BURNING PLASMA PHYSICS ISSUES IN A POSSIBLE JET UPGRADE

*C Gormezano, J Jacquinot, E Joffrin, G Saibene, R Sartori**

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, UK

1. Motivation

Record fusion yield (16MW) and fusion energy (22MJ) have been achieved in JET during the DTE1 campaign in 1997 [1], [2], respectively with an ELM-free H-mode and with an ELMy H-mode. Alpha heating has been observed [3] with alpha power in the range of 1.2MW. Significant fusion yield (up to 8MW) has been achieved with advanced scenarios [4]. These results have generated a large number of significant advances in the physics of fusion plasmas. It is felt that more significant burning plasma physics issues could be addressed in a JET upgrade. Increasing power capability would allow to access high confinement modes and to assess beta limits at full field. Increasing plasma volume would allow to increase plasma current and the fusion gain. Increasing plasma shaping would allow to operate at higher densities and to increase the ELM-free period of ELM-free H-modes. Increasing both plasma volume, plasma shaping and power capability would allow: i) to increase significantly JET performances, ii) to reduce errors in Next step extrapolation, iii) to operate at much higher values of fusion yield and alpha heating power and to tackle some burning plasma physics issues, which are needed to progress towards a fusion reactor.

2. Possible Upgrades in JET

JET is underpowered as compared to other machines such as Asdex-U, DIII-D and JT-60U. With the present power capability (16 to 18MW of Neutral Beam Injection (NBI) power and up to 10MW of Ion Cyclotron Resonance Heating (ICRH) power in ELMy plasmas), β_N values up to 1.3 and 2 have been achieved at a magnetic field of 3.4T, respectively in ELMy plasmas and in optimised shear plasma, while values considered for Next Step have to be at least 2.3. Also, it is necessary to access high confinement regimes (type I ELMs, ELM-free H-mode, Internal Transport Barriers) in order to optimise the fusion gain Q. At full field (up to 4T) it is estimated that up to 35 MW of power might be needed to produce high confinement ITBs.

Several options have been considered, but not yet decided, by the new EFDA JET sub-committee for some power upgrades in the period 2000-2002 in addition to the ICRH wide band matching system which might allow to increase the total combined power by 2 to 3MWs in the presence of ELMs. The first priority is to upgrade the 80kV power supply of one NBI box up to 130kV allowing the NBI power to be increased by 6 to 7MW. Other upgrade options which have not been considered could include one or more of the following:

- a third positive (or negative) NBI box delivering 10 to 15MW

* These are personal views.

- an Electron Cyclotron Resonance Heating System (ECRH) making use of the recent technical developments and delivering 10MW in the 140GHz range;
- develop techniques allowing to increase the voltage handling of the ICRH antennae. If not successful, two additional antennae could be installed in the torus allowing to make full use of the RF power plant;
- in-situ ionising system in front of the Lower Hybrid Current Drive (LHCD) launcher allowing to increase the coupling and to make full use of the LHCD plant.

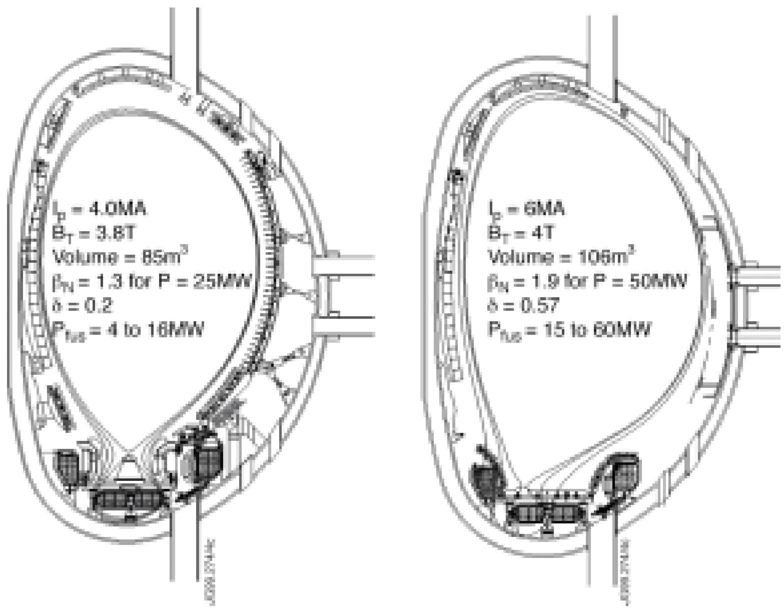

Fig. 1 Possible new JET upgrade configuration.

