Massachusetts Institute of Technology

PSFC

Plasma Science & Fusion Center

Magnetic Fusion Reactor Design & The Role of Technology

Dennis Whyte for the MIT fusion research team

Plasma Science and Fusion Center

Nuclear Science and Engineering

Frontiers in Fusion

York, April 2016

psfc.mit.edu

Summary

- Magnetic fusion needs technology advances to make fusion energy practical to develop and economically viable.
  - The fact that we know this is a "good" sign…we have to speculate very little on the physics of magnetic confinement.
  - The key requirements are power density & gain & availability.
- Disruptive technological solutions are available, but require both integrated knowledge of fusion systems + imagination / cleverness/ "un-knowledge" e.g.
  - New high-field, high-temperature superconductor magnets
  - Jointed, demountable toroidal field coils
  - Immersion liquid blanket
  - 3-D printed components for heat removal
- Your generation will be key in developing these choices

ITER provides a valuable lesson in the features of a viable fusion power plant

ITER

P_{fusion} = 500 MW S_{area} = 700 m^2 Cost ~ 20 G$ T_{wall} ~ 450 K f_{on}~0.1 (duty factor)

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ITER example

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$$\frac{\$\text{cost}}{\$_{\text{electric}}/\text{yr}} = \frac{20\times 10^9 \$}{P_f \eta_{th}\left(f_{on}\right)\left(8760 hr/year\right) 0.1\$/kW\ hr} \simeq 1800\ yr$$

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P_f / \$ → x 5

Power density

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P_f / $ → x 5

η_{th} x 2 → 0.5

Power density

High gain &
Thermal efficiency

ITER provides a valuable lesson in the features of a viable fusion power plant

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P_f / \$ → x 5

η_{th} x 2 → 0.5

f_{on} x 10 → 1

Power density

Energy gain & Thermal efficiency

High Availability

ITER provides a valuable lesson in the features of a viable fusion power plant

The immediate and obvious conclusion (to me anyway) is that in the absence of very new physics, "disruptive" technology options are required for these order-of-magnitude improvements

Power density

Energy gain & Thermal efficiency

High Availability

Let's focus on power density: P_{fusion} / $S_{blanket}$ what is the ideal?

- Because neutron slowing distances are ~ constant, P_{fusion} per unit blanket/wall area (S) is effectively the blanket volume power density

- The lifetime of the blanket solid components (dpa or He accumulation) is inversely dependent on P_f/S

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$$\left(P_f / S\right)_{avg} = \left(P_f / S\right)_{op} U =$$

Maximize time-averaged power output for economics

$$\left(P_f / S\right)_{op}\left(1 - \frac{0.8\left(P_f / S\right)_{op} F_{dpa}}{L_{dpa}} \Delta t_{rep}\right) = \left(P_f / S\right)_{op}\left(1 - \left(P_f / S\right)_{op} X_{wall}\right)$$

L_{dpa} ≡ dpa limit of blanket

F_{dpa} ~ 10 dpa / (MW_n-year/m^2)

Δt_{rep} ≡ blanket replacement time

Let's focus on power density: P_{fusion} / $S_{blanket}$ what is the ideal?

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Maximize function

$$\left(P_f / S\right)_{op} = \frac{1}{2\,X_{wall}} \rightarrow \left(P_f / S\right)_{avg} = \frac{1}{4\,X_{wall}}$$

Only depends on

$$X_{wall} \equiv 0.8 F_{dpa} \Delta t_{rep} / L_{dpa}$$

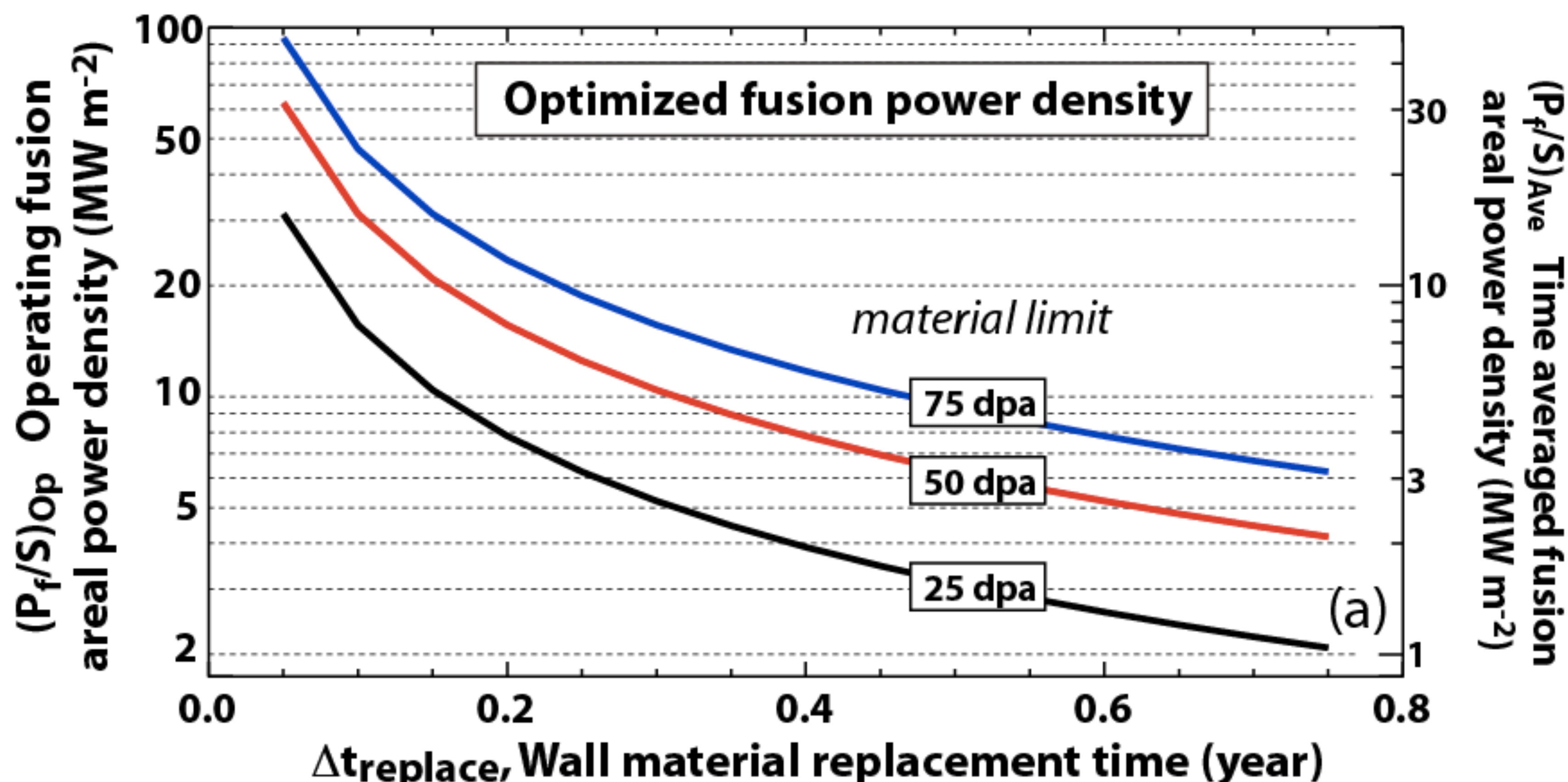
(m^2 / MW)

$L_{dpa} \equiv$ dpa limit of blanket

$F_{dpa} \sim 10$ dpa / (MW_n-year/m^2)

$\Delta t_{rep} \equiv$ blanket replacement time

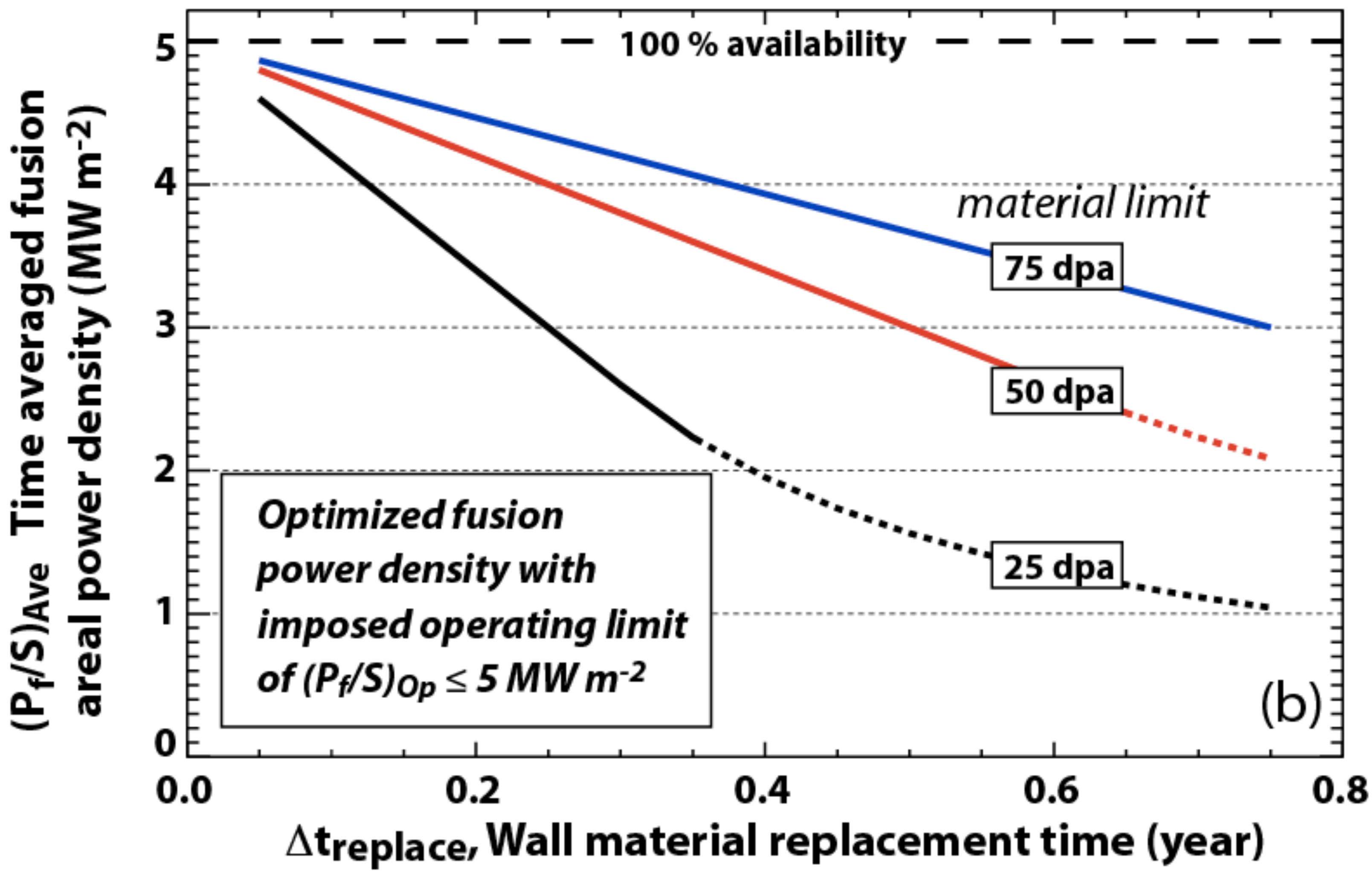
With reasonable blanket replacement times (~ 2-3 months) the ideal fusion power density should be order-of-magnitude higher than ITER or Demo



DEMO: 1.5 MW m^{-2} (R=9 m, P_f~2.3 GW)

ITER 0.7 MW m^{-2}

P_f / S is limited by heat removal…setting ceiling at US reactor design target of P_f/S=5 MW/m^2 reveals that blanket replacement time, not dpa, is most critical



So how do you make a fusion power plant economically viable? Sell lots of electricity, quickly

$$C_{Gain}\,[\frac{M\$}{m^2\ year}] = 10^{-6}\,\frac{8760\,hr}{year}\,POE_{[\$/MW-hr]} \times \left(P_f/S\right)_{op}\left(1-\left(P_f/S\right)_{op} X_{wall}\right)\eta_e$$

Electrical conversion efficiency

$$C_{fixed}\,[\frac{M\$}{m^2\ year}] = \left(\$_{overnight}/S\right)\frac{i\,(1+i)^n}{(1+i)^n-1}$$

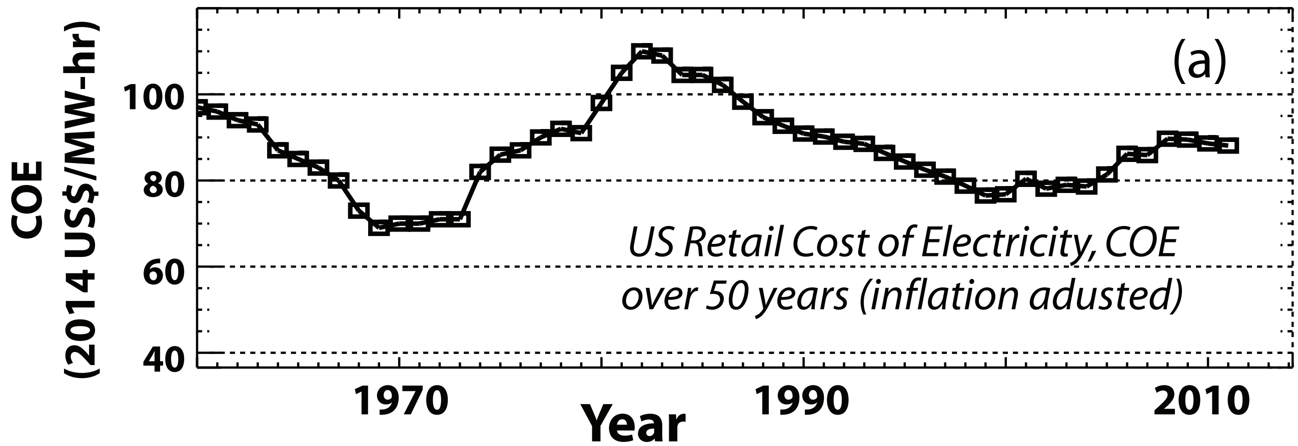
i: interest rate

$$C_{\text{blanket}}\,[\frac{M\$}{m^2\ year}] = \left(\$_{blanket}/S\right)\frac{0.8\left(P_f/S\right)_{op} F_{dpa}}{L_{dpa}}$$

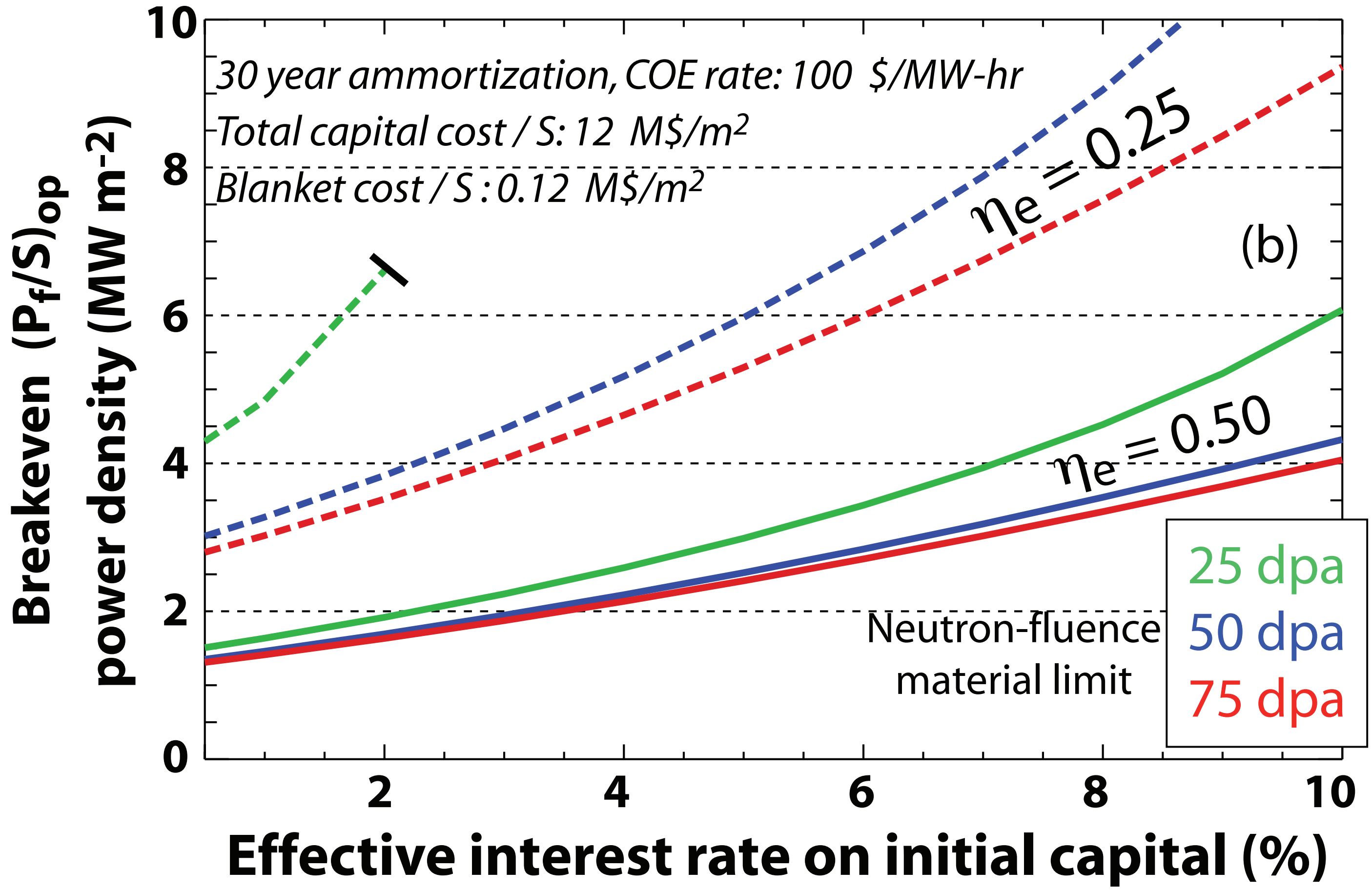
Blanket replacement costs

$$C_{gain} - C_{fixed} - C_{\text{blanket}} = 0$$

Economic breakeven

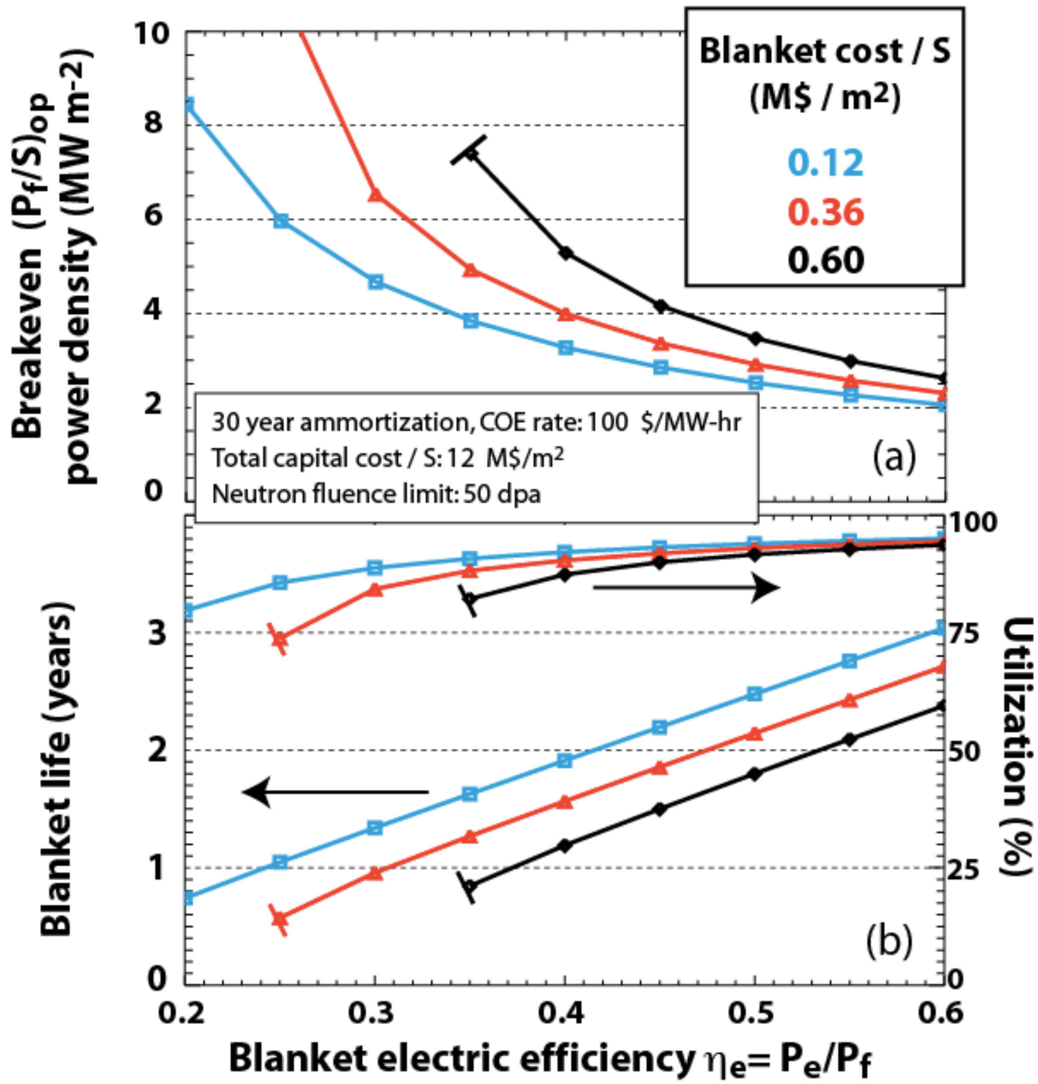


COE
(2014 US$/MW-hr)
100
80
60
40
(a)
US Retail Cost of Electricity, COE
over 50 years (inflation adusted)
1970
1990
2010
Year



Breakeven $(P_f/S)_{op}$
power density (MW m^{-2})
10
8
6
4
2
0
30 year ammortization, COE rate: 100 $/MW-hr
Total capital cost / S: 12 M$/m^2
Blanket cost / S : 0.12 M$/m^2
$\eta_e = 0.25$
(b)
$\eta_e = 0.50$
Neutron-fluence
material limit
25 dpa
50 dpa
75 dpa
2
4
6
8
10
Effective interest rate on initial capital (%)

And the blanket has to be cheap (< cost/weight of modern car) AND reliable AND efficient



