Fusion Nuclear Science Facility (FNSF), Accompanying R&D and Required Capabilities

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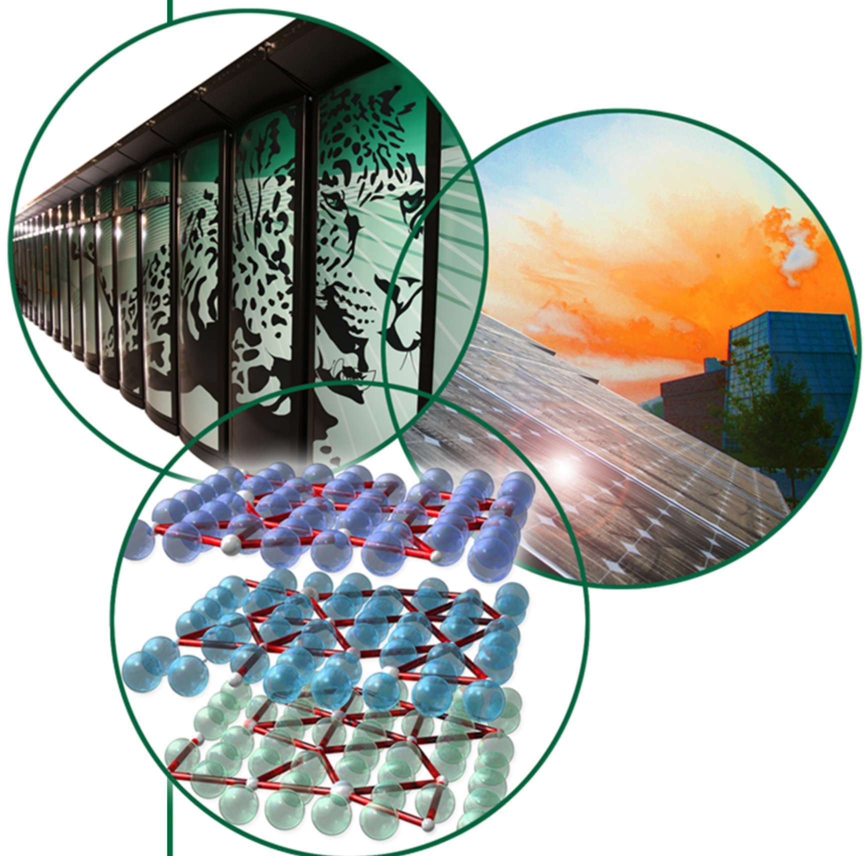

Fusion Power Associates Annual Meeting and Symposium

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U.S. DEPARTMENT OF ENERGY

Fusion Energy Division
OAK RIDGE NATIONAL LABORATORY

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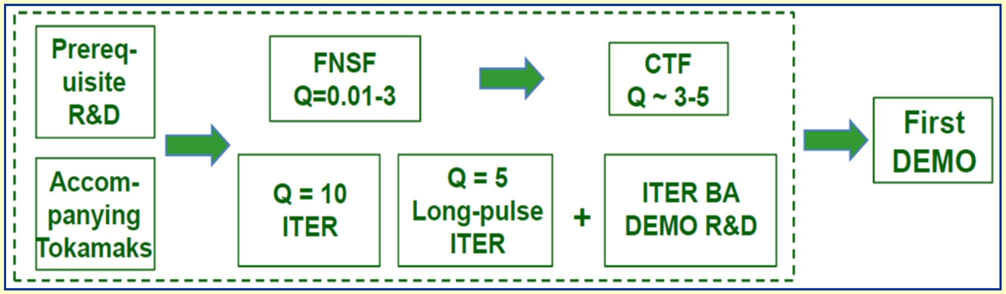
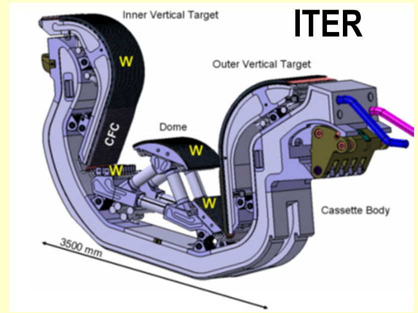
FNSF provides the environment to develop database for fusion materials in action

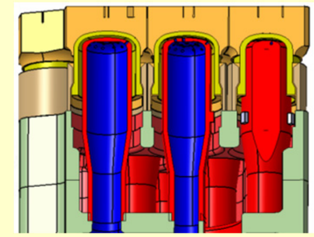
- **FNSF mission**: ***Provide a continuous fusion nuclear environment of copious neutrons, to develop experimental database on nuclear-nonnuclear coupling phenomena in materials in components for plasma-material interactions, tritium fuel cycle, and power extraction.***
- **Wide time and size scales of synergistic phenomena**: *ps to year, nm to meter, involving all phases of matter.*
- **R&D cycle**: *Test, discover, understand, improve / innovate solutions, and retest, until experimental database for DEMO-capable components are developed.*
- **Complement ITER objectives and prepare for CTF in ITER era**:
  - *Low Q (≤ 3):* ***0.3 x ITER***
  - *Neutron flux ≤ 2 MW/m^2:* ***3 x***
  - *Fluence = 1 MW-yr/m^2:* ***5 x***
  - *t_{pulse} ≤ 2 wks:* ***1000 x***
  - *Duty factor =10%:* ***3 x***