With the present divertor configuration, the plasma volume is limited to 80-85m^3, elongation (b/a) to 1.9, triangularity (δ) defined at the separatrix, to 0.35 and the plasma current to 4.5MA at 4T. Both in JET and in other machines, it has been found that beta increases with triangularity both in ELMy H-modes and in advanced scenarios. Moreover, the density normalised to the greenwald density can be significantly increased by increasing triangularity for a similar confinement [5]. Also, when δ is increased, the edge ballooning limit for MHD instabilities is increased and the time duration of an ELM-free H-mode is significantly prolonged. A configuration allowing to keep the divertor coils and to significantly increase the plasma volume and triangularity is shown in Fig. 1. It is to be noted that such a configuration is very flexible and large changes of elongation and triangularity are possible. A new divertor, using the existing coils and base structure, will have to be built.

3. Method of Extrapolation

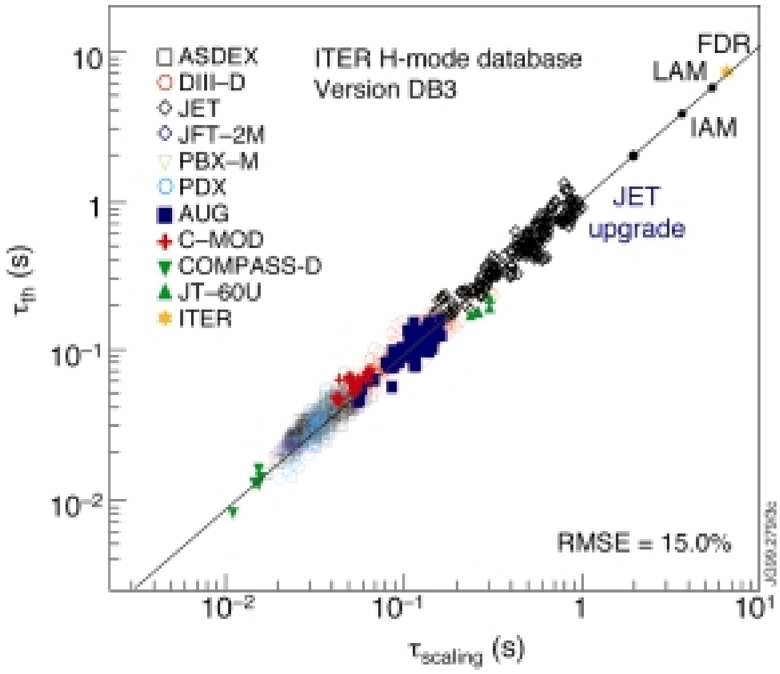

Fig. 2: JET upgrade in the ITER H-mode database.

Reference pulses have been taken from the JET database. ITER physics basis scaling laws have been used for extrapolation when available. If not, the own JET scaling has been used, for instance for the triangularity dependence, the Zeff dependence and for the advanced scenarios. In some cases, the transport modelling code JETTO has been used in a predictive way. The result is shown in Table 1 for the steady ELMy H-mode and for the transient ELM-free H-mode. It can be seen that the main effect of increasing the plasma volume is to increase the fusion gain Q. It can be shown that for similar β,q and ν^*, Q_{th} scales as $B^3 \times (a^3/R)^{5/4}$ assuming a gyro-Bohm scaling. Therefore, an increase of minor radius by 15% increases Q by 1.7. Increasing triangularity allows to operate at higher density still keeping a good confinement. Increasing power allows to operate at higher beta.

Extrapolation of the optimised shear scenarios is more difficult in the absence of established scaling laws. In JET, comparison of an ELMy H-mode with an optimised shear plasma at similar magnetic field (3.4T), plasma current (3.5MA) and additional power (25 to 28MW) shows an increase of β_N by a factor of 1.3 and a doubling of the fusion yield [8]. At 2.5 T, the threshold for ITB formation is ≈ 11 MW, and this increases to ≈ 19 MW of combined power for the ITB threshold at 4T. At 2.5 Tesla, the best results, in term of confinement, are produced with 24 MW combined power with a β_N~2.5. On this it is estimated that 36 to 40 MW would be needed to access good confinement regimes in optimized shear ITB plasmas at 4.0 T. Assuming the fusion yield can be taken as proportional to β_N^2 , it would increase by a factor 1.7at 4.0 T. From extrapolations made in table I, a fusion gain of almost 1 with $P_{in} = 37MW$ and $\beta_N = 2.5$ with $P_{in} = 50MW$ could be achieved in a quasi steady-state advanced scenarios.

