Smaller & Sooner:

How a new generation of superconductors can accelerate fusion's development

Dennis Whyte

Z. Hartwig, C. Haakonsen, L. Bromberg, H. Barnard, G. Olynyk, M. Greenwald, E. Marmar,

MIT PSFC

& Students of 22.63 Fusion Engineering

Fusion Power Associates

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Fusion's development is impeded by its large single-unit cost

- **The overnight cost of a fission power plant is ~ $4/W.**
- **First of kind fusion plants <u>at least</u> $10-20/W**
- **Which implies that developing fusion reactors at ~GWe scale requires 10-20 G$ "per try" e.g. ITER**
- **Chance of fusion *development* significantly improved if net thermal/electrical power produced at ~5-10 x smaller i.e. ~ 500 MW thermal.**

Steady-state tokamak reactor: robust and compact if the achievable B can be ~doubled from its present limitation of B~5-6 T to B~10 T

- **Reactor/DEMO criteria?**
  1) Adequate fusion power areal density $P_f / A_{blanket} \geq 4\ MW\ m^{-2}$
  2) High fusion (Q > 25) and electrical (Q_e*~5) gain.*

- **High fusion power density and thermal conversion are <u>not optional</u>**
  E.g. It would take ITER ~ 1800 years to pay off its principle even if operating 24/7 and selling electricity at 10 c/kW-hr.
  Problem? $P_{fusion} / A \sim 0.7\ MW/m^2$, water-cooled wall and 20B$

- **Robustly non-disruptive steady-state scenarios are also necessary**
  - Plasma pressure (p_{th}), determines the fusion power density ($\sim p_{th}^2$), will be ~ 1 MPa in all reactor designs [1]
  - So energy density a factor of 4-5 larger than in ITER where damage from disruptions/instabilities seems already unacceptable.

The *development schedule* of fusion power would be greatly accelerated if ‘1st DEMO’ could be designed with two extra criteria

‘1st DEMO’ plant criteria

3) Smallest size/volume, total power output and expense, and,

4) For the leading tokamak concept, robust steady-state operation.

- The only way to satisfy all of four these criteria is to increase B which can be seen from the simplified relationships at fixed R/a*

$$\frac{P_f}{A_{blanket}} \sim \left(\frac{\beta_N^2}{q^2}\right) R\, B^4 \quad , \quad \left(\frac{\beta_N H}{q^2}\right) R^{1/2} B^3 \geq C_{Ignition}$$

Power density *Gain*

* *See Appendix of FESAC WP for details*

Doubling B field to ~9-10 T solves the "Catch-22" of initial DEMOs

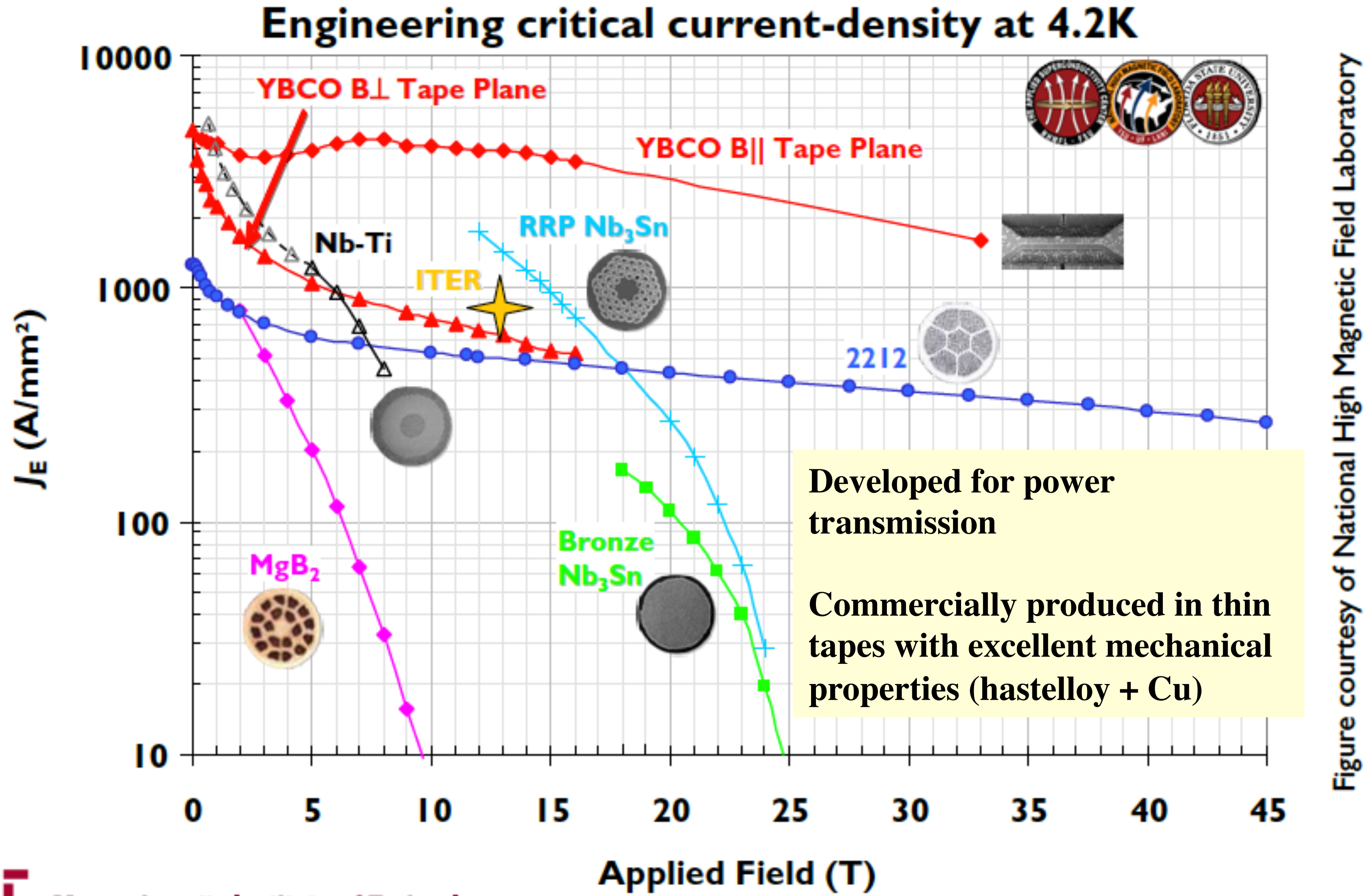
- **#1: At standard B~5-6 T the bracketed "plasma physics" must be pushed to and past intrinsic operational limits (e.g. q*~2, Beta_N~5-6) in order to keep size reasonable, R<6 m.**

- **#2: Yet exceeding any operational limits becomes essentially unacceptable due to reactor pressure/energy density!**

- **Doubling the B field provides x10-16 to simultaneously decrease plasma physics /operational risk (bracketed terms) and size and cost ($\$ \sim R^{2-3}$)**

A new generation of superconductors developed over the last decade allow ~doubling of B_{max} *compared to standard NbSn*

Sub-cooled high-temperature super-conductors have critical currents with very small degradation versus B field up to ~30 T

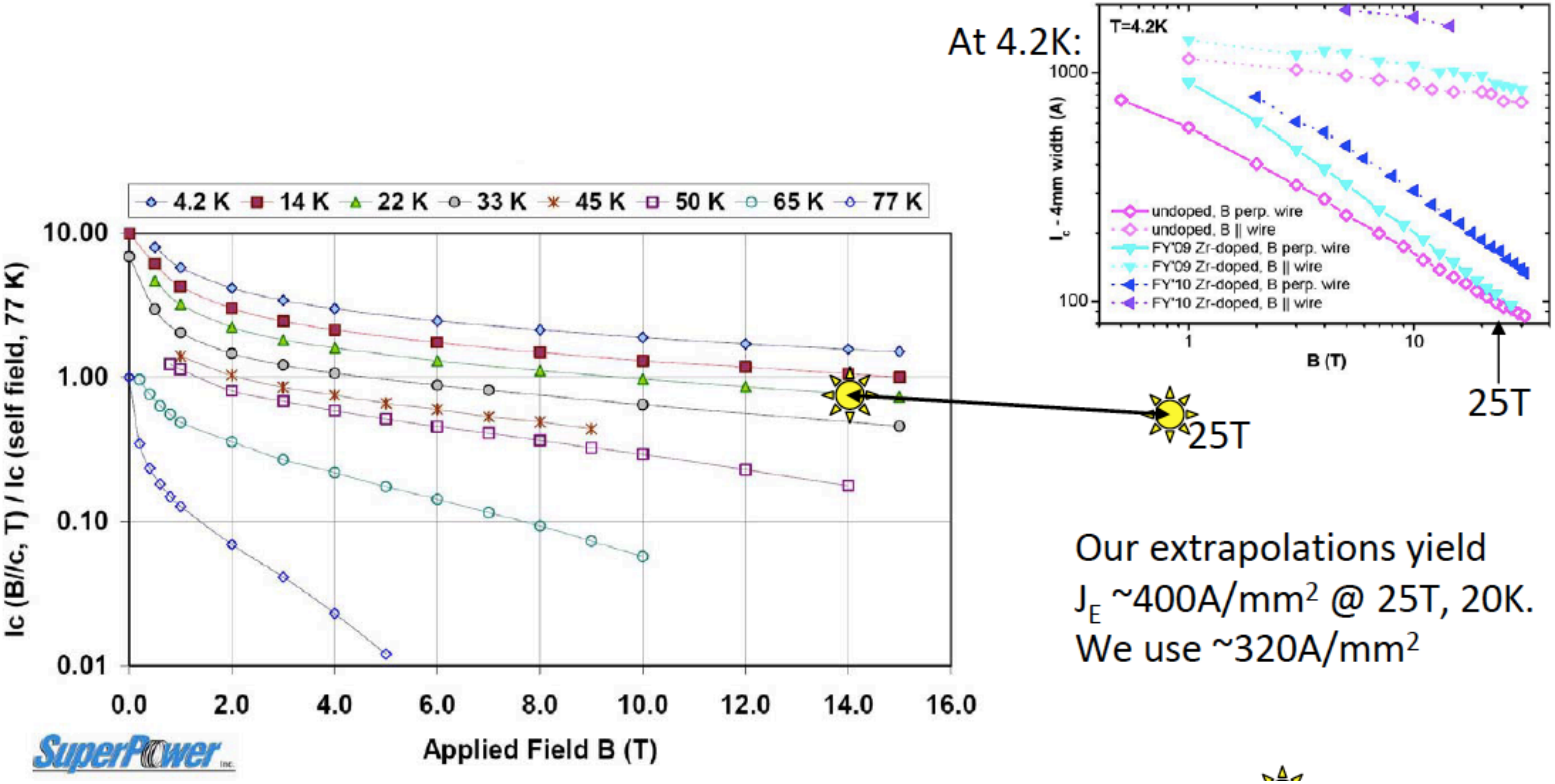


Developed for power transmission

Commercially produced in thin tapes with excellent mechanical properties (hastelloy + Cu)

HTSC tapes can use intermediate T ~ 20K (H cooling)
Design B primarily // to tape in high field regions

At 4.2K:



Our extrapolations yield
J_E ~400A/mm^2 @ 25T, 20K.
We use ~320A/mm^2

Recent MIT Design Effort* "Rules"