Example: fusion nuclear-nonnuclear coupling effects involving plasma facing material and tritium retention

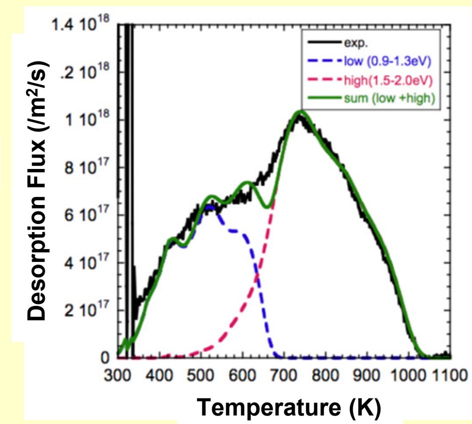
- **W, a promising Plasma Facing Material**
  - **- Low H permeation / retention**
  - **- Low plasma erosion**
  - **- DEMO-relevant temperatures**



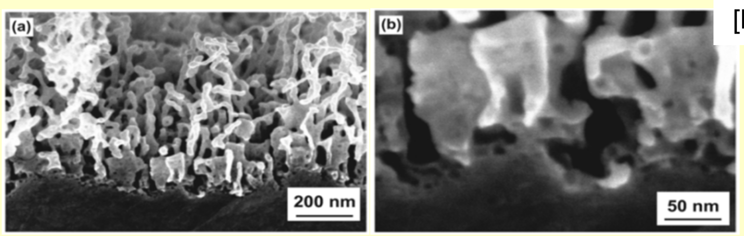


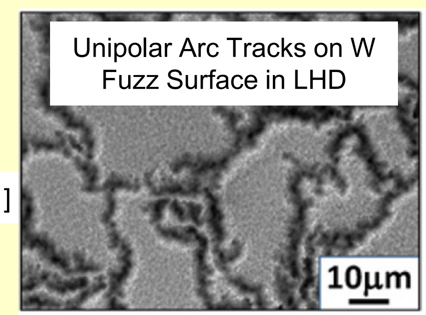
- **Worldwide R&D: Nano-composites; Nano-structure alloy; PFC designs, etc.**

- **Nuclear-nonnuclear coupling in PFC:**
  - **- Plasma ion flux induces tritium (T) retention**
  - **- Up 10x @ 2 dpa (W^{4+} beam) @ high temp** [Wright, NF, 2010]
  - **- Up 40% @ 0.025 dpa (HFIR neutrons)** [Shimada, JNM, 2011]
    ⇒ additional T trapping sites in material bulk
  - **- He induced W "fuzz" with He bubbles can trap T**



[Kajita, NF, 2009]



