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IMPACT OF THE ASPECT RATIO ON TOKAMAK REACTOR DESIGN

Application to DEMO using the 0-dimensional ScaLa model

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Abstract

The impact of the aspect ratio R/a (major over minor radius) on the design of tokamak reactors is addressed by means of the generic and comprehensive 0-dimensional ScaLa model for tokamak dimensioning. The European DEMO (fusion gain $Q=40$ and power $P_{\text{fus}}=2.037\text{GW}$) is taken as the target. Three scaling laws are considered for the energy confinement time, namely IPB98(y,2) used as the ITER reference, the electrostatic DS03 law and the recently upgraded ITPA20 one. First, it appears that the increase of the energy confinement time with A found in two of the scaling laws does not necessarily result in an advantage of working at large A , cross-dependencies leading to sometimes counter-intuitive – yet real – trends. Second, the opposite trends with respect to a scan in A which is observed regarding the product of the plasma volume times the square of the magnetic field – used as a proxy for the cost – does not provide a clear answer as to whether small or large aspect ratio tokamaks should be favoured. This mild conclusion pushes for consolidating experimental databases with tokamaks exhibiting aspect ratios departing from the common 3 value.

1. INTRODUCTION

Designing a tokamak reactor is usually addressed by first defining target fusion power P_{fus} and gain factor Q , the ratio of P_{fus} over the sum of auxiliary heating sources P_{aux} . It then consists, among others, in determining a suitable couple of major radius and magnetic field on magnetic axis (R, B). These critical parameters drive the cost – basically expected to scale like the magnetic energy $E_{\text{mag}} \sim B^2 R^3$ – and in many respects the feasibility of a given design. In such an exercise, empirical scaling laws play a key role in relating the energy confinement time τ_E – tightly linked to Q – to most relevant plasma and geometrical parameters. While ITER has been designed on the basis of the famous IPB98(y,2) scaling law [ITER1999], improved diagnostics, enhanced database and upgraded statistical tools have recently led to new scaling laws of the same ELMy H-mode regime, one of the reference scenarios of ITER. One of those is the so-called DS03 law [Petty2004], which exhibits a similar and very large scattering of the data as the former one, around 30% when including experiments with both carbon and tungsten divertor tiles, but with much better correlation [Sips2018]. From the dimensionless point of view, these two scaling laws mainly differ by the exponents associated to collisionality ν^* , plasma beta β and aspect ratio $A=1/\epsilon=R/a$ (with a the minor radius). DS03 has been explicitly constructed without any dependency on β , and it exhibits a larger exponent associated to ν^* (-0.14 vs. -0.01). Noticeably also, the aspect ratio exponent changes sign from one scaling law to the other, leaving uncertain the benefit of operating at large or small A . Last, the recently upgraded scaling law issued by the ITPA working group – named ITPA20 – has also been added to our analysis [Verdoolaege2021]. Most noticeably, it predicts an almost Bohm-like dependency of the energy confinement time, $\omega_c \tau_E$ (with ω_c the ion cyclotron frequency) scaling like $\rho_*^{-2.24}$. Similarly to DS03, it exhibits a positive scaling of $\omega_c \tau_E$ with the aspect ratio A .

In this work, we investigate the impact of the aspect ratio A on the design of tokamak reactors. To this end, the essentially 0-dimensional – up to refinements accounting for profile peaking factors – ScaLa model is used [Sarazin2020]. It proposes a comprehensive physical approach with prescribed parameters, mainly the safety factor and plasma geometry. The change of variables from density and temperature to Greenwald fraction and normalized beta allows one to constrain the accessible range of these free parameters on the basis of soft transport and MHD limits. It is shown that the model recovers the main ITER characteristics when using the IPB98(y,2) scaling law. The European DEMO design, targeting $P_{\text{fus}} \approx 2.037\text{GW}$ and $Q=40$ [Wenninger2017], is then explored for different values of A , depending on whether the IPB98(y,2), the DS03 or the ITPA20 scaling law is expected to hold. Contradictory trends are reported especially regarding the proxy used as an estimate of the cost, so that the present analysis does not provide a clear conclusion regarding the optimal choice of A .

The rest of the paper is organized as follows. The ScaLa model for reactor design is detailed in section 2 and shown to allow one to recover ITER main characteristics at the cost of a few approximations. It is then applied in section 3 to the DEMO design, focusing on the impact of the aspect ratio, which is one of the most critical yet weakly constrained geometrical parameter. Section 4 then provides a discussion and concluding remarks.

