Contribution ID: **1035** Type: **Regular Poster**

Impact of aspect ratio on tokamak confinement: nonlinear gyrokinetic evidence, WEST results and implications for DEMO

Thursday 13 May 2021 12:10 (20 minutes)

The aspect ratio $A = R/a$ is a central parameter for tokamak design in many aspects. In particular, it is expected to critically impact plasma vertical stability and heating, disruption forces, tritium breeding, maintenance and cost [1]. Yet, there is some freedom in its choice. Most of present tokamaks, including ITER, operate at $A \sim 3$, with notable exceptions like MAST ($A \sim 1.5$) and WEST ($A \sim 5$) operated at CEA Cadarache. This paper reports on three major new results regarding the impact of A on confinement: (1) how does it translate in terms of tokamak design? (2) What do we learn from global flux-driven gyrokinetic simulations? (3) What is the current input of WEST data in this debate?

(1) On the basis of empirical scaling laws (SL) of the energy confinement time τ_E, the benefit of operating at large or small A is uncertain. Indeed, two of the most refined SL using large tokamak data bases, IPB98(y,2) [2] and DS03 [3] –valid for ELMy H-mode regimes –exhibit roughly the same variance (16%) of experimental data. However, when expressed in dimensionless variables, the scaling exponent of A is of opposite sign in both SL: DS03 predicts an increase of τ_E with A ($\omega_c \tau_E \sim A^{1.3}$, with ω_c the ion cyclotron frequency), the opposite trend is observed for IPB98(y,2) ($\omega_c \tau_E \sim A^{-0.73}$). This uncertainty reflects the lack of data from tokamaks with sufficiently different A values in the database. Forthcoming data from the WEST tokamak will likely help alleviating the uncertainty [4]. Furthermore, there likely exists a bias for compact tokamaks which usually operate at larger normalized beta β_N values than more conventional ones, so that A and β_N may not be completely independent parameters in the database. We have explored the sensitivity of the European DEMO design [1] $-$ targeting the amplification factor $Q = 40$ and the fusion power $P_{fus} = 2.037$ GW $-$ with respect to A when considering the two equally satisfying SL. Results are plotted on Fig.1 in terms of major radius R and magnetic field B.

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The different values of β_N account for the different operational spaces for these two SL: DS03 predicts larger β_N (and lower plasma current) to achieve similar performance, which can reveal challenging in a reactor aiming at zero disruption [5]. Importantly, the variations with A of (R, B) solutions are opposite for the two scaling laws: R decreases (resp. increases) with A if IPB98(y,2) (resp. DS03) holds. The opposite is true for B. Especially, DS03 predicts that similar performance can be achieved at lower R (and slightly larger B) when reducing A.

(2) The issue of confinement and aspect ratio has also been addressed by means of flux-driven gyrokinetic simulations with GYSELA [6] in the ion temperature gradient driven regime of turbulence with adiabatic electrons. On the basis of first expected then observed SL of τ_E, the heating source was tuned to keep the profiles close to their initial state. A database of about 40 close-to-steady-state simulations has been obtained, covering the parameter range $A = [3.2, 4.4, 6]$ and the collisionality $\nu_* = [0.004, 0.02, 0.1]$. Also, the normalized ion gyro-radius $1/\rho_* = [150, 190, 250, 380]$ for $A = 4.4$ and $1/\rho_* = [190, 250, 380]$ for $A = 6$. Using standard regression [7], the dimensionless energy confinement time is found to scale like (Fig.2) $\omega_c \tau_E = 1.5 A^{0.88} \rho_*^{-2.40} \nu_*^{-0.14}$.

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The positive exponent of A, as for DS03, may suggest τ_E scales like the parallel transit time $\omega_c \tau_\parallel \sim qA/\rho_*$ (q=safety factor). Also, increasing A tends to reduce curvature and grad-B drifts, which are the generic drives for ITG. Note finally that the scaling exponent of A is not expected to change sign in regimes dominated by trapped electron modes since the trapped particle density scales like $A^{-1/2}$. This possible multiple dependency may actually result in a non-monomial SL with respect to A.

(3) WEST data have been collected in 2019 during the 4th experimental campaign. All considered shots are in L-mode, either purely ohmic P_Ω or with ion cyclotron resonance P_{IC} and lower hybrid P_{LH} heating. Radiative losses are in the range 45% to 65% of the input power $P_{in} = P_\Omega + P_{IC} + P_{LH}$ likely due to the increase of the impurity source with power. The energy confinement time has been estimated with 0.3s time window averages of the MHD energy divided by the heating power. We find the following SL: $\tau_E \sim I_p^{0.86} P_{eff}^{-0.84}$, with I_p the plasma current. The scaling exponents turn out to be relatively insensitive to the considered heating power, either the input or the effective $P_{eff} = P_{in} - P_{rad}$ power, although the scattering is lower with P_{eff}. Note that this SL is not dimensionally correct, in part due to the narrow parameter space. Yet, although operating at much larger aspect ratio than the tokamaks considered to construct the experimental database in L-mode, it exhibits similar scaling exponents with respect to both plasma current and heating power as the standard L-mode SL, respectively equal to 0.96 and -0.73 [2]. As a result, τ_E in WEST is in good agreement with the value predicted by the L-mode SL (Fig.3).

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The agreement of WEST confinement with the standard L-mode SL, which predicts almost no dependency in A, would suggest that this law can indeed be extrapolated to large A tokamaks. GYSELA results seem to qualitatively agree with DS03 SL in H-mode, favoring large A machines. These are potentially good news for WEST, which would then exhibit even better performance in H-mode than initially expected.

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Session Classification: P5 Posters 5

Track Classification: Magnetic Fusion Theory and Modelling