Summary of IEA Workshop on Burning Plasma Physics and Simulation

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The workshop was held under the Auspices of the IEA Large Tokamak Implementing Agreement from 4 to 5 July 2005 on the University Campus, in Tarragona, Spain, and followed the EPS conference during which the decision to built ITER in Cadarache was announced.

The scope of the workshop was burning plasma research in the areas of Plasma Transport and Confinement, MHD Stability and Fast Particle Confinement, Integrated Modelling of Burning Plasmas, and Diagnostics and Control for Burning Plasmas. The session on MHD stability and fast particle confinement was held in common with the ITPA MHD Group.

In each of the areas, a number of presentations were given. Following those, participants prepared in break-out sessions, a summary presentation in each of the areas in the spirit of a road map: where are we (review of the status), where do we want to go (identify the needs), and how do we get there (ways and means).

Based on those summary presentations, and the lively ensuing discussion, summaries were written and iterated after the workshop among the participants. Those summaries are given here, and provide a concise view of the participants on the topics. The views may be subjective, but, precisely because of their frankness and succinctness, could be interesting to illuminate the path ahead. The list of participants is given in Appendix. The full presentations and the summary presentations can be found under Workshop W60 on the IEA web site: http://www-jt60.naka.jaeri.go.jp/lt/index.html

1. Transport and Confinement

1.1. Introduction

There were four presentations in this session. Two presentations were the DT experiments from JET by D. Stork (UKAEA) and TFTR by R. J. Hawryluk (PPPL). Those presentations covered the area of transport, turbulence, stability, energetic particle, plasma-boundary physics and diagnostic development. The preliminary burning plasma simulation experiment to test the coupling between pressure and heating power was reported from JT-60U by H. Takenaga (JAERI). M. Peng (ORNL) reported on super-

Alfvenic ion driven modes and turbulence from NSTX. The discussions related to the transport and confinement were not fully covered in this session, however, the status and future directions were discussed among the members of this session through e-mail and summarized as follows.

1.2.Where are we?

(a) The international database activity started with the ITER CDA. A useful empirical confinement scaling law for ELMy H-mode was extracted from the database. However, the empirical scalings of β, ν^* or n/n_{GW}, isotope, L-H transition, and pedestal need further work. There is no clear information on rotation scaling, and little information on light (fuel-ion and helium ash) particle transport scaling.
(b) Extrapolation for other operating modes requires a more detailed understanding of the transport processes. It means that an empirical scaling of the formation conditions of an internal transport barrier (ITB) and the method of ITB sustainment are required. In particular, more benchmarking is necessary among the integrated transport models and experiments to optimize performance and to control pressure .
(c) As for the studies of turbulence transport, the understanding of ion-scale turbulence is making progress and new electron-scale turbulence diagnostics are coming on-line and beginning to be compared to the turbulence models.
(d) Finally, the importance of the wall conditioning for some improved confinement modes is well known. However, we do not have a comprehensive understanding of the relation between wall conditioning and confinement improvement.

1.3.Where do we want to go?

(a) It is necessary to develop predictive capability beyond the experimentally established empirical scalings. Especially important are improvements in empirical scalings for the L/H transition and for, β, ρ^*, ν^*, isotope, pedestal and rotation scaling for both energy and fuel-ion transport. It is further essential to identify and to optimize control techniques for optimized performance.
(b) A predictable capability of ITB formation and a method to sustain ITBs should be established. Since the collapse of an ITB causes a disruption in some case, the artificial control of transport may be necessary.
(c) The relationship between turbulence measurements and simulations should be clarified. In the measurements, one of the most important items is to clarify the causality.
(d) Deeper understanding of wall conditioning and choice of first wall material on improved confinements should be fully assessed.

1.4. How do we get there?

(a) As was done to obtain the ELMy H-mode scaling, multi-machine comparisons by well-diagnosed experiments should be fully utilized to increase the confidence of the prediction for L/H transition, pedestal temperature and density, energy confinement and light ion transport scaling with isotope, and rotation velocity. In the case of pedestal and energy confinement studies, special attention should be devoted to match the edge condition such as TF ripple.

(b) The following research is essential for other operating modes with ITBs

- Agreement should be obtained on the ground rules for comparison of these operating regimes between different machines (profile database);
- Comparative experiments should be performed using these ground rules and a predictive understanding should be established of criteria for onset and stable evolution of the ITB;
- Scaling studies should be carried out of access threshold, and dimensionless parameter scalings of energy and light ion particle confinement;
- The robustness of these regimes against impurity, and He ash accumulation, and disruptive instability, should be established.

