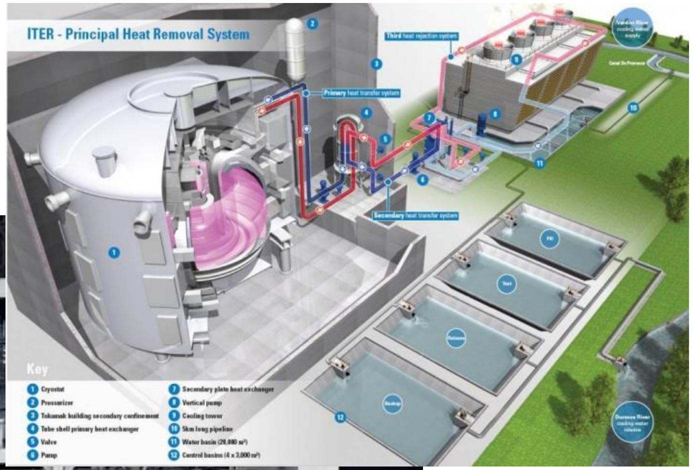
7. Integrated DEMO design and system development?

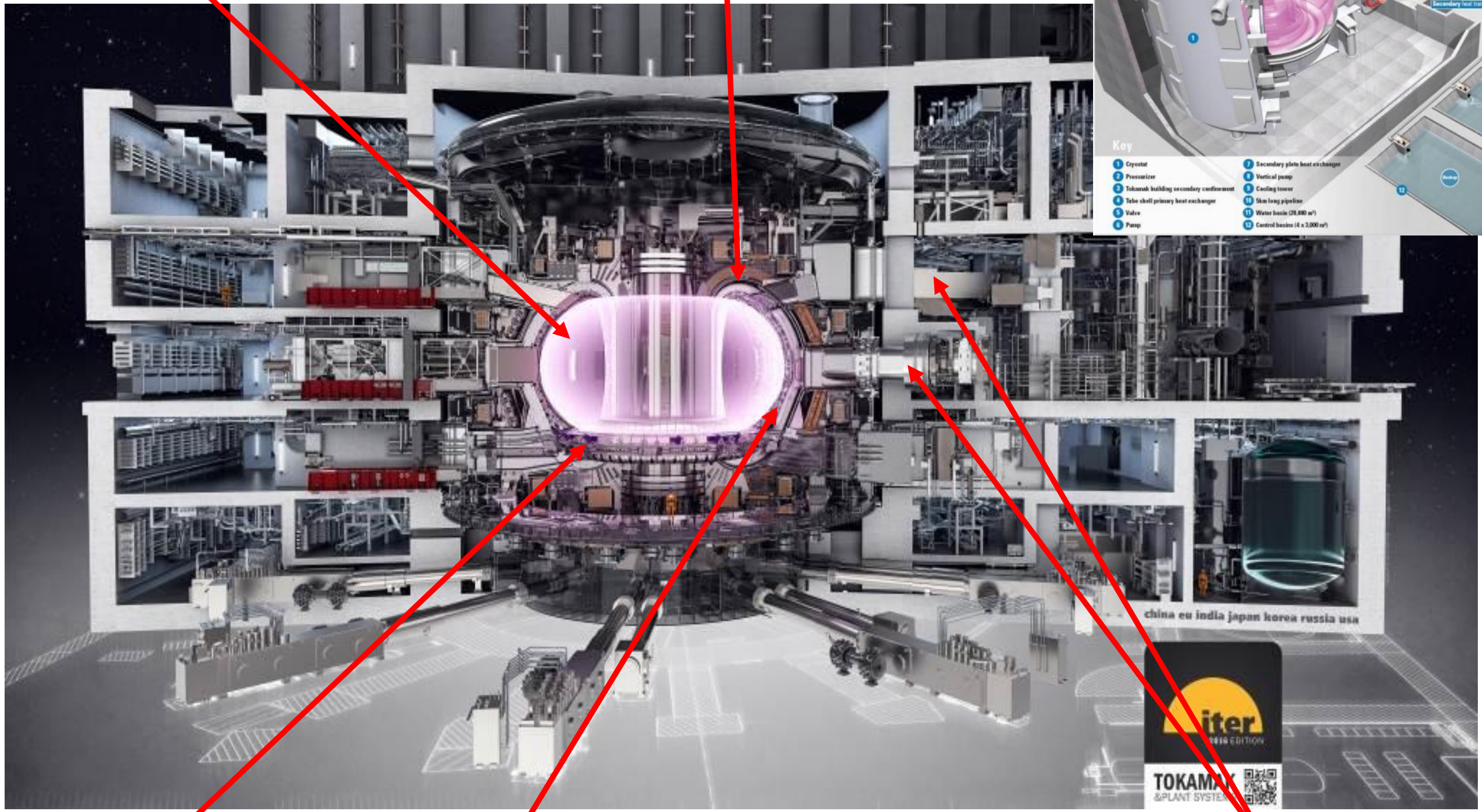
System design and integration? Modelling and simulation

Is ITER sufficient?

