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

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• 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 $^1T$, 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 ($A \sim 3$), pulsed tokamak pursued by CFS
  • Aspect ratio $A \leq 2$, 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.

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

3-10× present/planned at high $f_{BS}$

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 $\tau_{pulse}$

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?

- Define device performance targets
- Informed by 0D scaling models for physics, engineering
- 0D model to ID size, B, power, ...
- Define heating and current drive actuators, access
- Layout: TF, PF, OH, vessel, blankets, ...
- Transport and stability for profiles w/ fidelity hierarchy: scaled, reduced, full
- Free-boundary equilibrium calcs
- Divertor, first wall, power loading, heat-flux profiles
- Engineering design/analysis: structure, coils, in-vessel, ...

[Diagram showing the workflow with arrows connecting the steps.]
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
  - $B_{TF\text{-max}} = 18\text{T}$, $J_{WP\text{-TF}} = 50 \text{ MA/m}^2$

- $A \approx 2-2.4$ 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 $A$
  - $A < 2 \rightarrow$ partial non-inductive ramp
SHPD: $R=1.2-1.6\text{m}, A=2-2.5$, $P_{\text{aux/CD}} = 50\text{MW}$

- SHPD overlaps FPP values of:
  - Average pressure
  - Separatrix parallel heat flux
  - Surface-average heat flux $P_{\text{heat}}/S$
  - High-A, small radius SHPD would have excessive $P_{\text{heat}}/S$ ($3 \times \text{FPP}$)
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

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:
- $R_0 = 1.66\,\text{m}$, $B_T = 4.4\,\text{T}$, 20MW
- $\langle p \rangle = 0.37\,\text{MPa}$
- Approx. ½ of FPP at $A=2.5-3$

A=2.0 projections:
- $R_0 = 1.34\,\text{m}$, $B_T = 5.4\,\text{T}$, 20MW
- $\langle p \rangle = 0.5\,\text{MPa}$
- Comparable to FPP at $A=2.0$
SHPD profile projections for A=2.0 scenario

- $R_0=1.34\text{m}$, $B_T=5.4\text{T}$
- $P_{\text{aux-NNBI}} = 50\text{MW}$
- GLF23 + EPED1-NN + NSTX-like pedestal width scaling:
  - $T(0) \approx 10\text{keV}$
  - $I_p = 4.5\text{ MA (100\% NI)}$
  - $\langle p \rangle = 0.54\text{ MPa}$
  - $\beta_N = 3.7$, $\beta_t = 4.8\%$, $\beta_p = 1.9$
  - $f_G = 0.88$
  - $q_{\text{min}} = 2.2$
  - $f_{\text{BS}} = 0.69$
  - $H98(y,2) = 1.65$
  - $Q_{\text{DT(thermal)}} \sim 0.63$
**Example SHPD features**

- 10 HTS superconducting TF
- $B_{T_0} = 5.5$ to $6.0$T at $R_0 = 1.2$m 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

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

Idea pioneered by R. Goldston

Jacob Schwartz – PhD Thesis
September 2020
Princeton University

Continuing work by E. Emdee
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.

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

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

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

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

\[ R=1.4 \pm 0.2 \text{m}, \quad B = 4-6 \text{T}, \quad A = 2-2.5, \quad P_{H\&CD}=50\text{MW} \text{ attractive for SHPD} \]

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