- **Develop a *robust* conceptual design based on YBCO magnets of a high gain, net electricity producing magnetic fusion power plant at substantially reduced total thermal power ~ 500 MW (factor of ~5 reduction from typical designs).**
  - **No violation of basic core limits: kink, no-wall Troyon Beta, Greenwald to assure stable operation.**
  - **Fully non-inductive scenarios but robust external control**
  - **Minimize solid waste**
  - **Minimize capital cost ~ Surface area of plasma/blanket to assure best fusion economic outlook.**
  - **Q_electric > 4**

*22.63 MIT fusion design course Spring 2012

Acknowledgements

- **22.63 Design Course Students:**
  S. Arsenyev, J. Ball, J. Goh, C. Kasten, P. Le, F. Mangiarotti, B. Nield, T. Palmer, J. Sierchio, B. Sorbom, C. Sung, D. Sutherland

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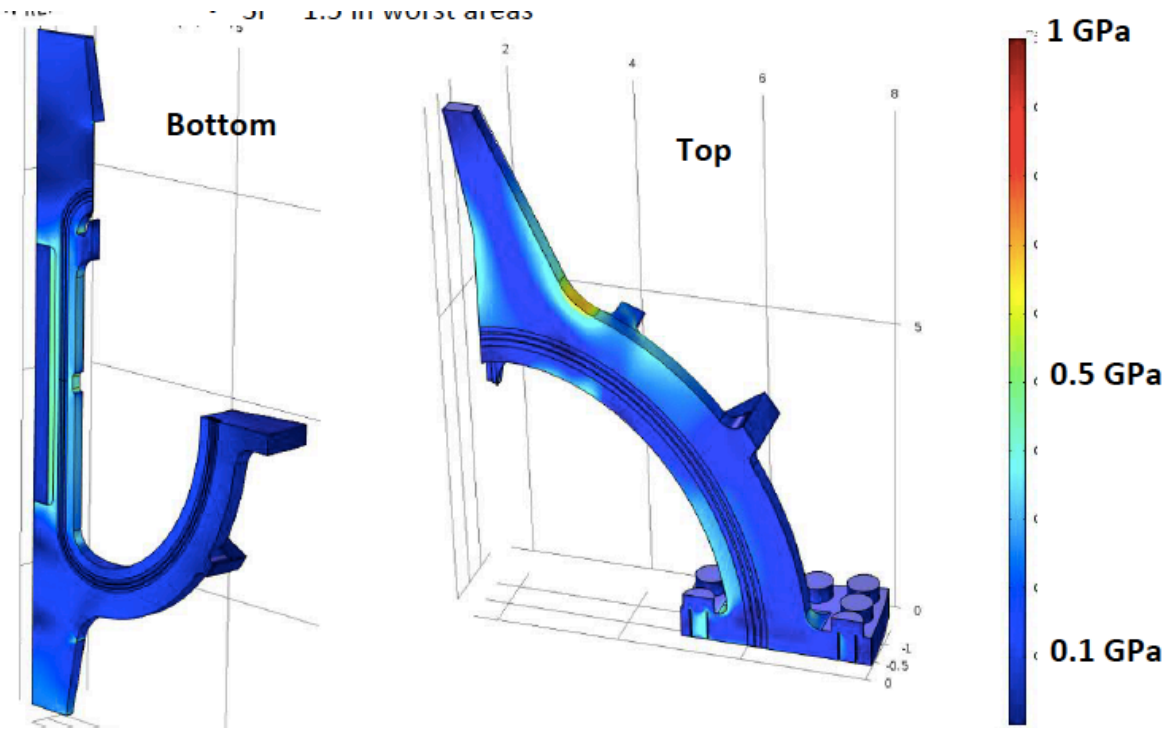
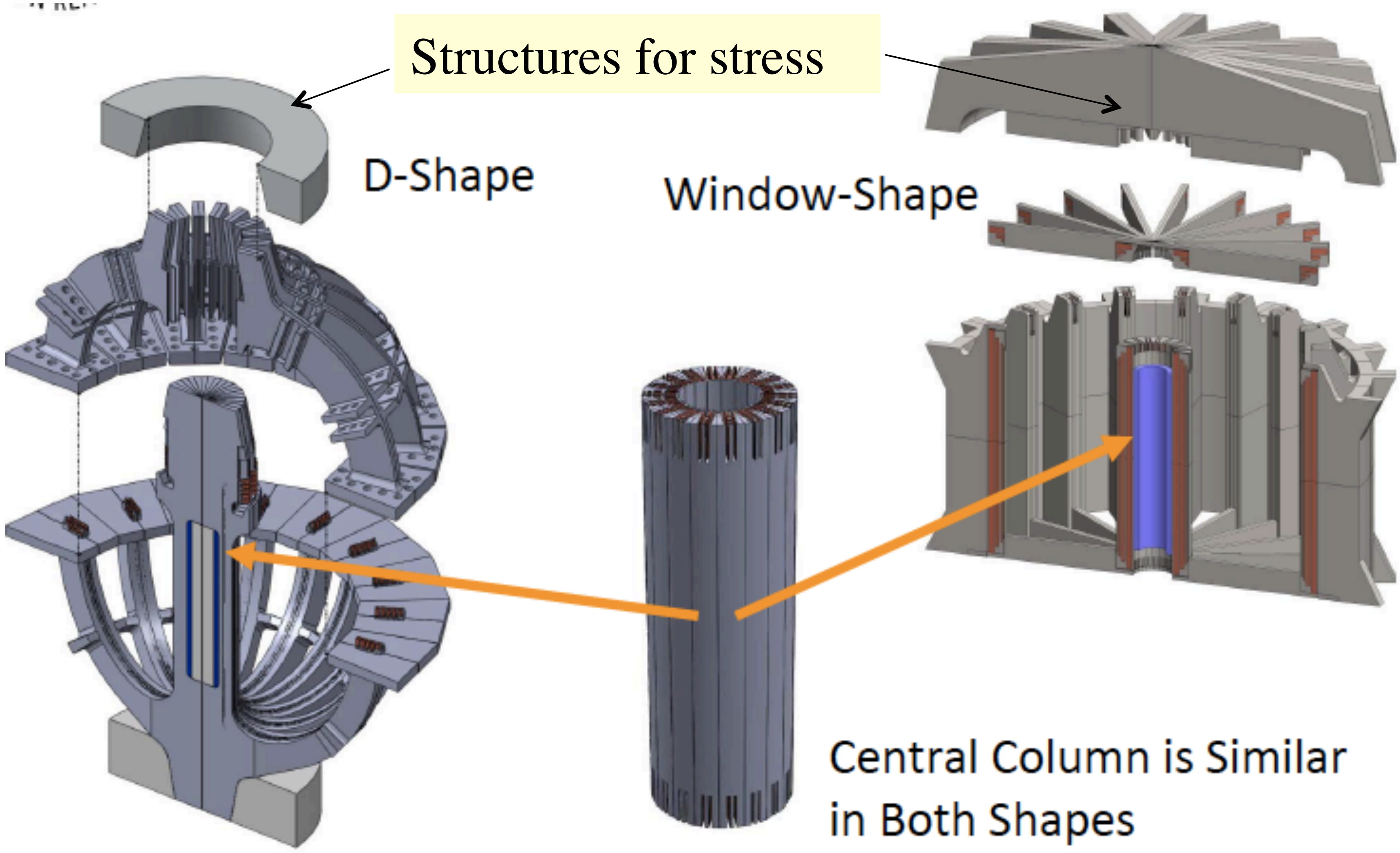
The limitation in B field is set by structural stress limits



- $B_{coil,max}$ in regime of 20-25 Tesla has been scoped.
- Preliminary design identified options for static stress
  - ➢ Dynamics not addressed.
- B_0 ~9.2 T on axis for R/a~3, 1 m shield

HTSC tapes also open the possibility that the SC coils are demountable
Design: low resistance normal joints

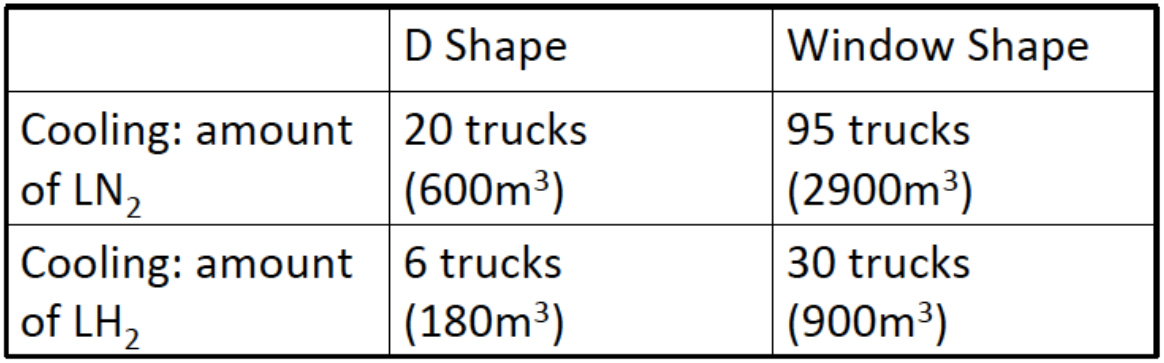


Structures for stress

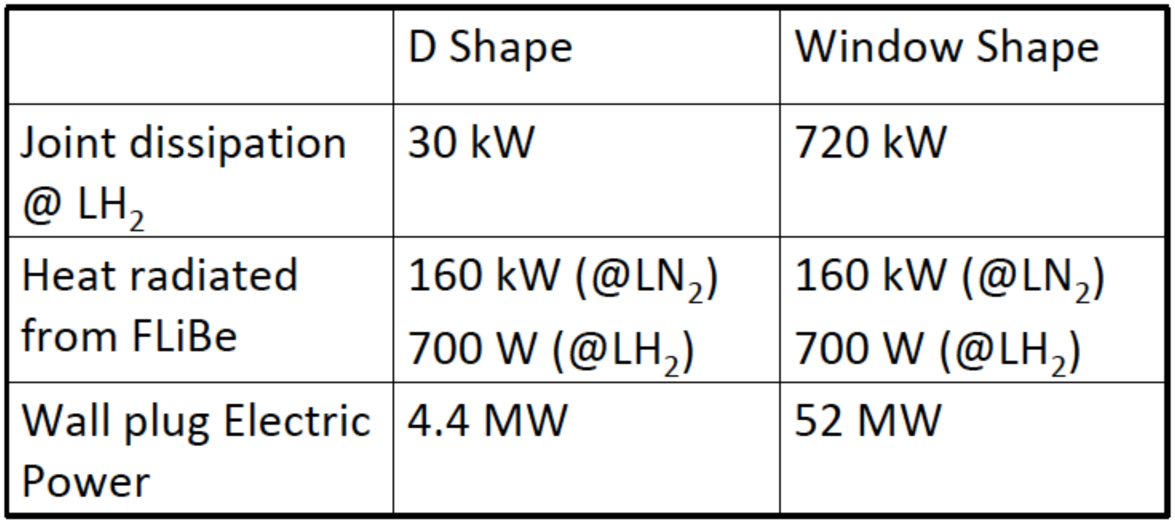
Central Column is Similar in Both Shapes

