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ABSTRACT.

Performance extrapolations to larger devices are commonly relying on the available confinement scaling laws. The well established H98y2 scaling [1] has been derived using a domain limited in normalised thermal pressure (β_{NTH}<2.2) using a large H-mode regime database. Using a more restricted database, the dependence in β has also been challenged by other scaling such as the Electrostatic Gyrobohm (ESGB) [2].

In recent experimental campaign, JET has produced a set plasma with identical plasma shape at high triangularity (δ~0.4), with confinement improvement of H~1.25-1.4 and toroidal field strength scanned from 1.1T to 2.3T, varying therefore ρ* from 3.5×10^{-3} to 6×10^{-3}. They are referred to as hybrid scenario (safety factor in the core close to 1 and 2.1< β_{NTH}<2.6). Since plasmas in the hybrid domain show a global confinement enhancement compared with present scaling with β_{NTH} >2.2, it is not obvious that the dependencies of these scaling can be used to extrapolate hybrid plasma performance to the domain of future devices.

1. EXTRAPOLATION USING SCALING LAWS

Using the above scaling laws and the prescriptions developed in [3] to characterise the performance by the fusion gain factor G = Q/(Q+5) that would be obtained in ITER, these plasmas are showing different performance for the hybrid scenario according to the scaling law used as shown in figure 1. The predictions using H98y2 are clearly less optimistic than those using the Electrostatic Gyrobohm scaling. There is also an apparent decrease of the performance with the toroidal field of the JET shots. This is appears to be due to a variation of the ion temperature peaking: as the plasma current, toroidal field strength and density are increased, the neutral beam ion heat deposition broadens. It shows, therefore that profiles effect remain important in the prediction and should be taken into account in the extrapolation of the predicted fusion power.

Both scalings above can be expressed in terms of the dimensionless parameters $\rho^* \sim (MT)^{1/2}/aB$, $\nu^* \sim qna/T^{-2}$, $\beta \sim nT/B^2$ and $q = qcyl = 5BR.\kappa/a^2Ip$, respectively as:

$$B.\tau_E = \rho^{*-2.69}\,\nu^{*-0.01}\,\beta^{-0.90}\,q^{-3.0} \qquad \text{and} \qquad B.\tau_E = \rho^{*-3}\,\nu^{*-0.14}\,\beta^{0}\,q^{-1.84}$$

These dimensionless scaling (both GyroBohm-like) have been derived in terms engineering parameters (plasma current I_p, input power P, toroidal field B, minor and major radius a and R and elongation $\kappa = S/\pi a^2$) and then translated to dimensionless variables assuming $T_i = T_e$ which is not the case for most of the existing devices and for the JET hybrids (T_i~$1.2-1.4T_e$). In addition, these expressions are showing dependencies which are very different than those obtained when one dimensionless parameter is modified while keeping the other terms constant. For example, specific experiments varying ν* only in DIII-D and JET have found a dependence in $\nu^{*-0.35}$, which could impact significantly on the fusion prediction for ITER since ν^*_{JET}/ν^*_{ITER} could be as high as 10. When a regression in the least square sense is carried out on the database of JET hybrid pulses using the measured ion temperature from charge exchange for the calculation of ρ^* and ν^*, the following dependences are found:

$$B.\tau_E \sim \rho^{*-2.07}\, \nu^{*-0.32}\, \beta^{-0.4}\, q^{-1.59}$$

Although the database used is very limited particularly in terms of β and q range, it is interesting to note that the dependencies found are close to individual parameter scan for the ρ^* dependence (Bohm-like) as found out recently between DIII-D and JET for similar discharge [4] or for the ν^* dependence as mentioned above. Even the q dependence looks consistent with individual scan ($\sim q^{-1.4}$) carried out on DIII-D [5] at constant shape. It should be noted that using the hypothesis $T_i = T_e$ for this set of discharge leads to slightly different exponent:

$$B.\tau_E \sim \rho^{*-2.35}\, \nu^{*-0.23}\, \beta^{-0.16}\, q^{-1.16}$$

but still not far from the exponents found using measured Ti within the error bars but both would lead to a power degradation of the order of $\sim P^{-0.5}$.

