EXPERIMENTAL TESTS OF CONFINEMENT SCALE INVARIANCE ON JET, DIIID, ASDEX UPGRADE AND CMOD

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Abstract

An international collaboration between JET, DIIID, AUG and CMOD has resulted in four sets of Tokamak discharges which are approximately identical as regards a set of dimensionless plasma variables. The data demonstrates some measure of scale invariance of local and global confinement but a more accurate matching of scaled density, power etc. is required to make firmer conclusions.

1. SCALE INVARIANCE OF CONFINEMENT

The scale invariance principle formulated by Kadomtsev [1] and Connor-Taylor [2] starts from models of heat flux q_{heat} and local diffusivity χ expressed as

$$q_{heat} = - en\, \chi \nabla T + q_c\, ,\ \chi = \chi_B\, F\, (\rho_*, \nu_*, \beta, q_\psi, \varepsilon, \kappa, \ldots..) \qquad (1)$$

where q_c is a convective heat flux and $\chi_B = T/B$ is the Bohm diffusivity; the dimensionless function F depends on dimensionless plasma parameters like normalised Larmor radius ρ_*, collisionality ν_*, β, safety factor q_ψ, inverse aspect ratio ε elongation κ. The function F depends on which equations (Vlasov, Boltzmann, MHD etc.) are chosen to describe confinement [2]; atomic physics and radiation effects are absent from Eq. (1). If the convective flux is related to a diffusivity and density gradient in the same manner as the diffusive flux then scale invariance implies that heat flux (single fluid for simplicity) can be scaled, say via minor radius, from one Tokamak to another to yield scaled density and temperature profiles; in such a scaling of dimensional parameters (a, n, T, I, B….) the function F and its arguments remain invariant. The global analogue of Eq. (1) involves a global average G of the unknown function F [3] and global averages of the dimensionless parameters in Eq. (1) (for definitions of $<\rho_*>$ etc. see [3])

$$\frac{e}{m} B\tau_E = <\rho_*^{-2}> \ \ / \ \ G\left(<\rho_*>, <\nu_*>, \beta_N, q_{95}, \varepsilon, \kappa \ldots\right) \qquad (2)$$

The scale invariance principle predicts that $B\tau_E$ is invariant under any transformation in which G and its arguments are invariant. For a scale transformation in which $<\rho_*>$ etc. are held fixed, the dimensional plasma parameters will scale with minor radius a as [4]

$$n \sim a^{-2},\ T \sim a^{-1/2}, B_a \sim a^{-5/4},\ I_\phi \sim a^{-1/4},\ \ P \sim a^{-3/4}\ \ \ ,\ \ q_{heat} \sim a^{-11/4},\ \ \tau_* \sim a^{5/4} \qquad (3)$$

In (3) the products na^2 etc. denote normalised density since these products depend only on the dimensionless parameters ρ_* etc. τ_* denotes timescales like the confinement time τ_E, the MHD time τ_{MHD}, slowing down time τ_{slow}. Thus ELM and sawtooth frequencies scale as $f \sim a^{-5/4}$. Eq. (3) dictates how to design "Identity" experiments on machines of different size a.

This paper will describe the results from a series of such experiments carried out as part of an international collaboration between JET, DIIID, ASDEX Upgrade (AUG) and CMOD. The accompanying paper [5] describes in more detail the confinement experiments on AUG and JET as well as the L→H transition studies made with matched dimensionless edge parameters. The variety of plasma shapes (including X-point location and strike zones) that are possible on JET makes it possible to compare confinement of JET plasmas with the confinement of plasmas in DIIID, AUG and CMOD. In each comparison it is attempted to make the plasmas as identical as possible w.r.t. shape and values of the dimensionless parameters in Eqs. (1-2). The minor radii for the four Tokamaks are

$$a(m) = 0.90 \text{ (JET)}, 0.57 \text{ (DIIID)}, 0.49 \text{ (AUG)}, 0.21 \text{ (CMOD)} \quad (4)$$

The scalings (3) and the values (4) demonstrate that JET is required to operate at the lower boundary of it operational space while DIIID, AUG and CMOD must operate at their upper boundaries.

