Nuclear Component Testing (NCT) Assessment

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& Nuclear Component Testing (NCT) Discussion Group

PPPL Discussion
July 2, 2007

1. Assessment of Demo R&D gaps and NCT R&D needs
2. Dependence and sensitivities of NCT parameters
3. Full remote handling concepts to meet the challenge of 30% duty factor for NCT

DOE FESAC is charged to address the U.S. fusion energy sciences program in the "ITER era"

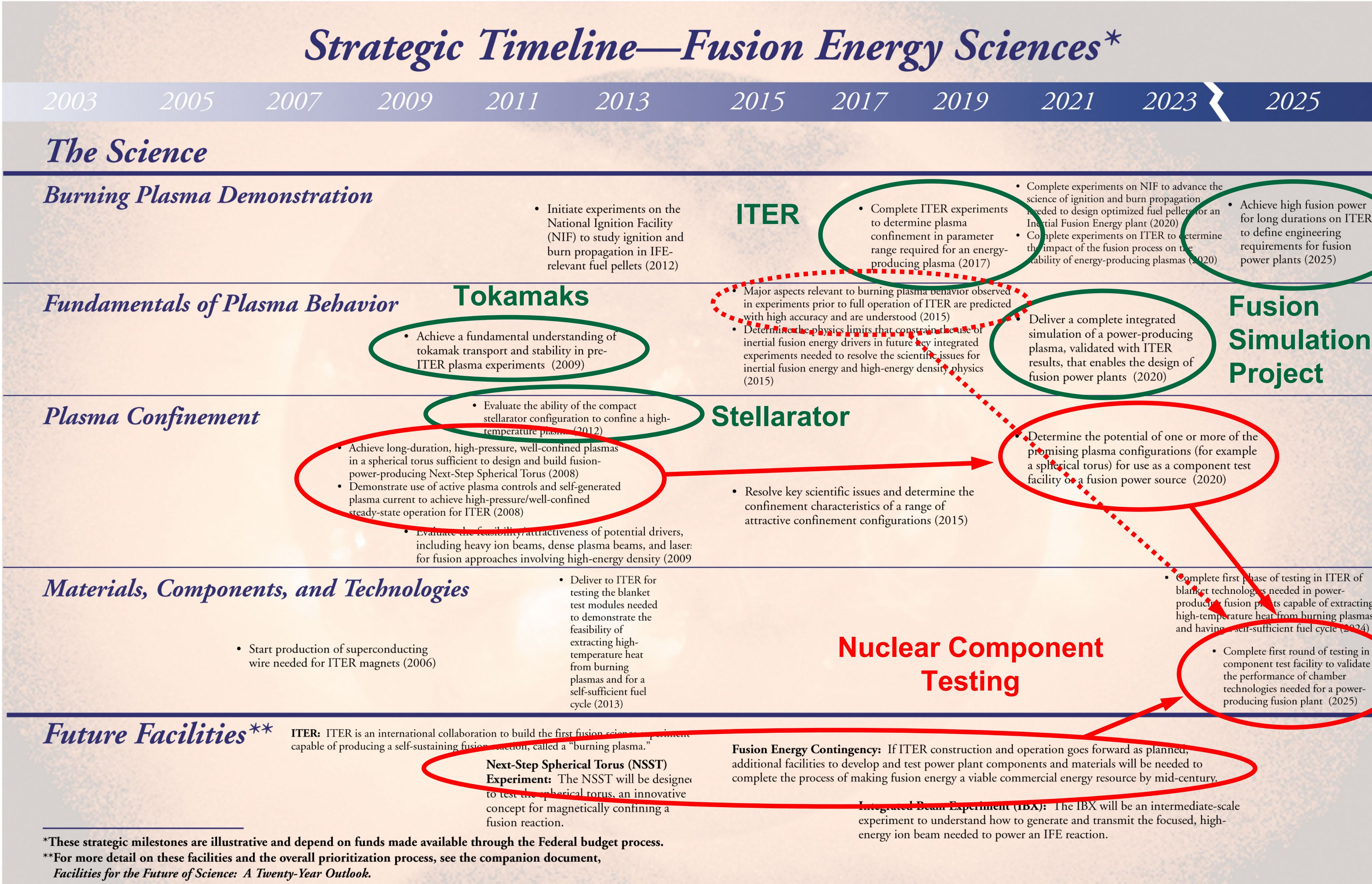
Identify the issues arising in the path to Demo, with ITER as a central part:

1) ***Identify and prioritize the broad scientific and technical questions to be answered prior to a Demo;***
2) ***Assess available means (inventory), including all existing and planned facilities around the world, as well as theory and modeling, to address these questions; and***
3) ***Identify research gaps and how they may be addressed through new facility concepts, theory and modeling.***

A second *charge will be issued asking FESAC to develop a long-term strategic plan.*

- ***Include a specific pathway to Demo within the context of the broader Office of Science Strategic Plan,***
- ***As well as other program elements needed in the comprehensive strategic plan for fusion research, and***
- ***Build on the results of this first charge.***

DOE plan includes Nuclear Component Testing (NCT), aiming to "*Complete first round of testing... (2025)*"



Draft NCT mission and conditions guide assessment

- **Nuclear Component Testing (NCT) Mission:**

  Use a lowered-risk, reduced-cost approach to test and develop components in a fusion nuclear environment beyond the ITER level and to help establish critically needed physical and engineering sciences knowledge base for Demo.

- **Simultaneous fusion nuclear conditions required for NCT# substantially exceed those planned for ITER**

Performance metrics	ITER	Required Conditions	Demo Goals
Fusion Power (MW)	500	75-150	~2500
Burning plasma energy gain Q	5-10	2.5-3.5	~20
Plasma control: H&CD (MW), fueling	~100	31-43	~100
Total area of (test) blankets (m^2)	~6	≥10 (test modules)	~670
Burning plasma operation	S*-H*-A*	HIHM	H-A
Divertor heat flux (MW/m^2)	~10	≤10**	~10##
Continuous operation	~hour	weeks	~months
14-MeV neutron flux on module (MW/m^2)	~0.8	1.0-2.0	~3
Total neutron fluence goal ($MW\text{-}yr/m^2$)	~0.3	6	~6-15
Duty factor goal	~1%	30%	~80%
Tritium self-sufficiency goal (%)	~0	~100	≥100

Abdou et al., Fusion Technology **29** (1996) 1;

* Operation modes: S = Standard, H = Hybrid, A = Advanced;

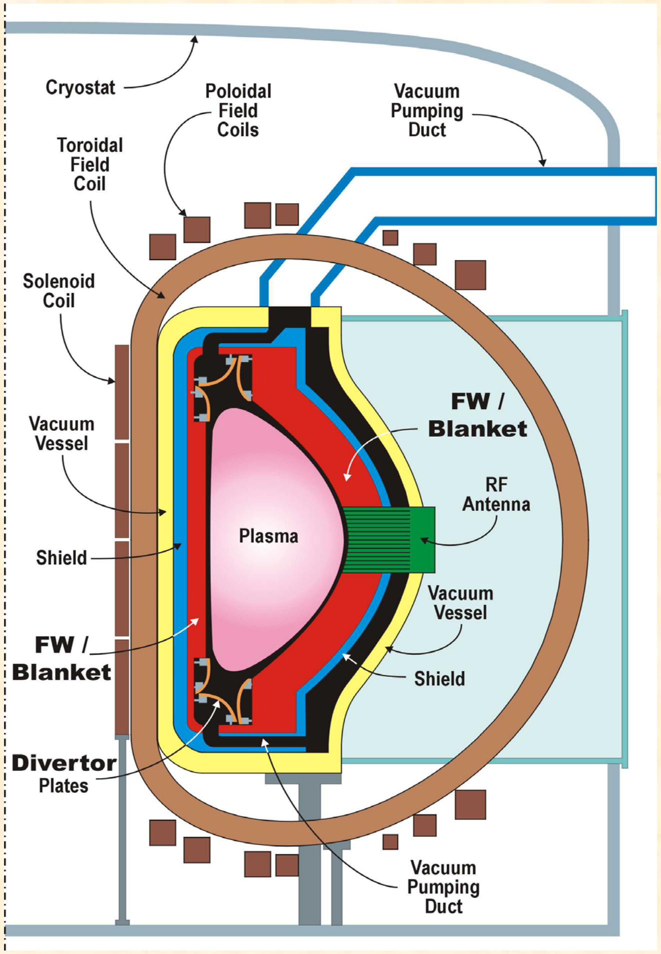
** SOL geometric flux expansion considerations only; ## Pacher et al, IAEA FEC 2006, FT/P5-42

Demo R&D areas with potentially large gaps beyond ITER and/or large R&D needs for Nuclear Component Testing (NCT)

Enabling Burning Plasma

- SBP-1: Abnormal events avoidance / mitigation
- SBP-2: Startup & steady-state operation
- SBP-3: Advanced operating regime
- SBP-4: Burning plasma fusion gain
- SBP-5: Divertor plasma performance
- SBP-6: Burning plasma predictive capability
- SBP-7: NB/RF/pellet systems performance
- SBP-8: Plasma diagnostics & control
- SBP-9: Power plant plasma performance

Areas with potentially large gaps to Demo and/or large R&D needs for NCT that are likely unique to NCT



Tokamak Reactor

Required Fusion Nuclear Technology

- FNT-1: S/C & N/C magnets
- FNT-2: Tritium self-sufficiency
- FNT-3: Tritium retention, accountability, safety, etc.
- FNT-4: Materials characterization
- FNT-5: Plasma facing surface performance & maintainability
- FNT-6: FW/blanket/divertor materials defect control
- FNT-7: FW/blanket/divertor components lifetime management
- FNT-8: Full remote handling
- FNT-9: Public safety & environmental protection
- FNT-10: Electricity generation at high availability
- FNT-11: Regulatory permit for Demo plant operation

NCT R&D gap-filling and need assessment – Questions to be addressed for each Demo R&D topic

1. *What is the envisioned Demo goal on this topic?*
2. *What are the physical and engineering sciences knowledge base expected to be established by a successful ITER and IFMIF?*
3. *What are the expected contributions from other planned experiments and technology test facilities?*
4. *What is the gap in R&D on this topic to bridge to Demo design and construction?*
5. *In what key ways can a NCT facility contribute to filling this gap?*
6. *What other approaches can also contribute to filling this gap partially or fully?*
7. *In what ways is a NCT facility unique, or not unique, in filling this gap?*
8. *What near-term (5-10 year) R&D are needed to enable design, construction, and operation of the needed NCT facility?*

We would like to solicit expert advice broadly.

