Fusion Nuclear Science Facility (FNSF) Overview, Physics Assumptions and Operating Space

C. E. Kessel and the FESS Team

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The Fusion Energy Systems Studies Team is Examining the Fusion Nuclear Science Facility

What does an FNSF have to accomplish?

How do we measure the FNSF progress for fusion development?

How does the FNSF accomplish its mission?

What is the pre-requisite R&D needed for an FNSF? What does the FNSF require from our program to succeed?

How does an FNSF fit in the larger fusion development program?

What critical insights about this facility can be uncovered, impacts of assumptions, technical choices and philosophies,…?

The FNSF must fill the tremendous gap between ITER and DEMO by providing the break-in to the ***fusion nuclear regime***

First strongly burning plasma

Demonstrate routine Power Plant Ops

No technical gaps

	ITER	**FNSF**	**DEMO**	**Power Plant**
Max damage	3 dpa	37-74 dpa	100-150 dpa	150+ dpa
Max plasma pulse	500-3000s	1-15 days	15-365 days	365+ days
TBR	~ 0	~ 1.0	1.05+	1.05
$T_{blanket}$, $T_{cool,exit}$	285C, 150C	550C, 650C	550C, 650C	550C, 650C
Materials	316SS, CuCrZr, Be, W, H_2O, SS304, SS430		RAFM, PbLi, He, SiC-c, Borated-RAFM, W, bainitic steel	

A nearer term facility like the FNSF requires a number of technical philosophies/approaches to be defined/ explored

Facility missions and metrics – what progress does the facility make on the pathway to a power plant

Physics strategy – how do we choose plasma parameters, what's their impact

Long term power plant relevance – design choices are made to keep the scientific/technology development on track, avoid diversions that do not contribute to the power plant vision

Minimal, Moderate, and Maximal FNSF

Qualification requirements to install a component/material in the FNSF – fusion neutron exposure to the dpa level, highly integrated non-nuclear testing.....plasma-vacuum systems are not consistent with "cook and look" approach to FNS, remote-maintenance

FNSF program plan – phases, material/temperature/dpa evolution, operation and maintenance

Blanket (divertor/launchers) choices and testing strategy – provide the process by which we test and advance fusion core components, and backups

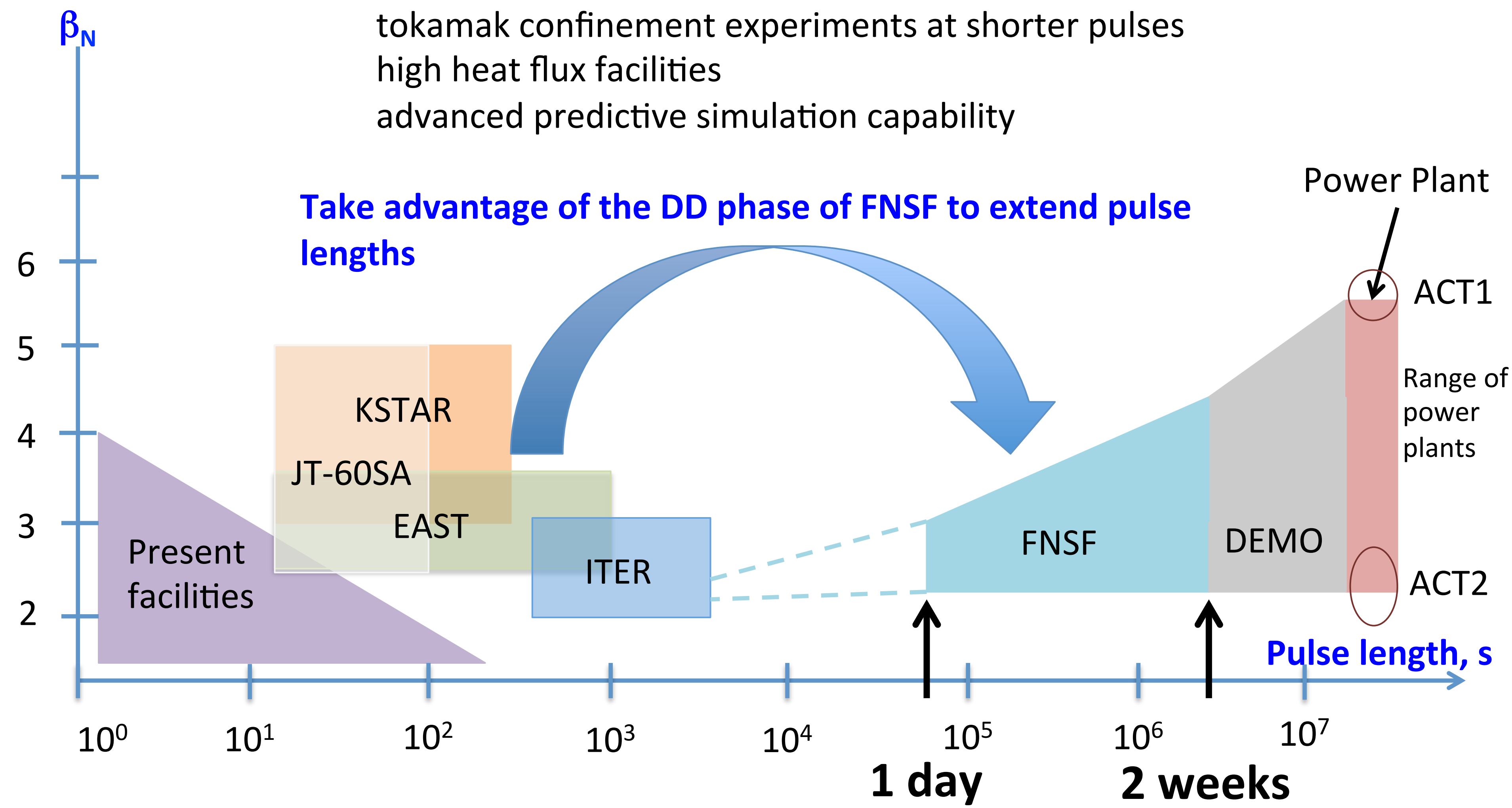
Hot Cell – how do we access and process the information from the FNSF operation

Pre-FNSF R&D – how do we see the R&D evolution to prepare us for the FNSF, design and operation

The Plasma Durations Required in the FNSF is a Large Leap Compared to Present/Planned Tokamaks

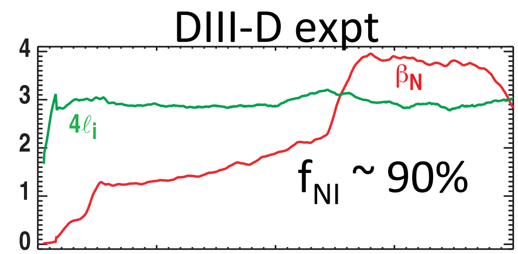
Before the FNSF, must combine

- ultra-long pulse linear plasma facilities
- tokamak confinement experiments at shorter pulses
- high heat flux facilities
- advanced predictive simulation capability

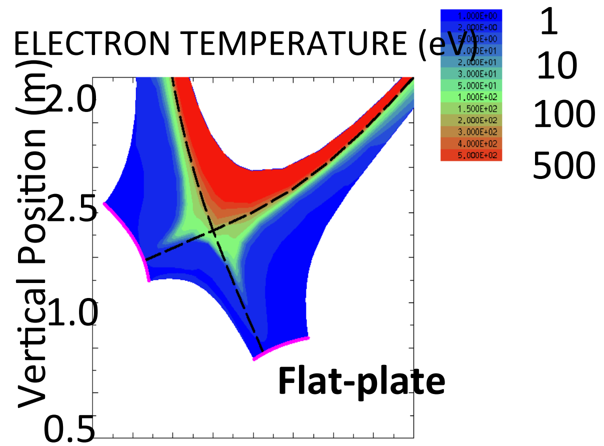


Physics Strategy for the FNSF Regime of long pulse, 100% non-inductive, burning plasma

Pursue $\beta_N \leq$ no wall limit to accomplish mission, but install appropriate feedback or other capability to exceed no wall limit → by how much?



