SMALLER & SOONER: EXPLOITING NEW TECHNOLOGIES FOR FUSION'S DEVELOPMENT

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With grateful acknowledgement to MIT colleagues and students

B. Sorbom, D. Sutherland, C. Kasten, C. Sung, T. Palmer, J. Ball, F. Mangiarotti, J. Sierchio, P. Bonoli, L. Bromberg, J. Minervini, G. Wallace, E. Marmar, M. Greenwald, B. Lipshcultz. Y. Podpaly, G. Olynyk, M. Garrett, Z. Hartwig, R. Mumgaard, C. Haakonsen, H.S. Barnard

SOFE 2015

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It is self-evident that smaller, modular fusion devices will accelerate fusion's development

	Shippingport: 1954 "Pilot" Fission Plant	ITER
$P_{thermal}$ (MW)	230	500
Core volume (m^3)	60	~1000
Cost (2012 US B$)	0.6	~ 20
Cost / volume (M$/$m^3$)	10	~ 20
Construction time (y)	~ 4	> 20

- Cost & time ∝ unit volume and mass

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- Cost & time ∝ unit volume and mass
- ITER is an invaluable science experiment for burning plasmas but is not an optimized size for modular fusion energy "pilots"
  - ITER is a trial of just one fusion concept, fission pilot tried four different cores!
- **Small size and modularity are self-reinforcing:** pilots of complex engineered systems as small as possible, yet sufficiently capable

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Sounds like a reasonable strategy but how do you do it?

- Cost & t
- ITER is an invaluable science experiment for burning plasmas but is not an optimized size for modular fusion energy "pilots"
  - ➢ ITER is a trial of just one fusion concept, fission pilot tried four different cores!
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Confinement physics strongly favors high B to produce fusion capable devices at smaller size

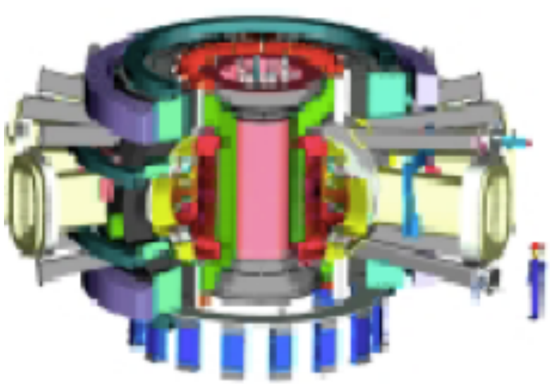
Gain $$nT\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

$$V \propto R^3$$

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

R (m)	**2.14**
V (m^3)	**30**
B_o (T)	**10**
Q_p	**>10**
Steady-state	**No**
Tritium breeding	**No**
$Q_{electric}$	**0**

Copper coil
pulse ~ 10 s



FIRE

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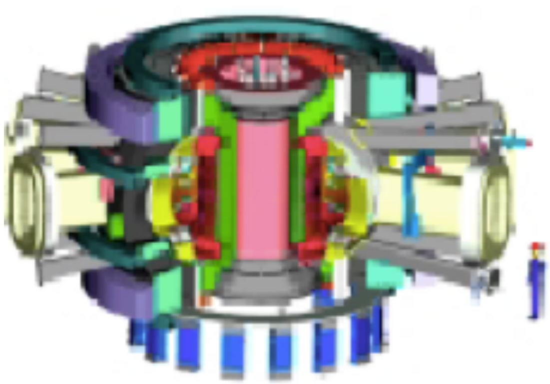
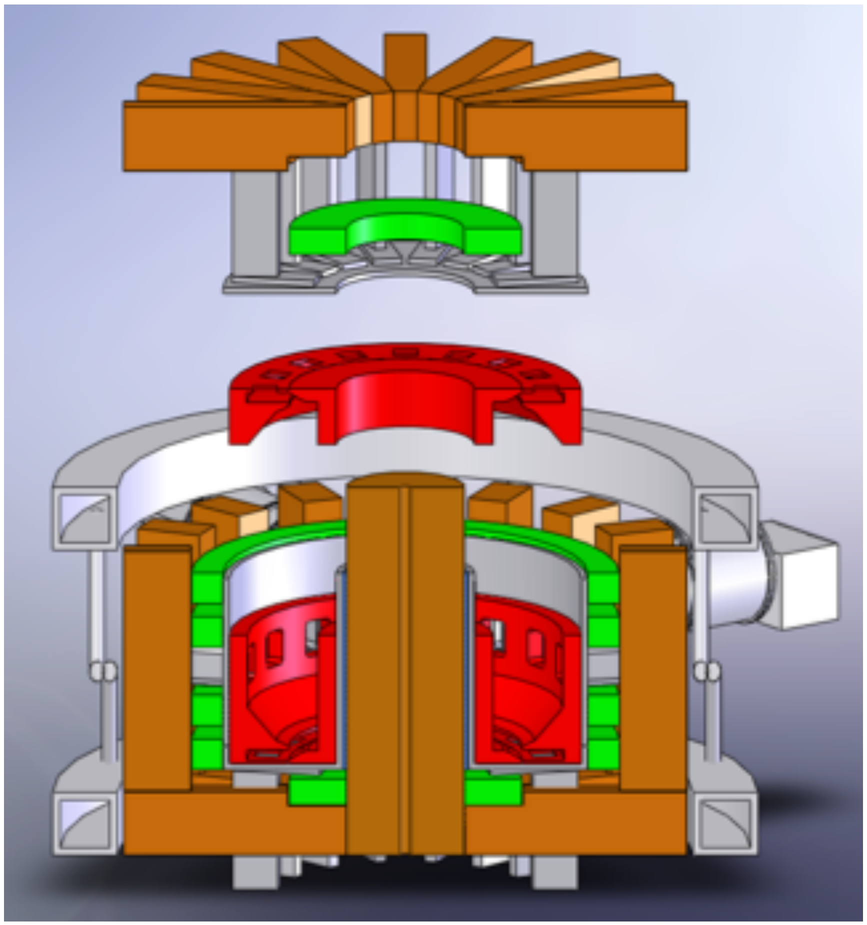


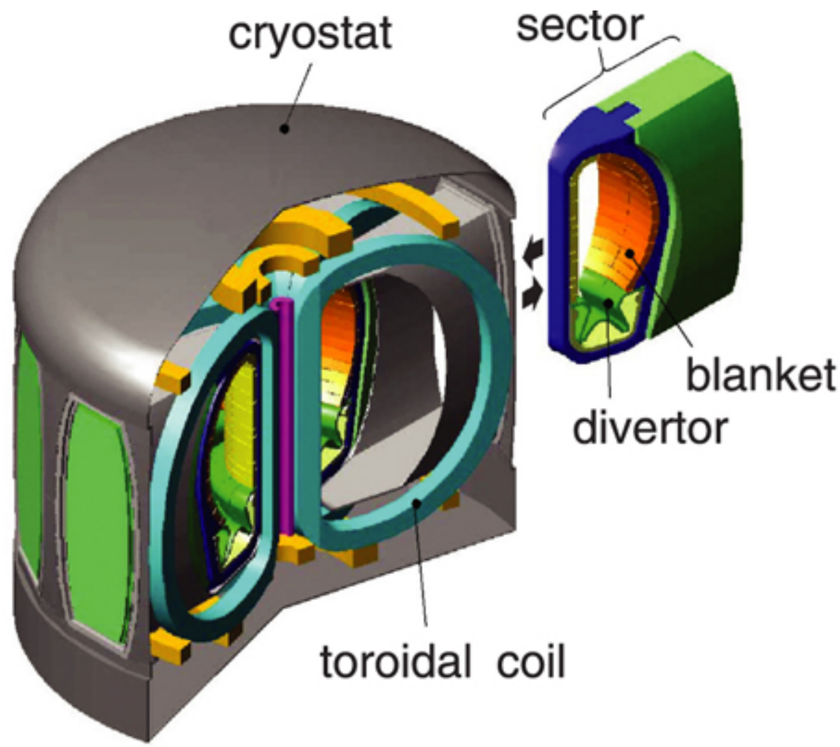
FIRE

Continuous /w High-B Superconductors?

Basic geometry favors demountable magnets to provide modularity for internal components

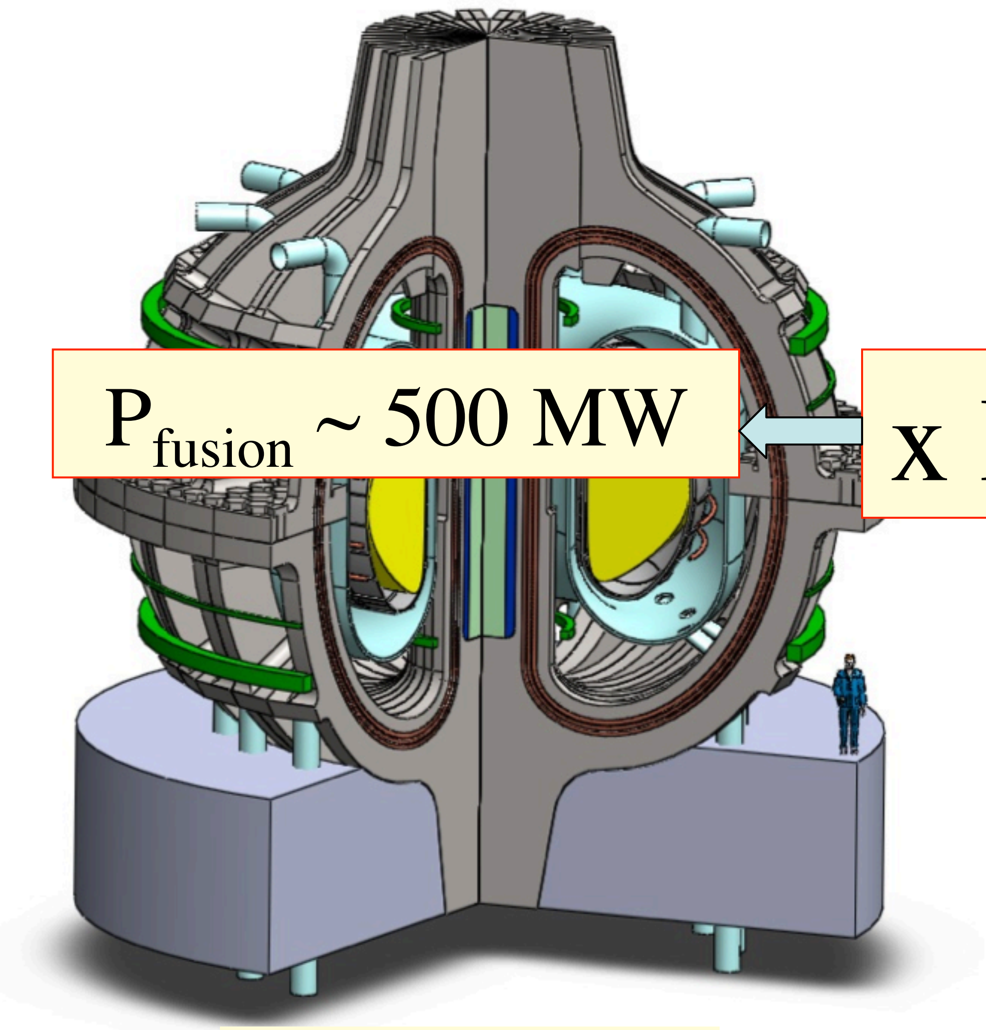


FNSF-AT V. Chan et al NF 2011

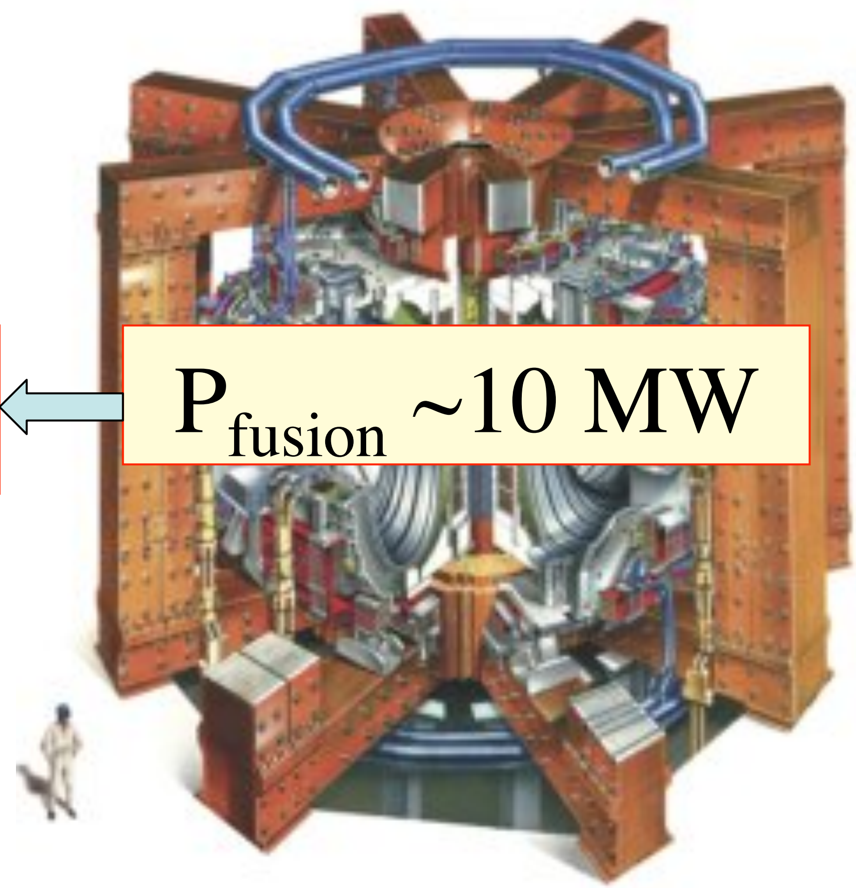


ARC conceptual design example of "smaller, sooner" fusion device using new superconductors

REBCO superconductor B = 9.2 T



Copper, B = 3.5 T

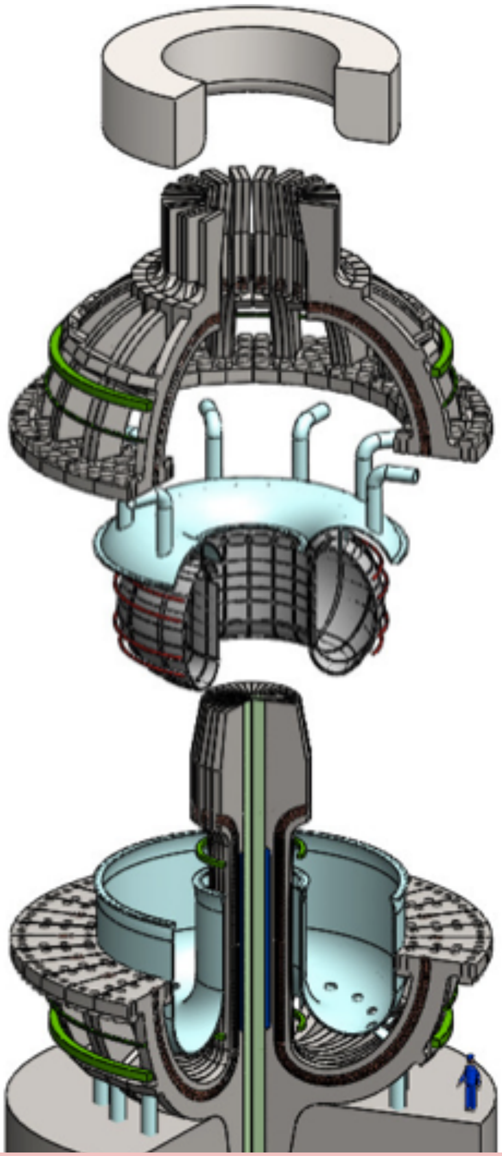


P_{fusion} ~ 500 MW ← x B^4 ← P_{fusion} ~10 MW

ARC: R ~ 3.2 m

JET: R ~ 3 m
~4 years construction

ARC conceptual design example of "smaller, sooner" modular fusion devices using new superconductors



B. Sorbom et al FED 2015 **SP6-62 Tue pm**

- Demountable magnetic field coils
- Single-unit vertical lift

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

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		Opportunities /w new technology
B_{coil} > 20 T	→	REBCO superconductors
SC Joints Demountable coils	→	REBCO: tape form REBCO: T~ 25 K
		↓
Small radial build neutronics	→	Immersion liquid blanket
		↓
Internal components with small space + high power density	→	Additive manufacturing of single-unit VV/PFC with advanced cooling capability

