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

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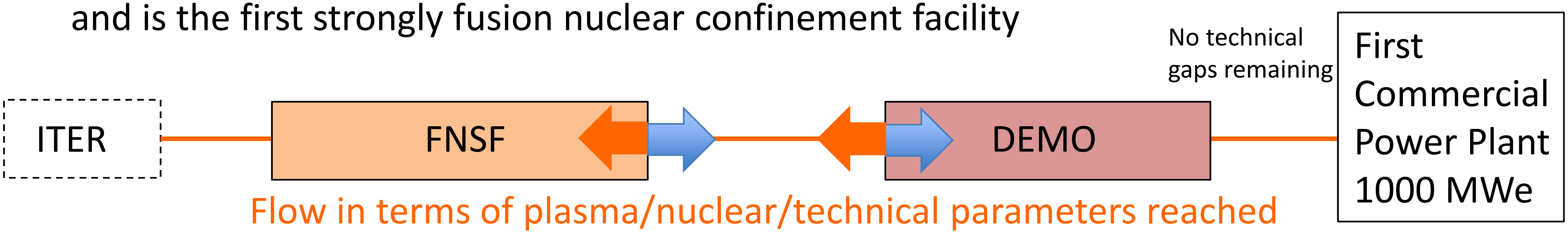
The Context for the FNSF within Fusion Development

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

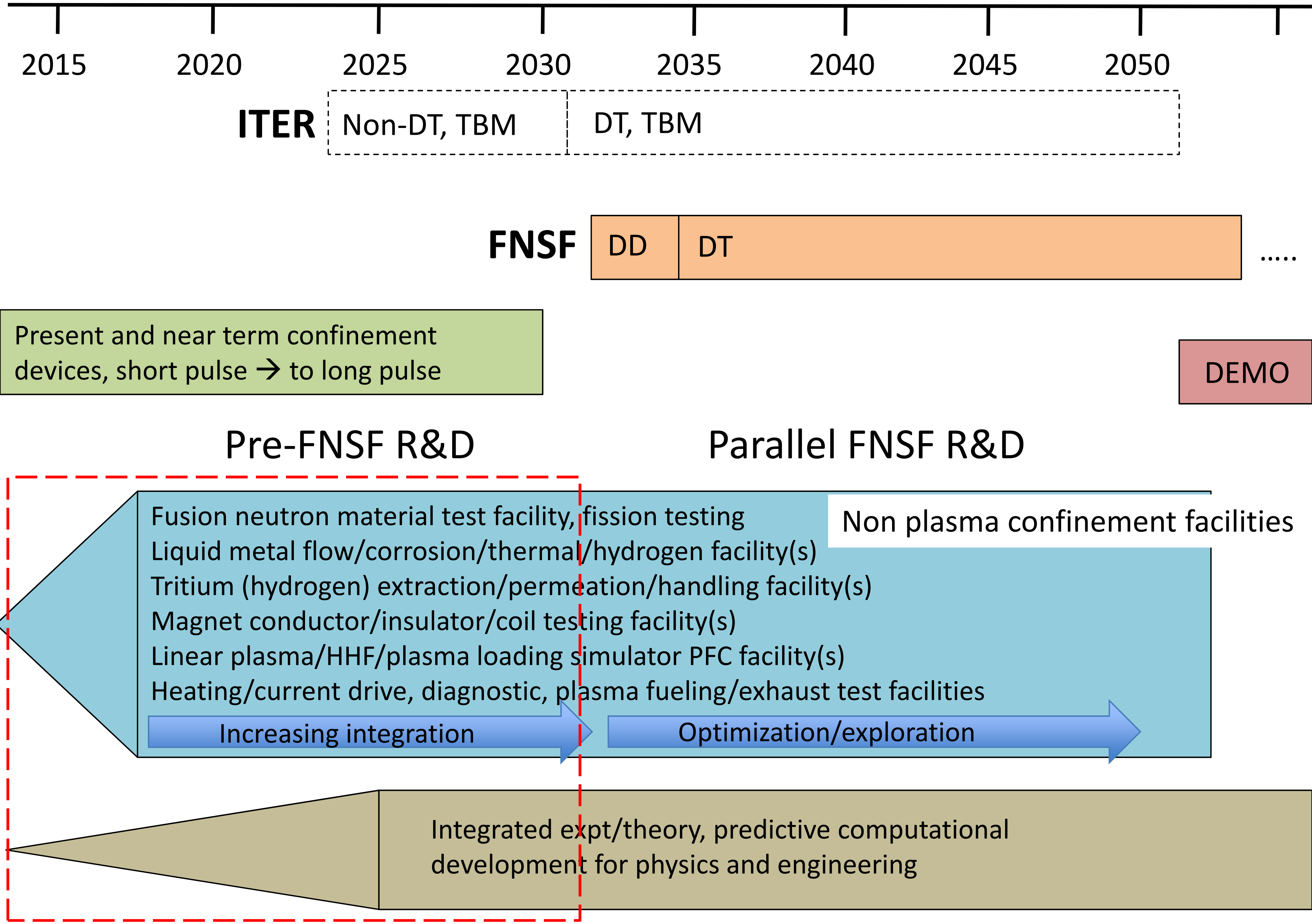


The FNSF is an intermediate step to accommodate the extreme fusion nuclear environment and the complex integration of components and their environment, as well as the nuclear science and plasma physics

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



2015 2020 2025 2030 2035 2040 2045 2050

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 →

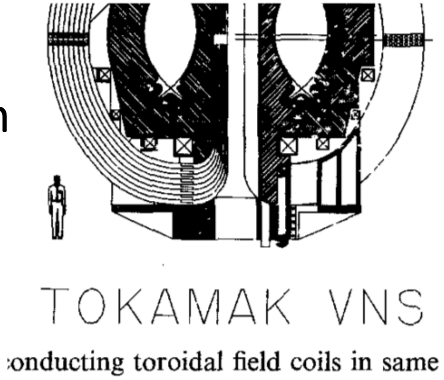
Integrated expt/theory, predictive computational development for physics and engineering