NCT Discussion Group is formed to address these questions

Leaders' Group

Subgroup 2 Enabling Burning Plasma

Subgroup 1 Fusion Nuclear Technology

Members	Contributions	Organization
Abdou, Mohamed	Fusion nuclear technology, VNS	UCLA
Gates, Dave	NSTX plasma experimentation	PPPL
Hegna, Chris	Fusion plasma theory	U Wisc
Hill, Dave	Fusion plasma experimentation	LLNL@GA
Najmabadi, Farrokh	Fusion power plant conceptual designs	UCSD
Navratil, Gerald	Advanced Tokamak, PACs	Columbia U
Parker, Ron	Tokamak, tokamak-CTF, ITER-EDA, **SG2 leader**	MIT
Peng, Martin	ST, **NCT DG Coordinator**	ORNL
Baylor, Larry	Plasma enabling systems	ORNL
Forest, Cary	Plasma science	U Wisc
Hillis, Don	Experimental collaboration	ORNL
Jarboe, Tom	Innovative confinement concepts, startup	U Wash
Kaye, Stan	Turbulence & transport, physics analysis	PPPL
Kotschenreuther, Mike	Turbulence theory, innovative divertors	UT-Austin
Mauel, Mike	Levitated Dipole Experiments, PACs	Columbia U
Sovenic, Carl	Numerical fusion simulation	U Wisc
Tynan, George	Plasma science, MFE and IFE	UCSD
Whyte, Dennis	Boundary physics, BPO	MIT
Burgess, Tom	Remote handling	ORNL
Cadwallader, Lee	Fusion safety and environmental protection	INL
El-Guebaly, Laila	Neutronics, safety & environment, **SG1 co-leader**	U Wisc
Galambos, John	Systems & costing analysis	ORNL
Holder, Jeffrey	Tritium	SRNL
McManamy, Tom	Nuclear core design	ORNL
Sawan, Mohamed	Fusion nuclear technology	U Wisc
Skinner, Charles	Plasma material interaction	PPPL
Snead, Lance	Material science	ORNL
Ying, Alice	Fusion nuclear technology, **SG1 leader**	UCLA

DOE contact: Eckstrand, Steve, OFES

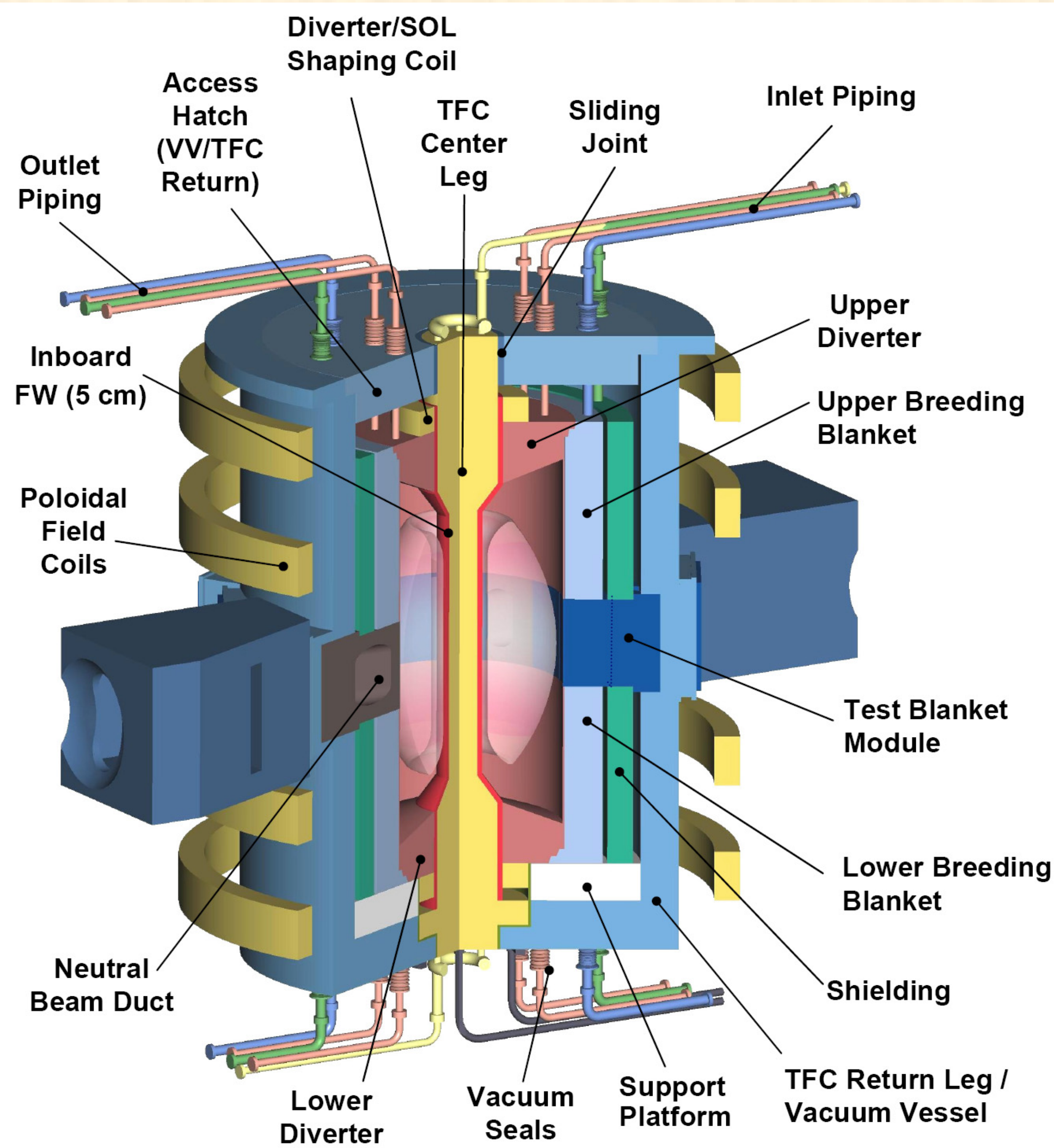
How well could or should NCT address these R&D gaps?
Preliminary estimates for review and improvement by NCT DG

Common Fusion Power R&D Issues	Planned expts.	Tech test facilities	ITER	IFMIF	NCT	EU Proto	Full Demo	Power Plant
Abnormal events avoidance / mitigation	2	TBD	3		C	R	R	R
Startup & steady-state operation	1	TBD	3		C	r	R	R
Advanced operating regime	2	TBD	3		2	r	R	R
Divertor plasma performance	2	TBD	3		C	R	R	R
Burning plasma fusion gain	1	TBD	3		2	R	R	R
Burning plasma predictive capability	2	TBD	3		C	C	R	R
NB/RF/pellet systems performance	1	TBD	3		C	R	R	R
Plasma diagnostics and control	1	TBD	3		C	R	R	R
Power plant plasma performance	1	TBD	3		2	C	C	R
Superconducting and normal conducting magnets	2	TBD	3(S/C)		3(N/C)	R	R	R
Tritium self-sufficiency	1	TBD	1		3	R	R	R
Other tritium issues	1	TBD	3		C	R	R	R
Materials characterization		TBD	1	3	C	R	R	R
Plasma facing surface performance & maintainability	1	TBD	3		C	R	R	R
FW/blanket/divertor materials defect control		TBD	1	2	3	3	R	R
FW/blanket/divertor components lifetime management		TBD	1	1	3	3	R	R
Full remote handling	2	TBD	2	1	3	R	R	R
Public safety & environmental protection	1	TBD	3	1	C	R	R	R
Electricity generation at high availability		TBD			1	3	3	R
Regulatory permit for Demo operation	1	TBD	2	1	3	C	R	R

Legend:

1	Will help to resolve the issue	C	Confirmation of resolution needed
2	May resolve the issue	r	Solution is desirable
3	Should resolve the issue	R	Solution is a requirement

An example of minimum-R_0, low-inboard-gap, moderate physics concept for NCT discussion



WL_tm [MW/m^2]	0.1	**1.0**	2.0
R0 [m]	**1.20**		
A	**1.50**		
kappa	**3.07**		
qMHD	13.4	**10.7**	8.7
qcyl	4.6	**3.7**	3.0
Bt [T]	1.13	**2.18**	
Itf [MA]	6.8	**13.1**	
Ip [MA]	3.4	**8.2**	10.1
Beta_N_total	**3.8**		5.9
Beta_T_total	0.14	**0.18**	0.28
Beta_p_total	0.99	**0.84**	0.85
Ne [E+20/m3]	0.43	**1.05**	1.28
fGW	**0.27**		
fBS	0.58	**0.49**	0.50
Tavgi [keV]	5.4	**10.3**	13.3
Tavge [keV]	3.1	**6.8**	8.1
HH98 (global)	**1.5**		
Q	0.50	**2.5**	3.5
Zeff	1.36	**1.38**	1.40
P_aux [MW]	15	**31**	43
P_CD [MW]	15	**31**	36
E_nbi [keV]	100	**239**	294
P_fusion [MW]	7.5	**75**	150
Test mod. height [m]	**1.64**		
A_test module [m^2]	**14**		
A_cyl_blanket [m^2]	**66**		
f-neutron captured	**0.76**		
∑P_tf [MW]	38	**173**	
∑P_elec input[MW]	101	**280**	323
[$M/yr] @ 4.5c/kWh	45	**120**	130
Mass_TF_CS (ton)	**140**		

