Mission and Configuration Studies for a U.S. Sustained High-Power Density Tokamak Facility*

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GENERAL ATOMICS

- 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

- 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
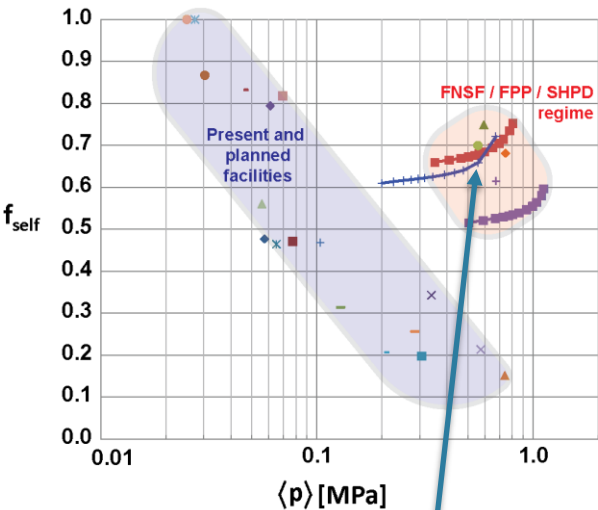
f_{BS} = 60-80%
$\langle p \rangle$ = 0.3-0.8 MPa
3-10× present/planned at high f_{BS}
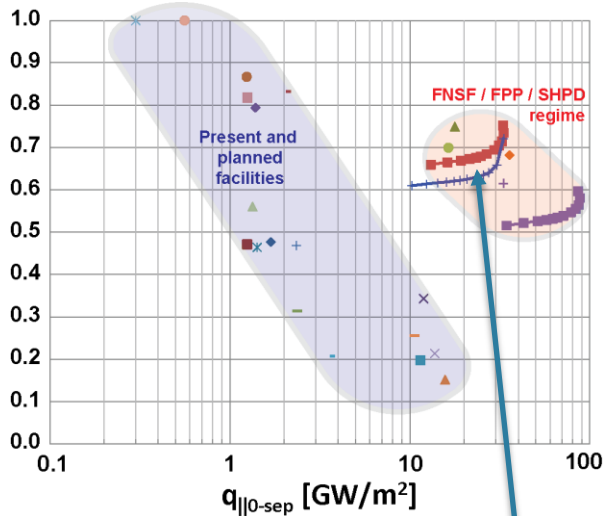
$q_{||0\text{-sep}}$ = 10-30 GW/m^2
3-8× present/planned at high f_{BS}

- **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)
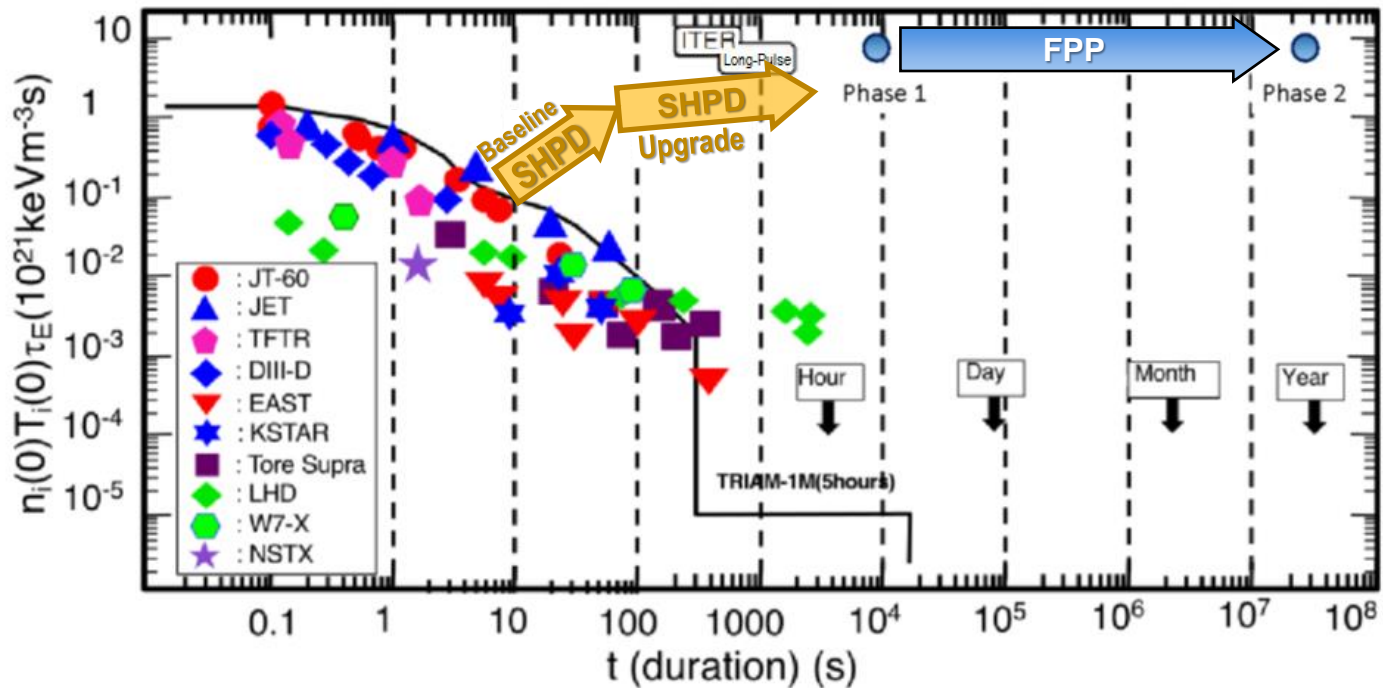
Systems, Scenario, and Device Configuration Modelling

