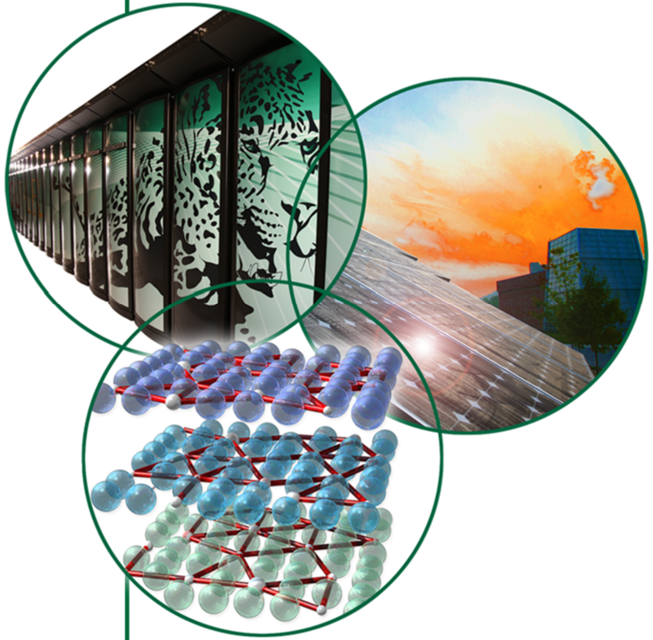
Fusion Nuclear Science Facility (FNSF) – Motivation, Role, Required Capabilities



YK Martin Peng, with contributions from

JM Park, JM Canik, SJ Diem, SL Milora, AC Sontag,
A Lumsdaine, M Murakami, Y Katoh, TW Burgess,
MJ Cole, K Korsah, BD Patton, JC Wagner,
GL Yoder (ORNL); PJ Fogarty (IDC);
M. Sawan (U Wisc.);

Joint Meeting of
5th IAEA Technical Meeting on Spherical Tori
16th International ST Workshop (ISTW2011)
2011 US-Japan Workshop on ST Plasmas

September 27-30, 2011
National Institute for Fusion Science
Toki, Japan

U.S. DEPARTMENT OF ENERGY

Fusion Energy Division
OAK RIDGE NATIONAL LABORATORY

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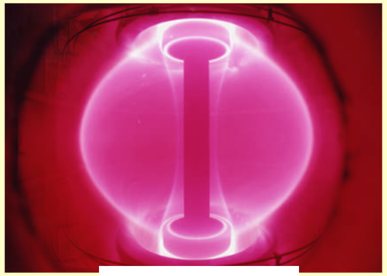
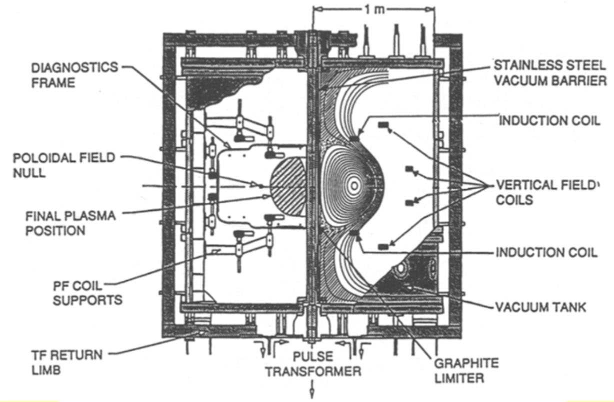
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

ST reactor concept with A=1.2 and extended divertors 1990 – during design and construction of START

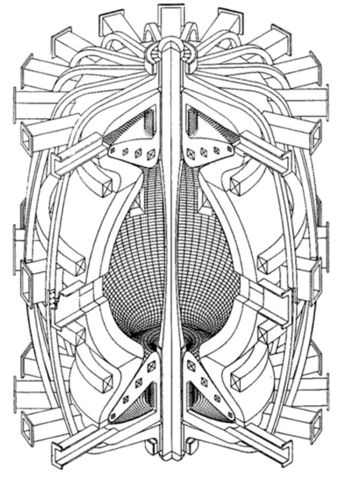
START (1990-2000)

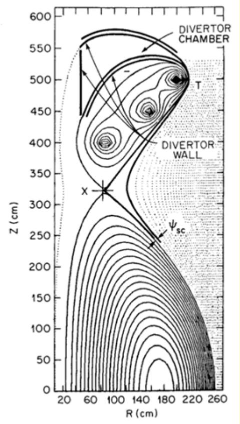


[β=40%, 1995]