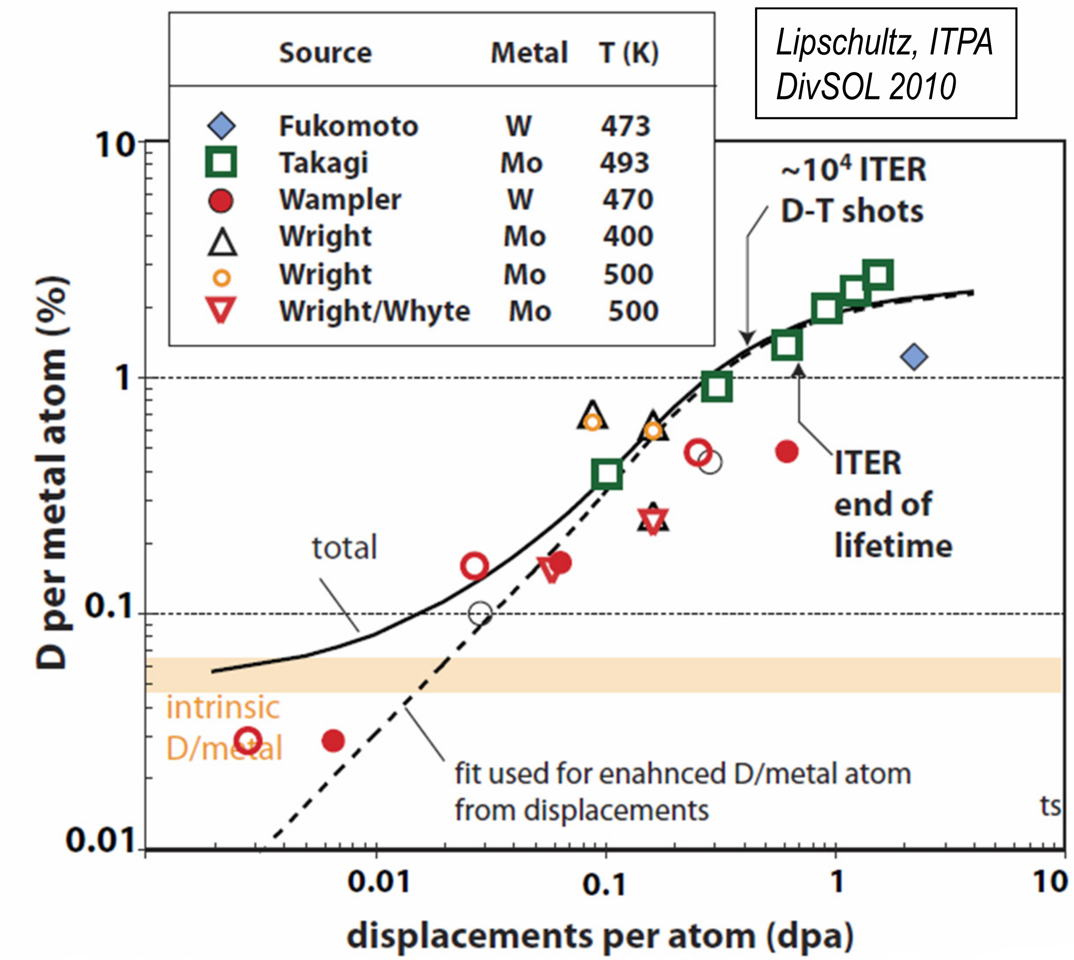


⇒ W dust exfoliated by unipolar arcs on fuzz [Tokitani, NF, 2011]
⇒ Large surface erosion & T retention in W dust

- ***Need tests in correct environment to develop solutions.***

Example: neutron damage in refractory metals

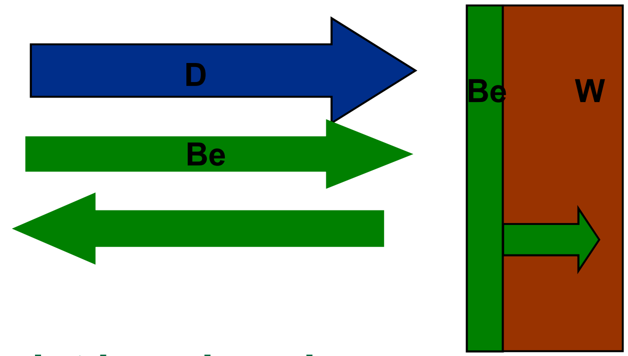
- Interstitials, vacancies, clusters of those, dislocation loops, voids, dynamics of these
- Hydrogenic retention
- Thermal conductivity (in particular for carbon based materials)
- Chemical composition (e.g. transmutation)
- Micro-structural changes (e.g. swelling)
- Mechanical properties (e.g. DBTT, He embrittlement)

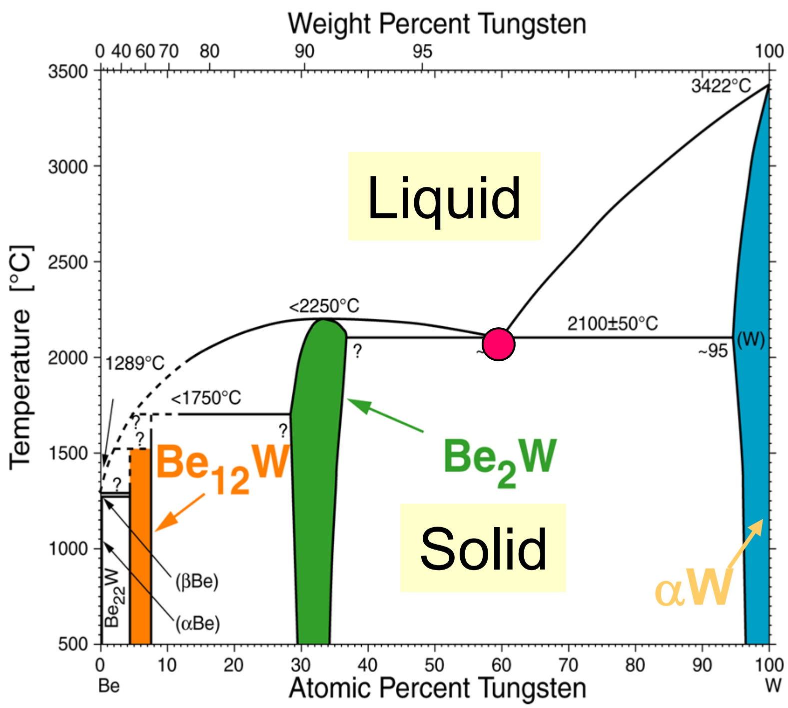


➢Suggest the need to test neutron irradiated samples up to 10 dpa at least.

Example: adding Be-W chemistry to the mix requires an integrated testing environment

→ enhanced W-sublimation / erosion?





Melting point is reduced with increasing Be concentration:

3422 K

↓

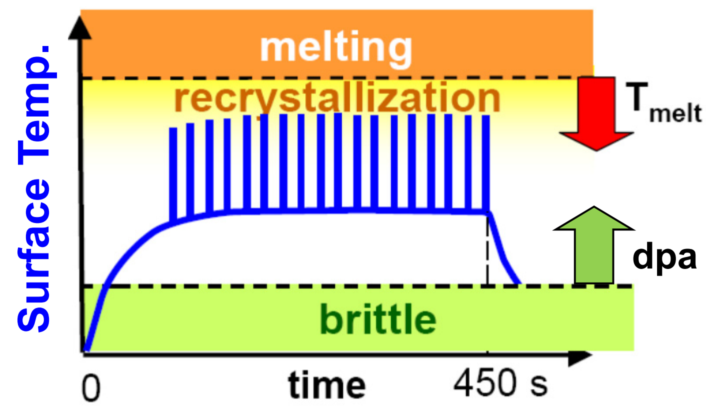
2100 K

↓

2250 K

↓

1570 K



➢ How do high fluxes and thermal loads influence intermixing and alloying, in presence of increasing neutron damage?

