The need and opportunity for NCT gap-filling capabilities

Martin Peng for the NCT Discussion Group

- **Mission of the Nuclear Component Testing (NCT) activity:**

  Design, build, and utilize a lowered-risk, reduced-cost facility to provide a fusion environment beyond the ITER level, to test, discover, innovate, and develop the remaining needed physical and engineering sciences knowledge base for Demo.

- **Recommended# simultaneous component testing capabilities substantially exceed those planned for ITER**

Performance metrics	ITER	Capabilities#	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	~80	31-43	~125
Burning plasma operation mode	S*-H*	HIHM*	A*
Divertor heat flux (MW/m^2)	~10	≤10**	~10##
Total area of (test) blankets (m^2)	~6	≥10 (test modules)	~670
Continuous operation	~hour	~day→2 weeks	~months
14-MeV neutron flux on module (MW/m^2)	~0.8	1.0-2.0	~3
Total neutron fluence goal (MW-yr/m^2)	~0.3	6	~6-15
Duty factor goal	~1%	30%	50%-70%
Tritium self-sufficiency goal (%)	~0	~100	≥100

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

* Operation modes: S = Standard, H = Hybrid, A = Advanced; HIHM = Hot-Ion H-Mode

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

Critical, open gaps in knowledge base are identified in NCT

- Identified 8 important, urgent, uncertain, and generic areas:
  - Tritium self-sufficiency (El-Guebaly, Sawan, UW) (presented)
  - FW/blanket/divertor reliability and lifetime (Ying, Morley, UCLA) (presented)
  - Full remote handling (Burgess, ORNL) (presented)
  - Plasma facing surface performance & maintainability (Skinner, PPPL) (presented)
  - Tritium retention, accountability & safety (Holder, SRNL):
    - Unknown tritium-aging effects in many fusion materials for Demo-relevant time scales and conditions; only NCT provides needed integral environment
  - FW/blanket/divertor materials defects & control (Snead, Katoh, ORNL):
    - Unknown combined thermo-mechanical response of sub-components and stressed joints; only NCT provides needed scalable experimental capabilities (back-up VUs)
  - Public safety & environmental protection (Cadwallader, INL, El-Guebaly):
    - Large uncertainties in knowledge of dust, tritium, activated coolant corrosion products, waste materials; only NCT provides needed continuous operation
  - Regulatory permit for Demo plan operation (Cadwallader, INL):
    - No database for regulatory-quality assurance of Demo materials, components, containment, safety, etc.; only NCT provides needed data for continuous conditions
- Only NCT provides the integral capabilities to test, discover, innovate and develop the knowledge base needed for Demo
- An opportunity for unquestioned U.S. leadership
  - U.S. competence in the enabling burning plasma & the fusion nuclear technology
  - Big opening in international program
- Recommend open, community-based, and common-basis assessments of viable options for component testing, to compete in the U.S. science community

Back-up slides
by NCT Discussion Group

- FW/Blanket/Divertor Material Defects & Maintainability (Snead, Katoh)
- NCT Discussion Group
- Minimum-R_0 options for NCT

Bridging Gap from Miniaturized Sample Data to Component Performance

L. L. Snead and Y. Katoh for NCT Discussion Group

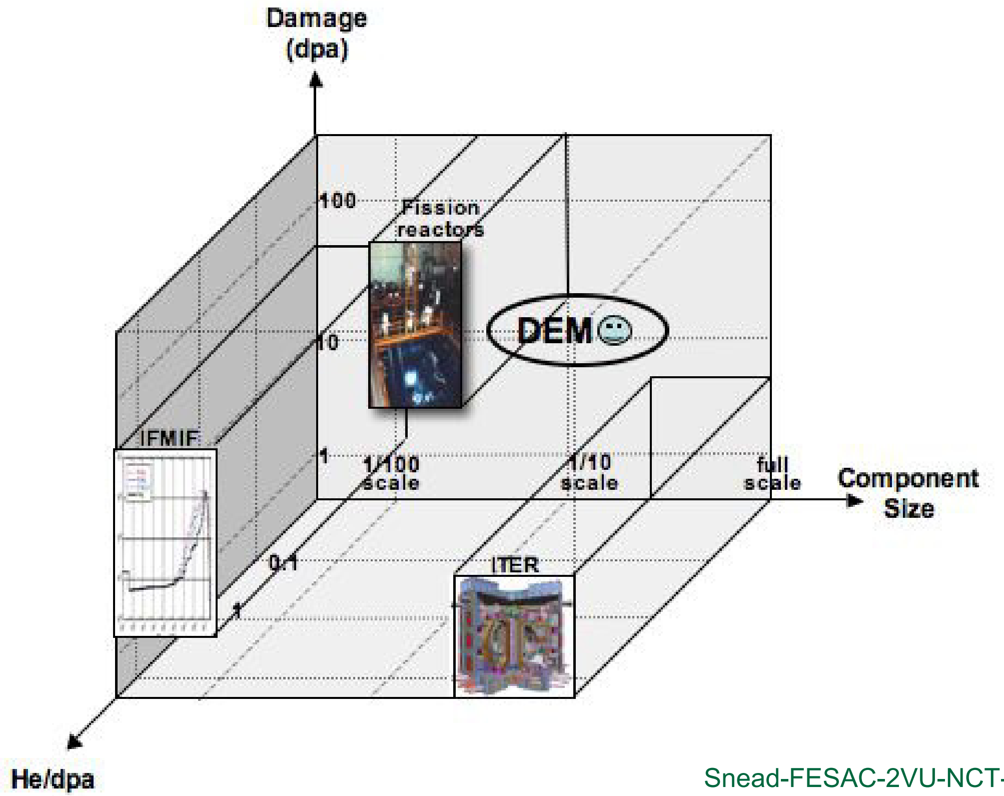
NCT FNT-6: FW / blanket / divertor materials

- **The effects of combined neutron damage, helium transmutation, and synergistic environmental effects on component behavior.**

What Is the R&D gap for [topic-issue]?

