PPPL
PRINCETON
PLASMA PHYSICS
LABORATORY

Fusion Nuclear Science Facility (FNSF) and PFC/PMI

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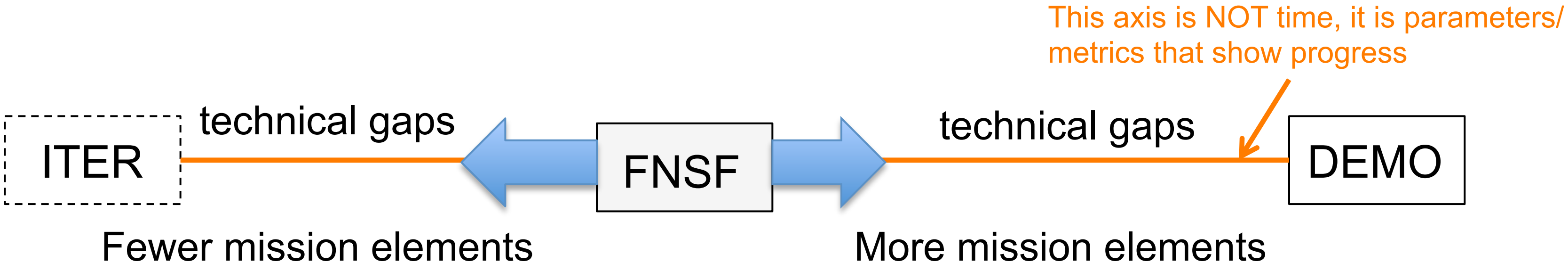
What is the FNSF….that's a good question



This axis is NOT time, it is parameters/ metrics that show progress

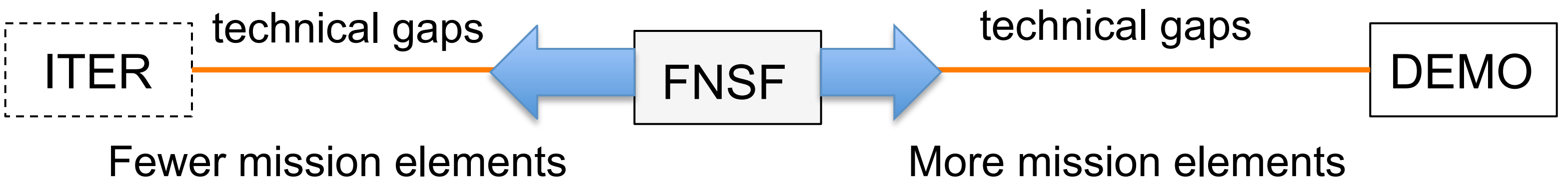
Plasma science program: confinement devices, offline facilities, theory…..

FNS base experimental program: offline facilities R&D, confinement devices,..

FNS base computational program: tool development, integration, validation

- We do not really know what the best FNSF to build is, although there are proposals FDF(GA), FNSF-ST(ORNL), Pilot Plant(PPPL)
- We have not really substantiated what must be demonstrated, work that needs to be done to prepare for DEMO
    - taking supportable technical risks to FNSF (based on preceeding research program)
    - how the FNSF program will evolve to provide required parameters, starting from feeble beginnings
    - and leaving only "manageable" gaps to DEMO (I don't need another FNSF to close gaps, or to re-define DEMO?)
- It is likely that this device will NOT be just for fusion nuclear science, but will have plasma mission elements, particularly PFC and PMI, plasma duration, and plasma fusion gain

Some parameters/metrics


ITER

technical gaps

FNSF

technical gaps

DEMO

Fewer mission elements

More mission elements

Life of plant peak neutron fluence, MW-yr/m^2

Peak neutron fluence to replace the first wall and blanket, MW-yr/m^2 (dpa)

Average and peak (outboard midplane) neutron flux, MW/m^2

Fusion power, MW

→ Tritium breeding ratio (sustainment)

Net tritium consumption over plant life, kg

Plasma fusion gain (P_{fuson}/P_{inject})

Engineering gain ($P_{elec,gross}/P_{recirculating}$)

→ Plasma performance, $\beta_N H_{98}/q_{95}$

→ Peak heat flux on divertor/FW, MW/m^2

→ Divertor/FW lifetime to replacement, years

→ Plasma on time in a year, %

Life of plant, years

→ Plasma pulse duration (what are limits), days

→ Plasma duty cycle

Overall plant availability…….