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

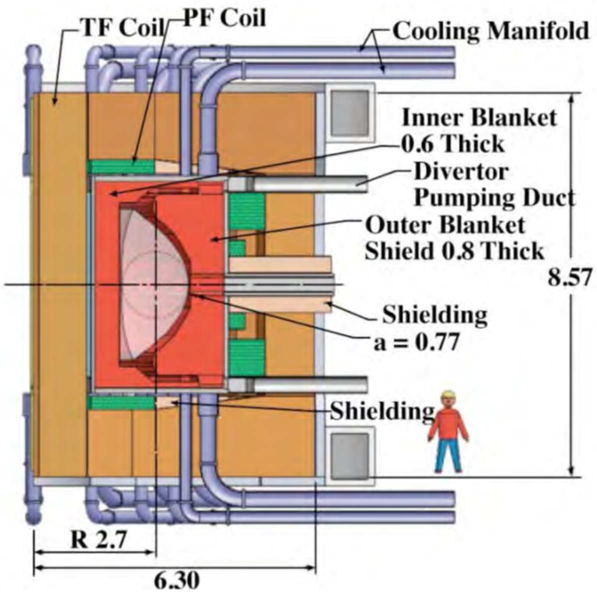
The FNSF can have a small mission scope, a large mission scope, or anywhere in between

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

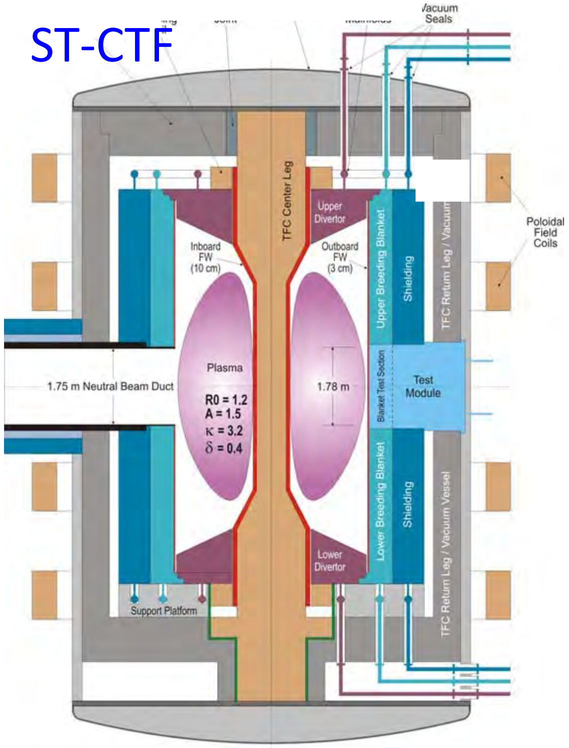
Volumetric neutron source



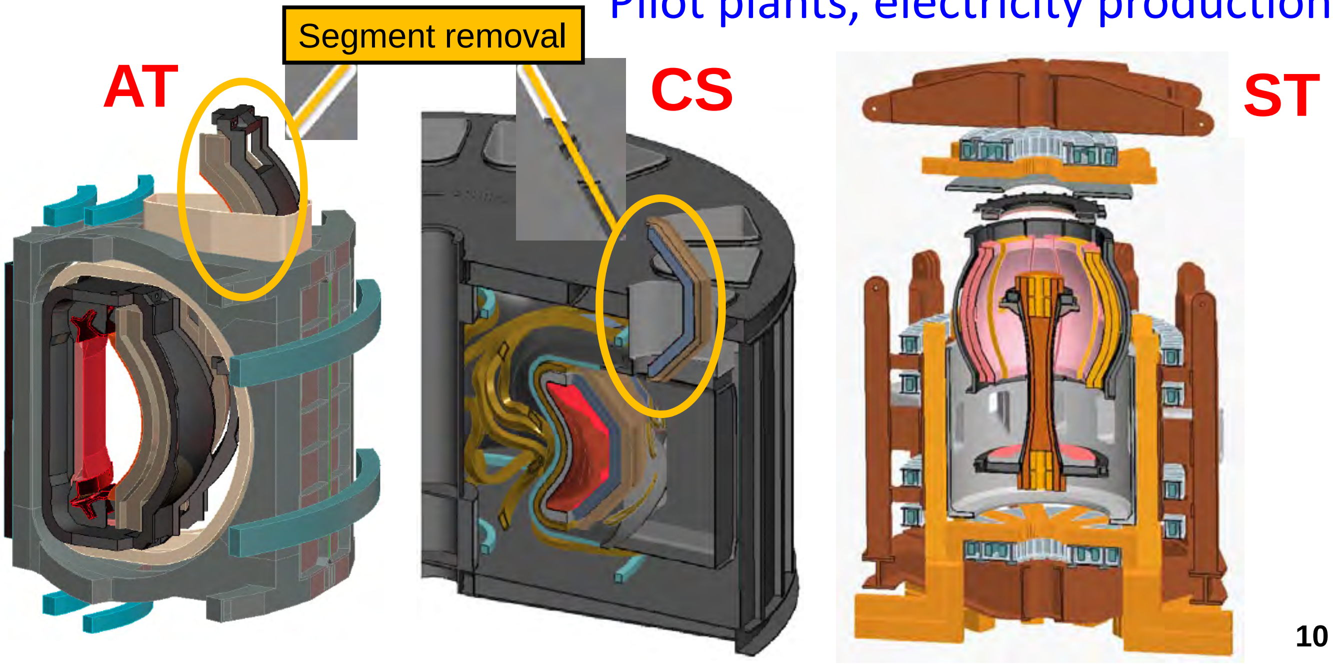
Fusion Development Facility



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 $\geq$ 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)	2.7×10^7 (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)