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, …
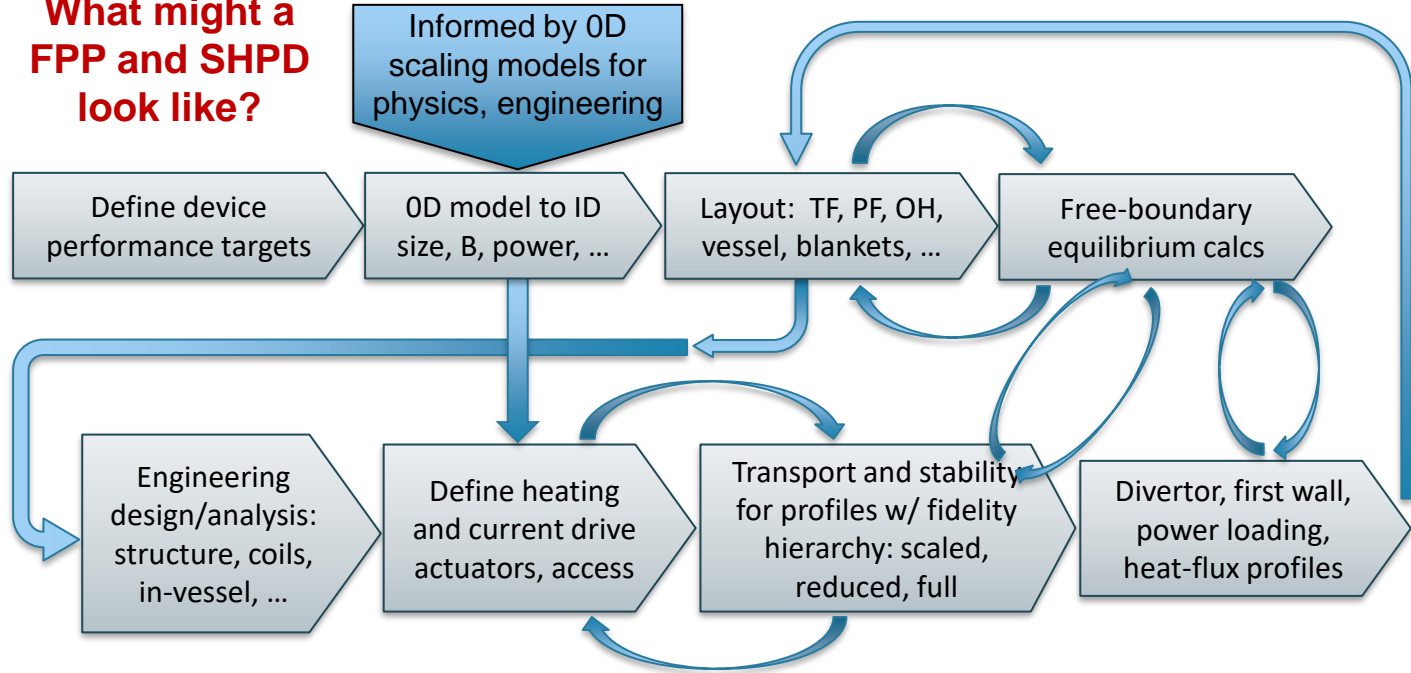
Layout: TF, PF, OH, vessel, blankets, …