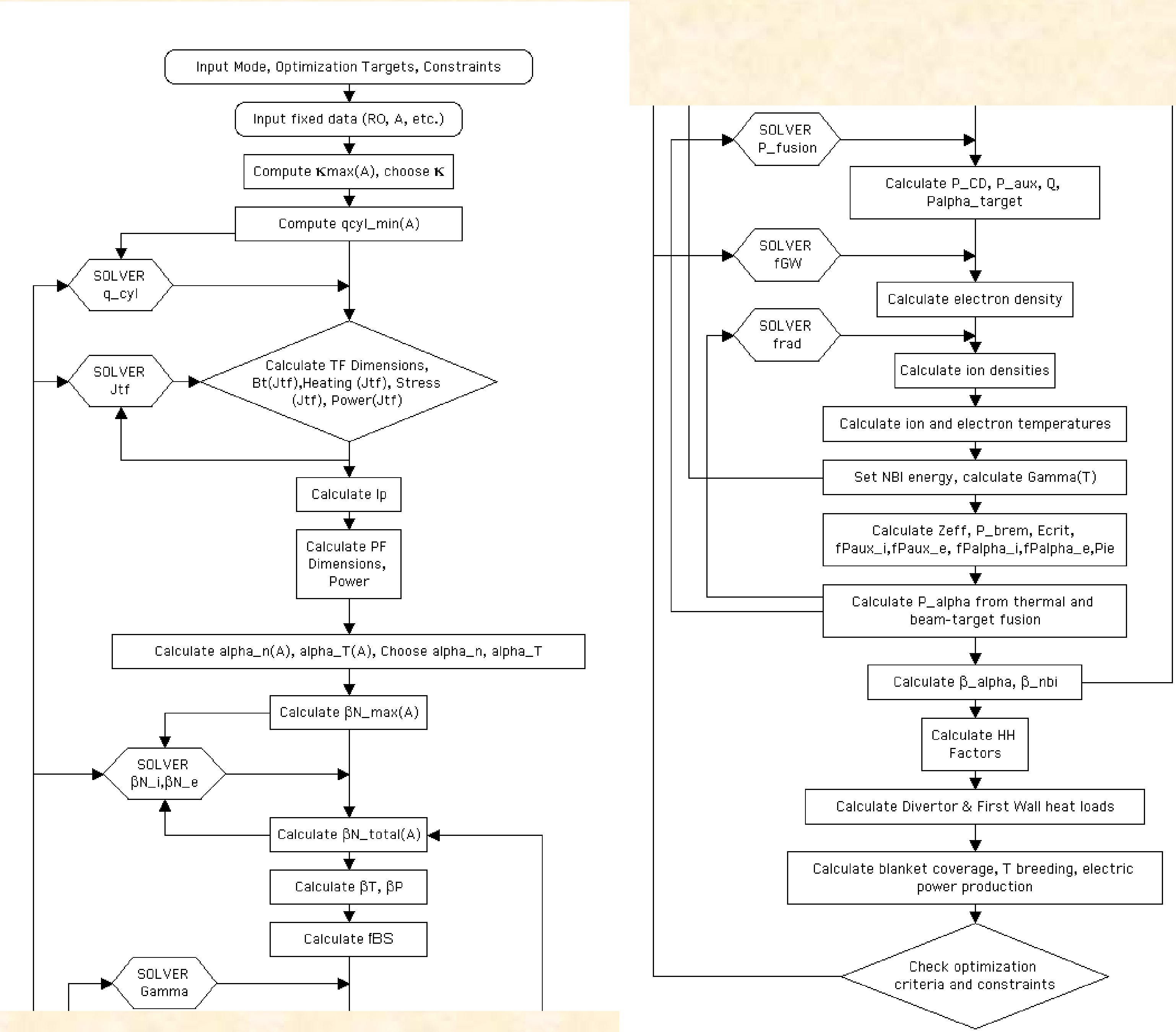
Working engineering assumptions

	Low-Gap ⇒ Low-A (5-cm inboard cooled wall)	High-Gap ⇒ Normal-A (50-cm inboard shield/wall)
Center Stack to Plasma Gap	5cm SOL + 5cm cooled wall	5cm SOL + 50cm shield/wall
TF Inner Leg Heating	Jcu determined by adjusting fraction of water (10m/s) to remove resistive and nuclear heating, keeping Tcu <= 150C	Jcu_avg <= 1.8kA/cm^2
TF Inner Leg Stress	Average Tresca Stress <=131MPA	
OH Solenoid	Iron Core 10% of cross section	Solenoid flux sufficient to ramp plasma to Ip flat top
OH Heating	n.a.	Jcu_avg = 4kA/cm^2
OH Stress	n.a.	Average Tresca Stress <=131MPA
NBI	E<=120keV then PINB with J=144A/m^2; E>120keV then NINB with J=40A/m^2	
Neutron flux distribution	Based on ARIES-ST	

Working plasma assumptions

A	1.4-3.5 for low-gap, 2.5-4.5 for high-gap	
R0	1.0-2.2m for low-gap, 2.5-3m for high-gap	
kappa	3.674/SQRT(A)	NHTX scaling
delta	0.5	
qcyl	IF(A<=2.5,1.1877+7.8128*A^-1-16.1953*A^-2+12.233*A^-3,2.5-0.265*(A-2.5))	1.06*[1]
beta_N	<=(6.43-1.02*A)/100	[1] for low-gap; 1.25*[1] for high-gap
α_n=α_T	(0.64-0.3/A)/2	[1]
peaking factor (pf)	∫(1-(r/a)^2)^α_n*(1-(r/a)^2)^α_T	[1]
kBS	0.344+0.195*A	[1]
fBS	Beta_P*kBS*pf^0.25/SQRT(A)	[1]
Confinement	Ti<>Te, HHi<=0.7 neoclassical, HHe<=0.7 ITER 98, global HH98<=1.5	
Solenoid Flux	High-gap: 85% Hirshman-Neilson flux, ramp-up only Low-gap: 10% CS area for iron core	
Non-inductive CD	NBI	Paux >= Pcd
		[1] Menard *et al*, PPPL-3779 (2003)

EXCEL Solver Non-Linear Optimizer



Solver finds solution that optimizes an objective function within equality and non-equality constraints, by adjusting variables in

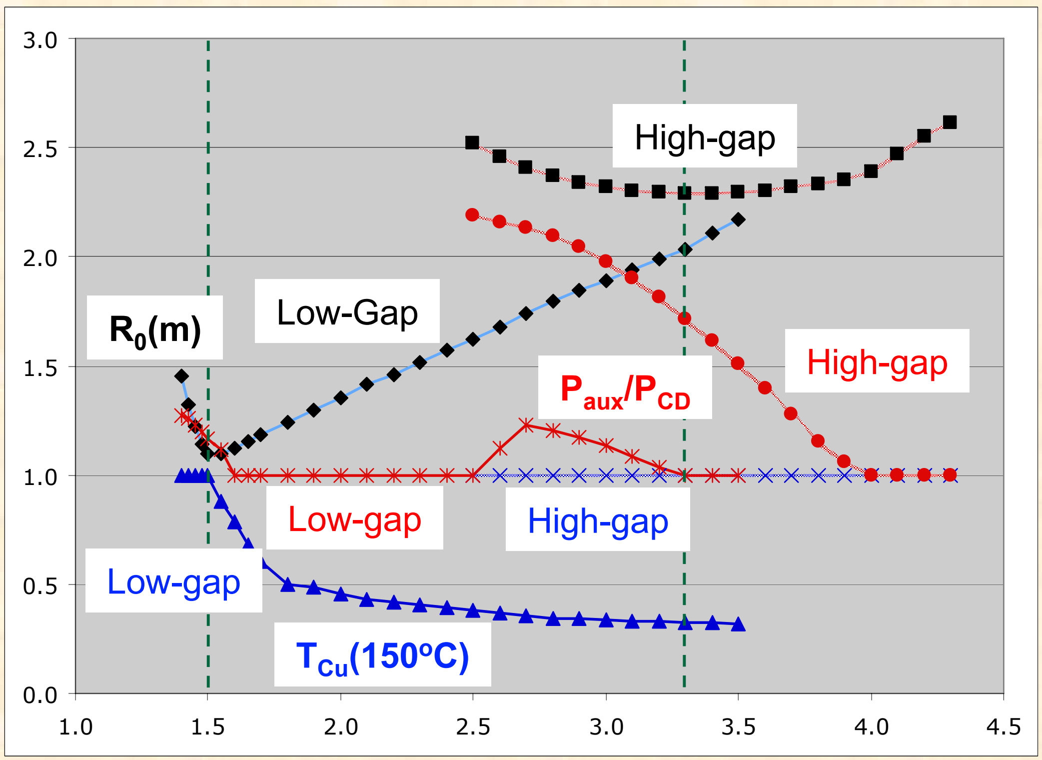
NCT sensitivities calculated:

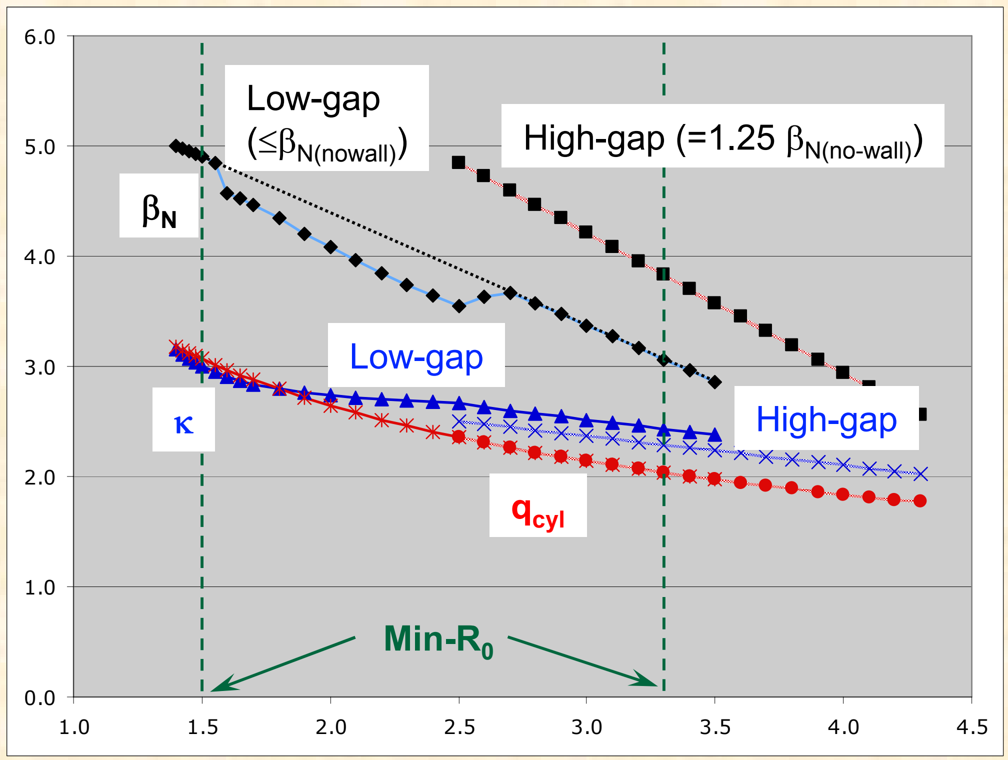
- A = 1.4 – 4.3
- 5-cm vs. 50-cm
- 0.8 – 1.2x $\beta_{N(\text{no-wall})}$
- q_{cyl} = 2.4 – 3.6
- H_{98e} = 1 – 2
- Iron core = 10-20% of CS area

Inboard wall/shield+SOL thickness ("gap") determines minimum-R_0 designs of A = 1.5 and A = 3.3 for W_L = 1 MW/m²

