The Fusion Nuclear Regime, Our Next Step What Does it Need to Do?

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SOFE Town Hall on Fusion Energy, June 4, 2019

The Compact Pilot Plant (CPP)

The Compact Pilot Plant is identified in the National Academy Study report

2nd Major Recommendation: the US should start a national program of interconnected science and technology research extending beyond what will be accomplished with ITER and leading to construction of a **compact fusion pilot plant** at the **lowest possible capital cost**

In first phase, pilot plant should be capable of **demonstrating fusion electricity** for periods lasting minutes…..

In the **second phase**, the pilot plant should be capable of **uninterrupted operation for many days allowing fusion materials and component testing** consistent with a commercial power plant……

What is compact? Size, cost, power……. Lowest possible cost, and leading to low COE?
Lower unit electric power plants as the end product?
Presumably fusion electricity is net electricity
Are two phases actually required? Do the two phases require different fusion cores?
Why is it called a Pilot Plant? Will this be a problem for the Office of Science?
What is the difference between a CPP and an FNSF?

What does a Compact Pilot Plant / Fusion Nuclear Science Facility Need to do?

Strongly advance fusion neutron exposure of all fusion core, near-core and ex-core components towards power plant levels

Utilize and advance fusion power plant relevant materials addressing radiation resistance, activation, operating temperatures, chemical compatibility, and plasma material damage

Operate in fusion power plant relevant environmental conditions; temperatures, pressures/stresses, flow rates, hydrogen, B-field, neutrons, and gradients

Produce tritium in quantities that closely approaches or exceeds consumption from fusion reactions, plant losses and decay

Extract, process, inject, and exhaust significant quantities of tritium in a manner that meets all safety criteria, requiring a high level of inventory prediction, control and accountancy

What does a Compact Pilot Plant / Fusion Nuclear Science Facility Need to do?

Routinely operate plasmas for long durations…….generally considered to be days to weeks, and ultimately ~ 1 year for a power plant

Advance and demonstration enabling technologies that support the very long duration plasma operations with sufficient performance and reliability to project to DEMO and power plants

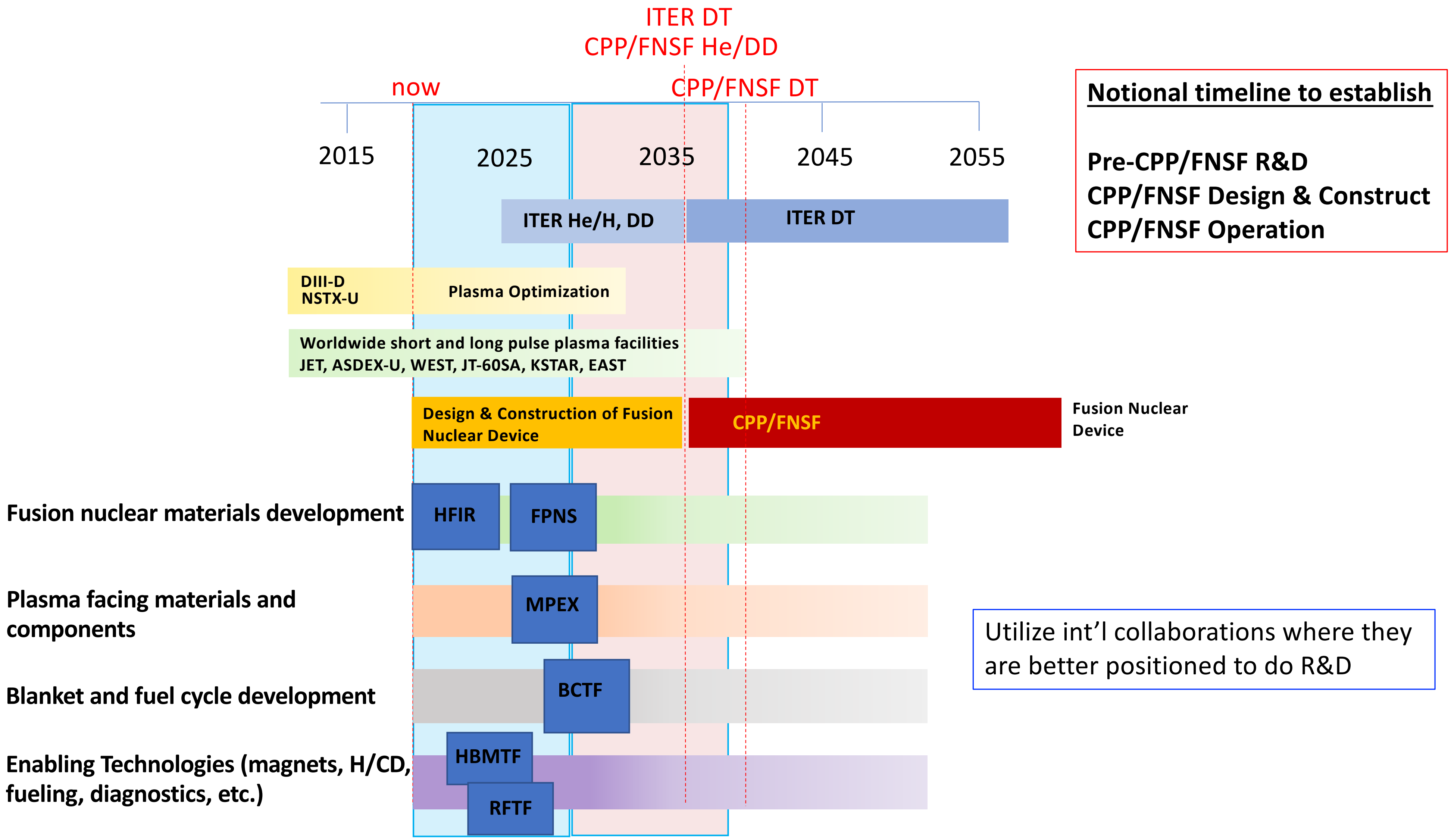
Demonstrate safe and environmentally friendly plant operations, in particular with respect to tritium leakage, hot cell operations, onsite radioactive material processing and storage, no evacuation plan and meet or exceed all regulatory aspects

Develop power plant relevant subsystems for robust and high efficiency operation, including net electricity production, heating and current drive, pumping, heat exchanger, cryo-plant, etc.

