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and JET-EFDA contributors

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ABSTRACT

The International Tokamak Physics Activity (ITPA) aims to develop a physics basis for burning tokamak plasmas. The topical group on steady state operation coordinates research in several areas. Joint experiments in several different machines are carried out, concerning the validation of candidates for steady state operation and hybrid operation in ITER. Benchmarking of the actuators available for heating and current drive is another important area of international collaboration. Recently, various simulations for lower hybrid current drive, ion cyclotron heating and electron cyclotron heating and current drive have been compared using the latest code developments. Integrated scenario simulations are performed to establish operating modes in ITER. Several codes used worldwide are compared with particular focus on code to code results, using the same set of input data and using the same energy transport model for the hybrid scenario simulations. Thus far, steady state simulations are focused on developing a range of q-profiles with 100% non-inductive current. This modelling activity can also used to design controllers and control algorithms for advanced scenarios. However, present focus on sharing the experience gained in this area between several experiments. Finally, particular issues for ITER are being addressed by the topical group, including documentation of the results obtained (Progress in the ITER Physics Basis) and optimisation of the plasma start-up phase.

1. INTRODUCTION

The International Tokamak Physics Activity (ITPA) promotes cooperation on an international level in developing a physics basis for burning tokamak plasmas. An activity useful for ITER [1] and tokamak research worldwide. Several physics research topics (topical groups) are defined under the ITPA. The Topical Group (TG) on Steady State Operation (SSO) covers several research areas. This topical group holds two meetings a year to coordinate the research and discuss the progress made. The last four meetings of the SSO TG were (i) in San Diego (USA) from 31 October 2005 to 3 November 2005, (ii) at JAEA (Japan) from 10 April 2006 to 13 April 2006, (iii) directly after the IAEA in Chengdu (China) from 23 October 2006 to 26 October 2006 and (iv) recently in Daejeon (Rep. of S. Korea) from 9 May 2007 to 11 May 2007. Useful is that these SSO TG meetings have been attended by the same core of people (~15), supplemented by experts/locals for discussion on certain topics. Some of the research is coordinated with the other topical groups of the ITPA in joint sessions during these meetings.

The research work of the SSO TG is structured into the following topics:

1. Collaboration (joint) experiments, coordinated by the ITPA topical group.
2. Modelling and benchmarking of heating systems (actuators).
3. Modelling of ITER (steady state) scenarios.
4. Real time control requirements.
5. Specific issues for ITER.

Efforts in these areas focus on the coordination of the world-wide efforts to demonstrate steady state operation and hybrid operation in ITER. For these scenarios the q-profile plays an important role. Candidates for steady state operation at Q~5 in ITER typically have reversed magnetic shear in the centre and q_{95}~5. Usually these reversed shear scenarios rely on the formation of an internal transport barrier (ITB) to improve the confinement and the bootstrap current fraction. Hybrid operation at high reliability aims to maximise the neutron fluence (integrated neutron wall load during a pulse) in ITER for material testing. H-modes discharges with low magnetic shear in the centre, typically q_{95}~4 exhibiting good confinement combined with good stability are candidates for hybrid operation in ITER.

For each of the five topics listed above the results obtained over the last two years are given in the following sections of this paper together with conclusions and the requirements for research in the near future.

2. COLLABORATION EXPERIMENTS

Joint experiments performed in several different machines mainly concern the validation of the steady state scenario and the hybrid scenario for ITER. Specific access conditions of these two scenarios are studied together with operation close to ITER conditions. Most of the joint experiments were not finished in 2005, as the two large devices (JET and JT-60U) had limited physics operation time. The topical group recommended more focussed aims for joint experiments in 2006. Most of the joint experiments proposed by the SSO TG have been incorporated in the experimental programs of the various machines, listed below a summary of the results obtained:

1. *SSO-1.1: DOCUMENT PERFORMANCE BOUNDARIES FOR STEADY STATE TARGET Q-PROFILE:*

The objectives of joint experiments are to define a common, reproducible, scenario in today's experiments with the target q-profile for non-inductive operation in ITER: Minimum q (q_{min}) in the range 1.5-2.5, with weak magnetic shear $q(0)-q_{min}=0.5$ and q_{95} near 5. DIII-D has been at the forefront in developing this scenario obtaining ~100% non-inductive operation, see Figure 1 [2]. In 2006 experiments in DIII-D focused on the influence of cross-sectional shape on the beta limits, showing a clear optimum in the beta limit for discharges sustained for several energy confinement times. The highest sustained normalised beta (β_N) was 3.8 [3]. In ASDEX-Upgrade, a scenario similar to the one developed in DIII-D is available for further study. In JET, extensive exploration of the beta limits of these q profiles has been performed during the 2006/2007 campaigns, with data currently being analysed. Using off-axis negative-ion based neutral beam injection JT-60U obtains a q profile consistent with the prescribed target [4]. The SSO TG reports slow but steady progress in this area. Full, or close to full, non-inductive discharges at high beta have been developed (DIII-D, JET, ASDEX UPGRADE and JT-60U) in preparation for ITER.

