How to design a Fusion Reactor

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- Introduction
- Fusion power and Q
- Pulse length and steady state
- Technology and overall power balance
- Some examples
- Conclusions

Introduction

Motivation for this talk

Design of Fusion Power Plant (FPP) combines physics and technology

Large number of parameters characterising a tokamak, strongly interlinked

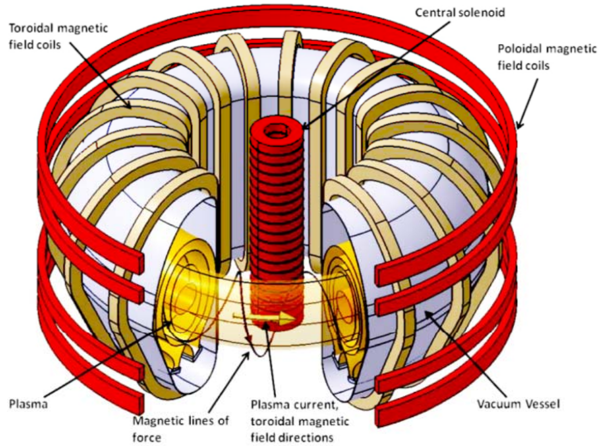
- talk outlines simple set of relations to outline a tokamak FPP
- sufficient to understand the principal boundary conditions
- indicates most important areas of present and future research

Note: present EU development path to an FPP:

- present devices: establish physics and technology basis
- ITER: demonstrate dominant self-heating, fusion energy production
- DEMO: demonstrate closed fuel cycle and reliable net energy output
- FPP: contribute to safe and economically attractive world energy supply

A set of parameters to describe a tokamak FPP*

Design parameters of the machine (hardware):



- vacuum vessel: major radius R, aspect ratio A
- toroidal magnetic field B_t
- auxiliary heating and current drive power P_{CD}

Plasma physics parameters (0-D)

- normalised pressure $\beta = \langle p\rangle/(B^2/(2\mu_0))$, limited by MHD stability
- normalised density, $f_{GW} = n/n_{GW}$ limited by empirical Greenwald limit
- safety factor $q = (r/R)(B_t/B_{pol}) \sim (1/I_p)$, limited by low-$q$ limit
- nomalised confinement $H = \tau_E/\tau_{E,scaling}$ assuming ITER scaling

Technology assumptions

- describe overall plant parameters by efficiencies η_{CD}, η_{TD}
- maximum B_t limited by technology (choice of superconductor)

***H. Zohm, Fusion Science and Technology 58 (2010) 613.**

Additional constraints from power exhaust

Tolerable heat flux on components limits P_{sep}

- exhaust similarity for

$$\frac{P_{sep}}{R\lambda_q} \propto \frac{P_{sep}}{R}\frac{B}{q} = const. \text{ but } P_{sep,LH} \propto f_{LH} n B R^2$$

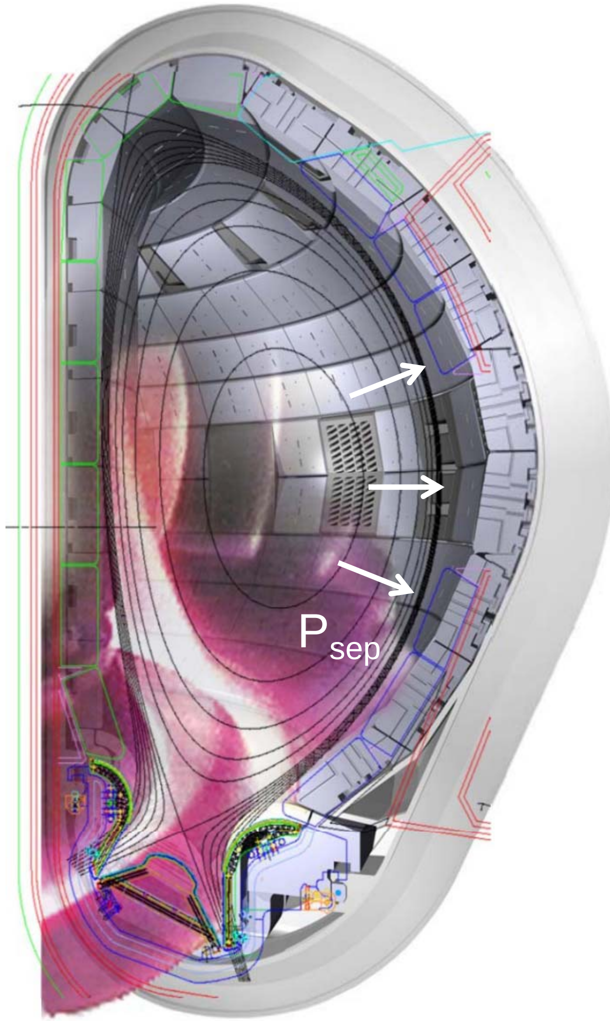
($P_{sep,LH}$ is the power to stay in H-mode)

$\Rightarrow$ P_{sep} window narrows with R and B

Need to dissipate power by radiation (impurity seeding) requires high density ($P_{rad} \sim n^2$)

- $n = f_{GW} \cdot n_{GW} \propto f_{GW} \cdot \frac{B_t}{qR}$ with $n_{GW} = \frac{I_p}{\pi a^2}$

$\Rightarrow$ achieving high absolute density more difficult in larger device!



Fusion power and Q

Simple scaling for fusion power and Q - Tokamak

In the optimum temperature range, fusion power is proportional to p^2V:

$$P_{fus} = c_1 \frac{\beta_N{}^2 B^4 R^3}{q_{95}{}^2 A^4} \qquad \text{with} \quad \beta_N = \frac{\beta}{I/(aB)} \quad \text{(Troyon-Limit)}$$

Loss power from plasma W/τ_E expressed by ITER98(p,y2) law:

$$\tau_E \sim H^{3.23} \tau_{Bohm} \rho*^{-0.7} \beta^{-0.9} q^{-3} A^{-0.73}$$

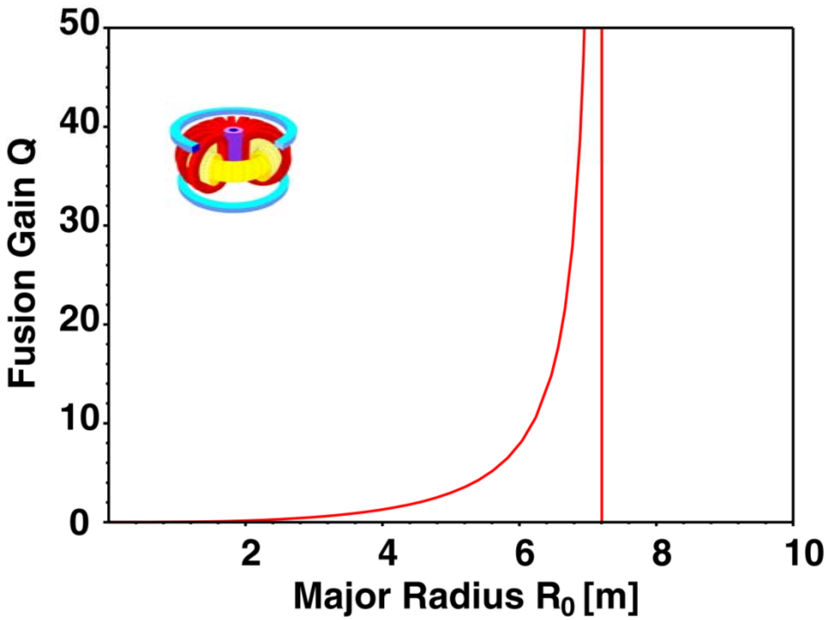
Insert this into the power balance and assume $T = T_{opt}$

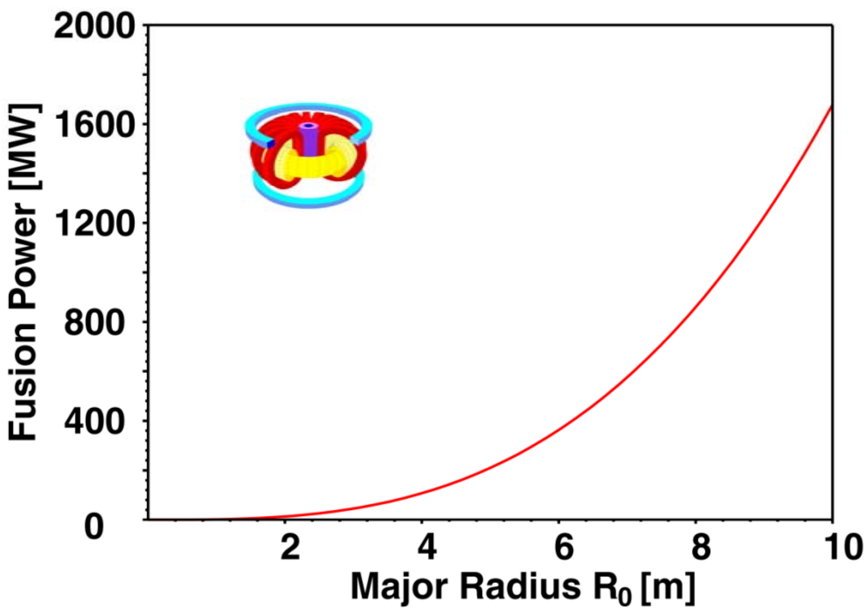
$$Q = \frac{P_{fus}}{P_{AUX}} = \frac{P_{fus}}{P_{loss} - \frac{1}{5} P_{fus}} = \frac{5}{5 \frac{c_2}{c_1} \frac{q^{3.1} A^{3.53}}{H^{3.23} \beta_N{}^{0.1} R^{2.7} B^{3.7}} - 1}$$

