Testing Strategy, Implications for R&D and Design

- What are the preferred blankets options for testing on FNF and what are the implications for R&D?
- Comparison of strategies for testing space allocation on NSFNF:
  a) all or most outboard occupied by test modules/test sectors
  b) base blanket with test modules in test ports (ITER type)
- Number of blanket concepts to be tested in NSFNF in 2 cases:
  a) Assuming ITER TBM is carried out
  b) With no US ITER TBM
- R&D required to place a test module on FNF (how does it compare to ITER TBM?)
- R&D required for base blanket

Strong sentiment that at least out board space be used for testing concepts

- **To grow confidence in real blanket concept, this Testing space will be needed to study**
  - Multiple module variations
  - Statistical variations
  - Intermodule interaction effects

  Why waste time and money on a development program with no future for fusion
- **At a minimum, the use of DEMO relevant structural material (RAFS) and coolant (He) is highly desirable**
  - Useful data on failures (MTBF) and maintainability (MTTR)
- **If this space is less maintainable than port based space, then use more conservative operating conditions (temperature/pressure ranges) than port-based tests to help maximize MTBF**

Possible Strategies for Testing

- **Role of "Base blankets" in testing**
  - Assumed that maintainability is significantly slower than port based blankets
    - designed and operated conservatively initially
    - "pushed" during final run weeks of scheduled campaign
  - Standardization of design/attachement, but with some automatic variations of wall load based on position
  - Some, but limited operational data
    - Inlet/outlet coolant temperatures/pressures/flowrates
    - Inter-module effects (maintaining flow partitioning)
    - System wide data (permeation/corrosion)
  - Significant PIE data and statistics on synergistic impacts of environment and loads on structures[3]

Options for base breeding blanket

- **ITER has designed a low temperature SS/H20 breeding blanket for fluence of 1MW.yr/m2 but SS should really be avoided**
  - Not relevant, low k, no clear advantage of larger database, mixed magnetic effects with test blankets
- **Any US or EU reference concepts with Ferritic steel could be realistically considered:**
  - Helium-Cooled Ceramic Breeder with Ferritic Steel structure will be the most tested concept in ITER TBM and (arguably) will have the most extensive R&D
  - Helium-Cooled or Dual Cooled Lead Lithium with Ferritic Steel structure
    - HCLL may seem more conservative, but DCLL may have higher reliability (some redundant systems, less complicated structure) and safety (e.g. tritium)
  - Self-cooled PbLi (depending FNF field and ability for FW cooling)
    - No helium, less complicated structure, sandwich or no FCIs

Testing Strategy for Port Based Test blankets

- **Assumed to be more maintainable, controllable and accessible**
  - Can be run less conservatively
  - Can be controlled individually (dedicated ancillary systems)
  - Can be highly instrumented
- **Test specially-designed act-alike (wrt most important phenomena) modules and submodules that can scale to best to DEMO**
- **Test sub-variations in concept design/material choices**
- **Test look-alike neutronics modules that require deployment/retrieval/replacement of passive/active nuclear diagnostics**
- **Test controlled temperature/environment material specimen submodules (also with deployment/retrieval)**

Testing Strategy, Implications for R&D and Design

- What should be the testing goals?
  - scientific & technical knowledge – discover, understand, innovate, to arrive at components ready for full testing (max time scales of interest)
  - component qualification leading to reliability growth (~2wk pulses)
- Which test components require very high remote handling access?
  - Blanket test modules: mid-plane and off mid-plane
  - Divertor modules
- What should be the stages and their goals for testing?
  - HH – commissioning with full hands-on capabilities
  - DD – before full fusion operation with limited hands-on
  - DT-1 – baseline fusion nuclear testing: ~1 MW/m2?
  - DT-2 – stretch goals: higher WL, more plasma performance
- Design for staged installation and upgrades to enable staged testing
  - Full modularization with remote handling of all activated components?
  - Flexibility of supporting systems: H_2O to He cooled systems?
  - Conservative design/performance vs. advance designs for testing?