2. *SSO-1.2: QUALIFY OTHER Q-PROFILES FOR STEADY STATE OPERATION:*

Advanced scenarios with strongly reversed q-profiles, are still being assessed for their capability to produce steady state operation for ITER or a reactor. The purpose of joint experiments is to map the beta limits for regimes with different values for q_{95}, qmin, q(0)-q_{min}. JET [5] and JT-60U [6] concentrate on operation using reversed q-profiles and wide ITB operation at high q_{95}~7-10. Experiments in 2007 (JET, to be analysed) and plans for 2007 (JT-60U) include further exploitation and optimisation of steady-state scenarios (with internal transport barriers) at high triangularity at lower q_{95}~5-6. DIII-D achieved β_N~4 for 2 seconds in reversed shear discharges (q_{min} near 2, q(0) ~ 6, and q_{95}=4-5), using highly shaped plasmas [7].

3. SSO-1.3: CONTROL OF HIGH BOOTSTRAP PLASMAS:

One of the key aspects of steady state operation for a reactor is the presence of a large bootstrap fraction (> 70%) [8]. Operation at high beta without flux consumption (including transformer-less operation) has been developed in various experiments but under widely different conditions. The control requirements should be investigated, as this is one of the major issues to assess the applicability of these scenarios in ITER or to future reactors. DIII-D could only perform a limited number of experiments in this area in 2006. In JT-60U a self-sustained state driven by the bootstrap current was achieved [9]. In the various feedback modes used (I_p feedback, constant OH current, or constant plasma surface flux) operation a completely self-driven system with negligible external current drive was obtained. However, ≤ collapses are often observed in which the internal transport barrier shrinks radially, or slowly degrades. The development of high bootstrap scenarios is challenging and a difficult areas of research to define real joint experiments as various machines have not found a robust scenario to propose joint experiments.

4. SSO-2.1: COMPLETE MAPPING OF HYBRID SCENARIO

The aim of these collaboration experiments for this specific scenario is to perform q_{95} scans and density scans in several devices (DIII-D [10], ASDEX Upgrade [11], JET [12] and JT-60U [13]) and to obtain operation closer to ITER conditions. The experiments show that the performance is maintained over a range of q_{95}=2.7- 5, with no change in the values for β_N obtained (2.7-3) More specifically, in DIII-D changes in rotation (using different neutral beam sources) lead to significant variations in many plasma phenomena that impact ITER performance [14]. Although energy confinement decreases and the 3/2 NTM amplitude increases for low Mach number, the performance still projects to Q > 10 in ITER with no rotation for q_{95}~3.2, but the margin is reduced compared to cases with rotation. In ASDEX Upgrade hybrid scenarios with significant ICRH heating have been developed with P_{ICRH} ~ P_{NBI} ~ 4MW. In addition, experiments show that operation at β_N ~3 at high density (f_{GW}~85%) is possible for this scenario [15]. JET completed during the 2006-2007 campaigns a large effort on the mapping of the hybrid scenario (again these results are being analysed). These experiments focussed on a range of density, heating scenarios, documenting the beta limit, comparisons with standard H-modes, extension of the regime in JET to lower q_{95}~3 and the use of impurity seeding to obtain small ELMs (type III). In JT-60U, after installation of ferritic inserts to reduce the TF ripple, the performance of long-pulse ELMy H-mode plasmas was improved in terms of sustained duration time for both high normalized beta ($\leq_N$) and high thermal confinement enhancement factor $H_{98}(y,2)$ [16]. High $\leq_N>2.3$ together with $H_{98}(y,2)\sim1$ was sustained for 23.1s ($\sim12\tau_R$) at $q_{95}\sim3.3$, with a bootstrap current fraction of 36%-45%. Also NSTX will be involved in mapping the operational space of the Hybrid scenario, ρ^* scaling and role of the MHD, using lithium to condition the walls for (controlled) low density operation at high beta. This will add important data from spherical tokamaks to the existing data. In summary, there has been a significant effort in this area from various experiments and thrust to qualify the hybrid scenario for ITER will continue.

