate after a large disruption moved tiles on the wall, active control of sawtooth period planned using a steerable EC launcher are planned. For JT-60SA operation scenarios are being developed using TOPICS, ACCOME, MARG3D (ideal MHD), OFMC and SONIC (divertor plasma).

ITER:
For ITER it is proposed to build the CS3L from available conductor (CSJA2), with other 5 modules to be built using alternative conductors developed to meet project requirements. Scenario simulations with reduced CS3L show that by using 5MW of heating during the ramp-up, ~500s of burn can be achieved.
Modelling of ramp up of C-Mod discharge(s) show that the various different transport models used cannot match the experimental observations. Data are now available from several devices to allow a comparison of ramp-up scenarios between all metal and CFC wall, with the density and impurity evolution being the key difference for high Z divertors compared to CFC (The IOS-TG will write a report in Spring 2013). However, we still need more data on a fast ITER ramp up (50s in ITER) and flux consumption.

A report was given on simulations for entry to burn for ramp up to 15MA in 100s (impurities: 2% Be, and 0.15% Ar). There is no benefit of preheating for the entry to burn (no shear or li dependence in transport). A slow density rise suppresses the fusion power overshoot when starting the burn. The sensitivity to Ar concentration studied in these simulations. Feedback on additional heating is effective on controlling the stored energy and the burn.

Baseline scenario simulations at low density of 65% fGW show the burn can be sustained until 1200s, combined with a slow ramp down this would give a high total neutron yields Simulations for 5MA hydrogen plasmas at 2.65T and 5.3T, using full 73MW of input power, show a risk of having current overdrive (current hole formation).

Long pulse operation in ITER (>1000s) can also be achieved at 11-15MA by reducing the plasma density. A summary of the results obtained shows that the pulse length increases and Q drops (both for n_e reduction and I_p reduction). These still could provide discharges for maximum neutron fluence for TBM tests. In 2012 several different codes have provided simulations: JINTRAC, TOPICS, ASTRA), MMM with ASTRA and CORSICA with good agreement between the various predictions.

Joint experiments on ITER baseline studies were reviewed. Experiments in DIII-D have simulated a complete ITER discharge sequence. Control experiments calculated $l_i(3)$ in real time and used the current in the CS to control the value of $l_i(3)$. The plasma ramp down used a kappa reduction. A full bore ramp-down, shows lower ELM frequency, no density decrease and occurrence of n=1 modes. The joint experiments will try to extend data set for Te=Ti using more dominant electron heating and will continued in 2013.

Modelling of hybrid and steady state scenarios:

The modelling of hybrid and steady state scenarios was the focus of the meeting in April 2012. Various codes are used:

- CORSICA is being improved to allow a better ITER scenario modelling. The current ramp-up rate and final flat top values were varied for hybrid scenarios. At low density the simulations obtain q_0>2 at start of the flat top and it takes ~600s to drop to 1.0. The pedestal profiles are according to EPED1 formulism. Steady state scenario simulations (3000s), using 16.5MW NBI, 20MW EC and 20MW LH give Q~5, betaN=2.64, for H98~1.6.
- TSC/TRANSP simulations for SS scenario exploration have been submitted to NF (F. Poli et al). The MHD stability has been analysed for the scenarios explored. The cases using LHCD can operate at higher betaN (transport model). For MHD stability one would need q_{min}>2 and rho-ITB > 0.5. Previous Steady state scenario simulations used ECCD from 3 EL sections in co-current. Newer simulations use 2 EL in co direction + UL. The UL is used to “fill-in” region of r/a=0.5-0.7. Going from 3EL to 2EL + UL gives higher central q (lower li), hence betaN and Q increased from 2.9 to 3.5 using day 1 heating systems.
- ASTRA simulations of 8 hybrid JET discharges were presented. With GLF23 the Te and Ti profile are well simulated, TGLF gives higher Te while the BgB model overestimates Ti but gives good agreement for Te. For all models the density is over-estimated (too strong density peaking) and scans show a sensitivity of the density simulation results to the wall sources.
- Both baseline scenario and SS scenario demonstrations at DIII-D are being modelled with ONETWO. An ITER baseline discharge at high density is ETG dominated, while for the low density the ITG/TEM are dominant. At low density a good agreement is only observed using TGLF with ExB shearing. For the steady state scenario, the transport dependence on q_{95} is reproduced by TGLF; the pedestal is important (40% of bootstrap). EPED1 predictions give lower pedestal at higher q_{95}, hence operation just below q_{95}~5 looks more attractive rather than trying to improve the (core) confinement at higher q_{95}~6.
- Scenario modelling codes at CEA include: HELIOS (0-D code), METIS 0.5D code is assisting preparation the input for CRONOS. In recent simulations EPED1 and MISHKA pedestal/MHD stability are included. FREEBIE used to check the compatibility of the simulation with PF coil limits. First principle based models (such as TGLF) are being implemented. With these upgrades, more validation is required