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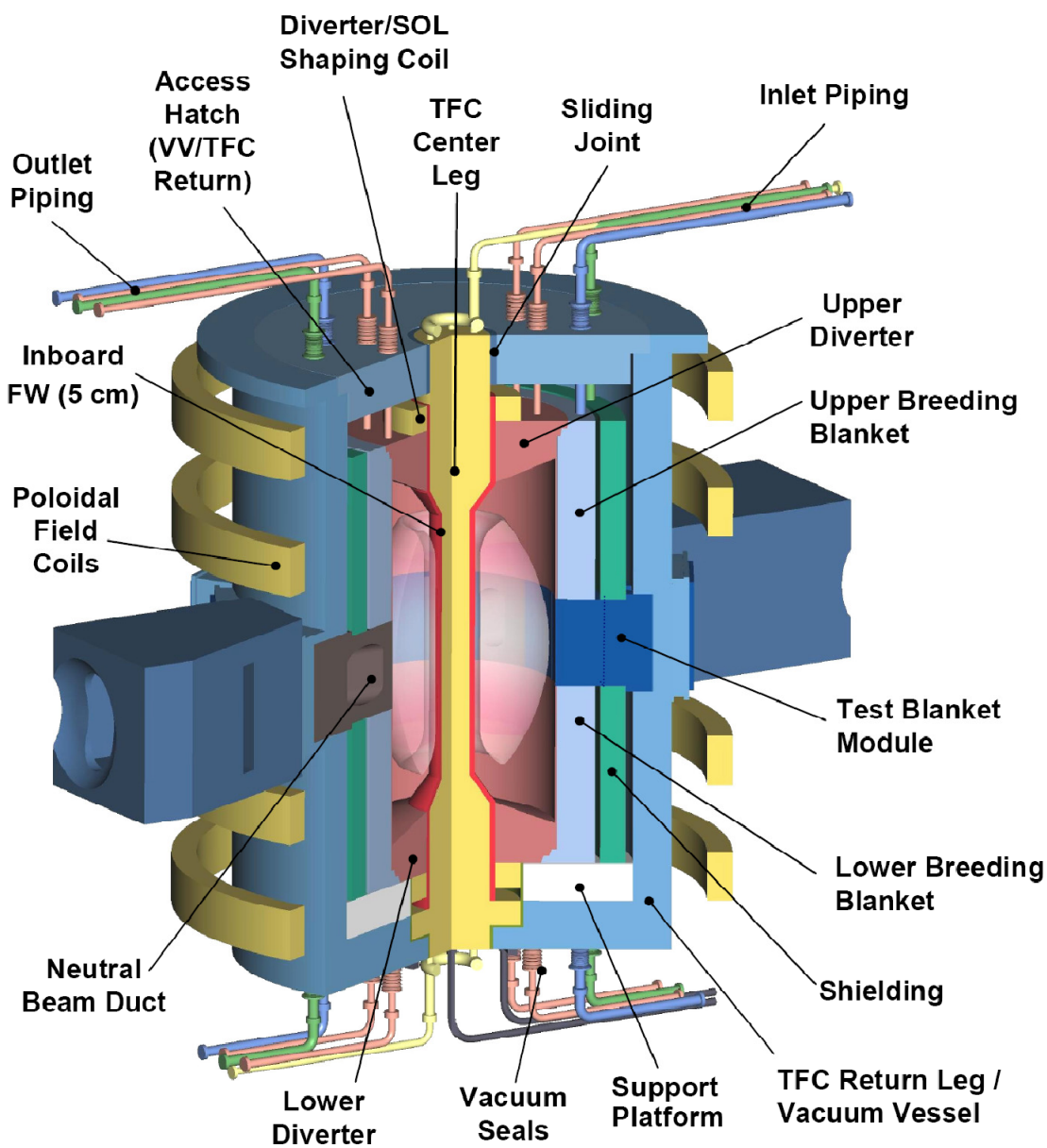
Fusion Development Facility – A Phased Approach