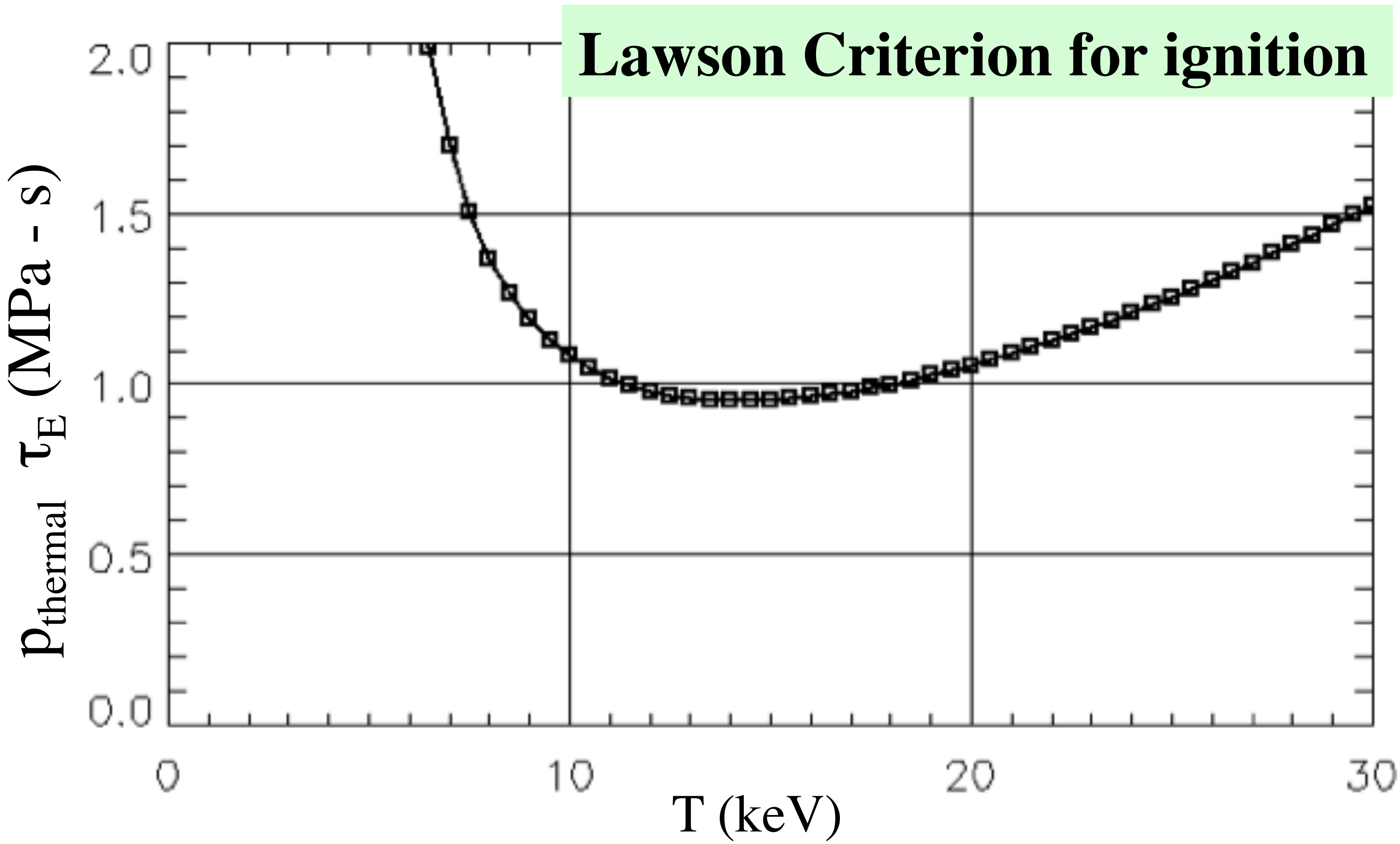
Pressure links power density, plasma stability and obtaining energy gain

$$\frac{P_f}{V} \sim n^2 T^2 \simeq 8\ p_{th}^2$$

$$p_{th} \sim \beta\ B^2 \sim \frac{\beta_N \epsilon}{q} B^2$$

$$\boxed{\frac{P_{fusion}}{S_{wall}} \sim \frac{{\beta_N}^2 \epsilon^2}{q_*^2} R B^4}$$

How to get high gain and power density is well known from nuclear and plasma science



How to get high gain and power density is well known from nuclear and plasma science

$$p_{th} = 10^{-2} \frac{\beta_N \epsilon \left(1+\kappa^2\right)}{q} \; B^2$$

Thermal pressure

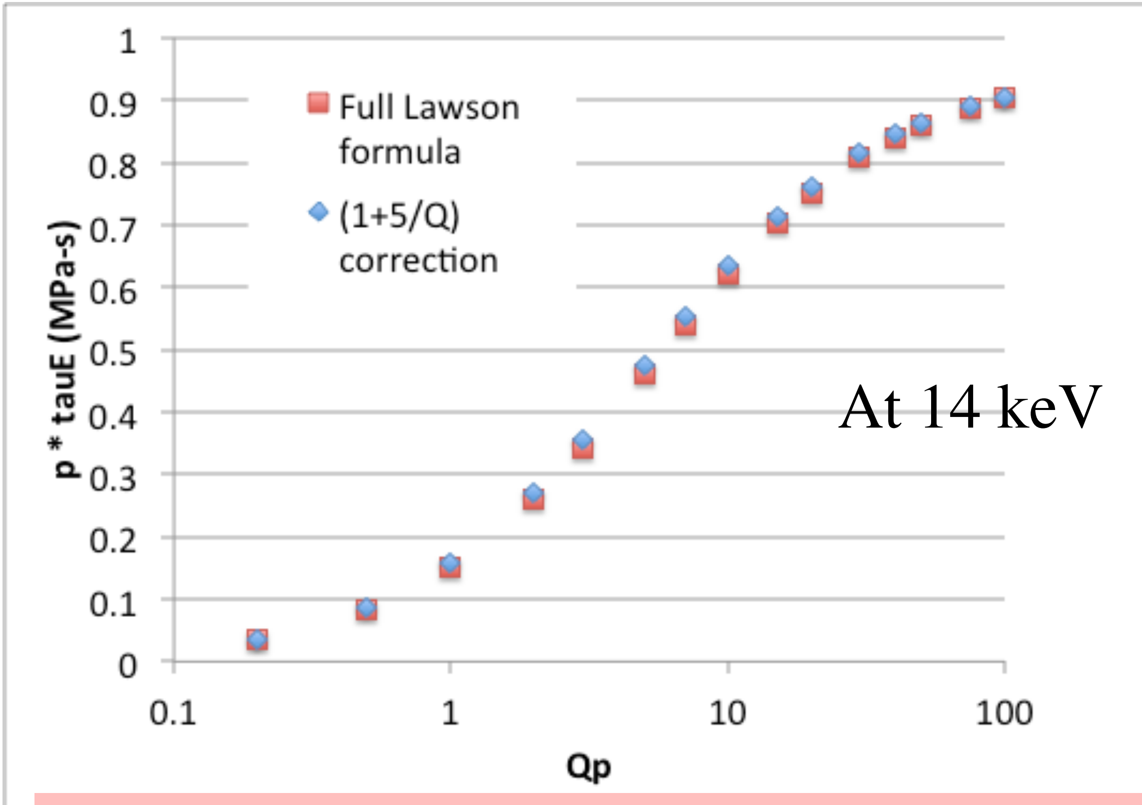
$$\tau_E = 0.08 H \; n_{20}^{0.1} I_{p,MA}^{0.85} R^{1.5} \epsilon^{0.3} \kappa^{0.5} B^{0.2} P^{-0.5}$$

$$P_{heat} = \frac{P_f}{5}\left(1+5/Q_p\right)$$

$$\tau_E = \frac{0.072 \; H \; n_{20}^{0.1} \; B^{1.05} R^{1.35} \; \epsilon^{1.5} \left\{\kappa^{0.5}(1+\kappa^2)^{0.6}\right\}}{q^{0.85}\left(\frac{P_f}{S}\right)^{1/2}\left(1+5/Q_p\right)^{0.5}}$$

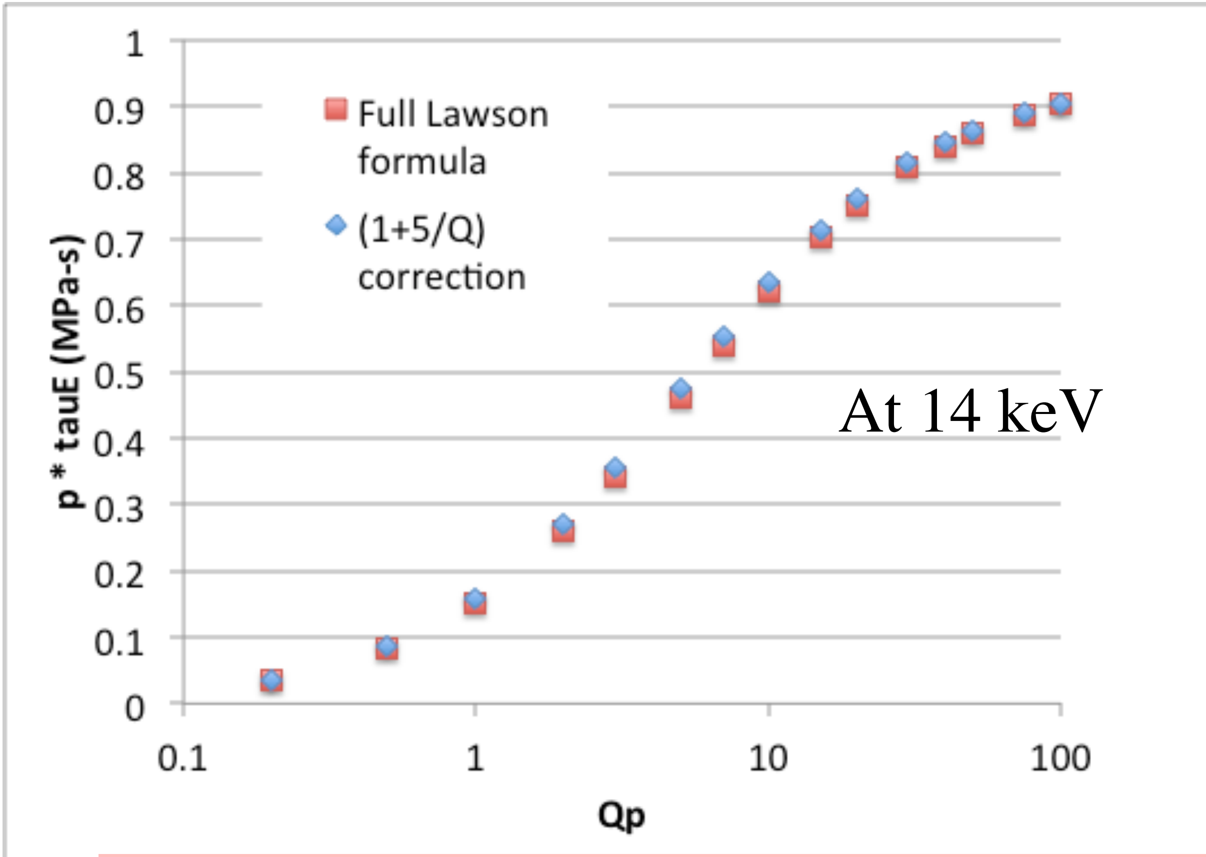
Energy confinement

How to get high gain and power density is well known from nuclear and plasma science



$$10^{-2}\,\frac{\beta_N \epsilon\left(1+\kappa^2\right)}{q}\;B^2\,\frac{0.072\,H\,n_{20}^{0.1}\,B^{1.05}R^{1.35}\,\epsilon^{1.5}\left\{\kappa^{0.5}(1+\kappa^2)^{0.6}\right\}}{q^{0.85}\left(\frac{P_f}{S}\right)^{1/2}\left(1+5/Q_p\right)^{0.5}}=\frac{0.95}{\left(1+5/Q_p\right)}$$

How to get high gain and power density is well known from nuclear and plasma science



$$H_{89}\left(1+5/Q_p\right)^{0.5}\left(\frac{P_f}{S}\right)^{-0.5}\beta_N\frac{R^{1.35}B^{3.05}}{q_*^{1.85}}\geq \text{constant}$$

With fixed plasma stability and confinement, magnetic field is biggest and best lever

Gain

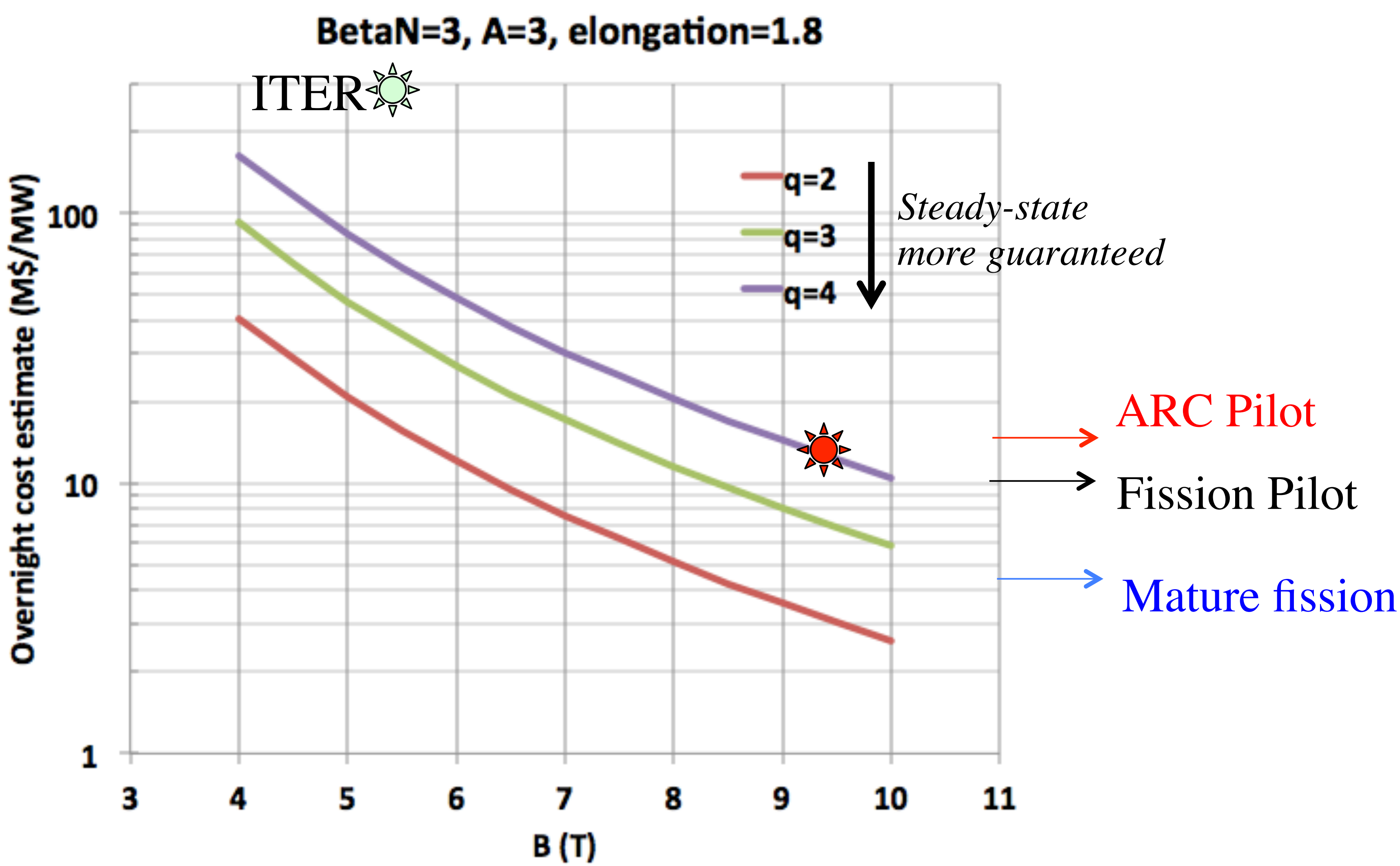
$$\boxed{p_{th}\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3}$$

$$\boxed{V \propto R^3 \propto \$}$$

Power density

$$\boxed{\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N{}^2 \epsilon^2}{q_*^2} R B^4}$$

"Smaller, sooner" fusion → Competitive fusion energy through high B + high power density

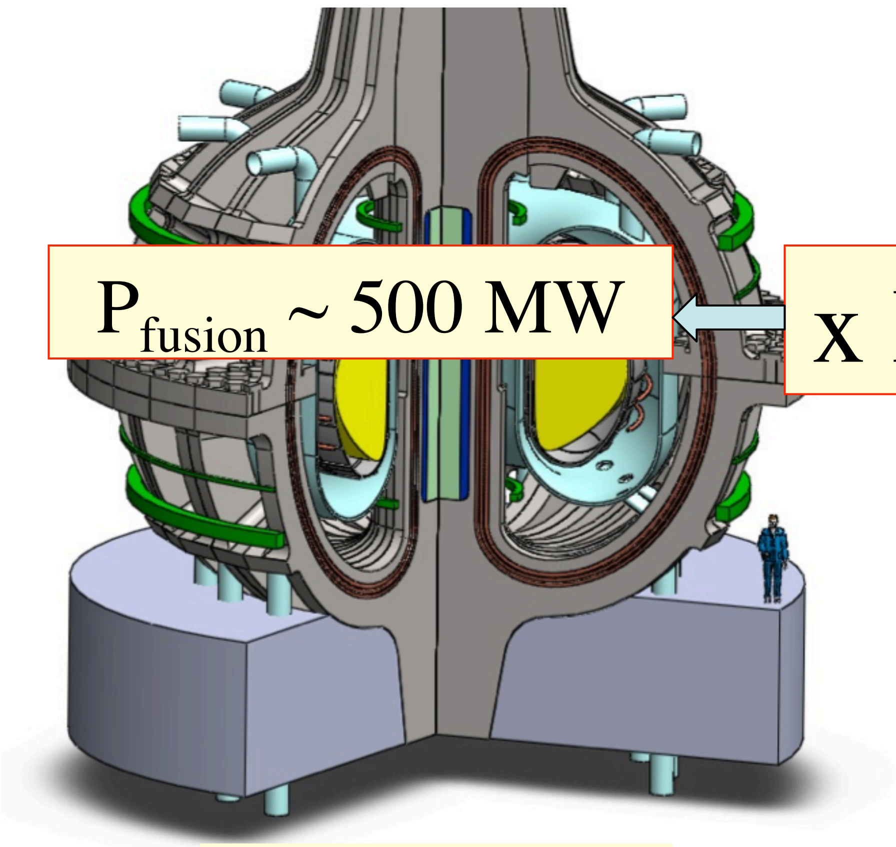


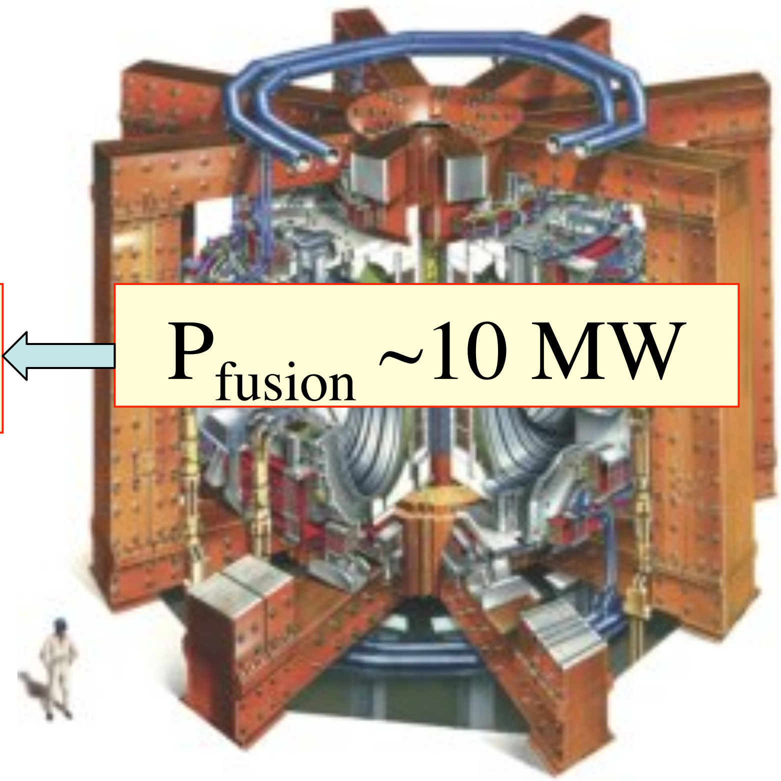
ARC conceptual design example of “smaller, sooner” fusion device using new technology

