Suggestions from FNSF for Consideration by CFETR

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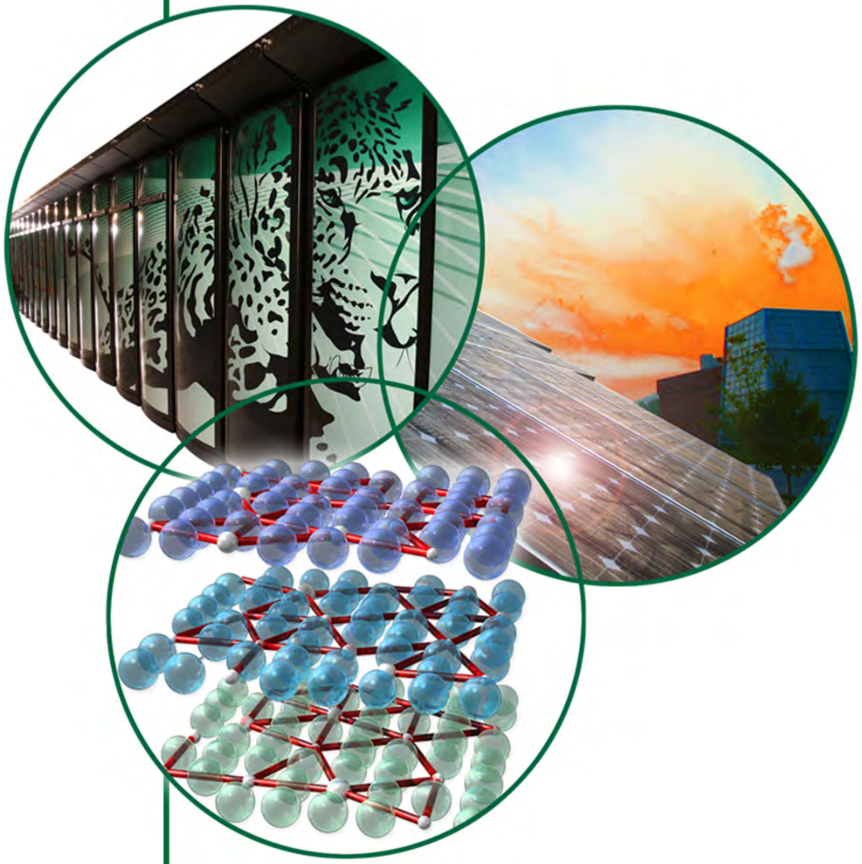

First Workshop on MFE Development Strategy
in China

January 5-6, 2012, Beijing, China

U.S. DEPARTMENT OF ENERGY

Fusion Energy Division
OAK RIDGE NATIONAL LABORATORY

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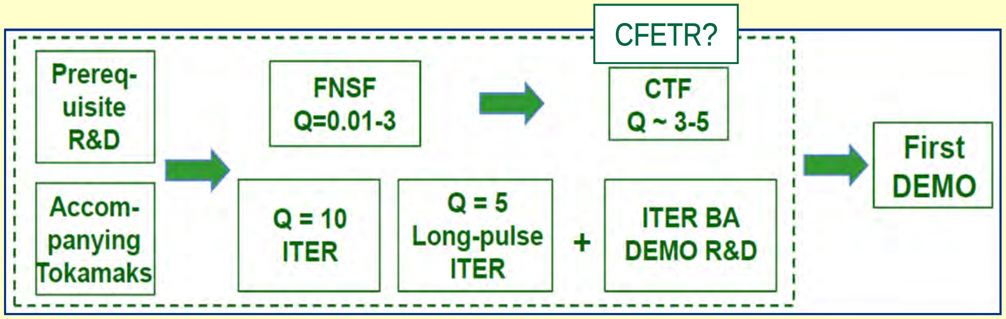
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

FNSF/CFETR 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 CFETR 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***



CFETR?

Prereq-uisite R&D

Accom-panying Tokamaks

FNSF Q=0.01-3

CTF Q ~ 3-5

Q = 10 ITER

Q = 5 Long-pulse ITER

\+

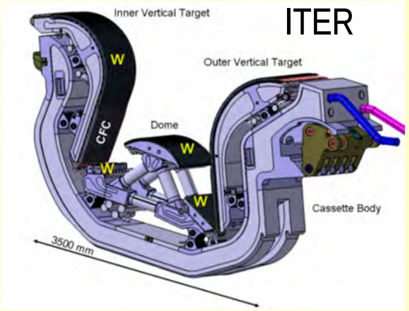
ITER BA DEMO R&D

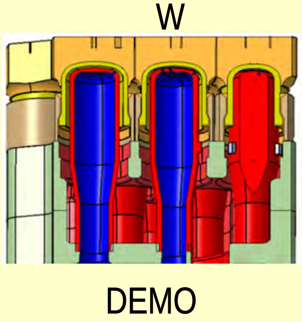
First DEMO

CFETR = superconducting magnet CTF?

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

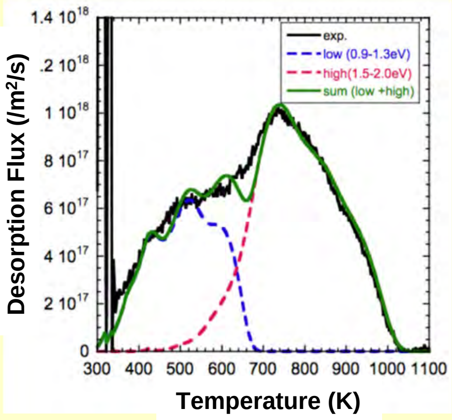
- **W, a promising Plasma Facing Material**
  - Low H permeation / retention
  - Low plasma erosion
  - DEMO-relevant temperatures

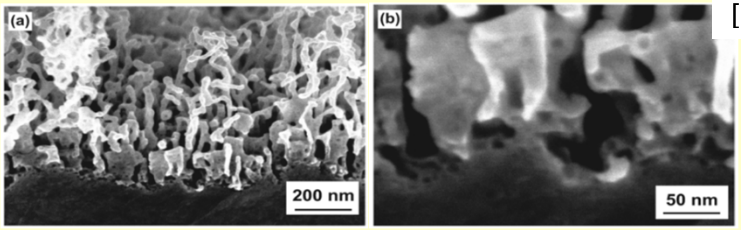




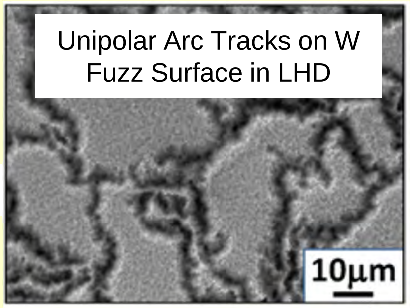
- **Worldwide R&D: Nano-composites; Nano-structure alloy; PFC designs, etc.**