Example: Test module area ≥ 10m²; W_L = 1 MW/m²; H_{98} ≤ 1.5

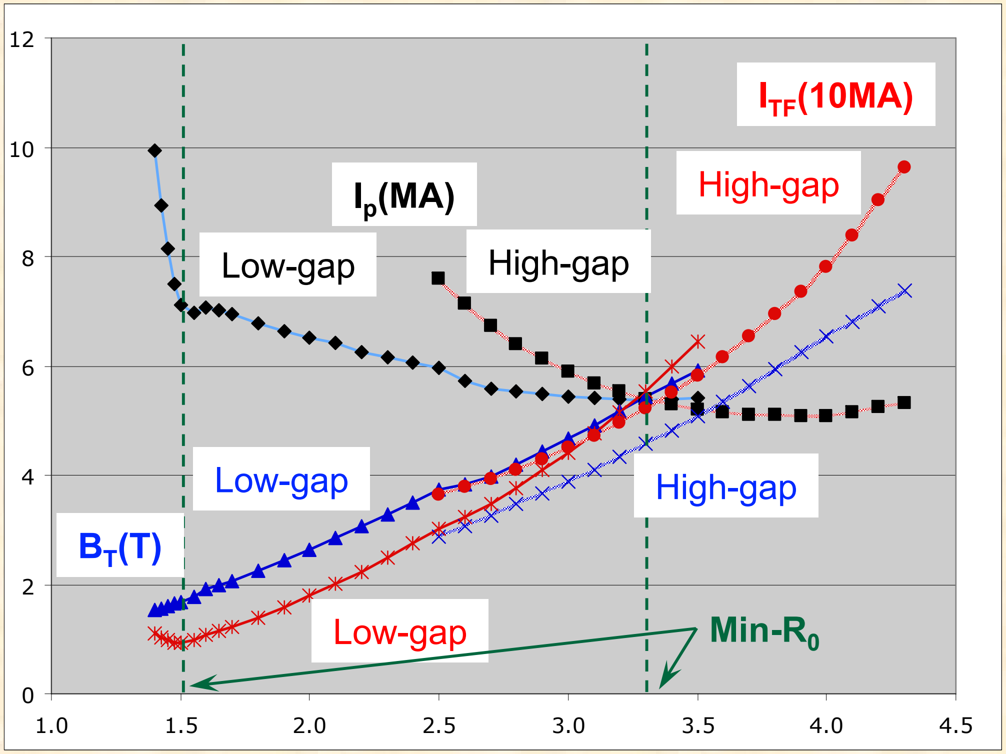
- **Low-gap**: 5-cm wall + 5-cm SOL ⇒ A = 1.5, R_0 ~ 1.1m
  - A < 1.5 cases constrained strongly by T_{Cu}
- **High-gap**: 50-cm shield + 5-cm SOL ⇒ A = 3.3, R_0 ~ 2.3m
  - A < 3.5 cases constrained by confinement (P_{aux}/P_{CD} ≥ 1)
- **Assume**: no-wall β_N(A) for low-gap; 1.25*no-wall β_N(A) for high-gap



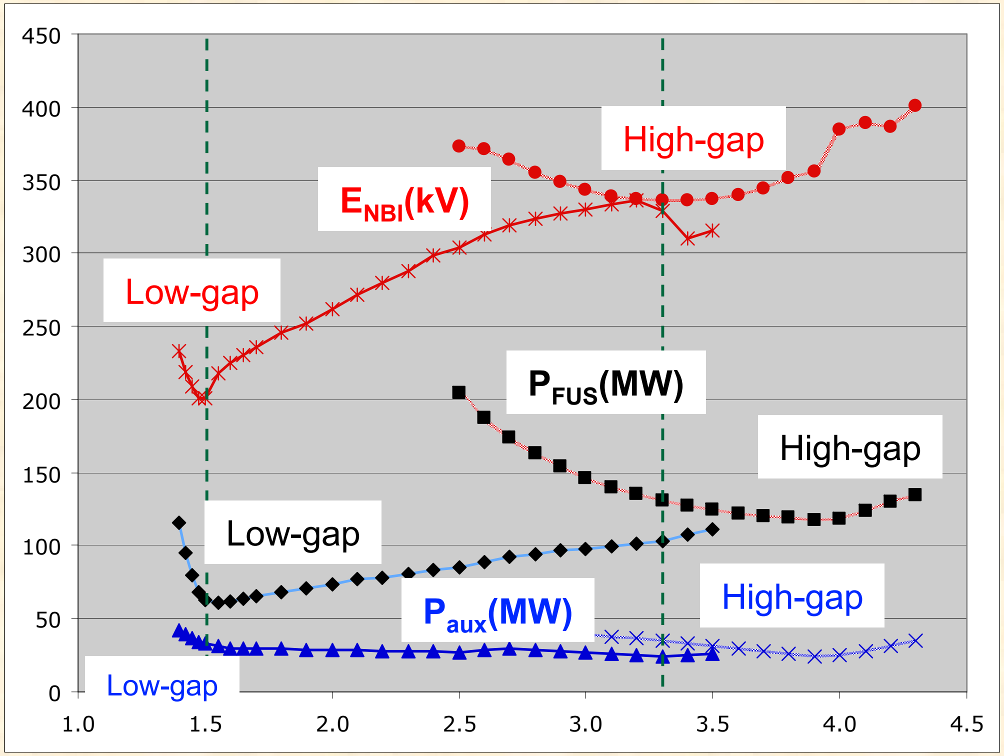


Plasma currents below 10 MA are likely adequate for NCT for both low-gap (low-A) and high-gap (normal-A)

	Low-Gap	High-Gap
Plasma current (MA)	7.1	5.4
Toroidal field (T)	1.7	4.6
TF current (MA)	9.2	52
Fusion power (MW)	61	131
Auxiliary power (MW)	33	35
NBI energy (kV)	200	336



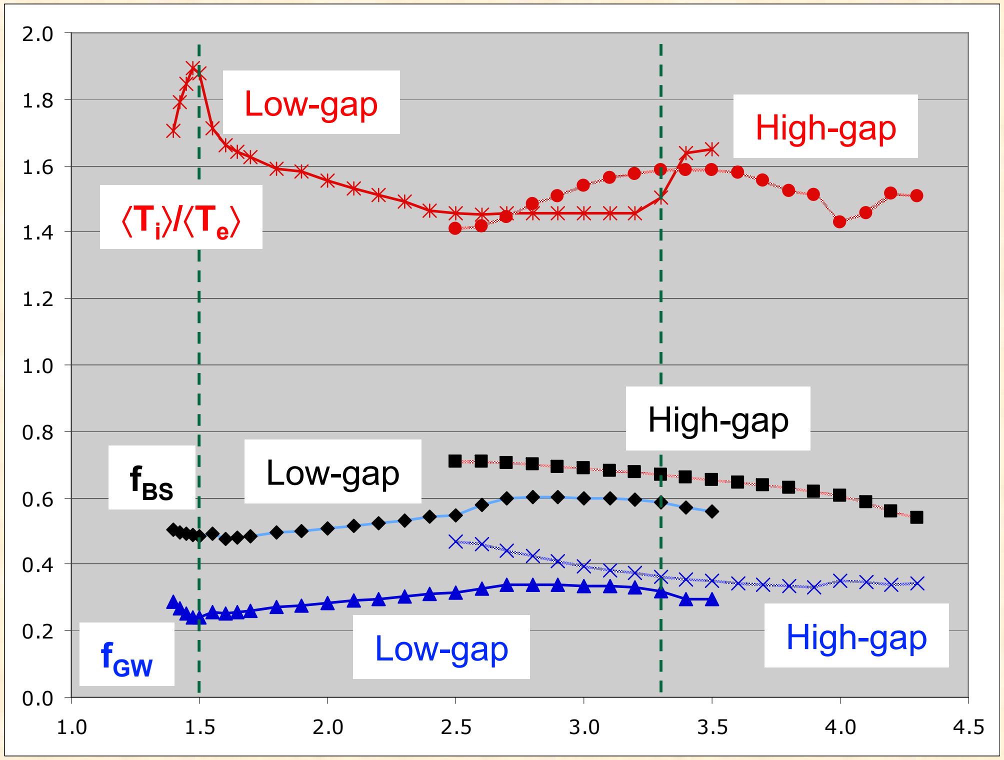
A →

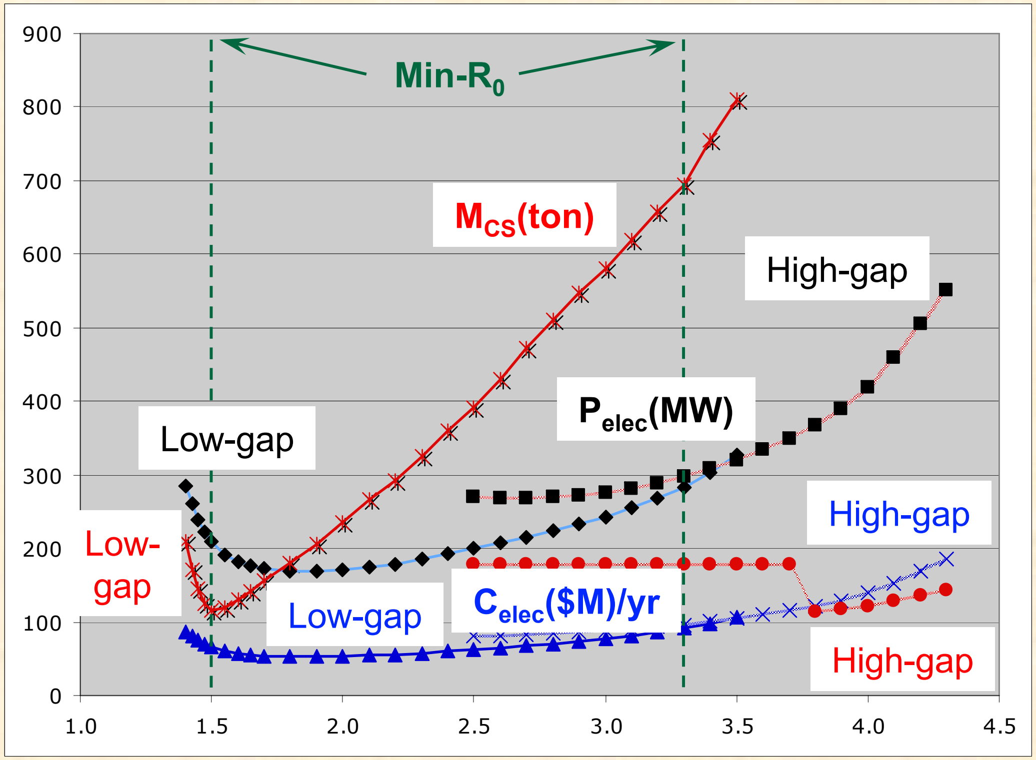


A →

Results suggest Hot-Ion H-Mode (HIHM) operation (T_i/T_e = 1.5-2) with substantial f_{BS} and moderate f_{GW}