REBCO superconductor B_0 = 9.2 T

Peak Field on coil B ~ 23 T

Copper, B_0 = 3.5 T



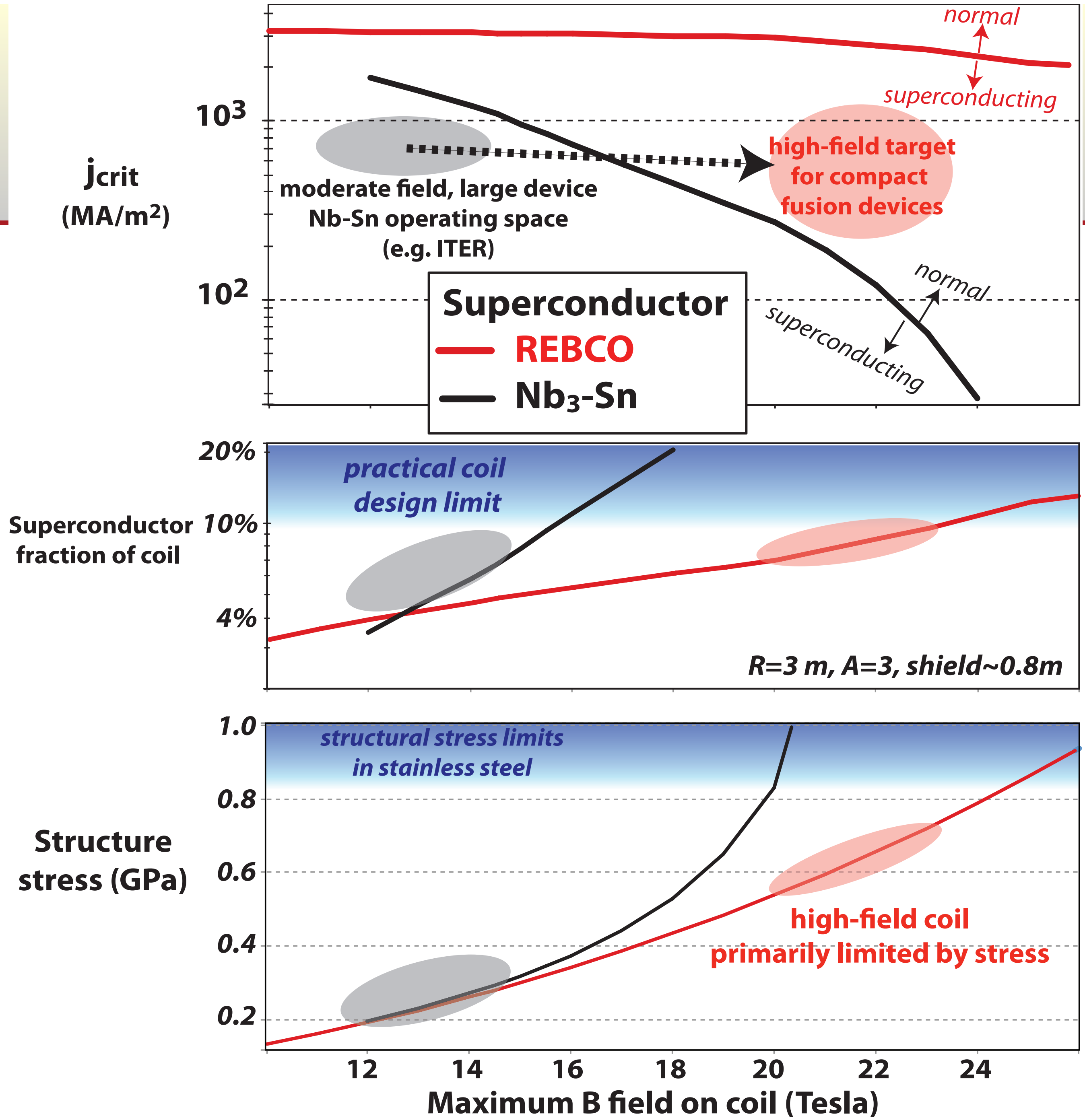


P_{fusion} ~ 500 MW ← x B^4 ← P_{fusion} ~10 MW

ARC: R ~ 3.2 m

JET: R ~ 3 m
~4 years construction

A revolution in superconductors in last 5 years: REBCO (Rare-Earth Barium Cu Oxide) remain superconducting at VERY high B-field and above liquid He temperatures



Multiple, linked engineering design challenges to smaller, modular path

Challenges

$B_{coil} > 20$ T

SC Joints

Demountable coils

Small radial build
neutronics

Internal components with
small space +
high power density

Multiple, linked engineering design challenges to smaller, modular path

Challenges

$B_{coil} > 20$ T

SC Joints

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Small radial build neutronics

Internal components with small space + high power density

Opportunities /w new technology

REBCO superconductors

REBCO: tape form

REBCO: T~ 25 K

Immersion liquid blanket

Additive manufacturing of single-unit VV/PFC with advanced cooling capability

Analytic assessment of magnet coil provides insight to limit in B field

jxB force

$$F_{jxB} = \int_a^b j_\theta \, B_z \, r \, d\theta \, dr \, dz$$

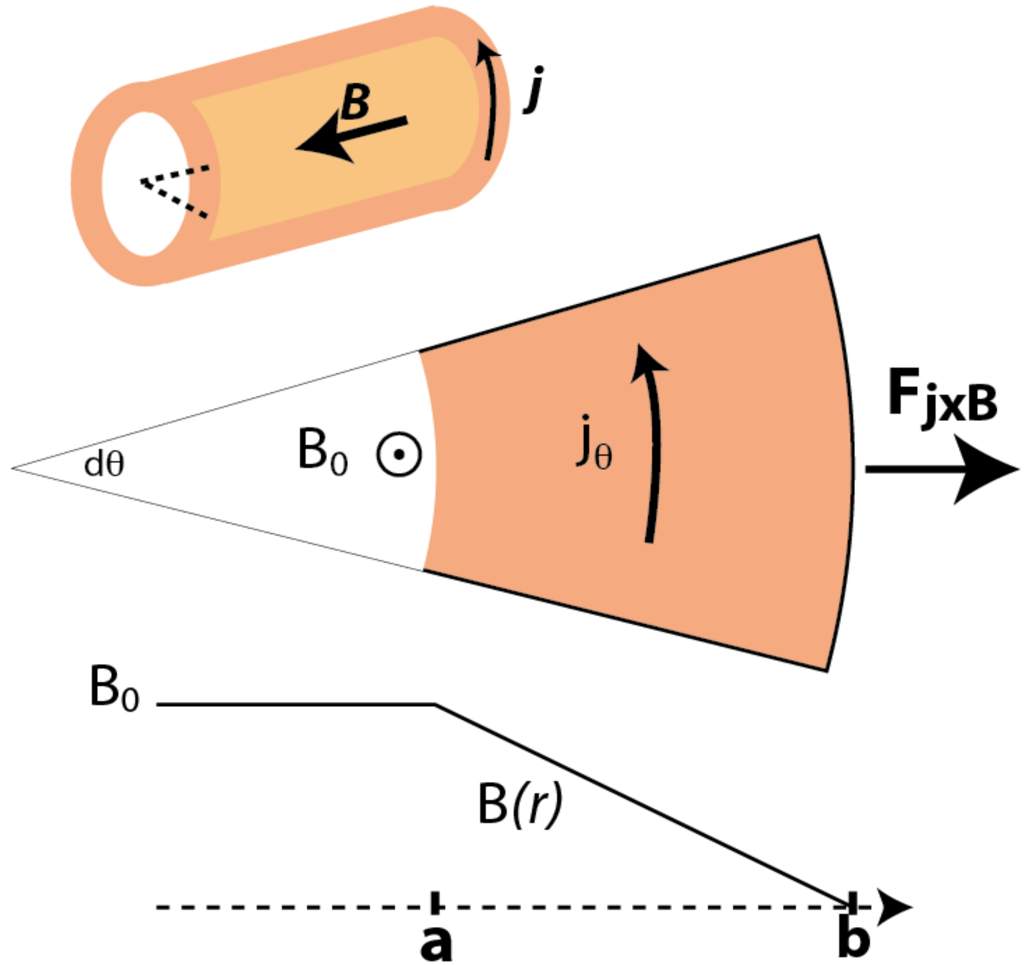
Amperes law /w uniform j

$$B_z(r) = \mu_0 \, j \, (b - r)$$

Outward force per segment

$$\frac{F_{jxB}}{d\theta \, dz} = j^2 \int_a^b (b-r) r \, dr$$

$$= \frac{B^2}{2\mu_0} \frac{2}{(b-a)^2} \int_a^b (b-r) r \, dr$$



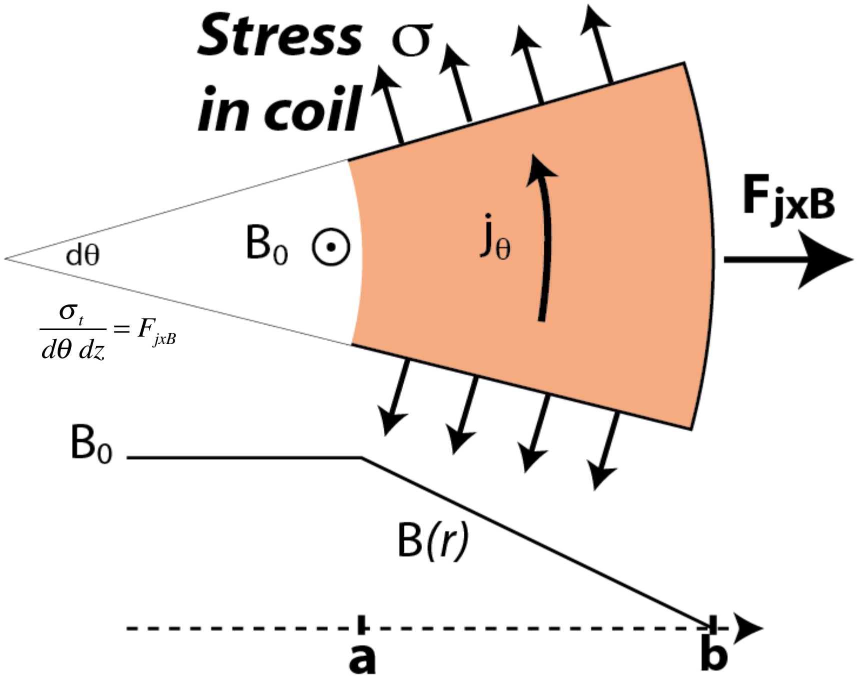
jxB forces must be taken by the stress in the coil, which has intrinsic limits

Tensile stress must balance jxB force

$$\int_a^b \sigma_t \sin\theta \, d\theta \, dr \, dz = F_{jxB}$$

$$\sigma_t = \frac{B^2}{2\mu_0} \frac{\int_a^b (b-r) r \; dr}{(b-a)^3}$$

$$\sigma_t = \frac{B^2}{2\mu_0} \left[\frac{2a+b}{3(b-a)} \right]$$



Fusion: want large bore for plasma
Coils: want small bore to reduce stress

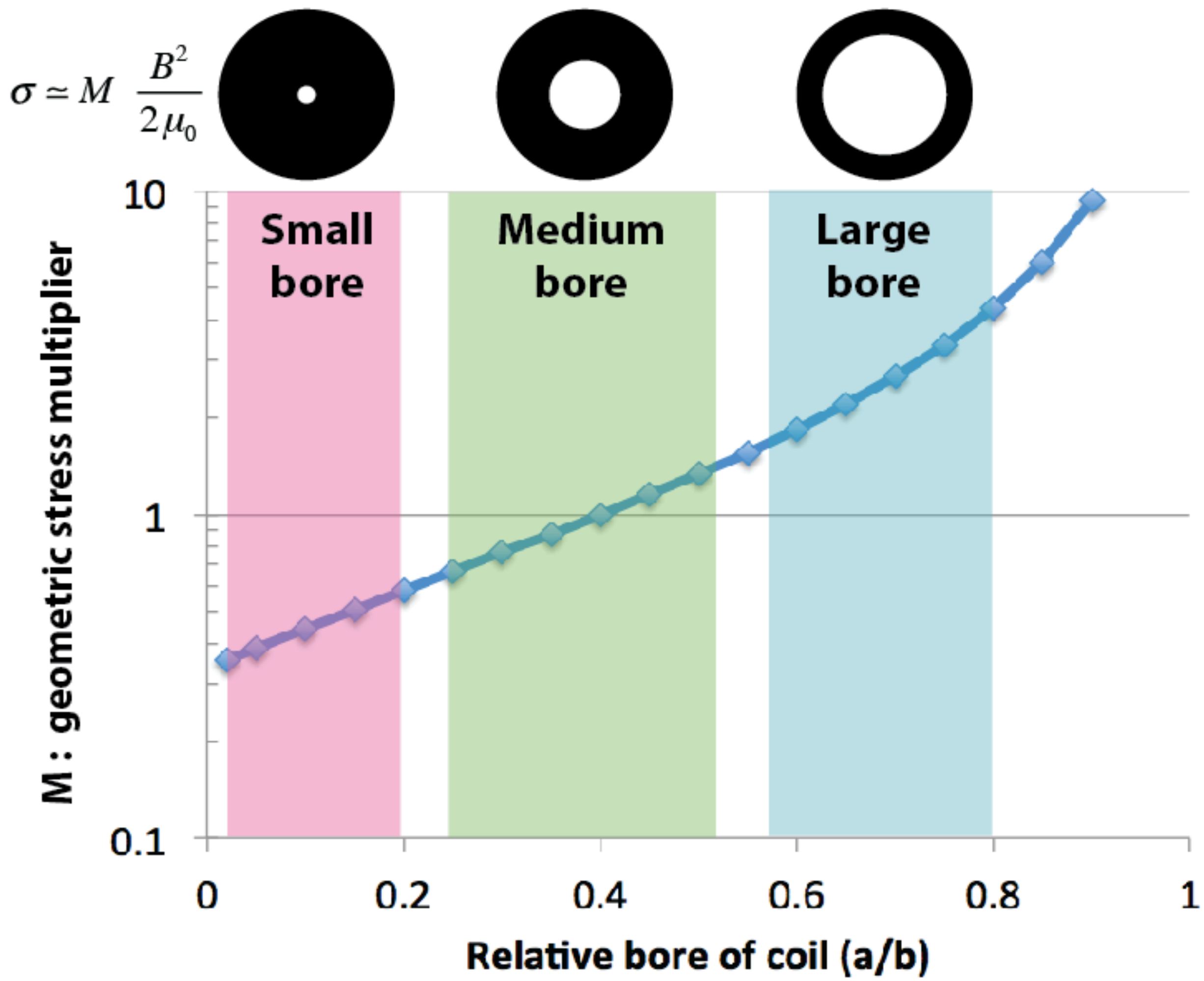
$$x \equiv \frac{a}{b}$$

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

B = 22.5 T →

$B^2/2\mu$ ~ 200 MPa

SS yield strength ~ 1000 MPa



Stress + Cooling eliminates copper for B > 20 T steady-state coils

Stress limit

B = 22.5 T

$B^2/2\mu \sim$ 200 MPa

$\sigma \sim 3 \times 200$ MPa

SS yield ~ 1100 MPa

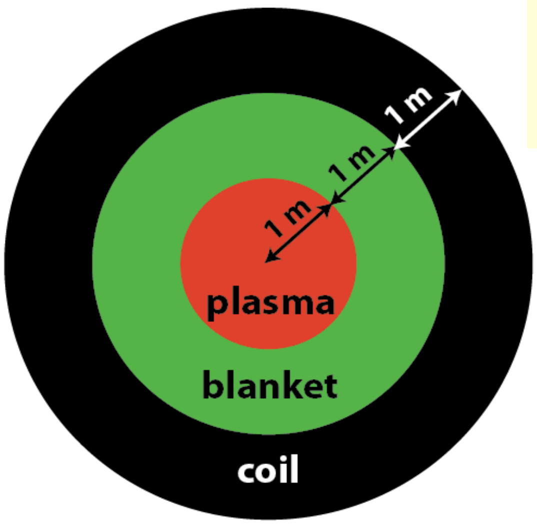
Copper cooling limit

B = 22.5 T

j ~ 18 MA/m^2

$\eta \sim 15$ nΩ m

$P_{cool} \sim 5$ MW/m^3



Superconductors eliminate cooling & $P_{electric}$ but are limited by critical current at high B (and still by the stress)

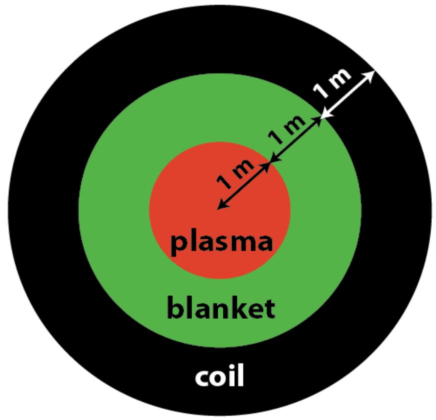
Stress limit

$B = 22.5$ T

$B^2/2\mu \sim 200$ MPa

$\sigma \sim 3 \times 200$ MPa

SS yield ~ 1100 MPa

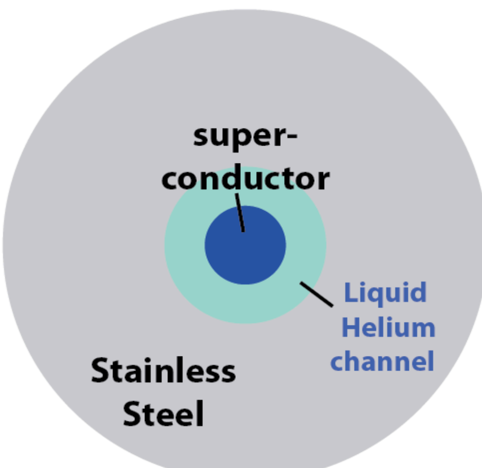


Cooling

$B = 22.5$ T

$j_{coil} \sim 18$ MA/m^2

$\eta = 0$



$B = 22.5$ T

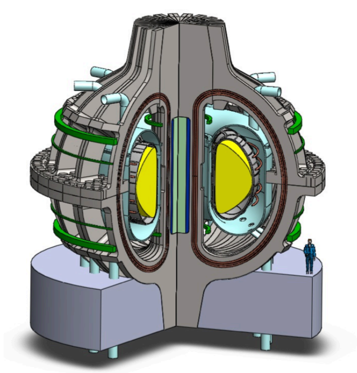
$j_{Superconductor} \sim 10 \times j_{coil} > 200$ MA/m^2

$j_{critical}$ @ 22.5 T < 100 MA/m^2

High-field, high-temperature demountable B coils would lead to much smaller options for MFE

Modest size
Modular replacement

Fusion power: 500 MW
Electrical power: 200 MW

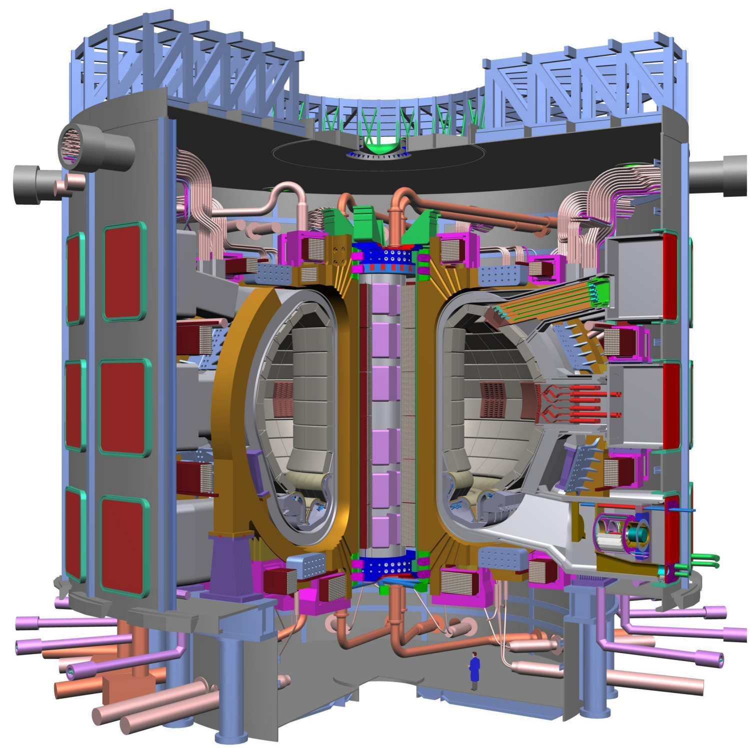


Same Science!

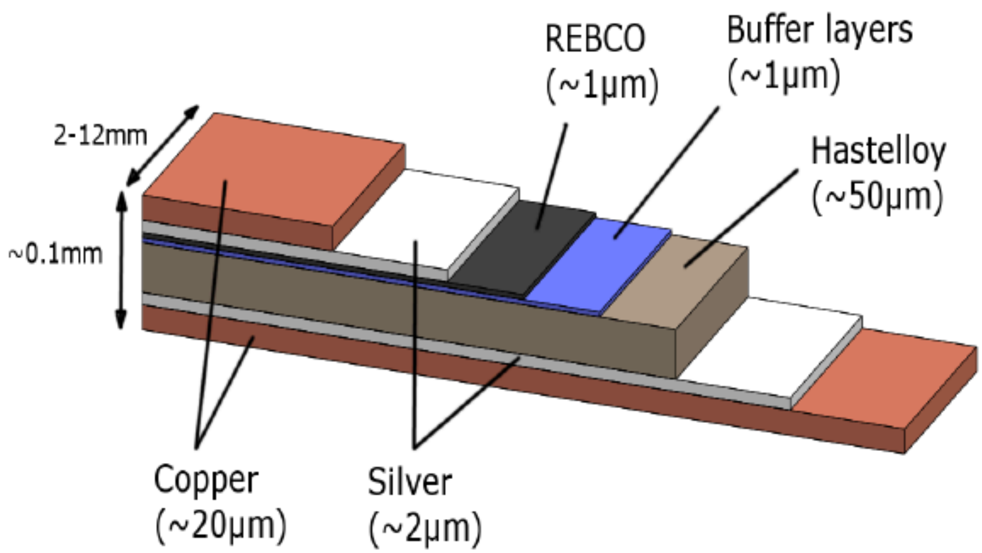
$$\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N^{2}\epsilon^{2}}{q_*^{2}} R B^4$$

Large size
Sector replacement

Fusion power: 500 MW

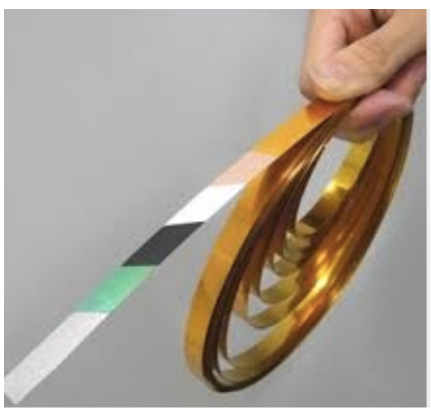


REBCO: coated superconductors in robust tape form, commercially available

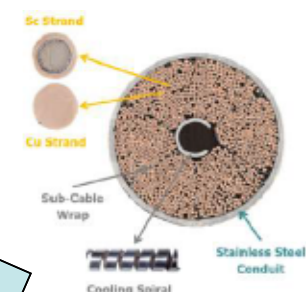


REBCO tape composition

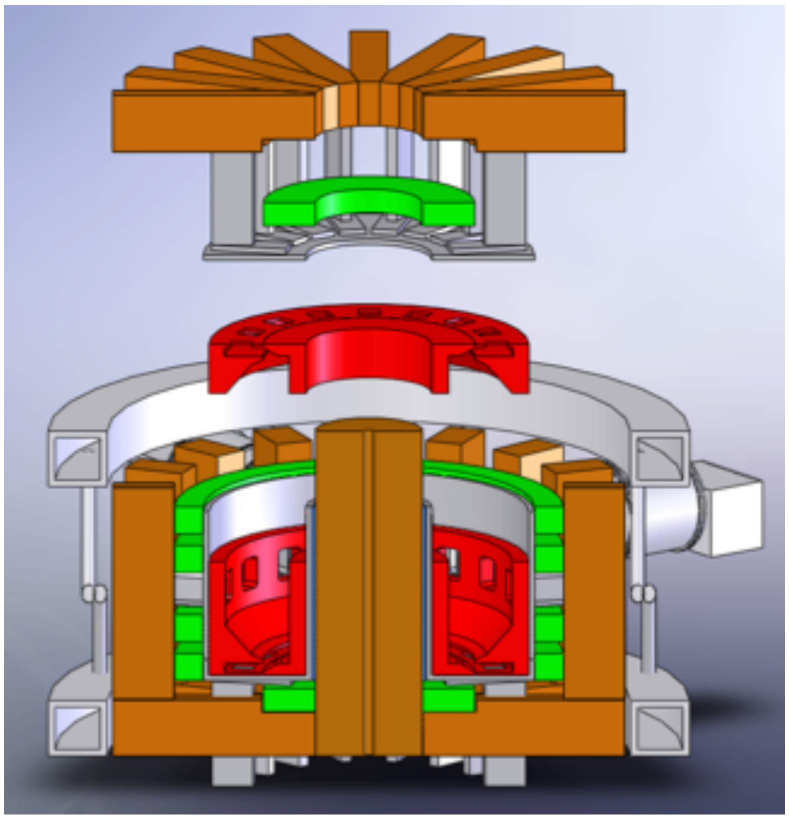
(not to scale)

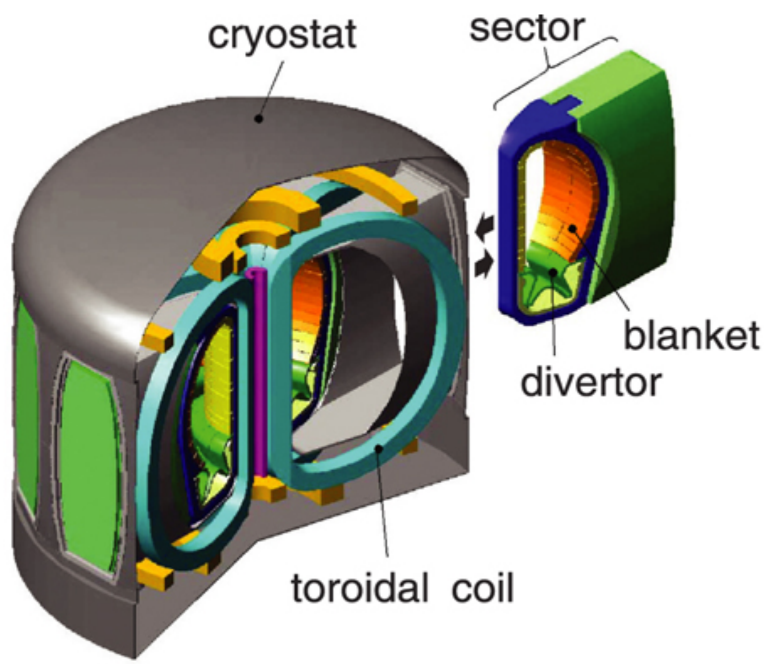


- Strong in tension due to steel
- Flexible
- Outer Cu coating → simple solder low-resistance joint
- Stark contrast with NbSn superconductor strand & CIC!