4. Burning Plasma Physics Issues

4.1 Heating by alpha particles and energetic particle stability effects

The alpha power might range from steady-state 4MW up to transient 14MW as compared to the transient 1.2MW in the alpha heating experiment of DTE1 where $P_\alpha / (P_{add} - P_{Fusion}) \sim 0.2$. Although the plasma will not be dominated by alpha heating since Q will reach, at best, 2 transiently, a much more complete assessment of the alpha heating

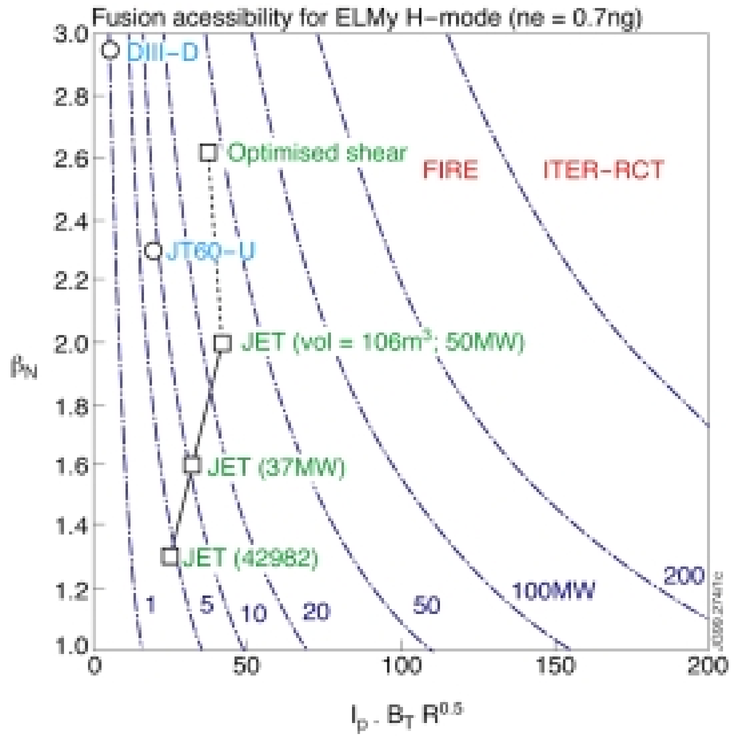

Fig. 3: Fusion accessibility for ELMy H-mode at n = 0.7ng

can be done. Initial estimate of the TAE stability indicates that TAE modes still appears marginally stable. But since their growth rate increases with electron temperature, an ERCH system would allow stability studies. As well, the instability growth rate increases with q_o^2. Therefore optimised shear plasmas with ERCH will be an ideal tool to study energetic particle stability effect. A detailed estimate remains to be made.

4.2 Reactor regime core confinement

As shown in Fig. 2, a substantial reduction in extrapolation for Next Step devices can be achieved in a JET upgrade. This is also illustrated in a fusion accessibility domain shown in Fig. 3 where β_N is plotted against $I_p.B_t.R^{0.5}$ which is a measure of the fusion gain. It shows the substantial step in fusion and β_N capability as compared to today's experiments.

4.3 Beta limit studies at full field

Assessing beta limits at operational limits is obviously a key issue. Recently the importance of the ρ* not only on confinement by also on beta limits has been discussed [7], possibly linked to neo-classical tearing modes. In Fig. 4, various scans in density, magnetic field, power and plasma current have been made to define an operational space in a diagram ρ^* versus β_N. It shows that the gap between today's databases and the various options of ITER-RC can be filled. It is also to be noted that an ERCH system could allow to assess stabilising effects on neo-classical tearing modes in reactor relevant regimes.

4.4 Other aspects

Several other aspects of burning plasma physics issues can also be studied such as scaling of advanced scenarios with Internal Transport barriers (power dependence, confinement scaling, ρ^* dependence) and tritium transport issues. Helium retention and fuelling optimisation can also be studied in reactor relevant regimes. The installation on JET of a high field side pellet launcher is ongoing and, if successful, could be adapted to tritium operation.

Without more profound and costly modifications, the time duration of the high power pulse will be limited to 5-8 seconds. Therefore only the quasi steady-state aspects of high performance plasmas (MHD stable pressure and current profiles) can be studied.

