TECH/2-4: Mission and Configuration Studies for a U.S. Sustained High-Power Density Tokamak Facility*

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ID: IAEA-CN-286/1013

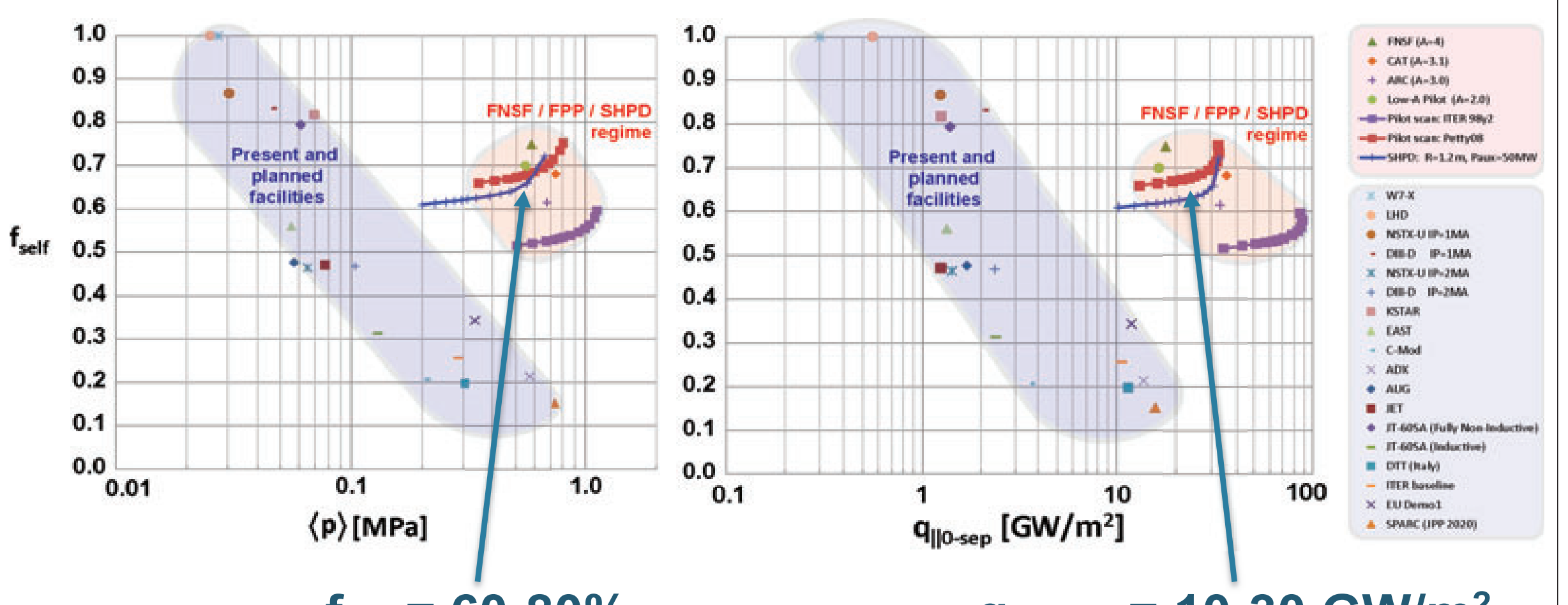
*This work was supported by US DOE Contract No. DE-AC02-09CH11466 and the DOE Laboratory Directed Research and Development program

Overview

- U.S. fusion community supports Fusion Pilot Plant (FPP) mission:
  - Produce net electricity from fusion
  - Establish capability of high average power output
  - Safe production and handling of T, feasibility of a closed fuel cycle
- Reduced-cost tokamak FPP may be feasible through compactness
- Novel high-B, high-J magnets pursued by several groups
  - Standard aspect ratio (A~3), pulsed tokamak pursued by CFS
  - Aspect ratio A ≤ 2, non-inductive pursued by Tokamak Energy
- Compact + steady-state + high-power integration challenge
- Sustained high power density (SHPD) facility to address challenge

FPP parameters not yet accessible (simultaneously)

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



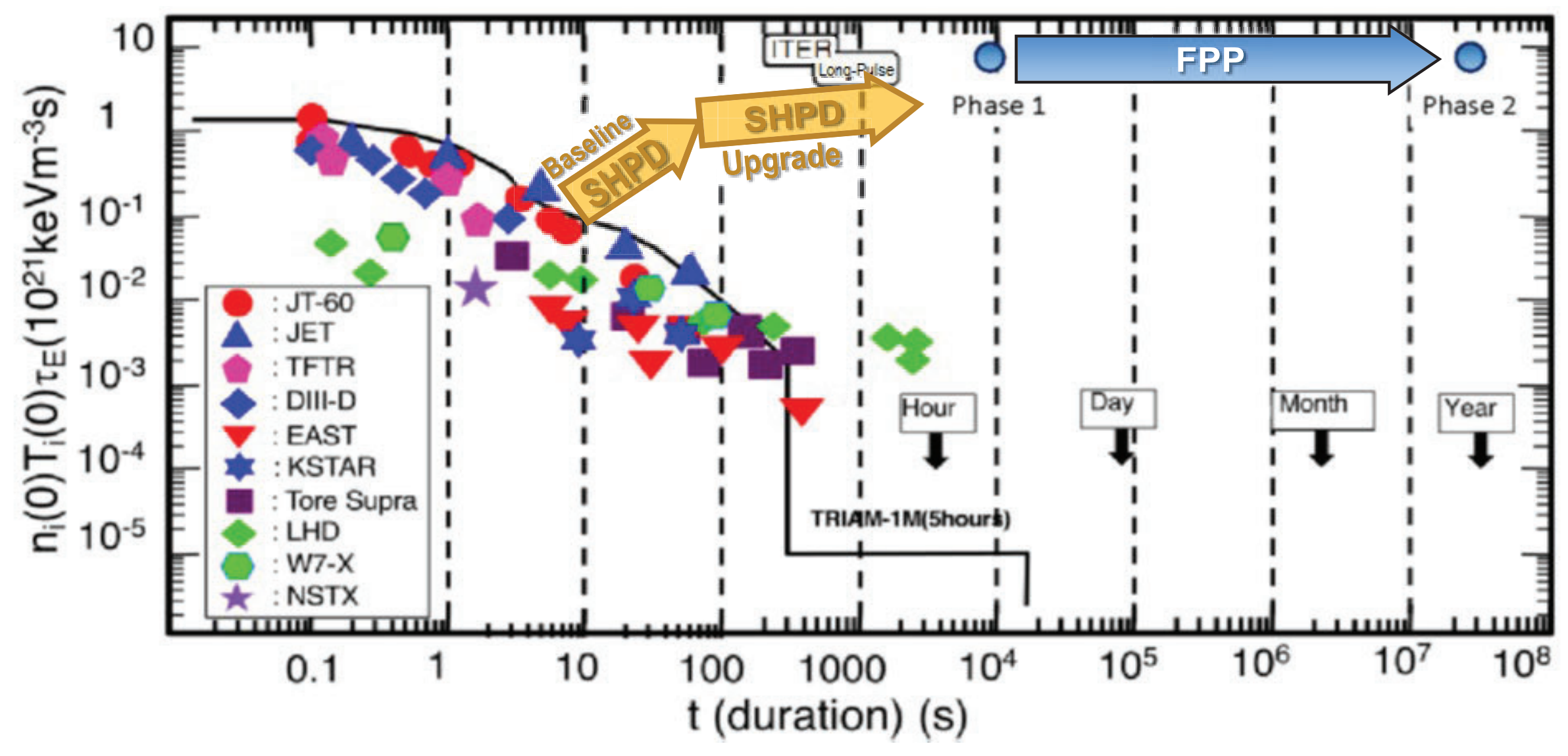
f_{BS} = 60-80%
⟨p⟩ = 0.3-0.8 MPa
3-10× present/planned at high f_{BS}

