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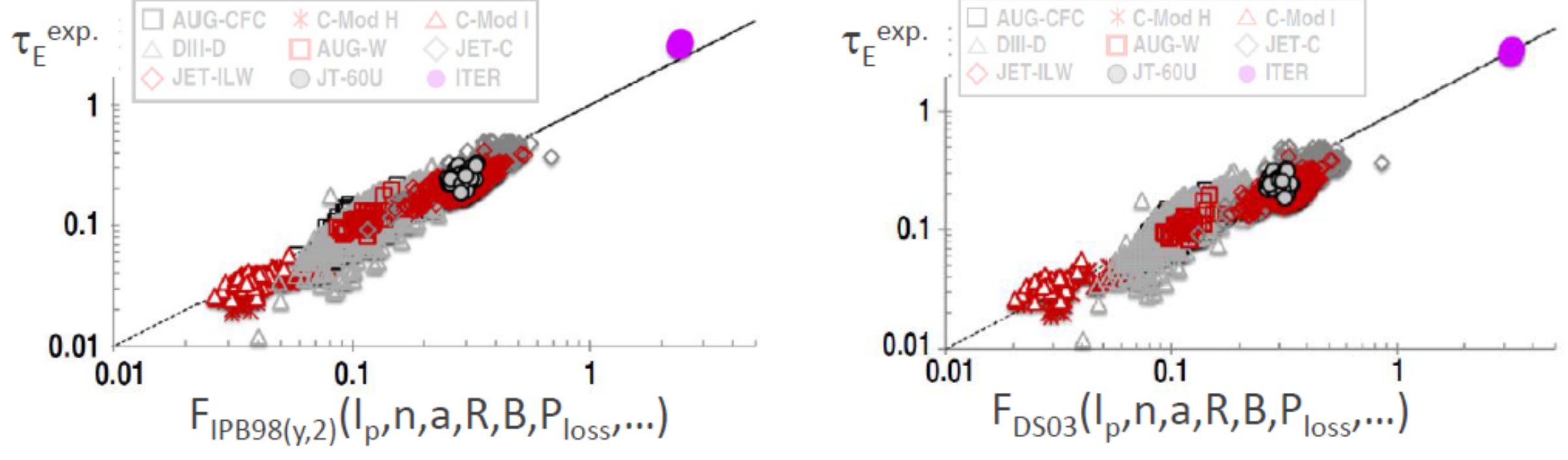
Impact of the aspect ratio on tokamak reactor design

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 × volume ~ $B^2 R^3$)
- The SCALA (**SCA**ling **LA**ws) comprehensive physical approach: [Sarazin NF 2020]
  - Essentially 0-dimensional + peaking factors
  - 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 → 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}

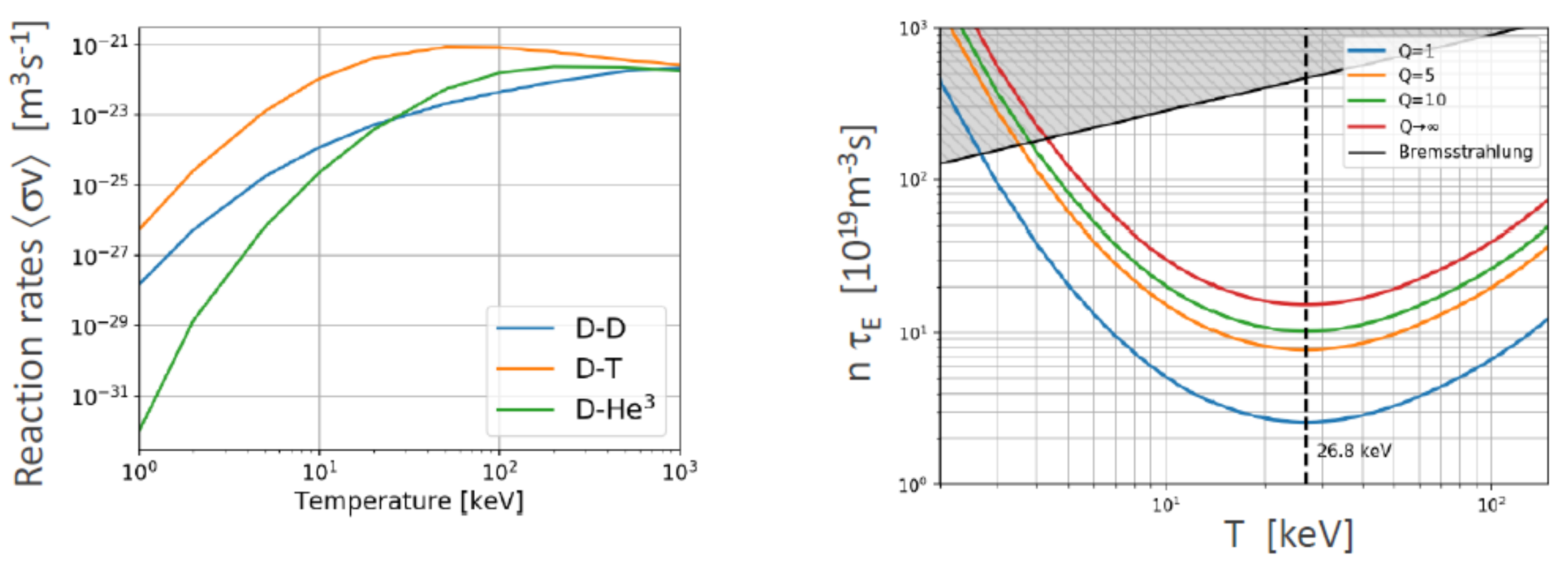
- $P_{fus} = \underline{n_D n_T} \, \underline{\langle\sigma v\rangle_{DT}} \, E_{DT} \mathcal{V} \longrightarrow \boxed{P_{fus} \sim R^3\, n^2 T^2}$

