The Case for High Field Fusion (abridged)

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Full version presented at APS-DPP 2017 available at firefusionpower.org

psfc.mit.edu

Case: The high magnetic field path is optimal to obtain our absolute science and energy goals

- **From plasma science viewpoint there are no serious "tradeoffs" in the design of your MFE burn/energy mission, you always maximize B field strength**

- **Achieving high B field with electromagnets has fundamental *science* limits; understanding this evolving science allows us as plasma physicists how to best meet our science and energy missions**

Why now?

- 15+ years since we talked about this.. many of our younger scientists don’t recall key features of debate about the “tactics” involved in achieving burning plasmas.

- And haven’t things changed meanwhile?
  - In physics of plasmas, magnets, etc.
  - Or maybe we just have more experience & insight

Volumetric fusion power density

$$\beta \equiv \frac{p_{th}}{p_{magnetic}} = \frac{p_{th}}{B^2 / 2\mu_o}$$

Troyon limit (tokamaks)

$$\beta_N = \frac{\beta\, q}{5\epsilon\, S(\kappa)}$$

$$+$$

$$P_f \simeq 8\, p_{th}^2$$

$$\Longrightarrow$$

Generic

$$P_f \sim \beta^2 B^4$$

Tokamak

$$P_f \sim \frac{\beta_N^2 \epsilon^2 S(\kappa) B^4}{q^2}$$

Troyon, Gruber Phys. Lett. ***110A*** *(1985)*

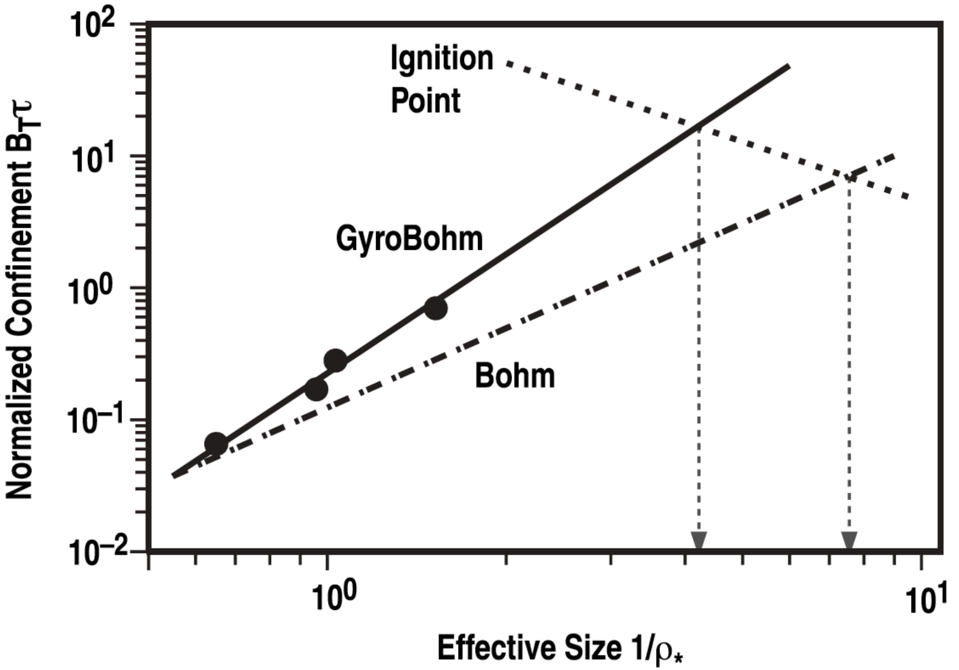
Confinement: tokamak

- **Expressing confinement through "wind-tunnel" dimensionless scaling laws**

$$B\,\tau \propto \rho_*^{3.1}\beta^{0}\nu^{-0.35}q_{95}^{-1.4}\kappa^{2.2}$$ *Petty*

Extract R, B at Fixed R/a

$$\tau \sim R^{3.1}B^{2.1}$$



ITPA
*Luce, Petty, Cordey PPCF **50** (2008)*

Energy gain at fixed physics & shape parameters

Target p_{th}	x		τ_E	=	*Target* $p_{th}\,\tau_E$
B^2		Generic	$R^2 B^2$		$R^2 B^4$
		H_{98}	$R^{2.7} B^{3.5}$		$R^{2.7} B^{5.5}$
		Petty	$R^{3.1} B^{2.1}$		$R^{3.1} B^{4.1}$
		ISS04	$R^{2.8} B^{2.2}$		$R^{2.8} B^{4.2}$

High B (+ strong shaping) enables stationary pedestal with high absolute pressure

