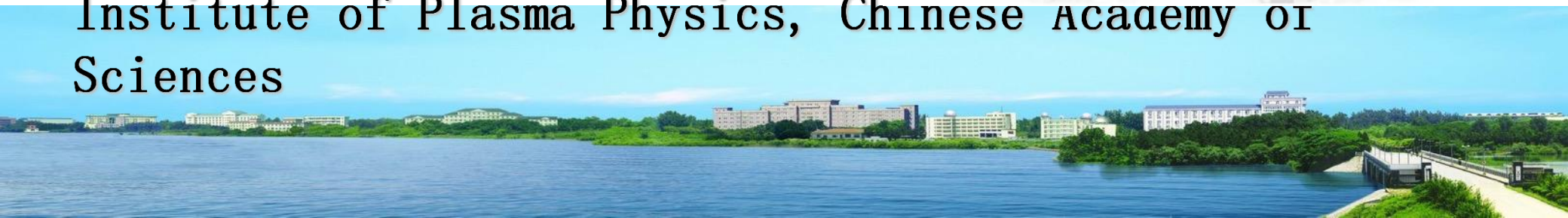


# Comparison between tokamak DEMOs with high-temperature and low- temperature superconducting coils

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Sciences



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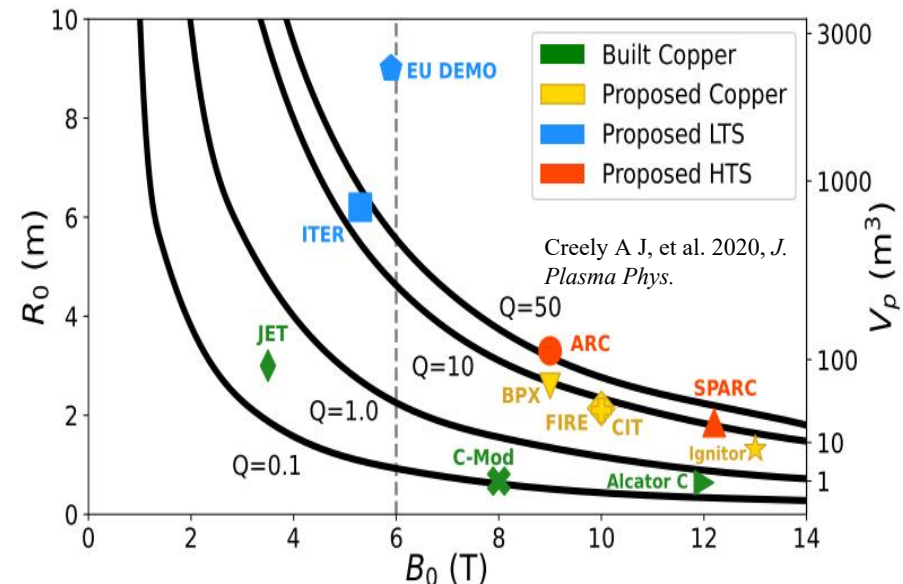
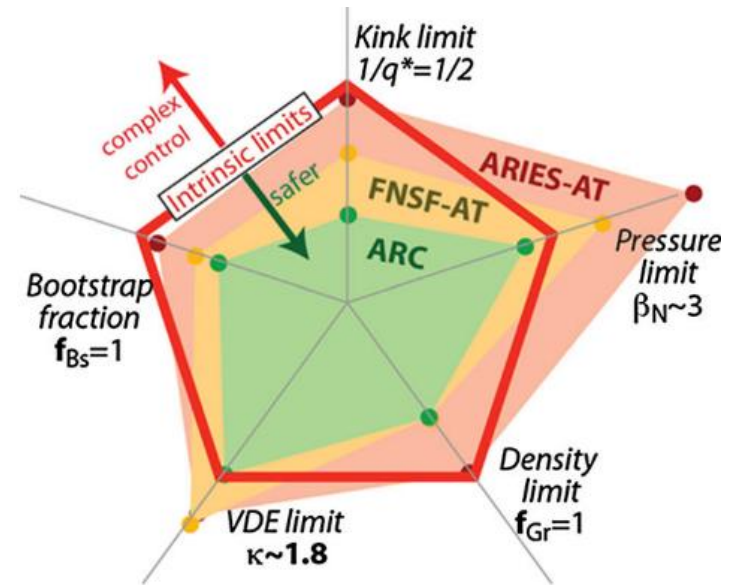
# Introduction

DEMO design involves issues related to the coupling of physics and engineering.

High temperature superconductor is potentially a game changer that makes high field path achievable.

## The advantages of high field path

- $P_{fus} \propto \frac{\beta_N^2}{q_{95}^2} R^3 B^4$ , smaller device size
- $n_{GW} \propto \frac{B}{R}$ , higher Greenwald density limit
- $q_{95} \propto \frac{R_0 B}{I_p A^2}$ , reduce disruption possibility
- $\beta_N \propto \frac{n T a}{B I_p}$ , far away from instability boundary
- $\rho_L \propto B^{-1}$ , better particle confinement
- $\tau_{98y2} \propto B^{0.15}$ , better energy confinement



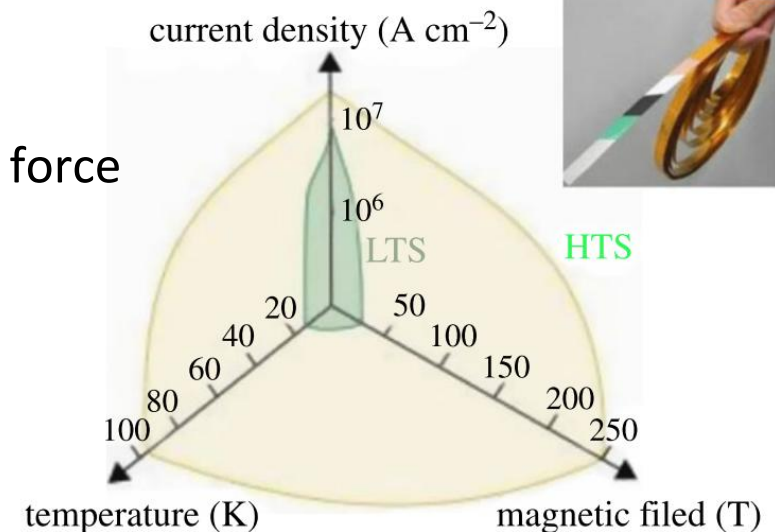
# Opportunities and challenges of HTS

## Opportunities:

- 1) The maximum toroidal field can reach over 20 T, **making size reduction possible.**
- 2) The central solenoid has higher capability of providing flux swing.
- 3) The coils have higher winding pack current density, resulting in smaller radial thickness.
- 4) The cryogenic system is more simplified due to higher critical temperature and wider temperature margin.

## Challenges:

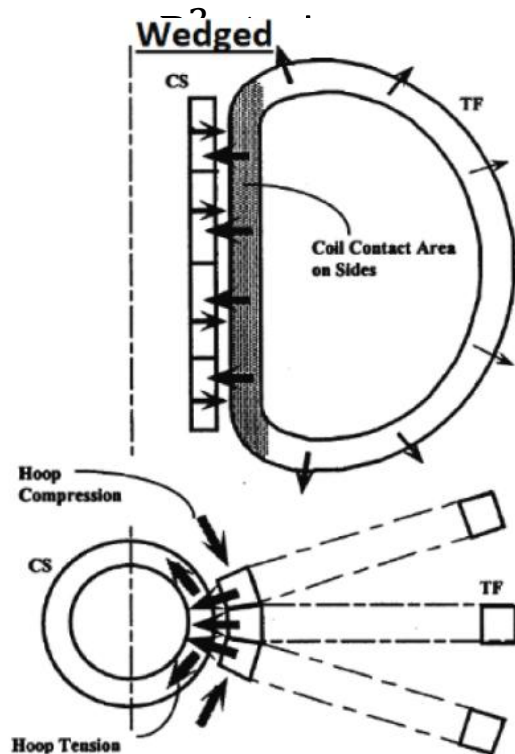
- 1) High field leads to excessive high electromagnetic force
- 2) The heating methods suitable for high magnetic field conditions are not yet mature.
- 3) Quench protection is much more difficult.
- 4) Divertor heat load and neutral wall load issues...