[1995-Sykes, Peng et al-AIPCP-v345-p110]





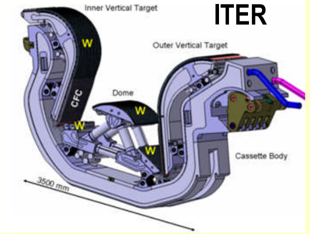
[Wright, NF, 2010]

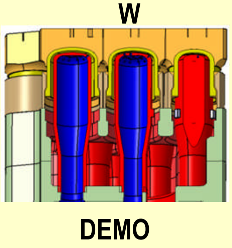
- R_0 = 1.46m, A = 1.22, B_T = 0.8T
- q_{95} = 6.4, I_p = 25MA, Bp = 2.2 T
- $\varepsilon\beta_p$ = 0.7, I_{BS}/I_p = 0.8
- $J_{TF\text{-}avg} \leq 4kA/cm^2$, I_{TF} = 5.9MA
- P-fusion = 1600MW
- P-electric = 500MW

What Happened?

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

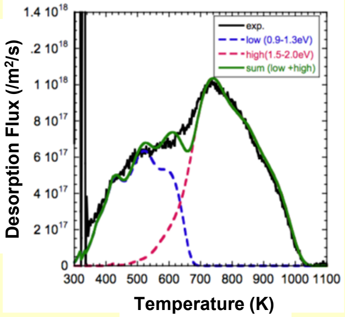
- **W, a promising Plasma Facing Material**
  - **- Low H permeation / retention**
  - **- Low plasma erosion**
  - **- DEMO-relevant temperatures**

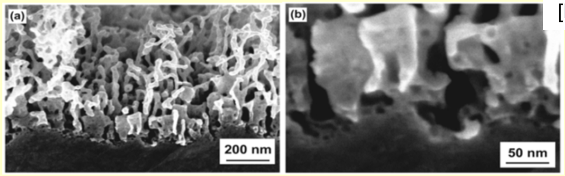




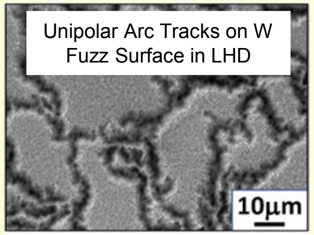
- **Worldwide R&D: Nano-composites; Nano-structure alloy; PFC designs, etc.**

- **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]



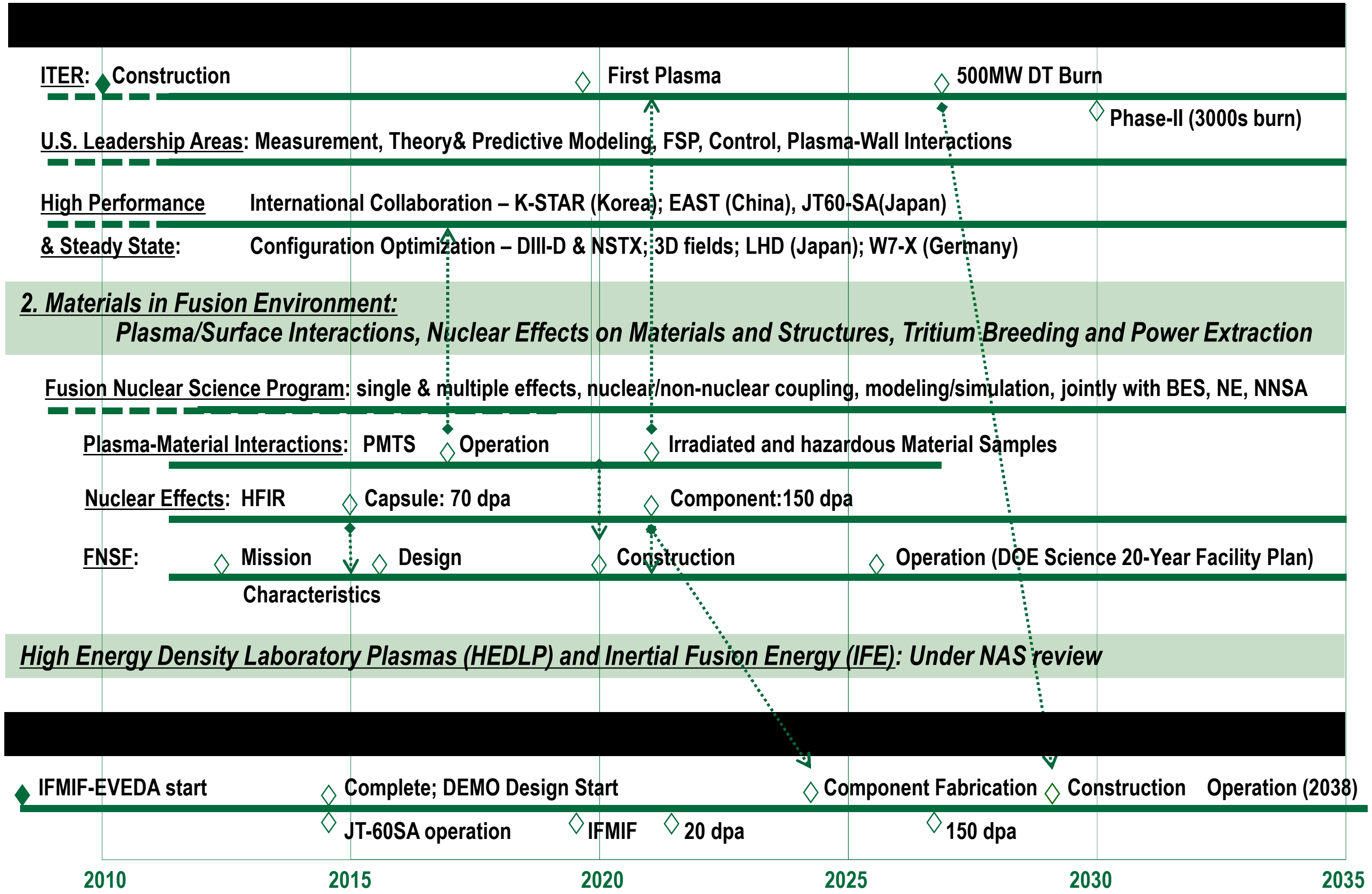
Unipolar Arc Tracks on W Fuzz Surface in LHD