~ Peeling-Ballooning Stability Limit

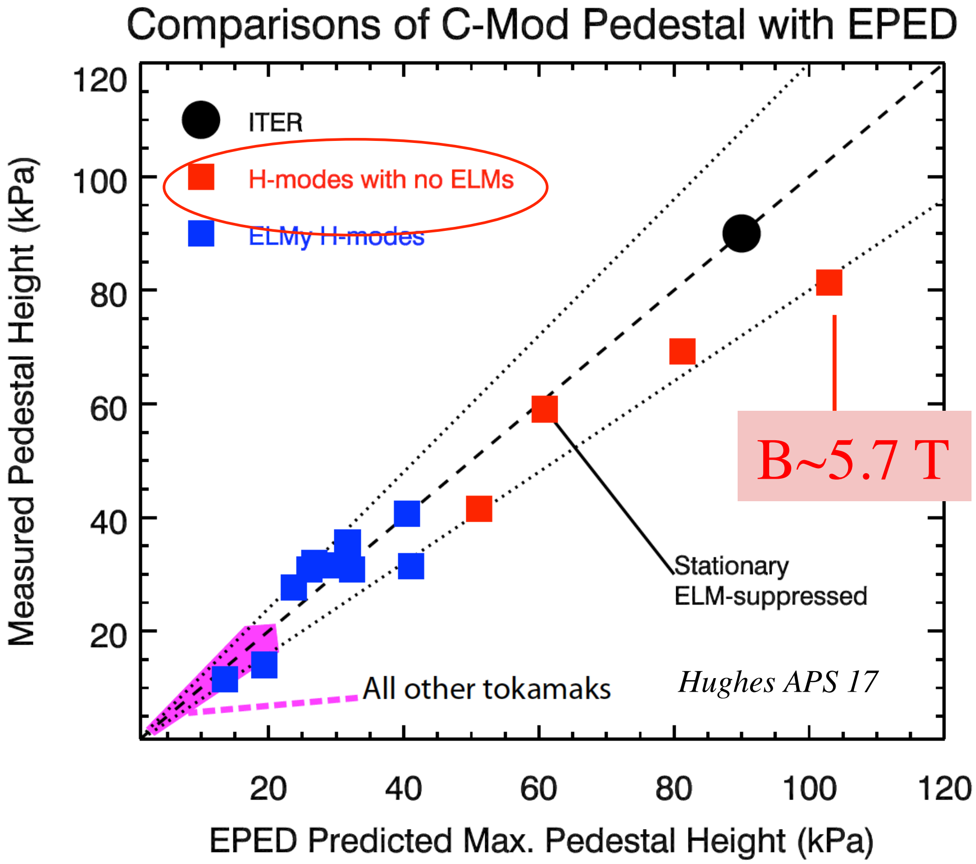
Snyder et al NF 2011

$$\beta_{N,Ped} \le \left(\frac{\Delta\psi_{ped}}{5\%}\right)^{3/4}$$

$$\beta_N \sim \frac{p_{ped}}{p_{magnetic}}\frac{q}{\epsilon}$$

$$\Downarrow$$

$$p_{ped} \le \left(\frac{\Delta\psi}{5\%}\right)^{3/4}\frac{B^2}{q}$$


Comparisons of C-Mod Pedestal with EPED

Hughes APS 17

Am I happy or sad?

Issue	Scaling	
Power density	B^4	😀
Confinement (generic)	$R^2\ B^2$	😀
Confinement (tokamak)	$R^{2.7}\ B^{3.5}$ (H_{98}) $R^{3.1}\ B^{2.1}$ (Petty)	😀
Confinement (stellarator)	$R^{2.8}\ B^{2.1}$	😀
Gain	$R^{2\text{-}3.1}\ B^{4\text{-}5.5}$	😀
Stable pedestal/I-mode	$\sim \beta_N\ B^2$	😀

Issue	Scaling	
Density (tokamak)	$R^{-1}\ B^1$	😀
Density (stellarator)	$\beta\ B^{2.5}$ (burning)	😀
Heat exhaust: min. f_Z	$R^{1.3}\ B^{0.9}$	😀
Heat exhaust: q//	B^{-1} (burning)	🤔
Runaway e- amp.	$\exp\ (R^{0.28}\ /\ B^{0.3})$	😀
Synchrotron: runaways	B^2	😀
Synchrotron:thermal	$\sim B^{1.5}$	🤔
TAE	$n \sim B,\ v_A \sim B$	😀

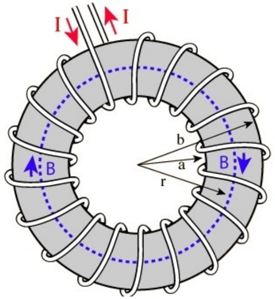
WORK IN PROGRESS

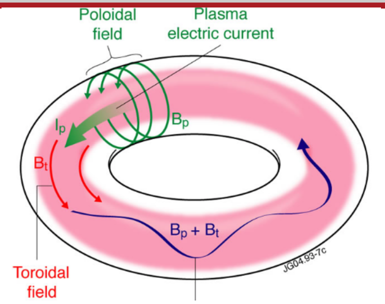
Am I happy or sad? *I'm happier than before*

Issue	Scaling	
Power density	B^4	😀
Confinement (generic)	R^2 B^2	😀
Confinement (tokamak)	$R^{2.7}$ 1998 2008 $B^{2.1}$ (Petty)	😀
Confinement (stellarator)	R 2005	😀
Gain	$R^{2\text{-}3.1}$ $B^{4\text{-}5.5}$	😀
Stable pedest 2010	2016 β_N B^2	😀

Issue	Scaling	
Density (tokamak)	R^{-1} B^1	😀
Density (stellarator)	β $B^{2.5}$ (burning)	😀
Heat exhaust: min. f_Z	2010-17 $^{0.9}$	😀
Heat exhaust: q//	B (burning)	🤔
Runaway e- amp.	2005-17 exp ($R^{0.28}$ / $B^{0.3}$)	😀
Synchrotron: runaways	B^2	😀
Synchrotron:thermal	$\sim B^{1.5}$	😀
TAE	$n \sim B$, $v_A \sim B$	🤔

Electromagnets & Tokamak plasmas: same physics





$\boxed{\nabla x \vec{B} = \mu_0 \vec{j}}$ Ampere’s law $\boxed{B \sim j}$

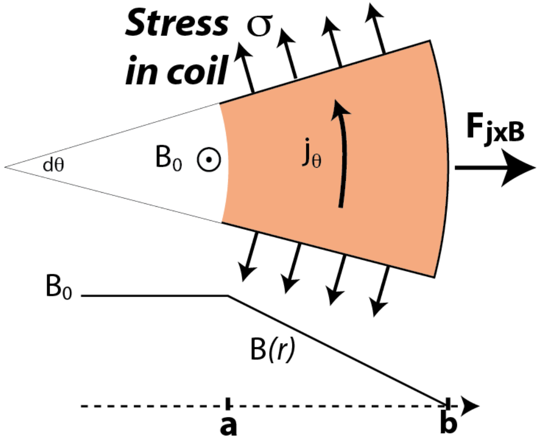
$\boxed{\nabla p = \vec{j} \times \vec{B}}$ Force balance $\boxed{p_{magnet} \sim B^2}$

