PPPL PRINCETON PLASMA PHYSICS LABORATORY

PPPL Low-Aspect-Ratio Next-Step Facility Scoping Studies*

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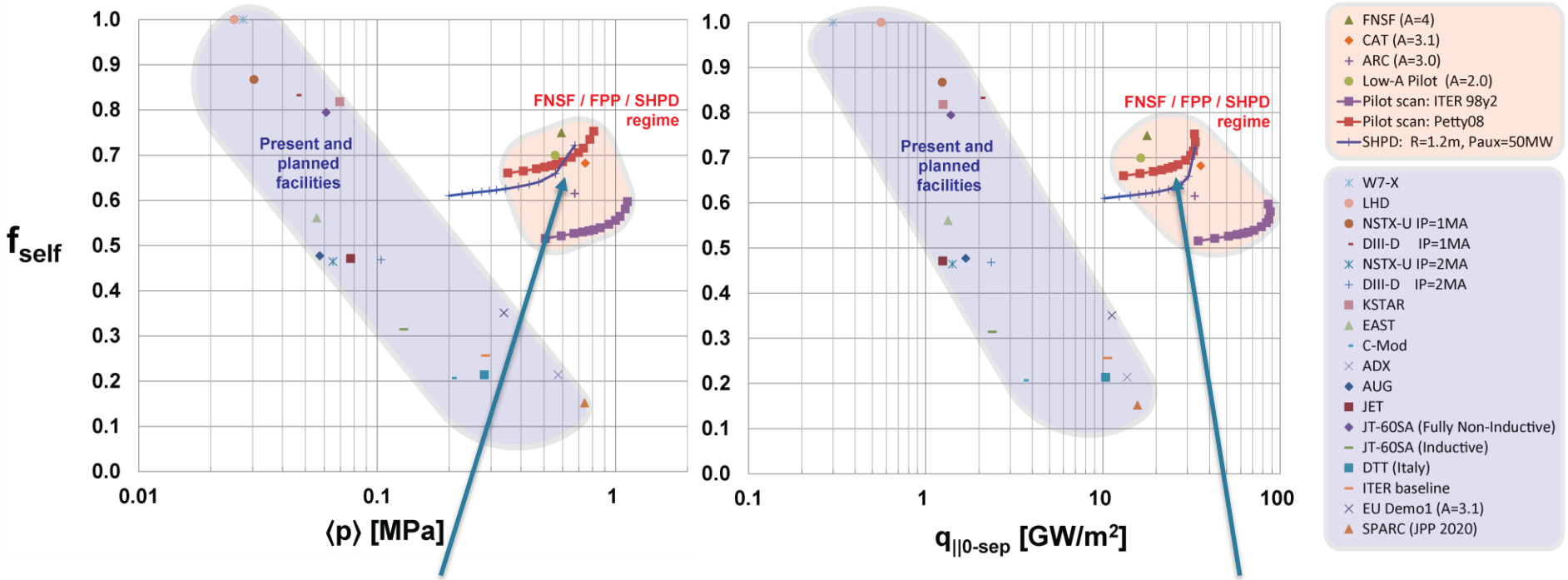
Overview

- Compact tokamak Fusion Pilot Plants (FPPs) with high B face challenge of integrating high core confinement and pressure, P_{heat}/S and divertor $q_{||}$
  - Motivates EXhaust and Confinement Integration Tokamak Experiment (EXCITE) facility
  - EXCITE and similar facilities are in a “sustained high power density” (SHPD) regime
- Specific core-edge integration (CEI) challenges include:
  - Edge density operating windows, choice of impurities for detached divertor operation
  - Potential access to turbulence-driven broadening of the scrape-off-layer heat fluxes
  - H-mode access and sustainment with high core radiation fraction
- **This presentation:**
  - **Identify SHPD/EXCITE device configuration(s) to narrow/close CEI gaps to FPP**
  - **Plans for ST Advanced Reactor (STAR) power plant configuration**

FPP parameters not yet accessible (simultaneously)

- Present / near-term planned facilities do not access FPP regime of combined high self-driven current + high core plasma pressure + high divertor parallel heat flux



f_{BS} = 60-80%, ⟨p⟩ = 0.3-0.8 MPa

3-10× present/planned at high f_{BS}

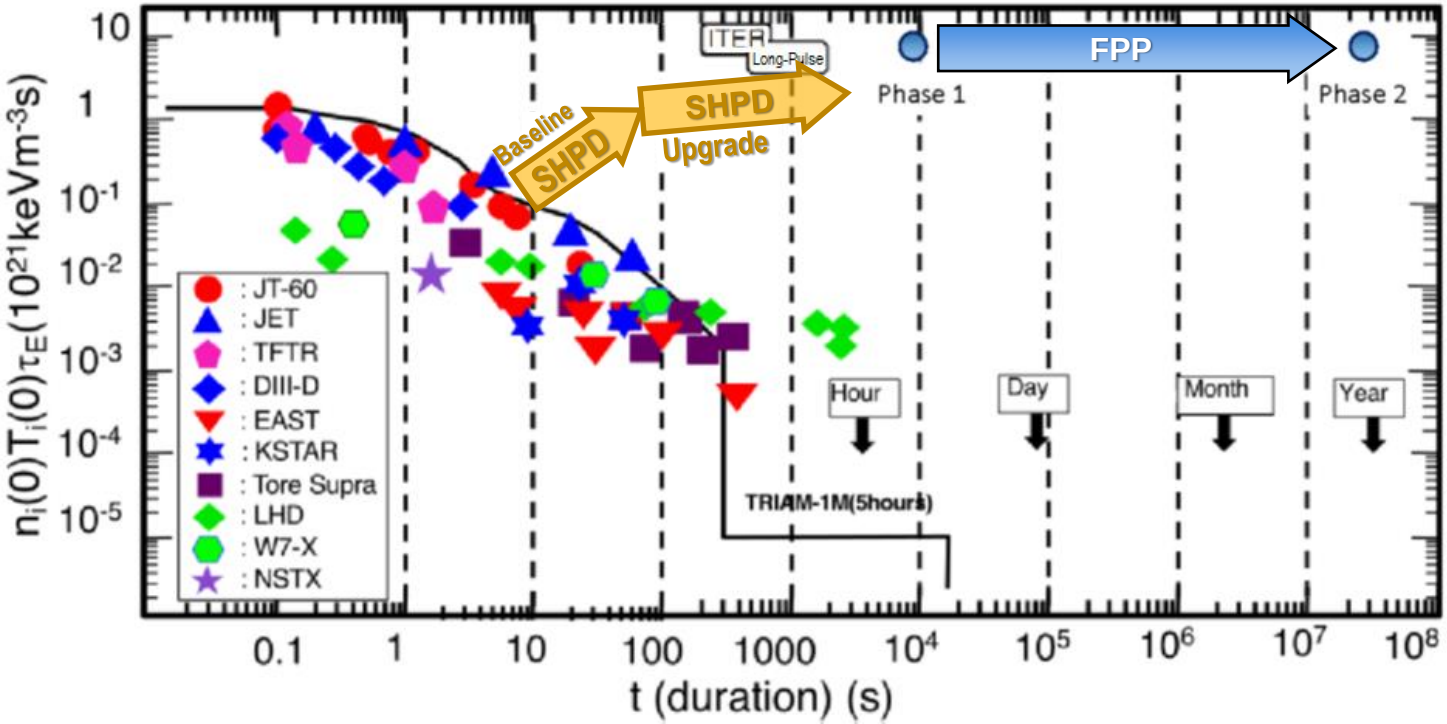
$q_{||0\text{-}sep}$ = 10-30 GW/m²

3-8× present/planned at high f_{BS}

Need to bridge $nT\tau_E$ and $\tau_{duration}$ gap to FPP

- **Gap: 2-3 orders of magnitude in both pulse duration and $nT\tau_E$**
- **Baseline SHPD device to narrow $nT\tau_E$ gap, Upgrade to narrow τ_{pulse}**