Advance toward high availability, including gains in subsystem and component **reliability**, progress in capabilities and efficiency of **remote maintenance operations**, accumulation of reliability and **failure rate data** that can be used to project and design future systems

What is the Fusion Nuclear Regime?

	ITER	CPP/FNSF	Power Plant (ACT1&2)	
Fusion power, MW	500	518	1800-2600	**Fusion power growing**
Major radius, m	6.2	4.8	6.2-9.8	**Devices getting larger?**
Ave neutron wall load, MW/m^2	0.57 (0.76 peak)	1.2 (1.75 peak)	1.5-2.5 (2.3-3.8 peak)	**Increasing rate of damage, He prod**
Plasma pulse length, s	500-3000	10^5 - 10^6	$3x10^7$	**Ultra-long plasma durations**
DT operation, years	20 (~ 1 FPY)	25 (7.8 FPY)	40 FPY	**High neutron exposure**
Peak material damage, dpa	3	7, 20, 30, 40, 40-80	150-200	**High damage, He and H production**
TBR		1.07	1.05	**Tritium self-sufficiency**
Materials	SS, CuCrZr, H_2O, W	RAFM, W, SiC-c, He, PbLi, Li_2TiO_3	RAFM, W, SiC-c, He, PbLi, Li_2TiO_3	**Transition to fusion nuclear relevant materials**
Operating temperatures	150-285 C	300-600 C	300-600 C	**Power plant operating environment**
Maintenance	Port based, small piece	Radial, Full sector	Radial, Full sector	**High availability**



ITER DT
CPP/FNSF He/DD
now
CPP/FNSF DT
2015
2025
2035
2045
2055
Notional timeline to establish
Pre-CPP/FNSF R&D
CPP/FNSF Design & Construct
CPP/FNSF Operation
ITER He/H, DD
ITER DT
DIII-D
NSTX-U
Plasma Optimization
Worldwide short and long pulse plasma facilities
JET, ASDEX-U, WEST, JT-60SA, KSTAR, EAST
Design & Construction of Fusion Nuclear Device
CPP/FNSF
Fusion Nuclear Device
Fusion nuclear materials development
HFIR
FPNS
Plasma facing materials and components
MPEX
Blanket and fuel cycle development
BCTF
Enabling Technologies (magnets, H/CD, fueling, diagnostics, etc.)
HBMTF
RFTF
Utilize int'l collaborations where they are better positioned to do R&D

Any Next Step Should be Fusion Nuclear, and Will Involve a Critical Materials-Component Exploration → Optimization

Establish the actual fusion in-service material and scientific/engineering database on all components in the fusion core and near core

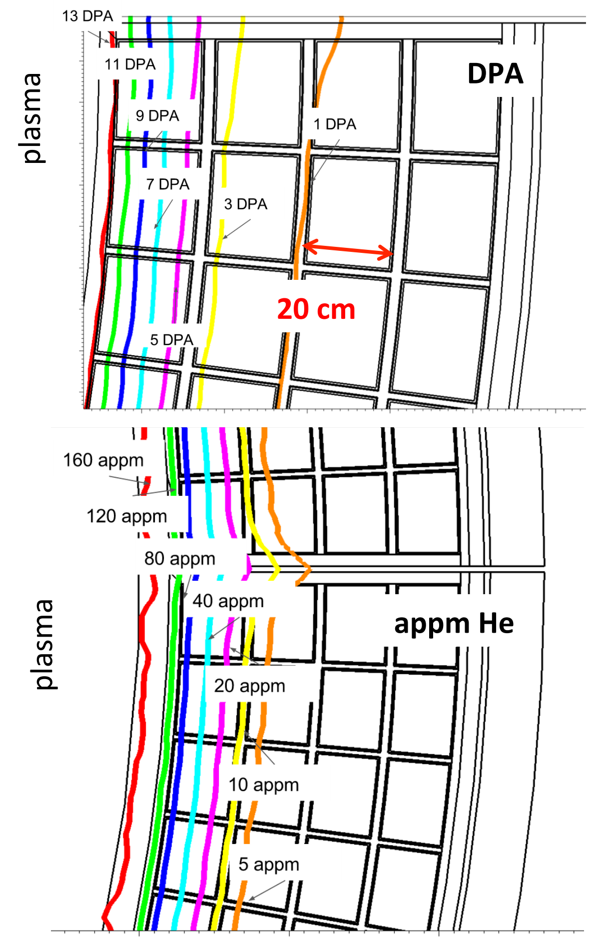
How do materials behave
How do components behave

Subject to high temperatures,
high stresses,
high neutron damage,
high He and H production,
hydrogen in material matrix (H, D, T)
multi-material interfaces
gradients in all these parameters

The CPP/FNSF needs to push to high nuclear exposures in a systematic way

We must prepare for the CPP/FNSF with 1) **fusion prototypic neutron source material exposures**, and 2) **highly integrated non-nuclear component testing**

1 FPY



Tritium, Making it, Retrieving it, Accounting for it, Controlling it

A CPP/FNSF will have to generate its own tritium, although it will have to start with an inventory produced somewhere else (fission plant?)