- Steady progress through sequenced objectives

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	← START UP →					← FIRST BLANKET TESTS →					← ADVANCED BLANKETS ADVANCED PLASMAS →					← ADVANCED PLASMAS HIGH FLUENCE →				
	H		D		DT	DT					DT					DT				
Fusion Power (MW)	0		0		125	125				250	250				≤400	≤400				≤400
P_N/A_{WALL} MW/m^2)					1	1				2	2				3.2	3.2				3.2
Pulse Length (Min)	1				10	SS				SS	SS				SS	SS				SS
Duty Factor	0.01				0.04	0.1				0.2	0.3				0.3	0.3				0.3
T Burned/Year (kG)					0.28	0.7				2.8	4.2				5	5				5
Net Produced/Year (kG)					0	0				0.56	0.84				1.0	1.0				1.0
Main Blanket	Shield (ss/H_2O)					T Producer					First Fusion Blanket					Second Fusion Blanket				
TBR					0	0.8				1.2	1.2				1.2	1.2				1.2
Test Blankets						1,2			3,4		5,6			7,8		9,10			11,12	
Accumulated Fluence (MW-yr/m^2)					0.06					1.2					4.1					8.9
P_{AUX}/P_{CD} (MW)	70/50				50/50	50/50				60/60	60/60				70/70	70/70				70/70

Device example has moderate parameters including tritium consumption



W_L [MW/m^2]	0.1	**1.0**	2.0
R0 [m]		**1.20**	
A		**1.50**	
kappa		**3.07**	
qcyl	4.6	**3.7**	3.0
Bt [T]	1.13	**2.18**	
Ip [MA]	3.4	**8.2**	10.1
Beta_N	**3.8**		5.9
Beta_T	0.14	**0.18**	0.28
n_e [10^{20}/m^3]	0.43	**1.05**	1.28
f_{BS}	0.58	**0.49**	0.50
T_{avgi} [keV]	5.4	**10.3**	13.3
T_{avge} [keV]	3.1	**6.8**	8.1
HH98		**1.5**	
Q	0.50	**2.5**	3.5
$P_{aux\text{-}CD}$ [MW]	15	**31**	43
E_{NB} [keV]	100	**239**	294
P_{Fusion} [MW]	7.5	**75**	150
T M height [m]		**1.64**	
T M area [m^2]		**14**	
Blanket A [m^2]		**66**	
$F_{n\text{-}capture}$		**0.76**	

FESAC Report on Opportunities, etc. identified 15 gaps for fusion energy – 9 in engineering and nuclear science and technology

3 Themes:

How Initiatives Could Address Gaps

Legend

Major Contribution	3
Significant Contribution	2
Minor Contribution	1
No Important Contribution	

