Configuration Studies for an ST-based Fusion Nuclear Science Facility

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FNS/1-1

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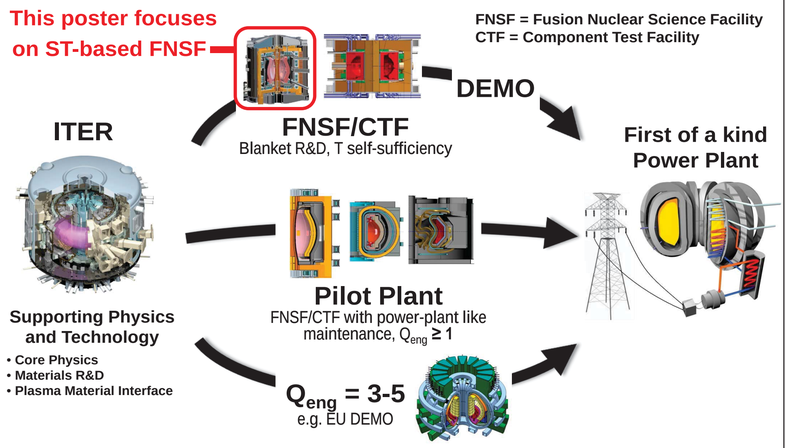
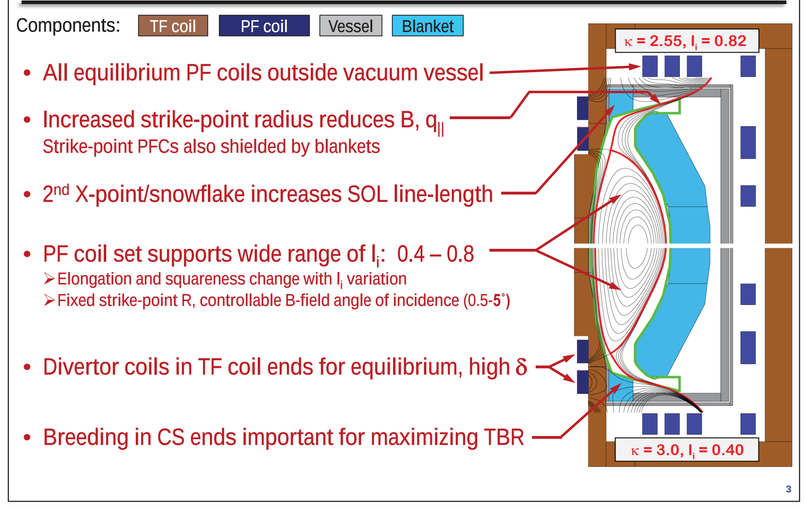
There are several possible pathways from ITER to a commercial fusion power plant



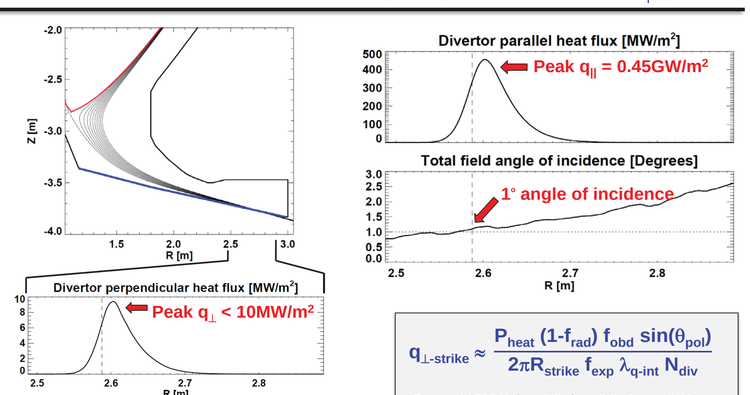
Overview

- Recent U.S. studies for ST-FNSF have focused on assessing achievable missions versus device size
- Possible missions:
  - Electricity break-even
    - Motivated 2010-12 analysis of R=2.2m ST Pilot Plant
  - Tritium self-sufficiency (tritium breeding ratio TBR ≥ 1)
    - Motivates present (2013-14) analysis of R=1m, 1.7m ST FNSF devices to address key questions:
      - How large must ST device be to achieve TBR ≥ 1?
      - How much externally supplied T would be needed for smaller ST?
      - What are device and component lifetimes?
  - Fusion-relevant neutron wall loading and fluence
    - STs studied here access 1MW/m^2, 6MW-yr/m^2 (surface-avg. values)

PF coil set identified that supports combined Super-X + snowflake divertor for range of equilibria



Up/down-symmetric Super-X/snowflake → $q_{\perp\text{-divertor}}$ < 10MW/m^2 even under attached conditions (if integral heat-flux width $\lambda_{q\text{-int}}$ > 2mm)



