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EXPERIMENTAL STUDIES OF ITER DEMONSTRATION DISCHARGES

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Experimental studies of ITER demonstration discharges

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Abstract
Key parts of the ITER scenario are determined by the capability of the proposed poloidal field coil set. They include the plasma initiation at low voltage, the current rise phase, the performance during the flat top phase, and a ramp down of the plasma. The ITER discharge evolution has been verified in dedicated experiments. New data are obtained from C-Mod, AUG, DIII-D, JT-60U and JET. Results show that breakdown at E<0.23-0.32V/m is possible un-assisted (ohmic) for large devices like JET and attainable in all devices with ECRH assist. For the current ramp up, good control of the plasma inductance is obtained using a full bore plasma shape with early X-point formation. This allows optimisation of the flux usage from the poloidal field set. Additional heating keeps l_i<0.85 during the ramp up to q_{95}=3. A rise phase with an H-mode transition is capable of achieving l_i<0.7 at the start of the flat top. Operation of the H-mode reference scenario at q_{95}~3 and the hybrid scenario at q_{95}=4-4.5 during the flat top phase was documented. Specific studies during the flat top phase provide data for the l_i evolution after the H-mode transition and the l_i evolution after a back-transition to L-mode. During the ITER ramp down it is important to remain diverted and to reduce the elongation. The inductance could be kept ≤1.2 during the first half of the current decay, using a slow I_p ramp-down, but still consuming flux from the transformer. Alternatively, the discharges can be kept in H-mode during most of the ramp down, requiring significant amounts of additional heating.

1. Introduction

Simulations and experiments are focused on 15 MA scenarios in ITER [1], the most challenging for the superconducting poloidal field (PF) coils. Recent studies [2,3,4] have concentrated on upgrading the originally proposed PF coil set to provide better control and to respond to plasma disturbances within a range of plasma inductance (used here $l_i=l_i(3)=2\int B_p^2 dV/(\mu_0^2 Ip^2 R)$, with B_p the poloidal magnetic field, I_p the plasma current and V plasma volume). Allowing for control margins [4], a range of l_i=0.7-1.0 is possible in ITER at 15MA. Until recently, detailed experimental data on the time evolution of ITER-like plasma discharges was not available. Moreover, the analyses performed in the framework of the ITER design review (2006-2008) highlighted that some of the assumptions made, in particular the evolution of the plasma inductance, are not consistent with experimental observations. Hence, dedicated experiments at C-Mod [5], AUG [6], DIII-D [7], JT-60U [8] and JET [9] have been performed on all aspects of the discharge scenario. These dedicated experiments have (in part) been coordinated by the Steady State Operation Topic Group of the International Tokamak Physics Activity. They are also supported by interpretation of the plasma discharges with several scenario modelling codes [10,11]. This paper summarises and compares the results obtained at plasma breakdown, for the current rise phase of the discharge, the current flat top phase of the H-mode reference scenario at q_{95}~3 as well as the hybrid scenario at q_{95}=4-4.5 and the current ramp down.

2. Low voltage breakdown experiments

Most devices have revisited low voltage plasma breakdown recently to match ITER conditions (0.33V/m). These dedicated experiments optimised the stray fields at breakdown using multiple poloidal field coils, similar to superconducting tokamaks.

Table I: *Recent ITER like low voltage breakdown studies.*

	R_0 [m]	B_T [T]	ECRH	Power (type)(1)	E (V/m) Ohmic	E (V/m) assisted	I_p/dt(3) [MA/s]
C-Mod	0.68	5.4	-	-	1.2-1.6	-	6.0
AUG	1.65	1.7-3.2	105-140 GHz	0.3-1 MW (X2,O1)	0.6	0.2	1.0
DIII-D	1.70	1.9-2.1	110 GHz	1-1.4 MW (X2)	0.43(2)	0.21(2)	1.0-1.3
TS	2.40	3.85	118 GHz	0.3-0.6 MW (O1)	0.3	0.15	0.8-1.3
JET	2.96	2.36	- (LHCD)	1.0-2.0 MW (LH)	0.23	0.18	0.5
JT-60U	3.32	3.5	110 GHz	0.4-2 MW (O1)	0.43[13]	0.26[14]	1.5-2

(1): O1: Fundamental O-mode, X2: Second harmonic X-mode. (2) In 1991, ref [12] documented minimum values of 0.25V/m for ohmic and 0.15V/m for ECRH assisted HFS breakdown studies. (3): During first 100-200ms.