Plasma Performances

Superconducting Magnets





Coolant System
→ BoP

Divertor: Heat Removal

Blanket → Breeding Blanket, Heat exchange

Heating & Current Drive Systems

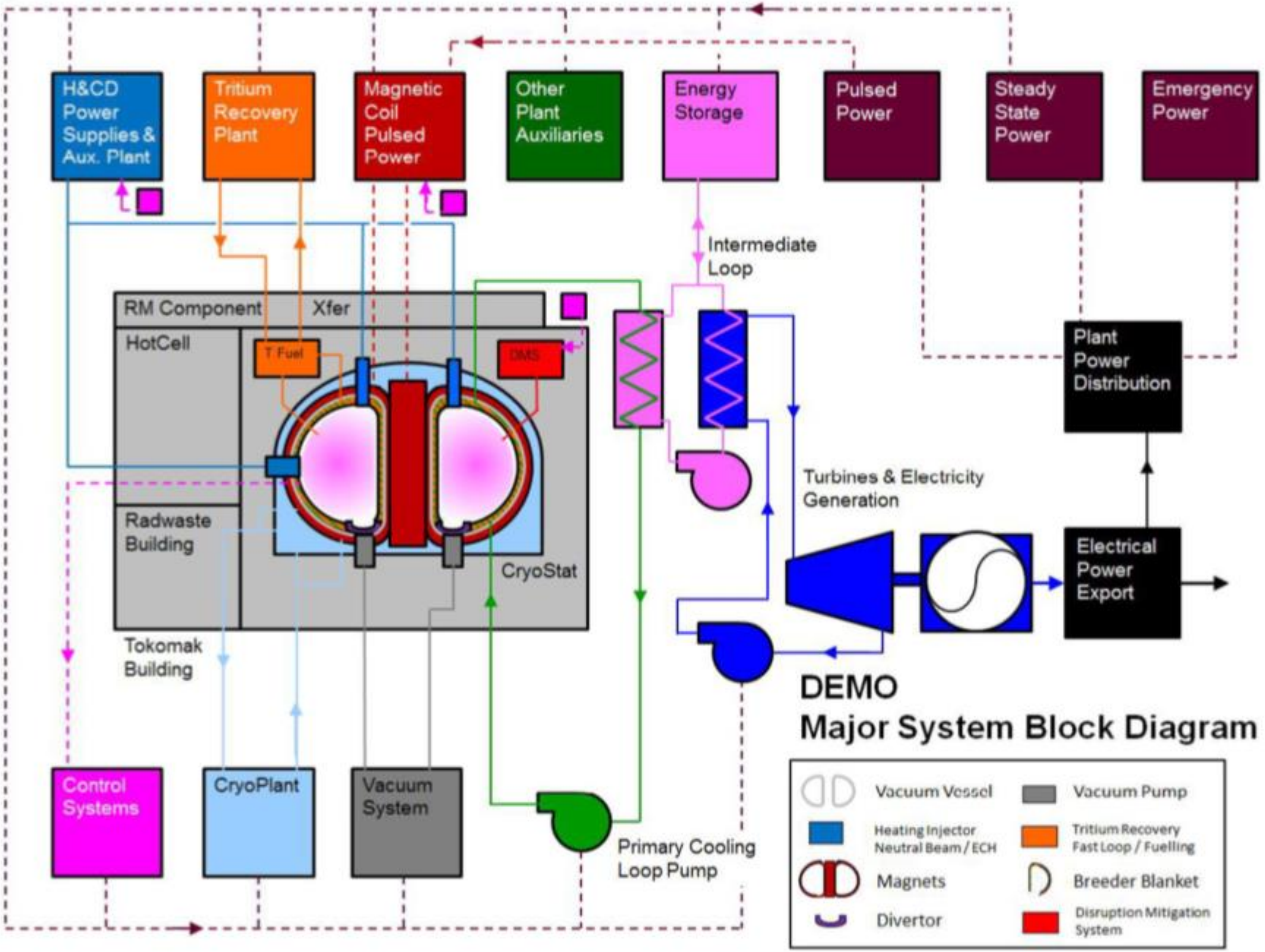
Difference between ITER and DEMO

ITER	DEMO
• Experimental device with physics and technology development missions.	• Nearer to a commercial power plant but with some development missions.
• 400 s pulses, long dwell time.	• Long pulses (>2 h) or steady state.
• Experimental campaigns. Outages for maintenance, component replacements.	• Maximize availability. Demonstrate effective and efficient maintenance and component replacement technologies.
• Large number of diagnostics.	• Typically, only those diagnostics required for operation. However, there may be the need to have diagnostics for component testing and qualification
• Multiple H&CD systems.	• Optimized set of H&CD systems.
• Large design margins, necessitated by uncertainties and lack of fully appropriate design codes.	• With ITER (and other) experience, design should have smaller uncertainties.
• Cooling system optimized for minimum stresses and sized for modest heat rejection.	• Cooling system optimized for electricity generation efficiency (e.g. much higher temperature.)
• Unique one-off design optimized for experimental goals.	• Move towards design choices suitable for series production.
• No tritium breeding requirement (except very small quantity in tritium breeding modules).	• Tritium breeding needed to achieve self-sufficiency.
• Conventional 316 stainless steel structure for in-vessel components.	• Nuclear hardened, novel reduced activation materials as structure for breeding blanket.
• Very modest lifetime n-fluence, low dpa and He production.	• High fluence, significant in-vessel materials damage.
• Licensed as nuclear facility, but like a laboratory, not a reactor.	• Licensing as nuclear reactor more likely. Potential for large tritium inventory on-site.
• Licensing as experimental facility.	• Stricter approach may be necessary to avoid large design margins.
• 'Progressive start-up' permits staged approach to licensing.	• 'Progressive start-up' should also be possible (e.g. utilize a 'starter' blanket using moderate-performance materials and then switch to blankets with a more advanced-performance material after a few MW yr/m^2).
• During design, licensing in any ITER party had to be possible.	• Fewer constraints.

