Magnetic Fusion Pilot Plant Studies

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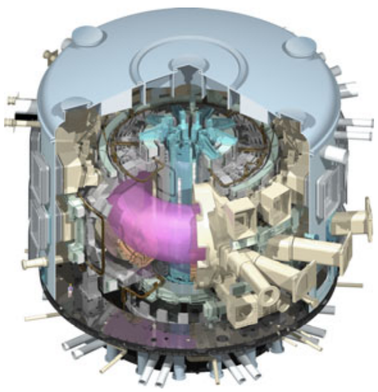
U.S. DEPARTMENT OF ENERGY

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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

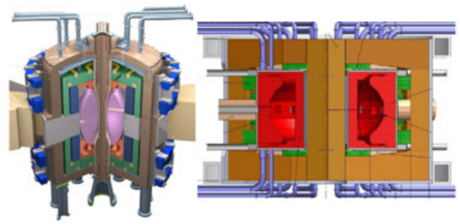
FNSF = Fusion Nuclear Science Facility
CTF = Component Test Facility

ITER



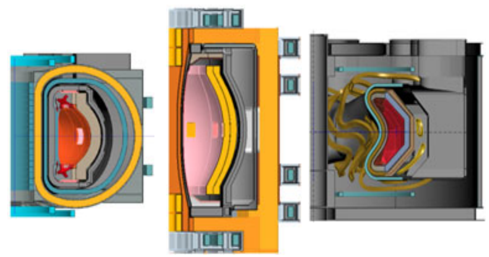
Supporting Physics and Technology

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



FNSF/CTF

- Blanket R&D, T self-sufficiency



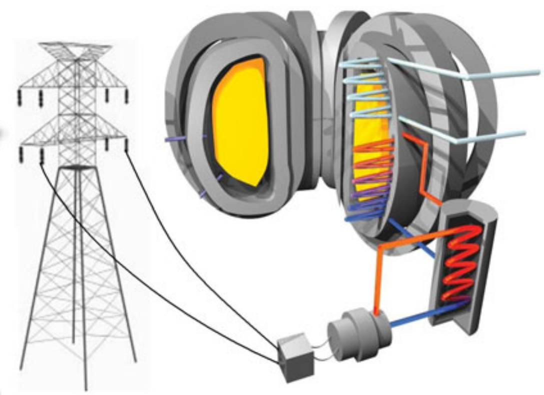
Pilot Plant

- Power-plant-like maintenance, $Q_{eng} = 1$

Q_{eng} = 3-5

- $P_{electric}$ near power plant levels

First of a kind Power Plant (= U.S. Demo)



Strategic purposes of the pilot plant study

1. Understand the characteristics of pilot plant
   - Role as step to commercial magnetic fusion energy (MFE)
   - Identify pre-requisite R&D, remaining gaps to MFE
2. Provide a menu (for comparison) of possible MFE roadmaps, with and without a pilot plant.
   - "Existence proof" of a path to MFE
3. Contribute to the national Pathways Activity.
   - Follow a "roll-back from Demo" approach.
   - Help define mission, needed characteristics, and R&D needs for a next-step facility.
   - Help define requirements for near-term research programs in materials-related research.

Pilot plant goals, capabilities

- Pilot Plant goal:

  Integrate key science and technology capabilities of a fusion power plant in a next-step R&D facility.

- Targeted ultimate capabilities:
  - Fusion nuclear S&T development, component testing
    - Steady-state operating scenarios
    - Neutron wall loading ≥ 1MW/m^2
    - Tritium self-sufficiency
  - Maintenance scheme applicable to power plant
    - Demonstrate methods for fast replacement of in-vessel components
  - Net electricity production

Q_{eng} ~ 1 requires improved technology and physics

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

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

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} = $P_{pump} + P_{sub} + P_{coils} + P_{control}$

