Prospects for pilot plants based on the tokamak, ST, and stellarator

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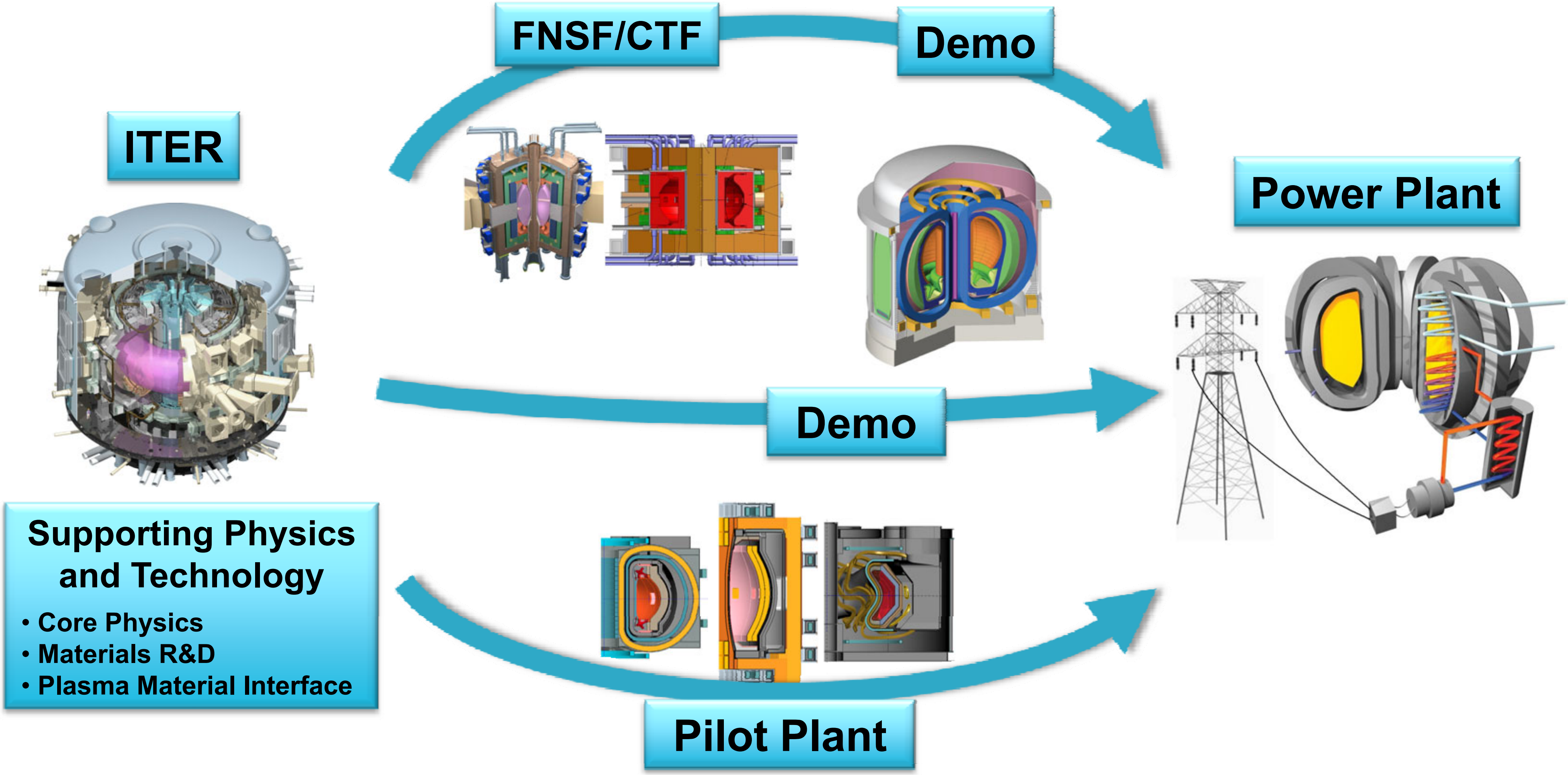
Exploring "Pilot Plant" as a possible pathway from ITER to commercial fusion power plant



ITER

FNSF/CTF

Demo

Demo

Pilot Plant

Power Plant

Supporting Physics and Technology

- Core Physics
- Materials R&D
- Plasma Material Interface

FNSF = Fusion Nuclear Science Facility
CTF = Component Test Facility

Overview of Pilot Plant study

- Goal of study:

  Assess feasibility of integrating key science and technology capabilities of a fusion power plant at reduced device size

- Targeted capabilities:
  - Fusion Nuclear Science research, Component Testing
    - Steady-state plasma operating scenarios
    - Neutron wall loading ≥ $1 MW/m^2$
    - Tritium self-sufficiency
  - Maintenance scheme applicable to power plant
    - Demonstrate methods for fast replacement of in-vessel components
  - Small net electricity production
    - Bridge gap between ITER/CTF and power plant (~1-1.5 GWe)

Motivation for studying 3 configurations:

- Advanced Tokamak (AT)
  - Most mature confinement physics, technology
- Spherical Tokamak (ST)
  - Potential for simplified maintenance, reduced cost
- Compact Stellarator (CS)
  - Low re-circulating power, low/no disruptions

Key pilot metric is overall electrical efficiency: Q_{eng}

$$Q_{eng} = \frac{\textit{Electricity produced}}{\textit{Electricity consumed}} = \frac{\eta_{th}(M_n P_n + P_\alpha + P_{aux} + P_{pump})}{\dfrac{P_{aux}}{\eta_{aux}} + P_{pump} + P_{sub} + P_{coils} + P_{control}}$$

$$Q_{eng} = \frac{\boxed{\eta_{th}\eta_{aux}Q}(4M_n + 1 + 5/Q + 5P_{pump}/P_{fus})}{5(1+\eta_{aux}QP_{extra}/P_{fus})}$$

η_{th} = thermal conversion efficiency
η_{aux} = injected power wall plug efficiency
Q = fusion power / auxiliary power

M_n = neutron energy multiplier
P_n = neutron power from fusion
P_α = alpha power from fusion
P_{aux} = injected power (heat + CD + control)
P_{pump} = coolant pumping power
P_{sub} = subsystems power
P_{coils} = power lost in coils (Cu)
$P_{control}$ = power used in plasma or plant control that is not included in P_{inj}
P_{extra} = $P_{pump} + P_{sub} + P_{coils} + P_{control}$

Blanket and auxiliary heating and current-drive efficiency + fusion gain largely determine electrical efficiency Q_{eng}

Pumping, sub-systems power assumed to be proportional to $P_{thermal}$ – needs further research

Assumptions and constraints

- Surface-average neutron wall loading: $\langle W_n \rangle \geq 1$ MW/m^2
- Blanket thermal conversion:
  - $\eta_{th} = 0.3, 0.45$ – this range incorporates leading concepts: **He-cooled pebble-bed (HCPB), dual-coolant lead-lithium (DCLL)**
- Steady-state operating scenarios:
  - AT/ST: fully non-inductive CD (BS+RF/NBI)
  - AT/CS: Superconducting (SC) coils, ST: Cu TF and SC PF
- Confinement and stability:
  - AT/ST: $\tau_E \propto$ ITER H-mode IPB98(y,2), β_N near/above no-wall limit
  - CS: $\tau_E \propto$ stellarator L-mode ISS-04, $\beta \leq 6\%$ (ARIES-CS)

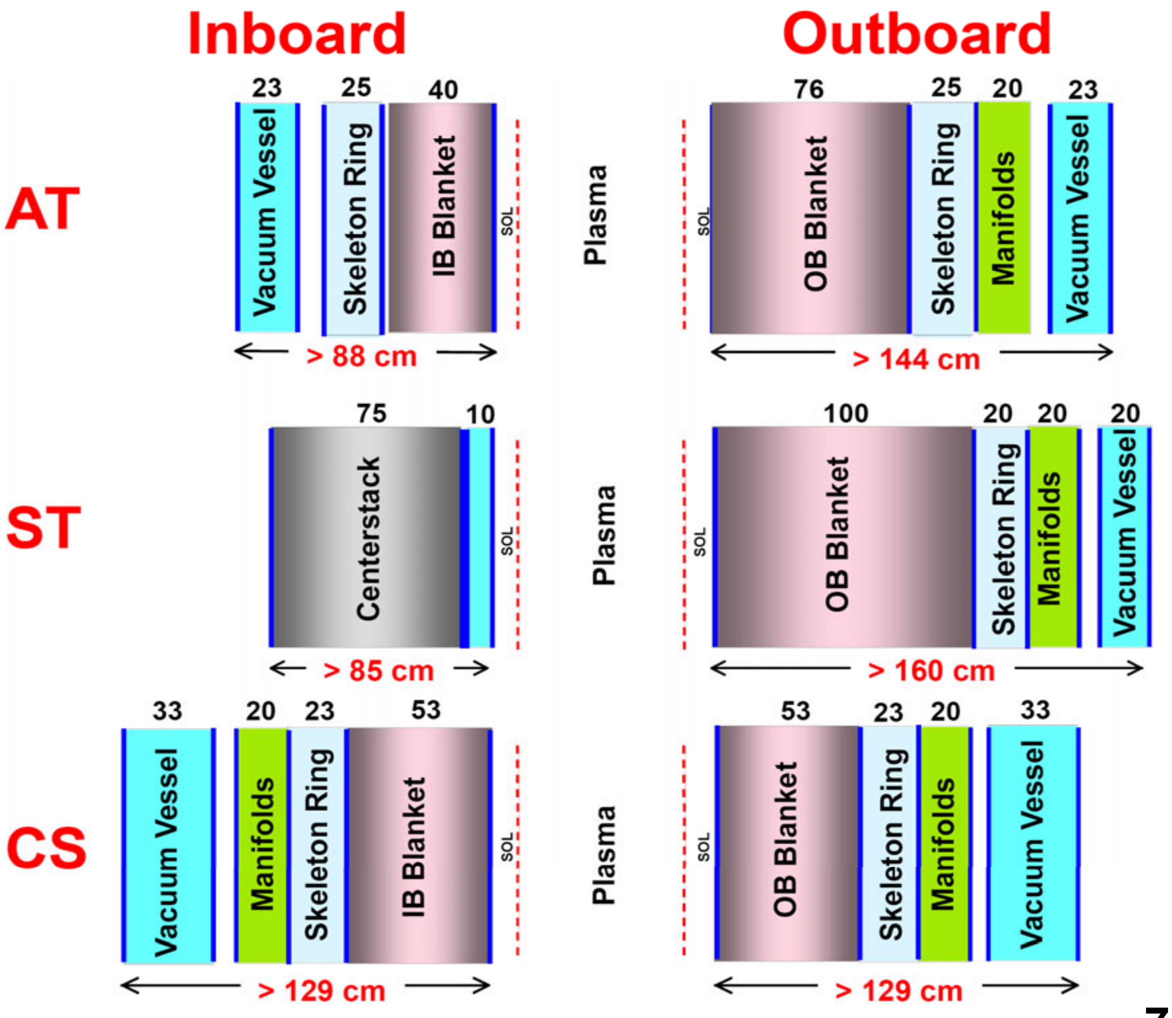
1D neutronics calculations used to develop preliminary pilot plant radial builds