2. DIMENSIONLESS APPROACH.

Given these observations, in the following it has been decided to carry out an extrapolation of one particular pulse of the data base Pulse No: 77933 (Ip = 2MA, B_T = 2.3T) for which H98y2 = 1.25 and H_{ESGB}=1.05). Three different steps are made: i) identity step ($n\sim a^{-2}$, $T\sim a^{-1/2}$. $Ip\sim a^{-1/4}$, $\omega_c\sim a^{-5/4}$), ii) ρ^* step ($n\sim B^{-4/3}$, $T\sim B^{2/3}$, $Ip\sim B$, $\omega_c\sim B^{1/3}.a^{-5/6}$), and iii) νc step ($n\sim B^0$, $T\sim B^2$, $Ip\sim B$, $\omega_c\sim B$). Here $\nu_c\sim Rn/T^2$ is chosen rather than ν^*. In this exercise, in addition to q, β and Mach number ($M_\phi = R.\omega_{tor}/c_s$) are maintained constant throughout as well as the plasma cross-section and aspect ratio. In this way the total energy content $W = 3.\beta_N.B_T.V.I_p/(200.a.4\pi\mu_o)$ is inferred directly from the imposed normalised pressure. The density normalised to the Greenwald density ($\pi a^2 n/I_p$) is only considered as a stability parameter. For each of these steps the dimensionless scaling are applied to the current the toroidal field and the density in order to compute the parameters of the plasma at each steps. The confinement time is calculated at each step using the individual dimensionless scaling and compared with various hypotheses. In this way, the impact on the performance of each exponent to the physical variable can be assessed. The fusion power calculation uses the exact DT cross-section, an approximate evaluation of the integrals of T_i and n_i^2 and uses the ITER Z_{eff} of 1.65.

In addition, the same steps have been carried out with the CRONOS suite of codes [6]. In these computations, the scaled temperature and density profiles are given as input at each step, maintaining the dimensionless parameters as in the 0D approach. The plasma equilibrium is calculated for each step (identity, ρ^* and ν^*), and the fusion power calculated using the Bosch-Hale formulation within CRONOS. The standard assumption regarding radiation and Z_{eff} for ITER are used: the discharge contains Be (2%) and Ar (0.12%) impurities, tied to the electron density profiles; the He profile is calculated by a 1D diffusion equation which imposes a ratio of 5 between the He particle confinement time and the global energy confinement time. This leads to a total effective mass of 1.65. The Z_{eff} measured in Pulse No: 77933 is 2.07. The plasma is comprised of a 50:50 D:T ratio.

Pulse No: 77933 is also simulated with predictive heat transport using GLF23 [7] with and without E×B to test the effect of rotation. The q-profile for this simulation is prescribed, and taken from equilibrium reconstruction with internal flux measurements calculations averaged over one thermal confinement time. GLF23 calculates the anomalous diffusivity between r/a = 0.25 and the pedestal top. Inside r/a = 0.25, a constant diffusivity is assumed on both the ion and electron channels in order to reproduce the experimental temperature gradients. From the pedestal top to the separatrix, a prescription is applied in order to set the GLF23 T_i and T_e boundary conditions at the pedestal top to be at close as possible to the experimental values.

Figure 2 shows that experimental data are well reproduced using GLF23 transport model without E×B shearing stabilisation but not with. Therefore the GLF23 model does not reproduce the JET pulse with its rotation, so rotation should be considered as an uncertainty in the extrapolation. The following table shows the results for each of the three steps together with the Pulse No: 77933 initial data, its GLF23 simulation with ExB and the CRONOS calculations.

All normalised coefficients are using the effective temperature inferred from the total energy content W_{th}. From this table, please note first that all these case are unlikely to be operationally viable in ITER: the identity case for example has too low plasma current and the ρ* case a density higher than the Greenwald density. It can be seen first of all that the 1.5D simulation does reproduce well each three steps of the extrapolation with the dimensionless parameters in terms of the stored energy. This suggests that the 1D model is consistent with the dimensionless scaling.

Secondly, the change in collisionality (last 2 columns) has, as predicted, a strong impact on the results since it has to be decreased by a factor of 7. This emphasize the need for the scaling to confirm the exponent in ν*, even if that exponent is relatively modest (~-0.35).

Thirdly, the fusion power finally obtained in the 1D scaling would lead to a fusion gain factor of almost 10 and a G factor of 0.6. This value according to figure 1 would be more consistent with the prediction of the H98y2 scaling than those of the ESGB scaling.

