An approach towards different design options for DEMO: Pulsed (conservative) versus steady-state (advanced) tokamak

w.biel@fz-juelich.de

Wolfgang Biel | Institute of Energy and Climate Research | Forschungszentrum Jülich GmbH | Germany

Development of 2 DEMO tokamak „working models“ for the German DEMO working group

- DEMO working models to serve as reference basis for the 13 sub-groups
- 2 tokamaks (pulsed vs. steady state) and 1 stellarator (see talk by C Beidler)
- Tokamak target requirements:

1) „Conventional“ pulsed DEMO tokamak (conservative, low complexity)
   - *output power 1 GW_{el}*
     → accessing the economic parameter range for a power plant
   - *pulse duration many hours*
     → minimising impact of cyclic loads
   - *low or zero HCD level*
     → minimising recirculating power
     → minimising development needs for HCD system
   - *physics and technology as of today*

2) „Advanced“ steady-state DEMO tokamak
   - *output power 1 GW_{el}*
   - *steady state via BS and HCD*
   - *moderate extrapolation in physics and technology*

0-D tokamak reactor model

Main elements:

- Fusion power calculated using the IBP98(y,2) confinement scaling

$$\tau_E / s = 0.173\, H_H I_M^{0.93}\ R_0^{1.39}\ a^{0.58}\ \kappa^{0.78}\ n_{20}^{0.41}\ B_0^{0.15}\ P_M^{-0.69}$$

- Pulse duration (OH and non-inductive)
- Heat + particle exhaust model to adjust divertor power and core radiation
- simple CoE estimation $CoE \sim V_{tokamak} / P_{electr.}$

Benchmarking: Fair agreement with

- Model by H. Zohm
- DEMO PPPT 2011 benchmark case (D. Ward, J. Johner)
- European PPCS-A study (D. Maisonnier NF 2007)

In this analysis, only the quantities marked in red are used as variables.

- Different sets of these parameters are chosen for the pulsed + steady-state case

Input data		Output data
R_0 / m		
a / m		
b = 1.8 m		c / m
κ , δ		f_{shape}
B_{max} = 13 T		B_0 / T
q_{95}		I_p / MA
$N_{GW} = n/n_{GW}$		n_e
$H_{H(IBP89\ y,2)}$		τ_E
τ_α^*/τ_E = 5		c_{He}
c_N = 0.01		c_{Ar}
$c_W = 5 \times 10^{-5}$		Z_{eff}
(P_{ext} / MW)	(or)	(P_{ext} / MW)
η_{therm} = 0.35		P_{therm} / MW
η_{HCD} = 0.4		P_{electr} / MW
		P_α / MW
		P_{Div} / MW
		$P_{Core,rad}$ / MW
		T_e=T_i / keV
		Q
		β_N, β_{pol}
		t_{pulse} / h
		$q_{Neutron}$ / MW/m^2

Boundary conditions and assumptions

Plasma current:	$q_{95} = 5 \frac{a^2 B_0}{I_M R_0} f \geq 3$	(safety factor)
Plasma density:	$N_{GW} \equiv \frac{n}{n_{GW}} = \frac{\pi a^2 n_{20}}{I_M} \leq 1.2$	(Greenwald, Angioni)
Plasma pressure:	$T_k \leq 0.39 \beta_{N,\max} \frac{B_0 a}{N_{GW}}$	(beta limit)
Plasma shaping:	$\kappa = 1.6 + 0.6 \frac{a}{R_0} ; \quad \delta = \frac{\kappa - 1}{2}$	(vertical stability)
Blanket thickness:	$b = 1.8 m$	(distance separatrix – TF coil)
Magnetic field:	$B_{\max} = 13 T$	(for TF coils and CS coil)
these determine B_0:	$B_0 = B_{\max} \left(1 - \frac{a+b}{R_0} \right)$	(magnetic field at $R = R_0$)
TF radial build:	$c = (a+b)/4$	(after J. Freidberg)