$\boxed{P = \eta j^2}$ Ohmic heating $\boxed{P_{magnet} \sim B^2}$

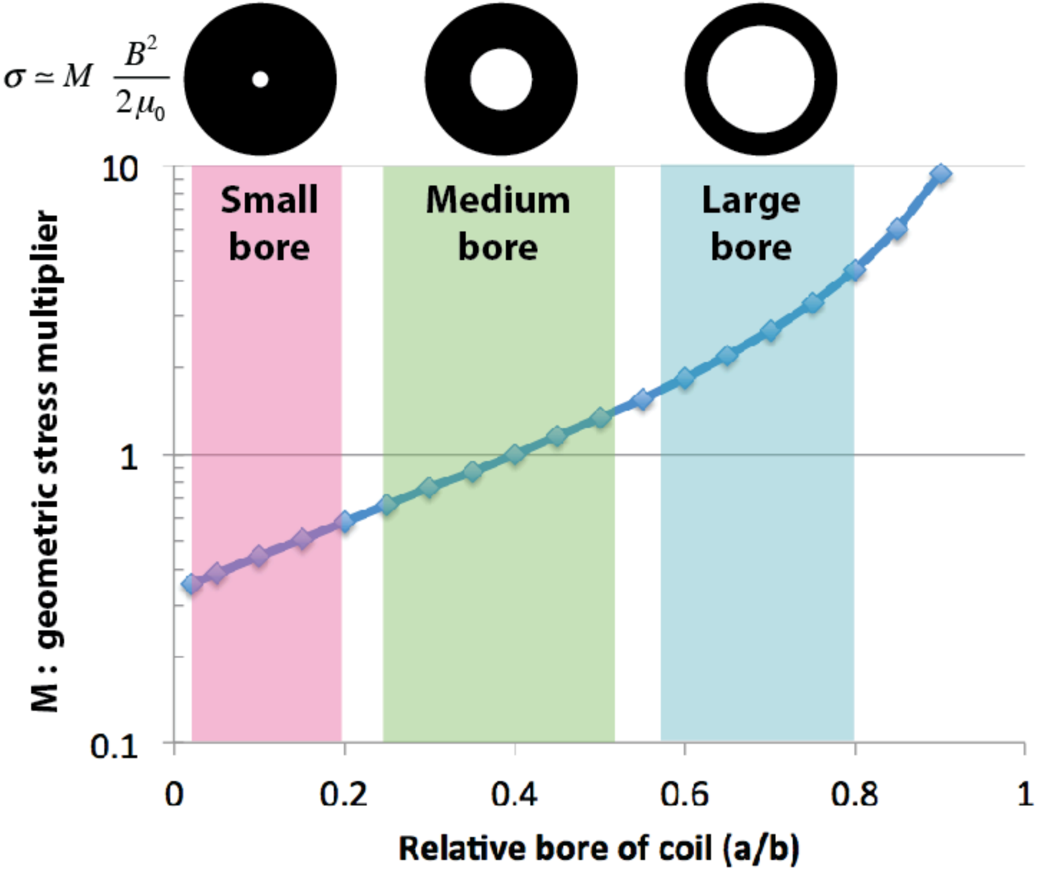
As in toroidal plasma physics, aspect ratio is a critical and complex optimization

