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Impact of the aspect ratio on tokamak reactor design

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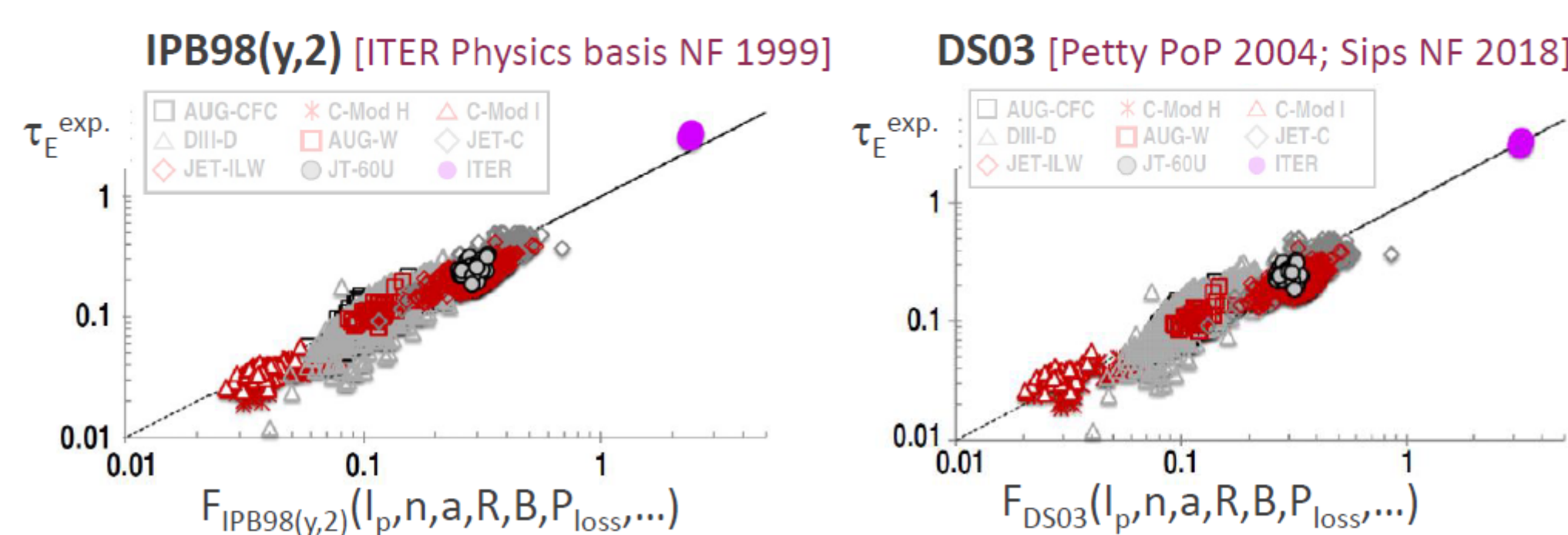
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Context - motivations

► 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 $A=R/a$)



► What **impact on Tokamak design** ?

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

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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)