- strongly nonlinear in *R*, i.e. will define ‚minimum size‘

Simple scaling for fusion power and Q - tokamak

Evaluating the constants from ITER Q=10 scenario*, one gets





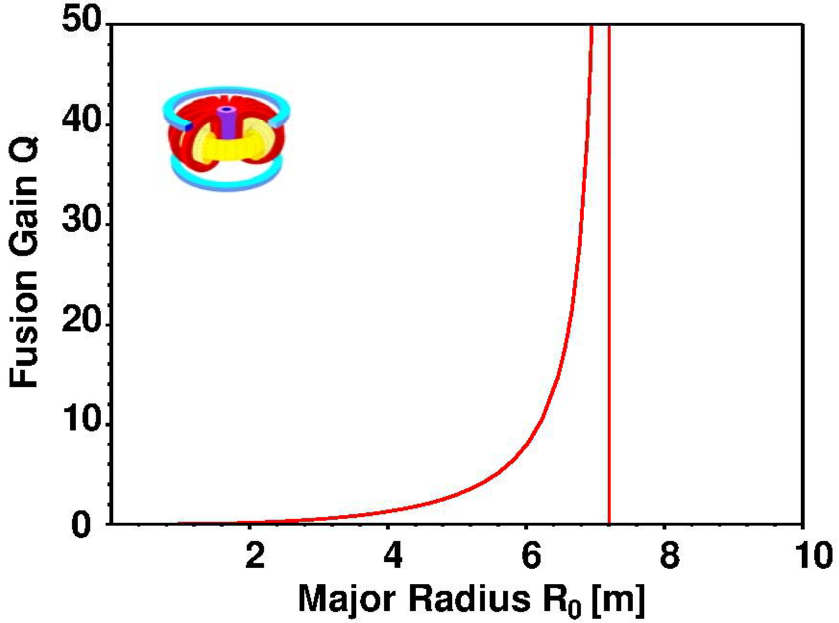
which ignites at R = 7.5 m while P_{fus} increases as R^3.

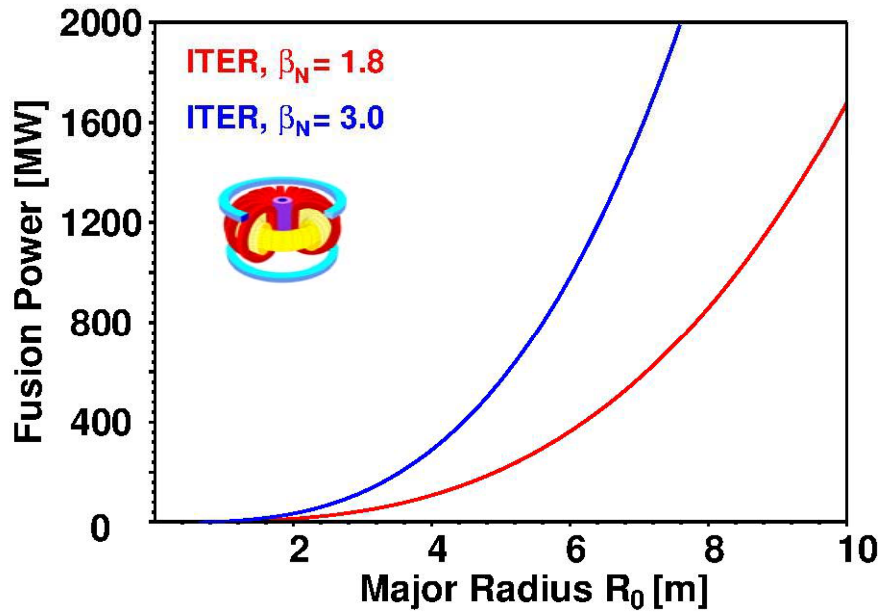
$\Rightarrow$ beyond ~ 7.5 m, Q is not determined by P_{heat}, but P_{CD} (see next section)

***(A=3.1, R=6.2 m, B_t=5.2 T, q_{95}=3.1, H=1, β_N=1.8, Q=10, P_{fus}=400 MW, P_{AUX}=120 MW)**

Simple scaling for fusion power and Q - tokamak

Evaluating the constants from ITER Q=10 scenario*, one gets





which ignites at R = 7.5 m while P_{fus} increases as R^3.

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Fusion power can be increased by raising β_N and/or B

***(A=3.1, R=6.2 m, B_t=5.2 T, q_{95}=3.1, H=1, β_N=1.8, Q=10, P_{fus}=400 MW, P_{AUX}=120 MW)**

Simple scaling for fusion power and Q - Stellarator

In the optimum temperature range, fusion power is proportional to p^2V:

$$P_{fus} = \frac{\tilde{c}_1 \beta^2 B^4 R^3}{A^2}$$

Loss power from plasma W/τ_E expressed by ISS04 law:

$$\tau_E \sim H^{2.52} \tau_{Bohm} \rho*^{-0.79} \beta^{-0.19} q^{-1.06} A^{0.0}$$

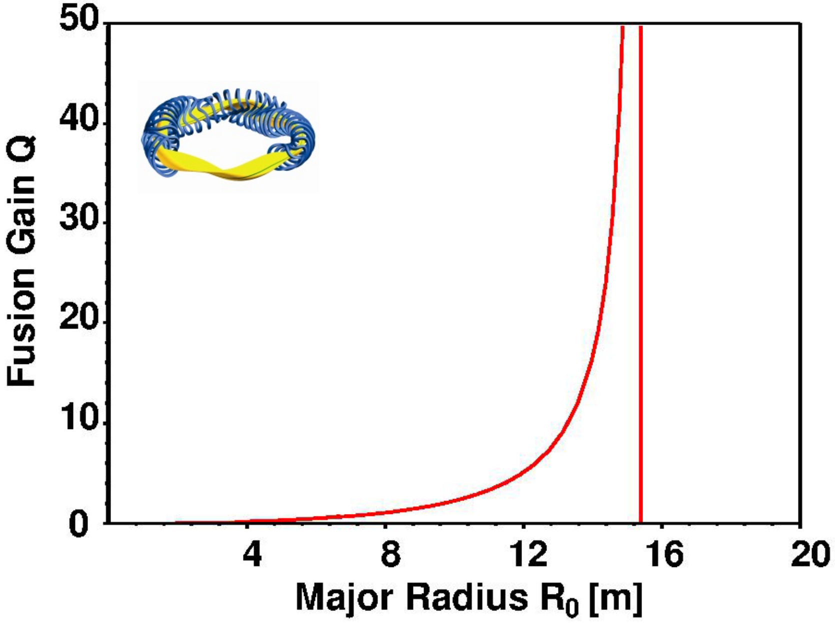
Insert this into the power balance and assume $T = T_{opt}$

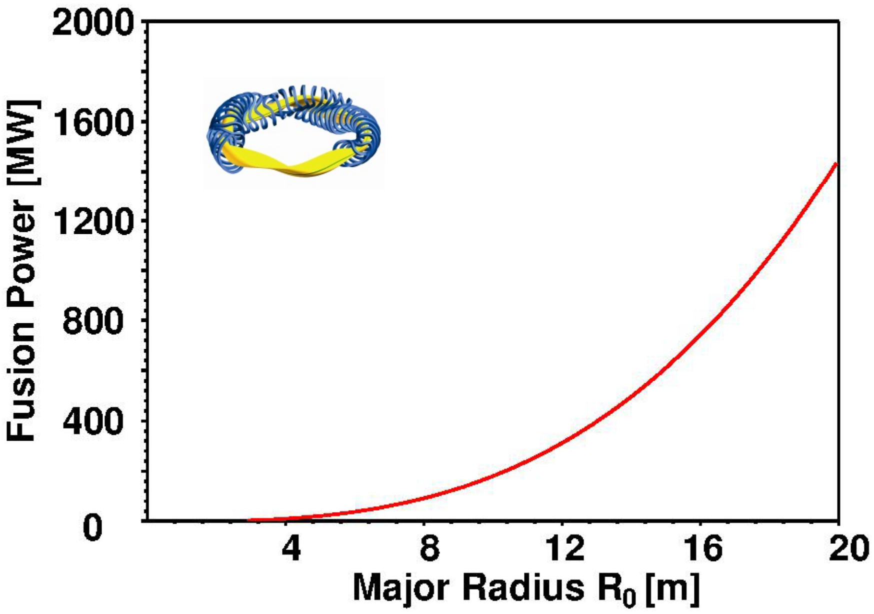
$$Q = \frac{P_{fus}}{P_{AUX}} = \frac{P_{fus}}{P_{loss} - \frac{1}{5} P_{fus}} = \frac{5}{5 \frac{\tilde{c}_2}{\tilde{c}_1} \frac{q^{1.06} A^{2.79}}{H^{2.56} \beta^{0.81} R^{2.79} B^{3.79}} - 1}$$

