

Fusion Nuclear Science Research – the Scientific Stage of CTF before Fusion Energy Development

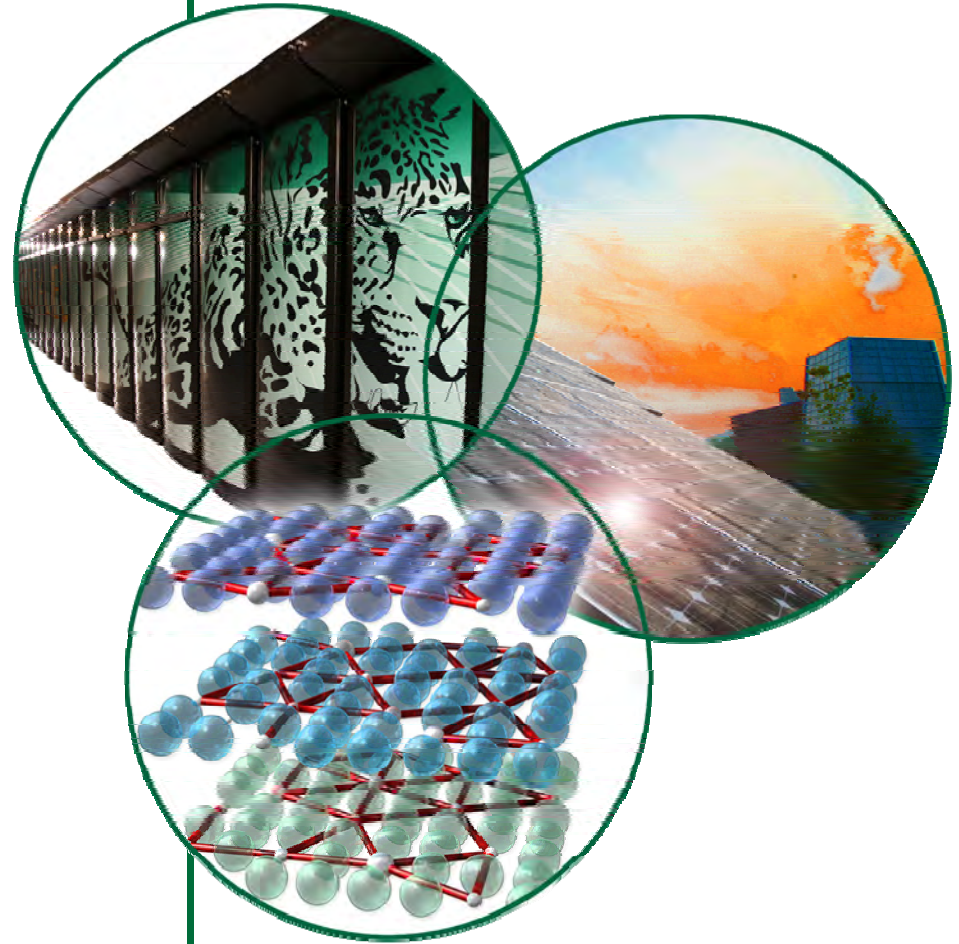
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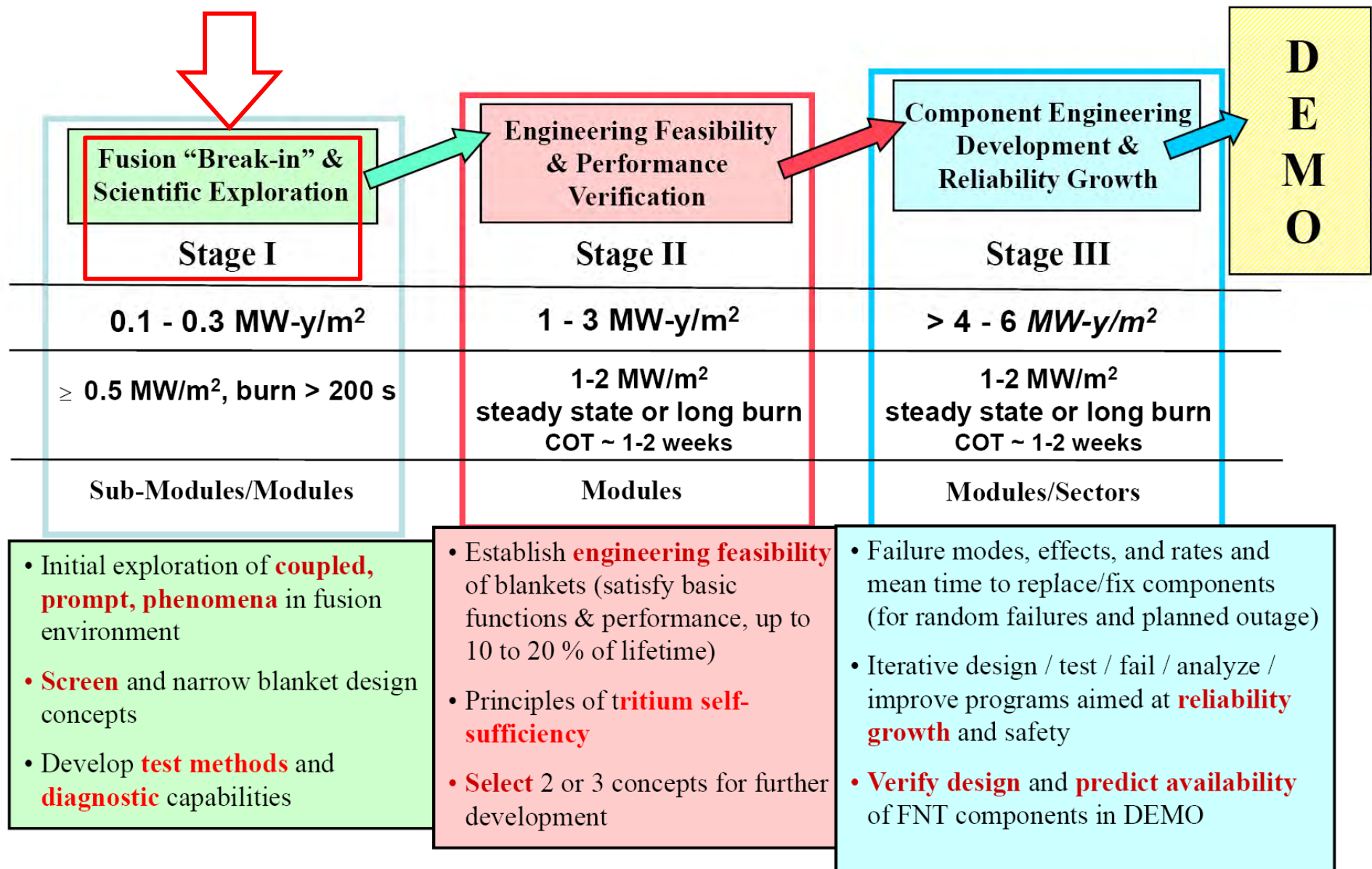
Presentation at ReNeW Workshop Theme 5 –
Optimizing the Magnetic Configuration