- **Combined thermo-mechanical response of scale-critical component, and stressed joints under relevant helium production, neutron damage, and environment. Prove validity of scaling and performance models.**

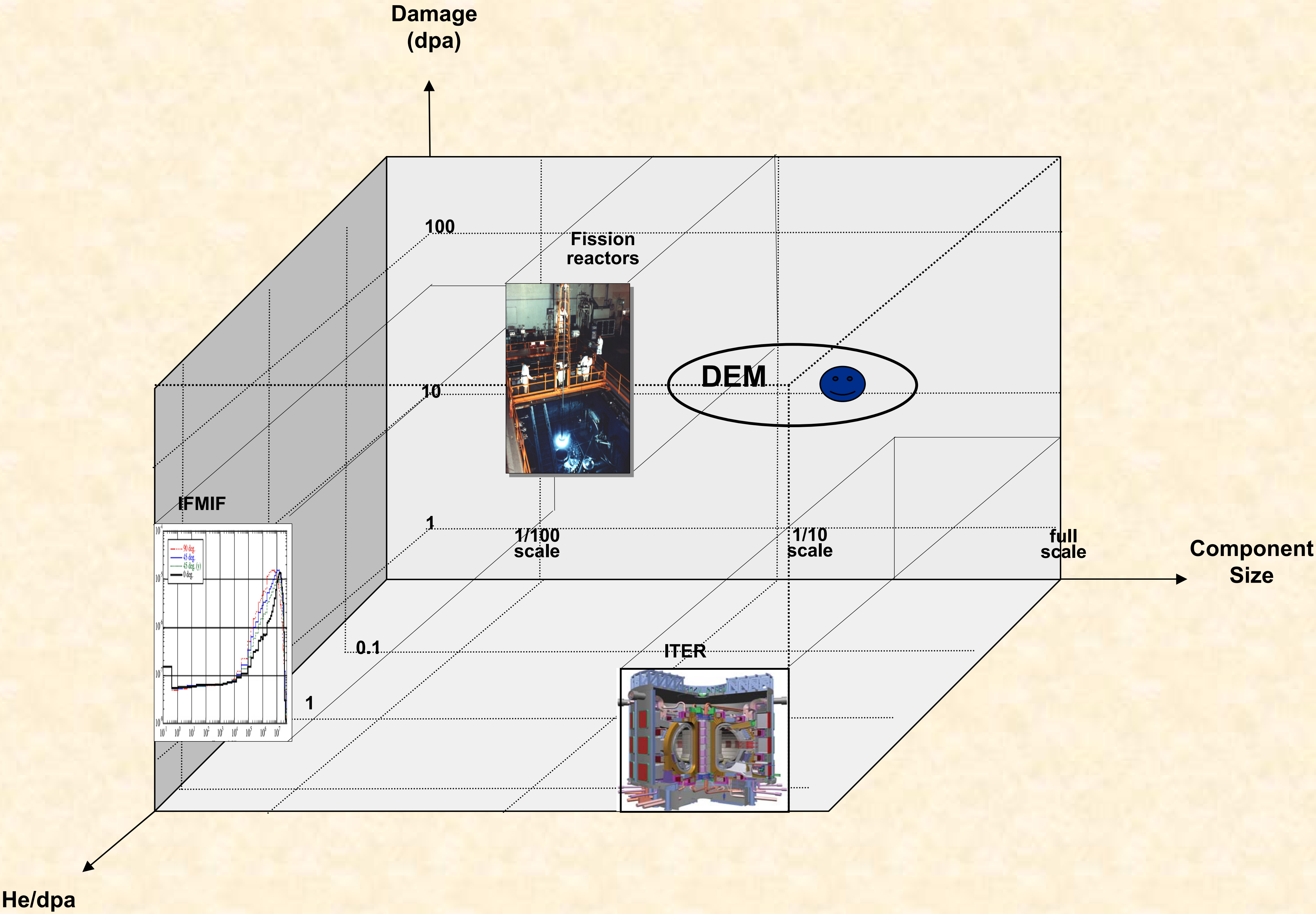
Performance Indicators	Existing Capabilities	ITER (IFMIF) Goals	Gap-Filling Capabilities	Demo Goal
Verified Performance	**Mixed-spectrum reactors.**	**Insight into helium effects**	**Combination of modeling and scaled experimental capability**	**Demonstration of Component Performance and Reliability**



IFMIF : Correct neutron spectrum.
Representative damage
Very small samples

Fission Reactors : Low He/dpa ratio
Representative damage
Intermediate size specimens