R&D and Capabilities required by this mission

Accompanying R&D: *to increase Mean Time Between Failure (MTBF) of test components*

Development of qualified internal component options, including

- ***Test divertors**, blankets, T breeders, FW, NBI, RF launchers, diagnostic systems, TF center post (for ST)*
- *Components to control plasma dynamics, H&CD, fueling, I&C*
- *Instrumentation for these*

FNSF Capabilities: *to increase duty factor and fluence, reduce Mean Time to Replace or Repair (MTTR)*

- *Reliable plasma operation with limited disruption, ELM, and impact*
- *Remote handling (RH) of modularized test components*
- *Hot cell facilities and laboratories, pre- and post-test investigation systems and tools.*
- *Device support structure and systems behind test modules and shielding – long facility life and upgradability to CTF mission.*

FNSF-ST, assessed to have good potential to provide the facility capability required in progressive stages

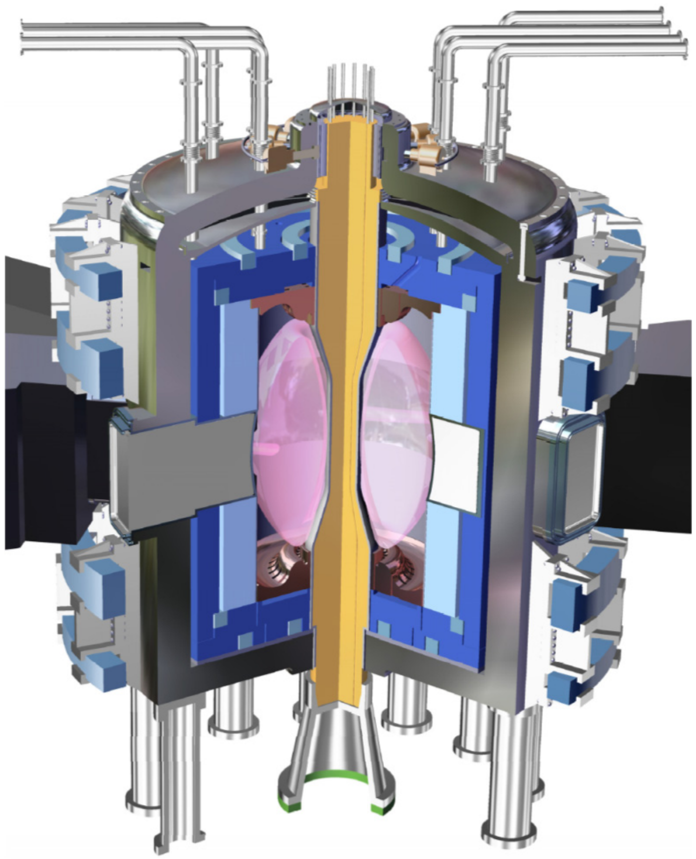
- R_0 = 1.3m, A = 1.7
- $H_H \le 1.25$, $\beta/\beta_N \le 0.75$, $q_{cyl} \ge 4$
- $J_{TF\text{-}avg} \le 4kA/cm^2$
- Mid-plane test area ≥ 10m²
- Outboard T breeder ~ 50m²

I-DD: 1xJET, verify plasma operation, PMI/PFC, neutronics, shielding, safety, RH system

II-DT: 1xJET, verify FNS research capability: PMI/PFC, tritium cycle, power extraction