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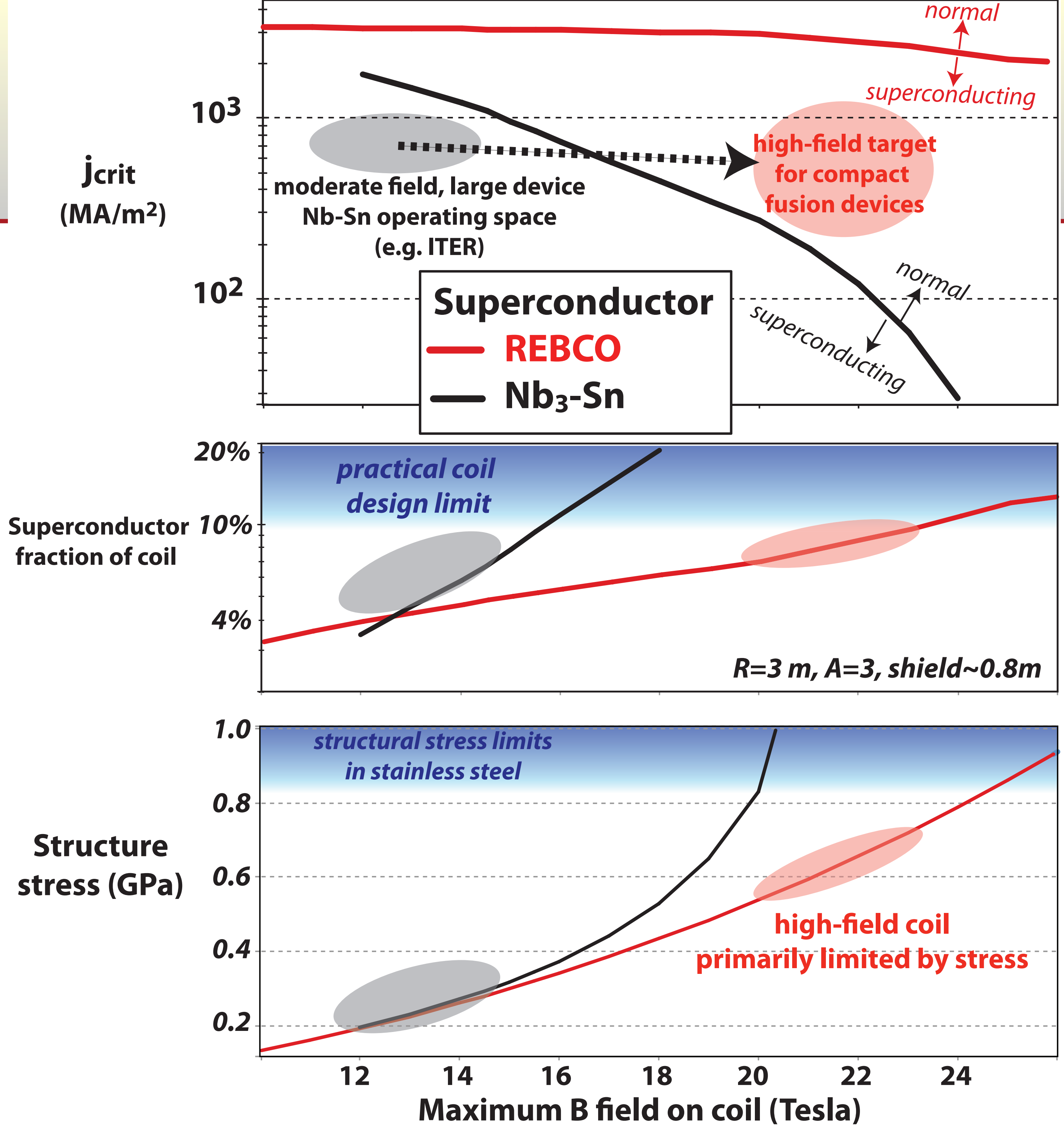
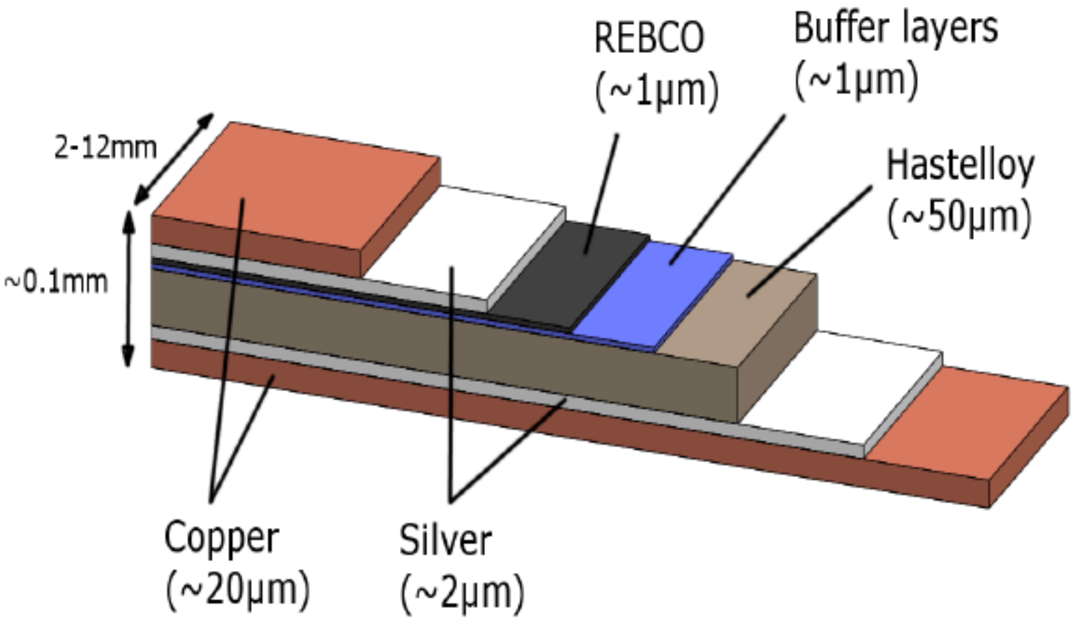
SC	rm K
Demou	
Small r neutronics	anket
Internal components with small space + high power density	Additive manufacturing of single-unit VV/PFC with advanced cooling capability

REBCO superconductors & Additive Manufacturing (3D printing) are new and rapidly developing technologies, so this is necessarily "work in progress"

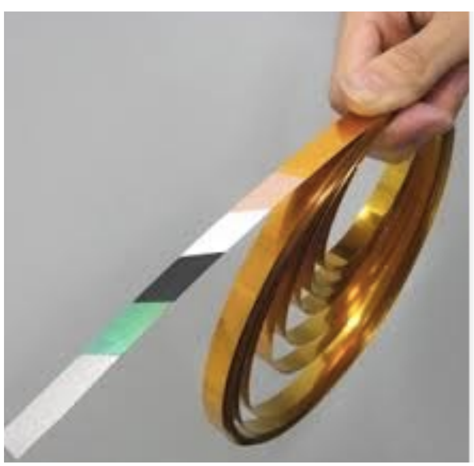
A revolution in superconductors in last 5 years: REBCO (Rare-Earth Barium Cu Oxide) remain superconducting at VERY high B-field and above liquid He temperatures



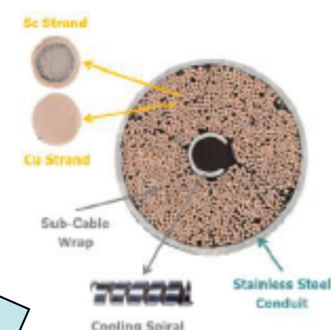
REBCO: coated superconductors in robust tape form, commercially available



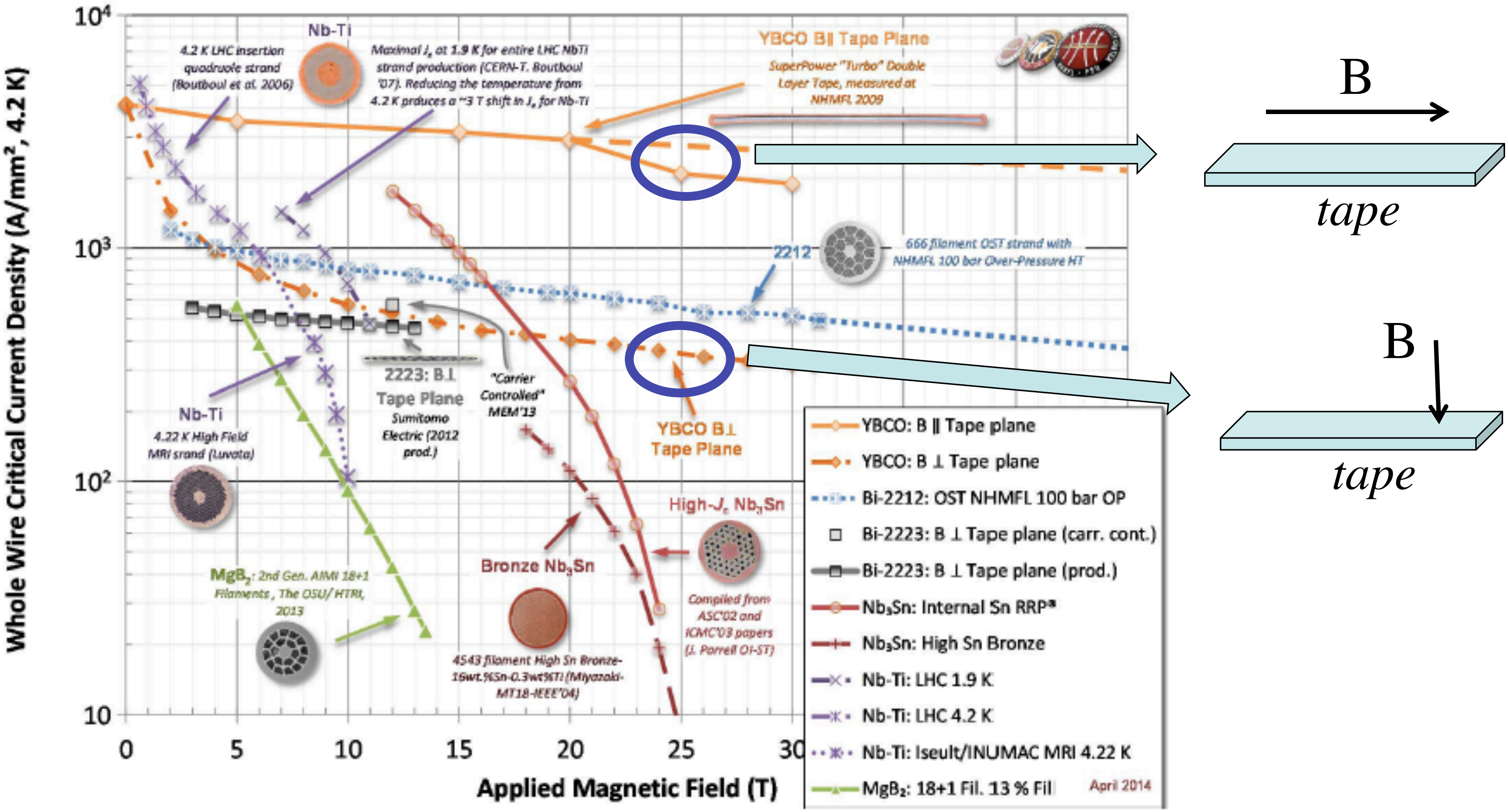
REBCO tape composition
(not to scale)



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



REBCO superconductors performance is constantly improving for application in high-B coils: E.g. Challenge of field anisotropy in j_{crit}



Data maintained by Peter Lee, NHMFL, http://fs.magnet.fsu.edu/~lee/plot/plot.htm

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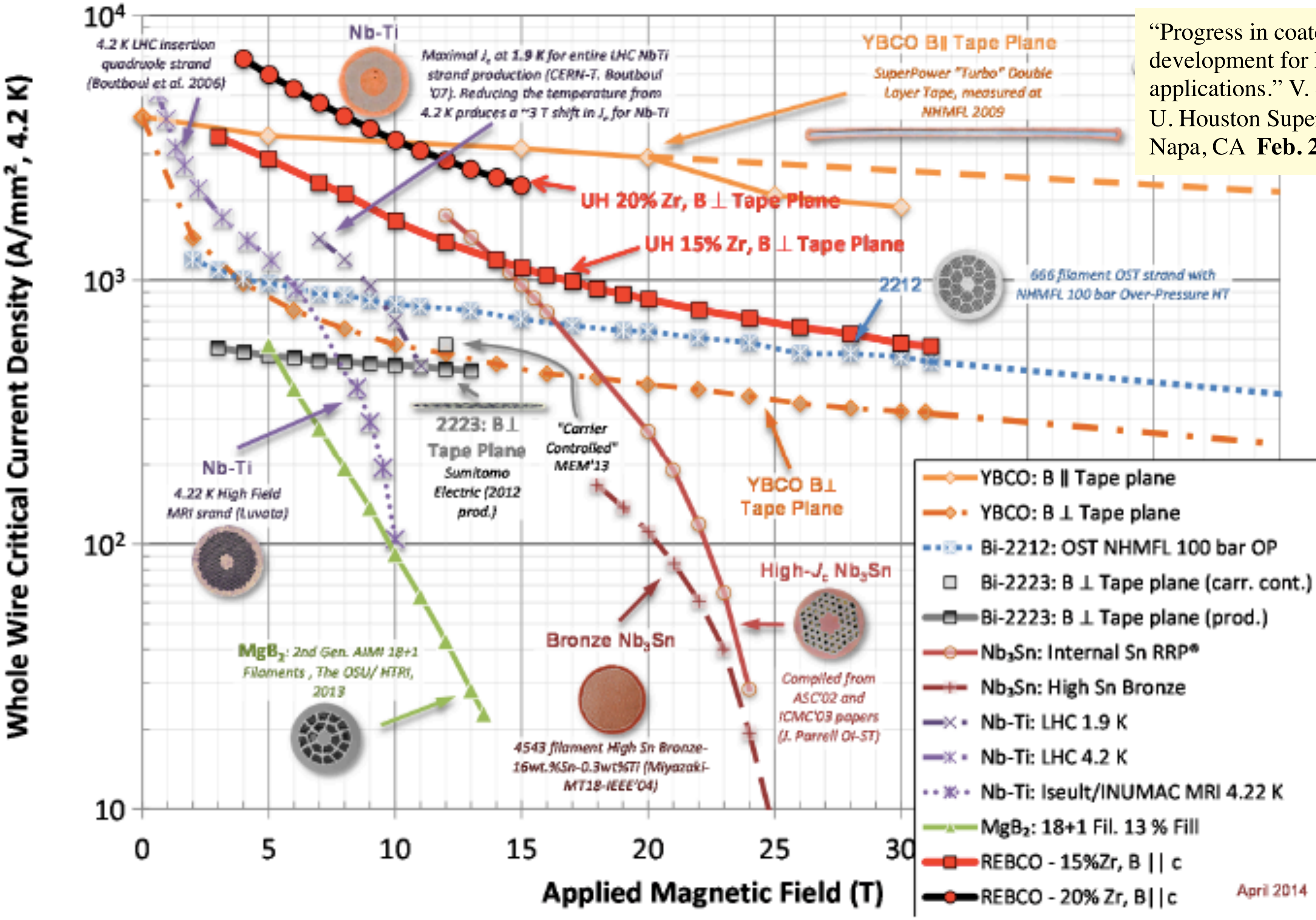
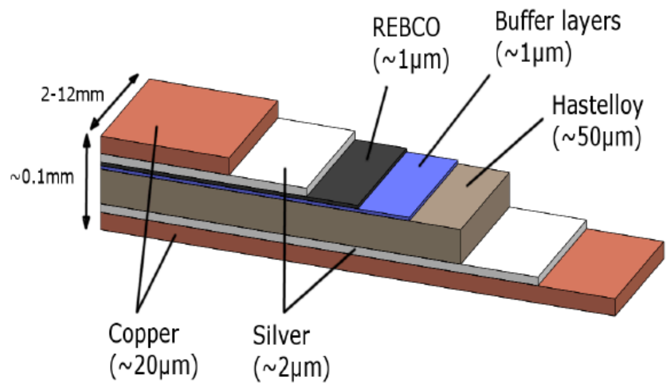


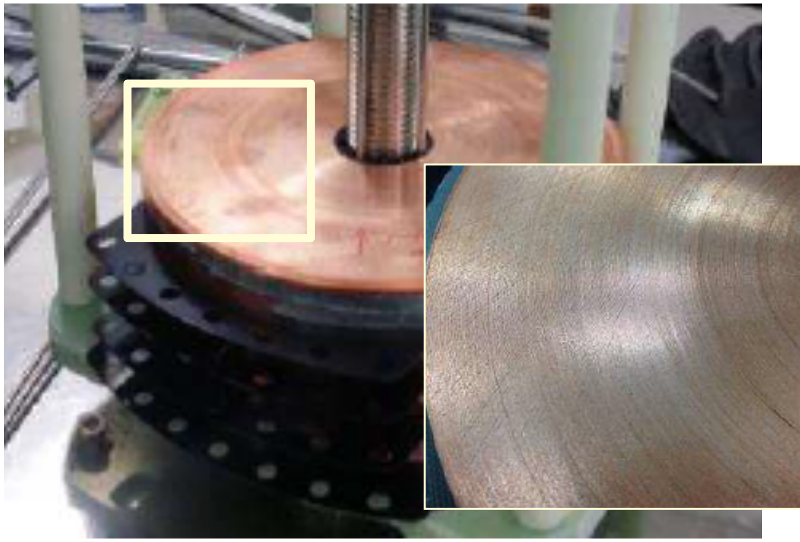
"Progress in coated conductor development for high magnetic field applications." V. Selvamanickam, et al. U. Houston Superconductor Workshop, Napa, CA **Feb. 2015**