5. SSO-2.2: MHD EFFECTS ON Q-PROFILE FOR HYBRID SCENARIOS

Neoclassical tearing modes (NTM) are commonly observed in hybrid scenarios, and the effects of the 3/2 NTM on current profile and confinement have been independently reported. The aim is to establish similar type of hybrid discharges in experiments with maximum duration with different MHD behaviour. In JT-60U, long-pulse high-β_p ELMy H-mode discharges were performed. Throughout the discharge, neither NTMs nor other large MHD activity (sawteeth, fishbones) were observed although $q(0)\sim1$ [17]. It was demonstrated that the evolution of a 3/2 NTM can be suppressed by electron cyclotron current drive (ECCD) using central co current drive at ~10% of I_p [18]. In ASDEX Upgrade, evolution of current penetration was compared between early and late NB heating at $q_{95}=4.0$ and $q_{95}=4.8$ in Improved H-mode discharges (Figure 2). For early NB heating, a 3/2 NTM appeared and q(0) is kept above unity, while for late NB heating only fishbones were observed, maintaining $q(0)\sim1$ without sawteeth activity [19]. At low-q ($q_{95}\sim3$), a good Improved H-mode condition could be obtained by NTM stabilization with narrow ECCD deposition [15,20]. In DIII-D, q(0) is kept above unity when a 3/2 NTM exists, while q(0) decreases below unity only when a 4/3 NTM exists. It was found that the amplitude of 3/2 NTMs was increased when torque input was reduced, which may also affect the evolution of q(0) [21]. The results of experiments in JET on the hybrid scenario and long pulse operation during the 2006/2007 campaign need to be analysed on the importance of MHD and q-profile evolution. So far analyses of results from JET suggest the q-profile can be sustained by the calculated non-inductive current contributions without the need of current redistributions by MHD [12].

6. SSO-2.3: R DEPENDENCE ON TRANSPORT AND STABILITY IN HYBRID SCENARIOS*

The aim of these experiments is to (i) make identity experiments for hybrid scenarios at the same ρ^* for detailed transport studies and (ii) to get the largest possible variation in ρ^* for confinement scaling and stability boundary scaling studies. Experiments have started, but require completion in 2007. Preliminary results indicate no effect on plasma stability by going to lower ρ^* [22] with core confinement close to GyroBohm. Data from these experiments should are now included in the global confinement database, to take advantage of the operational capabilities of this regime (high beta).

7. DOCUMENTATION OF THE EDGE PEDESTAL IN ADVANCED SCENARIOS:

This activity commenced in 2006 (mainly by the pedestal TG of the ITPA) and highlights the close coupling between edge and global confinement. It is found that edge confinement increases with input power in large part due to a broadening of the temperature pedestal at the plasma boundary, contributing to an overall increase in confinement [23]. On the other hand, even in discharges without internal transport barriers, variations are observed in the core confinement, showing that the tight edge-core coupling can be manipulated experimentally. New experimental results in this area, with improved machine capabilities and edge diagnostics, are planned for 2007.

3. MODELLING AND BENCHMARKING OF HEATING SYSTEMS (ACTUATORS)

Benchmarking of the actuators available for heating and current drive is an important area of international collaboration. Recently, various simulations for Lower Hybrid Current Drive (LHCD), Ion Cyclotron Heating (ICRH) and Electron Cyclotron Heating (ECRH) and Electron Cyclotron Current Drive (ECCD), have been compared using the latest code developments.

The benchmarking exercise for LHCD performed a few years ago was reviewed. The codes were used for the old ITER plasma conditions. Hence, a new benchmarking optimisation exercise for LHCD was started by the SSO TG. The predictions of several simulation models for LHCD were compared [24] using parameters typical of the steady state operating scenario in the ITER device (the so-called Scenario 4). The most complete LHCD simulation models that were used combined 2D velocity space Fokker Planck solvers with toroidal ray tracing packages [25, 26]. These models predict 2.0 – 2.6 MA (see Figure 3) of driven current for 30 MW of coupled LHRF power (although one LH antenna in ITER will couple less than 20MW). Also orbit-following Monte Carlo codes [27] were used to study the possible parasitic damping of LH waves on fusion generated alpha particles, considering the effect of magnetic field ripple and fast ion anomalous transport on the alpha population [28]. It was found that for a large anomalous diffusion coefficient ($1m^2/s$), the absorption on fusion alphas can be as high as 7.7% using a lower hybrid source frequency of 3.7 GHz. This result gives some confidence in the source frequency choice of ITER (5.0 GHz) based on minimising the possibility of this parasitic interaction.

ICRH codes continue to show progress in their development, and benchmarking (mainly code-code benchmarking). Various codes give similar results for the ion heating scheme in ITER (second harmonic tritium). Still not fully resolved is the damping on the alpha particles, requiring further comparison of the codes. Again, tests of ICRH codes against experimental data are encouraged. This benchmarking should also include the RF codes used in the scenario modelling. The TASK code [29] uses full wave calculations including finite larmor radius effects and proper fast particle distributions to get a realistic, self consistent assessment of power absorption (including alpha particles). TASK is now ready to proceed with calculations for ITER. The TORIC [30] and AORSA [31] code benchmarking now use ITER scenario 2, with plans to do a similar analysis for ITER scenario 4 (including current drive estimates). The differences in predicted (parasitic) power absorption on beryllium and helium4 need to be understood.