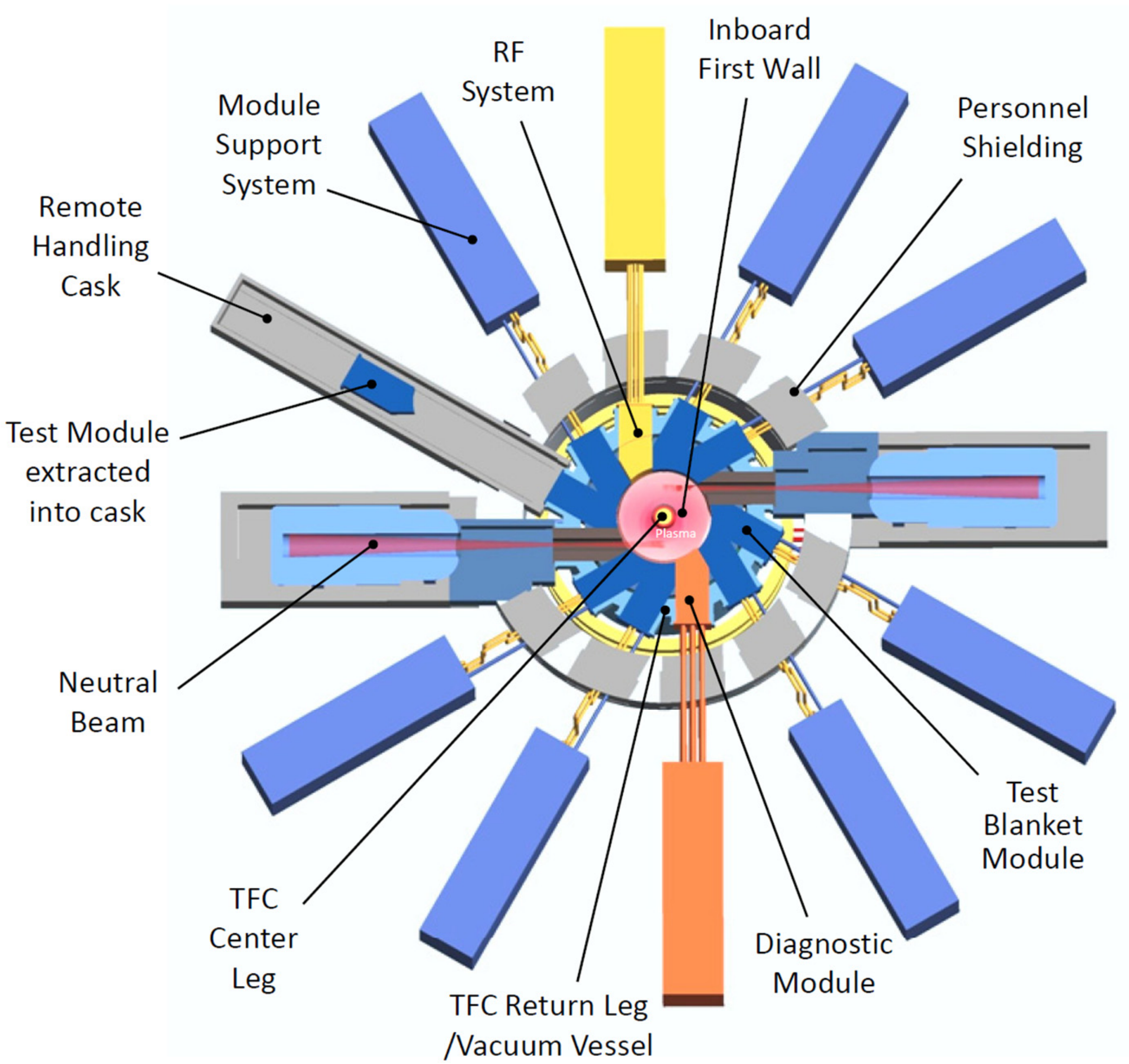
III-DT: 2xJET, full FNS research, basis for CTF

IV-DT: 3xJET, "stretch" FNS & CTF research



Stage-Fuel	I-DD	II-DT	III-DT	IV-DT
Current, I_p (MA)	4.2	4.2	6.7	8.4
Plasma pressure (MPa)	0.16	0.16	0.43	0.70
W_L (MW/m^2)	0.005	0.25	1.0	2.0
Fusion gain Q	0.01	0.86	1.7	2.5
Fusion power (MW)	0.2	19	76	152
Tritium burn rate (g/yr)	0	≤105	≤420	≤840
Field, B_T (T)	2.7	2.7	2.9	3.6
Safety factor, q_{cyl}	6.0	6.0	4.1	4.1
Toroidal beta, β_T (%)	4.4	4.4	10.1	10.8
Normal beta, β_N	2.1	2.1	3.3	3.5
Avg density, n_e ($10^{20}/m^3$)	0.54	0.54	1.1	1.5
Avg ion T_i (keV)	7.7	7.6	10.2	11.8
Avg electron T_e (keV)	4.2	4.3	5.7	7.2
BS current fraction	0.45	0.47	0.50	0.53
NBI H&CD power (MW)	26	22	44	61
NBI energy to core (kV)	120	120	235	330