PFC/PMI will play a strong role in a number of the measures for FNSF

Hidden in these metrics is A LOT of complex physics

Some FNSF parameters for tokamaks

	ITER		**FDF**		**Pilot-AT**		**ARIES-AT**
R, m	6.2		**2.7**		**4.0**		5.2
$\langle N_w \rangle$, MW/m^2	0.67		2.0		2.2		3.3
Q	10 (5)		6.9		8.5		42
$P_{fusion,}$ MW	500 (350)	**Materials transition**	**290**		**674**	**DEMO = 75% of PP**	1800
Q_{engr}	0		**0**		**1**		7
Plasma on-time/ year	$\leq$ 5%	**Operating temperature transition**	30%		30%		100%
LOP Fluence, MW-yr/m^2	0.3		7.6		12		6x20
$P_{aux+\alpha}$/R, MW/m	25	**What will the TBM's tell us?**	43		53		79
Plasma pulse, s	500-3000		1x10^6 (14 days)				3x10^7 (1 year)

The FNSF will provide the *fully integrated environment* (T, B, q'', q''', pressure/stress, chemical, vacuum, hydrogen, flows, fusion nuclear) for *fully integrated components* like the FW/blanket, divertor, and launchers/diagnostics

What will we have in hand when we begin design/construction/operation of a FNSF (in 15, 20, 25 yrs?)

Confinement devices like US/Int'l tokamaks (few to 20 s) and EAST/KSTAR to 300-1000 s high performance steady state plasmas exceeding core time scales

- What are the materials, heat and particle fluxes? Can we get higher temperature PFC operation?....

ITER provides 500-1000s inductive and maybe 3000s steady state plasmas in this time frame

- Materials are not relevant, operating temperatures are not appropriate, but we get burning plasma consistent with PFCs under strong loading

Linear plasma devices (presumed upgrades to approach FNSF parameters)

- Very long exposure times, relevant temperatures, particle and heat fluxes, what are the limitations to creating the actual toroidal environment?...strong connection to confinement devices

High heat flux testing and engineering design of divertor and FW components (incorporating other constraints like erosion, fusion neutron damage,…)

Nuclear exposure of PFC materials

- Fission neutron spectrum for small assemblies
- Fusion spectrum for small single material samples

Did I build a long pulse DD PMI device?

What progress on computational prediction was made?

So what does an FNSF have to do?

….the FNSF must provide a technical basis for DEMO by demonstrating

tritium breeding, extraction, fueling and exhaust, and processing, reaching a tritium breeding ratio of $\geq$ 1, providing self-sufficiency

the heat extraction and electricity production

the integrated blanket (first wall, breeding zone, shield, and vacuum vessel) concept

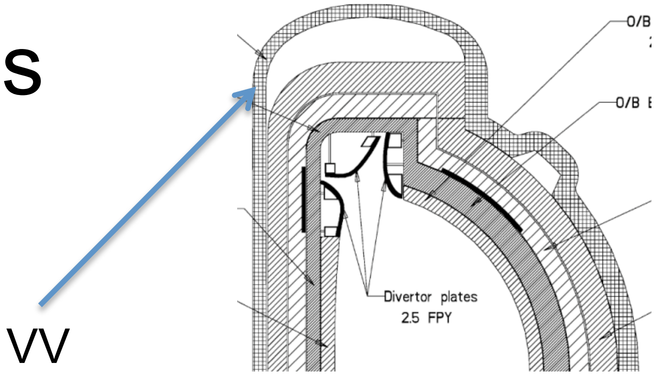
the power and particle handling in the plasma chamber, the divertor and first wall, and special PFC concepts

the long plasma durations

all support technologies (magnets, pellet injector, heating and current drive, vacuum systems, remote maintenance, diagnostics, etc.)

reliable, safe, maintainable, and inspectible operation

An FNSF will have features like a Power Plant



The VV will be behind ~ 1-1.5 m of structural, breeding and shielding material

There can be strong variations from the FW to the VV in temperature, B, neutron flux and energy spectrum, material interactions…..