The benchmarking of several ECRH codes is finished and will be published [32]. A detailed comparison of these codes is desirable since they use a variety of methods for modelling the behaviour and effects of the waves. The approach used in this benchmarking study is to apply these codes to a small number of representative cases. Following minor remedial work on some codes, the agreement between codes for off-axis application is excellent. The largest systematic differences are found between codes with weakly relativistic and fully relativistic evaluation of the resonance condition, but even there the differences amount to less than 0.02 in normalized minor radius. For some other cases, for example for central current drive, the code results may differ significantly due to differences in the physics models used.

A benchmarking of several codes for Neutral Beam Injection (NBI) current drive has not been performed. This now becomes an urgent task as in ITER the NBI system is used for (off-axis) current drive in all scenario simulations. Moreover, there are observations from ASDEX Upgrade suggesting the current drive may not be on-axis [33], while JT-60U data can neither confirm nor contradict this. Hence more experiments were done in 2006 [34] and detailed analyses are planned for 2007.

4. COORDINATED MODELLING OF ITER SCENARIOS

ITER scenario modelling continues to show very good progress, for the ITER Hybrid scenario (operating at ~12MA) and steady state scenario (9MA), especially with regards to getting a common set of simulations from several codes. Integrated simulations are performed to establish a physics basis, in conjunction with present tokamak experiments, for the operating modes in ITER. Many codes are available for ITER scenario modelling, but only one (ASTRA [35]) been used so far by the ITER physics team. The different codes have not been benchmarked using the same data for predictions. After the benchmarking, several codes can be used for ITER scenario modelling. The SSO TG has taken up the (high priority) task to define a common set of parameters for set of 0D-data and profile data for the ITER hybrid scenario to provide a comparison of 1.5D core transport modelling assumptions, source physics modelling assumptions, as well as numerous peripheral physics modelling [36]. Simulations are done using both fixed and free-boundary 1.5D transport evolution codes including CRONOS [37], ONETWO [38], TSC/TRANSP [39,40], TOPICS [41], and ASTRA [35]. The GLF23 energy transport model [42,43] was used, the injected powers are limited to the negative ion based neutral beam, ion cyclotron, and electron cyclotron heating systems. Initial results (see Figure 4) indicate that very strict guidelines will need to be imposed on the application of GLF23, to make useful comparisons. Some of the variations among the simulations are due to source models that vary widely among the codes used. In addition, there are a number of peripheral physics models that should be examined, some of which include fusion power production, bootstrap current, treatment of fast particles, and treatment of impurities. The simulations of the steady state operating mode are done with the same 1.5D transport evolution codes cited above, in addition exploring the possible use of lower hybrid current drive. The steady state simulations are in an earlier stage and are focused on developing a range of safety factor profiles with 100% non-inductive current [44].

In some more specific coordination work the TSC/TRANSP package using the GLF23 transport model has been benchmarked on DIII-D experimental results for the hybrid scenario. The RF package in TRANS/TSC has been upgraded, using second harmonic tritium heating. A sawtooth model can be used in the simulations. For application of the hybrid scenario in ITER, CRONOS simulation show that the central q will drop below 1 at 400s. Applying in these conditions co-ECCD (21 MW at ρ~0.4, giving I_{ECCD}=0.45 MA), delays the start of the sawteeth or more efficiently LHCD can be used (q(0) kept even longer above 1, compared to co-ECCD). In addition, ONETWO simulations show that fast wave current drive can contribute significantly to the control/evolution of q(0).

5. REAL TIME CONTROL REQUIREMENTS

Assessment of real-time control of advanced scenarios in ITER is an important issue involving collaboration on experiments and modelling. The ITPA encourages sharing the experience gained in this area between several experiments; current profile control is one of the most important topics in the SSO TG. At the recent meetings, DIII-D reported on the modelling of recent feedback results to match the observed current profile evolution and a comprehensive modelling of the plasma response with CORSICA [45]. The aim is to verify the use of transport modelling codes CRONOS and ONETWO for simulations of real time control. New results from Tore Supra were reported using n// and LH power for control to optimise discharges [46]. A report from JET presented the use of strongly coupled distributed-parameter systems for real time control with a large number of output parameters/profiles but a limited number of actuators [47]. Extensive work is in progress at JET to develop integrated control of the plasma shape, safety factor, kinetic profiles and primary flux consumption. Experiments were performed during the 2006/2007 campaigns (analyses pending). JT-60U reported control of q_{min} (~ q_0) with LHCD during high β_{pol} operation, together with rotation control to avoid beta limit when q_{min} passes 4. In several devices constant flux control is used in fully non-inductive scenarios.