(c) In order to develop the predictive capability of turbulence transport codes, profile and fluctuation data should be compared with the calculation by a hierarchy of codes in order to validate and establish the codes. Fluctuation diagnostics should be developed with an increased range of (k_θ and k_r) space. It is necessary to develop a fluctuation diagnostic for ITER , where ρ^*will be very small. The development and assessment should be done in existing experiments.

(d) A systematic study of wall conditioning and its effects on the core confinement is necessary. The importance of recycling should be assessed by very long pulse discharges with a saturated wall. In order to advance our knowledge of the scrape-off-layer and divertor, two- or three-dimensional measurements might be important. It is essential to develop and to improve integrated modeling codes. The effects of first wall material on the core confinement should be tested and assessed in the present machines.

2. MHD Stability and Fast Particle Confinement

2.1. Introduction

The understanding of the behavior of burning plasmas, i.e. plasmas with strong self-heating, represents the primary scientific challenge faced by ITER and a necessary step towards the demonstration of fusion as a source of energy. In D-T plasmas, self-heating is provided by the alphas generated at 3.5MeV by the D-T fusion reactions. Furthermore, other fast or energetic ions with energies in the MeV range, well above the thermal distribution of the plasma bulk, are generated by Ion Cyclotron Resonant Heating (ICRH) and Neutral Beam Injection (NBI). Transport and confinement of fusion alphas not only impact machine performance by affecting the fusion yield, but also, due to the large power carried by the alpha population, even minor alpha losses can damage the machine first wall. On the other hand, an excessive confinement in the plasma core of the slowed down alphas (helium ashes) would give rise to a dilution of the useful fuel and should be avoided. Reductions in the confinement of alphas and of fast ions produced by additional heating systems may be due to a combination of orbit losses due to an imperfect toroidal field (ripple losses) and to collective instabilities. Significant progress in the understanding of burning plasmas has been made in the past few years by using weakly self-heated plasmas and plasmas in which fast ions are produced by external additional heating schemes.

The discussion was structured according to four areas, yet considering their interconnection, an important feature of burning plasma regimes: (a) the effect of magnetic field ripple on fast particles, (b) the thermalisation of fast particles, (c) their (non-resonant) interaction with low frequency MHD, and (d) their (resonant) interaction with high frequency MHD.

2.2. Where are we?

(a) Ripple losses are relatively well understood in terms of single particle physics. The synergy between new observations and advanced modeling has led to an optimization of ferritic inserts in ITER to reduce ripple alpha losses with reversed shear configurations by more than one order of magnitude.

(b) The interaction of fast ions generated by additional heating with low frequency MHD has been investigated in a variety of experiments. Nonlinear modeling appears to be in qualitative agreement with experiments for fishbones, which are not expected to provide a significant threat to ITER high beta plasmas. The linear theory of kinetic ballooning modes and localized interchange modes is well advanced, though the comparisons with experiments are limited. The interaction of fast ions with sawteeth is understood qualitatively (and to some extent quantitatively). Despite many open questions on the basic physics of magnetic reconnection, methods to control the sawtooth period using additional heating such as ICRH have been demonstrated experimentally. Sawtooth have an important practical implication for ITER, in that they can provide the trigger for neoclassical tearing modes (NTMs). As sawteeth can be stabilized (i.e. their period can be made longer, and the crash correspondingly larger) by fast particles, these indirectly influence the behaviour of NTMs. New regimes for NTMS have been found, in which mode coupling limits deleterious effects on global plasma confinement. Control of sawteeth using electron cyclotron current drive has also become a routine technique in tokamaks, and is being integrated in a more general real time discharge control scheme.

(c) A large effort was dedicated to the development of methods to simulate fusion born alphas in plasmas without significant fusion reactivity. The main parameters determining the amount of free energy available for alphas to drive instabilities, β_{fast} and $R\nabla\beta_{fast}$, have reached values close to or even exceeding those predicted for ITER. Particle velocities normalized to the Alfvén speed span the operating space for ITER. On the other hand, in present devices the ratio between the alpha slowing down time and the energy confinement time, and the number of fast ion gyro-orbits contained within the plasma radius are much larger and much smaller, respectively, than in ITER. The slowing down was observed to be classical for minority T ions, and for alphas in weakly self-heated discharges in normal shear discharges. Additional information in weak and reversed shear discharges is needed. Experiments with NBI current drive indicate some anomaly in the radial transport and deposition of beam ions and the subsequent slowing down process, in the absence of collective resonant instabilities, which may indicate some coupling with the background plasma turbulence.