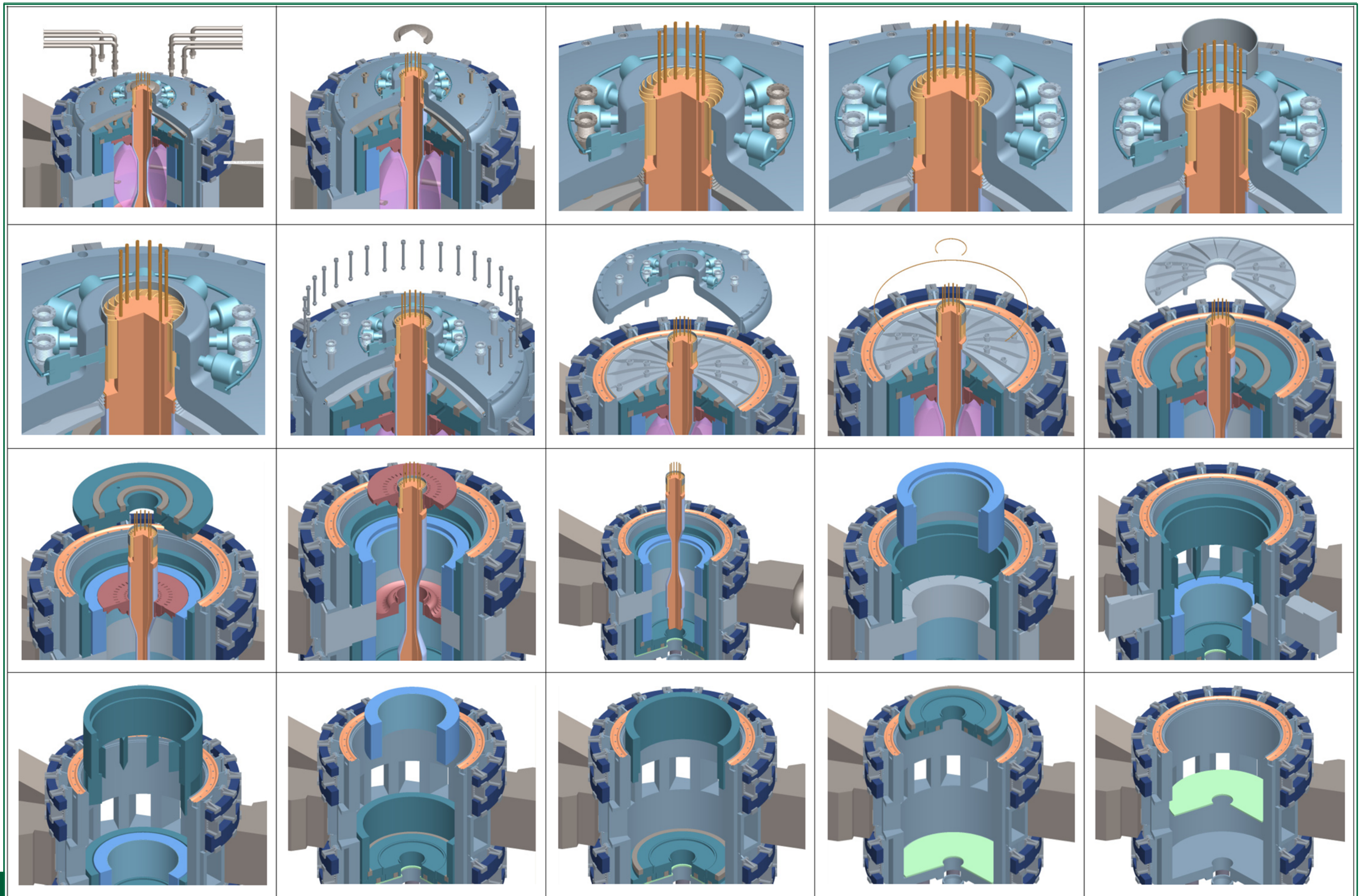
Mid-plane test modules, NBI systems, RF launchers, diagnostics are arranged for ready RH replacement



Mid-plane ports

- Minimize interference during remote handling (RH) operation
- Minimize MTTR for test modules
- Allow parallel operation among test modules and with vertical RH
- Allow flexible use & number of mid-plane ports for test blankets, NBI, RF and diagnostics

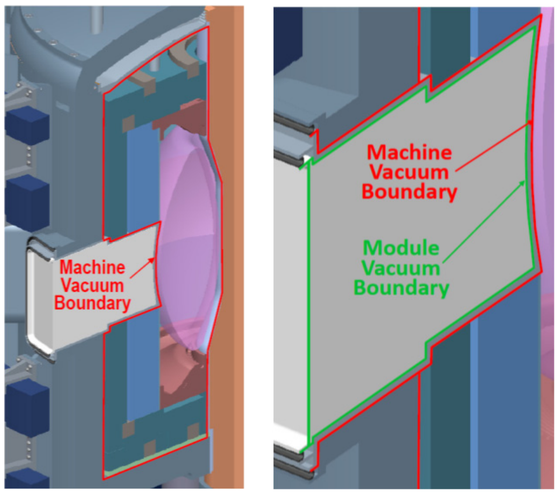
FNSF internal components assembly/disassembly concept support structure lifetime dose < 0.1 dpa enables staging



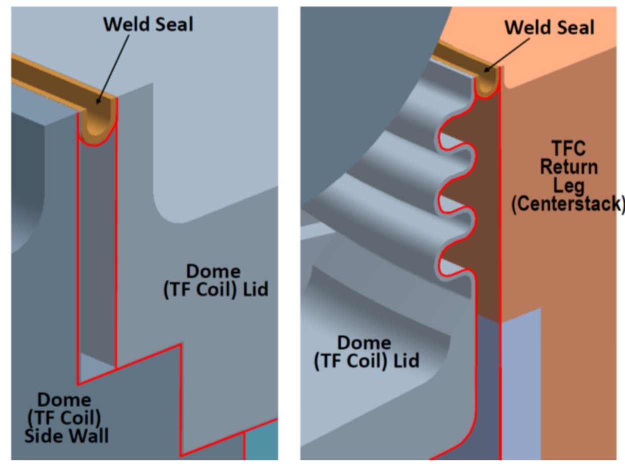
Ready replacements, shielded vacuum weld seals and bi-directional sliding joint are proposed to allow RH