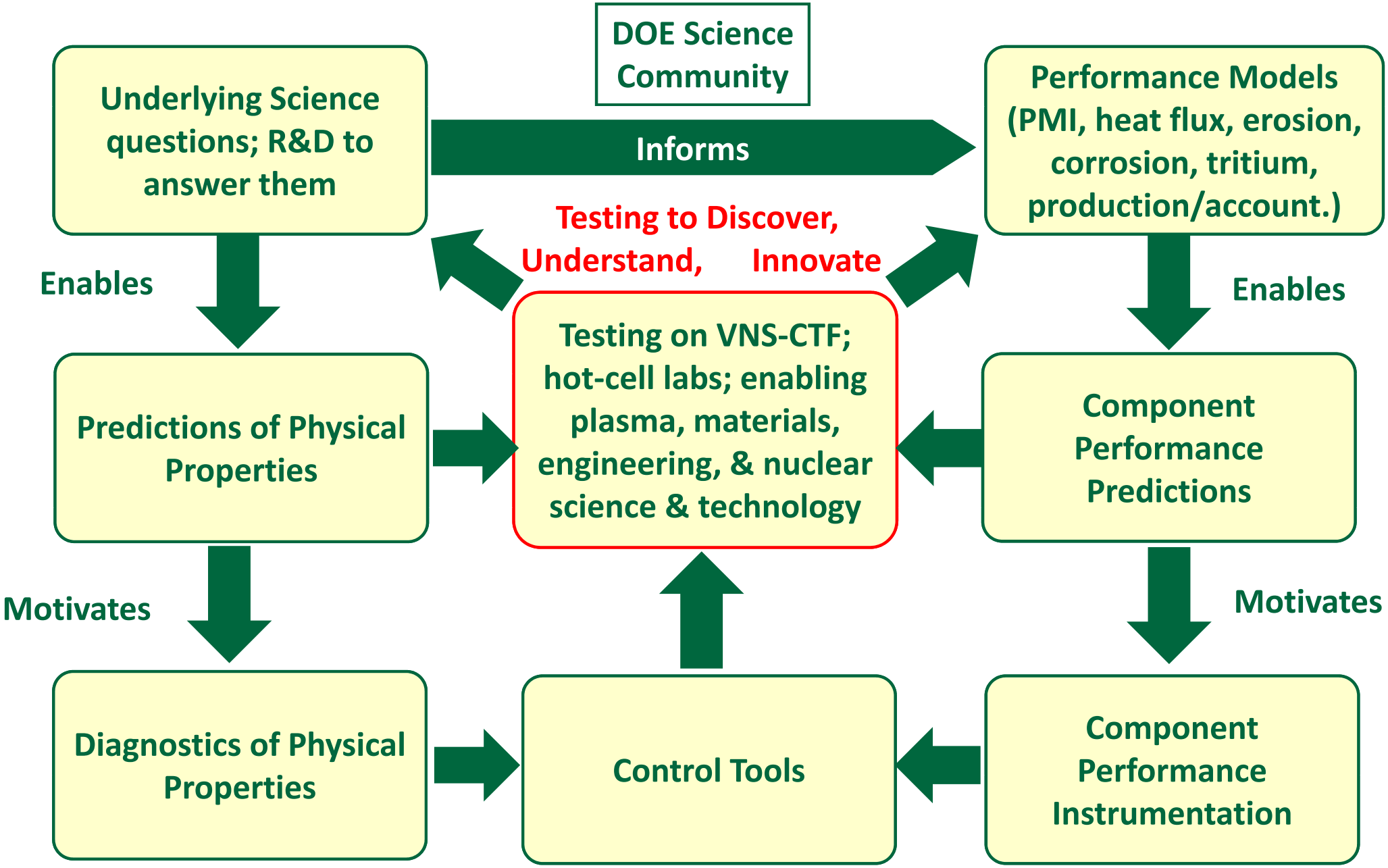
	A								B		C				
	G-1 Plasma Predictive capability	G-2 Integrated plasma demonstration	G-3 Nuclear-capable Diagnostics	G-4 Control near limits with minimal power	G-5 Avoidance of Large-scale Off-normal events in tokamaks	G-6 Developments for concepts free of off-normal plasma events	G-7 Reactor capable RF launching structures	G-8 High-Performance Magnets	G-9 Plasma Wall Interactions	G-10 Plasma Facing Components	G-11 Fuel cycle	G-12 Heat removal	G-13 Low activation materials	G-14 Safety	G-15 Maintainability
I-1. Predictive plasma modeling and validation initiative	3	2		2	2	3	1		2						
I-2. ITER – AT extensions	3	3	3	3	3		2		2	2	1	1		1	1
I-3. Integrated advanced physics demonstration (DT)	3	3	3	3	3	1	3	2	3	3	1	1	1	1	1
I-4. Integrated PWI/PFC experiment (DD)	2	1		1	2		2	1	3	3	1	1		1	1
I-5. Disruption-free experiments	2	1		2	1	3		1	1	1					
I-6. Engineering and materials science modeling and experimental validation initiative							1	3	1	3	2	3	3	2	1
I-7. Materials qualification facility							1			3	2	1	3	3	
I-8. Component development and testing			1				2	1		3	3	3	2	2	2
I-9. Component qualification facility	1	1	2	1	2		3	2	2	3	3	3	3	3	3

A - Creating predictable high-performance steady - state plasmas: ITER + stellarators + superconducting tokamaks + modeling; plasma control technologies (magnets, plasma heating and current drive, fueling etc.) – likely via international collaborations.