A CPP/FNSF will be the first complete tritium self-sufficient system

CPP/FNSF producing P_{fusion} = 518 MW

Tritium consumption = 28.8 kg /FPY (ITER lifetime consumption)

DT operation phases, plasma on-time (making neutrons):

Phase 3 – 274 days....21.6 kg Tritium consumed
4 – 460 days....36.3 kg
5 – 639 days....50.4 kg
6 – 894 days....70.5 kg
7 – 894 days....70.5 kg → 250 kg T consumed

Single plasma pulse is ~ 10 days long, requires 0.79 kg of T

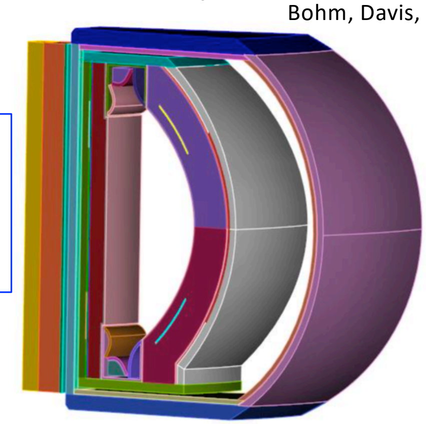
9.14×10^{-7} kg/s of T is consumed (1.82×10^{20} tritons/s)

A power plant would consume ~ 4000-5000 kg T in its life

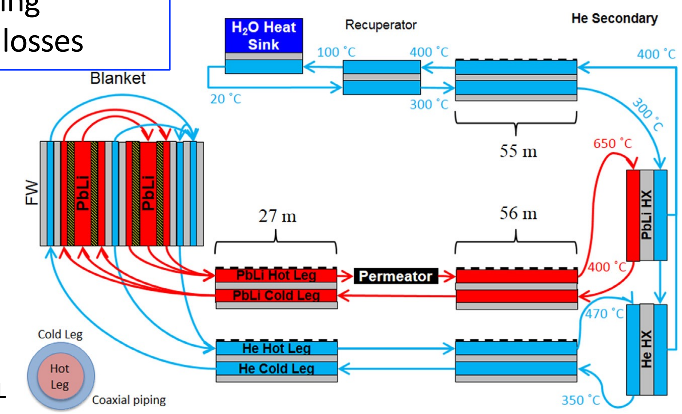
Tritium breeding ratio = 1.07

Including all penetrations for H/CD, TBM, MTM, diagnostics

Bohm, Davis, UW



Tritium migration modeling, tracking movement and losses



Humrickhouse, INL

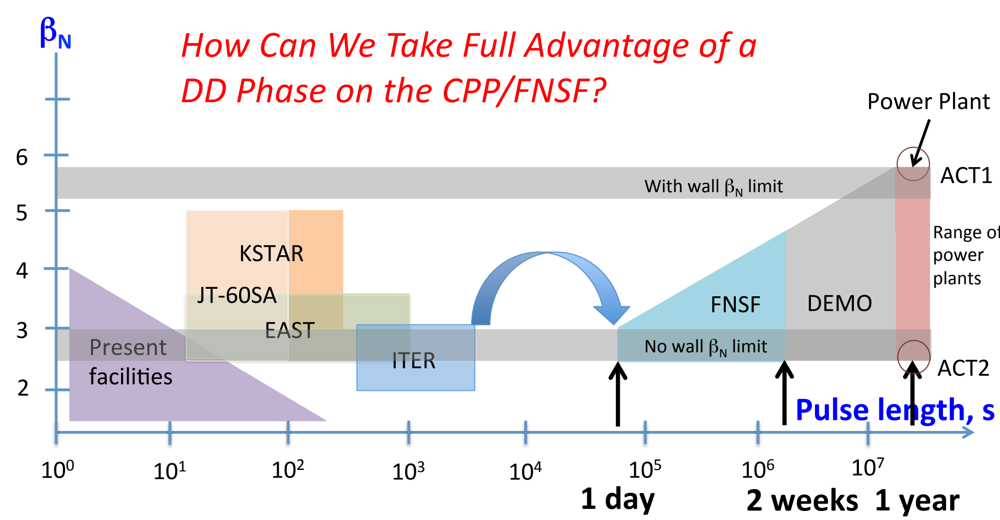
A CPP/FNSF Will Have Major Plasma Challenges

The plasma pulse length must grow by ~300 times for a CPP/FNSF and ~10^4 times for a power plant, beyond ITER

With plasma on-times per year advancing from 3×10^{-4} for present devices, to 0.05 for ITER, to 0.35 for CPP/FNSF, and 0.85 for power plants

Such long plasma durations raise many questions about the plasma operating point, and require major improvements for plasma support systems

Plasma facing components are metal, we think
What **beta** to assume? Above the no wall limit?
How high an **energy confinement** is credible?
100% **non-inductive plasma current**
Strong **plasma shaping**, **internal feedback coils**
Mitigated **disruptions**? No runaway electrons
ELMs
Density relative to **Greenwald density**
Radiative divertor solutions, DN or SN?

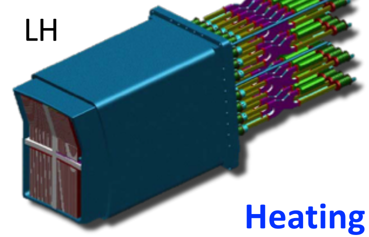


Plasma and Engineering Enabling Technologies, the Stuff That Makes it Work

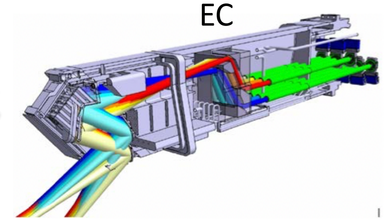
Transitioning to new materials
Transitioning to high temperatures
Long pulse plasma loading
Continuous operation
Nuclear damage and gamma rays
Limited access and resolution