- strongly nonlinear in *R*, i.e. will define ‚minimum size‘

Simple scaling for fusion power and Q - stellarator

Evaluating the constants from HELIAS Option A scenario*, one gets





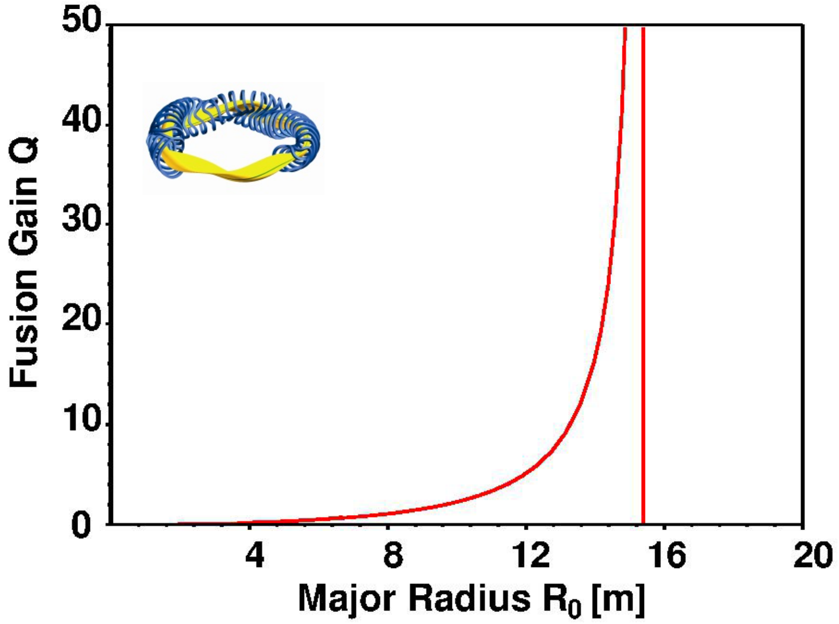
which ignites at R = 15.5 m while P_{fus} increases as R^3.

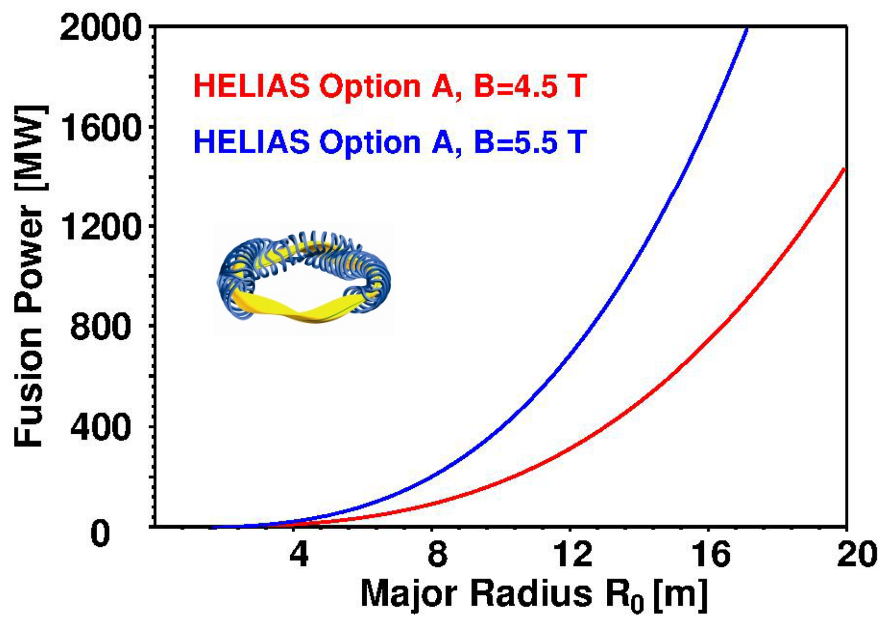
$\Rightarrow$ beyond ~ 15.5 m, P_{heat} is no longer an issue (different from the tokamak)

***(*A=10.5, R=14 m, B_t=4.5 T, q=1, H=1.8, β=4.3, Q=10, P_{fus}=500 MW, P_{AUX}=150 MW according to F. Warmer et al., Plasma Phys. Control. Fusion 2016)**

Simple scaling for fusion power and Q - stellarator

Evaluating the constants from HELIAS Option A scenario*, one gets





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Fusion power can be increased by raising β and/or B

***(A=10.5, R=14 m, B_t=4.5 T, q=1, H=1.8, β=4.3, Q=10, P_{fus}=500 MW, P_{AUX}=150 MW according to F. Warmer et al., Plasma Phys. Control. Fusion 2016)**

Simple scaling for fusion power and Q

$$Q = \frac{P_{fus}}{P_{AUX}} = \frac{5}{5\dfrac{c_2}{c_1}\dfrac{q^{3.1}A^{3.53}}{H^{3.23}\beta_N{}^{0.1}R^{2.7}B^{3.7}} - 1} \qquad P_{fus} = c_1 \frac{\beta_N{}^2 B^4 R^3}{q_{95}{}^2 A^4}$$

For an FPP designer, the following rules are important:

- q_{95} strongly enters into the ignition criterion, high I_p / iota is important
- improved confinement (H) can relax I_p requirement (increase q_{95})
- β does almost not enter into Q, but strongly into fusion power

N.B.: for fixed machine design (R, A, B_t):

- Q determined by H/q_{95}
- P_{fus} determined by β_N/q_{95}

$\Rightarrow$ Figure of merit $\dfrac{\beta_N H}{q_{95}{}^2}$ at constant Q, P_{fus}

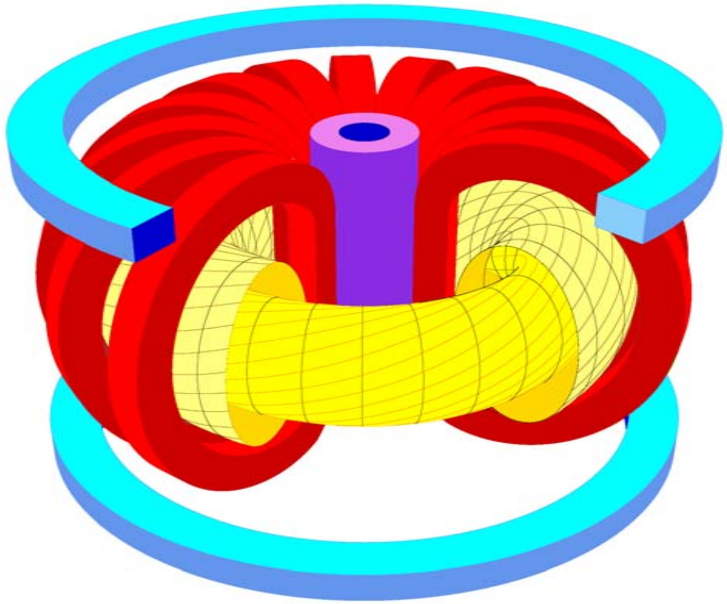
Pulse length and steady state

(tokamak only)

Simple scaling law for tokamak pulse length

Total solenoid flux Φ_{tot} is consumed by ramp-up Φ_0 and flat top Φ_{res}

$$\Phi_{tot} = \Phi_0 + \Phi_{res}$$



Φ_{tot} proportional to hole in the centre:

$$\Phi_{tot} = c_3 R_0^{\,2} \left(\frac{A-1}{A} - \frac{b}{R_0} \right)^2$$

(*b* accounts for blanket, vacuum vessel and TF)

The flux needed for ramp-up is given by

$$\Phi_0 = (L_p + \mu_0 c_{Ejima} R_0) I_p = c_4 \left(\frac{R_0}{A} \right)^2 \frac{B}{q_{95}}$$

with $L_p \sim R_0$ the internal inductance and c_{Ejima} accounting for resistive losses

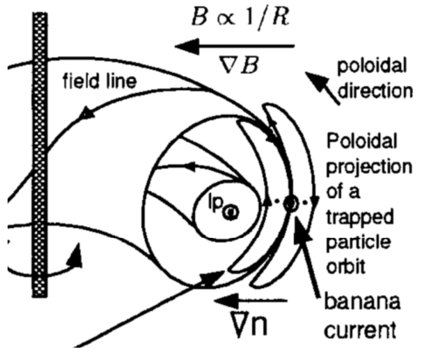
Simple scaling law for tokamak pulse length

The flux consumed in flattop is given by

$$\Phi_{res} = \tau_{pulse} \frac{2\pi R_0}{\kappa a^2 \langle \sigma \rangle} I_p^{\ *} = c_5 \tau_{pulse} \frac{B_t}{q_{95}} (1 - f_{CD} - f_{bs})$$

where $I_p^{\ *} = I_p (1 - f_{CD} - f_{bs}) = I_p (1 - f_{CD} - c_6 0.7 q_{95} \sqrt{A} \beta_N)$