Simplifications

Volume of the torus

$$n_D n_T = \frac{n^2}{4} \qquad \langle\sigma v\rangle_{DT} \sim T^2$$

(if 10.3<T<18.5 keV, alternatives otherwise)
[Collection CEA, 1987]



Constitutive relations: Q … hence τ_E

- $Q \doteq \dfrac{P_{fus}}{P_{add}}$

$$P_{fus} = P_\alpha + P_n = \lambda\, P_\alpha \qquad \lambda \approx 4.94$$
$$P_{net} \doteq P_\alpha + P_\Omega + P_{add} - \underline{P_{rad}} \doteq \gamma_{rad}(P_\alpha + P_{add})$$

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

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

- Link with τ_E → triple product

$$\tau_E = \frac{3nT\mathcal{V}}{P_{loss} - P_{rad}} \sim \frac{nTR^3}{P_{net}}$$
$$\Rightarrow \boxed{nT\tau_E \sim \frac{Q}{1+Q/\lambda}}$$
$$\downarrow$$

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

n and T constrained by plasma physics

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

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

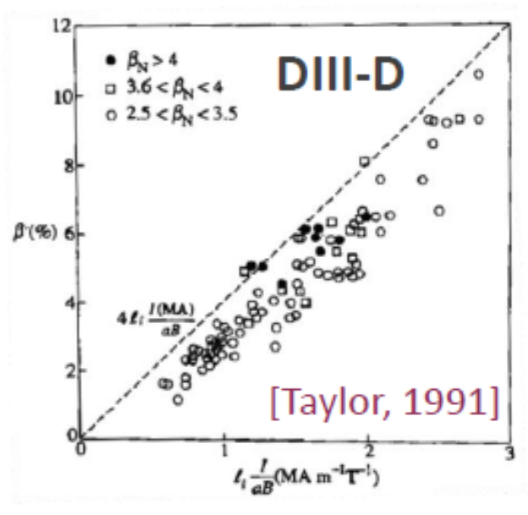
$$\Rightarrow \boxed{n_N = \frac{n}{n_G} \sim \frac{qR\,n}{B}}$$

[Greenwald, NF 1988, PPCF 2002]

No definitive understanding – evidence of plasma boundary effect

- **Beta limits** → critical β_N: $\beta_N = \beta_\% \dfrac{aB}{I_p}$

$$\beta_\% \sim \frac{nT}{B^2} \quad \Rightarrow \quad \boxed{nT \sim \frac{B^2}{q}\beta_N}$$



[Taylor, 1991]

Not specific (stability is profile and mode dependent)
Yet useful for a compact & analytic beta limit [Wesson 2004]

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

Final relations of the SCALA model

[Sarazin NF 2020]