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
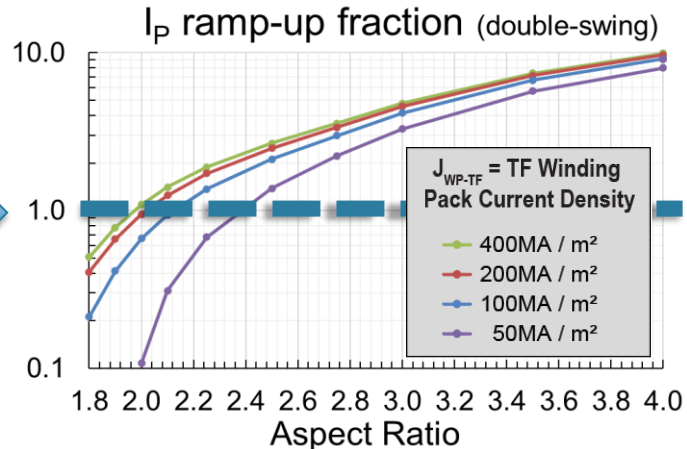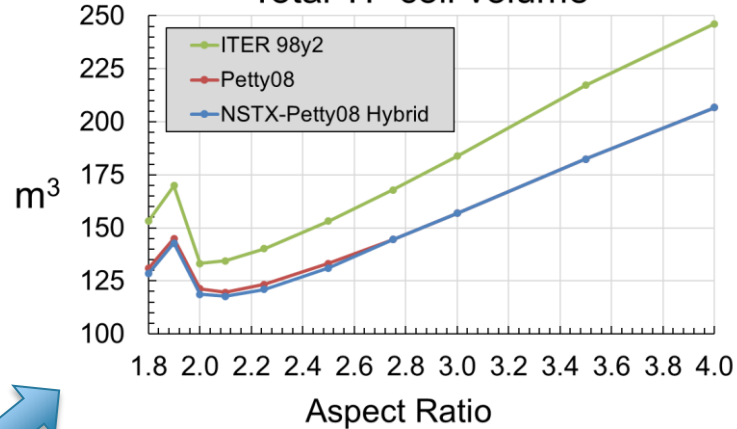
Pilot Plant example:

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

- 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

Total TF coil volume

- ITER 98y2
- Petty08
- NSTX-Petty08 Hybrid

m^3

I_P ramp-up fraction (double-swing)

J_{WP-TF} = TF Winding Pack Current Density
- 400MA / m^2
- 200MA / m^2
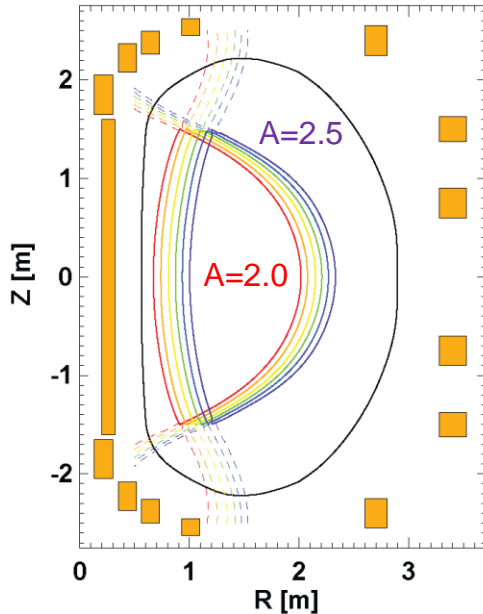- 100MA / m^2
- 50MA / m^2

Aspect Ratio

- 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)