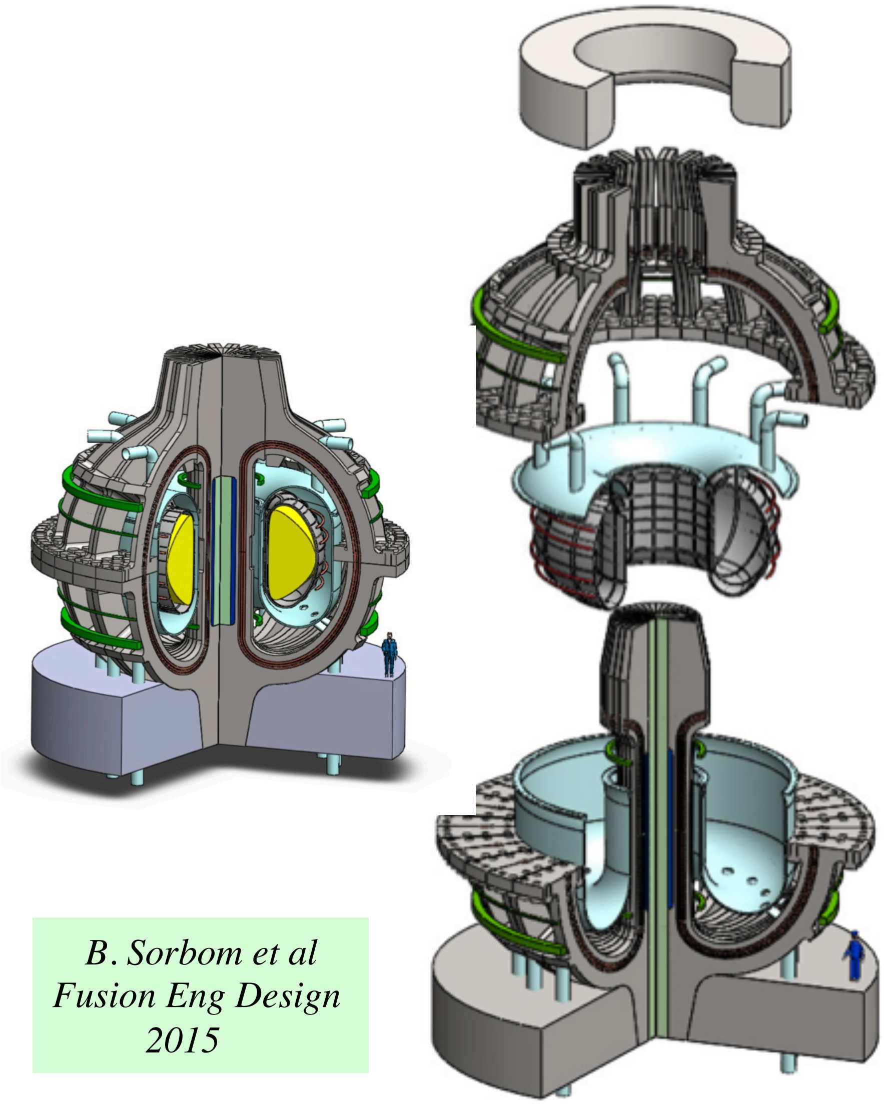
Basic geometry favors demountable magnets to provide modularity for internal components





FNSF-AT V. Chan et al NF 2011

ARC conceptual design example of "smaller, sooner" modular fusion electricity pilot plant using newly available superconductors



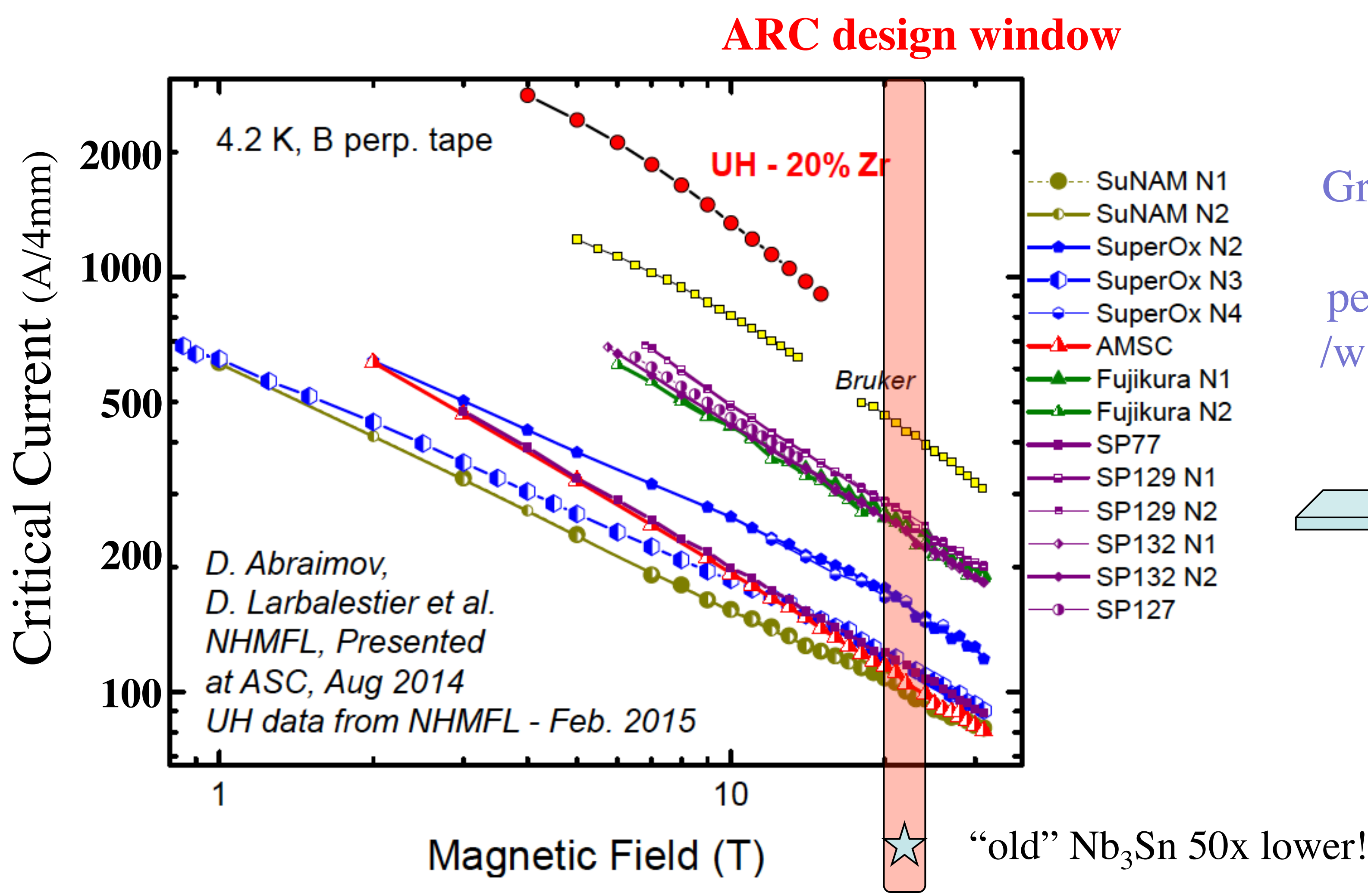
Affordable Robust Compact

- Demountable magnetic field coils
- Single-unit vertical lift
- Net electricity ~ 200-250 MW

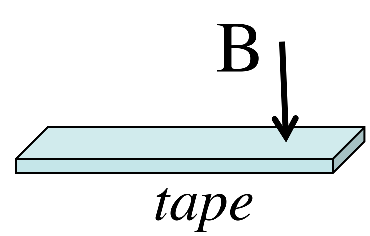
B. Sorbom et al
Fusion Eng Design
2015

Small, modular design features generically attractive to your favorite MFE choice: ST, stellarator, etc.

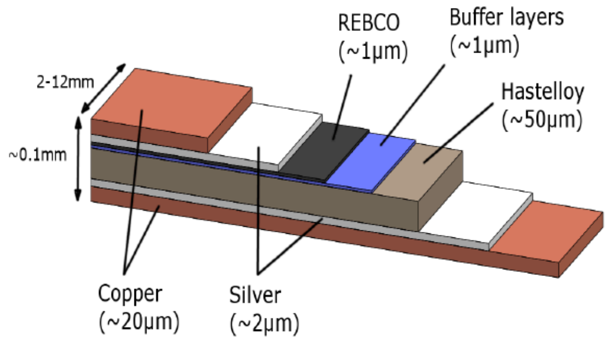
REBCO superconductor performance for high-field applications has remarkably increased over the last few years

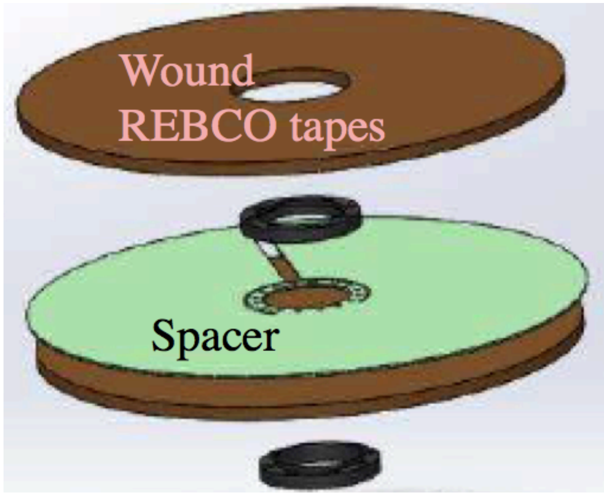


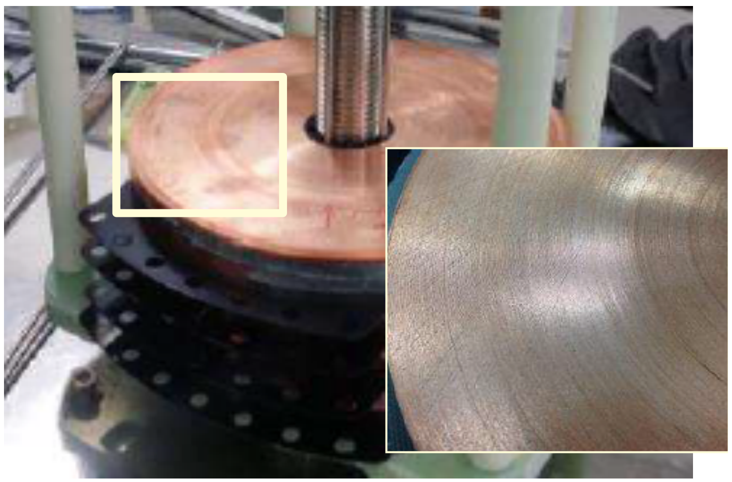
Graph shows **worst** performance /w B ⊥ tape!



Making coils from REBCO:
"No-insulator" tape winding highly attractive







S. Hahn et al. App Phys Lett 173511 (2013)

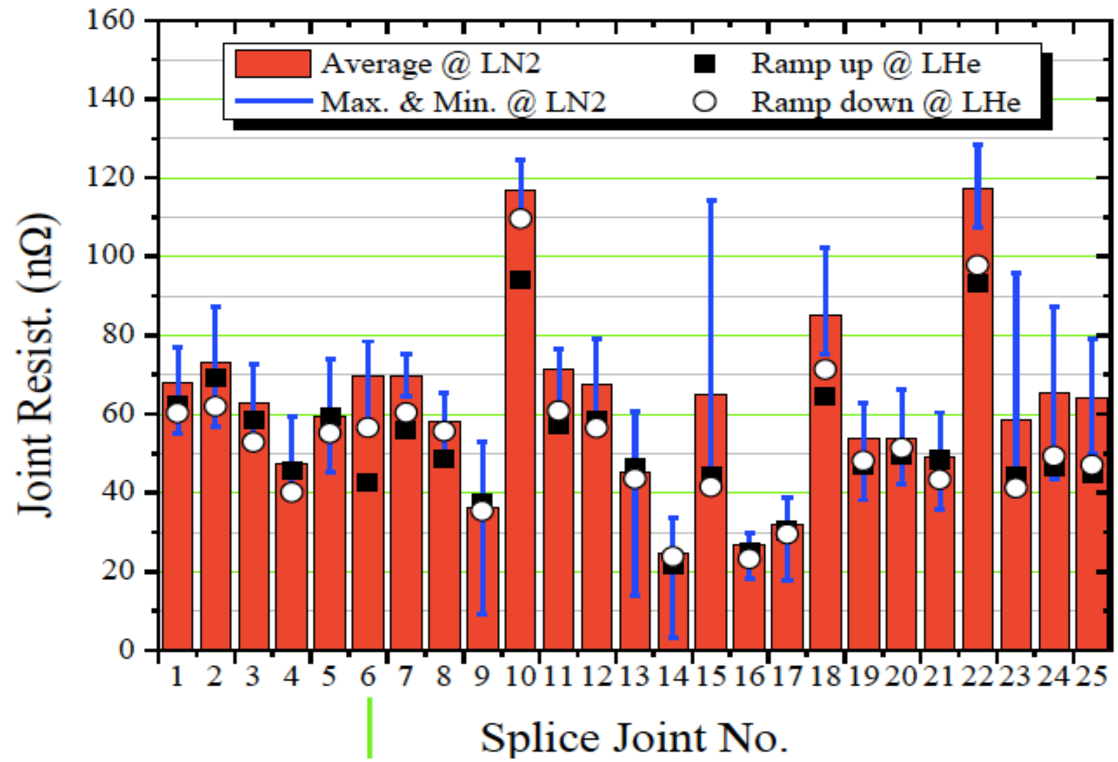
- Steel is "internal" insulator for each turn

- Benefits
  - ➢ Simple
  - ➢ Improved mechanical strength
  - ➢ Radiation resistance (insulators weakest link)
  - ➢ Self-protecting in quenches

Large coils made with REBCO actually *require* joints: Contact resistance at low-T is acceptable

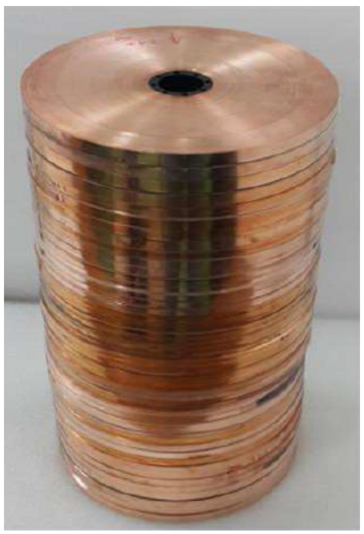
26 stacked coils

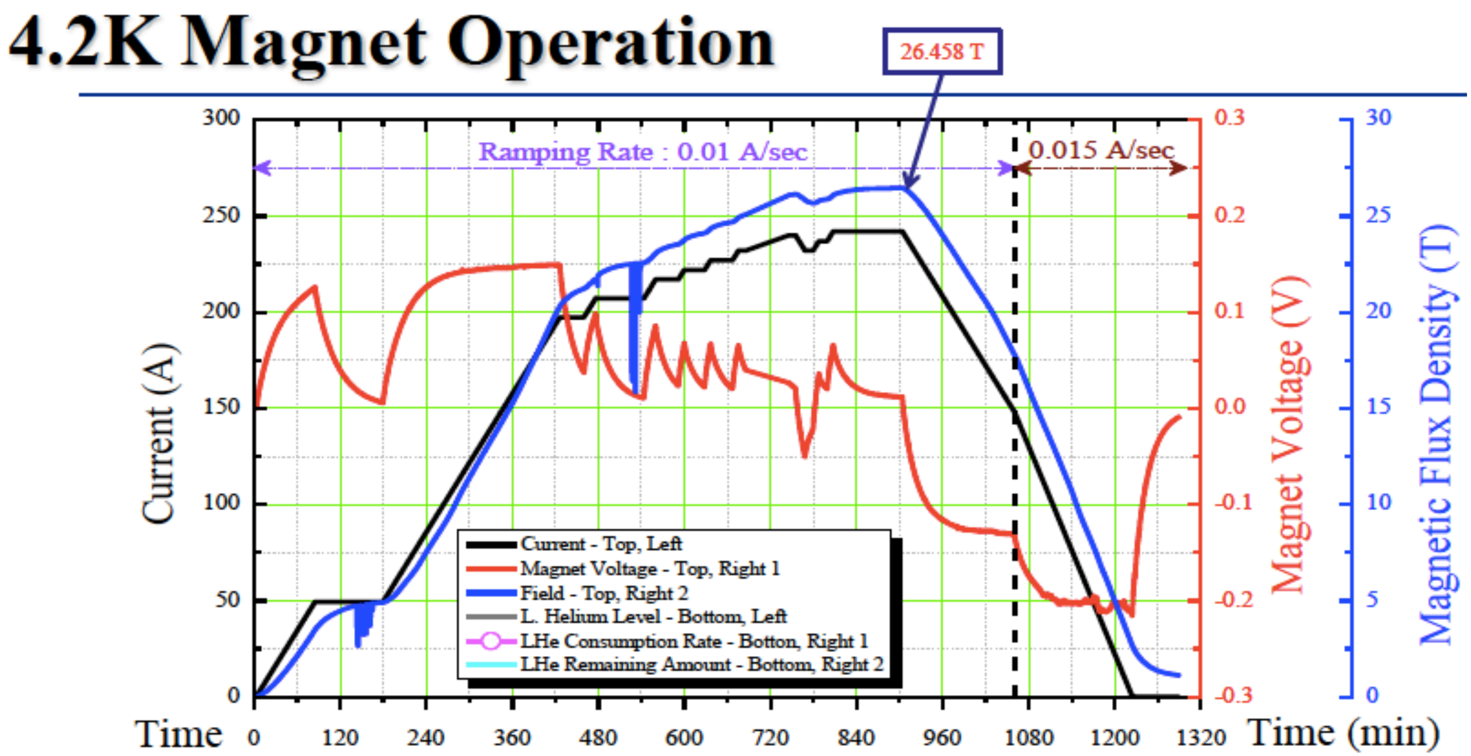
~300 m/coil consistent with maximum continuous length of high-performance tape



- Soldered joints!
- Mechanical attachment lowers resistance

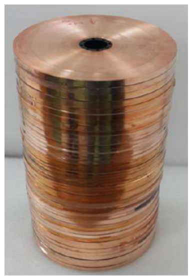
2015: New record of 26.5 Tesla with REBCO-only, “no-insulation” coil

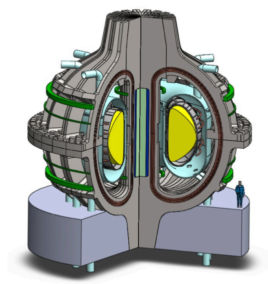




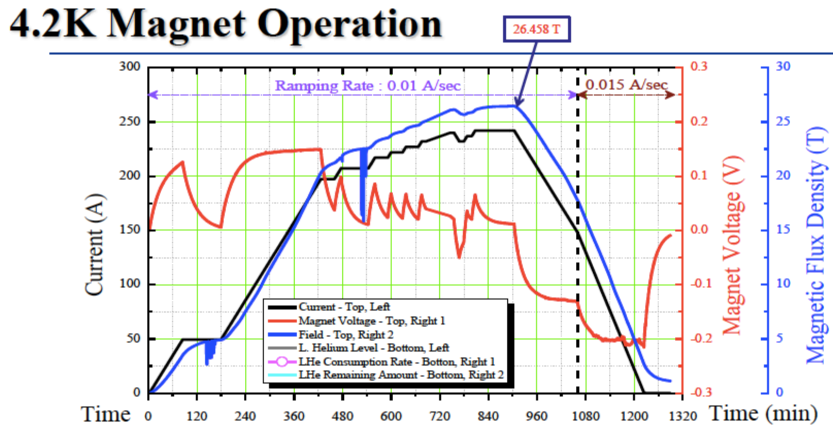
S. Yoon, J. Kim, H. Lee, S. Han, S-H.Moon “26 T 35 mm all-$GdBa_2Cu_3O_{7-x}$ multi-width no-insulation superconducting magnet” Supercond. Sci. Technol. 2016