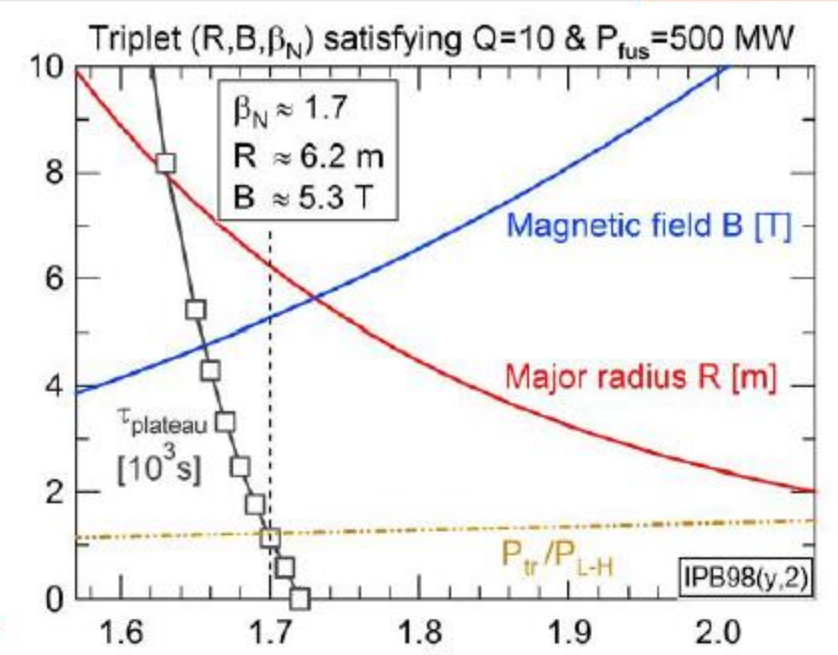
- From **scaling Law** $\boxed{\left(\dfrac{Q}{1+Q/\lambda}\right)^{\gamma_Q} \sim n_N^{\alpha_n} \beta_N R^{\gamma_R} B^{\gamma_B}}$
- From def. of **P_{fus}** $\boxed{P_{fus} \sim \beta_N^2 R^3 B^4}$
- Accounting for **refinements**:
  - Fraction f_α of α particles: $f_\alpha \doteq n_{\rm He}/n_e$
  - Temperature peaking factor: $f_p \doteq \langle T^2\rangle / \langle T\rangle^2$
  - Different T_e & T_i: $\theta_i \doteq T_i/T_e$
  - Geometry of poloidal cross-section [Johner, FST 2011]

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

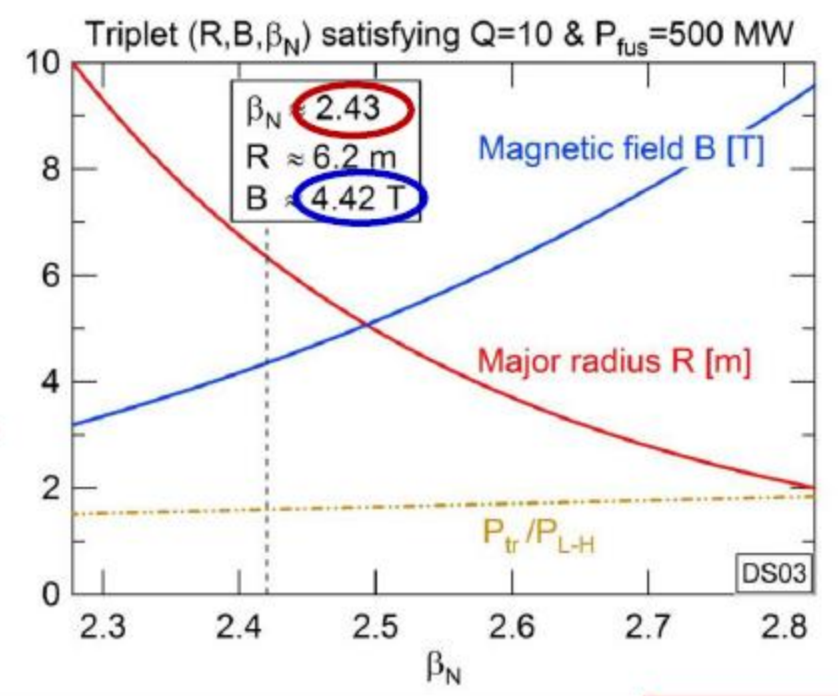
Finding suitable (R,B) solutions - ITER

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

- 4 unknowns (R,B,f_G,β_N), 2 equations
  ⇒ some freedom (here, f_G=0.85)
- Additional constraints:
  - Power flux on target plates
  - Magnets → "Radial Built"
  - Duration of inductive plateau current [Duchateau, FED 2014]