$q_{||0\text{-sep}}$ = 10-30 GW/m²
3-8× present/planned at high f_{BS}

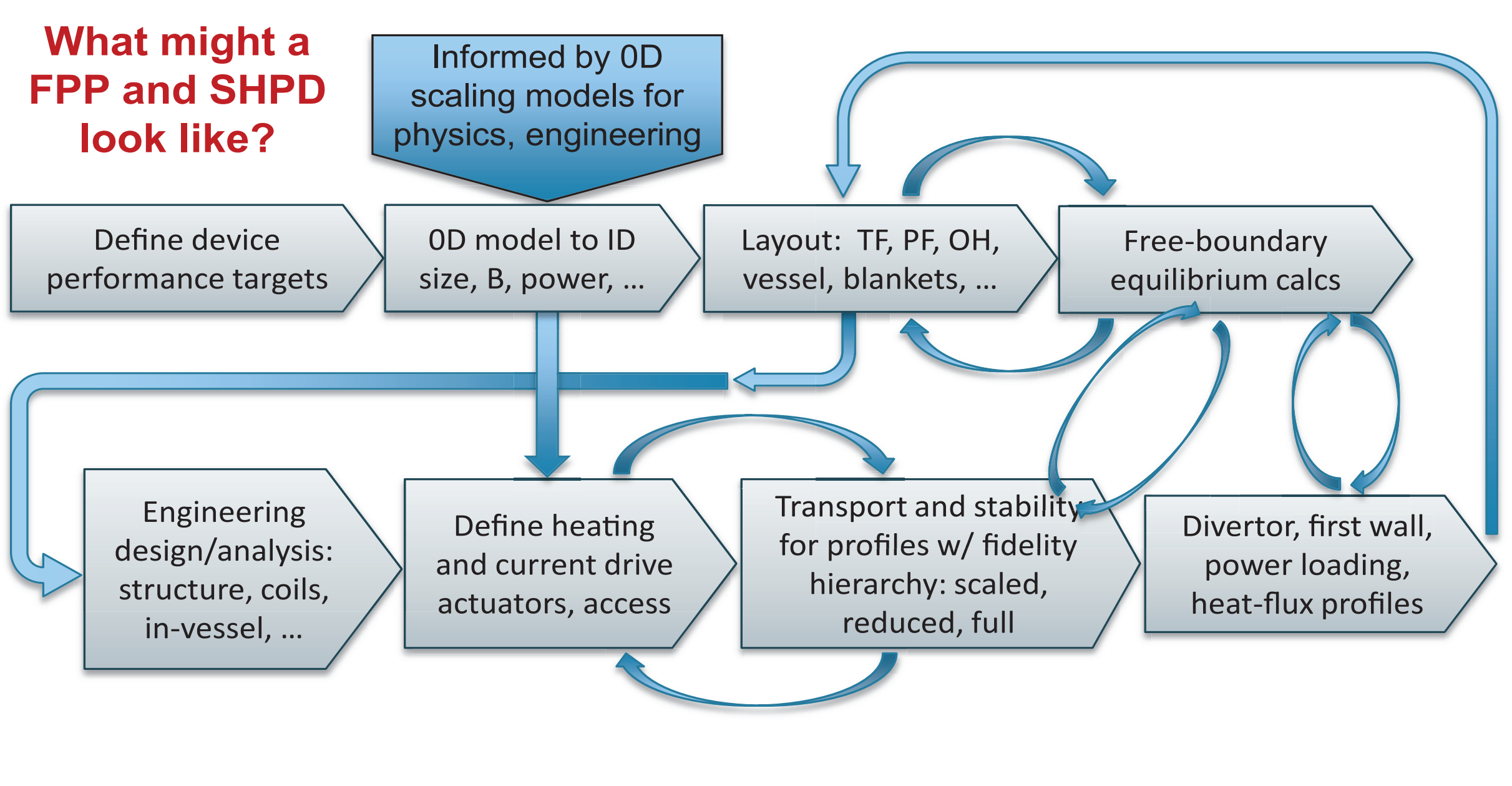
Need to bridge $nT\tau_E$ and $\tau_{duration}$ gap to FPP

- **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)



Whole system modelling workflow: physics + engineering



What might a FPP and SHPD look like?