Volume average pressure <p>

P_{heat} / S
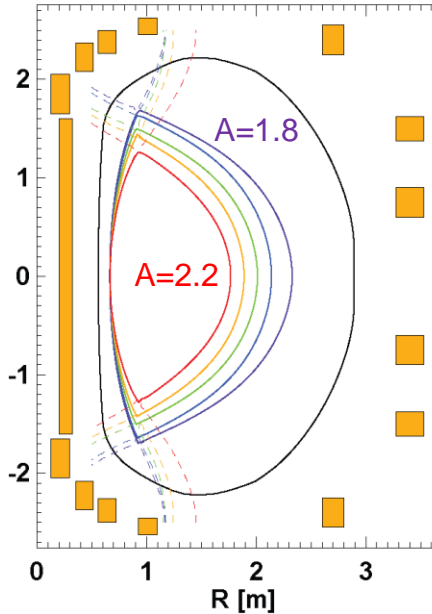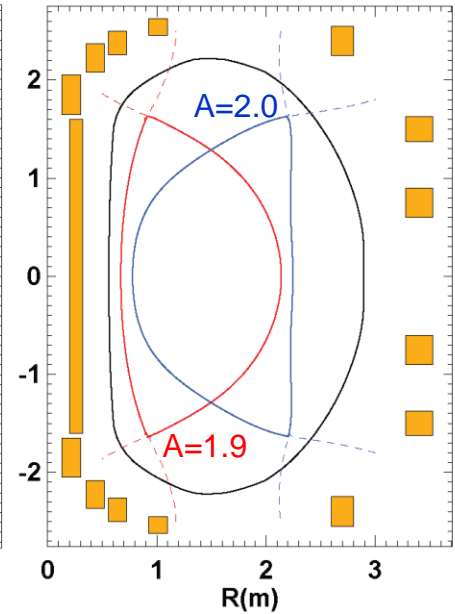

Separatrix heat flux $q_{\|0-sep}$
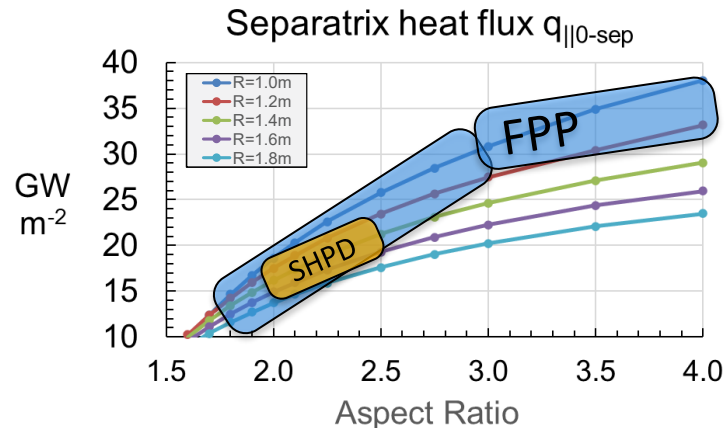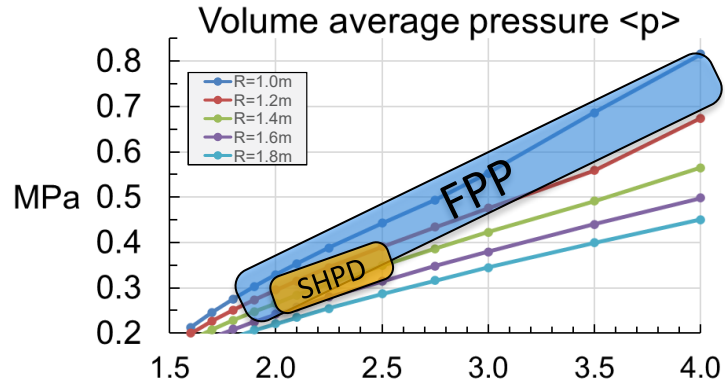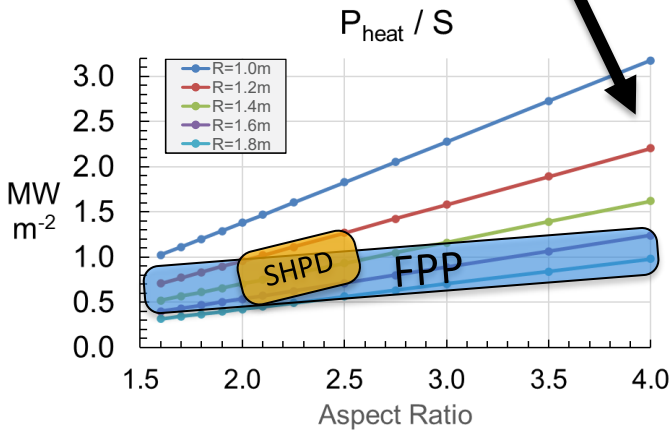
Aspect ratio scan Fixed shape δ=0.6, κ=2.2