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

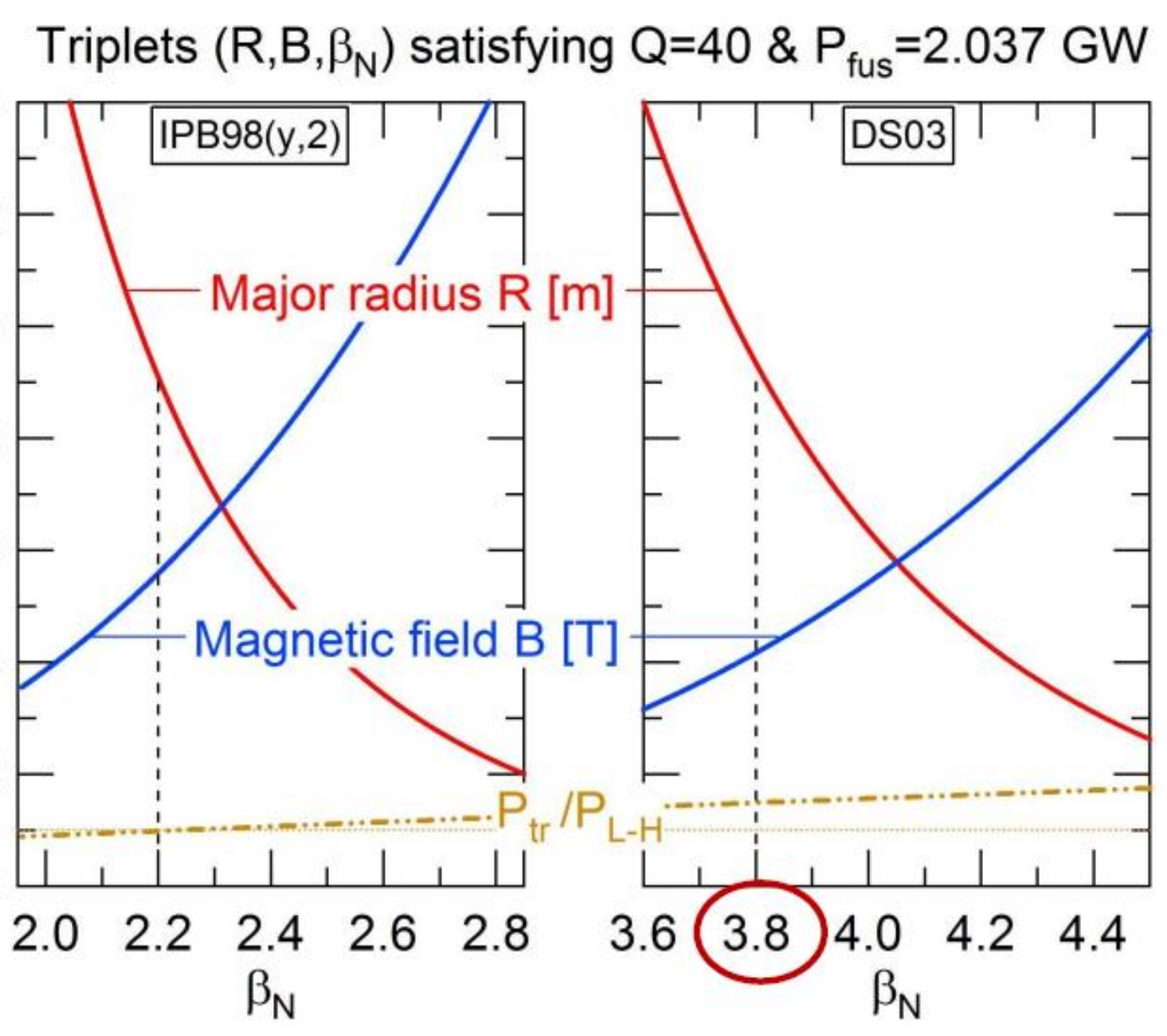


- Using **DS03 scaling law** [Petty PoP 2004, Sips NF 2018]
  → lower B, higher β_N
  ⇒ Possible issue: disruption threats