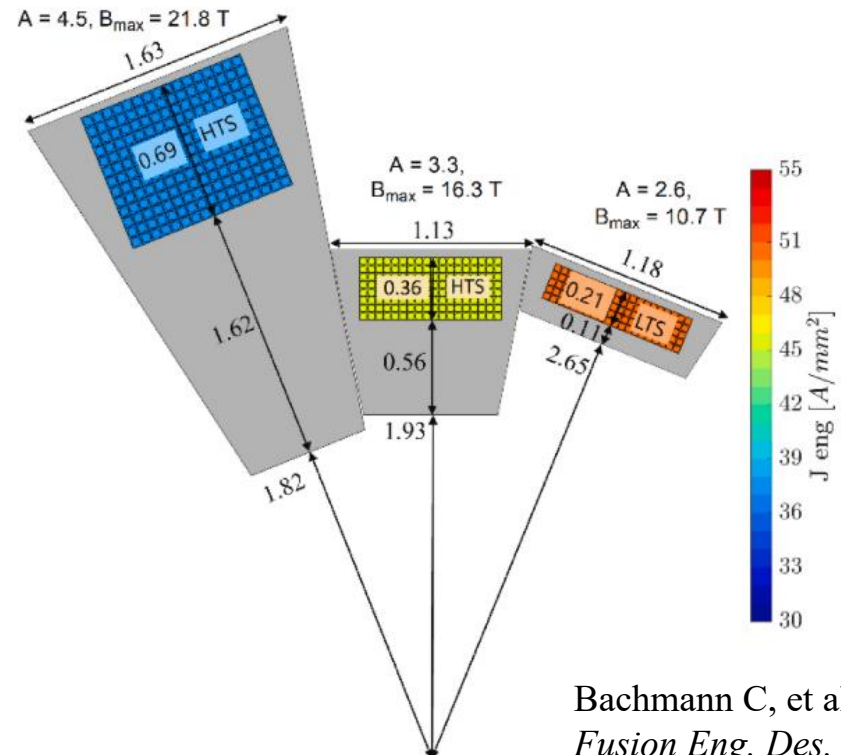
## Principles and features:

- 1) The D- shape enables “bending- free” operation, converting large EM forces mainly into tensile forces (rather than bending) → more uniform and efficient material usage
- 2) Inboard legs experience huge radial forces → wedged contact between adjacent coils forms a self- supporting vault, no reliance on the central solenoid (CS) or external structures

3) EM fo



al thickness:

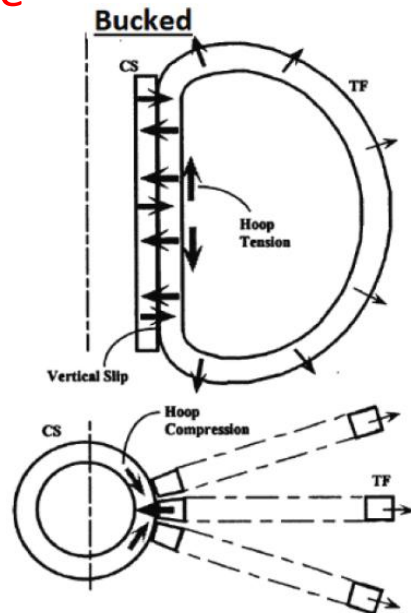


## Principles and features:

- 1) TF inboard legs directly bear against the outer surface of the central solenoid (CS)
- 2) The CS, designed to withstand internal pressure, provides outward radial support to the TF
- 3) This allows significant reduction of structural material in the TF inboard leg → **more compact machine**

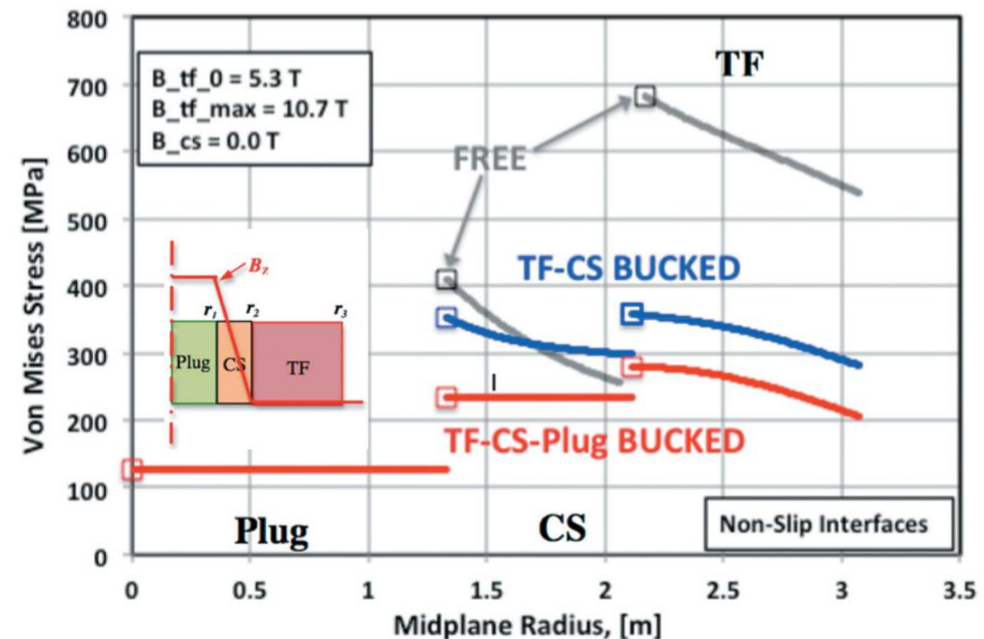
JET tokamak applied

Bachmann C, et al.  
2023, *Fusion Eng. Des.*



## Compared with wedged solution:

- 1) TF stress can be reduced by 45%
- 2) If CS is further bucked by a central plug, the reduction is ~60%.



Wade M R, and Leuer J A. 2021, *Fusion Sci. Technol.*

# Challenges of bucked solution

- **Difficult to Transfer Out- of- Plane Forces (Torque)**

Large out- of- plane forces arise from interaction between TF current and poloidal field. Relying solely on friction to transmit out- of- plane forces is not robust.

In a pure bucked design, these forces must be transferred via st TF and CS. However, shear keys are extremely difficult to install.

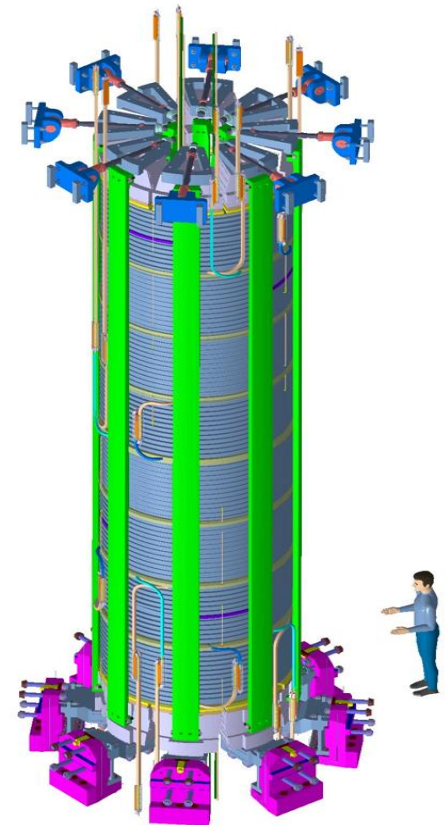
- **Engineering Integration Difficult**

The outer surface of the CS is occupied by feeders, cryogenic lines, etc. – direct TF contact interferes these systems severely.

Very tight assembly tolerances are required, which are impractical for large component.

**Conclusion: Pure bucked solution is unsuitable for DEMO- class high- field tokamaks. That is why JET applied bucked solution but ITER reverted to the conventional wedged solution.**

Bachmann C, et al. 2023, *Fusion Eng. Des.*



# Analytical Models for DEMO Design

We use a self-consistent 0.5D system code developed by ourself to design DEMO with wedged solution, has been benchmarked with other system codes.

TF stress (Tresca model) :

$$\epsilon_M = d_{in}/R_0$$

$$\epsilon_B = (a + dR + d_{out} + d_{sc})/R_0$$

$$\sigma_T = \frac{B_t^2 \ln[(1 + \epsilon_B)/(1 - \epsilon_B)]}{2\mu_0 \epsilon_M (2 - 2\epsilon_B - \epsilon_M)}$$

$$\sigma_C = \frac{2B_t^2 (2\epsilon_B + \epsilon_M)}{\mu_0 \epsilon_M (2 - 2\epsilon_B - \epsilon_M) (2 + 2\epsilon_B + \epsilon_M)}$$

$$\sigma_{TF} = \sigma_C + \sigma_T$$

CS stress (Tresca model) :

$$\alpha = \frac{R_{CSout}}{R_{CSin}}$$

$$x = \frac{7\alpha}{9(\alpha + 1)}, y = 2\alpha^2 + \frac{2}{7}\alpha + \frac{2}{7}, z = \frac{5}{12} \left( 2\alpha^2 + \frac{2}{5} \right)$$

$$f(\alpha) = \frac{2}{(\alpha - 1)^2} (xy - z)$$

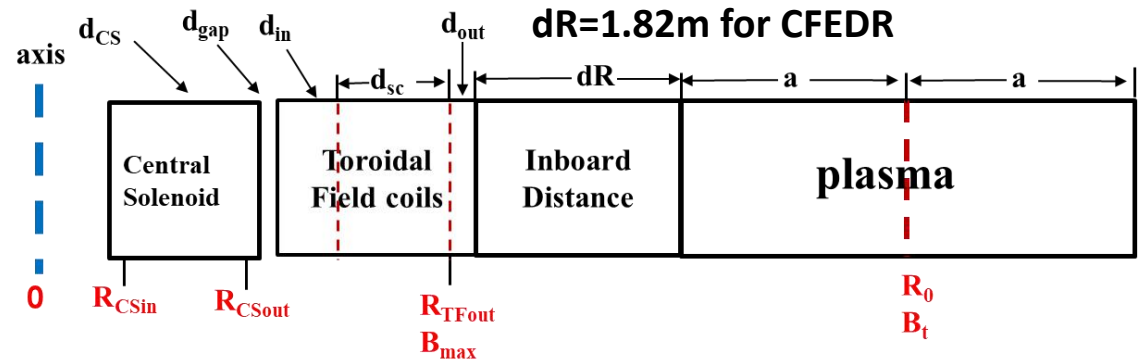
$$\sigma_{CS} = \frac{B_{CS}}{2\mu_0} f(\alpha)$$