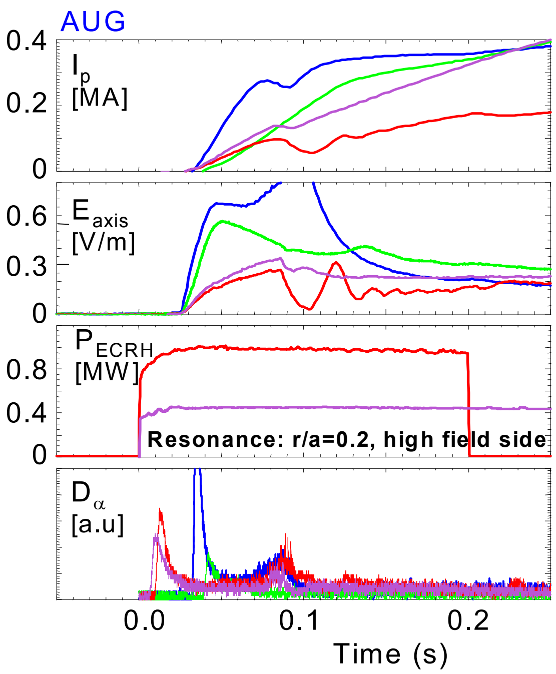

Fig. 1*: ECRH start up assist at AUG. The minimum required electrical field on axis is reduced to ~0.2V/m using 0.3-0.9 MW ECRH (X2).*

Recently, JET and DIII-D [15] have optimised low voltage start-up. AUG and Tore Supra [16] developed operation without resistor switches in the ohmic heating circuits. For un-assisted (ohmic) breakdown, the minimum achieved electric field (E) on-axis tends to decrease with machine size down to ~0.23V/m for JET (see Table I), a value well below ITER design value (0.33V/m). Most experiments have also tested ECRH breakdown assist. JET tested LHCD but observes no pre-ionisation of the filling gas. With ECRH, pre-ionisation is clearly observed (see Fig. 1) allowing a reduction of the loop voltage required for reliable breakdown in clean machine conditions or alternatively giving reliable breakdown at ~0.3-0.4V/m for a de-conditioned machine status (after a vacuum vent, after disruptions, following wall saturation experiments or experiments with argon seeding). JT-60U has not optimised specifically for ITER-like breakdown conditions in recent experiments but uses routinely 2MW ECRH to achieve robust breakdown, even in successive high recycling discharges. AUG tested the use of fundamental O-mode (105GHz at 3.2T) with the resonance position at 1.45m (HFS). This is equivalent to using 170GHz at 5.2-5.3T in ITER.

Hence, a dedicated ECRH system at 126GHz would not be essential for ITER. Tore Supra had an extensive campaign on optimising breakdown at low loop voltage; the results are published in [17]. All experiments observe a decrease of the initial (first 100-200ms) rate of rise of the plasma current going to lower loop voltage. The last column in Table I gives values of 0.5-1.3MA/s at ~0.2V/m. The slow rise gives current penetration without MHD reconnection, giving low l_i~0.3-0.6 just after breakdown. Hence, low voltage breakdown settings were used in most of the ITER scenario demonstration discharges (described below).

3. Current rise phase

One of the main aims of dedicated experiments was to demonstrate safe operation with $0.7<l_i<1.0$ throughout the current rise phase ramping to q_{95}~3 (high normalised current). The studies concentrated on four topics detailed below: (1) the optimum plasma shape evolution, (2) ohmic discharges, (3) use of additional heating, and (4) tools available for l_i control.