(d) The field of linear stability thresholds for collective instabilities was advanced through a large number of experimental results and significant progress in theoretical simulations. New experimental techniques to launch and detect stable modes have led to large experimental databases of damping rates and to information on the fast particle drive of modes of low toroidal mode numbers in the Alfvén Eigenmode frequency range. High frequency fluctuation measurements have provided large amounts of data on the instability thresholds, over a broad range of toroidal mode numbers. Damping and drive mechanisms are qualitatively understood, although quantitative predictions for specific modes are still to be established, especially in regimes in which fluid and kinetic models give significantly different results. Strong discrepancies between measured and predicted damping rates are observed for situations in which most of the damping is expected in the plasma core. An extreme sensitivity of the predicted damping on the plasma profiles, particularly at the plasma edge, is noticed. A new class of resonant modes affecting the fast particle profiles, the Energetic Particle Modes, can be driven significantly above marginal stability, and is predicted to give rise to significant fast particle redistribution in ITER. The understanding of the nonlinear phase of the interaction between waves and fast ions was significantly improved, particularly in the weakly nonlinear regime. Measurements of the modes are used to extract information about the background plasma and/or the fast ion population. The first self-consistent simulations of the mode nonlinear evolution coupled with that of the fast particles have been made, but the extreme sensitivity to the parameters and assumptions (including the linear stability properties) limits the possibility of extracting quantitative predictions for ITER. Limited information is available on the fast ion redistribution and losses, due to the difficulty in achieving large amplitude modes in present devices and in having sufficiently sensitive diagnostic tools to measure the energy and radial distribution of the fast ions. Further comparisons of detailed experimental measurements with nonlinear calculations are needed. In terms of using the wave-particle interactions to control the plasma burn, only very preliminary results on tests of isolated aspects of the control loop exist.

2.3. Where do we want to go?

(a) To complete the assessment of ripple effects in ITER, the influence of ITER test blanket module, which creates significant magnetic perturbations at the edge, should be fully assessed.

(b) Methods to control sawteeth using fast particles (i.e. to vary their period and their amplitude according to the experimental needs) should be made routinely available. The effect of sawteeth on the NTM island size should be determined. Progress is needed in NTM physics, namely in the area of the triggering mechanisms. Practical answers are expected urgently for optimizing the NTM control system using ECCD on ITER, e.g. on the exact injection geometry, and on the need to modulate the microwave power.

(c) The thermalisation of alphas in advanced scenarios should be measured (should D-T experiments become possible in the next few years, namely on JET), and the mechanism behind the observed anomaly in the NBI ions slowing down should be assessed.

(d) In terms of the linear stability of the high frequency MHD modes, we should address the questions of which modes are most unstable, in which ITER scenarios and of which parameters can be used to control the stability limits. Subsequently, we should identify which modes are most dangerous for alpha transport, and which limits do fast particle driven modes (if any) pose to the ITER operational scenarios. Ultimately, our community should be able to estimate the self-consistent fast particle profile in ITER. In terms of the diagnostic use of wave-particle interaction studies, reliable and routine measurements of $q_{min}(r,t)$ in reversed shear scenarios should be established, along with practical methods to extract information on D-T isotopic concentration and on the fast ion phase space distribution. To move towards an improvement in our capability of controlling the plasma burn, methods to detect changes in and affect the fast particle pressure profile need to be demonstrated.

2.4. How do we get there?

(a) Ripple experiments can be undertaken on JET and JT60-U, corroborated by theoretical modeling

(b) Progress in the understanding on low frequency MHD and its interactions with fast particles requires the use of more realistic theoretical tools, in particular for establishing the theoretical background for ICRH control methods. NTM issues will benefit from multi-machine combined experiments and experiment-theory comparisons.

(c) The open questions on fast particle (alpha) thermalisation should be addressed in additional D-T (or trace T) experiments, specifically performed in advanced tokamak scenarios. The significance of the interaction between drift-like plasma turbulence and fast ions should be investigated theoretically and in specifically designed experiments, possibly adopting novel diagnostics to reveal the properties of turbulence in the plasma core. Fast ion transport and slowing down should be assessed in weak and reversed shear discharges.