CS flux swing (fixed Bcs)

$$\Phi_{CS}(wb) = \frac{2\pi}{3} B_{CS} (R_{CSout}^2 + R_{CSin} R_{CSout} + R_{CSin}^2)$$

CS lifetime (Paris law)

$$N_{cycle} = \int_{\lambda_0}^{\lambda_c} \frac{d\lambda}{C(F\sqrt{\pi a} \sigma_{CS})^m} = \frac{1}{C(F\sqrt{\pi} \sigma_{CS})^m} \left[ \frac{\lambda_c^{1-\frac{m}{2}} - \lambda_0^{1-\frac{m}{2}}}{1 - \frac{m}{2}} \right]$$



Radial build on the high field side

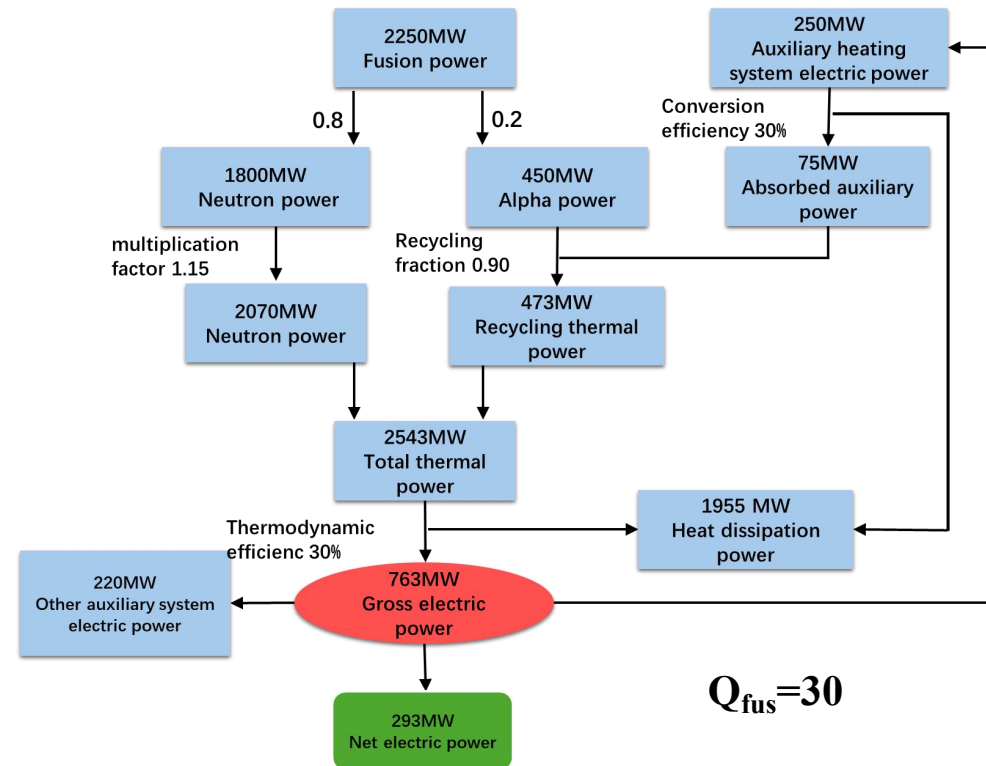
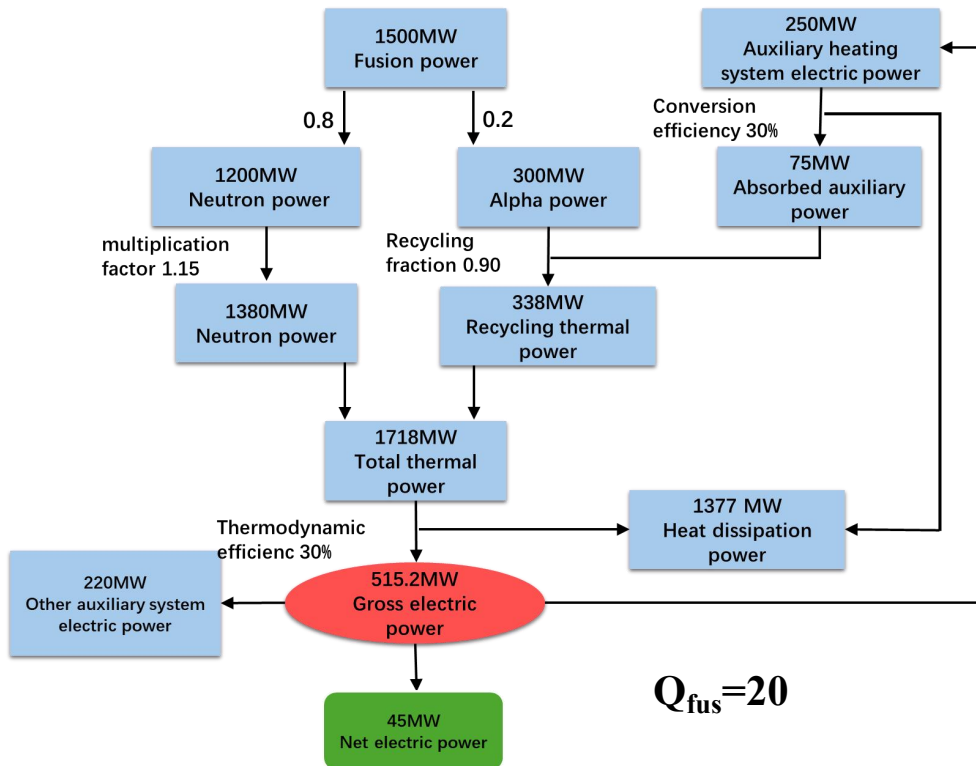
# DT DEMO power balance analysis

DT DEMO at the same conditions

$Q_{fus}=20$  achieves 1.5 GW fusion power and 45 MW net electricity power

$Q_{fus}=30$  achieves 2.25 GW fusion power and 293 MW net electricity power

Neutron energy multiplication factor	1.15
Fraction of power recycling from heating power	0.9
Wall plug efficiency	0.3
Thermodynamic efficiency	0.3
Auxiliary heating power [MW]	75
Other auxiliary system electric power [MW]	220



# Basic logic and conditions for the analysis

## Scanning logic:

- 1) Input  $a$  and  $R_{CSout}$
- 2) TF stress and magnet parameters determine TF radial thickness.
- 3) CS radial thickness is solved by 2 h pulse length and input  $R_{CSout}$ .

(a) If  $R_{CSout}$  is so small that 2 h pulse length is still unachievable when CS bore radius equals  $R_{CSout}$ , these design points must also fail to meet the constraints of CS stress and lifetime.

(b) If  $R_{CSout}$  is sufficiently large, the solutions with  $R_{CSin} < 0.5$  m will limit  $R_{CSin}$  to 0.5 m.