PPPL, March 16 - 19, 2009



What is Fusion Nuclear Science (FNS)?

The scientific knowledge that needs to be explored and understood in **Stage I of CTF using ~3 dpa** to determine appropriate component designs to be tested further in Stages II & III for “Engineering Feasibility ... Reliability Growth” **using up to ~60 dpa** [Abdou et al.]



What is a full fusion nuclear environment?

A full fusion nuclear environment has:

- Harsh fusion neutron fluxes
- Increasing neutron fluence and damages to materials
- Pervasive tritium distribution in varied media and materials
- High heat fluxes and material temperatures
- Uncommon materials and their combinations
- Sustained for up to 10^6 s (week)

Leading to:

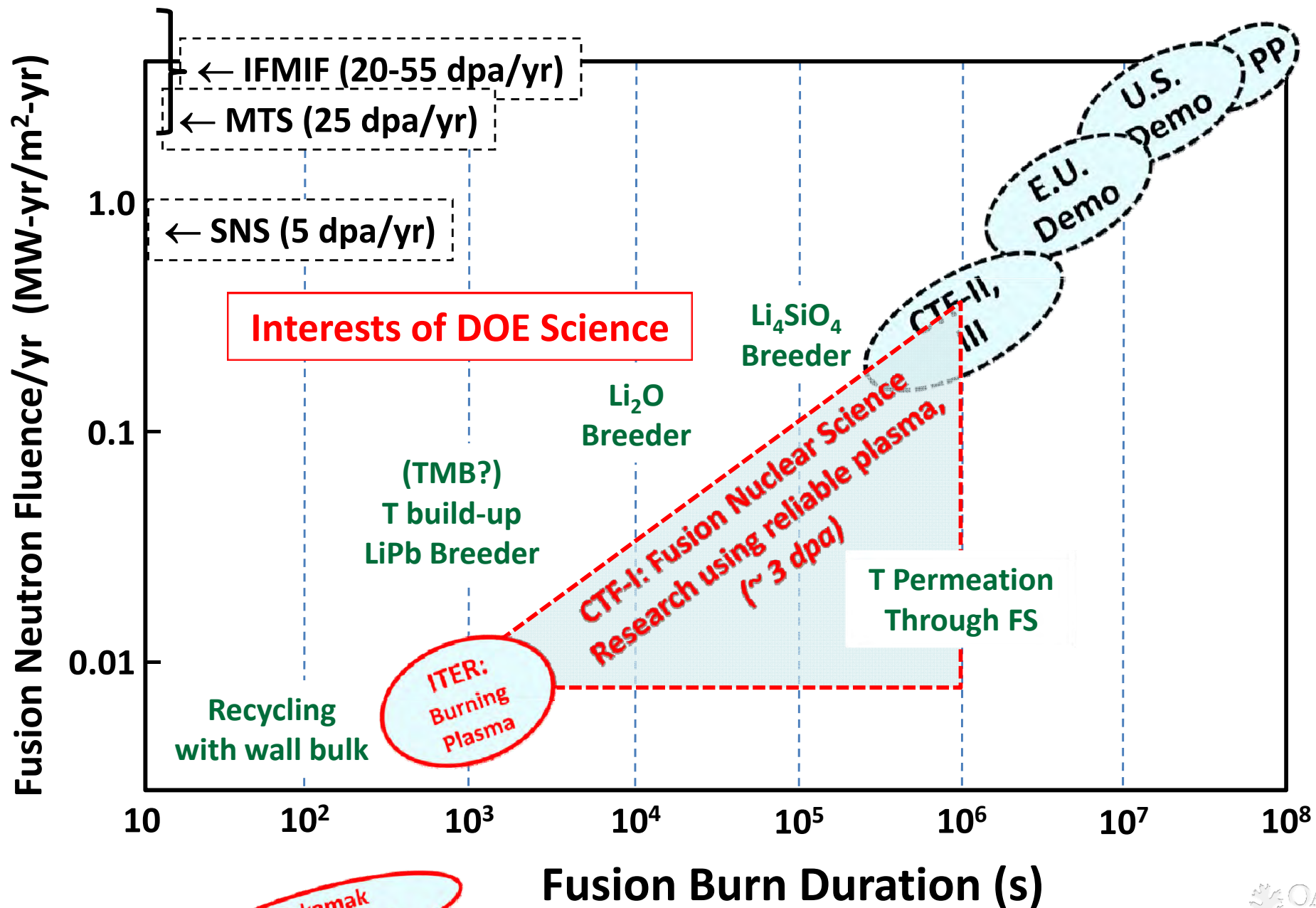
- Stringent safety and far-reaching RAMI requirements