- **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]

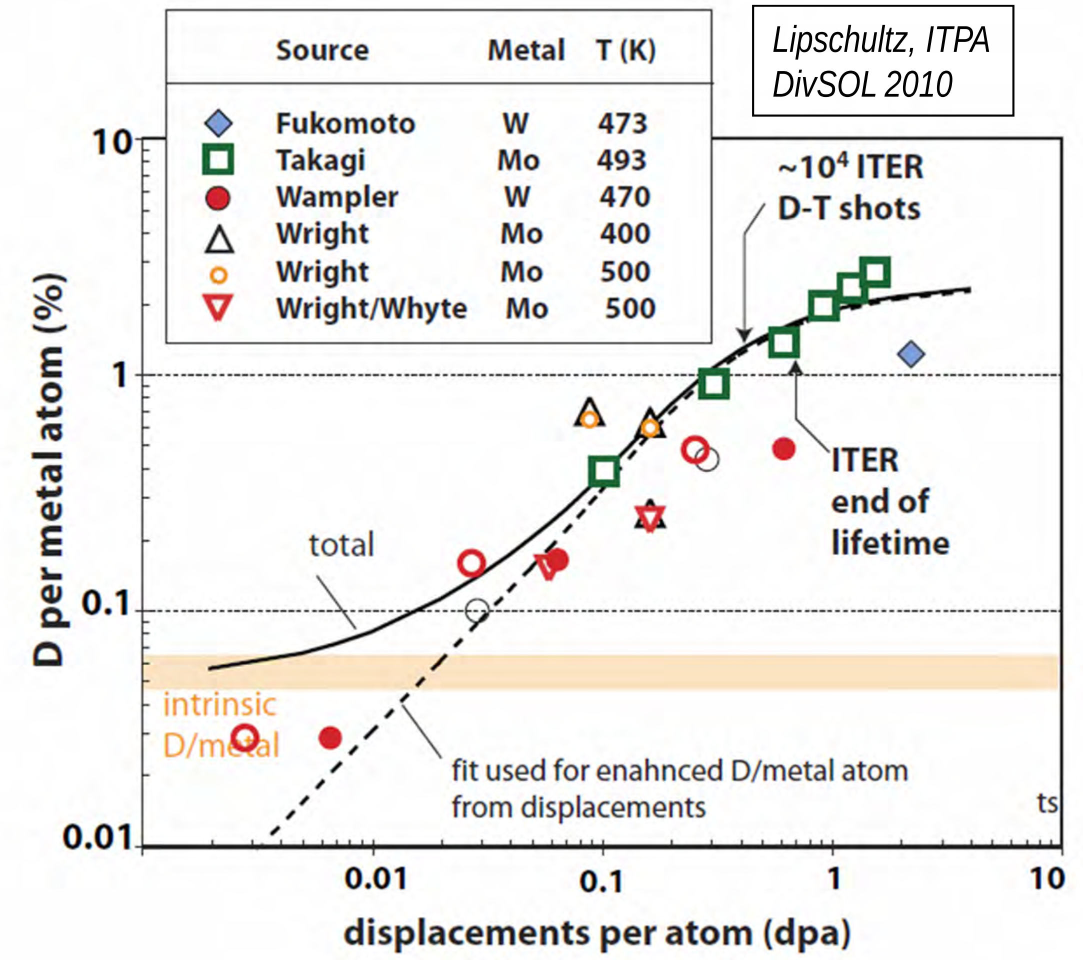

Unipolar Arc Tracks on W Fuzz Surface in LHD

⇒ 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)**

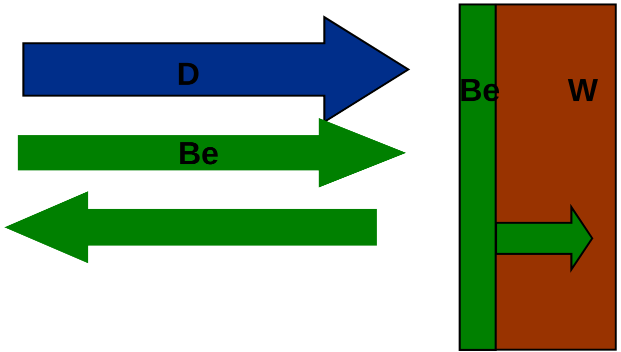


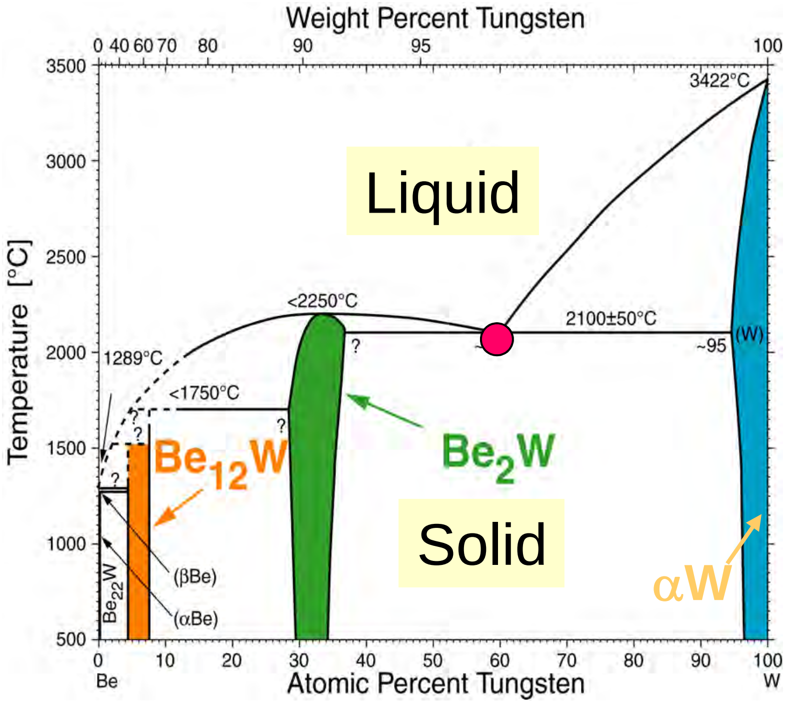
Lipschultz, ITPA DivSOL 2010

➢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

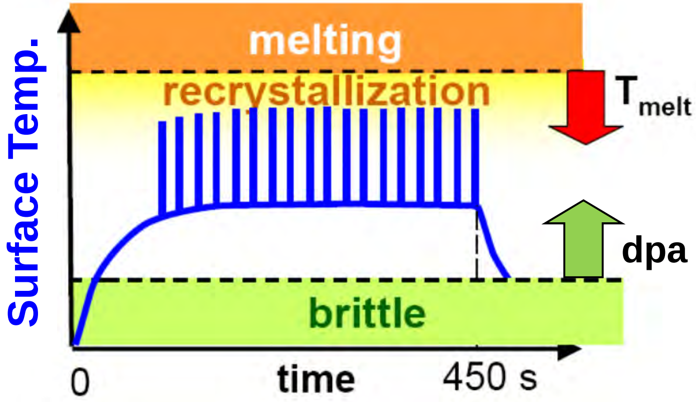
→ enhanced W-sublimation / erosion?