Adapted from Fig. 4.2 of NASEM report "Bringing Fusion to the U.S. Grid" (2021)



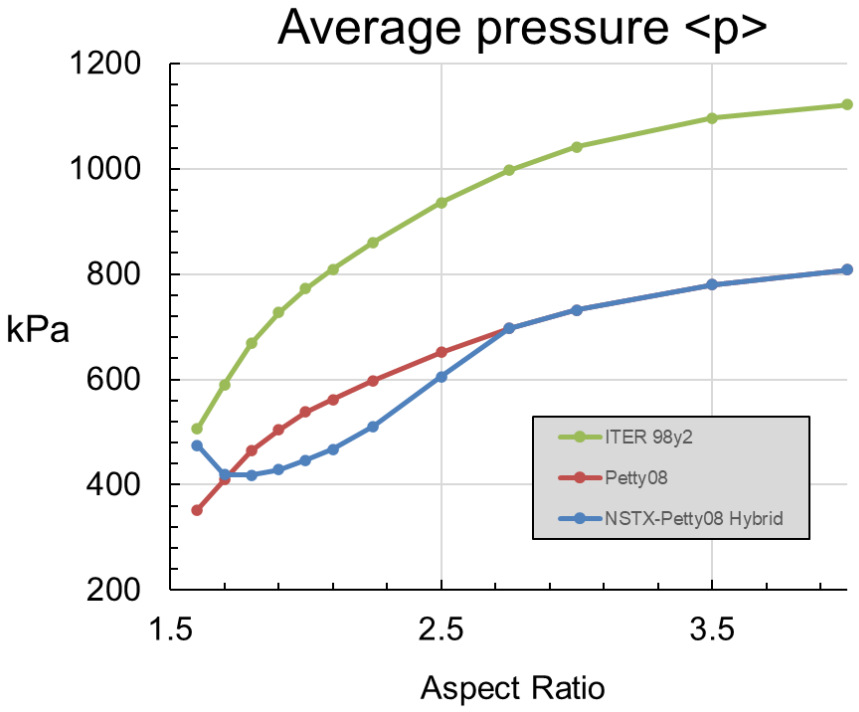
Possible SHPD/EXCITE mission options/phases

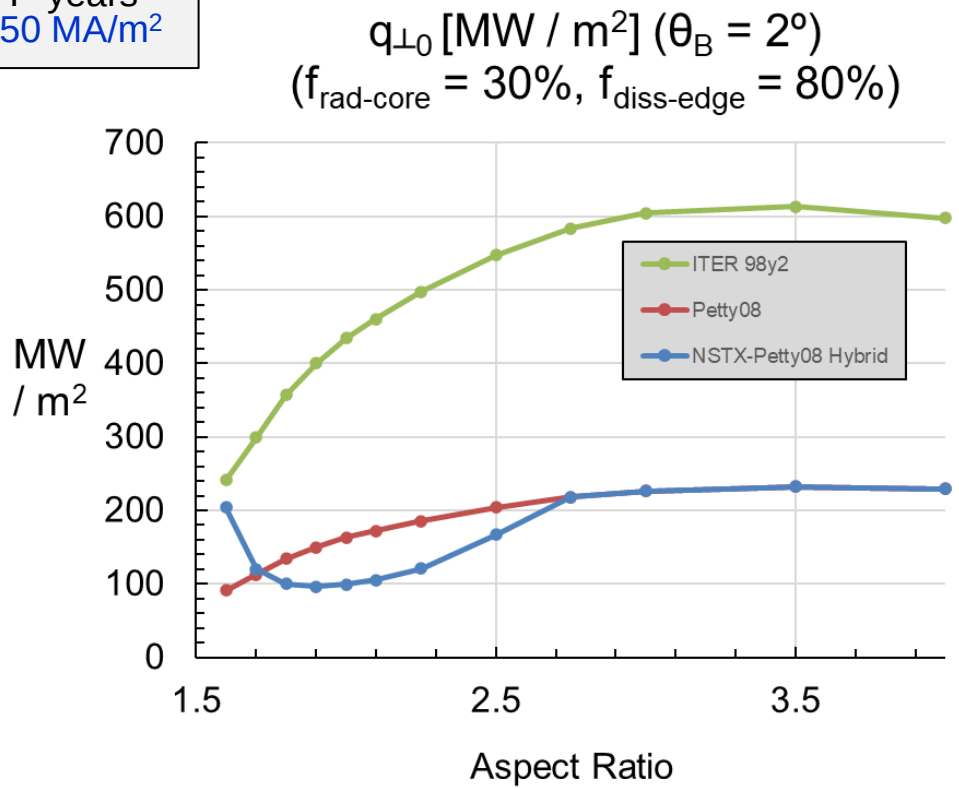
- **Baseline:** Integrate innovative divertor solutions + FPP-relevant high-performance core with high bootstrap fraction
  - Access FPP-level pressures to demonstrate relevant:
    - Divertor power densities
    - Pressure in SOL for representative detachment and control
    - First-wall erosion rate – short & long time-scale mass transport/migration
- **Upgrade:** Technology R&D to develop/test plasma facing components, actuators *for very long-pulses* at FPP conditions
  - Steady-state heating and current drive, fueling, mass removal, diagnostics, control, maintenance, …

FPP CEI regimes, SHPD/EXCITE parameters and configurations that narrow gaps to FPP

FPP plasma pressure, divertor heat flux reduced at lower A

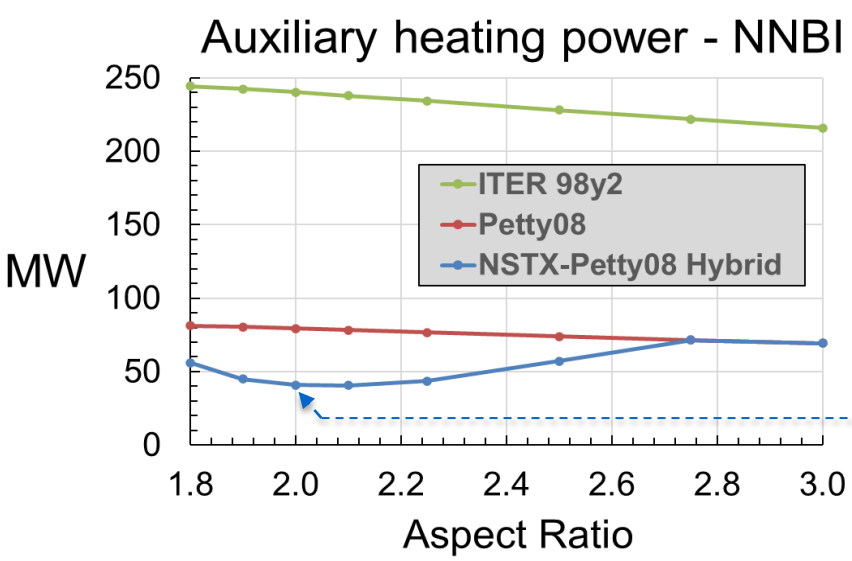
FPP fixed parameters:	• **Net electric power = 100MWe** • 100% non-inductive current drive • Tritium breeding ratio ≈ 1 • ReBCO TF lifetime = 10 FP-years • $B_{TF\text{-}max}$ = 18T, $J_{WP\text{-}TF}$ = 50 MA/m^2