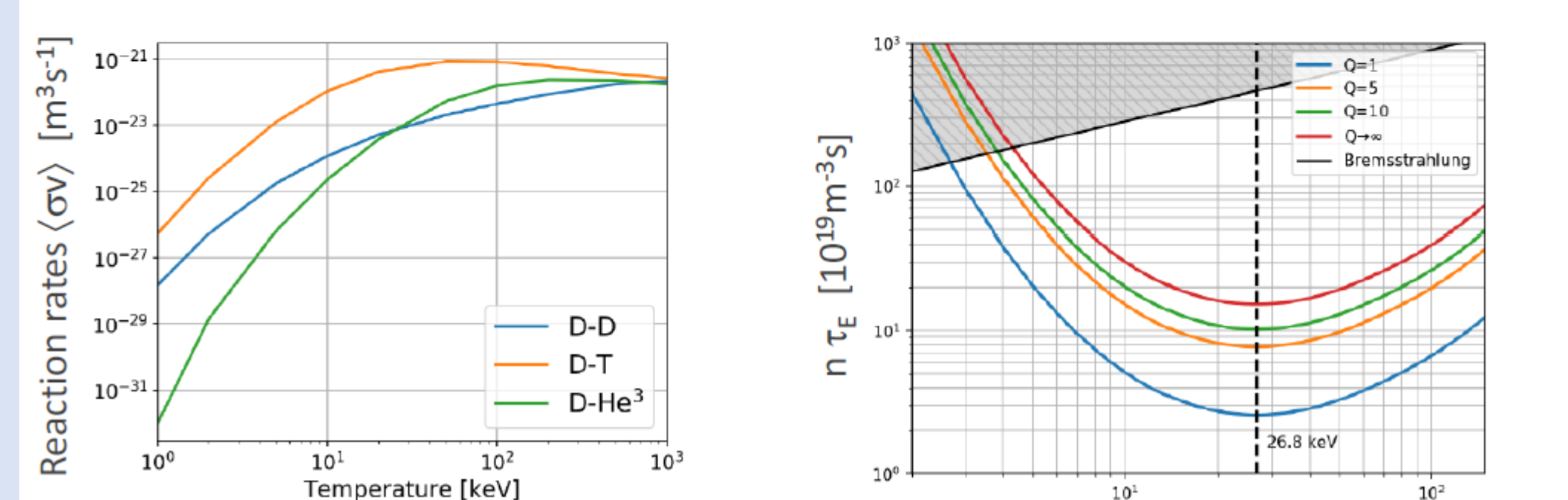
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Constitutive relations: P_{fus}

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

$$n_D n_T = \frac{n^2}{4} \quad \langle \sigma v \rangle_{DT} \sim T^2 \quad (\text{if } 10.3 < T < 18.5 \text{ keV, alternatives otherwise})$$

[Collection CEA, 1987]



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Constitutive relations: $Q \dots$ hence τ_E

$$Q = \frac{P_{fus}}{P_{add}} \quad \left\{ \begin{array}{l} P_{fus} = P_\alpha + P_n = \lambda P_\alpha \quad \lambda \approx 4.94 \\ P_{net} = P_\alpha + P_\Omega + P_{add} - P_{rad} = \gamma_{rad} (P_\alpha + P_{add}) \end{array} \right.$$

$$\Rightarrow P_{net} = \gamma_{rad} P_{fus} \frac{1 + Q/\lambda}{Q}$$

Simplification:
 $P_{rad} = (1 - \gamma_{rad})(P_\alpha + P_{add})$
 $0 \leq \gamma_{rad} \leq 1$

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

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

$$\Rightarrow nT\tau_E \sim \frac{Q}{1 + Q/\lambda}$$

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

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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 $I_p \sim \frac{RB}{q}$

$$\Rightarrow n_N = \frac{n}{n_G} \sim \frac{qRn}{B}$$

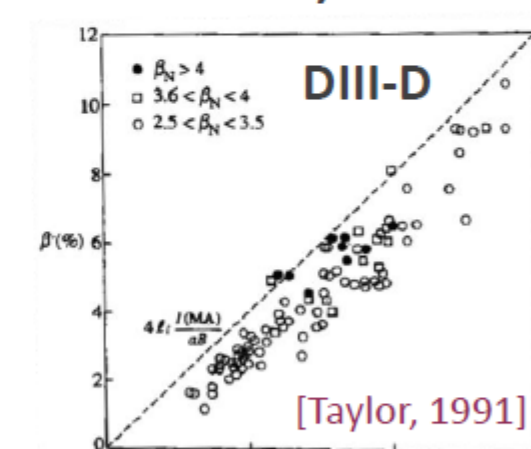
[Greenwald, NF 1988, PPCF 2002]

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



[Taylor, 1991]

► **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

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Final relations of the SCALA model

[Sarazin NF 2020]

► 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: $f_p = \langle T^2 \rangle / \langle T \rangle^2$
 - Different T_e & T_i : $\theta_i = T_i/T_e$
 - Geometry of poloidal cross-section [Johner, FST 2011]
- $$\Rightarrow \frac{M}{n_e} = \frac{5 - 2f_\alpha}{2(1 - f_\alpha)}$$
- $$\frac{n_i}{n_e} = \frac{1 - 2f_\alpha}{2}$$
- ...