Power and particle exhaust

Power balance:

$$P_{Heat} = P_\alpha + P_{ext} + P_{OH} = P_{Sync} + P_{ImpRad,core} + P_{Rad,edge} + P_{Div}$$

$$P_{Sep} = P_{Rad,edge} + P_{Div} > 1.3 P_{LH} \approx 2.2\, n_{20}^{0.78} B_0^{0.77} a^{0.98} R_0^{1.00}$$ (Y. R. Martin)

$$P_{Rad,edge} \approx P_{Matthews} - P_{ImpRad,core}$$

$$P_{Matthews} = 2.08 \left(Z_{eff} - 1\right)\left(1+\kappa\right) a\, R_0\, n_{20}^2$$ (Argon)

Assume that 2/3 of the divertor power is radiated:

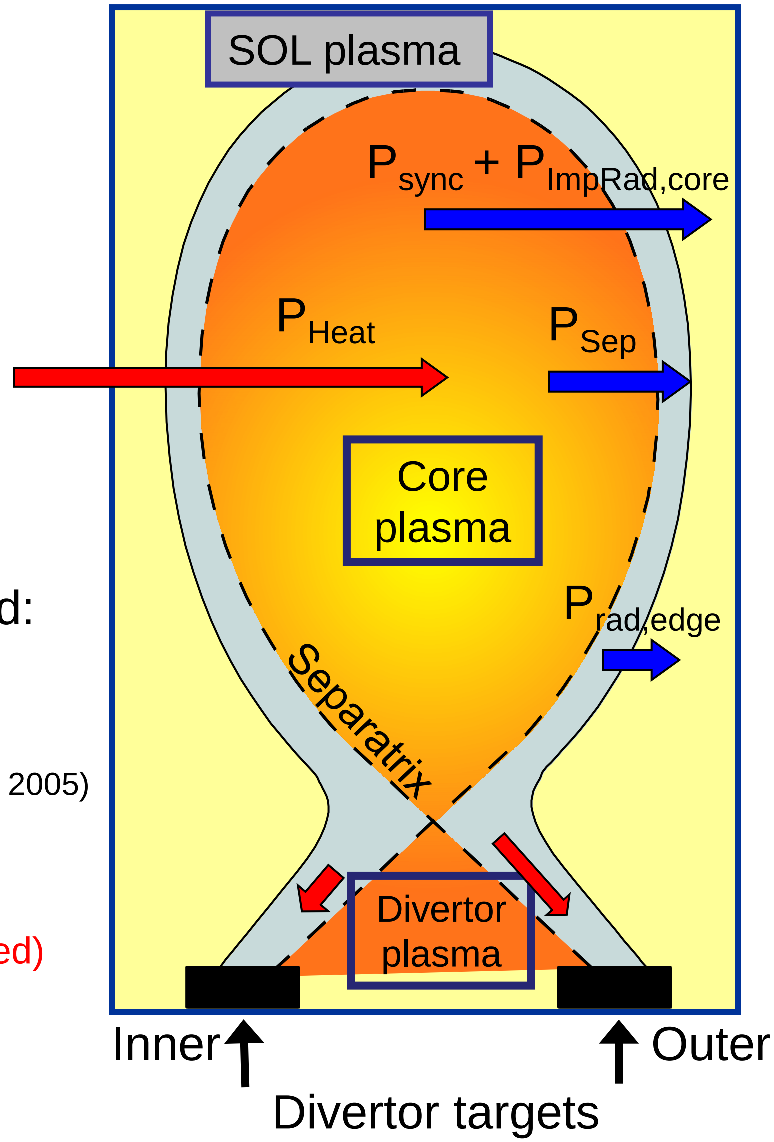
$$P_{Div} \approx 3 \times 1.5\, q_{\max}\, F_x\, \lambda_q\, 2\pi R_0$$ (D. Reiter, V. Kotov)

$$\lambda_q = 0.0008 \times R_0$$ (A. Kallenbach, J. Nucl. Mat. 2005)

$$F_x = 10$$

$$q_{\max} = 5\, MW/m^2$$ (q_{max} = 3 MW/m^2 preferred)

Particle exhaust: $\tau_\alpha^* / \tau_E = 5$



Heating and current drive / pulse duration

Pulse duration:

$$t_{Pulse} \approx \frac{\Phi_{CS} + \Phi_{BV} - \Phi_{ignition} - \left(\varepsilon_{ejima}\,\mu_0 R_0 + L_{plasma}\right) I_{Plasma}}{R_{Plasma}\; I_{Plasma}\left(1 - f_{BS} - f_{CD}\right)}$$