	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			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)

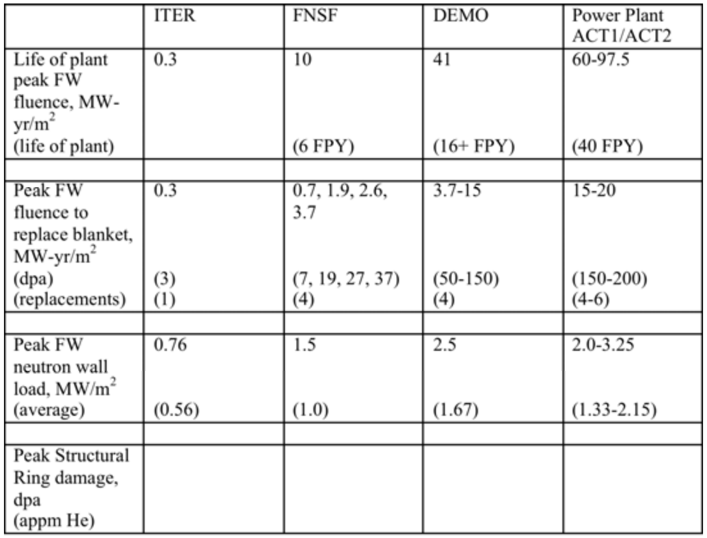
FNSF Mission and Metrics - Tables

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

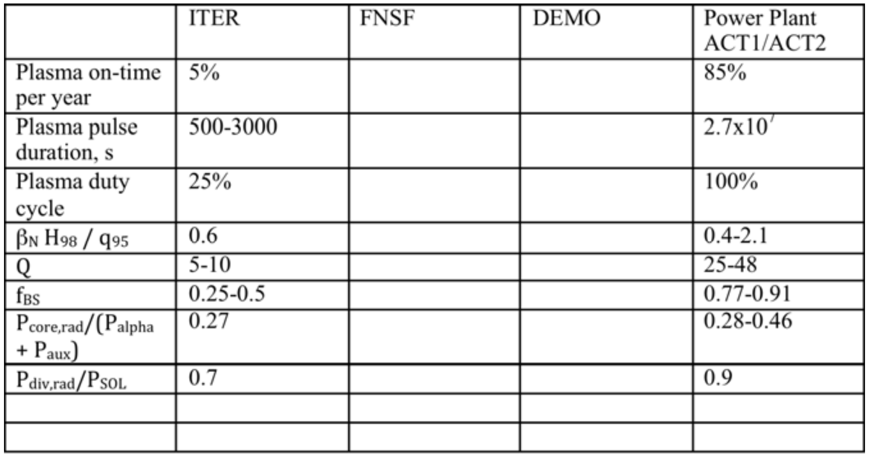
- Fusion neutron exposure (fluence and dpa)
- Materials (structural, functional, coolants, breeders, shield…)
- Operating temperature/other environmental variables
- Tritium breeding
- Tritium behavior, control, inventories, accounting
- Long plasma durations at require performance
- Plasma enabling 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

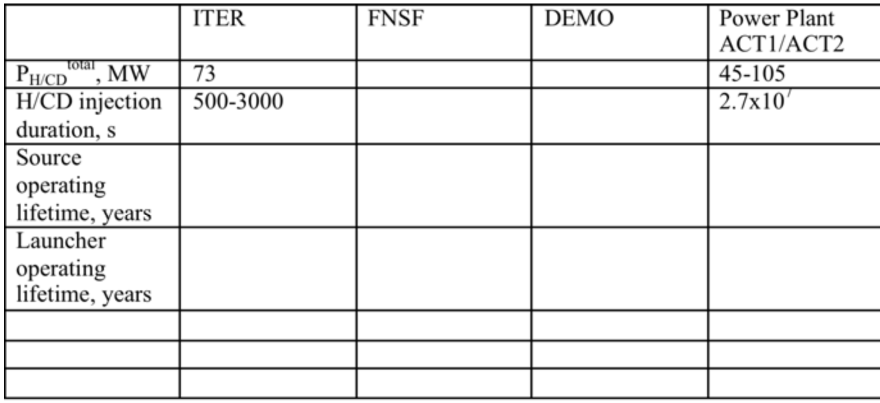
Expect to use ARIES-ACT2 as power plant example



	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%
$\beta_N H_{98} / q_{95}$	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