I_p^* = ohmic current, f_{CD} = fraction of external current,
f_{bs} = botstrap fraction



bootstrap current

$j_{bs} \sim \nabla p / B_{pol}$

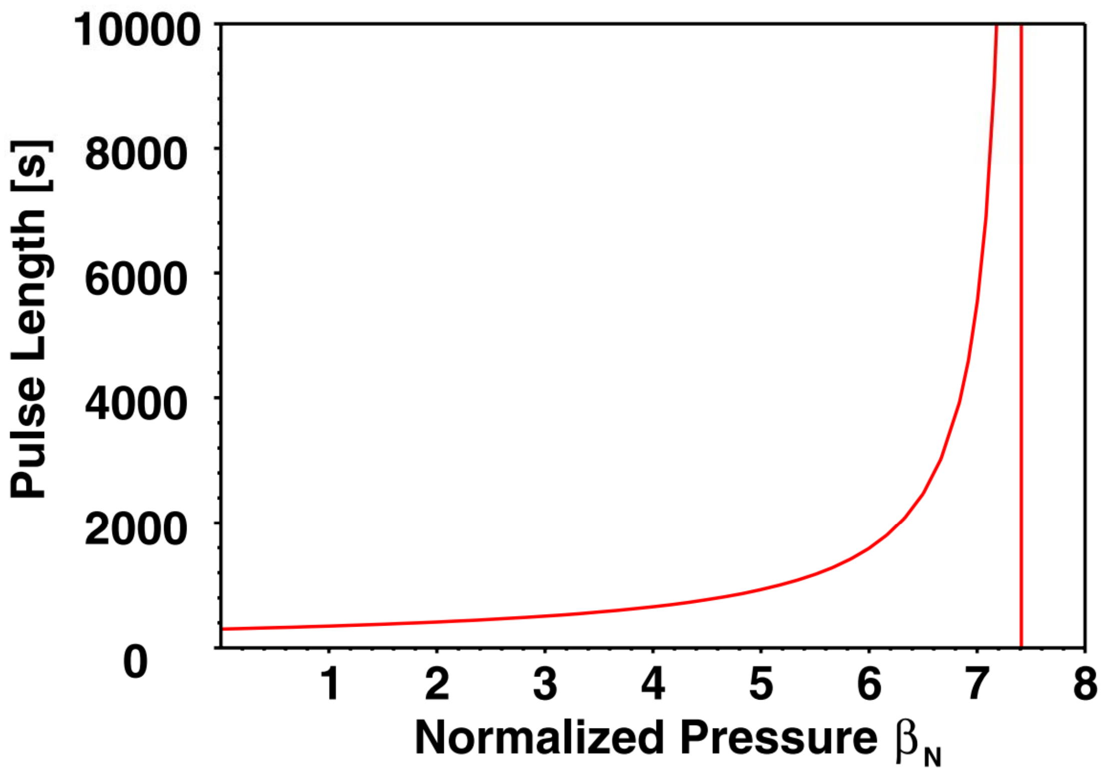
Pulse length can now be derived from the flux balance

$$\tau_{pulse} = R_0^{\ 2} \frac{c_3 q_{95} A^2 \left(\frac{A-1}{A} - \frac{b}{R_0} \right)^2 - c_4 B}{c_5 B A^2 (1 - f_{CD} - c_6 0.7 q_{95} \sqrt{A} \beta_N)}$$

$\Rightarrow$ again yields a ‚resonance denominator‘

Simple scaling law for tokamak pulse length

Evaluating the constants c_3-c_6 from ITER Q=10 scenario*, one gets

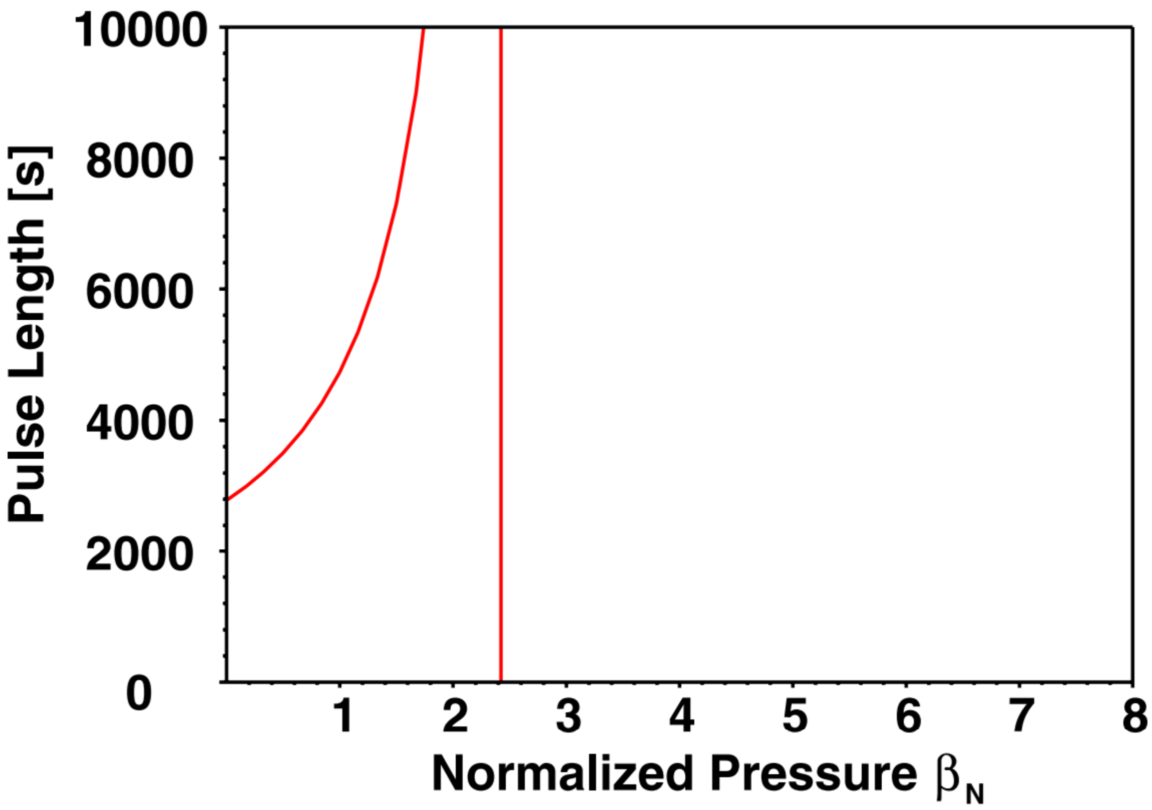


$\Rightarrow$ does NOT reasonably extrapolate to steady state (due to high I_p, low β_N)

***(A=3.1, R=6.2 m, B_t=5.2 T, q_{95}=3.1, b=2.8 m, β_N=1.8, f_{CD}=0.1, Φ_{tot}=, Φ_0=90 Wb, τ_{pulse}=400 s)**

Simple scaling law for tokamak pulse length

Using the ITER Q=5 scenario*, the steady state point can be reproduced!



…but at the expense of reduced Q and a lot of external CD power

(A=3.3, q_{95}=5.1, β_N=2.5, f_{CD}=0.5)

Simple scaling law for tokamak pulse length

A note on the external current drive requirements:

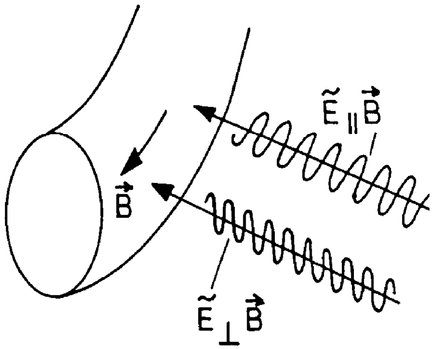
- for a number of systems, current drive efficiency scales like *T/n*:

$$P_{CD} = c_8(5 + Z_{eff}) I_p \frac{n}{T} R \left(1 - c_9 \cdot \frac{1}{\sqrt{A}} \beta_p\right)$$

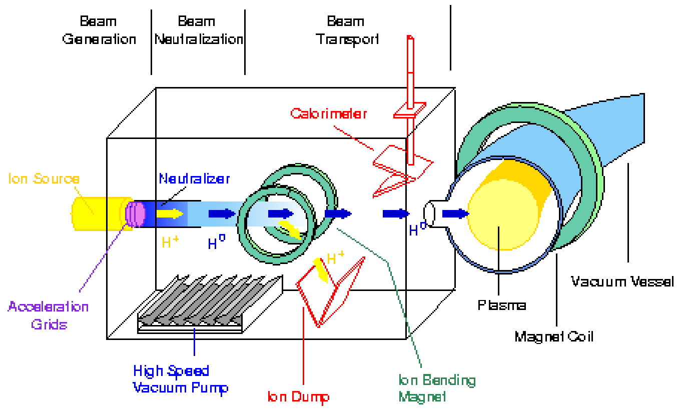
- can be re-written using the variables introduced before:

$$P_{CD} = \frac{c_8 c_3 c_5 c_7^3}{\pi^2} \frac{B}{q^2} \frac{f_{GW}^2}{\beta_N A} \left(5 + \frac{\pi^2 A^2 q^2}{C_6 C_7^2 f_{GW}^2 B^2} \left(\frac{P_{fus}}{5R} + \frac{P_{CD}}{R} - \frac{P_{sep}}{R}\right)\right) \left(1 - C_9 \sqrt{A} q \frac{c_4}{c_3} \beta_N\right)$$

$\Rightarrow$ P_{CD} does not increase with R unless P_{sep}/R increases Z_{eff}



Electron Cyclotron Current Drive (ECCD)



Neutral Beam Current Drive (NBCD)

Simple scaling law for tokamak pulse length

$$\tau_{pulse} = R_0^{\ 2} \frac{c_3 q_{95} A^2 \left(\frac{A-1}{A} - \frac{b}{R_0} \right)^2 - c_4 B}{c_5 B A^2 (1 - f_{CD} - c_6 0.7 q_{95} \sqrt{A} \beta_N)}$$

For an FPP designer, the following rules are important:

- increasing the major radius while not increasing I_p will give long pulses
- true steady state needs high q_{95} and β_N
- since at constant Q and P_{fus}, β_N/q_{95} and H/q_{95} are constant, H needs to be increased in proportion

$\Rightarrow$ Advanced tokamak scenarios simultaneously need high H and β_N

Technology and overall power balance

Simple scaling for overall power balance

The total thermal power is given by

$$P_{th} = 1.18 P_{fus} + P_{CD} + \eta_{BOP} P_{BOP}$$

where the **B**alance **O**f **P**lant power may contribute by a fraction η_{BOP}.