Maintenance requires few large pieces to be removed, rather than the MANY pieces on ITER….typically radially or vertically remove whole sectors or parts of sectors….a FNSF may actually require port-based and large piece

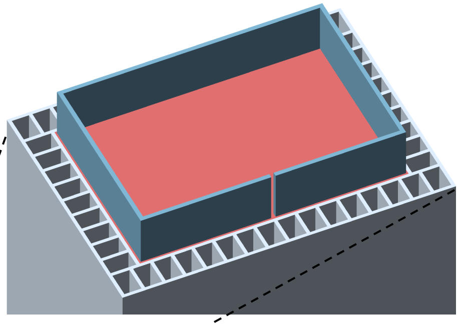
The PFCs and blankets will operate at high temperatures, for ferritic steel structures 450-650^{o}C, and probably higher for W components (800-1300^{o}C)

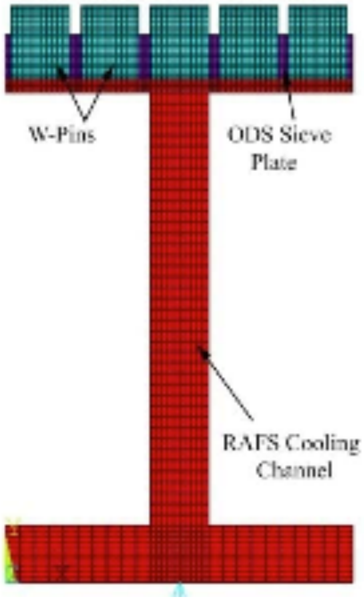
Materials must be long term relevant due to presence of significant neutron damage (ferritic steel, tungsten, SiC, LiPb, …)

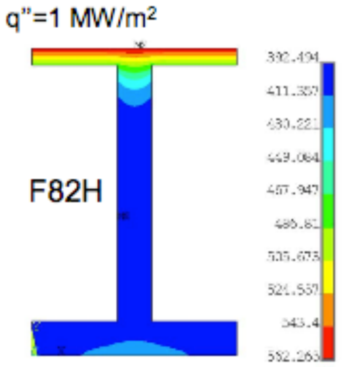
Tritium will be everywhere inside the VV! Bred tritium will diffuse into other parts of the blanket, tritium implanted in the FW/divertor can diffuse into the coolants

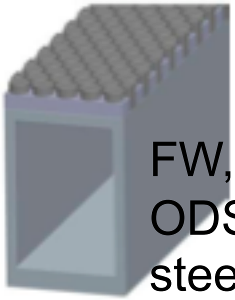
First wall and Blanket Design for Power Plant - Fe-steel/He/LiPb

