



HAL
open science

Impact of the aspect ratio on tokamak reactor design

Yanick Sarazin

► **To cite this version:**

Yanick Sarazin. Impact of the aspect ratio on tokamak reactor design. IAEA FEC 2021 - The 28th IAEA Fusion Energy Conference, May 2021, Nice (Virtual Conference), France. cea-03253683

HAL Id: cea-03253683

<https://cea.hal.science/cea-03253683>

Submitted on 8 Jun 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Impact of the aspect ratio on tokamak reactor design

Y. Sarazin, J.-L. Duchateau, X. Garbet, Ph. Ghendrih, R. Guirlet, J. Hillairet, B. Pégourié, A. Torre and R. Varennes

CEA, IRFM, F-13108 St-Paul-Lez-Durance, France

yanick.sarazin@cea.fr

Context - motivations

► Tokamak design relies on the use of **empirical scaling laws** for the **energy confinement time** τ_E [e.g. Zohm, NF 2013]

► These scaling laws exhibit **large variances** (~30%) and **different scaling regarding critical parameters** (e.g. aspect ratio $A=R/a$)

IPB98(y,2) [ITER Physics basis NF 1999]

DS03 [Petty PoP 2004; Sips NF 2018]

► What **impact on Tokamak design** ?

► What **consequences for ITER & DEMO** [Coleman, FED 2016] ?

Objectives: $(P_{fus}, Q) \rightarrow (R, B)$?

► Main targets: **fusion Power** P_{fus} and **fusion gain** $Q=P_{fus}/P_{add}$

► Find best suitable **major radius R** and **magnetic field B**
(cost ~ magn. Energy \times volume $\sim B^2 R^3$)

► The **SCALA** (SCALing LAws) **comprehensive physical approach**:
 - Essentially 0-dimensional + peaking factors [Sarazin NF 2020]
 - Prescribed parameters (safety factor q_a and geometry)
 - $(n, T) \rightarrow (n/n_G, \beta_N)$ to account for soft transport/MHD limits

► **Semi-analytical treatment** \rightarrow Complementary to system codes
 SYCOMORE [Johner, FST 2011; Reux, NF 2015] & PROCESS [Kovari, FED 2014]

► Can help **elucidating ITER possible sub-nominal achievements**

► Flexible tool for **reactor dimensioning** (e.g. DEMO)

Constitutive relations: P_{fus}

► $P_{fus} = n_D n_T \langle \sigma v \rangle_{DT} E_{DT} V \rightarrow P_{fus} \sim R^3 n^2 T^2$

Simplifications: $n_D n_T = \frac{n^2}{4}$, $\langle \sigma v \rangle_{DT} \sim T^2$ (if $10.3 < T < 18.5$ keV, alternatives otherwise) [Collection CEA, 1987]

Constitutive relations: $Q \dots$ hence τ_E

► $Q = \frac{P_{fus}}{P_{add}}$

$P_{fus} = P_\alpha + P_n = \lambda P_\alpha$ $\lambda \approx 4.94$

$P_{net} = P_\alpha + P_\Omega + P_{add} - P_{rad} = \gamma_{rad}(P_\alpha + P_{add})$

► Link with $\tau_E \rightarrow$ **triple product**

$\tau_E = \frac{3nTV}{P_{loss} - P_{rad}} \sim \frac{nTR^3}{P_{net}}$

► Empirical Scaling Law $\tau_E = F(n, I_p, R, B, P_{net}, \dots)$

n and T constrained by plasma physics

► **Soft limits in (n,T) set by plasma MHD (& turbulence?) instabilities**

► **Greenwald fraction** $n_G = \frac{I_p}{\pi a^2} \sim \frac{I_p}{R^2}$ with $I_p \sim \frac{RB}{q}$

$\Rightarrow n_N = \frac{n}{n_G} \sim \frac{qRn}{B}$ [Greenwald, NF 1988, PPCF 2002]

No definitive understanding – evidence of plasma boundary effect

► **Beta limits** \rightarrow critical β_N : $\beta_N = \beta\% \frac{aB}{I_p}$

$\beta\% \sim \frac{nT}{B^2} \Rightarrow nT \sim \frac{B^2}{q} \beta_N$

Not specific (stability is profile and mode dependent)
 Yet useful for a compact & analytic beta limit