2. EXPERIMENTAL SET-UP

Early tests of confinement scale invariance in ohmic plasmas showed a good agreement between PLT and Alcator C results [6]. The present series of experiments use Deuterium plasmas in the ELMy H-mode regime; the auxiliary heating is NBI except CMOD uses ICRH; pulses on AUG operating at high density have a combination of NBI and ICRH. All plasma configurations are elongated ($\kappa = 1.7 - 1.75$) single X-point (divertor) shapes. The values of the upper triangularities δ_u are slightly different in the JET ($\delta_u = 0.15$) and AUG ($\delta_u \approx 0$) comparison while they are matched at $\delta_u = 0.2$ in the JET-DIII case; the CMOD upper triangularity $\delta_u = 0.50$ is also more than the one used on JET ($\delta_u = 0.40$). The experiments on all four Tokamaks have involved scans of either density, power or q_{95} and includes a total of 91 pulses. The data on the confinement time is well described by the ELMy ITER97e scaling expression [7] with an RMS error ~ 13%; data on the thermal energy, i.e. total energy (diamagnetic measurement) corrected for fast ion energy W_f, has been used except for CMOD. The data on the enhancement factor show groups of pulses with $H_{97e} = 1.0$ whereas the degraded higher density pulses have $H_{97e} \approx 0.75$. Several of these pulses feature intermittent MHD oscillations, locked modes or global n=1, n=2 modes. Such pulses are eliminated in a search for globally identical pairs of pulses. From an initial study of the data on the global parameters of Eq. (2) we have selected pairs of matching pulses. The relevant data for the selected pulses are presented in the Table. For JET-AUG two pairs of pulses (low n and high n) are shown; a pair of JET-DIIID (high n) pulses are listed; for the pair of JET-CMOD pulses we select one of the intermittent ELM free periods (JET) to be compared with an ELM free pulse (CMOD); this is done to minimise differences from ELMs due to differences in shape. From four different Tokamaks there will be some variations in data availability. For JET-DIIID we use q_{95} calculated by the EFIT code otherwise q_{95} is evaluated from the formula in [3]. For JET-AUG the energy W is the thermal energy while otherwise it is the diamagnetic energy.

The appropriate matching of the global data in the Table for selected pairs of pulses demonstrate that these preliminary identity experiments confirm the scale invariance of global confinement. The normalised confinement time $B_\phi \tau_E$ is approximately constant in four separate transformations in ρ_*, ν_*, β_N, q_{95} space. The four pulse pairs differ however in various respects: the radiation fraction P_{rad}/P_{tot} is ~ 25% for JET-AUG, 35% for JET-DIIID, but 60-80% for JET-CMOD. The normalised frequencies $f^* = f\, a^{5/4}$ are matched for sawteeth but not for ELM's; the axial regions (confinement, heating) exhibit greater similarity than the edge regions (confinement, recycling).

	Pulse	$10^4\rho^*$	$10^3\nu^*$	β_N	q_{95}	$B_\phi\tau_E$	f^*_{ELM}	f^*_{saw}
JET	43868	3.6	13	1.4	3.0	0.28	25	3.5
AUG	11229	3.7	13	1.7	3.1	0.27	60	3.6
JET	43874,5,6	3.0	40	1.4	3.1	0.21-0.28	109	7.0
AUG	10718	3.0	42	1.7	3.2	0.21	96	8.8
JET	43872	3.7	21	1.7	3.5	0.29	9	6.9
DIIID	95309	3.8	21	1.8	3.6	0.29	28	
JET	43953	2.8	147	1.3	2.7	0.31	0	9
CMOD	971222008	2.7	123	0.9	3.3	0.31	0	11

The second row features the JET-AUG comparison at high density. We have included three JET pulses all of which have approximately the same values of $<\rho_*>$, $<\nu_*>$ and β_N; these values have been achieved at different power levels leading to a degradation of confinement time $B_\phi\, \tau_E$. The low density pulses in the first row have $H_{97e} = 1.0$ whereas the degraded higher density pulses have $H_{97e} \approx 0.75$. At the high density on AUG (1.1 10^{20} m^{-3}) the confinement is also degraded which can be seen by comparing $B_\phi\, \tau_E$ values in rows 1 and 2. Thus the physics associated with this degradation does not exhibit scale invariance to the degree demonstrated by the other selected pulses. An alternative interpretation though less appealing, is that scale invariance is not testable given the constraints imposed by (i) differences between the four Tokamaks and (ii) experimental measurement uncertainties.

3. PLASMA PROFILES

For selected ELMy pulses we choose time intervals over which the profile data on T_e, T_i, n_e and q_{heat} is time averaged; this is made to minimise aliasing effects between the measurements of T_e and sawteeth. For the two ELM free pulses we choose the time midpoint in the evolving ELM free phase. The LIDAR n_e and T_e profiles on JET have been smoothed in time and then in space. The JET profile data in the JET-AUG and JET-DIIID comparisons (n_e, T_e, T_i, q_{heat}) is based on mapping to EFIT equilibria and on the PENCIL code. The JET-CMOD comparison involves two TRANSP calculations. The AUG heat flux profiles derive from calculations with the ASTRA code. The results are summarised in the four graphs of Fig.1; x is normalised plasma radius; these graphs contain a lot of data because of space limitations.

The normalised temperature profiles are well matched in all four comparisons although the edge values are consistently higher on JET in all four comparisons. The density profile shapes are matched although the JET-CMOD values differ by more than has been intended. The normalised heat flux profiles show different shapes, i.e. different heat deposition; the ICRH on CMOD is more centrally peaked than the NBI on JET; the NBI on JET is more peaked than those on DIIID and ASDEX because of the high densities (> 7 10^{19} m^{-3}) in the latter two tokamaks. In designing these experiments we have not changed the beam energy E_b. The attenuation of a neutral beam varies as $\int n_e\, \sigma_{cx}\, dl$; the charge exchange cross section and that of ionisation vary as $E_b^{-1/2}$. The beam energy required to yield a scale invariant deposition profile then scales like $E_b \sim a^{-2}$. It is presently not possible to match the beam energies on JET and AUG. In future experiments on AUG it will be possible to increase E_b from 50keV to 100keV and on JET the 80keV beam should be used instead of the 140keV one.