Install passive stabilizers and feedback coils to provide higher plasma elongation, significantly expanding operating space



Operate below the Greenwald density limit $n/n_{Gr} \leq 1$, but not rely on low values to enhance CD

Plasma current is driven 100% non-inductively in flattop, however, a solenoid provides rampup assistance and flattop feedback

Peak heat flux tolerated in the divertor $\leq$ 10 MW/m^2, while pursuing high heat flux design/material solutions and 2D SOL/divertor plasma simulations

DN divertor

High radiation divertor solns

Pursuing high toroidal field in the plasma, targeting LTSC advances

Mitigated disruptions

Plasma *Performance and Duration* in DIII-D and JT-60U Looking at Experiments for Guidance

	JT-60U	JT-60U	DIII-D	DIII-D	DIII-D	DIII-D
β_N	2.4	1.7	3.5*	$\geq$ 3.5	2.0	3.1-3.4*
$\tau_{flattop}/\tau_{CR}$	2.8	2.7	2.0	~1.5	> 2	~ 0.4-1.0
q_{95}	4.5	~ 8	6.7	5.5-6.5	4.7	5.0-5.5
f_{BS}	45%	80%	40-50%	50-60%		~60%
f_{NI}	90%	100%	75%	~ 100%		80-100%
H_{98}	1.0	1.7	1.0	1.6	1.3	$\geq$ 1.2-1.3
q_{min}	~ 1.5		1.5	~1.0		1.4
	~ steady state	steady state	→ steady state, off-axis NB	→ SS hybrid, hi rot	QH-mode, no ELMs	steady state

EAST and KSTAR will soon contribute

*utilize active error field correction, plasma rotation, $\beta_N \sim 1.15 \times \beta_N^{no\ wall}$

Additional experiments on JT-60U, DIII-D, **AUG** have 1) approached and exceeded **density limit**, 2) **high radiated power** in the plasma and divertor, 3) avoiding or actively **suppressed NTMs**, 4) **low plasma rotation**, and 5) **PFC materials**

Systems Code Identification

Large scans over R, B_T, q_{95}, β_N, Q, Z_{eff}, n/n_{Gr}

$\langle j_{TF} \rangle = 15\ MA/m^2$

$f_{div,rad} = 90\%\ (\lambda_{pow}^{Fundamenski})$

Filters for solutions

$\beta_N \leq 2.6^*$

$q_{div}^{peak} \leq 10\ MW/m^2$

$N_w^{peak} \geq 1.5\ MW/m^2$

$B_T^{coil} \leq 16$ T (LTSC)

IB Radial build from neutronics:

$\Delta_{FW/blkt} = 50$ cm

$\Delta_{SR} = 20$ cm

$\Delta_{VV} = 10$ cm

$\Delta_{LT\ shield} = 23$ cm

$\Delta_{gaps} = 20$ cm

*examining benefits of RWM feedback to raise this toward 2.8-3.2

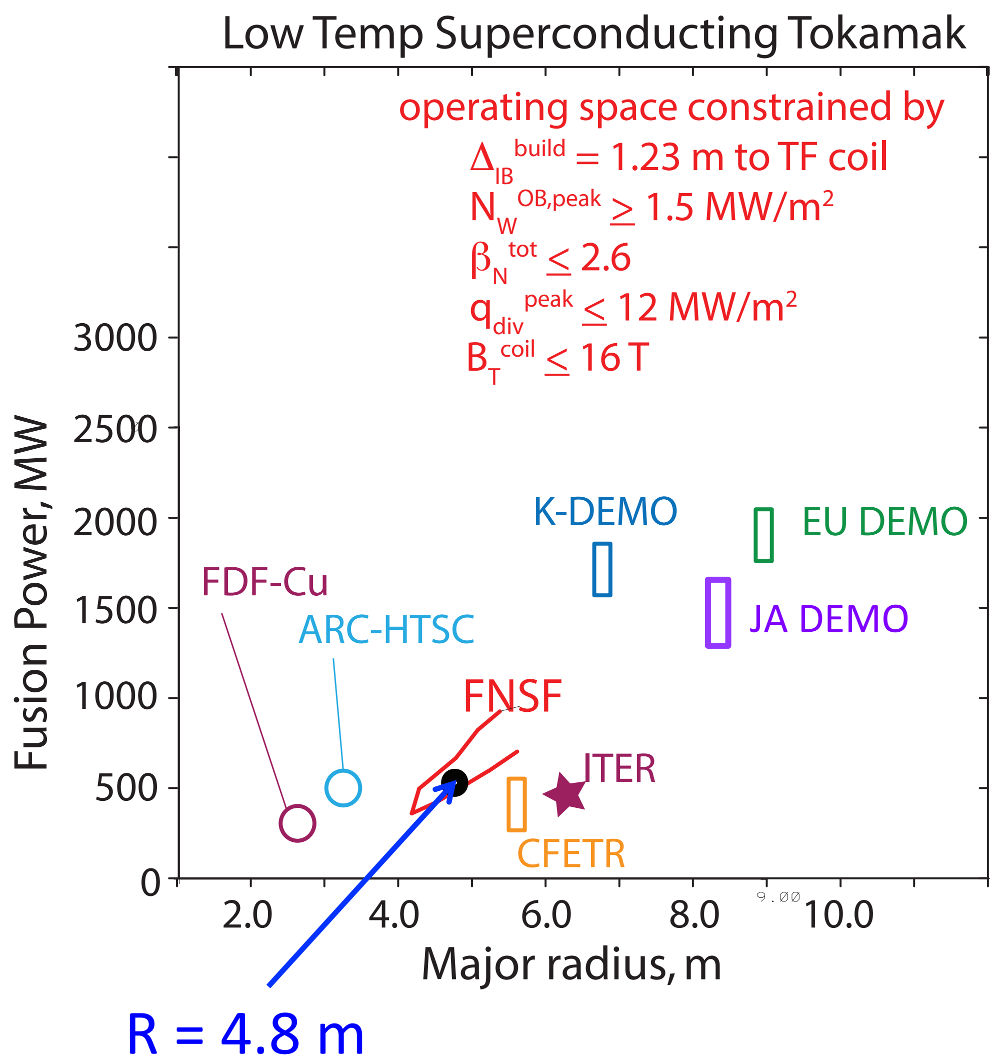
A = 4	
R, m	4.80
κ_X, δ_X	2.2, 0.63
I_P, MA	7.87
B_T, B_T^{coil}, T	7.5, 15.85
$\langle j_{TF} \rangle$, MA/m^2	15 MA/m^2
β_N^{th}, β_N^{fast}	2.2, 0.23
q_{95}	6.0
H_{98}	0.99
f_{BS}	0.52
Z_{eff}	2.43
n/n_{Gr}	0.90
$n(0)/\langle n \rangle$, $T(0)/\langle T \rangle$	1.4, 2.6
P_{fusion}, $P_{rad,core}$, $P_{rad,div}$, P_{aux}, MW	517, 60, 160, 130
Q, Q_{engr}	4.0, 0.86
η_{CD}, $A\text{-}m^2/W$	0.2 (assumed)
$\langle N_w \rangle$, N_w^{peak}, MW/m^2	1.18, 1.77
q_{div}^{peak} (OB, IB), MW/m^2	10.7, 3.9

The FNSF Would Be Smaller Than a DEMO Plant, to Reduce Cost and Facilitate a Break-in Program

Configuration for the FNSF study:

- Conventional aspect ratio (= 4)
- Conservative tokamak physics basis with extensions to higher performance (β_N < 2.6)
- 100% non-inductive plasma current
- Low temperature superconducting coils, advanced Nb_3Sn
- Helium cooling in blanket, shield, divertor, and vacuum vessel
- Focus on DCLL blanket concept with backup concepts (HCLL, HCCB/PB)
- Net electricity is NOT a facility target, but electricity generation can be demonstrated