Informed by 0D scaling models for physics, engineering

Define device performance targets → 0D model to ID size, B, power, … → Layout: TF, PF, OH, vessel, blankets, … → Free-boundary equilibrium calcs

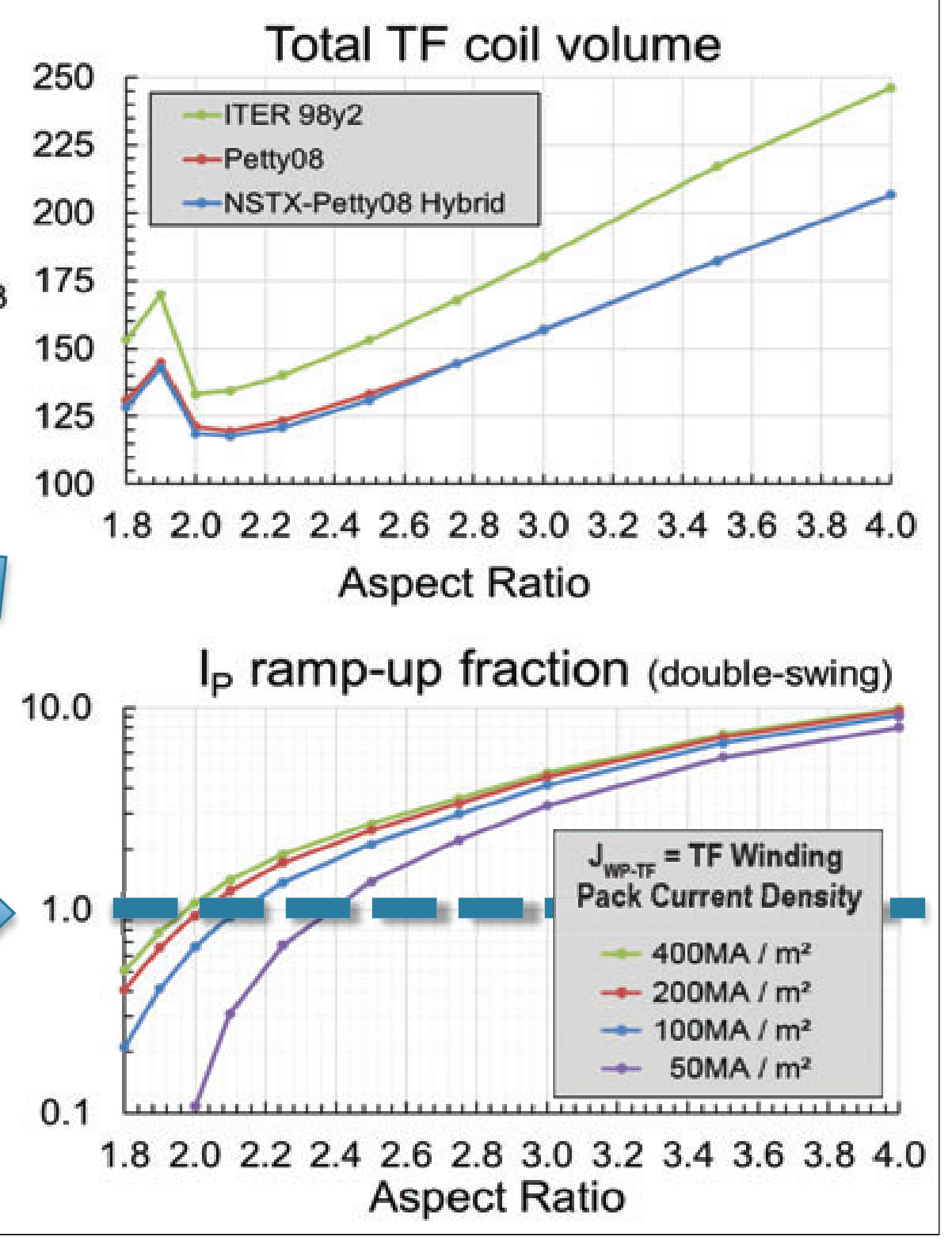
Engineering design/analysis: structure, coils, in-vessel, … → Define heating and current drive actuators, access → Transport and stability for profiles w/ fidelity hierarchy: scaled, reduced, full → Divertor, first wall, power loading, heat-flux profiles

Low-A reduces FPP magnet volume

Pilot Plant example:

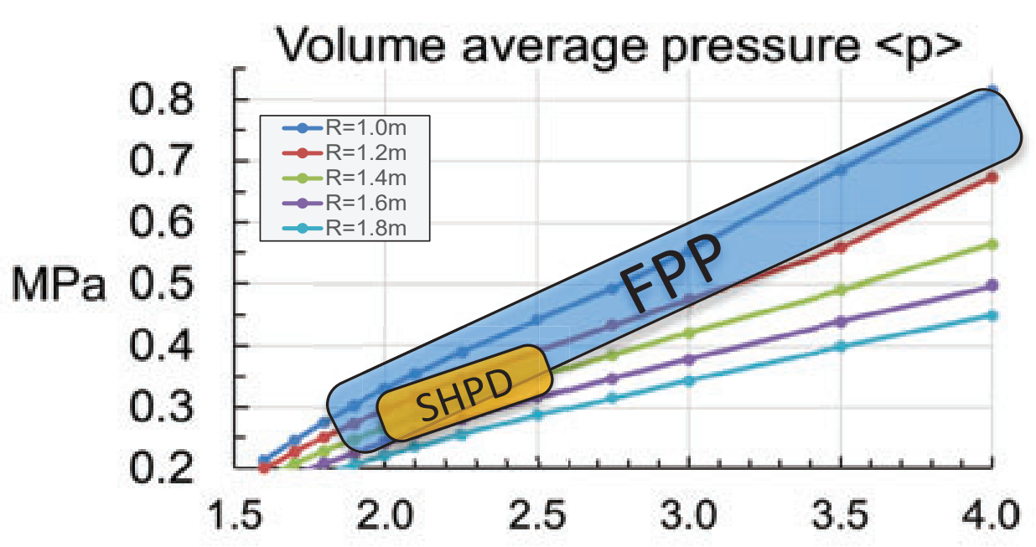
- Net electric power = 100MWe
- 100% non-inductive current drive
- Tritium breeding ratio ≈ 1
- ReBCO TF lifetime = 10 FP-years
  - $B_{TF\text{-}max}$ = 18T, $J_{WP\text{-}TF}$ = 50 MA/m²