Small size permits reasonable cool/warm time for structures during demounting

Different joints design → flexibility vs $P_{electric}$



	D Shape	Window Shape
Cooling: amount of LN_2	20 trucks ($600m^3$)	95 trucks ($2900m^3$)
Cooling: amount of LH_2	6 trucks ($180m^3$)	30 trucks ($900m^3$)

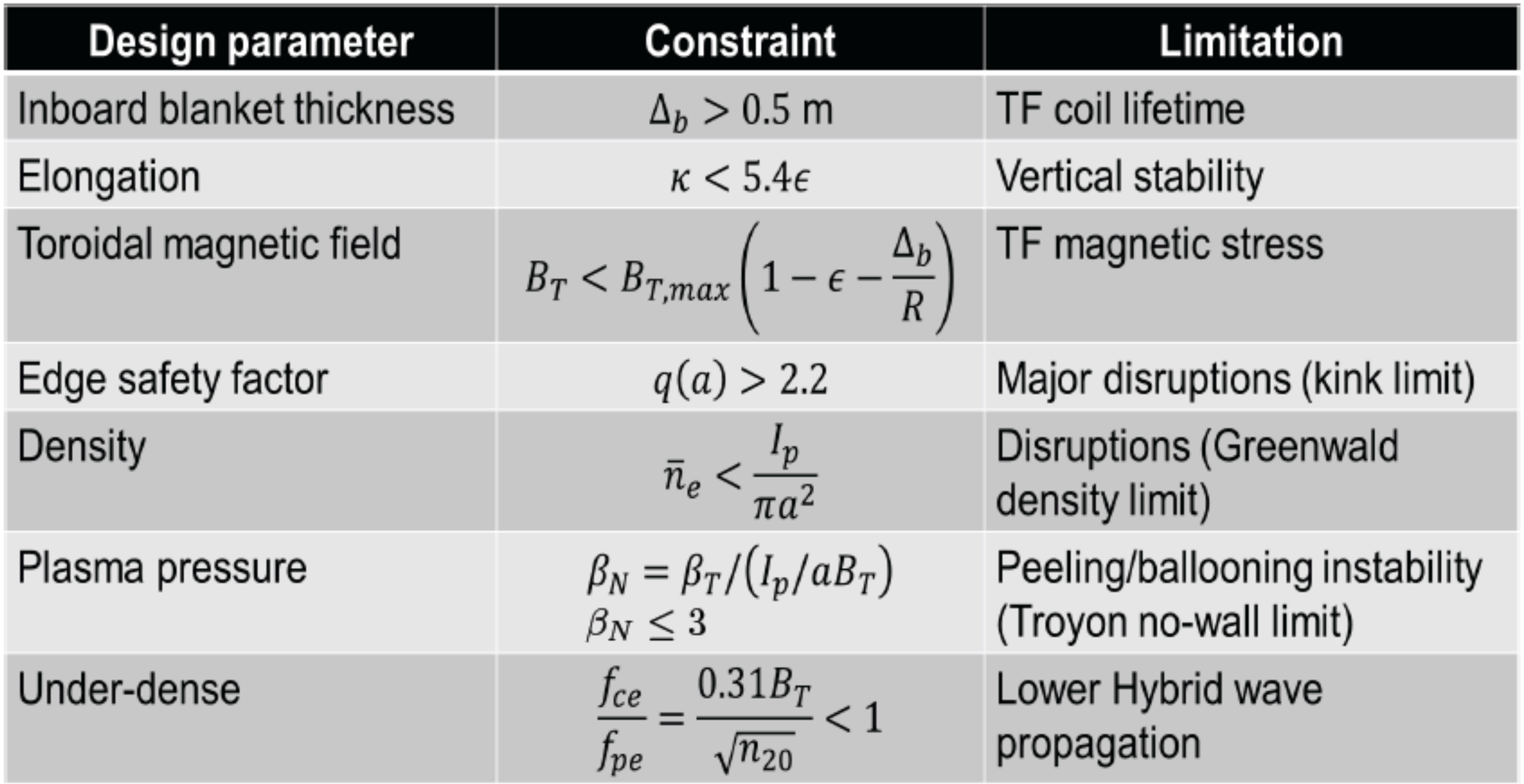


	D Shape	Window Shape
Joint dissipation @ LH_2	30 kW	720 kW
Heat radiated from FLiBe	160 kW (@LN_2) 700 W (@LH_2)	160 kW (@LN_2) 700 W (@LH_2)
Wall plug Electric Power	4.4 MW	52 MW

DEMO-like FNSF-like

- **Coil shape tradeoffs.**
- **Window-shape: easier design but longer down time + more electric power…use for more FNSF version?**
- **D-shape: more complex design, but quicker changes + lower electric power…more DEMO**
  - **Warmup ~ 3 days with dry air**
  - **Cool down ~1-2 days**

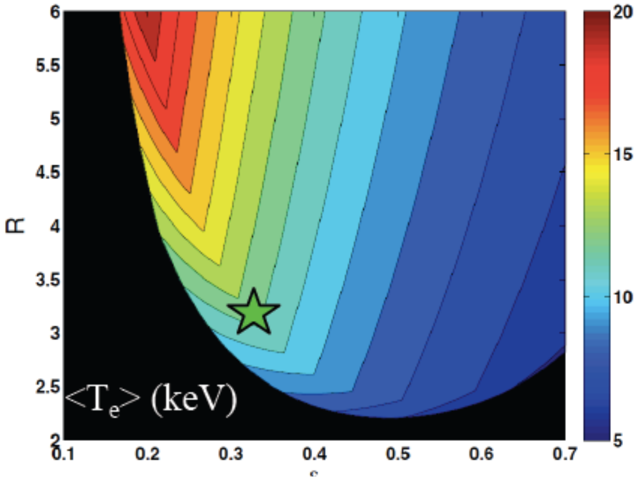
Analysis confirms high-B path to small size, high gain design away from operational limits

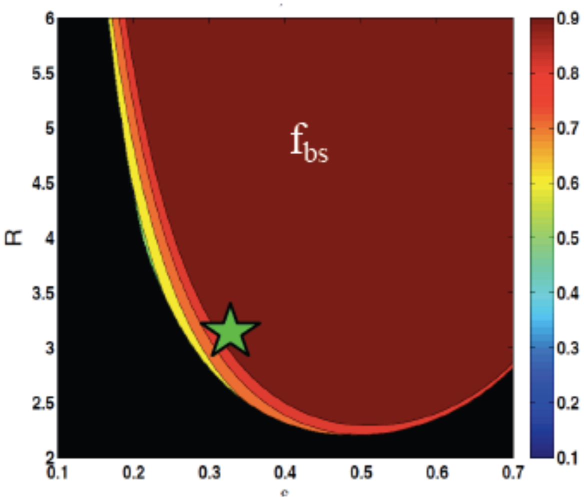


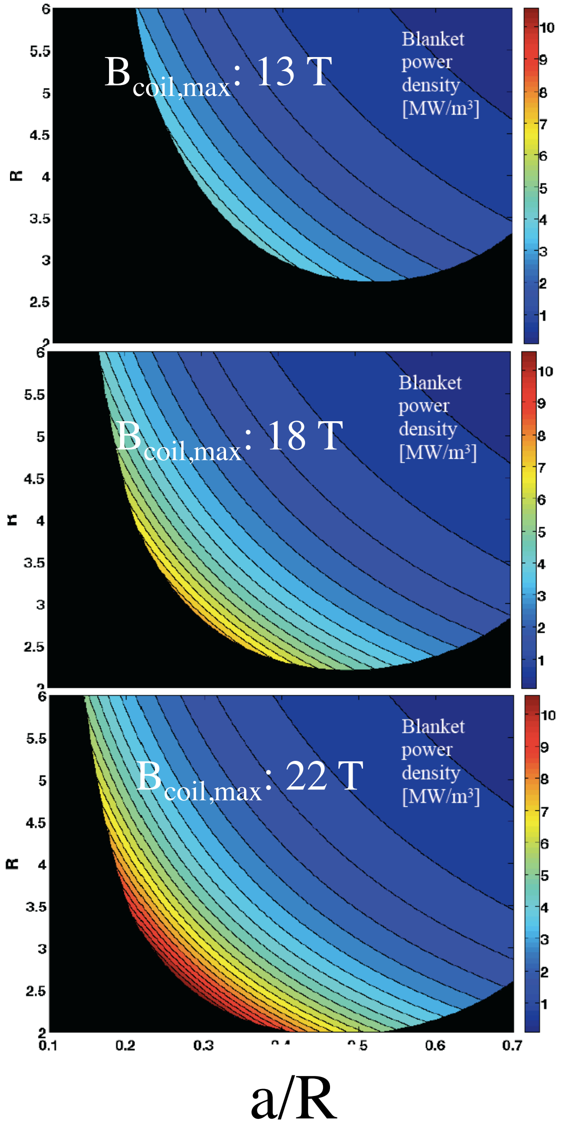
Design parameter	Constraint	Limitation
Inboard blanket thickness	$\Delta_b > 0.5$ m	TF coil lifetime
Elongation	$\kappa < 5.4\epsilon$	Vertical stability
Toroidal magnetic field	$B_T < B_{T,max}\left(1 - \epsilon - \frac{\Delta_b}{R}\right)$	TF magnetic stress
Edge safety factor	$q(a) > 2.2$	Major disruptions (kink limit)
Density	$\bar{n}_e < \frac{I_p}{\pi a^2}$	Disruptions (Greenwald density limit)
Plasma pressure	$\beta_N = \beta_T/(I_p/aB_T)$ $\beta_N \leq 3$	Peeling/ballooning instability (Troyon no-wall limit)
Under-dense	$\frac{f_{ce}}{f_{pe}} = \frac{0.31 B_T}{\sqrt{n_{20}}} < 1$	Lower Hybrid wave propagation

