The Fusion Nuclear Science Facility (FNSF), what is it and what challenges does it present?

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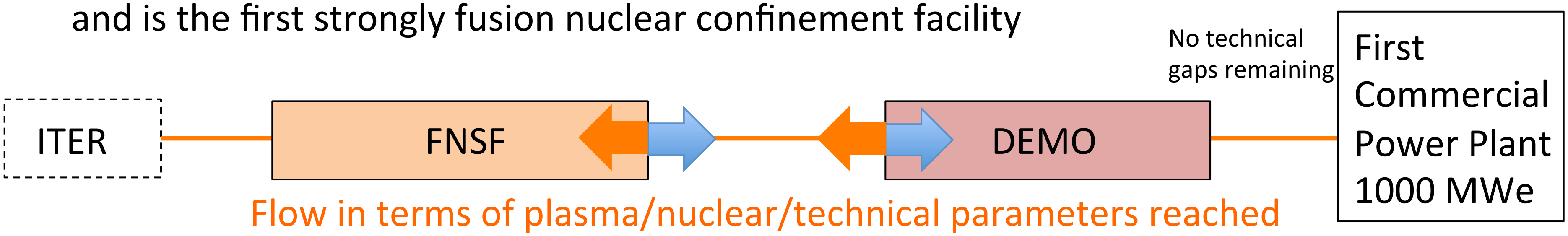
VLT Highlights, August 27, 2014

The Context for the FNSF within Fusion Development

The Fusion Nuclear Science Facility (FNSF) is part of the US fusion development view, and is the first strongly fusion nuclear confinement facility



ITER

FNSF

DEMO

No technical gaps remaining

First
Commercial
Power Plant
1000 MWe

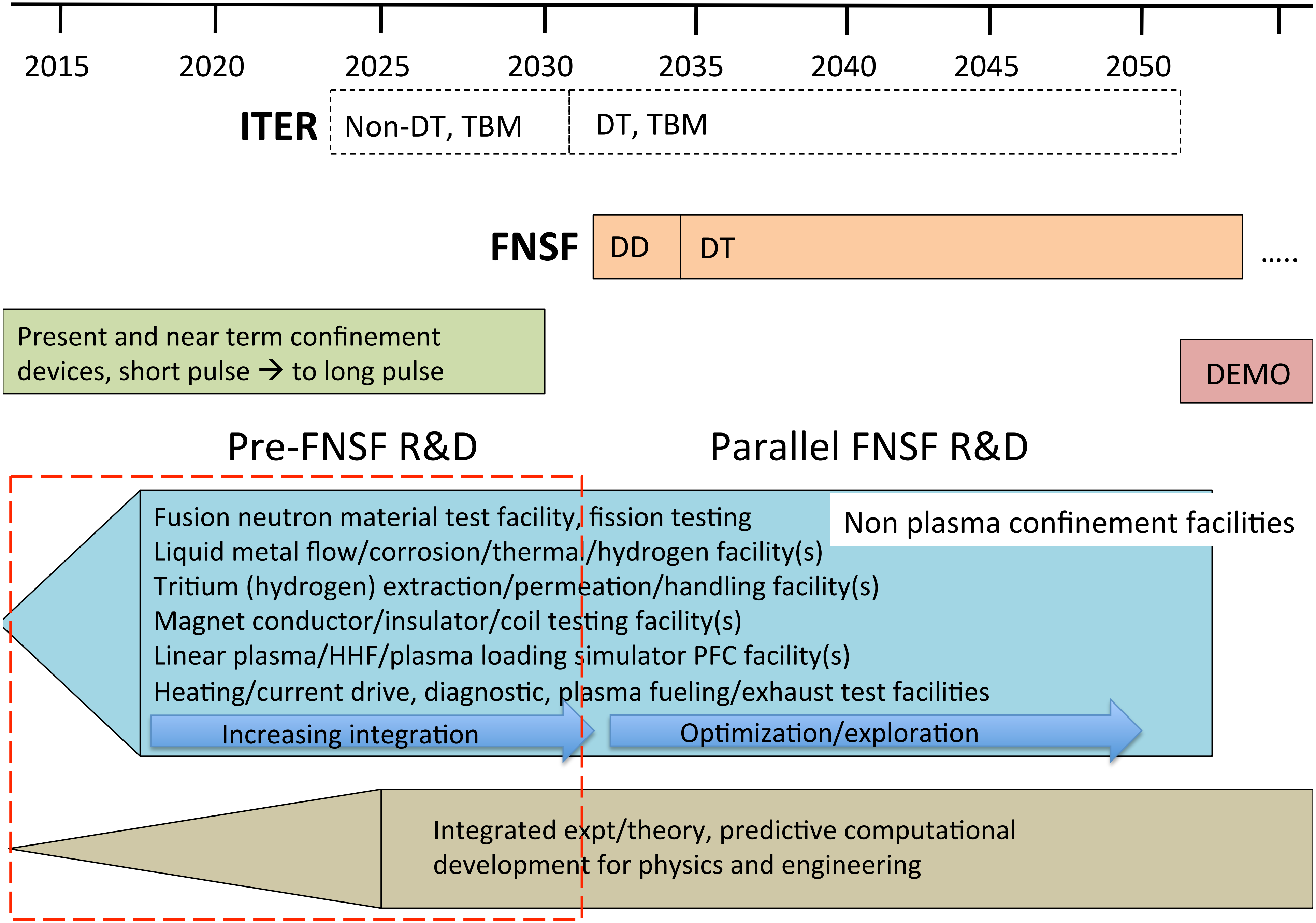
Flow in terms of plasma/nuclear/technical parameters reached

The FNSF is an intermediate step to accommodate the extreme fusion nuclear environment and the complex integration of components and their environment, as well as the nuclear science and plasma physics

The FNSF will operate with

- a very long pulse fusion neutron producing plasma and very high duty cycles,
- with completely integrated components first wall, blanket, shield, vacuum vessel, divertor, etc.,
- in the fully integrated environment (simultaneous) of fusion neutrons, volumetric and surface heating, hydrogen in materials, strong magnetic fields, pressure/stresses, high temperatures, vacuum interface with plasma, flowing breeder with material interactions, and PMI, all with significant gradients

Facilities and Time-Scales



ITER

Non-DT, TBM

DT, TBM

FNSF

DD

DT

…..

Present and near term confinement devices, short pulse → to long pulse

DEMO

Pre-FNSF R&D

Parallel FNSF R&D

Non plasma confinement facilities

Fusion neutron material test facility, fission testing
Liquid metal flow/corrosion/thermal/hydrogen facility(s)
Tritium (hydrogen) extraction/permeation/handling facility(s)
Magnet conductor/insulator/coil testing facility(s)
Linear plasma/HHF/plasma loading simulator PFC facility(s)
Heating/current drive, diagnostic, plasma fueling/exhaust test facilities

Increasing integration

Optimization/exploration

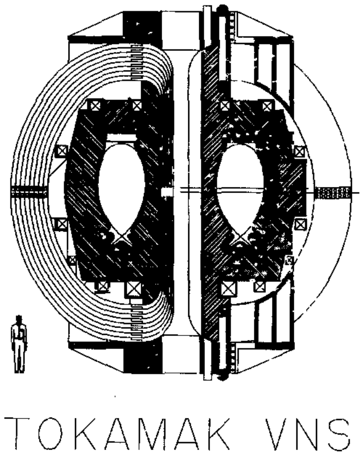
Integrated expt/theory, predictive computational development for physics and engineering

A number of proposals have been made for an FNSF (or similar) type device

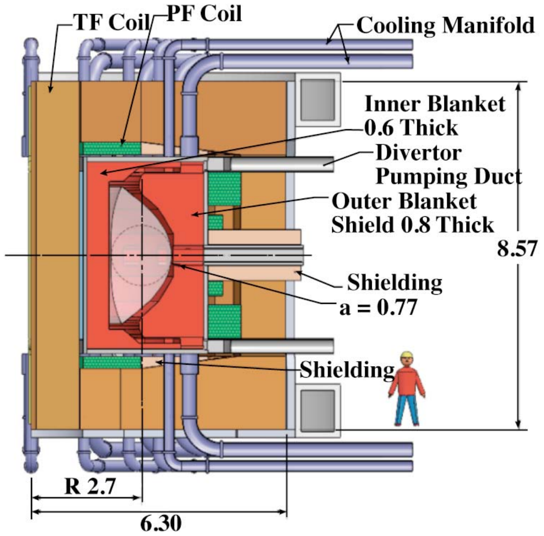
The FNSF can have a small mission scope, a large mission scope, or anywhere in between