Aspect ratio scan Fixed inner gap δ=0.5-0.6

Low A Positive and negative δ

A=2.5
A=2.0

A=1.8
A=2.2

A=2.0
A=1.9

- **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

(a)

A=2

A=2.5

Volume-averaged Total Pressure <p> (kPa)

(b)

A=2

A=2.5

Total Non-inductive Plasma Current I_p (MA)

NNBI R_{tan} (m)
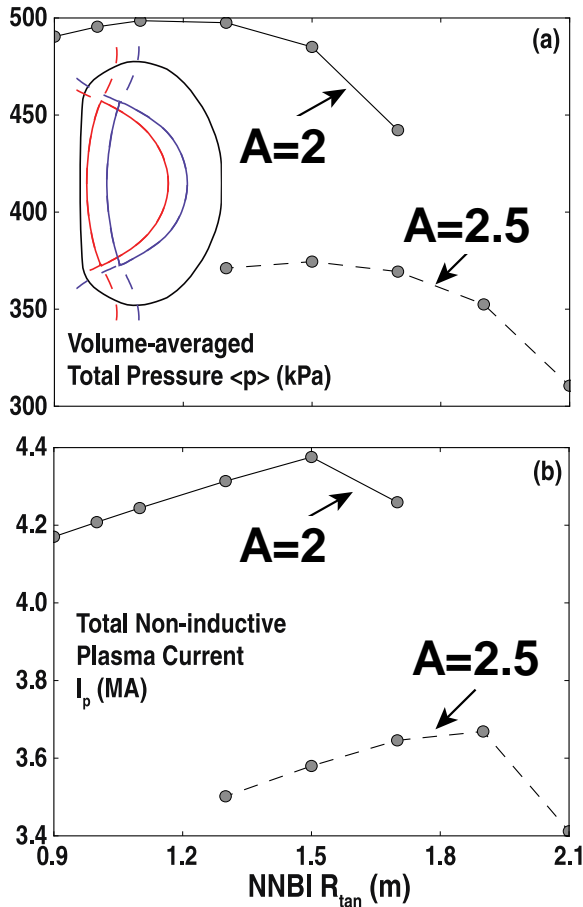
TRANSP PPPL **OMFIT**

- **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:**
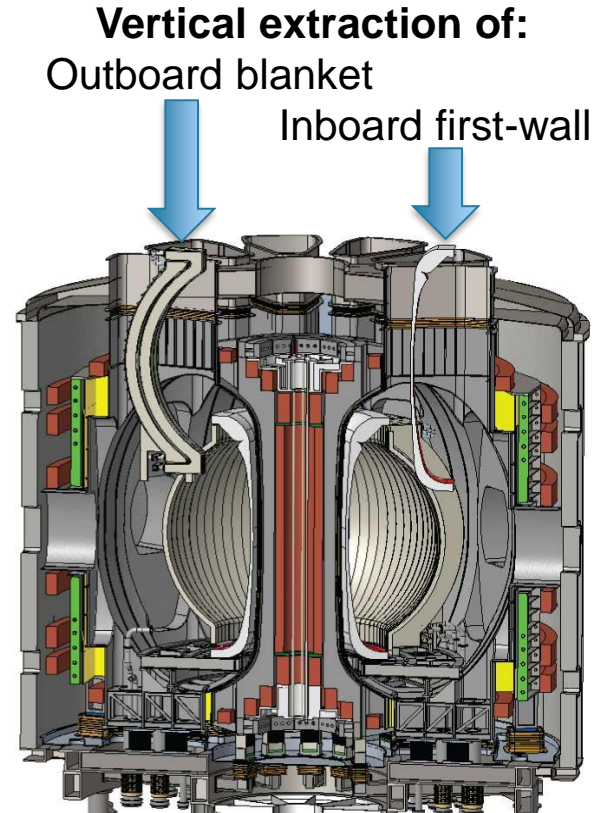 - R_0 = 1.34m, B_T = 5.4T, 20MW