ITER : Correct neutron spectrum
Near prototypic size components
Very low neutron damage


Damage
(dpa)
100
Fission
reactors
10
DEM
IFMIF
1
1/100
scale
1/10
scale
full
scale
Component
Size
0.1
ITER
1
He/dpa

NCT Discussion Group

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

Demo issues with large gaps in knowledge base beyond ITER

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

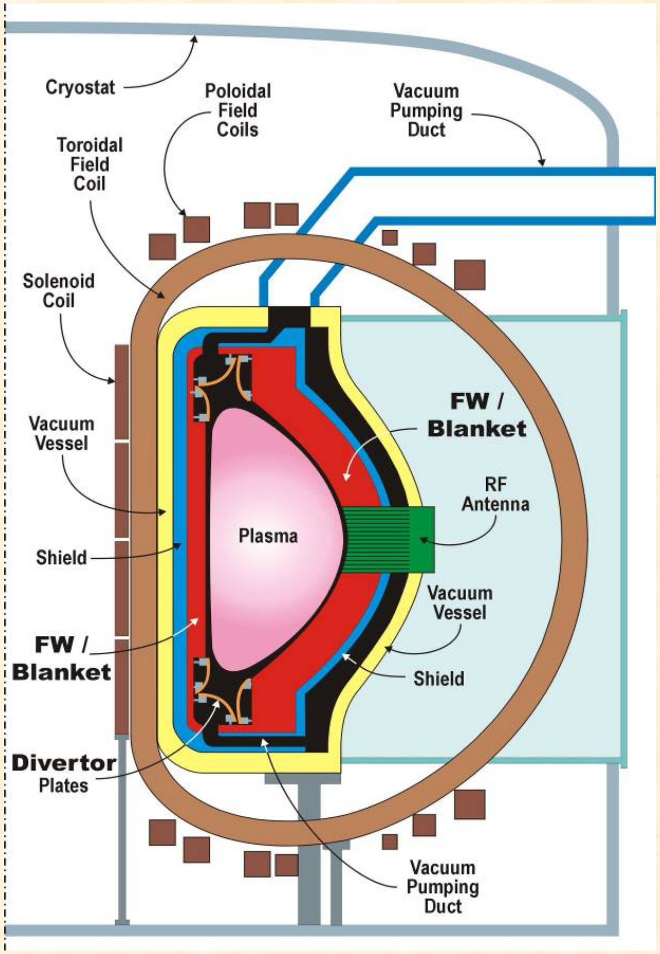
SBP-5: Divertor plasma performance

SBP-6: Burning plasma predictive capability

SBP-7: NB/RF/pellet systems performance

SBP-8: Plasma diagnostics & control

SBP-9: Power plant plasma performance



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 availability and lifetime

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

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

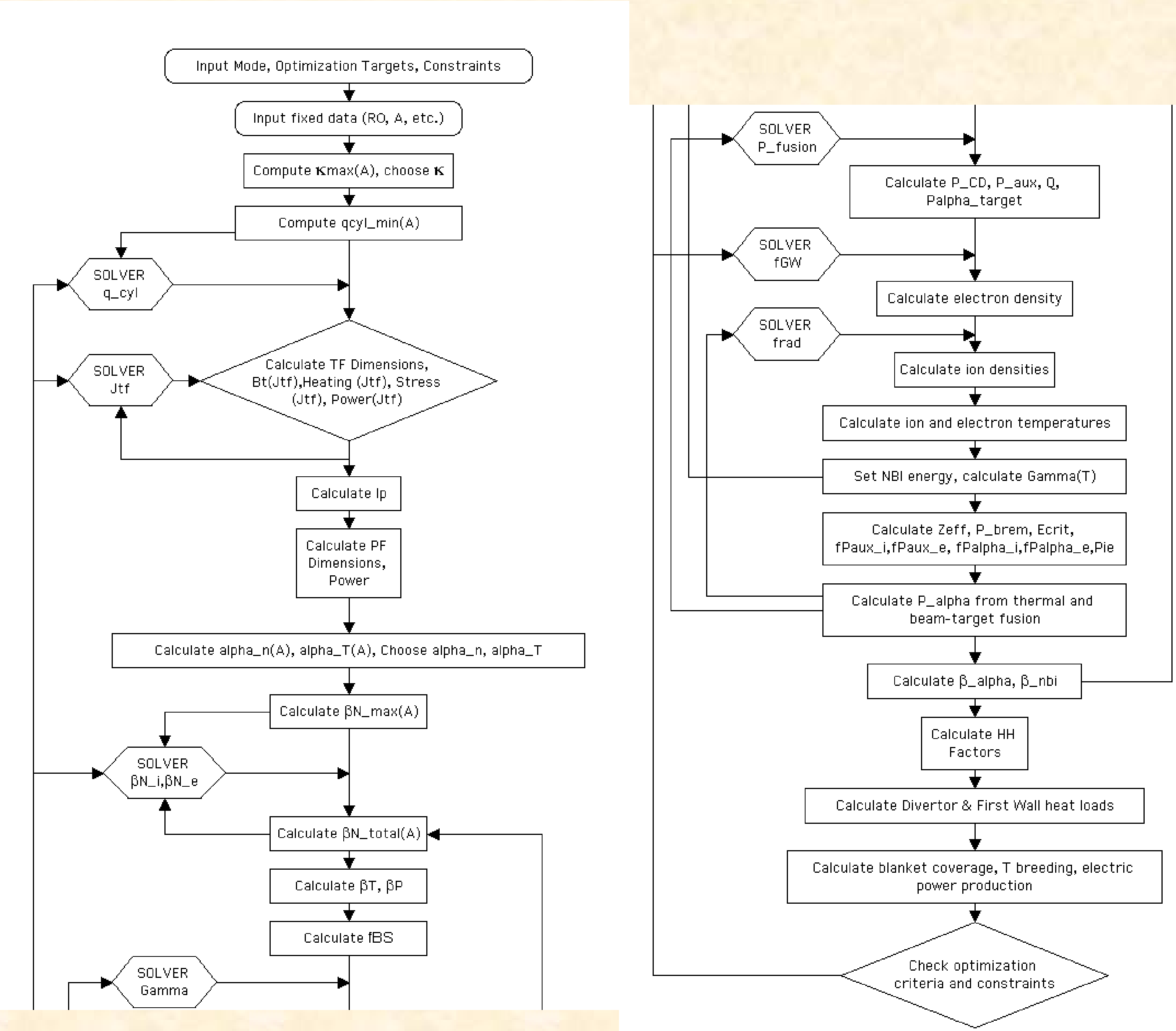
How well could or should NCT address these R&D gaps? Preliminary estimates for review and improvement by NCT DG