Bootstrap current:

$$f_{BS} = 0.7\sqrt{\frac{1}{A}}\,\beta_{pol}$$

Current drive:

$$\frac{I_{CD}[MA]}{P_{Ext}[MW]} = \gamma_{CD}(T) \cdot \frac{1}{n_{20} \cdot R_0}$$

using $\gamma_{CD}(T) = 0.4\,\frac{T / keV}{15}$ and $\eta_{CD} = 0.4$

(aiming for ECRH)

Plant power balance:

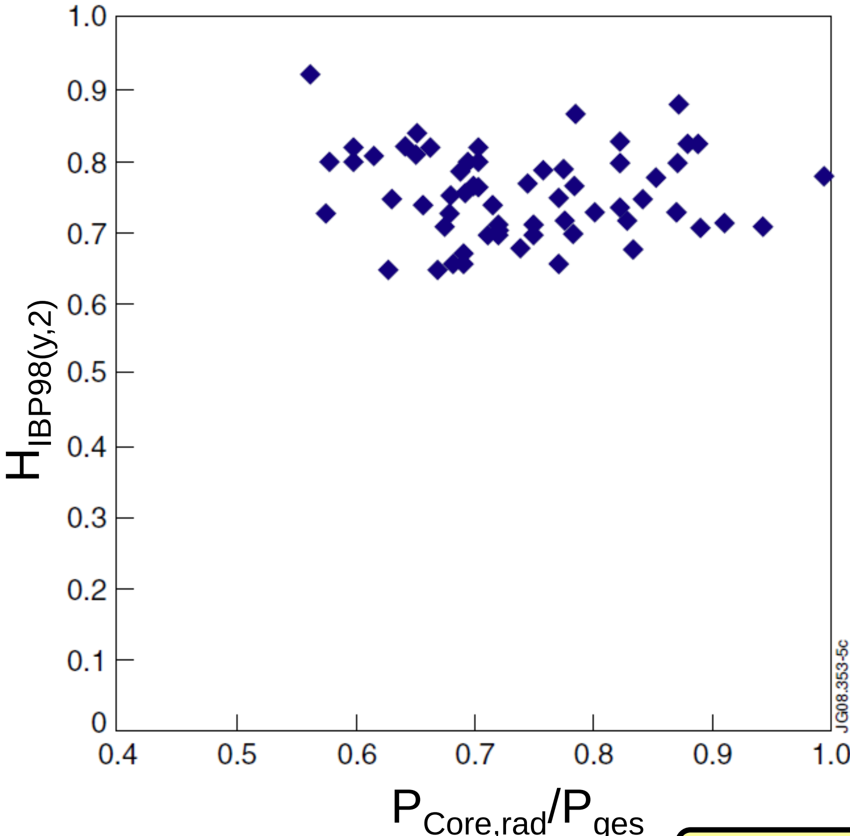
$$P_{el} = \eta_{th}\left(1.18 P_{Fus} + P_{HCD} + P_{OH}\right)$$

using $\eta_{th} = 0.35$ (conservative, leaving room for He cooling power)