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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**

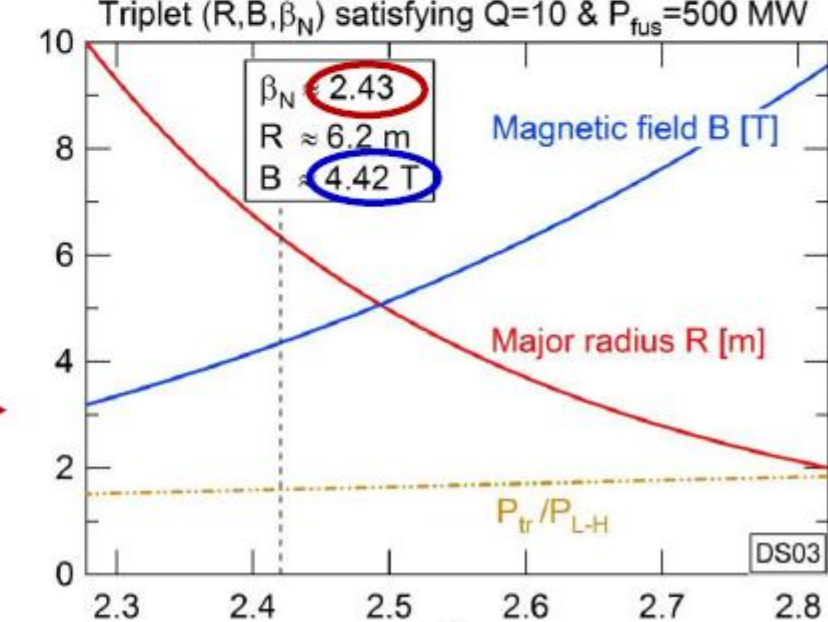
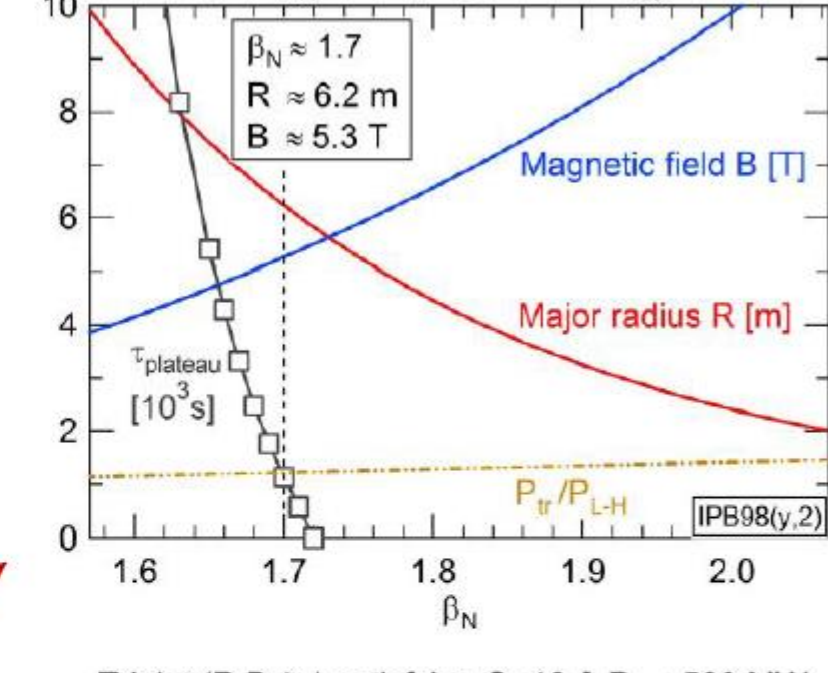
\rightarrow ITER specifications are recovered [ITER Physics basis, NF 1999]

► Using **DS03 scaling law** [Petty PoP 2004, Sips NF 2018]