RAFM structure,
He coolant,
SiC insulating sleeve,
LiPb breeder

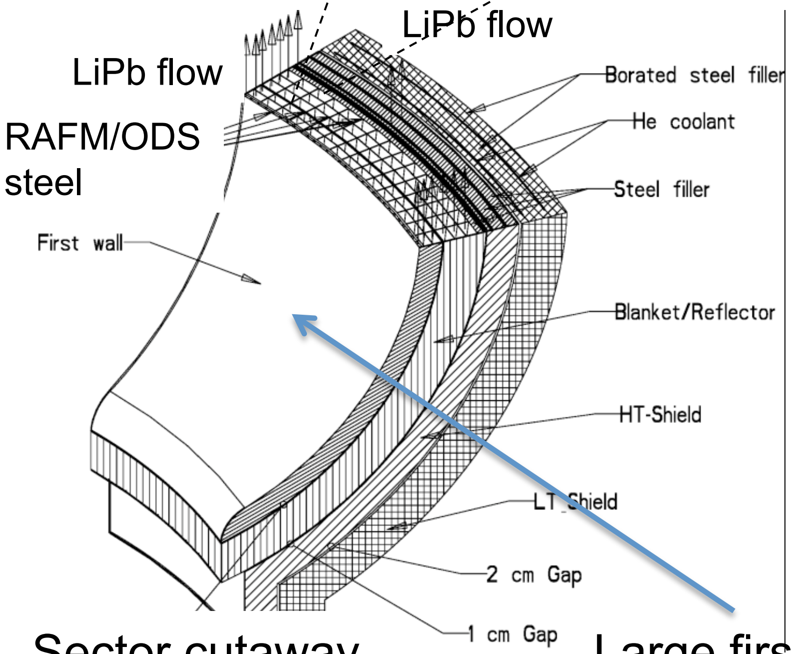








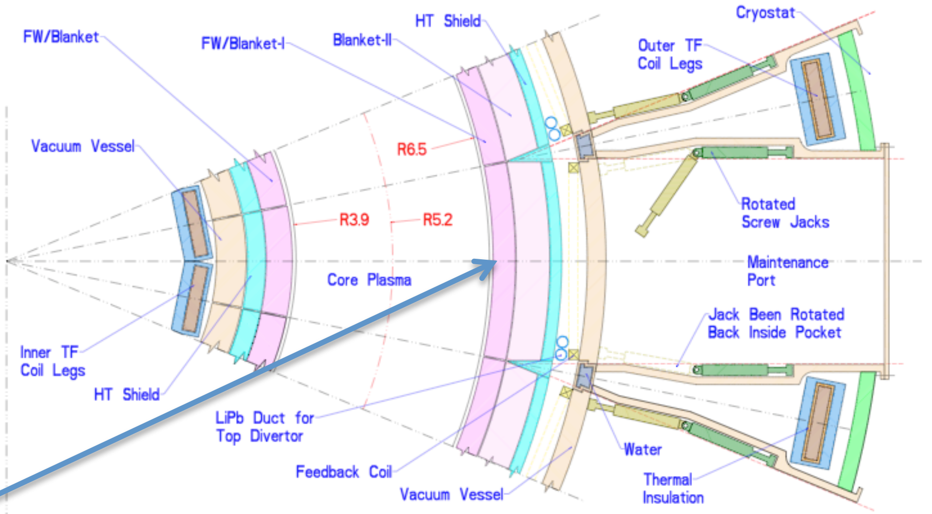
FW, W pins in ODS & RAFM steel



Sector cutaway

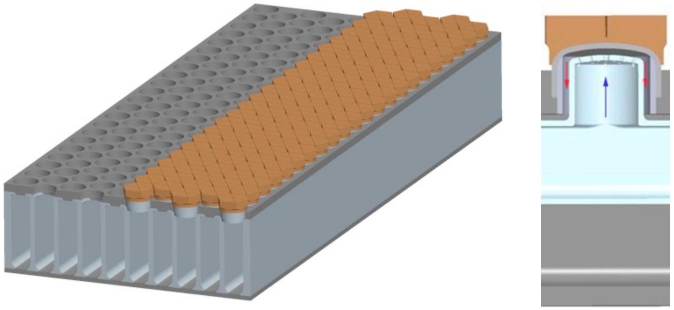
Large first wall panels

Large single piece maintenance, sectors

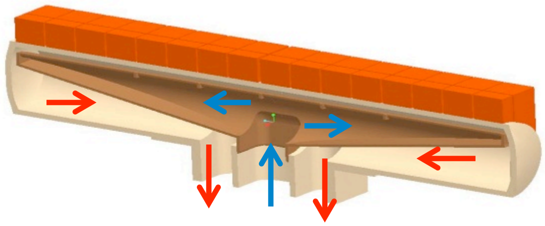


Divertor designs for power plants – He cooled tungsten