G. Federici et. als., "European DEMO design strategy and consequences for materials", Nuclear Fusion 57 (2017) 092002

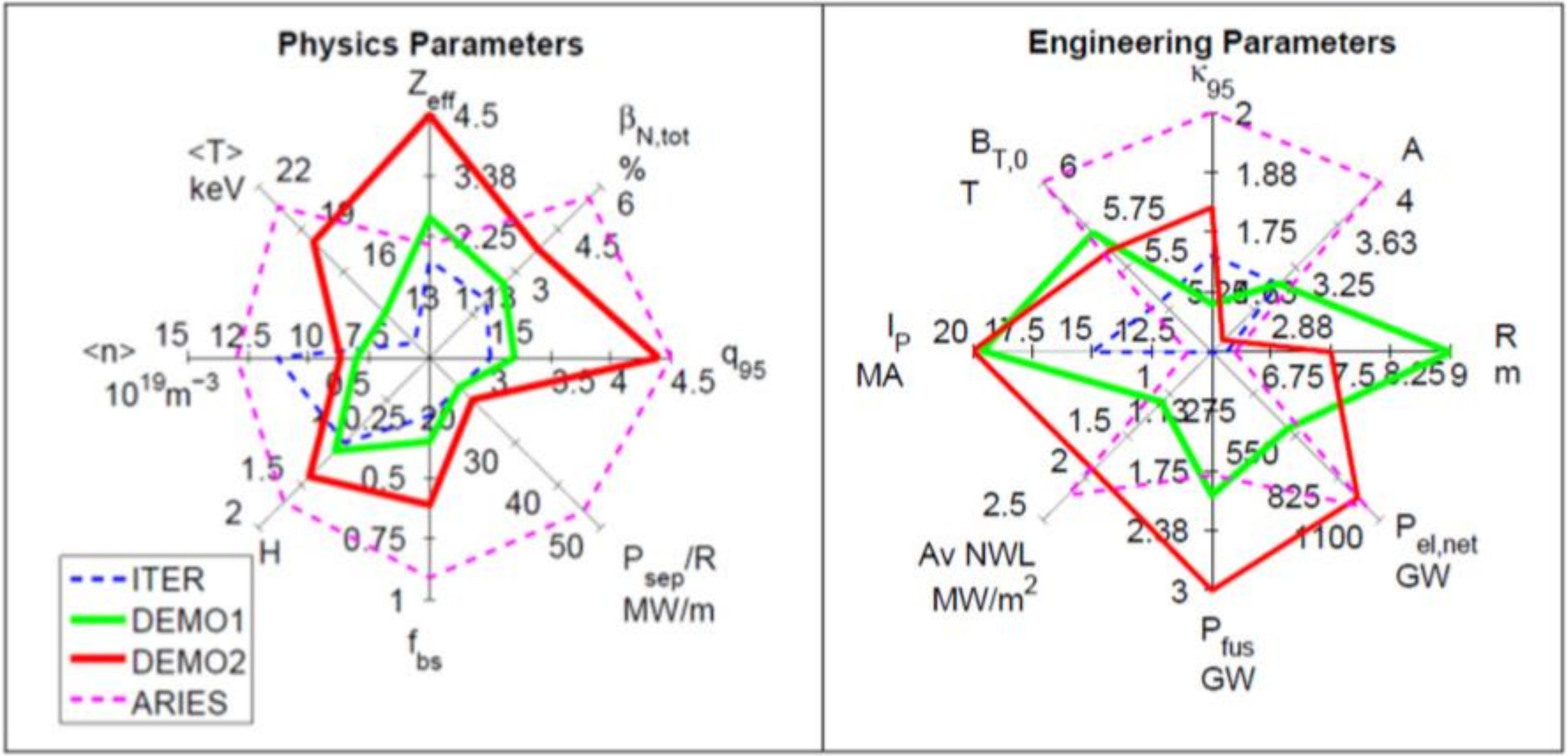
DEMO Power Plant Schematic

G. Federici et. als., Nuclear Fusion 57 (2017) 092002



DEMO Physics and Engineering Parameters

G. Federici et. als., Nuclear Fusion 57 (2017) 092002



DEMO Design Features and Key Parameters

G. Federici et. als., Nuclear Fusion 57 (2017) 092002

Main design features

– 2000 MWth ~ 500 MW_e
– Pulses > 2 h
– Single-null water cooled divertor; PFC armour: W
– LTSC magnets Nb3Sn (grading)
– B_{max} conductor ~12 T (depends on A)
– EUROFER as blanket structure and AISI ITER-grade 316 for VV
– Maintenance: Blanket vertical RH / divertor cassettes
– Lifetime: 'starter' blanket: 20 dpa (200 appm He); 2nd blanket 50 dpa; divertor: 5 dpa (Cu)

Open design choices

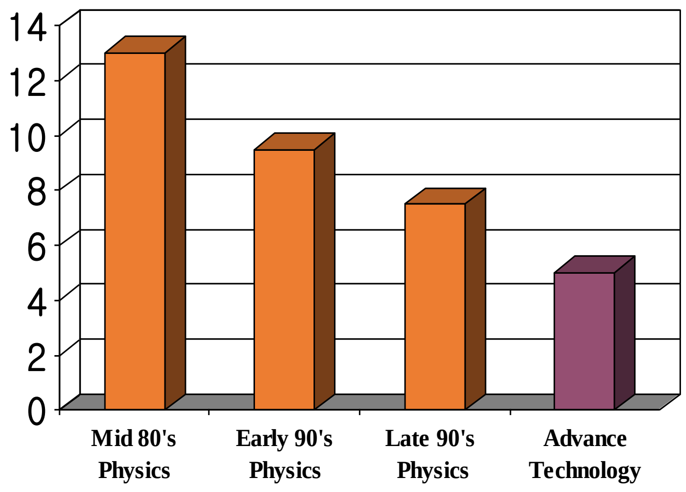
– Plasma operating scenario
– Breeding blanket design concept
– Protection strategy first wall (e.g. limiters)
– Advanced divertor configurations and/or technologies
– Energy conversion system
– Specific safety features, e.g. # of PHTS cooling loops
– Diagnostics and control systems

	ITER	DEMO1 (2015) A=3.1	DEMO2 (2015)A=2.6
R_0 /a (m)	6.2 / 2.0	9.1 / 2.9	7.5 / 2.9
K_{95}/ δ_{95}	1.7 / 0.33	1.6 / 0.33	1.8 / 0.33
A (m^2)/Vol (m^3)	683 / 831	1428 / 2502	1253 / 2217
H / β_N (%)	1.0 / 2.0	1.0 / 2.6	1.2 / 3.8
P_{sep}(MW)	104	154	150
P_F (MW) / P_{NET} (MW)	500 / 0	2037 / 500	3255 / 953
I_p (MA) / f_{bs}	15 / 0.24	20 / 0.35	22 / 0.61
B at R_0 (T)	5.3	5.7	5.6
$B_{max,cond}$ (T)	11.8	12.3	15.6
BB i/b / o/b (m)	0.45/0.45	1.1 / 2.1	1.0 / 1.9
<NWL>MW/m^2	0.5	1.1	1.9

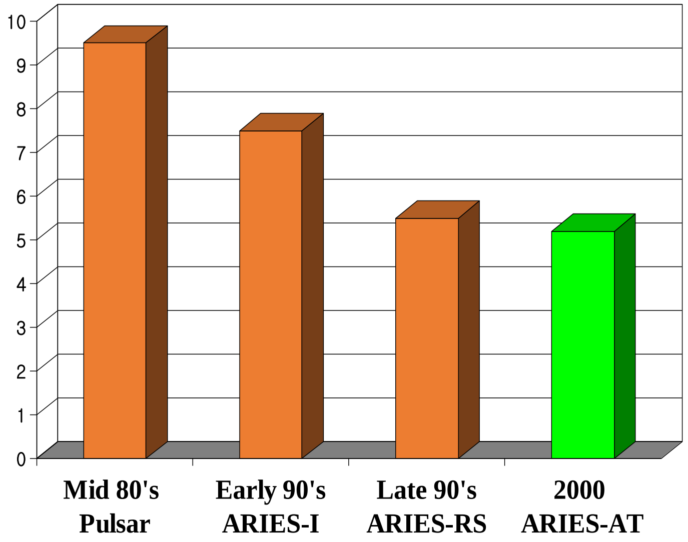
ARIES Studies in US

- Directly tied to advances in physics and Technology

Estimated Cost of Electricity (¢/kWh)