(JET and JT-60U discharges) in preparation for JT-60SA simulations (using CRONOS and TOPICS).

Plasma control:

A WG was set-up ~1 year ago to help define the ITER control system physics requirements. The aim is to produce a document describing the physics requirements. Final reports are due by October 2012, in time for the PCS CDR (November 2012). Control areas include: Vessel conditioning techniques, Magnetic control (various) + sophisticated fault response controller. Core fuelling systems (gas introduction, pellets, diagnostics), first wall heat flux coverage (note the high % of visible and IR camera coverage), rotation control (more R&D is required in this area), ….and many more.

Coupled DINA-CH and CRONOS scenario simulations include tests if scenarios developed with free boundary stay inside PF limits (with control) when coupled with an equilibrium solver. The transport is computed by CRONOS and all magnetics (including q-profile) by DINA-CH. However SS-scenario simulations with 600.000 time steps takes 3 weeks CPU to finish.

Control of burning plasmas remains a topic of research. The main question is if simple controls on power density or other averaged parameters would be sufficient to control the burn. So far feed-forward simulations with ASTRA have tested variation in power, density and argon concentration. The work is on-going.

Use of the CS to control the plasma inductance is relevant and can be the basic control scheme for li, combined with additional actuators (like ECCD). Feedback of li with V-CS demonstrated. This control model should be used for ITER ramp down simulations.

SS scenarios and actuators:

A new model for NB shine-through was installed in NUBEAM, using excited neutrals and the ADAS library. NNBI with H/D/T species can be computed, and impurity species in the target plasma, but not yet W. Application to the pre-nuclear ITER discharges show only a 6% reduction in shine-through power.

Using off-axis NB, DIII-D observes a significant change in pitch angle was observed. The computed NBCD deposition profile is in very good agreement with classical modelling of the current drive.

The contribution of the alpha-power to the power required for the H-mode DT plasma has been studied in simulations of L-mode plasma confinement. Forcing the plasma to stay in L-mode (no pedestal) gives at low flow shear 10-15MW of alpha heating.

IAEA papers proposed by the IOS-TG are:

1. Multi-machine comparisons of divertor heat flux mitigation by radiative cooling A. Kallenbach et.al.
2. Development of ITER scenarios for pre-DT operations, T. Casper et.al.
3. Integrated Magnetic and Kinetic Control of Advanced Tokamak Scenarios on DIII-D Based on Data-Driven Models, D. Moreau et.al.
4. On the use of Lower Hybrid waves at ITER relevant density, A. Tuccillo et.al.
5. Demonstrating the ITER baseline operation at q_{95}=3, A.C.C. Sips et.al.

The work required was agreed and deadlines for the IAEA FEC were clarified.

IOS-TG Meeting, 15-18 October 2012, La Jolla, USA

Meeting date and Venue:
The second IOS –TG meeting in 2012 was held from 15 October to 18 October 2012 at the Marriot Hotel, La Jolla, USA. A total number of 35 people attended the meeting. The Chairs thank the hosts General Atomics, and in particular C. Greenfield for the good organisation and hospitality.