These devices do not all use the same level of assumptions/goals as the FNSF



What is the actual maximum heat flux tolerable in the divertor, what can be developed from engr design and plasma physics optimization

Our present assumption for the peak allowed divertor heat flux is 10 MW/m^2

This represents the maximum capability of the plate jet divertor design….beyond this the thimble jet design is usually required

To achieve this we know that

Engineering design

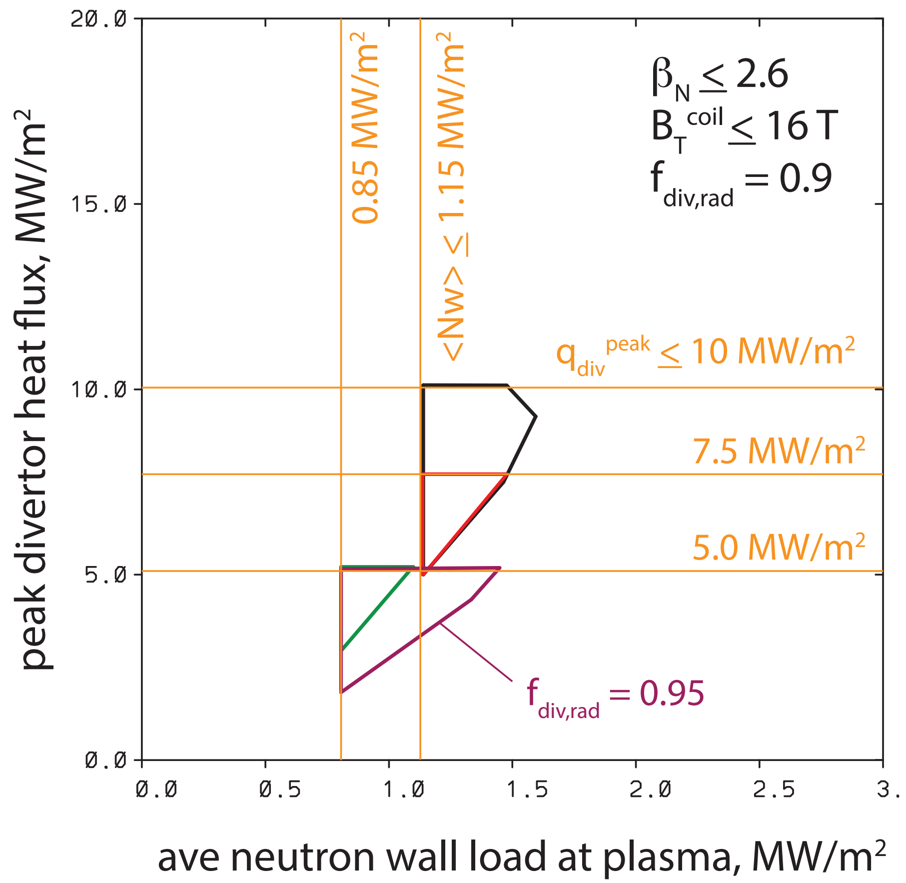
Plasma material interactions

Divertor/SOL plasma physics

are all required to reach a solution

What if we can not reach the 10 MW/m^2 that we desire…..

Taking a radiating divertor as the reference for FNSF



R = 4.8 m

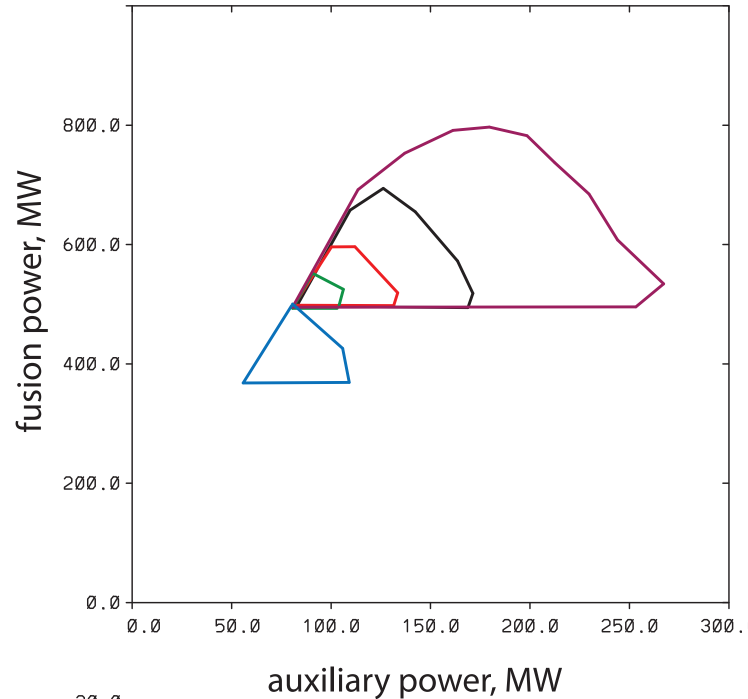
What is the reliably achievable radiated power fraction in the divertor?

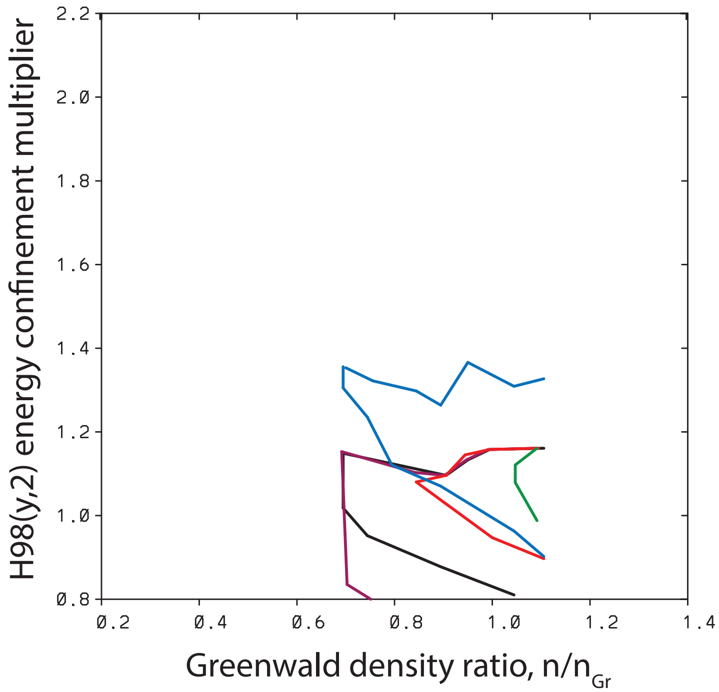
We assume a radiated power fraction $P_{div,rad}/P_{SOL}$ of 90% in systems analysis

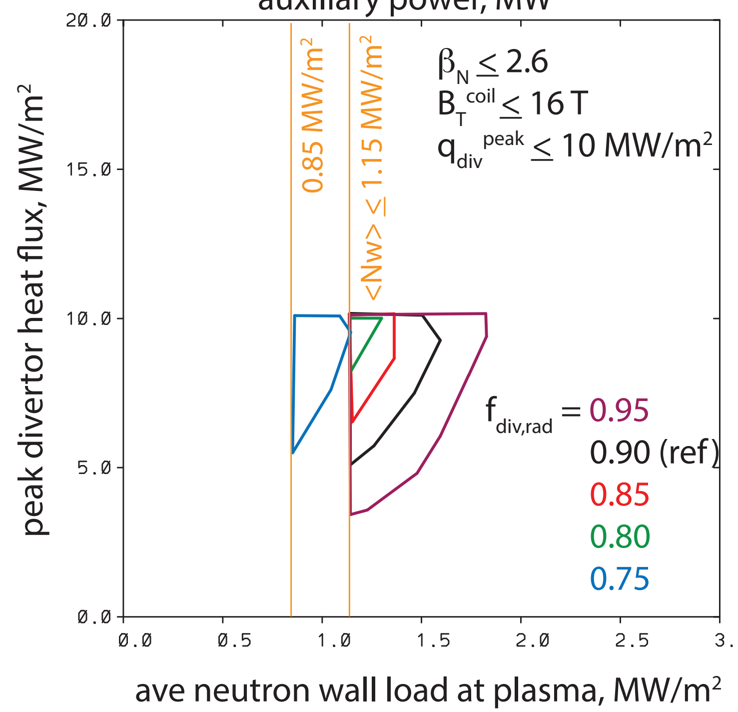
2D SOL analysis indicates:

Fully detached radiates ~ 100%

ITER-like divertor radiates ~ 75%







The Program on the FNSF Defines It, Not Its Operating Point

	He/H	DD	DT	DT	DT	DT	DT	Power Plant
Yrs	1.5	2-3	2.5	4.2	4.2	5.9	5.9	40 FPY
Neutron wall load, MW/m^2			1.78	1.78	1.78	1.78	1.78	2.25
Plasma on-time, % /year	10-25	10-50	15	25	35	35	35	85
Plasma pulse length, days		Up to 10	1	2	5	10	10	310
Plasma duty cycle, %		33-95	33	67	91	95	95	100
Neutron damage, dpa			7	19	26	37	37 or 74	100-150
blanket	RAFM 400C	RAFM 400C	RAFM 400C	RAFM ODS 450C	RAFM ODS (NS) 500C	RAFM ODS (NS) 5500C	RAFM ODS (NS) 5500C	

Plasma pulse extension
1 hr to 10 days

23 years of DT operations, 8.4 years of neutron exposure

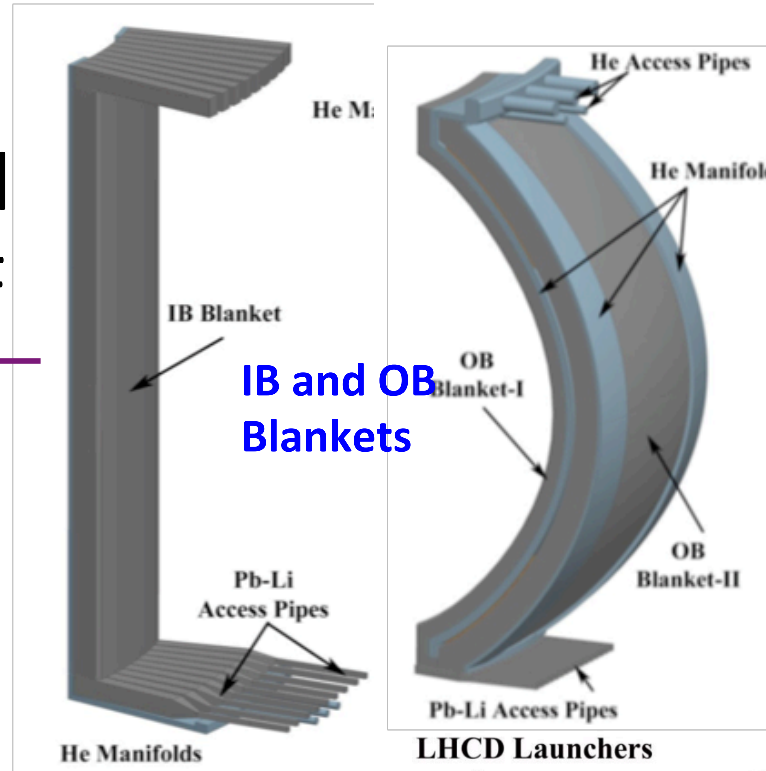
Higher N_W, faster plasma pulse development, and efficient maintenance/plasma operation distribution can reduce years

The FNSF Program is being studied further to address a range of issues

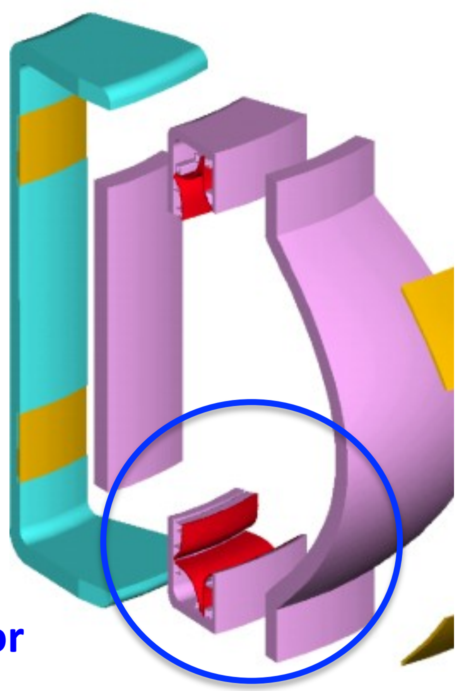
1) Can the DD Phase provide enough discharge time ranging from 1hr to 10 day pulse lengths, utilize higher diagnostic coverage
2) Provide higher or lower neutron wall loads would result in short or longer years to reach a dpa level
3) Low operating temperatures of the early DT phases require BOTH faster coolant flow and lower fusion power, longer time to reach dpa target
4) Desire to reach longest plasma durations early in the program, rather than spend the whole program progressively extending the plasma pulse length…still arriving at ~7 dpa at the end of the phase
5) Maintenance times associated with specific tasks (planned maintenance)
   Ex-vessel inspection
   In-vessel inspection
   Minor maintenance ex-vessel
   Minor maintenance in-vessel
   Major in-vessel maintenance (sector removal, 16 sector removal)
   → This should lead to a reduction in total operations time

Components in fusion core would be evolved and tested in the FNSF

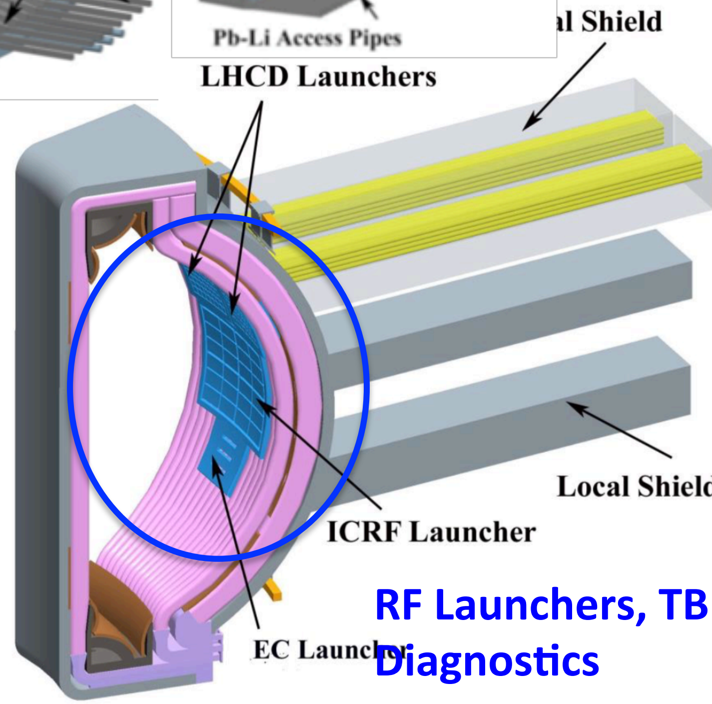
We have concentrated on the blankets, but there are others that may have a testing sequence…..materials, temperatures, design, etc.