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		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 reliability and lifetime		TBD	1	1	3	3	R	R
Full remote handling	2	TBD	2	1	3	R	R	R
Public safety & environmental protection	1	TBD	2	1	3	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

Non-linear optimizer flow chart for NCT parameter tradeoffs



Optimizer finds solution that maximizes an objective function within equality and non-equality constraints, by adjusting variables in ⬡

Sensitivities calculated:

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

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	

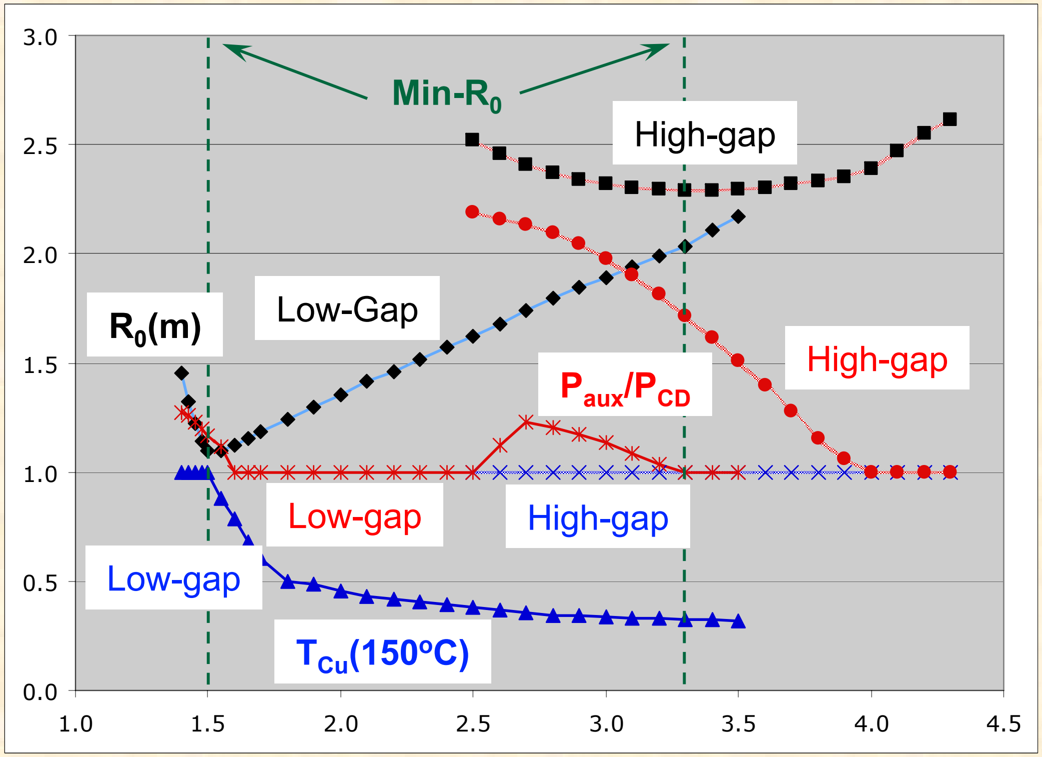
Working plasma assumptions

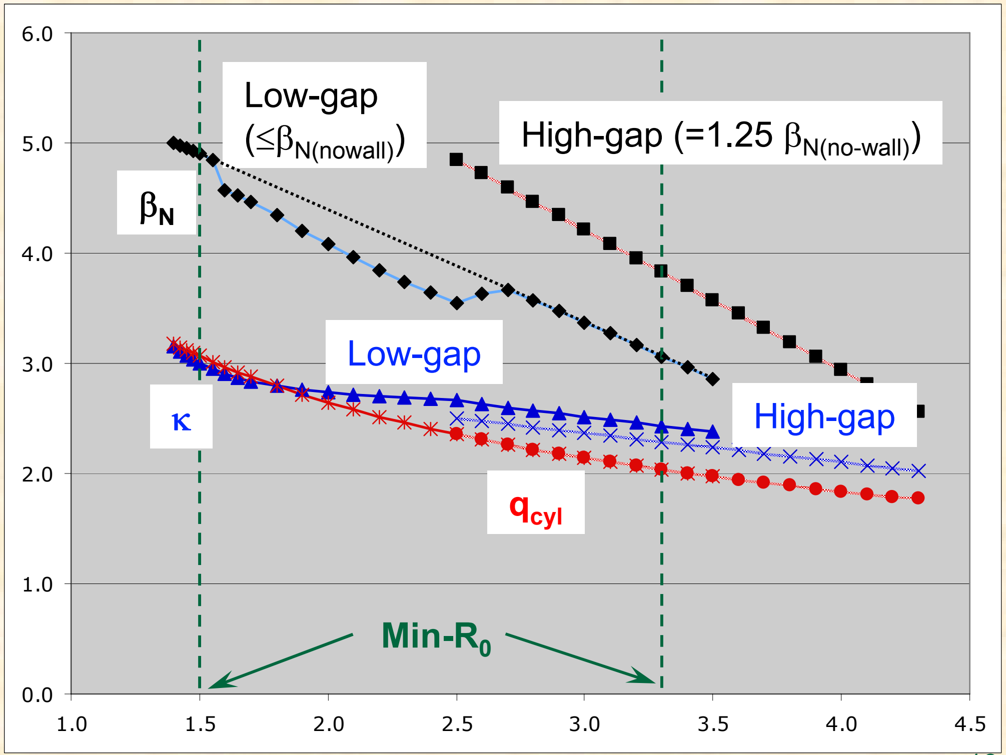
A	1.4-3.5 for low-gap, 2.5-4.5 for high-gap	
R0	1.0-2.2m for low-gap, 2.5-3m for high-gap	
kappa	3.674/SQRT(A)	NHTX scaling
delta	0.5	
qcyl	IF(A<=2.5,1.1877+7.8128*A^-1-16.1953*A^-2+12.233*A^-3,2.5-0.265*(A-2.5))	1.06*[1]
beta_N	<=(6.43-1.02*A)/100	[1] for low-gap; 1.25*[1] for high-gap
α_n=α_T	(0.64-0.3/A)/2	[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)

Inboard wall/shield+SOL thickness (“gap”) determines minimum-R_0 designs of A = 1.5 and A = 3.3 for W_L = 1 MW/m^2

Example: Test module area ≥ $10m^2$; W_L = 1 MW/m^2; 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