- 20 year plant lifetime, 6 full power years (FPY), 30% average availability,
- Blanket replacement: **AT:** 2.5 FPY, **ST:** 1.8/1.4 FPY IB/OB, **CS:** 1.7 FPY
- Skeleton-ring, vessel, SC coils are lifetime components, vessel re-weldable

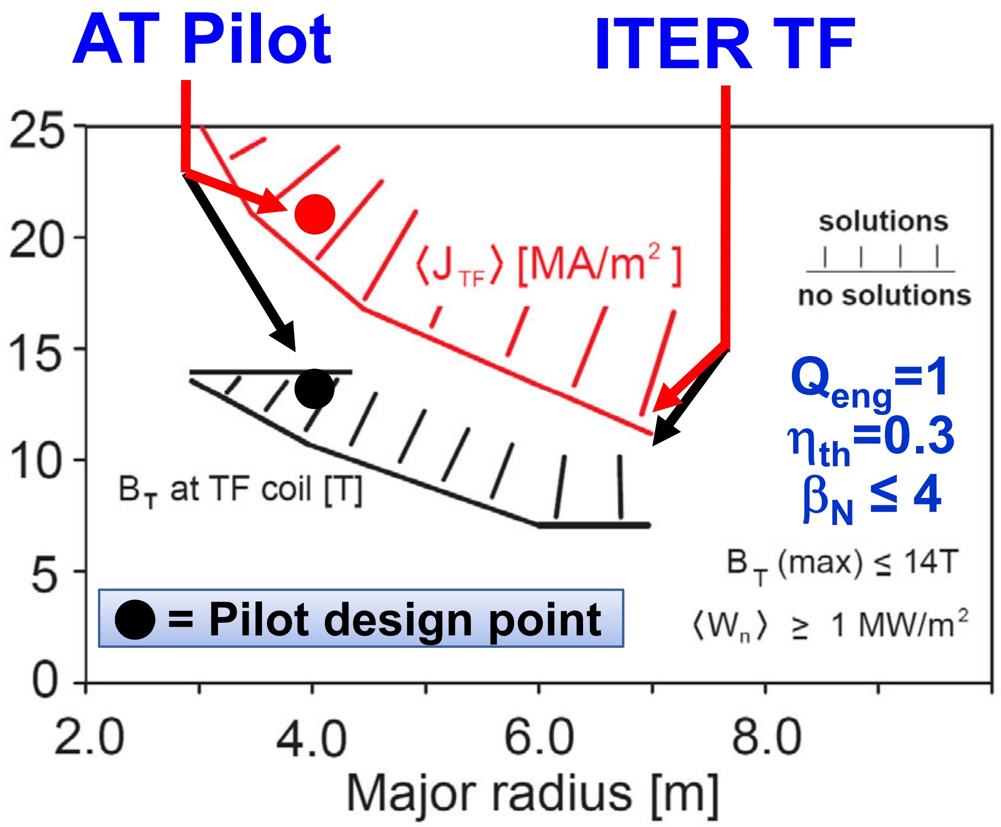
- **Use DCLL blankets**
- **TBR ~1.1 for 1.0 net**