B - Taming the plasma-material interface: plasma wall interactions (sputtering, melting etc), plasma facing materials and components (high heat flux, rf antennas etc.) under very high neutron fluence

C - Harnessing fusion power: tritium breeding & handling, high grade heat extraction, low activation materials, safety, remote handling

A Broadened Program of component testing will enable discovery, understanding, and innovation to bridge the gaps in knowledge



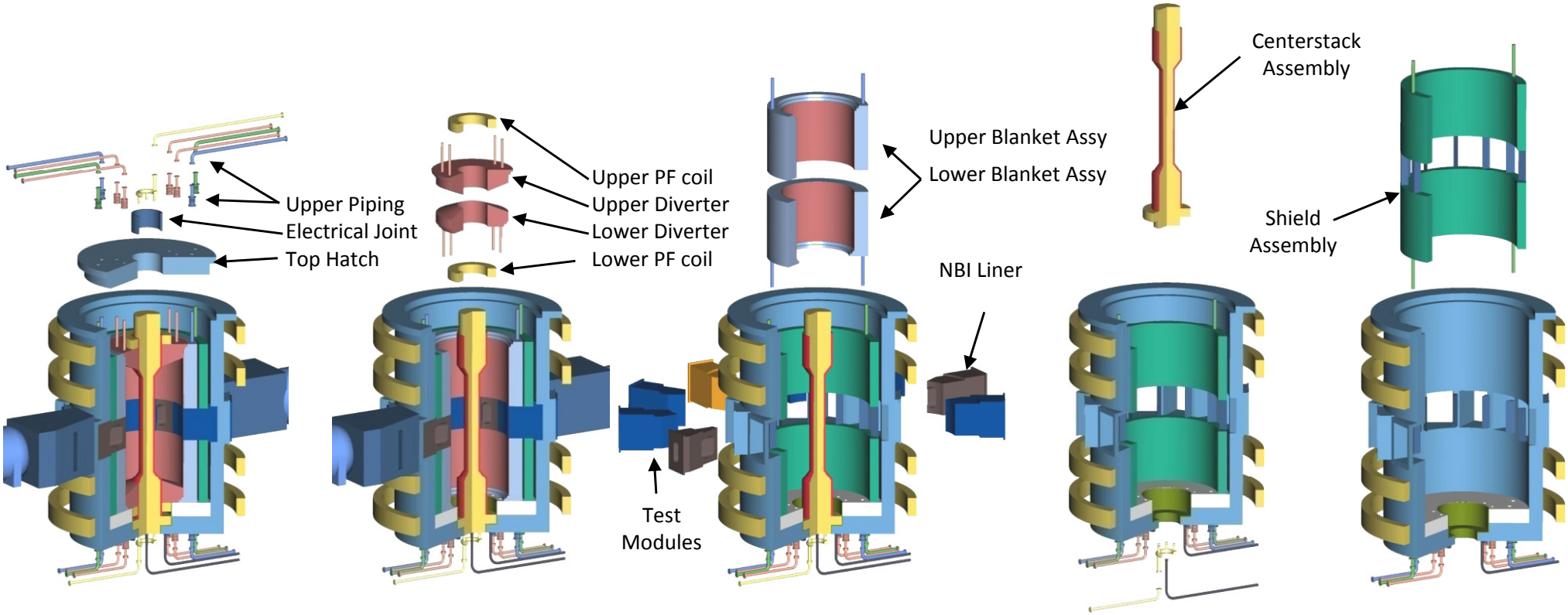
The required VNS-CTF pulse duration – key phenomena of interest that have the longest time scales

Areas with scientific & technical gaps	Phenomena that determine required VNS-CTF operation times, some examples
G9: Plasma-wall interactions	Wall particle sources via out-gassing
G10: Plasma facing components	Equilibration of hydrogen isotopes dissolved in plasma facing component materials
G11: Fuel cycle – tritium breeding and handling	Tritium production, retention, chemistry, solubility, and migration
G12: Heat removal – high grade heat extraction	Heat generation, diffusion, convection, and thermal equilibration
G13: Low activation materials	High performance interfaces, joints, diffusion barriers involving low activation materials; accumulation of transmutation products
G14: Safety	Accumulation of hazardous elements in safety and environment control areas
G15: Maintainability – remote handling	Conditions for “sticking” of adjacent material surfaces (duration, temperature, contact strain, vacuum, contaminants, radiation effects, etc.)