Diagnostics
Plasma Control

LH

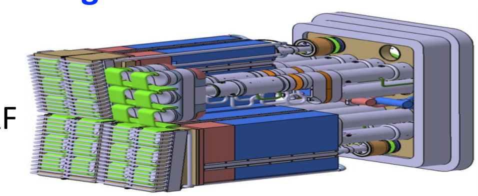


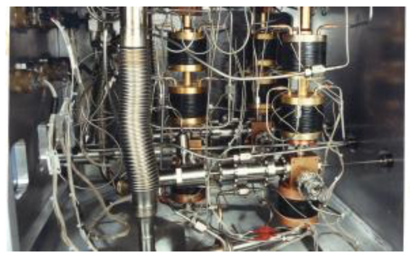
EC



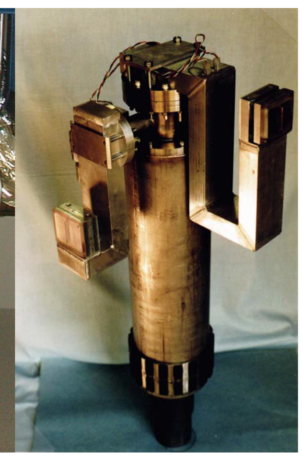
Heating and Current Drive

ICRF

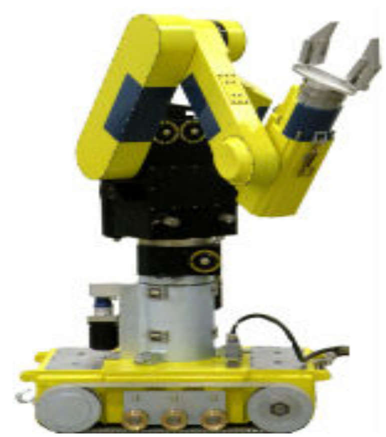




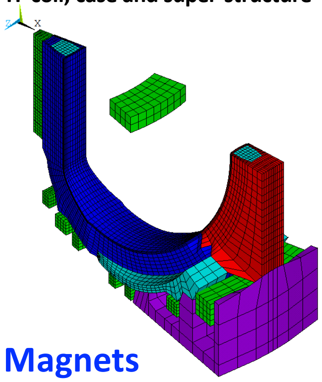
Pellet Fueling and Continuous Cryo-pumping



Remote Maintenance

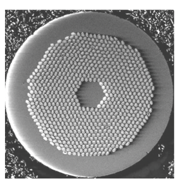


TF coil, case and super-structure

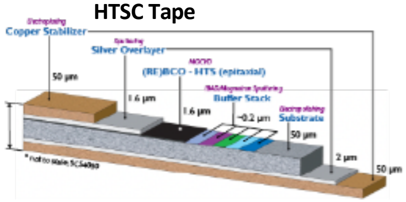


Magnets

Improved LTSC



HTSC Tape



How Compact Can a CPP/FNSF Be?

Inboard build determines the device size for a tokamak

Magnet radiation limits dominate requirements for shielding

Breeding zone thickness determined by TBR requirement

Aspect ratio can drive need for inboard breeding

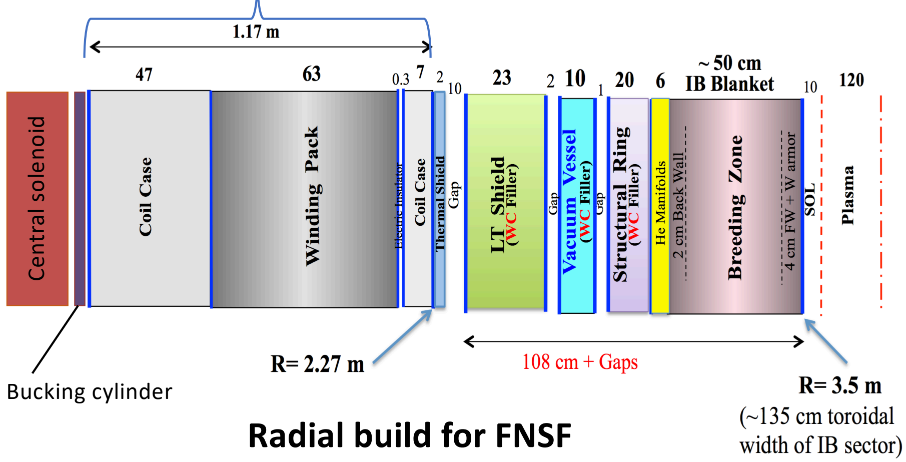
Material choices for shielding, breeding, structure
He vs H_2O, WC vs Borated-Fe, Cu vs SC

Actual TF/CS magnet builds (winding pack and structural), B and <j>

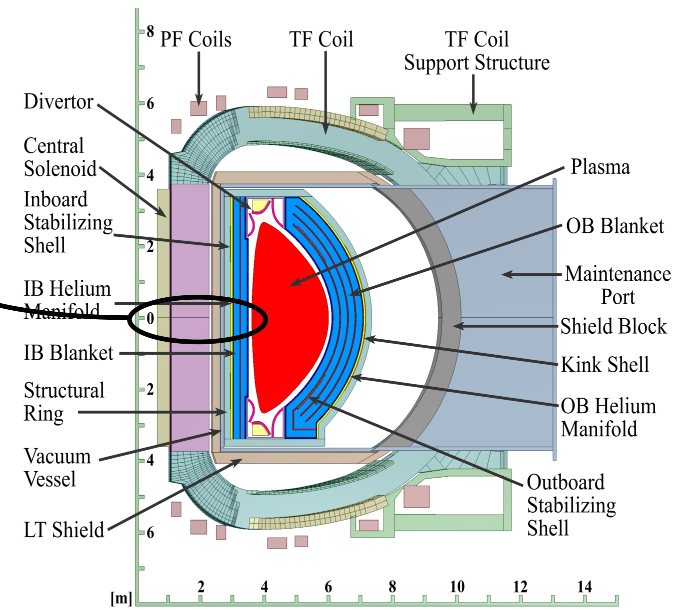
Burning out components or protecting for plant life