Simultaneously: Q_p>25, P_f/A>3 MW/m^2, non-inductive

Synergistic benefit: aspect ratio optimization allowed by demountablity







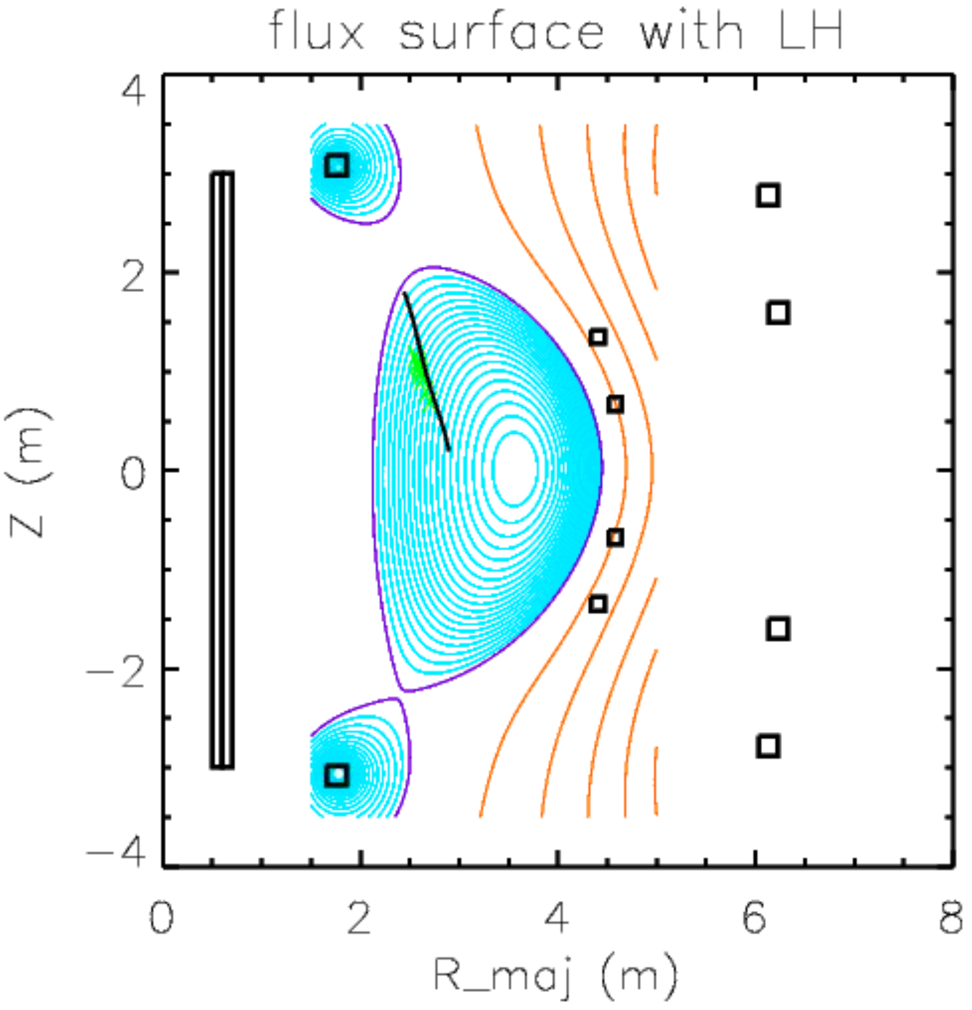
R	ϵ	a	κ	B_T	β_N	I_p	f_{bs}	q_{95}
3.2 m	1/3	1.07 m	1.8	9.2 T	~3	10 MA	~0.9	3.3

$$\frac{P_f}{A_{blanket}} \sim \left(\frac{\beta_N^2}{q^2}\right) R B_{coil,\max}^4 \left\{\epsilon^3\left(1-\epsilon-\frac{\Delta_b}{R}\right)^4 (1+\kappa^2)^2\right\}$$

Example 0-D point designs finds R/a~3 in order to minimize $A_{blanket}$ and \$\$

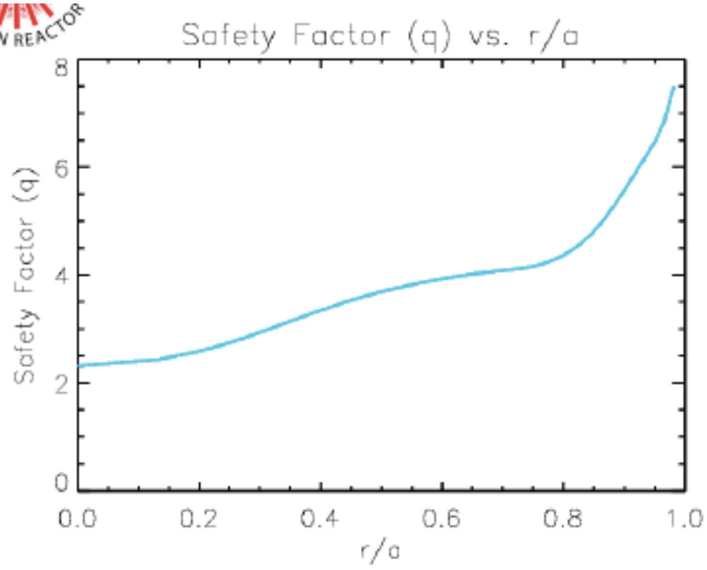
High-field side Lower Hybrid exploits favorable physics for robust penetration + Launcher survivability

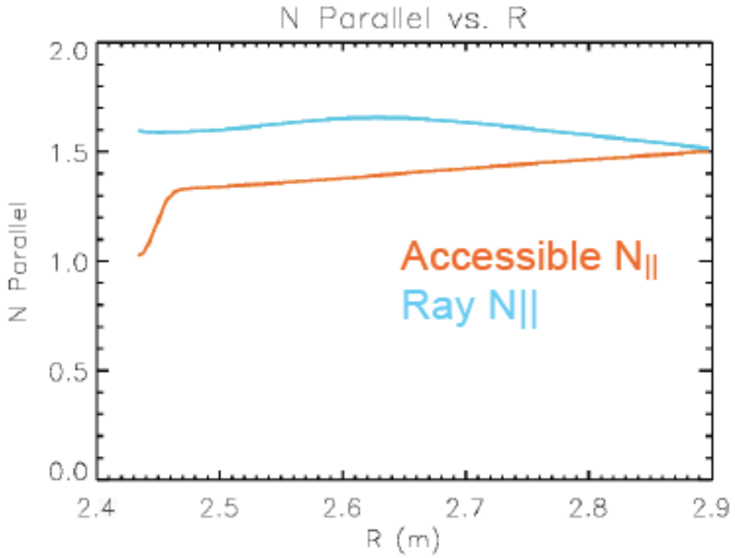
- **Developed for 24/7 tokamak to study PMI: VULCAN***
- **Launchers integrated into axisymmetric inner wall**
- **Placing launcher at good-curvature + quiescent SOL → controlled launcher PMI**
- **Launch point optimized near null point**
    - **Maximized radial propagation when poloidal field is minimum.**

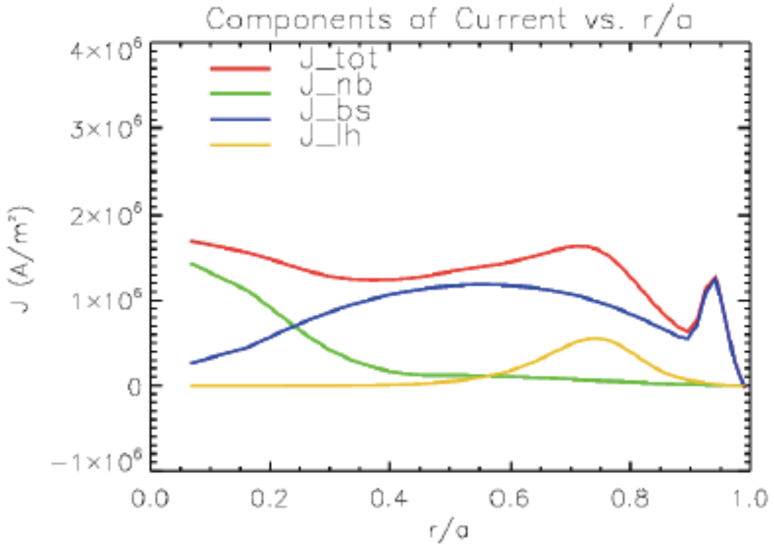


* *Fusion Eng. Design 2012*

Synergistic benefit: High-efficiency mid-radius current drive → SS scenario at lower bootstrap fraction ~80%







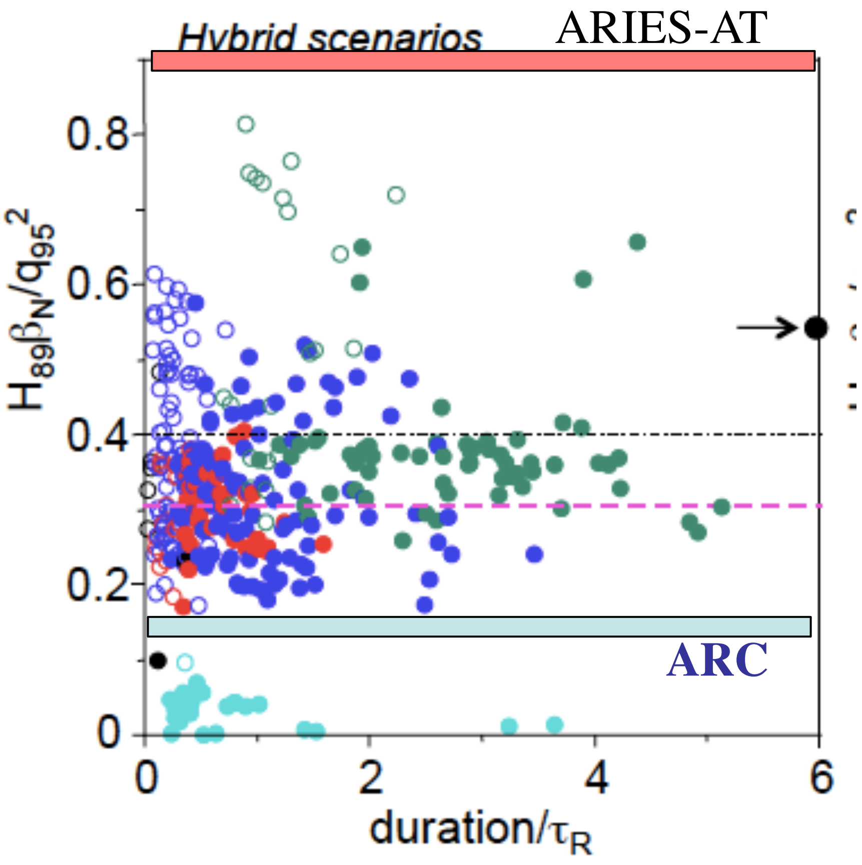
$N_{||}$ ~ 1.5 is damping at 10 keV.

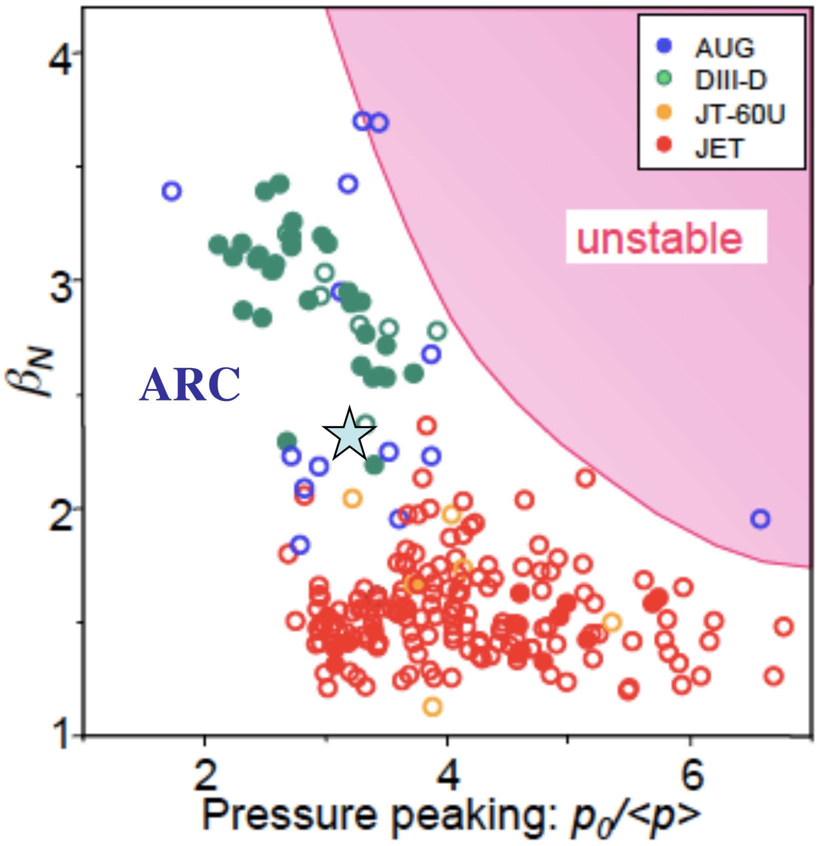
Cannot push $N_{||}$ lower due to accessibility and fast-wave conversion concerns.