(d) For high frequency MHD, a database for damping and drive for ITER relevant toroidal mode numbers should be established, using the new active MHD systems developed on C-Mod, JET, and possibly in the future on MAST. The comparisons with theory should be made systematically. Theory-theory benchmarking and sensitivity analyses should be performed. Radial and poloidal mode structures should be measured to unambiguously identify each mode within the large MHD spectrum for intermediate mode numbers. To progress on the understanding on the nonlinear evolution of the instabilities and their effect on the fast particle profiles, data on fast ion redistribution and losses should be obtained, enabling quantitative comparisons with theory. For this, scenarios with large modes (and radially overlapping) should be identified, and methods to excite large amplitude modes with external antennas should be explored. This activity should encompass the so-called nonperturbative (or Energetic Particle) modes, for which realistic geometry and conditions should be accounted for in the theoretical models. In terms of the diagnostic use of the fast particle driven modes, a systematic comparison with conventional diagnostics should be conducted. Finally, real time Alfvén instability control, using for example active MHD antennas to detect their stability limit, and the ICRH power as an actuator simulating alpha heating, should be demonstrated as a step towards burn control.

3. Integrated Modeling for Burning Plasmas

3.1. Introduction

The term “Integrated Modeling” is used to denote all modeling and simulation activities that combine one or more of the traditionally separate disciplines of plasma stability, plasma transport, heating and current drive physics, and edge plasma physics. There were a number of presentations addressing different forms of integration, and showing results of integrated simulations of ITER where the integration led to increased self-consistency of the different effects, including self heating by the alpha particles. The near-term plans of the different parties in this area were also discussed.

3.2. Where are we?

Mature 1½ D transport-timescale evolution code packages presently exist within each of the major parties. In Japan, as part of the Burning Plasma Simulation Initiative (BPSI) there are the TASK (Transport Analyzing System for Tokamak) and the TOPICS (Tokamak Prediction and Interpretation Code) projects. In the European Union, there is a newly formed Integrated Tokamak Modeling Task Force and the JET initiative, which includes the ASTRA, CRONOS, JETTO, and RITM codes. In addition, there is a project to couple the DINA and CRONOS codes to provide a free boundary evolution code with advanced source models. In the US, there is a new PTRANSP (predictive TRANSP) initiative that is building on the NTCC (National Transport Code Collaboration) structure, a project to couple the TSC and TRANSP codes (similar to DINA/CRONOS above), and several additional transport timescale codes including BALDUR, ONTEWO and CORSICA.

The 1½ D integrated modeling codes provide a reduced description of the evolution of the plasma in a tokamak. They each consist of a number of modules that describe the relevant transport processes, MHD instabilities and particle, momentum, and energy sources. These modules are normally not the most advanced models available but are chosen as a tradeoff between physics content and computational speed. There is a need for improved reduced modules in most areas. Turbulent transport models need to be improved, and their regions of validity need to be better quantified. Extended MHD and energetic particle modules need to be improved. There is a need for better particle and impurity transport models, and a general need for better benchmarking of all modules.

More fundamental physics models than what are used in the transport codes exist in most areas, in particular in the areas of 5D Gyrokinetics, nonlinear extended MHD with energetic particle effects, full wave RF codes coupled with Fokker-Plank solvers, and in edge/PSI (Plasma Surface Interaction) codes. These compute-intensive codes seek to describe isolated phenomena at a more fundamental level. All have had some success, but they are still under development and will be for some time. Also, the computer requirements in each of these areas for a full ITER simulation are beyond present capability, even for isolated phenomena.

Extended MHD and energetic particle codes need to be further developed and validated on existing experiments. Full 3D nonlinear sawtooth simulations are now possible for small tokamaks, but not yet for ITER. Good reduced semi-analytical models are available (Porcelli model), but the regime of validity needs to be better quantified. There has been some recent progress on ELM modeling (BOUT-Snyder, JOREK-Huysmans, NIMROD-Brennan, M3D-Strauss), but there is not yet a full 3D ELM simulation for even small tokamaks. Semi-analytical models of ELMs are being developed. (including ideal-MHD/Enhanced transport model with MARG2D in TOPICS). There is not yet a full 3D neoclassical tearing mode (NTM) simulation. The modified Rutherford equation (semi-analytical) model is widely used to model NTMs, but it neglects mode coupling effects that can sometimes be very important (for example, in the FIR regime). There is not yet a full 3D nonlinear model of the resistive wall mode (RWM) or for the locked mode threshold. For the toroidal Alfven eigenmode (TAE), 3D hybrid particle/fluid simulation models are possible for modeling short times and weakly nonlinear behavior, but full nonlinear integration with thermal particles is not yet possible. In the area of disruption modeling, axisymmetric modeling is in fairly good shape, but full 3D modeling is just beginning.