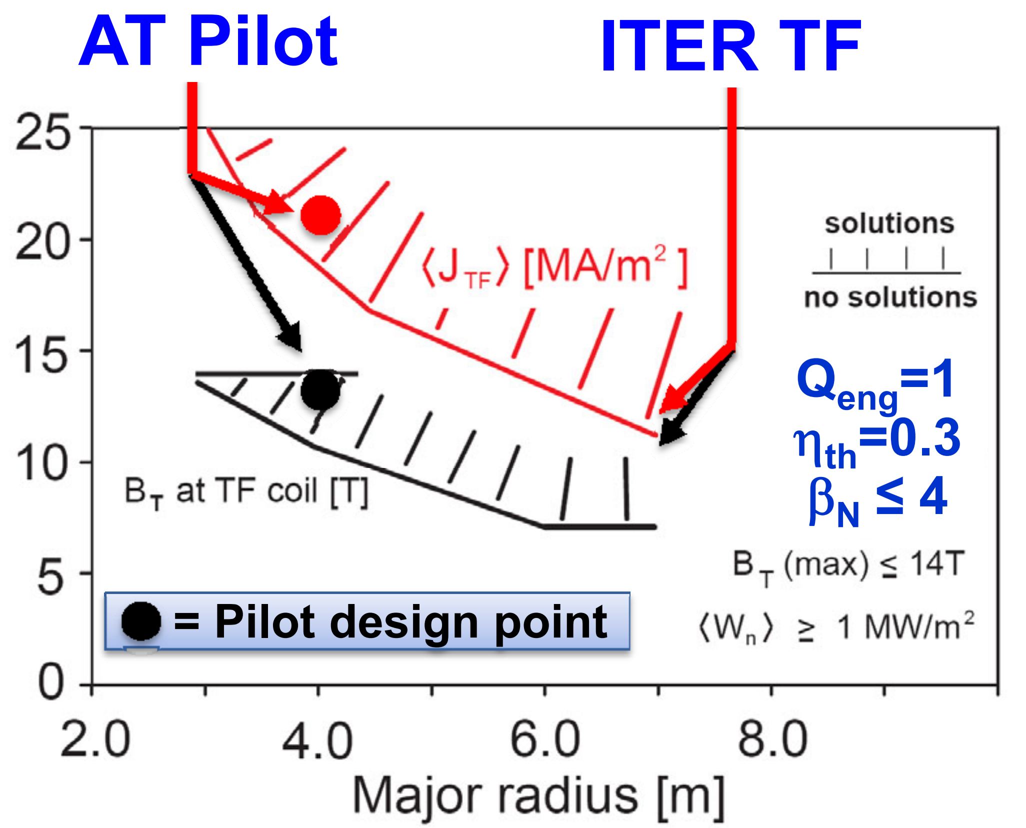
Blanket and auxiliary heating and current-drive efficiency + fusion gain largely determine electrical efficiency Q_{eng}

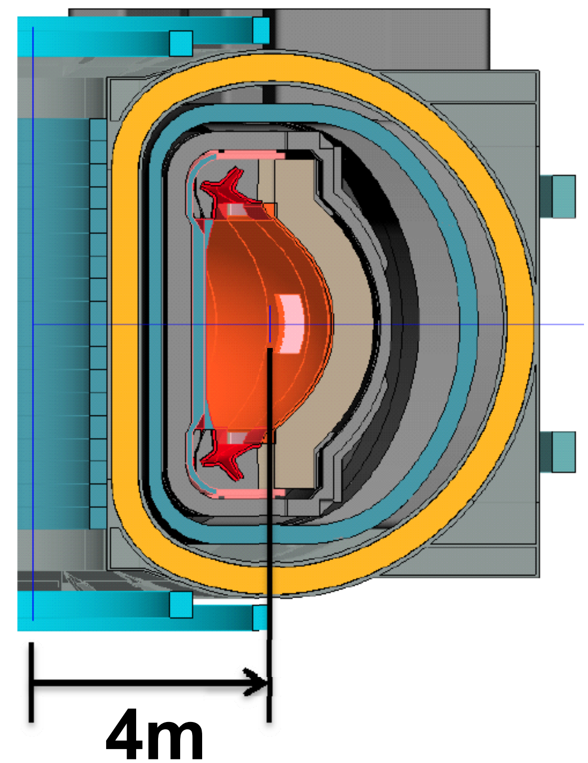
Pumping, sub-systems power assumed to be proportional to $P_{thermal}$ – needs further research