Major radius (m)



ARIES-AT parameters (based on ASC systems analysis):

Major radius:	5.2 m	Fusion Power	1,720 MW
Toroidal β:	9.2%	Net Electric	1,000 MW
Wall Loading:	4.75 MW/m^2	COE	5.5 ¢/kWh

ARIES System Code (ASC)

PPCS in EU

PPCS (Power Plant Conceptual Study) based on PROCESS systems analysis

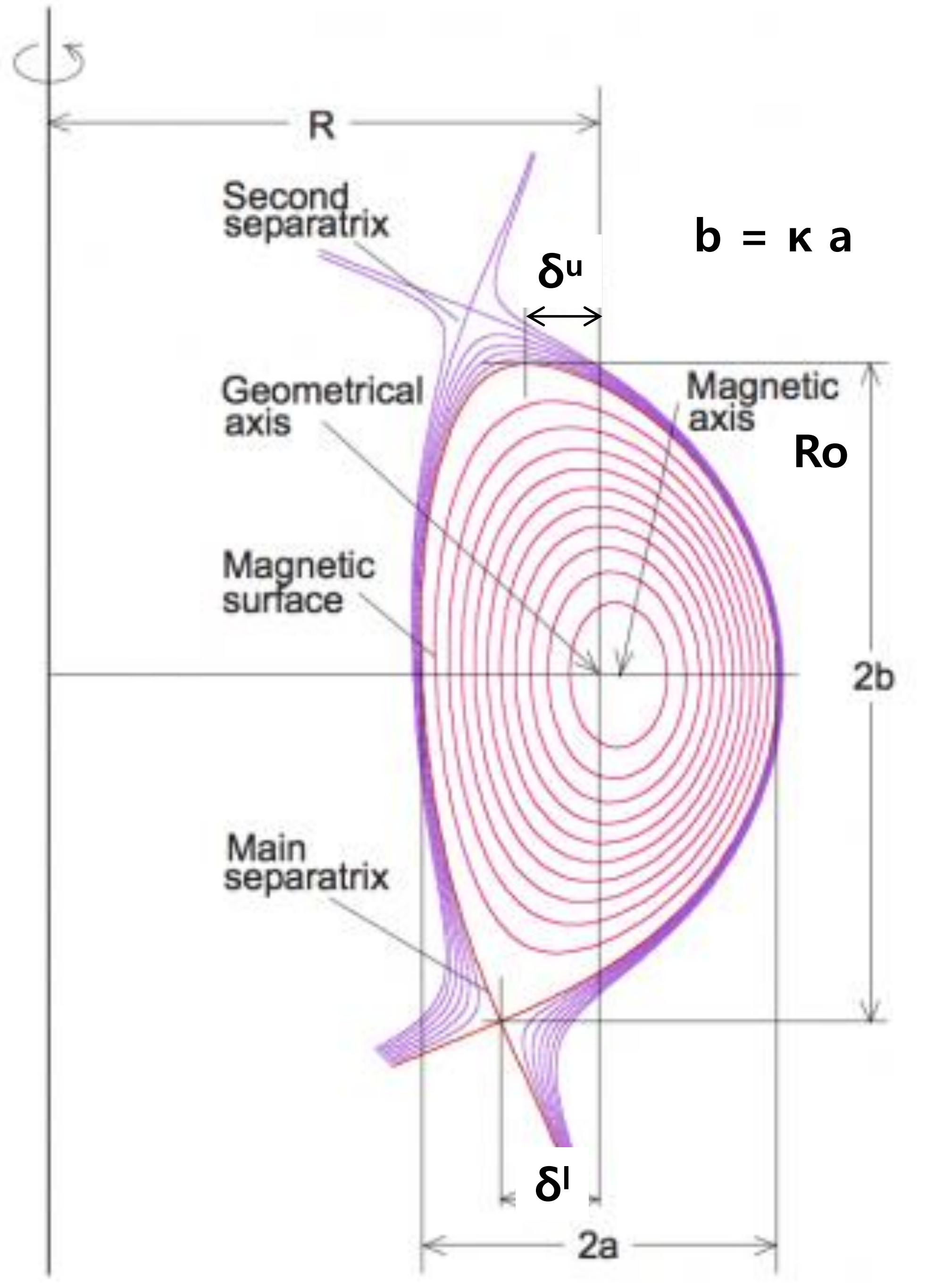
Parameter	*Model A*	*Model AB*	*Model B*	*Model C*	*Model D*	*ITER*
Blanket/cooling technology	WCLL	HCLL	HCPB	LL dual coolant	LL self cooled	-
Fusion Power (GW)	5.00	4.30	3.60	3.41	2.53	0.5
Plant net efficiency[1]	0.31/0.33[2]	0.35	0.36	0.42	0.60	-
Major Radius (m)	9.55	9.56	8.6	7.5	6.1	6.2
Plasma Current (MA)	30.5	30.0	28.0	20.1	14.1	15
β_N(thermal, total)	2.8, 3.5	2.7, 3.5	2.7, 3.4	3.4, 4.0	3.7, 4.5	2.5
H_H (IPB98y2)	1.2	1.2	1.2	1.3	1.2	1.0
Bootstrap Fraction	0.45	0.43	0.43	0.63	0.76	0.15
P_{add} (MW)	246	257	270	112	71	73
n/n_G	1.2	1.2	1.2	1.5	1.5	1.0
Q	20	16.5	13.5	30	35	10
Average neutron wall load (MWm^{-2})	2.2	1.8	2.0	2.2	2.4	0.5
Z_{eff}	2.5	2.6	2.7	2.2	1.6	2