This generates a total electric power with thermodynamic efficiency η_{TD}:

$$P_{el,tot} = \eta_{TD} P_{th}$$

The auxiliary power needed to run the plant is given by

$$P_{AUX} = \frac{P_{CD}}{\eta_{CD}} + P_{BOP}$$

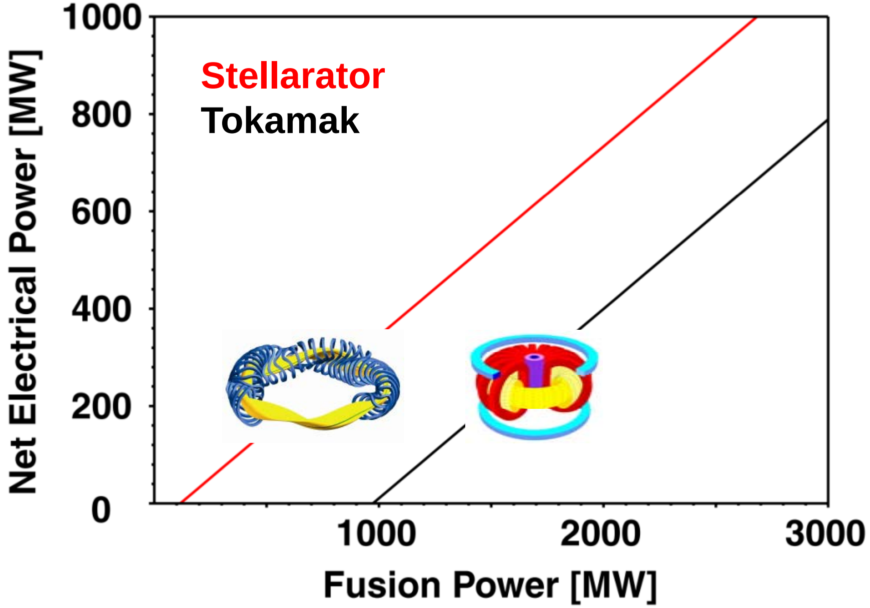
(η_{CD} = CD wall plug efficiency)

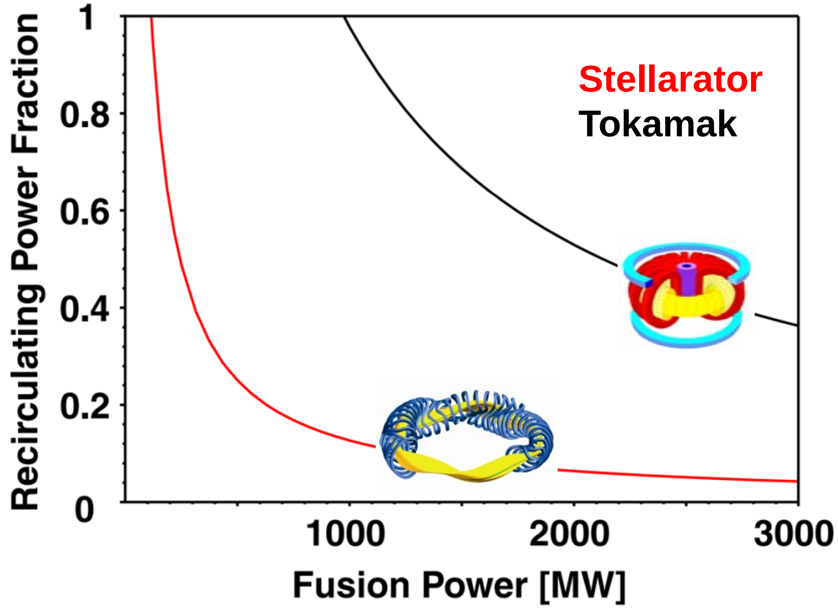
and the recirculating electrical power fraction is

$$f_{rec} = \frac{P_{AUX}}{P_{el,tot}} = \frac{P_{CD}/\eta_{CD} + P_{BOP}}{\eta_{TD}\left(1.18 P_{fus} + P_{CD} + \eta_{BOP}\right)}$$

Simple scaling for overall power balance

For realistic efficiencies*, conservative steady state DEMO** looks like this:





- net electricity only generated above 1 GW fusion power
- while an inherently stationary stellarator would look much better

*(η_{TD}=0.33, η_{BOP}=0.3 ,P_{BOP}=50 MW)
**(here: P_{CD} = 100 MW and η_{CD}=0.25)

Simple scaling for overall power balance

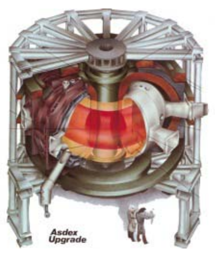
$$f_{rec} = \frac{P_{AUX}}{P_{el}} = \frac{P_{CD}/\eta_{CD} + P_{BOP}}{\eta_{TD}\left(1.18P_{fus} + P_{CD} + \eta_{BOP}\right)}$$

For an FPP designer, the following rules are important:

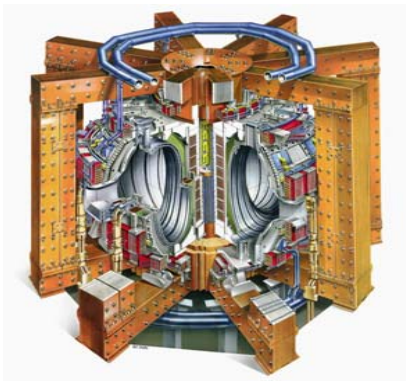
- the bigger the better: large 'offset' P_{AUX} which must be overcome by P_{fus}.
- external CD comes with high penalty and should be minimised
- increasing η_{TD} helps, but technologically challenging (He cooling)

Some examples

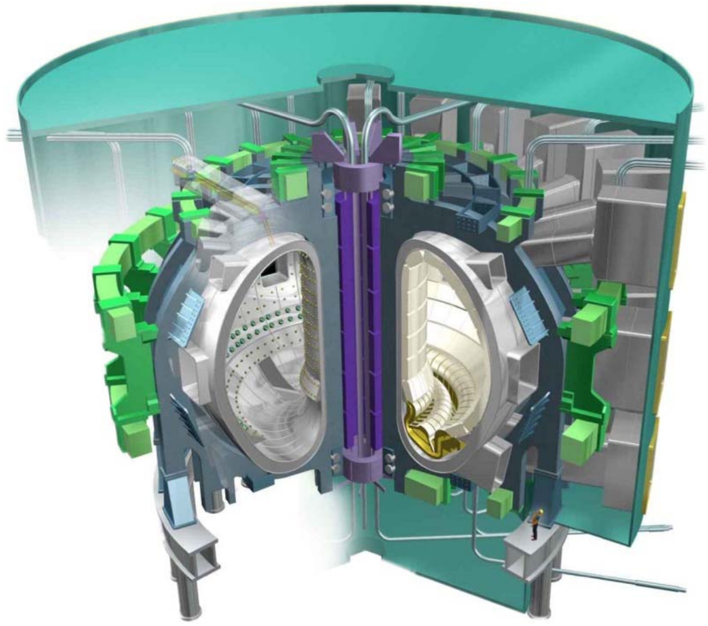
A stepladder approach: ITER-DEMO-FPP



ASDEX Upgrade



JET

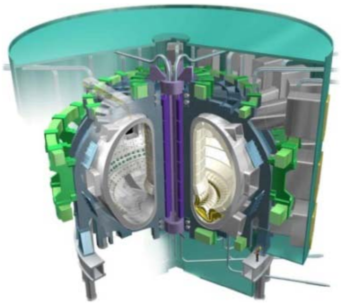


ITER

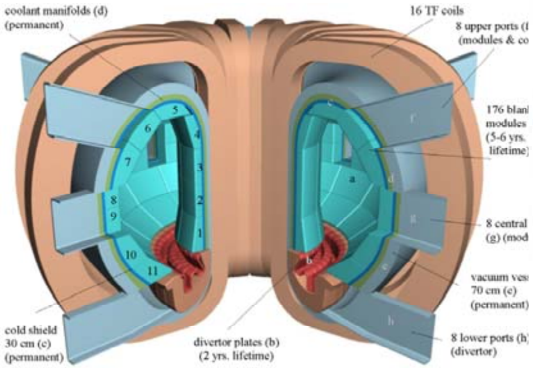
At present, the EU programme uses a stepladder approach towards developing operational scenarios: ASDEX Upgrade – JET - ITER