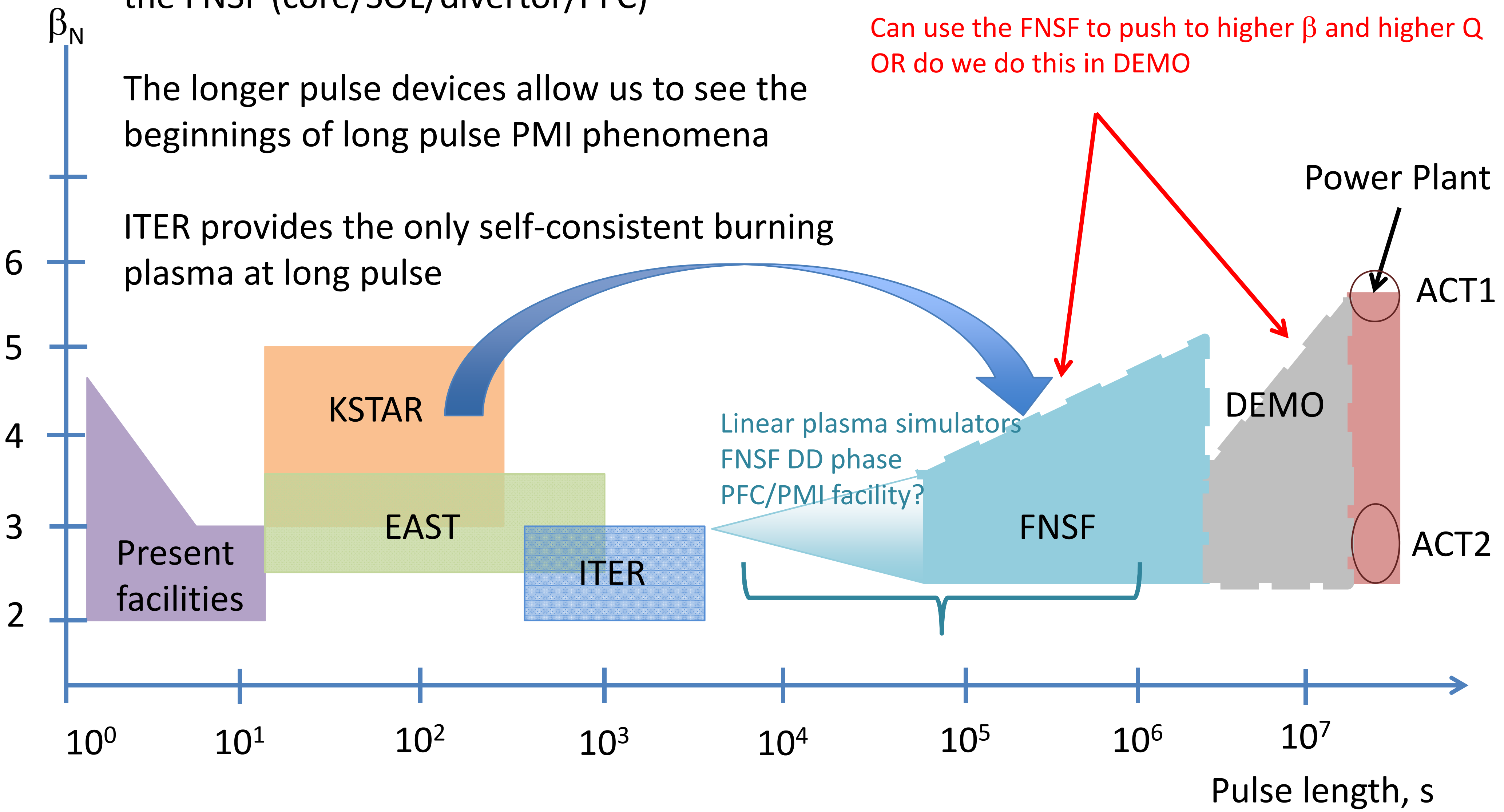
	ITER	FNSF	DEMO	Power Plant ACT1/ACT2
$P_{H/CD}^{total}$, MW	73			45-105
H/CD injection duration, s	500-3000			$2.7x10^7$
Source operating lifetime, years				
Launcher operating lifetime, years				

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



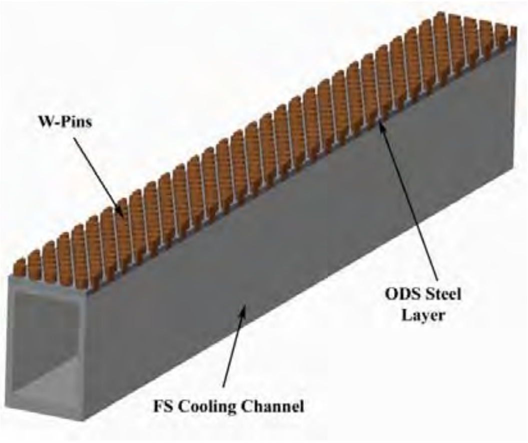
Can use the FNSF to push to higher β and higher Q OR do we do this in DEMO

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



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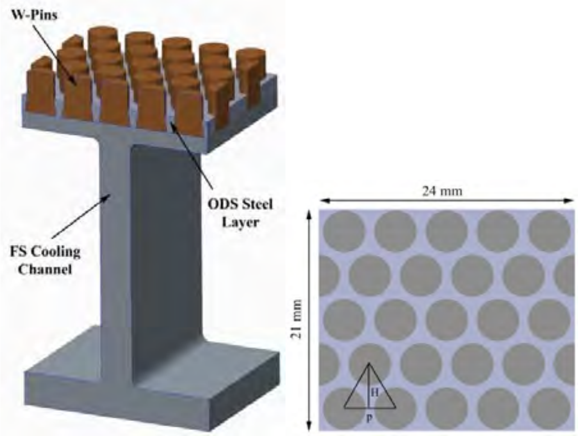
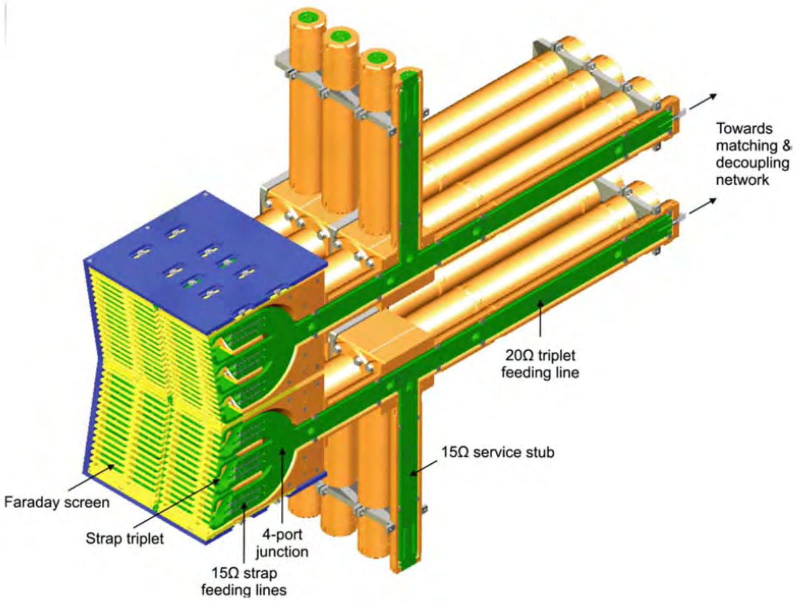
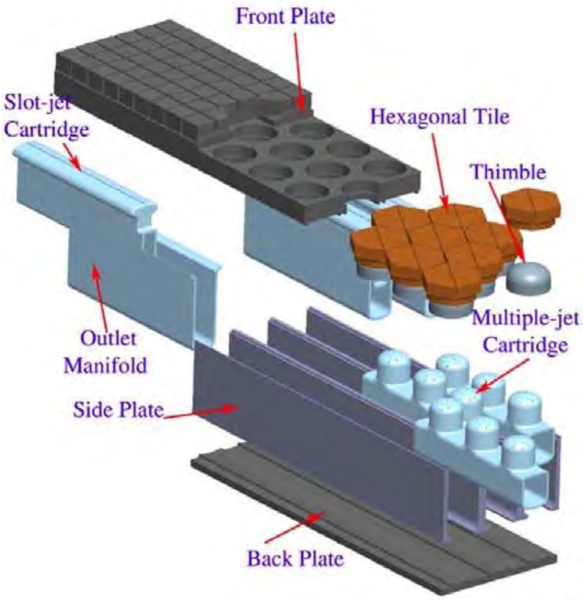