Equally challenges components that tame the plasma material interface & harness fusion power

ITER promises to sustain such an environment for $\sim 10^3$ s in ~ 2020 , *for the first time.*

FESAC “Opportunities ...” Report identified such an environment as an example that need to be used to close many of the Gap areas in Demo knowledge base.

FNS research addresses physical properties of increasing time constants, by progressively extending burn durations to 10^6 s in a full fusion nuclear environment – *for the first time*



Full fusion nuclear environment enables critical tests of potential materials synergistic effects *for the first time*

Kurtz at Theme IV meeting on fusion material issues:

- “Recent fusion materials R&D efforts have led to the development of high-performance reduced-activation structural materials with good radiation resistance for doses ~ 30 dpa and ~ 300 appm He.”
- “The mechanisms controlling chemical compatibility of materials exposed to coolants and erosion of materials due to interaction with the plasma are poorly understood.”
- “CTF: Nuclear facility to explore the potential for synergistic effects in a fully integrated fusion neutron environment. Data and models generated from non-nuclear structural test facilities, fission reactor studies and the intense neutron source will be needed to design this facility.”

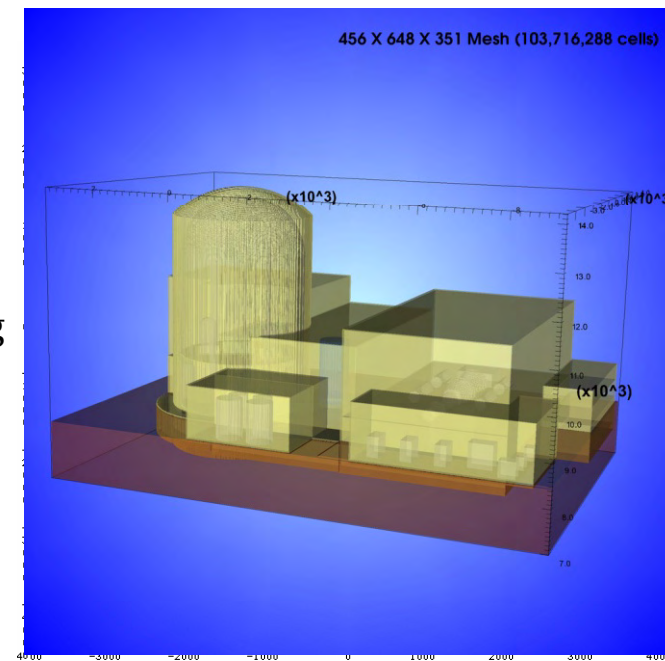
Fusion nuclear science research can use such structural materials to begin the exploration of potential synergistic effects using ~ 3 dpa and ~ 30 appm He, below ~ 100 appm He.

- Example: What is the migration rate of tritium, implanted under divertor surface, through damaged high-temperature armor, joining material, ferritic steel, and coolant tube into the coolant, under neutron bombardment?