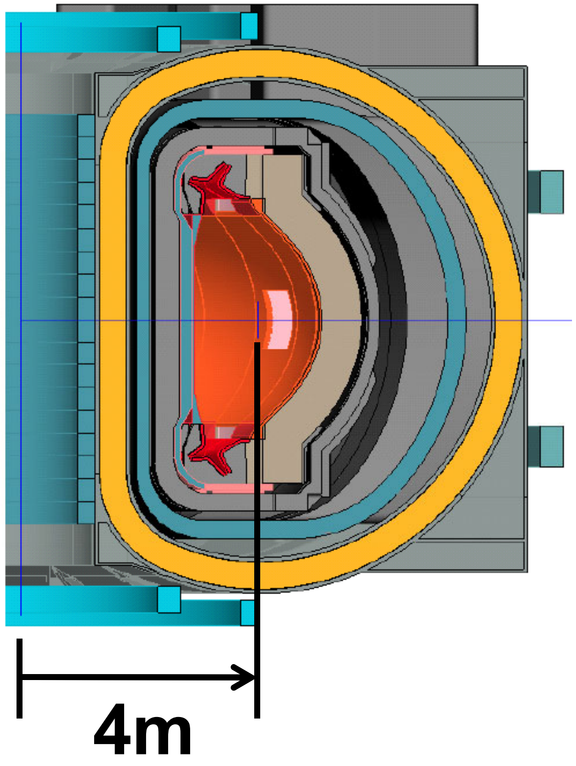
(assuming full blanket coverage)

- Damage to FS ≤ 80 dpa
- Re-weldability: ≤ 1 He appm
- SC magnets operated at 4K
  - Peak fast neutron fluence to Nb_3Sn (E_n > 0.1 MeV) ≤ 10^{19} n/cm^2,
  - Peak nuclear heating ≤ 2mW/cm^3,
  - Peak dpa to Cu stabilizer ≤ 6×10^{-3} dpa
  - Peak dose to electric insul. ≤ 10^{10} rads