  - <p> = 0.5 MPa
    - **Comparable to FPP at A=2.0**
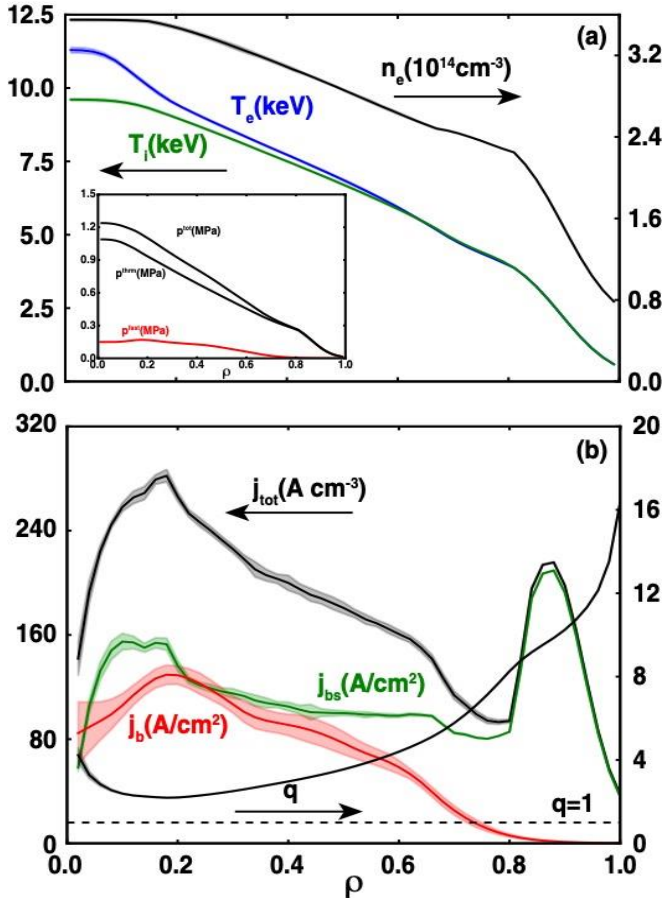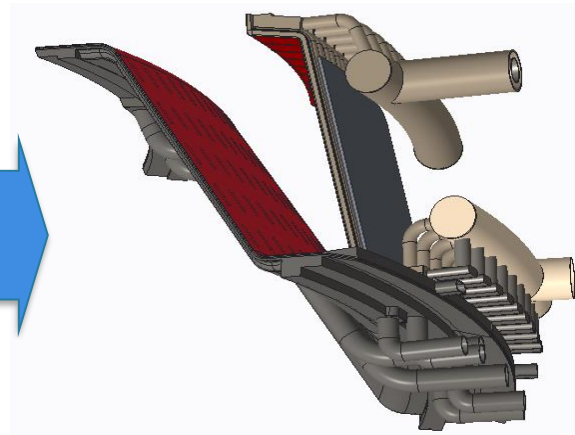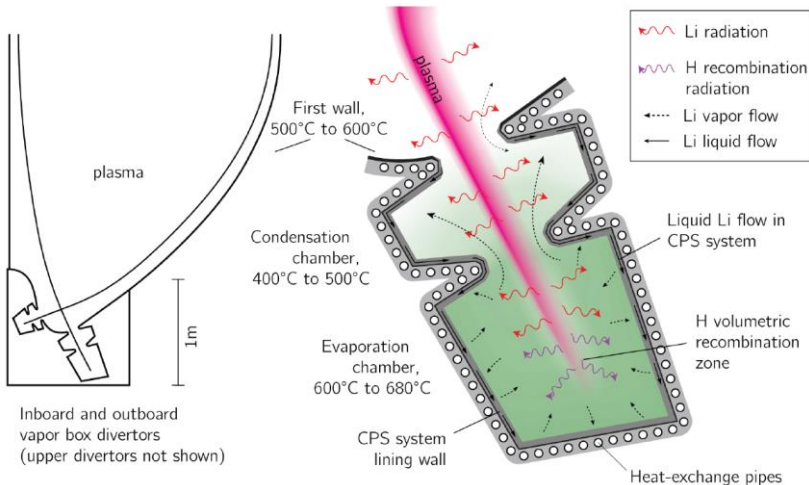
- R_0=1.34m, B_T=5.4T
- $P_{aux-NNBI}$ = 50MW
- GLF23 + EPED1-NN + NSTX-like pedestal width scaling:
  - $T(0) \approx 10$keV
  - I_P = 4.5 MA (100% NI)
  - $\langle p \rangle$ = 0.54 MPa
  - β_N = 3.7, β_t = 4.8%, β_p = 1.9
  - f_G = 0.88
  - q_{min} = 2.2
  - f_{BS} = 0.69
  - H98(y,2) = 1.65
  - Q_{DT}(thermal) ~ 0.63