## Parameter settings:

- 1) Magnet param. from BEST, SPARC, ITER and CFEDR
- 2)  $B_{t0}$ =6.3 T and 9 T are corresponding to 176 GHz and 252 GHz EC heating
- 3) Magnet structural material is N50 steel, 2/3 of its maximum stress is 1000 MPa.
- 4) dR=1.82m from CFEDR

	HTS DEMO	LTS DEMO	Hybrid DEMO
$B_{max}$ [T]	20 (SPARC)	13 (ITER)	18 (BEST CS)
$B_{t0}$ [T]	9	6.3	6.3
$j_{TF}$ [MA m <sup>-2</sup> ]	153 (SPARC)	17.5 (ITER)	25 (CFEDR)

Target and constraint		Operational condition	
$Q_{fus}$	≥30	$q_{95}$	4.0
$\tau_{pulse}$	≥2h	$f_{GW}$	1.0
$N_{cylce}$	≥30000	$H_{98y2}$	1.0
$P_{grid}$	≥50 MW	$R_{L-H} = P_{sep}/P_{L-H}$	2.0
$P_{aux}$	≤100 MW	Tungsten fraction $f_W$	10 <sup>-5</sup>
TF/CS stress	≤1000MPa	Argon fraction $f_{Ar}$	Core ref [1] SOL ref [2]
$R_{CSin}$	≥0.5m	dR	1.82 m

[1] T. Pütterich et al 2019 Nucl. Fusion 59 056013

[2] A. Huber and A.V. Chankin 2021 Nucl. Fusion 61 036049

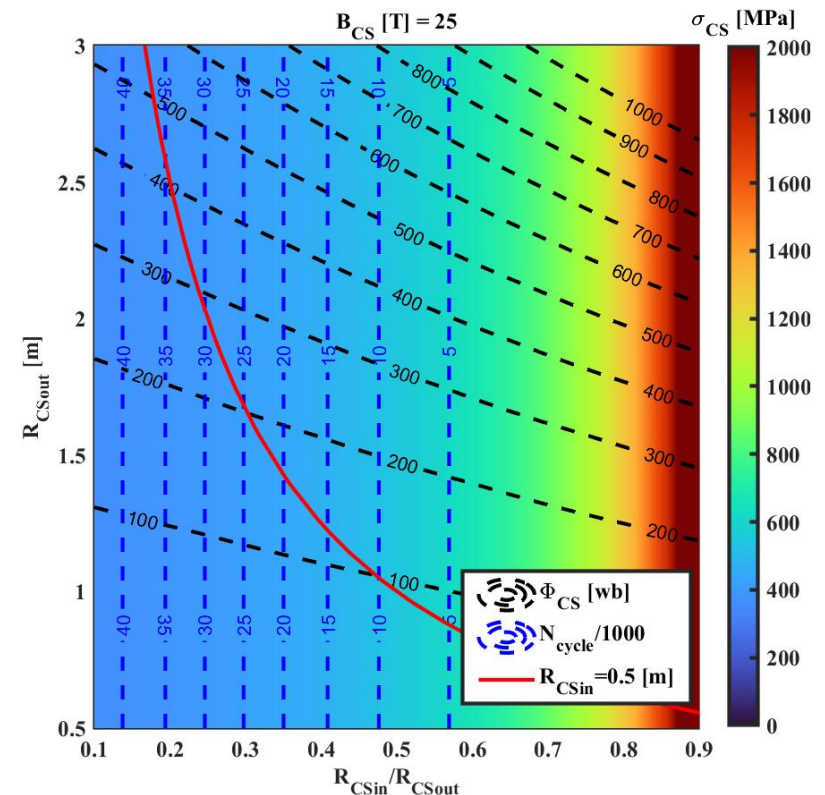
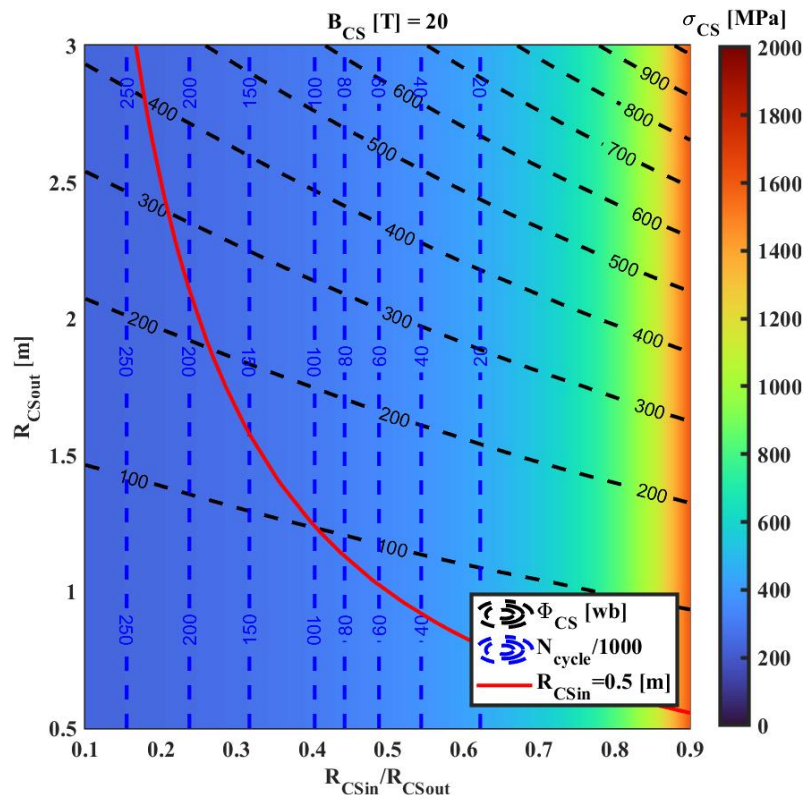
# Excessive high Bcs is unacceptable

## Scanning $R_{CSin}/R_{CSout}$ & $R_{CSout}$ for $\Phi_{CS}$ , $N_{cycle}$ and $\sigma_{CS}$

- 1)  $\sigma_{CS}$  and CS lifetime are very sensitive to  $R_{CSin}/R_{CSout}$  (relative bore of CS coil).
- 2) Higher  $R_{CSin}/R_{CSout}$  leads to higher  $\sigma_{CS}$  and lower CS lifetime.
- 3) CS flux swing capability is approximately proportion to  $R_{CSout}$ .
- 4) 2 h pulse length requires at least  $\sim 500$  wb flux swing.

**Conclusion: Bcs = 20T is much better than Bcs = 25T, due to wider Ncycle range and lower  $\sigma_{CS}$ .**

	Bcs=20 T	Bcs=25 T
$\Phi_{CS}$ [wb]	500	500
Ncycle/1000	0~200	0~40
$\sigma_{CS}$ [MPa]	250~1600	370~2500



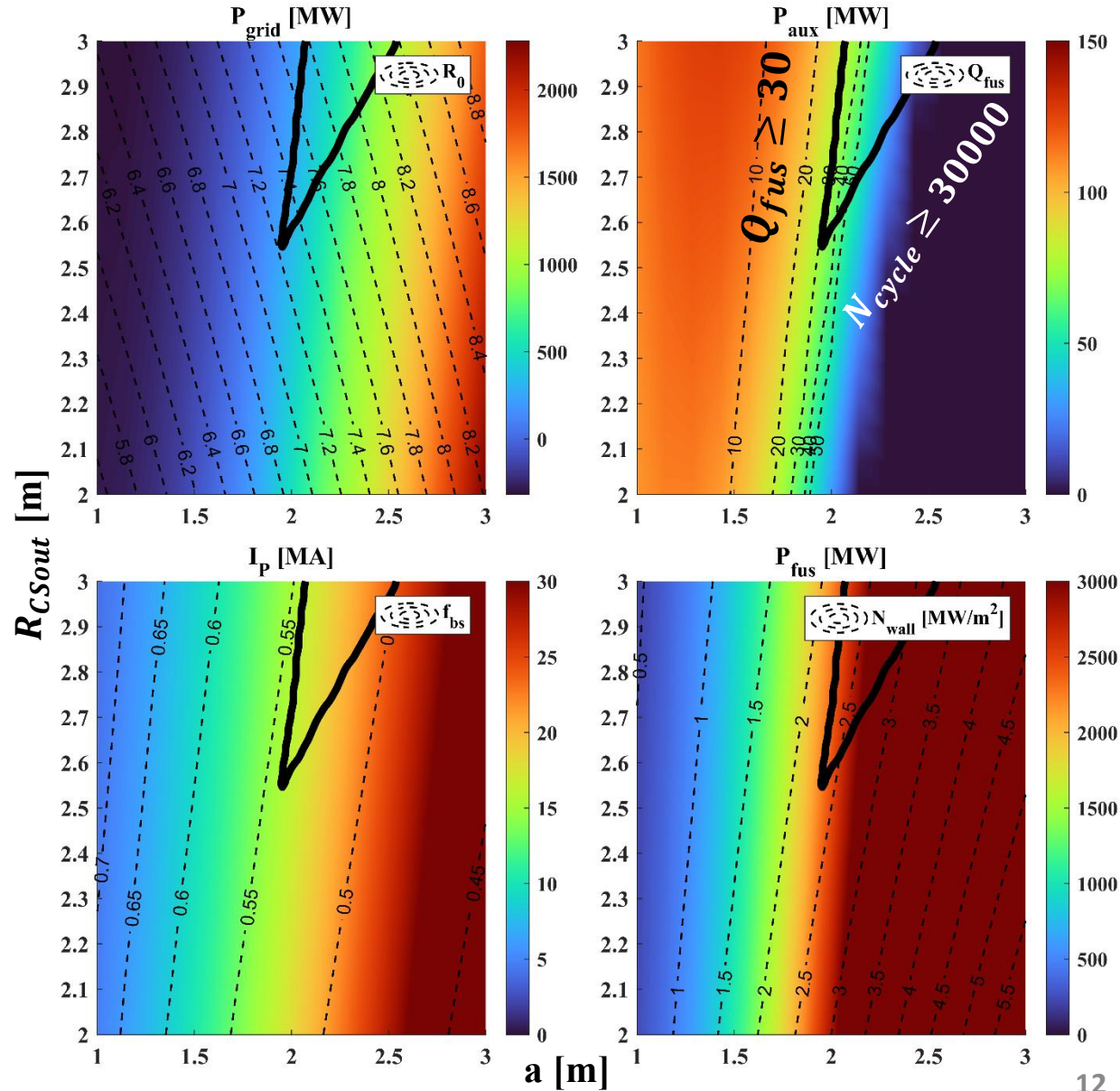
The influence of minor radius  $a$  is much greater than CS outer radius  $R_{CSout}$ .