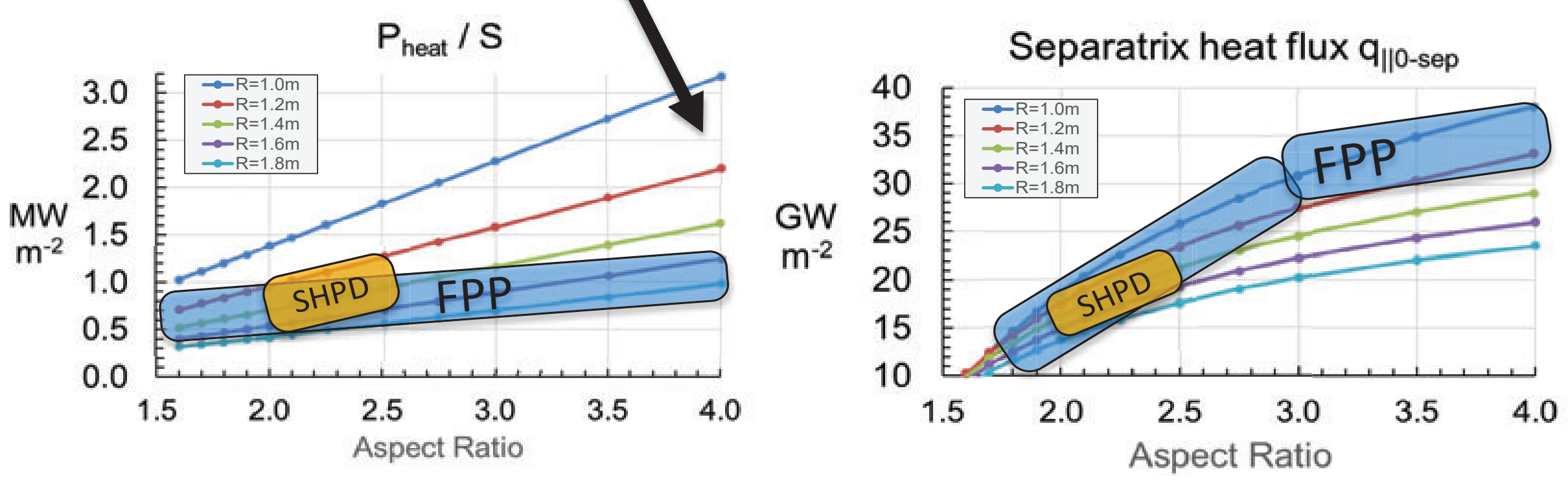
- A ≈ 2-2.4 reduces TF volume by factor of 1.5-2× vs. standard A
  - May reduce TF cost (TBD)
- Low-A also reduces size, space available for central solenoid
  - Pulsed operation favors high A
  - A < 2 → partial non-inductive ramp



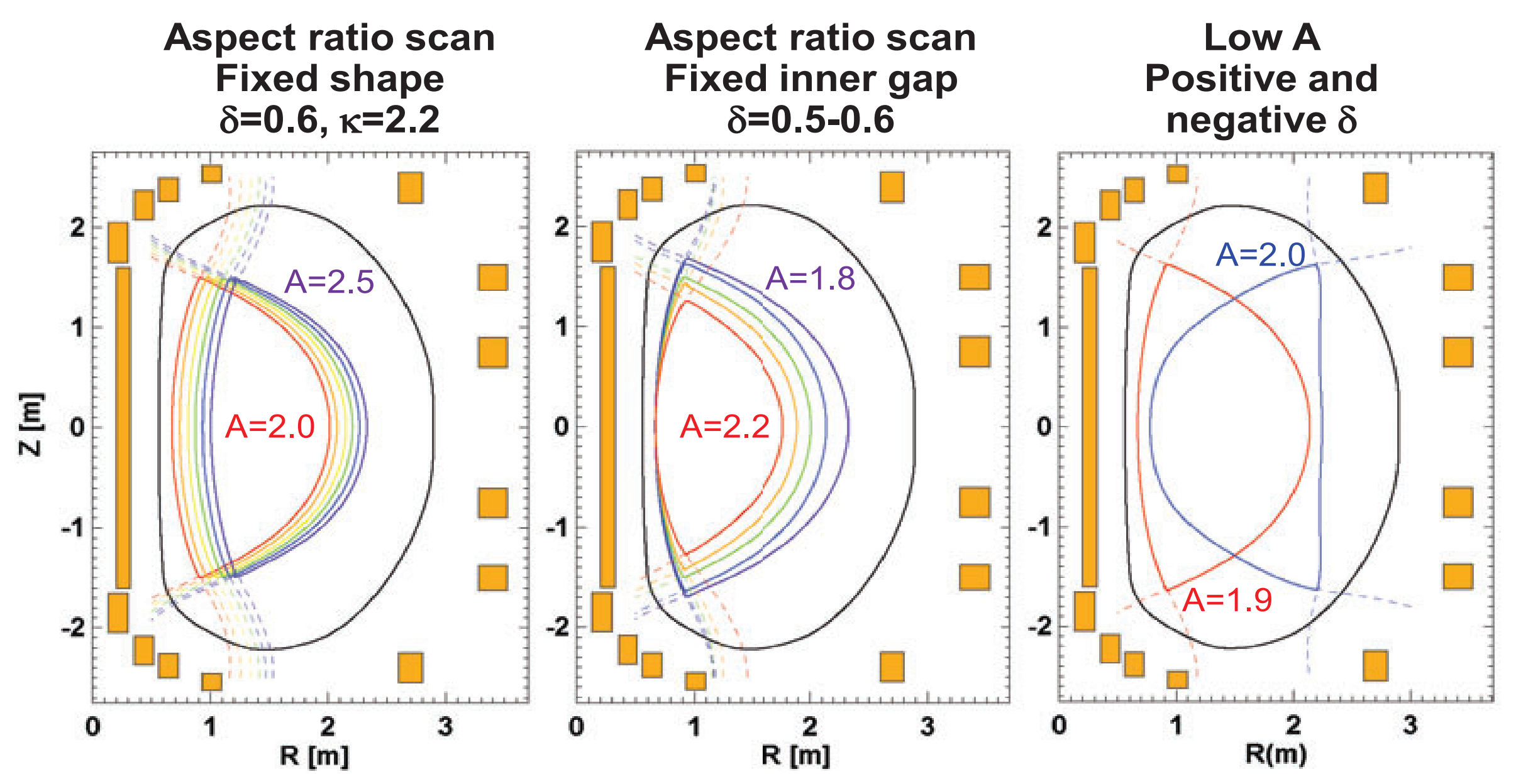
SHPD: R=1.2-1.6m, A=2-2.5, $P_{aux/CD}$ = 50MW

- SHPD overlaps 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)