Example Device Configuration

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-TF}

- Double null

- Outboard test blankets possible

- Vertical maintenance

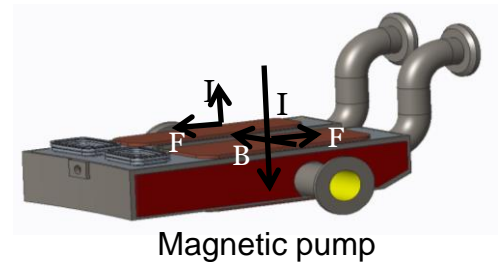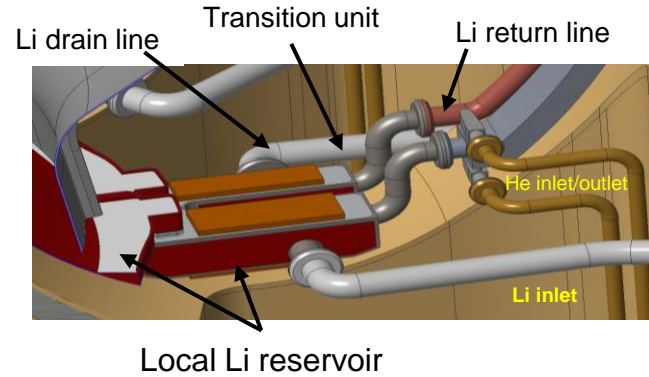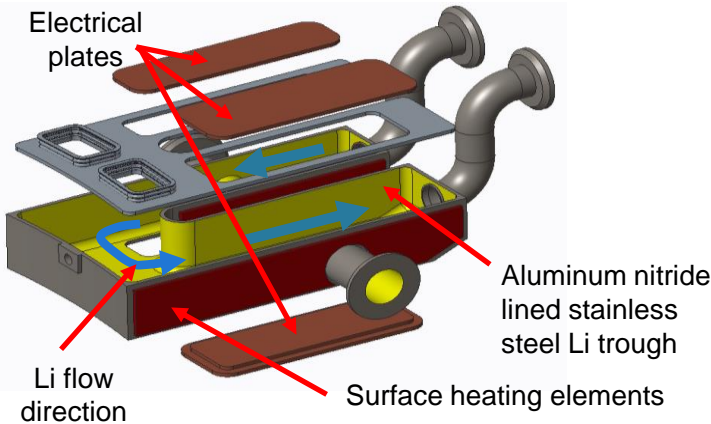- High-Z solid and liquid-metal walls

Vertical extraction of:
Outboard blanket
Inboard first-wall

Example Li vapor box divertor concept / idea

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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 15