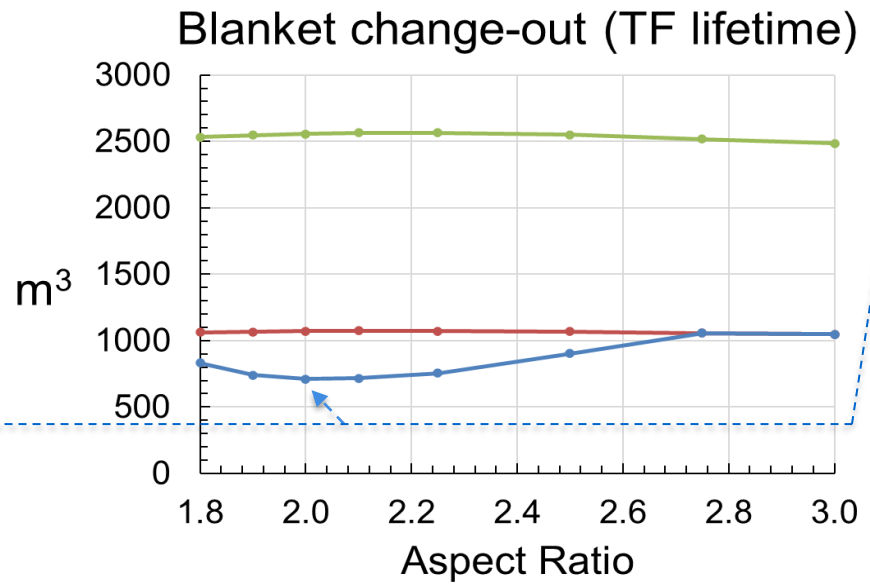




Low-A may reduce FPP aux heating, blanket change-out

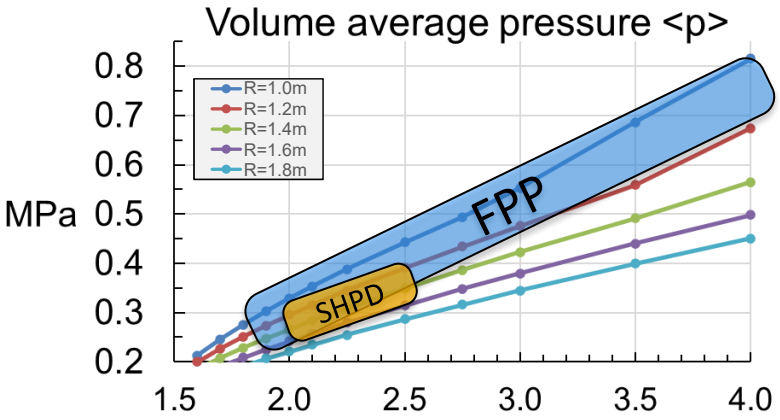
- FPP at ITER-98y2 level of confinement → very large auxiliary power ~200+ MW
- Electrostatic gyro-Bohm (Petty08) → more feasible P_{aux} = 50-100MW
- Blanket change-out volume reduced by factor 2.5× with Petty08 confinement
- If portion of favorable "ST" confinement persists above A=1.8, A ≈ 2 FPP attractive

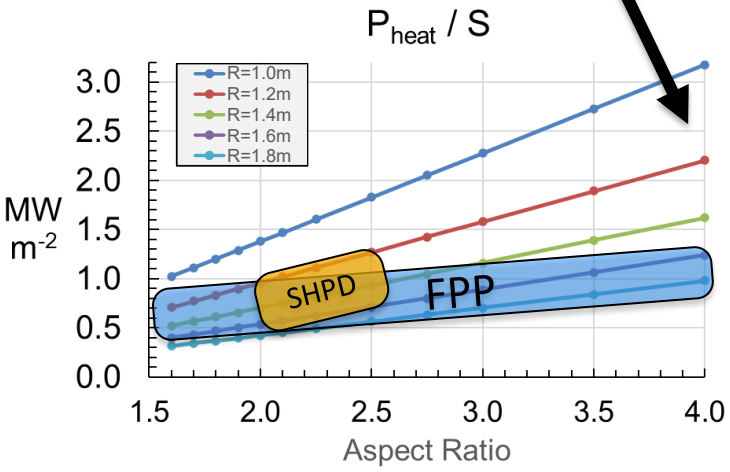


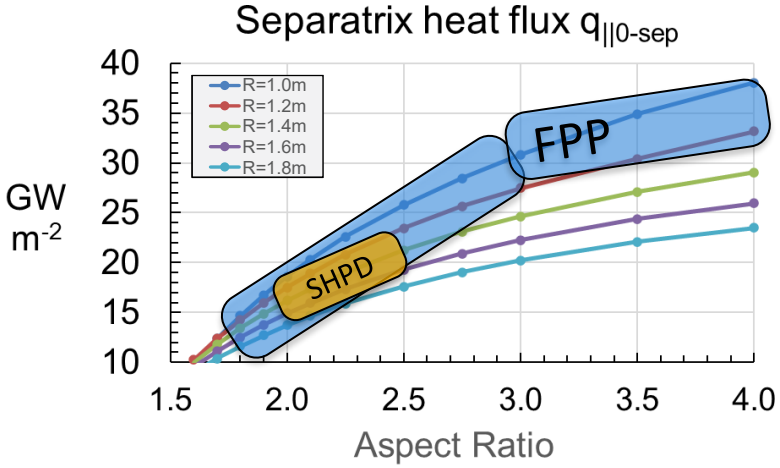


Optimal SHPD: R=1.2-1.6m, A=2-2.5, $P_{aux/CD}$ = 50MW

- Can overlap FPP values of:
  - Average pressure
  - Separatrix parallel heat flux
  - Surface-average heat flux P_{heat} / S
- High-A, small radius SHPD would have excessive P_{heat} / S (3× FPP)