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*

Suggested device Capabilities: *to increase duty factor (availability) 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

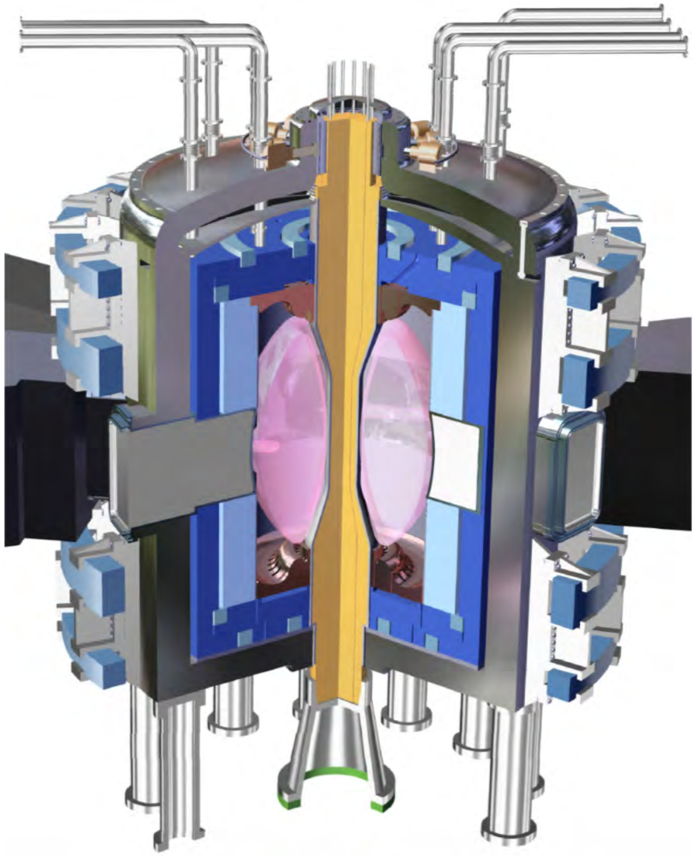
- $R_0 = 1.3m$, $A = 1.7$
- $H_H \lesssim 1.25$, $\beta/\beta_N \lesssim 0.75$, $q_{cyl} \gtrsim 4$
- $J_{TF\text{-}avg} \lesssim 4kA/cm^2$
- Mid-plane test area $\gtrsim 10m^2$
- Outboard T breeder ~ $50m^2$

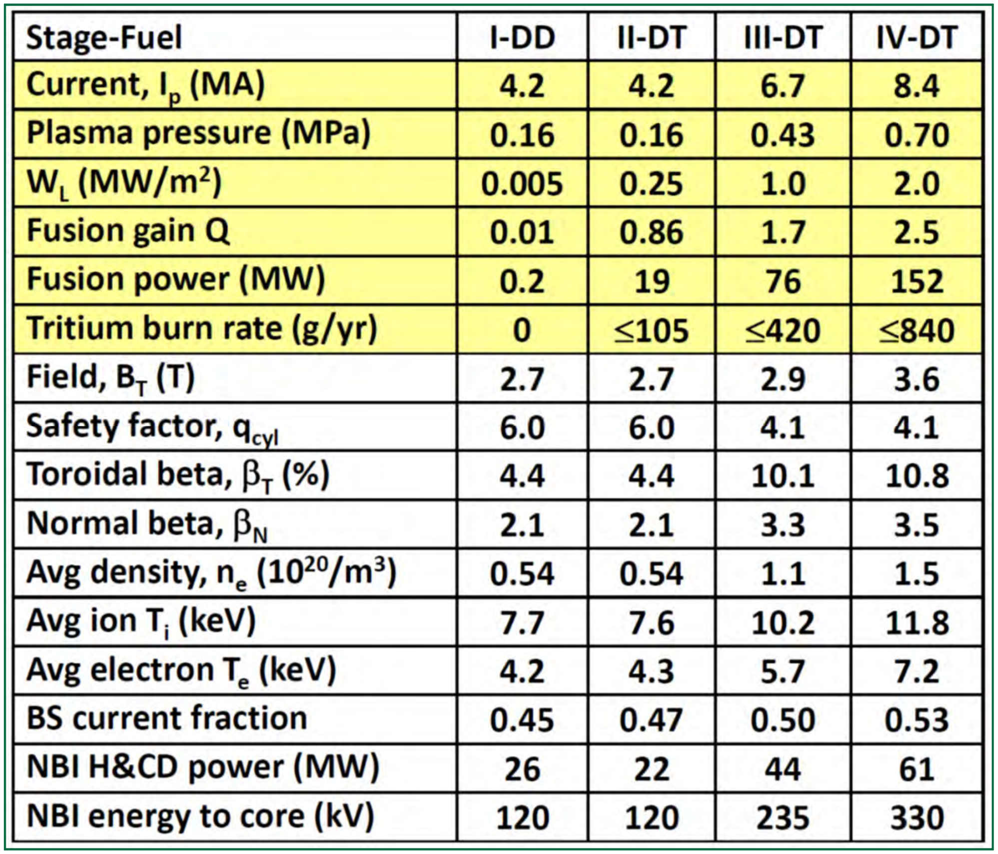
I-DD: 1xJET, verify plasma operation, PMI/PFC, neutronics, shielding, safety, RH system

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

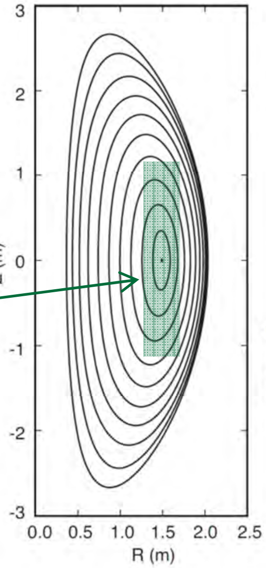




Stage-Fuel	I-DD	II-DT	III-DT	IV-DT
Current, I_p (MA)	4.2	4.2	6.7	8.4
Plasma pressure (MPa)	0.16	0.16	0.43	0.70
W_L (MW/m^2)	0.005	0.25	1.0	2.0
Fusion gain Q	0.01	0.86	1.7	2.5
Fusion power (MW)	0.2	19	76	152
Tritium burn rate (g/yr)	0	≤105	≤420	≤840
Field, B_T (T)	2.7	2.7	2.9	3.6
Safety factor, q_{cyl}	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