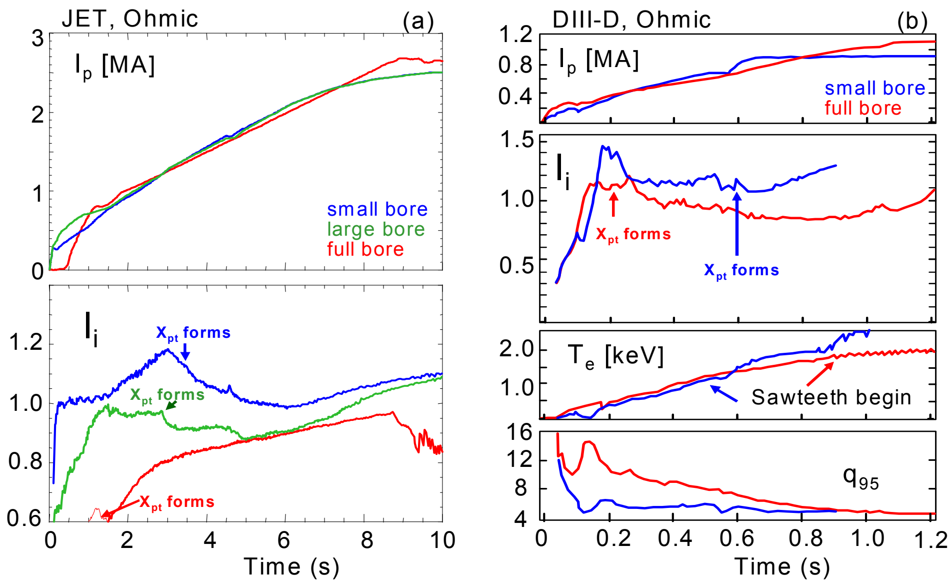

***Fig. 2**: Evolution of l_i for ohmic current rise phases at JET (a) and DIII-D (b). The evolution for the originally envisaged small bore start up for ITER is indicated in blue. Full bore ramp up discharges for both devices are indicated in red. The green curve for JET is a large bore outer limiter case with somewhat later X-point formation compared to the red discharge.*

Plasma shape: The original startup scenario envisioned for ITER [18] started with a small outboard limited plasma. The plasma cross section was expanded to keep constant q at the plasma boundary as the plasma current increases, diverting at 7.5MA. Experiments duplicating this scenario show a rapid (as designed) current penetration during the limiter phase, featuring high l_i>1, just before X-point formation. DIII-D, AUG, C-Mod and JET demonstrate that low plasma inductance was only achieved with a full bore limiter phase (limited on the outboard side to reproduce ITER conditions) and diverting as early as possible. This also allows early use of additional heating during the divertor phase. Fig. 2 shows results obtained in JET and DIII-D, comparing different cross section size during the early ohmic ramp-up phase. All experiments show excellent reproducibility of the full bore limiter, early X-point scenario, with good control of the plasma density.

Ohmic discharges: The density has been varied during the rise phase, showing a clear optimum for the current diffusion in ohmic conditions; a trade-off between achieving high T_e at low density ($\langle n_e\rangle/n_{GW}<0.2$) but rather higher Z_{eff}~1.5-2.5, or somewhat higher density ($\langle n_e\rangle/n_{GW}$~0.4) at reduced T_e but significantly lower Z_{eff}~1.2-1.5. In general, the results show that stable ohmic discharges at q_{95}~3 have the lowest l_i=0.8-0.85 when using the fastest current ramp rates available after the breakdown phase. For example, at fixed plasma shape, the I_p ramp rate was varied in JET from 0.36MA/s to 0.19MA/s, giving a variation of l_i =0.83-1.03, AUG varied dI_p/dt from 0.92MA/s to 0.66MA/s giving l_i=0.82-1.0. C-Mod changed dI_p/dt from 2.4MA/s to 1.3MA/s giving l_i=0.9-1.0. These results extrapolate to ITER having a fast current rise to 15MA of ~70s and a slow rise of ~100s. DIII-D can obtain l_i~0.65, but these discharges are MHD unstable leading to full current disruptions. Moreover, they extrapolate to a ramp up of 50s in ITER, too fast for the PF power supplies. During the flat top without additional heating, l_i increases to 1.1-1.2. In ITER such high l_i>1 is not accessible at 15MA with the available flux from the OH transformer [2,4], implying that ITER will have to start heating, at the latest, immediately after reaching 15MA.