Small REBCO coil for NMR science matches most local requirements for ARC design

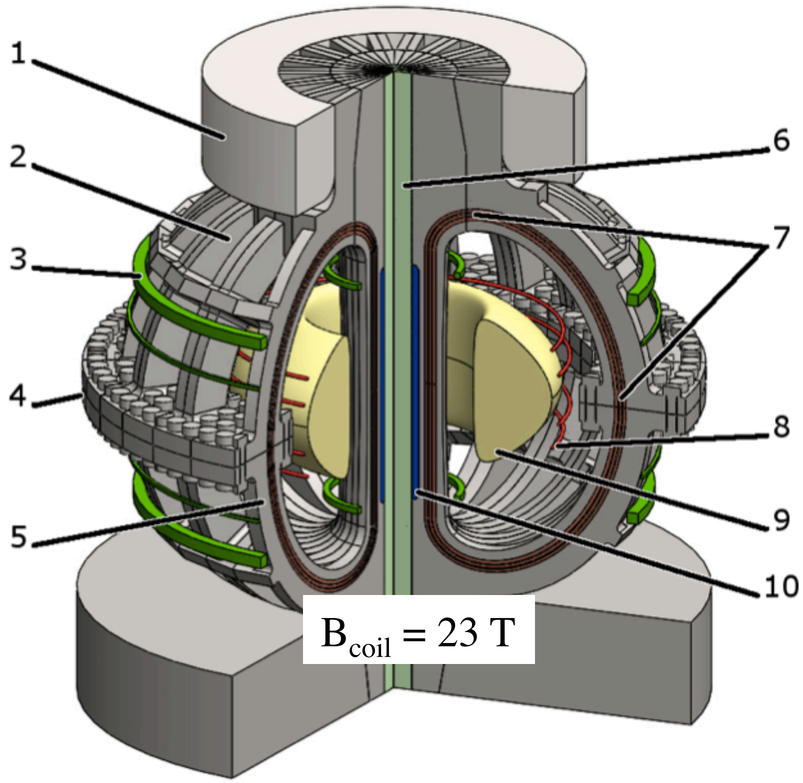




B_{coil}(T)	26.5	23
J_e (A/mm^2)	400	400-500
T (K)	4.2	25
Materials	REBCO, SS316L	
σ_{max} (MPa)	593	660
Diameter (m)	0.03	~ 6

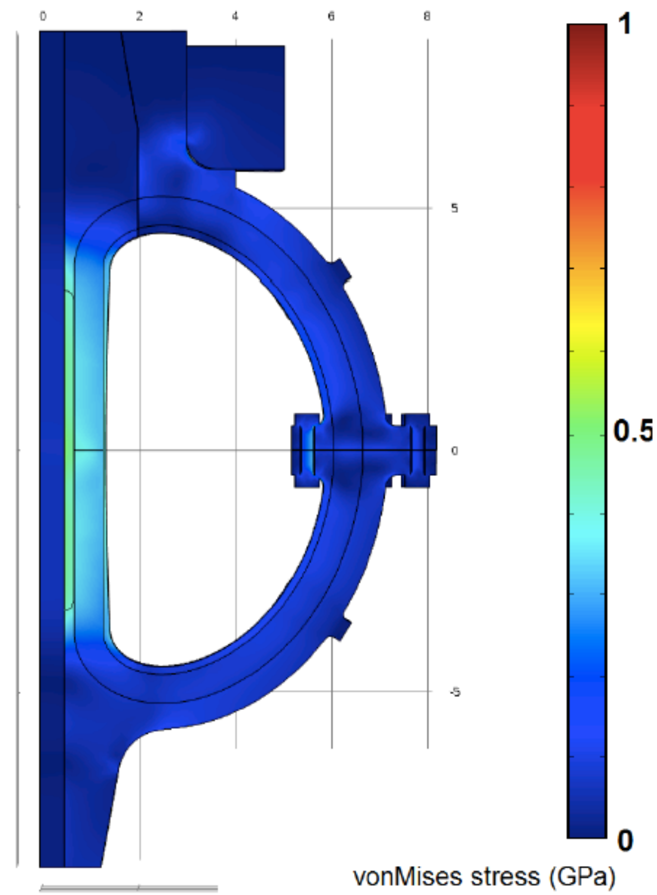


Large-bore challenge for high-B MFE magnet: requires optimized geometry & superstructure



1. Support ring, 2. Top TF leg
4. Mechanical joint
6. Epoxy enforcement

Peak stress ~ 0.67 Gpa
~65% of limit for 316SS LN

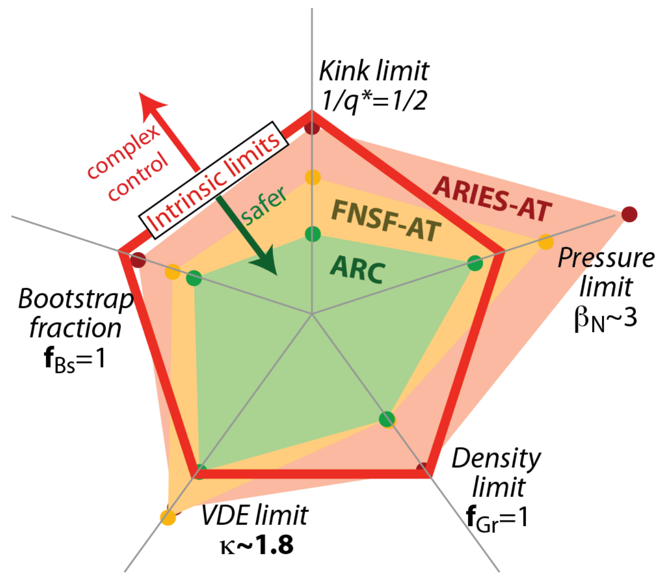


New technologies provide access to synergistic design advantages at high-B and small size: Robust steady-state far from disruptive limits

	DIII-D	ARIES-AT	ARC
q_{95}	6.3	3	7 .2
H_{98}	1.5	1.7	1.7
β_N	3.7	5.4	2.6
$G = \beta_N H_{98}/q^2$	0.14	0.90	0.09
$f_{bootstrap}$	0.65	0.91	0.63
$n / n_{Greenwald}$	0.5	0.9	0.65

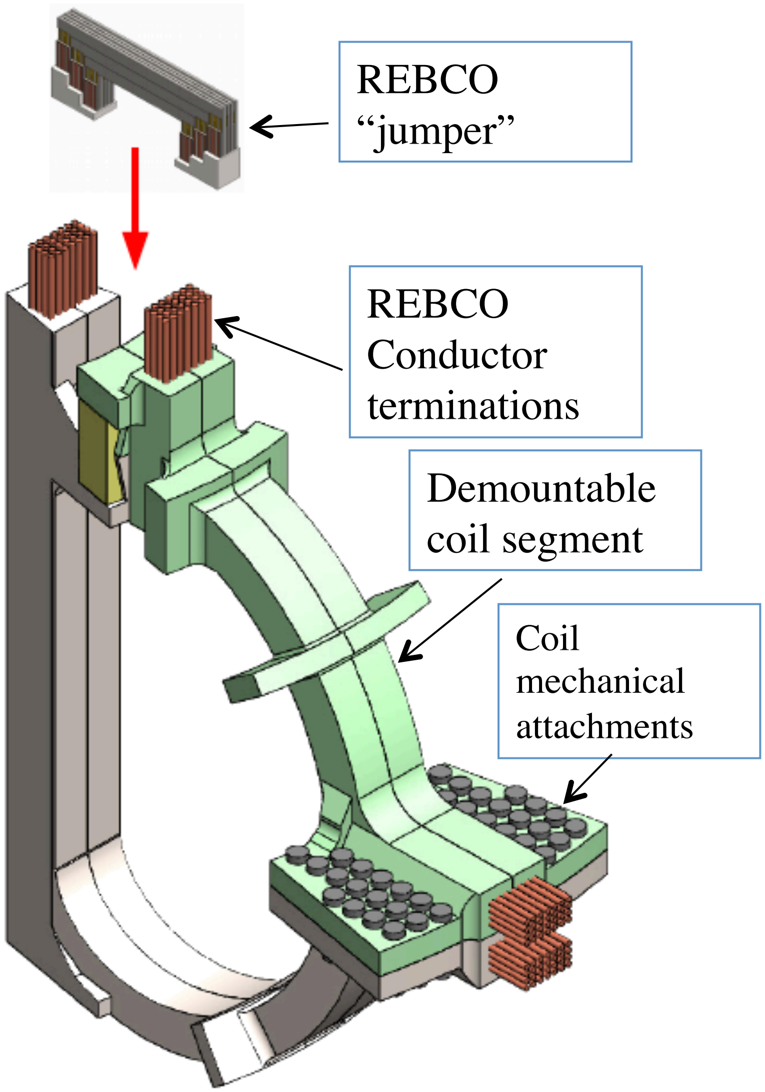
$$\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N{}^2 \epsilon^2}{q_*^2} R B^4$$

$$nT\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$



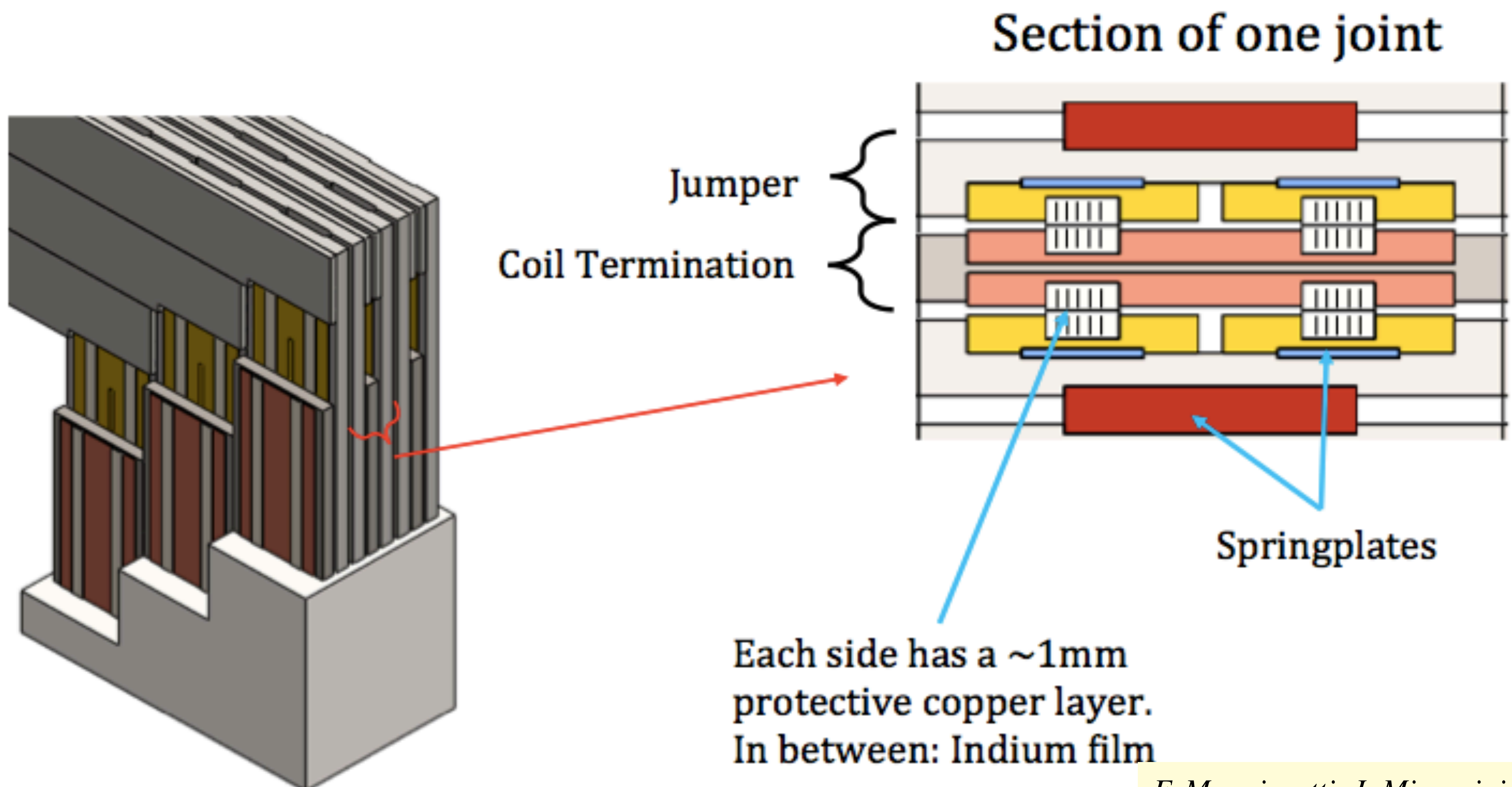
- **Steady-state scenario using high safety-factor, moderate Beta approach**
- **Scenario ACHIEVED in present moderate-B devices (e.g. DIII-D)**

Demountable TF coil: Evolving strategy → Separation of mechanical and electrical joints



F. Mangiorotti, MIT Ph.D. thesis

One design example: Plate terminations with edge joints



F. Mangiorotti, J. Minervini
MIT Ph.D. thesis

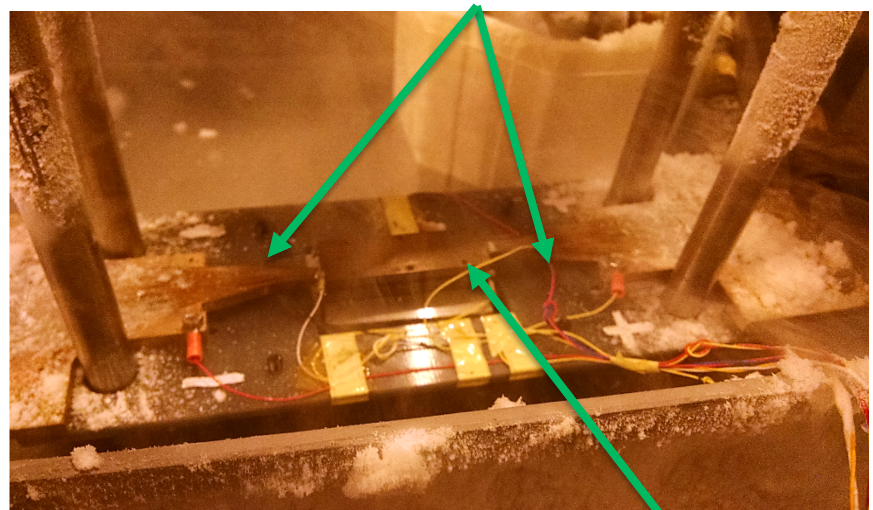
REBCO joint experiment:
80 tape, 3 kA cable ←→ 3kA cable

F. Mangiarotti (MIT) Ph.D. thesis

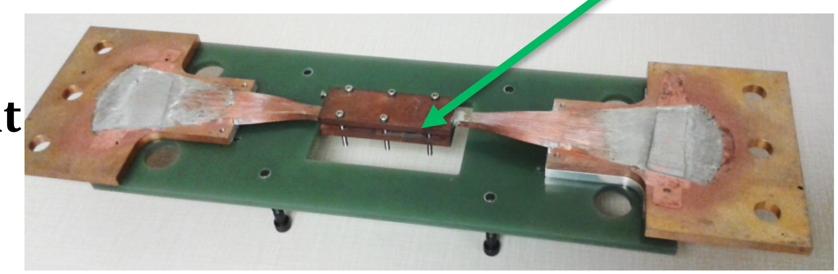
Load cell

Current leads

Voltage taps

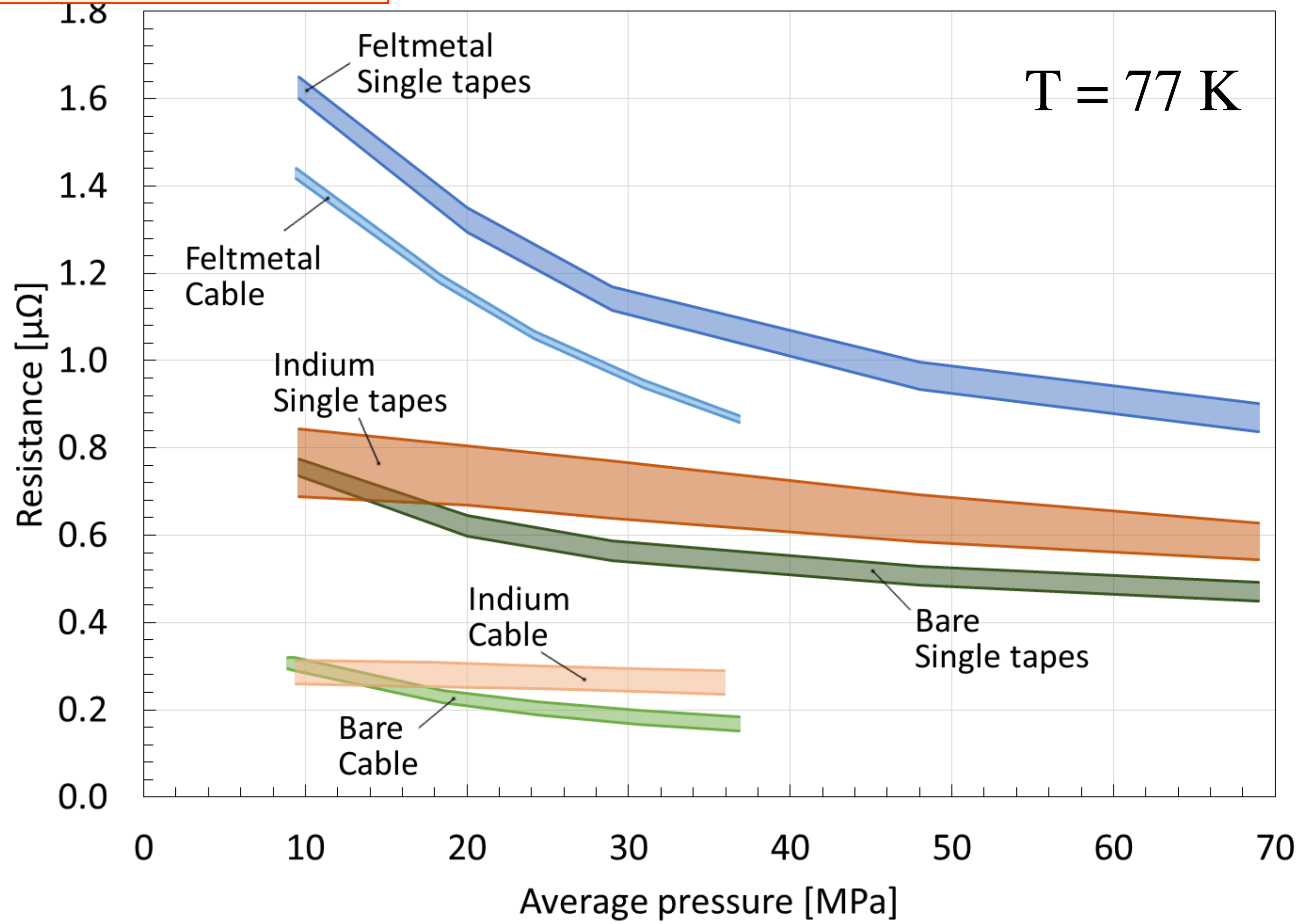


Joint samples



Acceptable resistance found in 80 tape cable-to-cable joint

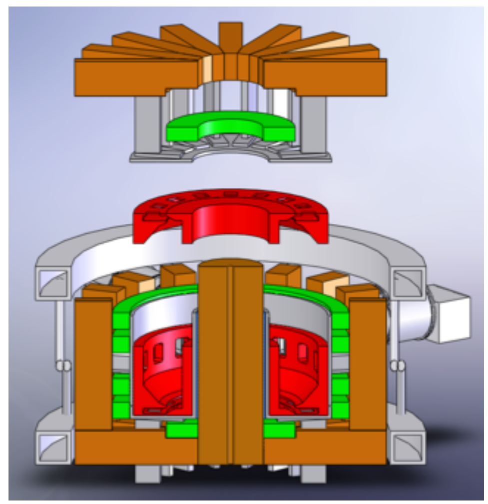
F. Mangiarotti (MIT) Ph.D. thesis



Operation of joints above 4 K liquid He temperatures is highly advantageous

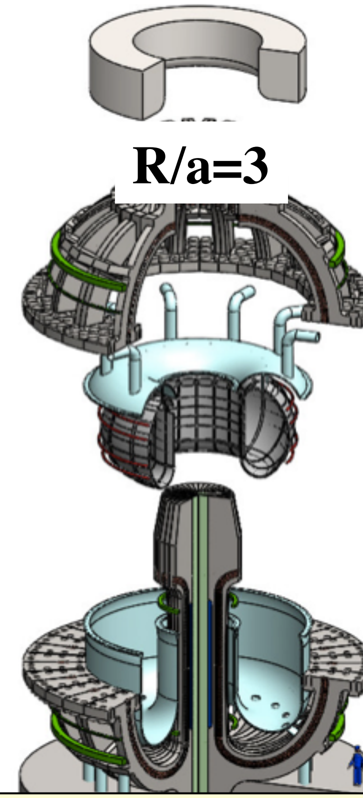
- Greatly reduces required cooling power (Carnot).
- Thermal stability due to higher heat capacity.
- Operation or ARC at T~25 K
  - Small power to joints
  - Liquid H or Ne for cooling options

R/a=3.5



Copper FNSF-AT
Coil P_{coil}~500 MW

R/a=3



ARC: Resistive joints /w REBCO superconductors
Coil P_{coil}~ 1 MW

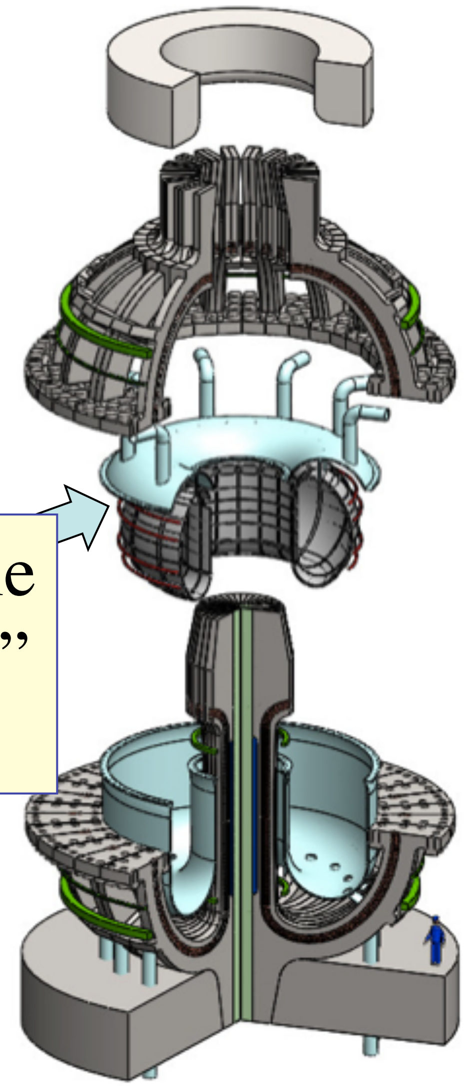
Demountable coils have a profound effect on modularity and design of interior fusion "core"

- Core is designed as a single integrated unit
  - Synergy with keeping design of small total mass and volume

- **Fabrication + qualification done completely off-site**
  - **Vacuum**
  - **Heating**
  - **Cooling**

- No connections made inside reactor volume!