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



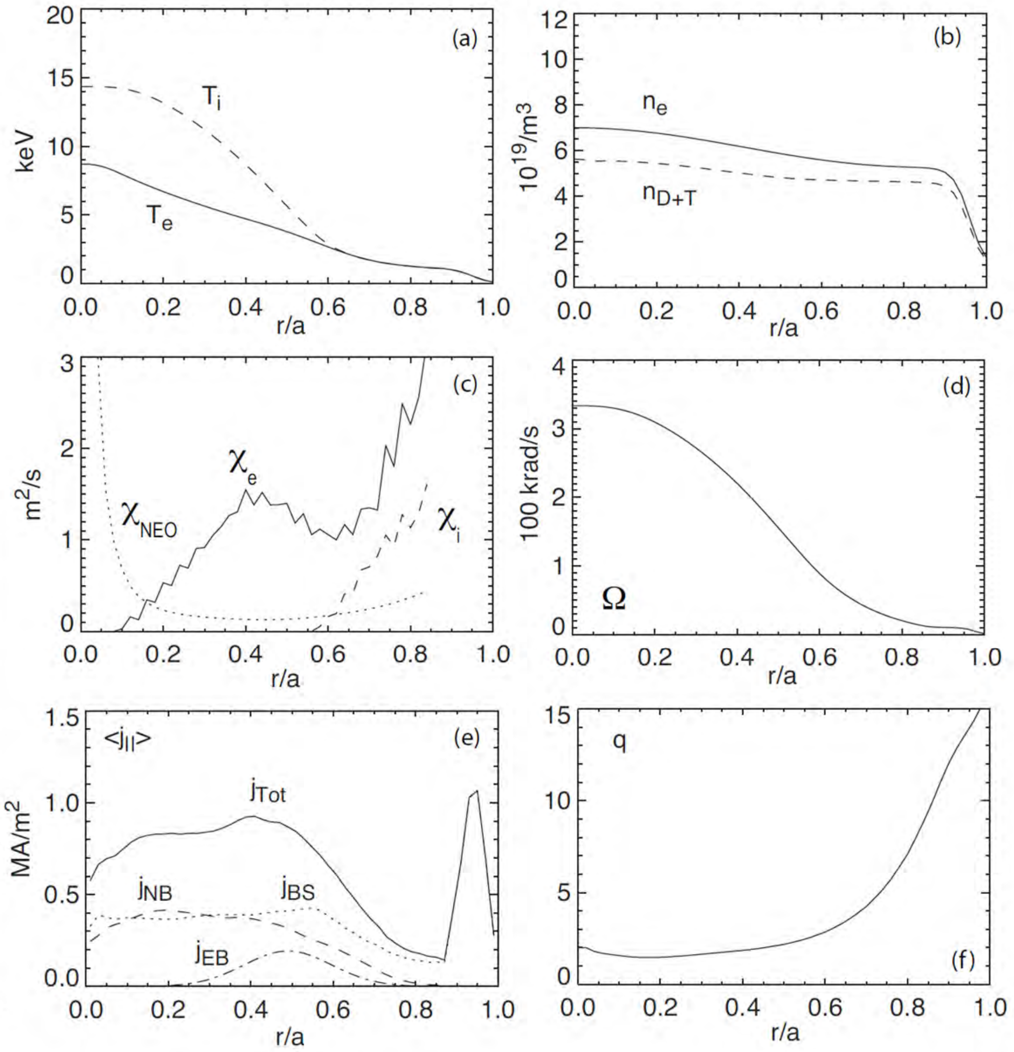
Tangential NBI

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

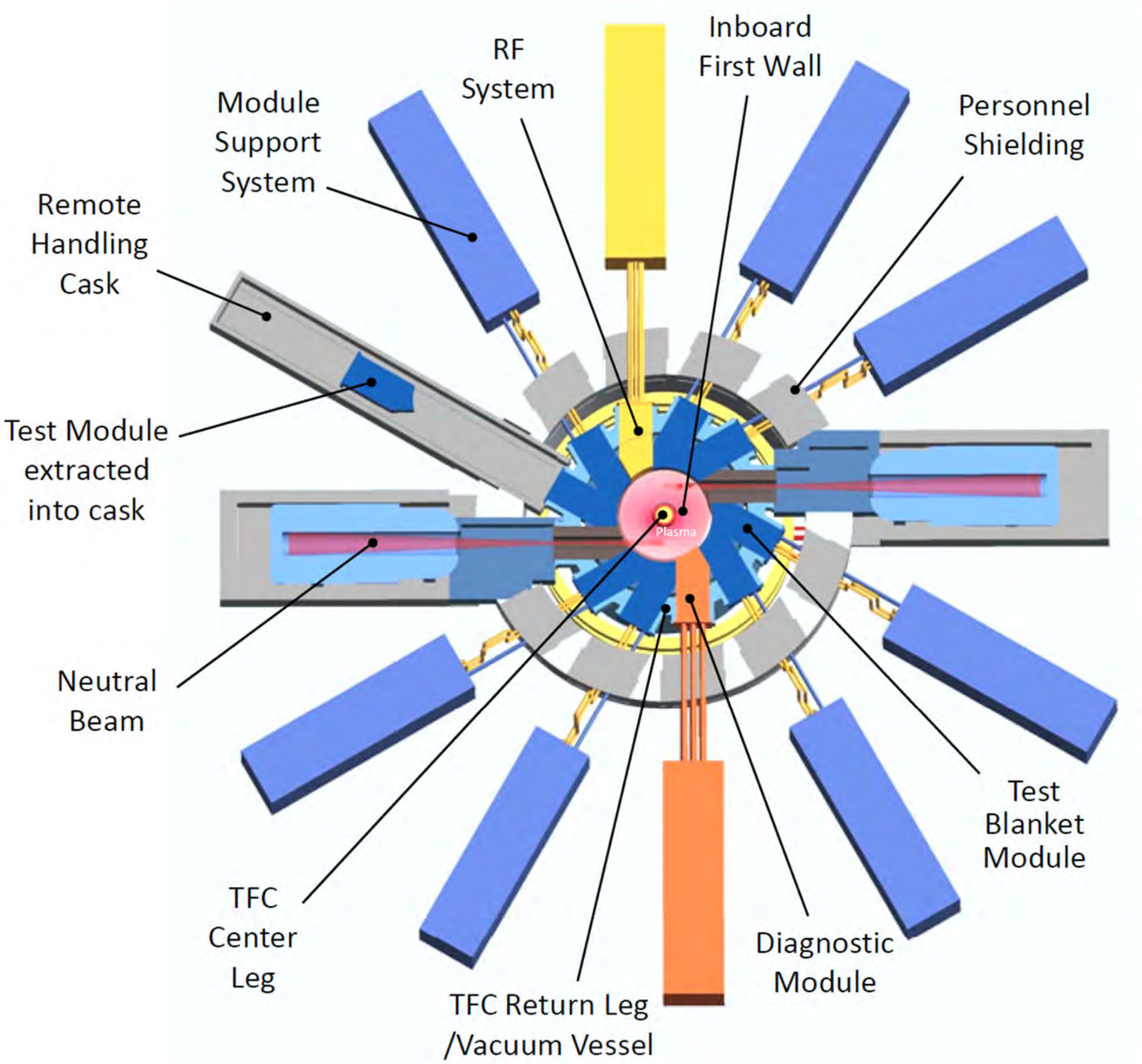
Hot-Ion H-Mode with Internal Transport Barrier