2. THE SCALA MODEL

Setting P_{fus} and Q as target values for a tokamak provides two essential constraints which contribute to defining suitable R and B values. The ScaLa model provides a comprehensive way of relating the couple (R,B) to (P_{fus},Q) on the basis of physical arguments [Sarazin2020]. It proceeds from several simplifications, most of which can be easily alleviated as discussed hereafter. The backbone consists in dealing with essentially 0-dimensional parameters, profile effects being accounted for via additional peaking factors. Its advantages are threefold: (i) the semi-analytical treatment is complementary to system codes such as SYCOMORE [Johner2011; Reux2015] and PROCESS [Kovari2014], (ii) it can help elucidating ITER possible sub-nominal achievements, and (iii) it is a flexible tool for reactor design, e.g. DEMO.

The first constraint is set by the definition of P_{fus} , involving the ion density $n_i=n/2$ (assuming 50%-50% of deuterium-tritium ions and with n the electron density), the plasma volume $V=2\pi^2\kappa\varepsilon^2R^3$ (κ the elongation and $\varepsilon=1/A$) and the D-T reaction rate $\langle\sigma v\rangle_{\text{DT}}$. The latter is approximated by $\langle\sigma v\rangle_{\text{DT}}=C_\sigma T^\sigma$, with $\sigma\in\{0,1,2,3,4,5\}$ for temperatures T ranging from 1.4keV to 100keV [CEA1987]. Since T is not known *a priori*, an *a posteriori* check is required to ensure that T lies well in the corresponding interval of the monomial approximation. One has:

$$P_{\text{fus}} = C_{\text{fus},\sigma} \kappa \varepsilon^2 n^2 T^\sigma R^3 \quad (1)$$

Care should be taken to dimensional issues which govern the numerical values of all the constants. In the case where $10.3\text{keV}<T<18.5\text{keV}$, then $\sigma=2$ and $C_{\text{fus},2}\approx 1.64 \cdot 10^{-3}$, with n in 10^{19}m^{-3} and T in keV.

The second constraint comes from the energy confinement time τ_E , which is governed by two different expressions which should be equal to each other, obviously. The first one derives from the power balance, stating that the net power P_{net} going to the plasma – $P_{\text{net}}=P_\alpha+P_{\text{aux}}-P_{\text{rad}}$ – balances the power lost due to transport processes $P_{\text{tr}}=W/\tau_E$, with $W=C_{\text{tr}}\kappa\varepsilon^2nTR^3$ ($C_{\text{tr}}\approx 0.095$ with powers in MW) the plasma internal energy. Here, two options can be considered: either assuming that the radiated power is simply proportional to the source power $P_{\text{rad}}=(1-\gamma_{\text{rad}})(P_\alpha+P_{\text{aux}})$ with $0<\gamma_{\text{rad}}<1$, or estimating it from the Bremsstrahlung emission $P_{\text{rad}}\approx P_{\text{Brem}}=C_{\text{Brem}}\kappa\varepsilon^2n^2T^{1/2}R^3$. The latter neglects other contributions which are expected to be subdominant, except in the presence of strong line radiation when heavy impurities reach the plasma core. This situation especially occurs in the new generation of tokamaks with tungsten divertor tiles. For this reason, we will rely on the γ_{rad} approximation hereafter. Then, using the definition of $Q=P_{\text{fus}}/P_{\text{aux}}$ and the fact that $P_\alpha=P_{\text{fus}}/\lambda$ ($\lambda\approx 4.94$ when accounting for relativistic effects) leads to the following relationship:

$$n \tau_E = C_{\text{tr}}/(C_{\text{fus},\sigma} \gamma_{\text{rad}}) T^{1-\sigma} Q/(1+Q/\lambda) \quad (2)$$