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



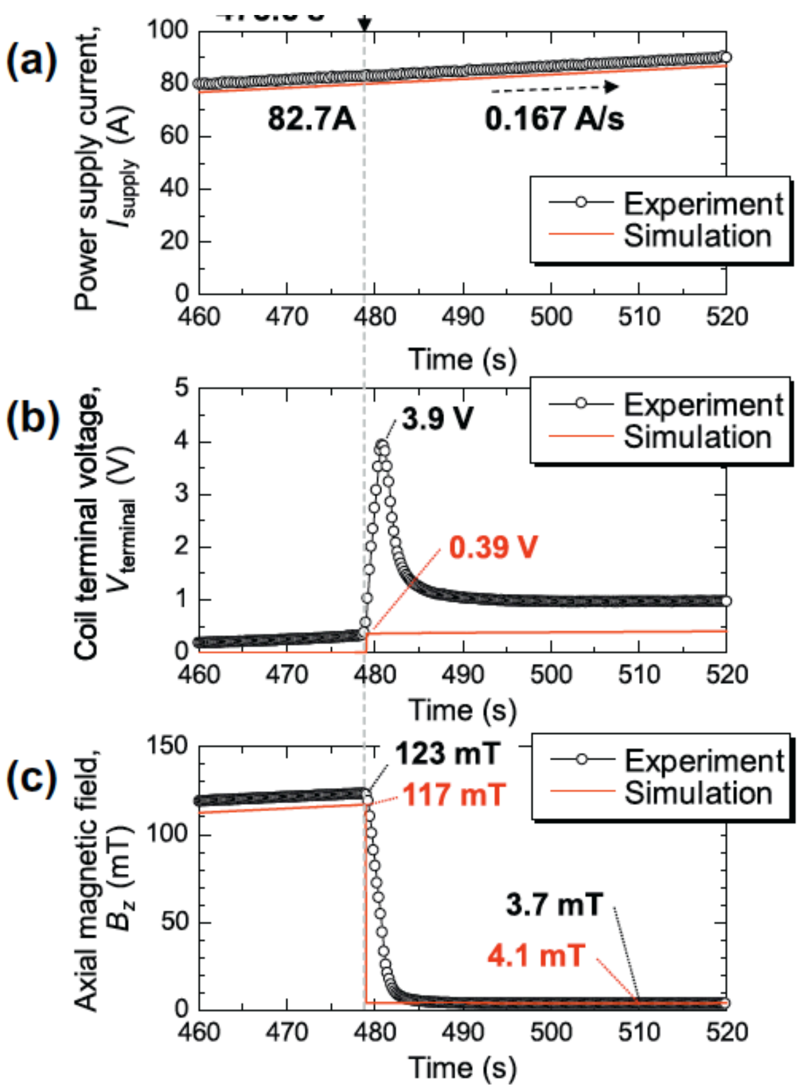
- Steel is "internal" insulator for each turn

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

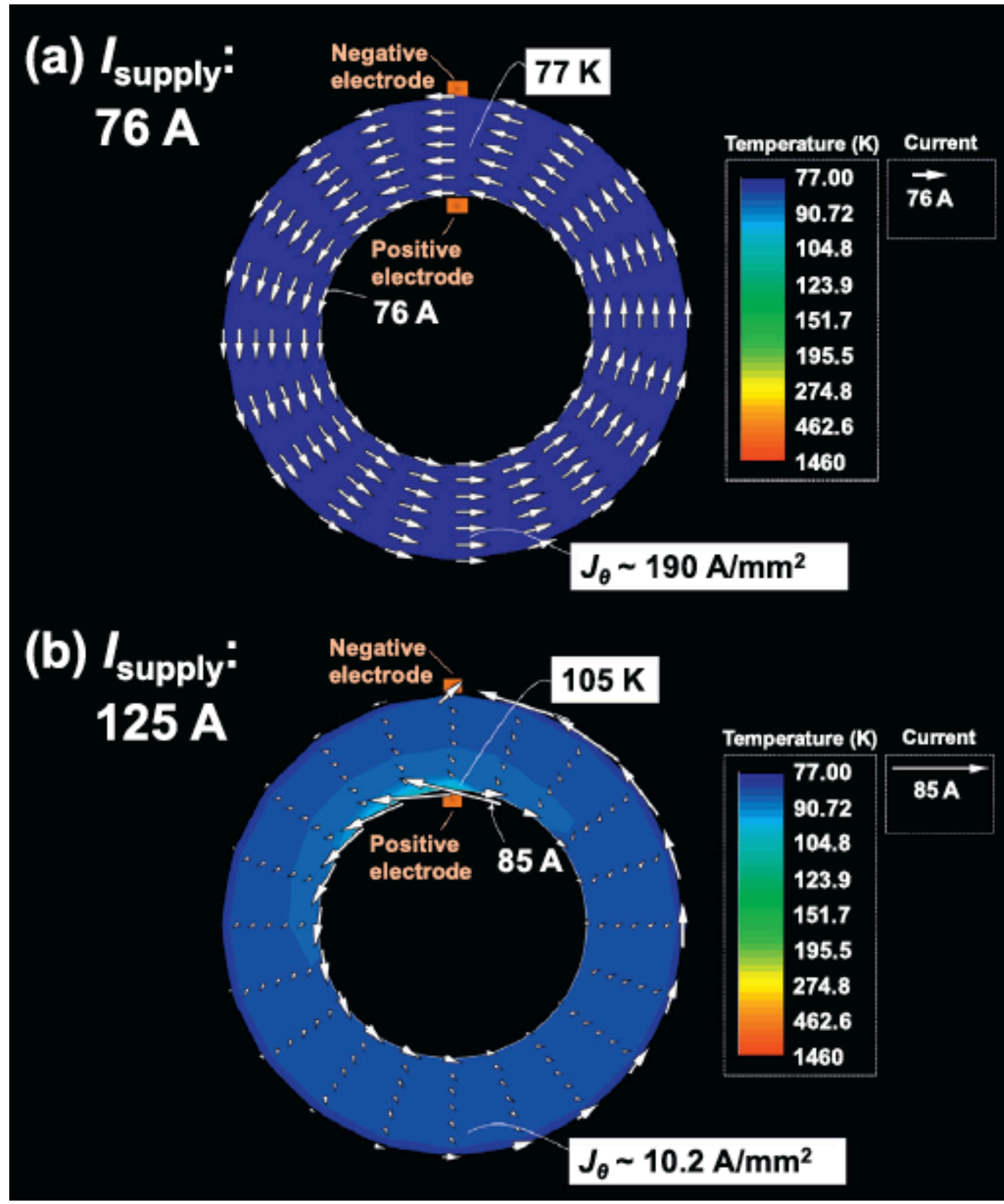


S. Hahn et al. App Phys Lett 173511 (2013)

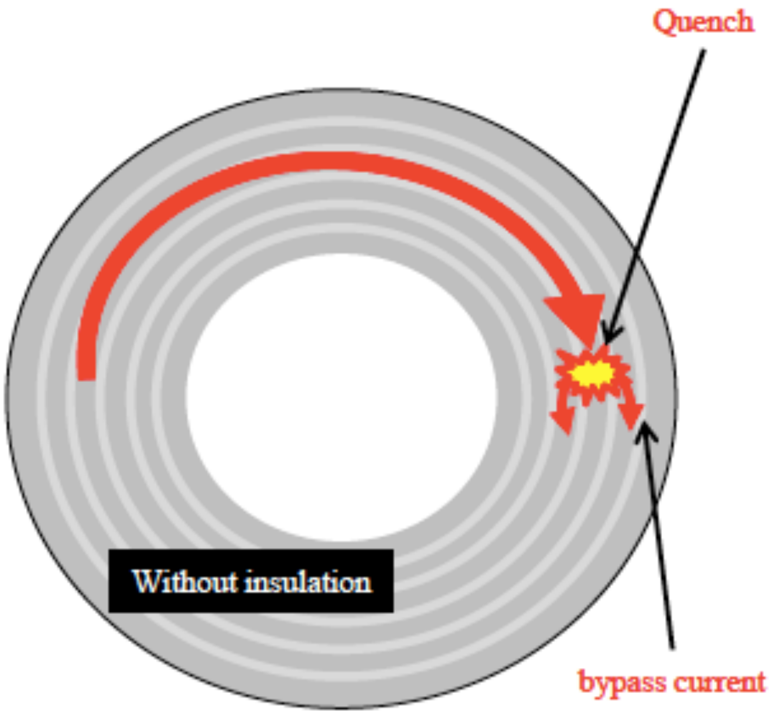
No-insulator coil self-heals via internal redistribution of j → "Single-turn mode" → Immediate drop in B, energy distributed in coil

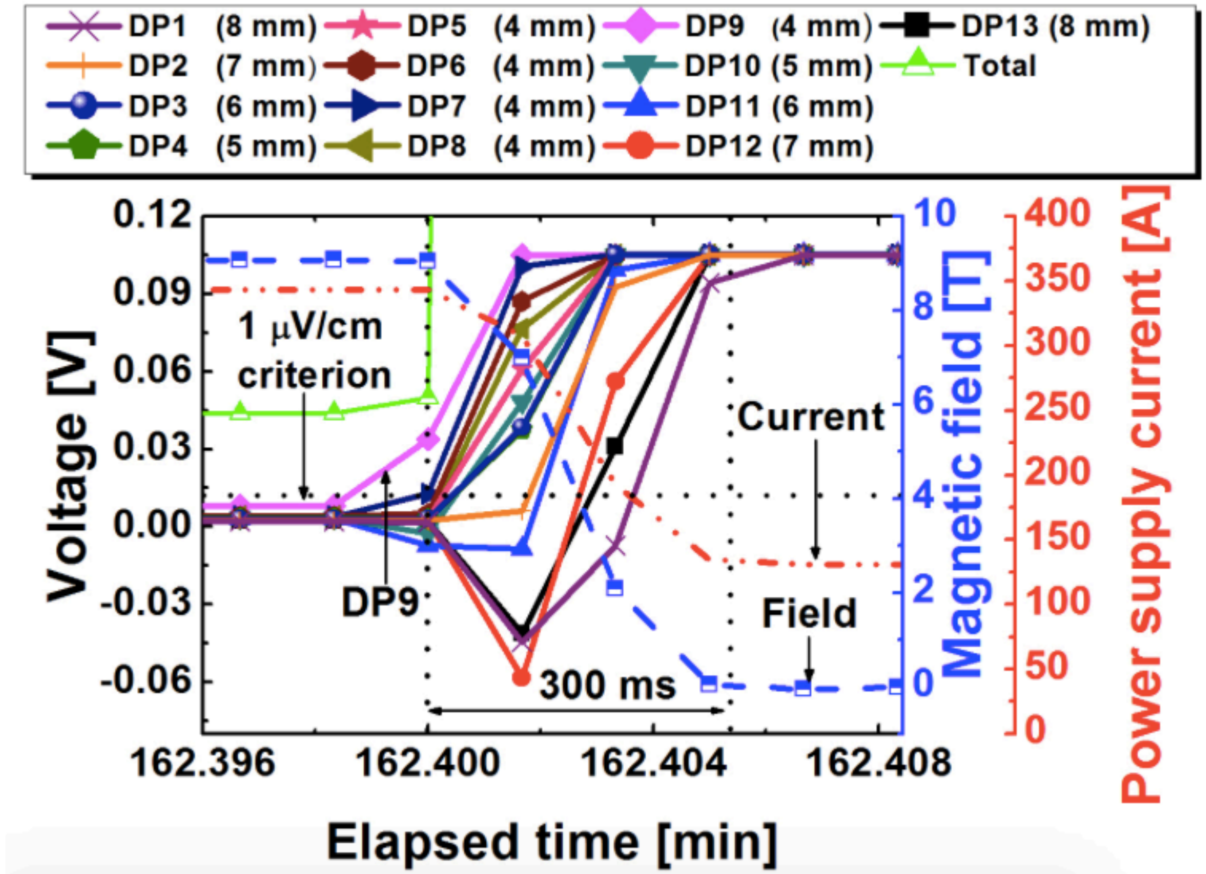


Yanagisawa *et al*. *Physica Scripta C (2014) 40*



“No-insulator” winding provides intrinsic quench protection in coil.





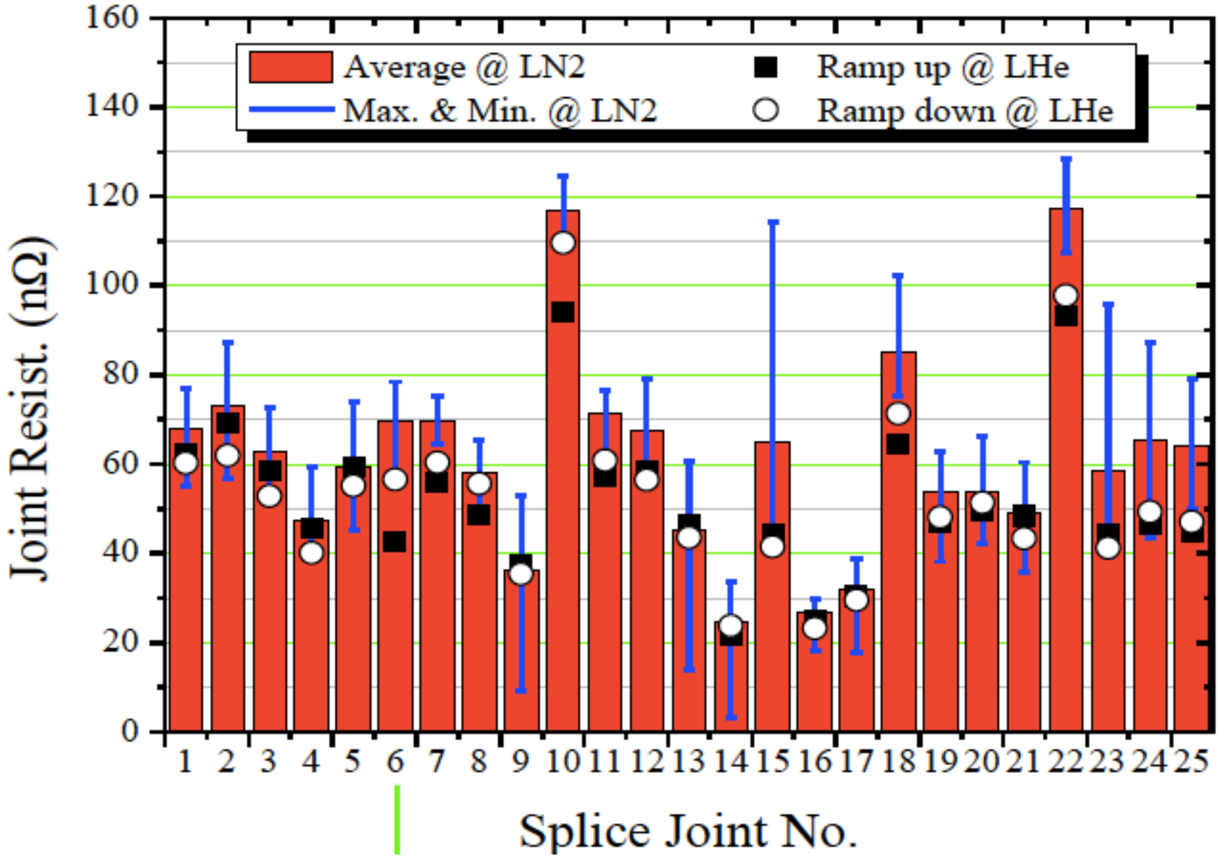
Quench at 9 Tesla: No damage to stacked double pancake coil (2014)