[Tokitani, NF, 2011]

⇒ W dust exfoliated by unipolar arcs on fuzz surface
⇒ Large surface erosion & T retention in W dust

Need tests in fusion environment to develop solutions.

A FNSF* roadmap to complement and support world DEMO



[redacted]

ITER: Construction — First Plasma — 500MW DT Burn — Phase-II (3000s burn)

U.S. Leadership Areas: Measurement, Theory& Predictive Modeling, FSP, Control, Plasma-Wall Interactions

High Performance & Steady State: International Collaboration – K-STAR (Korea); EAST (China), JT60-SA(Japan)

Configuration Optimization – DIII-D & NSTX; 3D fields; LHD (Japan); W7-X (Germany)

2. Materials in Fusion Environment:
Plasma/Surface Interactions, Nuclear Effects on Materials and Structures, Tritium Breeding and Power Extraction

Fusion Nuclear Science Program: single & multiple effects, nuclear/non-nuclear coupling, modeling/simulation, jointly with BES, NE, NNSA

Plasma-Material Interactions: PMTS — Operation — Irradiated and hazardous Material Samples

Nuclear Effects: HFIR — Capsule: 70 dpa — Component:150 dpa

FNSF: Mission Characteristics — Design — Construction — Operation (DOE Science 20-Year Facility Plan)

High Energy Density Laboratory Plasmas (HEDLP) and Inertial Fusion Energy (IFE): Under NAS review

[redacted]

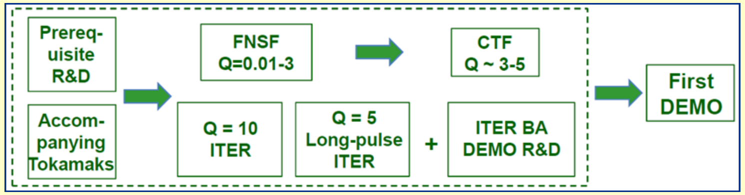
IFMIF-EVEDA start — Complete; DEMO Design Start — Component Fabrication — Construction — Operation (2038)

JT-60SA operation — IFMIF — 20 dpa — 150 dpa

*2011-Peng-FST-v60-n2-p441

Fusion Nuclear Science Facility (FNSF) is to address this need of experimental database

- **FNSF objective**: ***Provide a continuous fusion nuclear environment of copious neutrons, to develop experimental database on nuclear-nonnuclear coupling phenomena in materials in components of 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*



Prereq-uisite R&D

Accom-panying Tokamaks

FNSF Q=0.01-3

CTF Q ~ 3-5

Q = 10 ITER

Q = 5 Long-pulse ITER

+

ITER BA DEMO R&D

First DEMO

Capabilities required to fulfill this mission

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

- *Development of qualified internal component options, including material choices, e.g., DCLL, WCSB, blanket designs.*
- *Instrumentation for 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*