A similar stepladder can be conceived for developing an FPP

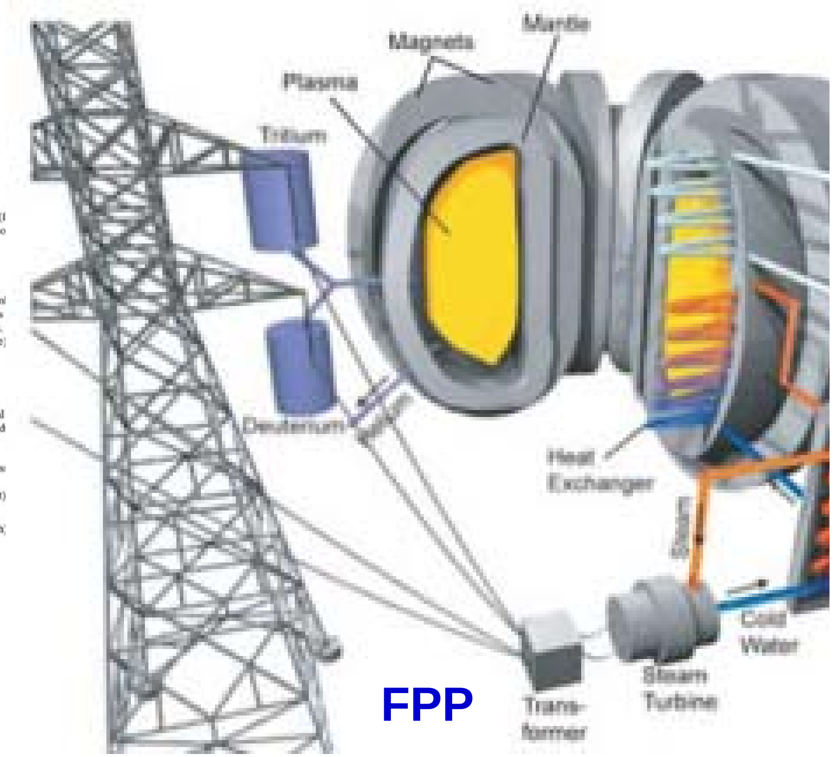
A stepladder approach: ITER-DEMO-FPP



ITER



DEMO



FPP

Assumption: plasma scenario for an FPP has to be developed in ITER and DEMO and should be ‘ready’ after DEMO

Strategy: aim at attractive FPP scenario, scale down to DEMO, and then look if we can run it in ITER

A stepladder approach: ITER-DEMO-FPP

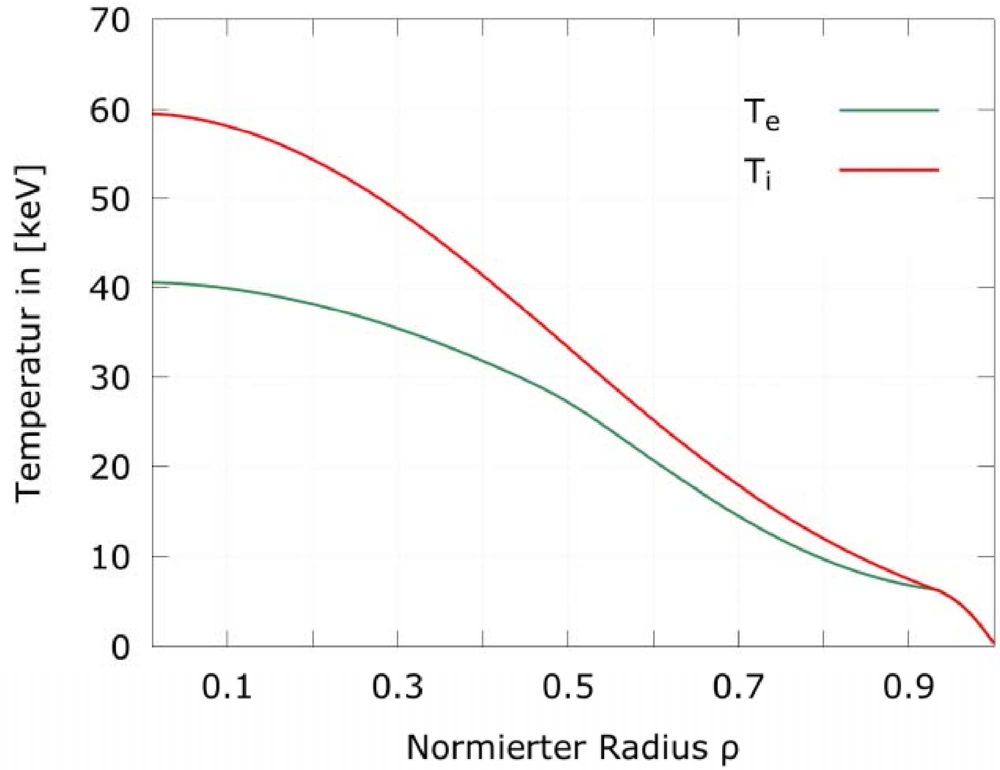
	ITER	DEMO	FPP
q_{95}	4.5	4.5	4.5
f_{GW}	1.2	1.2	1.2
n_e	8.4	8.4	8.4
β_N	3.5	3.5	3.5
H	1.4	1.2	1.2
f_{bs}	0.62	0.62	0.62
$P_{sep}B/qR$	23	23	23

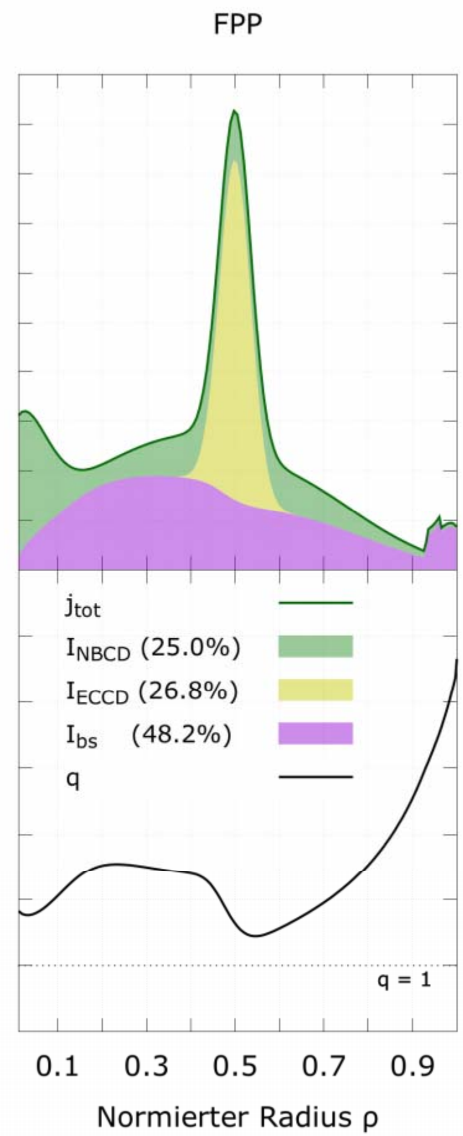
	ITER	DEMO	FPP
R	6.2	7.85	8.5
B	4.5	5.6	6.1
I_p	9	14	16.6
P_{fus}	0.4	2	3.5
P_{CD}	0.1	0.115	0.12
$P_{el,net}$	n/a	0.5	1
f_{LH}	1-2.4	1-1.25	1
$f_{rad,core}$	0.3-0.7	0.72-0.78	0.825
Q	3.3	ignited	ignited

Dimensionless parameters: constant

Absolute parameters: stepladder

Stepladder from 1-D transport code (ASTRA)





