Current rise studies at ASDEX Upgrade and JET in preparation for ITER

<u>A.C.C. Sips</u>[1], P. Lomas[2], O. Gruber[1], J. Hobirk[1], G.M.D. Hogeweij[3], L.D. Horton[1],
F. Imbeaux[4], M. Mattei[5], F. Köchl[6], X. Litaudon[4], E. de la Luna[7], A. Lyssoivan[8], Y-S Na[9],
I. Nunes[10], V. Parail[2], V. Plyusnin[10], J. Kim[9], J. Romero[7], G. Saibene[11], J. Seol[9], J. Stober[1],
L. Zabeo[2], and the AUG Team[1] and JET EFDA contributors[12,*]

[1] *Max-Planck-Institut für Plasmaphysik, EURATOM-Association, D-85748, Garching, Germany.*
[2] *EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon OX14 3DB, UK.*
[3] *FOM Institute for Plasma Physics Rijnhuizen, Ass EURATOM-FOM, Nieuwegein, The Netherlands.*
[4] *Association Euratom-CEA, Cadarache 13108 Saint Paul Lez Durance, France.*
[5] *Associazione Euratom-ENEA-CREATE, DIMET, Università degli Studi di Reggio Calabria, Italy.*
[6] *Association EURATOM-ÖAW/ATI, Vienna, Austria.*
[7] *Asociacion Euratom-CIEMAT, ES Avenida Complutense 22, E-28040 Madrid, Spain.*
[8] *Lab. for Plasma Physics, ERM/KMS, Ass. EURATOM-Belgian state, Brussels, Belgium.*
[9] *National Fusion Research Institute, 52 Yeoeun-Dong, Yusung-Gu, Dejeon, 305-333, Rep. of Korea.*
[10] *Euratom/IST Fusion Association, Centro de Fusao Nuclear, Lisboa, Portugal.*
[11] *FUSION FOR ENERGY, Joint Undertaking, 08019 Barcelona, Spain.*
[12]*JET-EFDA, Culham Science Centre, Abingdon OX14 3DB, UK.*
* *See the Appendix of M.L. Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA, (2006)*

1. Introduction: ITER requires routine operation at 15MA, with a robust current rise phase. The working margins are small (reduced operational space) compared to today's experiments. One example is the necessity to stay within l_i~0.7-1.0 at 15MA [1]; the minimum l_i~0.7 set by the ability of the poloidal field coils to keep a divertor configuration, the maximum l_i~1.0 is given by limitations of the transformer to provide enough flat top pulse length (400s). Simulations of the ITER current rise phase need to be validated by a coordinated set of experiments. Data from dedicated experiments in AUG and JET are used to document the requirements for the current rise and breakdown phase in ITER. The results obtained provide input to scenario simulation codes, used to predict the current rise phase for ITER [2]. The focus here is on breakdown phase and control of l_i during the current rise phase, not only to stay within the planned ITER hardware limitations, but to provide a range of target q-profiles for the burn phase, and target plasmas for advanced scenarios.
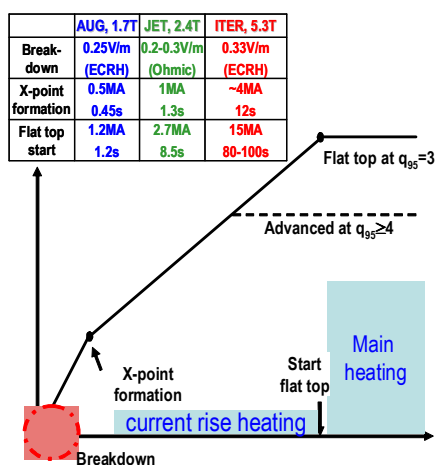

	AUG, 1.7T	JET, 2.4T	ITER, 5.3T
Break-down	0.25V/m (ECRH)	0.2-0.3V/m (Ohmic)	0.33V/m (ECRH)
X-point formation	0.5MA 0.45s	1MA 1.3s	~4MA 12s
Flat top start	1.2MA 1.2s	2.7MA 8.5s	15MA 80-100s

Fig. 1: The current rise scenario used in the dedicated experiments.