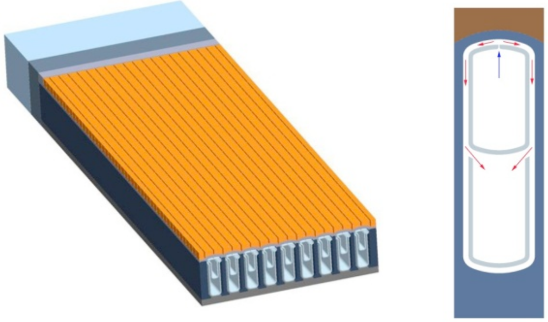
1. HCPF(He-cooled Combined Plate and Finger)

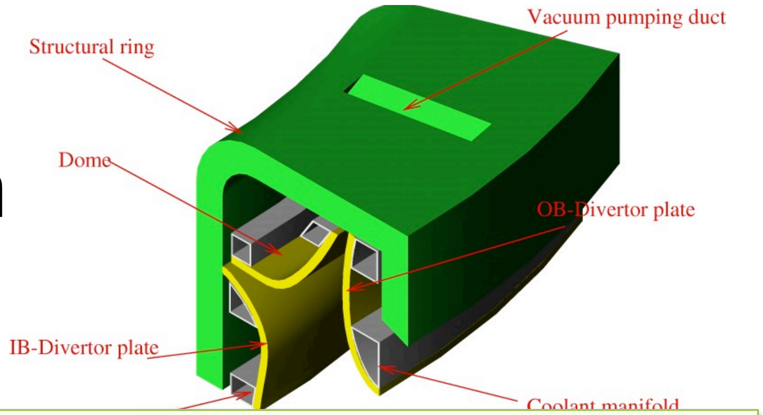


2. HCTT(He-Cooled T-Tube)



3. HCFP(Helium-cooled Flat Plate) divertor



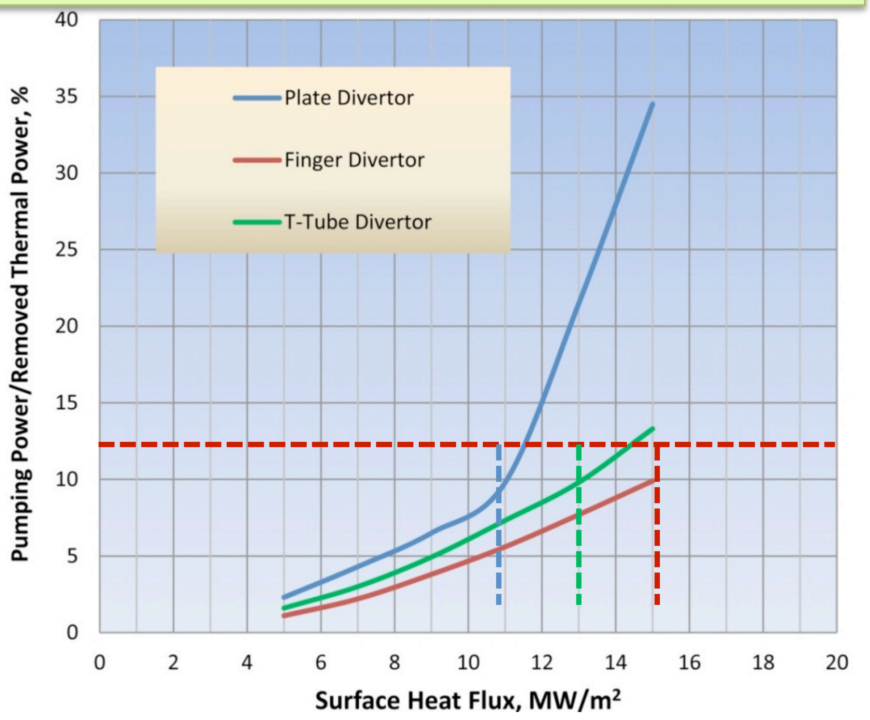


Design limits :

✓Minimum temperature of the W structure 700 °C (embrittlement)

✓Maximum temperature of the W structure 1300 °C (recrystallization)

✓Pumping power 10% of thermal power removed.