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

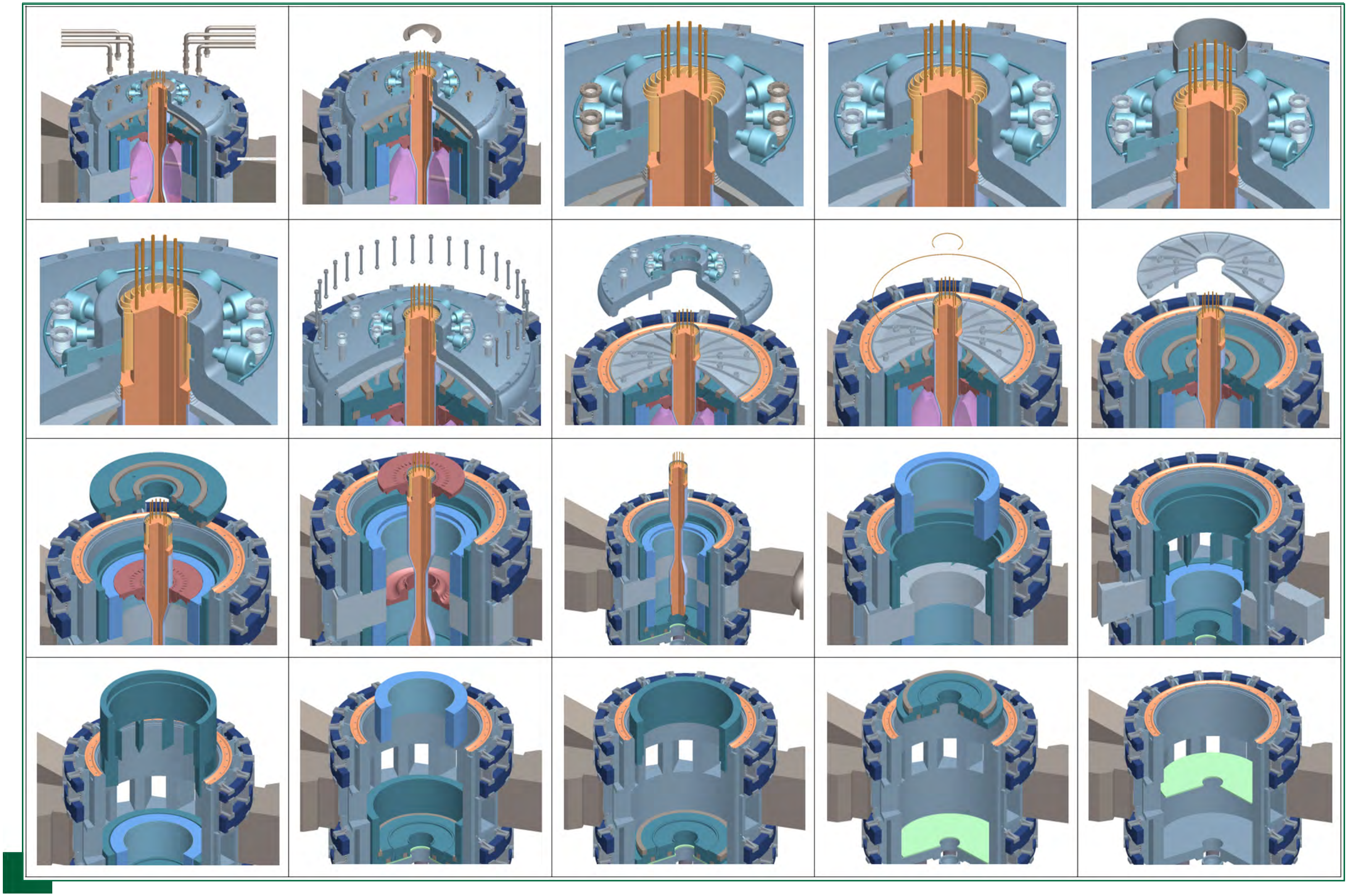


Mid-plane ports

- **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**

Internal components assembly/disassembly concept

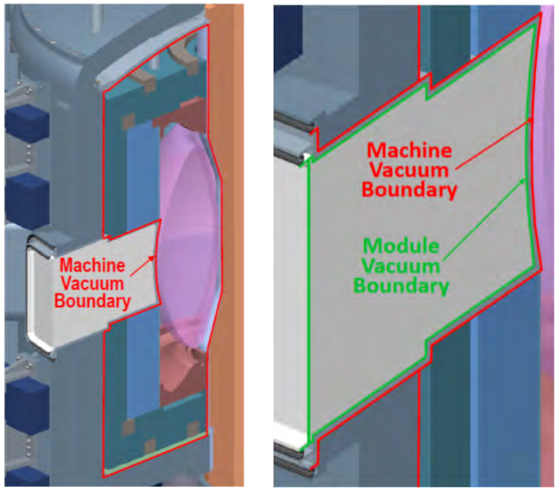
support structure lifetime dose < 0.1 dpa enables staging