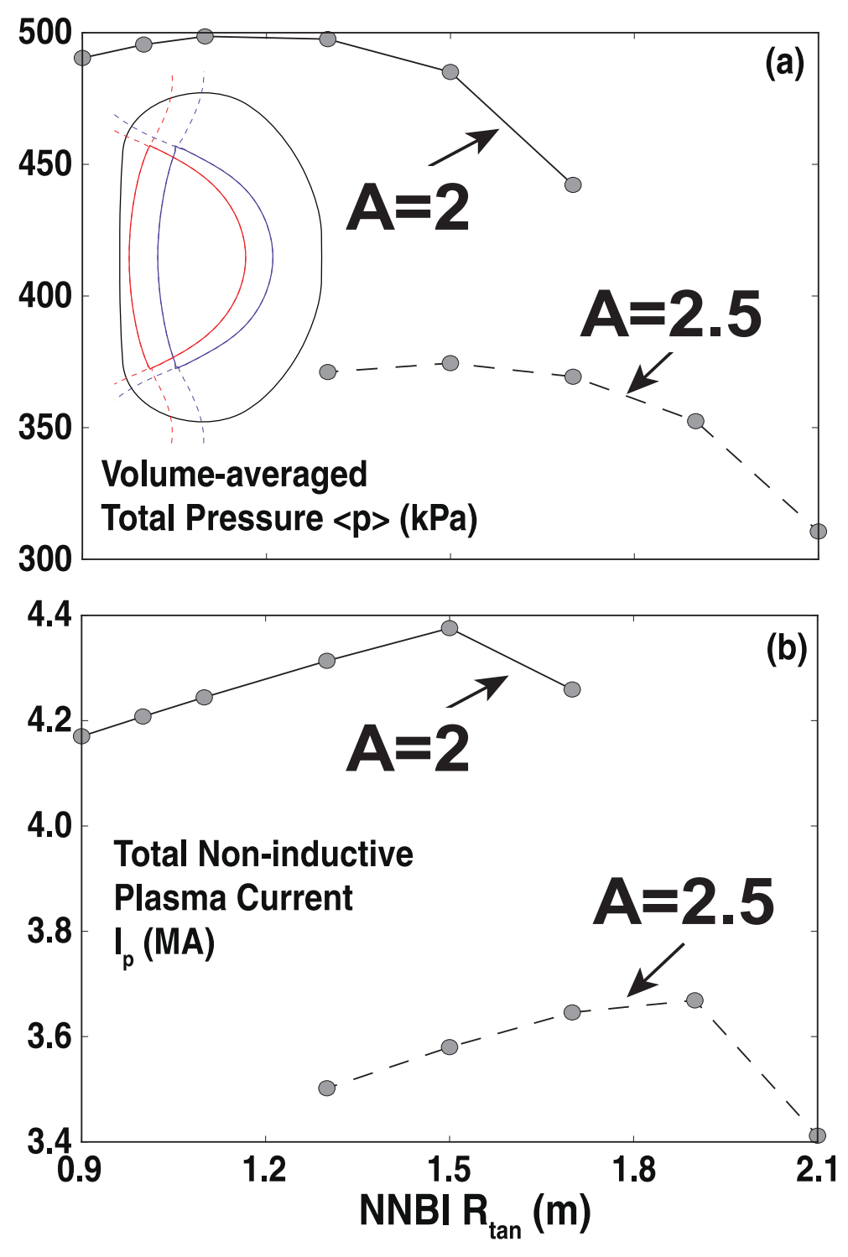


Examples of shape flexibility with present SHPD coils



- **Present PF set can access A=1.8-2.5 in single device**
- **Caution:** Need to assess in-vessel component and exhaust compatibility
- **Future:** Explore long-leg / super-X / X-point-target at higher A=2.3-2.5

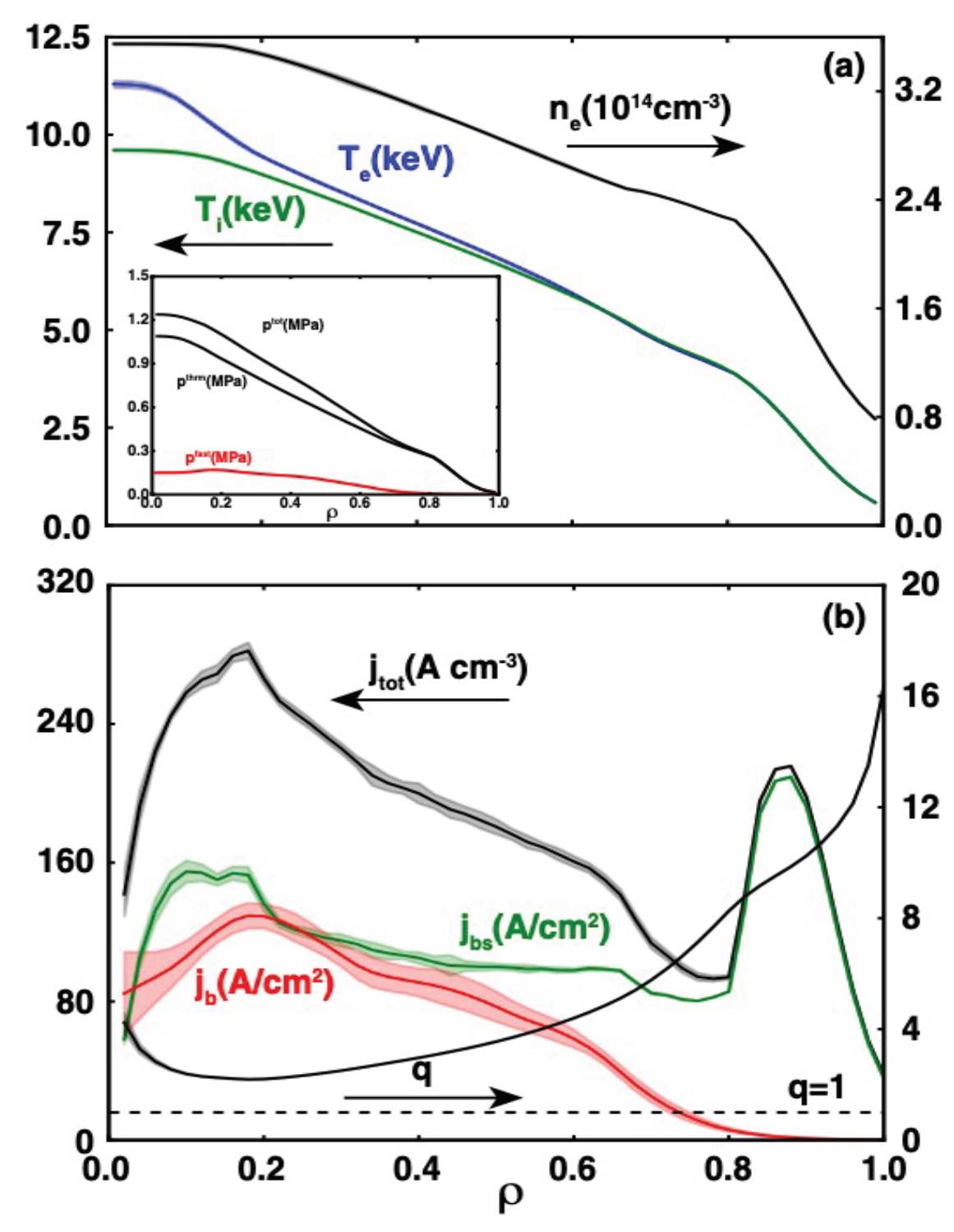
SHPD steady-state performance projections