Assumptions for q_{div}^{peak}, β_N, H_{98}, B

LTSC TF Coil in FNSF



Radial build for FNSF



The FNSF Can Actually Provide Both Missions Described in the NAS report for the Pilot Plant

The FNSF design reference operating point for the plasma, was constructed to reflect the power plant regime, but many operating points are available to the device

		FNSF-ref					
Plasma gain (P_{fus}/P_{aux})	Q	4	5	6	7	8	9
Engr gain (P_{elec}/P_{rec})	Q_{engr}	0.77	0.98	1.12	1.26	1.40	1.53
Beta	β_N	**2.5**	**2.5** - 3.3	**2.5** - 3.3	**2.8** - 3.3	**2.8** - 3.3	**3.0** - 3.5
Energy confinement	H_{98}	**1.0**	**1.2** - 1.6	**1.3** - 1.6	**1.4** - 1.6	**1.4** - 1.6	**1.5** - 1.6
Density/density limit	n/n_{Gr}	0.9	0.45 - 0.9	0.6 - 0.9	0.7 - 0.9	0.7 - 0.9	0.8 - 0.9
Net electric power	$P_{net,elec}$, MW_e	-80	-10 - 17	14 - 27	45 - 60	54 - 95	87 - 114

A facility like the FNSF can produce net electricity by being somewhat more aggressive on plasma physics

Any Compact Pilot Plant will be very similar to the FNSF

Net electricity can be produced with somewhat more aggressive plasma physics than assumed for the reference operating point in the FNSF, in the same device with the same fusion core

The NEXT step in the US fusion development path **MUST be Nuclear**, but is not a power plant……whatever you want to call it, a CPP, a FNSF

- Establishing the strongly fusion nuclear & plasma in-service environment for the first time, and optimizing the fusion core material-components
- Establishing the first tritium self-sufficient facility
- Establishing the first sustained ultra-long pulse plasmas and the multiple enabling technologies that support these
- Provide the first integrated operation of a strongly fusion nuclear plant with all relevant subsystems

Backup Slides

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

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

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 and engineering strategy – 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

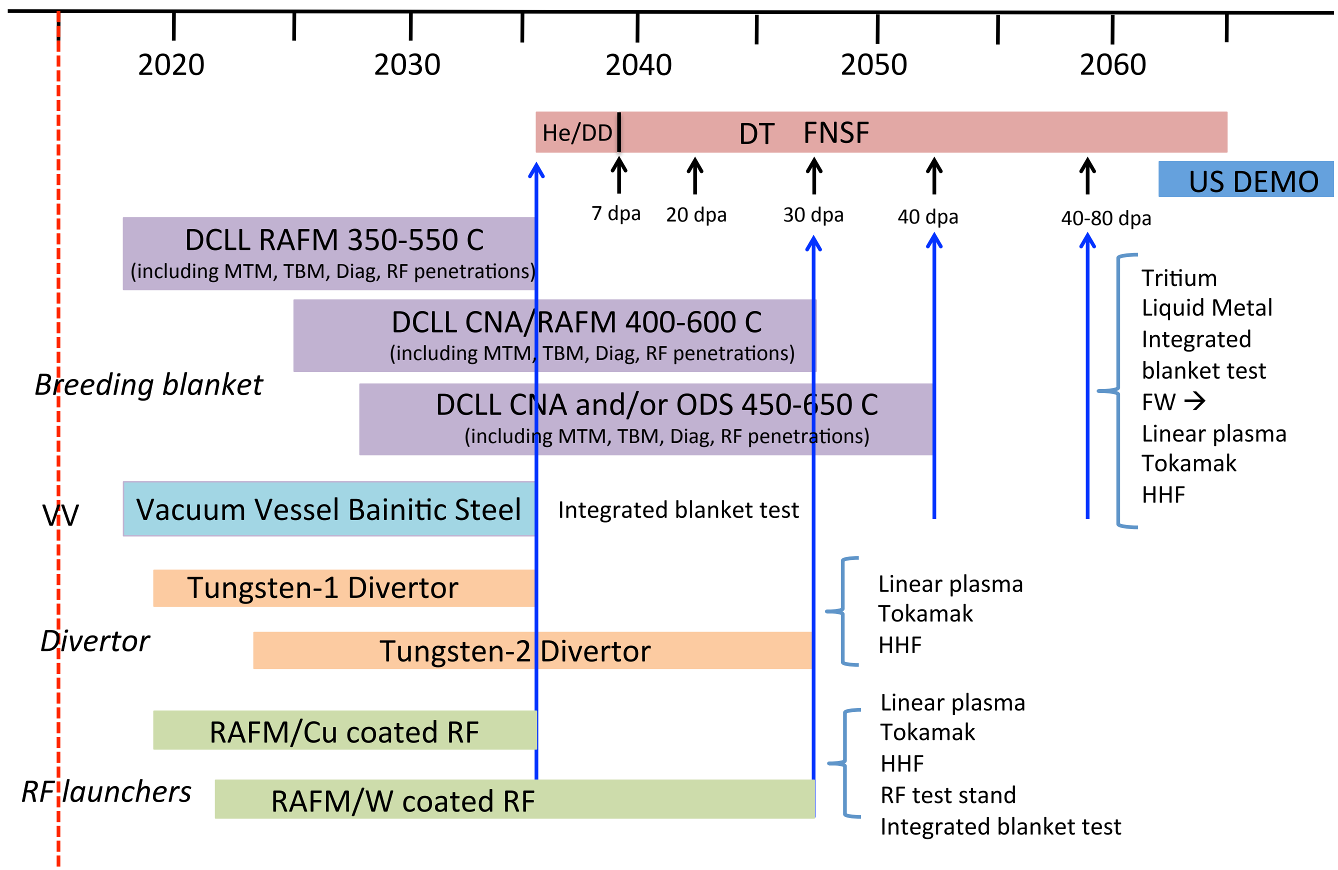
Qualification requirements to install a component/material in the FNSF – fusion neutron exposure to the dpa level, highly integrated non-nuclear testing…..plasma-vacuum systems are not consistent with "cook and look" approach to FNS, remote-maintenance