\rightarrow lower B, higher β_N

\Rightarrow Possible issue: disruption threats

Triplet (R, B, β_N) satisfying $Q=10$ & $P_{fus}=500$ MW



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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 $\beta_N \sim 3.8$

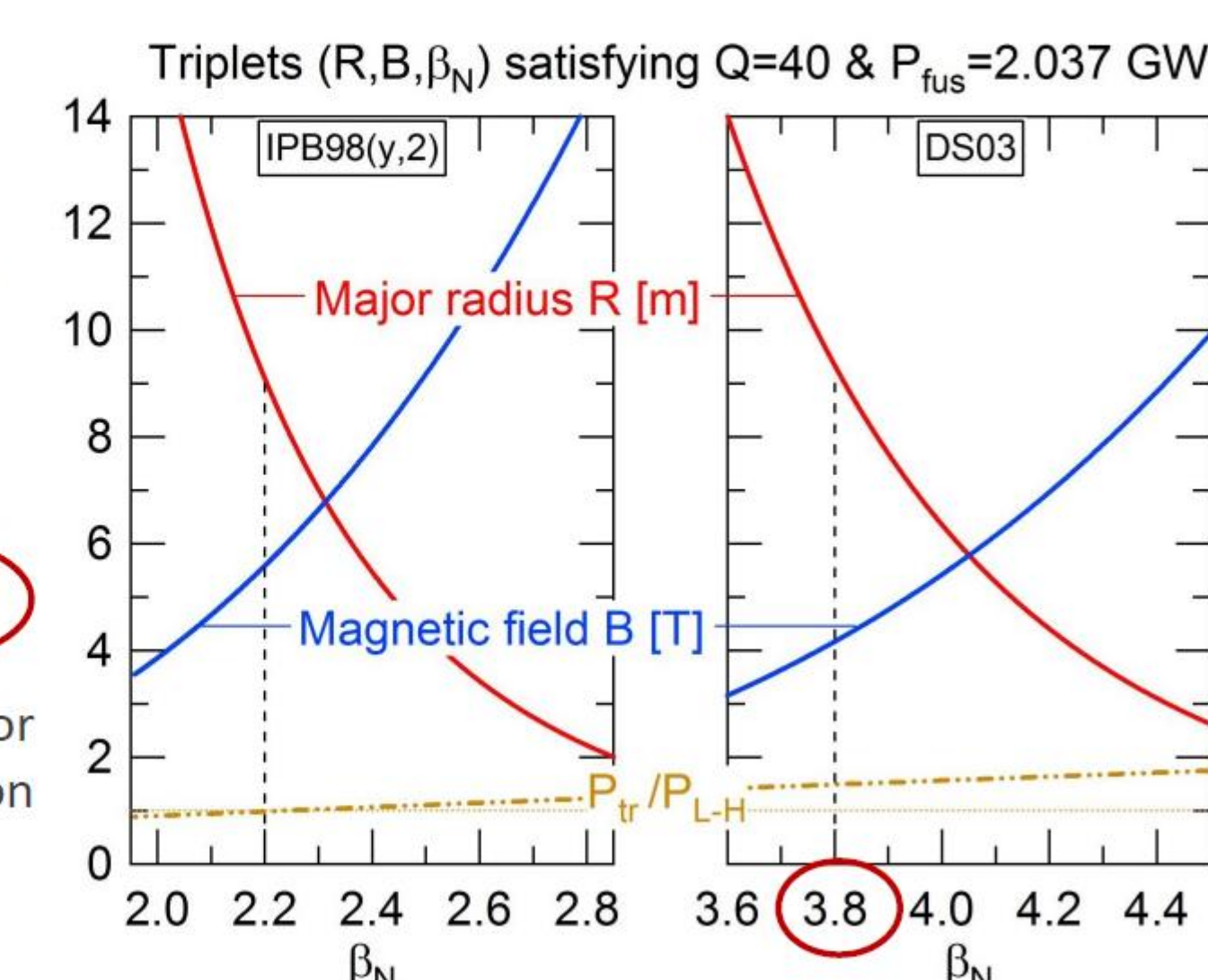
Challenging in a reactor which aims at 0 disruption

► 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]