S. Hahn et al. Bitter Magnet Lab, MIT

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

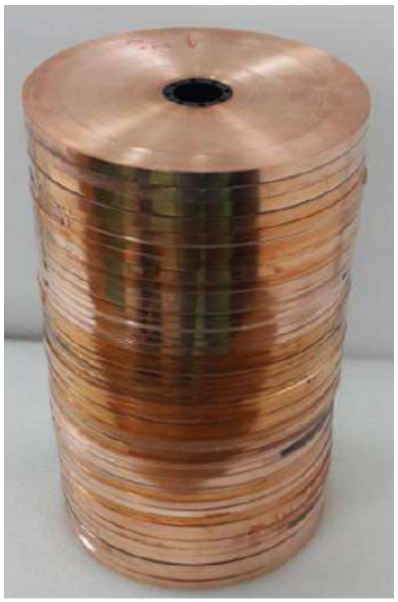
26 stacked coils

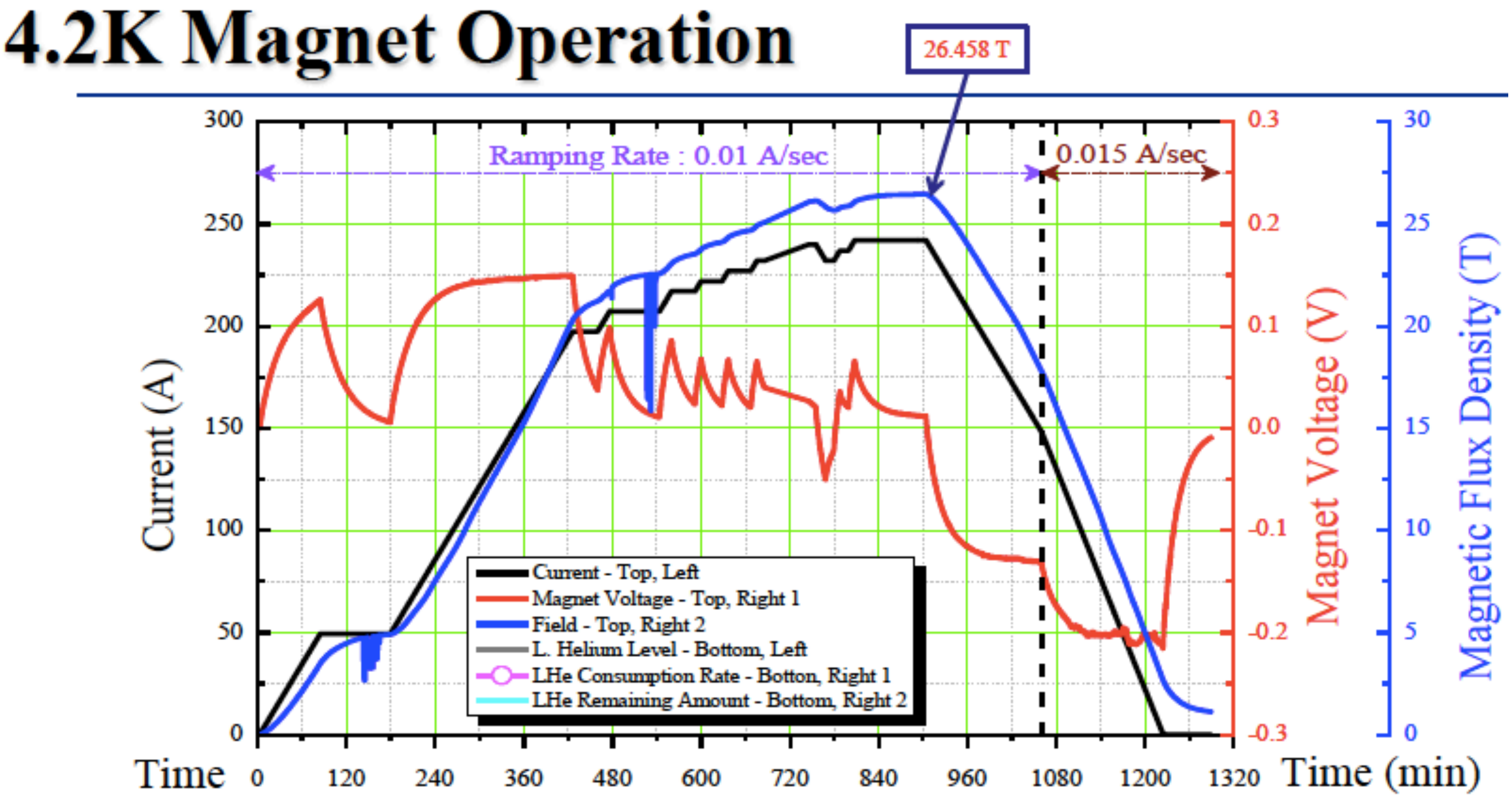
~300 m/coil consistent with maximum continuous length of high-performance tape



- Soldered joints!
- Mechanical attachment lowers resistance

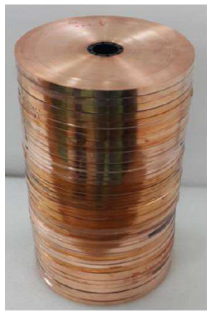
April 2015: New record of 26.5 Tesla with REBCO-only, "no-insulation" coil

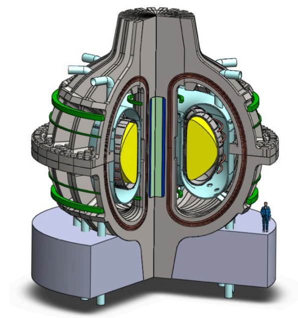




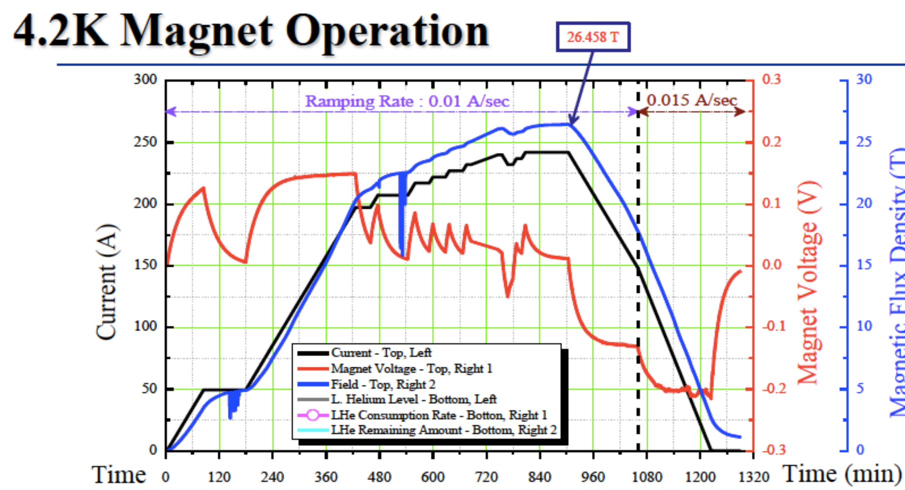
S. Hahn, J.M. Kim, et al.
NNFML, FSU, SUNAM, MIT

Scaled-down REBCO coil matches most requirements for ARC design

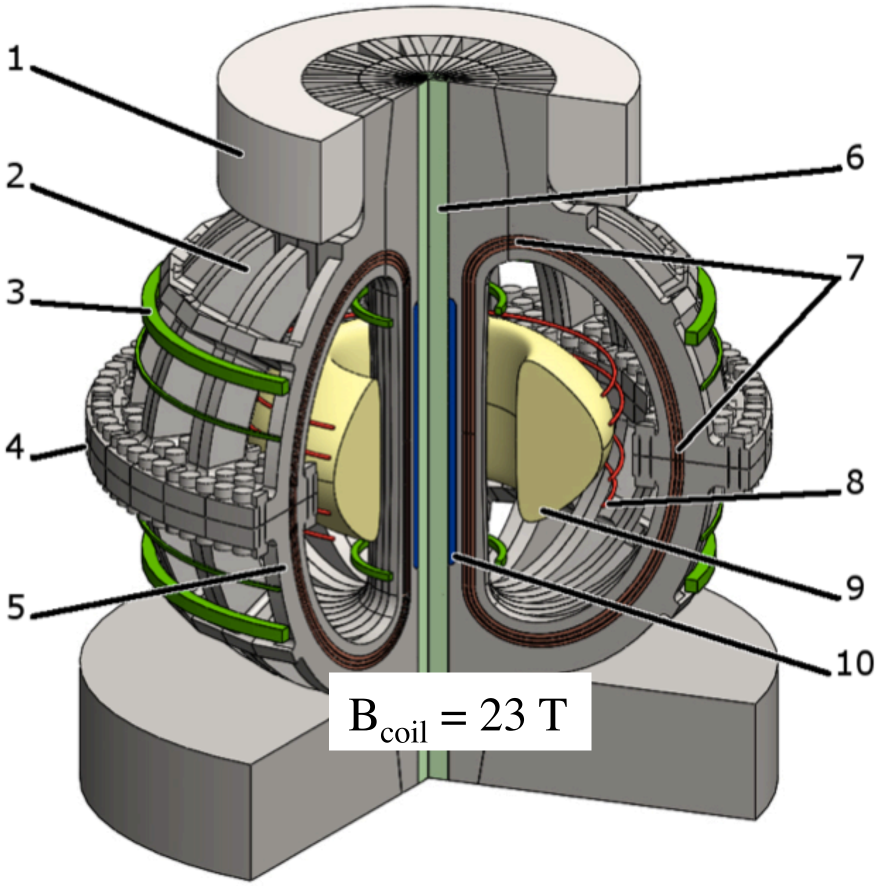




B_{coil}(T)	26.5	23
J_e (A/mm^2)	400	400-500
T (K)	4.2	25
Materials	REBCO, SS316L	
σ_{max} (MPa)	593	660
Diameter (m)	0.03	~ 6

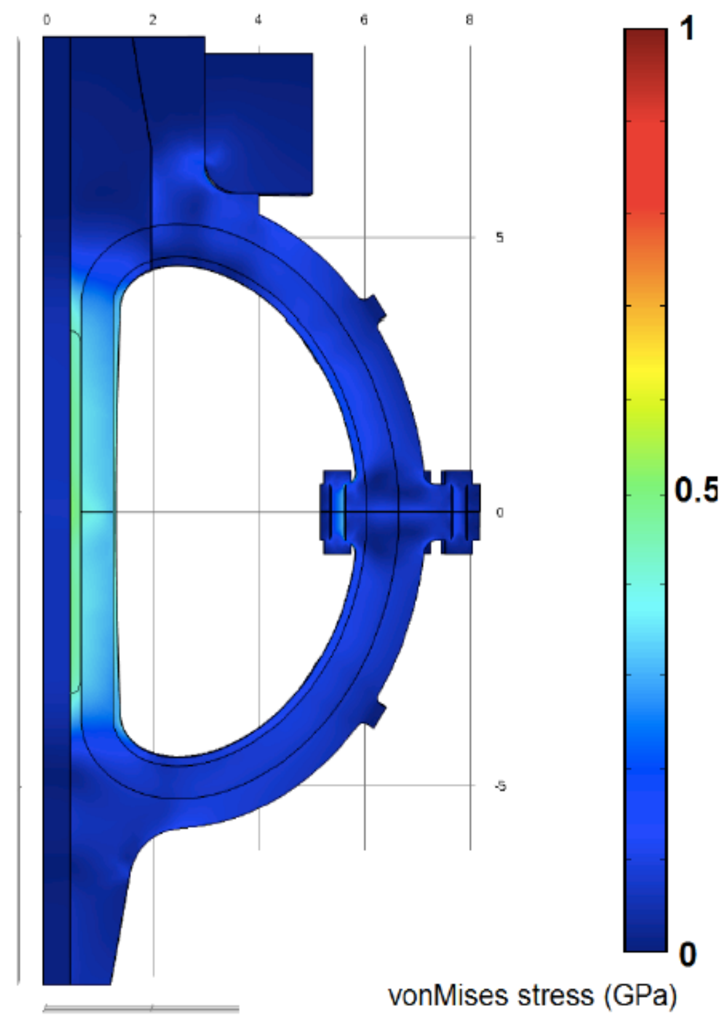


Large-bore challenge for high-B MFE magnet: requires optimized geometry & superstructure

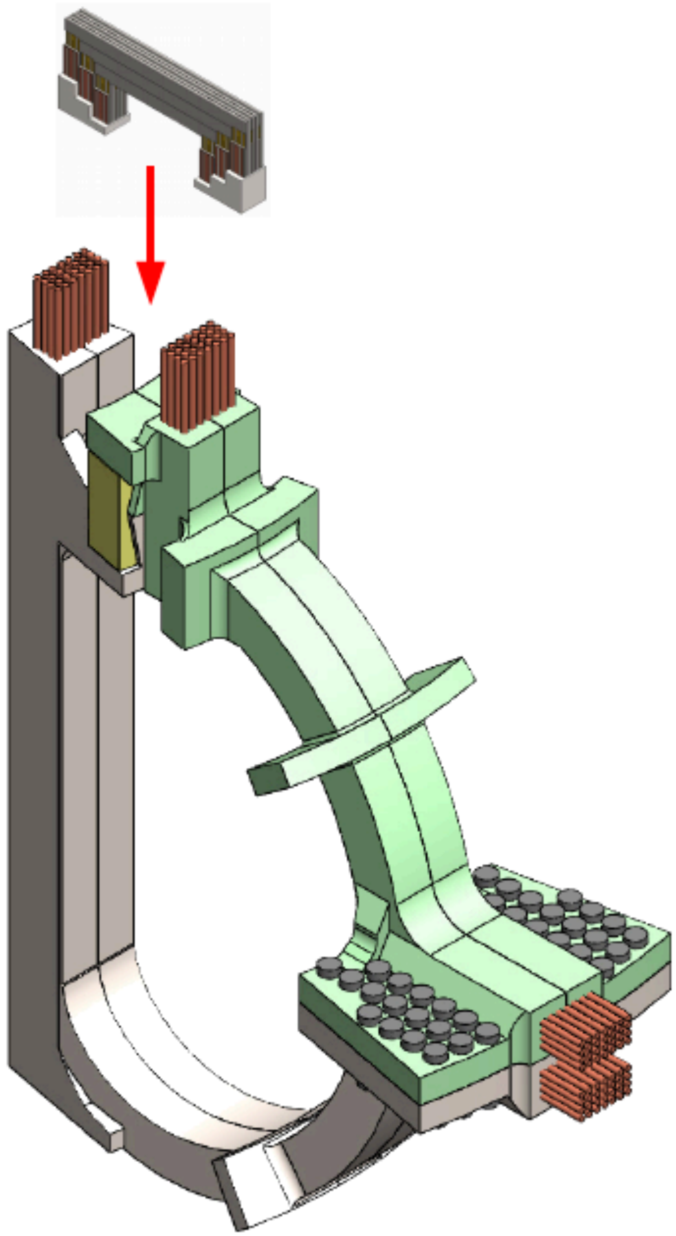


1. Support ring, 2. Top TF leg
4. Mechanical joint
6. Epoxy enforcement

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

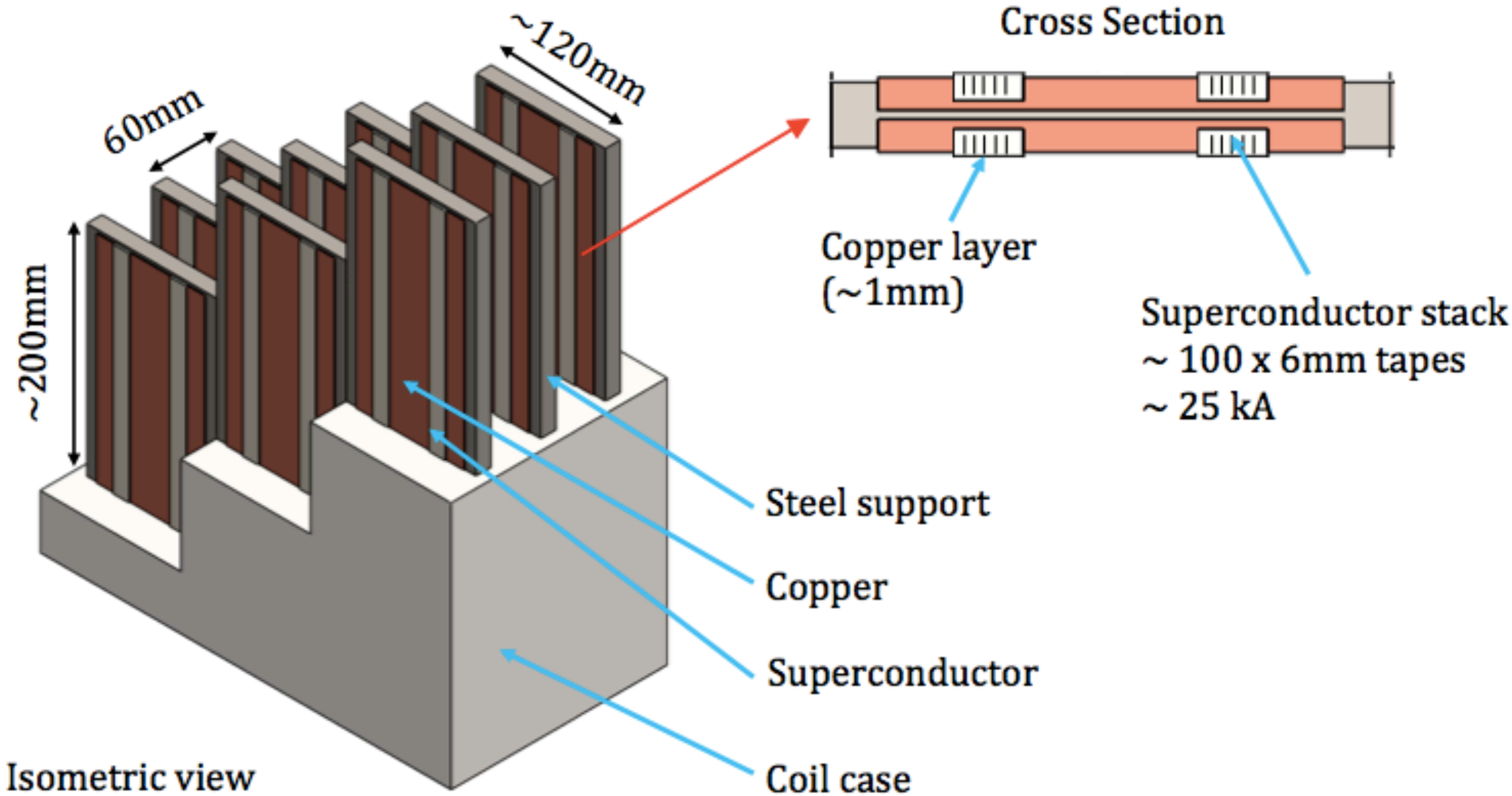


Demountable TF coil: Evolving strategy → Separation of mechanical and electrical joints