► **Constitutive relations:** $F_{1,2}(n, T, I_p, R, B) = 0 \Leftrightarrow G_{1,2}(n_N, \beta_N, q, R, B) = 0$
 \rightarrow Change of variables

Final relations of the SCALA model

► From **scaling Law** $\left(\frac{Q}{1+Q/\lambda}\right)^{\gamma_Q} \sim n_N^{\alpha_n} \beta_N R^{\gamma_R} B^{\gamma_B}$

► From def. of P_{fus} $P_{fus} \sim \beta_N^2 R^3 B^4$

► Accounting for **refinements**:

- Fraction f_α of α particles: $f_\alpha = n_{He}/n_e$
- Temperature peaking factor: $f_p \sim \langle T^2 \rangle / \langle T \rangle^2$
- Different T_e & T_i : $\theta_i \equiv T_i/T_e$
- Geometry of poloidal cross-section [Johner, FST 2011]

$\Rightarrow \frac{M}{n_e} = \frac{5 - 2f_\alpha}{2(1 - f_\alpha)}$
 $\frac{n_i}{n_e} = \frac{1 - 2f_\alpha}{2}$...

Finding suitable (R,B) solutions - ITER

ITER target: $P_{fus} = 500$ MW, $Q=10$

► 4 unknowns (R, B, f_G, β_N) , 2 equations
 \Rightarrow some freedom (here, $f_G=0.85$)

► Additional constraints:

- Power flux on target plates
- Magnets \rightarrow "Radial Built"
- Duration of inductive plateau current [Duchateau, FED 2014]

► Using **IPB98(y,2) scaling law**
 \rightarrow ITER specifications are recovered [ITER Physics basis, NF 1999]

► Using **DS03 scaling law** [Petty PoP 2004, Sips NF 2018]
 \rightarrow lower B, higher β_N

\Rightarrow Possible issue: disruption threats

DEMO should operate at large β_N if DS03 holds

EU-DEMO target: $P_{fus} = 2.037$ GW, $Q=40$ [Wenninger, NF 2017]

► Typical parameters are recovered with **IPB98(y,2) scaling law**:
 $R \sim 9.1$ m, $B \sim 5.6$ T, $\beta_N \sim 2.2$

► Much larger β_N with **DS03 scaling law**:
 $R \sim 9.1$ m, $B \sim 4.2$ T, $\beta_N \sim 3.8$

Challenging in a reactor which aims at 0 disruption

► Much larger B with **ITPA20 scaling law**:
 $R \sim 9.1$ m, $B \sim 7.0$ T, $\beta_N \sim 1.4$ [Verdoolaege NF 2021]

What aspect ratio for DEMO? A scan @ $R=Cst$

► Aspect ratio $A=R/a$

- Central design parameter (plasma stability, disruption forces, tritium breeding, maintenance, cost, ...)
- Some freedom in its choice

► Opposite scalings of τ_E

IPB98(y,2): $\omega_c \tau_E \sim A^{-0.73}$
 DS03: $\omega_c \tau_E \sim A^{+1.30}$
 ITPA20: $\omega_c \tau_E \sim A^{+1.70}$

► Favorable scaling of with A does **NOT** guarantee the advantage of working at large A

► Assuming prescribed $R=9.1$ m

- B increases with A
- Cost \sim Volume $\times B^2$ increases with A

What aspect ratio for DEMO? A scan $\beta_N @ Cst$

► Assuming prescribed β_N :

- Opposite trends for R, B, Volume and "Cost"

\Rightarrow No clear conclusion

Conclusions

► Development of the **simple and comprehensive 0D model SCALA** for tokamak design (DEMO) + performance evaluation (ITER)

► ITER and DEMO characteristics are recovered when using IPB98(y,2) scaling law \rightarrow robustness of the approach

► To achieve the same performance (Q, P_{fus}):

- DS03 scaling law requires to operate at larger β_N
- ITPA20 scaling law requires to operate at larger B

► Increase of $\omega_c \tau_E$ with aspect ratio $A=R/a$ DOES NOT automatically imply that large A tokamaks should be favored

► Scaling laws leave unclear the benefit of large/small A
 \rightarrow consolidate scaling laws with $A \neq 3$ (e.g. WEST data $A \sim 5$)