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

Size of AT pilot driven by magnet technology

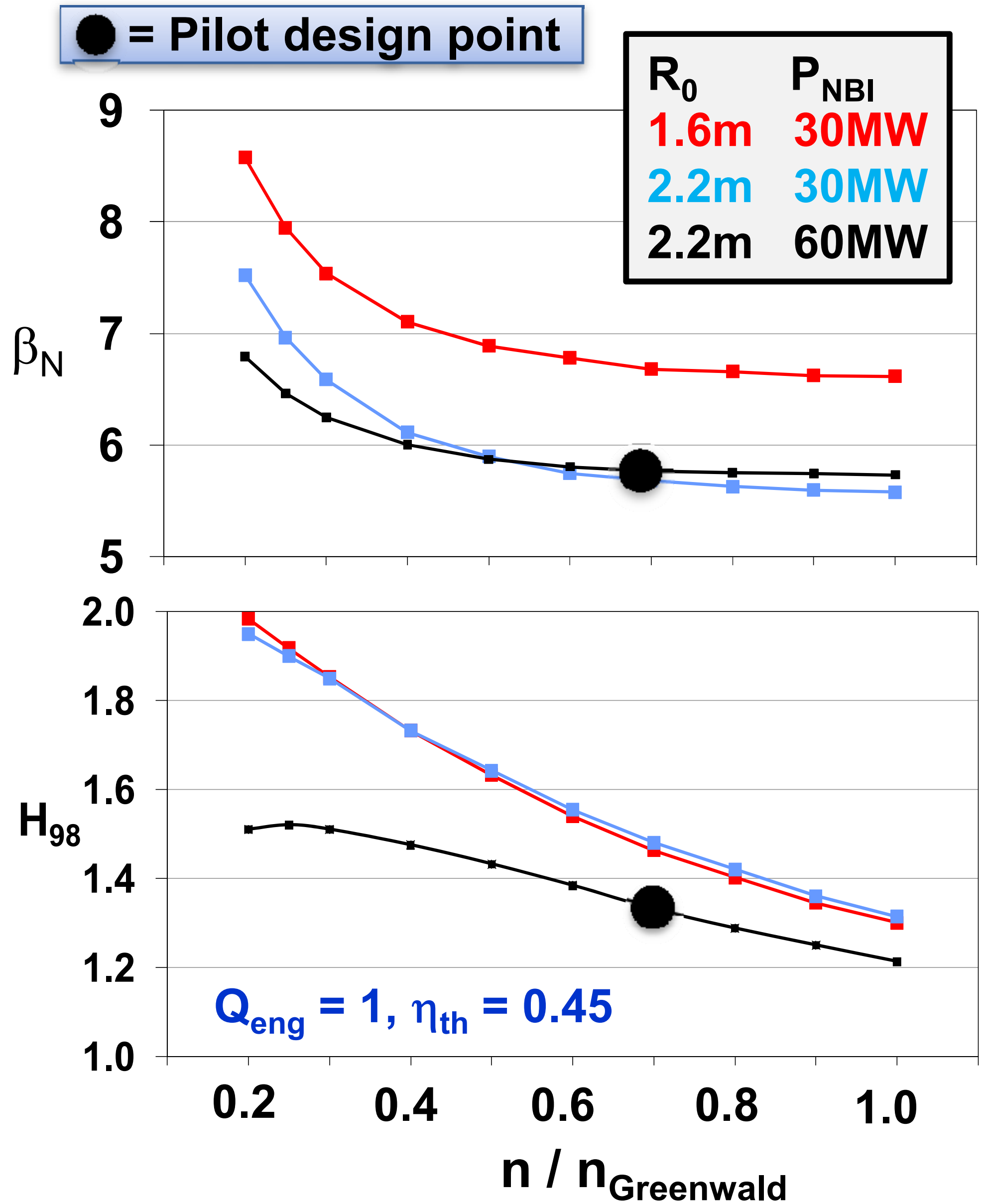


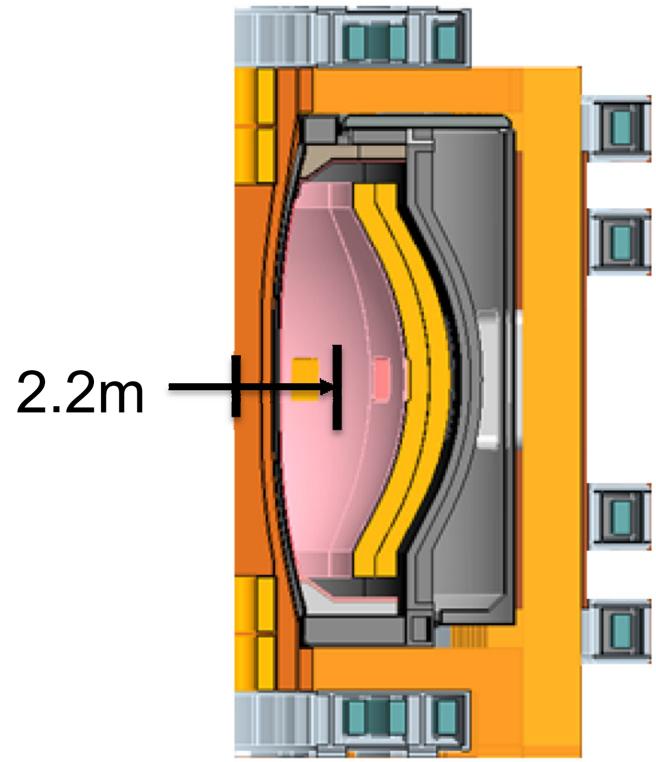


- For ITER TF magnet parameters, AT pilot would have R_0 = 6-7m