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

One design example:
Plate terminations with edge joints



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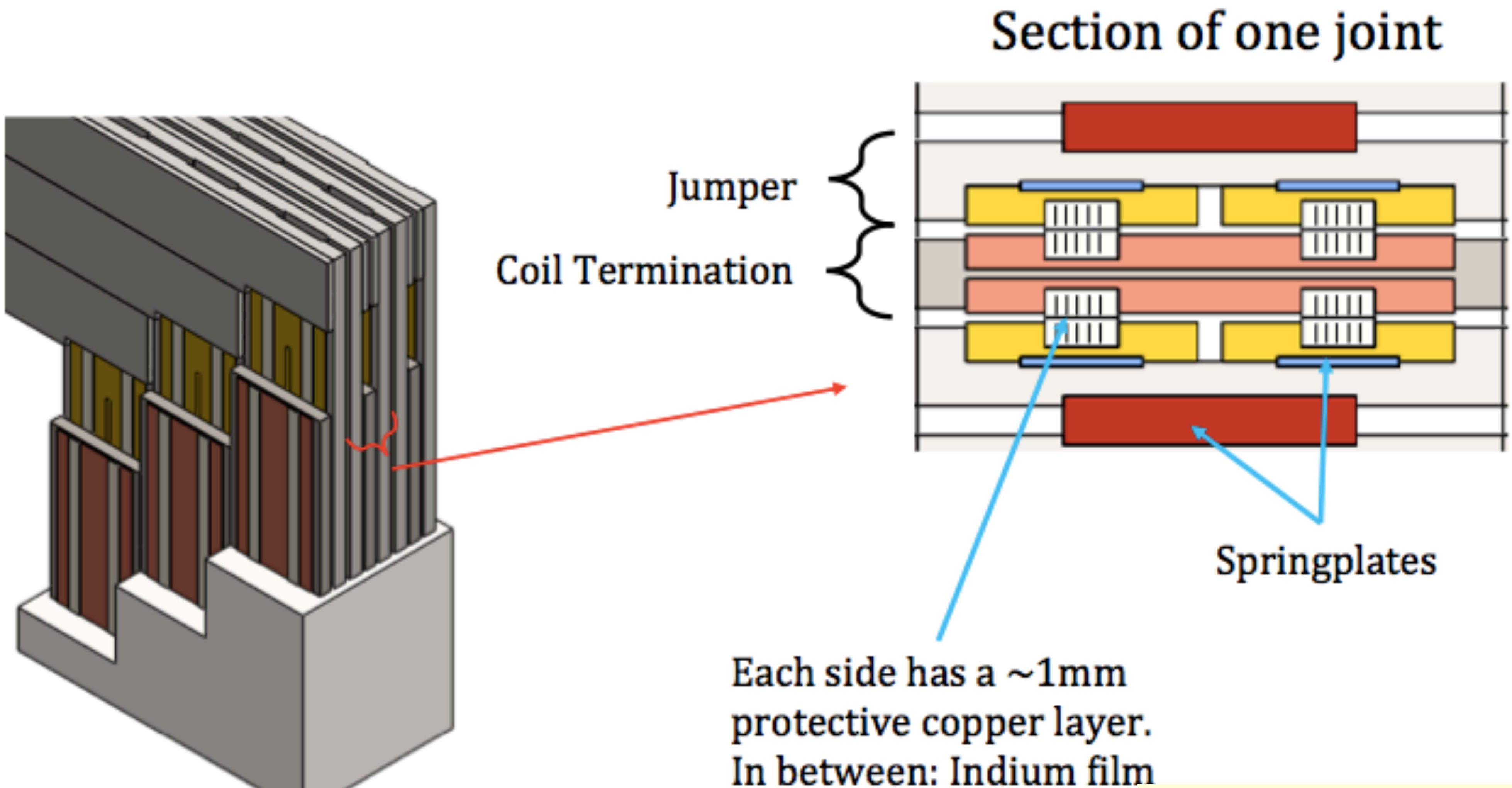
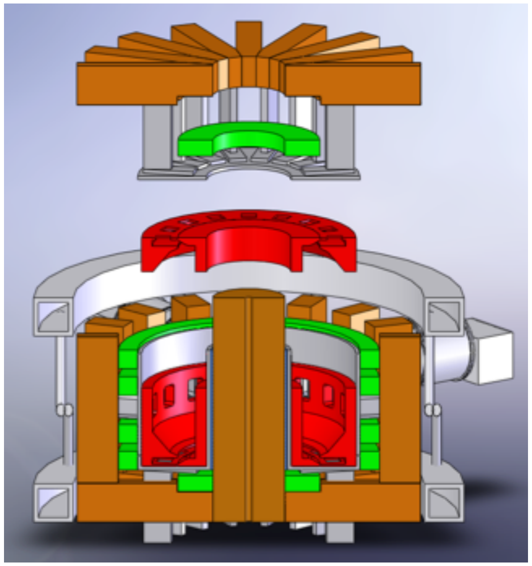


F. Mangiorotti, J. Minervini
MIT Ph.D. thesis

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

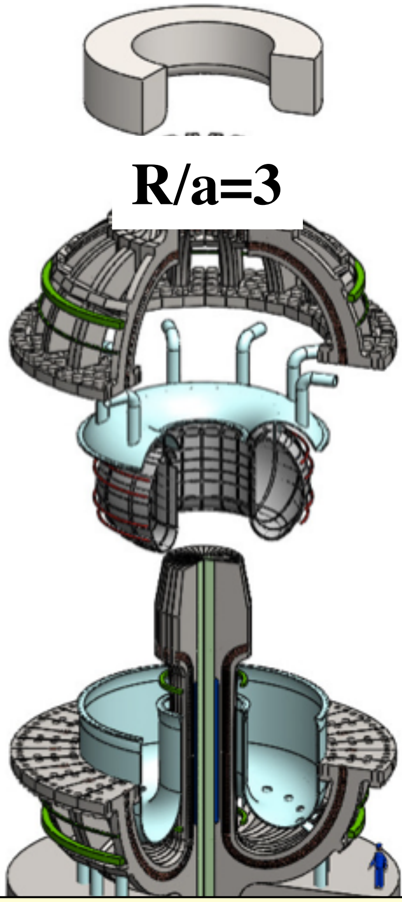
- Greatly reduces required cooling power (Carnot).
- Thermal stability due to higher heat capacity.
- Operation or ARC at T~25 K
  - Small power to joints
  - Liquid H or Ne for cooling options

R/a=3.5



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

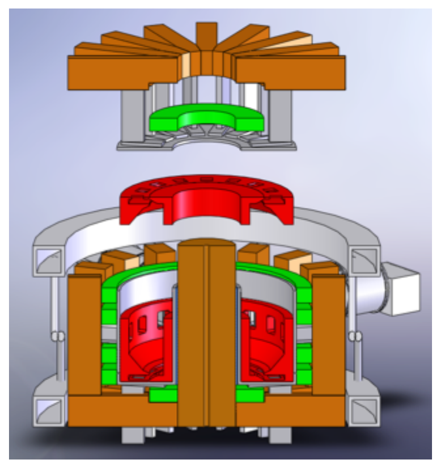
R/a=3



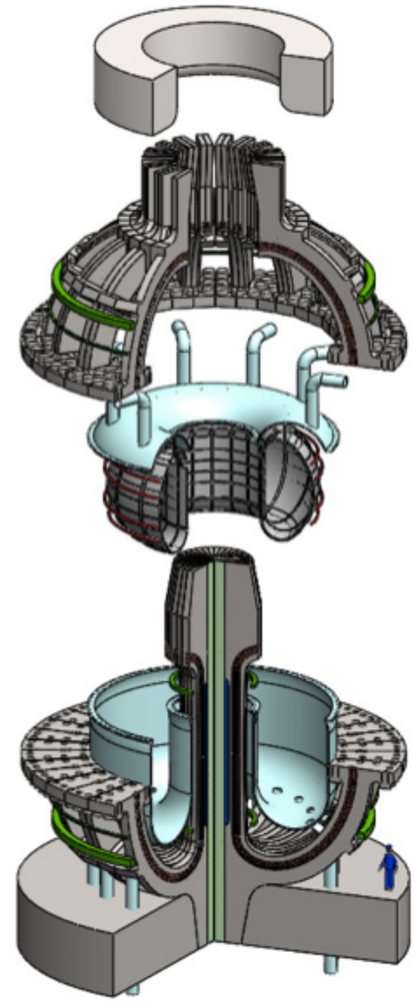
ARC: Resistive joints /w REBCO superconductors
Coil P_{coil}~ 1 MW

Demountability seems complicated… is it really worth it? Yes, for FNSF/Pilot

- Demountable design transfers complex, integrated risk away from the speculative nuclear components and places it on "non-nuclear" mechanical/electrical engineering.
  - ➢ Nuclear components have "Catch-22" problem: needs FNSF to test its own components!
  - ➢ Can demonstrate demountable joints at small scale.
  - ➢ Device maintenance with modular coils: single leg failure of TF can be tolerated



Copper FNSF



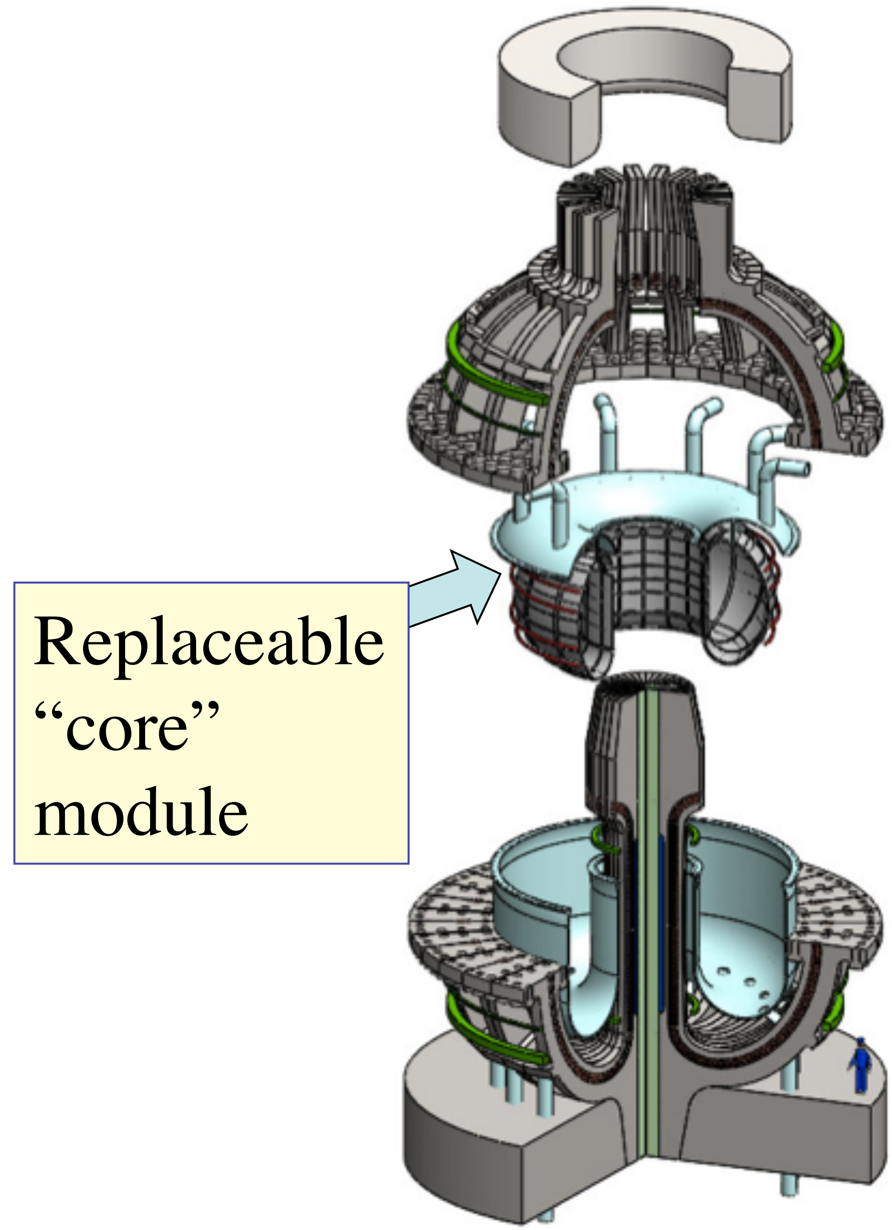
ARC

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

- Core is designed as a single integrated unit
  - PFCs, vacuum vessel, blankets
  - Synergy with keeping design of small total mass and volume

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

- No connections made inside TF

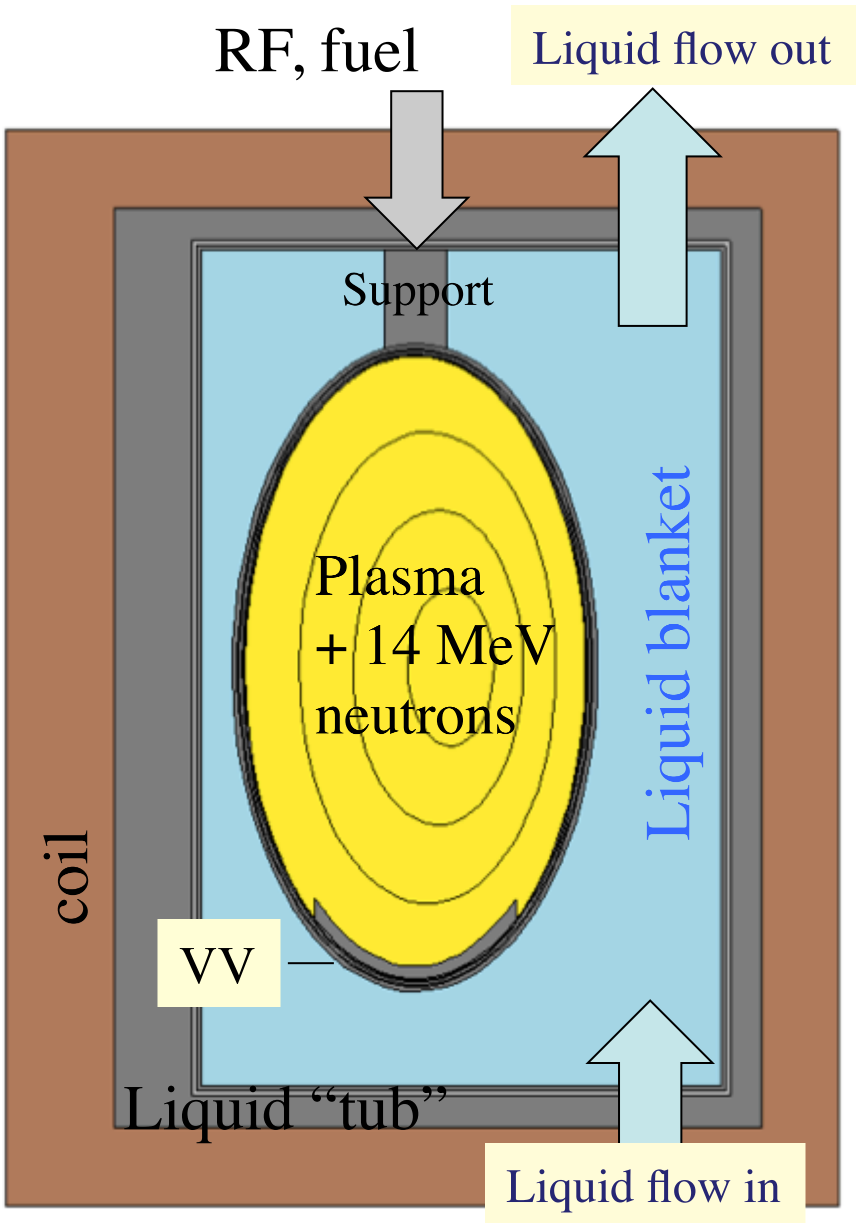


Modular core can have a profound effect on fusion design: e.g. the immersion blanket