3. SENSITIVITY STUDY WITH ZEFF, TI/TE AND ROTATION

Also, using the final ITER shape with (κ = 1.7), fusion power sensitivity to Zeff with CRONOS has been looked at by setting 2.07 instead of 1.65 (increasing the Be and Ar concentrations). This typically reduces the fusion power by 20%, due primarily to fuel dilution and brings the fusion power more in line with that predicted by the 0D analysis.

Also the sensitivity to the assumption of $T_e = T_i$ has also been examined by setting $T_e = 1.1T_i$ while keeping the energy content constant. This has the effect to decrease the fusion power by typically 10% (figure 3).

Finally, the effect of rotation should also be assessed for the final ITER configuration since ITER will likely operate with very low toroidal rotation (~ a few 10^4 rd/s) because of the small momentum input from the 1MeV neutral beam injection. It is known that rotation gradients act on transport but GLF23 does not seem to capture its effect as seen in figure 2. The toroidal rotation for

ITER used here from the dimensionless ordering of the rotation frequency as shown above (see table). The result from GLF23 shows again that the case without E×B shear stabilisation is consistent with the ion temperature scaled values. The case with E×B shear would increase the fusion by about 30% in excess of 516MW instead of 390 without rotation.

SUMMARY

This exercise suggests that the scaling in ν^* in particular could play an essential role in the ITER extrapolation in contrast to what H98y2 is suggesting with a very weak dependence in $\nu^{*-0.01}$. According to dimensionless ordering, the ITER hybrid scenario could produce plasma with Q in excess of 5. The effect of rotation on transport remains an issue for the predictions even before the fuel dilution and Ti/Te. Further work will focus on the analysis of the whole hybrid database using this 0D approach and testing the various hypothesis of the dimensionless confinement scaling laws.

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	77933 (2.3T)	**CRONOS + GLF23**	**Identity 0D**	**CRONOS**	**ρ^* step 0D**	**CRONOS**	**ν^* step 0D**	**CRONOS**
a (m)	0.93	0.93	1.985	1.981	1 .985	1.982	1 .985	1.982
R (m)	2.905	2.905	6.2	6.199	6.200	6.199	6.200	6.199
I (MA)	2	2	1.655	1.655	6.036	6.029	9.966	9.954
B (T)	2.27	2 .27	0.880	0.881	3.21	3.21	5.3	5.3
Vol (m^3)	75.78	75.75	736.82	733.835	736.82	733.83	736.82	731.135
a/R	0.320	0.320	0.320	0.320	0.320	0.320	0.320	0.320
κ	1.53	1.53	1.528	1.551	1.528	1.550	1.528	1.547
I/aB	0.947	0.947	0.947	0.948	0.947	0.948	0.947	0.948
n (10^{20} m^{-3})	0.544	0.544	0.119	0.120	0.670	0.670	0.670	0.685
Greenwald fraction	0.739	0.739	0.893	0.892	1. 375	1.372	0. 833	0.849
qcyl	2.582	2.582	2.582	2.614	2.582	2.615	2.582	2.610
ρ^*	$4.88 10^{-3}$	$5.04 10^{-3}$	$4.88 10^{-3}$	$5.07 10^{-3}$	$2.30 10^{-3}$	$2.38 10^{-3}$	$2.30 10^{-3}$	$2.37 10^{-3}$
β	$2.16 10^{-2}$	$2.28 10^{-2}$	$2.16 10^{-2}$	$2.33 10^{-2}$	$2.16 10^{-2}$	$2.32 10^{-2}$	$2.16 10^{-2}$	$2.32 10^{-2}$
ν_c	$7.82 10^{-1}$	$7.02 10^{-1}$	$7.82 10^{-1}$	$6.76 10^{-1}$	$7.81 10^{-1}$	$6.86 10^{-1}$	$1.05 10^{-1}$	$9.70 10^{-2}$
ω_c [rd/s]	$1.16\ 10^5$	1.16105	$4.50\ 10^4$	-	$6.92\ 10^4$	-	$1.14\ 10^5$	-
W_{th} [MJ]	5.034	5.312	7.355	7.898	97.870	103.880	266.803	284.350
P_{FUS} [MW]	-	-	0.029	0.038	26.66	34	421.68	477.83
Q					**0.53**	**0.68**	**8.42**	**9.54**