Replaceable solid "core" module



Demountable coils have a profound effect on modularity and design of interior fusion "core"

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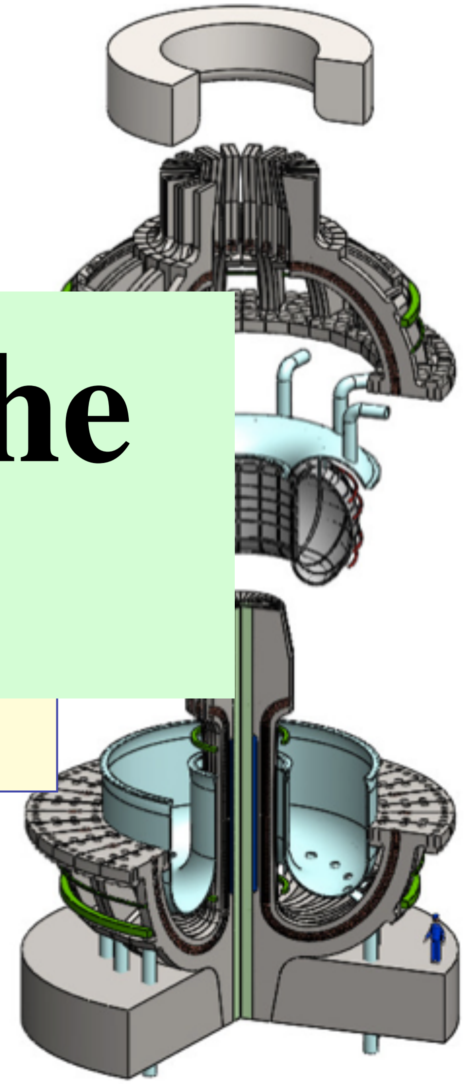
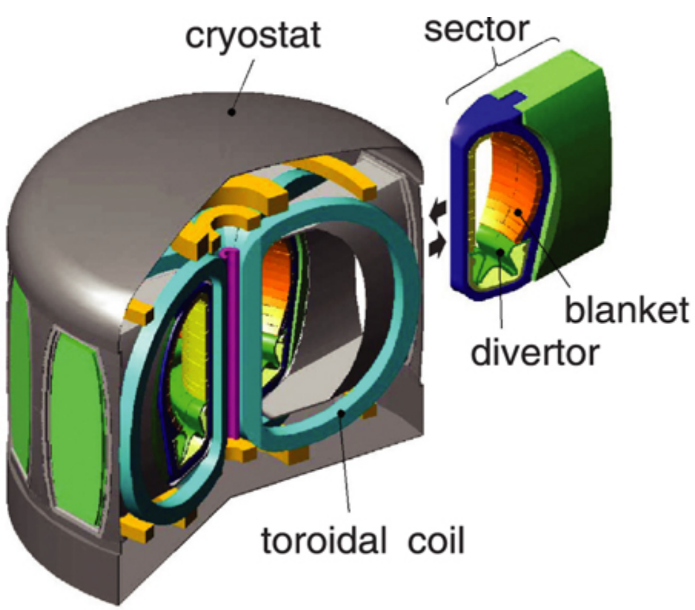
  - Synergy with keeping design of small total mass and volume
- **Fabricati** **done com**
  - **Vacuu**
  - **Heatin**
  - **Cooling**
- No connections made inside reactor volume!

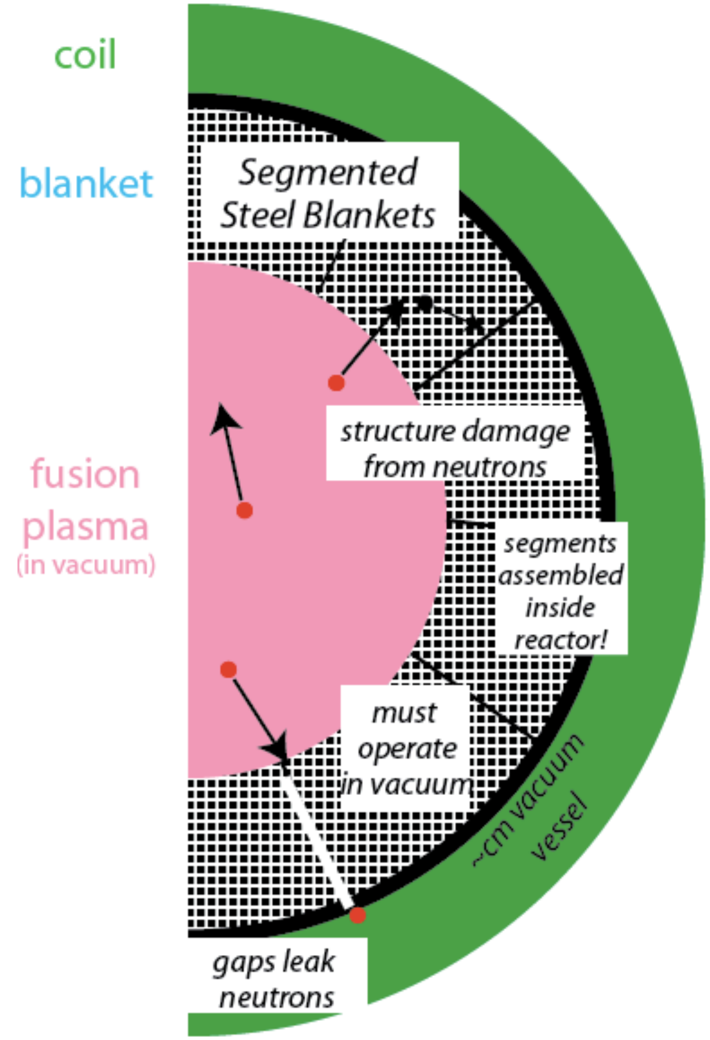
module

But where's the blanket?



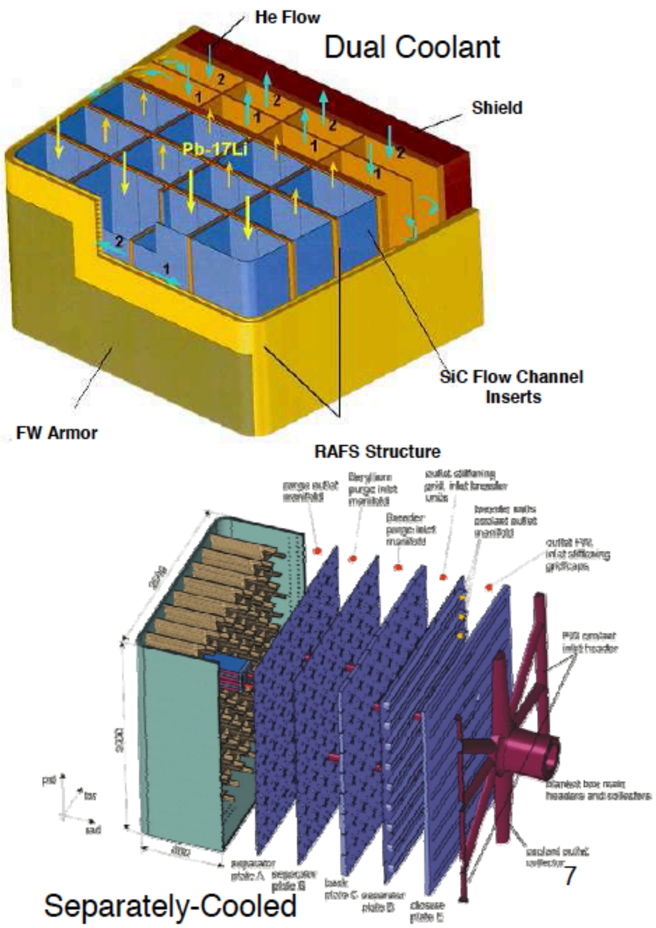
Standard fusion blankets are a daunting nuclear technology challenge: sector insertion/removal, severe D-T neutron damage, must work in vacuum

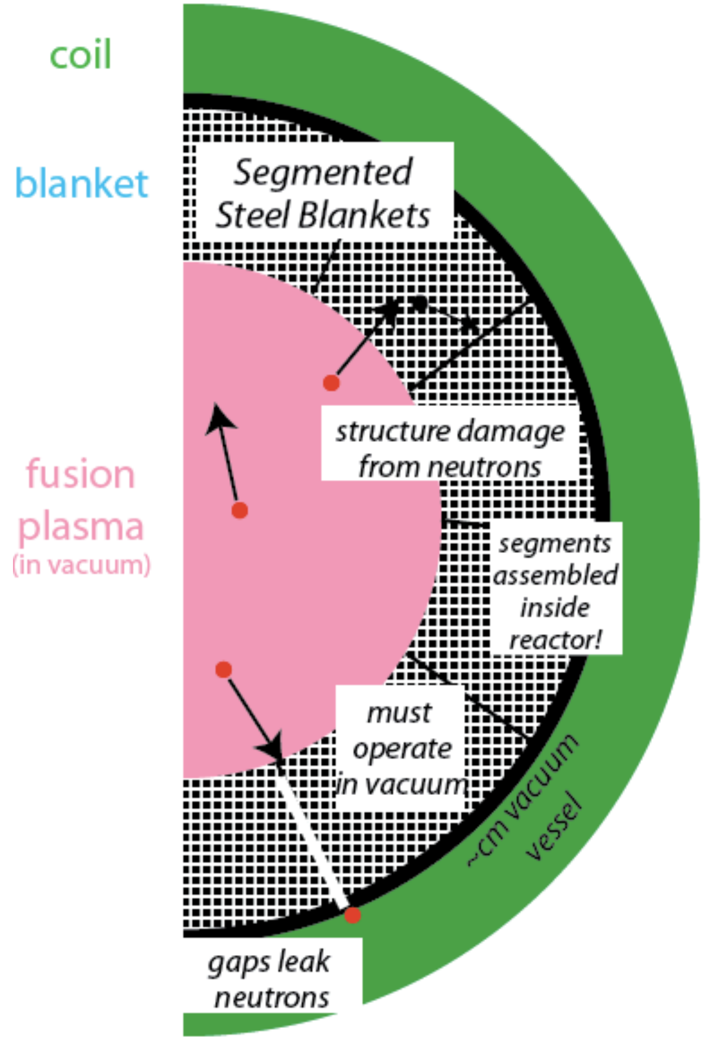




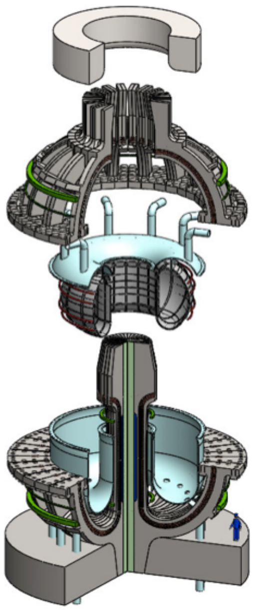
Standard fusion blankets are a daunting nuclear technology challenge: sector insertion/removal, severe D-T neutron damage, must work in vacuum

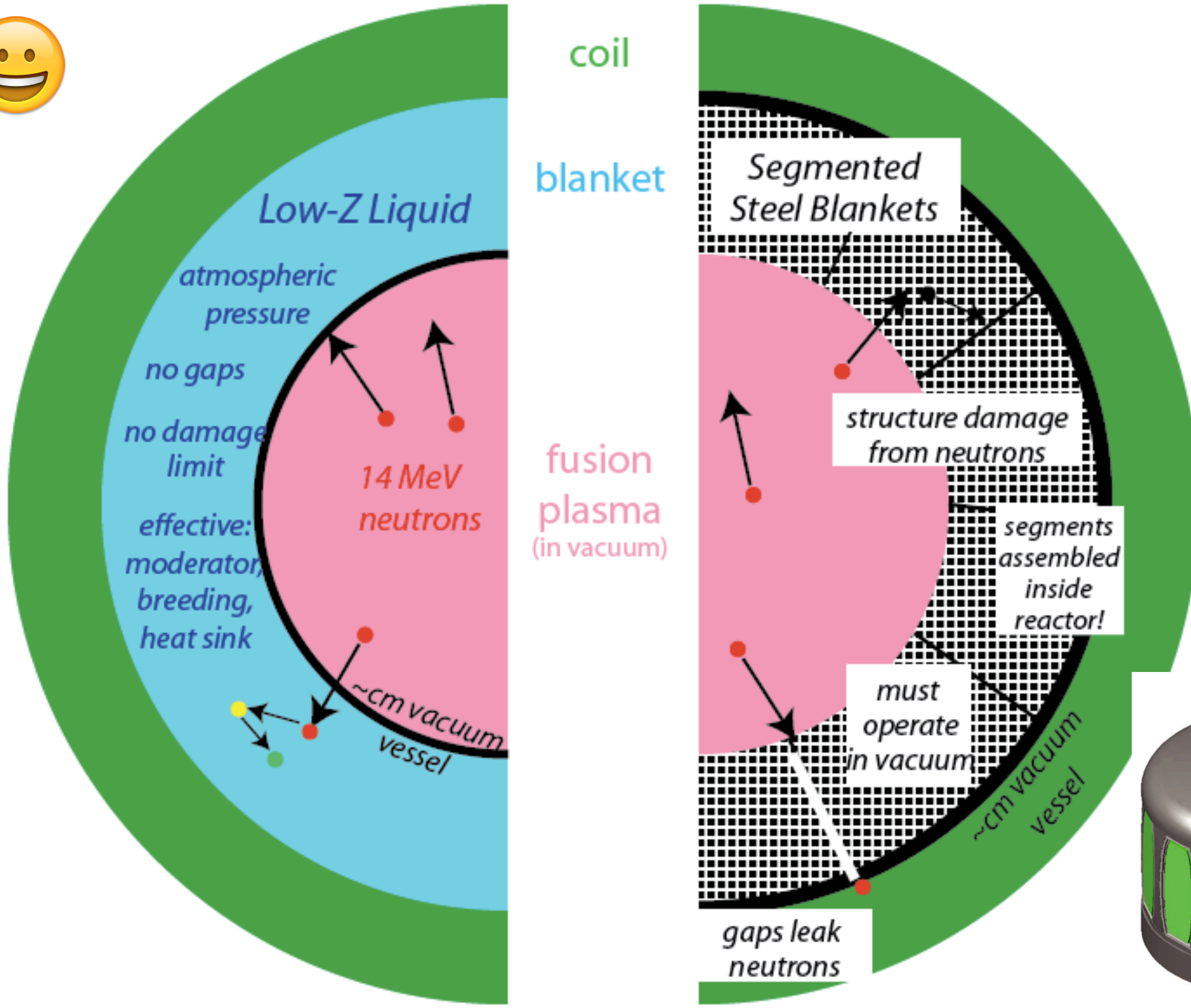
Complex!

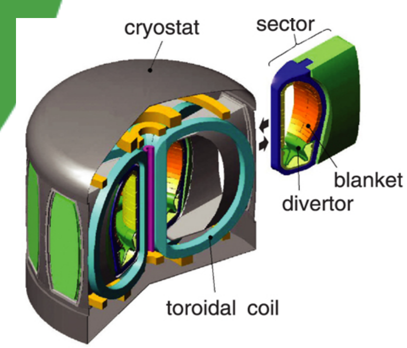




Demountable coils allow for much more robust and attractive nuclear technology for D-T neutrons: The Immersion Blanket





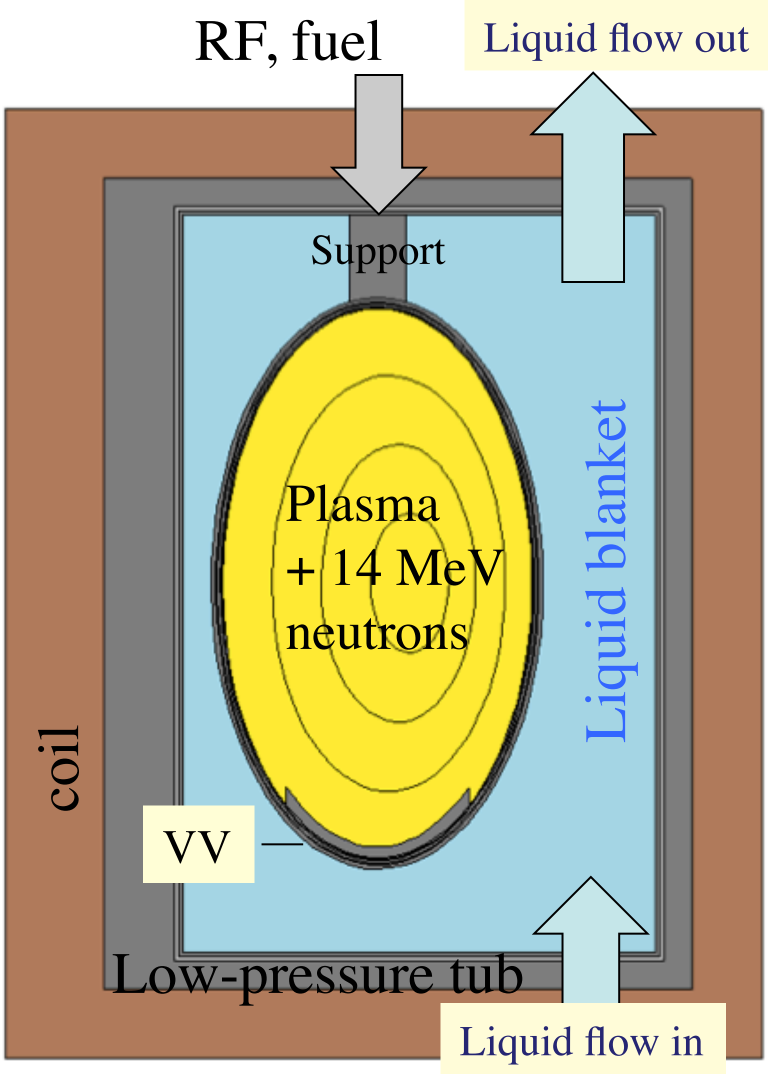


Demountable coils allow for much more robust and attractive nuclear technology for D-T neutrons: The Immersion Blanket

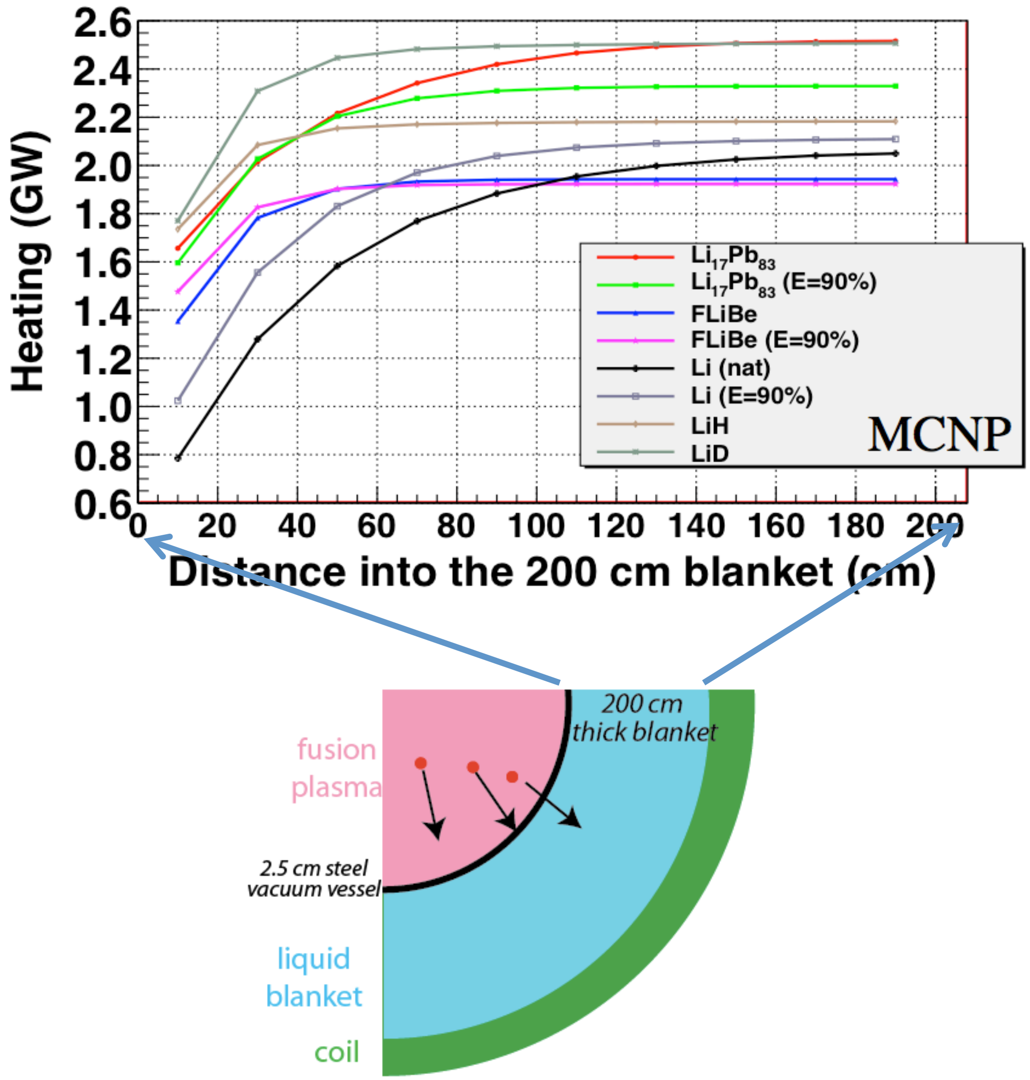
- **Replaceable Vacuum Vessel is immersed in liquid blanket:**