In the special case where $\sigma=2$, one recovers the familiar expression of the triple product $nT\tau_E$ as a function of Q only. The other expression of τ_E is obviously provided by the scaling law. It involves the plasma current I_p , among others, which can be related to R , B and the edge safety factor q through the Maxwell–Ampère equation integrated over the whole plasma poloidal cross-section: $I_p=C_I(\varepsilon^2/q)RB$ ($C_I=5F$ with I_p in MA and F the form factor associated to the length of the poloidal cross section $L_{\text{cs}}=2\pi aF$; F depends on aspect ratio ε , elongation κ and triangularity δ [Johner2011]). One then obtains:

$$n \tau_E = (C_{\text{SL}} C_{\text{tr}}^{\alpha_P} C_I^{\alpha_I} M^{\alpha_M} \kappa^{\alpha_\kappa} \varepsilon^{\alpha_\varepsilon+2\alpha_I+2\alpha_P} q^{-\alpha_I} n^{1+\alpha_n+2\alpha_P} T^{\alpha_P} R^{\alpha_R+\alpha_I+3\alpha_P} B^{\alpha_B+\alpha_I})^{1/(1+\alpha_P)} \quad (3)$$

where the various exponents of the scaling law are given TAB. 1.

TABLE 1. Coefficient and exponents of three scaling laws

Scaling Law	C_{SL}	α_M	α_κ	α_ε	α_n	α_I	α_R	α_B	α_P
IPB98(y,2)	0.0562	0.19	0.78	0.58	0.41	0.93	1.97	0.15	-0.69
DS03	0.028	0.14	0.75	0.30	0.49	0.83	2.11	0.07	-0.55
ITPA20	0.053	0.20	0.80	0.35	0.24	0.98	1.71	0.22	-0.669

A such, temperature can hardly be constrained on physical ground provided it exceeds the thermal stability limit. One way to proceed further consists in making the following change of variables: $(n, T) \rightarrow (n_N, \beta_N)$, with $n_N = n/n_G$ the density normalized to the Greenwald density $n_G = C_n I_p / \varepsilon^2 R^2$ ($C_n \approx 3.18$) [Greenwald2002] and $\beta_N = \beta\% / (I_p / \varepsilon R B)$ the ratio $\beta\% = C_\beta n T / B^2$ ($C_\beta \approx 0.805$) of the kinetic over the magnetic pressures normalized to $I_p / \varepsilon R B$. It then follows:

$$n = C_n C_1 n_N B / q R ; \quad T = (C_n C_\beta)^{-1} \varepsilon R B \beta_N / n_N \quad (4)$$

Replacing n and T by the above expressions depending on n_N and β_N in eqs.(2-3) and equating these two equations leads to, in the case $\sigma=2$:

$$\{Q / [\gamma_{\text{rad}} (1+Q/\lambda)]\}^{1+\alpha_P} = C_{\text{SL}} C_n^{\alpha_n} C_1^{\gamma_I} C_{\text{fus},2} / (C_\beta C_{\text{tr}}) P_{\text{fus}}^{\alpha_P} M^{\alpha_M} \kappa^{\alpha_\kappa} \varepsilon^{\gamma_\varepsilon} q^{-\gamma_I} n_N^{\alpha_n} \beta_N^{\gamma_R} R^{\gamma_B} B^{\gamma_B} \quad (5)$$

with $\gamma_I = 1 + \alpha_n + \alpha_I$, $\gamma_\varepsilon = 1 + \alpha_\varepsilon + 2\alpha_I$, $\gamma_R = \alpha_R + \alpha_I - \alpha_n$ and $\gamma_B = 2 + \alpha_B + \alpha_n + \alpha_I$. Also, eq.(1) can be recast as follows:

$$P_{\text{fus}} = (C_{\text{fus},2} C_1^2 / C_\beta^2) (\kappa \varepsilon^4 / q^2) \beta_N^2 R^3 B^4 \quad (6)$$

Equations (5-6) provide the two independent relations which relate the 4 unknowns (R, B, n_N, β_N) to (Q, P_{fus}) . At prescribed Q and P_{fus} , there are still 2 variables out of 4 which can be chosen freely. In other words, the 2 equations draw a surface in a 4-dimensional space. Working with n_N and β_N rather than with n and T allows one to restrict the range of accessible values. Indeed, n_N and β_N are associated to soft stability limits due to either transport processes and/or MHD instabilities. In turn, n_N is expected to remain below unity – although peaked density profiles can well operate above this value – while β_N should not exceed a few units – $\beta_N = 2.8$ corresponds to the so-called Troyon limit [Wesson2004].