Launchers



Tungsten divertor



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

Where can we operate the most robustly?

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

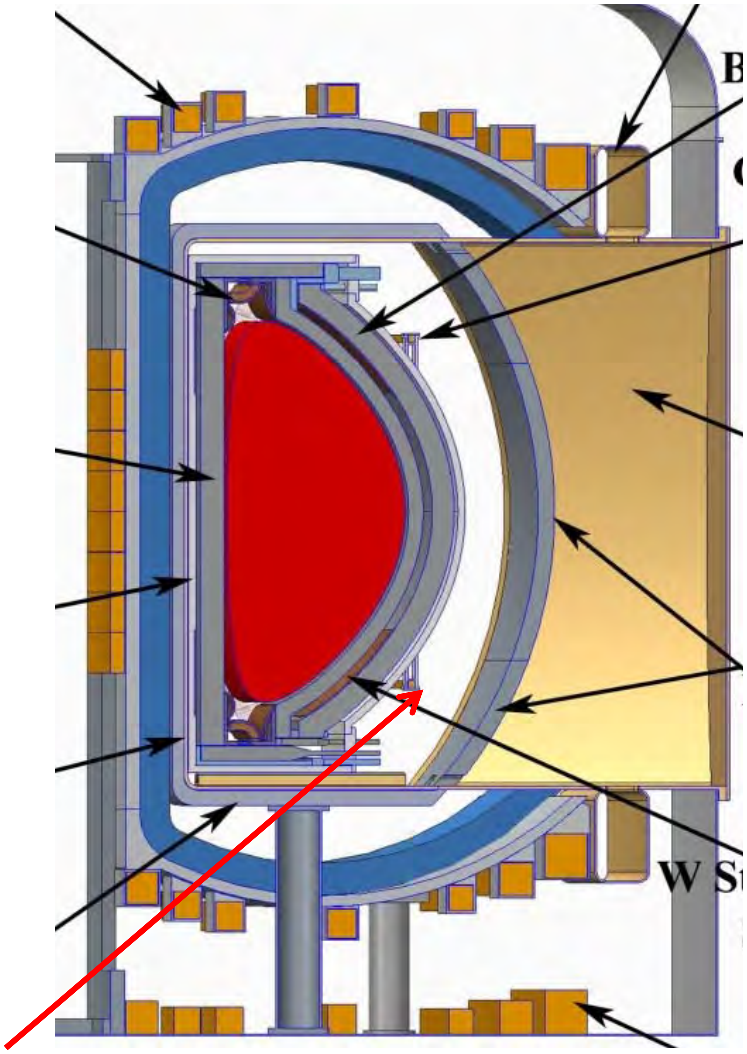
$\beta_N^{\text{no wall}} < \beta_N < \beta_N^{\text{wall}}$