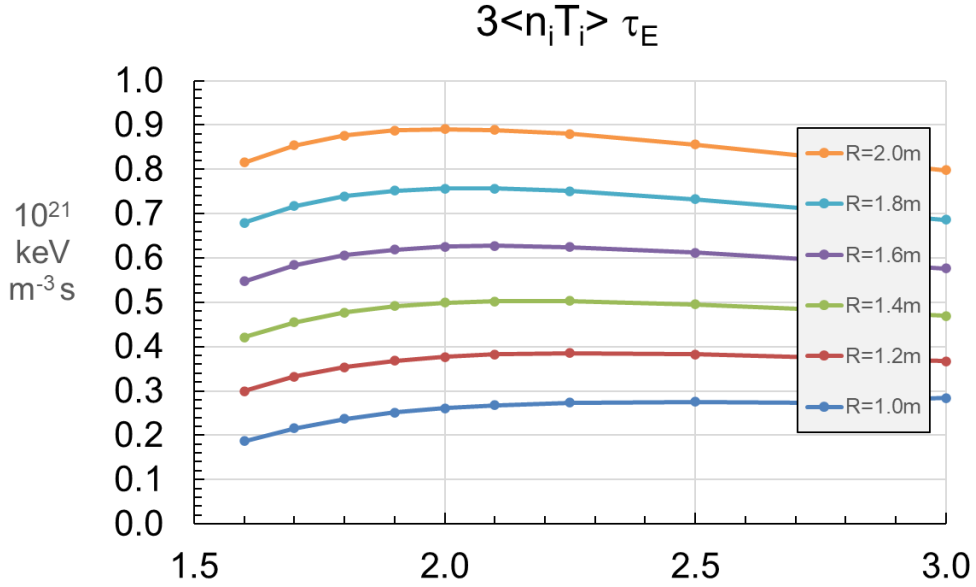


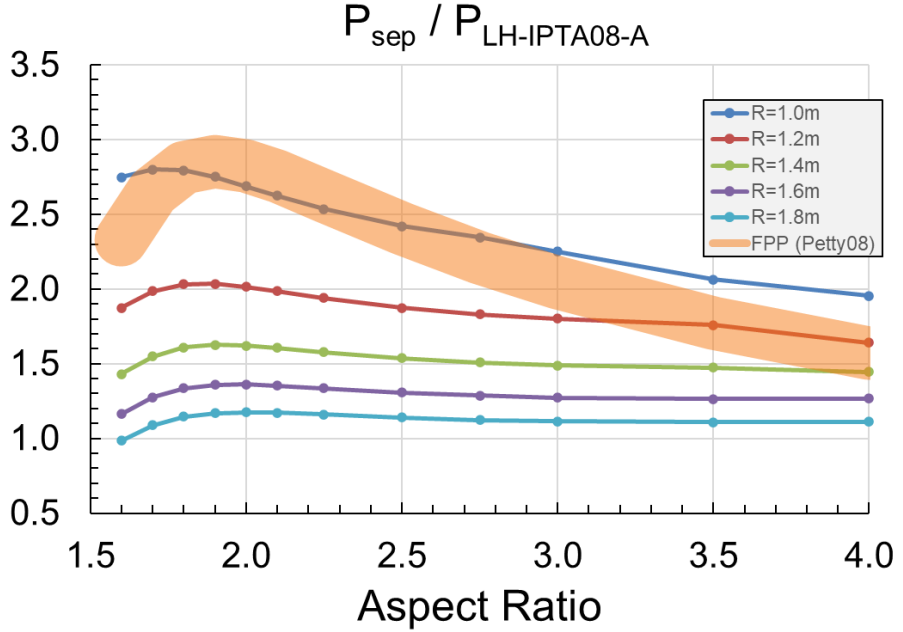




Core plasma performance and H-mode access versus size

- Larger SHPD/EXCITE facility size increases triple-product
- …but reduces margin to H-mode sustainment in steady-state

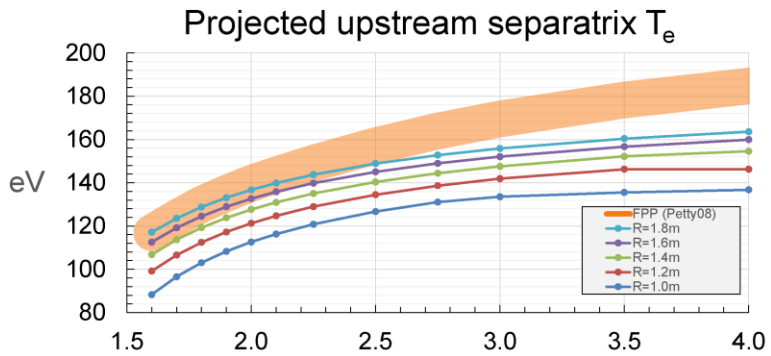


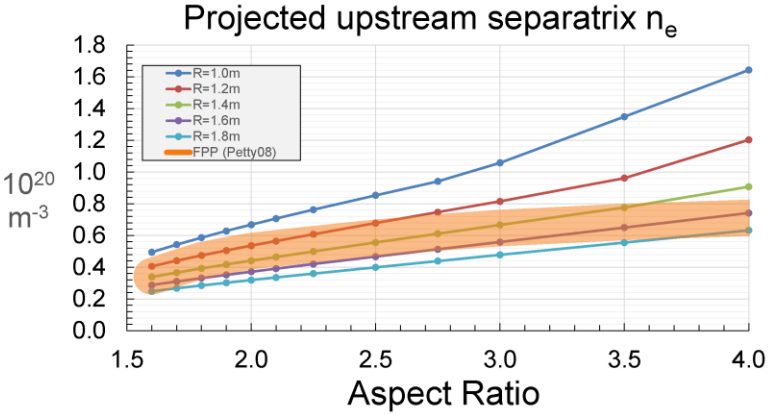


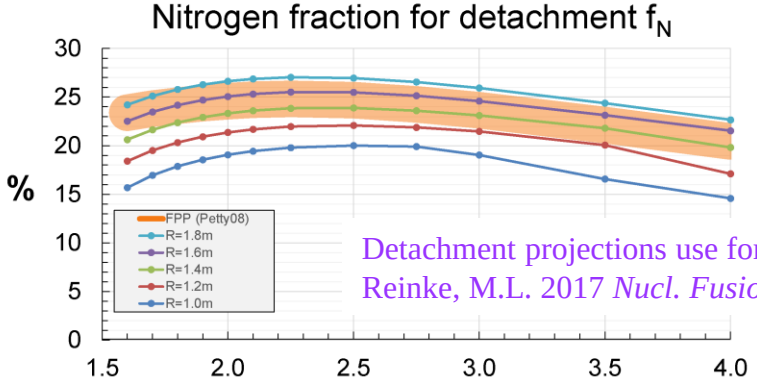
- P_{aux} = 50MW, 30% core radiation fraction

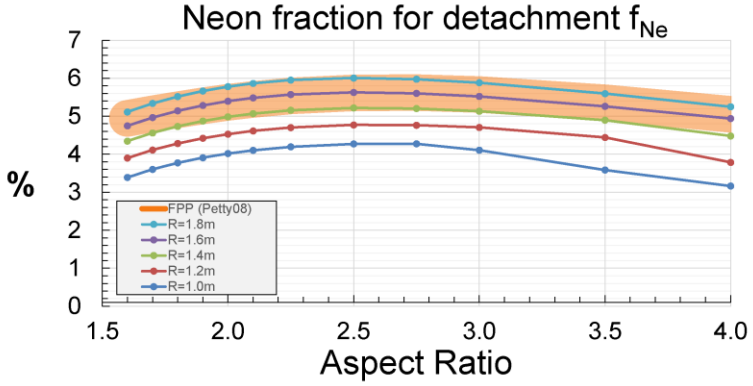
Optimal SHPD can access FPP detachment scenarios

- Larger SHPD can match FPP separatrix parameters and impurity fractions for detachment
  - SHPD would need to operate at ½ normalized density of FPP (i.e. FPP → SHPD $n_{e\text{-}sep} / n_{e\text{-}bar}$ = 0.4 → 0.2)