With increasing  $a$  :

- 1) Due to better energy confinement,  $P_{grid}$ ,  $P_{fus}$  and  $Q_{fus}$  increase,  $P_{aux}$  decreases.
- 2)  $I_p$  increases with  $a$ , which leads to the decrease of  $\beta_p$ , therefore  $f_{bs}$  decreases.

$Q_{fus} \geq 30$  and  $N_{cycle} \geq 30000$  are key constraints that define the design space:

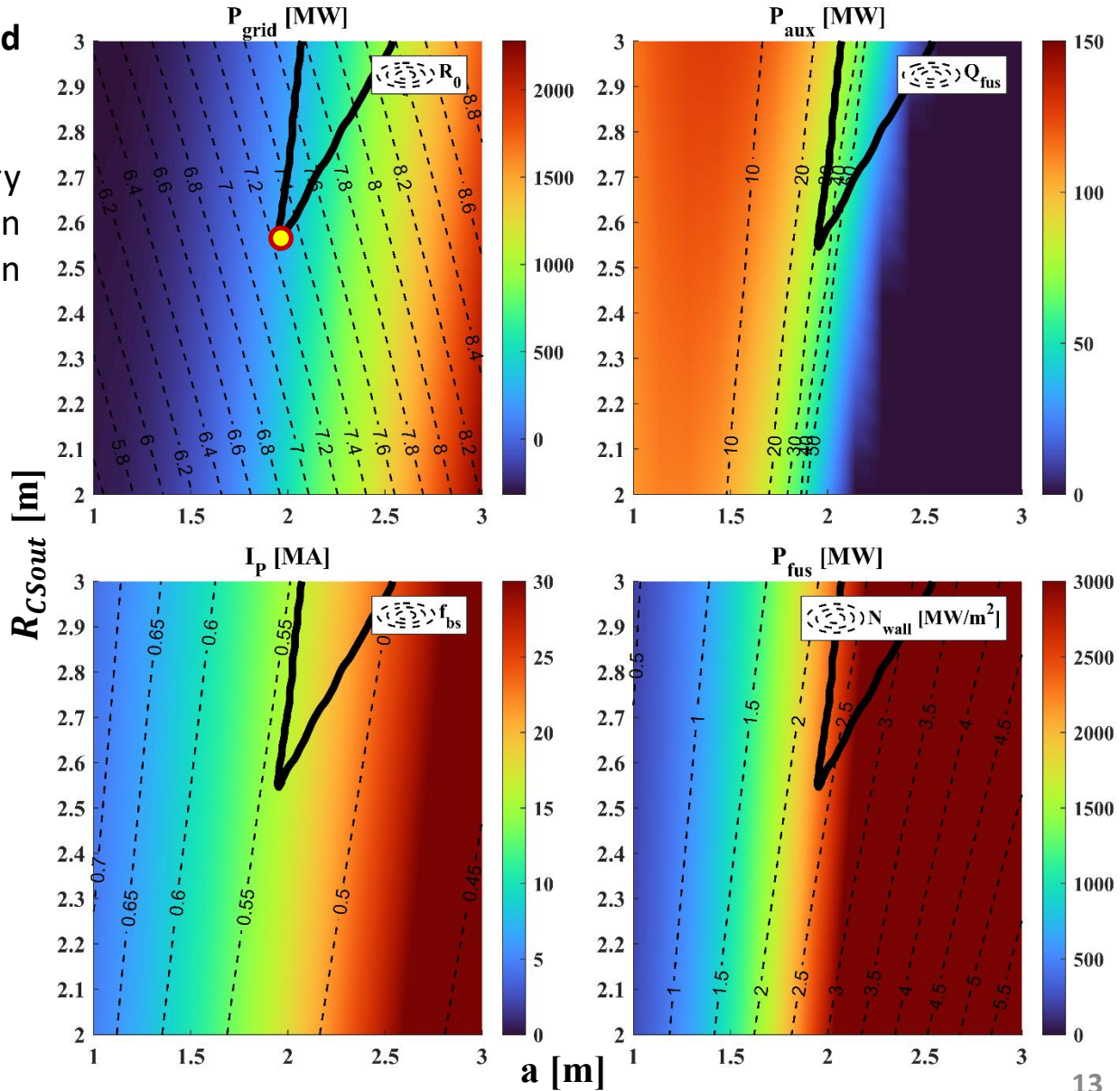
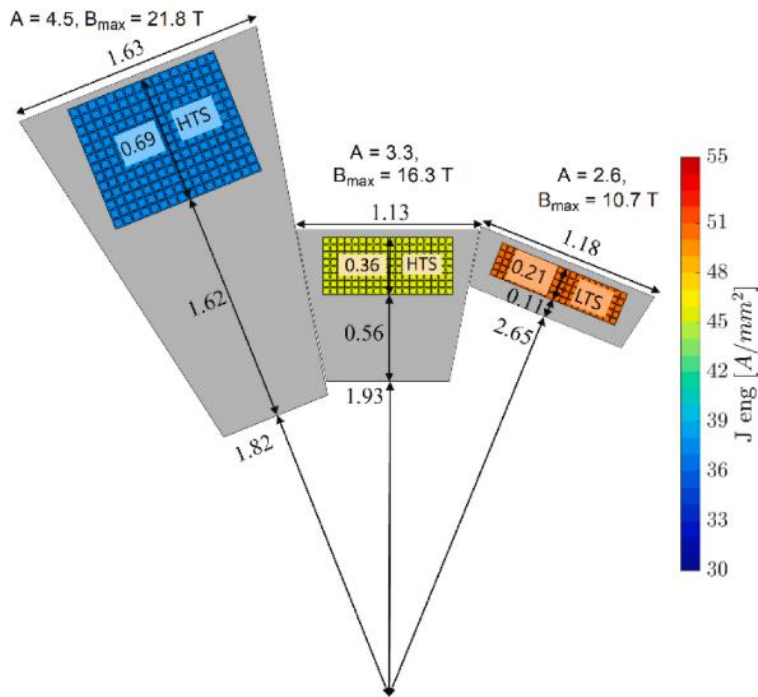
- 1)  $Q_{fus} \geq 30$  requires sufficiently large  $a$  to achieve sufficient large  $I_p$  and energy confinement.
- 2) To achieve 2 h pulse length, CS requires a sufficient large bore to provide flux swings, while at the same time, a sufficient radial thickness must also be ensured to resist EM force and exceed the minimum  $N_{cycle}$  constraint. Therefore, sufficiently large  $R_{CSout}$  is required.



# HTS DEMO

The minimum size for HTS DEMO is obtained at  $R_0=7.25\text{m}$ ,  $a=1.96\text{m}$ ,  $R_{CSout}=2.55\text{m}$