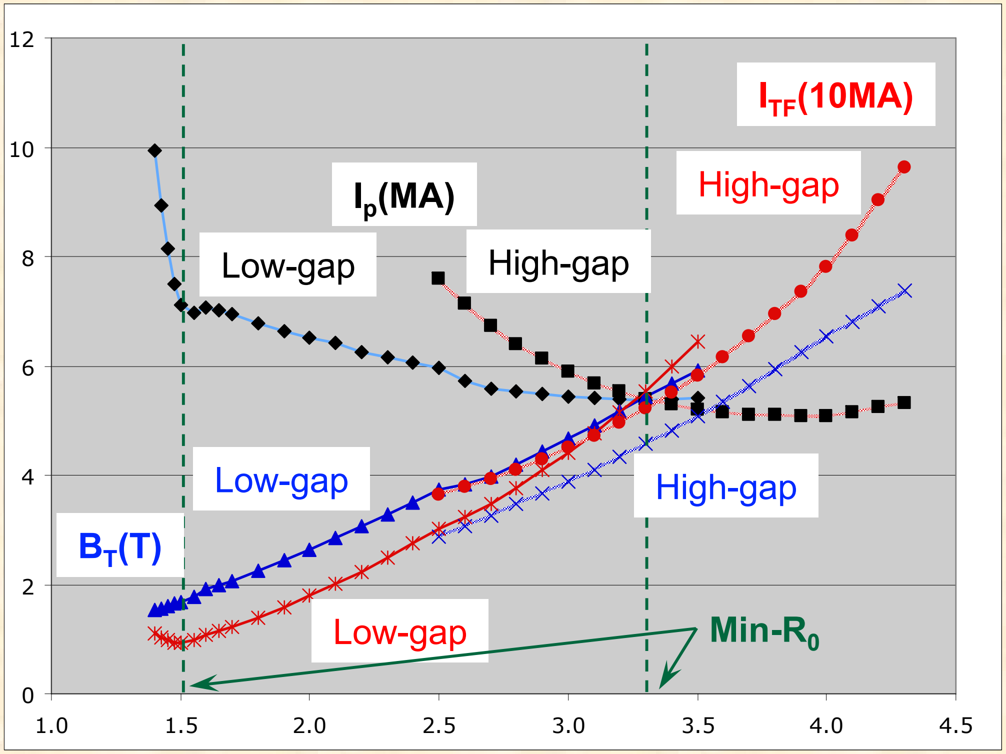


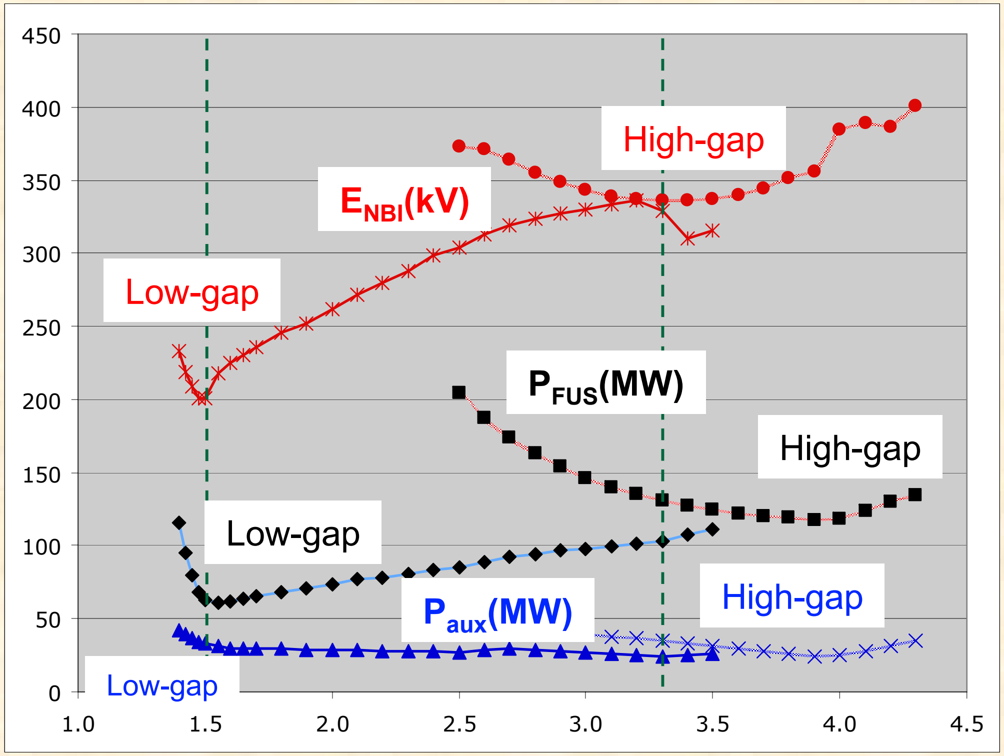


A →

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