Specific real-time control objectives are incorporated in the proposals for in the joint experiments, to continue the exchange of personnel (know how) and to demonstration control of the target q-profile in advanced scenarios. A new proposal for joint experiments has been defined for dedicated open loop modulation of actuators for current profile and pressure control, with the aim of collecting a well defined data set for various devices (JET, JT-60U, DIII-D, ASDEX Upgrade, Tore Supra). Data that will be taken can also be used to develop (cross) machine models for real time control of the current density profile j(r) and/or the pressure profile p(r). For the modelling of real time control requirements, the scenario simulation codes discussed in section 4 can be used. However, models utilized for the actuators (section 3) play a crucial role.

6. SPECIFIC ISSUES FOR ITER

Assessment of the requirements for ITER is an ongoing activity, including documentation of the results obtained (Progress in the ITER Physics Basis), the optimisation of plasma start-up phase and use of the additional heating systems (see section 3 of this paper).

PROGRESS IN THE ITER PHYSICS BASIS: CHAPTER 6, "STEADY STATE OPERATION" [48]

During the last few years the SSO TG finished Chapter 6 on "Steady State Operation" of the ITER Physics Basis Update. This chapter reports on significant progress made in the area of advanced modes of operation that are candidates for achieving steady state conditions in a fusion reactor. The corresponding parameters, domain of operation, scenarios and integration issues of advanced scenarios are discussed. A review of the presently developed scenarios, including discussions on operational space is given. The chapter reports on progress made in the domain of heating and current drive in recent years, especially in the domain of off-axis current drive, which is essential for the achievement of the required current profile. The specific control issues for steady state operation are discussed. The achievable parameters for the ITER steady state and hybrid scenarios with foreseen heating and current drive systems are discussed using integrated modelling (including actuators), allowing an assessment of achievable current profiles. Finally, a summary is given including outstanding issues and recommendations for further research and development.

OPTIMISATION OF PLASMA START-UP PHASE IN ITER

The SSO TG sees this topic as a high priority research item: Steady state and hybrid scenarios require continuously elevated central q values (>1) during the current rise phase of ITER, preferably in divertor geometry to allow additional heating. The capability of the ITER (mainly poloidal field systems) for plasma start-up and early current rise needs to be documented and assumptions used in developing the start-up of ITER scenarios need to be verified. The ITER start-up scenario (see Figure 5) is on the outboard, using ECRH during plasma initiation at low loop voltage. New joint experiments have been proposed with the goal to verify the proposed ITER startup scenarios. These experiments are in progress on JET, DIII-D, and are planned for ASDEX Upgrade. The data obtained will be used for validating and (if necessary) improving the models used to optimise the ITER startup scenario. TSC/TRANSP simulations of the ITER start-up phase show that without additional heating the current penetration gives sawteeth at around 15 s (I_p~3MA), before the divertor phase. Hybrid scenarios would require 5 to 8 MW of heating to keep q(0) just above 1 during the current rise, starting 10s after breakdown (limiter phase). DIII-D, JET and ASDEX Upgrade report that both plasma breakdown phase and a full bore plasma start-up are important for achieving the desired q-profile (q(0)≥1, or reversed shear).

CONCLUSIONS

The SSO TG will continue the work on the areas outlined in this paper. High priority research for 2007 are: (i) continue the focussed modelling activity on ITER hybrid and steady state scenarios, using standard (and common) sets of input data. (ii) Assess requirements for real-time control in ITER and increase collaboration in joint experiments. (iii) Code benchmarking of LHCD and NBCD and implications for ITER. (iv) Verify the requirements for the ITER start up phase. (v) Together with the pedestal TG of the ITPA: Experiments to document pedestal in advanced scenarios, modelling of pedestal in scenario modelling codes and predict the pedestal conditions in ITER (maximum pedestal temperature allowed in ITER).

The research coordinated by the SSO TG is beneficial for a range of experiments, specifically for the new experiments (being) constructed with the main aim of achieving steady state operation. Scenario simulations for these new experiments (including ITER) have access to improved integrated modelling codes and simulation codes for the actuators. In addition, the SSO TG proposes that current experiments (JET, JT-60U, DIII-D, ASDEX Upgrade, Tore Supra, NSTX, MAST), should duplicate experimental conditions proposed in these new experiments to verify the advanced scenarios achievable.