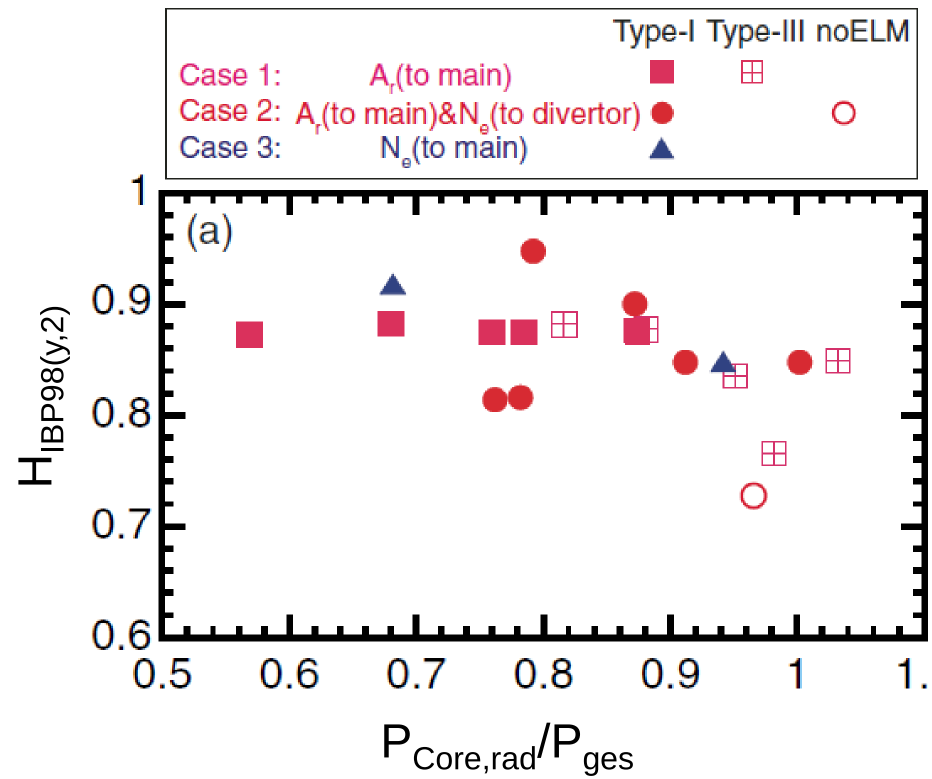
Radiative H mode: Plasma scenario for the „conservative“ pulsed DEMO tokamak

Experimental results from JET and JT-60-U:

JET (J. Rapp Nucl. Fusion 2009)



JT-60U (N. Asakura Nucl. Fusion 2009)