- Advances in SC TF coil technology and design needed (also needed for CS pilot)

- 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



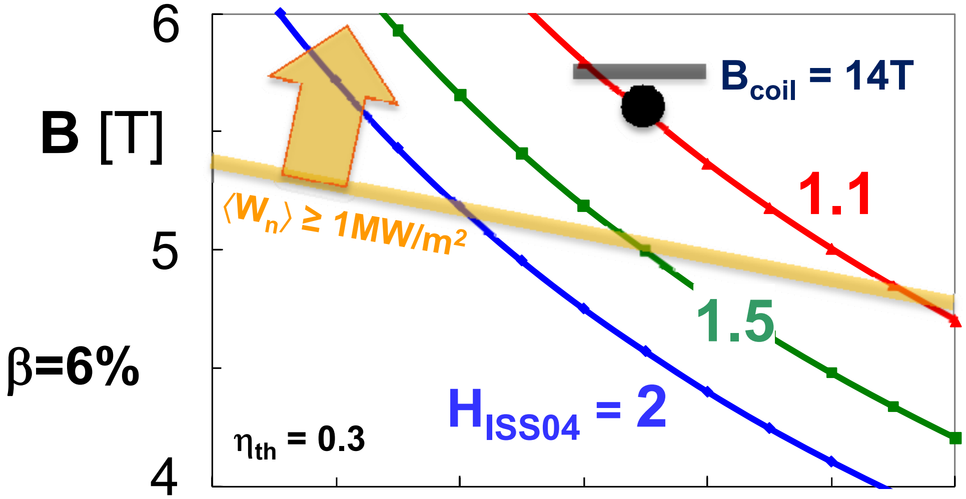


- $A = 1.7 = 2.2m / 1.3m$
- $B_T = 2.4T$, $I_P = 18\text{-}20MA$
- Avg. $W_n = 1.9\text{-}2.9\ MW/m^2$
- Peak $W_n = 3\text{-}4.5\ MW/m^2$