These preliminary experiments have attempted to study measures of scale invariance of local and global confinement: a ratio of 55 between heat fluxes on CMOD and JET yields the right ratio of temperatures; a ratio of 5.5 between heat fluxes on AUG and JET gives the right temperature ratios at two densities. The experiments and the resulting profiles have also demonstrated that there is ample scope for improvement: the heat deposition profiles need to be better matched, possibly by the use of ICRH on AUG since JET cannot couple below $B_\phi = 1T$; the difference in edge T_e between JET and the other three Tokamaks needs to be understood. Future experiments on these four Tokamaks may be carried out to meet such a challenge.

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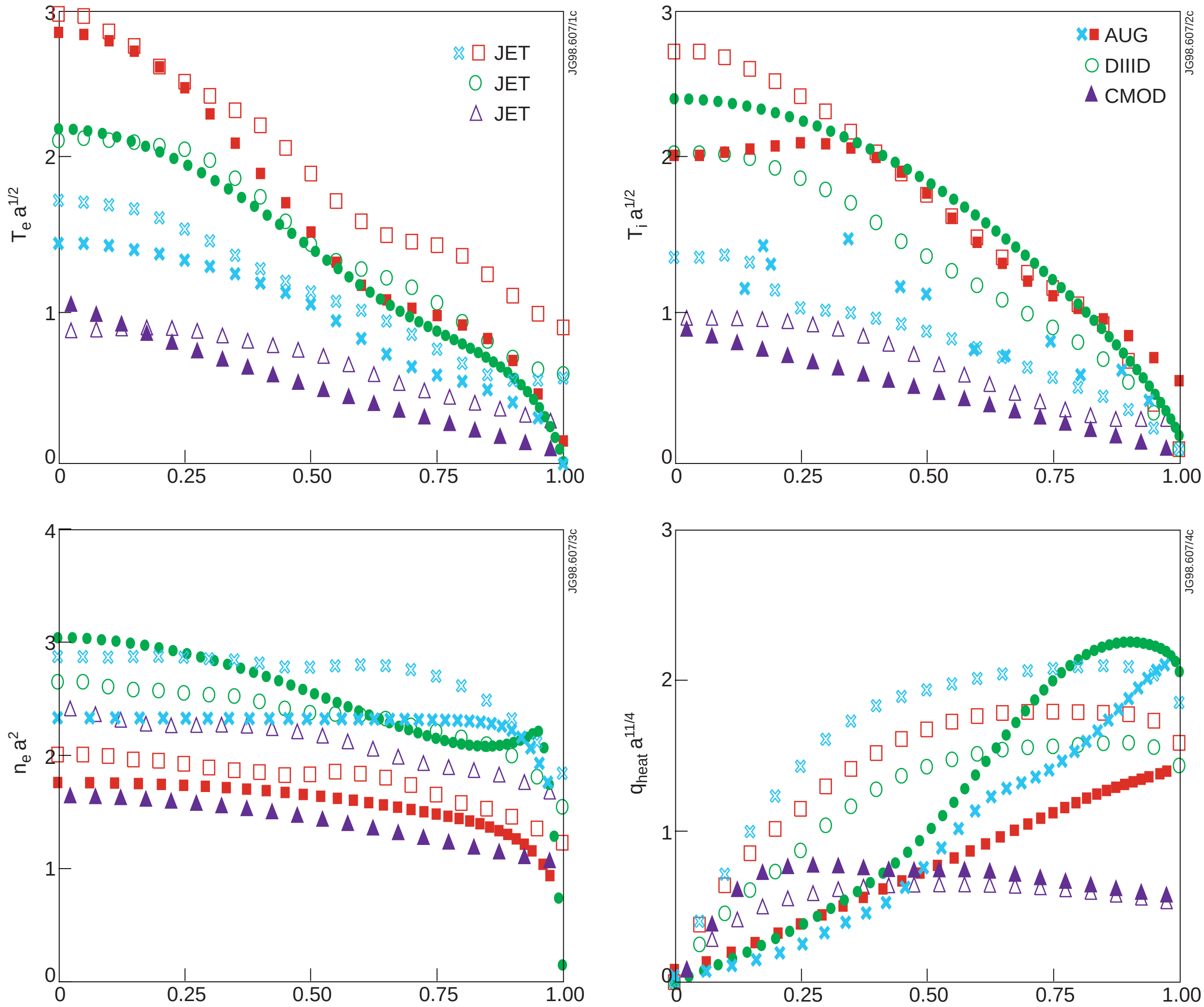

Fig.1. Normalised profiles of electron temperature, ion temperature, density and heat flux from eight elected discharges: the open symbols represent JET while the solid symbols represent AUG, DIIID and CMOD; X is normalised radius and is proportional to the square root of poloidal flux. The largest differences are for the heat flux, i.e. open vs closed squares.