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 $\beta_N \sim 3$

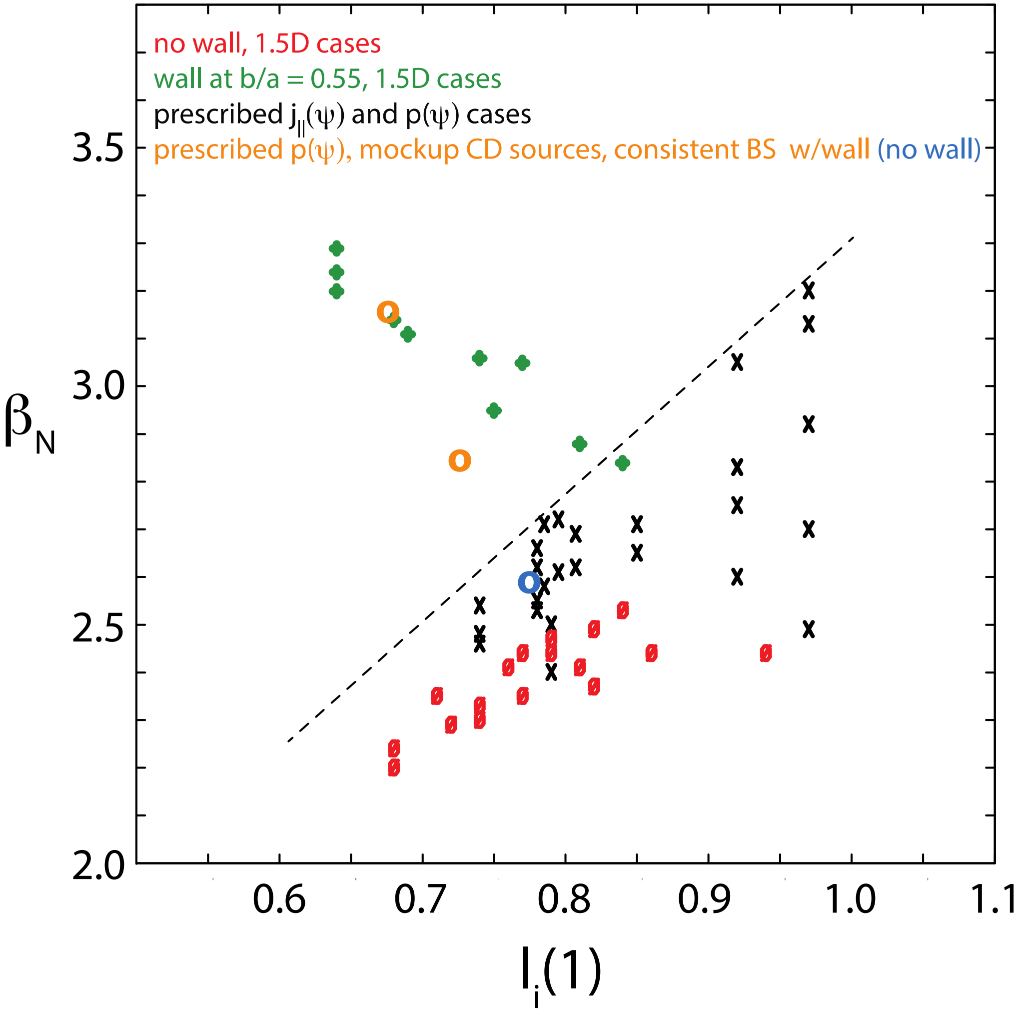
Tolerate lower peak B-fields at TF coil

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

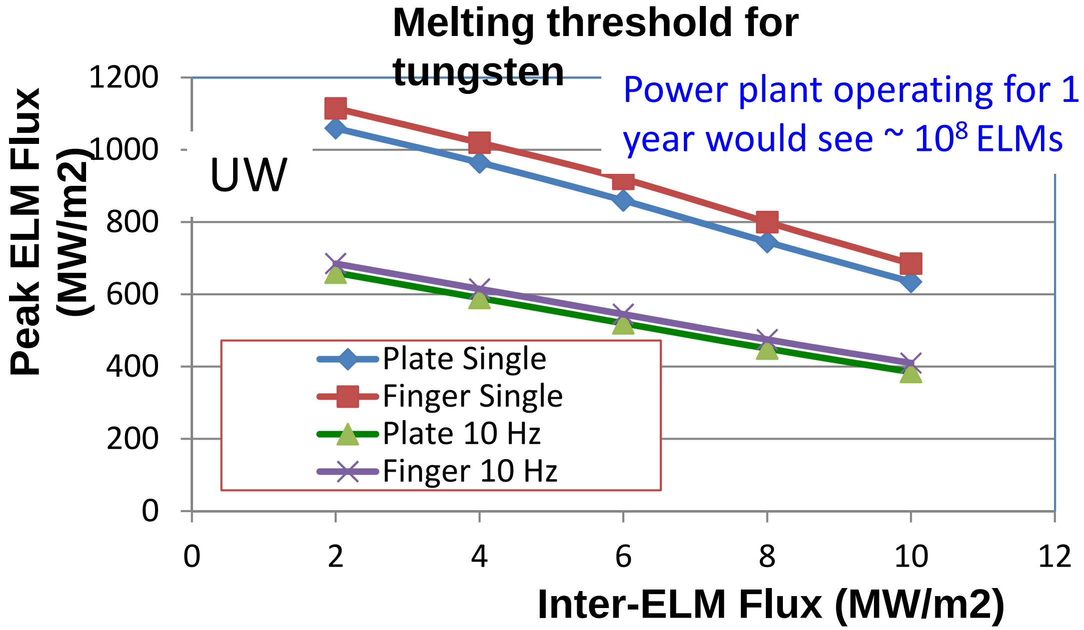
The divertor will need both a physics and an engineering solution, this is a critical interface area on the FNSF

Radiative standard divertors
- Slot geometry
- Detachment regime and stability

Advanced magnetic geometries
- Super-X
- Snowflake
- X-divertor

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?

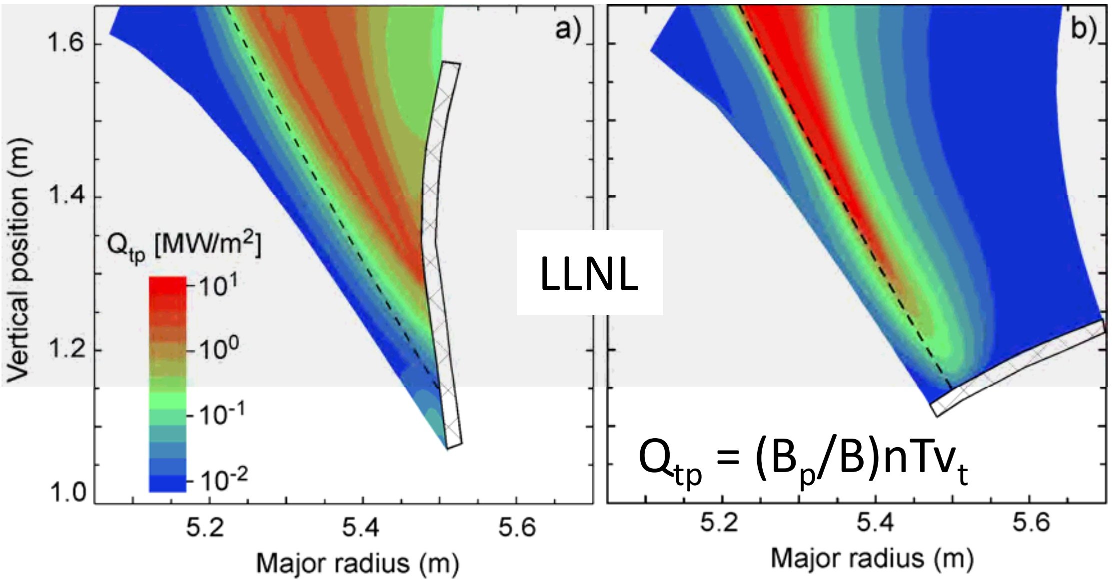
Should we pursue SN or DN?