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* ***of all viable options***
- *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

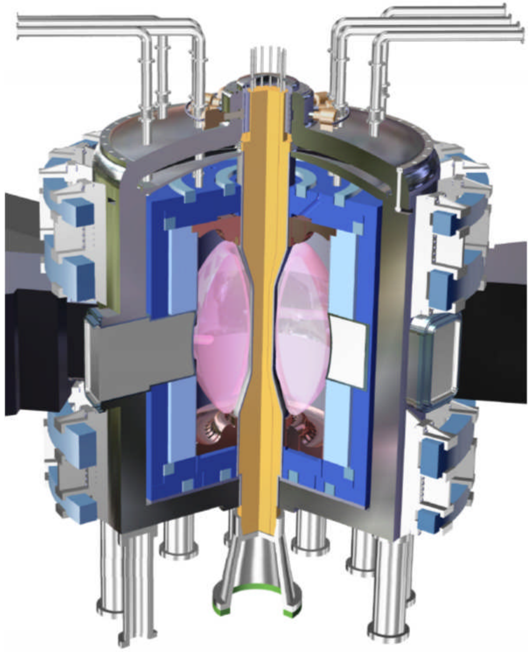
- $R_0 = 1.3\text{m}$, $A = 1.7$
- $H_H \leq 1.25$, $\beta/\beta_N \leq 0.75$, $q_{cyl} \geq 4$
- $J_{TF\text{-}avg} \leq 4\text{kA/cm}^2$
- Mid-plane test area $\geq 10\text{m}^2$
- Outboard T breeder ~ 50m^2

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

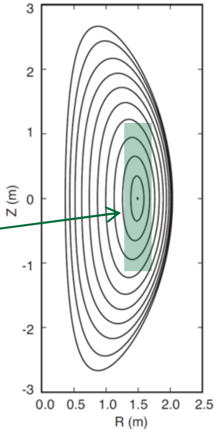
IV-DT: 3xJET, “stretch” FNS & CTF research



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	$\leq$105	$\leq$420	$\leq$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 ($10^{20}/\text{m}^3$)	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

Steady state plasma operation at JET DT level is simulated using benchmarked TGLF (GA), awaiting ST-Upgrade data

	Unit	JET level
I_p	MA	4.2
B_T	T	1.0
W_L	MW/m^2	0.33
β_T	%	23.7
β_N		4.74
q_{95}		11.5
l_i		0.68
$\langle n_e \rangle$	$10^{20}/m^3$	0.6
T_{i0}	keV	14.4
T_{e0}	keV	8.7
$\langle T_i \rangle$	keV	5.5
$\langle T_e \rangle$	keV	3.4
f_{NI}		1.005
f_{BS}		0.564
f_{NB}		0.341
f_{EB}		0.1
P_{NB}	MW	20
E_{NB}	kV	120