요소기술:	Near	Far
COE:	9 €-cents/kWh	5 €-cents/kWh

System Code Development

Input parameters

	VEST	KSTAR	ITER	K-DEMO	EU DEMO1
R [m]	0.4	1.8	6.2	6.8	9.0
a [m]	0.31	0.5	2.0	2.1	2.9
elongation, κ	1.8	2.0	1.7	1.8	1.6
triangularity, δ	0.2	0.8	0.33	0.63	0.33
I_p [MA]	0.10	2.0	15.0	12.0	20.0
B_o [T]	0.1	3.5	5.3	7.4	5.9
P_H [MW]	0.100	28.0	73.0	120.0	50.0
β_N	4.0	5.0	1.8	4.0	2.6
l_i	0.6	0.7	1.0	1.0	1.0
Z_{eff}	4.0	2.0	1.7	1.5	1.5



System Code Development

Plasma performance with operational limits

Tryon beta limit

$$\beta[\%] = \beta_N l_i I_P[MA]/a[\mathrm{m}]B_o[T]$$

$$\beta \equiv \frac{<p>}{B^2/2\mu_o} = \frac{n_e kT_e + n_i kT_i}{B^2/2\mu_o} \approx \frac{2nkT}{B^2/2\mu_o}$$

$$< p > = < n_e kT_e + n_i kT_i >$$
$$= 2nkT = \beta\,(B_o^2/2\mu_o)$$

Greenwald density limit

$$n_{G,lim}[10^{20}m^{-3}] = I_P[MA]/\pi a[m]^2$$

$$n[10^{20}m^{-3}] = n_G\; n_{G,lim}$$

$$W_{th} = < 1.5p > V$$

$$kT[keV] = \frac{< p >/2}{16.09n[10^{20}m^{-3}]}$$

System Code Development

Plasma power balance

Fusion power and alpha heating

$$P_f = N_D N_T (B^4 / 16\mu_o^2)\, \beta^2\, E_f\, <\sigma v>/k^2 T^2$$

$$P_\alpha = P_f / 5$$

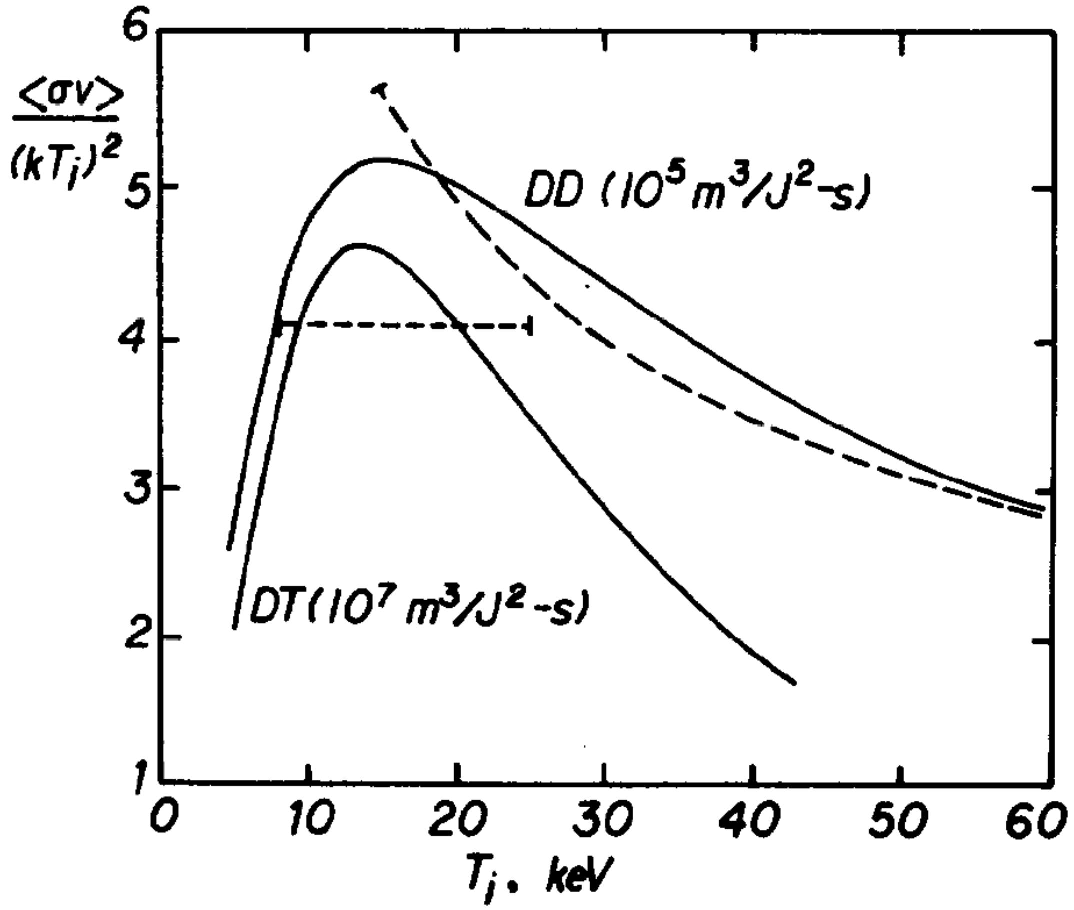
$$P_\Omega = \eta\langle j^2\rangle = 1.0\times 10^5 \left(\frac{Z_{eff}}{T^{3/2}}\right)\left[\frac{1}{q_o(q_a - q_o/2)}\right]\left(\frac{B_\phi}{R}\right)^2$$

$$q_o = 2B_\varphi / (\mu_o j_o R)$$

$$q_{cyl} = 2\pi a^2 \kappa B_\varphi / (\mu_o I R)$$

$$q_\psi \approx \left(\frac{5a^2 B_{TF}}{RI_p}\right)\left(\frac{1+\kappa^2}{2}\right)\left(\frac{A}{A-1}\right)$$

$$q_{95} = \frac{2\pi}{\mu_0}\frac{B_t a^2}{RI_p}\frac{1.17 - \frac{0.65}{A}}{\left(1 - \frac{1}{A^2}\right)^2} \times \frac{1 + \kappa_{95}^2(1 + 2\delta_{95}^2 - 1.2\delta_{95}^3)}{2}$$



T. J. Dolan, Fusion Research, Pergamon Press, 2000

$$\frac{<\sigma v>_{DT}}{(kT_i)^2} \approx 4.1 \times 10^7 \ m^3/J^2\text{-s} \quad (\pm 15\ \%\ \text{for}\ 8 \leqq T_i \leqq 25\ \text{keV})$$