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: Fusion Core Components, Evolution to Integrated Component Testing (Blanket, Divertor, RF Launcher)

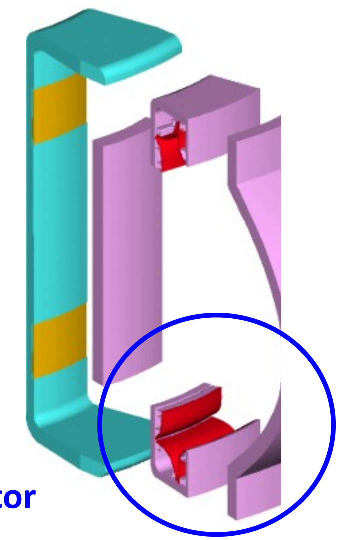


Phase	1	2	3	4	5	6	7	
	He/H	**DD**	**DT**	**DT**	**DT**	**DT**	**DT**	**PP**
years	1-2	**2-3**	**2.75**	**4.5**	**5.0**	**6.5**	**6.5**	**40 FPY**
N_w^{peak}, MW/m^2			1.75	1.75	1.75	1.75	1.75	2.25
Plasma on-time, %/year		**15-50**	**15** **55 d**	**25** **91 d**	**35** **128 d**	**35** **128 d**	**35** **128 d**	**85** **310 d**
Plasma duty cycle, % (pulse/dwell)			33 (1d/2d)	67 (2d/1d)	91 (5d/.5d)	95 (10d/.5d)	95 (10d/.5d)	100%
Total maintenance time, days			550 d 200 d/yr	1131 d 229 d/yr	1120 d 224 d/yr	1495 d 230 d/yr	1495 d 230 d/yr	2585 d 55 d/yr
Peak dpa			**7.2**	**19.7**	**30.6**	**39.8**	**39.8/79.6**	**150-200**
Max/min blanket structure op temp, °C	< 550	< 550	**550/400**	**550/400**	**600/450**	**650/500**	**650/500**	**650/500**
Blanket Structure material	RAFM Gen1	RAFM Gen1	RAFM Gen1	RAFM Gen1	RAFM-CNA	RAFM-CNA & ODS	RAFM-ODS	

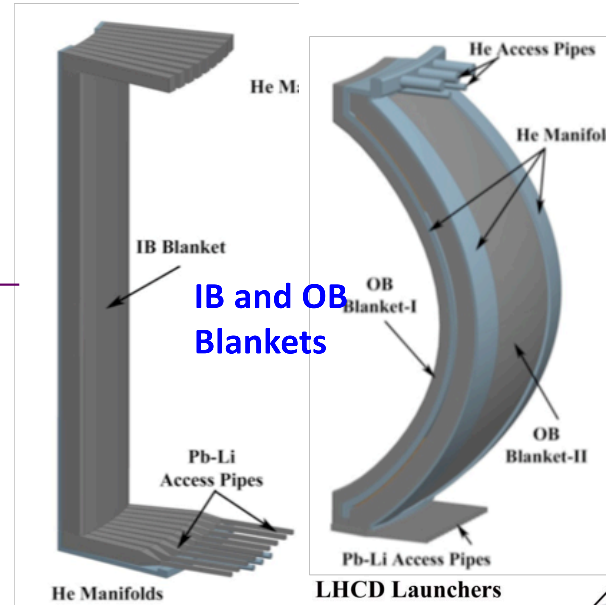
25.3 years DT, 7.8 years neutrons, 650 plasma pulses

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

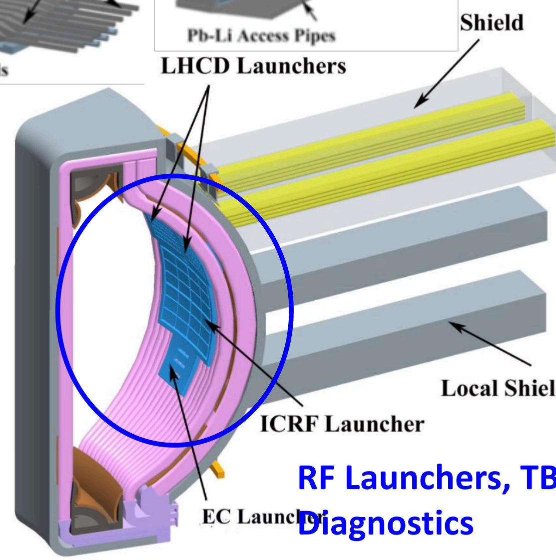
We concentrate on the blankets, but there are others that may have a testing sequence…..materials, temperatures, design, etc.