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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: $\omega_c \tau_E \sim A^{+1.30}$

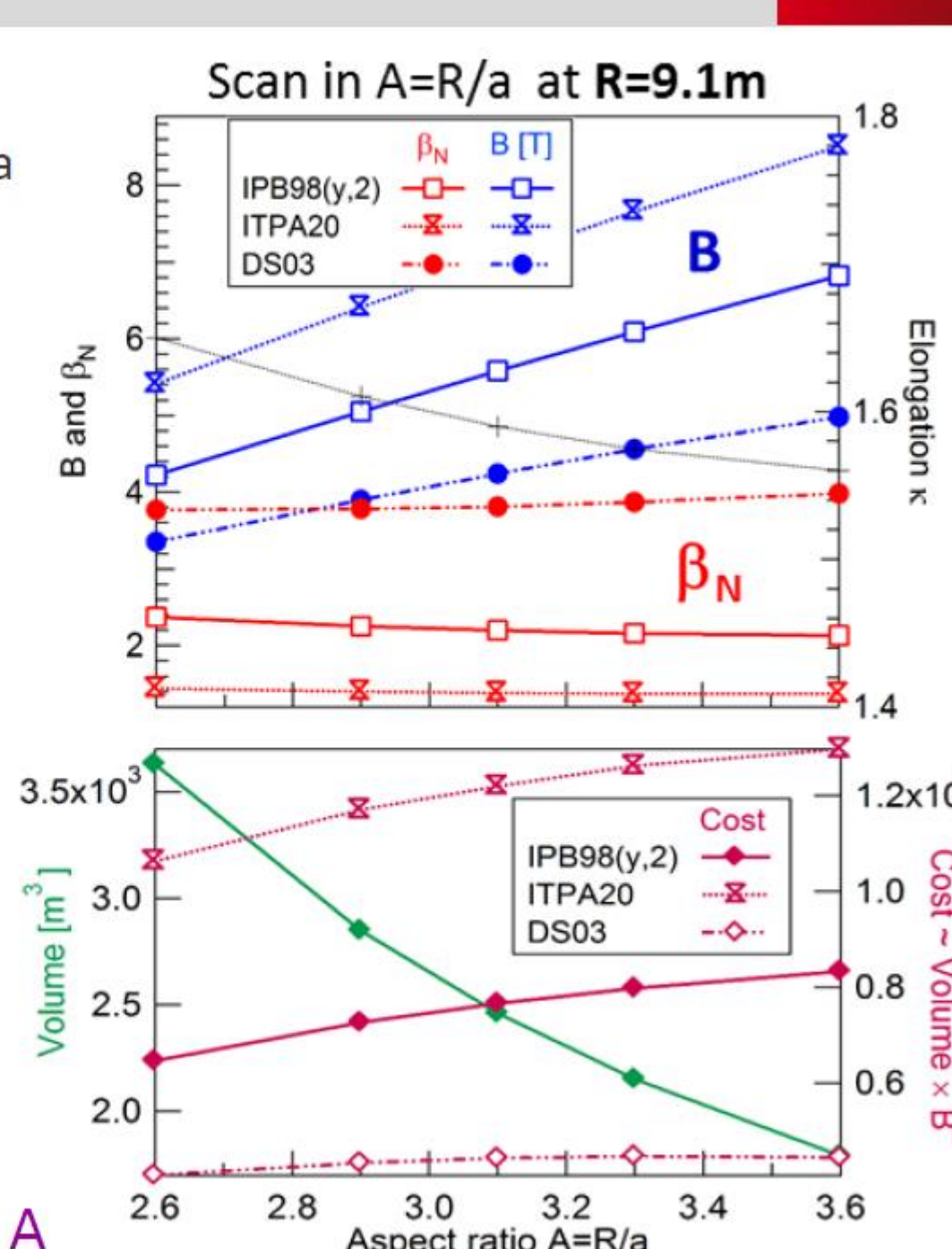
ITPA20: $\omega_c \tau_E \sim A^{+1.70}$