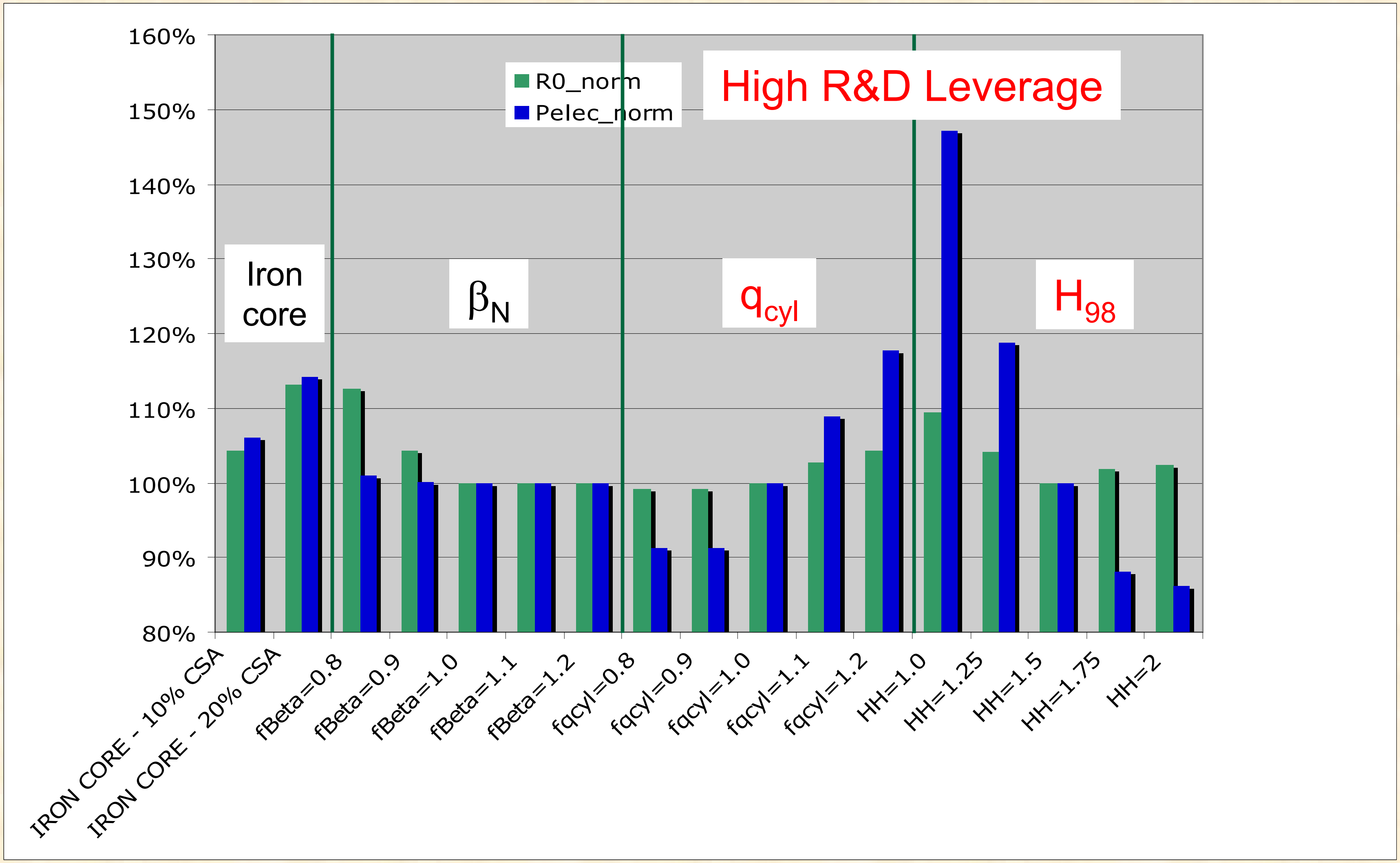
	Low-Gap	High-Gap
⟨Ti⟩/⟨Te⟩	1.9	1.6
f_{BS}	0.49	0.67
f_{GW}	0.24	0.36
Electric power (MW)	209	385
Power cost ($M/yr @ 4.5c/kWh)	89	166
TFC CS mass (ton)	115	734



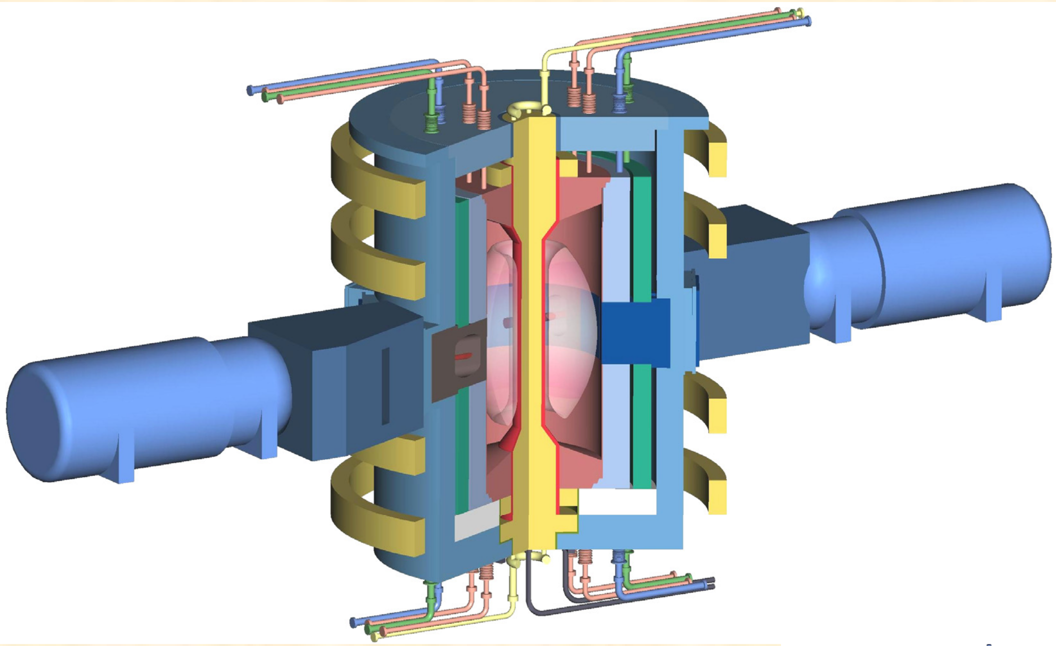


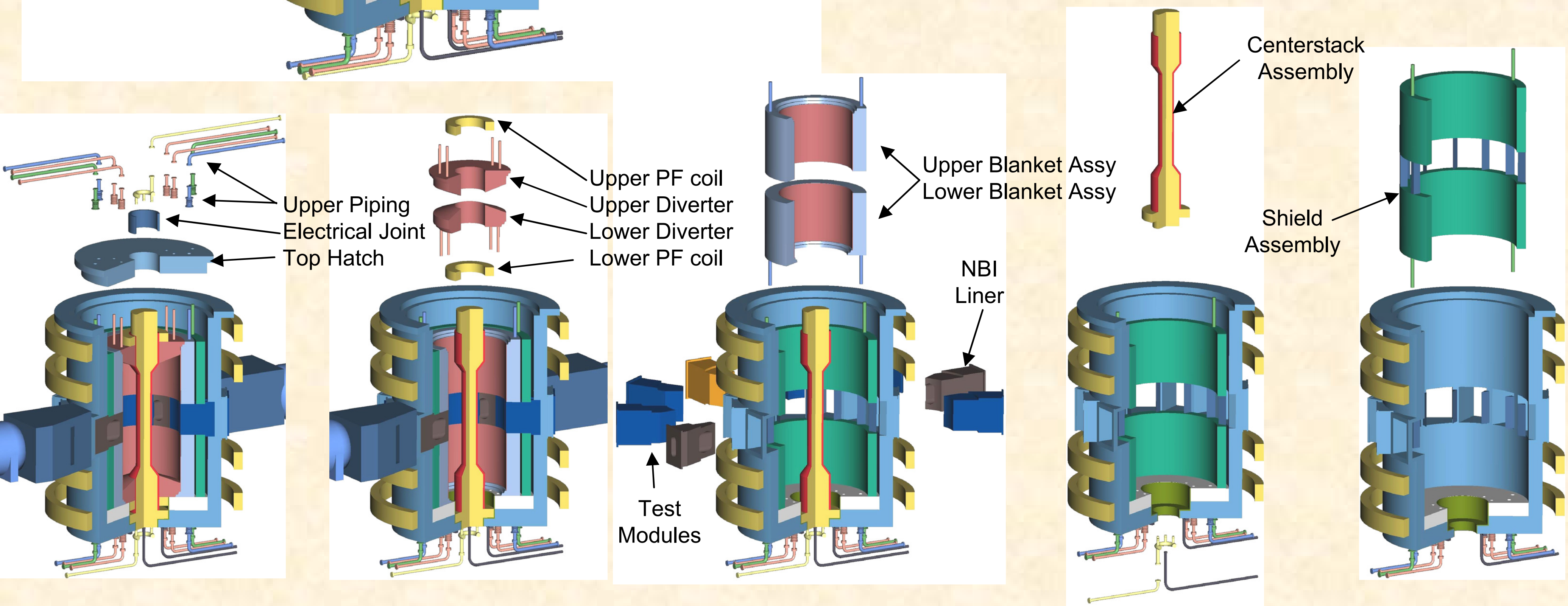
P_{aux} depends strongly on H_{98}, and P_{TFC} substantially on q_{cyl} → indicating R&D priorities for NCT

- **Improving H_{98} (HIHM) and q_{cyl} (kink stability) has high R&D leverage**
- **Wide variations in β_N and modest iron core size have weak (~10%) impact**



Low-gap NCT configuration allows fully modularized core components and hence fully remote assembly and disassembly