Long term relevance is important when you only have 2 devices to a power plant

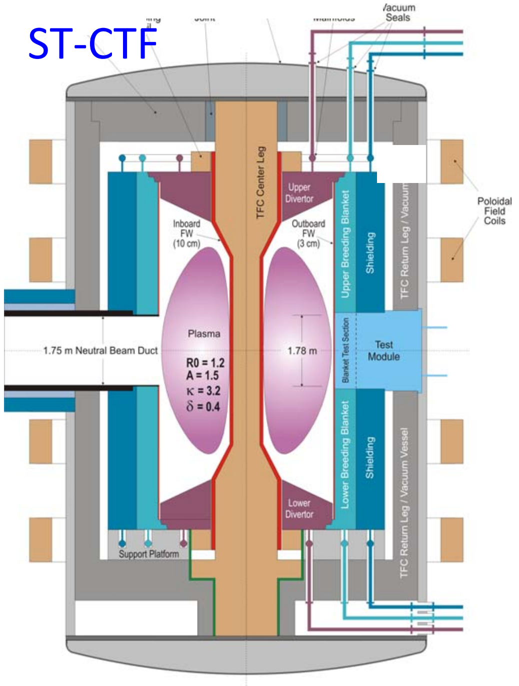
Volumetric neutron source



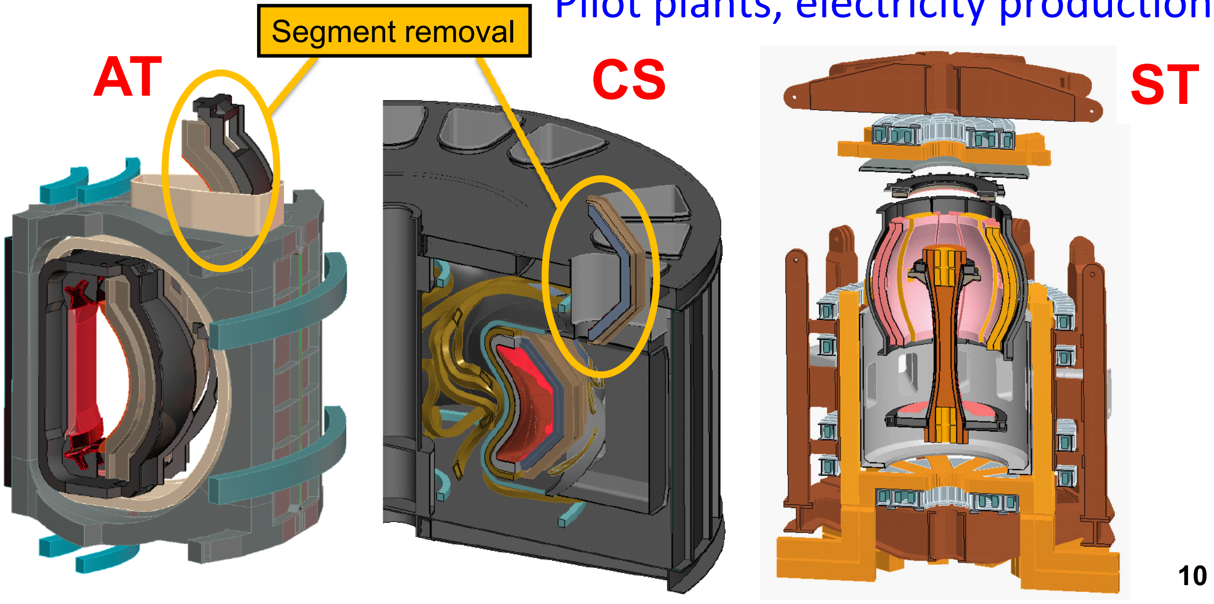
Fusion Development Facility



ST-CTF



Pilot plants, electricity production



The FNSF is VERY different from ITER in a number of ways

- The neutron exposure of materials is ~ 30x higher
- The materials are all different, except for tungsten
- The structures surrounding the plasma will operate at ≥ 3x higher temperatures
- Tritium is bred in the FNSF, not purchased like ITER
- The plasma is "on" making neutrons for 7x longer per year, and plasma pulses are 1000x longer
- Maintenance of the fusion core is few-large-pieces, not by blanket module….and there are others

	ITER	**FNSF**	**Power Plant, 1000 MW_e**
Neutron exposure life of plant $MW\text{-}yr/m^2$, dpa	0.3, 3.0	8.5, 85	60-98, 600-980
Materials	316SS, CuCrZr, Be, W, H_2O, SS304, SS430	RAFM, PbLi, He, SiC-c, Borated-RAFM, W, bainitic steel	RAFM, PbLi, He, SiC-c, Borated-RAFM, W, bainitic steel
Operating temperature, ^oC	100-150	400-600	600-700
Tritium breeding ratio	~ 0.003	~ 1.0	1.05
Plasma on-time in a year, %	5	~10-35	85
Plasma pulse duration, s	500-3000	~10^6 (2 weeks)	$2.7\text{x}10^7$ (10.5 months)

VERY long plasma durations are needed to show fusion power generation is credible

FNSF needs long neutron producing plasma durations to provide the neutron exposure of all fusion core components (first wall, blanket, divertor, shield, launchers, ….out to the VV and on to magnets), and core processes like tritium migration, corrosion, …which each have specific time-scales

The major PFC/PMI long pulse issues of erosion/re-deposition/migration, dust production, and tritium retention will be of great importance here

As we see it now, the FNSF will advance the plasma duration and plasma pulse duty cycle as its primary way of increasing the neutron exposure (fluence = flux x time)

A FNSF program schedule

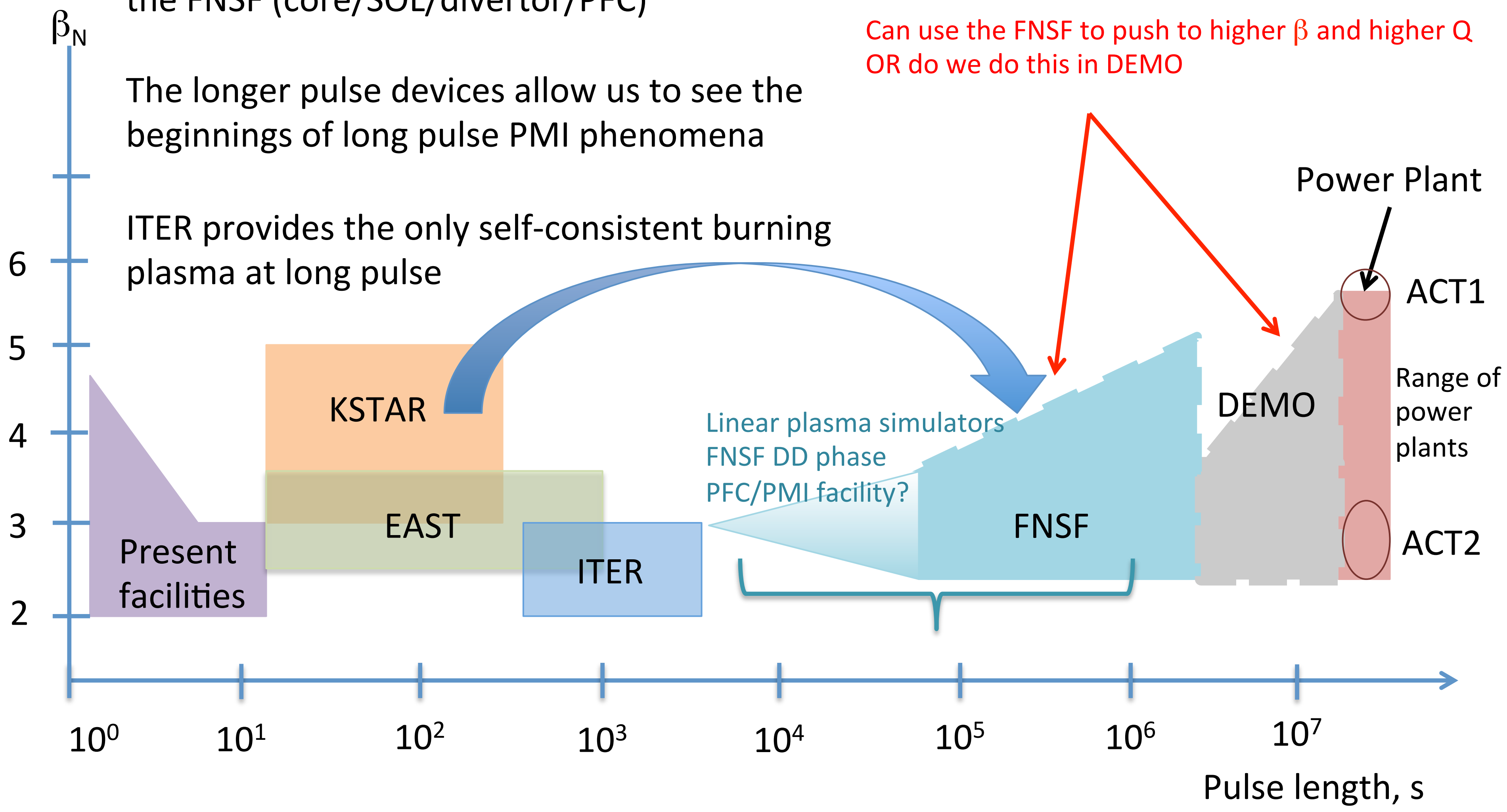
	He/H		**DD**		**DT**		**DT**		**DT**		**DT**
Phase time, yr	1-2		2-3		3		5		5		7
Plasma on-time, %	10-25		10-50		10-15		25		35		35
Plasma duty cycle			0.33-0.95		0.33		0.67		0.91		0.95
Plasma pulse/dwell, days			1/2-10/0.5		1/2		2/1		5/0.5		10/0.5
Peak fluence, MW-yr/m^2 (dpa)					0.45-0.68 (4.5-6.8)		1.88 (18.8)		2.63 (26.3)		3.68 (36.8)

The demands on plasma pulse length and duty cycle are tremendous

Present facilities and long pulse devices provide the basis for potential scenarios for the FNSF (core/SOL/divertor/PFC)

The longer pulse devices allow us to see the beginnings of long pulse PMI phenomena

ITER provides the only self-consistent burning plasma at long pulse



Can use the FNSF to push to higher β and higher Q OR do we do this in DEMO

FNSF Mission and Metrics - Tables

Missions Identified: (shown as ITER – FNSF – DEMO – Power Plant)

- Fusion neutron exposure (fluence and dpa)
- Materials (structural, functional, coolants, breeders, shield…)
- Operating temperature/other environmental variables
- Tritium breeding
- Tritium behavior, control, inventories, accounting
- Long plasma durations at require performance
- Plasma enabling technologies
- Power plant relevant subsystems at high efficiency
- Availability, maintenance, inspectability, reliability advances toward DEMO and power plants

Each mission contains a table with quantifiable metrics (except for the last one)…still developing these

Expect to use ARIES-ACT2 as power plant example

	ITER	FNSF	DEMO	Power Plant ACT1/ACT2
Life of plant peak FW fluence, MW-yr/m^2 (life of plant)	0.3	10 (6 FPY)	41 (16+ FPY)	60-97.5 (40 FPY)
Peak FW fluence to replace blanket, MW-yr/m^2 (dpa) (replacements)	0.3 (3) (1)	0.7, 1.9, 2.6, 3.7 (7, 19, 27, 37) (4)	3.7-15 (50-150) (4)	15-20 (150-200) (4-6)
Peak FW neutron wall load, MW/m^2 (average)	0.76 (0.56)	1.5 (1.0)	2.5 (1.67)	2.0-3.25 (1.33-2.15)
Peak Structural Ring damage, dpa (appm He)				