To reduce Mean Time to Replace (MTTR) and achieve 10% Duty Cycle

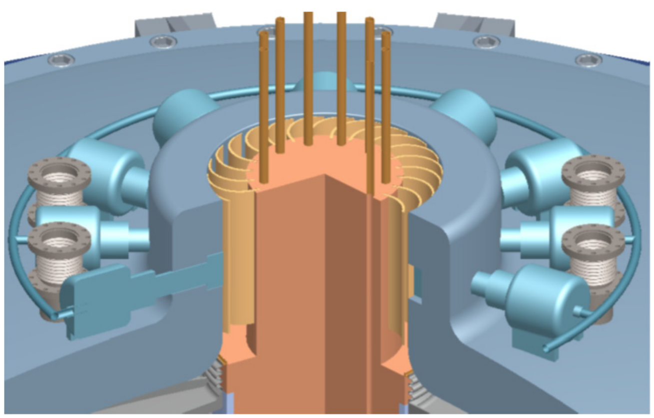
Mid-Plane Test Module Access

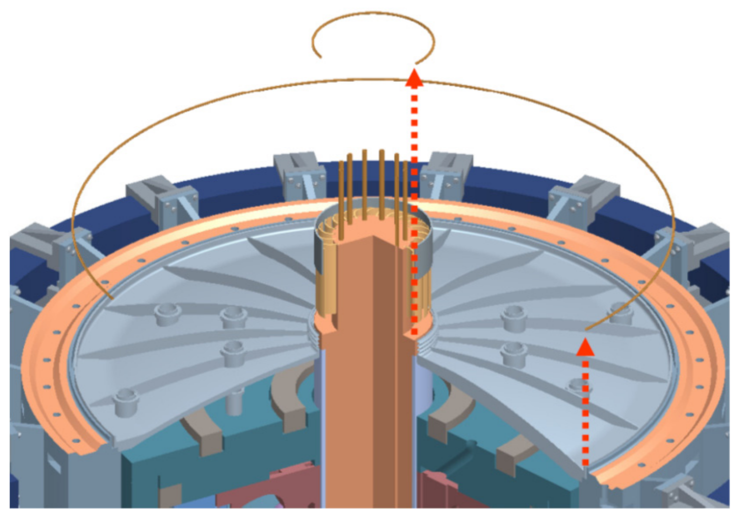


Top TF Conductor Lid



Bi-Directional Sliding Joint





Structural analysis of optimally designed center-post (Arnie Lumsdaine, 28-3P-19)

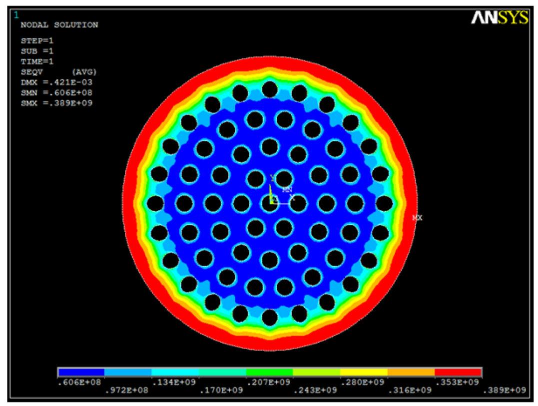
Objective: minimize peak Von Mises stress by varying radius and positions of cooling channels

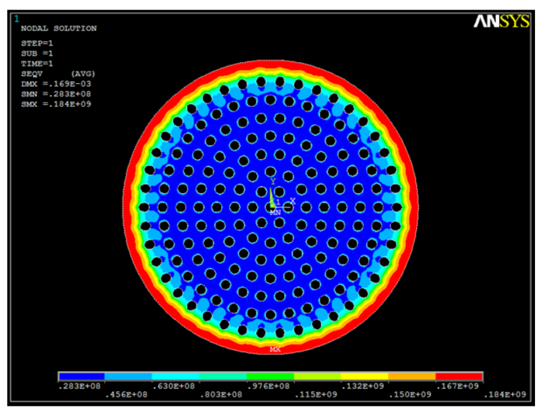
Assumptions:
- *Nuclear and Joule heating*
- *Constant water flow*
- *Constant Copper thermal & electrical conductivities*
- *≥5 mm between channels and to surface*

Optimization approaches:
- *Sequential quadratic*
- *Particle swarm*
- *Broyden, Fletcher, Goldfarb, Shanno algarithm*
- *VisualDOC linked to ANSYS*

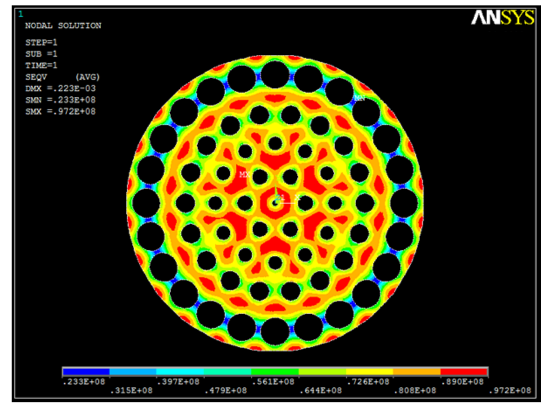
Better with 8 roles of channels:
For W_L=2MW/m^2
- *Peak stress reduced to 1/3 to ~100 MPa*
- *Peak Δ temp reduced to 60C*