Divertor



IB and OB Blankets

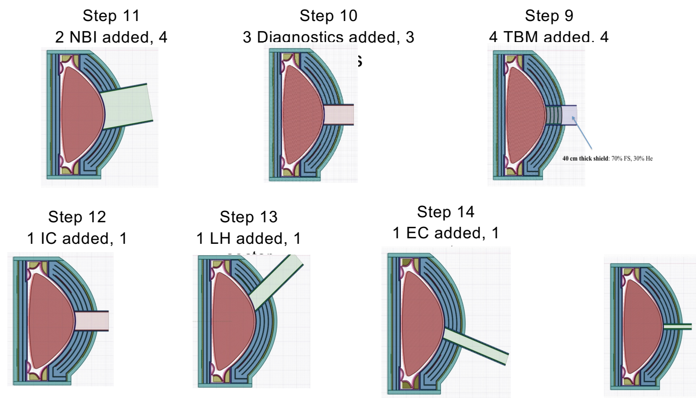


RF Launchers, TBMs, Diagnostics

Blanket Layout and Testing

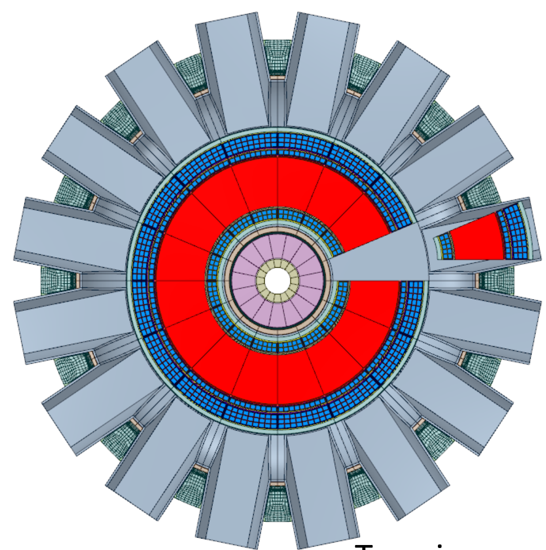
There are several DIFFERENT blanket geometries due to multiple functions in the FNSF

Nuclear analysis of different sectors



A. Davis, UW

DCLL 550/400C RAFM (some are taken for autopsy)		**4**
DCLL 550/400C RAFM/ **LH**		**1**
DCLL 550/400C RAFM/ **EC**	**combined diag**	**0**
DCLL 550/400C RAFM/ **NB**		**2**
DCLL 550/400C RAFM/ **IC**		**1**
DCLL 600/450C RAFM CNA **(next phase T and RAFM)**		**2**
DCLL 550/400C RAFM/ **MTM**		**1**
DCLL 550/400C RAFM/ **TBM-HCLL**		**1**
DCLL 550/400C RAFM/ **TBM-HCCB(PB)**		**1**
DCLL 550/400C RAFM/ **Diagnostic**		**3**
		16



Top view

Divertor Testing, must fit into the allocated envelope

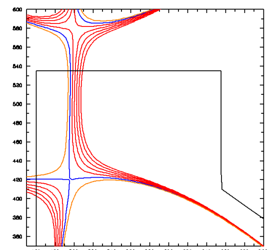
What will be the preferred W or other divertor material?

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

Will there be variants like RAFM?
Structure & armor design

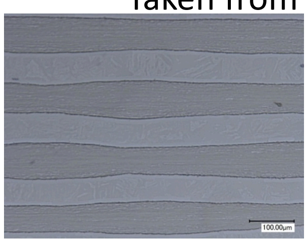
Magnetic geometries

Structure Temperature ranges

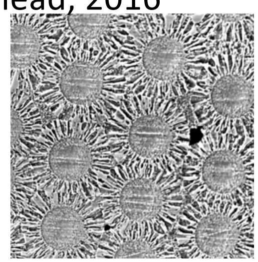


X-divertor, KDEMO
Covelle, Univ Texas

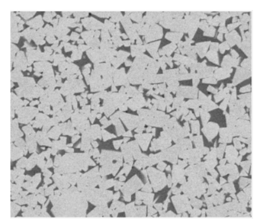
Taken from Snead, 2016



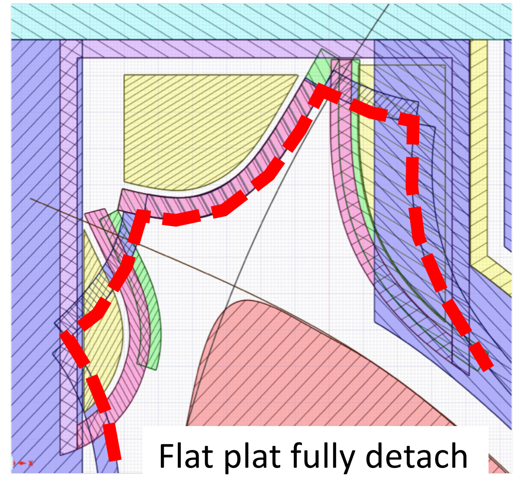
W/RAF laminate (Garrison)