Example gaps in Demo scientific knowledge that require R&D in a full fusion nuclear environment

- **Fuel Cycle**: The knowledge to ensure lower tritium loss than burn up fraction per fueling cycle \Leftrightarrow Themes I-II (fueling) & III (PWI-recycling)
- **Power Extraction**: The knowledge to produce and transport high grade heat in breeding blankets while maintaining adequate tritium containment
- **Materials**: The knowledge to control tritium retention, transport, migration, and permeation in plasma facing component materials to close fuel cycle \Leftrightarrow Theme III (PWI & PFC)
- **Safety**: The knowledge to measure the concentration and distribution of tritium in vessel and blankets with adequate accuracy to comply with tritium related safety rules \Leftrightarrow safety compliance of ITER
- **RAMI**: The knowledge to provide high availability and low MTTR using tritium-accountable remote handling systems that are applicable to Demo
- **Modeling**: The knowledge to simulate and predict neutron transport accurately to account for >30 orders of magnitude in neutron dose rates, needed in a full fusion nuclear environment including safety systems

New hybrid (Monte Carlo/deterministic) radiation transport methods/codes enable the use and accuracy of Monte Carlo for problems that would otherwise be computationally prohibitive

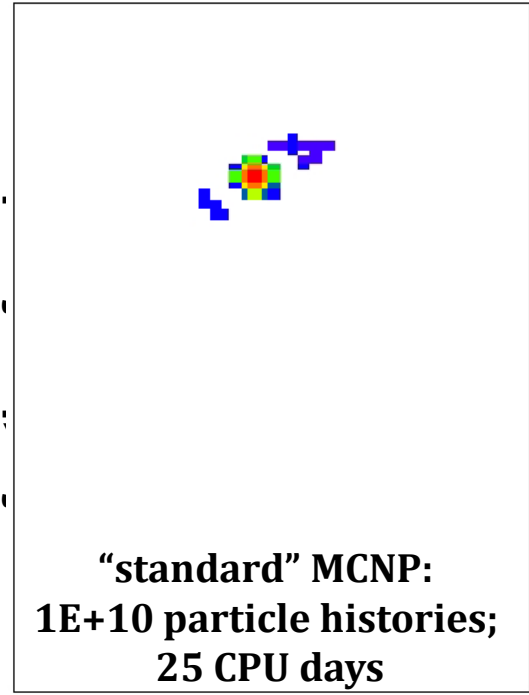


- **METHOD:** Forward-Weighted Consistent Adjoint Driven Importance Sampling (FW-CADIS)
- **EXAMPLE:** Determination of dose throughout an actual full-scale PWR facility, including containment, auxiliary, turbine, and transformer buildings
 - Model extent: 85 × 125 × 70 meters

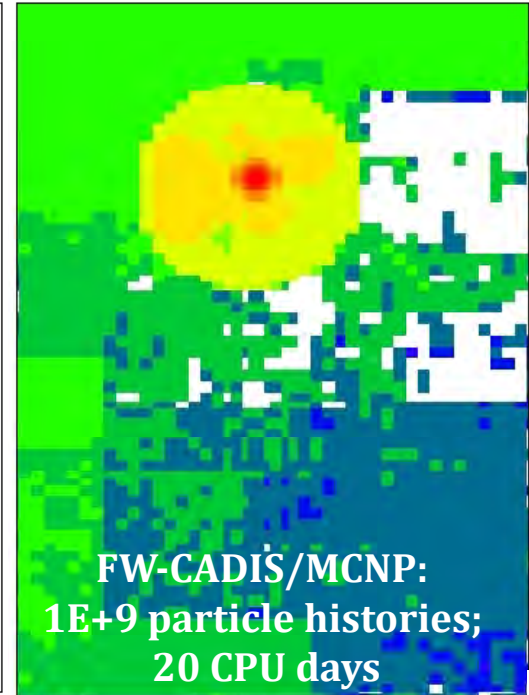
Simulation not possible with "standard" Monte Carlo (MCNP)

Simulation enabled with hybrid methods/code (FW-CADIS/ADVANTG-MCNP)