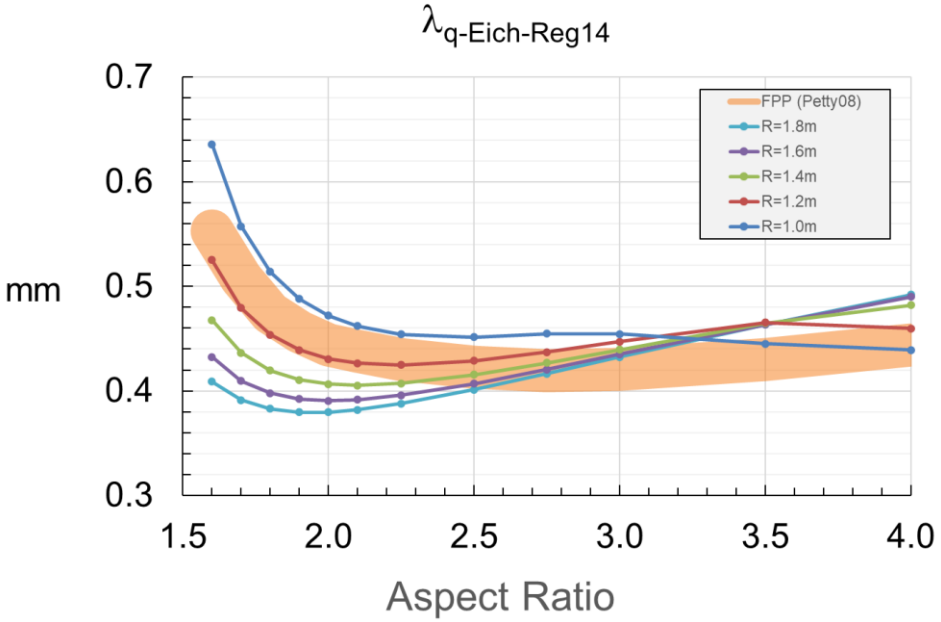


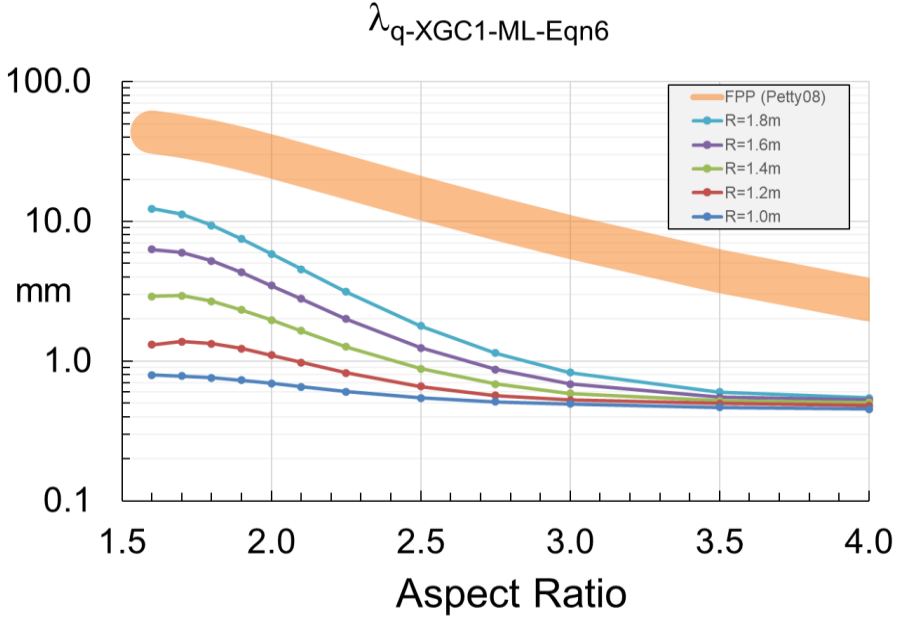


Detachment projections use formulae in Reinke, M.L. 2017 *Nucl. Fusion* **57 034004**

XGC1+ML projects wide heat flux width in FPP

- Eich scaling projects to narrow 0.4-0.5mm heat flux width for FPP and SHPD/EXCITE
- Machine learning on XGC1 simulations projects to 3-30mm in FPP
- **Only lower-A SHPD projected to access significant turbulent heat-flux broadening**





Chang, C.S. *et al* 2021 *Phys. Plasmas* **28** 022501

$$\lambda_{q\text{-XGC1-ML-Eqn6}} = \lambda_{q\text{-Eich-Reg14}} \left[1 + 1.08\times10^{-10} \left(B_{p\text{-mp}}\,[T]/\rho^{*}_{i,pol}\right)^{4}\right]$$

Example engineering design concept for EXCITE

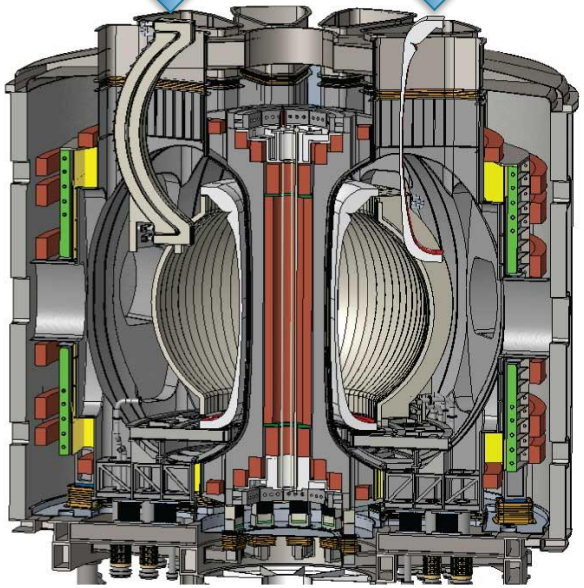
Example features

- 10 HTS superconducting TF
- B_{T0} = 5.5 to 6.0T at R_0 = 1.2m depending on J_{WP} of TF
- Superconducting solenoid for I_P ramp-up, flux depends on $J_{WP\text{-}TF}$
- Double null
- Outboard test blankets possible
- Vertical maintenance
- High-Z solid and liquid-metal walls

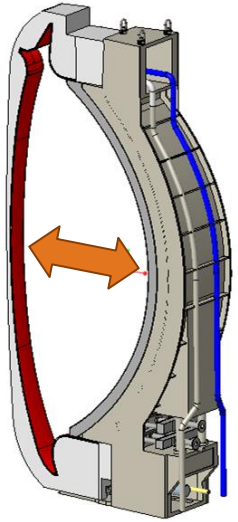
Vertical extraction of:

Outboard blanket

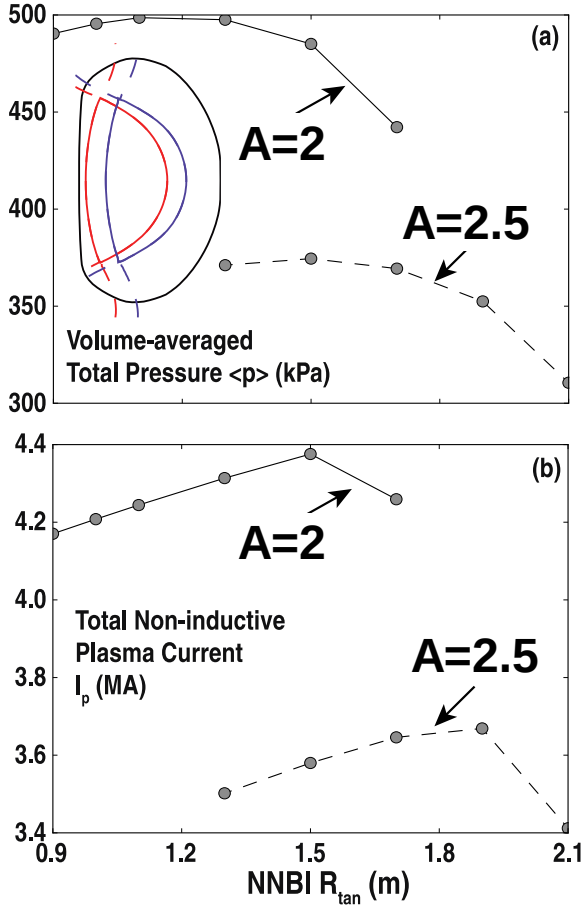
Inboard first-wall



Investigating radially collapsible IB / OB blanket + first-wall module for maintenance