TRANSP 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**

SHPD profile projections for A=2.0 scenario

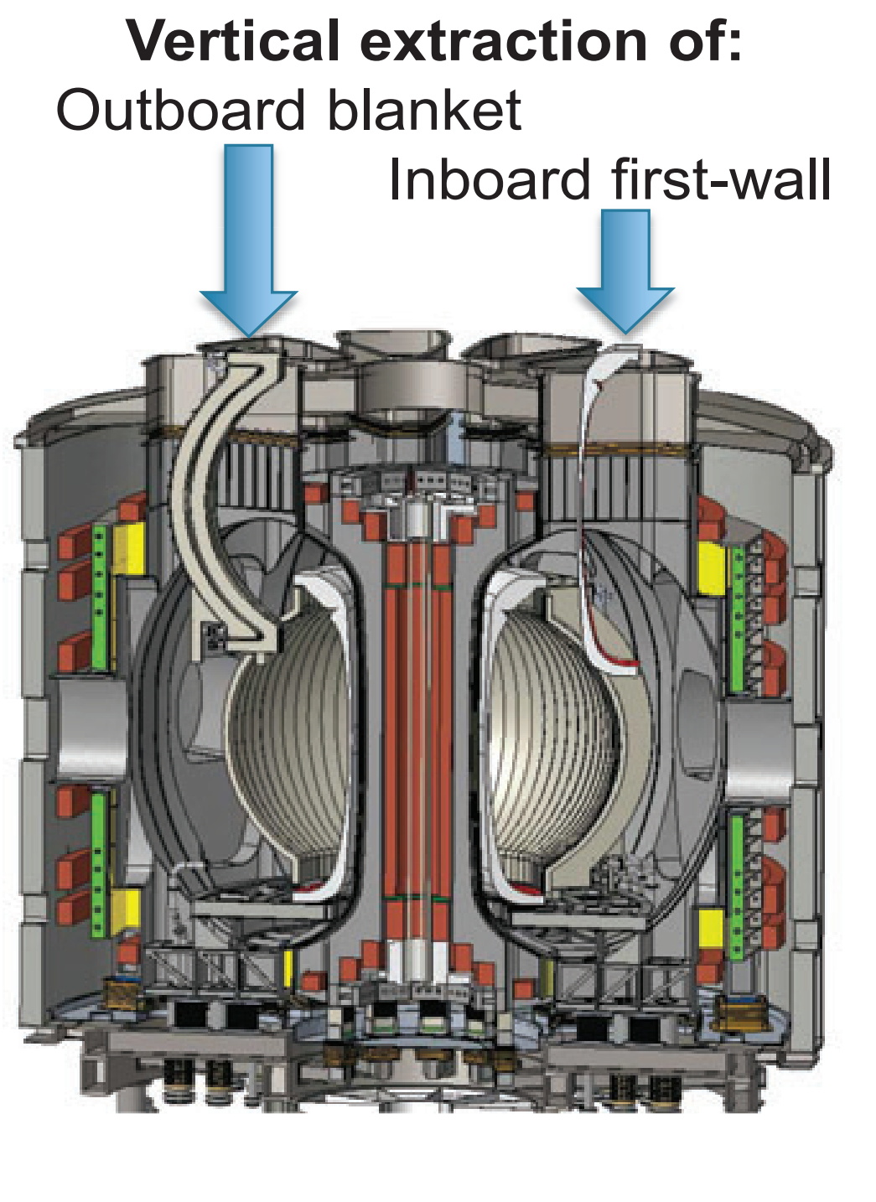


- R_0=1.34m, B_T=5.4T
- $P_{aux\text{-}NNBI}$ = 50MW
- GLF23 + EPED1-NN + NSTX-like pedestal width scaling:
  - T(0) ≈ 10keV
  - I_P = 4.5 MA (100% NI)
  - ⟨p⟩ = 0.54 MPa
  - β_N = 3.7, β_t = 4.8%, β_p = 1.9
  - f_G = 0.88
  - q_{min} = 2.2
  - f_{BS} = 0.69
  - H98(y,2) = 1.65
  - Q_{DT}(thermal) ~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