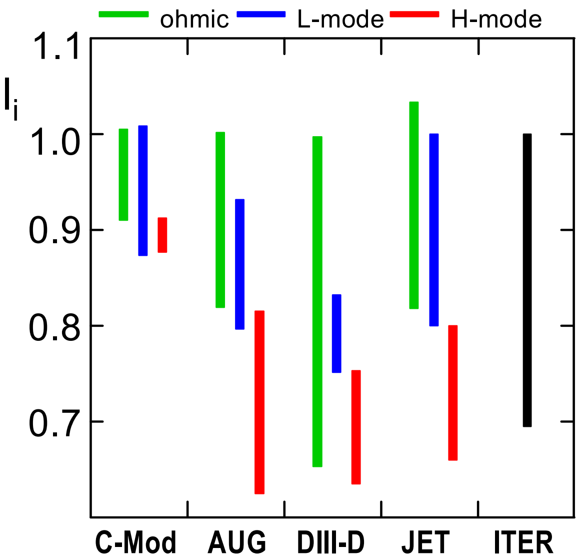

***Fig. 3**: Range of l_i achieved during the current rise in various devices for ohmic (green), L-mode (blue) and H-mode (red). ITER range for l_i is indicated in black.*

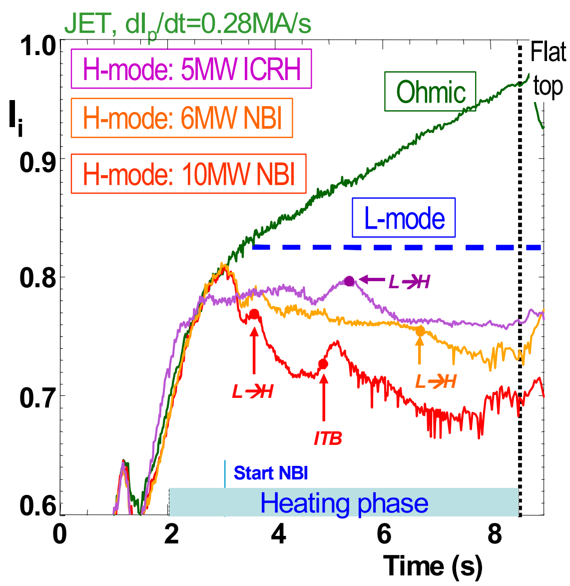

***Fig. 4**: JET current rise for dI_p/dt=0.28MA/s. Variation of l_i with heating during the current rise. Experiments in L-mode usually have l_i~0.85 (blue dotted line). Transitions to H-mode and an ITB are also indicated.*

Additional heating: AUG, JET and C-Mod show that heating during the limiter phase gives a rapid increase of Z_{eff} to 2-3 for AUG (W-wall, using the outboard limiters) and C-Mod (Mo-wall, touching both inboard and outboard limiters), while Z_{eff} reaches ~4 in JET (C-wall, Be coated, outboard limiters). In the various experiments, the type and level of heating during the divertor phase of the current rise was varied. AUG used NBI with on-axis and off axis injection (1.5-5MW) or ECRH at 0.5 MW. JET applied both on axis or off-axis ICRH (2-6MW), or LHCD up to 2.2MW or NBI up to 10MW. DIII-D utilised NBI (1-5MW) and C-Mod used central ICRH (1-3MW). A clear result is that heating during the current rise, in L-mode or in H-mode, gives a capability of significantly varying l_i from 0.97 to 0.63 at fixed dI_p/dt. An overview of all experiments is given in Fig. 3, details for JET are shown in Fig. 4. In L-mode, l_i values as low as 0.8 are reached. JET shows no difference in the l_i achieved at q_{95}=3, using 3MW central ICRH, or 2.2MW LHCD or 4 MW NBI. Code simulations [2] show that the heating effect on l_i dominates over any current drive effect from either NBI or LHCD. Within the range of heating power available, transitions to H-mode are observed in DIII-D, AUG and JET, giving access the lowest l_i=0.63-0.75 with reversed q-profiles. In AUG and JET, discharges with an H-mode current rise phase save 25%-30% of the transformer flux required for an ohmic current rise. In AUG for example, target plasmas with l_i~0.63 at q_{95}=3 are used for the hybrid regime. In H-mode, the bootstrap current near the pedestal plays an important role. In addition, a broad T_e profile helps in forming broad current density profiles.