$$x \equiv \frac{a}{b}$$

$$M = \frac{2x+1}{3(1-x)}$$

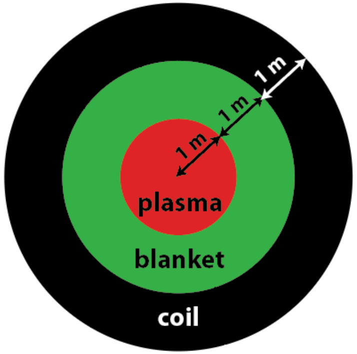


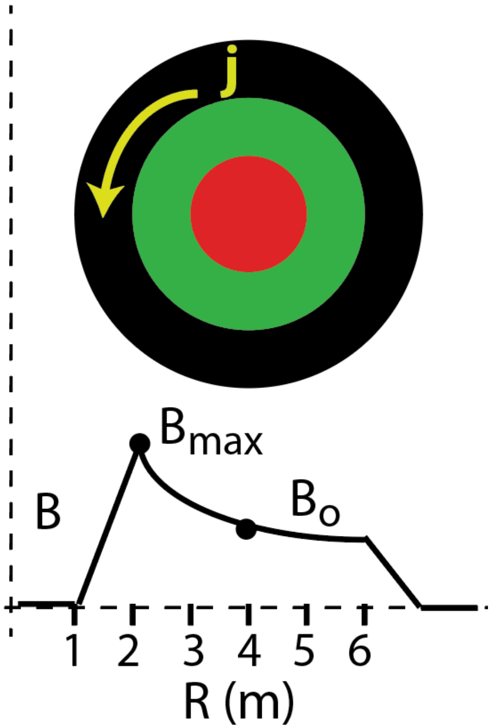
$$\sigma \simeq M \frac{B^2}{2\mu_0}$$



Simple toroidal "solenoid" to explore limits

R=4 m, A=4, $B_0=B_{max}/2$





$$B = \frac{\mu_0 \int j_Z \, \pi R \, dR}{2\pi R}$$

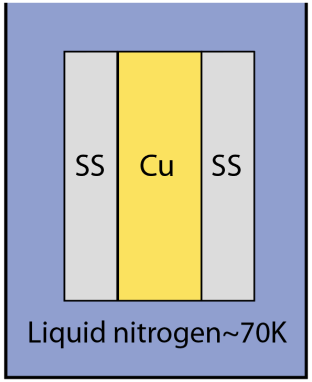
$$B_{\max} = 0.3\pi \; j_{MA/m^2}$$

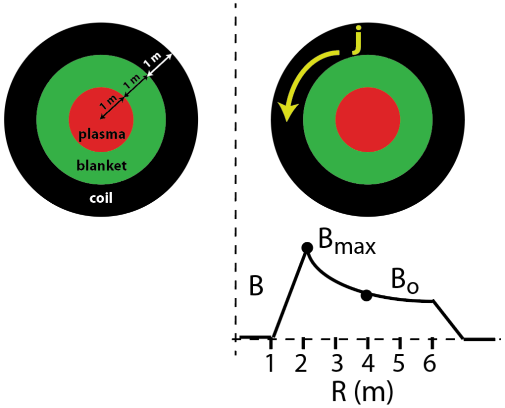
$$x \equiv \frac{a}{b} = \frac{2}{3}$$

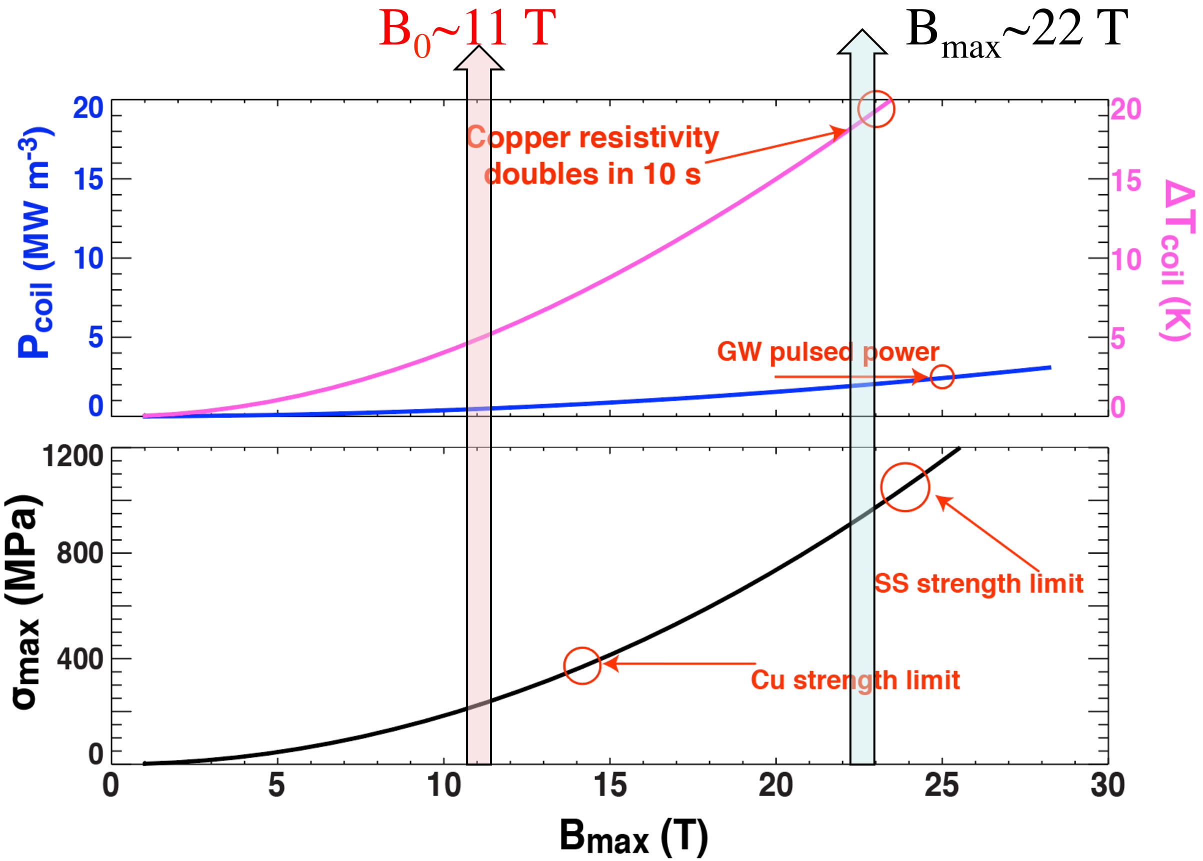
$$M = 2.3$$

$$\Rightarrow \sigma_{\max}[MPa] \simeq M \frac{B_{\max}^2}{2\mu_o}$$

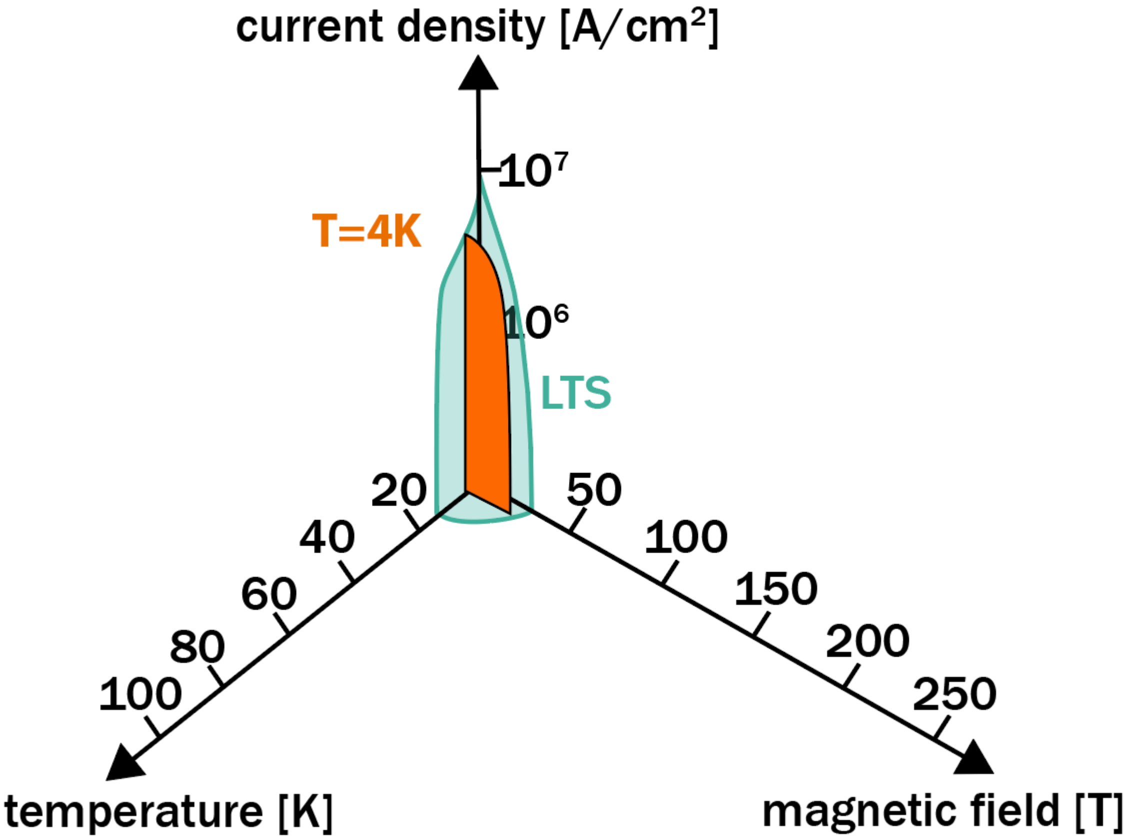
LN-cooled copper + steel for stress loading
Pulsed due to lack of active cooling



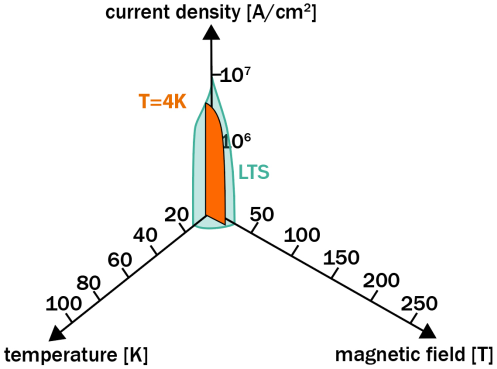


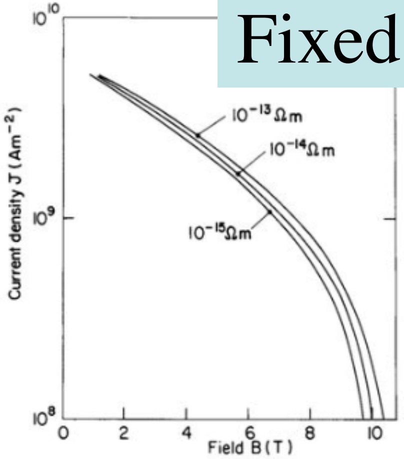


Superconductors: zero resistivity, but a restricted operating space in T, j and B



Superconductors: critical current, at fixed T, depends on SC type and B





Fixed T

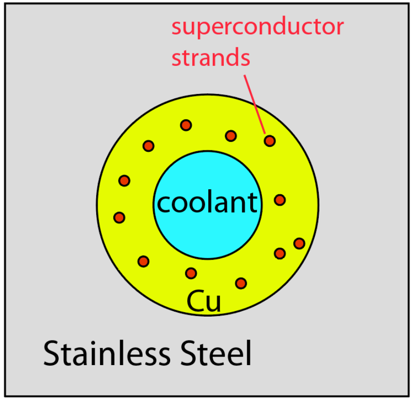
$$\frac{J_c}{J_{c,0}} = \left(\frac{B}{B_0}\right)^{-\alpha}$$