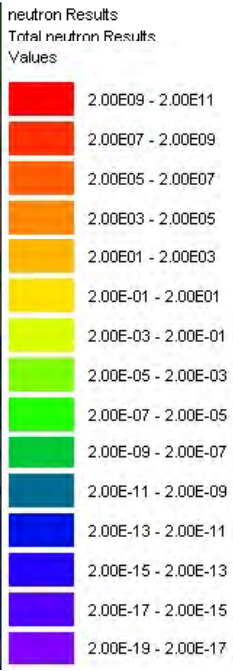
-- Neutron dose rate --



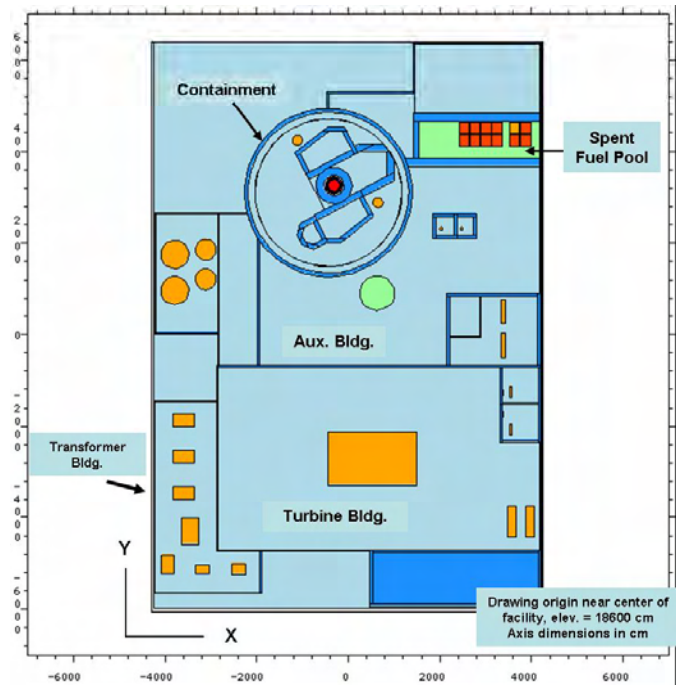
**"standard" MCNP:
1E+10 particle histories;
25 CPU days**



**FW-CADIS/MCNP:
1E+9 particle histories;
20 CPU days**



Note: scale is >30 orders of magnitude

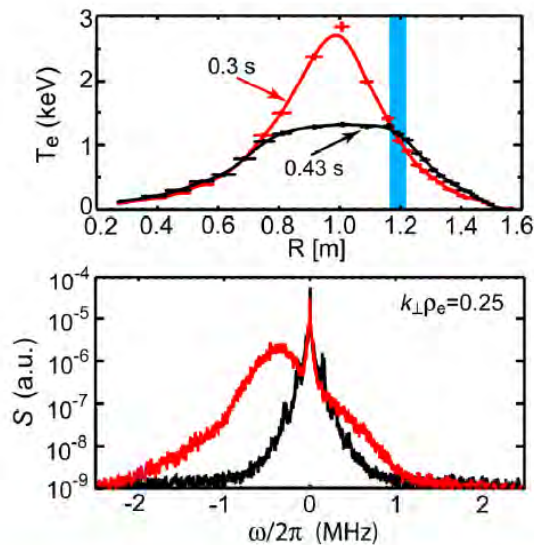
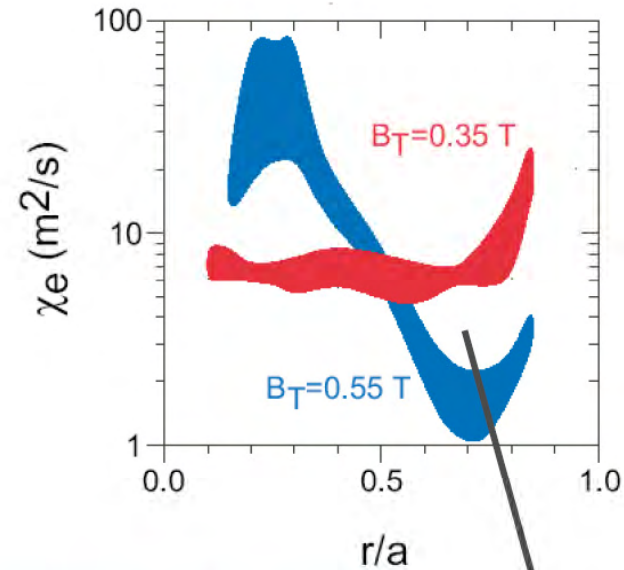
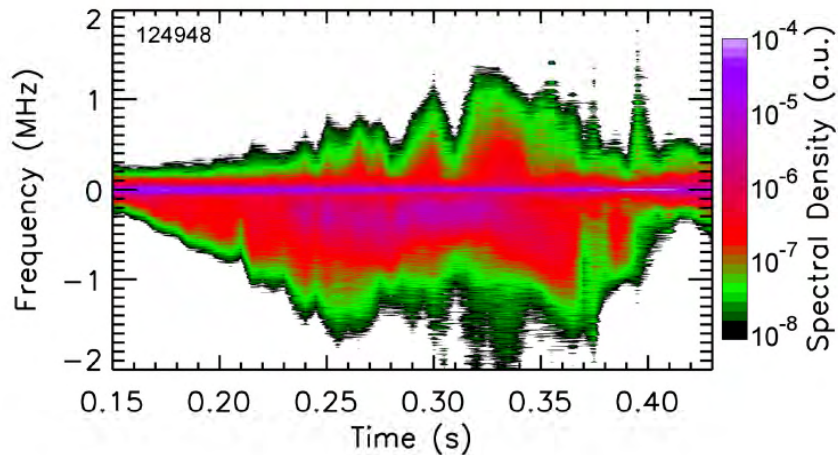


FESAC TAP Report: “*Great commonality of underlying physics between the ST and the Tokamak*”