→ 10 keV volume averaged reactor optimal for efficient LHCD at mid-radius.

→ Favors smaller reactors.

High field permits high fusion gain with reduced scenario requirements → Shifts risk from plasma physics to magnets





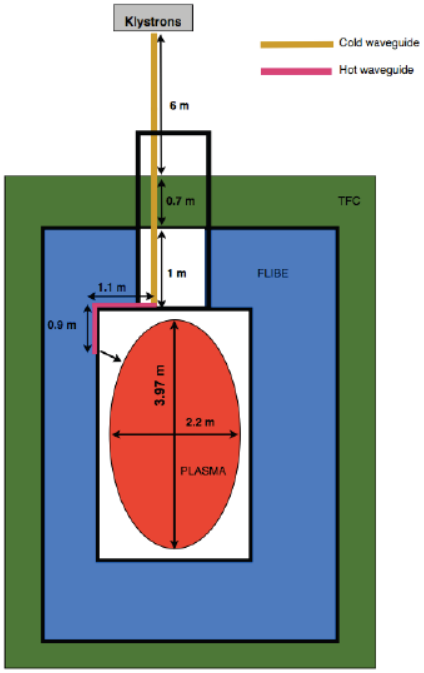
Sips IAEA & Zarnstorff MFE roadmapping

B ~ 9.2T + <T> ~ 10 keV + high η_{CD} → High gain + robust steady-state + Q_e~5

Parameter	Result
Fusion Power	511 MW
LHCD Coupled Power	20 MW
Q_p	25
B_T	9.2 T
I_p^*	7.66 MA
I_{CD}	1.26 MA
f_{BS}	83.6%
η_{CD}	0.37 x 10^{20} $AW^{-1}m^{-2}$
q_{95}	~6

$$Q_e = \frac{\eta_{th}((1+M_n)P_{fusion} + P_{heat} + P_{dissipated})}{\frac{P_{coils}}{\eta_e} + P_{LH} + P_{\cancel{pump}}}$$

Parameter	Result
Q_e	5.12
P_{th}	640 MW*
P_e	270 MW
Plant efficiency	42%



Location	Transmitted Power
Wall plug	55.6 MW
Klystrons	27.8 MW
Cold waveguide	24.0 MW
Hot waveguide	22.4 MW
RF launcher	20.0 MW

Demountablity → Liquid immersion blanket → reduce solid waste ~x50

Legend

Green – ZrH$_2$

Brown – Vacuum (Insulating Gap)

Dark Grey – Inconel 718

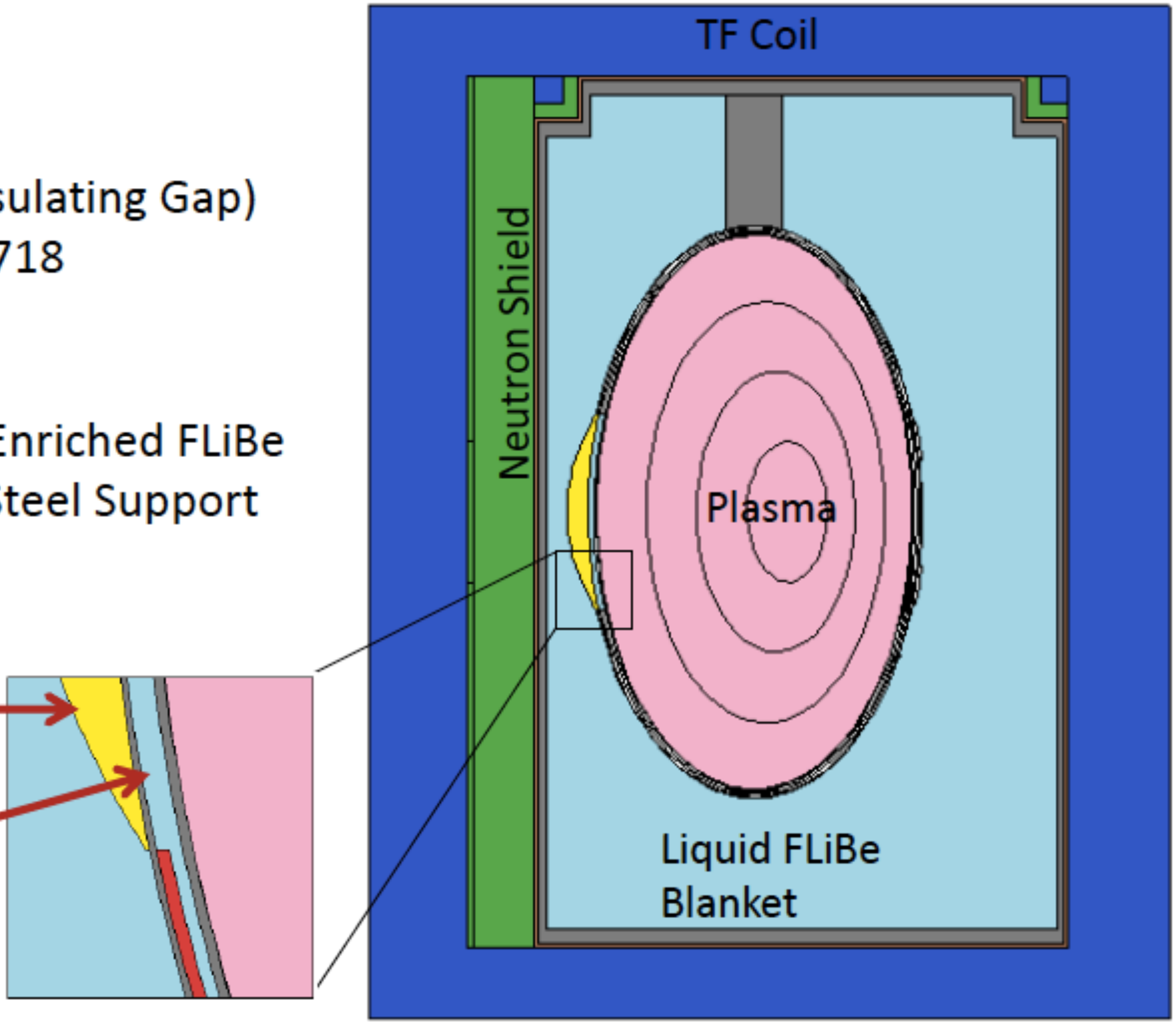
Red– Beryllium*

Yellow – Tungsten

Light Blue – 90% ^{6}Li Enriched FLiBe

Dark Blue – YBCO + Steel Support

Pink – Plasma



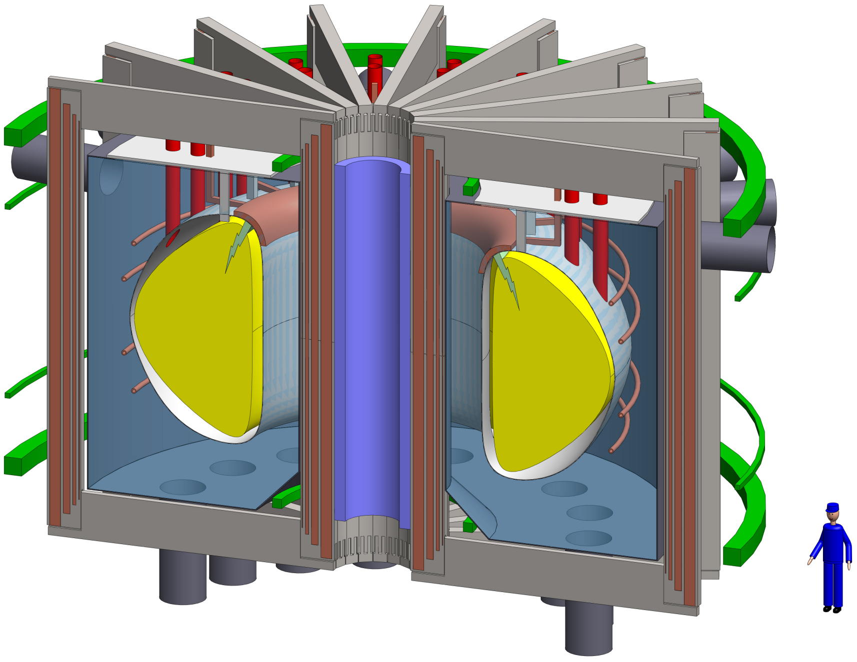
Midplane Tungsten Neutron Shield

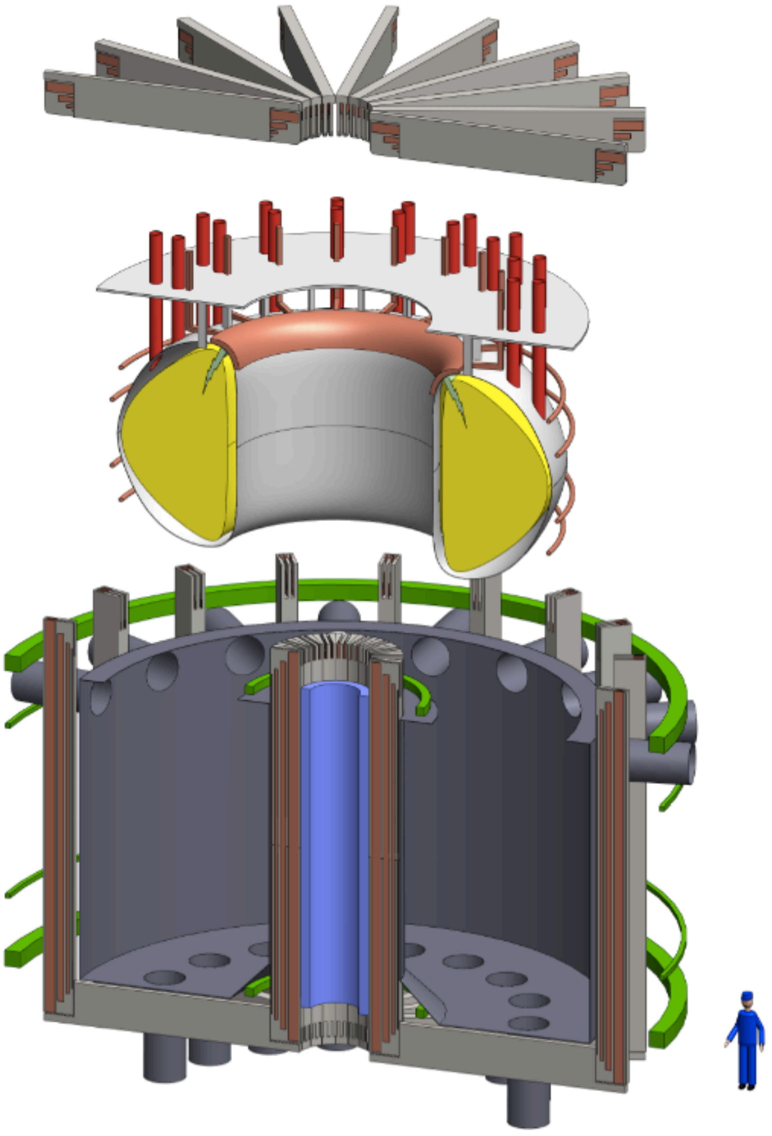
Cooling Channel

*not structural material

Full modular replacement: no connections ever made inside TF Transition FNSF → DEMO