	ITER	FNSF	DEMO	Power Plant ACT1/ACT2
Plasma on-time per year	5%			85%
Plasma pulse duration, s	500-3000			2.7x10^7
Plasma duty cycle	25%			100%
β_N H_{98} / q_{95}	0.6			0.4-2.1
Q	5-10			25-48
f_{BS}	0.25-0.5			0.77-0.91
$P_{core,rad}/(P_{alpha} + P_{aux})$	0.27			0.28-0.46
$P_{div,rad}/P_{SOL}$	0.7			0.9

	ITER	FNSF	DEMO	Power Plant ACT1/ACT2
$P_{H/CD}^{total}$, MW	73			45-105
H/CD injection duration, s	500-3000			2.7x10^7
Source operating lifetime, years				
Launcher operating lifetime, years				

FNSF Program - Table

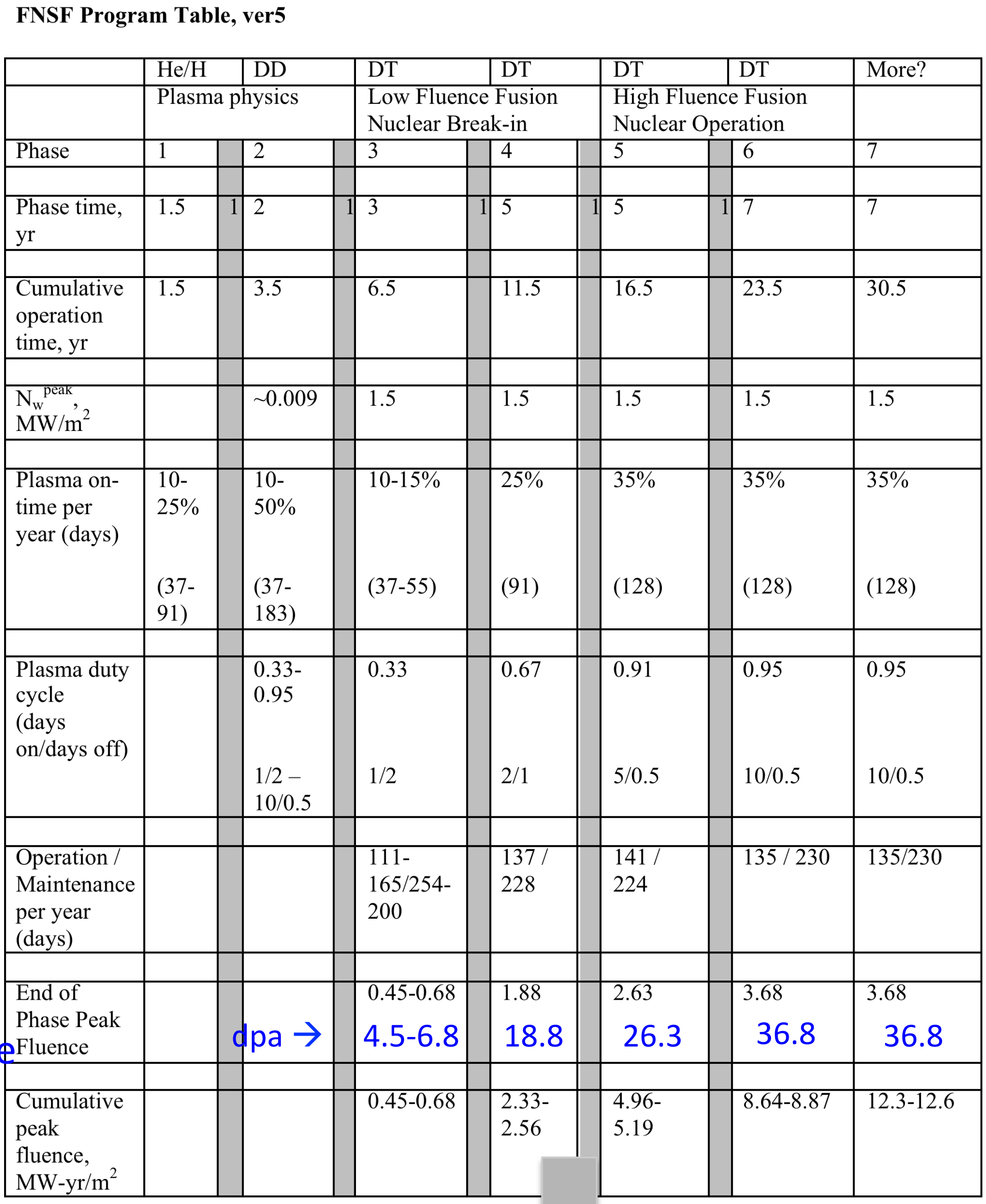
We have a tentative phased program on the FNSF establishing

- Time frames
- Neutron exposure, dpa
- Plasma ops/maintenance
- Plasma on-time/duty cycle
- Plasma pulse extension in DD phase
- Added another phase #7 as either increased exposure or as a way to absorb unanticipated events

Phase time, yr

N_W^{peak}

Peak Fluence



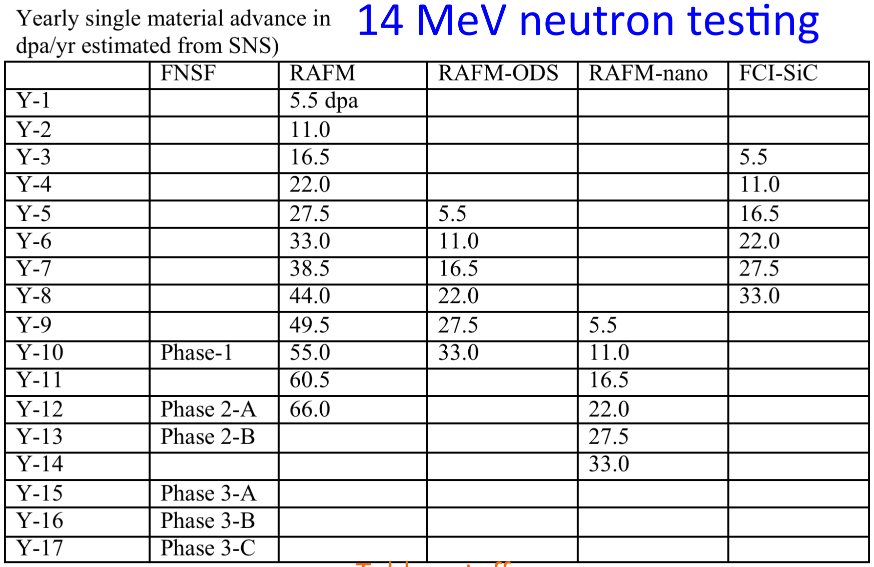
FNSF Program Table, ver5

	He/H		DD		DT		DT		DT		DT	More?
	Plasma physics				Low Fluence Fusion Nuclear Break-in				High Fluence Fusion Nuclear Operation			
Phase	1		2		3		4		5		6	7
Phase time, yr	1.5	1	2	1	3	1	5	1	5	1	7	7
Cumulative operation time, yr	1.5		3.5		6.5		11.5		16.5		23.5	30.5
N_w^{peak}, MW/m^2			~0.009		1.5		1.5		1.5		1.5	1.5
Plasma on-time per year (days)	10-25% (37-91)		10-50% (37-183)		10-15% (37-55)		25% (91)		35% (128)		35% (128)	35% (128)
Plasma duty cycle (days on/days off)			0.33-0.95 1/2 – 10/0.5		0.33 1/2		0.67 2/1		0.91 5/0.5		0.95 10/0.5	0.95 10/0.5
Operation / Maintenance per year (days)					111-165/254-200		137 / 228		141 / 224		135 / 230	135/230
End of Phase Peak Fluence			dpa →		0.45-0.68 4.5-6.8		1.88 18.8		2.63 26.3		3.68 36.8	3.68 36.8
Cumulative peak fluence, MW-yr/m^2					0.45-0.68		2.33-2.56		4.96-5.19		8.64-8.87	12.3-12.6

Table continues

Using the FNSF Program Table – Begin Laying Out the Blanket Testing Plan

14 MeV neutron testing

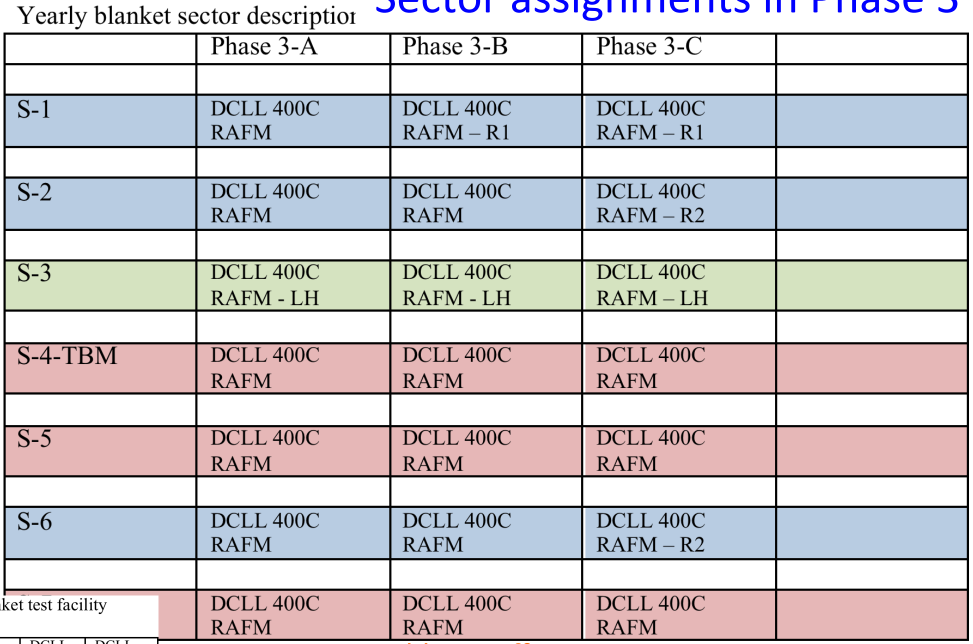


Yearly single material advance in dpa/yr estimated from SNS)