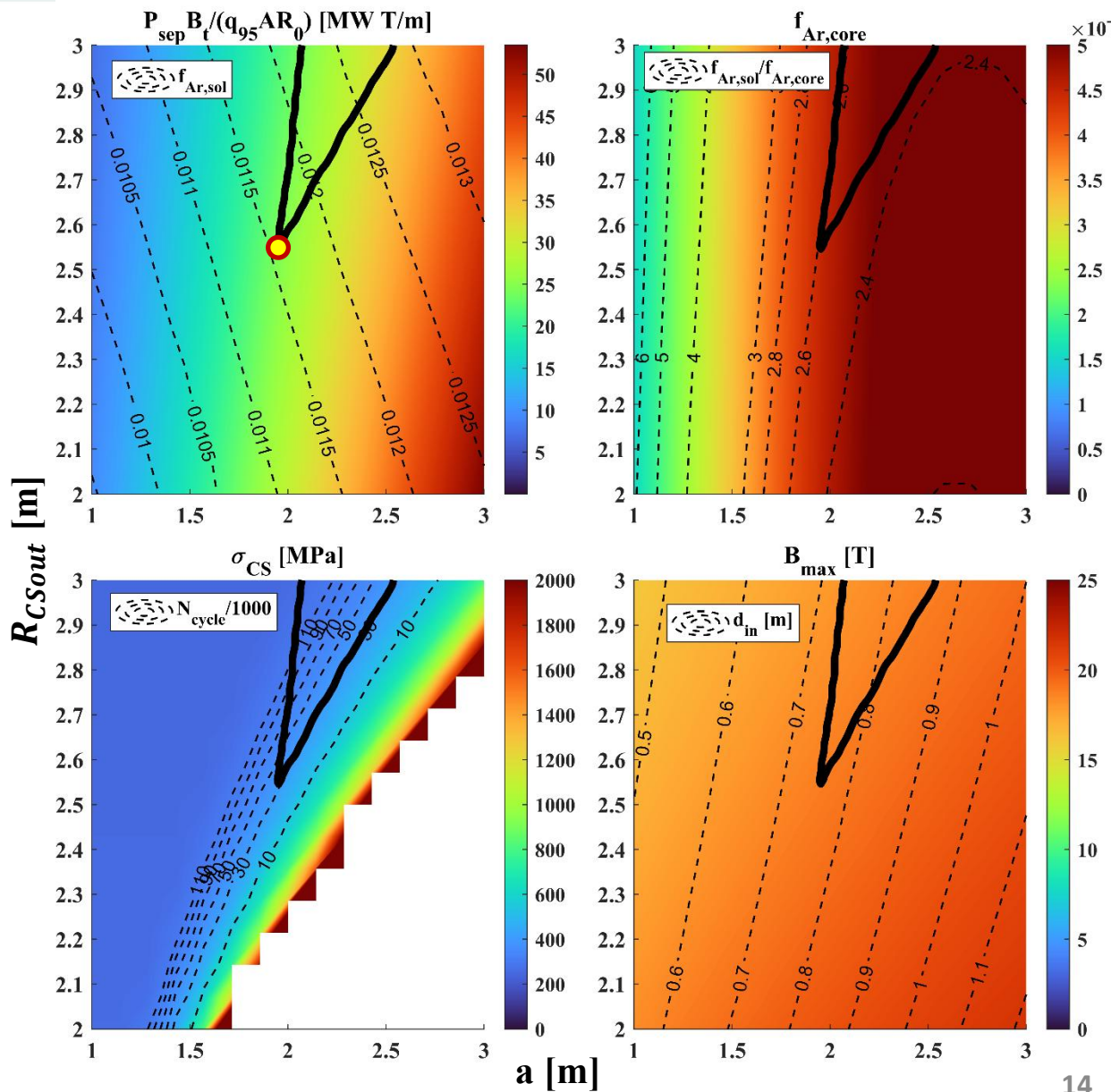
Mainly due to the limitation of stress, very thick TF coil case  $d_{in}$  is required, resulting in the device size not being much smaller than that with LTS DEMO.



# HTS DEMO

The minimum size design is obtained at  $R_0=7.25\text{m}$ ,  $a=1.96\text{m}$ ,  $R_{CSout}=2.55\text{m}$

$P_{sep}B_t/(Aq_{95}R_0)$	24.5
$f_{Ar,sol}$ (%)	1.16
$f_{Ar,core}$ (%)	0.45
$f_{Ar,sol} \cdot f_{Ar,core}$	2.6
$N_{cycle}/1000$	30
$\sigma_{CS}$ [MPa]	402
$B_{max}$ [T]	19
$d_{in}$ [m]	0.76



# HTS DEMO

With increasing  $a$  :

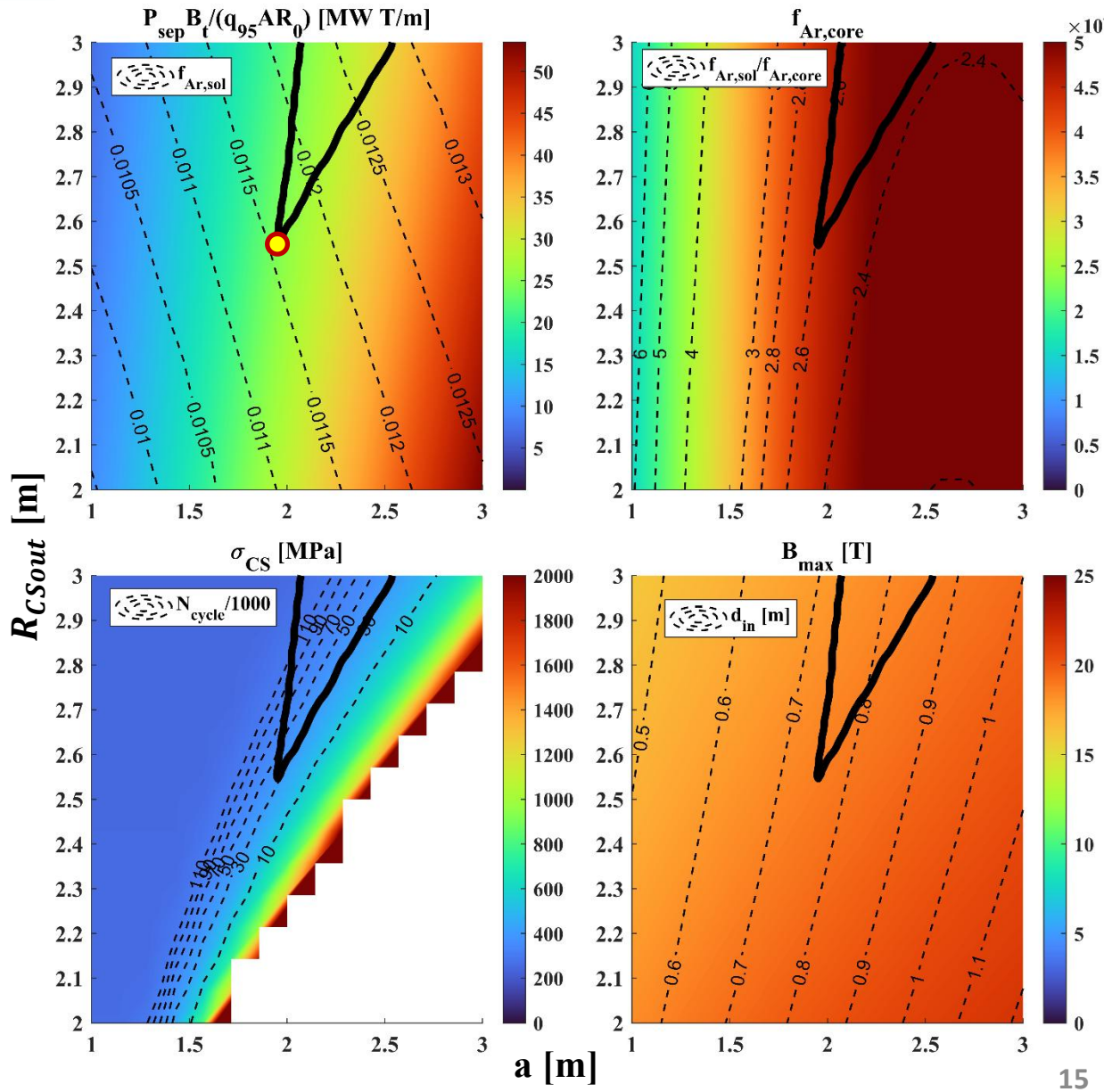
1)  $\frac{P_{sep} B_t}{q_{95} A R_0}$  increases and more Ar fraction is required to alleviate the divertor heat load.

For the minimum size design,  $\frac{P_{sep} B_t}{q_{95} A R_0} \sim 25 > \left(\frac{P_{sep} B_t}{q_{95} A R_0}\right)_{ITER} = 9.2$ , about 1.15% Ar (SOL) fraction is needed to achieve detachment.

2) Due to better energy confinement,  $P_{fus}$  increases and the tolerable impurity concentration at core  $f_{Ar,core}$  increases. The ratio of  $f_{Ar,sol}/f_{Ar,core}$  decreases, indicating easier impurity transport control.

3) Due to increasing  $I_p$ , CS requires larger bore to sustain 2h pulse length, which leads to CS radial thickness reduction, increasing CS stress and finally reducing  $N_{cycle}$ .

4) TF bore is proportion to  $a$ , therefore larger radial thickness of TF coil case  $d_{in}$  is required to sustain TF stress at 1000 MPa.