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

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

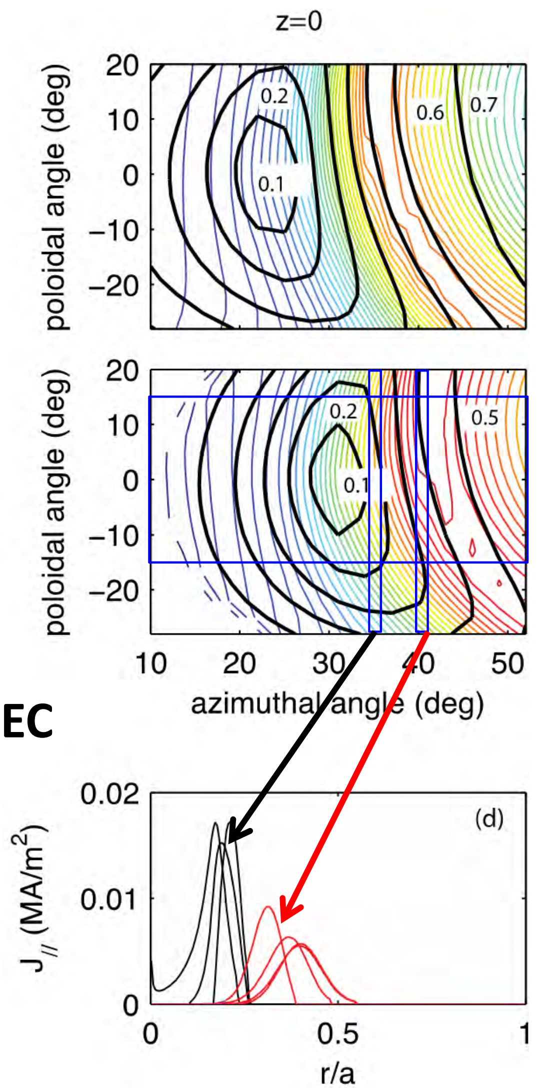
Heating and current drive systems will be driving a lot of the plasma current

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

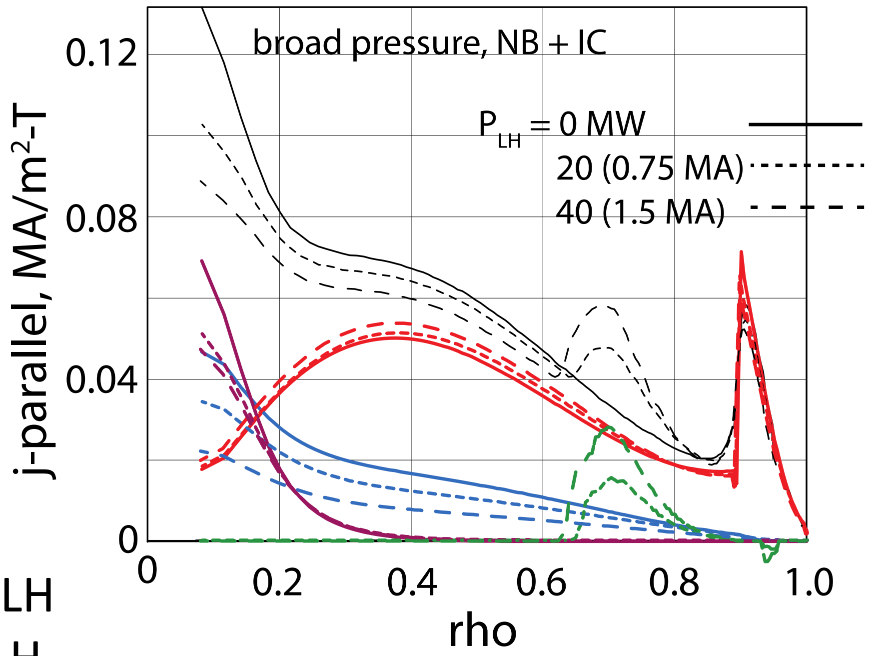
EC



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

ICRF/FWCD
NBCD
LHCD



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)

Inductive operation is a significant change, and likely requires some sophisticated dwell time enhancements (NICD), or NICD assist….it changes the operating point and results in cyclic loading

Depending on transport and the external CD sources, the safety factor may be monotonically increasing, flat or reversed…however we will probably remain at the lower end of β_N

> DIII-D's observation of fewer disruptions at higher β_N and higher q_{95} is interesting