Size of AT pilot driven by magnet technology

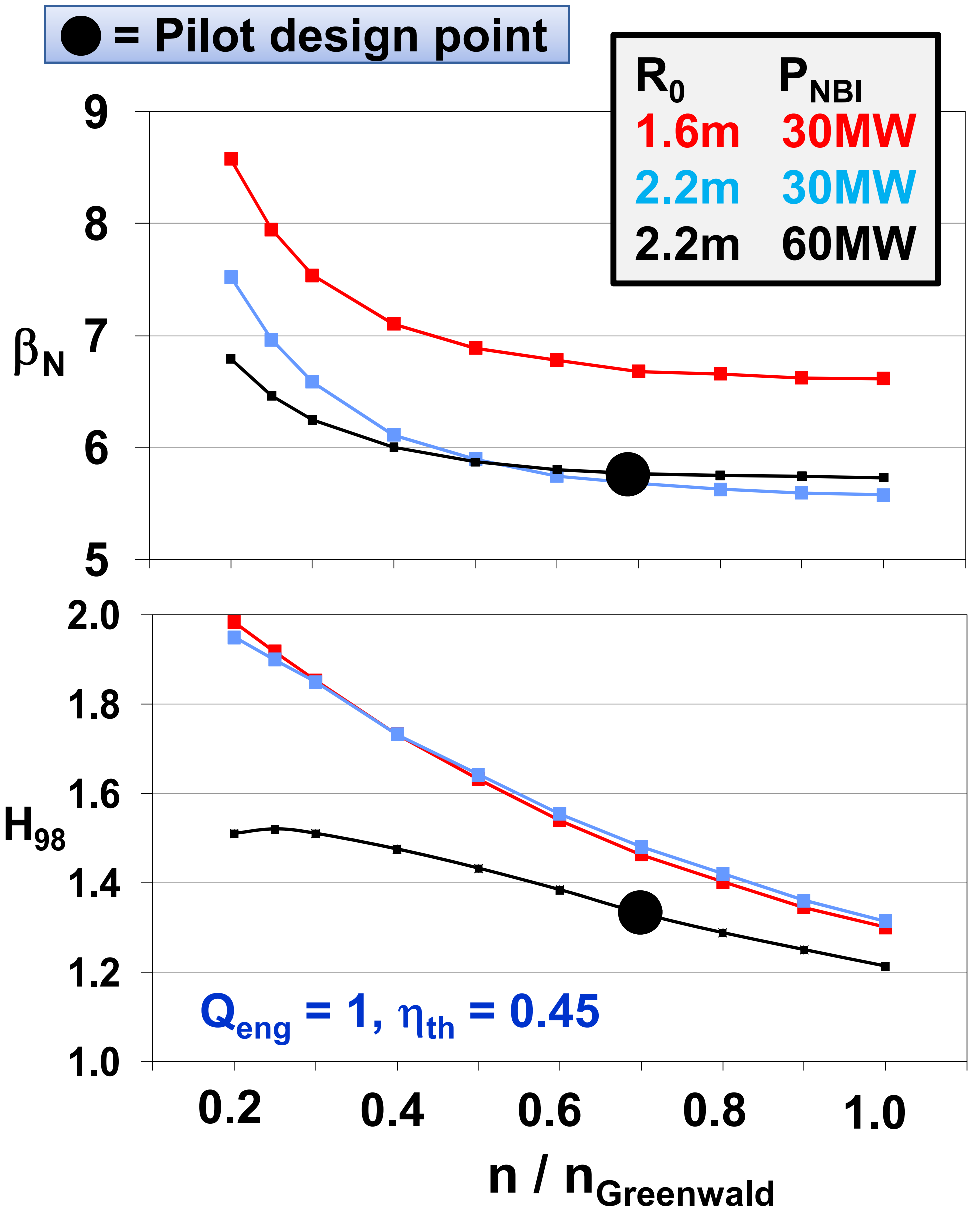


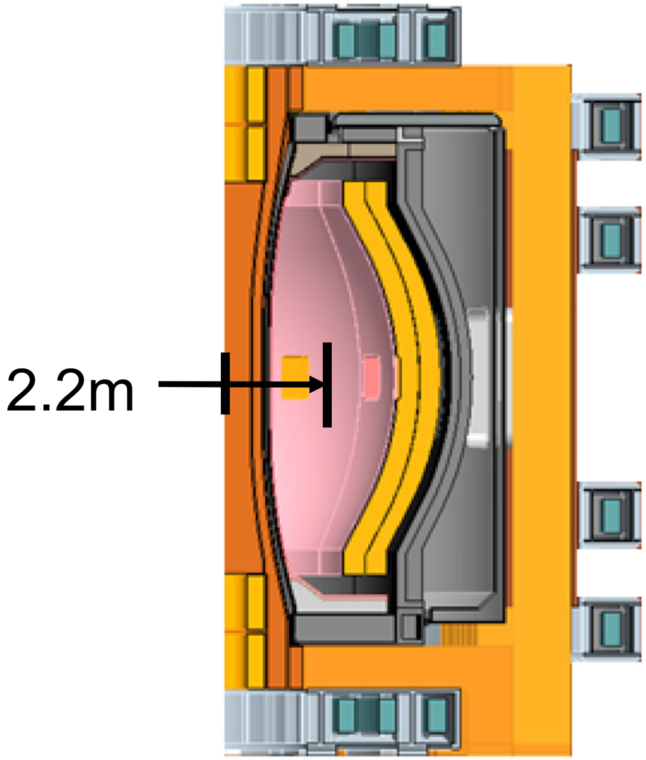


- For ITER TF magnet parameters, AT pilot would have R_0 = 6-7m
- Advances in SC TF coil technology and design needed (also needed for CS pilot)

- A = 4 = 4m / 1m
- B_T = 6T, I_P = 7.7MA
- Avg. W_n = 1.3-1.8 MW/m^2
- Peak W_n = 1.9-2.6 MW/m^2

Size of ST pilot depends primarily on achievable β_N



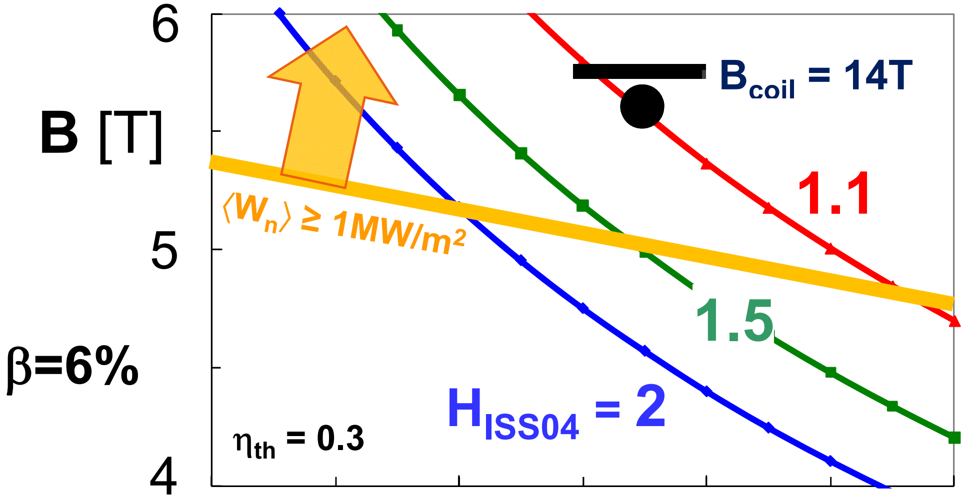


- A = 1.7 = 2.2m / 1.3m
- $B_T = 2.4T$, $I_P = 18\text{-}20MA$
- Avg. $W_n = 1.9\text{-}2.9\ MW/m^2$
- Peak $W_n = 3\text{-}4.5\ MW/m^2$