Electrical plates

Li flow direction

Surface heating elements

Aluminum nitride lined stainless steel Li trough

Li drain line

Transition unit

Li return line

He inlet/outlet
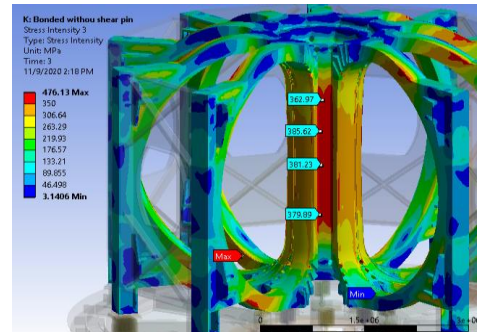
Li inlet

Local Li reservoir

Magnetic pump

- **5-10 m/s Li flow velocity for 10 MW/m^2 convective heat removal**
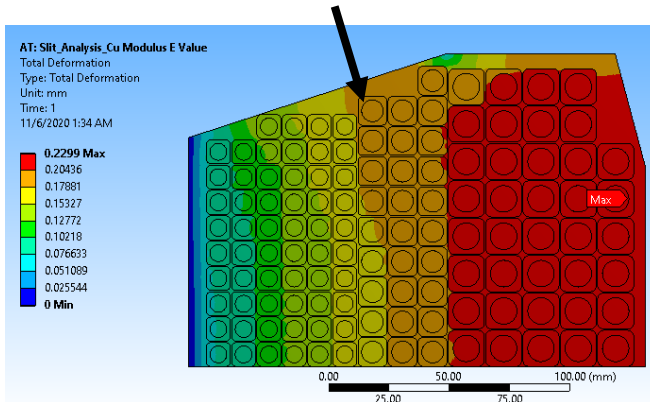- **Combinations of vapor box and fast-flow also being explored**
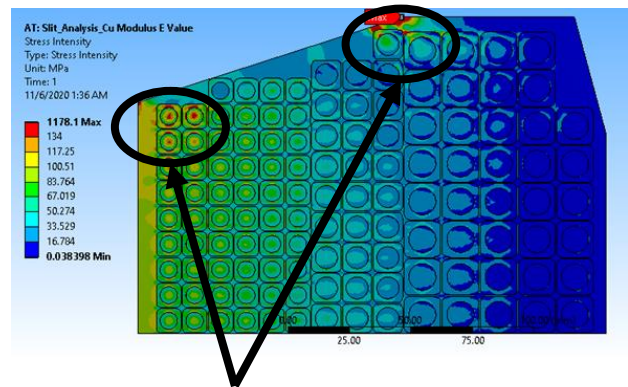
Initial Engineering Analysis
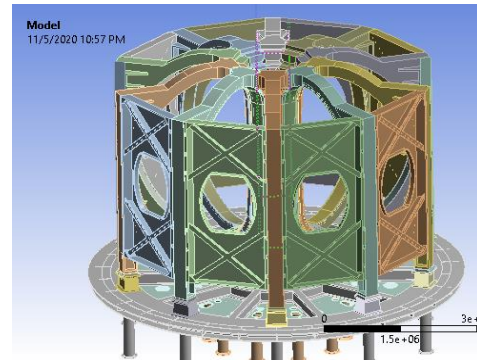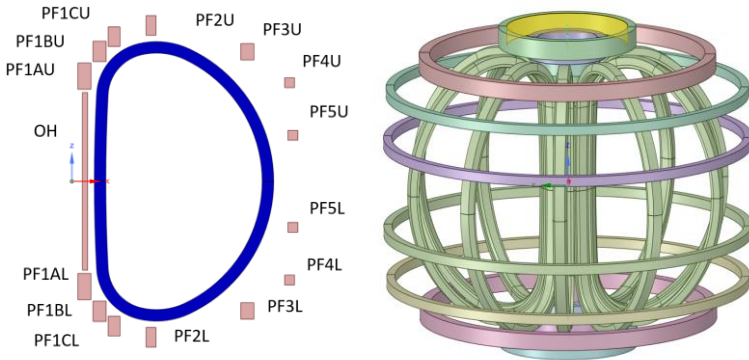
Electromagnetic structural load
TF coils + casings + PF coil load
Peak Stress= 380MPa
is within allowables
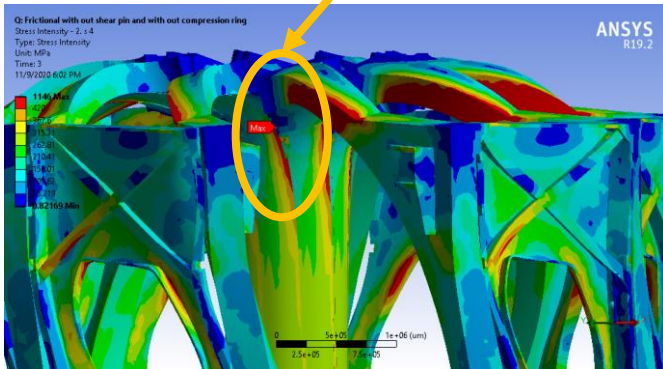
Total Deformation

Overall Stress Intensity

Max stress concentration areas
in bundle corner regions

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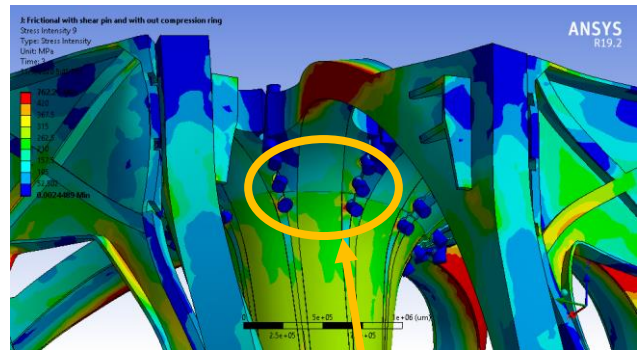but some regions near casing corners need further optimization**

No shear pins:
Large sliding and gap opening TF-to-TF

With shear pins:
Small sliding and gap opening TF-to-TF

1st shear pin region take max load

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

- 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 $\pm$ 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