Some of the coefficients are refined to take into account particle dilution due to the fraction of α particles $f_\alpha = n_{\text{He}}/n$, temperature peaking $f_T = \langle T^2 \rangle / \langle T \rangle^2$ (where $\langle \dots \rangle$ stands for volume average) and different ion and electron temperatures $\theta_i = T_i / T_e$: $C_{\text{fus},2} \rightarrow C_{\text{fus},2} \times (1 - 2f_\alpha)^2 \theta_i^2 \times f_T$, $C_{\text{tr}} \rightarrow C_{\text{tr}} \times (1 + \theta_i - f_\alpha \theta_i) / 2$, $C_\beta \rightarrow C_\beta \times (1 + \theta_i - f_\alpha \theta_i) / 2$. The atomic mass number M then reads $M = (5 - 2f_\alpha) / 2(1 - f_\alpha)$. Taking $\varepsilon = 1/3.1$, $q = 3$, $\kappa = 1.7$, $\delta = 0.33$, $\gamma_{\text{rad}} = 0.7$, $f_\alpha = 0.035$ (leading to $M = 2.554$), $f_T = 1.35$, $\theta_i = 1/1.15$ and $n_N = 0.85$ allows one to recover ITER characteristics. Indeed, targeting $Q = 10$, $P_{\text{fus}} = 500 \text{ MW}$ and using the IPB98(y,2) scaling law (cf. TAB. 1) leads to the following possible solution: $(R, B, \beta_N) = (6.2 \text{ m}, 5.3 \text{ T}, 1.7)$. The corresponding density, temperature, plasma current and energy confinement time are $n \approx 10^{20} \text{ m}^{-3}$, $T \approx 9.0 \text{ keV}$, $I_p \approx 14.9 \text{ MA}$ and $\tau_E \approx 3.1 \text{ s}$. Conversely, if the DS03 scaling law holds, the same Q and P_{fus} can be achieved in ITER (i.e. at $R = 6.2 \text{ m}$) at reduced magnetic field $B \approx 4.42 \text{ T}$ but larger normalized beta $\beta_N \approx 2.43$. The corresponding physical variables are $n \approx 8.4 \cdot 10^{19} \text{ m}^{-3}$, $T \approx 10.7 \text{ keV}$, $I_p \approx 12.5 \text{ MA}$ and $\tau_E \approx 3.1 \text{ s}$. In both cases, the power P_{tr} crossing the separatrix exceeds the L-H power threshold estimated from the scaling proposed in reference [Martin2008].

The same analysis can be performed for the European DEMO, which targets $P_{\text{fus}} \approx 2.037 \text{ GW}$ and $Q = 40$ [Wenninger2017]. In this case, slight changes are applied to some of the prescribed parameters to account for the specificity of this new machine. Especially, one takes $\varepsilon = 1/3.1$, $q = 3.2$, $\kappa = 1.59$, $\delta = 0.33$, $\gamma_{\text{rad}} = 0.56$ (accounting for the larger expected Bremsstrahlung radiation and the need to radiate a significant fraction of the power), $f_\alpha = 0.1$ (leading to $M = 2.67$), $f_T = 1.5$, $\theta_i = 1/1.1$ and $n_N = 1.2$. Also, an H factor of 1.1 is considered ($C_{\text{SL}} \rightarrow H \times C_{\text{SL}}$), assuming 10% better confinement than in standard H-mode possibly due to optimized magnetic geometry. The (R, B) solutions are plotted as functions of β_N on FIG. 1 for the two considered scaling laws. It readily appears that DEMO should operate at much larger β_N if DS03 holds. In particular, considering a reactor of major

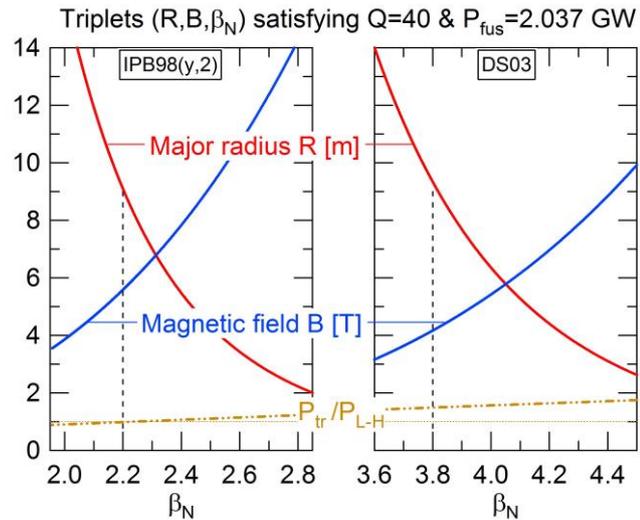


FIG. 1: Values of R and B as a function of β_N which fulfill both eqs.(5-6) when using the IPB98(y,2) (left) or DS03 (right) scaling law (from [Sarazin2020]).