- **VV is right beside plasma**
- **VV is immersed in liquid blanket**

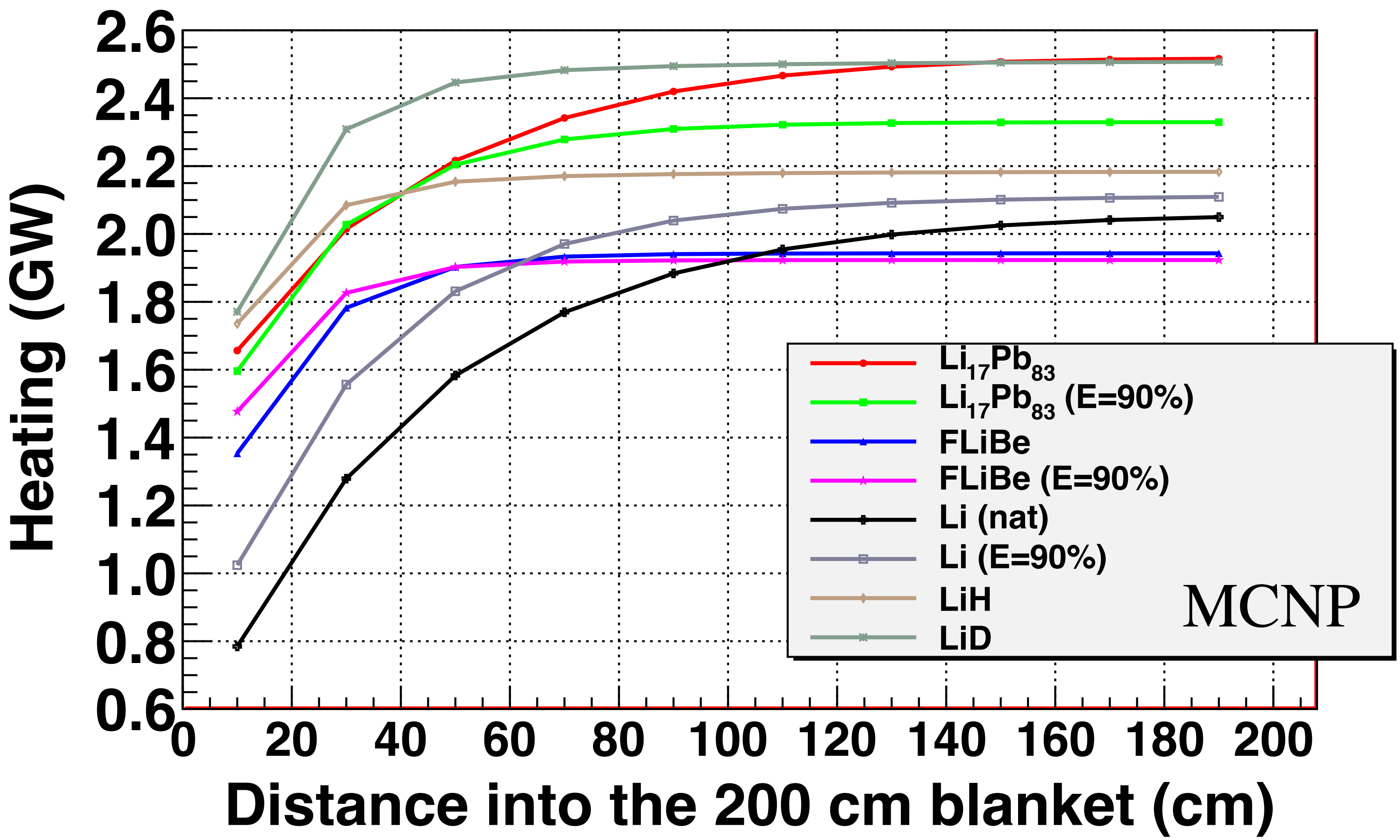
<u>Advantages</u>

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



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

Heating with 2mm W first wall, 2.54cm Inconel-625 vessel



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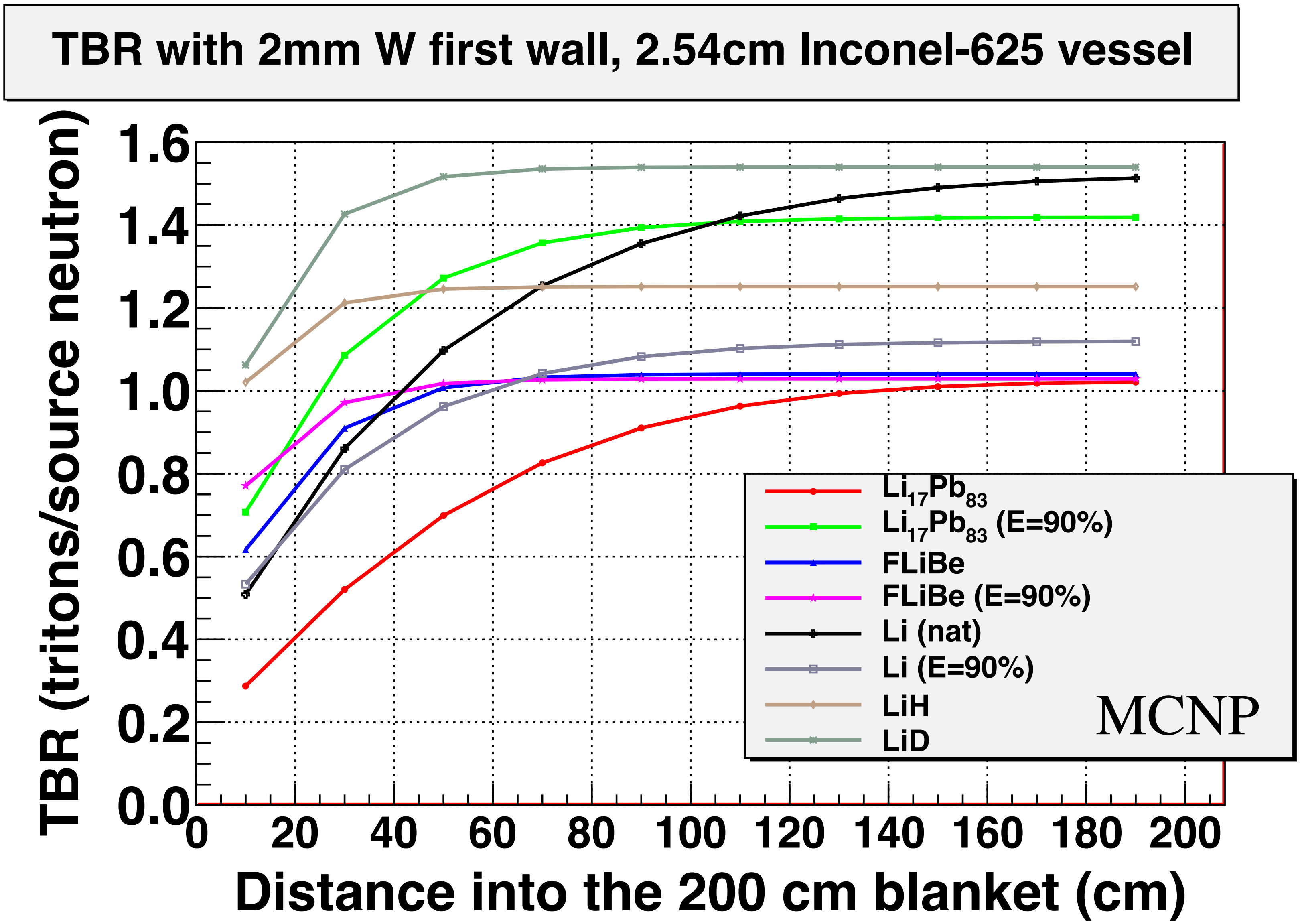
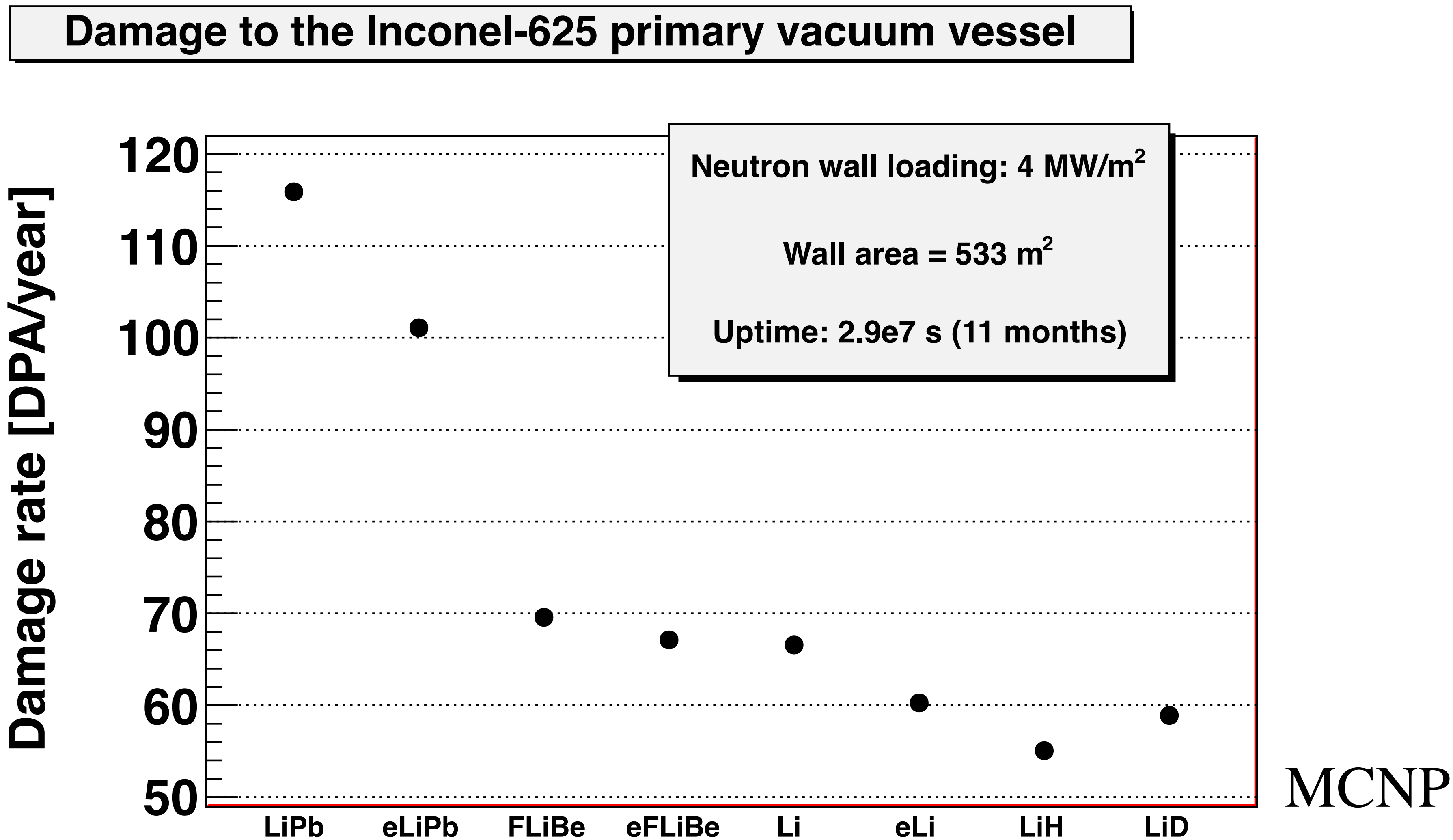


Immersion blanket: Solid, replaceable components (plasma-facing materials, vacuum vessel) receive minimized neutron damage immersed in low-Z fluid



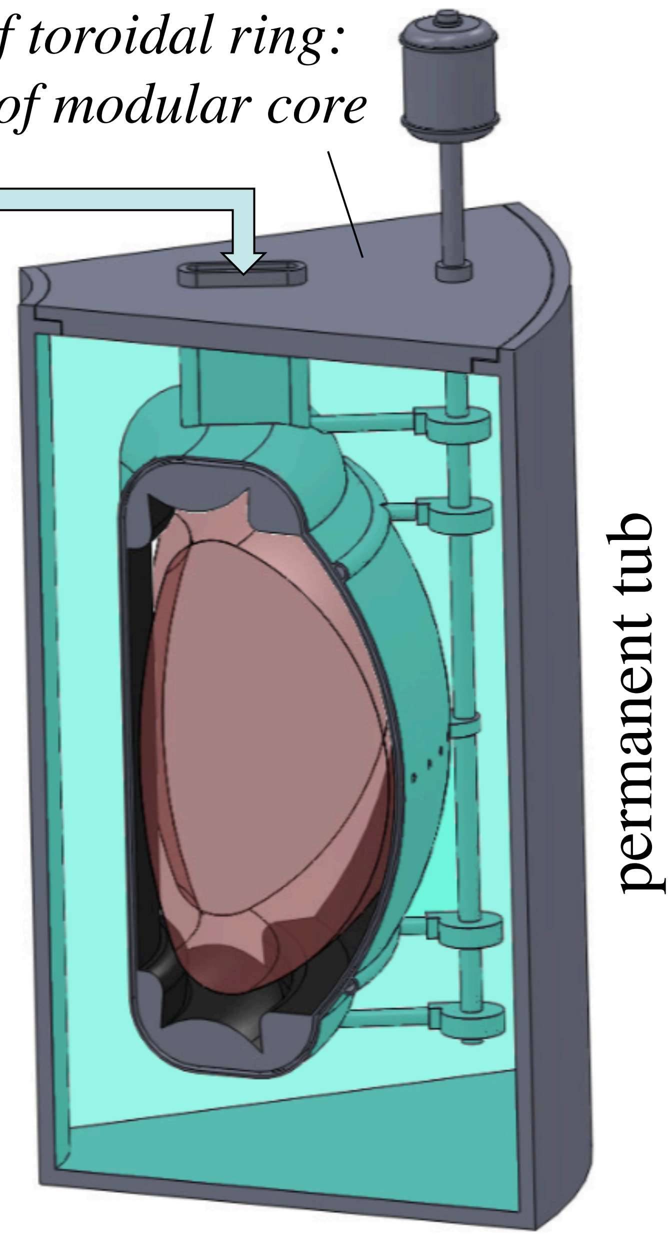
Z. Hartwig, C. Haakonsen MIT

While in many ways, immersion blanket is ideal (see fission!) it does limit areal access to plasma

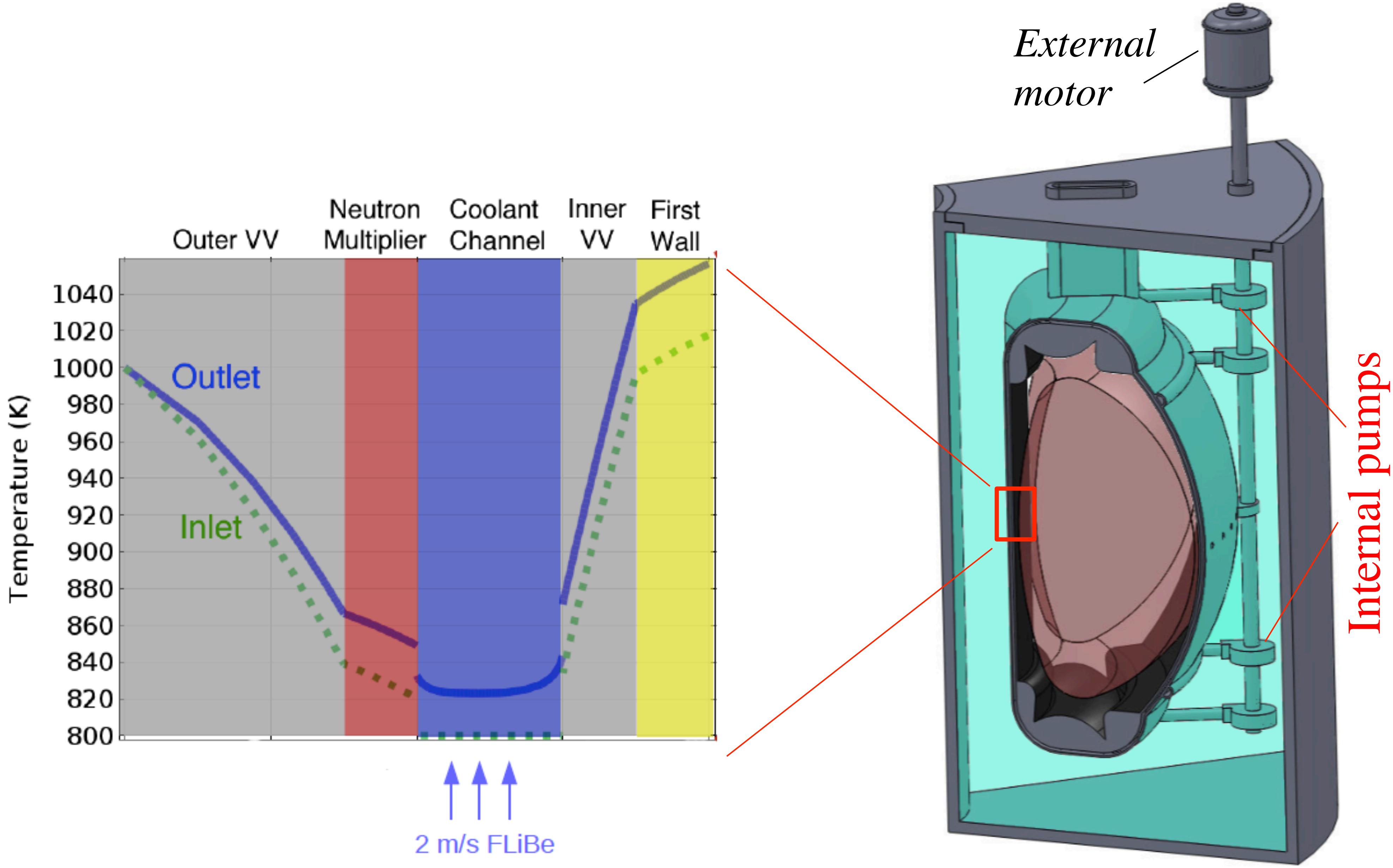
- Heating, pumping, diagnostics must wind through supports