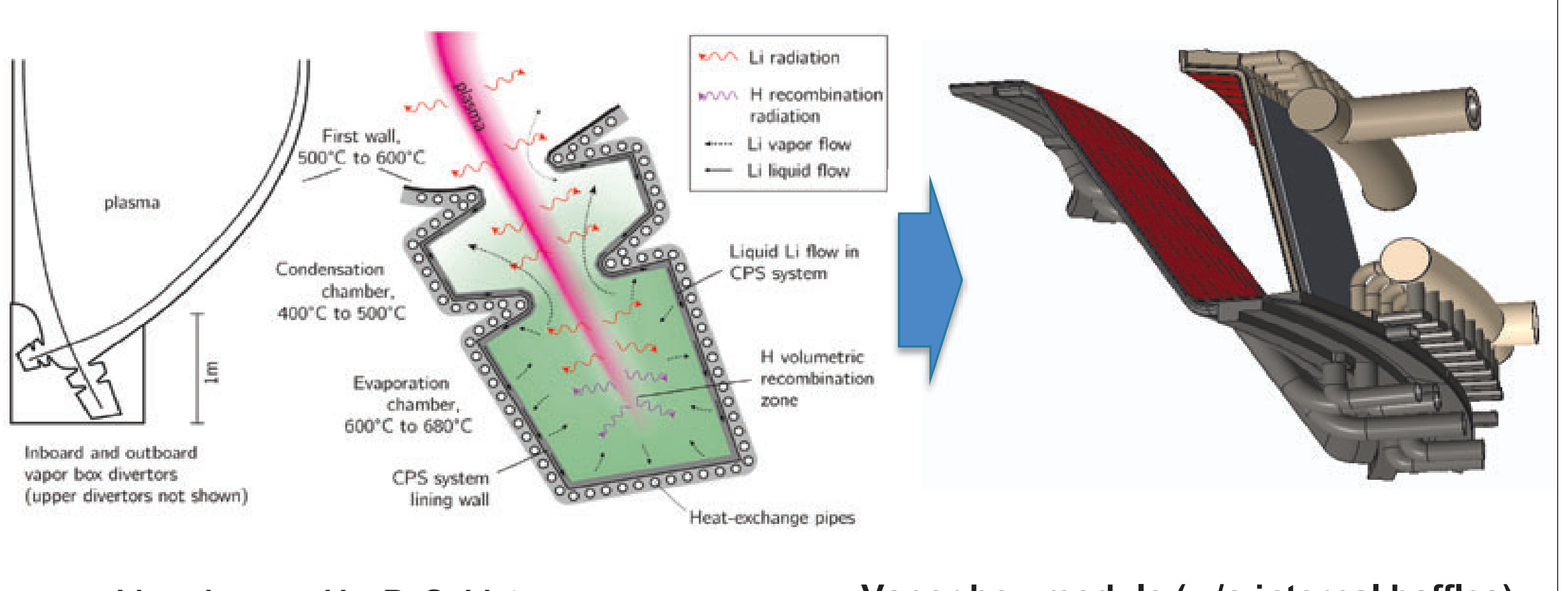
Example engineering design concept

Example SHPD 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



Example Li vapor box divertor concept / idea



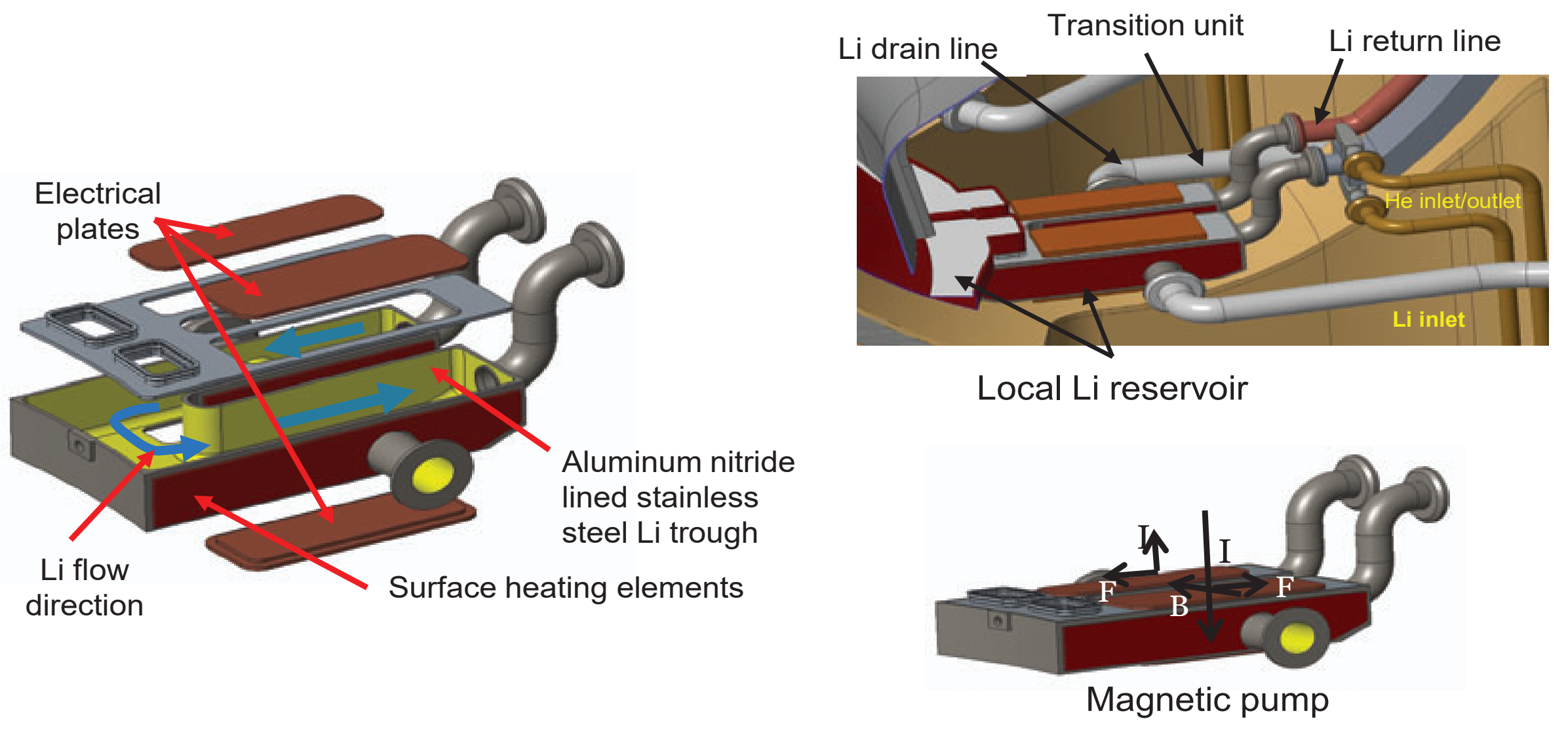
Idea pioneered by R. Goldston

Jacob Schwartz – PhD Thesis
September 2020
Princeton University

Continuing work by E. Emdee

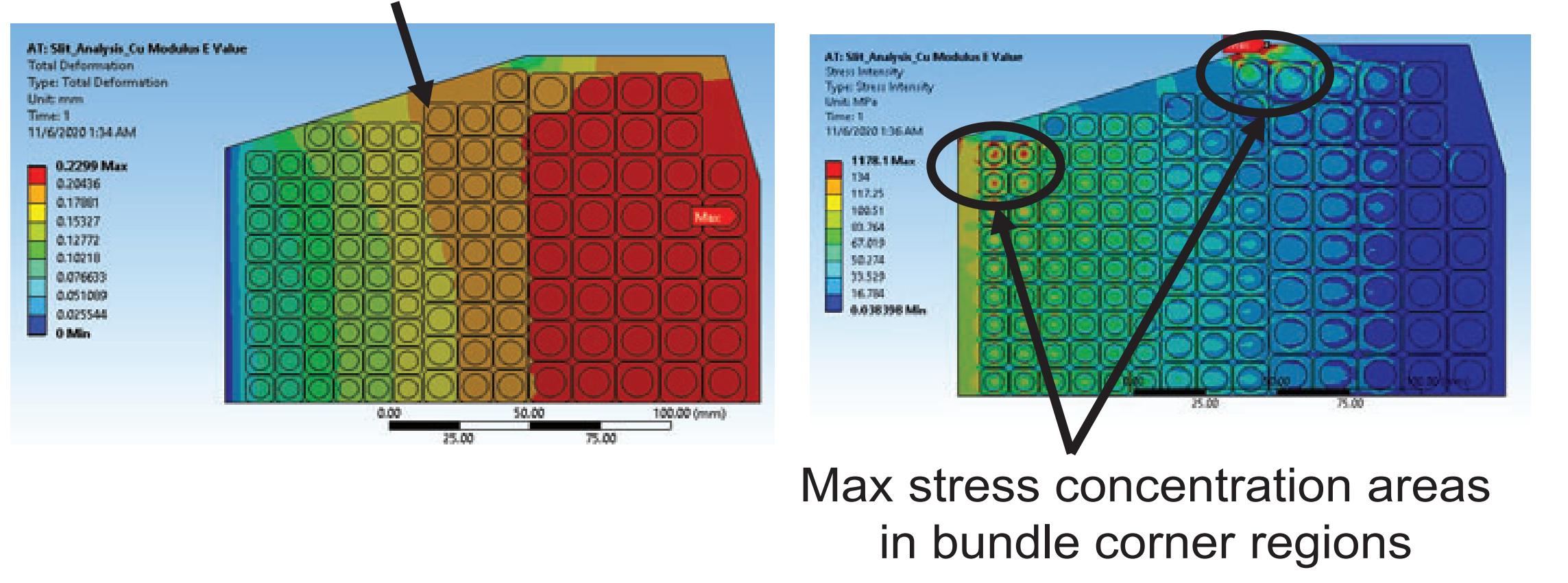
Vapor box module (w/o internal baffles) with lithium manifolds included
Much more R&D to do!

Example Li magnetic pump system for fast flow



- **5-10 m/s Li flow velocity for 10 MW/m² convective heat removal**
- **Combinations of vapor box and fast-flow also being explored**

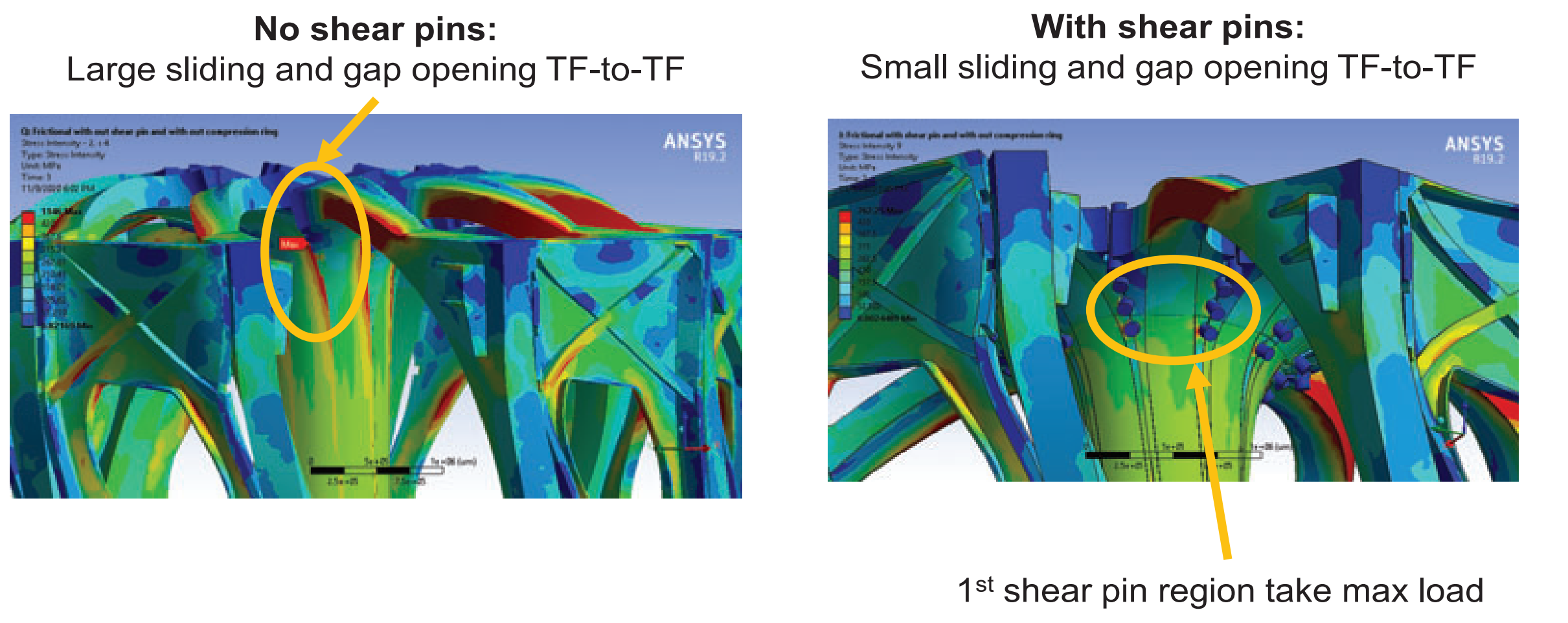
Analysis indicates TF design is feasible



Max stress concentration areas in bundle corner regions

Deformation and stress through bulk of coil are within allowables, but some regions near casing corners need further optimization

Shear pins mitigate torsional loads on TF coils



1st shear pin region take max load

Compression ring + shear-pins promising combination to reduce sliding and gaps to acceptable levels

Summary

- Present/near-term planned facilities will not access FPP regime
- Need dedicated facility (or FPP itself) to simultaneously explore:
  - High fraction of self-driven current
  - High core plasma pressure
  - High surface-average and divertor parallel heat flux
- R=1.4 ± 0.2m, B = 4-6T, A = 2-2.5, $P_{H\&CD}$=50MW attractive for SHPD
- Systems studies and initial integrated predictive modelling indicate FPP regime should be accessible with the above SHPD parameters
- Initial device configuration and physics design integrates:
  - High current density and high B_T toroidal field magnets
  - Lower aspect ratio / strong shaping to maximize f_{BS} and pressure
  - Liquid metal systems (divertor, first wall, blankets) to prototype FPP
- Engineering calculations show pre-conceptual design is feasible