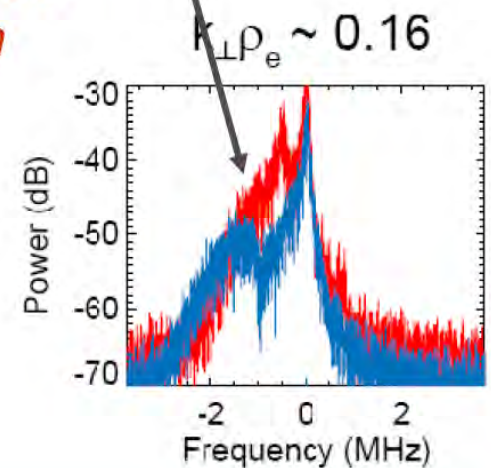
- Spherical Torus (ST) goal for the ITER era: “*Establish the ST knowledge base to be ready to construct a low aspect-ratio fusion component testing facility that provides high heat flux, neutron flux, and duty factor needed to inform the design of a demonstration fusion power plant.*”
- Possible for Tokamak to bridge same gap; collaborate to determine optimized A design
- Also need broad parallel efforts in materials and engineering science
- Identified 4 “Tier-1” issues, and proposed ST research thrusts
 - Start-up and ramp-up: Helicity injection & EBW – **proof-of-principle physics experimentation on Pegasus, MAST, NSTX** \Leftrightarrow start-up in normal aspect ratio
 - Electron energy confinement: establish needed knowledge – **leadership research on NSTX, MAST, LTX (low recycling effects)** \Leftrightarrow research on tokamaks
 - High heat flux: Super-X Divertor (SXD) to reduce peak heat flux by factor 3-5 to below 10 MW/m^2 – **SXD physics experimentation on MAST, NSTX; high plasma heat flux (up to $\sim 10 \text{ MW/m}^2$ on target); PMI experimentations on test stand at high heat flux for long durations ($10^3 \rightarrow 10^6 \text{ s}$)** \Leftrightarrow SXD and “snowflake” research on DIII-D
 - Magnets: single turn magnets with small MIC solenoid – **upgrades on NSTX, MAST; design & prototyping of goal-relevant TF and MIC magnets** \Leftrightarrow ELM control coils
- Strengthen theory, modeling and simulation – **update extensive tokamak predictive simulation capabilities to low A, thus also guiding R&D on “Tier-2” and “Tier-3” issues**

Electron-Scale Turbulence is Observed on NSTX and is Consistent With Expectations for ETG Modes