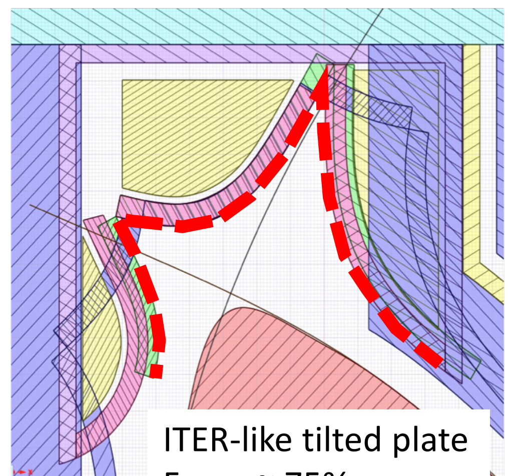
FZJ



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



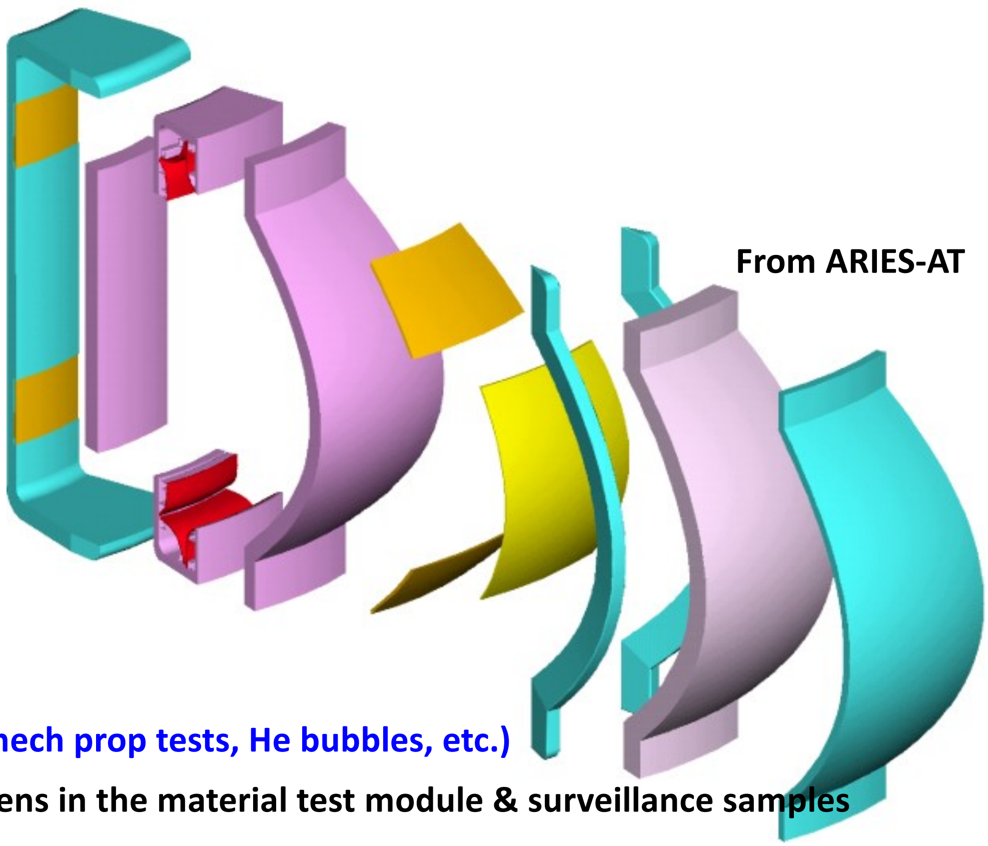
Flat plat fully detach
$F_{div,rad}$ ~ 100%



ITER-like tilted plate
$F_{div,rad}$ ~ 75%

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
- ……



From ARIES-AT

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

Also examine the test specimens in the material test module & surveillance samples

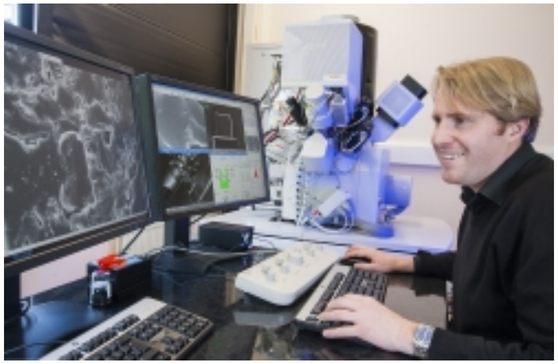
Hot Cell

We are anticipating a hot cell sequence from large intact sectors progressively down to small material samples, requiring a transfer from hot cell 1 to hot cell 2, etc.…***we want information quickly***

Robotic and computer controlled systems would dominate the processing

10,000 Sv/hr dose at FW vs 6 mSv/year background

Issues include 1) high dose and hardened equipment, 2) complex processing (tritium, surface materials), 3) decay heat, and 4) need for rapid turnaround

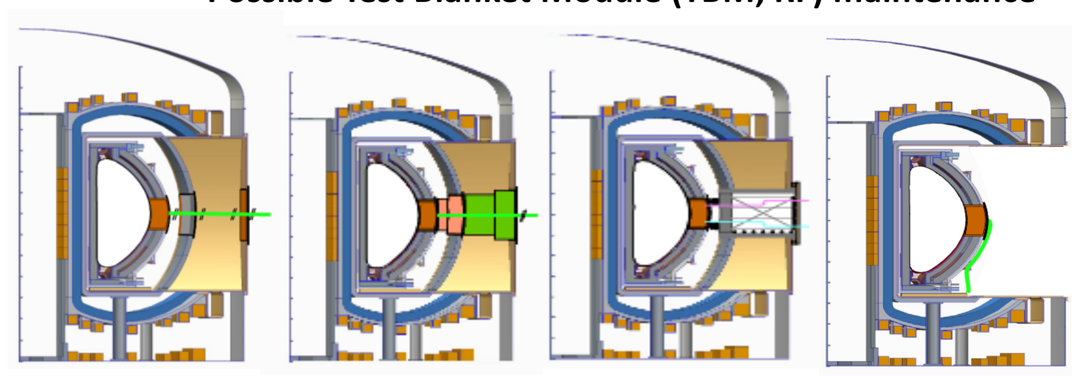


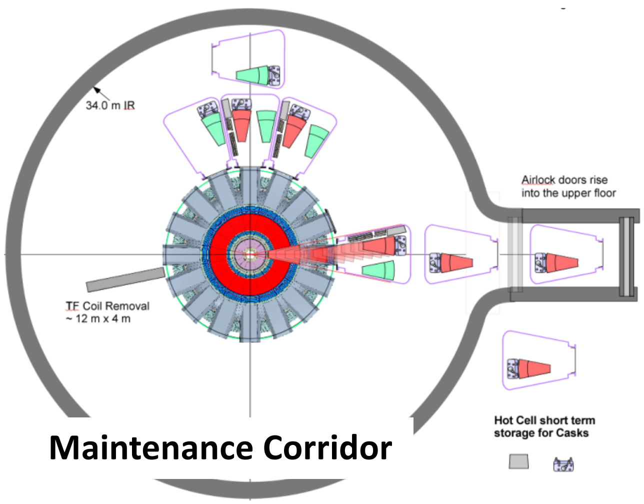
Full Sector Maintenance is Pursued to Provide Fast, Flexible and Reliable Approach

Possible Test Blanket Module (TBM, RF) maintenance

Inspection
Minor Maintenance
Major Maintenance

How much time does it take?





Maintenance Corridor

Maintenance Cask