Control of l_i: At DIII-D, feedback control of l_i was developed during the divertor phase of the current rise of large-bore startup discharges, using the current ramp rate as the means of changing l_i [11]. The ramp rate was varied from 0.34MA/s to 1.5MA/s. Control of l_i in purely inductive current rises and with various levels of NBI during the current rise was demonstrated successfully. As expected, the inductive cases without heating require higher current rampup rates to achieve lower l_i. Increasing levels of auxiliary heating lead to slower current ramp up rates to maintain the same level of l_i. More sophisticated control schemes using density, heating, and current ramp rate are under development in DIII-D [19] for generating a specified q profile. At JET, control of l_i by additional heating was developed, and applied in scenarios with a current rise to q_{95}=4 (2MA/2.4T). Control was demonstrated with either ICRH or NBI. Requesting l_i=0.8, a target q-profile with q(0) just above 1 at the start of the flat top was produced requiring modest heating powers (ICRH~3MW, NBI~5MW). DIII-D and JET have demonstrated that at even lower I_p with q_{95} near 5, central q values near 2 can be produced in an ITER like current rise. This would be required as a target for advanced scenarios with the aim of producing Q~5 in full steady state conditions.

The implications for ITER resulting from these experiments are that a full bore start up is strongly recommended and heating during the current rise seems to be a requirement. Combining the experimental data from the different devices, variations of the plasma resistivity, with a $T_e^{3/2}$, a^2, Z_{eff} dependence describes the data well. Code simulations for ITER indicate [10,11] a requirement to divert at 3.5MA and to heat during the current rise with P_{tot} = 5-15MW, depending on the l_i values required.

4. Performance during the flat top phase

In ITER, the "nominal" 15 MA ELMy H-mode plasma is characterized by I_p=15MA, B_T=5.3T, R=6.2m, a=2.0m, κ=1.85, $\langle n_e\rangle/n_{GW}$=0.85, l_i=0.8, β_p=0.8, β_N=1.8, P_α=80MW, P_{aux}=40MW, P_{LH}=80MW (H-mode power threshold in a 50:50 DT mix, using the latest scaling law [20]). The majority of the devices studying ITER relevant ramp-up scenarios continued the studies during the flat top phase for the H-mode inductive scenario at q_{95}~3. The experiments aimed at obtaining H_{98}~1 and β_N~1.8. Apart from C-Mod (ICRH), the dominant heating power was neutral beam heating, although typically $T_i(0)$~$T_e(0)$ was obtained in these discharges. In C-Mod, DIII-D and JET, $\langle n_e\rangle/n_{GW}$=0.6-0.65 was achieved during the flat top phase without additional gas fuelling. AUG obtained $\langle n_e\rangle/n_{GW}$=0.78 using gas fuelling (Φ_D=8•10^{20}/s). No active ELM mitigation or radiation seeding was used in these discharges. Table II gives an overview of the results obtained in these experiments.