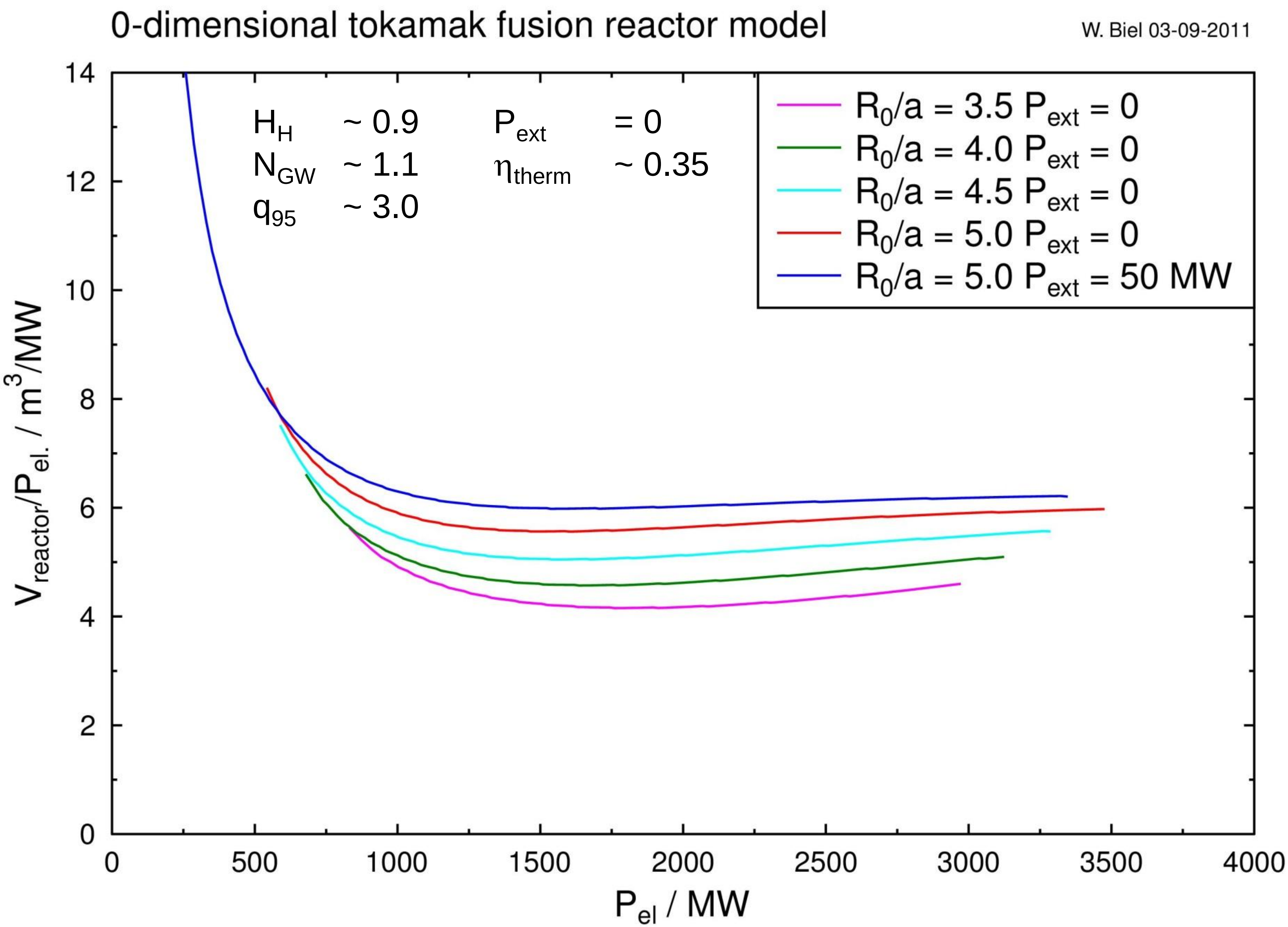


taking into account radiation explicitely → H_H = 0.9

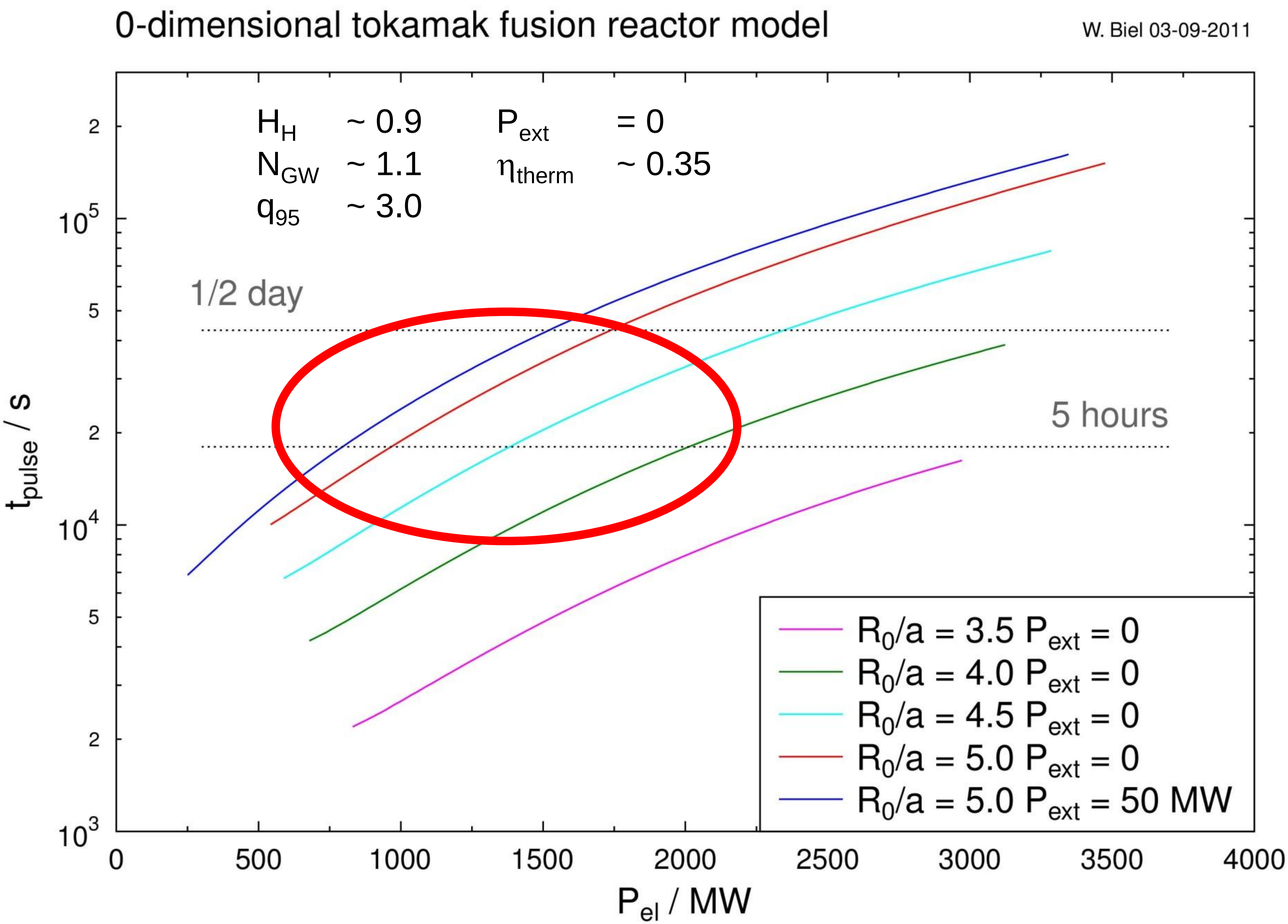
Summary of results:

- consistent parameter set $H_H = 0.85$ with $N_{GW} = 1.0$ and $P_{core,rad}/P_{ges} = 0.6 \ldots 0.9$
- ELM size strongly reduced (Type III ELMs)

Pulsed tokamak: „Cost of Electricity (CoE)“



Pulsed tokamak: Plasma pulse duration



Parameter range for pulsed tokamak DEMO model (P_{el} = 1 GW, R_0/a = 5, κ = 1.72, δ = 0.36, P_{ext} = 0)

H_H	n/n_{GW}	q_{95}	a /m	R_0 /m	CoE	$q_{neutron}$ /MW/m^2	$P_{RadCore}/P_{Heat}$	T_{pulse} /h
0.9	1.1	3.0	2.25	11.25	5.9	1.87	0.56	5.3
0.85	1.0	3.2	2.62	13.10	8.1	1.38	0.56	9.0

Approach for pulsed tokamak DEMO

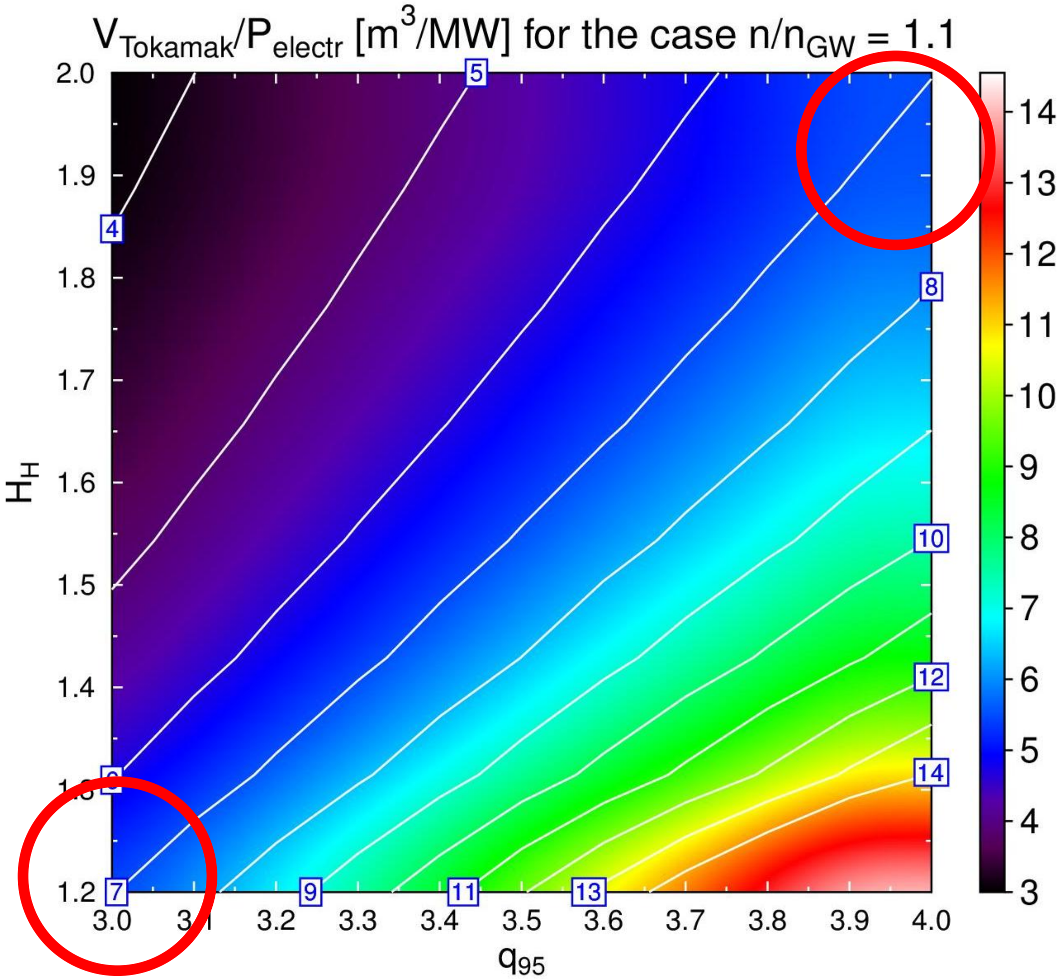
- choose large aspect ratio to allow for large CS coil and long pulse duration
- operate near the maximum possible n/n_{GW} and plasma current (low q_{95})
- External heating essential only for start-up