Dependence on scale of T_e

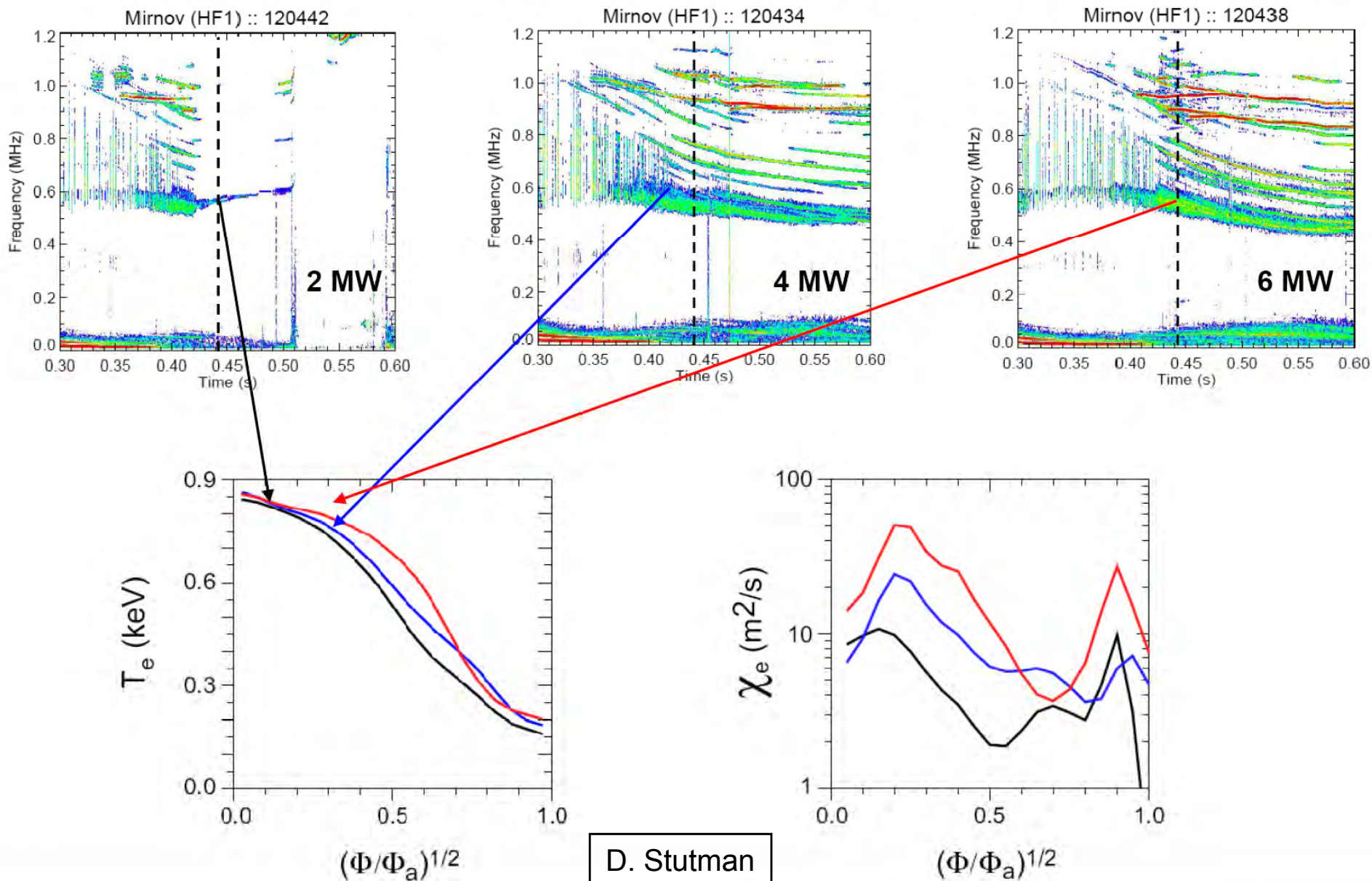


Microwave scattering indicates increase in high- k fluctuation levels at lower B_T



S. Kaye, E. Mazzucato, D. Smith

Recent Observations Indicate High-Frequency Core E-M Fluctuations May Also Cause Electron Transport