In the area of fundamental turbulence simulations, the focus is presently on core turbulence: ITG, ETG, ITG/ETG coupling, finite β effects, transition from Bohm to gyro-Bohm, and turbulence spreading. There is a need to develop a long-time (transport timescale) predictive simulation capability, to calculate particle diffusivities from transport simulations and to calculate impurities and helium ash transport, to integrate turbulence and neoclassical simulations, to better understand and be able to predict mechanisms for transport barrier formation, and to better integrate pedestal region and core-edge simulations. Also, we need to understand how best to couple turbulence calculations with the 1 ½ D transport timescale codes

In the area of edge-plasma integrated modeling, we note that a full 3D predictive edge model is lacking. However, numerous edge codes exist to provide qualitative understanding and quantitative results for specific phenomena. For edge transport, there are the CSD, SONIC, UEDGE, SOLPS (B2-Eirene), EDGE2D-NIMBUS codes. For kinetic edge turbulence, there are the PARASOL, DALF codes. For collisional edge turbulence, there is the BOUT code. There are also local codes for erosion/deposition such as ERO, and coupled Core-Edge codes: COCONUT:JETTO-SANCO-EDGE2D-NIMBUS. SOLPS is beginning to target disruptions and ELMs. There is a semi-analytical/empirical NTCC PEDESTAL module suitable for incorporating in 1 ½ D codes. Dynamic models for pedestal formation and ELM cycles are used in the JETTO and ASTRA codes. There is now increasing evidence that ELMs are triggered by current-driven MHD modes. In order to calculate this quantitatively, the MARG2D ELM model has been incorporated into TOPICS. In the U.S, several Fusion Simulation Projects have been proposed to study integrated edge-plasma. However, many issues remain in this area: a fundamental description of the L-H transition and pedestal physics; nonlinear ELM crash, transport, and pedestal recovery; density limit and impurity transport; material erosion including redeposition and dust formation (there is work in progress to integrate plasma and plate (SOLPS5-B2)—need to characterize mixed materials. To truly calculate integrated phenomena, there is a need to move physics from edge transport codes into edge turbulence codes, and also a need to include drifts into edge transport codes, and to move to a 1D neoclassical description where appropriate.

In the area of RF, NBI, α-particle, and fueling sources, we note the following: Comprehensive suites of RF and neutral beam codes exist and are being used in integrated modeling calculations. Integrated computations between full-wave ICRF and Fokker-Plank (FP) solvers are underway, but not yet in routine use. Integrated modeling that combines advanced ICRF antenna modules with full-wave solvers are underway. RF and NB source modules have been combined with 1 ½ D transport timescale codes, but generally not the most advanced RF packages. RF/FP Codes need to be coupled to MHD codes in order to simulate instability control. Modeling of mode conversion physics in ITER scale plasma is not yet possible. There is a need to incorporate all RF and NB systems together with FP for ions and electrons self-consistently, and with energetic particle MHD. There has been a coupling of SPOT (for α-particles) and DELPHINE (for LH wave propagation and absorption and calculation of the electron distribution function) within the CRONOS framework.

3.3. Where do we want to go?

In the foreseeable future, we want to continue to have a hierarchy of codes with a range of compute speeds and physics accuracy. There will continue to be a need for reliable validated transport-timescale code packages with improved modules for all processes *with reliable ranges of validity*. By this, we mean that we want to use reduced models to interpolate between regimes in which more fundamental model results exist, and not to extrapolate into parameter regimes for which more fundamental results are lacking.

This implies that we also need to have improved fundamental "first principles" nonlinear models that can quantitatively reproduce existing experimental results and future regimes. These are needed in the areas of turbulent transport, extended MHD, RF full-wave RF physics, and plasma edge modeling discussed above.

In addition to these more fundamental first principles models, we need to begin to develop *coupled* fundamental models to examine strongly interacting physics issues. Examples of these are the RF stabilization of MHD, turbulence effects on MHD modes, and core/edge/materials coupling.