- ARC: Total ~ 4-5 m^2
  - RF heating: ~1 m^2
  - Support: ~ 1-2 m^2
  - Pumping ~ 0.5 m^2

- Tradeoff: more port area vs. TBR, neutron streaming



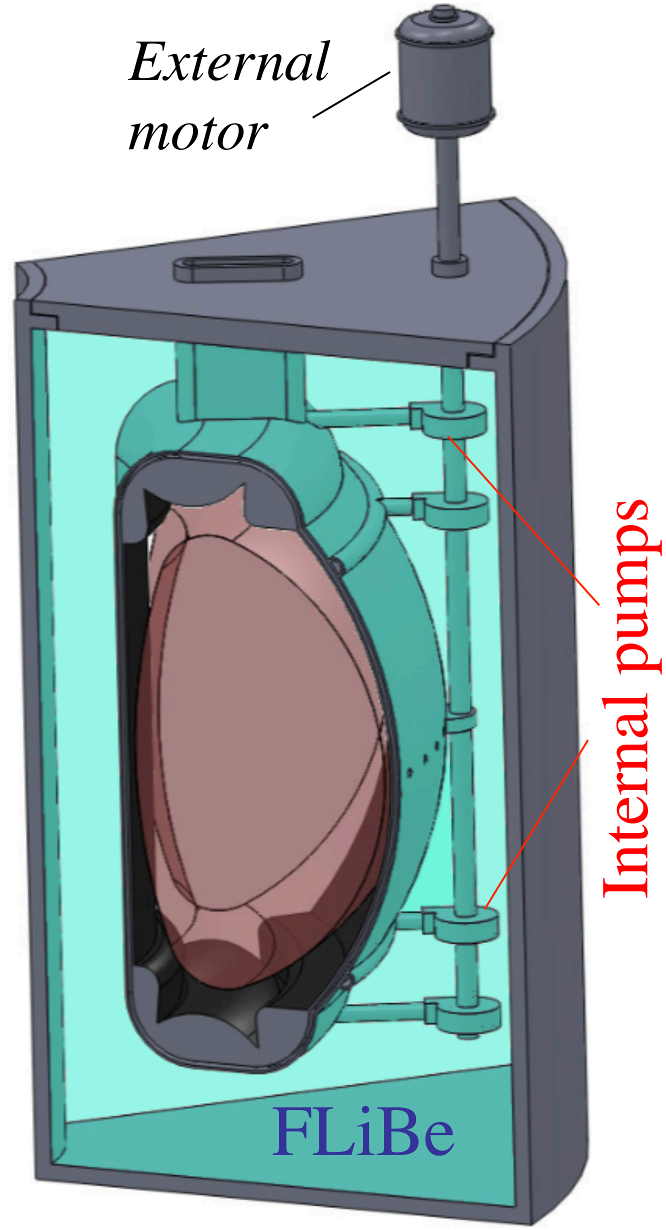
Immersion blanket: Very large heat sink in close proximity to internals provides fundamental improvement in heat exhaust



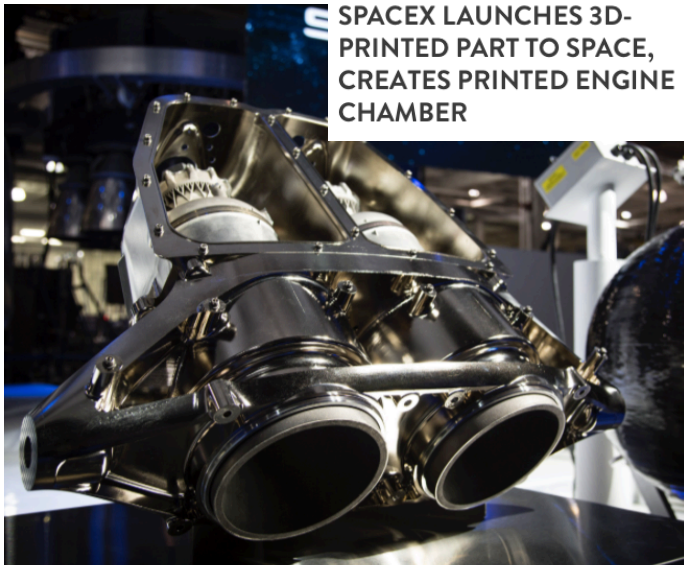
Immersion blanket: high-T molten salt FLiBe Single-phase, low-pressure flow with minimum MHD effects

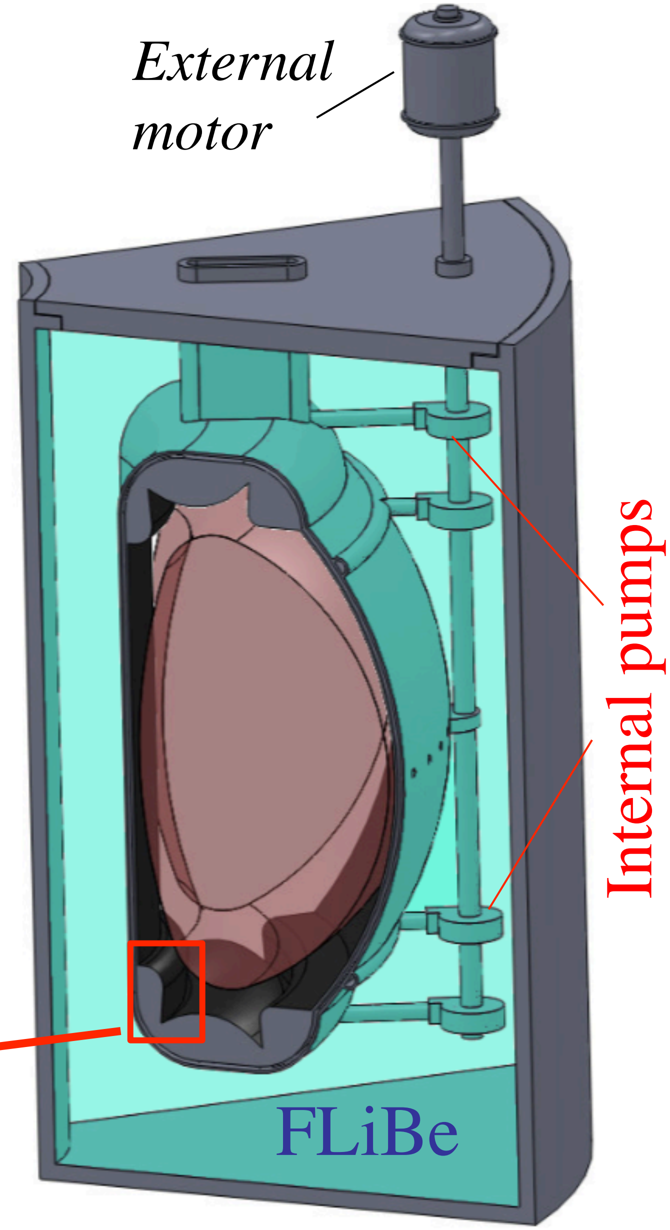
Property	FliBe [7]	Water
Melting Point (K)	732	273
Boiling Point (K)	1700	373
Density (kg/m^3)	1940	1000
Specific Heat (kJ/kg/K)	2.4	4.2
Thermal Conductivity (W/m/K)	1	0.58
Viscosity (mPa-s)	6	1

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



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



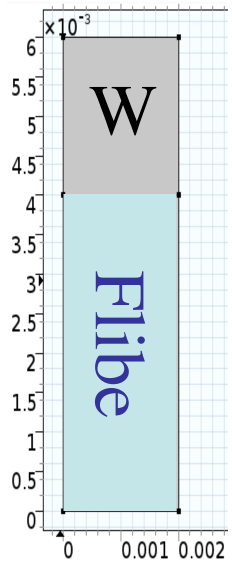


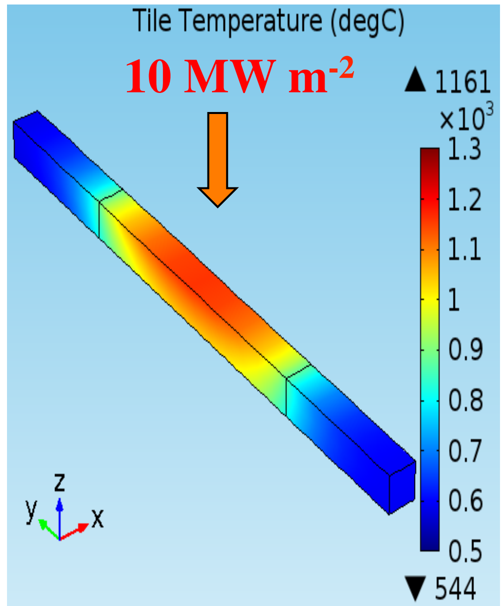
- TBR ~ 1.14
- High thermal efficiency ~ 0.4 - 0.5
- Shielding: 10 full-power coil lifetime
- Exploit FLiBe + Immersion blanket + Additive manufacturing to address high heat flux regions?

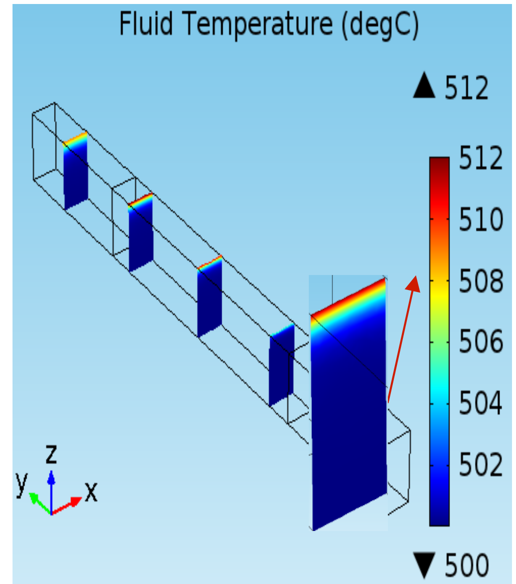
Preliminary study: Improved surface heat removal with FLiBe + 3-D printed cooling channels