Table II: *Overview of ITER demonstration discharge parameters.*

	I_p [MA] / B_T [T]	P_{tot} [MW]	$\langle n_e\rangle$ [$10^{19}m^{-3}$]	β_p / β_N	H_{98}	f_{GW}	P_{tot}/P_{LH}(1)	l_i (end of FT)
AUG	1.0 / 1.7	5.0	9.8	0.85 / 1.9	0.95	0.78	1.5-1.7	0.85
DIII-D	1.5 / 1.9	4.5	8.0	0.65 / 1.8	1.1	0.65	1.0-1.5	0.65
JET	2.5 / 2.35	19.0	6.4	0.7 / 1.8	0.95-0.98	0.70	1.9-2.1	0.80
ITER	15 / 5.3	40+80(2)	10.0	0.8 / 1.8	1.0	0.85	1.1-1.5(3)	?

(1): $P_{L\text{-}H}$ [MW] =2.15*$n_{e20}^{0.782}$*$B_T^{0.772}$*$a^{0.975}R^{1.0}$ [ref 20, eq. (3)], the range indicated for $P_{tot}/P_{L\text{-}H}$ is due to a rise in density during the H-mode phase. (2) Projected α-power in ITER. (3) For a 50:50 D-T mix.

A few specific issues were documented during the flat top phase: (1) The evolution of the plasma inductance, (2) entry into a stationary H-mode phase and (3) the discharge evolution following a back-transition to L-mode.

After the transition to H-mode, the experiments extended the heating phase to several resistive diffusion times (τ_R) during flat top (limited by the magnet coils and/or pulse length of the additional heating systems). The maximum pulse duration used in these experiments is AUG~2-3τ_R, DIII-D ~3τ_R and JET~1-1.5τ_R. The l_i reached at the end of the flat top (FT), is given in the last column of Table II. Fig. 5 shows the l_i evolution for the current rise and flat top phase of the discharges given in Table II. During H-mode, a slow evolution of l_i to values ≤0.85 is observed. The value at the end of the flat top phase is independent of the starting values at the beginning of the current flat top. The discharges for DIII-D and JET shown in Fig. 5 have a current rise giving l_i=0.85-0.9. However, the current rise can be

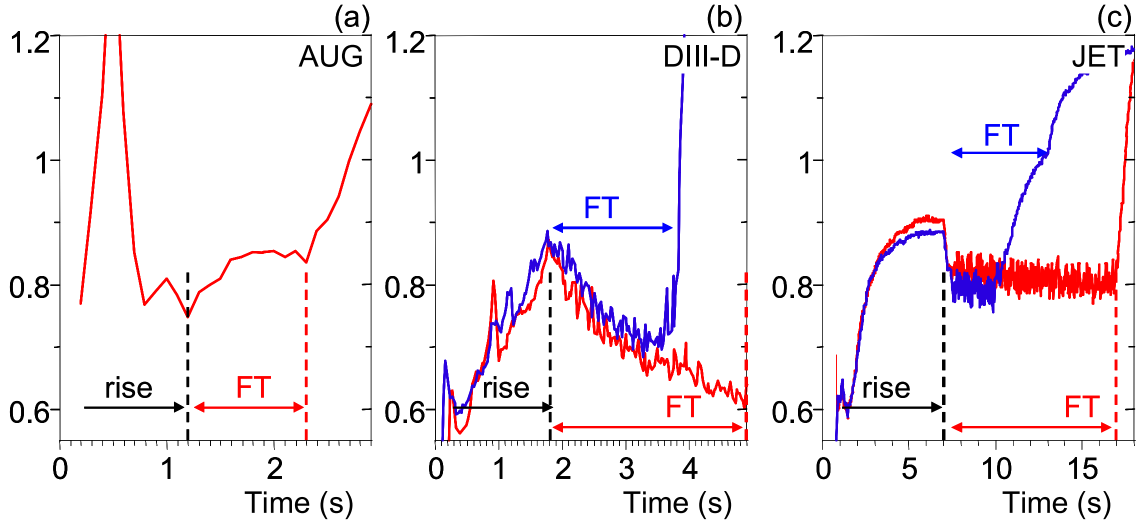

Fig.5: *The l_i evolution for ITER demonstration discharges at q_{95}=3. All discharges enter H-mode at the start of the flat top. On the left (a) data from AUG, in the middle (b) data from DIII-D and on the right (c) data from JET. The red curves for DIII-D and JET with the longest flat top phase available. The discharges indicated in blue have a deliberate step down of the heating power at 3.5s for DIII-D and at 10s for JET to provoke a transition back to L-mode.*

controlled (heating power) to give the same l_i value the start of the flat top as the end of the flat top. DIII-D and C-Mod both matched the ITER shape, having low ELM frequency or long ELM free periods, DIII-D having the lowest values for l_i~0.65, see ref. [21].