Advantages

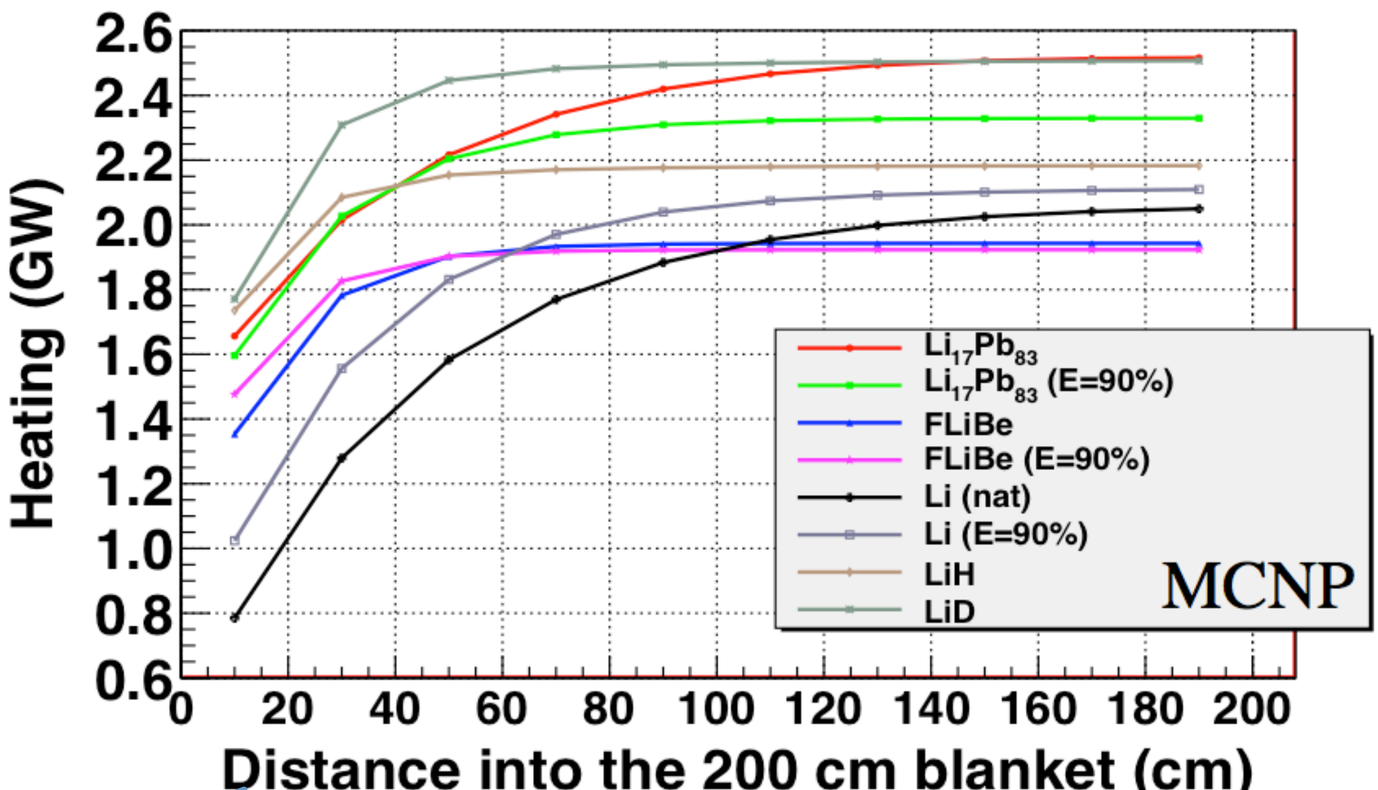
- **Simple**
- **Neutronics/nuclear engineering at atmospheric pressure.**
- **No gaps**
- **Energy & tritium extraction with single-phase low-velocity flow**
- **No damage limits in blanket**
- **Minimized solid waste**
- **Tub is robust safety boundary**

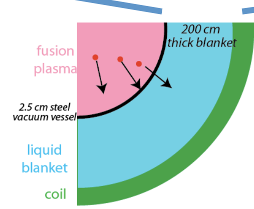


“Ideal” immersion fusion blanket explored



Immersion blanket: Many liquid choices & lack of internal structure optimizes neutron thermalization, energy capture and tritium breeding → Small radial build





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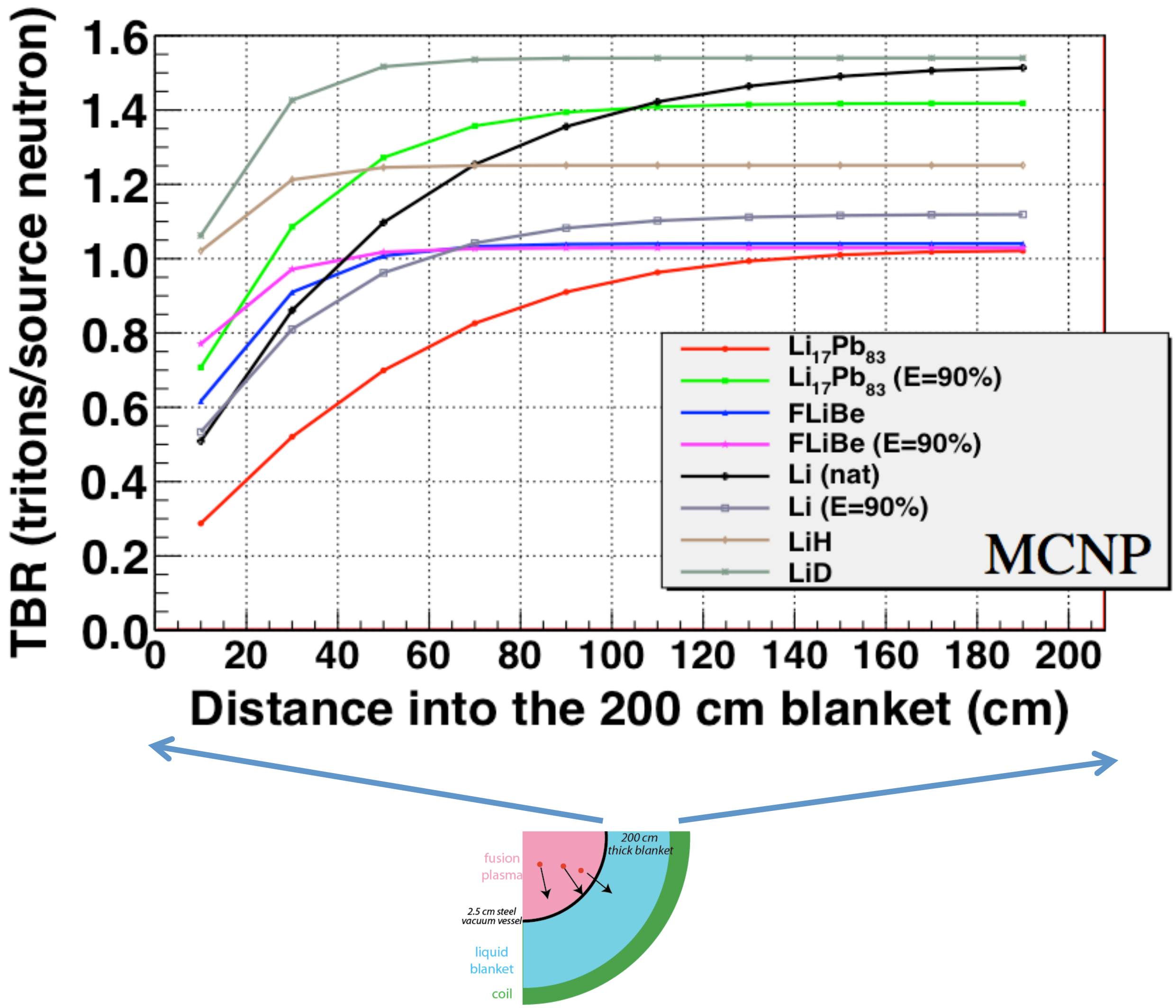
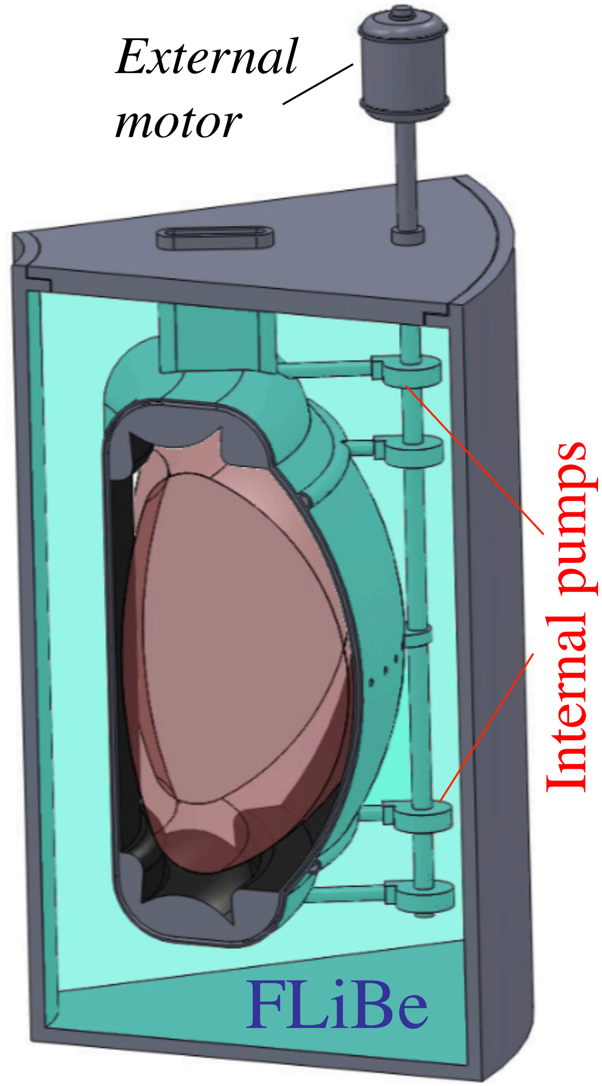


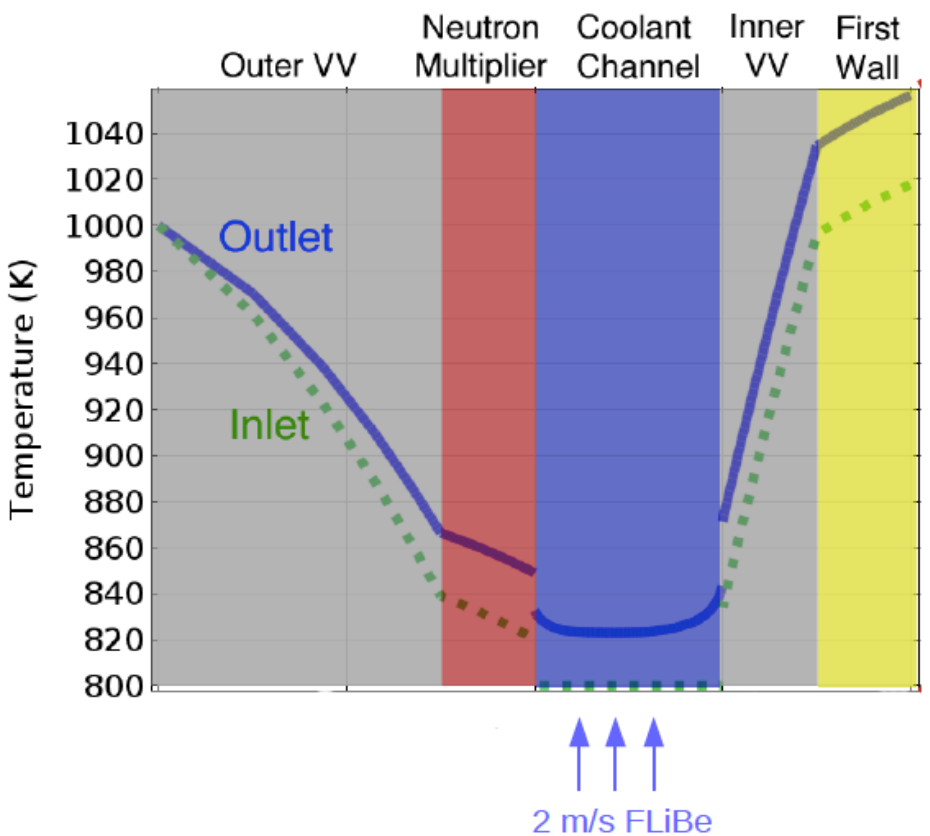
Immersion blanket: high-T molten salt FLiBe Single-phase, low-pressure flow with minimum MHD effects

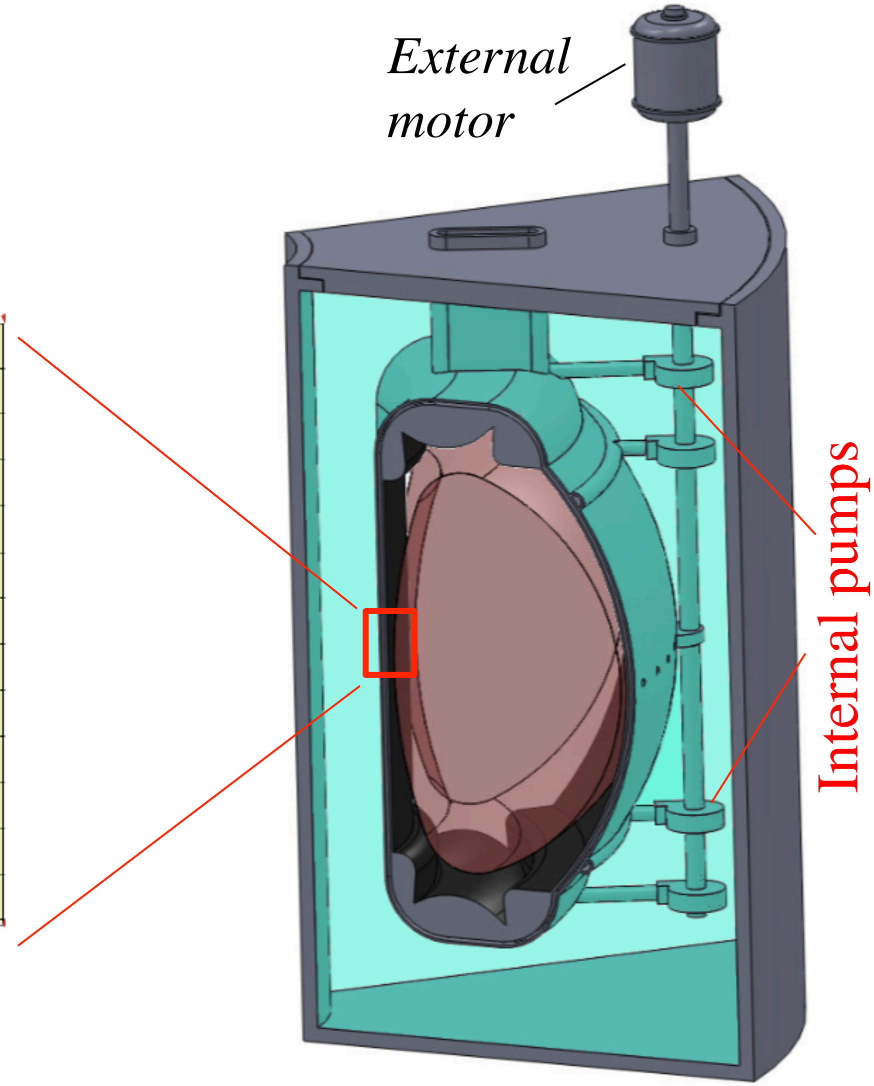
Property	FliBe [7]	Water
Melting Point (K)	732	273
Boiling Point (K)	1700	373
Density (kg/m³)	1940	1000
Specific Heat (kJ/kg/K)	2.4	4.2
Thermal Conductivity (W/m/K)	1	0.58
Viscosity (mPa-s)	6	1

- TBR ~ 1.14
- High thermal efficiency ~ 0.4 - 0.5
- Shielding: ~10 FPY coil lifetime



Immersion blanket: Very large heat sink in close proximity to internals provides fundamental improvement in heat exhaust





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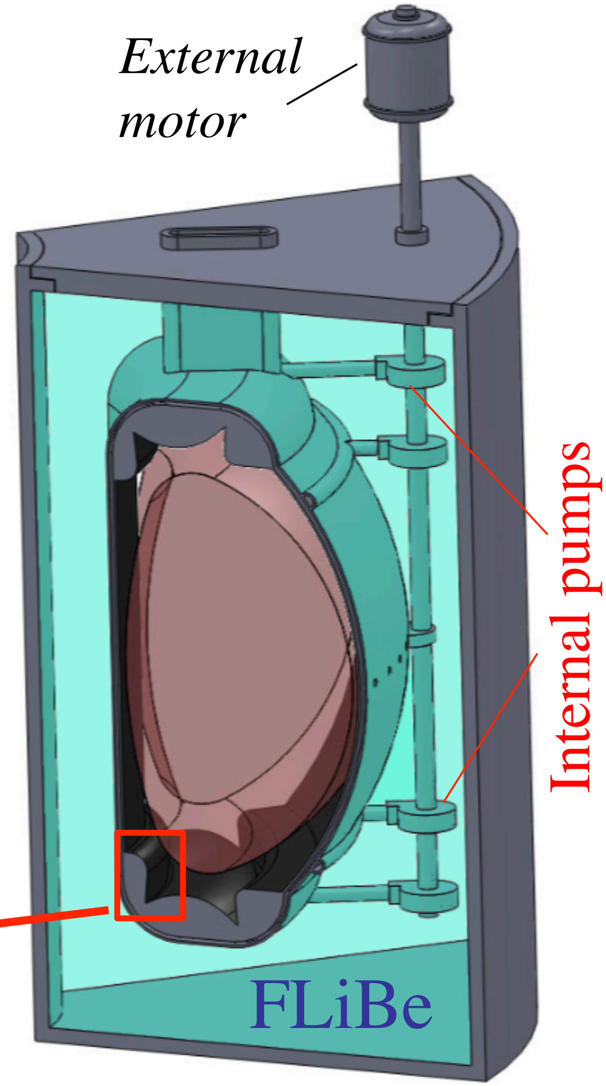

- TBR ~ 1.14
- High thermal efficiency ~ 0.4 - 0.5
- Shielding: 10 full-power coil lifetime
- Exploit FLiBe + Immersion blanket + Additive manufacturing to address high heat flux regions?

Student: "Ah ha! Now you're in trouble…power exhaust much harder in high-field, compact tokamak." Well, not really…

- Work by Eich, Goldston, et al showed that outer mipdlane heat flux only scales like local poloidal magnetic field… not size.

$$q_{//} \sim \frac{P_{SOL}}{R\,\lambda}\frac{B}{B_{pol}} \sim \frac{P_{SOL}\,B_{pol}}{R}\frac{B}{B_{pol}} \sim \frac{P\,B}{R}$$

$$q_{//} \sim \left(\frac{P}{S}\right) B\,R \sim B\,R$$

But P/S~P/R[2] is a requirement

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$$q_{//} \sim \left(\frac{P}{S}\right) B\,R \sim B\,R$$

But $P/S \sim P/R^2$ is a <u>requirement</u>

But gain is also <u>requirement</u>

$$p_{th}\,\tau_E \sim R^{1.3} B^3$$

$$q_{//} \sim B\frac{1}{B^{3/1.3}} \sim B\frac{1}{B^{2.3}} \sim \frac{1}{B^{1.3}}$$

Student: "Ah ha! Now you're in trouble…power exhaust much harder in high-field, compact tokamak." Well, not really…

$$q_{//} \sim \frac{1}{B^{1.3}}$$

$$n_e \le \frac{I_p}{\pi a^2}$$

Greenwald density limit

$$n_e \sim \frac{B}{q R}$$

Atomic physics + 2 point-model

$$P_{rad,divertor} \sim n_{div}^2 \sim n_e^4$$

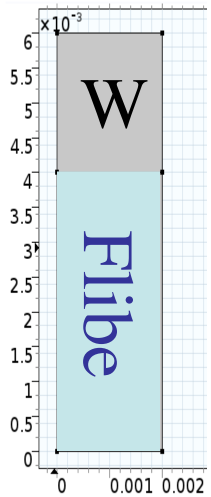
$$\frac{P_{rad}}{q_{//}/R} \sim \frac{B^4/R^4}{B^{-1.3}R^{-1}} \sim \frac{B^{5.3}}{R^3}$$

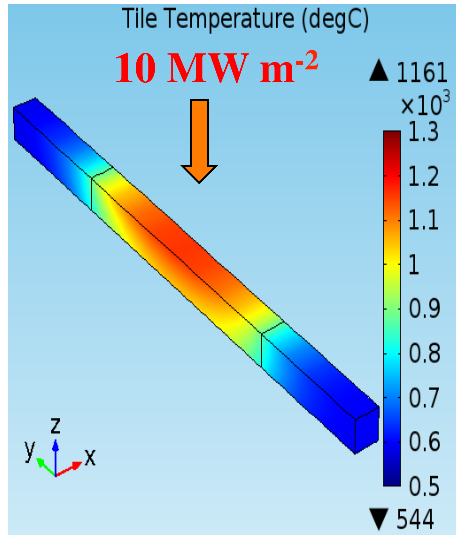
Divertor dissipation

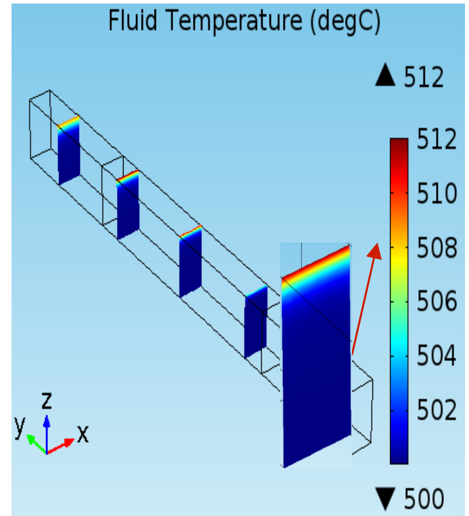
Preliminary study: Improved surface heat removal with FLiBe + 3-D printed cooling channels