ASTRA stepladder implementation:'hybrid' scenario

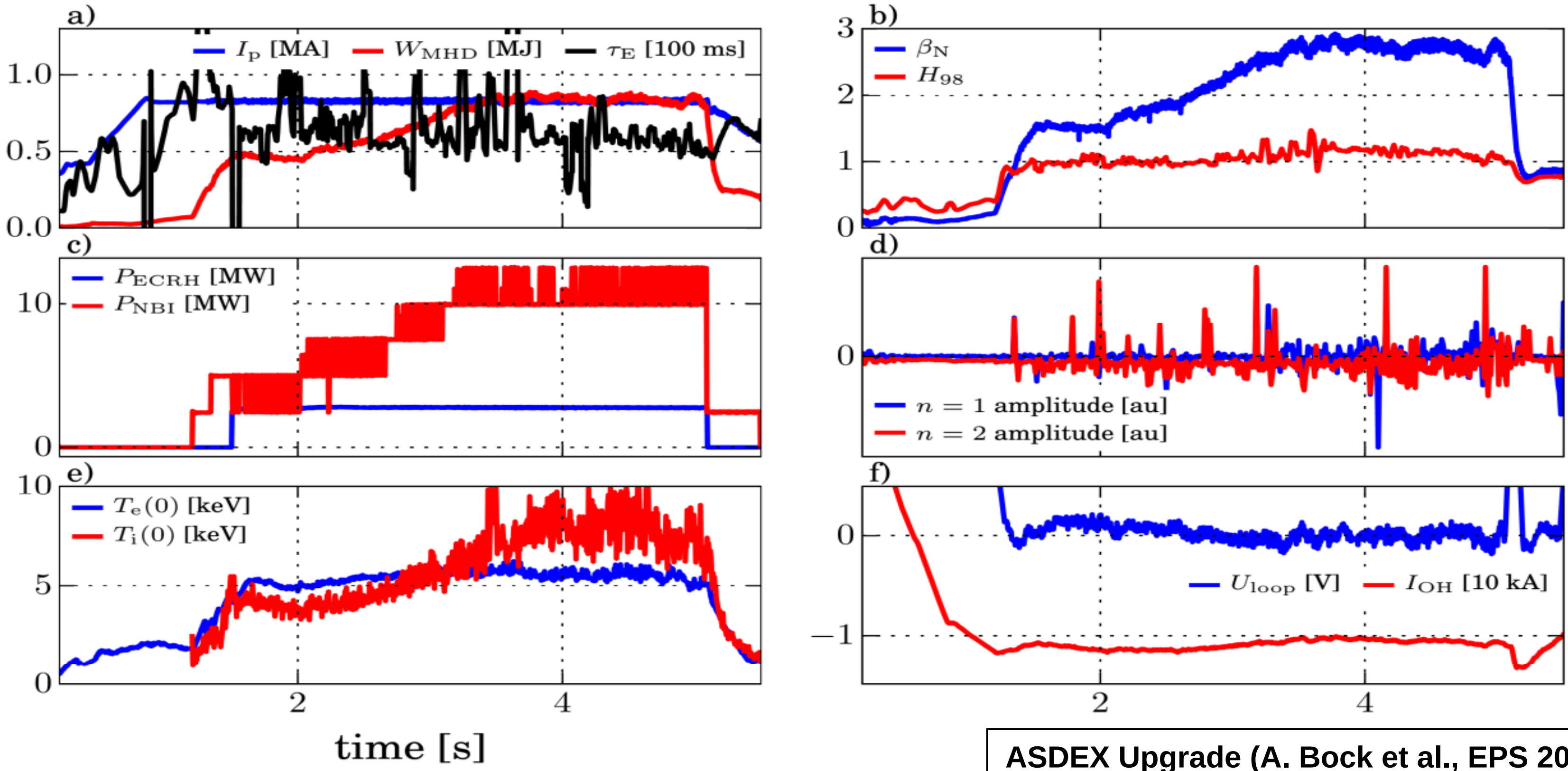
- Stiff temperature profiles plus H-mode pedestal
- Density limit by $n_{ped} < n_{GW}$, peaking from TGLF
- Current profile for flat elevated q (NBCD + ECCD)

Stepladder from 1-D transport code (ASTRA)

	ITER		DEMO		FPP	
	ASTRA	0D-Ansatz	ASTRA	0D-Ansatz	ASTRA	0D-Ansatz
$P_{fus}\,[MW]$	390	400	2000	2000	3650	3500
$R_{tor}\,[m]$	6.2	6.2	8.09	7.85	9.28	8.5
$a\,[m]$	2.066	2.066	2.695	2.616	3.089	2.833
$B_{tor}\,[T]$	4.50	4.50	5.77	5.60	6.66	6.10
$I_P\,[MA]$	9.00	9.00	14.85	14.00	19.80	16.60
H	1.3	1.4	1.2	1.2	1.2	1.2
β_n	2.99	3.5	2.96	3.5	3.02	3.5
q_{95}	4.8	4.5	4.87	4.5	4.62	4.5
f_{bs}	0.546	0.62	0.475	0.62	0.482	0.62
$f_{rad,core}$	0.512	0.3 - 0.7	0.709	0.72 - 0.78	0.814	0.825
Q	3.92	3.3	17.4	∞	30.4	∞
f_{LH}	1.45	1.0 - 2.4	1.24	1.0 - 1.25	0.876	1

- R and I_p increased in DEMO/FPP (at T > 25 kev, P_{fus} no longer ~ T^2)
- β_N slightly lower (effect of profiles and fast particle pressure)
- FPP close to the L-H threshold due to exhaust limit on P_{sep}

Towards a credible steady state scenario for DEMO



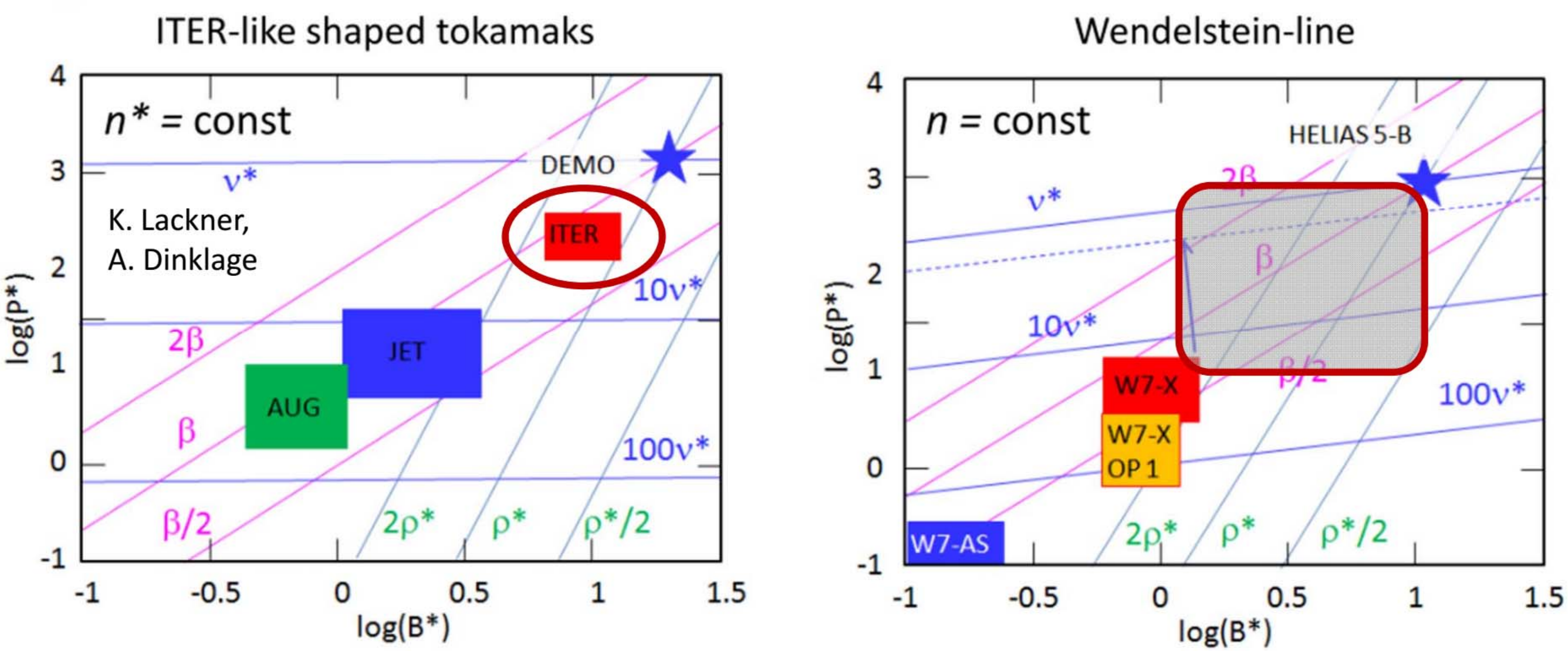
ASDEX Upgrade (A. Bock et al., EPS 2016)

q_{95}=5.4, β_N=2.7, f_{bs}~50%, stationary

Try to verify this scenario in present devices

- ASDEX Upgrade experiments achieve stationary conditions
- Needs further development, but encouraging step in right direction

Stellarator next step: ITER or DEMO?

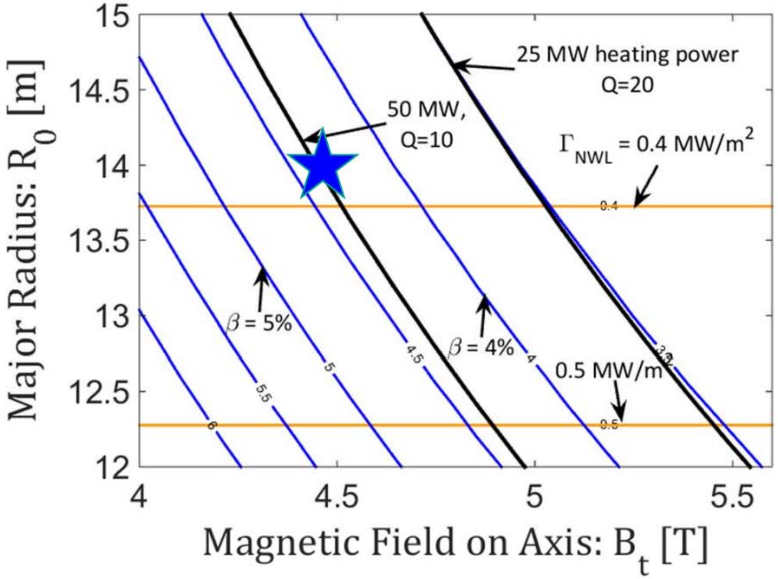


Assuming success of W7-X, what is the right size for the next step?