DEMO should operate at large β_N if DS03 holds

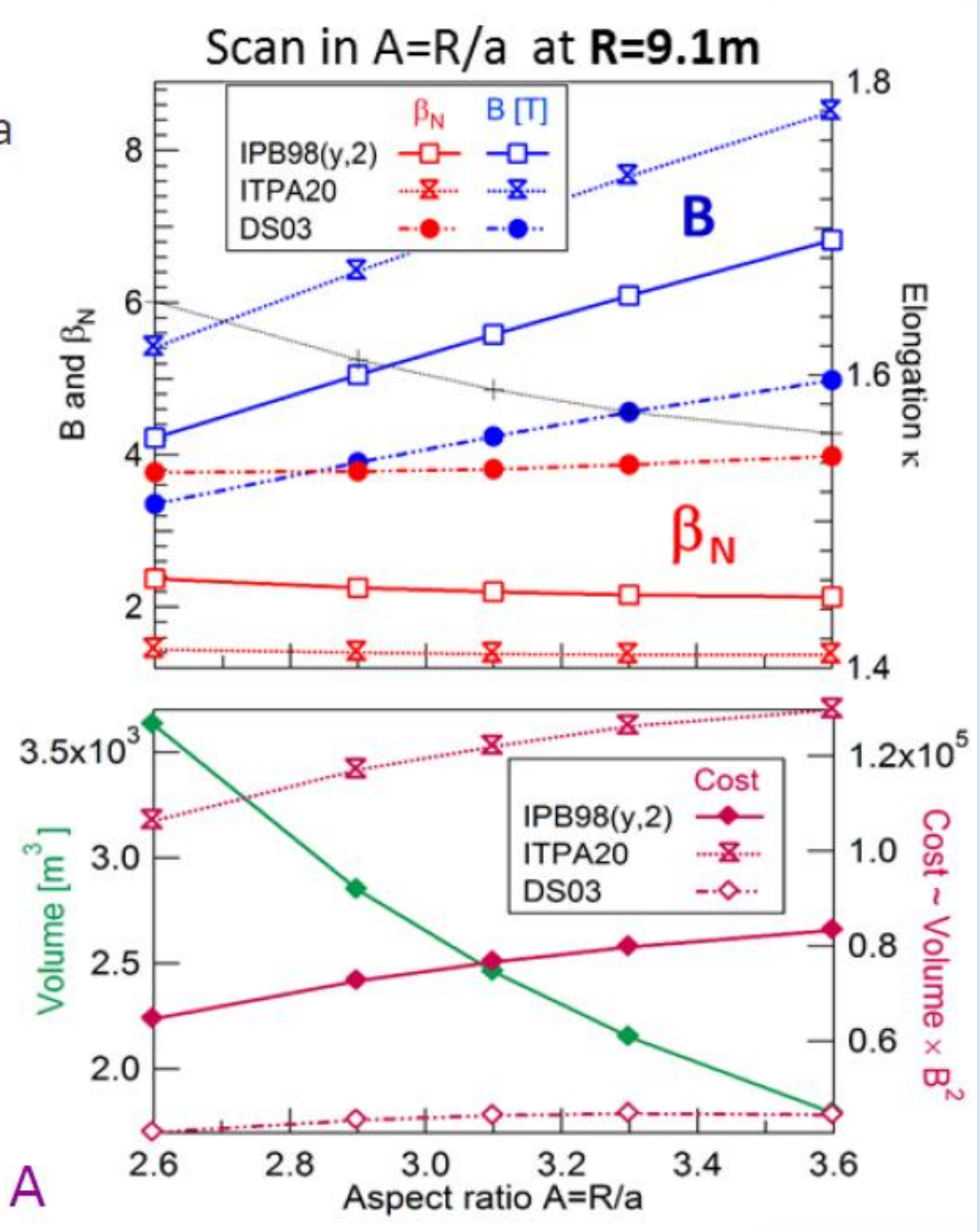
EU-DEMO target: P_{fus}=2.037 GW, Q=40 [Wenninger, NF 2017]

- Typical parameters are recovered with **IPB98(y,2)** scaling law:
  R~9.1m B~5.6T β_N~2.2
- Much larger β_N with **DS03** scaling law:
  R~9.1m B~4.2T β_N~3.8
  Challenging in a reactor which aims at 0 disruption
- Much larger B with **ITPA20** scaling law:
  R~9.1m B~7.0T β_N~1.4 [Verdoolaege NF 2021]