Energy confinement factors of H_{98}~1 are obtained as necessary for ITER. The input power level required to obtain β_N~1.8 is compared to the latest H-mode scaling [20] and comparable to (1.1-1.5)·$P_{L\text{-}H}$, predicted for ITER. After entering H-mode, the experiments take ~2τ_E to reach maximum stored energy and a minimum of ~4-6τ_E to reach stationary electron density values. Fig. 5 shows DIII-D and JET discharges that have a deliberate power step down to provoke a back-transition to L-mode. For DIII-D (blue trace, Fig. 5b), the neutral beams were turned off at 3.5s, inducing a H-L back-transition at 3.73s (after an ELM-free phase), followed by a disruption at 3.86s. The JET discharge (blue trace, Fig. 5c) reduced NBI from 17MW to 3MW at 10s, showing that l_i rises to ~1.0 within 3s.

Hybrid scenario: Experiments have extended studies of ITER scenario demonstrations (breakdown, rise phase and flat top) to q_{95}=4-4.5. All, including C-Mod which used LHCD [22], show that the required target q-profile with q(0) just above or near 1 can be obtained. Low magnetic shear has been achieved in the core in DIII-D and AUG. High beta and high confinement properties are observed in AUG, DIII-D, JET and JT-60U. In these experiments, hybrid discharges obtaining β_N~3 have l_i=0.6-0.75. In the demonstration discharges, both DIII-D and AUG have 1.2<H_{98}<1.45 capable of achieving Q~10 in ITER at q_{95}=4-4.5. The confinement is documented for a range of conditions including the lowest ρ^* values obtained in JET and JT-60U. New JET results show that H_{98}=1.2-1.4 can be obtained [23]. Long pulse capability was demonstrated in JT-60U, sustaining β_N=2.6 and H_{98}>1 for 25 seconds at somewhat lower q_{95}~3.2 [8]. More data are required from ITER hybrid scenario studies, focussing on achieving H_{98}>1.2 at T_i=T_e and low plasma rotation, as shown in DIII-D [24].

5. Current decay phase

Experiments have also studied discharge shut-down scenarios. This particular area of the ITER scenario has not been studied in detail yet. However, it is an important phase of the discharge, as it must provide a (vertically) stable ramp down of the plasma current, staying within the available full swing of the transformer while exiting the burn, transitioning from H-mode to L-mode, allowing control over the radiation fraction, keeping below the density limit and avoiding overheating of first wall components.

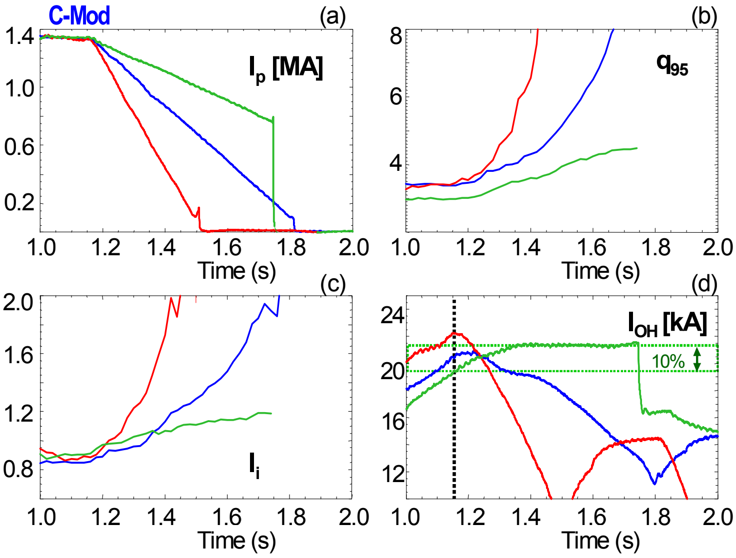

Fig. 6: Current ramp down experiments in C-Mod, varying the I_p ramp down rate from 4MA/s (red curves) to 2MA/s (blue curves) and 1MA/s (green curves).