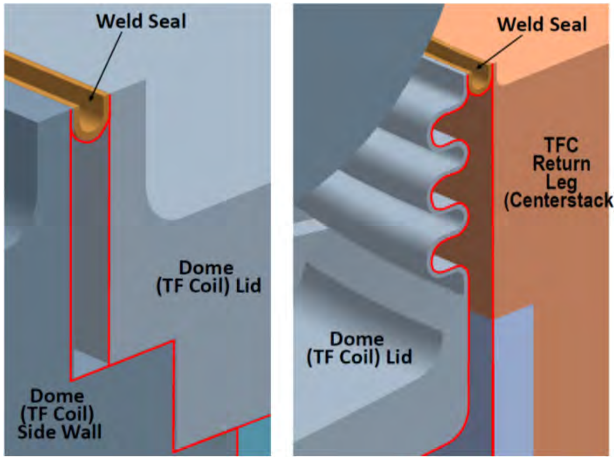
Ready replacements, shielded vacuum weld seals and bi-directional sliding joint are proposed to allow RH

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

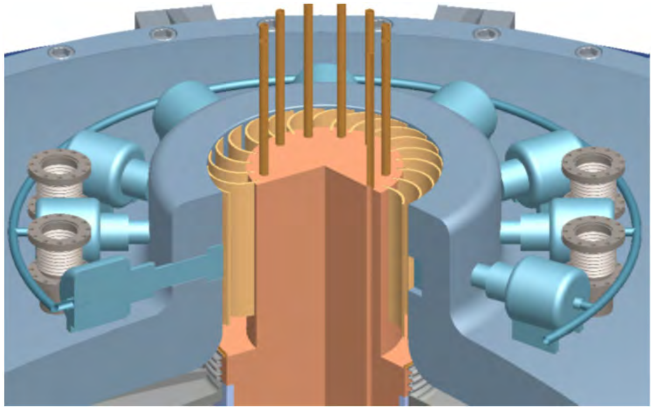
Mid-Plane Test Module Access

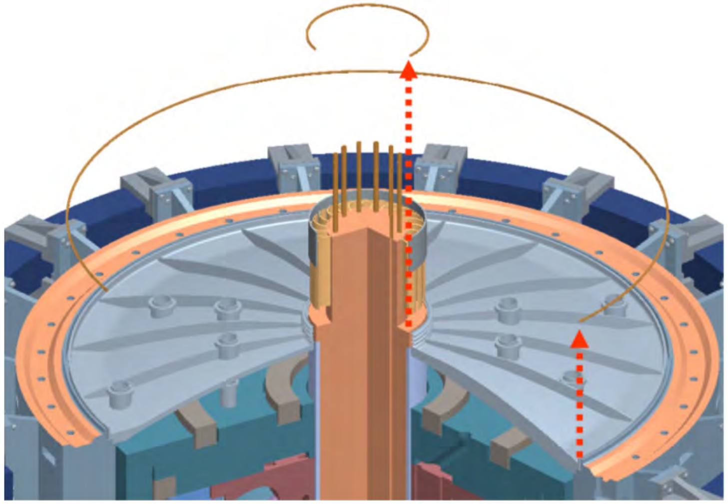


Top TF Conductor Lid



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**

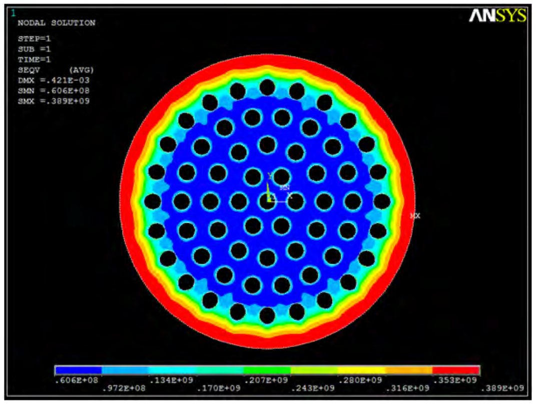
Assumptions:
- ***Nuclear and Joule heating***
- ***Constant water flow***
- ***Constant Copper thermal & electrical conductivities***
- ***≥5 mm between channels and to surface***