- Disconnect upper piping
- Remove sliding electrical joint
- Remove top hatch

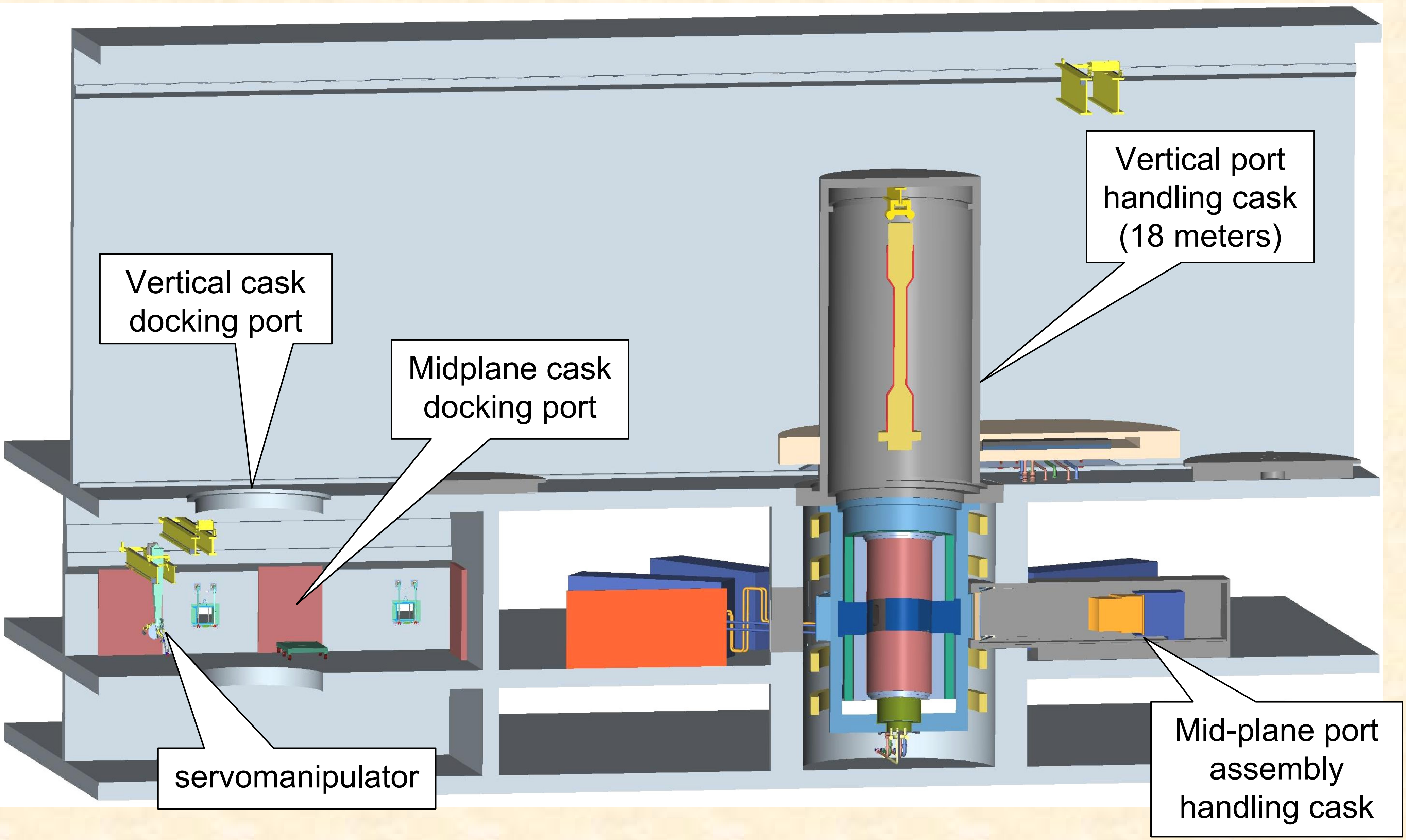
- Remove upper PF coil
- Remove upper diverter
- Remove lower diverter
- Remove lower PF coil

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

- Remove centerstack assembly

- Remove shield assembly

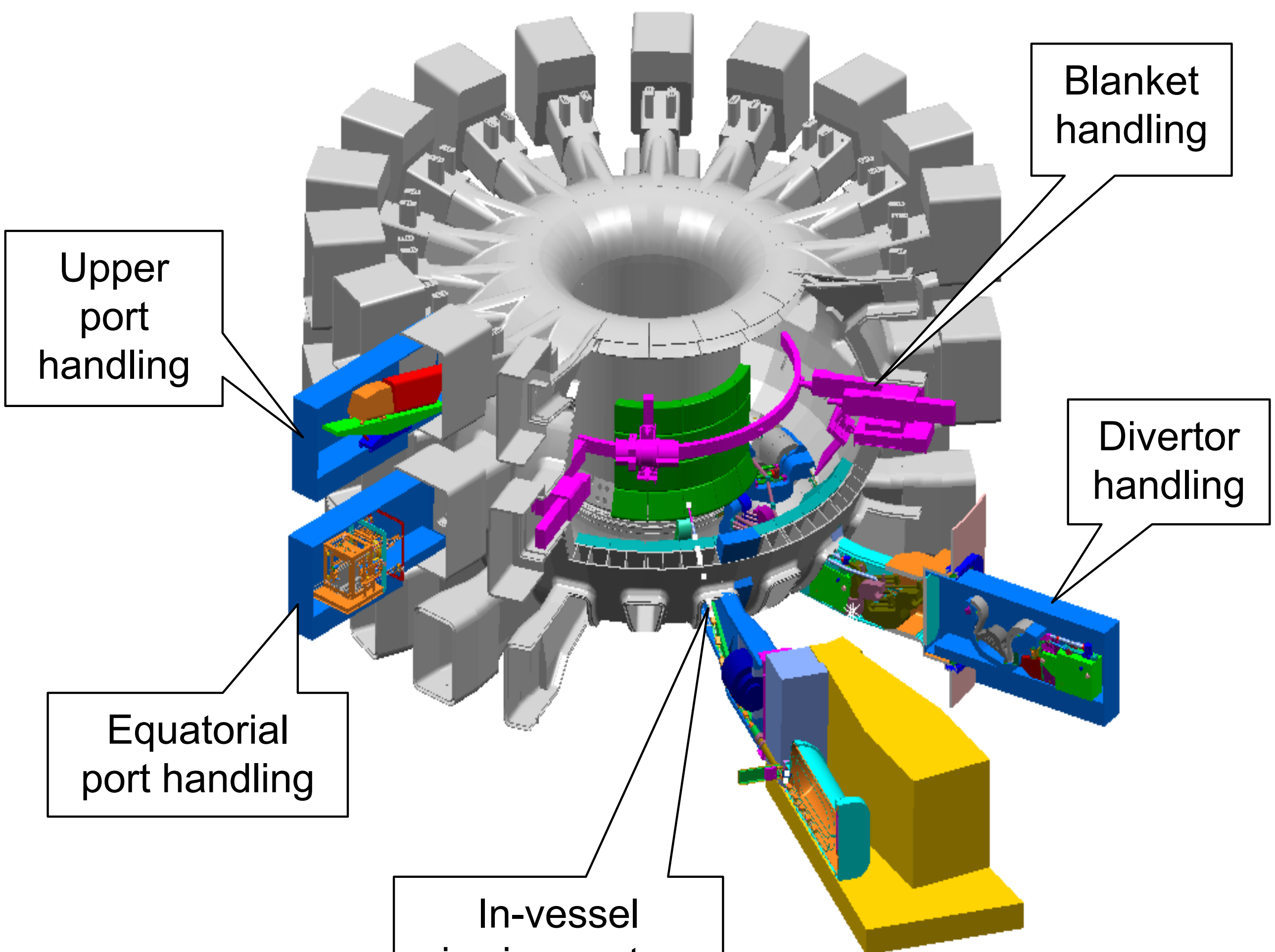
Extensive remote handling equipment and hot cells will further be required to achieve high duty factor goal of 30%



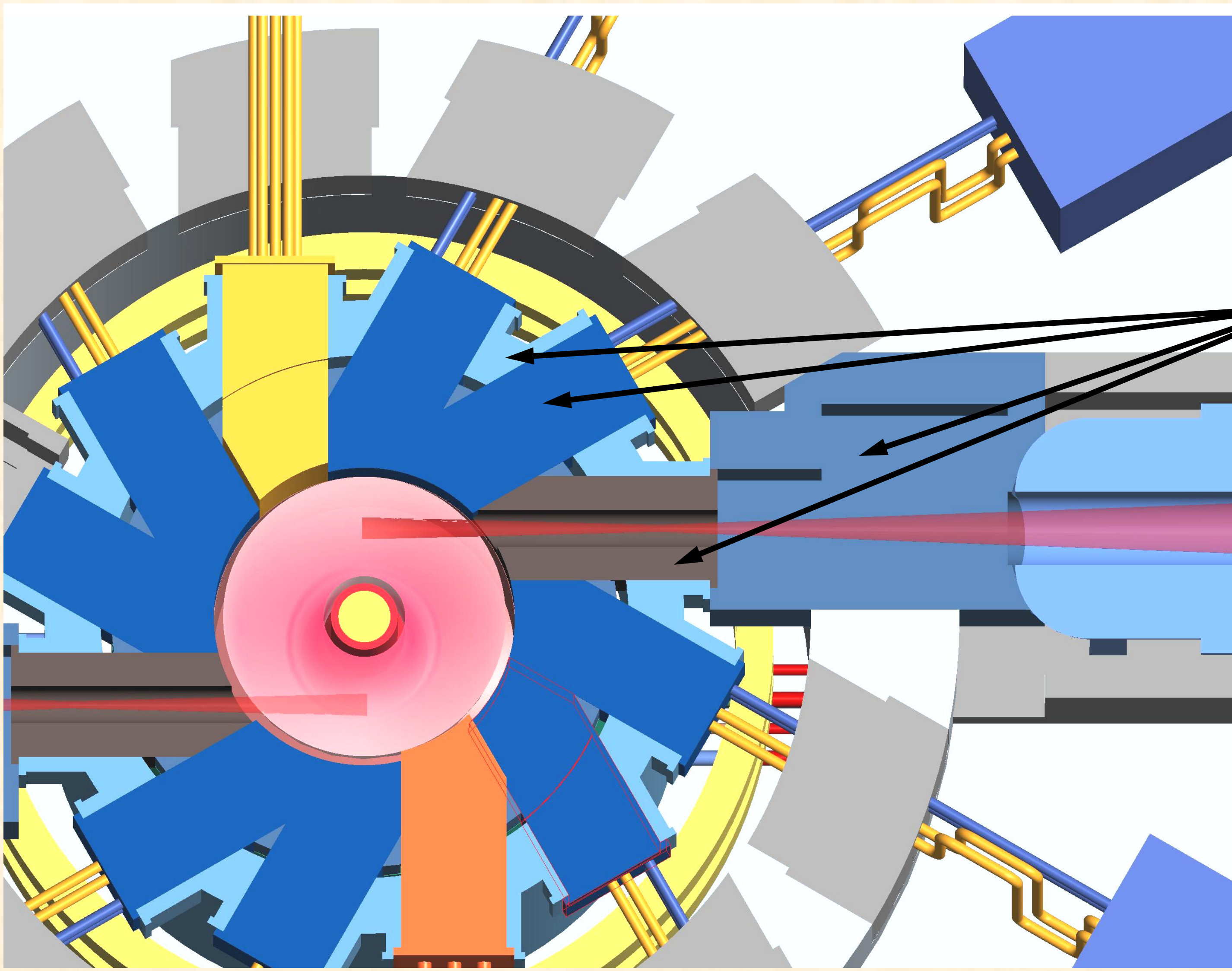
NCT can build on ITER remote handling designs

- ITER remote handling designs can be applied directly
- Low ex-vessel activation levels permit hands-on maintenance