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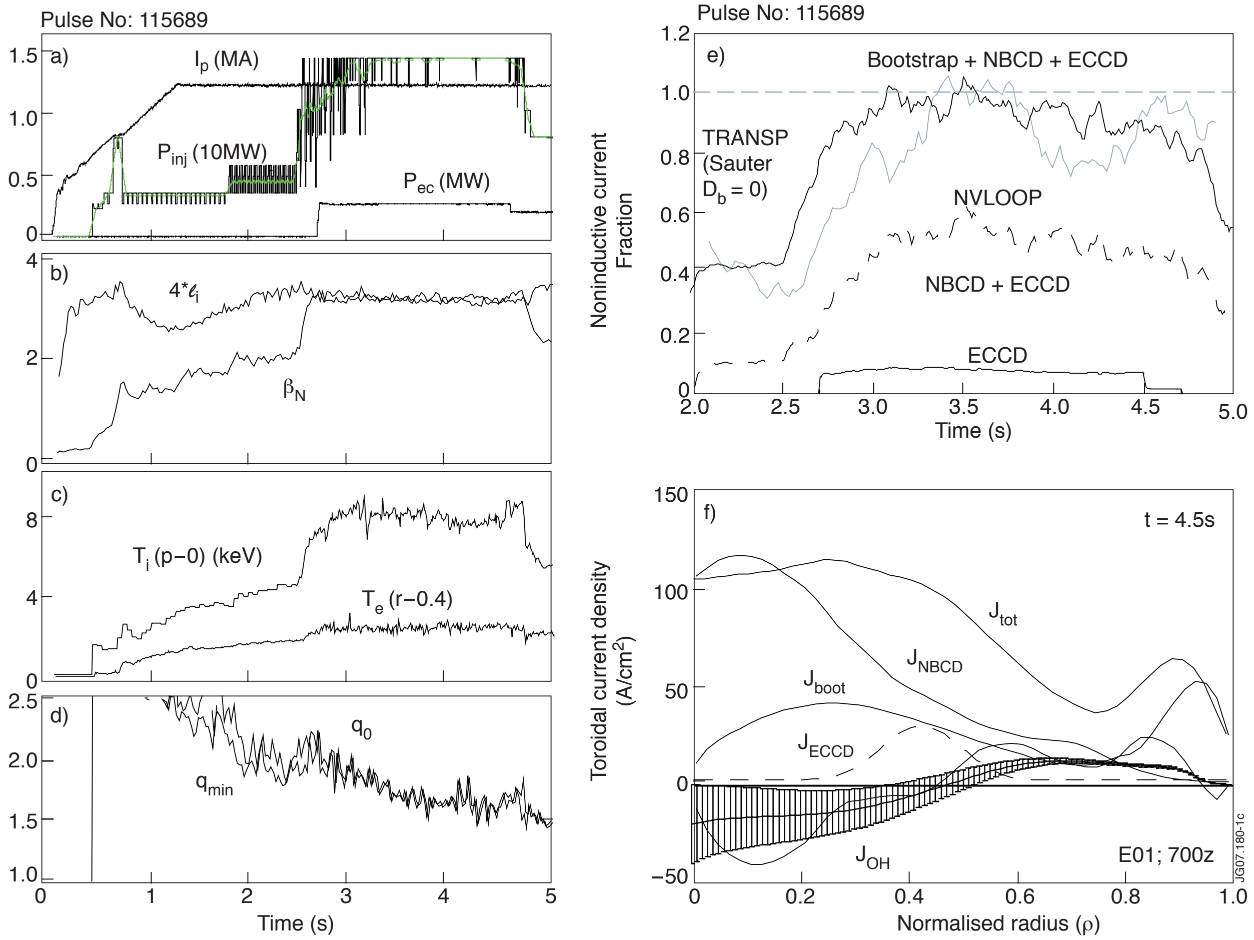

Figure 1: DIII-D full current drive discharge with q(0) ~ 1.5 [2].. Typical waveforms, evolution of non-inductive currents and break-up of the current profiles are shown. (a) Plasma current (I_p), neutral beam power (P_{inj}) and ECCD power (P_{EC}). (b) Four times the plasma inductance (l_i) and normalised beta (β_N). (c) Electron temperature at r/a~0.4 ($T_e(\rho\sim0.4)$) and ion temperature in the centre ($T_i(\rho=0)$). (d) The central q-value (q_0) and minimum q-value (q_{min}). (e) Various non-inductive current contributions (f) Profiles of the current density contributions at t=4.5.