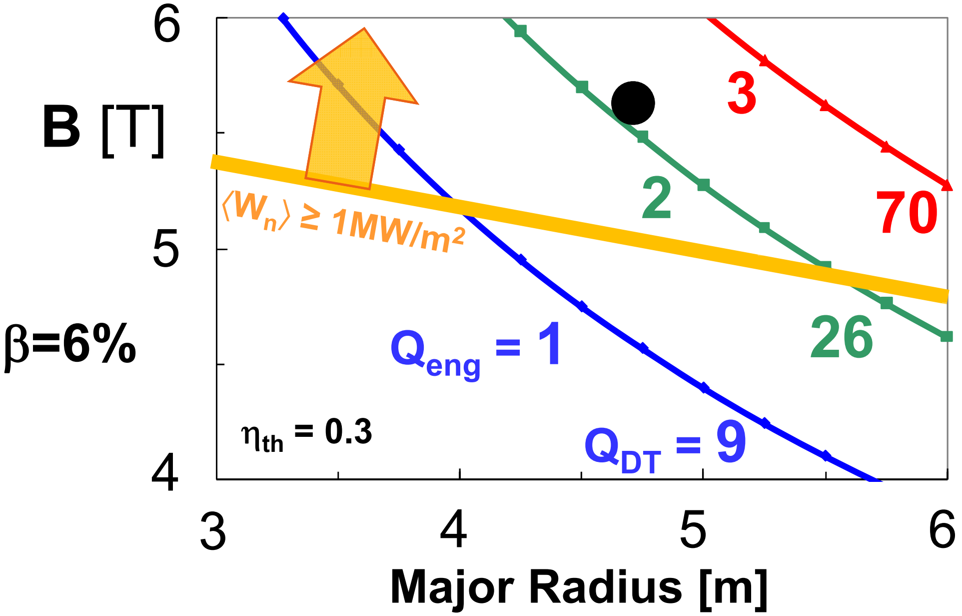
Higher density favorable for reducing β_N and H_{98} (also fast ion fraction)

Size of CS pilot driven by magnet technology and neutron wall loading, but not Q_{eng}

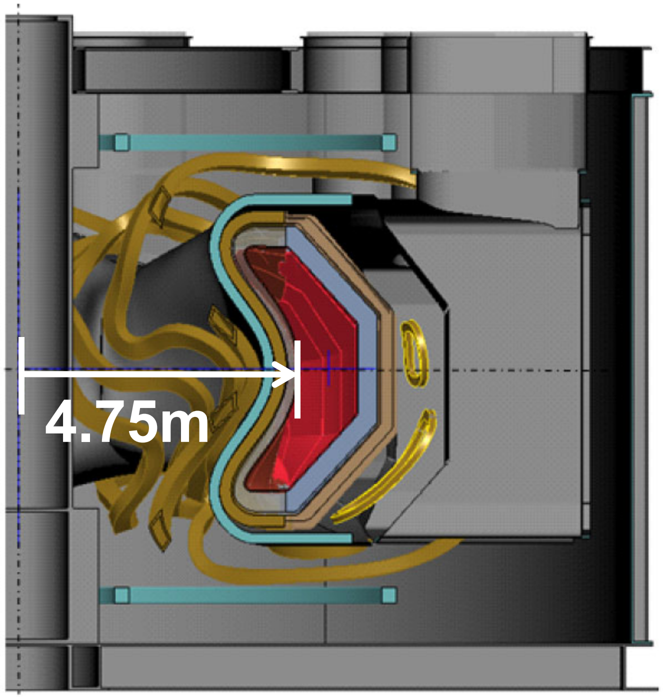
Q_{eng}=1.1 accessible at H_{ISS04} ≥ 1.1



H_{ISS04}=2 → Q_{eng}=2-3, high Q_{DT}



● = Pilot design point



- A = 4.5 = 4.75m / 1.05m
- B_T = 5.6T, I_P = 1.7MA (BS)
- Avg. W_n = 1.2-2 MW/m²
- Peak W_n = 2.4-4 MW/m²

Pilot plant parametric trends:

	AT		ST		CS	
η_{th}	0.30	0.45	0.30	0.45	0.30	0.45
A = R_0 / a	4	4	1.7	1.7	4.5	4.5
R_0 [m]	4	4	2.2	2.2	4.75	4.75
P_{fus} [MW]	553	408	990	630	529	313
P_{aux} [MW]	79	100	50	60	12	18
$\langle W_n \rangle$ [MW/m^2]	1.8	1.3	2.9	1.9	2	1.2
Peak W_n [MW/m^2]	2.6	1.9	4.5	3.0	4.0	2.4
Q_{DT}	7.0	4.1	19	10.5	42	17
Q_{eng}	1	1	1	1	2.7	2.7

Size:

~2/3 linear scale of ARIES-AT/ST/CS

Fusion power:

AT, CS = 0.3-0.6GW, ST 1.5-2× higher

Neutron wall loading:

ST highest due to higher P_{fusion}

$Q_{DT,}$ Q_{eng}:

- Higher η_{th} reduces Q_{DT} ~ factor of 2
- CS Q_{eng} highest due to small P_{aux}

Peak neutron wall loading ~1MW/m^2 accessible at modest performance:

Example: AT/ST with P_{fus}~200MW, Q_{DT}=2.5/3.5, β_N=2.7/3.9

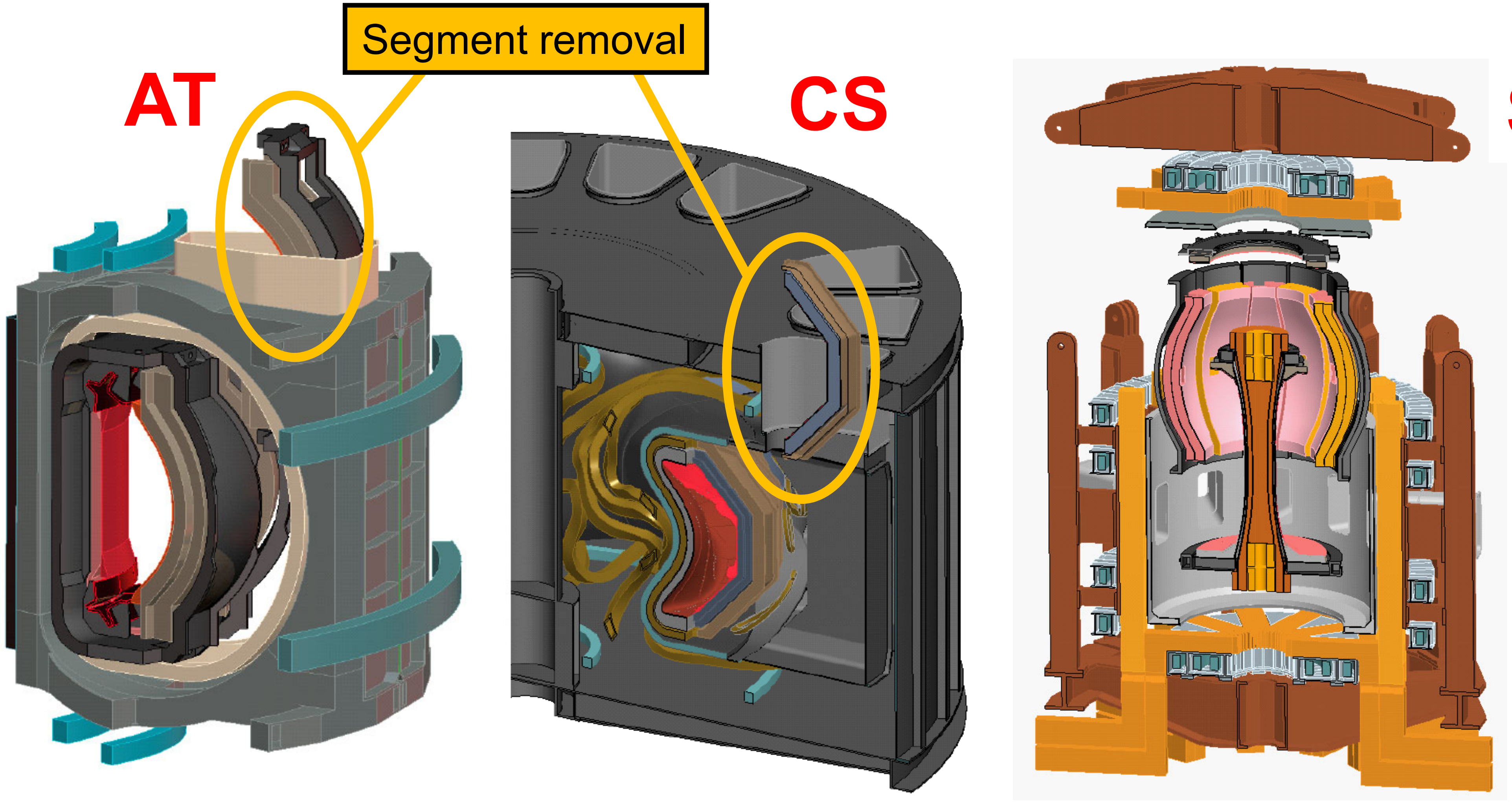
Pilot Plant can perform blanket development

- $Q_{eng}=1 \rightarrow P_{fus}=0.3\text{-}1$ GWth → 17-56kg of T per FPY
  - World T supply (CANDU) peaks at ~25-30 kg by 2025-2030
  - ITER + T decay projected to consume most of this amount
- Blanket development requirements: [Abdou, M. A., et al. Fus. Technol. 29 (1996) 1]
  - Local $W_{neutron} \geq 1$ MW/m^2, test area ≥ 10 m^2, volume ≥ 5 m^3
  - Three phases:
    - I. Fusion break-in ~ 0.3 MWy/m^2
    - II. Engineering feasibility ~ 1−3 MWy/m^2
    - III. Engineering development, reliability growth, ≥ 4-6 MWy/m^2 accumulated
- All three pilots have sufficient testing area, volume
- To achieve Phase III 6MWy/m^2 (peak) → 45-72 kg T

➔ Need TBR ≈ 1 (Example: need TBR ≥ 0.9 for 5-7 kg available T)