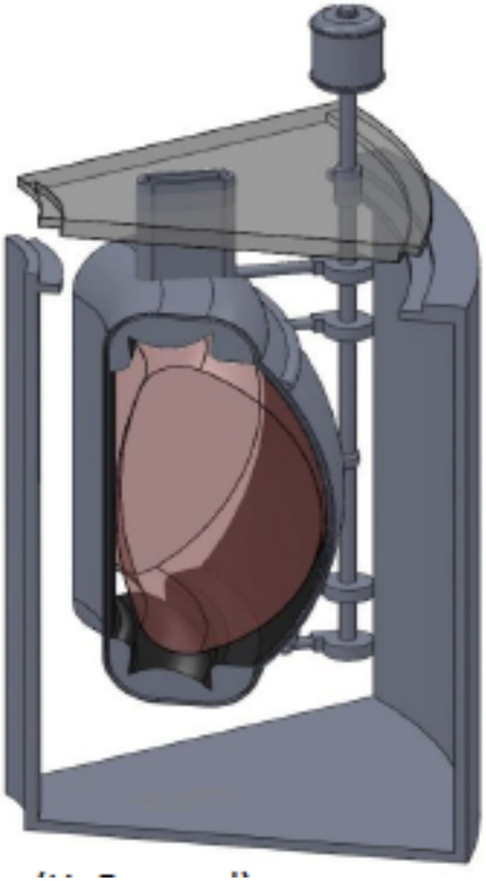
- R=3.3m, R/a=3, B=9.2T
- $P_f/A \sim 3.3\ \mathrm{MW/m^2}$, $A \sim 180\ \mathrm{m^2}$
- VV/core can be single lifted
- All construction/QA offsite





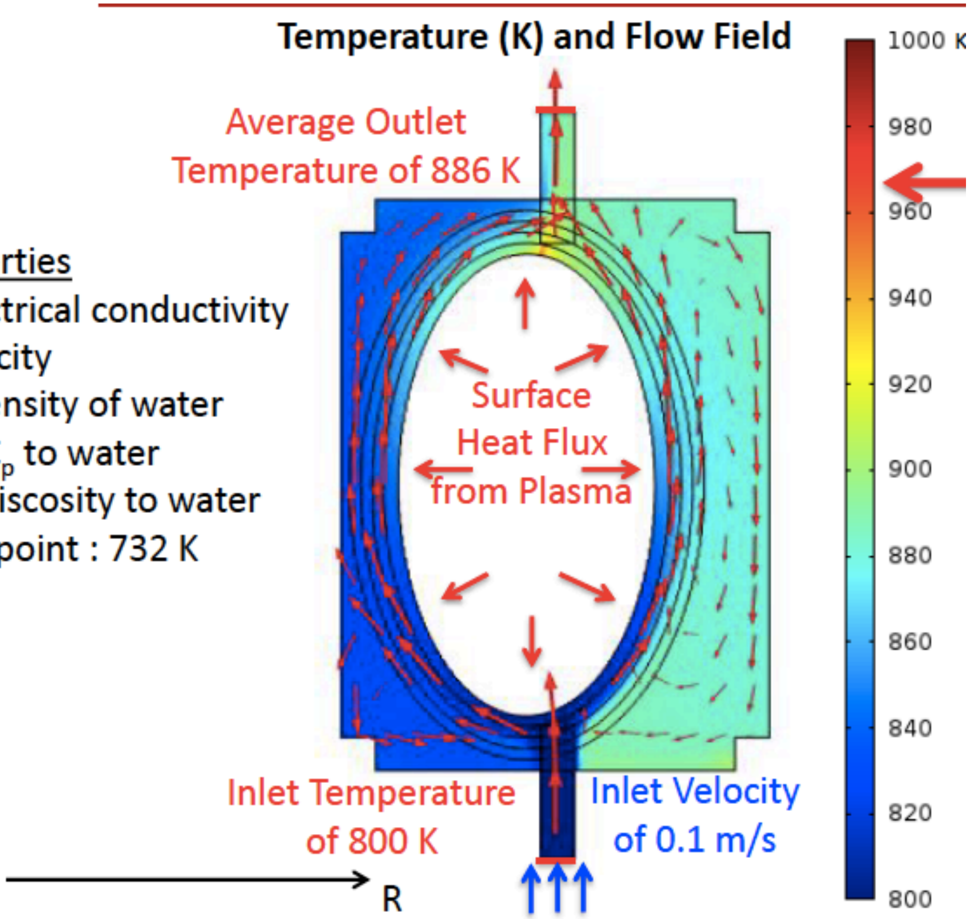
Simplified single-fluid cooling scheme at high temperature like molten-salt reactors

$P_{heat}/S \sim 0.65\ MW/m^2$ matched by Alcator C-Mod



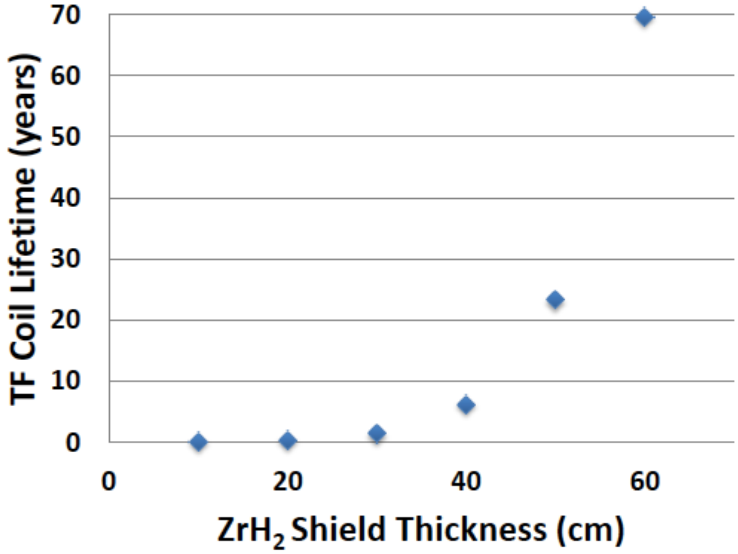
FLiBe Properties

- Low electrical conductivity
- Low toxicity
- Twice density of water
- Similar C_p to water
- Similar viscosity to water
- Melting point : 732 K



Design activity indicates acceptable TF lifetime and TBR.

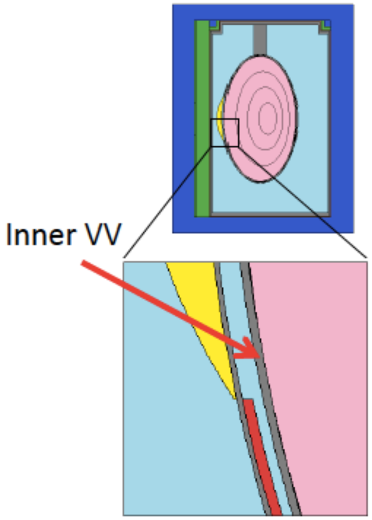
Vacuum vessel has dpa limit rather than blanket



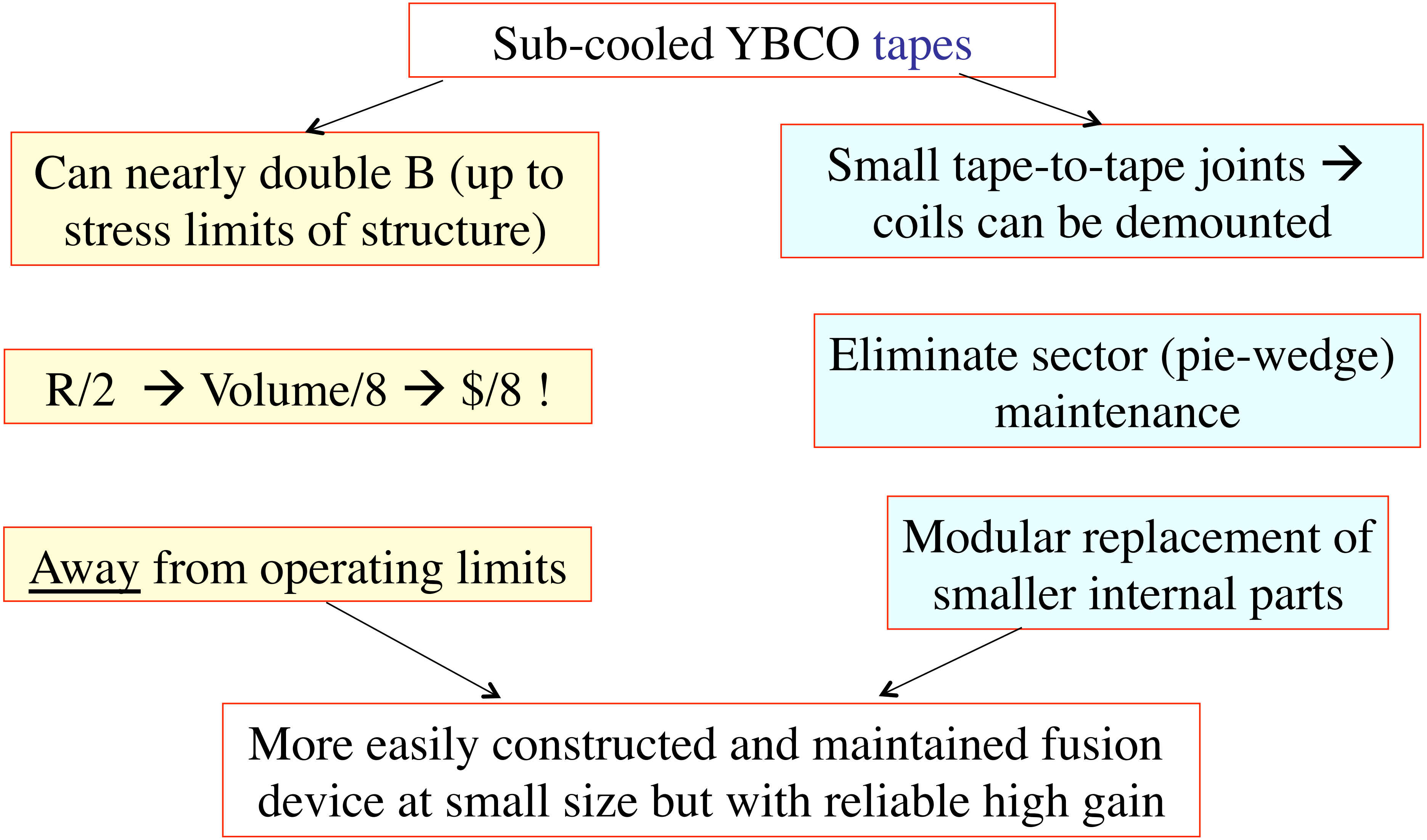
Use 90% Enriched ^{6}Li FLiBe with 2cm Be Multiplier to Achieve TBR of 1.14

Inner VV Thickness (cm)	Blanket TBR	Channel TBR	Total TBR
0.5	0.931	0.263	1.194
1	0.890	0.268	1.158
1.5	0.864	0.276	1.140
2	0.822	0.280	1.102

Material Layer	Alphas (appm)	Displacements per Atom
Tungsten FW	4	14
Inner VV	320	43
Outer VV	180	27
Be Multiplier	3100	15
FLiBe Blanket	**N/A!**	**N/A!**
Tungsten Shield	0.5	4
Blanket Tank	0.1	0.02
ZrH$_2$ Shield	0.003	0.008



New high-T superconductors can provide the path to smaller & sooner fusion: Higher B + Detachable coils



Sub-cooled YBCO tapes

Can nearly double B (up to stress limits of structure)

R/2 → Volume/8 → $/8 !