radius $R=9.1\text{m}$, (B, β_N) should be approximately equal to $(5.6\text{T}, 2.2)$ with IPB98(y,2) and $(4.2\text{T}, 3.8)$ with DS03. The latter value reveals challenging in a reactor which aims at zero disruption. In this case, the values of density, temperature, plasma current and energy confinement time are $n \approx 8.7 \cdot 10^{19}\text{m}^{-3}$, $T \approx 12.9\text{keV}$, $I_p \approx 19.6\text{MA}$ and $\tau_E \approx 4.6\text{s}$ for IPB98(y,2) and $n \approx 6.6 \cdot 10^{19}\text{m}^{-3}$, $T \approx 17\text{keV}$, $I_p \approx 14.9\text{MA}$ and $\tau_E \approx 4.6\text{s}$ for DS03.

Not shown here is the case of the ITPA20 scaling law. When performing the same analysis, one finds that (B, β_N) should be approximately equal to $(7.0\text{T}, 1.4)$. This results in $n \approx 1.1 \cdot 10^{20}\text{m}^{-3}$, $T \approx 10.2\text{keV}$, $I_p \approx 24.7\text{MA}$ and $\tau_E \approx 4.6\text{s}$. The two noticeable features are the required magnetic field and plasma current which are large as compared to the two other scaling laws.

3. IMPACT OF THE ASPECT RATIO ON DEMO DESIGN

The aspect ratio $A=1/\varepsilon=R/a$ (with a the minor radius) is a central design parameter which is involved in many aspects, including plasma stability issues, disruption forces, tritium breeding, maintenance and cost. Yet, as stated in [Wenninger2017], there is some freedom in its choice. Conservatively, many tokamaks operate at $A \sim 3$ – and so will ITER, with notable exceptions exploring compact tori like MAST $A \sim 1.5$ [Morris2012] or large aspect ratio like WEST $A \sim 5$ [Bucalossi2011]. The relatively narrow range of the available A parameters in the databases which are used for energy confinement time scaling laws likely explains the opposite trend reported in IPB98(y,2) on the one hand and DS03 and ITPA20 on the other hand, when expressed in dimensionless – or physical – variables: while IPB98(y,2) predicts a degradation of the confinement with A ($\omega_c \tau_E \sim A^{-0.73}$, with ω_c the ion cyclotron frequency), DS03 and ITPA20 suggest a benefit of working at large A ($\omega_c \tau_E \sim A^{1.30}$ and $\omega_c \tau_E \sim A^{1.70}$, respectively). Given this uncertainty, it is worth exploring the impact of A on a reactor design.

To this aim, equations (5-6) are solved for 5 different values of A ranging from 2.6 to 3.6, all other parameters being equal to those used for FIG. 1 (cf. section 2). Two cases are discussed hereafter: either at prescribed major radius $R=9.1\text{m}$, or at prescribed β_N . In this latter case, accounting for the fact that DEMO should operate at different β_N depending on the scaling law, β_N is taken equal to 2.2, 3.8 and 1.38 for IPB98(y,2), DS03 and ITPA20, respectively. In these analyses, the elongation is varied with A to account for vertical stability limits. The adopted formula $\kappa = 0.06 A^2 - 0.462 A + 2.4456$ is a fit of published data (cf. Tab.1 in [Wenninger2015]).

3.1. Scanning A at prescribed R

The results of this scan are displayed on FIG. 2. It appears that β_N is almost independent of A in the considered interval, while B increases with A ($2.6 < A < 3.6$) for all scaling laws, from 4.2T to 6.8T, 3.3T to 5.0T and 5.4 to 8.5, respectively. This similar trend despite opposite dependencies of τ_E with respect to A in the scaling laws is not intuitive. It results from the multiple dependencies on A which result in intricate scaling. This point is highlighted in section 3.2.