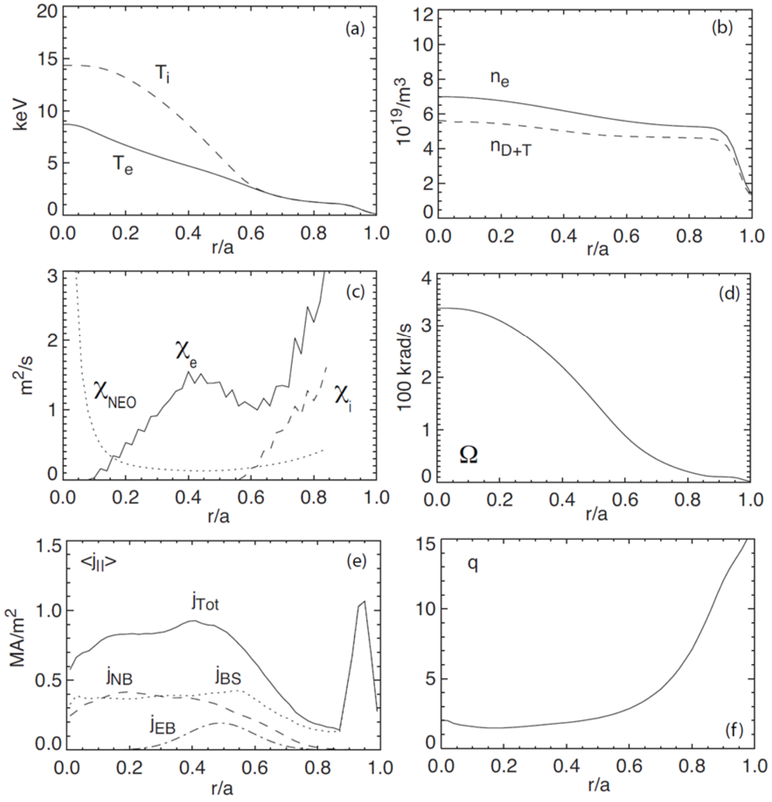
Tangential NBI

$\chi_{fast\text{-}ion} = 5m^2/s$

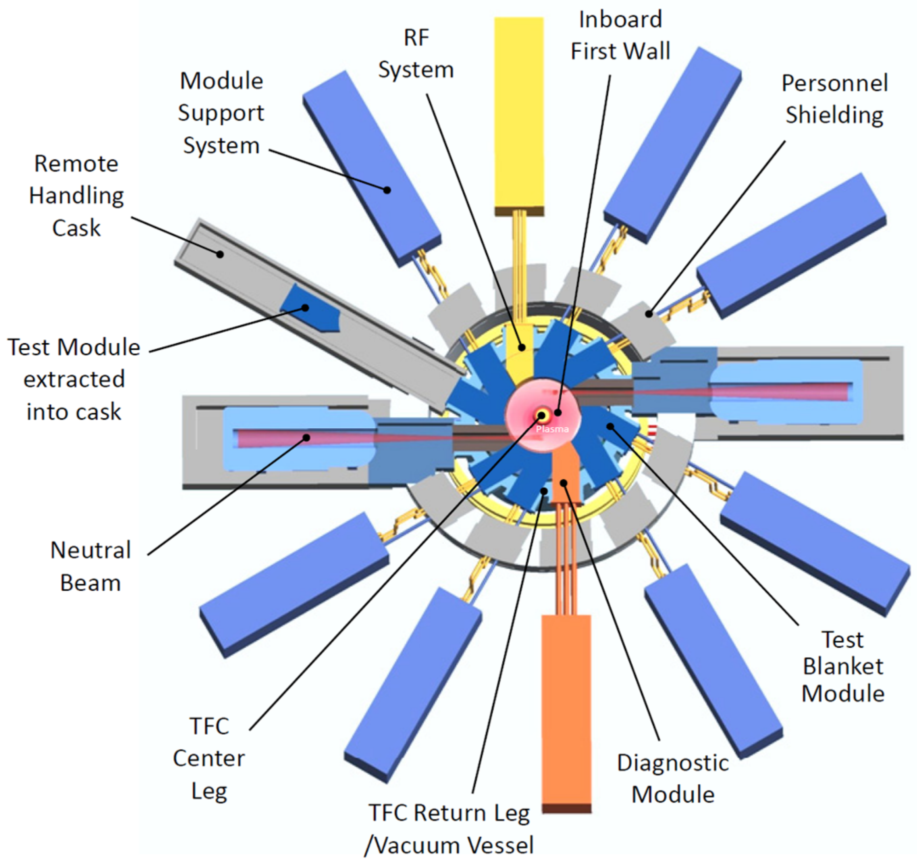
Hot-Ion H-Mode with Internal Transport Barrier