4.32×10^7 $\pm 6\%$, for $9 < T_i < 20$ (2D10)

$$\frac{<\sigma v>_{DD}}{(kT_i)^2} \approx 4.0 \times 10^5 \left(\frac{30\ \text{keV}}{T_i}\right)^{\frac{1}{2}} m^3/J^2\text{-s} \quad (\pm 10\ \%\ \text{for}\ 15 \leqq T_i \leqq 70\ \text{keV})$$

(2D11)

System Code Development

Plasma power balance

Radiation losses

$$P_{rad} = P_{br} + P_{IR} + P_{sync}$$

$$P_{br} = 5.36\times10^{-37} Z^2 n_e n_Z T_e^{1/2} V = 5.36\times10^{-37} Z_{eff} n_e^2 T_e^{1/2} V$$

$$P_{IR} = n_I n_e R(T_e)$$

$$\approx n_e^2 S(Z_{eff} - 1)/7$$

* Impurity radiation model, ADAS code 와 연계

G.F. Matthews et al., Nucl. Fusion 39, 19 (1999)

$$P_{sync} = (1 - r)^{1/2} B^2 n_e T_e V$$

* Trubnikov, B.A., in Reviews of Plasma Physics (Leontovich, M.A., Ed.), Vol. 7, (1979) 345.

$$P_{syn} = 1.32\times10^{-7}(BT_{ave})^{2.5}\sqrt{\frac{An_e}{R}}\left(1+\frac{18}{A\sqrt{T_{ave}}}\right)V$$

H. Zohm et al., Nucl. Fusion **57**, 086002 (2017)

Zohm, Journal of Fusion Energy 38, 3-10(2019)

Power balance

$$P_\alpha + P_H = P_{loss} = P_{con} + P_{rad}$$

$$P_{con} = \langle Wth \rangle / \tau_E$$

Energy confinement time

System Code Development

Plasma confinement and additional heating

$$P_{con} = < Wth > / \tau_E$$

Ohmic confinement

$$\tau_E = (n/10^{20}) a^2 / 2$$ Alcator scaling

$$\tau_{nA}\ (ms) = 0.09\ n_e\ q\ \sqrt{\kappa}\ a\ R^2$$ neo-Alcator scaling

L-mode confinement

$$\tau_{89P\text{-}L}\ (ms) = 48\ I^{0.85}\ R^{1.2}\ a^{0.3}\ \kappa^{0.5}\ B^{0.2}\ A^{0.5}\ n_e^{-0.1}\ P^{-0.5}$$ ITER 89P-L scaling

H-mode confinement

$$\tau_{Eth}^{ELMy} = 0.0562\ I_p^{0.93}\ B^{0.15}\ P^{-0.69}\ n^{0.41}\ A_i^{0.19}\ R^{1.97}\ \varepsilon^{0.58}\ \kappa^{0.78}\ (s, MA, 10^{19}\ m^{-3})$$

$$\tau_E \equiv < Wth > / P_{con} = \tau_{Eth}^{ELMy} H$$

$$P_{con} = < Wth > / \tau_{Eth}^{ELMy} H$$

* P in scaling law is defined differently in various system codes.

Additionally required heating

$$P_H = P_{con} + P_{rad} - P_\alpha$$

Ex) PROCESS : “loss power” P_L, which we interpret as power transported out from the “core” by charged particles

$$P_L = P_H + P_{OH} + P_\alpha - P_{rad}$$

$$P_{loss} = P_\alpha + P_{ohmic} + P_{aux} - P_{brem} - P_{cycl} - P_{line}/3$$

System Code Development

Reactor criteria

Lawson Criteria : P_{loss} < $P_f/3$ $\quad n_D = n_T = n/2$

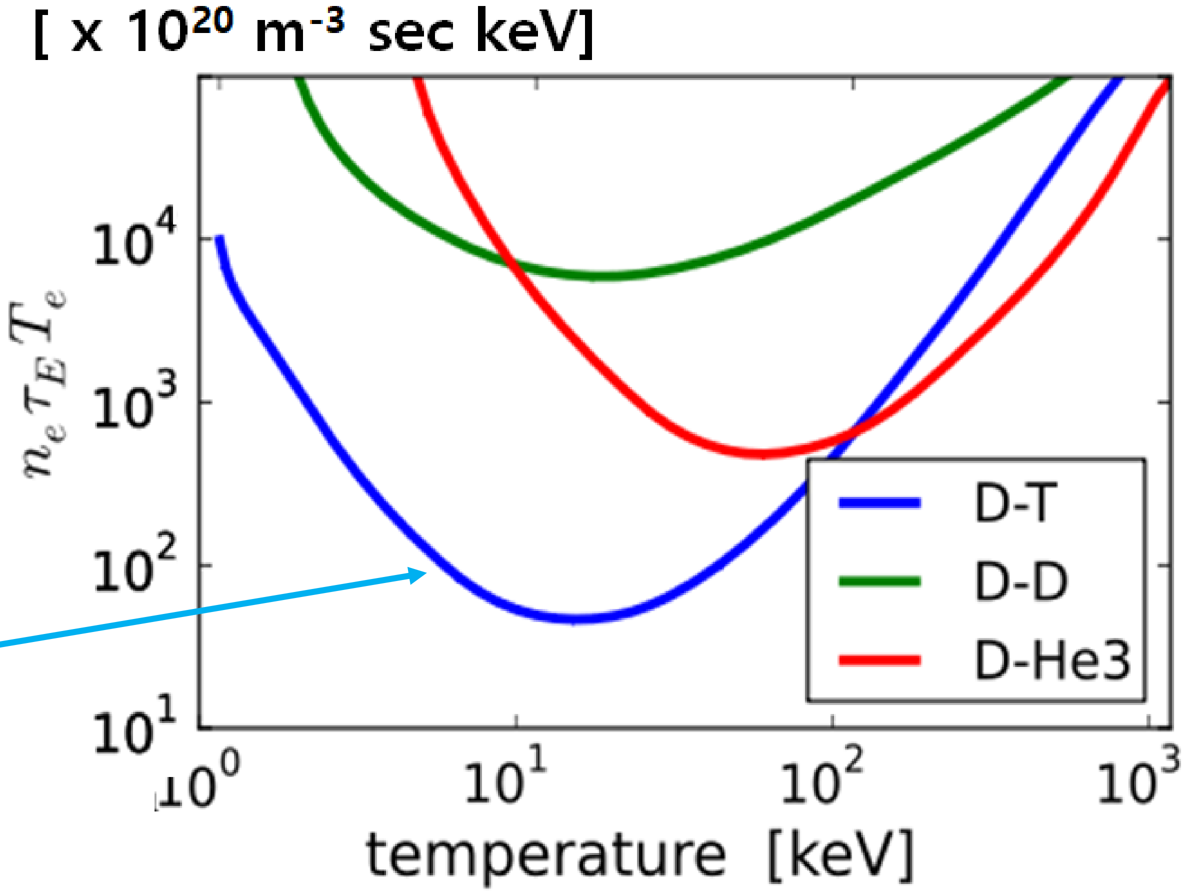
$$P_{loss} = 3nkT/\ _E < P_f/3 = n^2\langle\sigma v\rangle E_f\ /12$$