2. Experimental set-up: Scaled down (Fig. 1) from ITER (resistivity~$T_e^{3/2}a^2$), current rise studies at q_{95}=3 in AUG operated at 1.0MA/1.7T reaching full current in 1.0s-1.2s. JET operated at 2.7MA/2.4T, with a rise phase variable from 6s to 10s. Both devices used low voltage (0.2-0.3V/m) during the plasma initiation phase (section 4). Preliminary experiments at JET duplicated an (earlier) ITER proposal using a strong aperture expansion during the limiter phase. Recently, AUG and JET developed alternatives using full bore plasma configurations with early divertor formation (Fig. 1). This provides better control of the plasma density, Z_{eff}

and allows additional heating for a significant part of the rise phase. The temperature of the current rise plasma was varied by applying NBI or ECRH heating at AUG. ICRF, LHCD or NBI heating was used at JET. In all cases the heating was applied after X-point formation. In addition, current rise discharges to q_{95}=4 were developed to document the requirements for preforming the current density profile in the hybrid scenario for ITER.
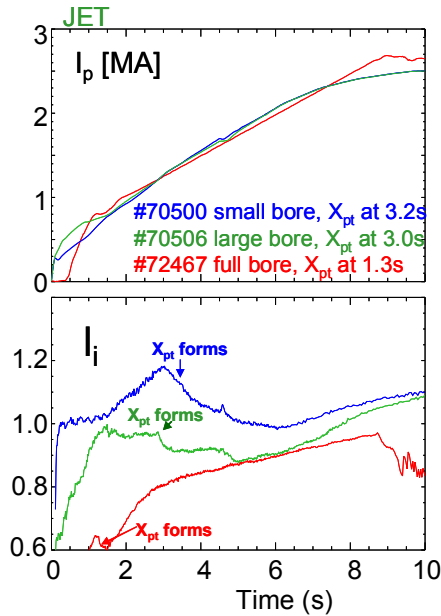

Fig. 2: JET (dI_p/dt~0.28MA/s): *Variation of l_i with plasma size during limiter phase (ohmic).*

3. Results: Both AUG and JET show that low plasma inductance can only be achieved with a full bore limiter phase and diverting as early as possible. Three ohmic discharges at JET are compared with different plasma size during the limiter phase, and different timing of the X-point formation (Fig. 2). The discharges (e.g. #72467) with maximum aperture during the limiter phase and early X-point formation readily achieve low l_i during the first part of the current rise phase, having hollow temperature profiles. Moreover, for all experiments described below, JET and AUG showed excellent reproducibility of the full bore limiter, early X-point scenario. Using this scheme, the density was varied in ohmic conditions from very low density ($<n_e>/n_{GW}$~0.2) to intermediate density ($<n_e>/n_{GW}$~0.4) in JET. These discharges show no variation of l_i as the Z_{eff} reduces from 1.6 to 1.2 respectively, while $<T_e>$ decreases by 25%, leading to similar plasma resistivity. Only when the density is further increased to ($<n_e>/n_{GW}$~0.6), as performed at AUG, Z_{eff} remains constant and $<T_e>$ decreases with $<n_e>$, leading to higher l_i. For ohmic discharges, 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=0.82-0.96. Without heating during the flat top, l_i is observed to increase
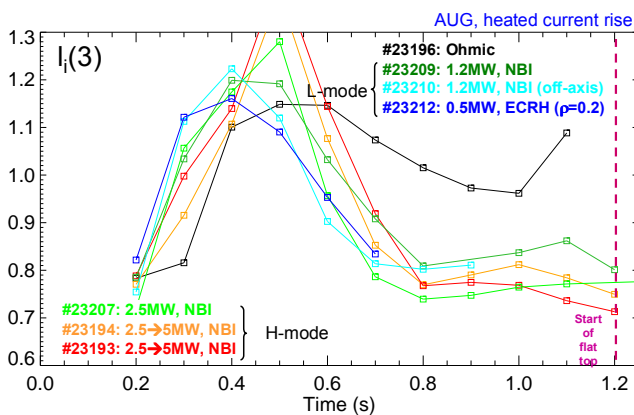