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

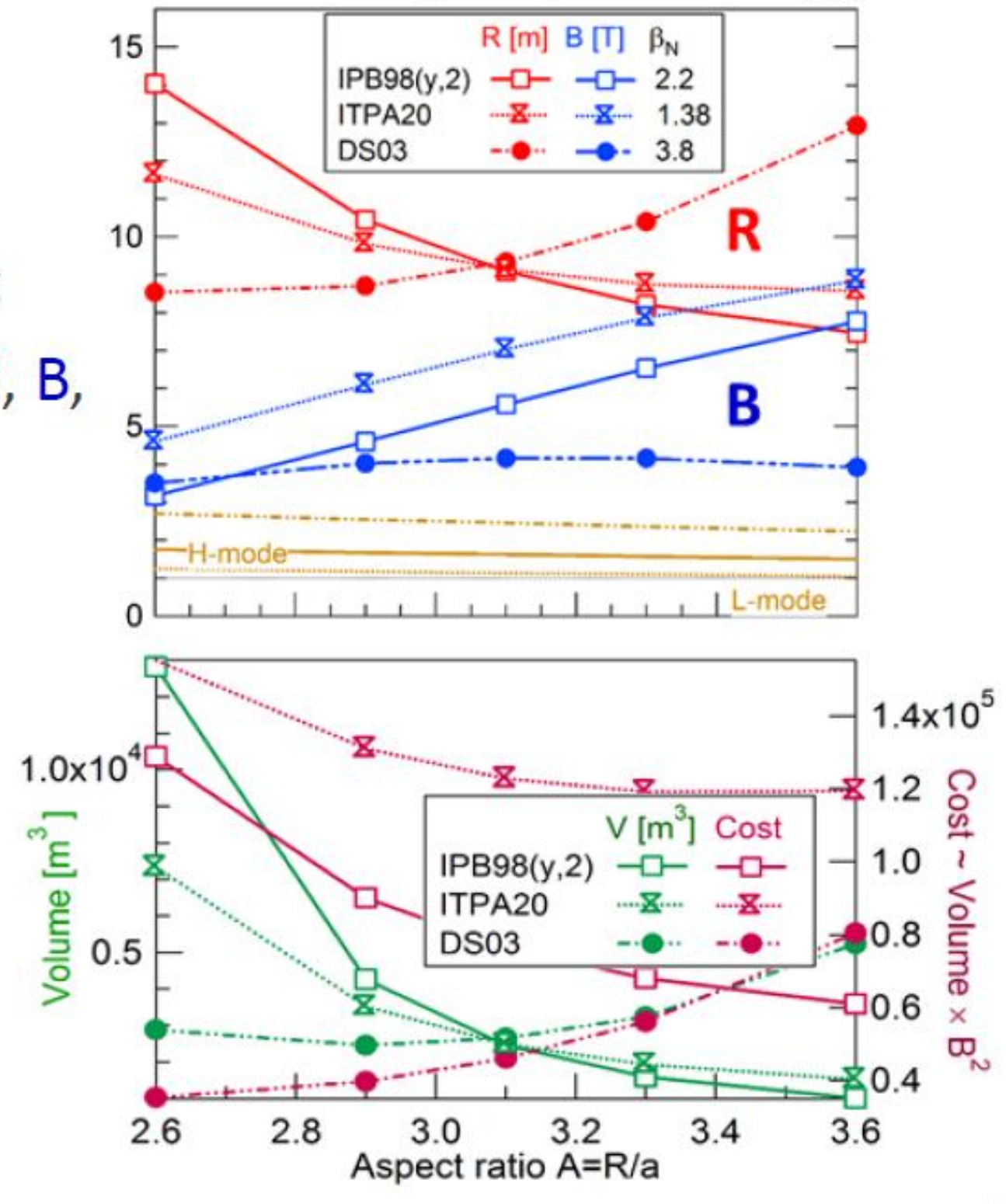
- Aspect ratio A=R/a
  - Central design parameter (plasma stability, disruption forces, tritium breeding, maintenance, cost, …)
  - Some freedom in its choice
- Opposite scalings of τ_E
  IPB98(y,2): $\omega_c\tau_E \sim A^{-0.73}$
  DS03: $\omega_c\tau_E \sim A^{+1.30}$
  ITPA20: $\omega_c\tau_E \sim A^{+1.70}$
- Favorable scaling of with A does NOT guarantee the advantage of working at large A
- Assuming **prescribed R**=9.1m
  - B increases with A
  - Cost~Volume×B² increases with A



What aspect ratio for DEMO ? A scan β_N@ =Cst

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

⇒ 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 → 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
  → consolidate scaling laws with A≠3 (e.g. WEST data A~5)