1T, 4.2 MA, β_T = 24%, q_{cyl} = 4, Q = 0.9

P_{NB} = 20 MW, P_{EBW} = 4 MW, W_L = 0.3 MW/m^2



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

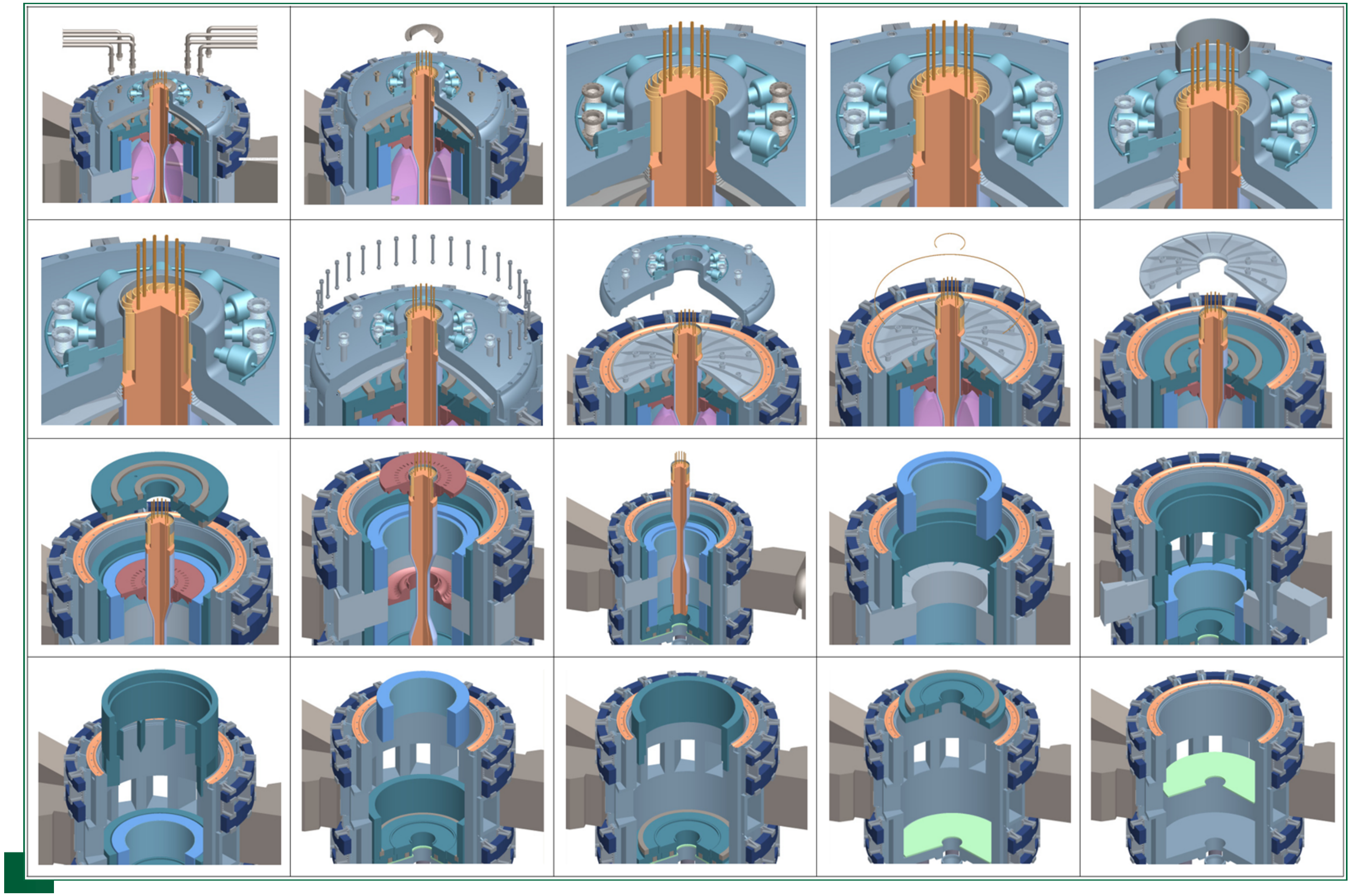


Mid-plane ports

- 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

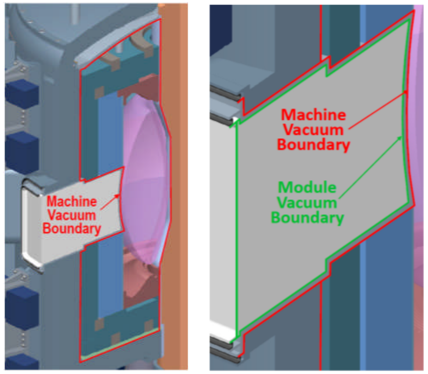
support structure lifetime dose < 0.1 dpa enables staging



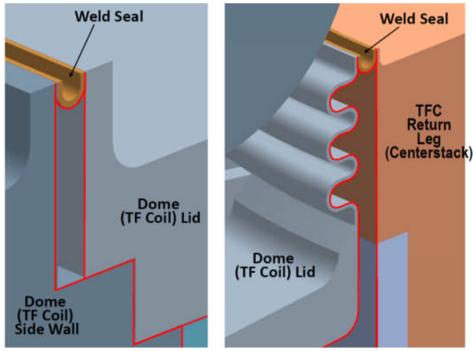
Ready replacements, shielded vacuum weld seals and bi-directional sliding joint are proposed to allow RH