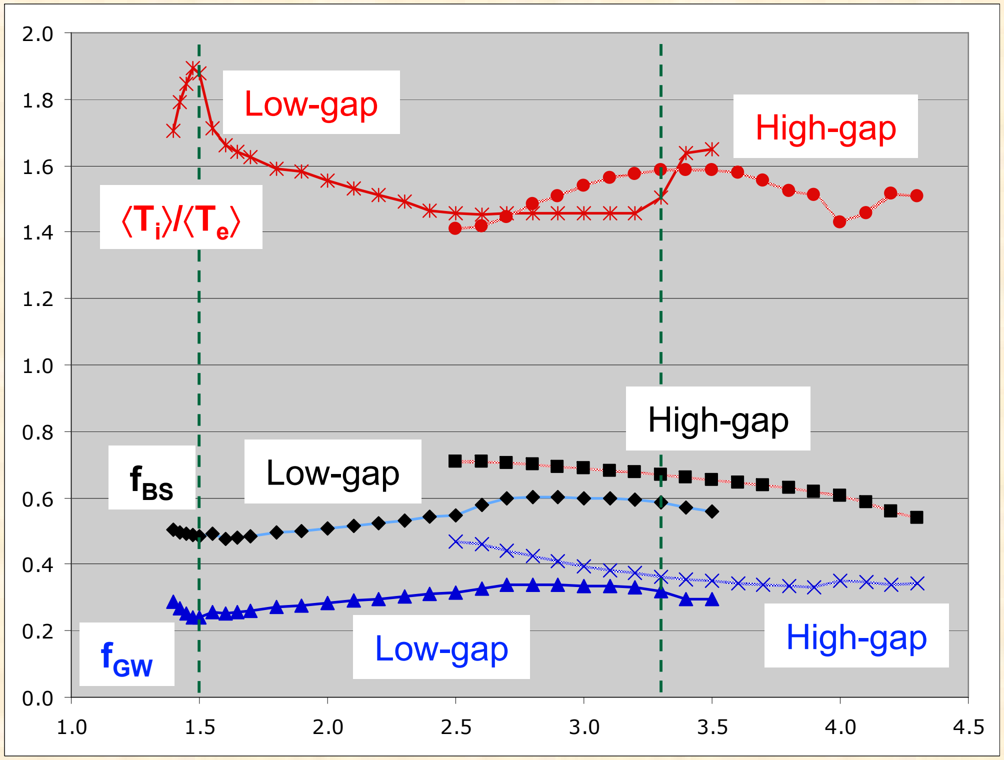


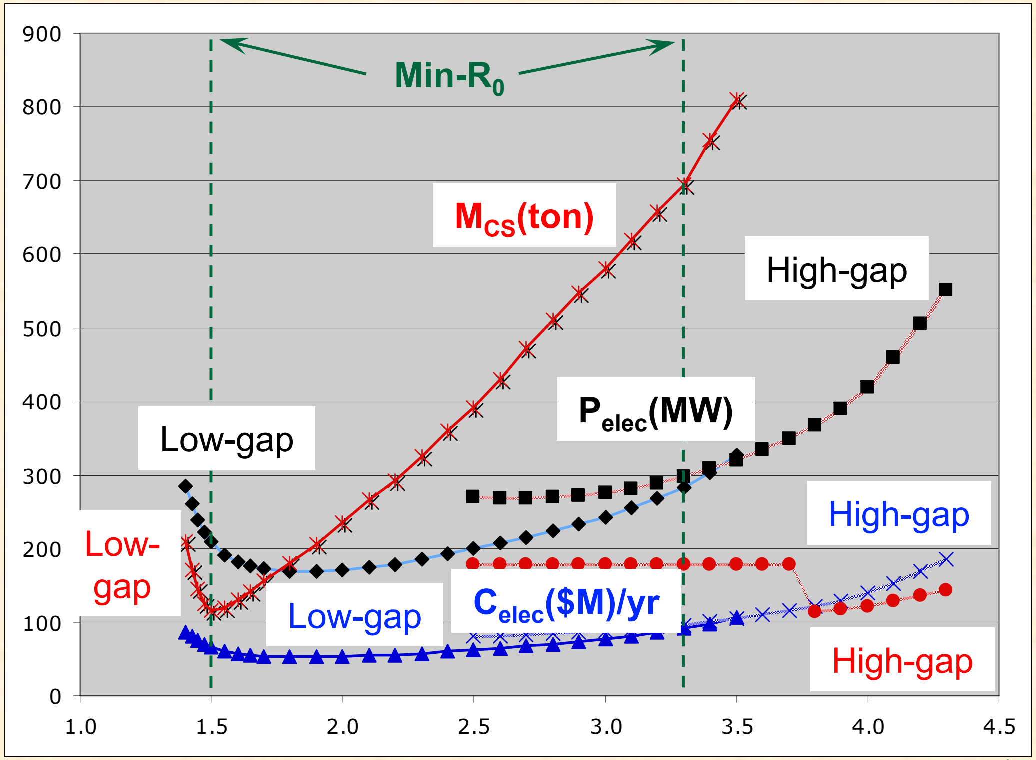


A →

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

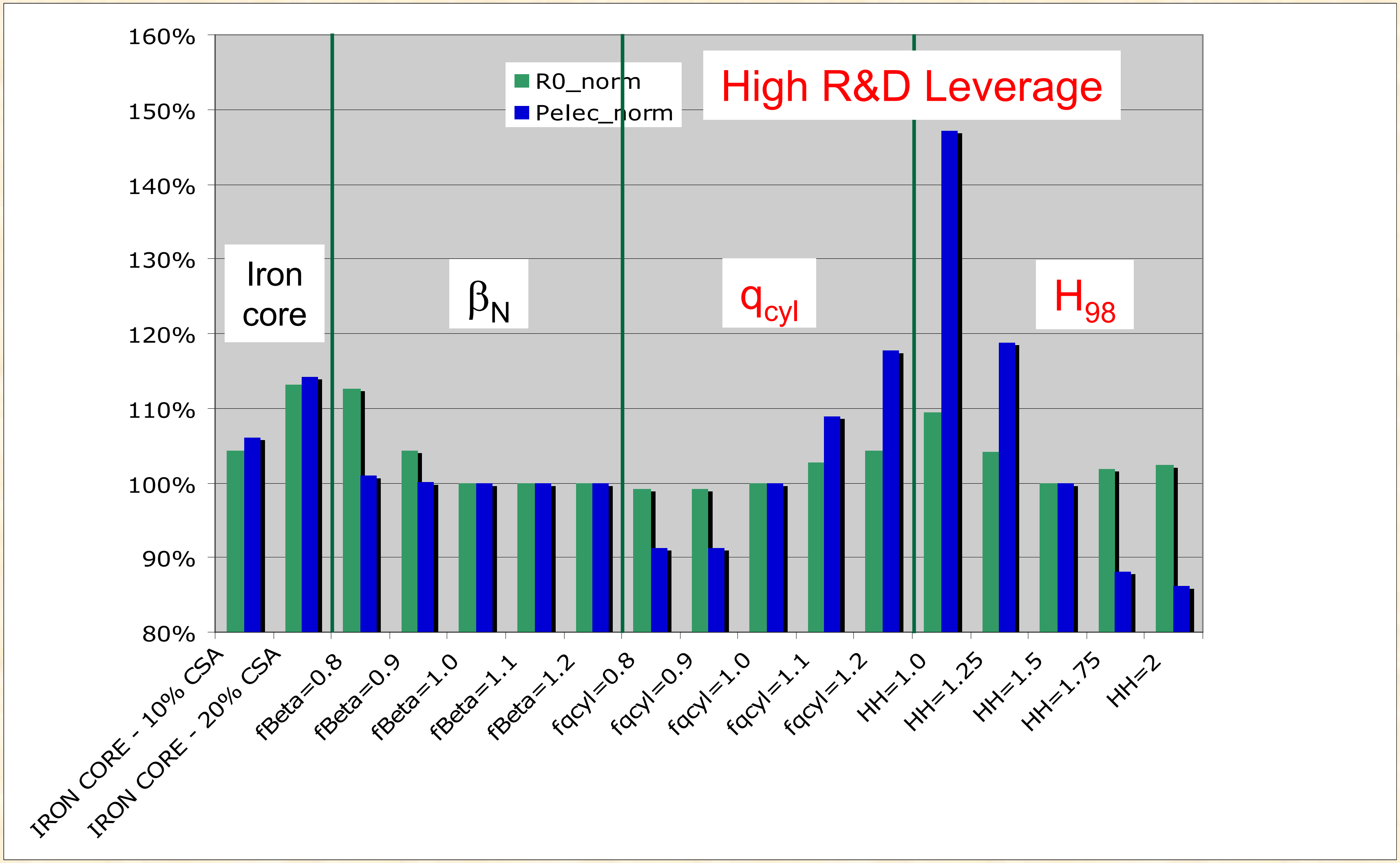
	Low-Gap	High-Gap
⟨Ti⟩/⟨Te⟩	1.9	1.6
f_{BS}	0.49	0.67
f_{GW}	0.24	0.36
Electric power (MW)	209	385
Power cost ($M/yr @ 4.5c/kWh)	89	166
TFC CS mass (ton)	115	734