IB and OB Blankets



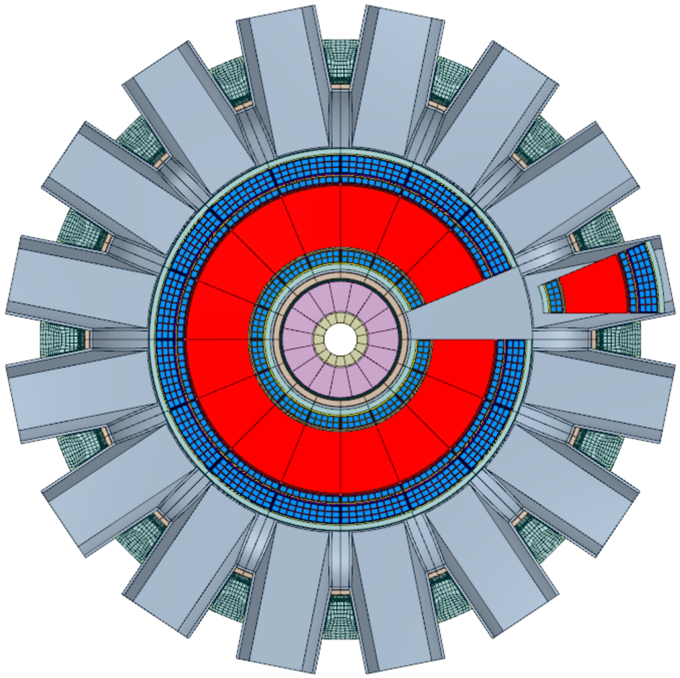
Divertor



RF Launchers, TBMs, Diagnostics

Blanket Testing

DCLL 400C RAFM (some are taken for autopsy)
DCLL 400C RAFM/ **H&CD**
DCLL 450C RAFM (higher T)
DCLL 450C RAFM GII **(next phase T and FS)**
DCLL 400C RAFM/ **MTM**
DCLL 400C RAFM/ **TBM-HCLL**
DCLL 400C RAFM/ **TBM-HCCB(PB)**
DCLL 400C RAFM/ Diagnostic



	Phase X – part 1	Phase X – part 2	Phase X – part 3	….
S-1	DCLL 400C RAFM	DCLL 400C RAFM – R1	DCLL 400C RAFM – R1	
S-2	DCLL 400C RAFM	DCLL 400C RAFM	DCLL 400C RAFM – R2	
S-3-H/CD*	DCLL 400C RAFM – LH/EC	DCLL 400C RAFM – LH/EC	DCLL 400C RAFM – LH/EC	
S-4-MTM*	DCLL 400C RAFM	DCLL 400C RAFM	DCLL 400C RAFM	
S-5	DCLL 400C RAFM	DCLL 400C RAFM	DCLL 400C RAFM	
S-6	DCLL 400C RAFM	DCLL 400C RAFM	DCLL 400C RAFM – R2	
S-7	DCLL 400C RAFM	DCLL 400C RAFM	DCLL 400C RAFM	
S-8	DCLL 400C RAFM	DCLL 400C RAFM – R1	DCLL 400C RAFM – R1	
S-9	DCLL 450C RAFM GenII	DCLL 450C RAFM GenII	DCLL 450C RAFM GenII	
S-10-H/CD	DCLL 400C RAFM – NB	DCLL 400C RAFM – NB	DCLL 400C RAFM – NB	
S-11-H/CD	DCLL 400C RAFM - IC	DCLL 400C RAFM - IC	DCLL 400C RAFM - IC	
S-12	DCLL 450C RAFM	DCLL 450C RAFM	DCLL 450C RAFM	
S-13-H/CD	DCLL 400C RAFM - NB	DCLL 400C RAFM - NB	DCLL 400C RAFM – NB	
S-14	DCLL 450C RAFM GenII	DCLL 450C RAFM GenII	DCLL 450C RAFM GenII	
S-15-TBM/HCCB	DCLL 400C RAFM / HCCB	DCLL 400C RAFM / HCCB	DCLL 400C RAFM / HCCB	
S-16-TBM/HCLL*	DCLL 400C RAFM / HCLL	DCLL 400C RAFM / HCLL	HCLL 400C RAFM / HCLL	

Divertor Testing, must fit into the allocated envelope

What will be the preferred W or divertor material?

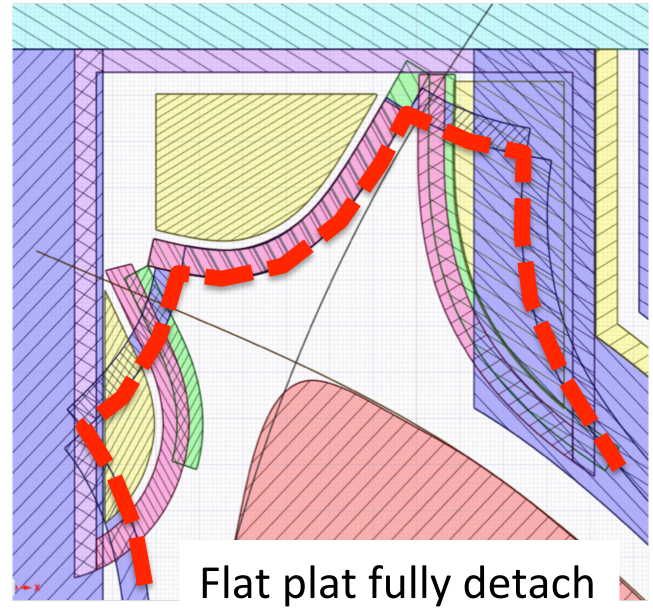
- W or W-alloy
- W/X composites
- W_f/W_m composites
- ???

Will there be variants like RAFM?

Structure & armor

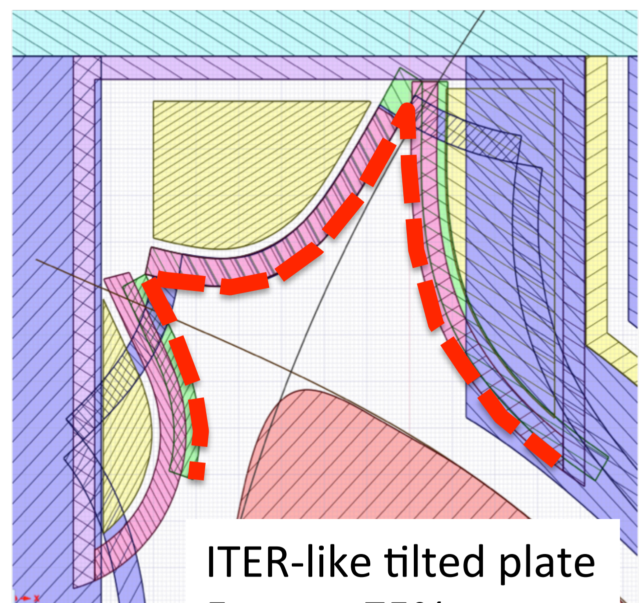
Magnetic geometries

Temperature ranges



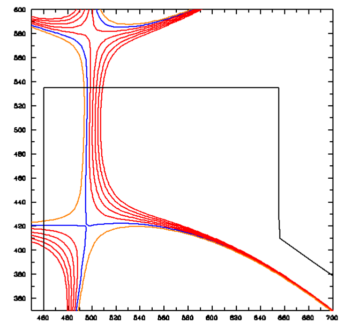
Flat plat fully detach

$F_{div,rad}$ ~ 100%



ITER-like tilted plate

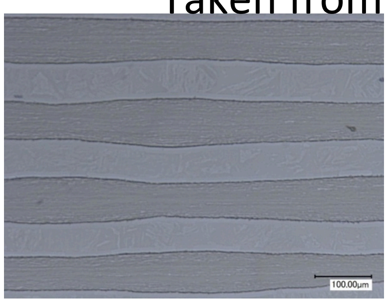
$F_{div,rad}$ ~ 75%



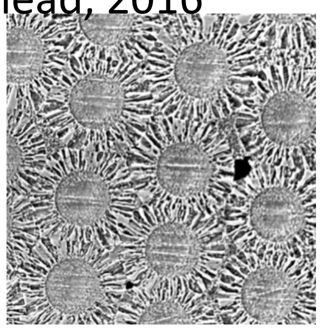
X-divertor, KDEMO

Covelle, Univ Texas

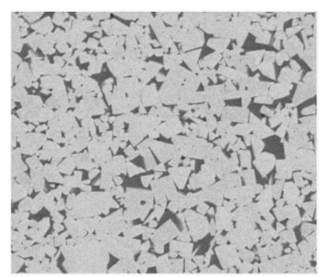
Taken from Snead, 2016



W/RAF laminate (Garrison)