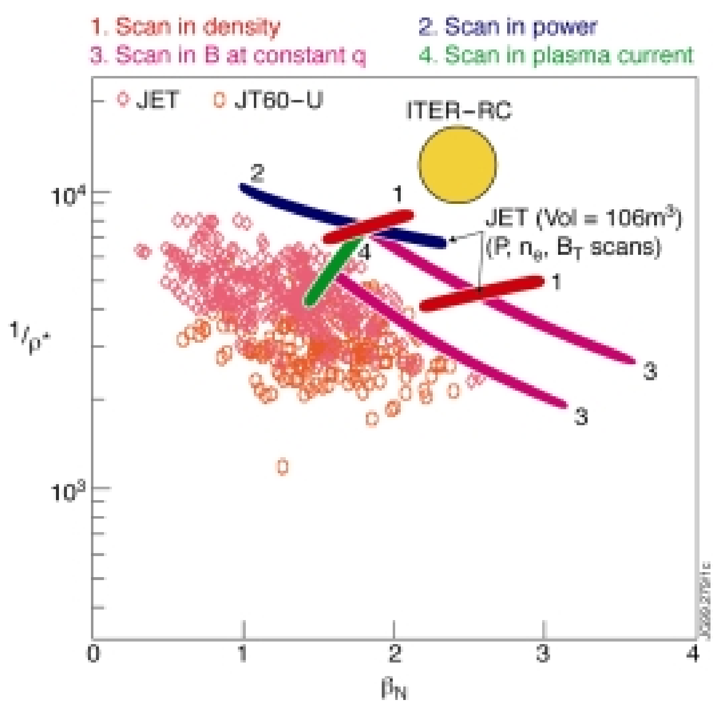

Fig. 4: ρ^*/β_N operational space for JET upgrade

5. Summary and Conclusion

JET performances can be significantly improved by increasing: i) the plasma volume (increase I_p, increase Q), ii) the plasma triangularity (higher density), iii) the additional power (up to 40MW to access high performance regimes, up to 50MW to assess beta limits).

Extrapolations have been made for the ELMy H-mode (steady-state), the Optimised Shear mode (steady) and the ELM-free H-mode (transient). The presently achieved fusion yield in the JET DTE1 could be multiplied by a factor up to 4. The following burning plasma physics issues can be explored:

- substantial heating by alpha particle ($0.5 < Q < 2$);
- energetic particles instabilities, in particular in high T_e plasmas obtained with ERCH and optimised shear plasmas;
- the domain ρ^*/β_N can be significantly increased;
- beta limits at full field;
- extrapolation uncertainties for ITER scaling can be substantially reduced and scaling of advanced scenarios at full field can be done.

In addition, the remote handling capability allows to have flexibility with the divertor and to test different choices of first wall material.

Relatively modest upgrades of the JET facility would allow substantial progress in burning plasma physics issues in a time scale which is much shorter than the time required to build and operate a larger, more powerful tokamak such as ITER/RC.

References

[1] Keilhacker M et al, Nucl Fusion, **39**, 189 (1999).
[2] Jacquinot J et al, Nucl Fusion, **39**, 209 (1999).
[3] Thomas P et al, Phys Rev Lett, **80**, 5548 (1998).
[4] Gormezano C Phys Rev Lett, **80**, 5544 (1998).
[5] Horton LD et al, submitted to Nuclear Fusion.
[6] Lomas P, private communication.
[7] Goldston R, this conference.
[8] Gormezano C, High performance Operation Regimes, to be published in Plasma Phys, Cont. Fusion (1999 EPS).

Table 1

	Steady-State ELMy H-mode			Transient ELM-free H-mode		
	Ref pulse 42982 V = 83m^3 δ = 0.22	V = 106m^3 δ = 0.57		Ref pulse 42976 V = 85m^3 δ = 0.57	V = 106m^3 δ = 0.57	
B_t (T)	3.86	4	4	3.66	4	4
I_P (MA)	3.27	6	6	4	6	6
P_{in} (MW)	24.5	37	50	25.6	37	50
n/n_G	0.56	0.7	0.7	0.29	0.5	0.5
T_{io} (keV)	7.4	8.6	9.7	26	20	21.3
Z_{eff}	2.4	1.8	2.0	2.6	1.75	1.9
β_N	1.3	1.7	1.9	2.04	2.5	2.7
P_{Fus}^{th} (MW)	1.65	15.2	15.8	9.5	63	64.7
P_{Fus}^{tot} (MW)	4.4	21	21.9	16	71.7	73.5
Q_{tot}	0.18	0.57	0.44	0.63	1.94	1.47