► 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

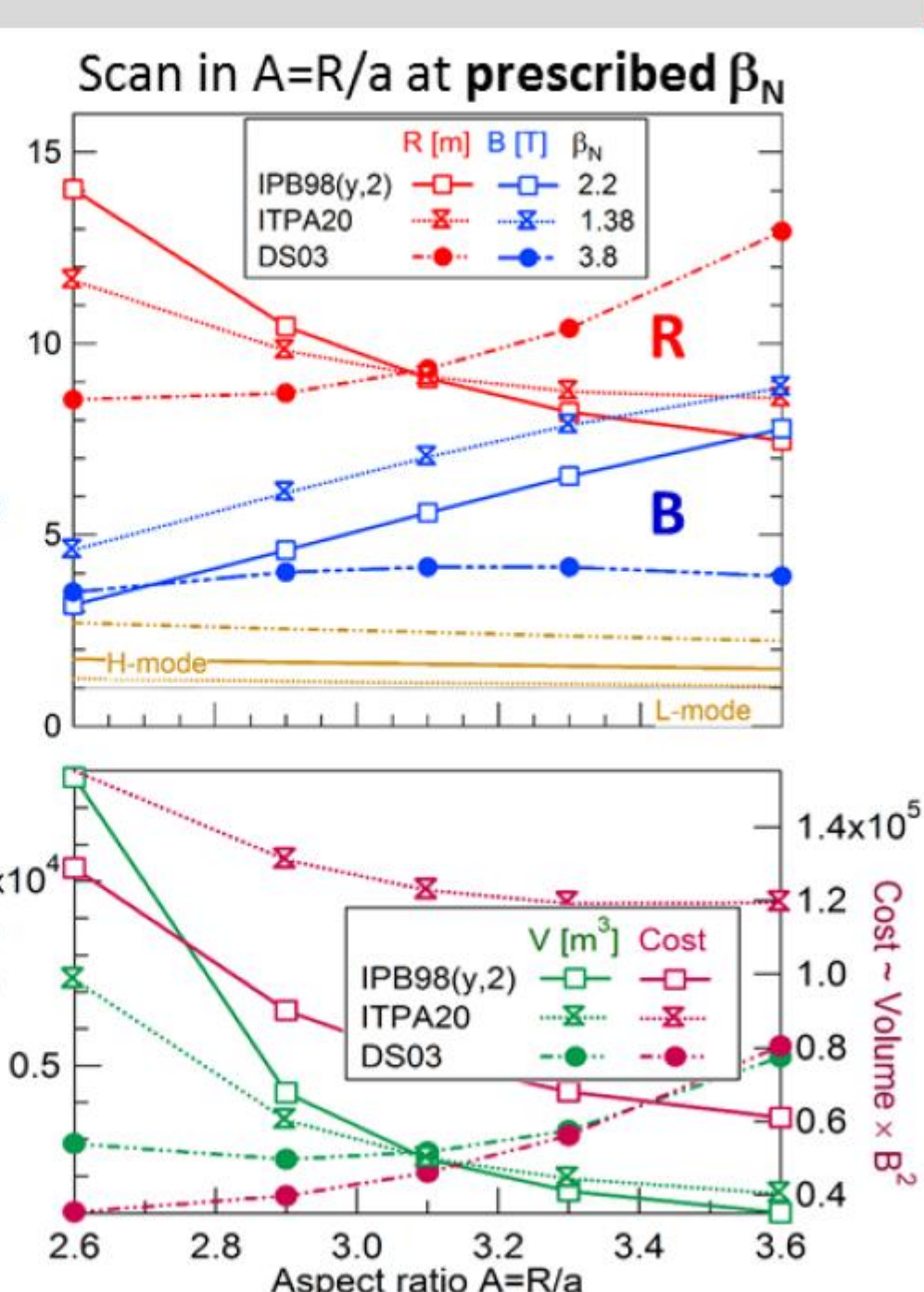


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What aspect ratio for DEMO ? A scan $\beta_N @ Cst$

- Assuming prescribed β_N :
- Opposite trends for R, B, Volume and "Cost"

\Rightarrow No clear conclusion



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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 $A \sim 5$)

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