Actions from the previous meeting:
The actions for this meeting were reviewed. The discussion of the actions was followed by a detailed presentation on 1 of the actions regarding the NB shine-through calculations for helium and hydrogen plasmas in ITER based on model cross-section calculations that do not include excited states for helium or impurities. The first wall panels have some parts with high incidence angles and a maximum power load up to 4.7MW/m2. This will give a minimum density for using hydrogen NBI in He plasma of 2.7e19m-3, and for pure hydrogen 4.3e19m-3. Further work is required and it is proposed to open a joint activity on H-NBI injection modelling. The IOS-TG is concerned as to the margins for operation at 5-7MA.

ITER:
The status of ITER was given and discussed, including changes to the organisation, staffing, and focus on non-active operation with 63MW of heating. Changes to the CS as proposed by the US-DA, reduces the total flux by another 3Wb. Long pulse scenario modelling (10-15MA at low density) is progressing including EPED1/SOLPS models. Details of a paper in preparation were discussed. The Core-SOL modelling of L-H and H-L transitions in ITER is progressing using JINTRAC with a free boundary code, and models for the pedestal and L-H threshold. Simulations of the H-L back transition were discussed giving a heat flux to the inner target of 1GW for ~10ms. Quite different simulation results are obtained between global and local models for the L-H transition. PTRANSP is now available using TGLF, GLF23 and NEO (modular and parallel). Comparisons performed with XPTOR (previous simulations) show good agreement. PTRANSP is planned to replace TSC. Hydrogen and Helium scenarios for ITER have been simulated using two different codes: CORSICA and JINTRAC (this was also presented at the IAEA). A simulation performed at 0.85nGW show 15MA L-mode operation is possible for several 10s of seconds. At full Bt hydrogen or helium only go to dithering H-mode at very low density using 63MW. At ½ field, the hydrogen H-mode is just accessible at 63MW input power. Helium operation (assuming same threshold as deuterium) would have no problem with accessing H-mode. The PF coil set can easily run 7MA discharges; the simulation results only depend on the L-H threshold for ITER.

Joint experiments:
For the joint experiments an overview table of operation in 2013 was provided for all experiments. For the ITER demonstration at q_{95}=3 and seeding, contributions were given at the IAEA. For plasma breakdown studies with EC, HL-2A showed new results. The pre-ionisation is at the resonance position, while the current channel forms at the field null. As in other experiments, applying loop voltage before ECRH (like ITER) may even provide some synergy (shorter delay with V_{loop}+ECRH for X2, perpendicular injection). Lowest electrical field used is ~0.05V/m, with up to 0.5-1MW ECRH (ohmic assist ~0.35V/m) depending

strongly on wall conditions, prefill pressure, field null and injection angle. AUG obtains similar results. TS, FTU and KSTAR are still planning experiments.

For joint experiments on steady state and hybrid scenarios, assessing the beta limit for the ITER recommended q–profile has not progressed for years and will be stopped as joint experiment. The access conditions for SS and Hybrids use a database analysis to document the role of q-profile, power, shape, density, etc. From the analyses, new experiments are being proposed. Also AUG and MAST have collected new databases, to be merged with the DIII-D and JET data. MAST can access q-profiles with elevated core q values at the start of the heating and 136 discharges for the database (including the scenario development discharges) have been collected. The details of the trends were discussed.

The data for dedicated ρ^* scans for hybrid discharges in DIII-D and JET, have been reprocessed and validated. The proposed journal paper is progressing. AUG will do experiments in 2013 and a comparison with new JET data with the ILW is being considered.

For the collisionality scaling of hybrids, no dedicated shots were performed in 2012. Large databases have strong dependencies of ρ^* with ν^*. Real experiments are needed. Some detailed analyses on DIII-D does show strong dependence of $B\tau$ on ν^* at fixed ρ^*. Experiments have been proposed in 2013 for JET, DIII-D and AUG.

For ICRH coupling studies, the experiments do not show strong evidence for direct ionisation near the antenna (no extra density in measured profiles). JET, AUG, DIII-D and KSTAR see some local effects, TS sees no evidence for local effect at all. The effect of puffing on confinement needs to be documented. So far the application of power has little effect on SOL density profiles.