Fig. 3a: AUG (dI_p/dt=0.66MA/s): *Change of l_i with heating during the current rise, using CLISTE values without MSE data. L - and H-mode shots indicated.*

rapidly, implying that ITER will have to start heating to burn immediately after reaching 15MA. The type and level of heating during the current rise phase was varied in a large number of discharges. First, heating during the limiter phase is not effective (no change in l_i) as this gives a significant increase of Z_{eff} to 3-4, while Z_{eff} ~ 2 in divertor configuration. At AUG, NBI was used with on-axis and off axis injection up to 5MW, ECRH was used at 0.5 MW. At JET, both on axis (3-5MW) and off-axis (3-6MW)
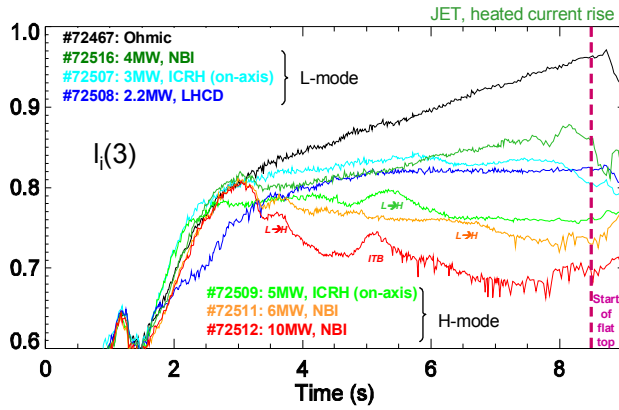
Fig. 3b: JET (dI$_p$/dt=0.28MA/s): Variation of l$_i$ with heating during the current rise, showing EFIT values of l$_i$ without MSE data.

ICRH was used. The off-axis ICRF heated cases giving large increase of Z_{eff}, requiring more optimisation. As well, LHCD was used in JET at 2.2MW and NBI at somewhat higher density to allow injection at various power levels (3MW to 10MW). From both experiments, a clear result is that the electron temperature during the current rise determines the current diffusion with the capability of varying l$_i$ significantly (0.68-0.97) at fixed dI$_p$/dt (Figs. 3a, 3b).

Code simulations show that the heating effect on l$_i$ dominates over any current drive effect from either NBI or LHCD. For example, off-axis NBI heating at AUG gives lower l$_i$ (0.80)
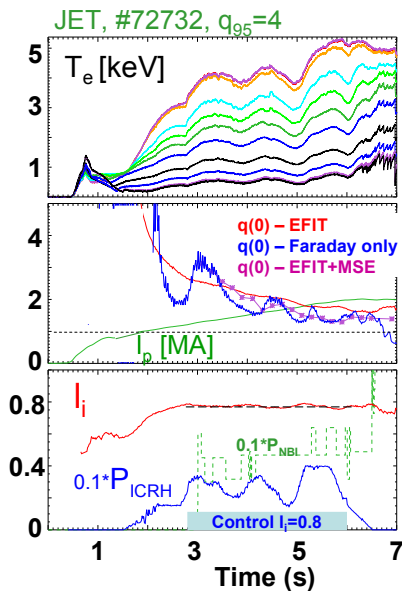

Fig. 4: JET (dI$_p$/dt=0.28MA/s) at q$_{95}$=4: Control of l$_i$ with ICRH, giving q(0)>1 at 6s. P$_{NBI}$ to give same l$_i$=0.8 is indicated.

compared to central NBI (0.84) in L-mode conditions. With the range of heating power available, transitions to H-mode are observed both in AUG and JET, giving access to reversed q-profiles, with l$_i$ =0.68-0.75. Hence, control of l$_i$ by additional heating was developed at JET, and applied in scenarios with a current rise to q$_{95}$=4 (2MA hybrid discharges). 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 (Fig. 4) requiring modest heating powers (ICRH~3MW, NBI~5MW). The (shape of the) q-profile of the target plasma is key for high performance hybrid discharges [2]. Moreover, these experiments show 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.