FZJ

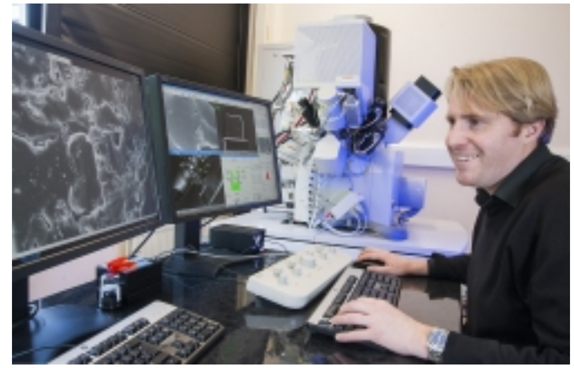


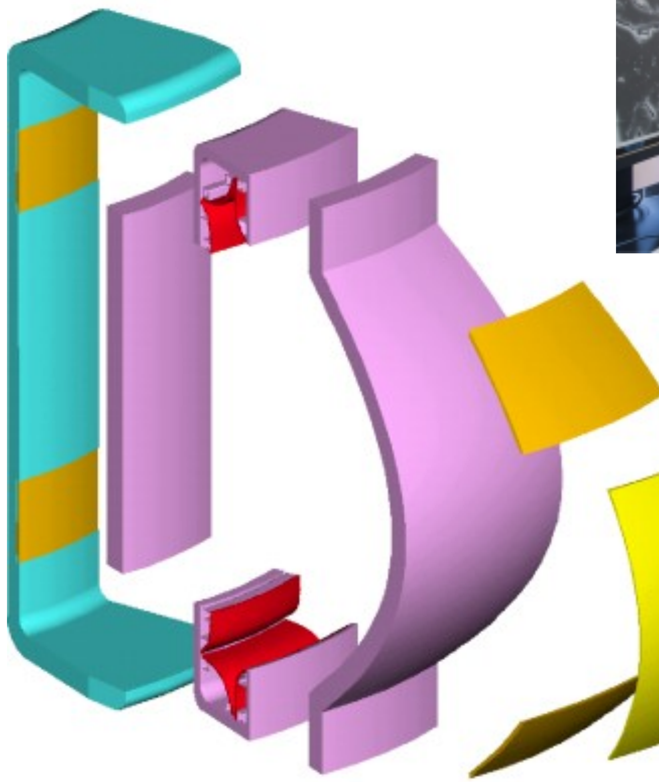
WC in Fe matrix (Álvarez et al., 2015)

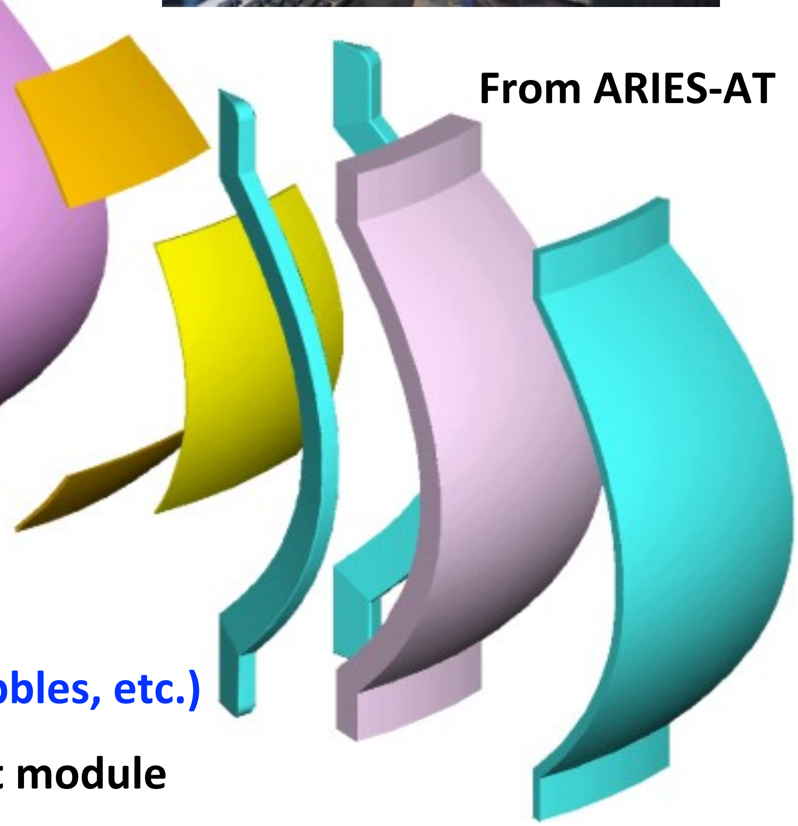
What do we do with the Sectors: Blankets, Divertors, Launchers in the Hot Cells?

Inspect
Decontaminate (clean off)
Inspect
Dismantle
Inspect
Examine untreated surfaces
Examine mounts/connectors
Cut samples
- FW
- Side wall
- Grid plates
- Mounting hardware
- SR
- Div armor
- Div structure
- FCI
- W stabilizer
- ……

Material examinations (PIE, mech prop tests, He bubbles, etc.)







From ARIES-AT

Also examine the test specimens in the material test module

The Hot Cell – a critical aspect of the FNSF

The performance of materials in the components of the fusion core is not accessible prior to the FNSF

What is accessible: 1) DONES/IFMIF or similar fusion relevant neutron exposure, 2) fission neutron, ion and doping approaches testing, 3) non-nuclear highly integrated component testing.....would we proceed if #1 was missing?

The in-service conditions include more than neutrons and temperature (like IFMIF)

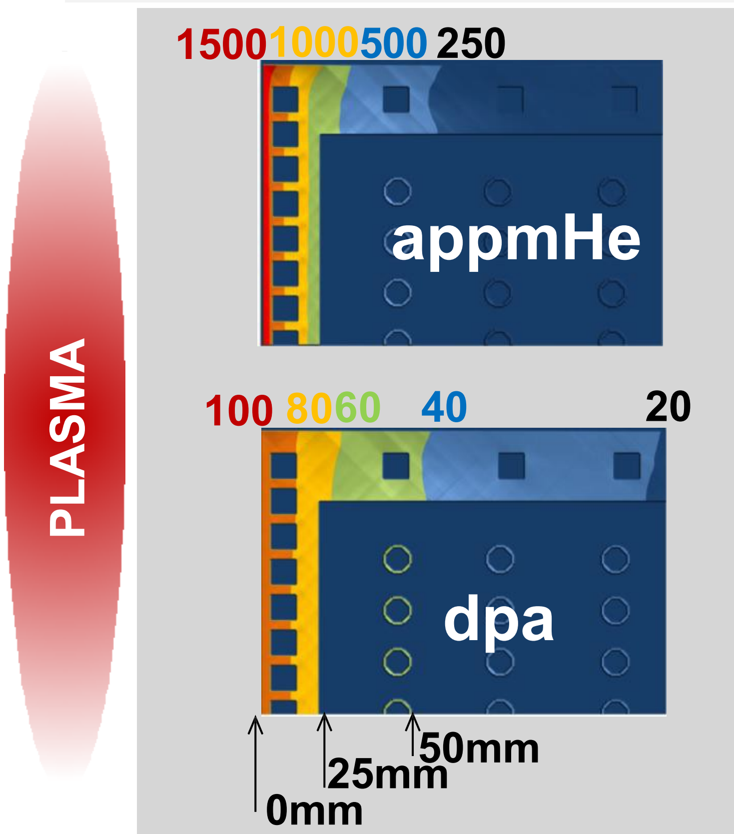
Materials are under stress (pressure)
Materials have hydrogen in their matrix, tritium and transmutation hydrogen
Materials have contact with liquid metal in B-field (MHD, other flow properties, chemical reactions)
Materials see strong neutron damage, and He production gradients into material
Materials see heating, temperature and stress gradients