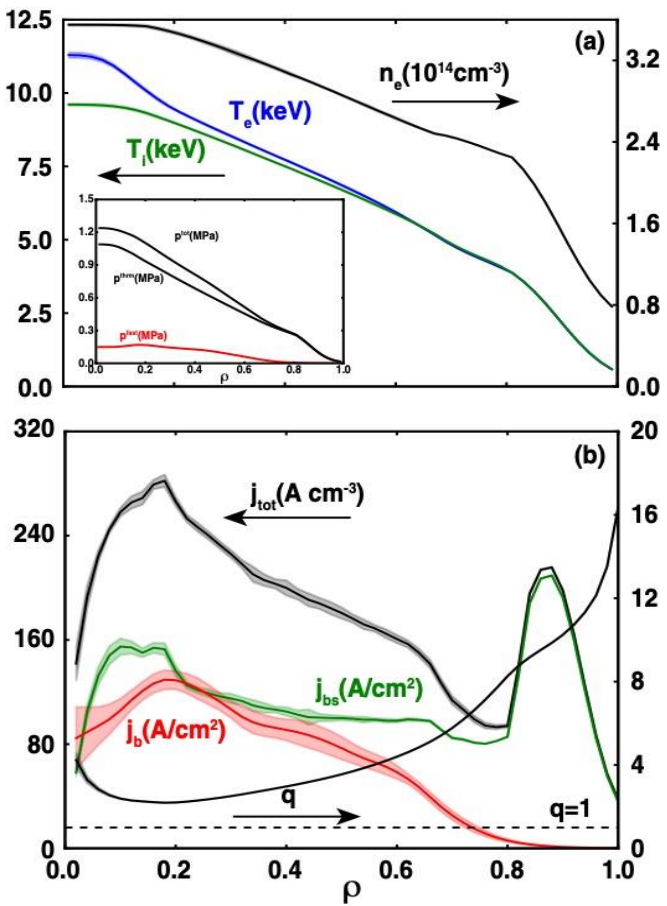
Steady-state performance projections



TRANSP PPPL OMFIT

- **Model assumptions:**
  - D-NNBI at 0.5 MeV, f_G = 0.7-0.8
  - TRANSP, NUBEAM for H&CD
  - EPED1-NN for pedestal
  - GLF23 for core transport
- **A=2.5 projections:**
  - R_0 = 1.66m, B_T = 4.4T, 20MW
  - <p> = 0.37 MPa
    - **Approx. ½ of FPP at A=2.5-3**
- **A=2.0 projections:**
  - R_0 = 1.34m, B_T = 5.4T, 20MW
  - <p> = 0.5 MPa
    - **Comparable to FPP at A=2.0**

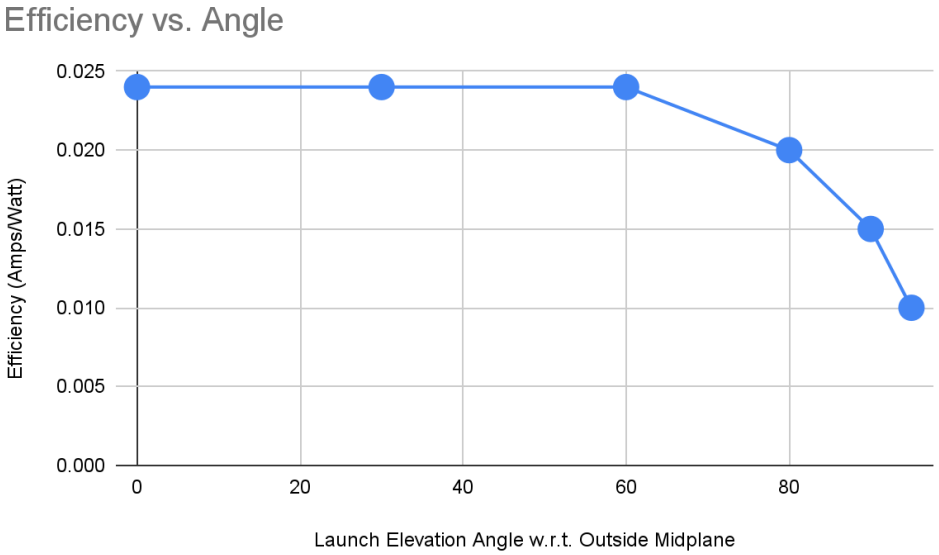
Profile projections for A=2.0 scenario

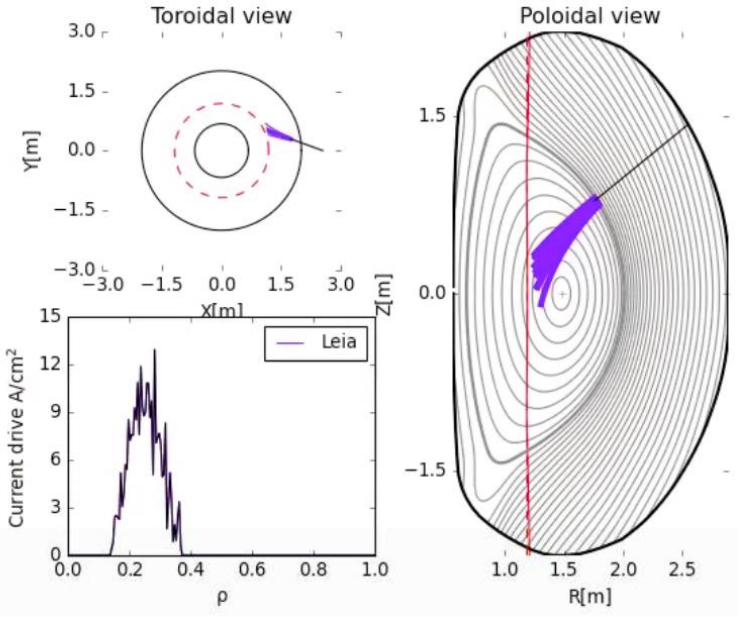


- R_0=1.34m, B_T=5.4T
- $P_{aux\text{-}NNBI}$ = 50MW
- GLF23 + EPED1-NN + NSTX-like pedestal width scaling:
  - T(0) ≈ 10keV
  - I_P = 4.5 MA (100% NI)
  - ⟨p⟩ = 0.54 MPa
  - β_N = 3.7, β_t = 4.8%, β_p = 1.9
  - f_G = 0.88
  - q_{min} = 2.2
  - f_{BS} = 0.69
  - H98(y,2) = 1.65
  - Q_{DT}(thermal) ~ 0.63