As these integrated modeling codes become more mature, they will be called upon to perform a number of tasks needed to effectively operate a large burning plasma experiment such as ITER. They will be used extensively in experimental preparation. It is unlikely that any experimental proposal will be prepared unless there are extensive modeling results to support them.

Post-discharge analysis will also be a very big application. Running the codes in an interpretive mode will be a major high-level diagnostic that will allow physicists to understand what physical processes were active in a particular discharge.

In addition to these "traditional" uses for integrated modeling codes, there is a potential need for very fast codes for real time forecasting and control. These codes will be used in ways that are now not possible, improved equilibrium and discharge reconstruction, real-time profile control, and disruption prediction and mitigation.

3.4. How do we get there?

Each of the major parties has self-organized to some extent and is developing integrated modeling frameworks and projects. We encourage each of the parties to continue their modeling projects, and at the same time to begin interacting more with the other parties.

Since these projects involve a large number of people and will span many years, it is important to utilize modern software practices in the development of these large integrated modeling packages. It is essential that the projects have good documentation and conform to agreed upon standards. There is a great benefit to be had from interacting with the Computer Science and math communities. This is one way to transfer the experience from other communities to the fusion community.

International collaboration could take the form of periodic workshops devoted to comparative modeling. For example, having each team look at certain specified discharges in depth, and comparing results is a good way of finding areas of agreement and disagreement, allowing participants to focus on the underlying reasons for the latter. These periodic workshops would also be a good place to develop international standards that would facilitate software exchange between parties. The standards might start out to be relatively non-controversial things such as a fusion-specific international standard for physical units or certain types of file formats, but could develop into more fusion-specific items.

In order to develop meaningful integrated modeling packages, there needs to be increased emphasis on verification and validation at all levels. This applies to the individual physics modules, to the entire “reduced model” code predictions, and to the “first principles” codes predictions. There are a variety of methods for accomplishing this, but it needs to be the dominant focus of the integrated modeling activities for many years into the future. The standardized discharges for comparative analysis will play an important role in this activity. It has been suggested that we make use of the ITPA profile database for this activity.

Finally, we note that developing large integrated modeling packages will require continued support and recognition by funding agencies in the different parties. To ensure this, we encourage all parties to maintain visibility by highlighting their accomplishments at appropriate conferences and other venues, and to ensure that their software products are of the quality and usefulness that lead to a growing user base.

4. Control and Diagnostics

4.1. Introduction

In the session on control and diagnostics a number of presentations were given that focused on specific aspects of control and on diagnostics. The discussion session after the presentations largely addressed those topics that were mentioned before in the separate papers. For control these were fuel control, ELM and RWM control as well as integrated profile control. Therefore, the roadmap presented in this section is largely devoted to these topics. Control of power and particle exhaust has almost not been discussed and therefore, nothing specific is mentioned in this roadmap.

4.2. Where are we?

Control:

In the field of *density control* it has been concluded that there is not much flexibility in the fuelling of ITER. The question is whether pellet fueling can handle everything. Indeed, though pellet fuel can reach well beyond the edge pedestal region, it cannot penetrate to the magnetic axis (even using an equatorial HFS launcher). It is not clear whether the plasma can be adequately fuelled to provide the peaked density profile shape that is the most beneficial for having a high fusion gain. At present there is not enough data on advanced fuelling systems. A technique brought up at the meeting is Compact Toroid (CT) injection, which was suggested to be able to cope with the penetration shortcoming of pellet fuelling, but may have issues with interaction with the magnetic surfaces. The technique has been tested at TdeV and other moderate sized tokamaks with mixed results. It is not clear whether other fuelling techniques exist.

Concerning the control of *Edge Localized Modes* (ELMs) one has not yet enough understanding of type I ELMs. Neither does one understand how to establish regimes with the more benign type II ELMs (in some machines scenarios have been developed, but in other machines the same scenarios don't work). At present the projections of ELMs for ITER vary from tolerable to intolerable.

The control of *Resistive Wall Modes* (RWMs) is reasonable understood. In principle these modes can be well controlled by internal and/or external coils. In this respect internal coils are to be preferred.

In the development of *integrated control scenarios,* the real-time control of at most a few parameters is reasonably understood and has been demonstrated on several magnetic confinement devices. Techniques are being developed to control simultaneously several parameter profiles, such as current and pressure profiles, and to integrate it with the control of plasma shape and equilibrium, internal transport barriers, and of the primary flux for steady state operation. Experiments have started on JET and further experiments are planned in 2006.