ITER Remote Handling Systems



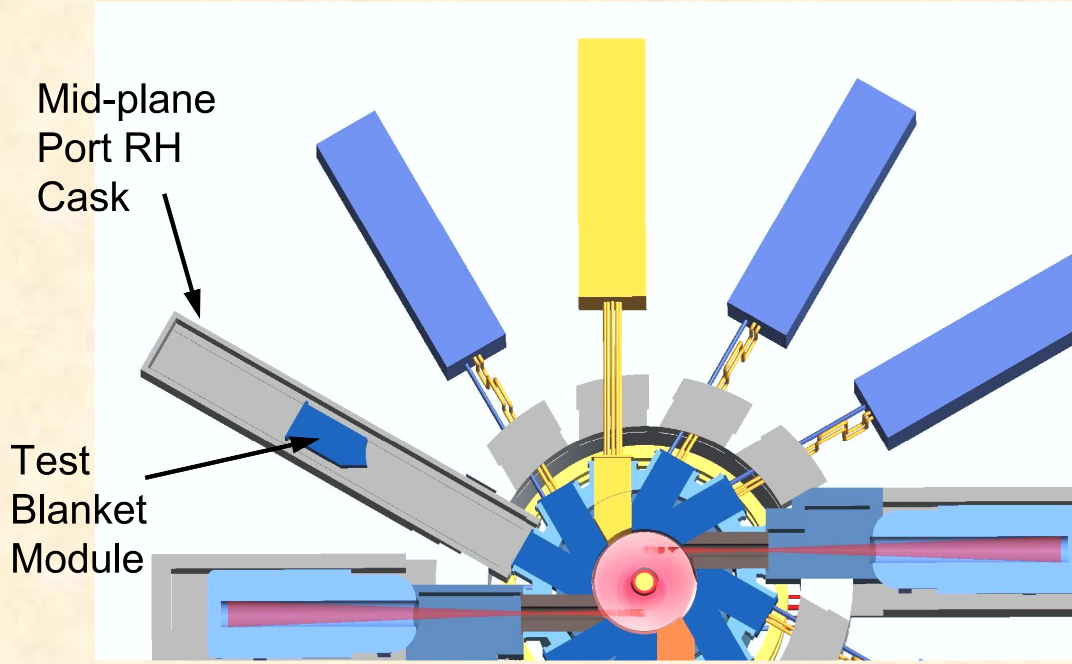
Extensive shielding of vacuum vessel, blanket, and port assemblies enable the needed ex-vessel hands-on access

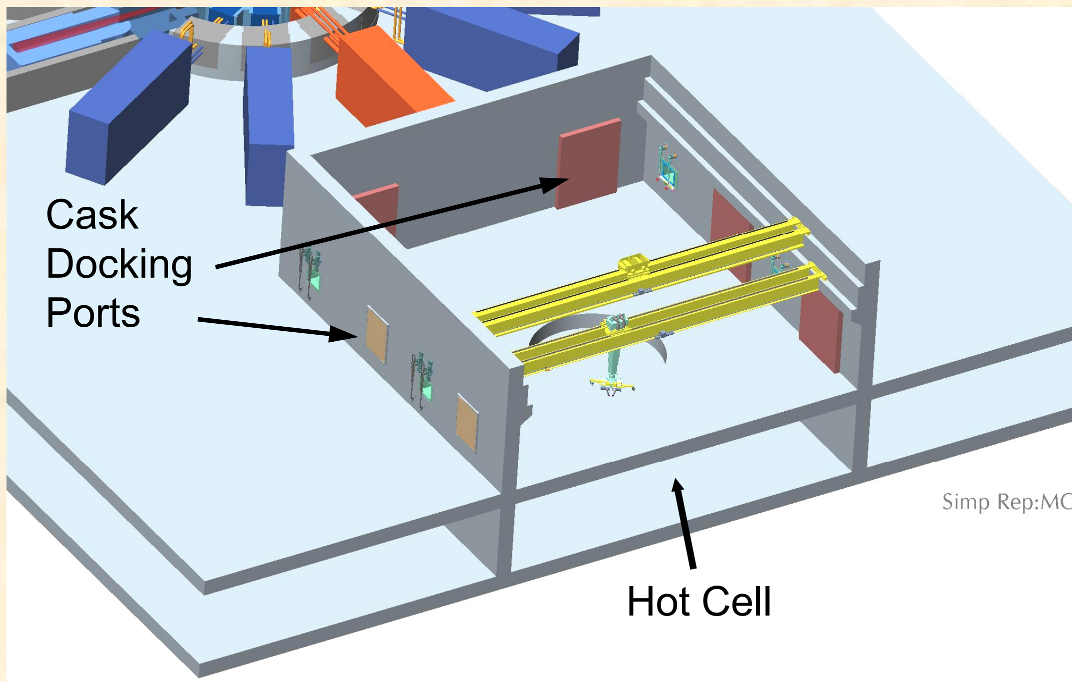


VV, blanket and port shielding (steel & water)

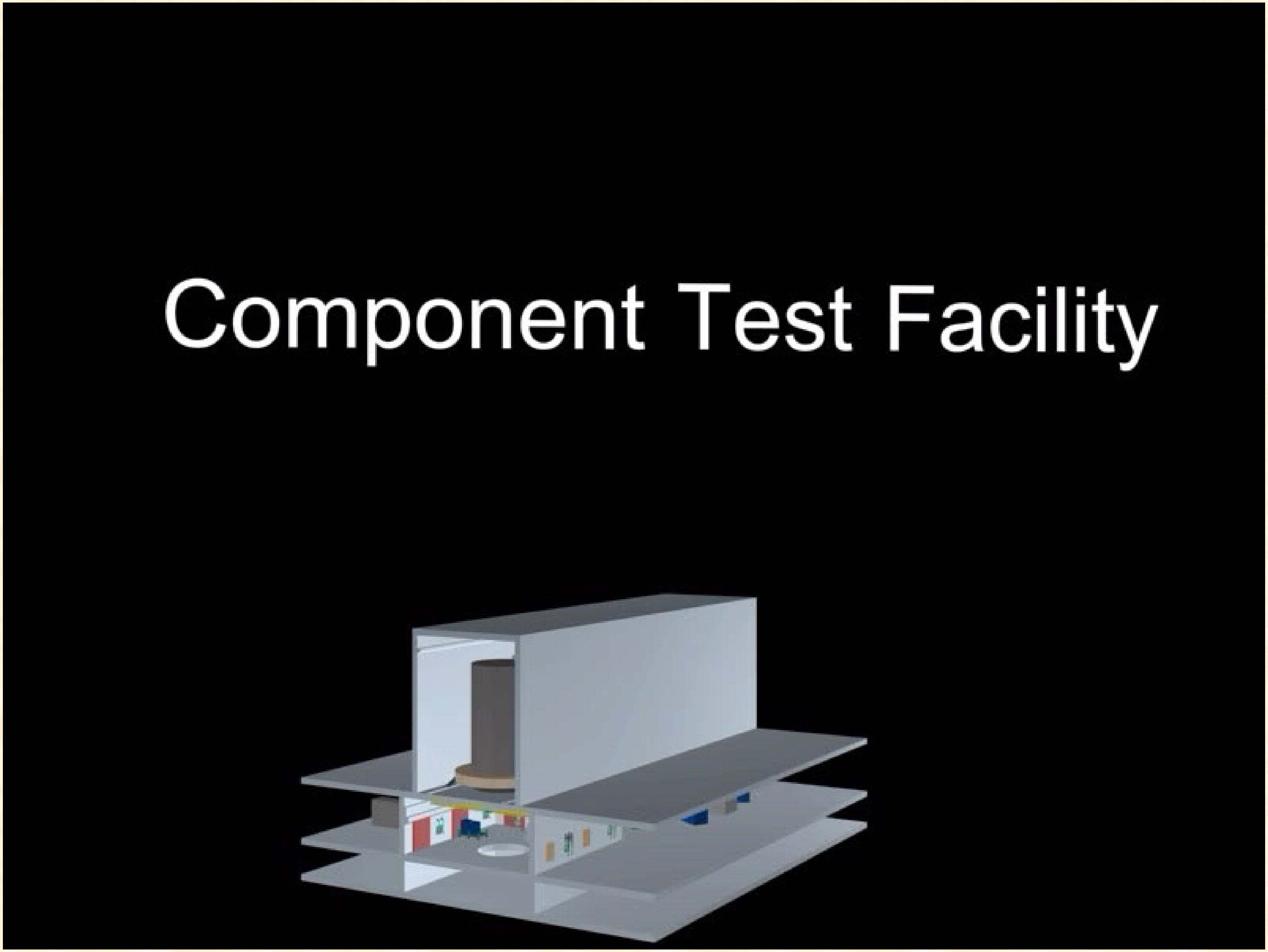
Mid-plane test blanket, heating, and diagnostic modules are transferred to and from hot cells by RH casks

- Mid-plane ports enable fast remote access to test blanket modules, and heating and diagnostic systems.
- Mid-plane components fit in standard shielded enclosures and are removed as complete modules and transferred to hot cell
- In-vessel contamination is contained by sealed transfer casks that dock to VV ports
- Hands-on disassembly and assembly of service connections and preparation of VV closure plates precede and follow remote operations