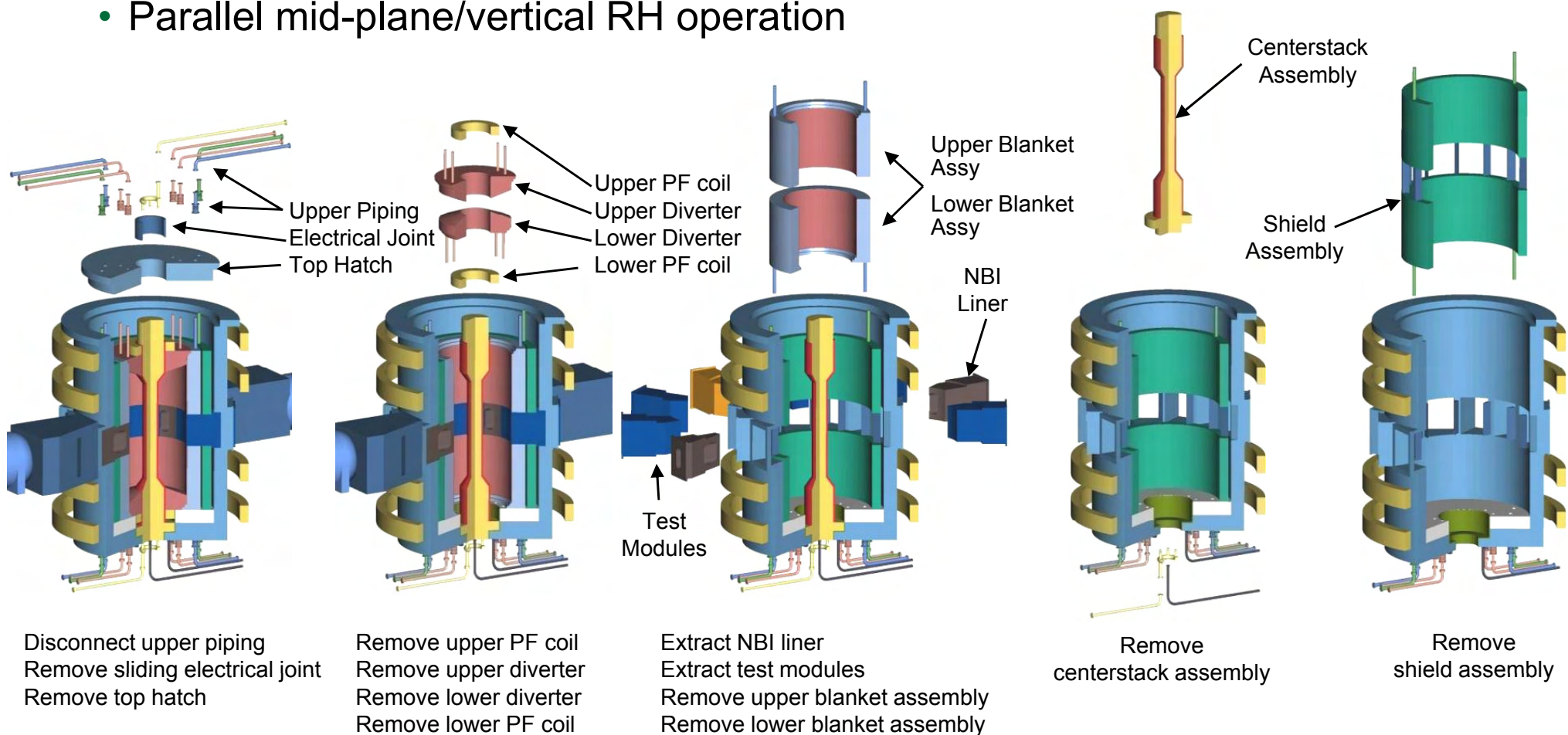


Required FNS R&D technical capabilities

- Fusion neutron flux ranging from 0.01 – 1.0 MW/m²: from threshold of tritium monitoring to tritium breeding rates as function of neutron flux
- Continuous fusion duration progressing from 10³ s to 10⁶ s
- Extensive instrumentation and diagnosis of in-situ physical, chemical and radiological properties of all test components
- Irradiation of candidate material samples and material combinations under precise temperature and environmental control to yield multi-parameter datasets for comparison with models
- Efficient, safe remote handling of test components for installation and removal to “hot-cell laboratories”, with
- Advanced manipulators and material characterization instruments at macro, micro, and nano scales, under high dose rates (~10⁶ Rem/hr)
- A FNS facility availability of ~50% (2 x ITER) and operational duty factor of 10% (2 x ITER) [Ref: van Houtte, ITER RAMI program]
- Total fluence up to ~0.3 MW-yr/m² (3 dpa, 30 appm He), well within FS and copper material damage limits – **no need for IFMIF materials test data**
- Fully modular design readily upgradable to CTF-II and CTF-III operation – **confirm IFMIF data [Ref: R. Kurtz] in fusion environment progressively → 60 dpa**

ST CTF has High Maintainability, Low MTTR, Ready Upgrade Path, Using Large Integrated In-Vessel Modules

- Similar to fission power plants, large vertical top access with large component modules with simple vertical motion expedites remote handling, minimizes MTTR and maintenance outages
- All welds are external to shield boundary are hands-on accessible
- Parallel mid-plane/vertical RH operation



Required FNS plasma operational capability of the full fusion nuclear environment

- Disruption-free plasma operation for durations progressively increased from 10^3 s to 10^6 s – plasma parameters must be controlled far (e.g., factors of 1/2, 1/3, 1/4, etc.) to significantly below all known plasma stability limits (beta, safety factor, density, field errors, etc.) to ensure adequate reliability
- Control of plasma conditions and profiles using long time scale actuators (heating, current driving, fueling, etc.) – to keep plasma in strongly stable regime free of disruption
- Flexible plasma and facility operation, progressively increasing the fusion neutron flux from 0.01 MW/m^2 in steps to 1.0 MW/m^2 : ranging from such as K-Star, JET, and 2 x JET levels of plasma performance.

Required FNS plasma operational capability of the full fusion nuclear environment (cont.)

- Benefit from “stretch ST R&D goals” in plasma conditions (beta, confinement, disruption-free durations, etc.) to enable higher neutron flux or to improve RAMI
- FDF, if operated similarly, also enables similar FNS R&D

Example ST range of plasma performance for FNS R&D with increasing fusion neutron flux

Fusion nuclear science levels	Thresholds	Verification	Neutron Flux Dependence	
Equivalent tokamak knowledge	K-Star level	JET level	2 x JET	3 x JET
Fusion neutron flux (MW/m ²)	0.01	0.25	1.0	2.0
Major radius, R ₀ (m)	1.2			
Toroidal field at R ₀ , B _T (T)	2.1	2.2		
Cylindrical safety factor, q _{cyl}	8.5	6.7	3.7	3.0
Plasma current, I _p (MA)	3.4	4.2	8.2	10.1
Toroidal beta, β _T	0.05	0.05	0.18	0.28
Normal beta, β _N	2.0	2.7	3.8	5.9
Average density, n _e (10 ²⁰ /m ³)	0.43	0.65	1.1	1.3
Average ion temp., T _i (keV)	5.4	5.6	10.3	13.3
Average elec. Temp., T _e (keV)	3.1	3.6	6.8	8.1
Bootstrap current fraction	~0.6	~0.6	0.49	0.50
NBI H&CD Power (MW)	15	20	31	43
Fusion Power (MW)	0.8	18	75	150
Peak divertor heat flux (MW/m ²)	~3	~4	~7	~10

Fusion Nuclear Science Research – the Scientific Stage of CTF before Fusion Energy Development

- Aims to establish the scientific knowledge base for fusion energy within DOE Science mission, the Stage I of CTF research
- Establish knowledge needed to inform DOE decision whether to enter Energy Development via CTF-II and CTF-III to develop engineering and technology
- Provide a full fusion nuclear environment to extend small scale, fundamental effects research to levels needed to close all HFP and TPMI gaps identified by FESAC “Priorities ...” Report
- Rely on all fusion and fission technology capabilities to create the first test components, to carry out the tests, to discover new or changed properties, and to innovate based on the fusion nuclear science knowledge gained
- Consistent with FESAC TAP Report recommendations on R&D to get ready
- Recommend common-based benefit-cost-risk assessments of options across aspect ratio (ST, Tokamak, or in-between), fusion neutron flux ($W_L = 0.01 - 2.0$ MW/m²), peak divertor heat flux (3 – 10 MW/m²), disruptivity ($q_{cyl} = 3 - 8.5$), etc.
- Offer a Science-Based vision of progress toward fusion energy development, relying on ST research & upgrades, tokamak research & upgrades, new high plasma heat flux test stand capabilities, etc.