$$\longrightarrow \quad nkT\tau_E > 36k^2T^2/\langle\sigma v\rangle E_f$$

Ignition : P_{loss} < P_α $\quad E_\alpha = E_f\ /5$

$$P_{loss} = 3nkT/\ _E < P_f/5 = n^2\langle\sigma v\rangle E_f\ /20$$

$$\longrightarrow \quad nkT\tau_E > 60k^2T^2/\langle\sigma v\rangle E_f$$

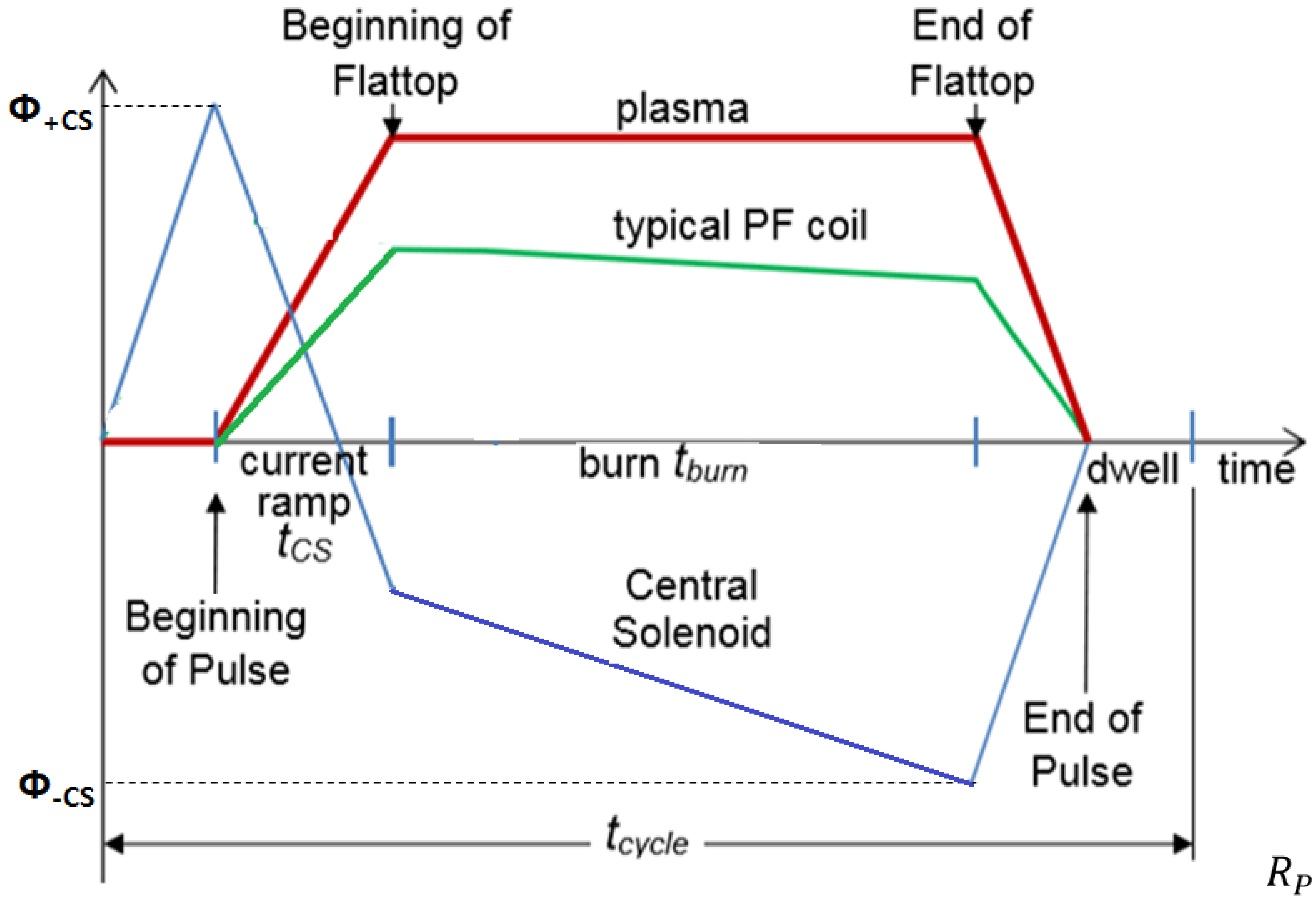


Ignition with radiation losses specified

$$P_{loss} = 3nkT/\ _E + P_{rad} < P_f/5 = n^2\langle\sigma v\rangle E_f\ /20$$

Inductive Start-up

Ohmic operation and flux consumption



Flux consumptions during start-up

$$\Delta\Phi_{CS} + \Delta\Phi_{PF} = -(\Delta\Phi_{res} + \Delta\Phi_{ind})$$

$$\Delta\Phi_{res} = C_E\, \mu_o\, I_p\, R_o$$

$$\Delta\Phi_{ind} = L_p\, I_p$$

$$L_p = L_e + L_i = \mu_o R_o \left(\ln\frac{8Ro}{a} + \frac{l_i}{2} - 2 \right)$$