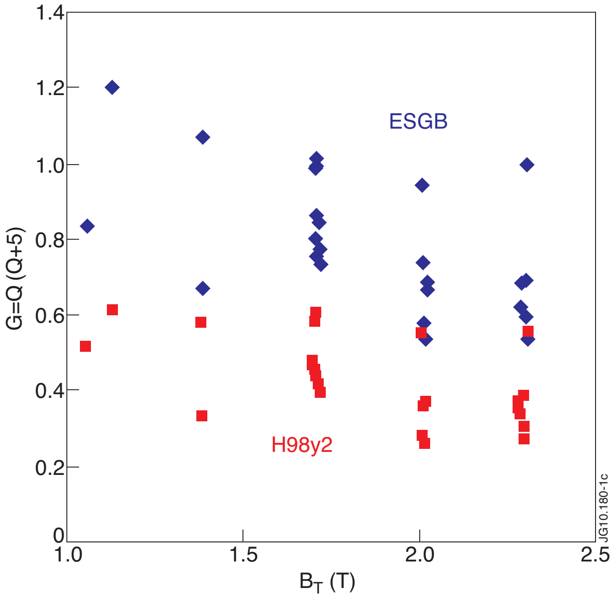

Figure 1: Fusion gain factor of the set of JET hybrid discharges with H factor from 1.25 to 1.4 extrapolated to ITER at 5.3T estimated from the scaling derived in [3] for the H98y2 scaling (red squares) and the ESGB scaling (blue diamonds) as function of the toroidal field.

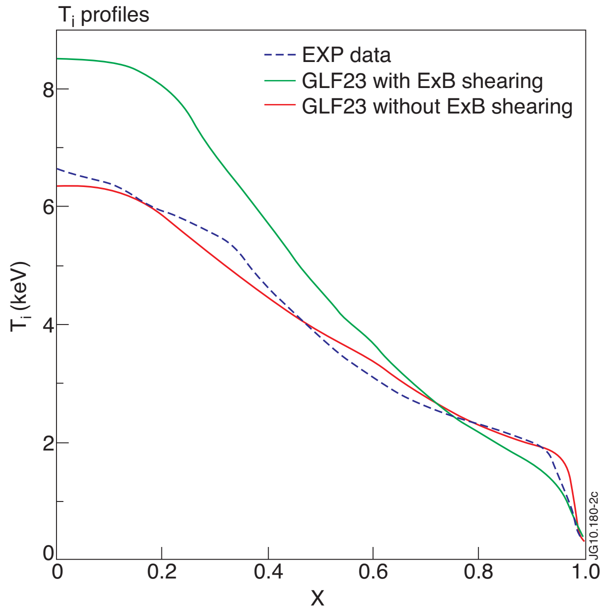

Figure 2: Comparison of experimental profiles from charge exchange (dashed) and GLF23 prediction with and without E×B shear stabilisation for Pulse No: 77933 used as a starting point for the extrapolation.

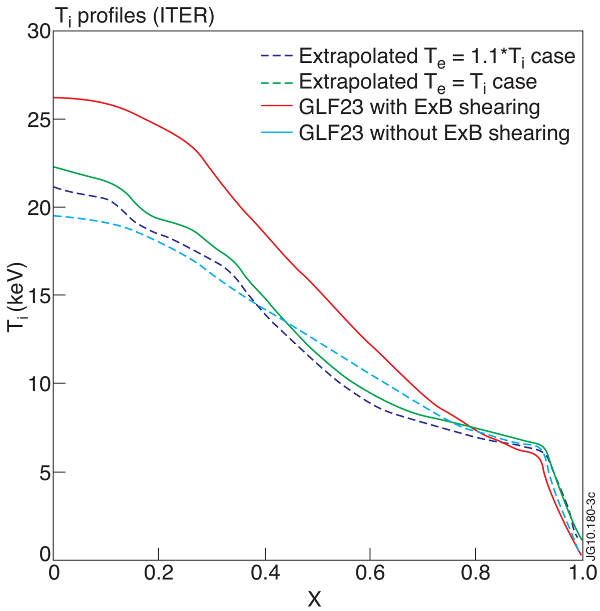

Figure 3: Comparison of ion temperature profiles scaled in a dimensionless manner to ITER for $T_e = T_i$ and $T_e = 1.1{\times}T_i$ (dashed) and GLF23 prediction with and without E×B shear stabilisation.