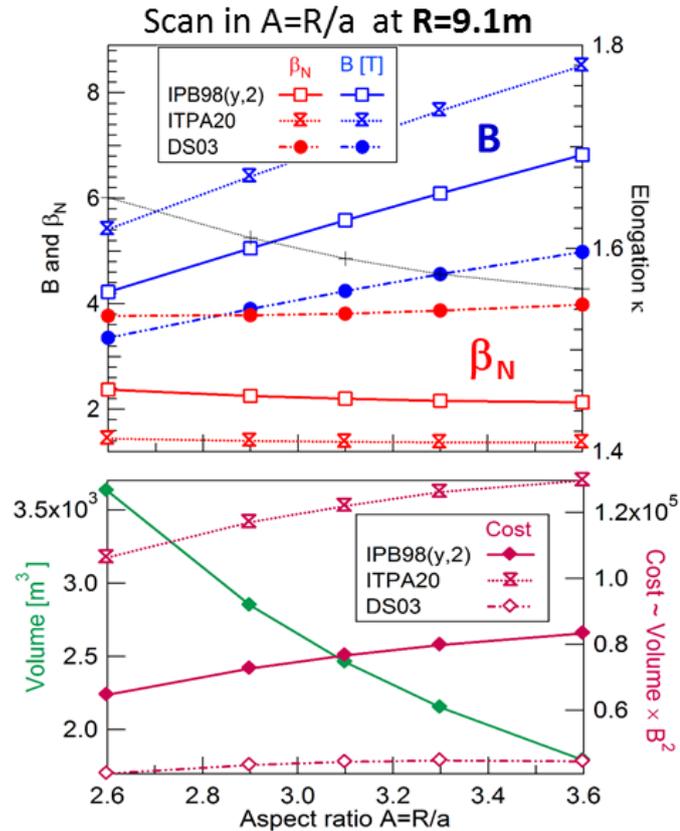


FIG. 2: Top: β_N (red) and B (blue) solutions for DEMO as a function of $A=R/a$ at fixed $R=9.1\text{m}$ for IPB98(y,2) (plain lines), DS03 (dashed lines) and ITPA20 (dotted lines) scaling law. Bottom: Volume (green, left) and "cost" (purple, right) for these scaling laws.

The bottom graph shows the plasma volume (green curve), which decays like A^{-2} at fixed R , irrespectively of the scaling law ($V \sim A^{-2}R^3$). This decrease does not compensate the large increase of B (by about 62%, 51% and 57% with increasing A , so that the overall estimate of the cost (purple curve) – assumed to scale like $V \times B^2$ – increases

modestly with A in each case. Because of the need of a larger magnetic field, ITPA20 leads to the largest estimated cost.

3.2. Scanning A at prescribed β_N

The scan at constant β_N can be analyzed as follows. Equations (5-6) allow one to express β_N as a function of R , B and $\varepsilon=1/A$. Scanning A at constant β_N then requires $B \sim \varepsilon^{-1} R^{-3/4}$ (cf. eq.(16) in [Sarazin2020]). Inserting β_N in eq.(5) and using the above constraint on B then leads to the following scaling with respect to A (cf. eq.(17) in [Sarazin2020]): $R \sim A^{(\gamma_c - \gamma_B)/(\gamma_R - 3\gamma_B/4)}$ and $B \sim A^{1 - 3(\gamma_c - \gamma_B)/(\gamma_R - 3\gamma_B/4)}$. One would then expect $R \sim A^{0.39}$ and $B \sim A^{0.71}$ for IPB98(y,2), $R \sim A^{4.65}$ and $B \sim A^{-2.49}$ for DS03 and $R \sim A$ and $B \sim A^{0.25}$ for ITPA20. These trends are mainly recovered in FIG. 3 (top), except for R which decreases with A for IPB98(y,2) and ITPA20. This is due to the hidden dependency on A of the C_I coefficient (refined expression of the length of the poloidal cross section) and of κ which appears to be sufficient to invert the scaling of R with respect to A . Finally, the power P_{tr} crossing the separatrix is always above the power threshold estimated from reference [Martin2008] for all scaling laws, although marginally for ITPA20.