High Maintainability via Modularity

Extensive modularity expedites remote handling:

- **Large components with linear motion**
- **All welds external to shield boundary**
- **Parallel mid-plane/vertical RH operation**



Disconnect upper piping
Remove sliding electrical joint
Remove top hatch

Remove upper PF coil
Remove upper diverter
Remove lower diverter
Remove lower PF coil

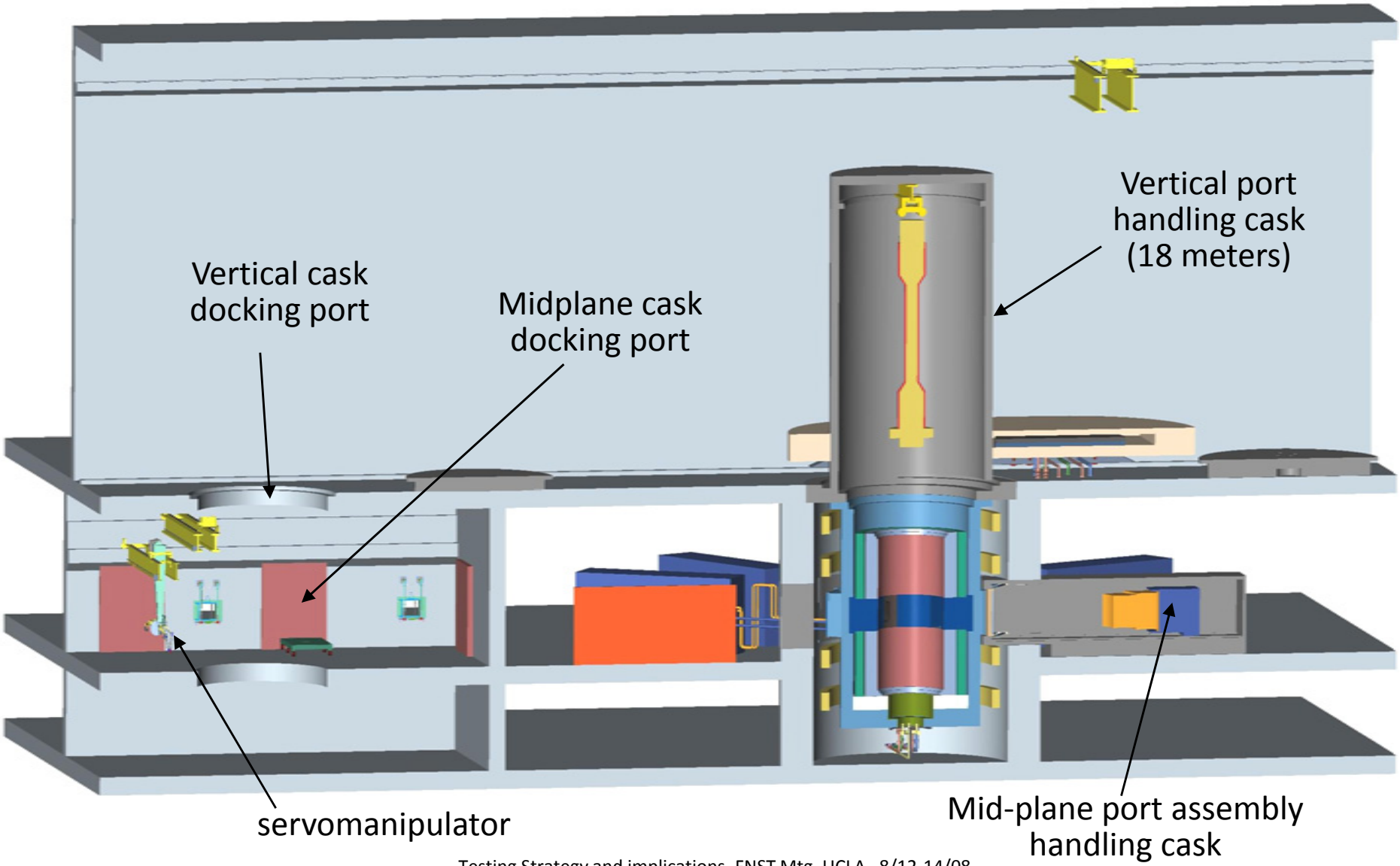
Extract NBI liner
Extract test modules
Remove upper blanket assembly
Remove lower blanket assembly