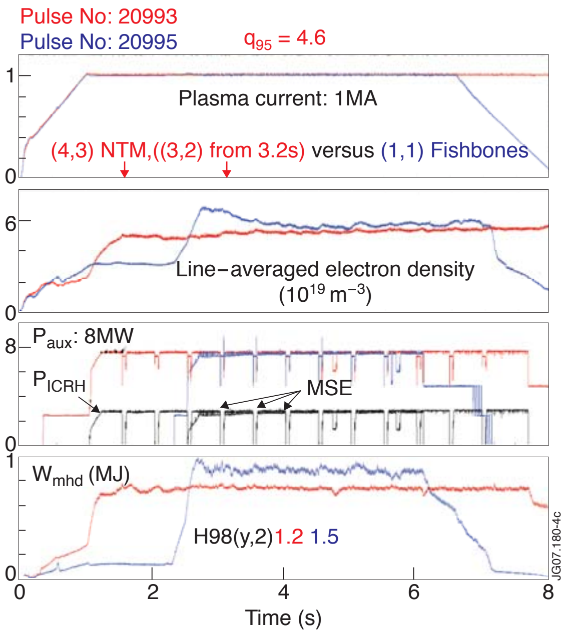

Figure 2: Comparison of a discharge with (early) heating during the ramp-up (Pulse No: 20993, red curves) and a discharge with (late) heating during the flat top ramp-up (Pulse No: 20995, blue curves). The stored energy is significantly higher for the late-heating case. Since operational parameters are almost identical this shows up directly in the H-factors, which are 1.2 and 1.5 respectively, using the IPB-H98(y, 2) scaling.

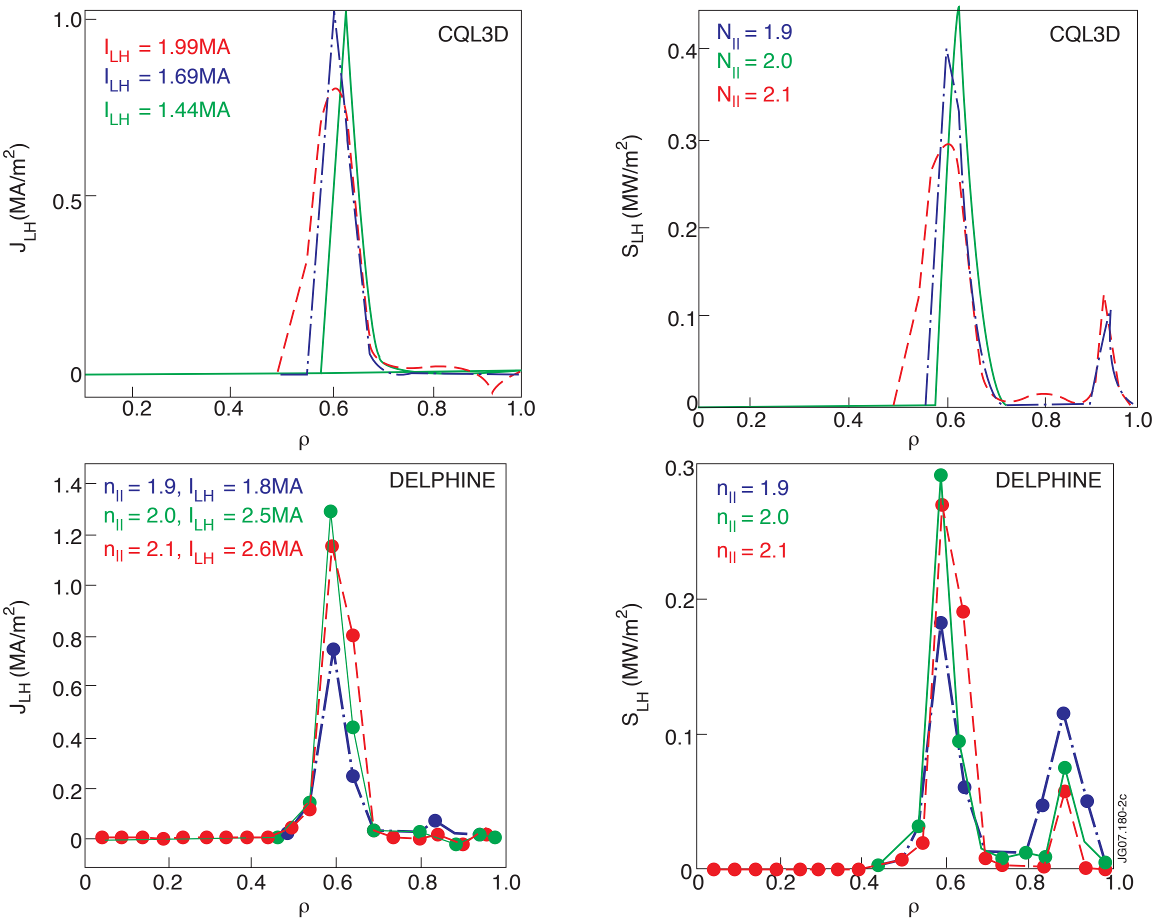

Figure 3: Summary of LHCD simulations from CQL3D, DELPHIN. Plotted are the predicted LH current density on the left and the corresponding LH power density on the right [24].