Main properties

- minor radius a ~ 2.2 m .. 2.6 m, 10% .. 30% larger than ITER
- pulse duration several hours, inductive drive
- moderate plasma core radiation, q_{max} = 5 MW/m^2

Steady state tokamak solutions:
N_{GW} = 1.1, $P_{electr,net}$ = 1 GW, R_0/a = 3, κ = 1.8, δ = 0.4

$$CoE \sim V_{tokamak} / P_{electr,net}$$



2 different possible approaches with comparable performance:

- Advanced scenario with q_{95} = 4 (q(r) > 2 everywhere) and very high confinement (H_H > 1.6)
- Standard H mode with q_{95} = 3 and somewhat improved confinement (H_H = 1.2)

Parameter range for steady-state tokamak DEMO model (P_{el} = 1 GW, R_0/a = 3, κ = 1.8, δ = 0.4)

H_H	n/n_{GW}	q_{95}	a /m	R_0 /m	CoE	$q_{neutron}$ /MW/m^2	$P_{RadCore}/P_{Heat}$	T_{pulse} /h
1.6	1.2	4.0	3.2	9.6	7.1	2.3	0.70	∞
1.2	1.1	3.0	3.16	9.5	6.9	3.07	0.68	∞

Optimisation strategy for steady-state tokamak

- Two different routes:
  - either advanced tokamak with q_{95} = 4 (q > 2 everywhere) and very high confinement factor H_H (preferrable due to lower HCD power needed)
  - otherwise more conventional H mode tokamak with q_{95} = 3 and confinement-optimisation (H_H = 1.2) similar to the PPCS model A / AB

Main properties

- minor radius a > 3 m, > 50% larger than ITER
- full steady-state operation, current drive with P_{HCD} > 200 MW
- high plasma core radiation, q_{max} = 5 MW/m^2

Comparison of the two reference cases

Issue	Pulsed	Steady-state
H_H / q_{95}	0.9 / 3.0	1.6 / 4.0
CoE (rel. units)	1	1.2 + cw HCD system
FW lifetime (75dpa) / y	4.0	3.2
c_{Ar}	0.3%	1.0% (→ FW sputtering)
Need for HCD	Start-up + control	> 200 MW steady-state
Need for profile control	No	Yes
Load cycling	Medium	low

Issues for further elaboration:

- Plasma scenario
- First wall lifetime
- Disruptions
- Plasma control
- Plant availability

Issues (1): Plasma scenarios

JÜLICH FORSCHUNGSZENTRUM

Pulsed tokamak with large aspect ratio R_0/a and radiative H mode

- plasma scenario with high radiation fraction, high density and small ELMs exists
  - ➢ *needs further optimisation and testing on ITER, JT60SA, …*
- possible issue with LH threshold (?), ELM size may be still to large (?)
- parameters are not fully compatible with settings chosen for for IBP98(y,2) database
  - ➢ *develop new database and scaling law for radiative H mode*
  - ➢ *clarify density scaling, beta scaling, radiation scaling, …*

Steady-state tokamak with advanced scenario / improved H mode

- real steady-state performance still to be demonstrated
  - ➢ *experiments on ITER, JT60SA, …*
- Required HCD level, radiation level and confinement scaling to be explored
  - ➢ *optimisation needed to make this approach attractive*
- Scenario depends on feasibility of economic current drive and control systems

→ DEMO physics basis to be developed

Issues (2): First wall lifetime (P3, T2, T3 working groups)