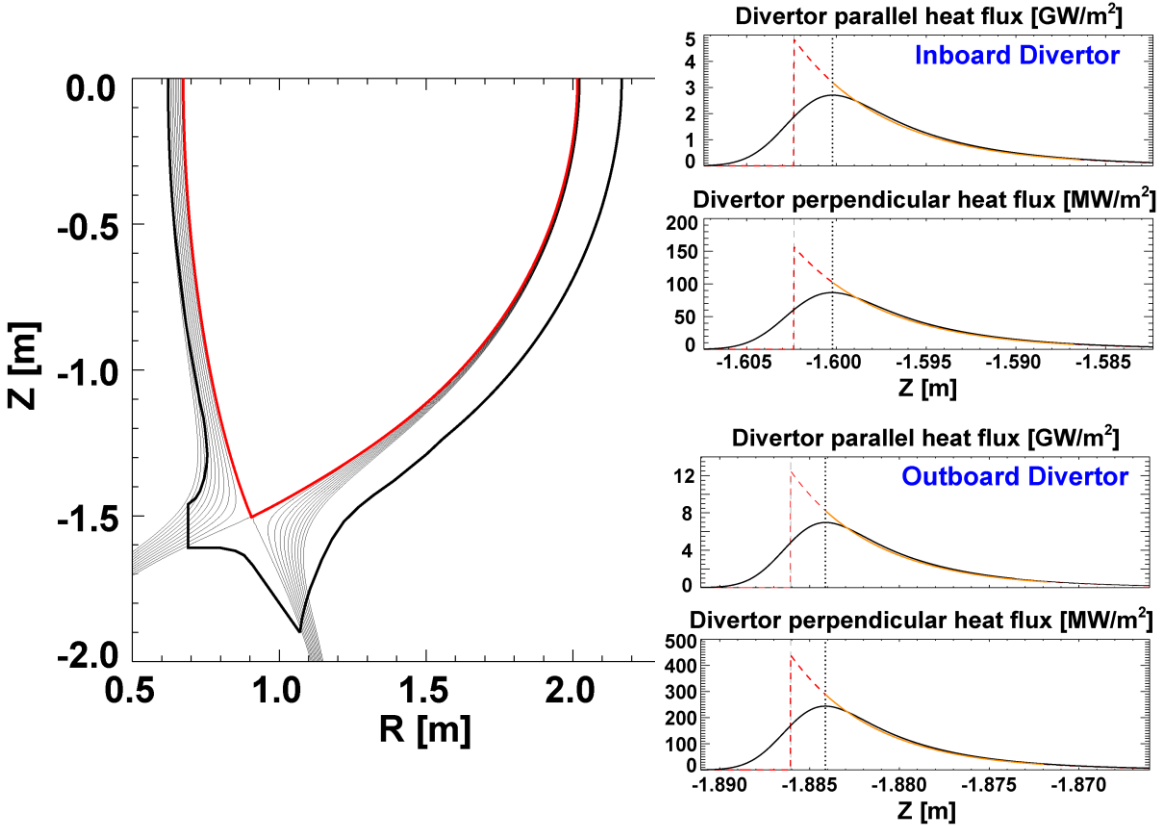
HFS ECCD attractive for sustaining SHPD regime

- A=2 with B_T =5.5-6T well matched to 170GHz ITER gyrotrons
- Upper outboard launch maximizes CD efficiency (top launch not well absorbed)
- EC CD efficiency comparable to 0.5MeV NNBI ($\eta_{CD\text{-}NNBI}$ = 0.027 A/W)
- Simulations include transport response





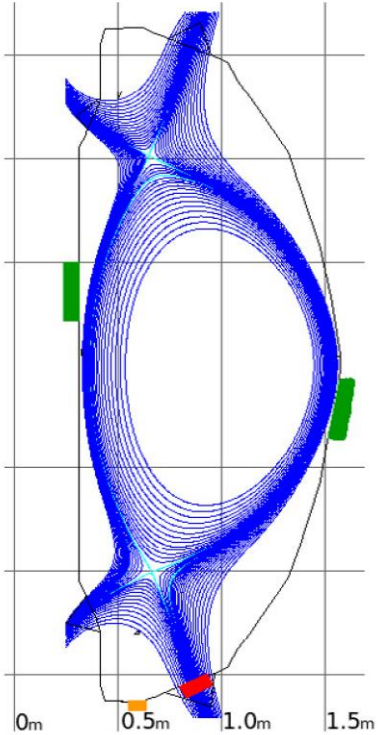
Unmitigated divertor peak heat fluxes: 80-250MW/m²

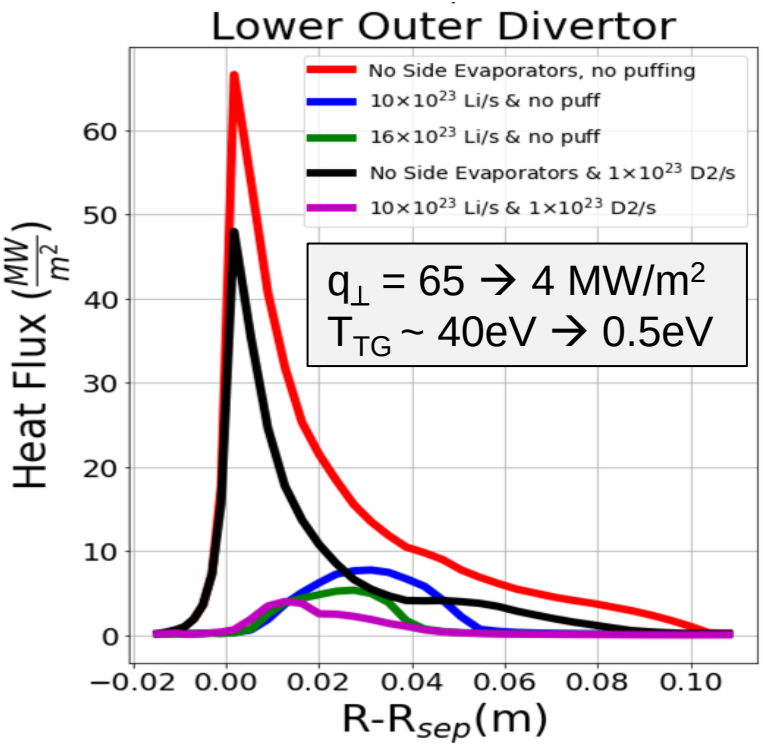


- Outboard heat flux 3× inboard heat flux
- Heat flux broadening + detachment needed for $q_{\perp\text{-div}} < 10$ MW/m²
- Novel approaches using liquid metals also likely needed for heat flux mitigation

Vapor box divertor promising for heat flux reduction

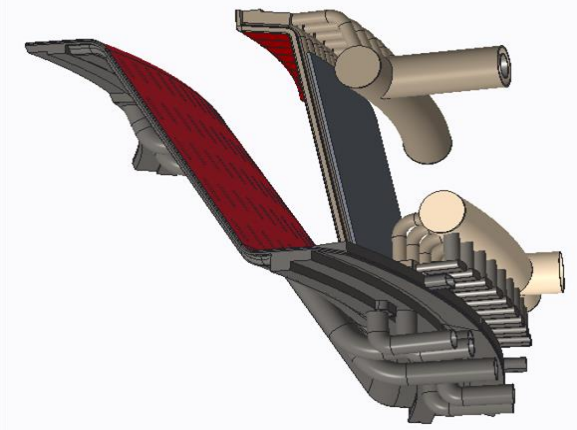
NSTX-U modelling: Li evaporation from target + D_2 puffing in private flux region very effective for heat flux reduction (15-20×)