	FNSF	RAFM	RAFM-ODS	RAFM-nano	FCI-SiC
Y-1		5.5 dpa			
Y-2		11.0			
Y-3		16.5			5.5
Y-4		22.0			11.0
Y-5		27.5	5.5		16.5
Y-6		33.0	11.0		22.0
Y-7		38.5	16.5		27.5
Y-8		44.0	22.0		33.0
Y-9		49.5	27.5	5.5	
Y-10	Phase-1	55.0	33.0	11.0	
Y-11		60.5		16.5	
Y-12	Phase 2-A	66.0		22.0	
Y-13	Phase 2-B			27.5	
Y-14				33.0	
Y-15	Phase 3-A				
Y-16	Phase 3-B				
Y-17	Phase 3-C				

Table cutoff

Sector assignments in Phase 3

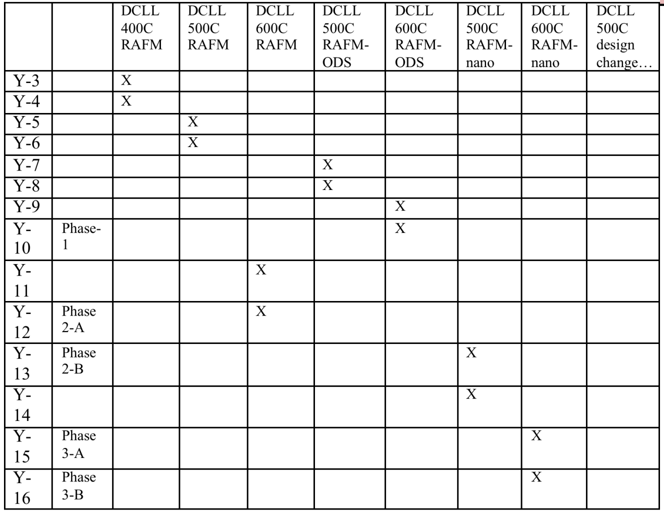


Yearly blanket sector descriptior

	Phase 3-A	Phase 3-B	Phase 3-C	
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	DCLL 400C RAFM - LH	DCLL 400C RAFM - LH	DCLL 400C RAFM – LH	
S-4-TBM	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	
	DCLL 400C RAFM	DCLL 400C RAFM	DCLL 400C RAFM	

Table cutoff

Non-nuclear blanket testing



Yearly non-nuclear integrated blanket test advance in integrated blanket test facility (assume 2 year testing)

		DCLL 400C RAFM	DCLL 500C RAFM	DCLL 600C RAFM	DCLL 500C RAFM-ODS	DCLL 600C RAFM-ODS	DCLL 500C RAFM-nano	DCLL 600C RAFM-nano	DCLL 500C design change…
Y-3		X							
Y-4		X							
Y-5			X						
Y-6			X						
Y-7					X				
Y-8					X				
Y-9						X			
Y-10	Phase-1					X			
Y-11				X					
Y-12	Phase 2-A			X					
Y-13	Phase 2-B						X		
Y-14							X		
Y-15	Phase 3-A							X	
Y-16	Phase 3-B							X	

Table cutoff

Each of 16 sectors has a blanket assignment

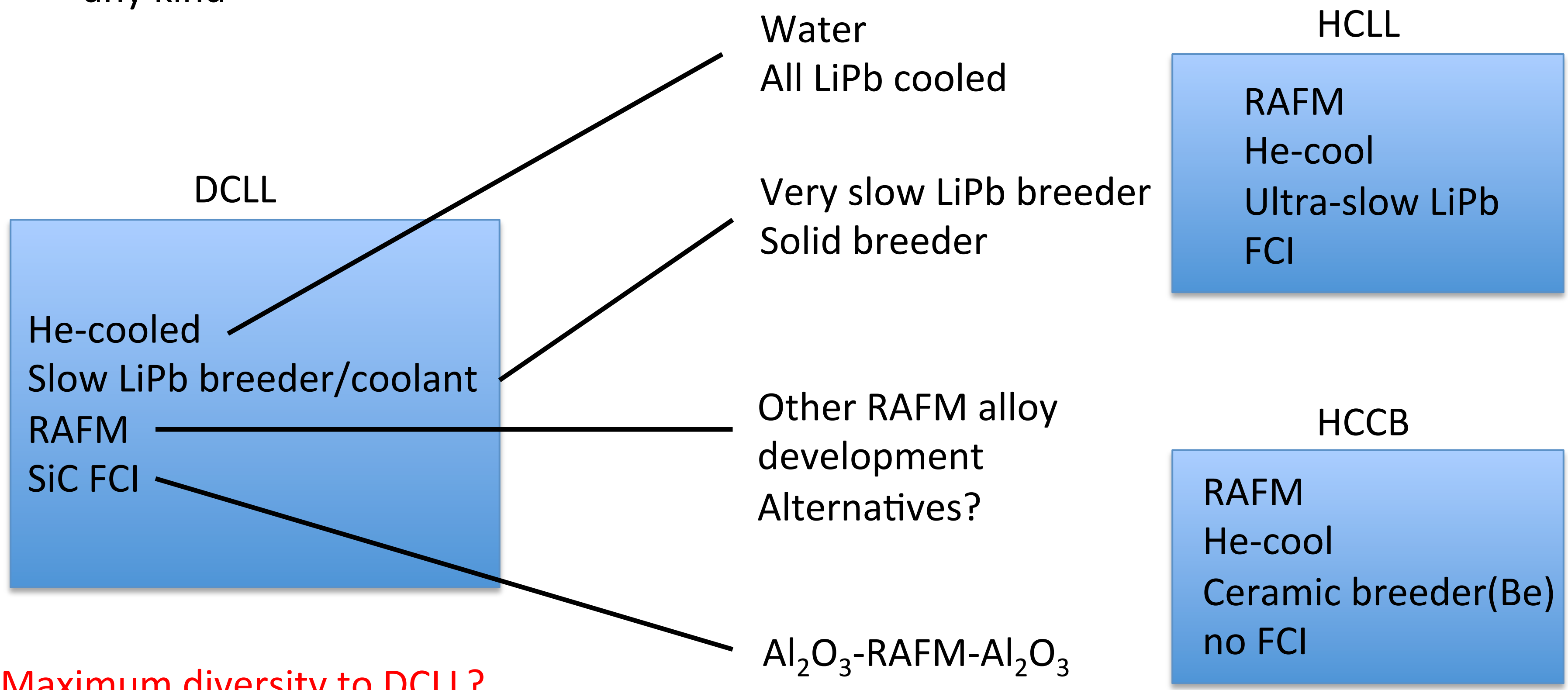
Offline 14 MeV neutron source provides exposure to materials ahead of use on the FNSF

Offline integrated blanket testing facility provides non-nuclear qualification

What is our backup blanket strategy?

The US power plant studies and TBM activities have gravitated toward the Dual Coolant Lead Lithium (DCLL) blanket concept

However, we have a very immature experimental database for fusion blankets of any kind



DCLL

He-cooled
Slow LiPb breeder/coolant
RAFM
SiC FCI

Water
All LiPb cooled

Very slow LiPb breeder
Solid breeder

Other RAFM alloy development
Alternatives?

Al_2O_3-RAFM-Al_2O_3

HCLL

RAFM
He-cool
Ultra-slow LiPb
FCI

HCCB

RAFM
He-cool
Ceramic breeder(Be)
no FCI

Maximum diversity to DCLL?
Minimum effort to develop/carry along backup?
Share R&D program with int'l parties?

We do have back-off capability (T, v,..)
What are neutron synergies?
Identify failure mechanisms

DEMO Program - Table

A tentative DEMO program has been outlined in order to establish

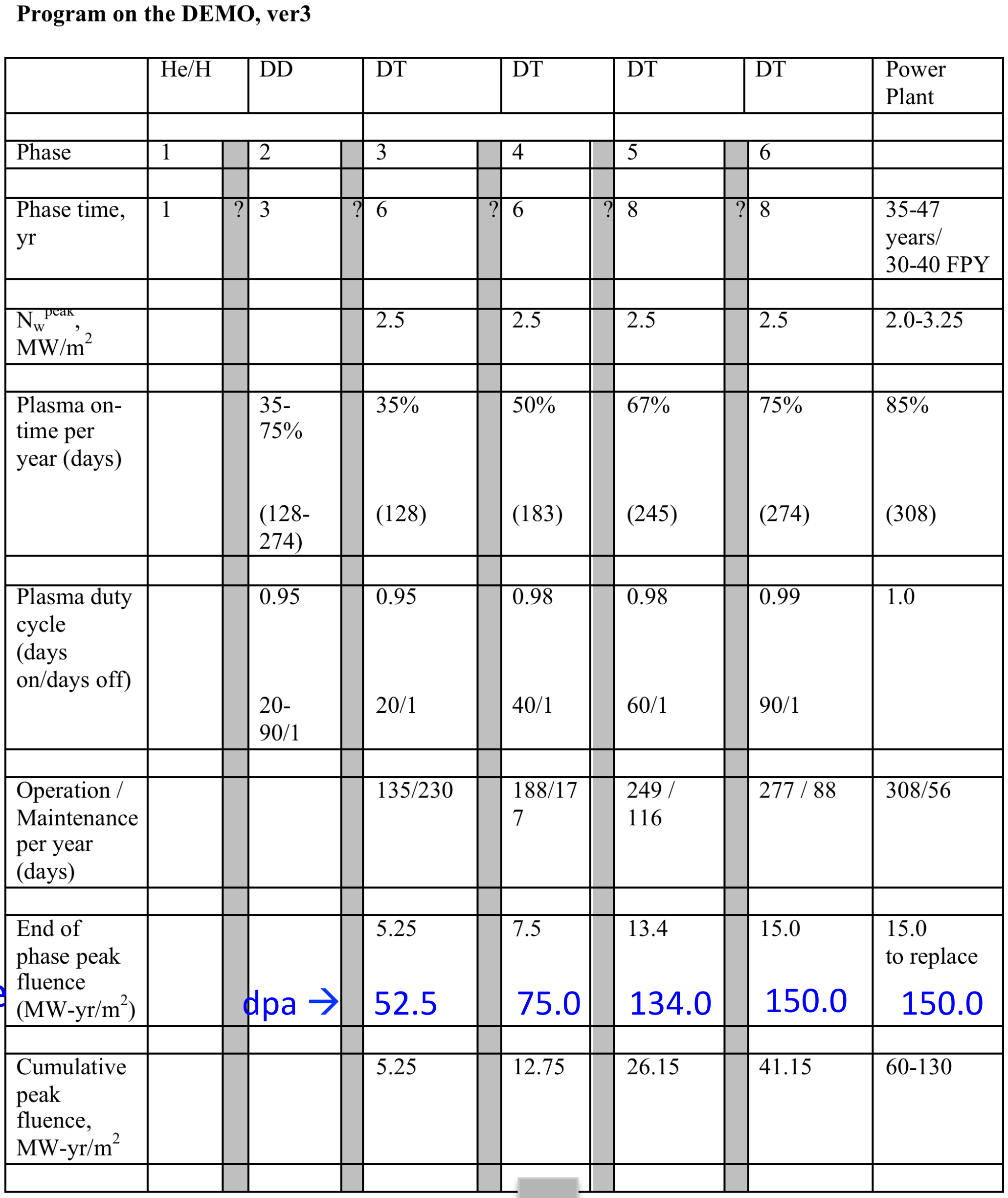
- Rampup neutron exposure to life-limiting level, 100 or 150 dpa? Rapid increase
- Very long plasma durations pushed toward power plant levels, months to year
- Operate at power plant exposures and maintenance repeated at least once
- Generating electricity throughout program