The (lack-of) LH CD at high density was reviewed in an IAEA paper by A. Tuccillo. A NF paper is planned. Cross modelling (codes of 1 group applied to data of others) of the data is progressing very well. New results from EAST using 2.54GHz showing reduced CD at higher density. There is a lot of discussion of the LH experts on the interpretation of probe data.

Specific discussion session: Seeding and plasma termination:
A special discussion session was organised on seeding and plasma termination (following a paper by A. Kallenbach at the IAEA):

The results from AUG were discussed in detail for ECRH X3 and ICRH core heating at q_{95}~3. Compared to a carbon reference pulse, the β_N in the W discharge is higher (β_N=2.2 vs β_N=1.8). Similar to JET, H_{98} increases with β_N (and stronger compared to carbon). New experiments should include lower heating power and N2 seeding at q_{95}~3. Simultaneous Ar (main chamber) and N2 (divertor) seeding has been very successful at AUG. In DIII-D a puff and pump method is used to create a radiative mantle. The dependence on gradB drift was studied. With increasing argon dosing rate, the core radiation increases to 35%, and an assessment of the peak heat has been performed. New IR cameras in 2013 will allow strike point locations closer to the pump plenum. Techniques for low-Z seeding in C-Mod include the use of N2, Neon and Argon. H_{98} is well correlated with $P_{net}=P_{in}-P_{rad,core}-dW/dt$. Strong I_p dependence on maintaining H_{98}~1, at higher I_p, the H_{98} drops. Low-Z seeding improves ICRF reliability. However, robust observers for feedback control are still being identified.

Terminating (seeded) discharges in C-Mod and AUG requires heating during ramp down. In JET the ramp down scenario in carbon and ILW were compared. With the ILW the discharge stays longer in H-mode (lower L-H threshold). Details of the JET discharge termination strategy were given in case of a soft stop.

Plasma Control:

An overview of the Conceptual Design Review of the ITER control system was presented by J. Snipes: Several areas for the control have been specified. The Review panel will meet in November 2012. PCS includes all aspects of plasma control, but not control of the TF, baking, or steady Glow Discharge Cleaning. Triggers for protections via CIS, which is the central interlock system. The Central Safety System covers all plant safety issues. The pulse sequence for ITER was explained as well as the safety layers of the PCS, interlocks and safety limit. Areas for control include: Wall conditioning, shape control, density, fuel mix, heat flux control, kinetic control, current density profile, MHD, disruptions and actuator sharing. A PCS forecasting system is planned, which would be faster than real time and initially based on simple algorithms. PCS will assist the CIS to help avoiding active CIS triggers, optimise control, and alternate pulse schedules after events. PCS will continue to evolve together with the ITER RP. Questions were asked on flexibility and rigid version control and retesting (commissioning time) requirements.

In the area of plasma control, model-based control loops for q-profile optimisation were presented. Interestingly, predictions aimed to create a flat q-profile with q just above 1, give an I_p overshoot with central heating followed by a ramp down with off axis ECCD, similar to hybrid experiments in JET. Control of the plasma can be helped by a state model combining model and measurements and could detect faults in the measurements or even disruptions.

Control in DIII-D (as presented at the IAEA) of poloidal flux, 1/q and β_N has been demonstrated with examples of (1) simultaneous control of the poloidal flux profile and β_N and (2) control of the q-profile. Simulations results were shown of the application of the controller to ITER using METIS, including burn control. DIII-D is preparing control of the NBI that mimics burning plasma by calculating a P_{alpha} from kinetic profiles (including real time T_i). Applications envisaged are sub critical burn control with power, which will be a priority activity for the IOS-TG.

A review of burn control at JET and JT-60U was given. Numerical simulations for ITER at Q~10 leave 1/3 of the power for control, which can be quite effective. Burn control simulations with CORSICA for ITER using neutron feedback control is very stable (stiff transport). However, NBI in ITER is not that flexible for power control, maybe IC and EC can provide enough power variation for control. To assess D:T mixture variations for burn control we need particle transport modelling for burn control.