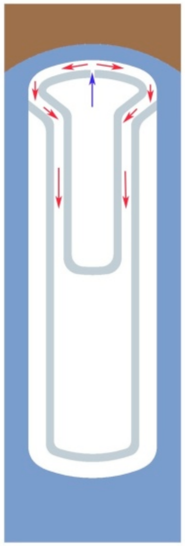


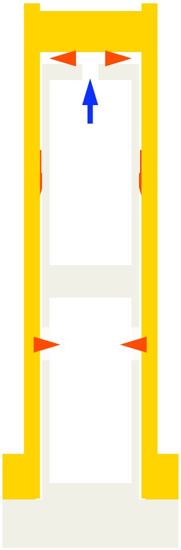
What are we trying to do on ARIES power plant studies

- Determine heat and particle loads to the divertor, first wall PFCs from ITER design criteria
  - Steady state ($P_{alpha} + P_{aux} - P_{rad}$), P_{rad}, …
  - Transient (ELMs)
  - Off-normal (disruptions

In spite of uncertainty

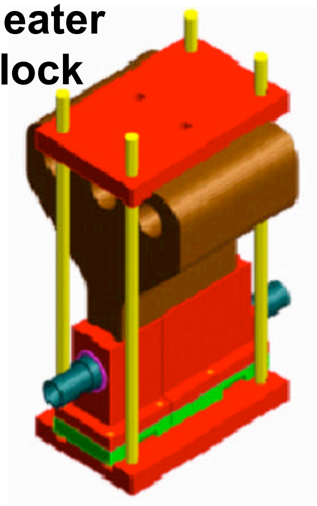
- Optimize material/coolant designs for high heat flux and erosion….W-He
- Thermo-mechanical and computational fluid dynamics analysis of steady and transient loading
- Experiments at Georgia Tech on dimensionless parameters and engineering similarity for advanced high heat flux W-He designs
- SOL/divertor analysis with UEDGE/fluid neutrals (LLNL)
- Disruption loading on conducting structures (TSC simulation to mechanical analysis of W plates, strong back structures, VV….)

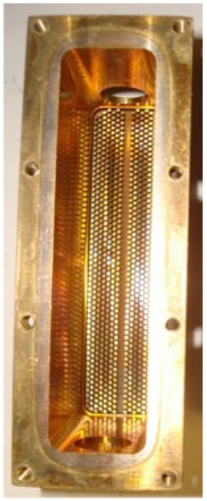




Al cartridge

Heater block





How do we reach 2 week pulses and 30% plasma on-time in a year

Present tokamaks have plasma pulse lengths of a few to 20+ seconds when in high performance

The duty cycle (plasma pulse/total cycle time between pulses) for these discharges is < 0.5%

KSTAR and EAST are expected to provide 300-1000 s long discharges (plasma pulse), duty cycle??

ITER is targeting 500 s for its reference 15 MA inductive discharges and ~ 3000 s for its advanced scenarios non-inductive discharges

The anticipated duty cycle is 25%

We expect a steady state power plant to run for ~ 1 year before routine maintenance (assumed not established), with a duty cycle of 100%

A FNSF device is expected to require plasma pulse length of ~ weeks duration, and high duty cycles……at least as determined by fusion nuclear aspects such as flow and thermal equilibrium times, tritium release and permeation, corrosion, etc.

time for plasma pulse > 3 x longest time constant
time for plasma to be off will also be constrained

Making progress on fusion nuclear issues in an FNSF puts considerable pressure on plasma pulse length, duty cycle and fraction of a year spent operating

Neutron wall loading……peak neutron wall loading ~ 1.5 x average at outboard

Assuming $<N_w>$ = 1 MW/m^2 on the OB (so peak is 1.5), if I would like to demonstrate 15 dpa of neutron damage