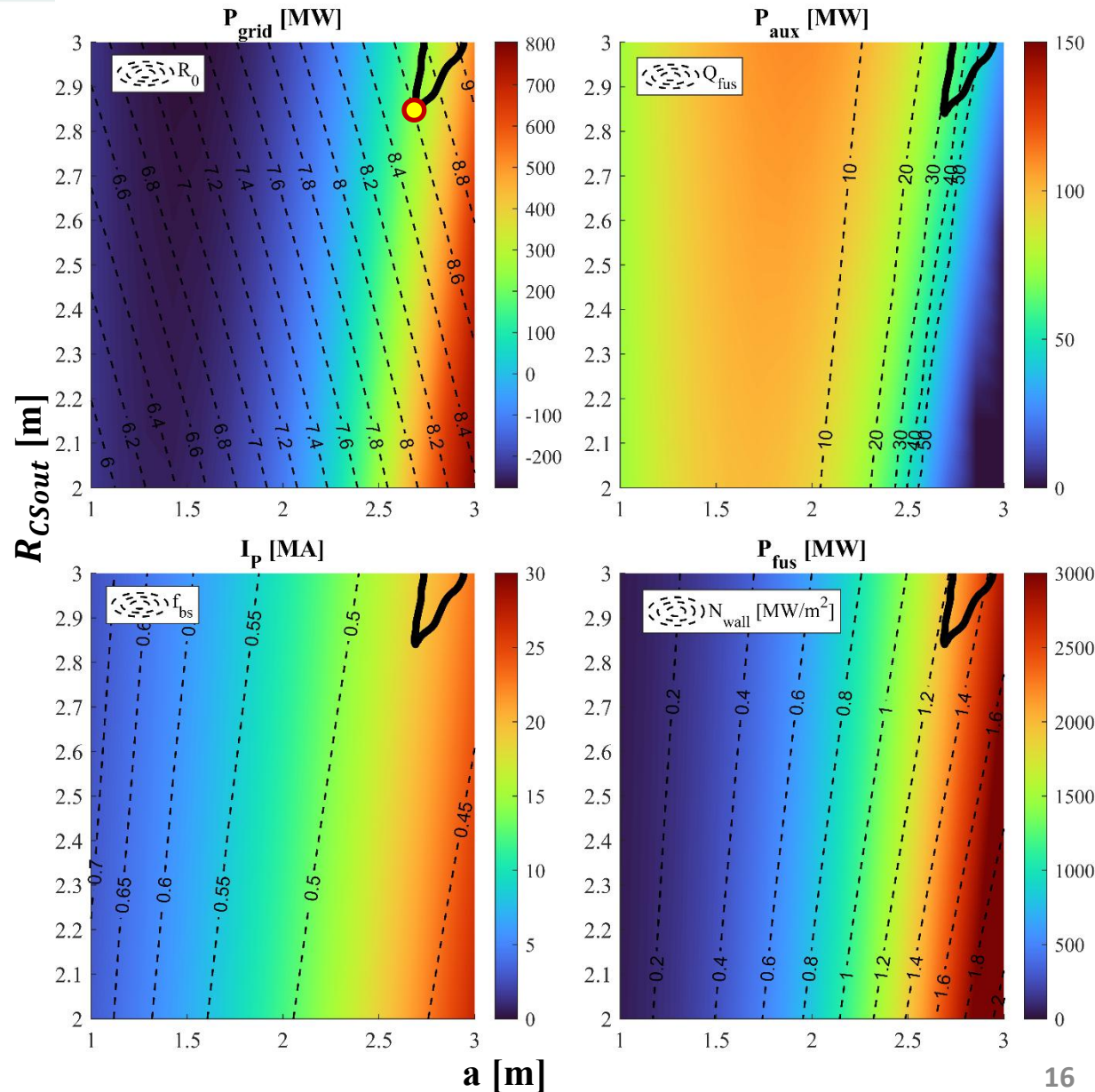


# LTS DEMO with ITER-TF-CS

The minimum size design is obtained at  $R_0=8.61\text{m}$ ,  $a=2.69\text{m}$ ,  $R_{CSout}=2.85\text{m}$

- 1) Due to smaller  $B_{CS}$ , larger CS size is required to provide sufficient flux swing.
- 2) Due to smaller  $B_t$ , larger  $a$  and  $I_p$  are required to achieve sufficiently high energy confinement for  $Q_{fus} \geq 30$ .
- 3) Smaller TF winding pack current density also leads to a thicker winding pack layer.

$R_0$ [m]	8.61
$P_{grid}$ [MW]	233
$P_{aux}$ [MW]	64
$Q_{fus}$	31
$I_p$ [MA]	18.9
$f_{bs}$	0.47
$P_{fus}$ [MW]	1988
$N_{wall}$ [MW m <sup>-2</sup> ]	1.24

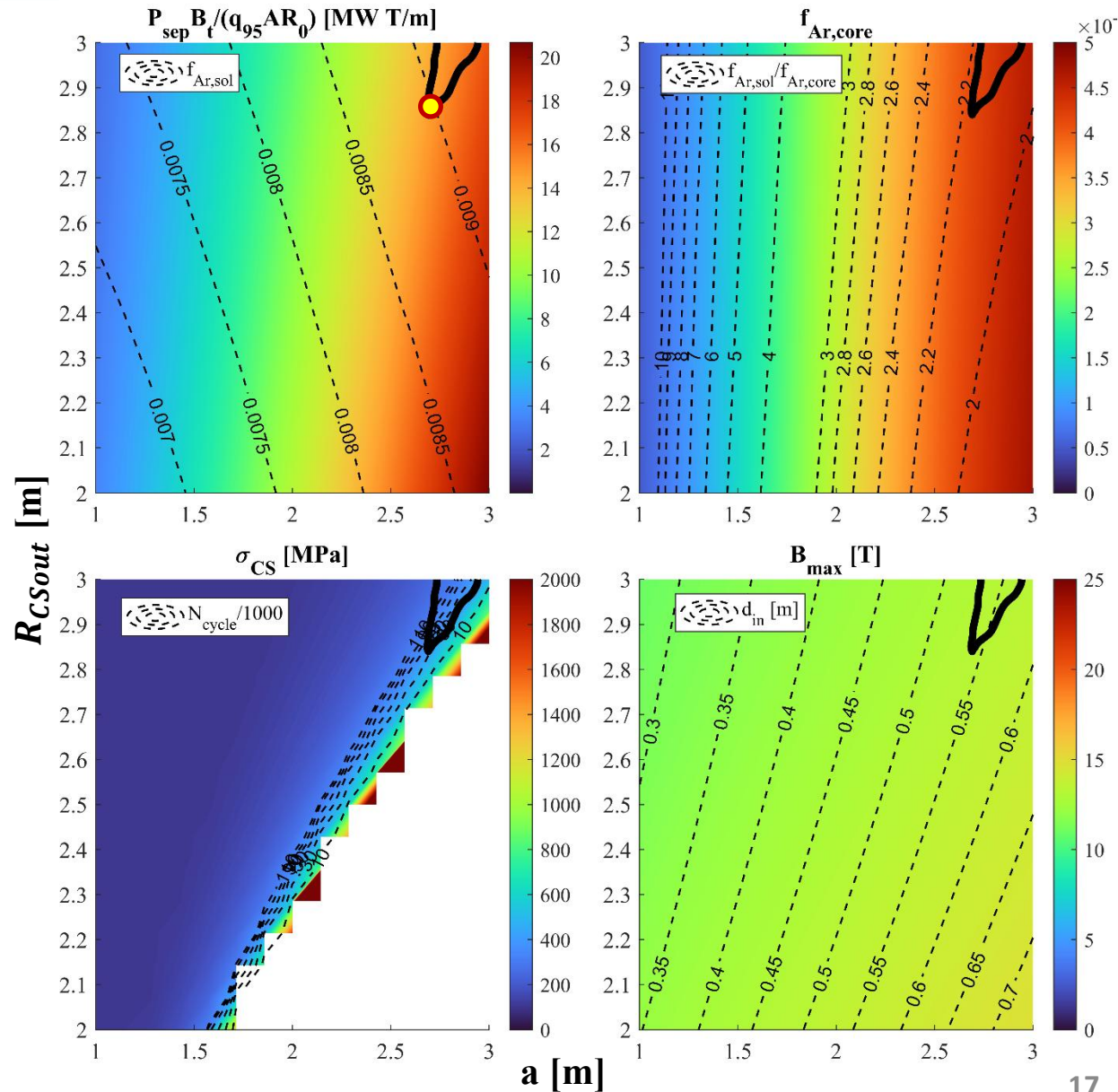


# LTS DEMO with ITER-TF-CS

Compared with HTS design, LTS brings some advantages :

- 1)  $\frac{P_{sep}B_t}{q_{95}AR_0}$  is much smaller, so that impurity transport control is easier.
- 2) CS has sufficient space to accommodate both the  $N_{cycle}$  and stress relief.
- 3) The radial thickness of TF coil case is smaller.