Next major design study: ARC divertor & cooling

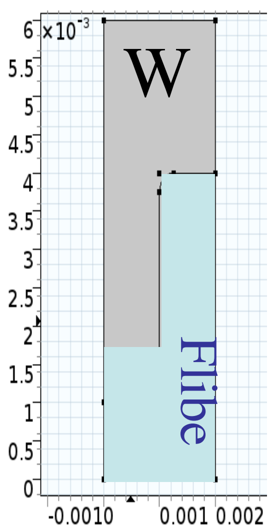
2 mm thick W tile

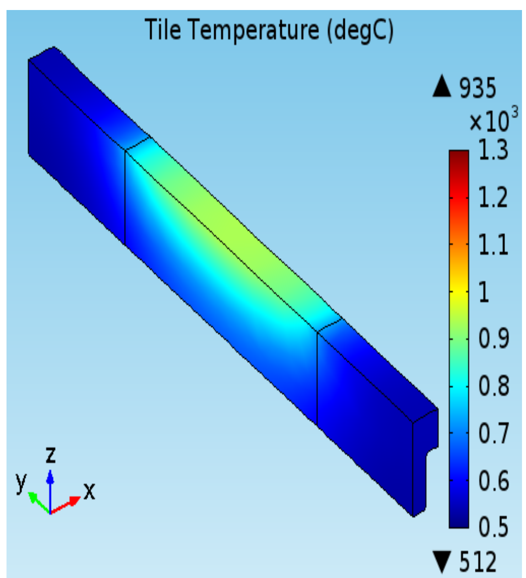


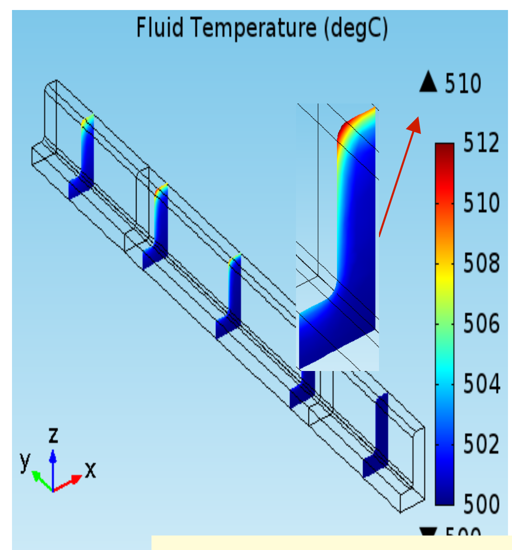




2 mm thick W tile + Internal Fin







10 m/s

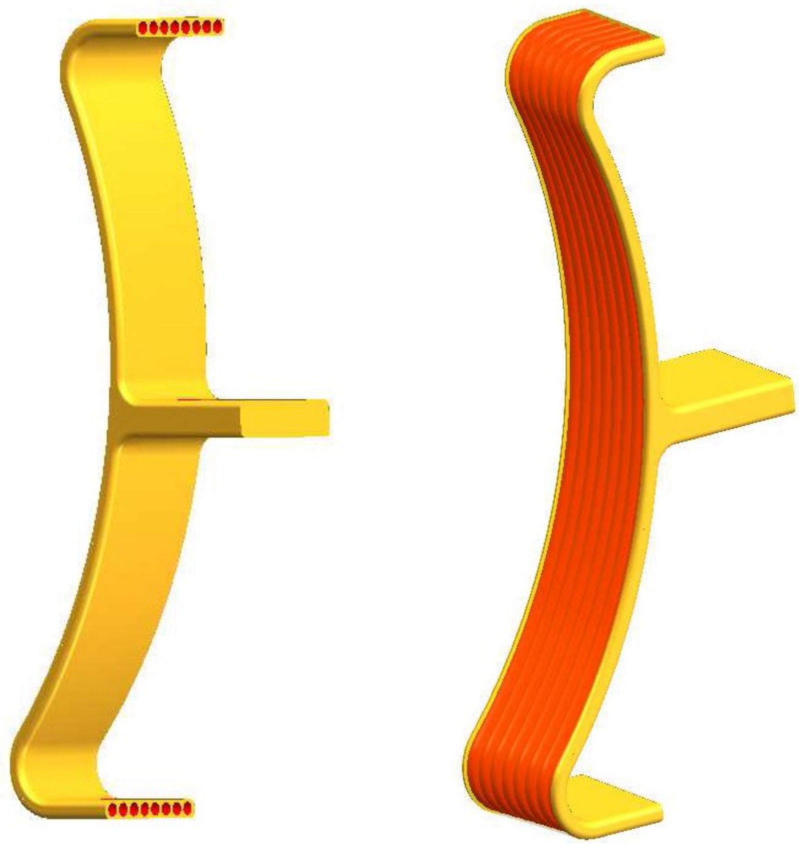
~ 1 bar pressure drop

L. Zhou, R. Vieira MIT

Strong benefits of 3D printing for actively cooled launchers too

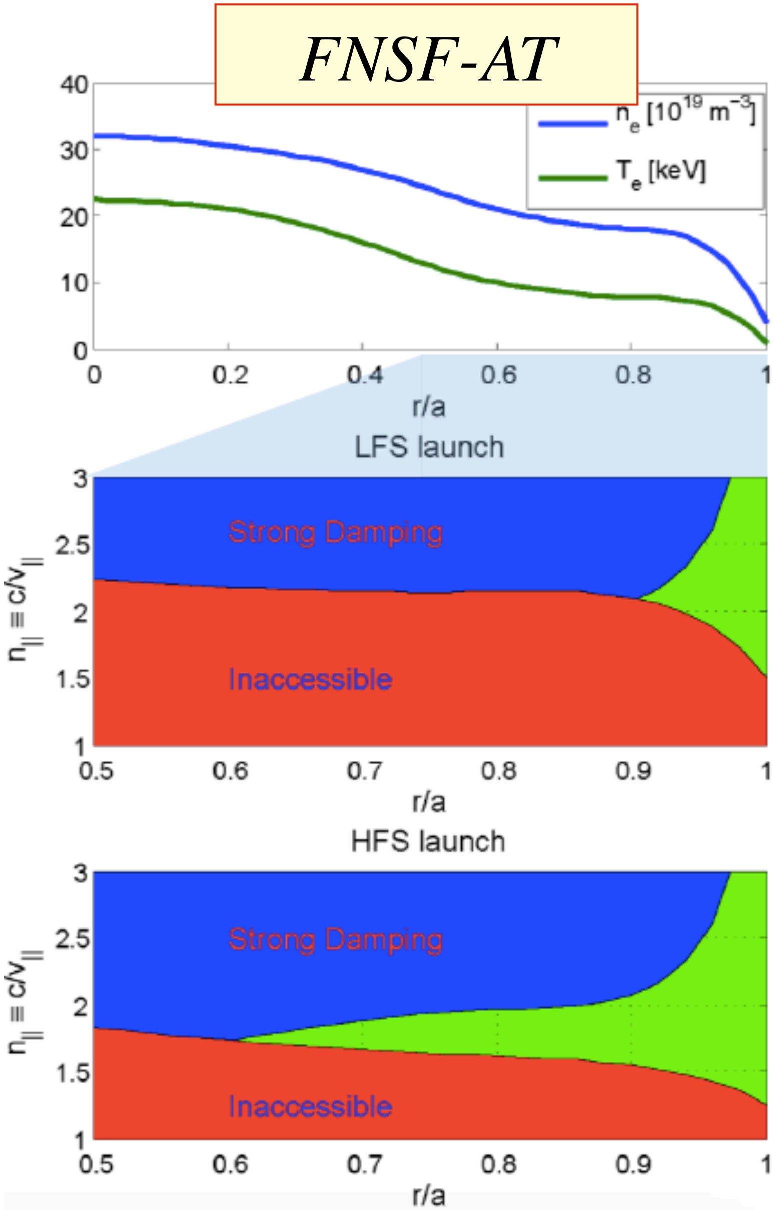
Example RF antennae strap

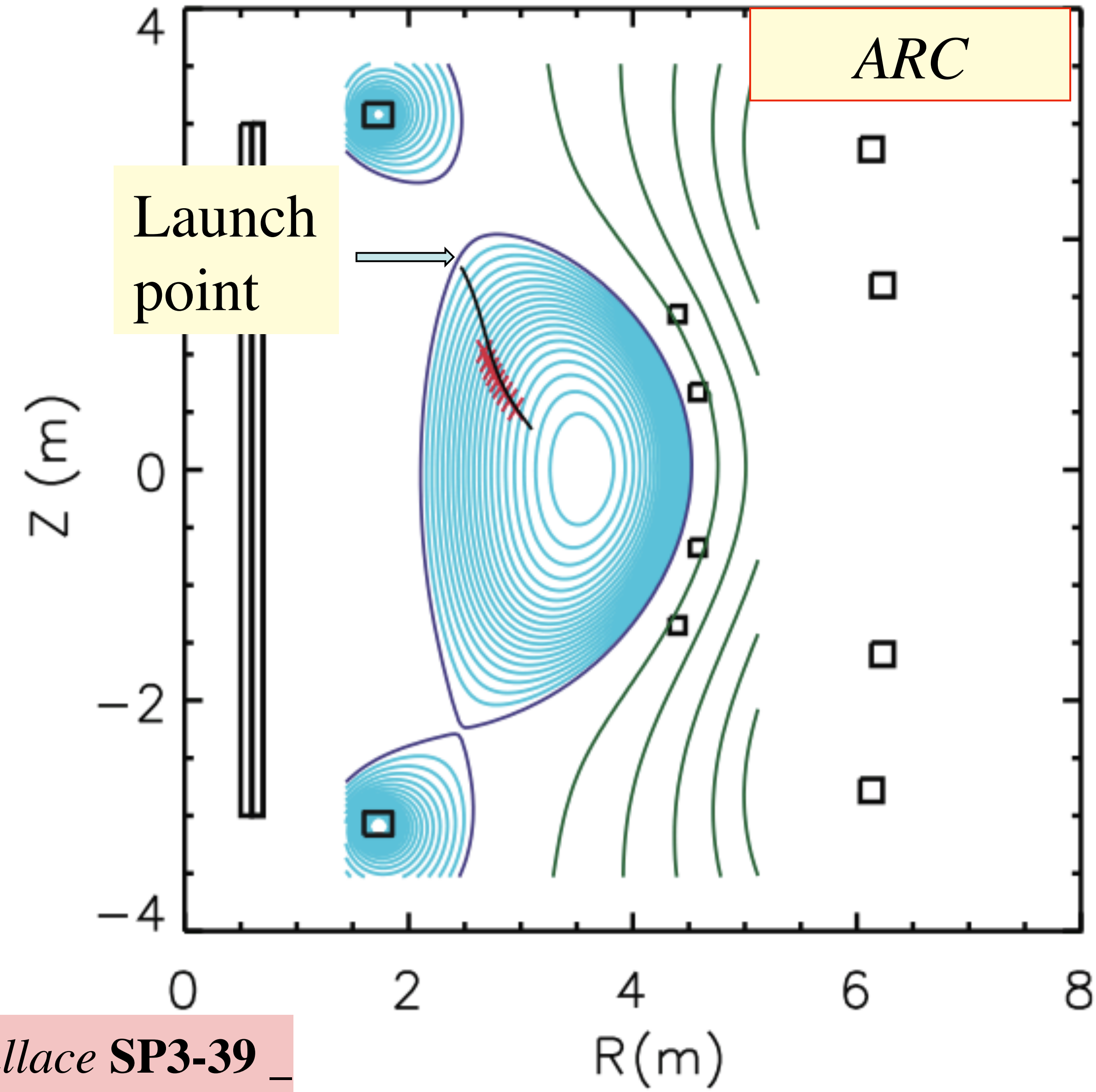
Integrated, near-surface cooling channels impossible /w standard manufacturing



S. Wukitch
Tue pm
SO15

New technologies provide access to synergistic physics design advantages at high-B and small size:
High-field side launch → + 50% CD efficiency





Wallace **SP3-39** _

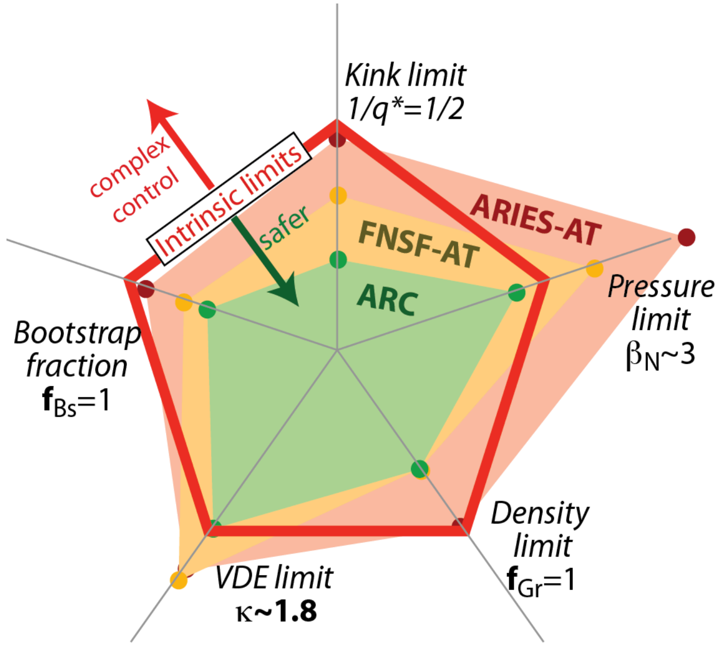
New technologies provide access to synergistic design advantages at high-B and small size: Robust steady-state far from disruptive limits

	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

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

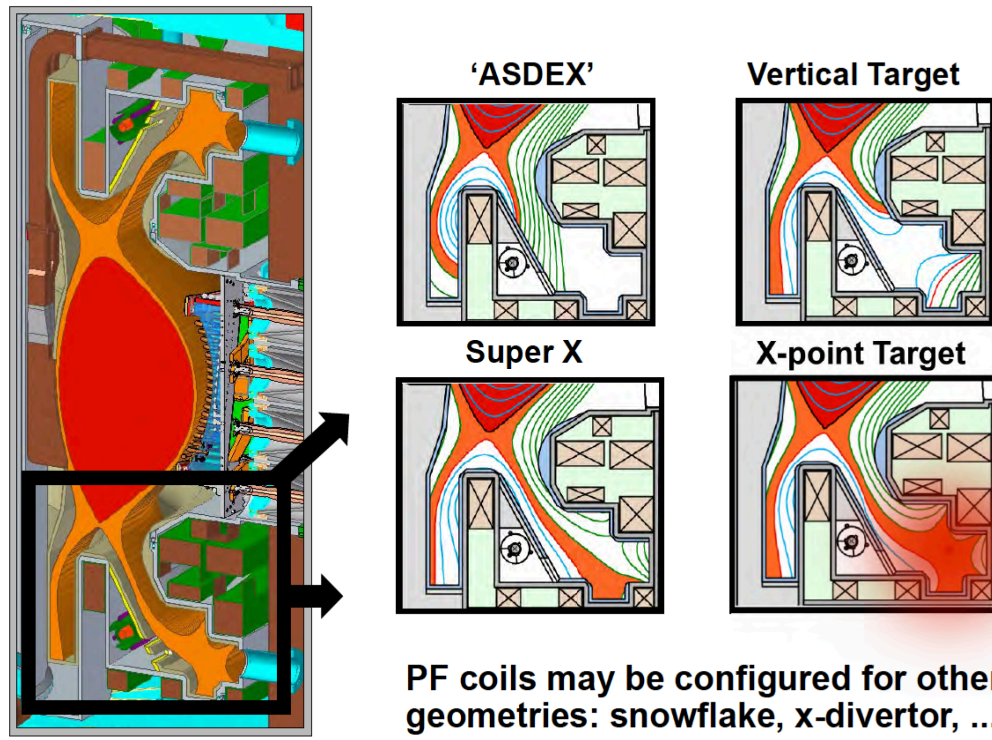
$$nT\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

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



Modularity and small size should be enabling to solving critical issue of divertor heat exhaust

- Large linear size, low B unfavorable for heat exhaust
  - At fixed fusion power density, Eich scaling → **q// ~ R B**
  - Lawson criterion: $R \sim 1/B^{2.3}$
  - **q// ~ 1 / $B^{1.3}$**
- Advanced divertor coils built into modular core as replaceable components
  - Exploit physics advances from expanded volume divertors

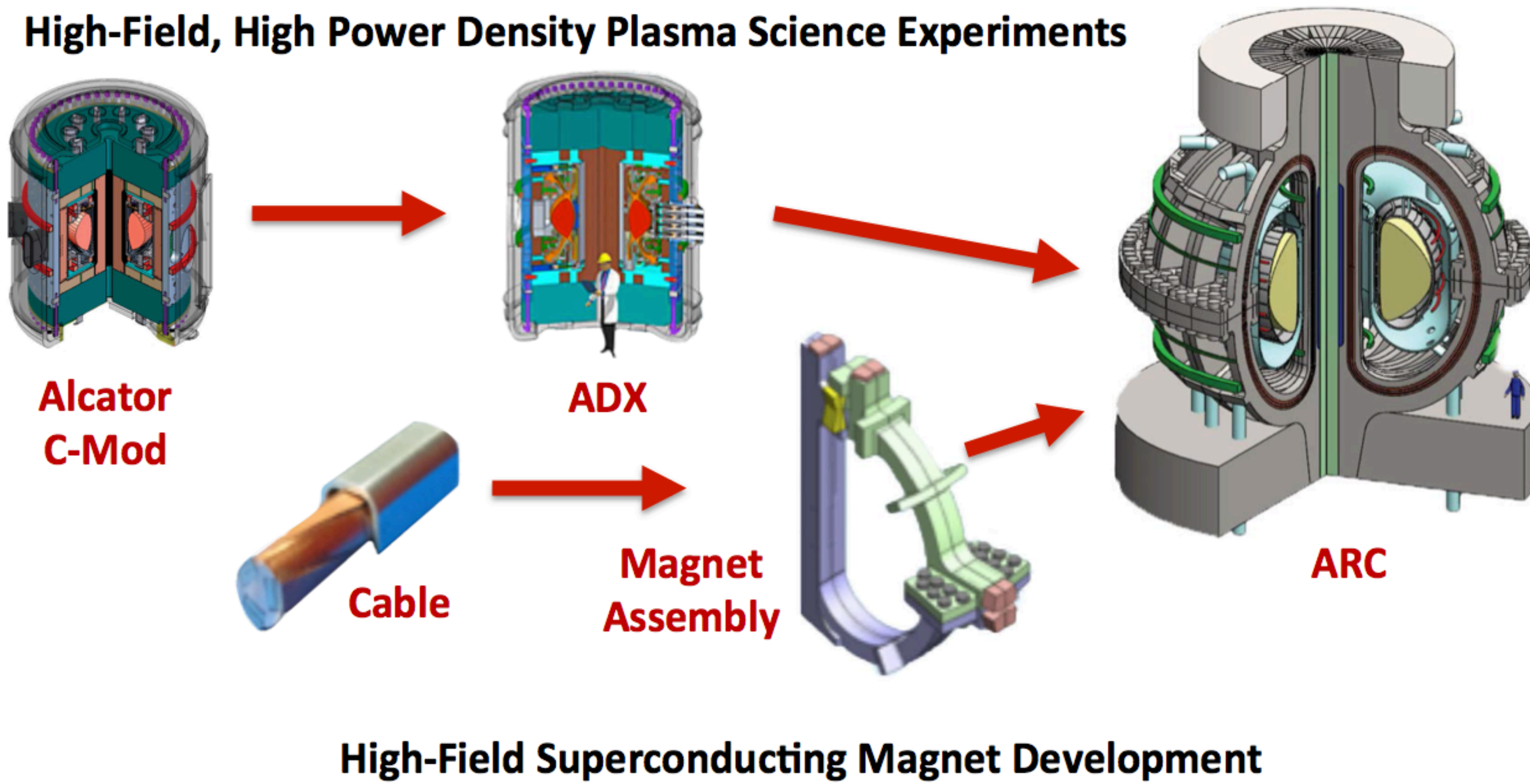


ADX presentations

LaBombard **SO10-3 Tue AM**

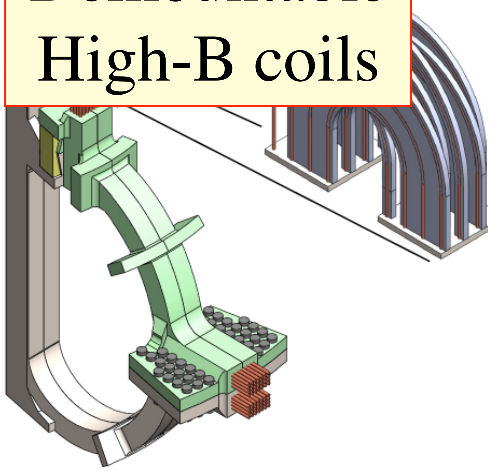
Posters**: SP3 Tue PM**

Near-term, *small-scale* research can pursue this exciting path for fusion energy

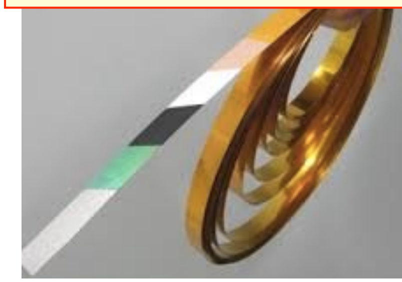


The disruptive innovation of high field, high-T superconductors

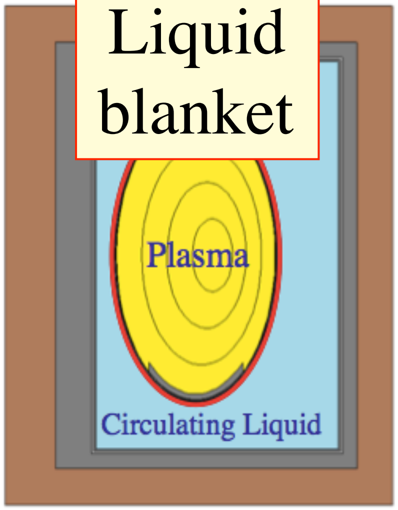
Demountable High-B coils



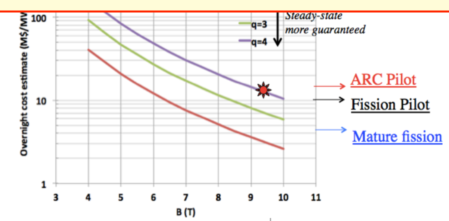
Superconductor



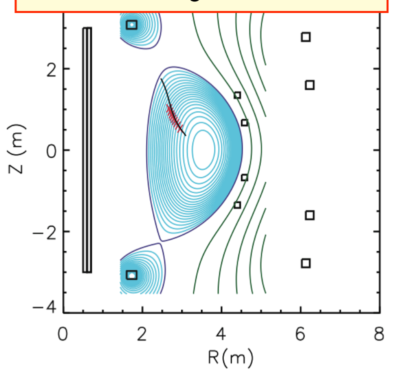
Liquid blanket

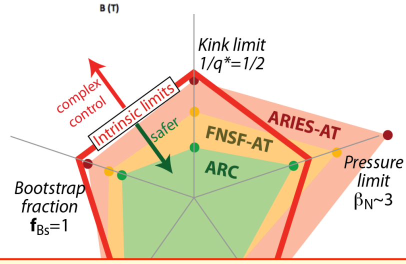


Smaller, sooner Viable fusion energy



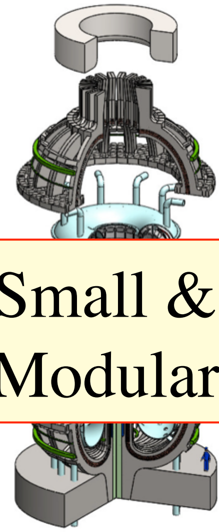
Steady-state





Operation robustness

Small & Modular



Summary

- Fusion is hard …as a community we need to be continually looking for both technology and science innovations that will accelerate fusion's development

- Exciting technology opportunities recently available:
  High-temperature, high-field superconductors
  Additive manufacturing

- Conceptual reactor design shown here give a sense of technology limits and integrated effects on magnetic fusion… those effects appear to be positive and revolutionary

- **The near-term pace of fusion science development will also be accelerated by exploiting these technologies**