Phase time, yr

N_W^{peak}

Plasma on-time

Peak Fluence



Program on the DEMO, ver3

	He/H		DD		DT		DT		DT		DT	Power Plant
Phase	1		2		3		4		5		6	
Phase time, yr	1	?	3	?	6	?	6	?	8	?	8	35-47 years/ 30-40 FPY
N_w^{peak}, MW/m^2					2.5		2.5		2.5		2.5	2.0-3.25
Plasma on-time per year (days)			35-75% (128-274)		35% (128)		50% (183)		67% (245)		75% (274)	85% (308)
Plasma duty cycle (days on/days off)			0.95 20-90/1		0.95 20/1		0.98 40/1		0.98 60/1		0.99 90/1	1.0
Operation / Maintenance per year (days)					135/230		188/177		249 / 116		277 / 88	308/56
End of phase peak fluence (MW-yr/m^2)			dpa →		5.25 52.5		7.5 75.0		13.4 134.0		15.0 150.0	15.0 to replace 150.0
Cumulative peak fluence, MW-yr/m^2					5.25		12.75		26.15		41.15	60-130

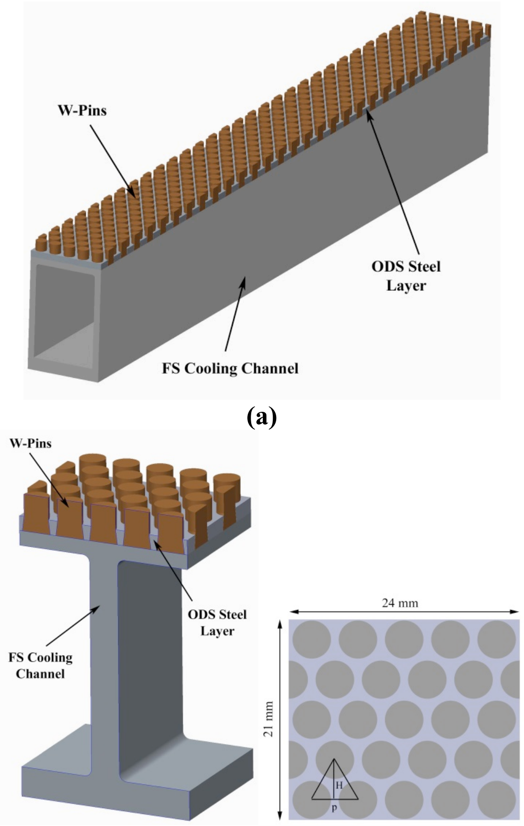
Table continues

Ultimately, we need to extend the time between required action related to PFC/PMI

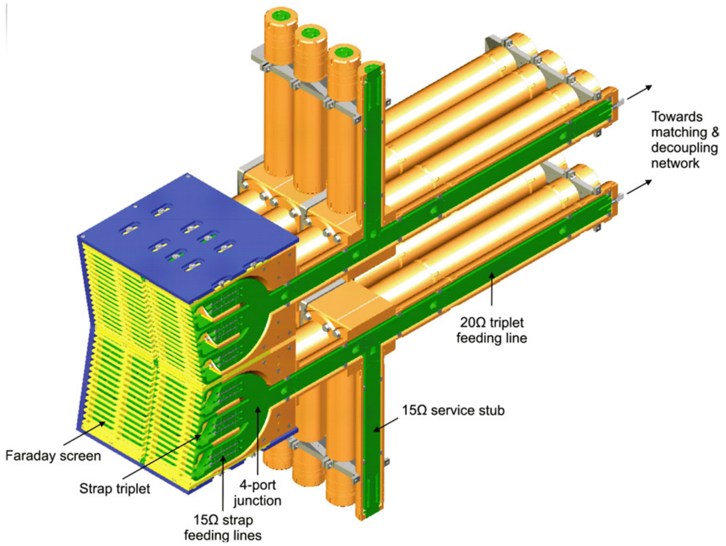
Design of PFCs, what are the simultaneous loading conditions?

- Heat loads
- Particle loads/erosion
- Transients?
- Operating history and material evolution

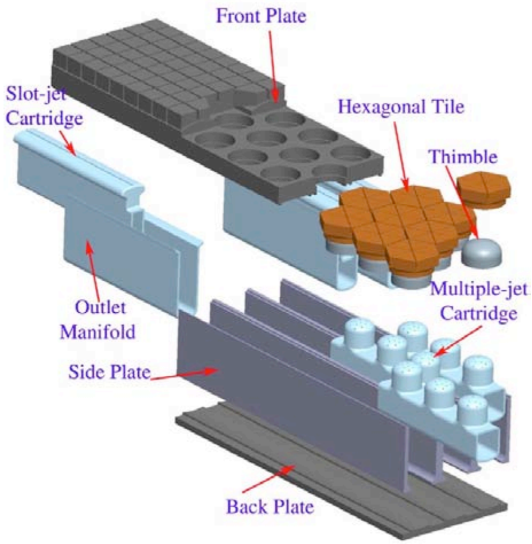
Tungsten pin / RAFM steel FW



Launchers



Tungsten divertor



Several Material's Issues are Arising in Examining the FNSF Program

What is the maximum allowable dpa we should assume for targeting the development program?

- Fast reactor program showed ~ 100-150 dpa for austenitic, Ni-alloys and ferrtiic steels at 500+ ^{o}C…..in fission spectrum, recommended value of ~ 100 dpa for fusion
- Impact on power plant economics, looking for the knee in the curve

The Reduced Activation Ferritic Martensitic (RAFM) steel "family", what is the alloy evolution, how do we work this into the FNSF program?

- **Generation I Reduced Activation Ferritic Martensitic (Gen I RAFM)**
- **Generation II RAFM** (controlled thermo-mechanical processing, modifications to N, C, W, Ta, maintain strength at higher temperature, large number of **nano**-scale particles in matrix, helium trapping)
- **ODS(NS)** steel (mechanical alloying, Oxide Dispersion Strengthened, maintain strength at higher temperature)
  - ODS alloys with 9-12% Cr, EUROFER-97-ODS (0.3 wt.% Y_2O_3)
  - ODS alloys with >12% Cr, Fe(12-14)CrWTi-ODS (0.3 wt.% Y_2O_3)

→ Better determine the # samples, temperatures, materials, for fusion neutron testing….strong pace setting element of R&D program

→ What can facilities offer, IFMIF, accelerators?

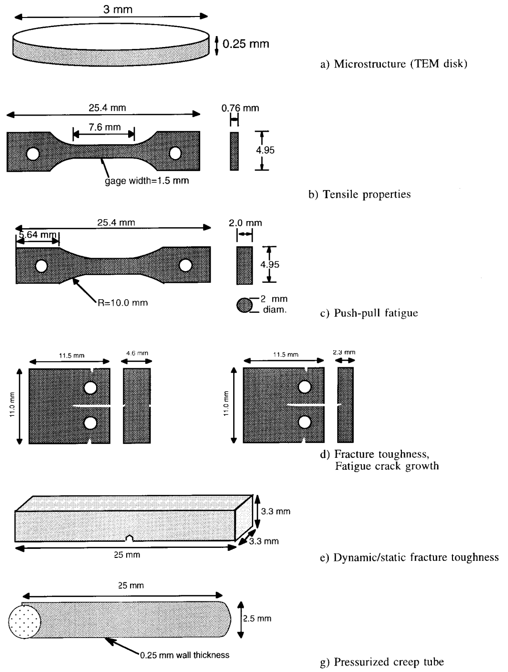
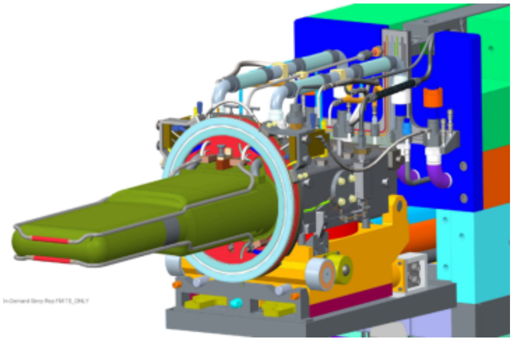
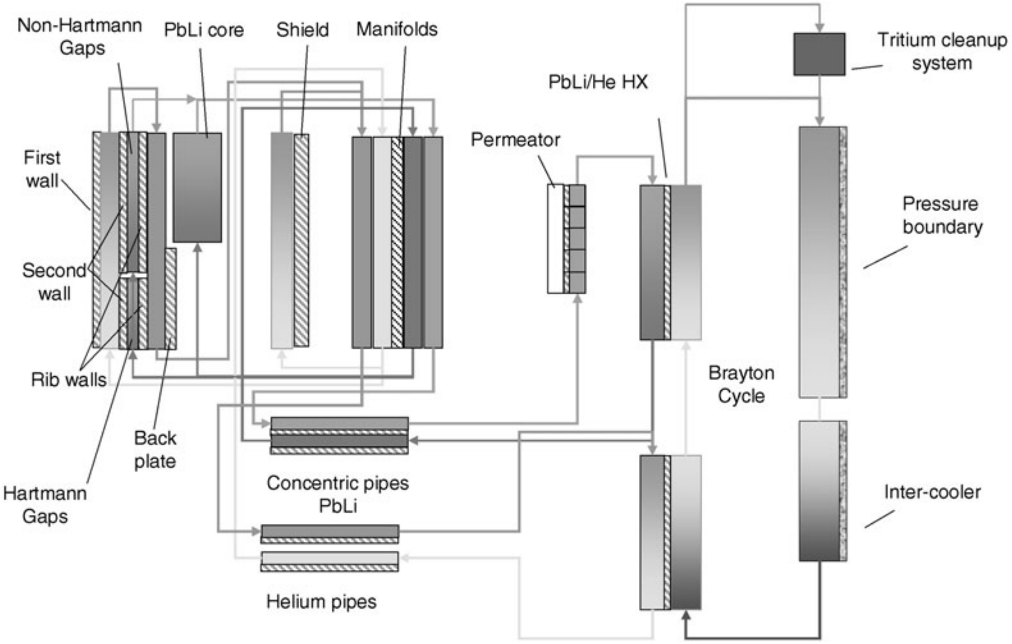


Fig. 1. Proposed reference geometries of structural material specimens for the high flux region of IFMIF [11].