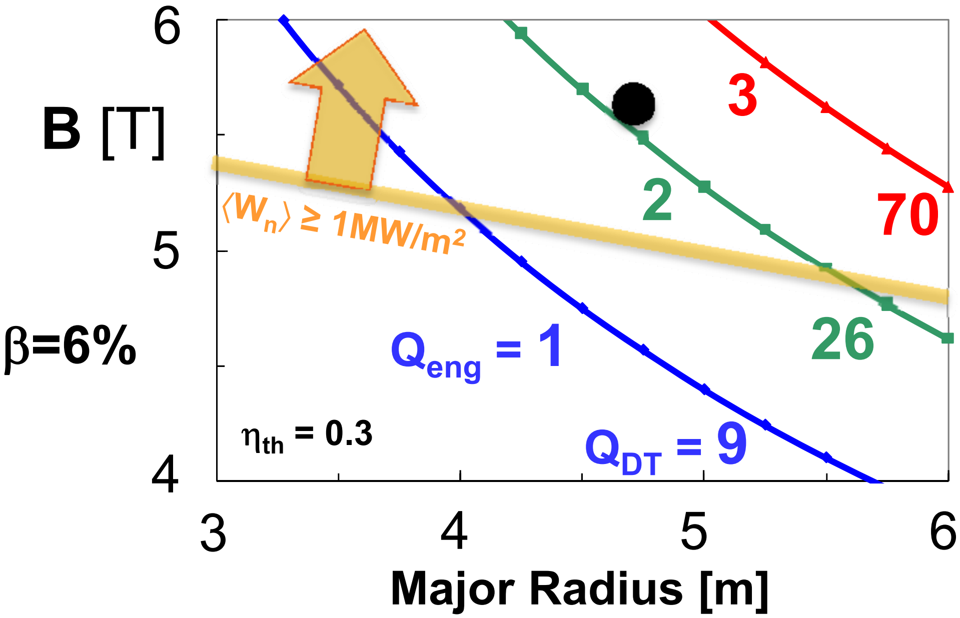
Higher density favorable for reducing β_N and H_{98} (also fast ion fraction)

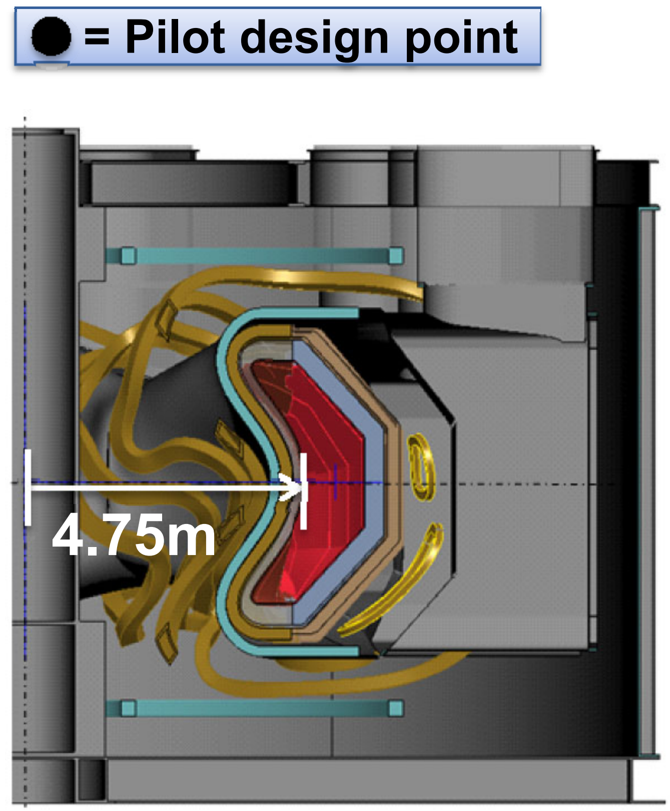
Size of CS pilot driven by magnet technology and neutron wall loading, but not Q_{eng}