	J_{c0}	B_0	α
Nb-Ti	10^3	5	3
Nb_3-Sn	10^3	10	3

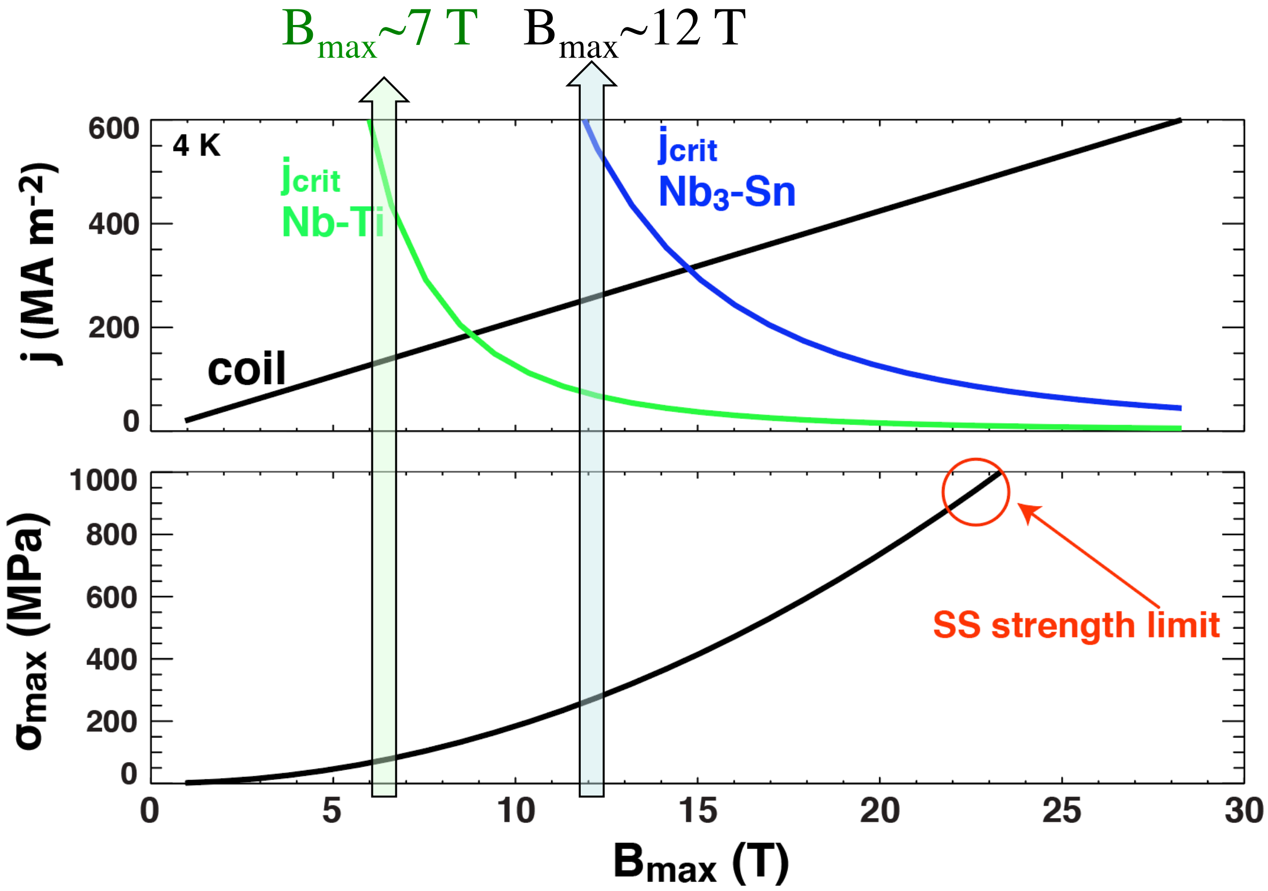
$T \sim 4\ K,\ B > B_0$

Nb-Sn superconductors:
B limited by critical current at T~ 4K

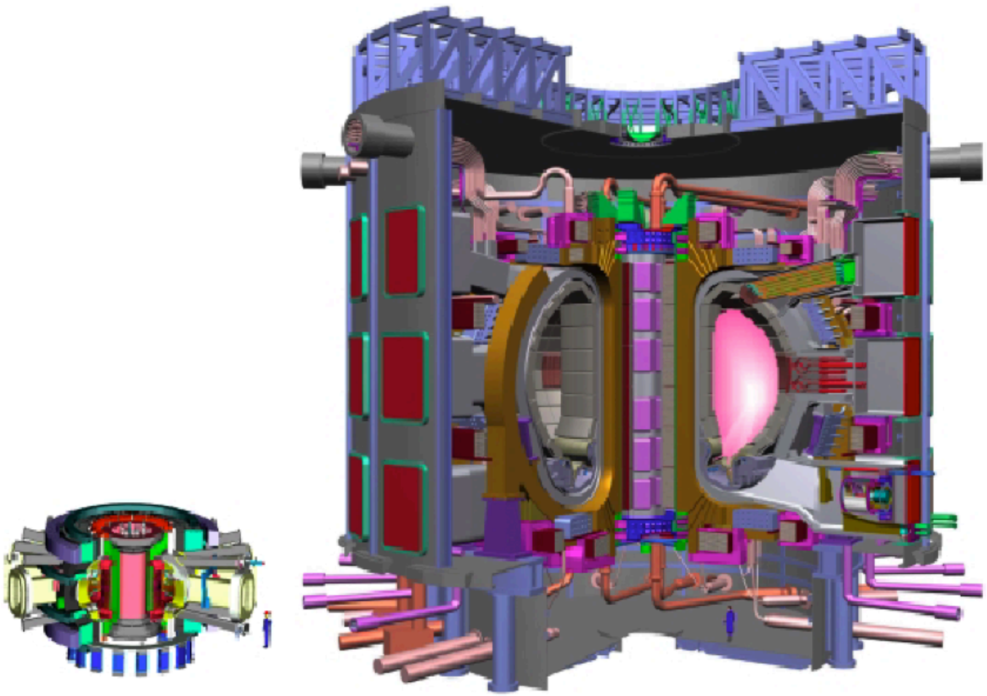
Coil Cross-section



50% SS
22% cool
25% Cu
3 % SC



NAS study: Cryogenic Cu could study burning plasma science at 25x smaller volume than Nb_3Sn