The sectors of the fusion core will be removed to determine property changes, surface changes, microstructure changes.....*this is done in the Hot Cell, and will produce the database upon which DEMO can be based*

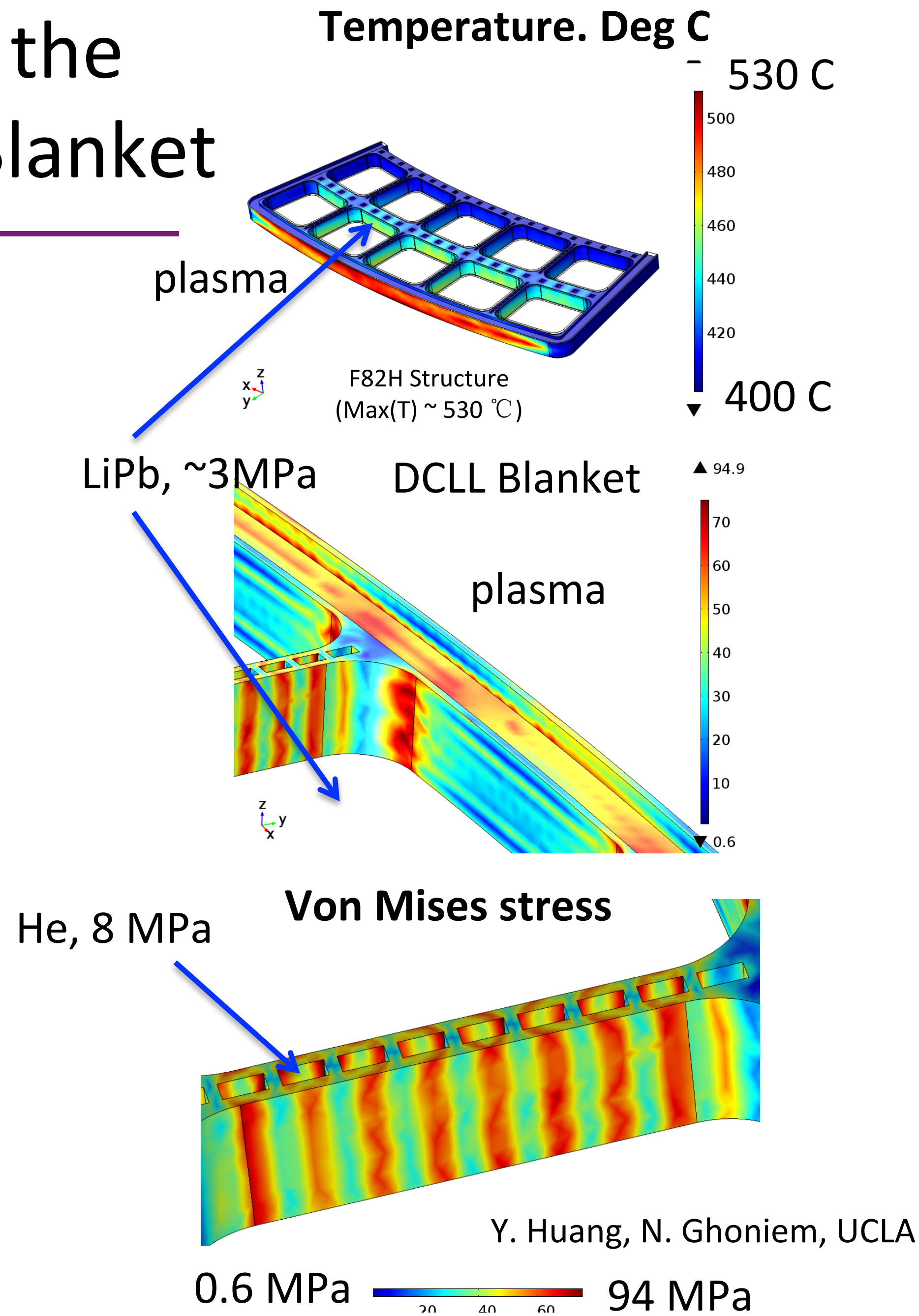
we need to make decisions about the materials/components behavior for next phases based on this information in the FNSF itself.....turnaround must be fast, materials will be HOT (radioactive)

The Complex Variations of the Service Environment in a Blanket

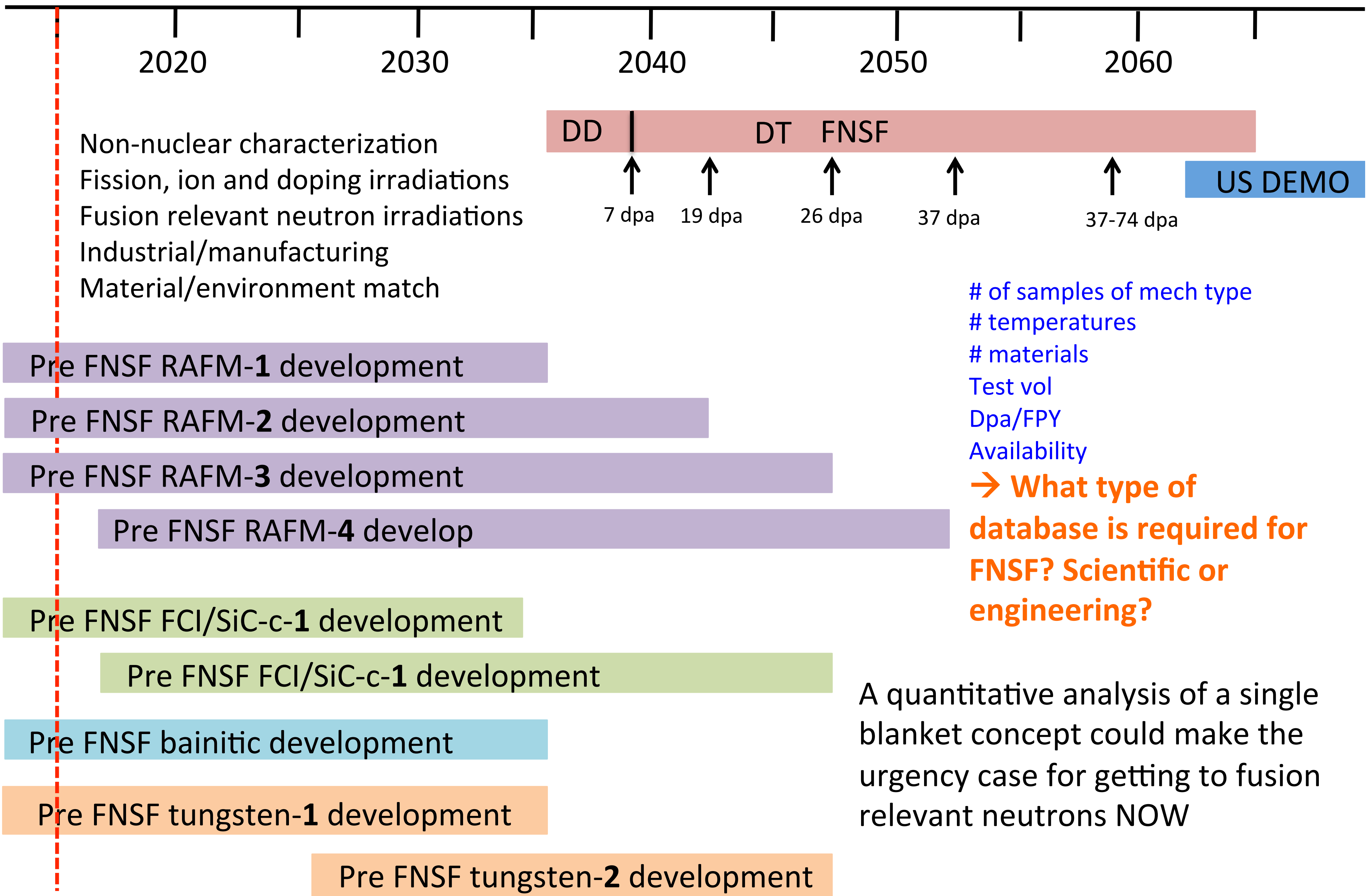
Helium production (appm) for 100 dpa at plasma facing side