	HTS	LTS
$P_{sep}B_t/(Aq_{95}R_0)$	24.5	14.5
$f_{Ar,sol}$ (%)	1.16	0.9
$f_{Ar,core}$ (%)	0.45	0.41
$f_{Ar,sol}/f_{Ar,core}$	2.6	2.2
$N_{cycle}/1000$	30	38
$\sigma_{CS}$ [MPa]	402	379
$B_{max}$ [T]	19	13
$d_{in}$ [m]	0.76	0.54

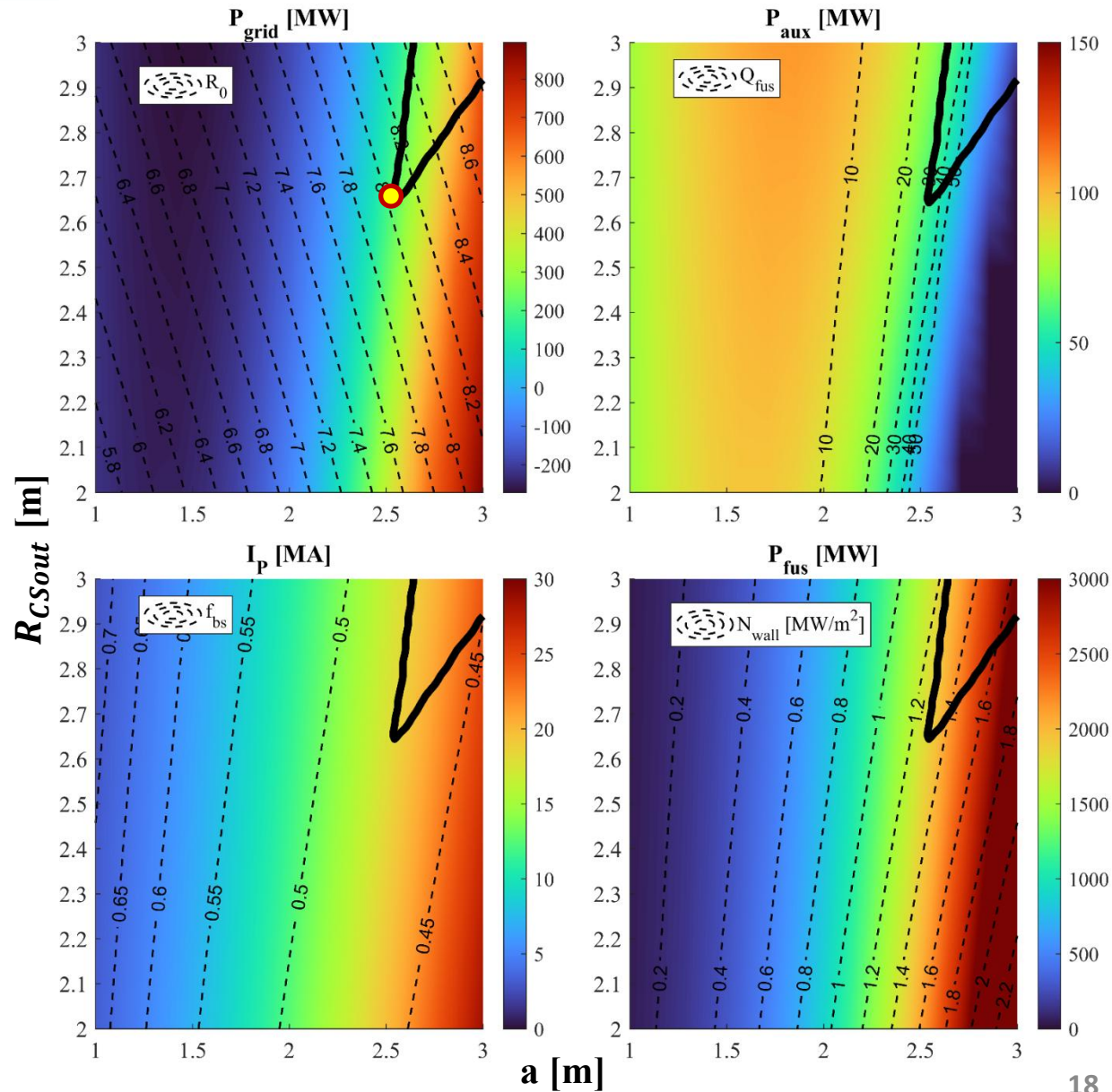


# Hybrid DEMO with CFEDR-TF-CS

With the CFEDR hybrid-CS and LTS-TF, the minimum size design is obtained at  $R_0=8.01\text{m}$ ,  $a=2.53\text{m}$ ,  $R_{CSout}=2.63\text{m}$

The plasma performance is close to those of LTS design, but the size is smaller than LTS DEMO and larger than HTS DEMO.

$R_0$ [m]	8.01
$P_{grid}$ [MW]	211
$P_{aux}$ [MW]	60
$Q_{fus}$	30
$I_p$ [MA]	18
$f_{bs}$	0.47
$P_{fus}$ [MW]	1822
$N_{wall}$ [MW m <sup>-2</sup> ]	1.3



# Comparisons of three DEMO designs

## The comparisons show :

- 1) HTS DEMO has smaller size than LTS DEMO and Hybrid DEMO, but not by much. This is mainly because **the HTS DEMO TF coils are much thicker**.
- 2) Smaller bore of TF coil results in smaller TF stress. The HTS DEMO's  $a$  is about 70% of those of the other two DEMO. However, its TF coil case thickness is 140% of them.
- 3) The radial thickness of CS coil for HTS, hybrid and LTS are 1.1 m, 0.9 m and 0.5 m, respectively, which are the results of taking into account both flux swings and CS lifetime. However, the  $R_{CSout}$  is the factor that truly affects  $R_0$ , and HTS DEMO has smaller  $R_{CSout}$ .
- 4) The three DEMOs have similar  $P_{fus} \sim 2$  GW and triple product of  $1 \times 10^{22} \text{ m}^{-3} \text{ keV s}$ . However, HTS DEMO faces a more severe divertor heat load issue. This is because of smaller device volume and higher L-H transition power associated with high  $B_t$ .
- 5) Due to smaller volume, HTS DEMO has much higher neutron wall loading.

	HTS	LTS	Hybrid-CS & LTS-TF
$R_0, a$ [m]	7.25, 1.96	8.61, 2.69	8.01, 2.53
$R_{CSout}, R_{CSin}$ [m]	2.55, 1.47	2.85, 2.34	2.63, 1.74
$\Phi_{CS}$ [wb], $\tau_{pulse}$ [s]	520, 7200	550, 7200	548, 7200
$n_{e0}, \langle n_e \rangle$ [ $10^{20} \text{ m}^{-3}$ ]	1.55, 1.17	0.95, 0.77	1.04, 0.83
$T_{e0}, \langle T_e \rangle$ [keV]	30.6, 11.7	29.7, 11.3	28.2, 10.7
$n_{i0} T_{i0} \tau_E$ [ $10^{21} \text{ m}^{-3} \text{ keV s}$ ]	10.5	10.1	9.5
$\beta_N, \beta_t, \beta_p$	2.11, 1.88, 1.13	2.08, 2.33, 0.93	2.09, 2.38, 0.92
$\langle n_\alpha \rangle / \langle n_e \rangle, \beta_\alpha / \beta_t$ (%)	0.52, 15.16	0.46, 14.47	0.42, 13.77
$I_p$ [MA], $f_{bs}$	15.7, 0.54	19, 0.47	18, 0.47
$P_{grid}, P_{fus}$ [MW]	274, 2294	233, 1988	211, 1822
$P_{sep}, P_{aux}$ [MW]	292, 73	255, 64	238, 60
$N_{wall}$ [ $\text{MW m}^{-2}$ ]	<b>2.36</b>	<b>1.24</b>	<b>1.30</b>
$P_{sep} B_t / (A q_{95} R_0)$	<b>24.5</b>	<b>14.5</b>	<b>14.7</b>
$f_{Ar,sol}, f_{Ar,core}$ (%)	1.16, 0.45	0.9, 0.41	0.84, 0.39
$\sigma_{CS}$ [MPa], $N_{cycle}/1000$	402, 30	379, 38	400, 31
$B_{CS}, B_{max}$ [T]	20, 19	13, 13	18, 13.8
<b>TF case thickness <math>d_{in}</math> [m]</b>	<b>0.76</b>	<b>0.54</b>	<b>0.51</b>

# Conclusions

- With conventional wedged solution and constraints from magnet stress and lifetime, HTS DEMO is smaller ( $R_0 = 7.25$  m) than LTS (8.61 m) and Hybrid (8.01 m), **but not by much, mainly due to much thicker TF coils required for high field.**
- Although HTS DEMO also has a thicker CS coil, its  $R_{CSout}$  is much smaller due to high flux swing capability contributed by high field.
- Without adopting bucked support, the size advantage of HTS over LTS is modest (~1.4 m in major radius). **A true breakthrough in compactness would require solving the engineering challenges of bucked or other advanced structural concepts. Whether pure bucked solution suitable for DEMO-class high-field tokamaks is still uncertain.**
- The three DEMOs achieve similar fusion performance, **but HTS DEMO suffers higher divertor heat load and neutral wall load issues.** A higher neutral wall loading requires a thicker blanket, which makes the device size even bigger.
- Therefore, **currently DEMO with hybrid magnet like CFEDR could be the best choice,** which balance device size and engineering challenges.

Thank you