Away from operating limits

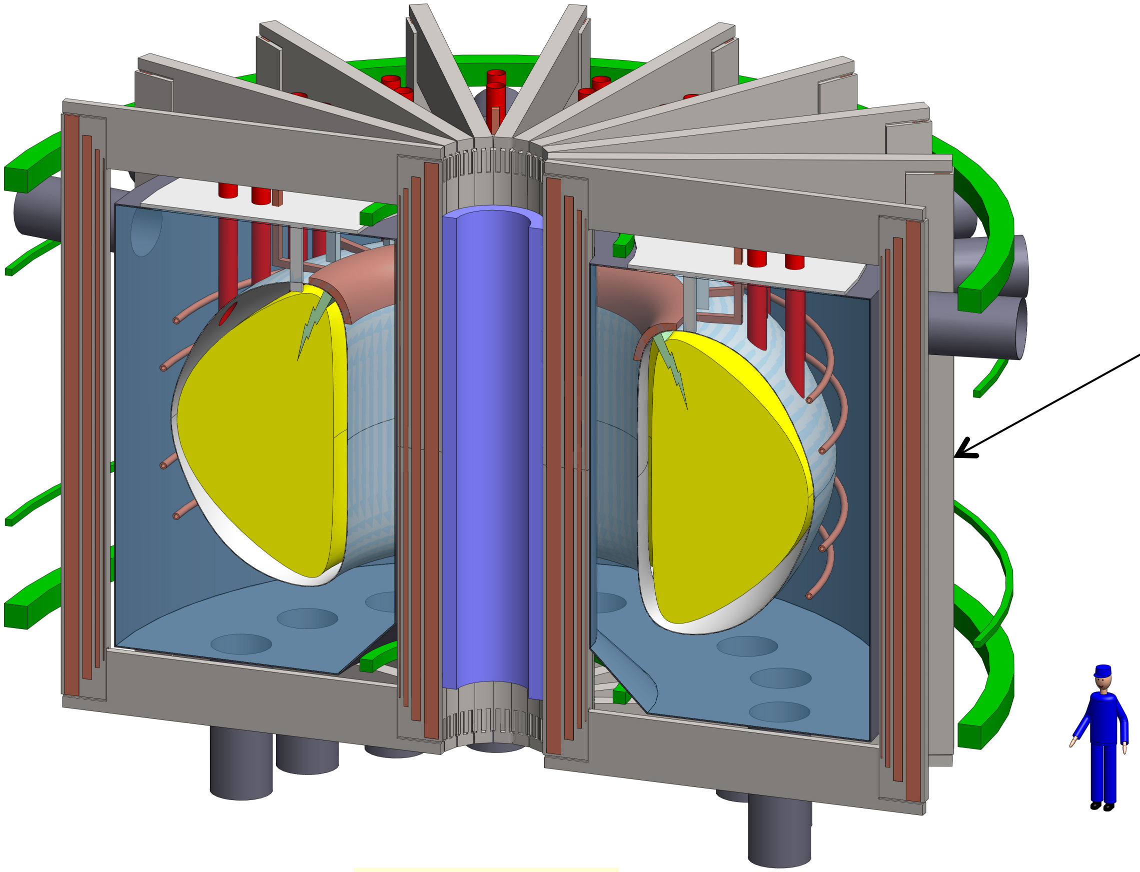
Small tape-to-tape joints → coils can be demounted

Eliminate sector (pie-wedge) maintenance

Modular replacement of smaller internal parts

More easily constructed and maintained fusion device at small size but with reliable high gain

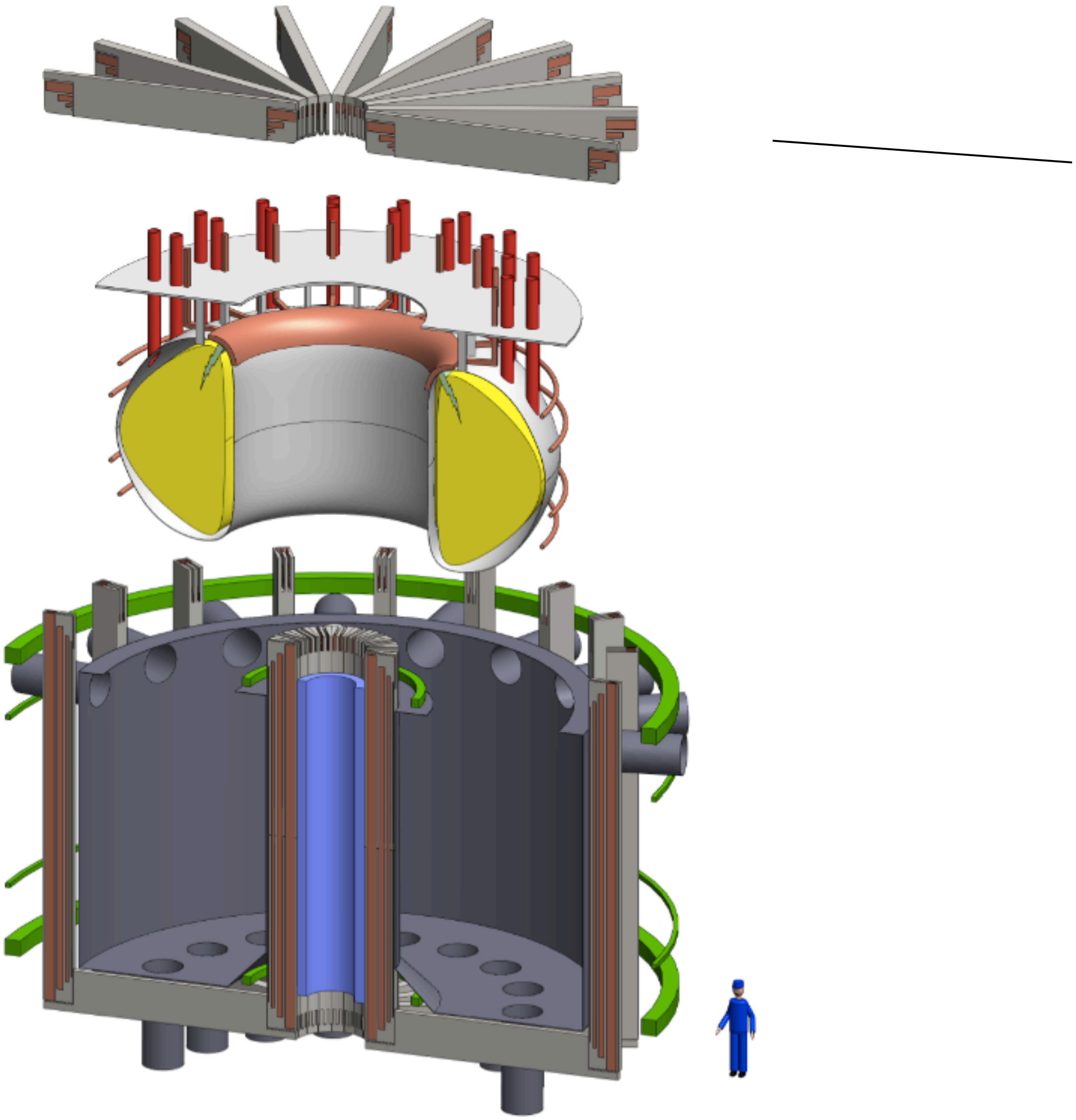
Key innovations towards achieving design goals



Integrated YBCO + structure to achieve 9.2 T on axis without large electrical costs

R=3.2 m

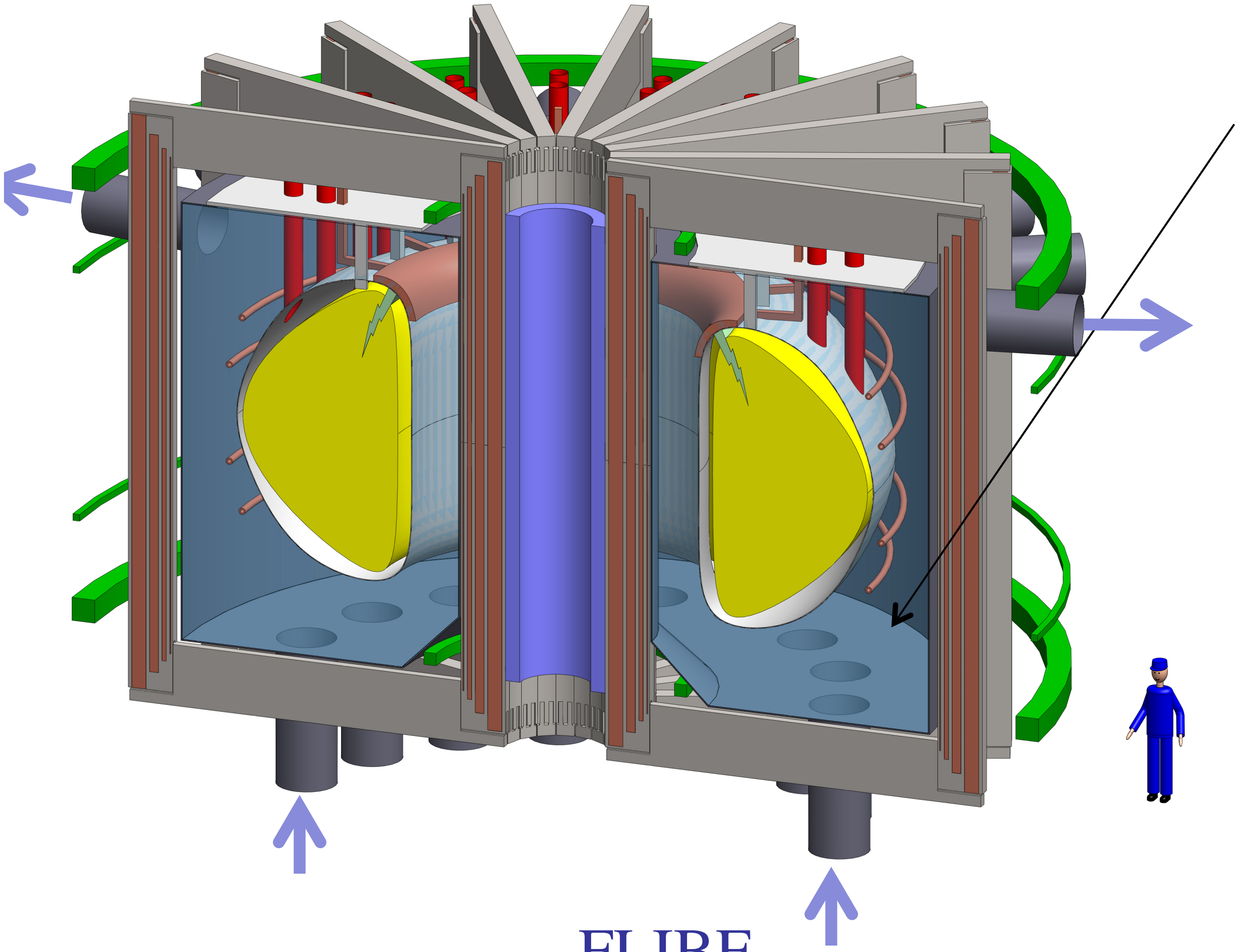
Key innovations towards achieving design goals