→1.5 MW-yr/m^2 provides ~ 15 dpa (actually depends on the material)

> →1.5 MW/m^2 for one year long pulse
> OR
> 2 years with 2 week pulses separated by 2 week down times
> OR
> 3 years with 2 week pulses separated by 2 week down times, operating these cycles for ¾ of a year

The FNSF itself appears to have a major mission to extend the plasma on-time

An important activity to pursue in the US fusion program will be to define better the missions for a FNSF, and to develop the metrics by which we judge options for a FNSF

Several features must be advanced in a FNSF through a series of phases in its operation, since the range of parameters between the ITER and DEMO environments is quite large

Although the FUSION NUCLEAR Science Facility is focused on several nuclear science issues, its success relies critically on long time sustainable plasma operation to make neutrons

The achievable plasma durations and turn-around to the next pulse will depend on PMI physics and PFC operation, control and optimization

Our facilities for understanding the PFC/PMI physics and engineering before FNSF are

- Present tokamaks
- Longer pulse Asian tokamaks (a PFC/PMI device?)
- ITER
- Offline facilities (linear plasma, high heat flux,…)
- Nuclear materials testing

FNS-PA

Fusion Nuclear Science Pathways Assessment

http://www.pppl.gov/pub_report//2012/PPPL-4736-abs.html

"…is targeting the identification of research activities necessary to advance fusion nuclear science within the US fusion program over the next 5-10 years, ….. the research should establish the technical basis for a fusion nuclear science facility (FNSF) and ultimately a demonstration fusion power plant (DEMO). "

Focused on 8 areas:

- Material science (structural, blanket, corrosion, magnet, diagnostic, design criteria)
- Power extraction and tritium sustainability
- Plasma facing components and PMI
- Safety and environment
- Enabling Technologies
  - Magnets
  - Heating and current drive systems
  - Fueling, pumping, and particles
  - Measurement issues

- Section on DEMO/power plant description/assumptions
- Section on Plasma duration and sustainment

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FNS-PA: PFC and PMI section

I tried to collect the several PFC/PMI research activities and their motivations, but ended up with a 4 hour presentation…please read the sections of report

What is important do right now?....a sampling

On US tokamaks (up to 10s pulses), establish

1) SOL/divertor measurement initiative
2) Initiative to eliminate disruptions in routine operation (mitigation)
3) Initiative to reduce/control transient heat/particle loading (ELMs)
4) Significant edge plasma and PMI computational initiative to coordinate with #1
5) Prepare to transfer this (#1-4) to EAST/KSTAR for longer pulses

Develop linear plasma devices with FNSF/DEMO anticipated loading conditions to the extents possible, and real time in-situ diagnostics

Begin PFC engineering design and experiment activity for integrated solutions (including plasma loading, PMI, high T, and fusion nuclear, *not just high heat flux*) for all plasma facing environments (divertor, FW, other)….begin using designs on confinement devices and linear facilities

Uncertainty is high for PFC materials…study of advanced magnetic configurations, liquid metal concepts and graphite should also be pursued as well as tungsten

FNS-PA: Plasma Duration and Sustainment

Both the present US tokamaks (pulse lengths ~5-10 s) and the Asian long pulse tokamaks (pulse lengths ~300-1000 s) can, in combination, address the development of integrated plasma configurations with flattop durations that exceed the longest core timescale.

…other longer time scale phenomena will need to be addressed as pulse limiting candidates. These are typically attributed to the plasma edge and materials interaction, such as erosion/re-deposition, dust or debris production, tritium retention in plasma facing components (PFCs), and lifetime limitations of PFCs, which can include the first wall, divertor, and launching or diagnostic structures.

Accessing increased plasma performance regimes in combination with viable edge plasma / divertor regimes (like detached divertor)

Particle control….injection of fuel and impurities, plasma exhaust (fuel, He, impurities), eroded materials and their migration, tritium consumption and retention, and core plasma particle transport

Control strategies for the edge plasma, divertor, dust/debris removal, heat flux…..integrated with core plasma control