Issue	Pulsed	Steady-state
H_H / q_{95}	0.9 / 3.0	1.6 / 4.0
FW lifetime (75dpa) / y	4.0	3.2
c_{Ar}	0.3%	1.0% (→ FW sputtering)

Limitation of power flux density to the target plates (q_{max} = 5 MW/m^2) via radiation

→ enhanced (core and edge) radiation

→ limitation of $P_{sep} = P_{Heat} - P_{RadCore}$

→ moderate power density (→larger machine volume for a given P_{el})

First wall sputtering: ~ main chamber 0.1 mm / y (Brooks), in divertor probably more

Observations:

- For the case of a „traditional divertor“, the pulsed tokamak with radiative H mode may have lower neutron damage rate, lower sputtering by impurities
- In comparison, the steady-state tokamak seems less attractive unless there would be a different approach for power handling
- However, load cycling issues to be quantified

Issues (3): Disruptions (P4 working group)

Energy released in a disruption on DEMO

(assuming operation near density limit and beta limit):

- Current quench: W_{ind} ~ a^3B^2/Aq_{95}^2 ~ 1 GJ (several 10 ms)
- Thermal quench: W_{th} ~ a^3B^2/q_{95} ~ 1 GJ (a few ms)

An unmitigated disruption would release the stored energy W_{th} to the divertor plates → factor 30 .. 100 about damage threshold (M. Lehnen)

Disruption mitigation aiming at uniform spread of thermal energy via core radiation

- Since S_{Wall} ~ 1500 .. 3000 m², the mean energy density is ~ 0.5 MJ/m²

High risk of wall damage for each disruption with non-uniform energy release

Since W/S ~ a, the damage risk increases with machine dimensions

Issues (4): Plasma control (P5 working group)

Diagnostics and actuators on a fusion reactor will be quite limited

- limited access and performance (large coverage of breeding blanket needed)
- limited lifetime (diagnostic+control components mainly behind the blanket)

Pulsed tokamak with large aspect ratio R_0/a and radiative H mode

- control of global / averaged plasma quantities:
  - q_{95}, $\langle n \rangle / n_{GW}$, beta, P_{rad}, P_{fus}, …
- plasma position and shape, heat fluxes,wall temperatures
- instabilities (disruption avoidance/mitigation)

Steady-state tokamak with / advanced scenario

- additionally control of local plasma quantities / plasma profiles is needed:
  - n(r), T(r), j(r), …
- Feasibility of control system may limit the achievable complexity of the DEMO plasma scenario

Issues (5): Availability (cross-topic)

5 different types of downtimes / load variations to be distinguished

- Large shutdown for 1st wall replacement (intervals 3-4 y)
- Scheduled maintenance (e.g. removal of dust or stored tritium)
- unscheduled maintenance (repair of damage)
- power variations requested due to economic reasons (off-peak periods)
- break between 2 pulses (only pulsed tokamak)

Pulsed tokamak (A = 5): **Estimation of dwell time** between 2 pulses

- plasma termination (current ramp-down) ~ a few minutes
- Re-charging of CS coil (r_{CS} = 6 .. 7 m) ~ 20 .. 30 min (P = 100 MW)
- Pump-down time estimated to ~ 20 min (C. Day)
- plasma startup ~ a few minutes
- thermal time constant of 1st wall ~ several minutes
- minimum total break between 2 pulses ~ 1 hour
- AC operation under consideration (2 divertors)
- coverage of break by thermal storage to be considered

Summary and conclusions

- 2 DEMO tokamak working models (P_{el} = 1 GW) are being discussed in the German DEMO WG
  - Pulsed large aspect ratio tokamak (t_{pulse} ~ several hours)
  - steady-state (advanced) tokamak (P_{HCD} > 200 MW)
- Main issues:
  - plasma scenarios to be further developed (→ „DEMO physics basis")
  - 1st wall lifetime
    - *limited by sputtering and neutron embrittlement (< a few years)*
  - Disruptions
    - *are an essential problem for any DEMO tokamak*
  - plasma control likely to be a critical issue, in particular for
    - *disruption avoidance*
    - *1st wall protection*
    - *profile control*
  - Availability
    - *not too different for both DEMO tokamak models, if load cycling is not a problem*