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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SMN =.606E+08
SMX =.389E+09
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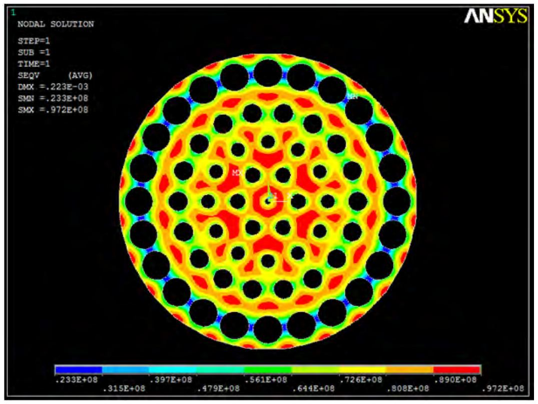
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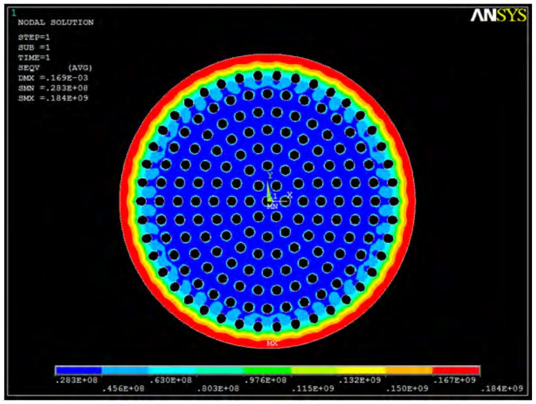
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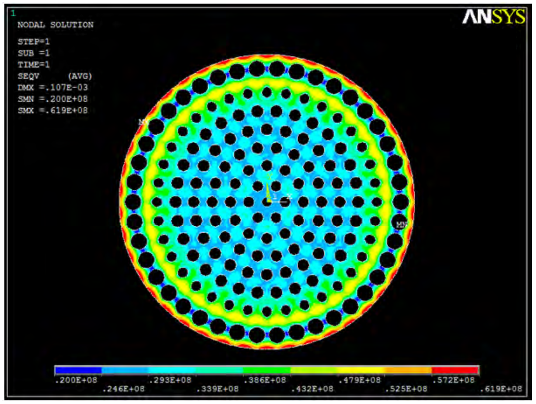
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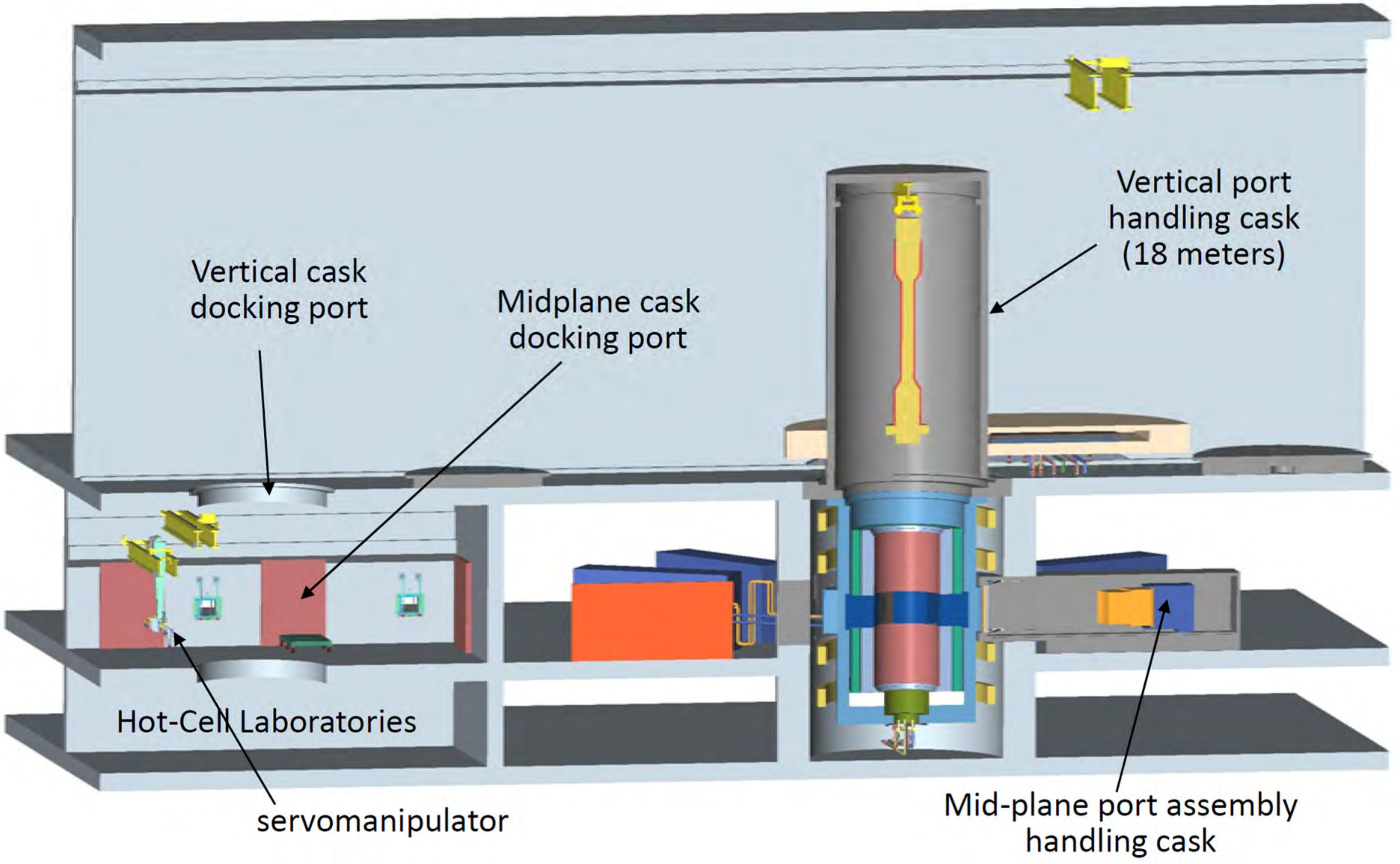
Extensive remote handling systems, including hot-cell laboratories, will be required