$$\boxed{p_{th}\tau_E \sim R^{2.7} B^{5.5}}$$

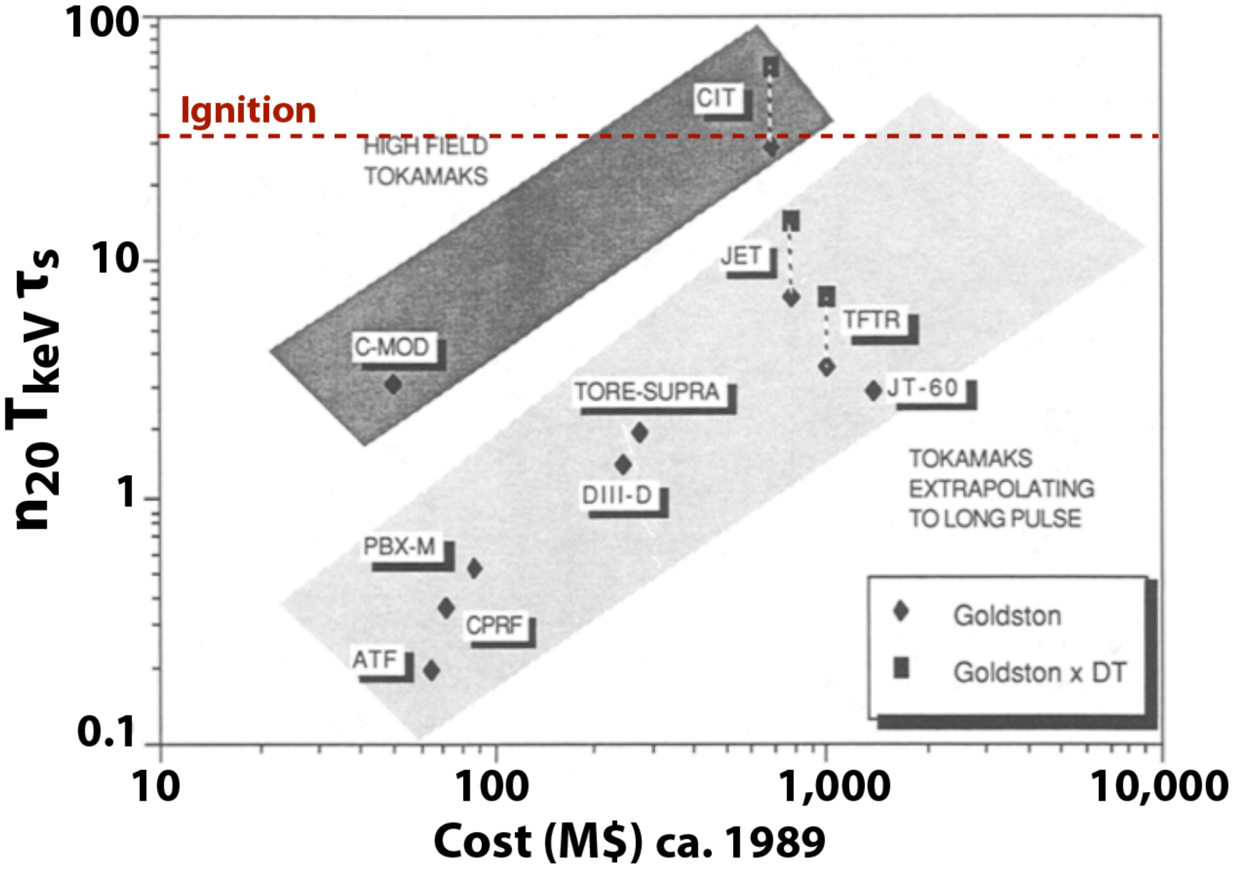
$$\text{Volume} \sim R^3 \sim 1/B^5$$

	FIRE	**ITER**
B (T)	10	5.3
R (m)	2.14	6.2
Q	10	10
τ / τ_{CR}	> 1	> 1
V_p (m^3)	**30**	**800**

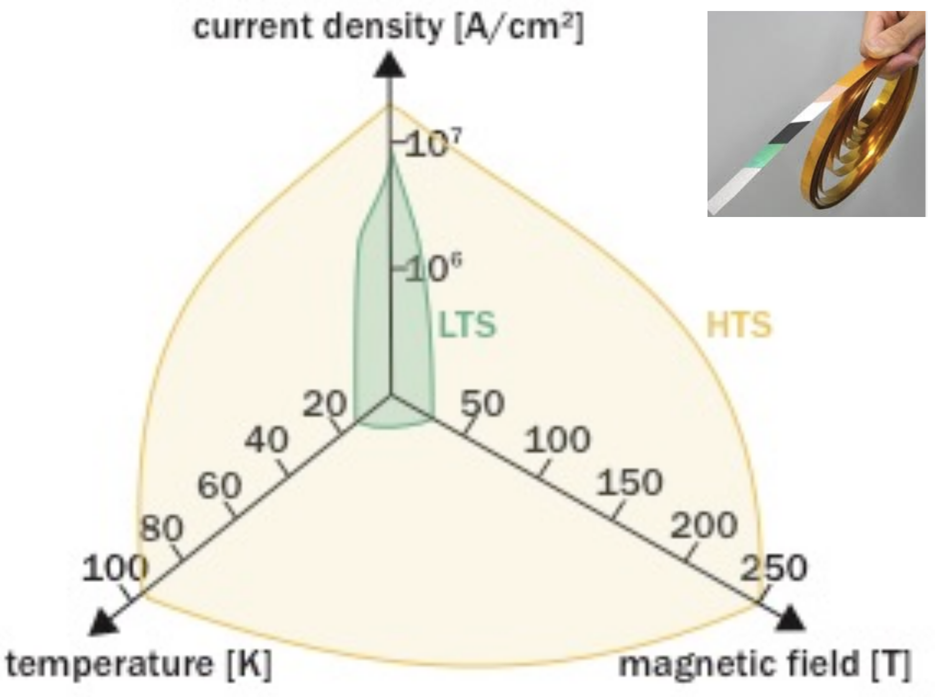
$\xrightarrow{\quad}$ 25x

Tactics? High-B, compact was known to have ~10-fold performance to cost ca. 1990 but pulsed