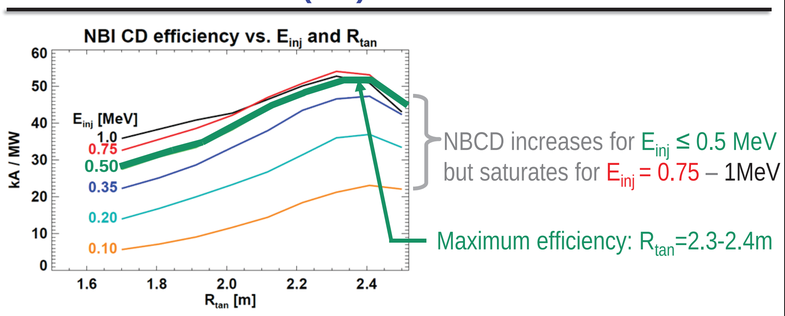
$$q_{\perp\text{-strike}} \approx \frac{P_{heat}\,(1-f_{rad})\,f_{obd}\,\sin(\theta_{pol})}{2\pi R_{strike}\,f_{exp}\,\lambda_{q\text{-int}}\,N_{div}}$$

- P_{heat} = 115MW, f_{rad}=0.8, f_{obd}=0.8, θ_{pol} = 2.1°
- R_{strike} = 2.6m, f_{exp} = 1.4, $\lambda_{q\text{-int}}$ =2.05mm, N_{div} = 2

Partial detachment expected to further reduce peak $q_\perp$ factor of 2-5×

Eich NF 2013: $\lambda_{q\text{-int}} = \lambda_q + 1.64 \times S$, λ_q **= 0.78mm, S ≈** λ_q (closed divertor)

0.5 MeV NNBI favorable for heating and current drive (CD) for R=1.7m ST-FNSF

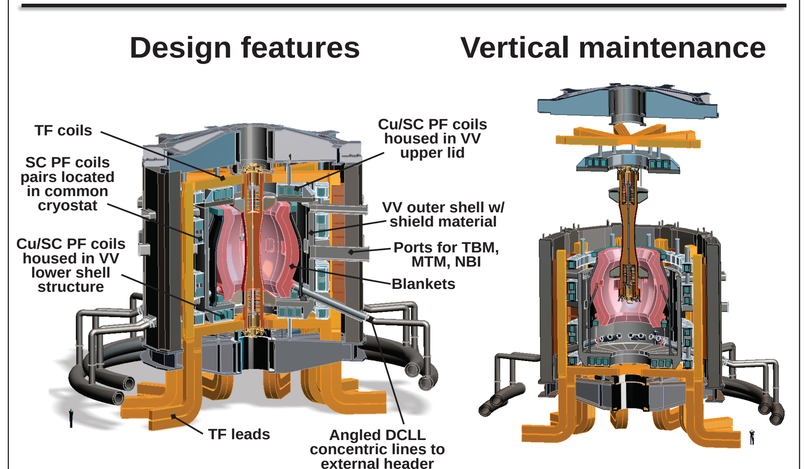


- Fixed target parameters in DD:
  - I_P = 7.5MA, β_N = 4.5, l_i = 0.5
  - n_e / $n_{Greenwald}$ = 0.75, $H_{98y,2}$ = 1.5
  - A=1.75, R=1.7m, B_T = 3T, κ = 2.8
  - $\langle T_e \rangle$=5.8keV, $\langle T_i \rangle$=7.4keV

Optimal tangency radii: 1.7m ≤ R_{tan} ≤ 2.4m

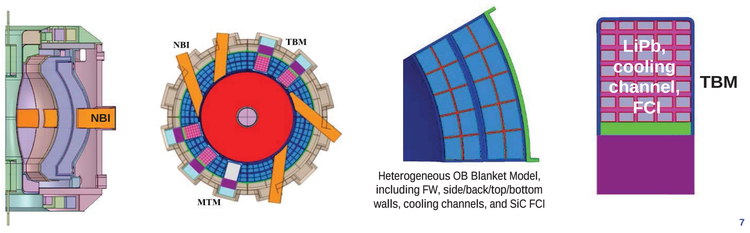
Control q(0), q_{min} | Shine-thru limit

R=1.7m configuration with Super-X divertor



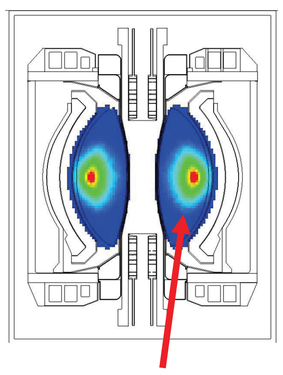
ST-FNSF shielding and TBR analyzed with sophisticated 3-D neutronics codes