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

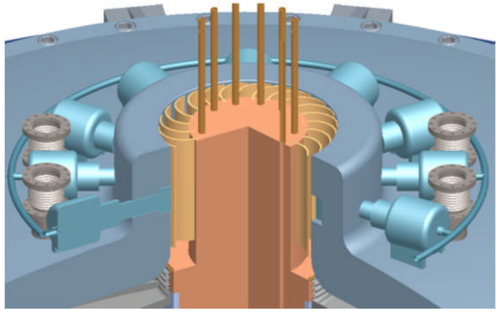
Mid-Plane Test Module Access

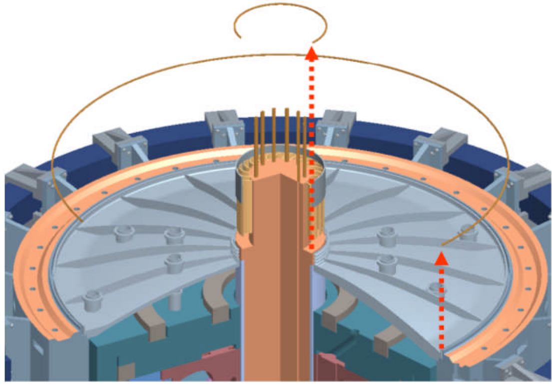


Top TF Conductor Lid



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:

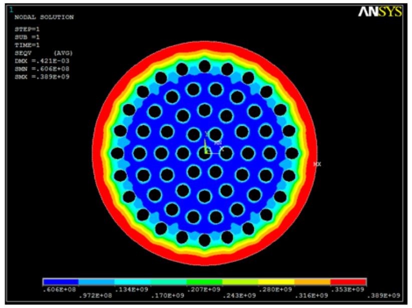
- *Sequential quadratic*
- *Particle swarm*
- *Broyden, Fletcher, Goldfarb, Shanno algarithm*
- *VisualDOC linked to ANSYS*

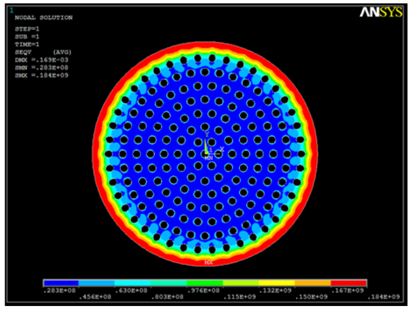
Better with 8 roles of channels:

For W_L=2MW/m^2

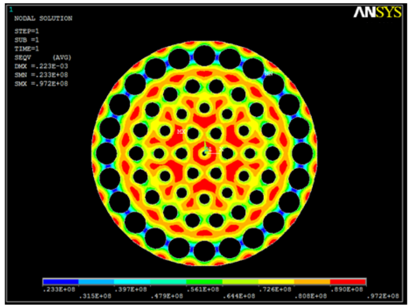
- *Peak stress reduced to 1/3 to ~100 MPa*
- *Peak Δ temp reduced to 60C*