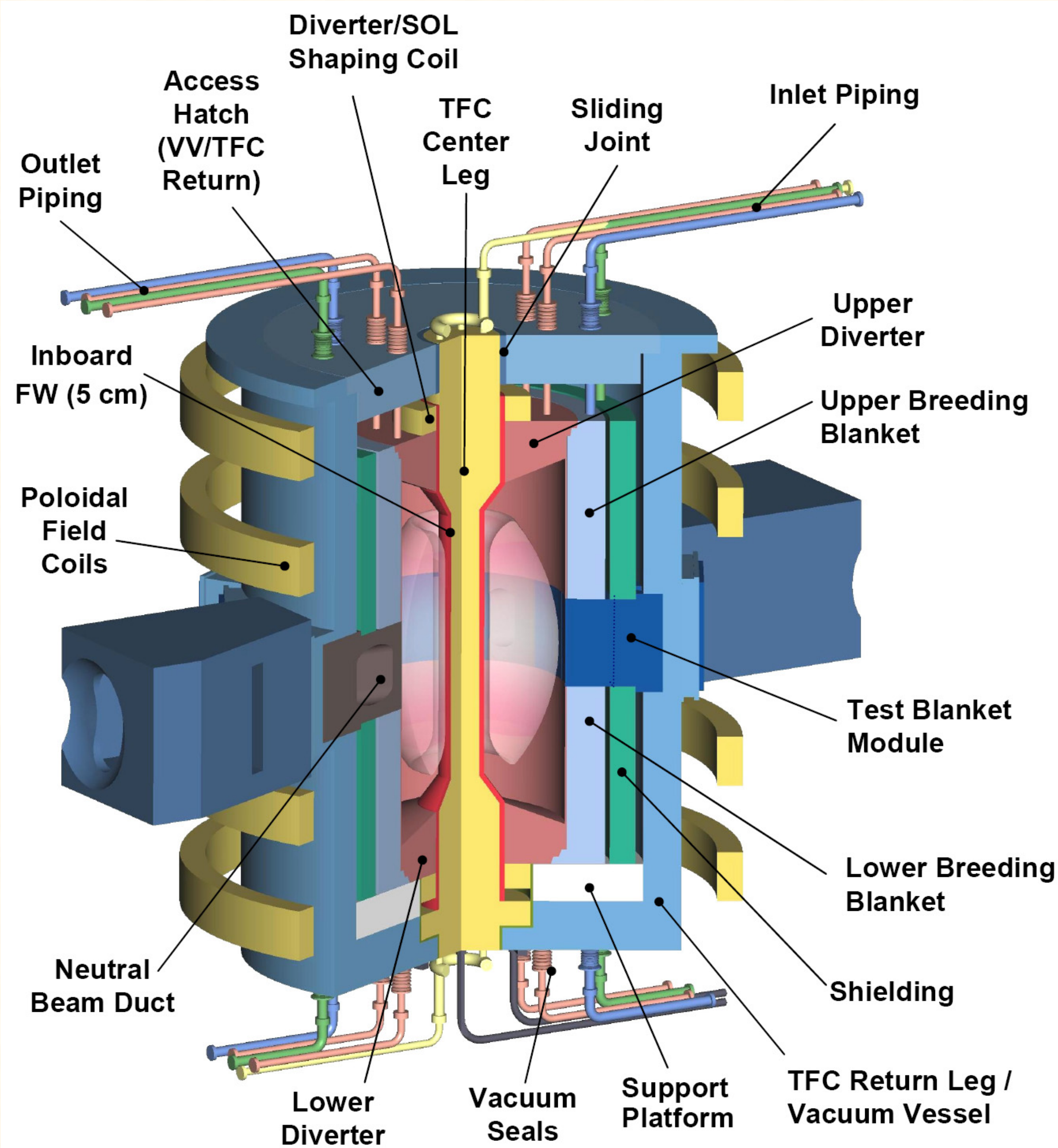


P_{aux} depends strongly on H_{98}, and P_{TFC} substantially on q_{cyl} → indicating R&D priorities for NCT

- 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



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



W_L [MW/m²]	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}/m³]	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-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 [m²]		**14**	
Blanket A [m²]		**66**	
$F_{n-capture}$		**0.76**	