Compact Tokamak
Ignition Concepts
J. Willis
J. Fusion Energy **1989**



High-Temperature (HTS) REBCO superconductors



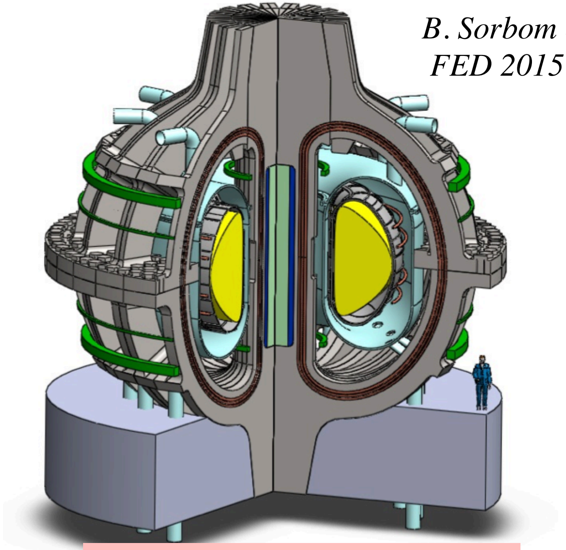
$$\frac{J_c}{J_{c,0}} = \left(\frac{B}{B_0}\right)^{-\alpha}$$

	J_{c0}	B_0	α
Nb-Ti	10^3	5	3
Nb_3-Sn	10^3	10	3
REBCO	$2.5\text{x}10^3$	5	0.6

$T \sim 4\ K,\ \ B > B_0$

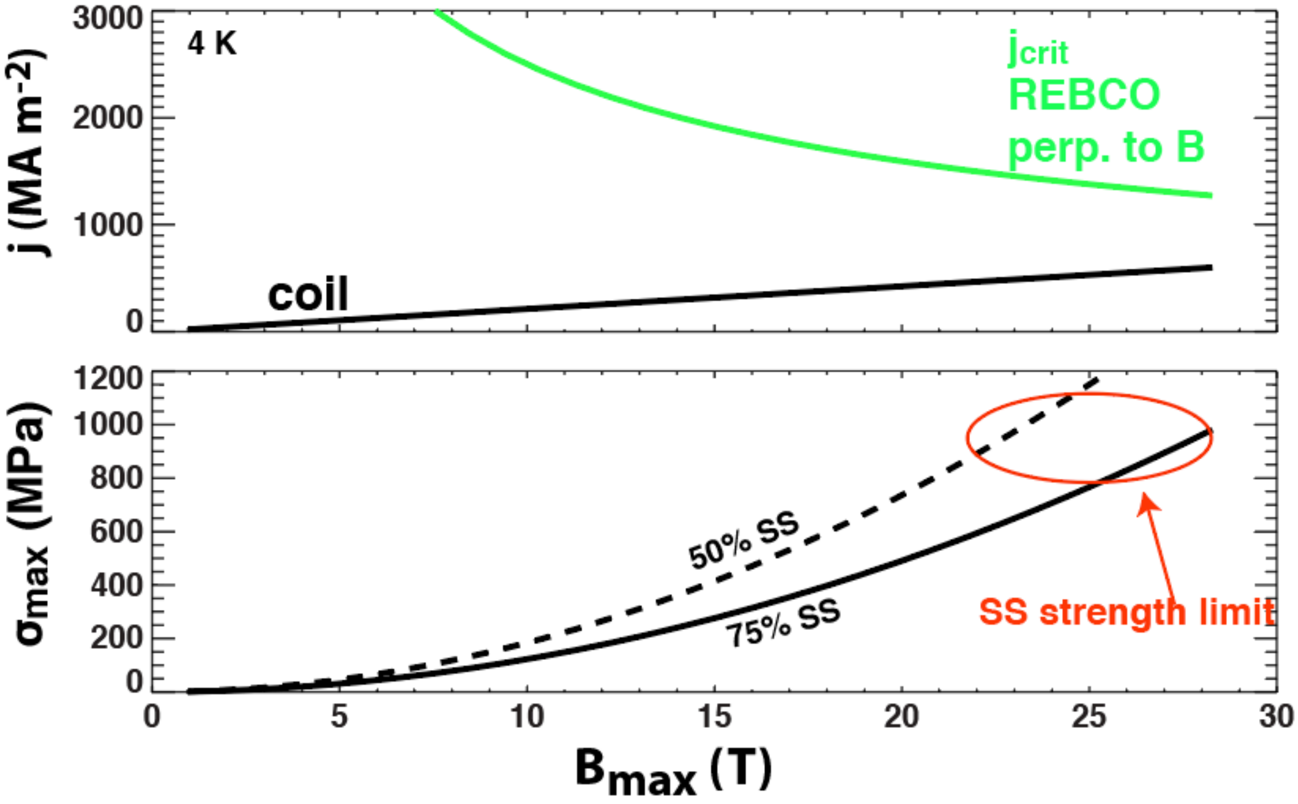
With HTS magnets, stress is the only limit → multiple design choices to achieve B_{max} > 20T

ARC



B. Sorbom et al
FED 2015

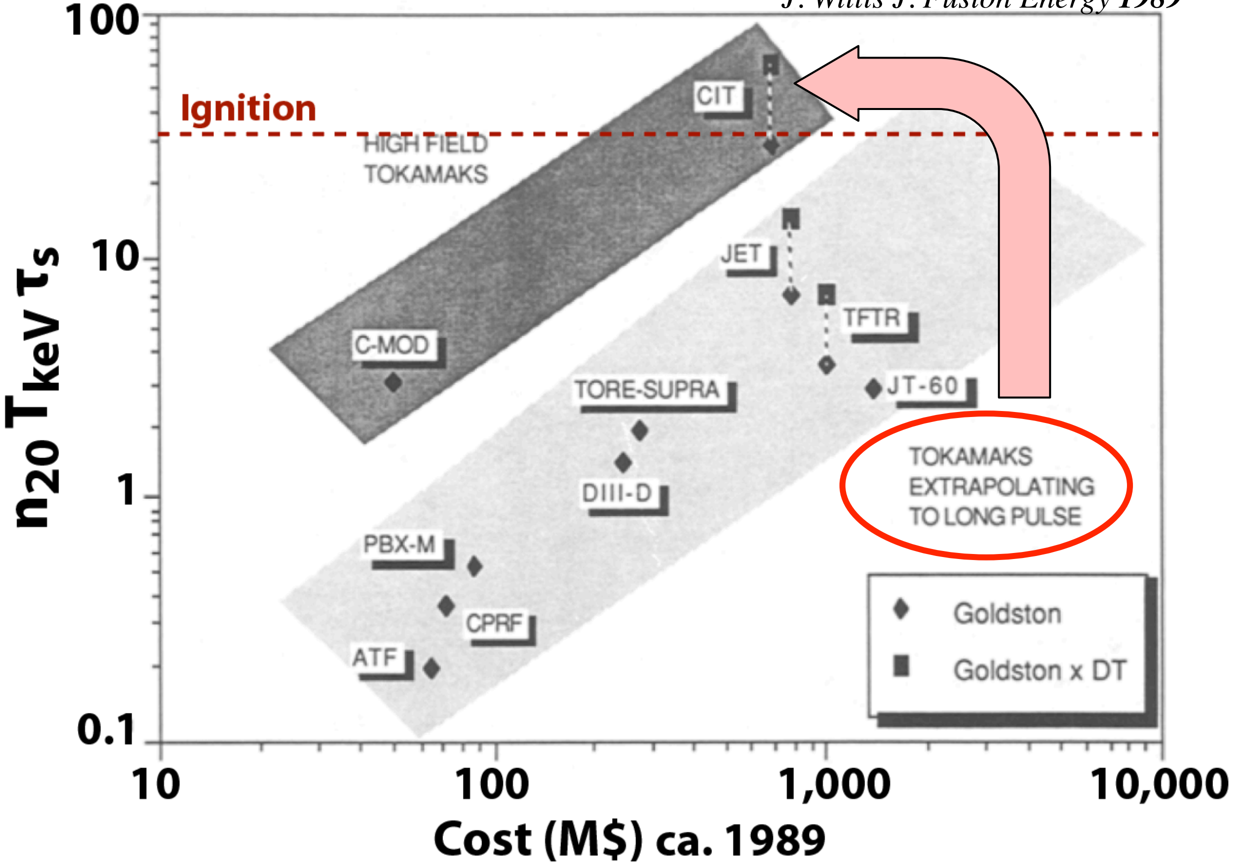
B_{max}~23T
B_0 ~ 9.2 T
σ_{max} ~700 MPa