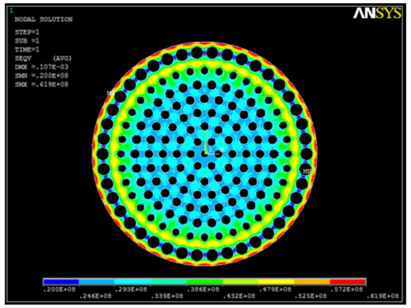
Initial





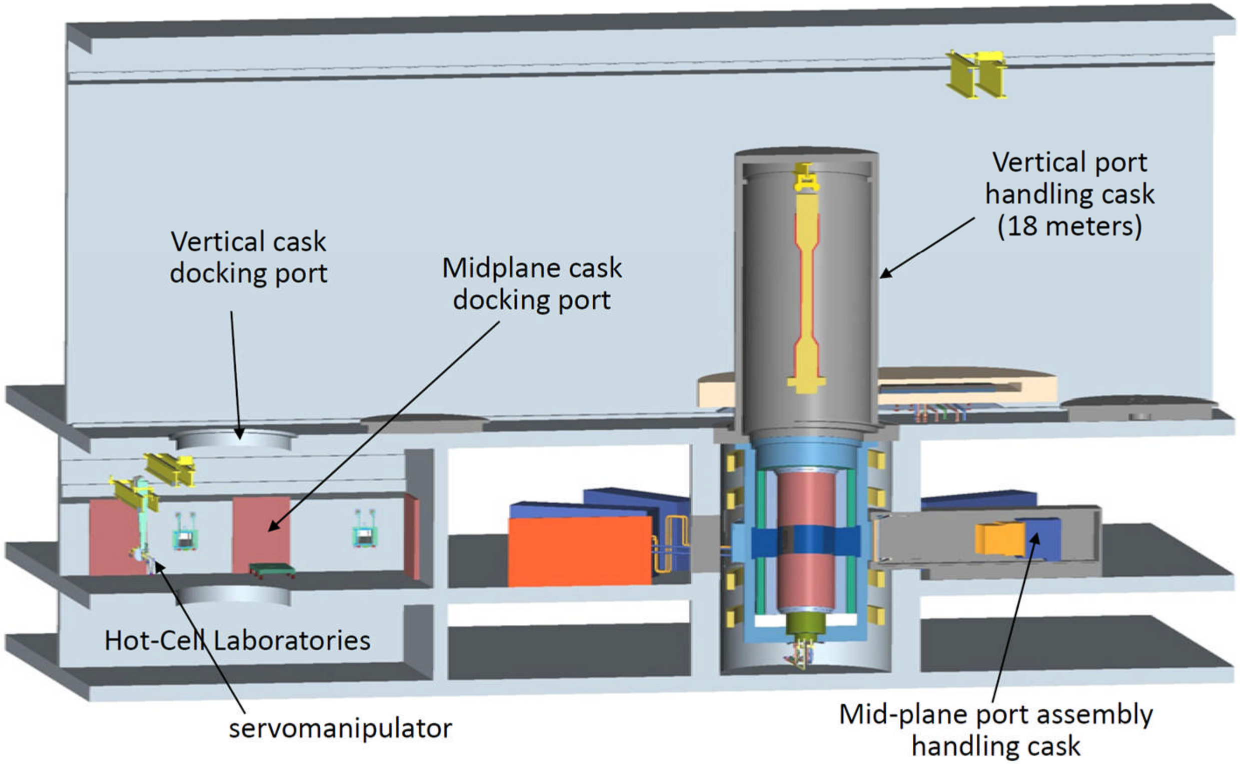
Optimized





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

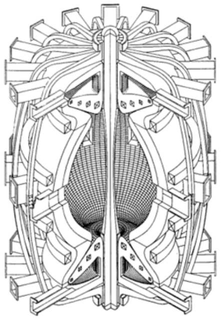


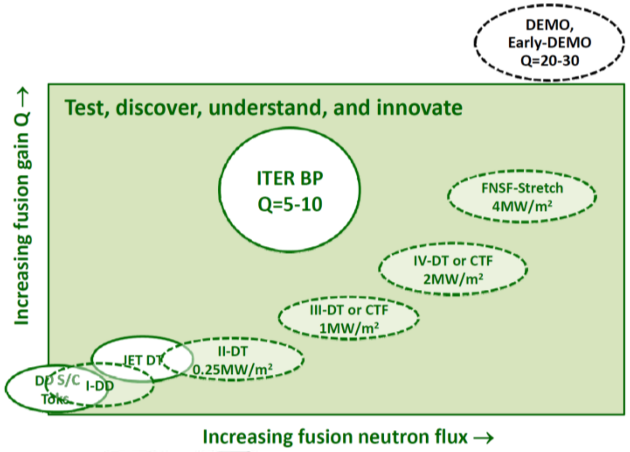
To manage the risks, requisite R&D can be defined addressing the FNSF features (STs & Tokamaks)

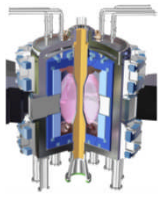
- Solenoid-free plasma start up, using ECW/EBW, Helicity Injection (STs).
- Hot-Ion H-Mode operational scenarios with strong tokamak database (STs & Tokamaks).
- SOL-Divertor with improved configurations to limit heat fluxes ≤10 MW/m^2, and control fuel and impurities (extended divertor – MAST-U).
- 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 aims to carry out cost & time effective fusion nuclear science R&D for DEMO







- **Complements & supports world DEMO.**
- **Complements & parallels ITER in concert with accompanying R&D; increase MTBF.**
- **Uses remote handling, hot cells, shielded vacuum seals, bi-directional sliding joint, etc. to reduce MTTR.**
- **Compact, modest Q, reliable plasma, low P_{fusion}, high W_L, low tritium usage.**
- **Low risk: starts with JET-level Q<1 plasma and moderate W_L~0.3MW/m^2.**
- **Advances Q and W_L in stages , from DD to DT & from FNS to CTF, ending with possible electricity generation modules.**
- **Wide design parameter space available: R = 0.8-1.3m, W_L = 0.6-2.0 MW/m^2, P_{DT} = 18-150MW. ⇔ performance, cost, R&D, time scale, and risk tradeoffs (w. CCFE).**
- **ST DEMO has even wider design parameter space, such as A = 1.2 – 2.0.**