4. Plasma initiation phase: AUG and JET also tested low voltage plasma initiation (breakdown). AUG, typically starts the plasma at E~0.8V/m, and JET at E~0.7V/m using resistor switches in the ohmic heating circuits. Switch-less operation is a new development for AUG, achieving E~0.25V/m. For JET switch-less operation was re-optimised giving E=0.18-0.32V/m. In comparison, ITER plans to use 0.32V/m. At E~0.25V/m, AUG must use ECRH for pre-ionisation at either 2nd harmonic X-mode (105GHz at 1.7T, 140GHz at 2.3T) or fundamental O-mode (105GHz at 3.2T). The resonance of ECRH was positioned on the high field side, making 105GHz at 3.2T similar to using 170GHz at 5.2-5.3T in ITER. JET used LHCD to assist breakdown down to E=0.18V/m, ohmic breakdown was achieved
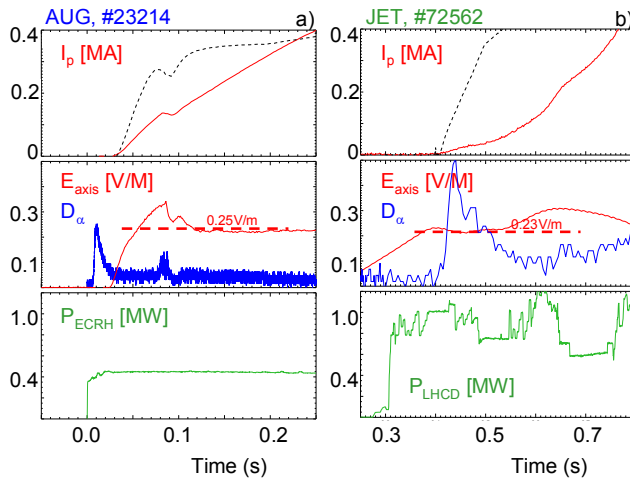
Fig. 5: Low voltage (E~0.25V/m) plasma initiation at AUG and JET. D_α indicates plasma formation. Dashed lines (I_p) give reference cases at higher voltage.

down to E=0.23V/m. Using low voltage schemes, breakdown was still achievable after high current (q_{95}=3) disruptions. Both experiments optimised the stray fields at breakdown using multiple poloidal field coils, similar to configurations used in superconducting tokamaks like ITER or KSTAR for maximising the available loop voltage. Important for the current rise studies is that at low voltage the initial current rise is slow (Fig. 5), with full control over the current rise rate by the transformer voltage in contrast to the high voltage

breakdown cases with resistor switches where I_p rapidly rises to 300kA (AUG) or 500kA-800kA (JET).

5. Interpretation and conclusions: These experiments are supported by interpretation and simulation of the discharges with the transport codes CRONOS and JETTO. The experimental profiles of an ohmic current rise at JET were taken. Employing both scenario codes in a predictive mode, the evolution of the current density profile was calculated,
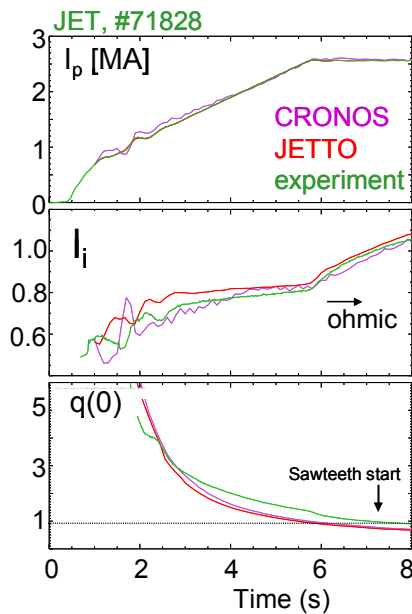

Fig. 6: JET (dI_p/dt=0.36MA/s): CRONOS, JETTO simulations.

showing good agreement with the experimental observations. Similar studies have been started for AUG. Details of the interpretation of the results and predictions for ITER can be found in [1]. The breakdown and current rise studies in AUG and JET show great similarity and provide confidence in the experimental approach used. The results from the two devices will be used in a step-ladder approach in predicting the results to ITER. The main conclusions from these experiments is that (1) low voltage breakdown works reliably at AUG using ECRH at JET ohmic or LHCD assisted, (2) ITER should use full bore plasmas just after plasma initiation with X-point formation as early as possible, (3) additional heating during the current rise is required and (4) control of l_i with the heating systems is possible. In ITER, this would allow to provide different target plasmas for the burn phase at q_{95}=3 and advanced scenarios at q_{95}=4 and q_{95}=5.

References: [1]   Mattei M. et al *2008*, this conference (P4.078)
[2]   Hogeweij G.M.D et al *2008*, this conference (P5.034).
[3]   Stober J.K. et al *2007*, Nucl. Fusion **47**, 728.