- CAD coupled with MCNP using UW DAGMC code
- Fully accurate representation of entire torus
- No approximation/simplification involved at any step:
  - Internals of two OB DCLL blanket segments modeled in great detail, including:
    - FW, side, top/bottom, and back walls, cooling channels, SiC FCI
  - 2 cm wide assembly gaps between toroidal sectors
  - 2 cm thick W vertical stabilizing shell between OB blanket segments
  - Ports and FS walls for test blanket / materials test modules (TBM/MTM) and NNBI

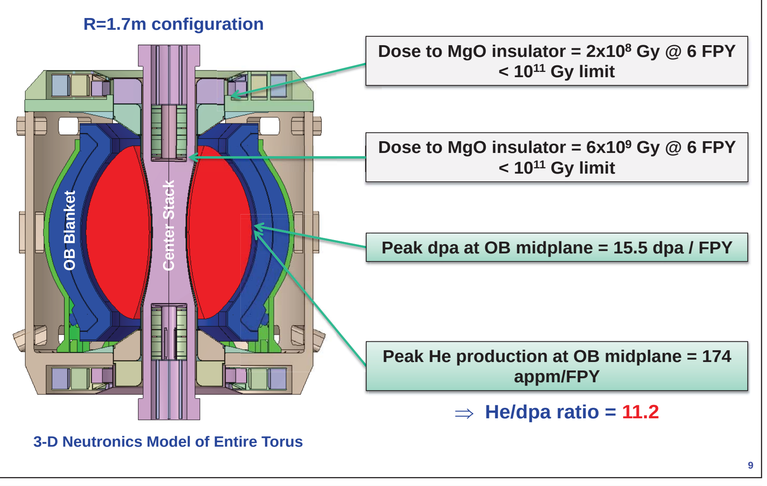


Two sizes (R=1.7m, 1m) assessed for shielding, TBR

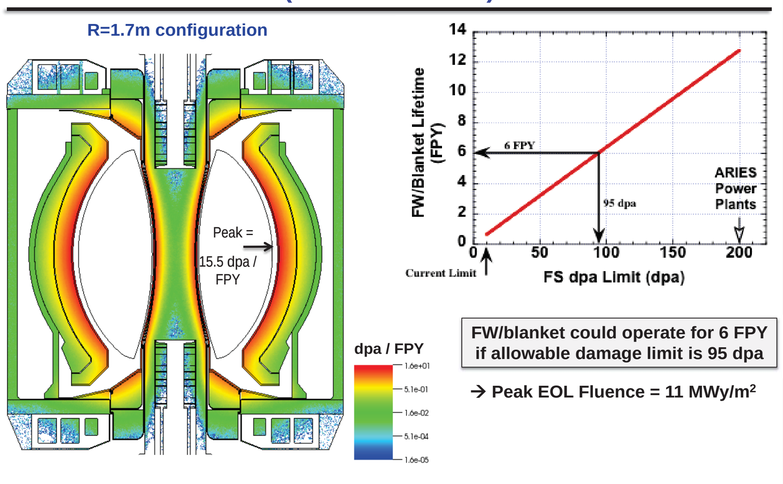
Parameter:		
Major Radius	1.68m	1.0m
Minor Radius	0.95m	0.6m
Fusion Power	162MW	62MW
Wall loading (avg)	1MW/m^2	1MW/m^2
TF coils	12	10
TBM ports	4	4
MTM ports	1	1
NBI ports	4	3
Plant Lifetime	~20 years	
Availability	10-50% 30% avg }	6 Full Power Years (FPY)



Peak Damage at OB FW and Insulator of Cu Magnets



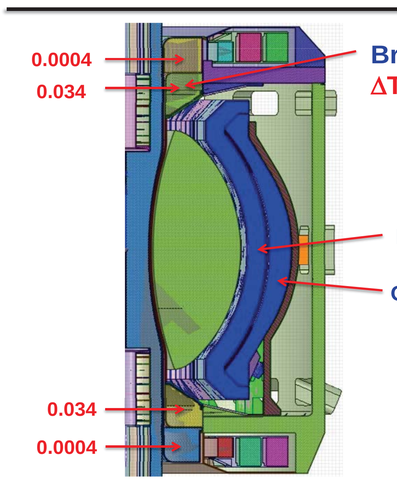
Mapping of dpa and FW/blanket lifetime (R=1.7 m Device)