Actuators:

Current drive using Helicon waves at high beta could provide sufficient current drive for ITER and DEMO. Single pass absorption increases with beta for the electrons and machine size. Code calculations are benchmarked for DIII-D. Simulations for ITER at 500MHz would allow a 10cm gap with the launcher, while still being able to couple the power. Calculations show that for DIII-D and T15-MD 500MHz, X-mode, off-axis (r/a~0.6) provides 0.1MA/MW. ITER prediction would give similar 0.1MA/MW efficiency, so 50MW can drive 4-5MA. A travelling wave antenna could couple 600-800MHz in ITER.

An overview of the EC system in ITER was given by M. Henderson. The EC system in ITER has many functions, from burn-through, ramp-up, burn, MHD control and ramp down. The EL has 3x8 entries with co and counter capability. Each UL has 8 feeds. Calculations for two plasma scenarios at 9MA and 15MA were performed. At r/a>0.5 only the UL can be used. STAC proposes to change the EL launcher. Poloidal slots (steering) for the EL would double the current drive efficiency for r/a>0.5. Moreover, this would give 900kA of CD at r/a=0.4. NBCD would only give 1-1.2MA. Discussion: For breakdown assist the design for ITER should NOT emphasise the 1st reflection and hence limit co-counter beta to 20 degrees. Also pointing down provides a good heating capability during the ramp down.

LH coupling and current drive experiments in EAST improve coupling by local gas puff and study CD at high density. With 2MW LH, no local gas, the H-mode phase has H-L-H-L phases. The impurity production is reduced with Li-coating and local gas puffing. A reduction of CD above 3e19m-3 (from HX measurements) is observed but improves with more Li coating (as in FTU), but not with SMBI.

Machine status (KSTAR and JT-60SA):
For experiments in KSTAR, the focus was on iso-flux control, 10s H-mode, H-mode physics studies and ELM control/pacing. The current campaign finishes in December 2012. Within 5 years, an increase in NBI to 8MW, LHCD to 2MW and ECCD to 2MW is planned. Modelling on momentum gives good agreement of simulated and measured rotation profiles.

A summary of different ITB types for JT-60U with details of high beta-poloidal, and reversed shear discharges was given. This is in view of providing JT-60U data for modelling and the release of the data in collaboration with the EU is progressing. Modelling with TOPICS and CRONOS are underway. JT-60U has been disassembled and parked in a different hall. Assembly of JT-60SA will start soon and first plasma is scheduled for March 2019.

Joint modelling (W during the ramp-up phase):
There was a discussion for the joint modelling activities on the new JET and AUG data for ramp-up with metal walls. At the next meeting there will be a presentation/discussion on the modelling of W and implementation of W transport/radiation models in simulations for ITER.

The next meeting will be at the ITER-IO, 15-18 April 2013.

Integrated Operation Scenarios (IOS)
Publications in 2012

G. Sips (chair), T. Luce (deputy-chair), J. Snipes (IO deputy-chair)

5 papers at the FEC in San Diego, 2012

1. Multi-machine comparisons of divertor heat flux mitigation by radiative cooling, by A. Kallenbach et.al.
2. Development of ITER scenarios for pre-DT operations, by T. Casper et.al.
3. Integrated Magnetic and Kinetic Control of Advanced Tokamak Scenarios on DIII-D Based on Data-Driven Models, by D. Moreau et.al.
4. On the use of Lower Hybrid waves at ITER relevant density, by A. Tuccillo et.al.
5. Demonstrating the ITER baseline operation at q_{95}=3, by A.C.C. Sips et.al.

4 journal papers (in addition to the FEC)

1. Experimental Study of Plasma Breakdown by Toroidally Injected EC waves in Heliotron J, by B. Lu, K. Hagasaki et al
2. Development of Advanced Inductive Scenarios for ITER, by T. Luce et.al.
3. Stability and Performance of ITER Steady State Scenarios with ITBs, by F. Poli et al
4. Lower Hybrid CD at high density in the multi-pass regime, by G. Wallace et al