All 3 configurations employ vertical maintenance

- AT and CS: segments translated radially, removed vertically
- ST: Top TF legs demountable, core/CS removed vertically
- Future work: maintenance schemes for smaller components



Substantial R&D needed for FNSFs, pilots

- Improved magnet technology:
  - SC AT/CS: Higher TF magnets at ~2× higher current density
  - ST: Large single-turn radiation-tolerant Cu TF magnets
  - CS: Further R&D of shaping by trim coils, HTS monoliths
- High-efficiency non-inductive current drive for AT/ST
- Advanced physics:
  - AT/ST pilot: 100% non-inductive, high κ and β, low disruptivity
  - ST additionally requires non-inductive I_P ramp-up
  - QAS CS: need basis for simultaneous high confinement & β
- Plasma-material interface capabilities beyond ITER:
  - Long-pulses (~10^6s), high duty-factor (10-50% availability goal)
  - High power-loading (P/S_{wall}~$1MW/m^2$, P/R~30-60MW/m, W/S~0.5-$1MJ/m^2$)
  - High-temperature first-wall (T_{wall} ~ 350-550C, possibly up to 700C)

Summary

- Identified Pilot Plant configurations sized between FNSF/CTF and a conventional Demo incorporating:
  - Radial builds compatible with shielding requirements, TBR~1
  - Neutron wall loading ≥ 1MW/m^2 for blanket development
    - Average W_n up to 2-3 MW/m^2 → accelerated blanket development
  - Maintenance schemes applicable to power plants
  - Small net electricity to bridge gap to GWe power plant

Appears feasible to integrate R&D capabilities needed for fusion commercialization in modest size device

Pilot Plant could be last step before first-generation commercial fusion system

Backup slides

Limit on SC TF coil effective current density is driven primarily by structural limits

- Possible ways to increase effective current density:
  - Alternative structural concepts: bucking versus wedging
  - Increased allowable stress via reduced cycling of magnet
  - Increased structural fraction by improvements in conductor:
    - superconducting properties, quench detection schemes resulting in decreased Cu requirements, decreased He
  - Grading of the conductor

Estimate that improvements above could increase effective current density by factor ≥ 1.5 *(L. Bromberg)*

- Reference:
  - J.H. Schultz, A. Radovinsky, and P. Titus, Description of the TF Magnet and FIRE-SCSS (FIRE-6) Design Concept, PSFC report PSFC/RR-04-3

More details on assumptions and constraints

- Surface-average neutron wall loading: $\langle W_n \rangle \geq 1$ MW/m^2
  - Neutron wall load peaking factors (peak/avg): AT/ST/CS = 1.43/1.56/2.0
- Blanket thermal conversion:
  - η_{th} = 0.3, 0.45 – this range incorporates leading concepts: **He cooled pebble-bed (HCPB), dual-coolant lead-lithium (DCLL)**
    - **M_n = 1.1, blanket coolant pumping power $P_{pump} = 0.03 \times P_{th}$, $P_{sub} + P_{control} = 0.04 \times P_{th}$**
- Steady-state operating scenarios:
  - Fully non-inductive CD (BS+RF/NBI) for AT/ST
    - **$\eta_{aux} = 0.4$, $\eta_{CD} = I_{CD}R_0n_e/P_{CD} = 0.3 \times 10^{20}$A/Wm^2**
  - Superconducting (SC) coils for AT/CS, SC PF for ST
- Confinement and stability:
  - AT/ST: $\tau_E \propto$ ITER H-mode IPB98(y,2), β near/above no-wall limit
    - **$\beta_N \leq$ present experimental values, density at or below Greenwald limit**
  - CS: $\tau_E \propto$ stellarator L-mode: ISS-04, $\beta \leq 6\%$ (ARIES-CS)
    - **Quasi-axisymmetry (QAS) for tokamak-like confinement, but higher n, lower T**

Pilot plant parameters at $Q_{eng} \geq 1$:

	AT		ST		CS	
η_{th}	0.30	0.45	0.30	0.45	0.30	0.45
$A = R_0 / a$	4	4	1.7	1.7	4.5	4.5
R_0 [m]	4	4	2.2	2.2	4.75	4.75
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Q_{DT}	7.0	4.1	19	10.5	42	17
Q_{eng}	1	1	1	1	2.7	2.7

	AT		ST		CS	
κ	2	2	3.3	3.3	1.8	1.8
B_T [T]	6	6	2.4	2.4	5.6	5.6
I_P [MA]	7.7	7.7	20	18	1.7	1.7
q_{95}	3.8	3.8	7.3	7.8	1.5	1.5
q_{cyl}	2.4	2.4	2.8	3.0	-	-
f_{BS} or iota from BS	0.59	0.5	0.89	0.85	0.2	0.2
n_e/n_G	0.9	0.8	0.7	0.7	-	-
H_{98} or H_{ISS04}	1.2	1.1	1.35	1.3	2	1.6
β_T [%]	4.6	3.9	39	30	6	6
β_N	3.6	3	6	5.2	-	-