Diagnostics:

In the field of *diagnostics*, there is confidence that it is possible to measure the plasma parameters for the basic control of the ITER ELMy H-mode. The diagnostics for advance control in ITER are much less well developed (alpha particle parameters, profiles of various parameters, etc.). At this stage there are some parameters in ITER for which proper diagnostic solutions do not yet exist (escaping alphas). Apart from that there are still many open issues in the field of irradiation effects on diagnostic components or assemblies, and erosion/deposition effects on first mirrors which call for urgent research.

4.3. Where do we want to go?

Control:
Adequate techniques should be developed for *fuel control* that establish and/or preserve the optimum pressure profile for a high fusion gain.
Scenarios/methods should be developed to suppress, reduce and/or control type I *ELMs*. This could be either done by developing robust scenarios that do not feature type I ELMs or by using ELM pacing techniques (e.g. by pellet injection) to create smaller and less harmful ELMs.
Full stabilization of *Resistive Wall Modes* (RWMs) should be achieved by a combination of induced rotation and internal coils.
Integrated control algorithms should be developed further to support the advanced operational scenarios (hybrid and steady-state) in burning plasma conditions and in ITER. (e.g. control of multiple parameter profiles in real-time together with MHD, radiation and particle/power exhaust, development of 'orthogonal' multi-variable-actuator loops, development of waterproof methods for disruption mitigation and control)

Diagnostics:
In the area of *diagnostics* it is important to identify and develop techniques that are rugged in the ITER environment and that can measure the various plasma parameters that are needed for adequate plasma control and discharge tailoring. In cases where rugged diagnostics cannot be developed for whatever reason, it should be tried to develop rugged components for existing techniques. The diagnostics for many plasma parameters should be compatible with the real-time control algorithms.

4.4. How do we get there?

It will be evident that there is still an enormous amount of outstanding work that should be addressed on present devices. Specifically for the points raised above.

Control:
New *fuelling techniques* should be tested on present devices. Given the prospects of CT injection, a test on a relatively large device is highly desirable. Pellet fuelling from the high field side equatorial plane should be tested in plasmas with high edge temperatures and close to operational boundaries to judge its merits.
Methods to control *ELMs* (pacing, suppression) should be further developed. More effort is needed to study ELM stabilization by ergodizing the edge magnetic field. Detailed measurements of the structure and time evolution of ELMs are needed to reach a complete understanding of this instability and to support modeling efforts in the field non-linear algorithms.
Comparison of *RWM* stabilization experiments on various devices including a comparison with theoretical models is needed in order to check the robustness of RWM stabilization to profile variations (in particular to variations in the q-profile)
Control algorithms that have been developed for present magnetic confinement devices should be extrapolated to high density, burning plasma conditions (e.g. mimicking the

effect of a large alpha-particle heating and high bootstrap current by linking some ICRH power to the measured neutron rate and thus simulating burn conditions). It is important that the current profile control techniques be tested in such conditions and in DT plasmas. This would require higher LH power in JET, but is essential in order to prepare for the choice of the ultimate H&CD systems mix for advanced scenarios in ITER. Techniques to mitigate/ameliorate/predict disruptions should also be developed.

Diagnostics:
In order to develop diagnostics that are reliable in the ITER environment, diagnostic development and prototyping, aimed directly at ITER applications, should become an accepted part of the programs of present machines (and where possible supported national programs!). Fine-tuning of the measurements requirements for ITER is needed based on validated simulations and modeling. This work should guide diagnostic developments in the near-term future.

Appendix. List of registered participants

Appel, L.
Baylor, L.
Bindslev, G.
Budny, R.
Coster, D.
Costley, A.
Donné, A., chair of session on “Control and Diagnostics”
Fasoli, A. , chair of session on “`MHD Stability and Fast Particle Confinement”
Ferron, J. , Organizer
Firpo, M.
Fisch, N.
Fonck, R.
Gonçalves, B. , Scientific Secretary
Gorelenkov, N.
Guenter, S.
Hammamatsu, K.
Hawryluk, R.
Hellsten, T.
Jardin, S. , chair of session on “Integrated Modelling for Burning Plasmas”
Jaun, A.
Kessel, C. Jr
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Noterdaeme, J-M., Organizer

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