Q_{eng}=1.1 accessible at $H_{ISS04} \geq 1.1$



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

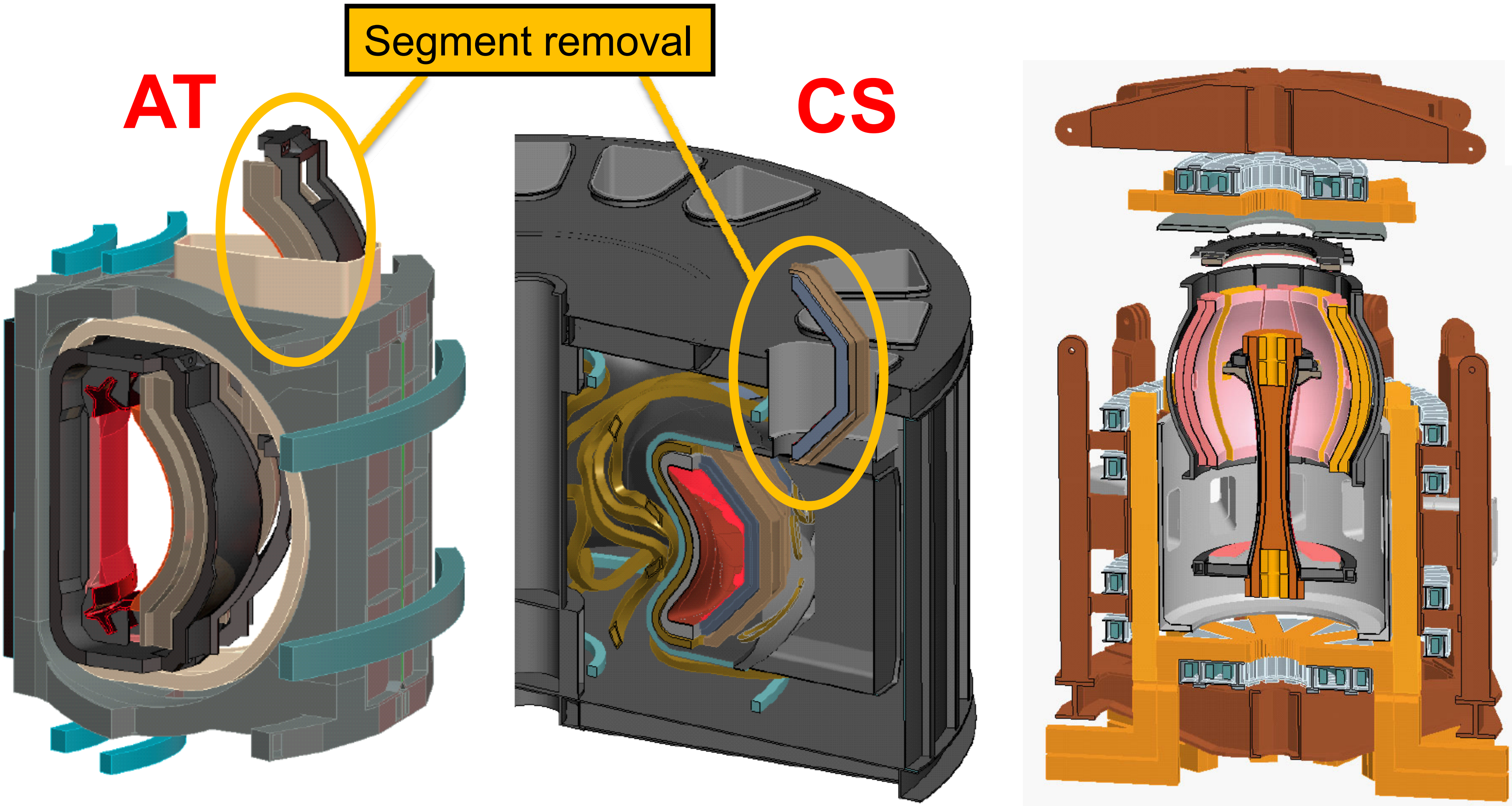




- A = 4.5 = 4.75m / 1.05m
- B_T = 5.6T, I_P = 1.7MA (BS)
- Avg. W_n = 1.2-2 MW/m^2
- Peak W_n = 2.4-4 MW/m^2

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



Pilot Plant can perform blanket testing

- Blanket development requirements:
  - 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

Abdou, et al. Fus. Technol. 29 (1996) 1

- $Q_{eng} \geq 1$ → P_{fus}=0.3-1 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

- 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)

Summary of initial technical assessment

- 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

Pilot Plant could be last step before a first of a kind fusion power plant

Backup slides

Demo Mission: Readiness for Commercial MFE

from STARLITE study, 1995

- **Technology and Performance**: Demonstrate the technologies and plasma operating regimes planned for commercial power plants.
- **Integration and Scalability**: Demonstrate all systems working as an integrated unit, close to commercial scale (~75% in P_{ELEC}).
- **Economics**: Demonstrate cost-competitiveness.
- **Safety, Licensing, Waste Disposal**: Demonstrate that fusion lives up to its promise of safe, clean energy.
- **Reliability, Maintainability, Availability**: Demonstrate availability competitive with other energy sources, <1 unscheduled shutdown per yr.
- **Operability**: Demonstrate ease of operation, with routine emissions below allowable values.

U.S. Demo is a first-of-a-kind fusion power plant, the penultimate step to commercial MFE.