C-Mod, AUG, DIII-D and JET have developed ramp down scenarios that keep the plasma diverted as long as possible, using an elongation reduction (from 1.85 to 1.5) to keep the plasma vertically stable. So far the experiments have concentrated on documenting the requirements for keeping l_i<1.6 before 50% of the flat top current value is reached. At l_i>1.6 and high plasma current, the growth rates for vertical displacements probably can not be stabilized in ITER, although more detailed studies are needed. All experiments show that for ohmic or L-mode plasmas l_i rises to >1.6 for moderate to fast ramp down rates. Only discharges with very slow ramp rates keep the l_i excursion below 1.6. An example from C-Mod is given in Fig. 6 (note the discharge with the slowest ramp down did not have a reduction in elongation to keep the plasma vertically stable). Only a 1MA/s ramp down (slow for C-Mod) keeps l_i below 1.6. However, this ramp down requires an additional 10% of transformer current as indicated in Fig 6d. At JET, ohmic ramp down discharges at 0.28MA/s, keeping constant current in the transformer, show an increase of l_i to 1.8. Consequently, scenarios that maintain H-mode throughout the ramp down phase have been studied. Preliminary results from AUG, DIII-D and JET show that the current can be ramped down without additional flux consumption while keeping l_i low enough. However, H-mode can only be kept throughout the current decay phase with constant heating at a level of >50% of the heating required during the flat top phase and at relatively slow current ramp down rates. Moreover, control of the plasma density is more difficult in H-mode. The requirements for the ramp down seem challenging for ITER; hence a modelling effort for the decay phase of ITER using these new experimental data is urgently required. Nevertheless, significant levels of additional heating may be required until the current has reached I_p ~ 3MA in ITER.

6. Summary and conclusions

The experimental verification of ITER scenarios has provided new data for all phases of the discharge. They include studies of the plasma initiation at low voltage. These show that the minimum electric field for reliable ohmic (un-assisted) breakdown decreases with machine size to values of ~0.23V/m in JET. For assisted breakdown, using ITER relevant ECRH schemes, all experiments using this technique have established reliable breakdown at or below ITER values of 0.32V/m in clean or de-conditioned machine circumstances. The current rise phase has been studied in detail in these new experiments. Ramping to q_{95}=3, the current profile can be tailored to obtain a large variation of the plasma inductance. It is strongly recommended to use full bore plasmas with early X-point formation during the current rise phase. Using full bore plasma configurations, the highest l_i=1.05 is obtained for ohmic discharges with a relatively slow current ramp up rate. The lowest l_i=0.63-0.68 is achieved in discharges heated to H-mode during the rise phase. During the flat top phase experiments have reproduced the requirements for reaching Q=10 at q_{95}=3. Data on the evolution of the plasma parameters, in particular the slow evolution of the plasma inductance to values of 0.65-0.85, provide useful data for studying the requirements for the poloidal field coil set in ITER. The current decay phase deserves more attention. Experiments clearly show that in ohmic and L-mode conditions only a very slow current ramp down can keep l_i<1.6 during the first half of the current decay. Translated to ITER a 300s ramp down phase would be required, likely to consume transformer flux (in such conditions, C-Mod requires 10% additional current in the main OH coil). Results from ramp down experiments in H-mode have been obtained recently, indicating the possibility to keep l_i low enough. However, the requirements for the heating systems to provide sufficient heating to stay in H-mode during most of the ramp down phase need to be assessed. Several areas for ITER scenario demonstration remain to be explored, such as burn control and RF-dominated heating schemes with low rotation. Advanced ITER scenarios will be the focus of future experiments.

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