HTS magnets clearly change the tactical landscape for magnetic fusion

- ✓ **Diversification**
- ✓ **Risk distribution**
- ✓ **Speed**

J. Willis J. Fusion Energy ***1989***



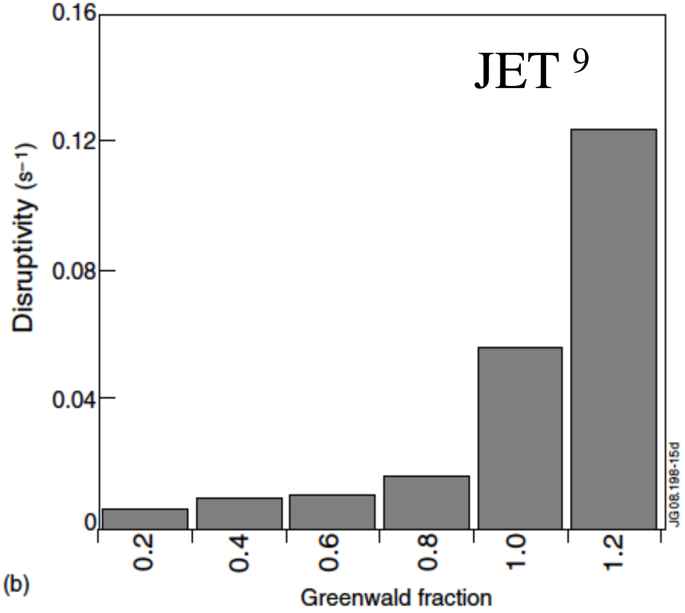
PSFC

Plasma Science and Fusion Center
Massachusetts Insitute of Technology

psfc.mit.edu

Density: tokamak

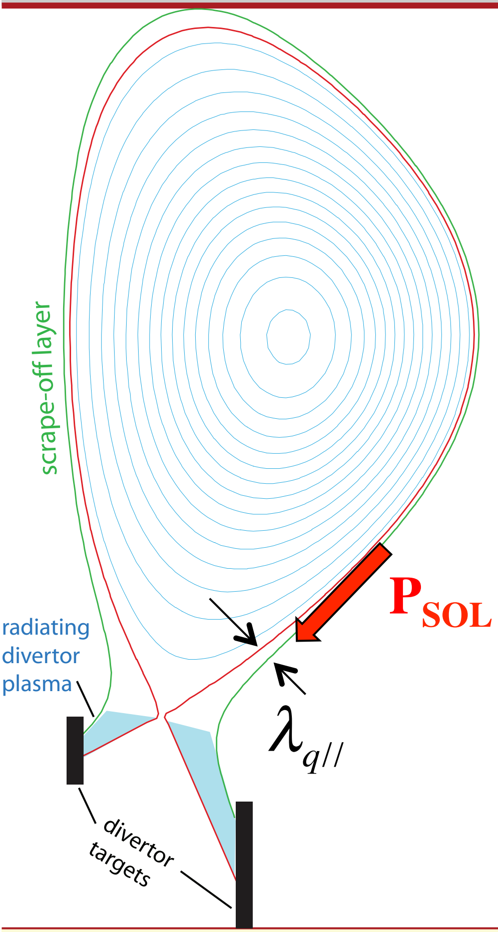
Empirical Greenwald density
is a disruptive limit in tokamaks

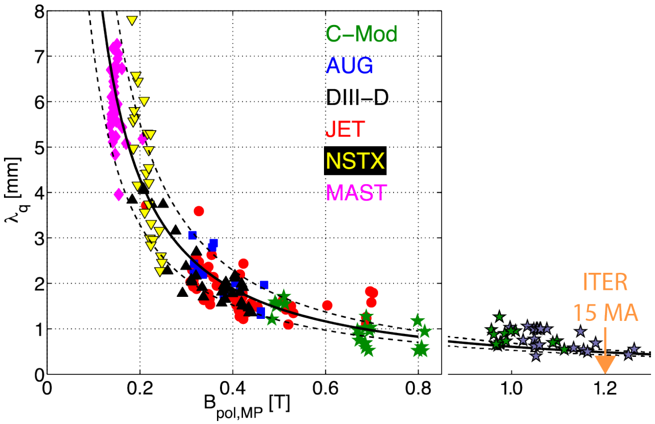


De Vries, et al. Nucl. Fusion ***49*** *(2009)*

$$n \le n_{Gr} = \frac{I_p}{\pi a^2} \propto \frac{S(\kappa)}{q}\frac{B}{R}$$

Power exhaust: tokamak divertor Solutions





$$P_{rad} \sim n_{div}^2 f_z F(T_e)$$

$$n_{div} \sim n_{core}^2$$

$$n_{core} \propto \frac{S(\kappa)}{\epsilon} \frac{B}{R}$$

Required impurity Fraction to Detach[1]

$$c_Z \propto \frac{P_{SOL}}{B_p f_{Gr}^2}$$

$$\lambda_{q//} \propto \epsilon \rho_{pol} \sim 1 / B_{poloidal}$$

$$q_{//} \propto P_{SOL} B / R$$

Required impurity Fraction to Dissipate Psol in H-mode[2]

$$f_Z \sim B^{0.9} R^{1.3}$$

[2] M.L. Reinke. Nucl. Fusion **57** (2017)

[1] Goldston et al PPCF 2017, APS17