SNS, fusion material test station



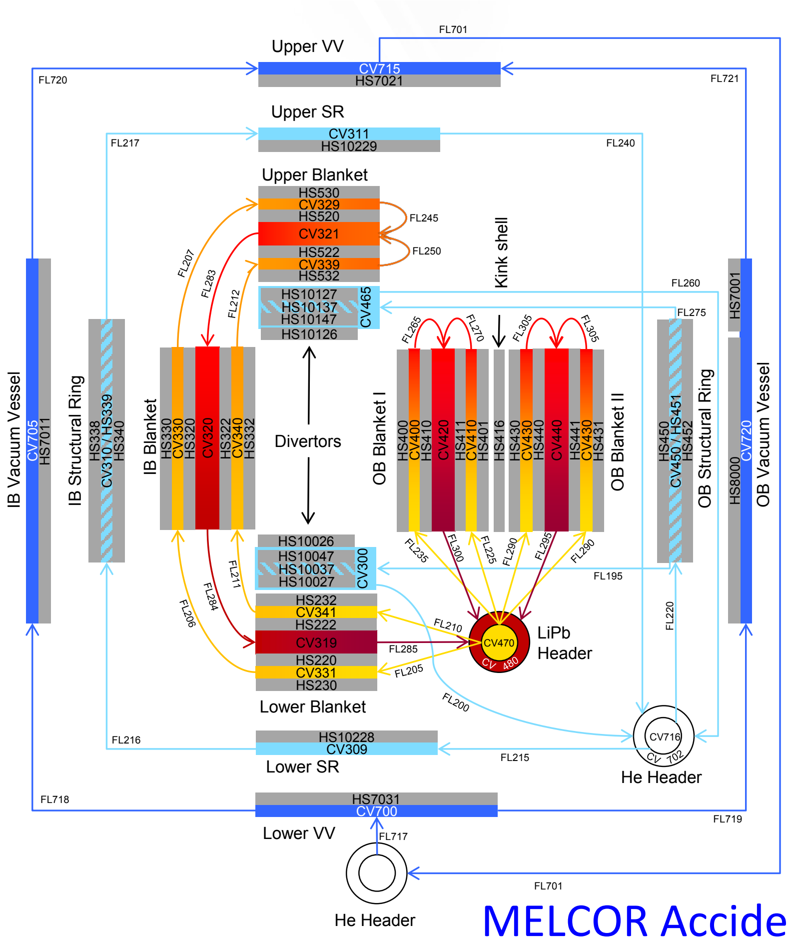
Routine tritium behavior and accident analysis is needed to optimize the FNSF fusion core



TMAP tritium inventory modeling – ARIES-CS

- More routine use of TMAP by generating required geometry in systems code
    - Impacts of materials, temperature, fluids and parameter choices
    - Also produce geometry input for MELCOR

- Establish a wider range of accidents to examine and assess
    - Standards like LOCA, LOFA, etc.
    - Include "smaller" accidents



MELCOR Accident modeling – ARIES-ACT1

Magnets…which kind? How do we obtain high reliability

Cu TF and PF coils have been proposed to allow a smaller device, and lower cost….is it all true?

- Cu coils likely do cost less to make than SC (LT or HT), but the cost to operate the Cu coils will likely nullify this…what do we learn from Cu coils?
- Can one really obtain smaller shielding of the magnets…..inorganic insulators have been proposed, but this insulator takes up too much volume, while organic insulators have lower dose capability….the Cu also has strong reduction in elongation if kept below water boiling temperature?

LTSC's have a basis from ITER development

- Can we improve on it? The Koreans and EU next accelerator magnet developers think so, maybe up to 16 T at the TF coil
- Other options to optimize the ITER CICC for the FNSF application? Insulators, structural steel, conduit material

HTSC's are becoming the focus of magnet development

- Do we need what they can offer, higher operating T, higher J-B combinations, work without He
- Can we make a fusion magnet, high field with large volume?

There are other magnets too, error field correction, vertical position feedback, other control magnets

We need to examine the Cu and LTSC trade-offs, and maintain an assessment of HTSC progress

Operating at higher β can allow higher neutron wall loads, but we need a robust operating point

Where can we operate the most robustly?

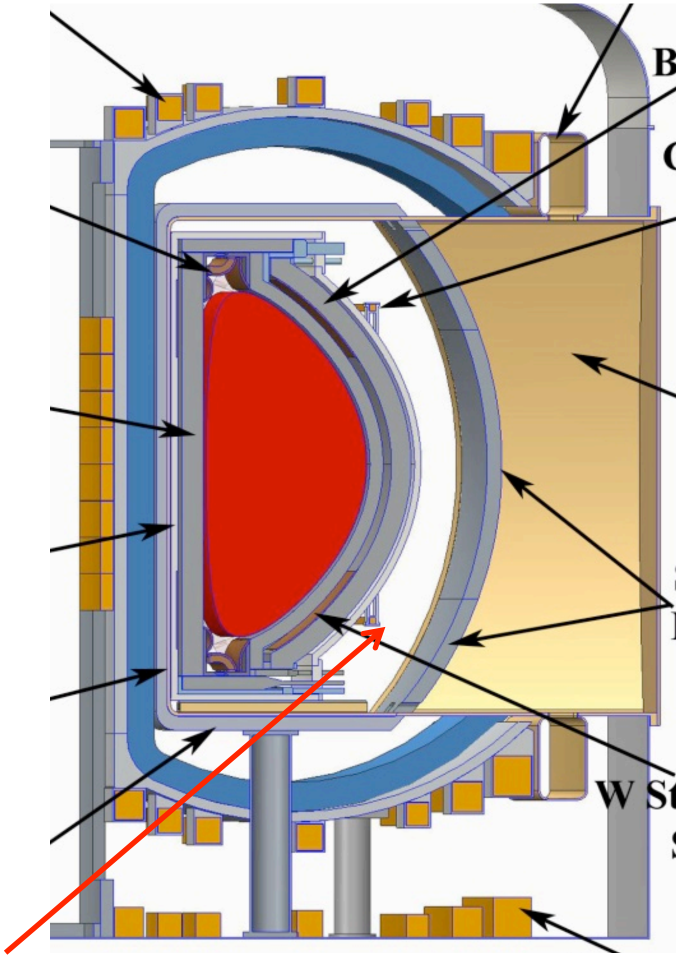
$\beta_N < \beta_N^{\text{no wall}}$
$\beta_N^{\text{no wall}} < \beta_N < \beta_N^{\text{wall}}$

This likely depends on other parameters, like q_{95}, conducting wall location, feedback coil locations

Feedback coils will need to be located behind the blanket and shield, and likely are normal Cu

What is the connection of the error fields, plasma response, static/dynamic error field control, resistive wall modes, resistive wall mode feedback, kinetic stabilization, and plasma rotation

- Can we identify the hardware to access higher β?
- Can we project the physics from present devices?
- Can we establish a highly robust baseline, and possible extensions to higher β?



Location of feedback coils

ARIES-ACT2

ACT2 (so-called conservative) power plant study examined beta limits without and with wall

Red points show no wall maximum beta-N

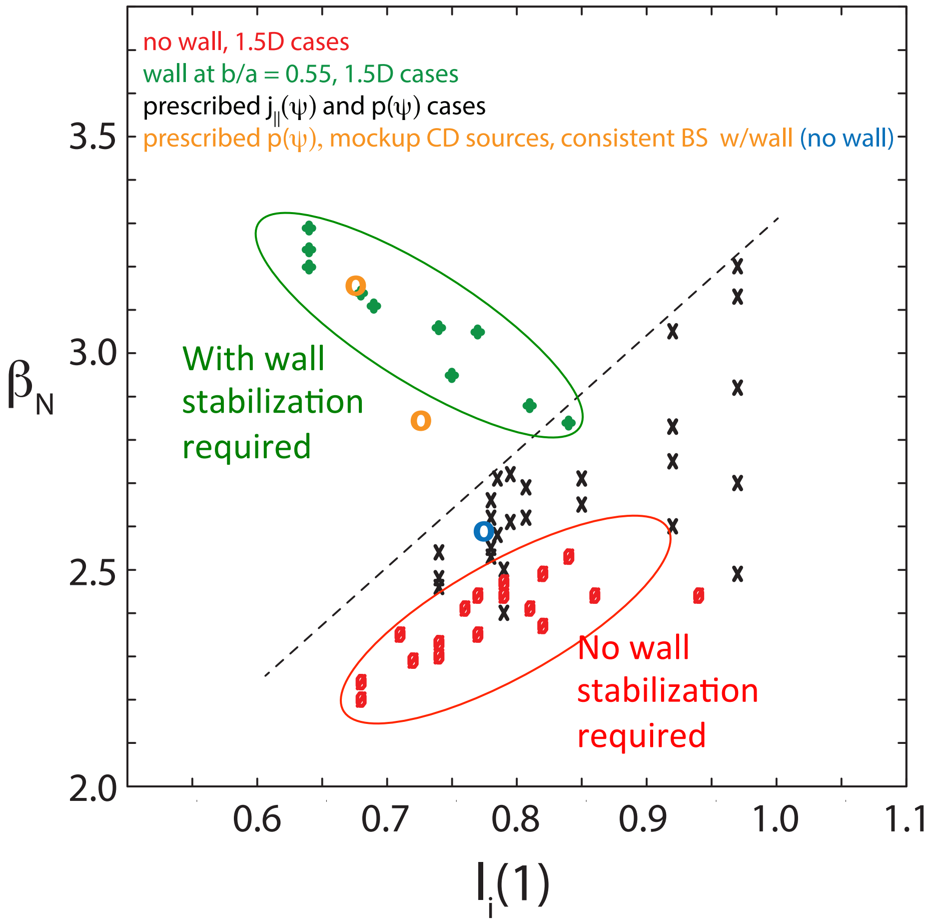
Green points show with wall maximum beta-N, b/a = 0.55, conductor behind shield