FY 2011 Pilot Study Goals

1. Identify characteristics and prerequisites for MFE Demo.

2. Sketch out various roadmaps to commercial MFE to better understand potential roles of pilot plants, CTFs, etc.
   - Options with and without FNSF/CTF
   - Options with and without pilot plant
   - Identify risks/benefits, pre-requisite R&D needed for CTFs, pilots

3. Enhance development of ST option for FNSF/CTF
   - Develop a design, provide some engineering support
   - Collaborate with Culham/MAST, others on design strategies

4. Conduct design activities in support of above goals

Pilot studies support DOE-FES strategic planning

Series of DOE-chartered community studies

Greenwald and Toroidal Alternates Reports
(2007-08)

Description of **S&T issues and knowledge gaps** between now and MFE Demo.

Research Needs Study (ReNeW)
(2008-09)

Themes

1. Burning plasmas
2. Steady-state
3. Plasma-material interface.
4. Fusion nuclear S&T.
5. Magnetic configurations.

Description of **ITER-era research requirements** to close Greenwald- and TAP-identified gaps.

As requested by DOE, ReNeW had:

- Complete menu
- No prioritization
- Some time-ordering

Pathways Assessment
Activity
(2010-11)

DOE request:
Describe **a subset of research requirements in enough detail** for them to issue solicitations **now (for FY-2012)** and design programs in materials-related research.

DOE's charge to Pathways Activity

(E. Synakowski, 23 July 2010)

Overarching aim: identify and clarify requirements in materials-related research to increase fusion's credibility

- Build on Greenwald, ReNeW
- Identify research requirements to the point of enabling FES to craft calls for proposals and design programs
  - Start with our best understanding of the integrated requirements for a DEMO and roll back
  - Center of attention should be on the research that is required before a major new facility, but that can help define that facility
- Discuss future activities in the context of what is going on in the US domestic program

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R&D needed for Pilot Plants

- 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)

Pilot study has broad community participation

Magnets

- Leslie Bromberg, Joe Minervini, MIT

Blankets & Structural Materials

- Laila El-Guebaly, Mohamed Sawan, Univ. of Wisconsin
- Siegfried Malang, consultant
- Neil Morley, UCLA
- Rick Kurtz, PNNL

PMI, Divertor / First Wall

- Dennis Whyte, Bruce Lipschultz, Amanda Hubbard, MIT
- Rob Goldston, PPPL

Configuration / Maintenance

- Brad Nelson, ORNL
- Les Waganer, consultant
- Tom Brown, PPPL

Diagnostics and Instrumentation

- Alan Costley, CCFE (UK)

Strategy Inputs

- John Sheffield, Univ. of Tenn.
- Abraham Sternlieb, Israel M.O.D.
- David Ward, CCFE (UK)
- Farrokh Najmabadi, UCSD
- Jiangang Li, ASIPP Director (China)

Plasma Configurations / Analysis

- Rich Hawryluk, Chuck Kessel, Jon Menard, Hutch Neilson, Stewart Prager, Mike Zarnstorff, PPPL
- Tommy Gerrity, MIT student
- Daniel Dix, Rob Kastner, Princeton Univ. students