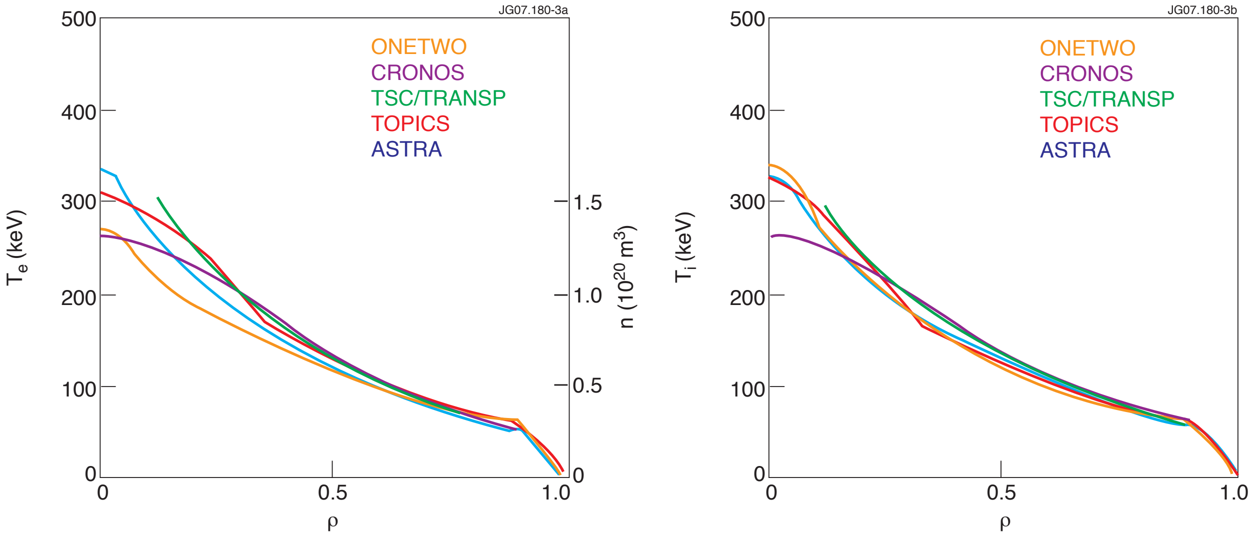

Figure 4: Calculation of the electron temperature and ion temperature profiles by various transport codes, using the GLF32 transport model. Simulation for a hybrid scenario in ITER (12MA/5.3T), with a fixed density profile same set of assumption as given in [36].

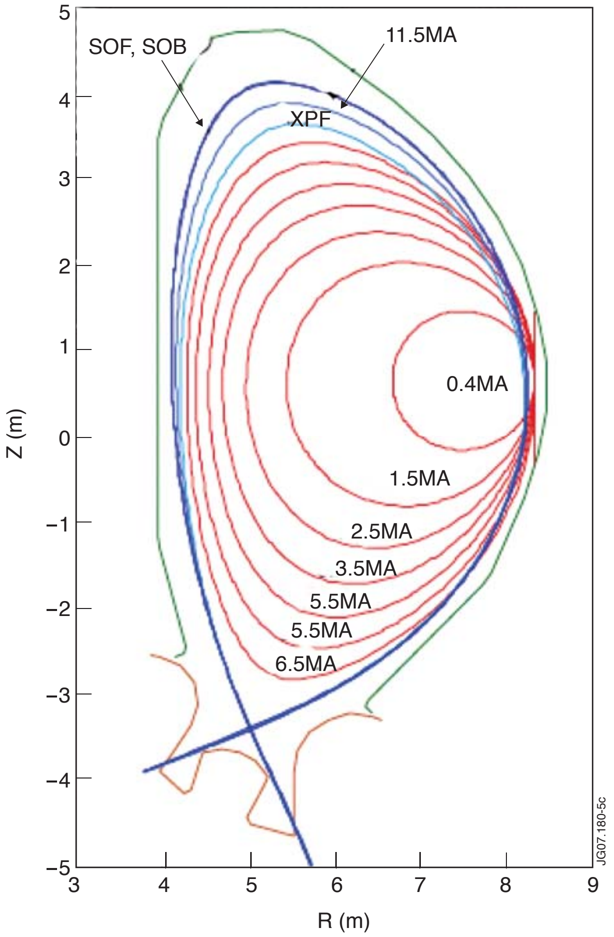

Figure 5: Evolution of the plasma cross section of an ohmic current rise in ITER to 15MA (senario2)