FW/blanket could operate for 6 FPY if allowable damage limit is 95 dpa

→ **Peak EOL Fluence = 11 MWy/m^2**

TBR contributions by blanket region



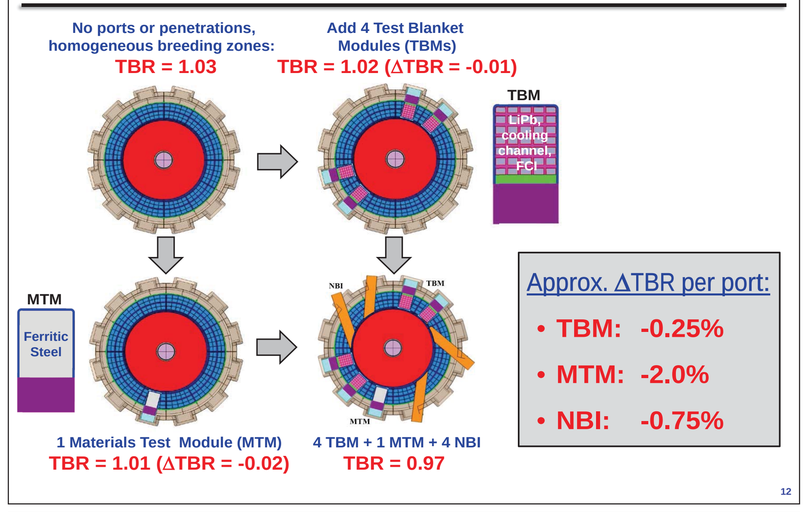
Breeding at CS ends important: ΔTBR = +0.07

Inner Blanket Segment = 0.81

Outer Blanket Segment = 0.15

Total TBR ~ 1.03 with no penetrations or ports (heterogenous outboard blanket)

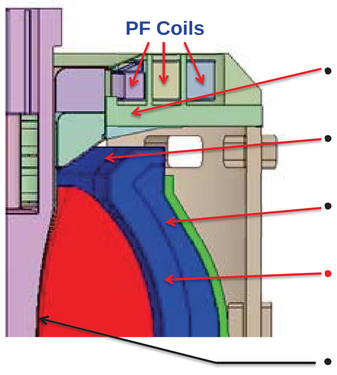
Impact of TBM, MTM, NBI ports on TBR



Approx. ΔTBR per port:

- TBM: -0.25%
- MTM: -2.0%
- NBI: -0.75%

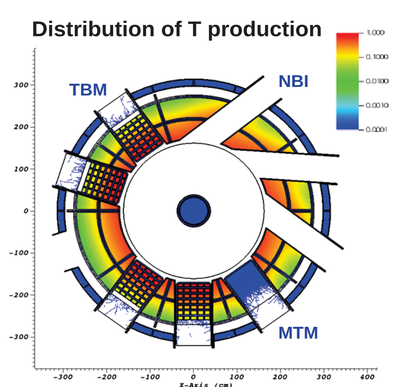
Options to increase TBR > 1

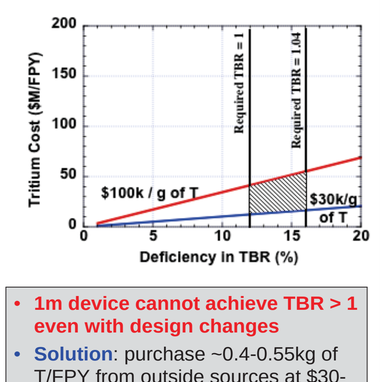


- Add to PF coil shield a thin breeding blanket (ΔTBR ~ +3%)
- Smaller opening to divertor to reduce neutron leakage
- Uniform OB blanket (1m thick everywhere; no thinning)
- Reduce cooling channels and FCIs within blanket (need thermal analysis to confirm)
- Thicker IB VV with breeding

Potential for TBR > 1 at R=1.7m

R_0 = 1m ST-FNSF achieves TBR = 0.88





- **1m device cannot achieve TBR > 1 even with design changes**
- **Solution**: purchase ~0.4-0.55kg of T/FPY from outside sources at $30-100k/g of T, costing $12-55M/FPY

Summary: R = 1m and 1.7m STs with Γ_n = 1MW/m^2 and Q_{DT} = 1-2 assessed for FNS mission

- Ex-vessel PF coil set identified to support range of equilibria and Super-X/snowflake divertor to mitigate high heat flux
- 0.5MeV NNBI optimal for heating & current drive for R=1.7m
- Vertical maintenance approach, NBI & test-cell layouts identified
- Shielding adequate for MgO insulated inboard Cu PF coils
  - Outboard PF coils (behind outboard blankets) can be superconducting
- Calculated full 3D TBR; TBR reduction from TBM, MTM, NBI
- **Threshold major radius for TBR ~ 1 is R_0 ≥ 1.7m**
- **R=1m TBR = 0.88 → 0.4-0.55kg of T/FPY → $12-55M/FPY**
- R=1m device will have lower electricity and capital cost → future work could assess size/cost trade-offs in more detail