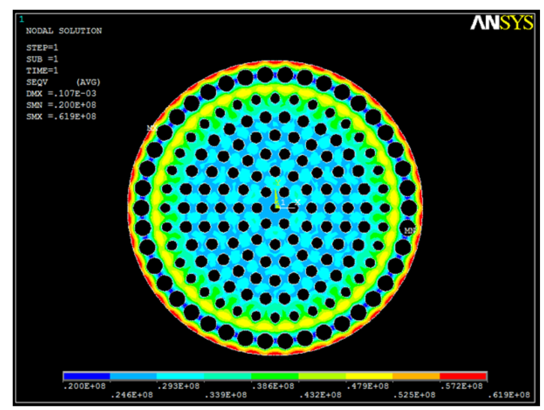
Initial





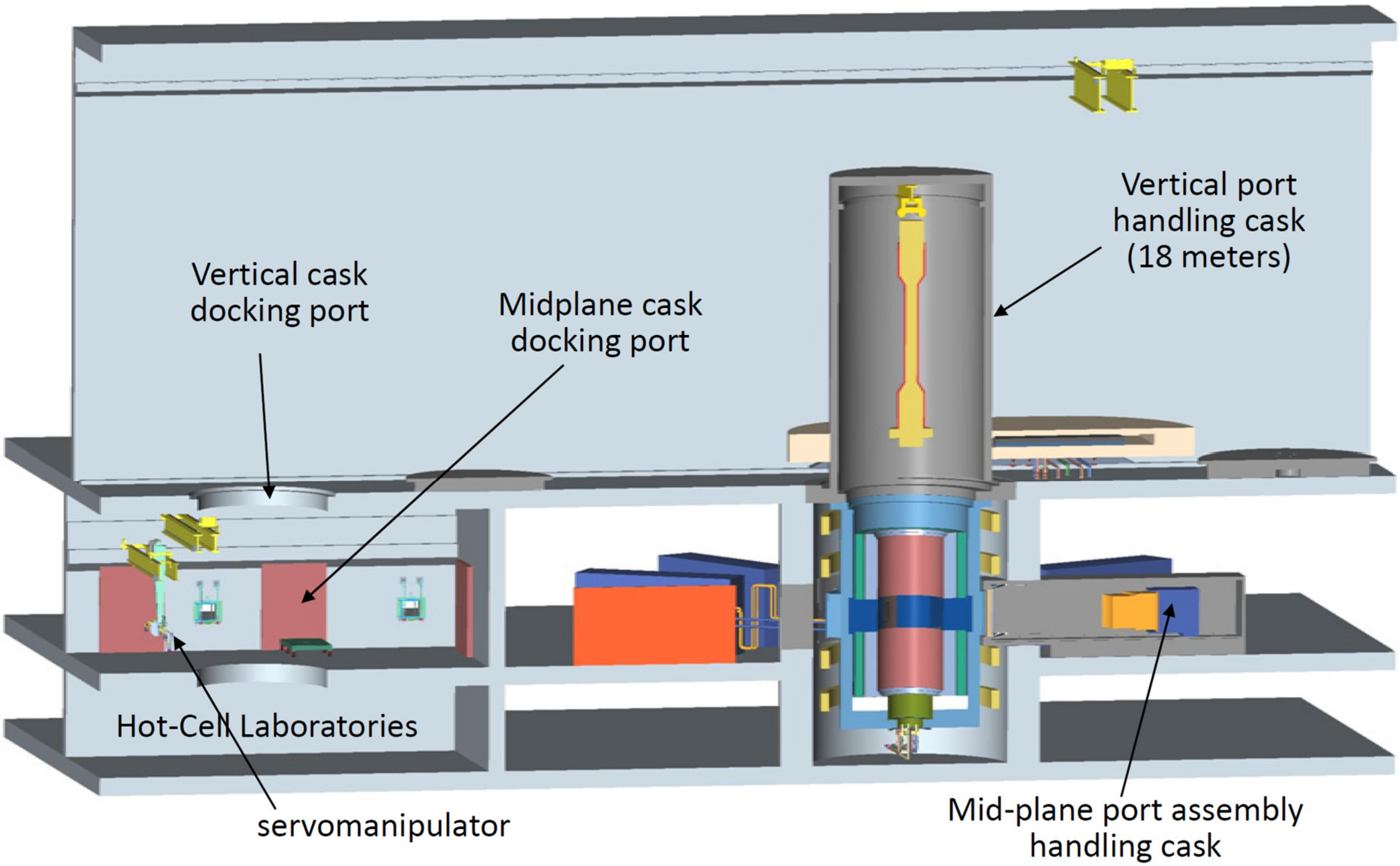
Optimized





Extensive remote handling systems, including hot-cell laboratories, will be required

Remote handling equipment for hot cell laboratories to enable fusion nuclear sciences R&D



To manage the risks, requisite R&D can be defined addressing the FNSF features (STs & Tokamaks)

- Solenoid-free plasma start up, using ECW/EBW, Helicity Injection (STs).
- Hot-Ion H-Mode operational scenarios with strong tokamak database (STs & Tokamaks).
- SOL-Divertor with improved configurations to limit heat fluxes ≤10 MW/m^2, and control fuel and impurities (extended divertor – MAST-U).
- Continuous, disruption-minimized, non-inductive plasma operation in regimes removed from stability boundaries (STs & Tokamaks).
- Continuous PI NBI (JET-like?) & 60 GHz gyrotrons (Tsukuba?)
- Single-turn TF coil center post engineering and fabrication (industry).
- Remote handling (RH) systems and modular internal components, to minimize MTTR to achieve a duty factor of 10% (nuclear R&D facilities).
- RH-enabled maintenance and research hot-cells (nuclear R&D facilities).
- Low dissipation, low voltage, high current, dc power supply with stiff control of current (HTSC based generators?).
- Nuclear grade R&D users' facility infrastructure (national labs).

Accompanying FNS R&D Program to develop, design, instrument, and operate all internal components & options, in concert with FNSF.

FNSF with accompanying R&D aim to carry out cost & time effective fusion nuclear science R&D for DEMO, in progressive stages