The consequence is that we observe opposite trends for the plasma volume and device cost for the scaling laws. IPB98(y,2) and ITPA20 would favor cheaper large aspect ratio devices. Rather counter intuitively, it turns out that the cost of the device would increase with A should DS03 hold, despite the favorable scaling of the energy confinement time with A in this case. The small decrease of B does not compensate the even larger increase in plasma volume. Yet, the estimated cost remains smaller than for the IPB98(y,2) scaling law up to $A \approx 3.4$ due to smaller required volume and magnetic field. Finally, it may reveal difficult to take advantage of the small decrease of the cost when A increases for the ITPA20 scaling law. Indeed, since it results from both the decrease of R and increase of B at large B , one may possibly face prohibitive constraints regarding solid structures and superconductors.

4. DISCUSSION AND CONCLUSION

The comprehensive and essentially 0-dimensional ScaLa model reveals a flexible tool to address tokamak design. In this work, it is used to explore the impact of the aspect ratio $A=R/a$ on the dimensioning of the European DEMO, targeting fusion gain $Q=40$ and power $P_{fus}=2.037\text{GW}$. It turns out that the answer depends on the adopted scaling law for the energy confinement time. Three such laws have been considered: the ITER-reference IPB98(y,2) one, the recently revisited DS03 law and the upgraded one provided by the ITPA working group – so-called ITPA20. These three scaling laws foresee plasma operation at different values of β_N to achieve the same performance, making DS03 the most challenging one since requiring the largest β_N : $\beta_N \approx 3.8$. Also, ITPA20 suggests one may need a higher magnetic field, which translates into larger constraints on the solid structures. Scans in A , ranging from 2.6 to 3.6, have been performed at either constant major radius $R=9.1\text{m}$ or constant β_N (adapted to each scaling law). The considered figure of merit is the cost, assumed to scale like the plasma volume times the magnetic energy. It appears that the favorable scaling of the energy confinement time with A , as obtained with DS03 and ITPA20, does not necessarily result in a benefit of working at large A . All in all, the reported opposite trends leave unclear the benefit of working at large or small aspect ratio. Consolidating the experimental databases with

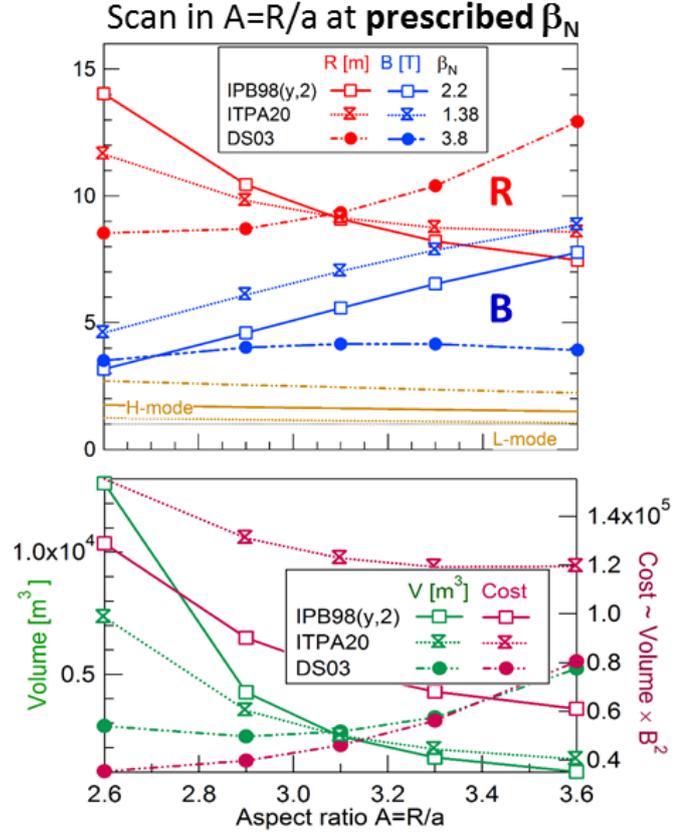


FIG. 3: Top: R (red) and B (blue) solutions for DEMO as a function of $A=R/a$ at fixed β_N for IPB98(y,2) ($\beta_N=2.2$, plain lines), DS03 ($\beta_N=3.8$, dashed lines) and ITPA20 ($\beta_N=1.38$, dotted lines) scaling law. Bottom: Volume (green, left) and "cost" (purple, right) for these scaling laws.

tokamak devices operating in the ITER regime and featuring aspect ratios significantly different than 3 – possibly like the WEST tokamak – is mandatory to reach a clear conclusion regarding this important parameter.

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