Demountable coils → Modular replacement of vacuum vessel + components → full off-site construction + QA of all internal components → No connection ever made inside TF

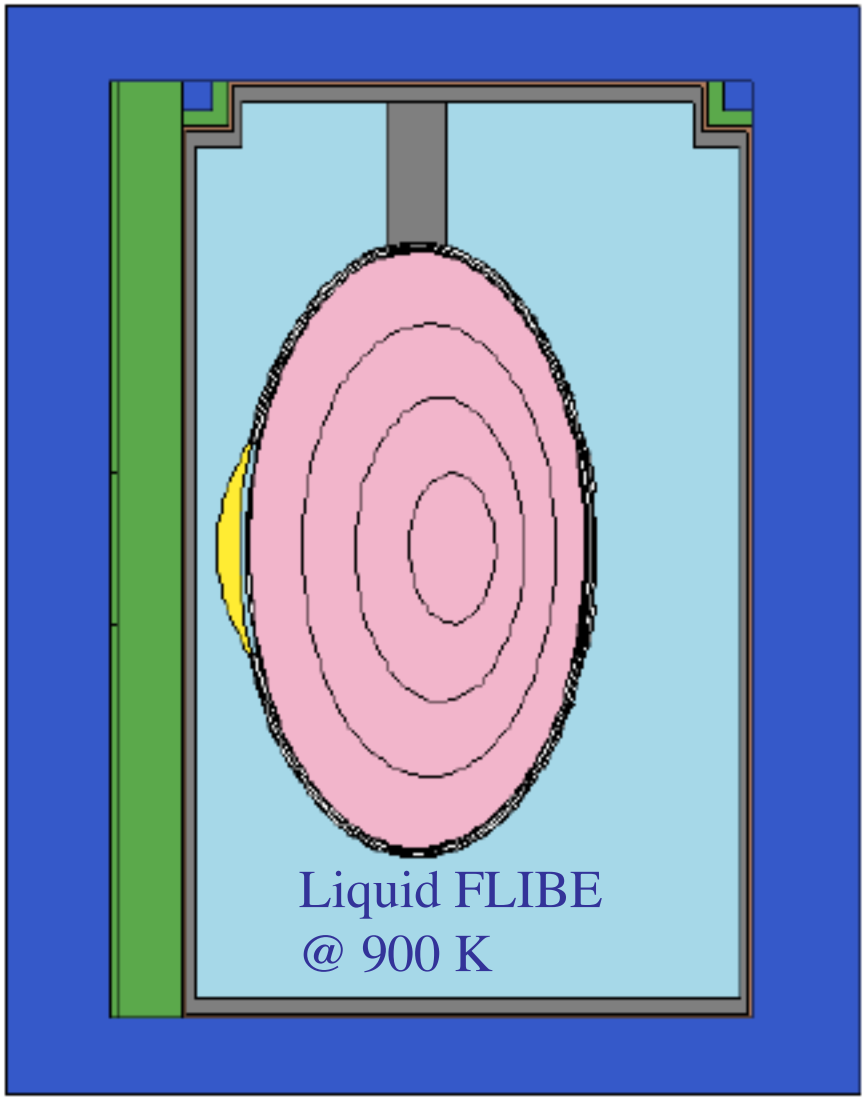
= Paradigm shift to standard sector maintenance

Key innovations towards achieving design goals


FLIBE

Immersion liquid FLIBE blanket → No materials radiation damage in blanket → ~50-fold reduction in solid waste → full coverage high-TBR blanket

Demountable coils → Attractive liquid immersion blanket



Key Features

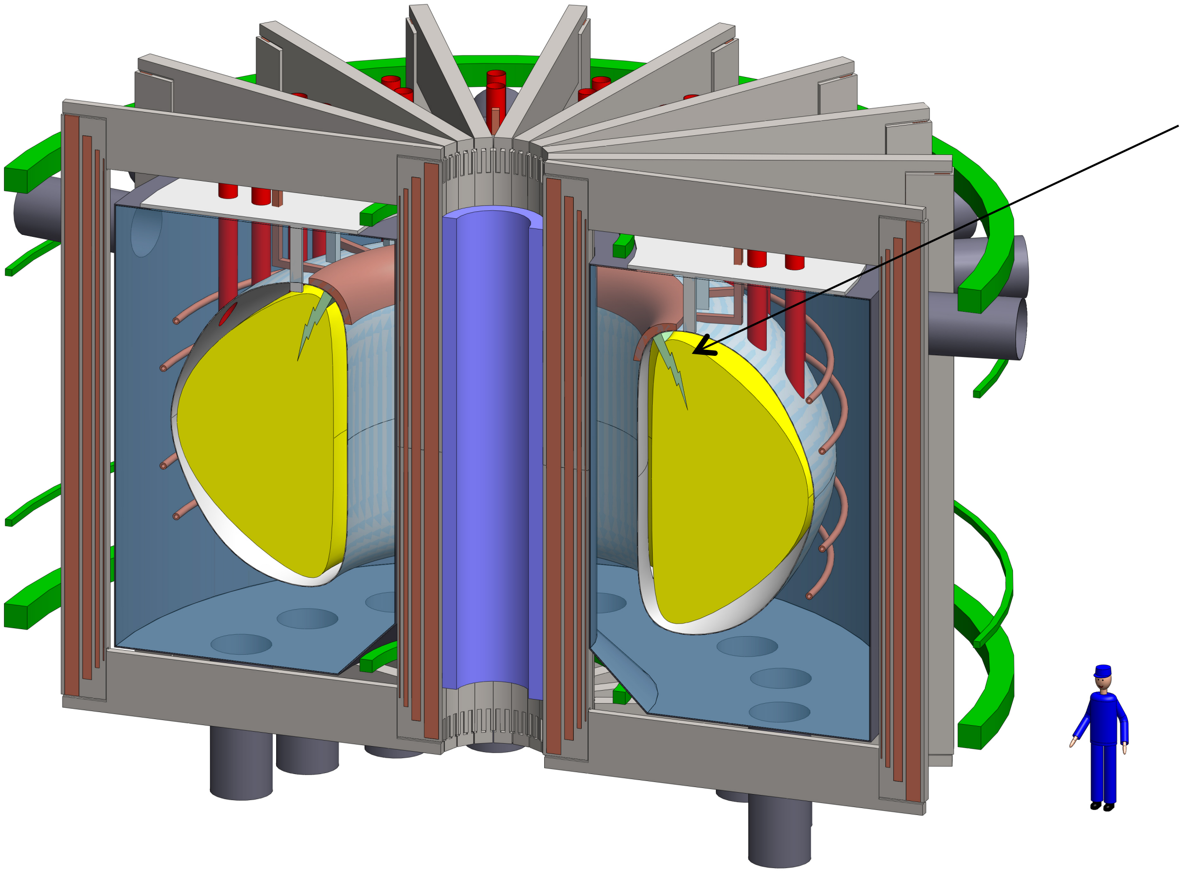
Tritium breeding ratio: 1.15
Excess T in FPY: ~3 kg

High thermal efficiency
Low recirculating power

30+ year lifetime of coils from radiation damage

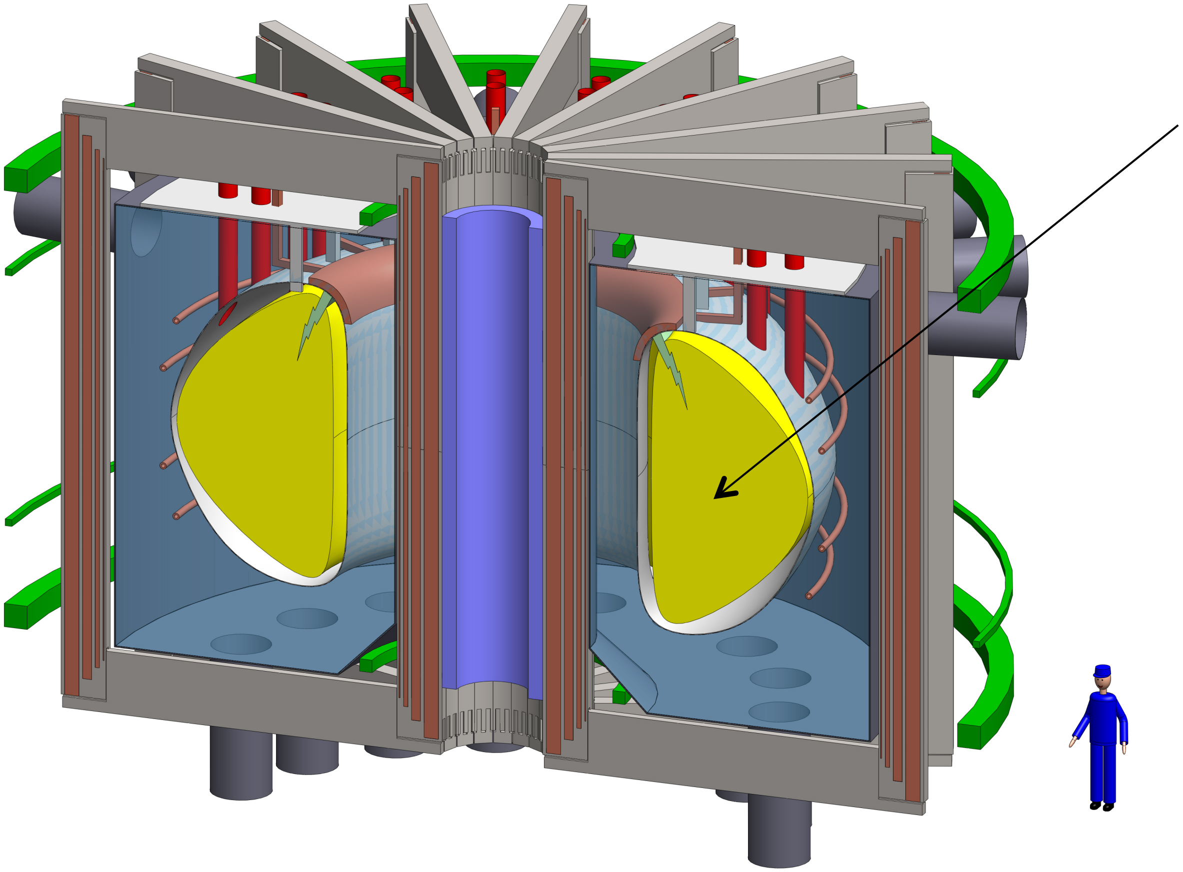
Solid waste reduced x50 compared to standard blanket

Key innovations towards achieving design goals



Lower Hybrid CD with high-field side launch → near theoretical max. for CD efficiency at mid-radius → ~20% external control of current profile

Key innovations towards achieving design goals



~4 keV pedestal not regulated by ELMs → + high CD efficiency → high fusion gain with moderate bootstrap fraction **= Robust steady-state scenarios producing ~250 MWe**

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