Ignore the others please

Preliminary systems analysis of FNSF are showing benefits to reaching $\beta_N \sim 3$

- Tolerate lower peak B-fields at TF coil
- Smaller major radii, smaller H/CD power
- Higher $\langle N_w \rangle$, shorter times to reach dpa limits
- Easier to provide an electricity demonstration at smaller size

Low n Ideal MHD analysis from ARIES-ACT2



*does not include kinetic stabilization effects

Divertor solutions

The divertor will need both a physics and an engineering solution, this is a critical interface area on the FNSF

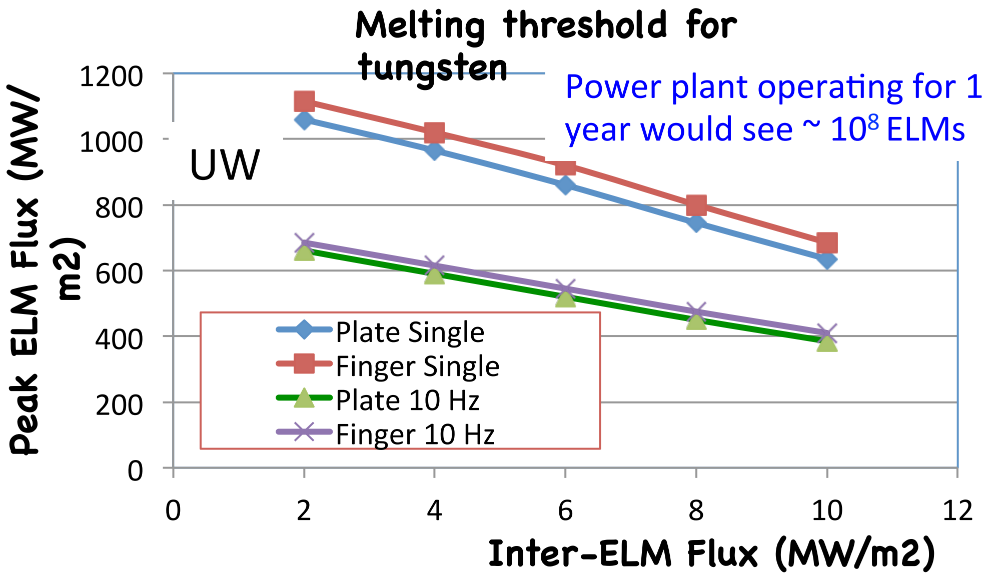
Radiative standard divertors
    Slot geometry
    Detachment regime and stability

Advanced magnetic geometries
    Super-X
    Snowflake
    X-divertor

We need to get at PMI – erosion estimates

Is there a liquid metal design that fits in the typical envelope for a divertor? Can we do it on the top and the bottom?

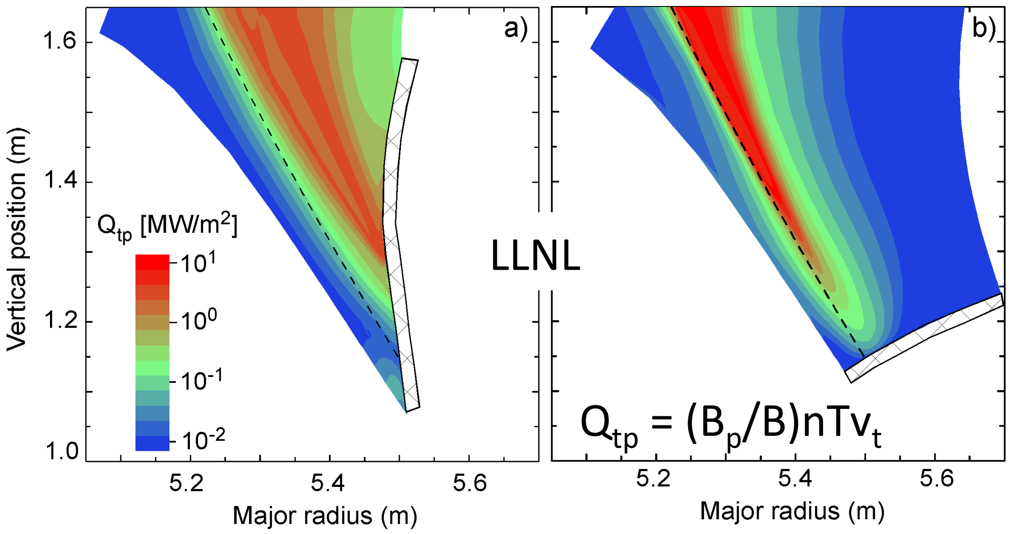
Should we pursue SN or DN?



Power plant operating for 1 year would see ~ 10^8 ELMs

Tilted-plate partial detachment has strong in/out asymmetry

Flat-plate full detachment provides gas cushion on both sides of separatrix



$Q_{tp} = (B_p/B)nTv_t$

Partial detachment provides $f_{div,rad}$ ~ 0.75 ITER-like

Full detachment provides $f_{div,rad}$ ~ 100% ARIES-ACT

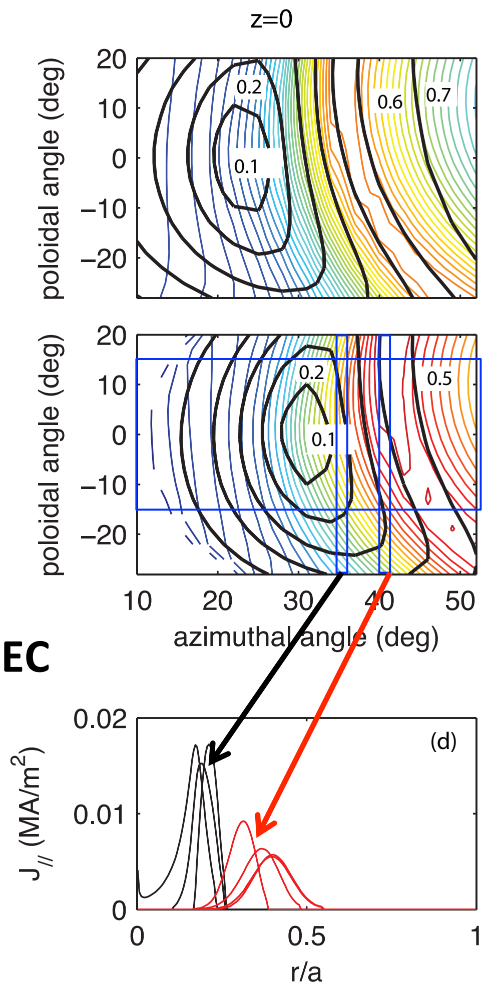
Heating and current drive systems will be driving a lot of the plasma current

Since $f_{BS} \sim \beta_N q_{95}$, and we are targeting robust plasma scenarios, we typically have to drive 20-50% of Ip

I anticipate examining all sources, to get assessments of impacts on

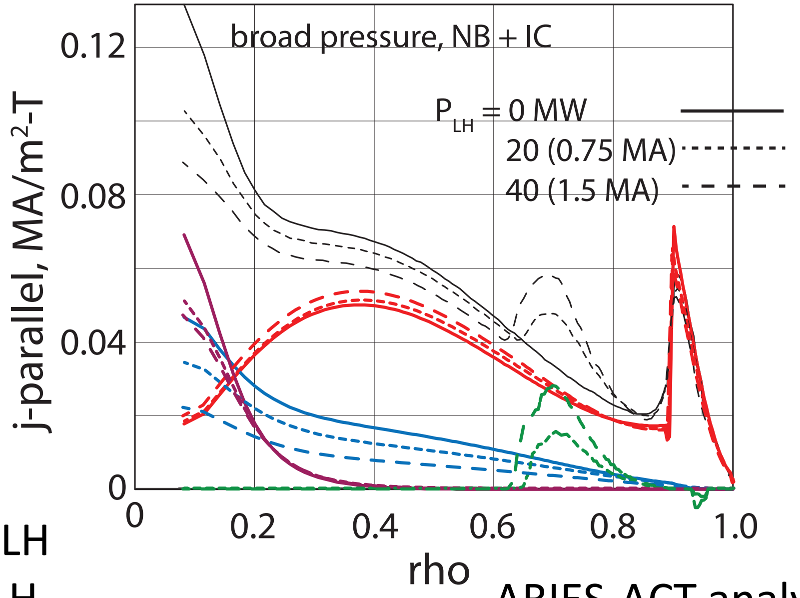
- CD efficiency
- Impact on power balance
- Tritium breeding
- Neutron shielding/streaming

EC



We will need real designs with the materials, operating temperatures, and loading conditions (PMI)

Solid – no LH
Short dash – 20 MW LH
Long dash – 40 MW LH



ARIES-ACT analysis

What is the operating plasma scenario

In general, producing a wide range of plasma configurations is NOT the goal, but a small set of robust operating points, with margin to accommodate things that don't go our way (B_T^{max} did not reach 16T, or SS β_N does not reach 3…)

The preferred operating mode is steady state, 100% non-inductive current (bootstrap + external CD)

Strong shaping is still desirable for margin to MHD limits, pedestal and transport benefits, and possible benefits to high density operation

- High n/n_{Gr} fractions are likely, consistency with radiating divertor

What is the operating plan for the DD phase of the FNSF, plasma operations to establish ultra-long pulses (*without DT fusion*)

<u>Preliminary systems analysis searching for operating points:</u>

Provide $N_W^{OB,peak} = 1.5$ MW/m^2

Assume:

- 88 cm IB build + 20 cm gaps
- LTSC ($B_t^{max} < 15.5$ T, $\langle j \rangle < 15$ MA/m^2)

$\beta_N^{total} < 2.5$, $q_{div}^{peak} < 10$ MW/m^2
$R \geq 4.5$ m

$\beta_N^{total} < 3.0$, $q_{div}^{peak} < 10$ MW/m^2
$R \geq 3.75$-4.0 m

$Q_{engr} > 1$ (electricity)
$\beta_N^{total} < 2.5$, $q_{div}^{peak} < 10$ MW/m^2
$R \geq 4.5$ m

$\beta_N^{total} < 3.0$, $q_{div}^{peak} < 10$ MW/m^2
$R \geq 3.75$-4.0 m

Fueling, pumping, particle control and vacuum systems

The VV in the FNSF and future devices becomes a large can inside which the blankets, divertors, and shield are placed

As far as we know only a small fraction (5-15%) of the tritium and deuterium injected is consumed, the rest is exhausted, processed and re-injected….so we send A LOT of tritium through the fueling/exhaust system, about 10x what we consume (or breed)

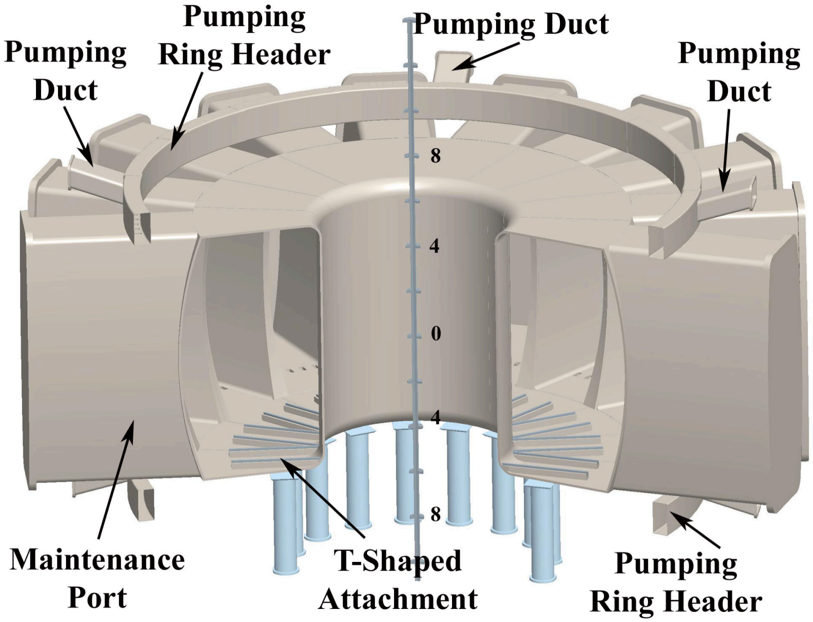
The sectors are mounted next to each other, and come in contact when hot (and due to swelling over time)….what is going to be the particle behavior in this system

Maintenance of the device plays a large role in the configuration shapes and components

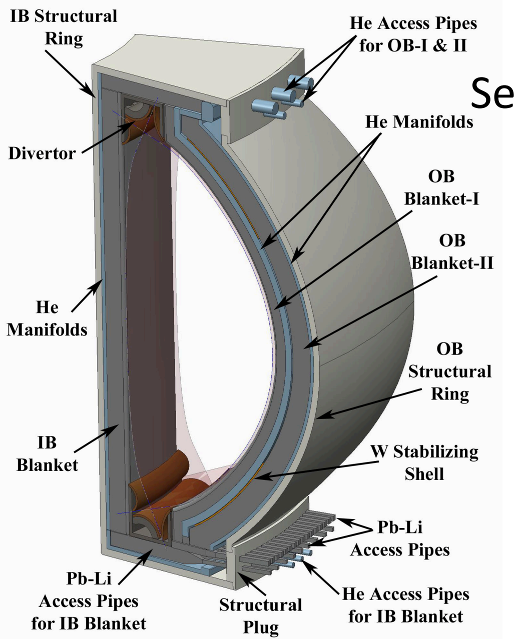
Need to establish a vacuum/fuel/exhaust design solution

ARIES-ACT

Vacuum vessel



Sector, 1/16



Disruptions

Although we will operate on the assumption that disruptions can and will be avoided to a significant extent, the FNSF will need to be designed to withstand them

At a minimum the disruption can not lead to an accident

Disruption mitigation will be assumed to be available, based on experimental developments

Transfers thermal quench deposition (mostly) to first wall

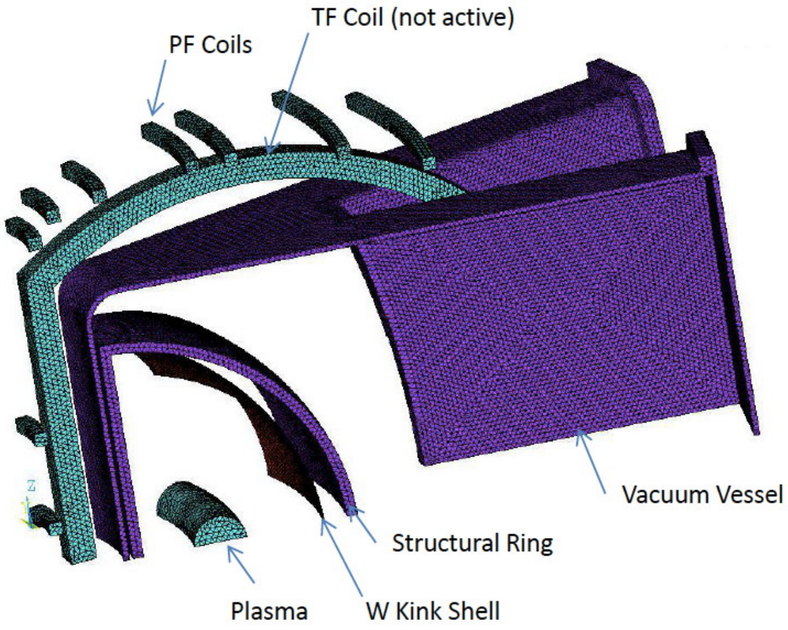
Electromagnetic forces of current quench remain (halo current loads reduced)

Runaway electrons will be assumed to be quenched by mitigation scheme (we can not use armor to withstand these due to tritium breeding)

Strong back or structural ring which surrounds ea

Tungsten shells are used for vertical position stability and low-n kink (RWM) stability due its good electrical conductivity and high temperature capability

Modeling is going on for the electromagnetic forces, expanding the model to contain more elements like blanket box and divertors



What can we measure?

We need a CRITICAL assessment of measurements needed for the FNSF, with an eye to the environment they must withstand

ITER already provides a challenging environment and difficult constraints on many diagnostics we use today…GOOD PLACE TO START, with hierarchy of priority for control and hardware protection to high fidelity physics measurements

What simulations with synthetic diagnostics can replace or augment a measurement?

Can time-dependent simulations be used to track the plasma or engineering system in real-time?

Materials become a major development area for diagnostics, operation under neutron and gamma radiation, understanding the prompt irradiation signal pollution and long term damage signal modifications

Performing measurement degradation experiments on present DD devices offers a way to understand the impacts and ability to replace or restore measurement capability

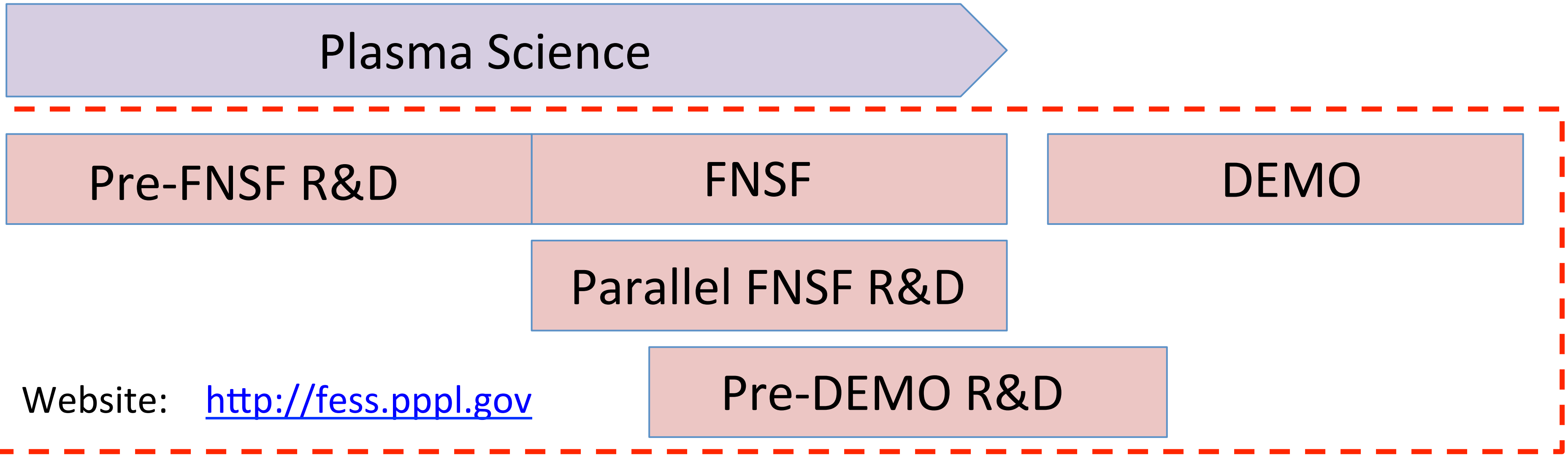
Measurements of engineering systems have been barely examined, especially those that would be inside the first wall/blanket/shield

The FNSF provides an important step on the pathway to fusion energy, but it is a significant change from ITER and present plasma facilities

The facility's missions focus is on nuclear science and the basis for fusion energy production…having only 2 devices weighs heavily on decisions for the FNSF

HOWEVER, it is also the step where the plasma and nuclear science come together like never before…tremendous advances will have to take place

Plasma performance is critical to delivering the nuclear mission, so that demonstrating the ultra-long pulses and robustly stable operating modes (*and enabling systems that support it*) is central to its mission



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