$$\frac{L_e}{\mu_0 R_0} = \frac{f_a(1-\epsilon)}{(1-\epsilon) + \kappa f_b}$$

Low aspect ratio

Total flux consumptions

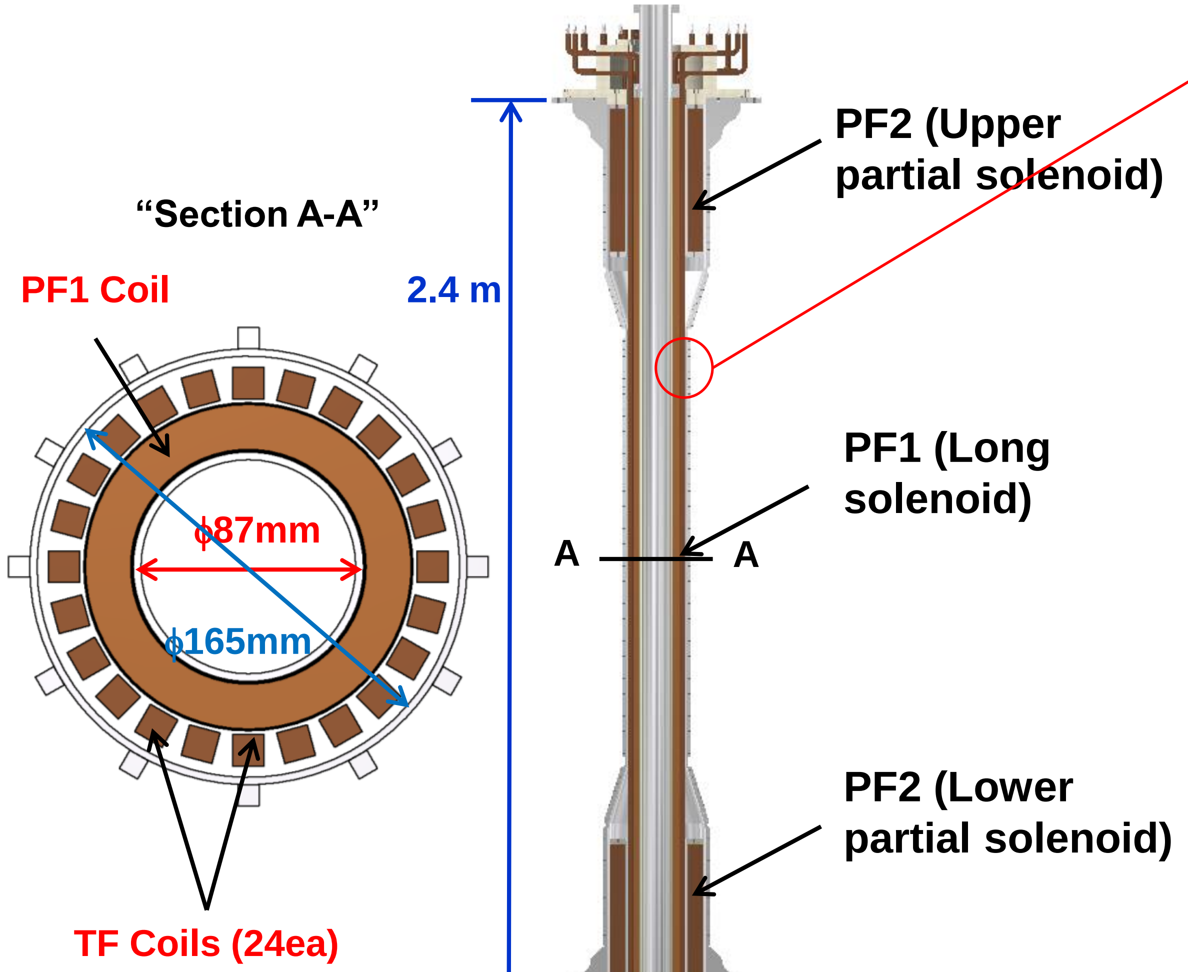
$$\Phi_{tot} = \Delta\Phi_{res} + \Delta\Phi_{ind} + \Phi_{burn}$$

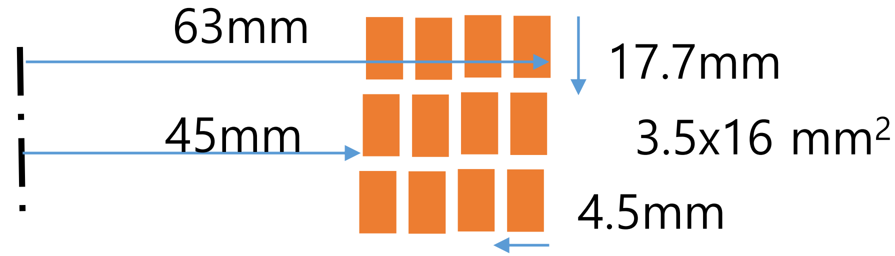
$$\Phi_{burn} = V_{burn}\, t_{burn}$$

$$V_{burn} = I_p\, R_p$$

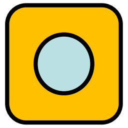
$$R_P = 5\times 10^{-5} \times \ln\Lambda \times Z_f \times \frac{2R}{a} \times T_e^{-\frac{3}{2}}$$

TF and PF Magnets





8.33kA/0.1T
→ 7.2kA/cm²



OFHC Cu
(12x12, ϕ6)

Stress limit:
Tensile strength of Cu ~ 70 MPa

Parameters	PF1	PF2
Initial Goal	**Large plasma of 30 kA**	**Small plasma of 10 kA**
Volt-sec [mV-s]	**~ 55**	**~ 20**
Required A-T [MA]	**5.2**	**0.21**
R_{in} / R_{out} [m]	0.045 / 0.063	0.08 / 0.125
Coil length [m]	2.8	0.5
Wire size [mm²]	56.0 (3.5 x 16)	56.0 (3.5 x 16)
N [#]	632 (4 x 158)	250 (10 x 25)
I_{Peak} [kA]	**7.3**	**0.84**
Driving Circuit	RLC double swing	RLC double swing
R [mΩ]	68	52 each
L [mH]	1.6	3.7 each
C [mF]	200 / 1 / 500	10 / 0.2 / 50
V_0 [kV]	+1.0 / +1.0 / -2.0	+0.7 / +0.7 / -0.5
Max. achievable V-s [mV-s] @stress limit	**130**	**545**
I_{Peak} [kA] @stress limit	**27.3**	**14.0**
B_{Peak} [T] @stress limit	**7.4**	**8.0**
Max. sustaining time @thermal limit (90°C)	**~ 50 ms**	**~ 180 ms**