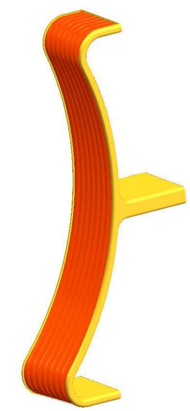
Design class: ARC divertor & cooling

2 mm thick W tile

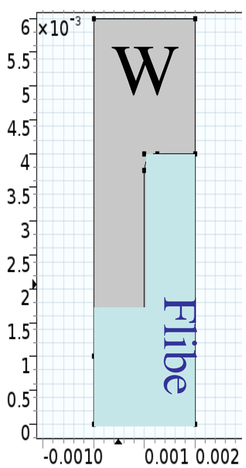


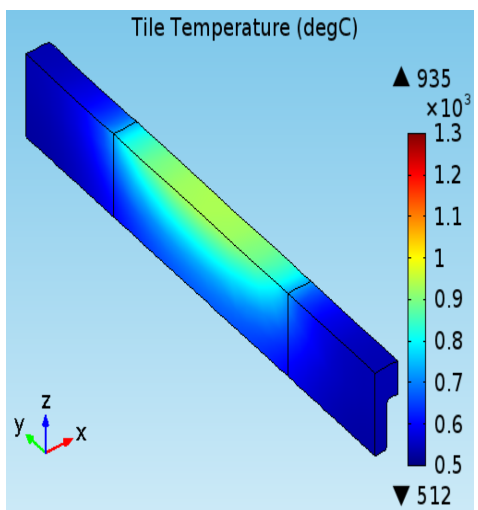


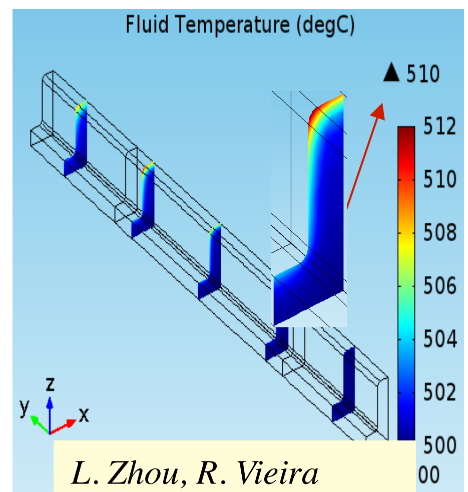




2 mm thick W tile + Internal Fin





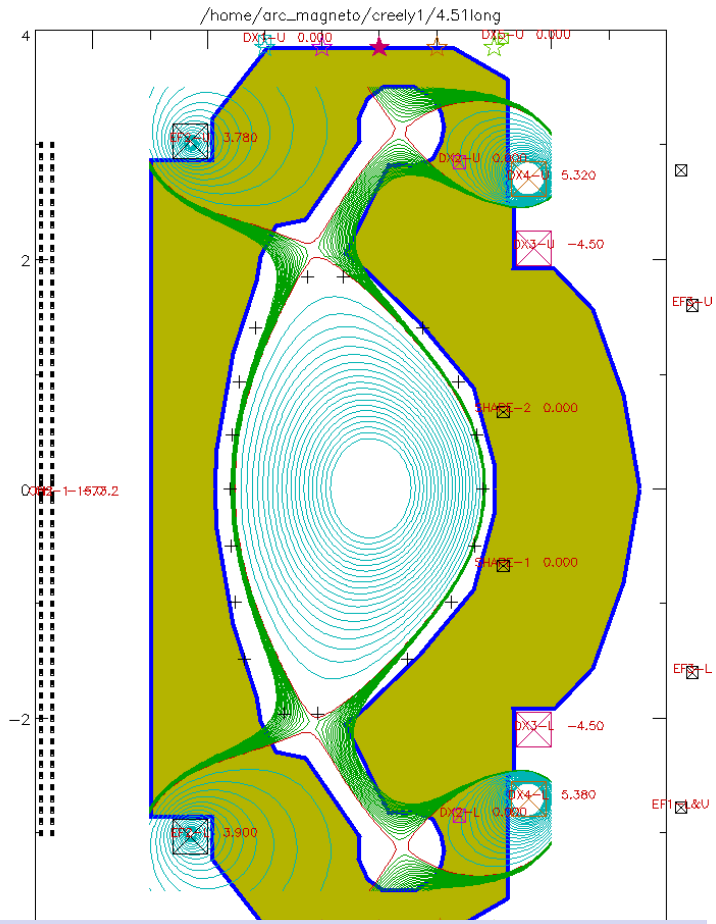


10 m/s

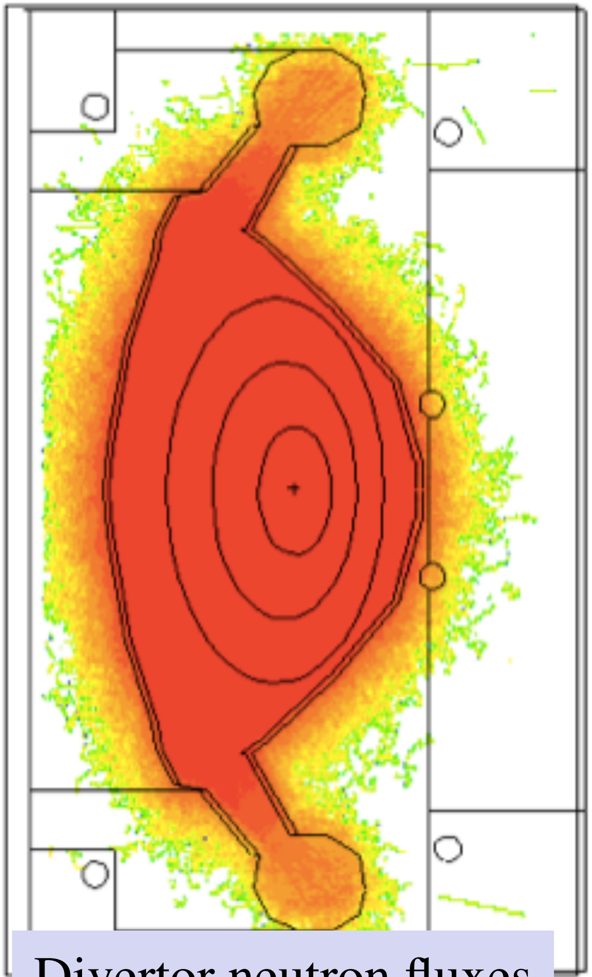
~ 1 bar pressure drop

L. Zhou, R. Vieira MIT

Preliminary results of ARC divertor design using modular + FLiBe technology

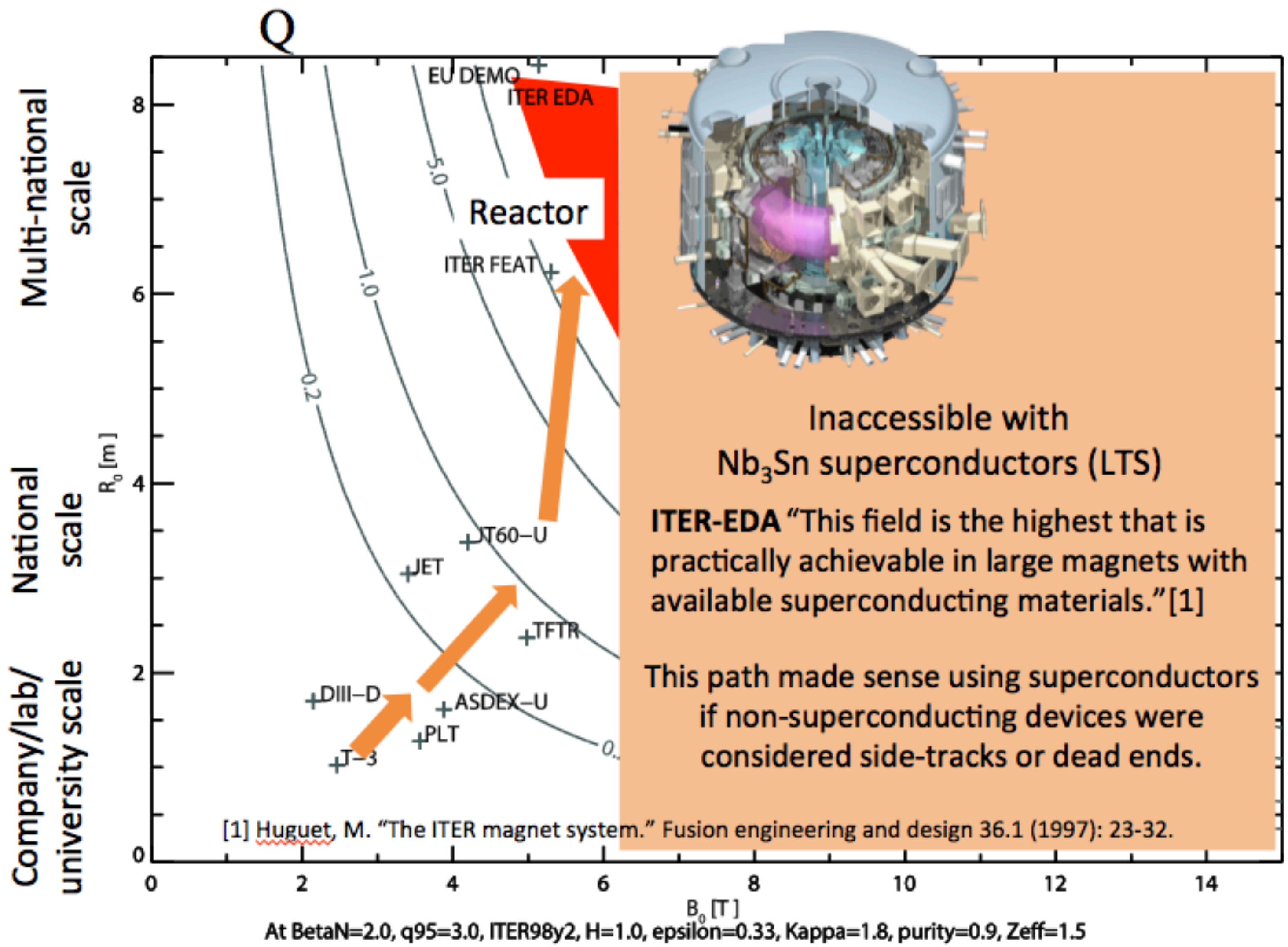


Advanced divertor equilibrium with PF coils inside TF

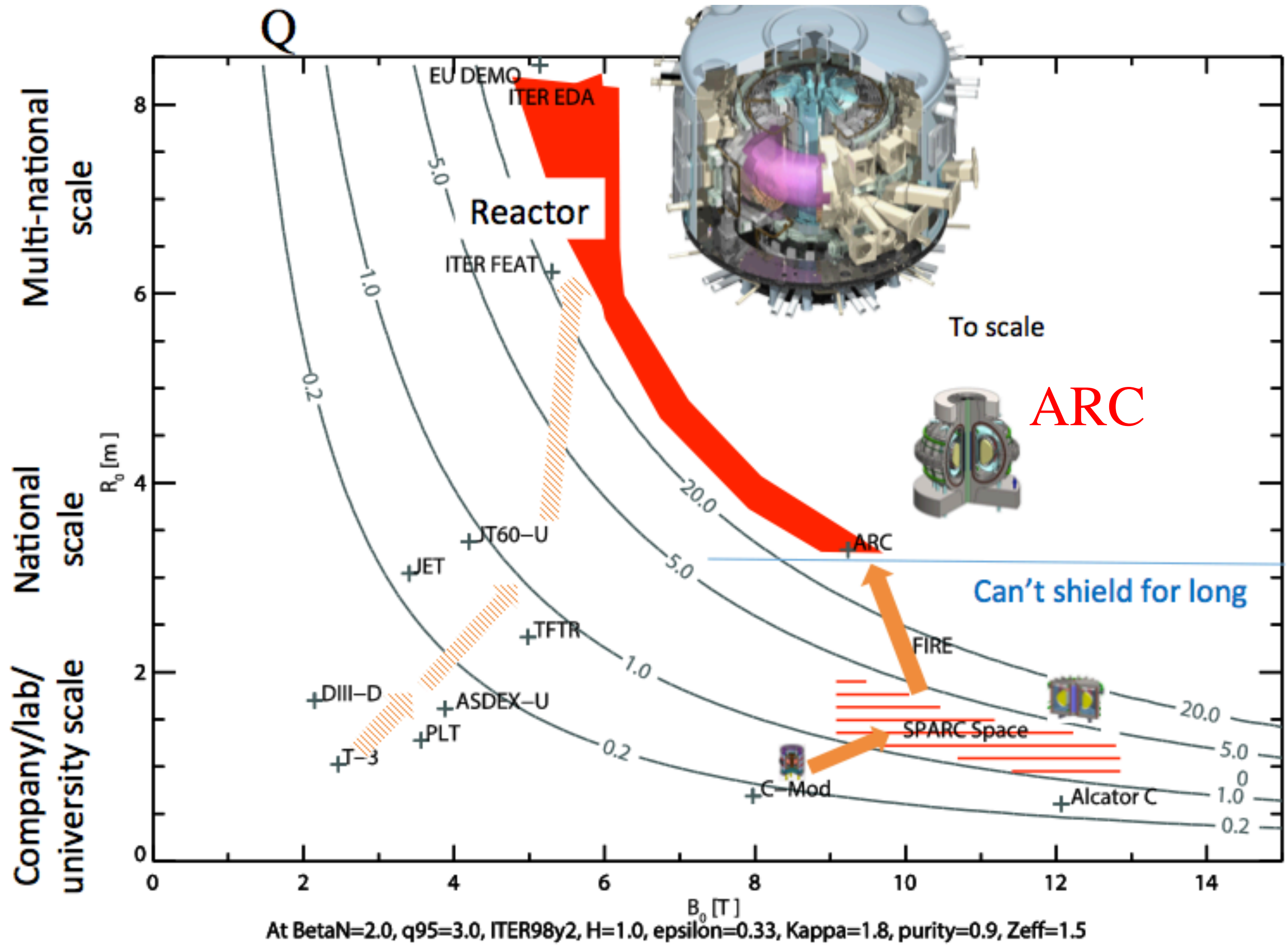


Divertor neutron fluxes greatly reduced

The 20+ year-old magnet technology forces ITER to be large

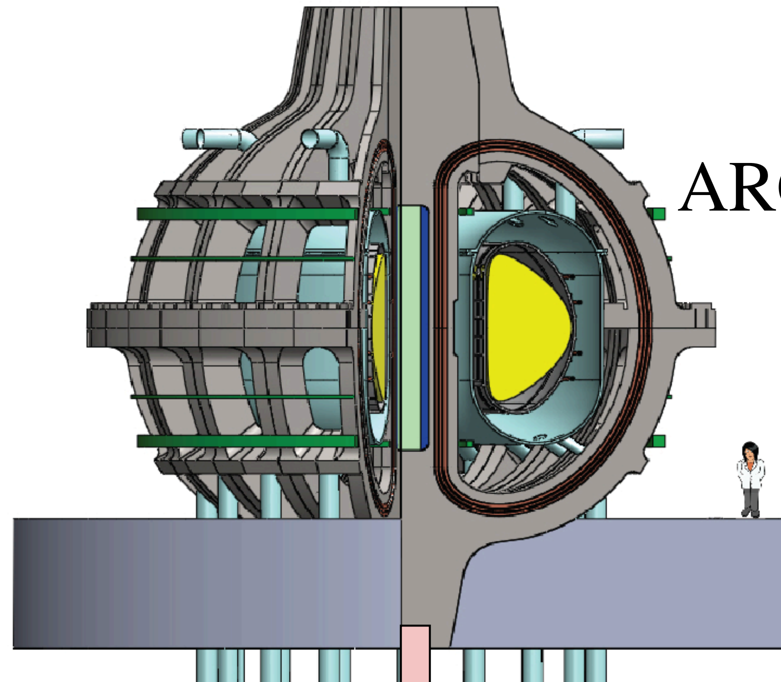


REBCO opens up fusion energy gain at very small scale for short time periods



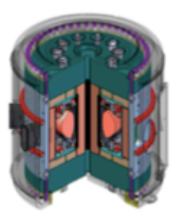
Smaller/sooner Privately-funded ARC: SPARC

- REBCO superconductor coils
  - High B ~ 10 tesla
- Fusion energy gain in compact high-field field torus

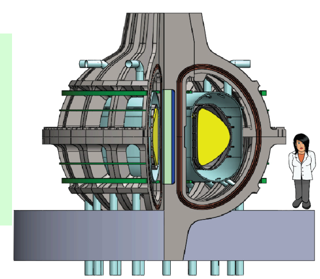


ARC

High-B copper
Alcator at MIT
(existing)



$$\frac{P_{fusion}}{P_{in}} > 2$$



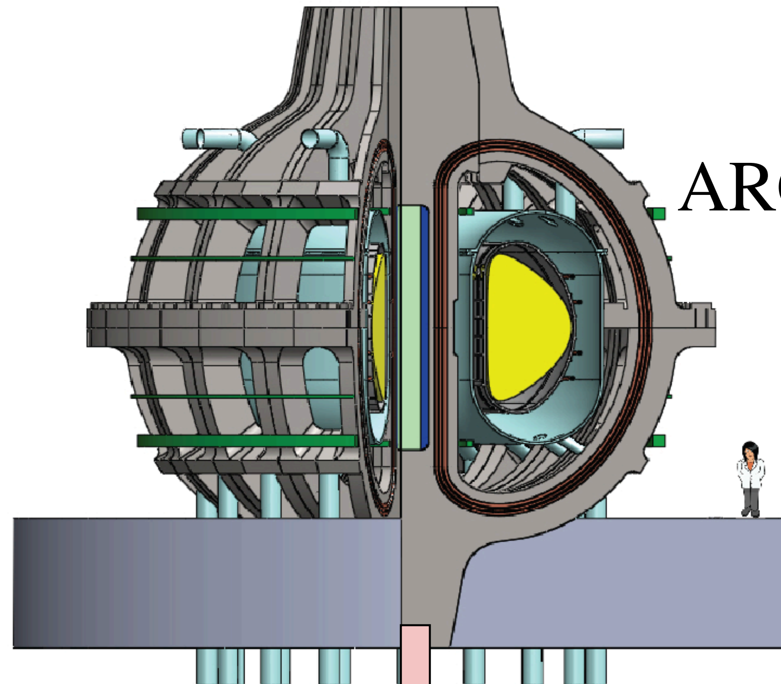
SPARC

Soon as Possible ARC: SPARC

- REBCO superconductor coils
  - High B ~ 10 tesla
- Fusion energy gain in compact high-field field torus

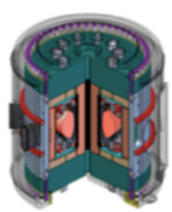
How small?

- Can afford it / sell it:
  ~1% volume of ITER → ~250 M$
- Can build it quickly:
  Sited at MIT
- Achieves D-T gain /w Alcator physics for ~ 10 seconds:
  R ~ 1.5 m ✓



ARC

High-B copper Alcator at MIT (existing)



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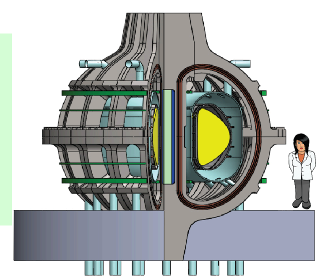
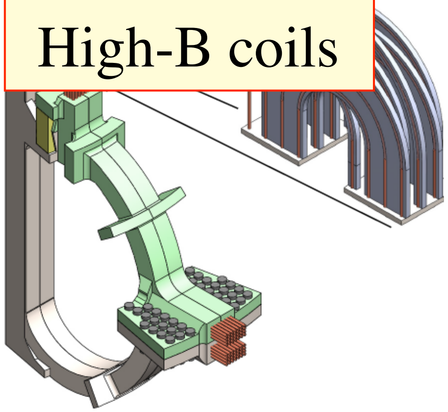


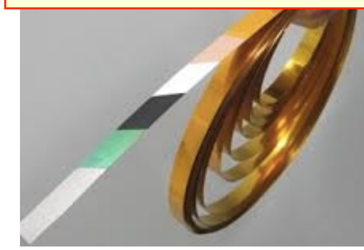
SPARC

The disruptive innovation of high field, high-T superconductors

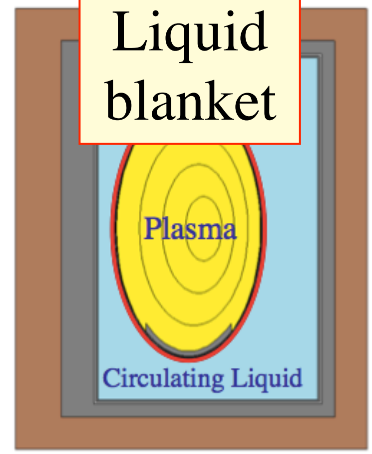
Demountable High-B coils



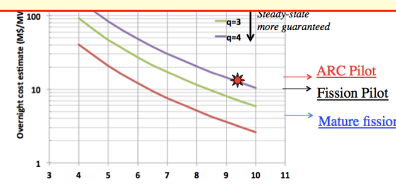
Superconductor



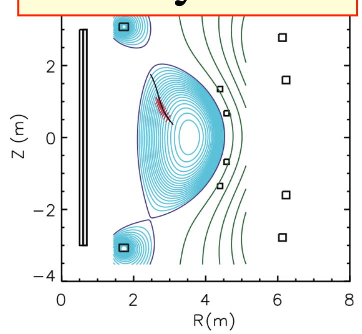
Liquid blanket

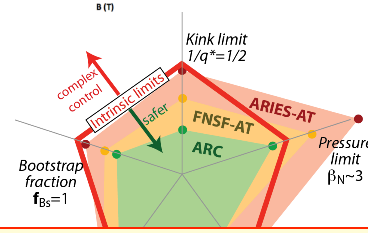


Smaller, sooner
Viable fusion energy



Steady-state





Operation robustness

Small & Modular

Summary

- Magnetic fusion <u>needs</u> technology advances to make fusion energy practical to develop and economically viable.
  - The fact that we know this is a "good" sign…we have to speculate very little on the physics of magnetic confinement.
  - The key requirements are power density & gain & availability.

- Disruptive technological solutions are available, but require both integrated knowledge of fusion systems + imagination / cleverness/ "un-knowledge" e.g.
  - New high-field, high-temperature superconductor magnets
  - Jointed, demountable toroidal field coils
  - Immersion liquid blanket
  - 3-D printed components for heat removal

- Your generation will be key in developing these choices

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Thank you

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