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

Etc……still examining what plasma parameters can deliver the FNSF mission

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

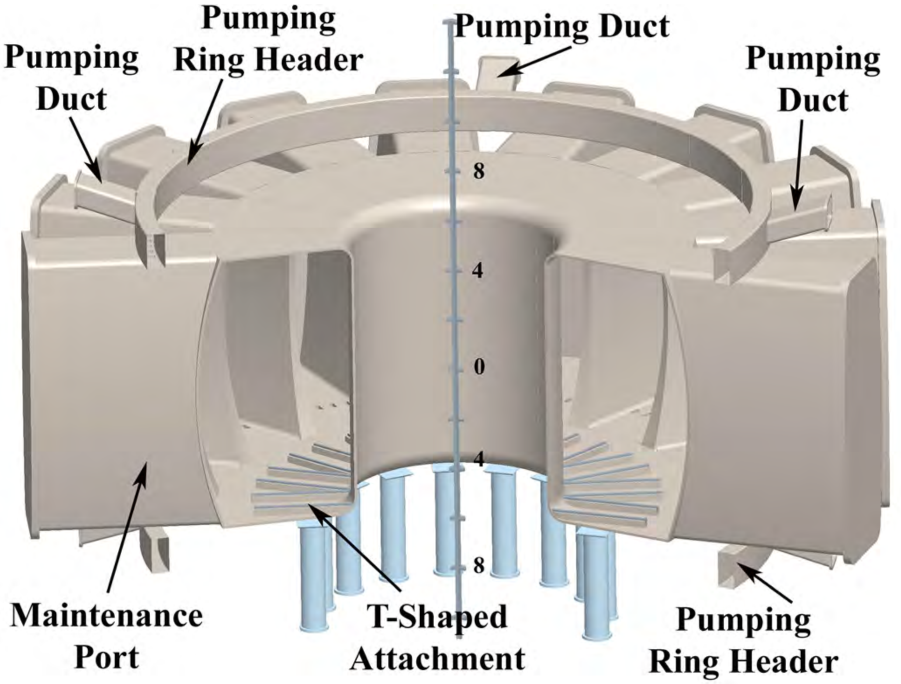
As far as we know only a small fraction (5-15%) of the tritium and deuterium injected is consumed, the rest is exhausted, processed and re-injected….so we send A LOT of tritium through the fueling/exhaust system, about 10x what we consume (or breed)

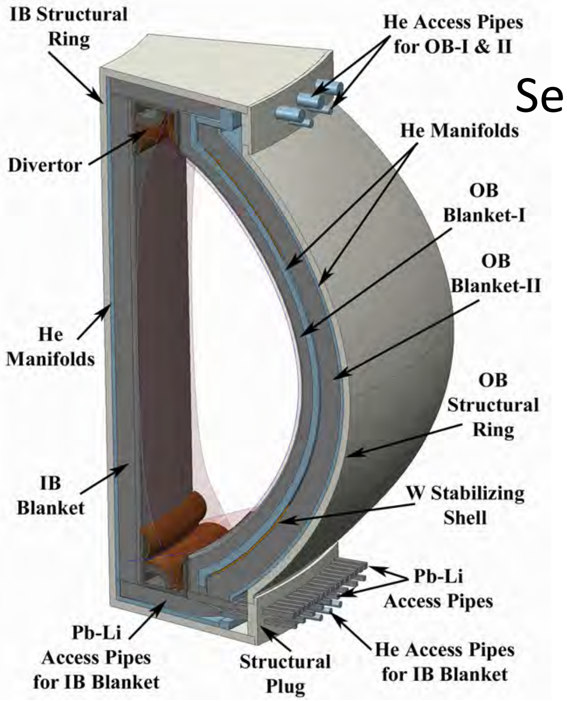
The sectors are mounted next to each other, and come in contact when hot (and due to swelling over time)….what is going to be the particle behavior in this system

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

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

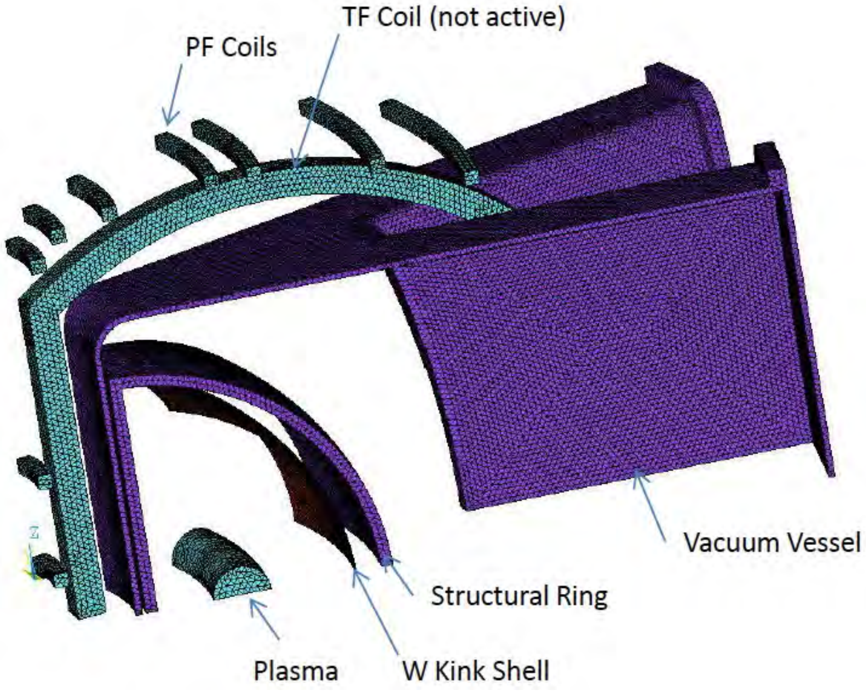
Disruption mitigation will be assumed to be available, based on experimental developments

  Transfers thermal quench deposition (mostly) to first wall
  Electromagnetic forces of current quench remain
  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 each sector

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 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 take place

Plasma performance is critical to delivering the nuclear mission, so that demonstrating the ultra-long pulses and robustly stable operating modes is central to its mission

If you are interested in examining plasma configurations produced in the study, and get involved in discussions about the plasma physics on FNSF we welcome it…..

> We will post EQDSK, profile data, evolution simulations, etc. as they become available
>
> We should have another discussion about the FNSF several months from now

Yes, I left out a number of important physics and enabling science topics for the sake of time…..

Fast particle instabilities leading to redistribution and losses
Particle, energy, momentum transport projections
SOL and divertor physics
Self-consistent core-SOL-divertor evolution
Plasma material interactions and their impact on the core plasma
Plasma control
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