H. Tanigawa, E.Wakai 2012



Pre-FNSF: Fusion Nuclear Materials Science, how do we see providing tested materials in the form of components to the FNSF

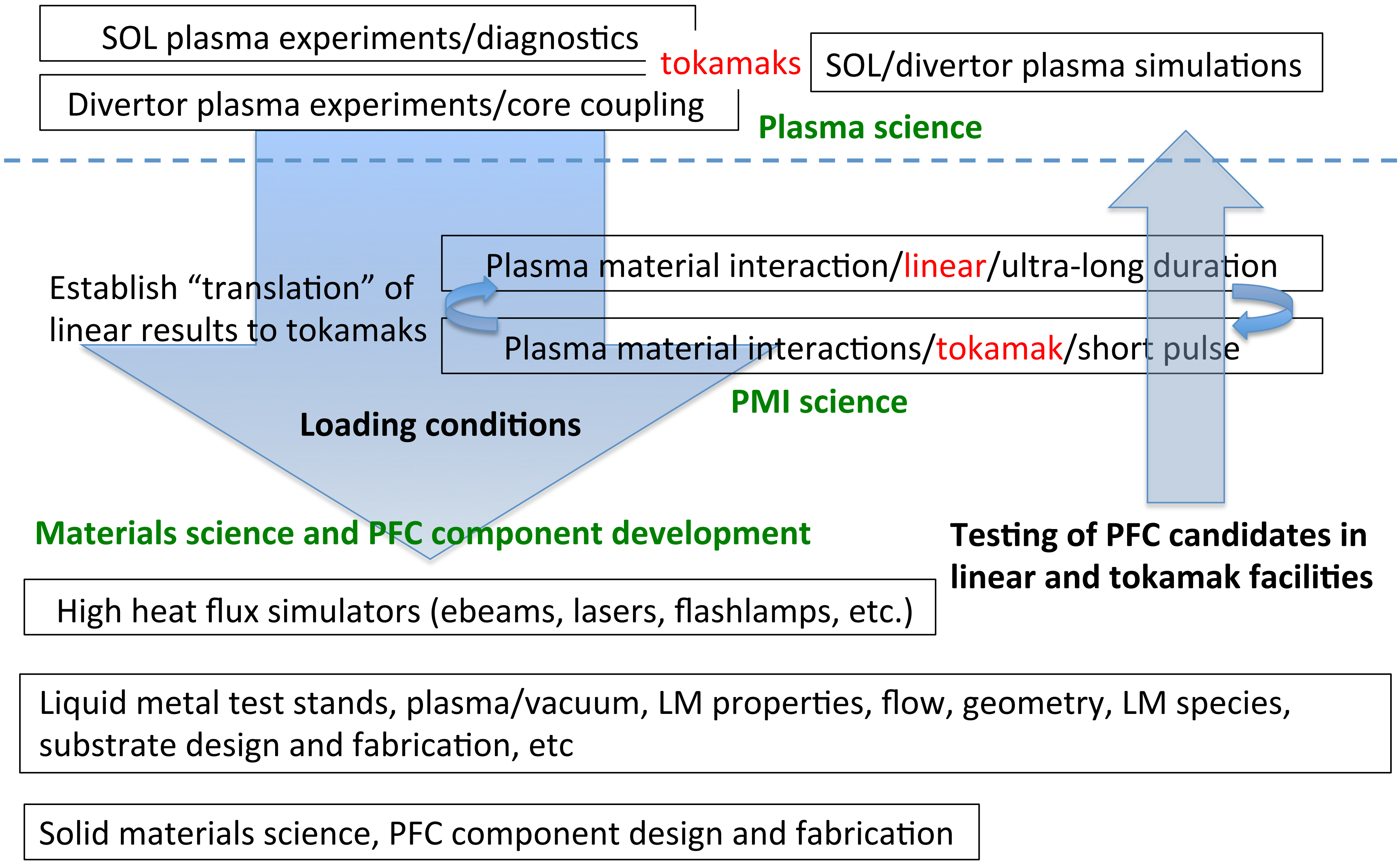


# of samples of mech type
temperatures
materials
Test vol
Dpa/FPY
Availability

→ What type of database is required for FNSF? Scientific or engineering?

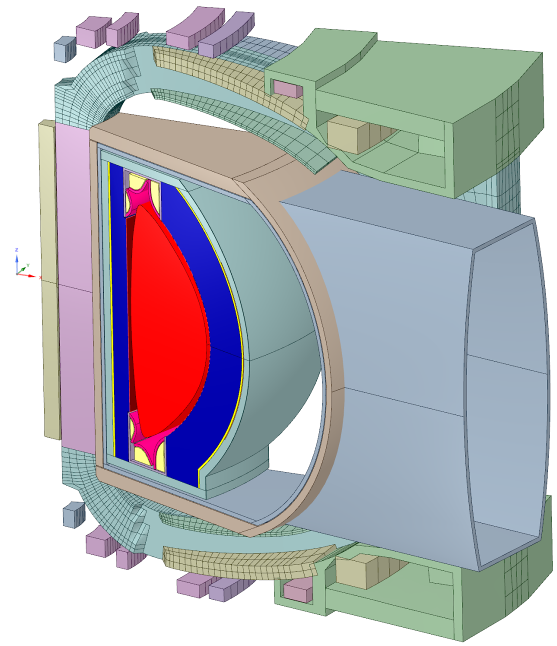
A quantitative analysis of a single blanket concept could make the urgency case for getting to fusion relevant neutrons NOW

Starting point for organizing the pre-FNSF: PFC/ PMI area from the FNSF perspective



The FNSF is the Critical First Step into the Fusion Nuclear Regime and Fusion Power Production

The complex step of combining the fusion neutron, multi-factor environment, and integrated components requires the appropriate technical platform → *this demands a smaller intermediate device step*



Explore the component material responses to the complete/correct FUSION environment

Establish the ultra-long plasma pulse length with associated plasma material interactions

Establish the credibility of generating tritium, predicting/controlling its movement and retention, and minimizing its losses plantwide

Strongly advancing most features toward a fusion power plant, with significant fusion relevance imposed in our technical choices

Understand the demands on the facility (hot cell, maintenance, diagnostics) to provide the needed measurement, inspection, access, and feedback on plasma and fusion core operations

TUESDAY 1:15 PM

L. El-Guebaly, Overview of Nuclear Analysis for US Next Step Facility
J. Blanchard, Effects of ELMs and Disruptions on FNSF Plasma Facing Components
L. Garrison, The Influence of Microstructure on Deuterium Retention in Polycrystalline Tungsten…**poster Monday**

Poster Tuesday, Y. Zhai, Modeling Imperfect Nb3Sn SC Wire Under Transverse Loading

WEDNESDAY 8:50 AM

P. Titus, IN-Plane and Out-of-Plane TF Coil Support for the US FNSF Reactor
A. Davis, Overview of State-of-the-Art Neutronics Code Development…**poster Monday**

WEDNESDAY 10:30 AM

P. Humrickhouse, Safety in the Fusion Nuclear Science Facility

THURSDAY 10:15 AM

Y. Katoh, Progress in US/JA PHENIX Project for the Technical Assessment of Plasma Facing Components for DEMO Reactor