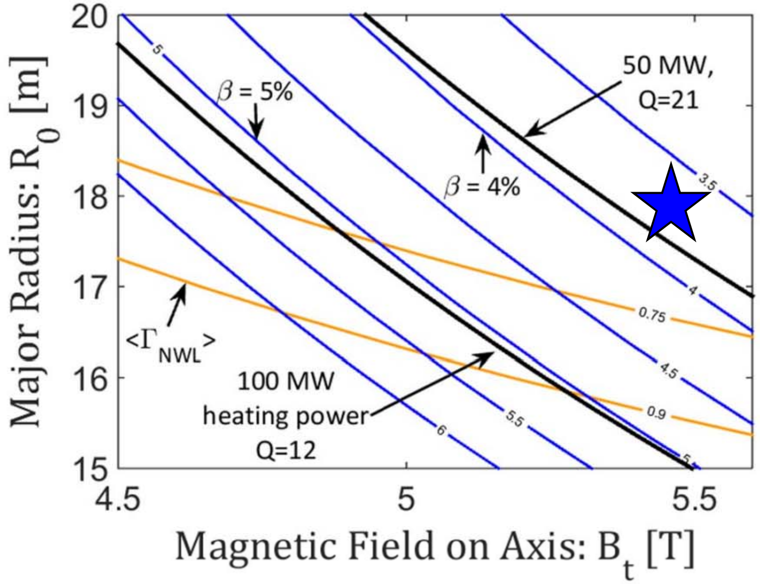
- ITER-like: burning plasma, but T supplied externally
- DEMO-like: closed fuel cycle and net electricity production

Stellarator next step: ITER or DEMO?

Option A



Option C

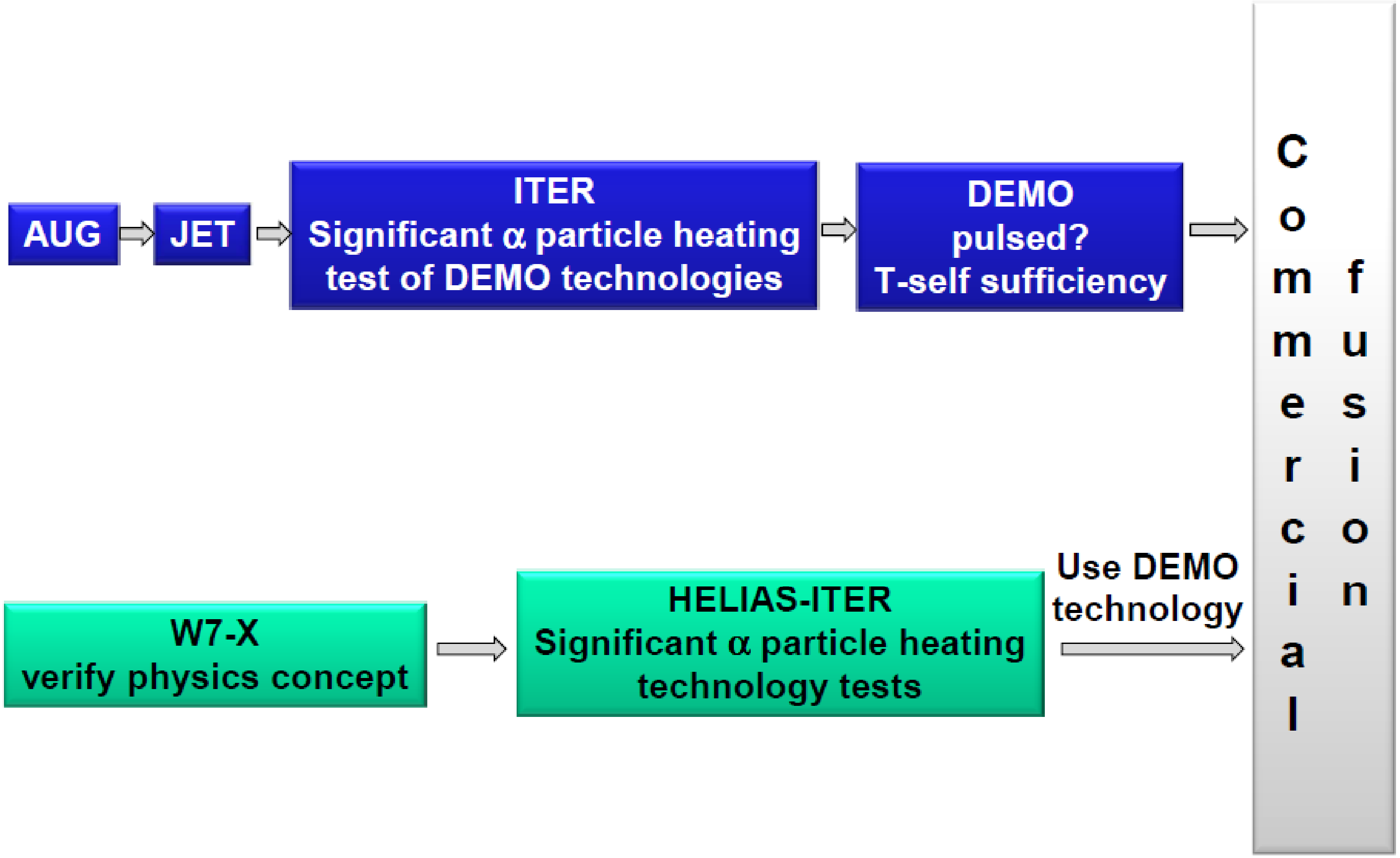


- ‚ITER-like', Q=10, no P_{el}
- No T-breeding
- Existing technology (NbTi)

- ‚DEMO-like', Q=20, P_{el} = 200 MW
- T self-sufficient
- Advanced technology (Nb_3Sn)

F. Warmer, et al., PPCF (2016)

A possible roadmap to a stellarator FPP

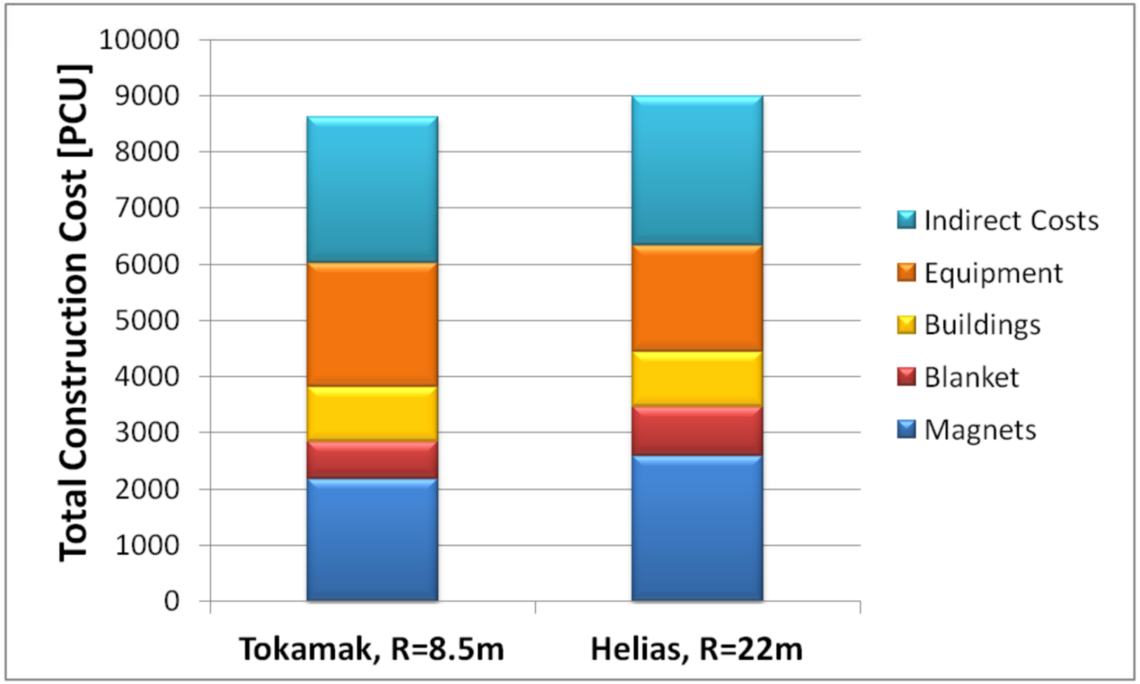


- Using technology developed on a tokamak DEMO, stellarator can be candidate for a Fusion Power Plant in the 2050s

First estimates indicate comparable cost (!)

- **Cost breakdown (share of total construction cost)**

Device	Tokamak	Helias
Equipment	26%	21%
Buildings	11%	11%
Magnets	25%	29%
Blanket	8%	10%
Indirect	30%	30%
Cold Mass	44kt	40kt
SC Mass	~1.8kt	2.9kt



Using common approach to estimate cost of tokamak and stellarator DEMO

- Stellarator magnets more expensive, but outweighed by external CD

F. Warmer et al., Fus. Eng. Des. 2015

Summary

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A simple set of scaling laws has been shown to describe FPP designs

- more sophisticated models exist, but this on gives physics insight
- can easily be used to explore a wide range of parameters

The size of an FPP is determined by several elements

- ignition prescribes minimum major radius (roughly R = 7.5 m / 15.5 m)
- pulse length drives system to larger q and β_N, requiring also higher H
- economic attractiveness drives P_{fus} up (to overcome ‚offset' P_{CD})

At present, these designs are mainly used to evaluate basic trends

- FPP will be built ~ 2050, future improvements can be incorporated
- more sophisticated analysis needed before spending several B€ ☺

Note: parallel development of stellarator line so we could ‚switch horses'