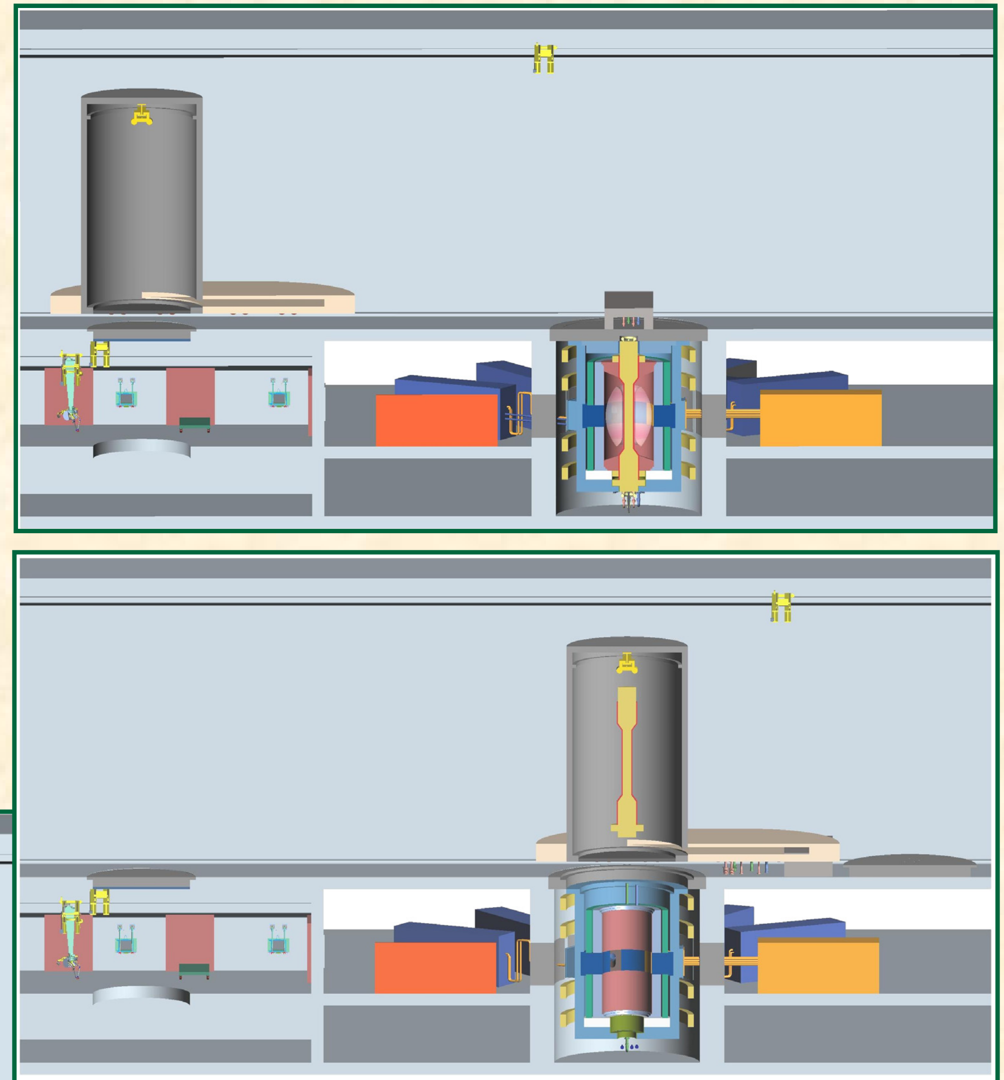


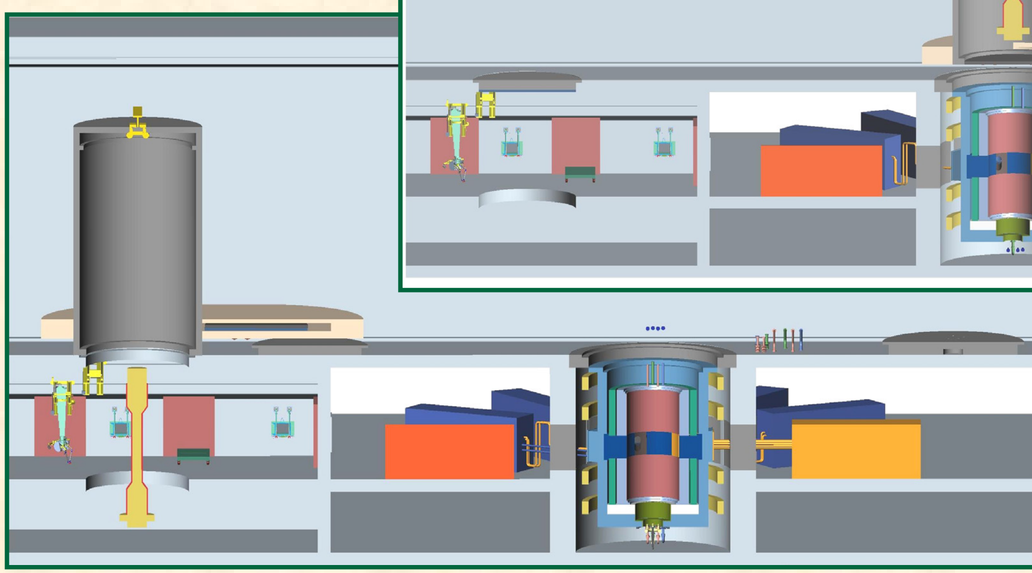
Simulation of remote handling of mid-plane modules



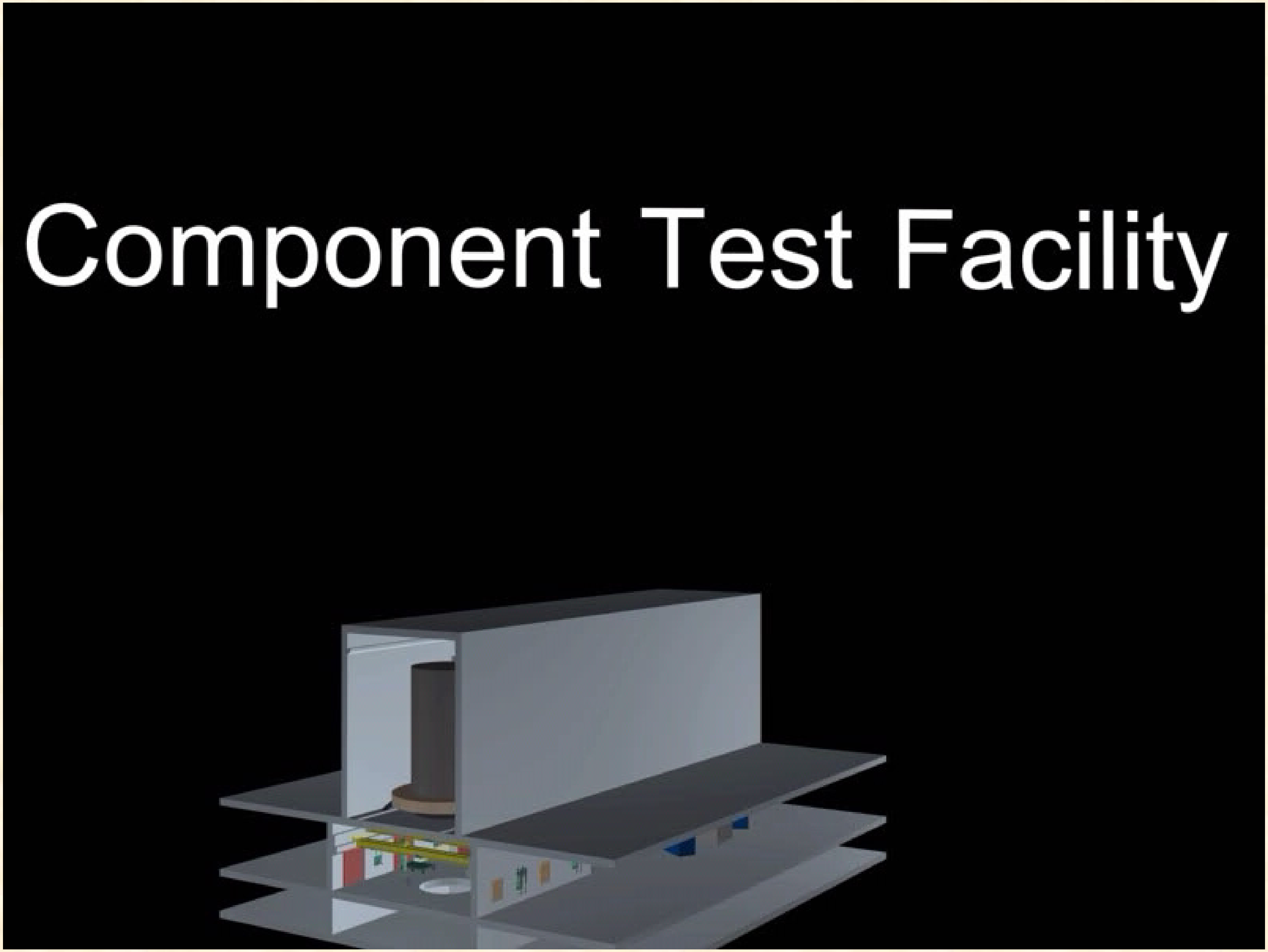
Full remote vertical access and extensive hot-cell facilities must further reduce MTTR and increase MTBF

- Replacement of all other activated components via vertical access would **reduce MTTR** (mean time to replace).
- Extensive hot-cell facilities for the **expert groups** to examine and repair components and prepare backups, would **increase MTBF**.
- Aim for maximum achievable duty factor.





Simulation of remote handling of all other activated components via vertical access



Remote handling classification of components will guide design optimization to minimize MTTR

- Remote handling that minimizes MTTR (mean time to replace) is anticipated to set stringent facility design and component interface requirements

Class 1 (Relatively frequent)	**Class 2 (Relatively infrequent)**	**Class 3 (Not expected but possible)**	**Class 4 (Hands-on)**
Upper and Lower Divertor Modules / Coils Midplane Port Assemblies: Test Blankets, RF Heating, Diagnostics Neutral Beam Ion Source replacement In-vessel Inspection (viewing/metrology probe)	Upper and Lower Breeder Blanket Center Stack Neutral Beam Components	Vacuum Vessel Sector / TF Coil Leg Shields	Poloidal Field Coils Ex-vessel Services

Minimization of the required component replacement frequency and time will introduce major design challenges

Component	RH Class	Expected Frequency	Maintenance Time Estimate*
Divertor Module	1	TBD, replacement rate ~ at least once every 2 years?	Upper module: ~ **4 weeks** Upper and lower**: ~ 6 weeks (assuming center stack not removed)**
Midplane Port Assemblies			**~ 3 weeks** per port assembly
Neutral Beam Ion Source			**~ 1 week** per NBI
In-vessel Inspection (viewing/metrology probe)	1	Frequent deployment	Single shift **(8-hr)** time target (deployed between plasma shots, at vacuum & temp.)
Upper and Lower Breeder Blanket	2	TBD, replacement rate ~ several times in life of machine ?	Upper: ~ **6 weeks** Upper and Lower: **TBD (significant if all midplane port assemblies must be extracted)**
Center Stack (Class 1?)			**~ 6 weeks**
Neutral Beam Internal Components			**TBD, ~ 2 to 4 weeks**
Vacuum Vessel Sector / TF Coil	3	Replacement not expected	**TBD**, replacement must be possible and would require extended shutdown period
Shield			

* Includes active remote maintenance time only. Actual machine shutdown period will be longer by ~ > 1 month. Time estimates are rough approximations based on similar operations estimated for ITER and FIRE.

New assessment supports FESAC and prepares the grounds for studies of Nuclear Component Testing (NCT)

- **A NCT Discussion Group with broad participation is assessing Demo R&D gaps and NCT R&D needs, in support of FESAC**
- **NCT facility concepts and sensitivities are being explored to support this assessment and identify important issues and opportunities**
- **Full remote handling concepts are explored to help meet the great challenge of 30% duty factor, which would also reduce cost and risk, and improve upgradeability for NCT**

This work contributes important information to the planning of cooperative R&D activities under the IEA ST agreement