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

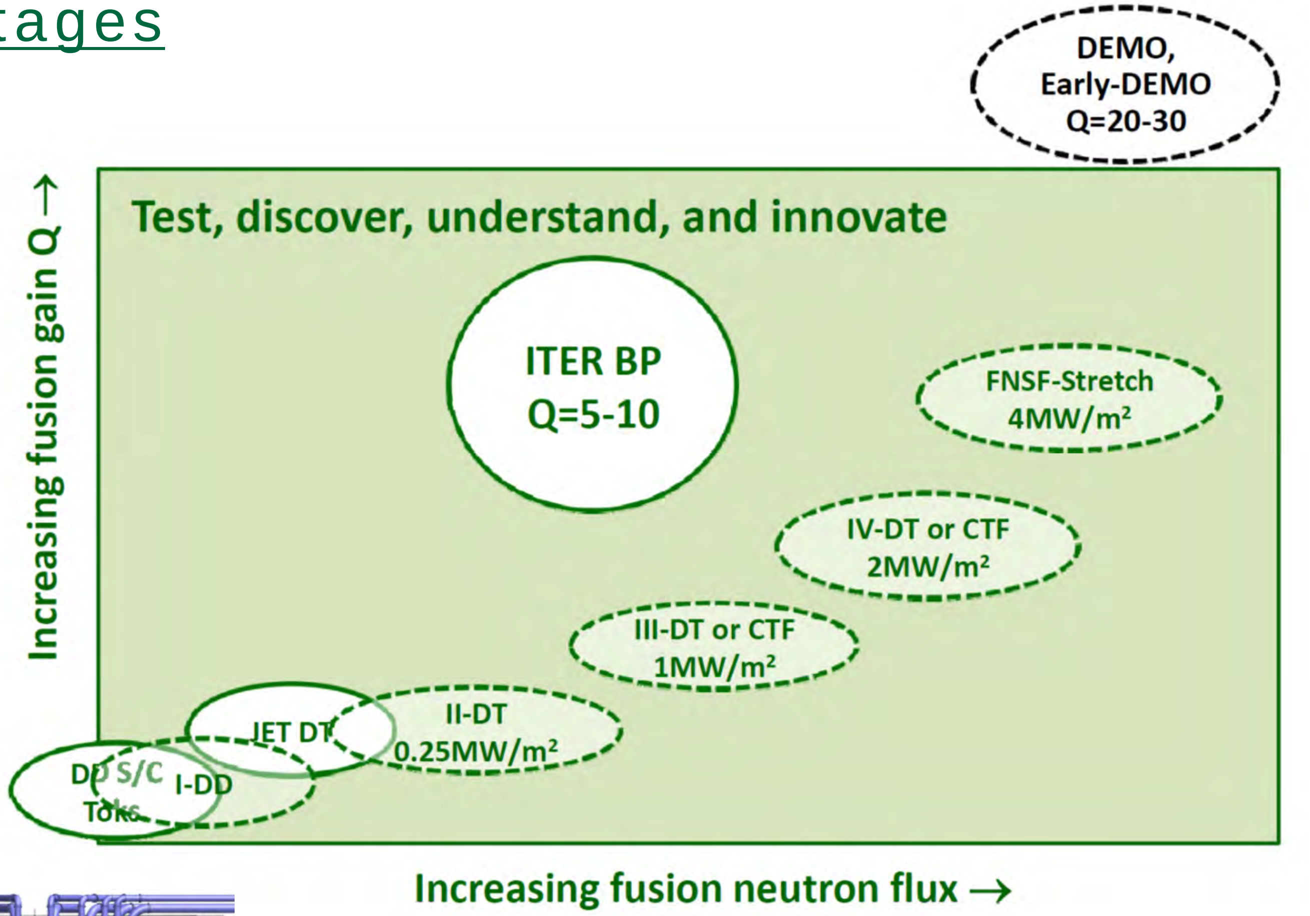


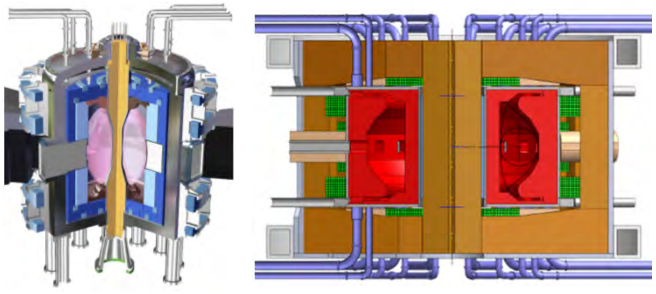
To manage the risks, requisite R&D can be defined addressing the device features (dependent on options)

- **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 integrated research.

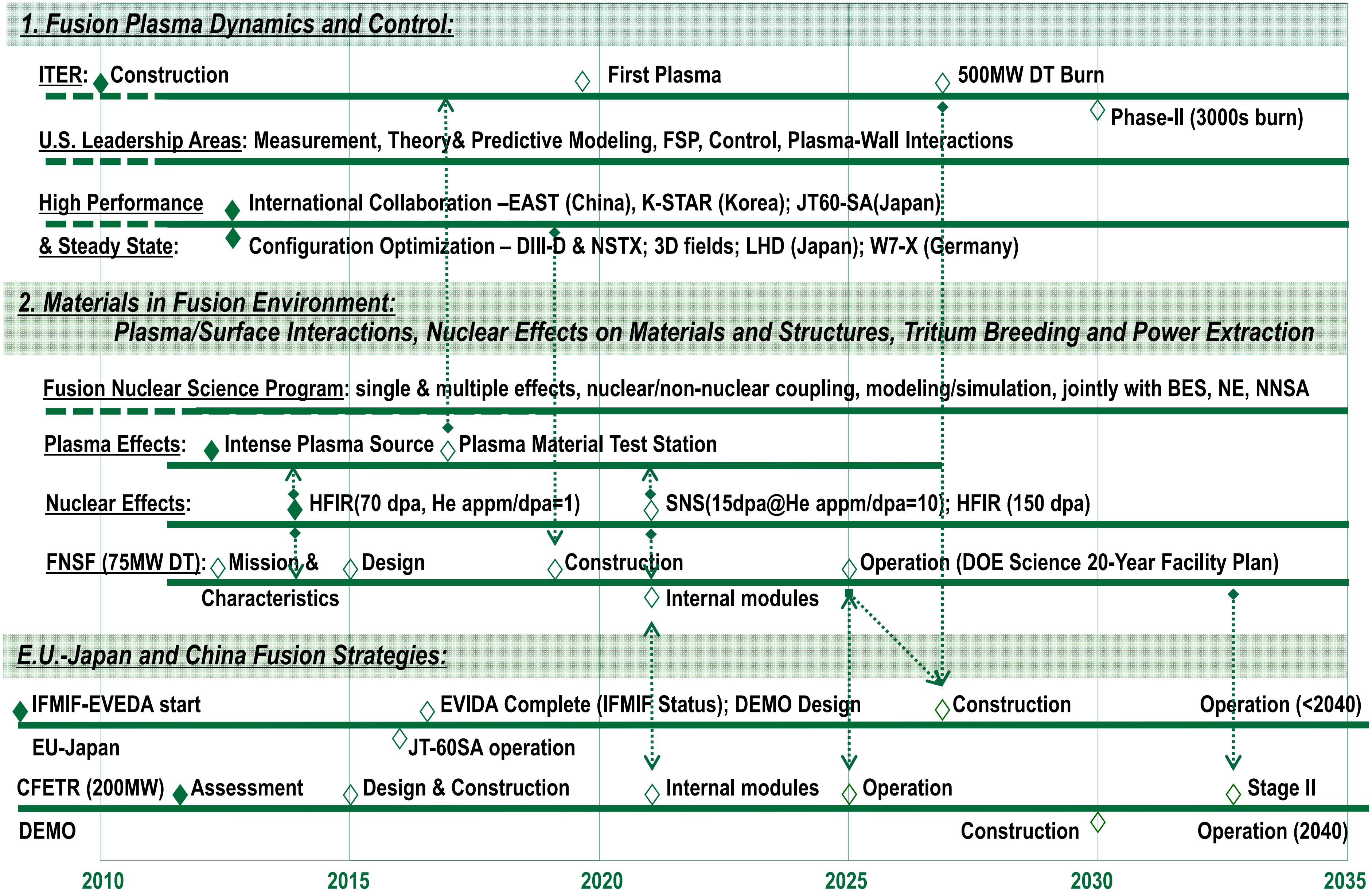
FNSF/CFETR with accompanying R&D aim to test, discover, understand, and innovate fusion nuclear science and engineering solutions for DEMO, in progressive stages





Scenario also relevant to fusion-fission hybrid blanket R&D

A roadmap to complement and support world MFE



1. Fusion Plasma Dynamics and Control:

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 –EAST (China), K-STAR (Korea); 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 Effects: ◆ Intense Plasma Source ◇ Plasma Material Test Station

Nuclear Effects: ◆ HFIR(70 dpa, He appm/dpa=1) ◇ SNS(15dpa@He appm/dpa=10); HFIR (150 dpa)

FNSF (75MW DT): ◇ Mission & Characteristics ◇ Design ◇ Construction ◇ Internal modules ◇ Operation (DOE Science 20-Year Facility Plan)

E.U.-Japan and China Fusion Strategies:

◆ IFMIF-EVEDA start ◇ EVIDA Complete (IFMIF Status); DEMO Design ◇ Construction Operation (<2040)

EU-Japan ◇ JT-60SA operation

CFETR (200MW) ◆ Assessment ◇ Design & Construction ◇ Internal modules ◇ Operation ◇ Stage II

DEMO Construction ◇ Operation (2040)