Assumptions and constraints

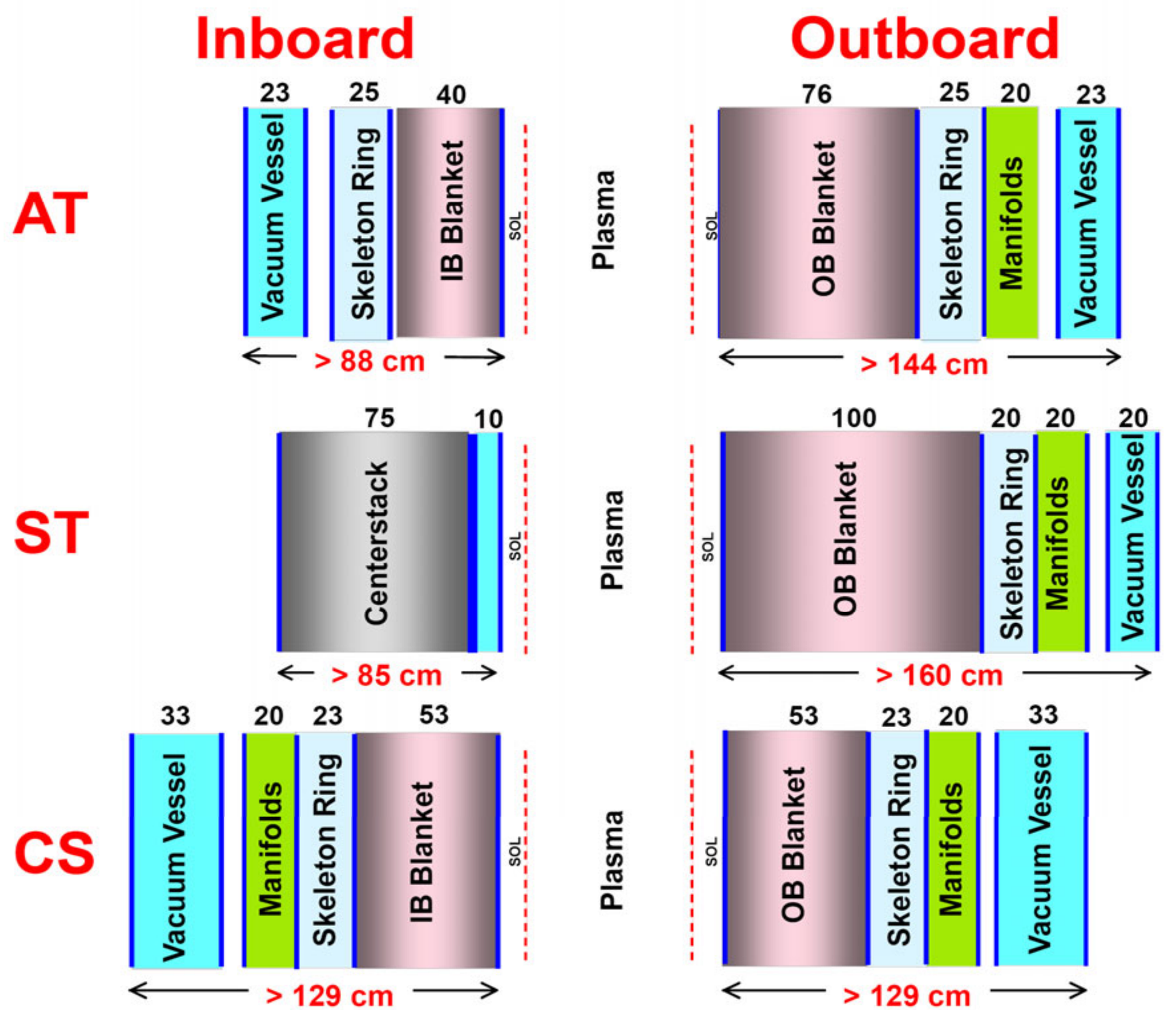
- Surface-average neutron wall loading: $\langle W_n \rangle \geq 1$ MW/m^2
  - Neutron wall load peaking factors (peak/avg): AT/ST/CS = 1.43/1.56/2.0
  - Blanket thermal conversion:
  - η_{th} = 0.3, 0.45 – this range incorporates leading concepts: He cooled pebble-bed (HCPB), dual-coolant lead-lithium (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
    - **η_{aux} = 0.4, $\eta_{CD} = I_{CD} R_0 n_e / P_{CD} = 0.3 \times 10^{20}$ 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**

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



Key Radiation Limits and Design Parameters
(CS Example)

Machine Average NWL (@ FW)	~1.9	MW/m^2
Peak NWL	~3.8	
Average Major Radius	4.75	m
Average Minor Radius	1.05	m
Damage to FS Structure	10-80	dpa
Helium Production (for reweldability of FS)	1	He appm
TF S/C Magnets (@ 4 K):		
Peak fast n **fluence** to **Nb_3Sn** (E_n > 0.1 MeV)	10^{19}	n/cm^2
Peak nuclear **heating**	2	mW/cm^3
Peak **dpa** to Cu stabilizer	6×10^{-3}	dpa
Peak **dose** to electric insulator	$\sim 10^{10}$	rads
Plant Lifetime	~20	years
Availability	10-50%	
	30% average	

6 Full Power Years (FPY)

L. El-Guebaly, M. Sawan, Univ. of Wisconsin

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

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 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
P_{fus} [MW]	553	408	990	630	529	313
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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	-	-