E. Emdee et al., *Nucl. Mater. Energy* ***27*** (2021) 101004

Next steps:
Apply to EXCITE / FPP

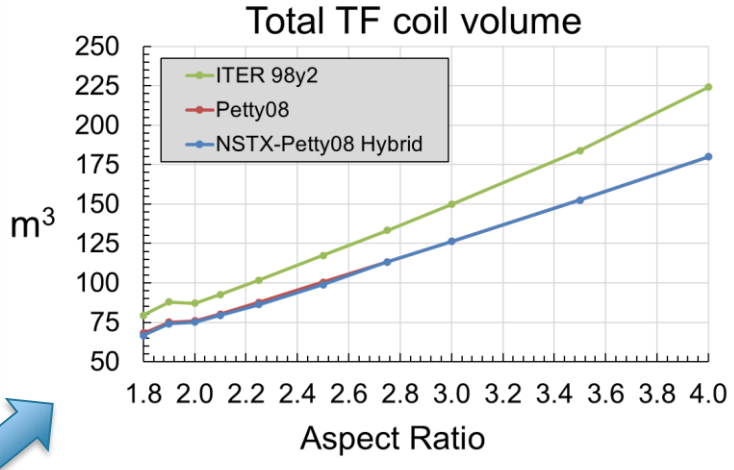


T. Brown et al, Fus. Eng. Design (2021)
E. Emdee et al, Nucl. Fusion (2019)
J. Schwartz and R. Goldston, NME

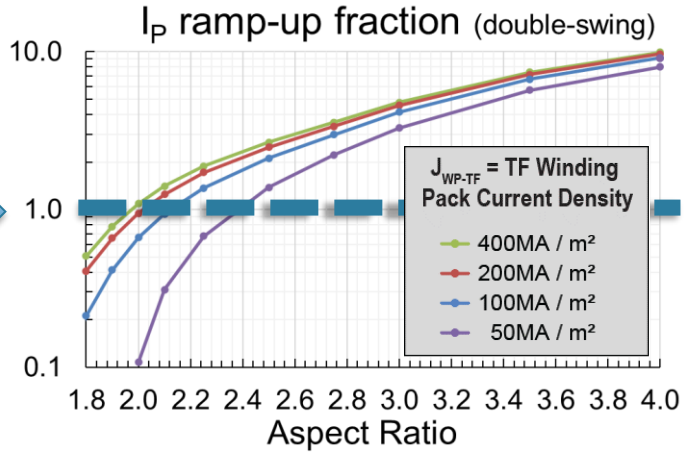
Upcoming ST reactor studies

FPP magnet volumes are strong function of A

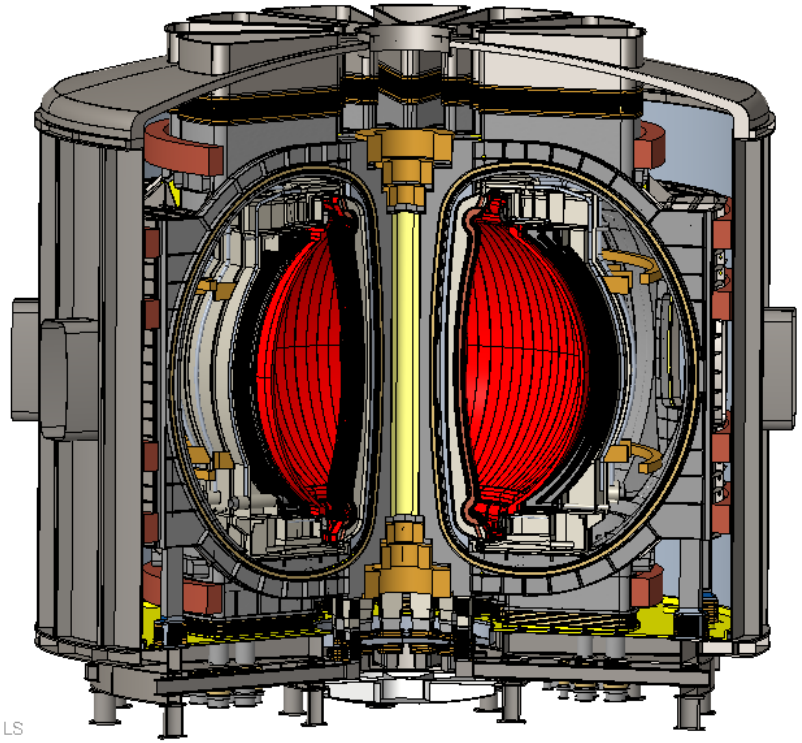
FPP fixed parameters:	• **Net electric power = 100MWe** • 100% non-inductive current drive • Tritium breeding ratio ≈ 1 • ReBCO TF lifetime = 10 FP-years • $B_{TF\text{-}max}$ = 18T, $J_{WP\text{-}TF}$ = 50 MA/m²



- A ≈ 2-2.4 reduces TF volume by factor of 1.5-2× vs. standard A
  - May reduce TF cost (TBD)
- Low-A also reduces size, space available for central solenoid
  - Pulsed operation favors high A
  - A < 2 → partial non-inductive ramp



ST Advanced Reactor (STAR) Power Plant



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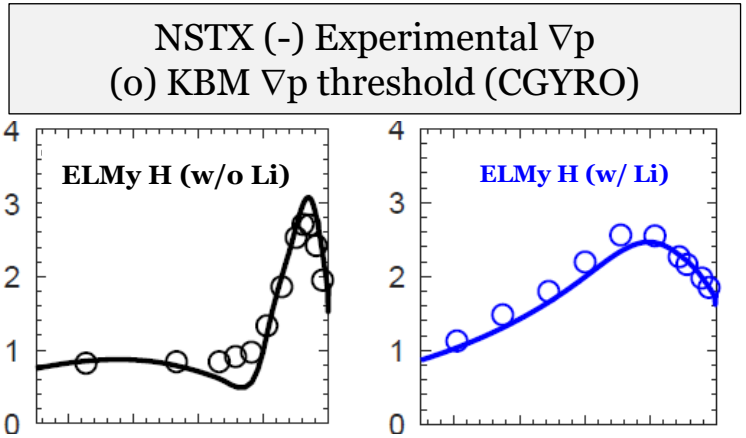
STAR Parameters (example):

- R_0 = 4 – 4.5m, A = 2.0, κ = 2.5
- 12 TF coils
- B_0 = 5.1 T, B_{max} = 20.2 T
- HTS winding at 20 K
- Vapor box double null divertor
- Option for liquid metal first-wall
- P_{net} = 100-500MWe depending on major radius, confinement, wall stabilization, blanket thermal efficiency

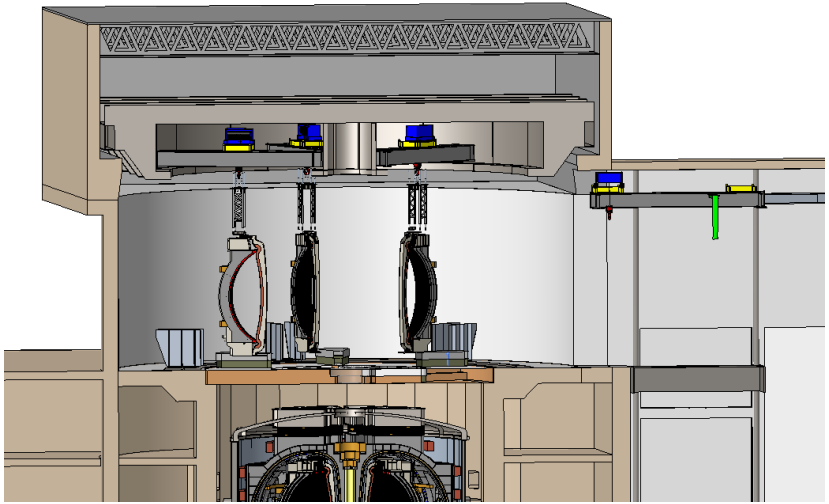
Upcoming STAR development activities

- TRANSP/NUBEAM for non-inductive / partially inductive CD, time-dependent ramp-up/down
- Emphasis on pedestal structure, stability (CGYRO for KBM, M3D-C1 for stability)



- Investigate role of recycling (Li-wall) on expected profiles and fusion performance
- Explore SOL turbulence broadening

- Machine layout initiated in 2022, magnet, vessel stress analysis starting
- Simultaneous multi-segment vertical maintenance for increased availability



THANK YOU!

Any questions?