Remove centerstack assembly

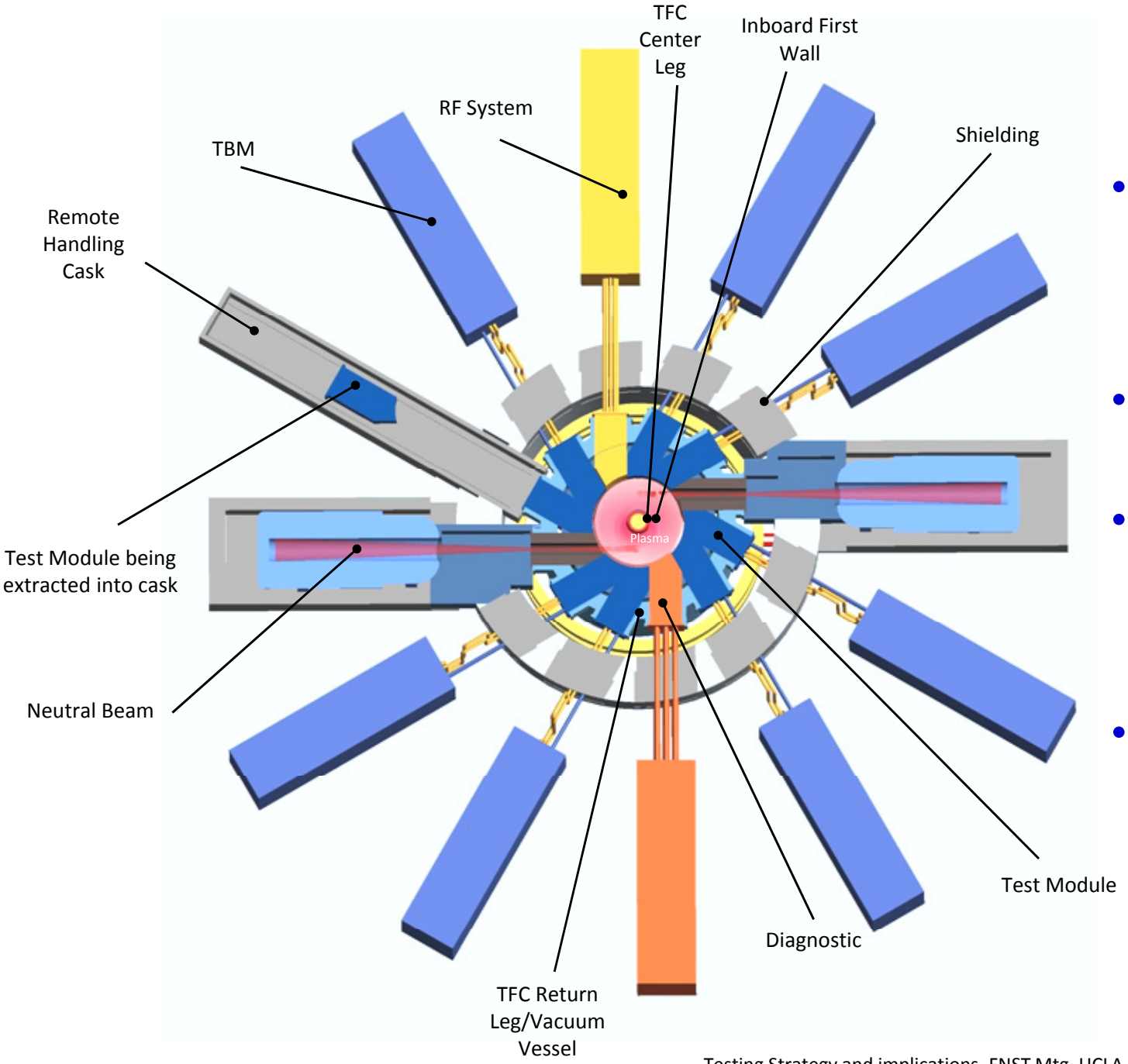
Remove shield assembly

Extensive hot cell laboratories

Remote handling equipment includes hot cell laboratories for accompanying fusion nuclear sciences R&D



Compact design allows close-fitting shielding and ex-shield hands-on access, reducing MTTR



Mid-plane ports

- Minimize interference during remote handling (RH) operation
- Minimize MTTR for test modules
- Allow parallel operation among test modules and with vertical RH
- Allow flexible use & number of mid-plane ports for test blankets, NBI, RF and diagnostics