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

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With grateful acknowledgement to MIT colleagues and students
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June 2015

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!
- **Small size and modularity are self-reinforcing,** make pilots of complex engineered systems as small as possible, yet sufficiently capable

Confinement physics strongly favors high B to produce fusion capable devices at smaller size

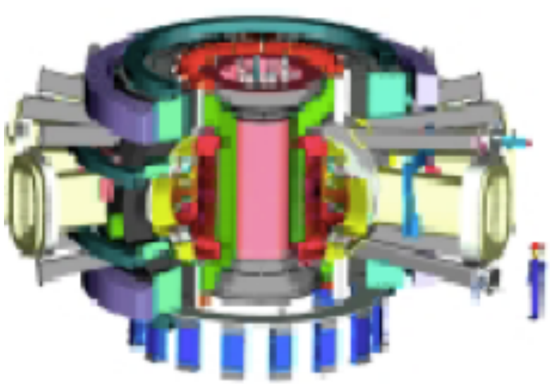
Gain $nT\,\tau_E \sim \dfrac{\beta_N H}{q_*^2} R^{1.3} B^3$

$V \propto R^3$

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

R (m)	2.14
V (m³)	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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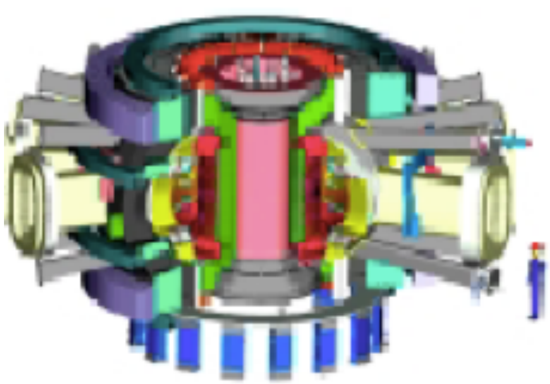

FIRE

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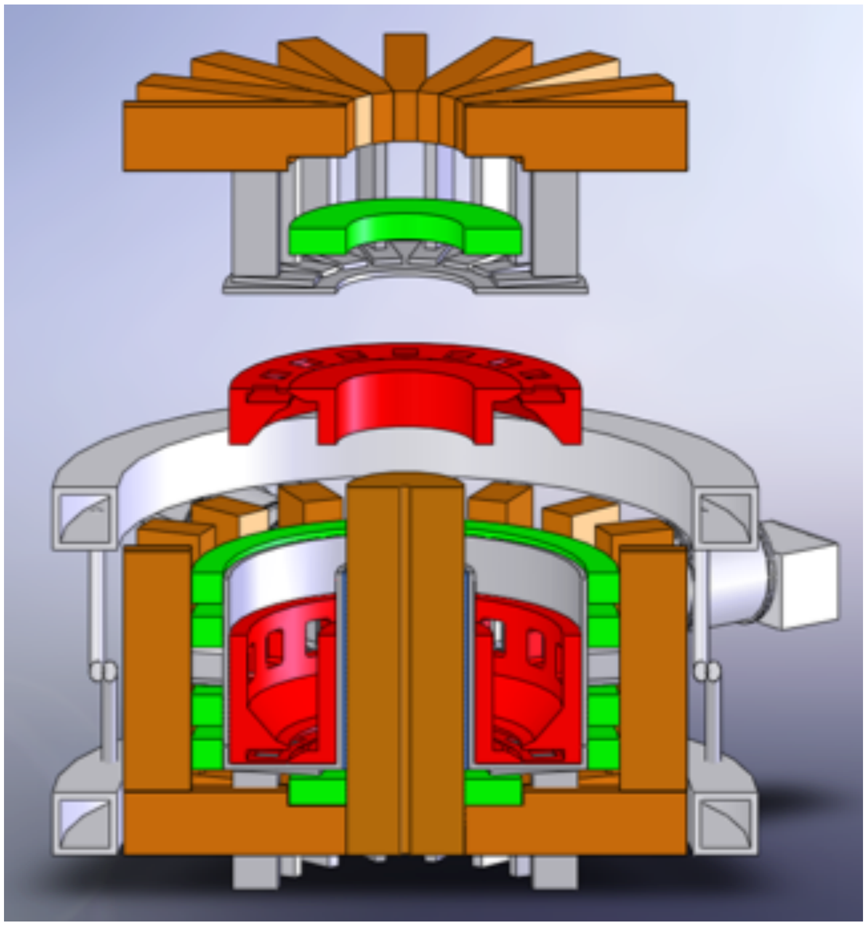
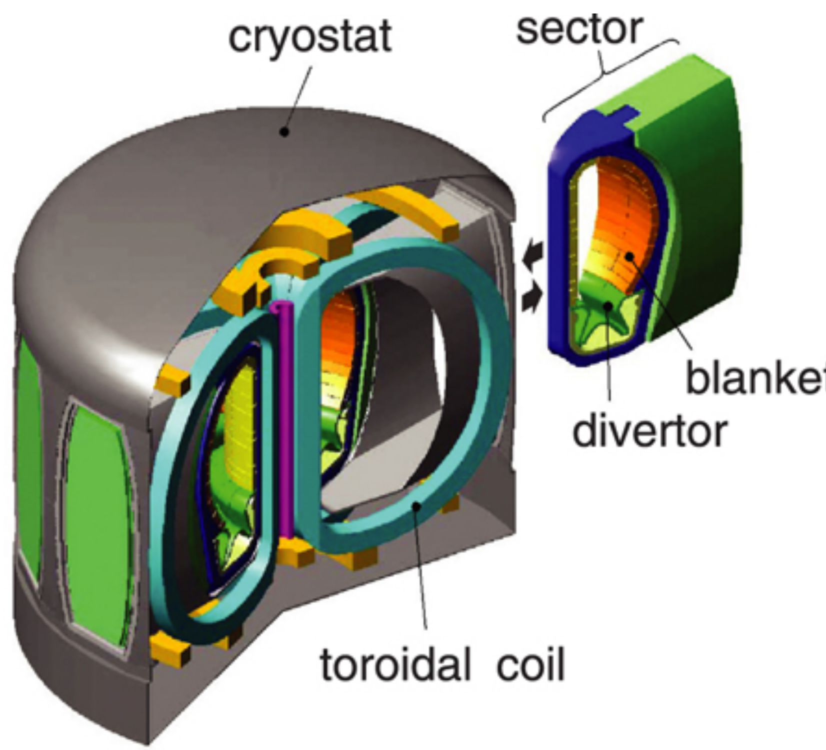
Continuous /w High-B Superconductors?

Basic geometry favors demountable magnets to provide modularity for internal components

😀



FNSF-AT V. Chan et al NF 2011



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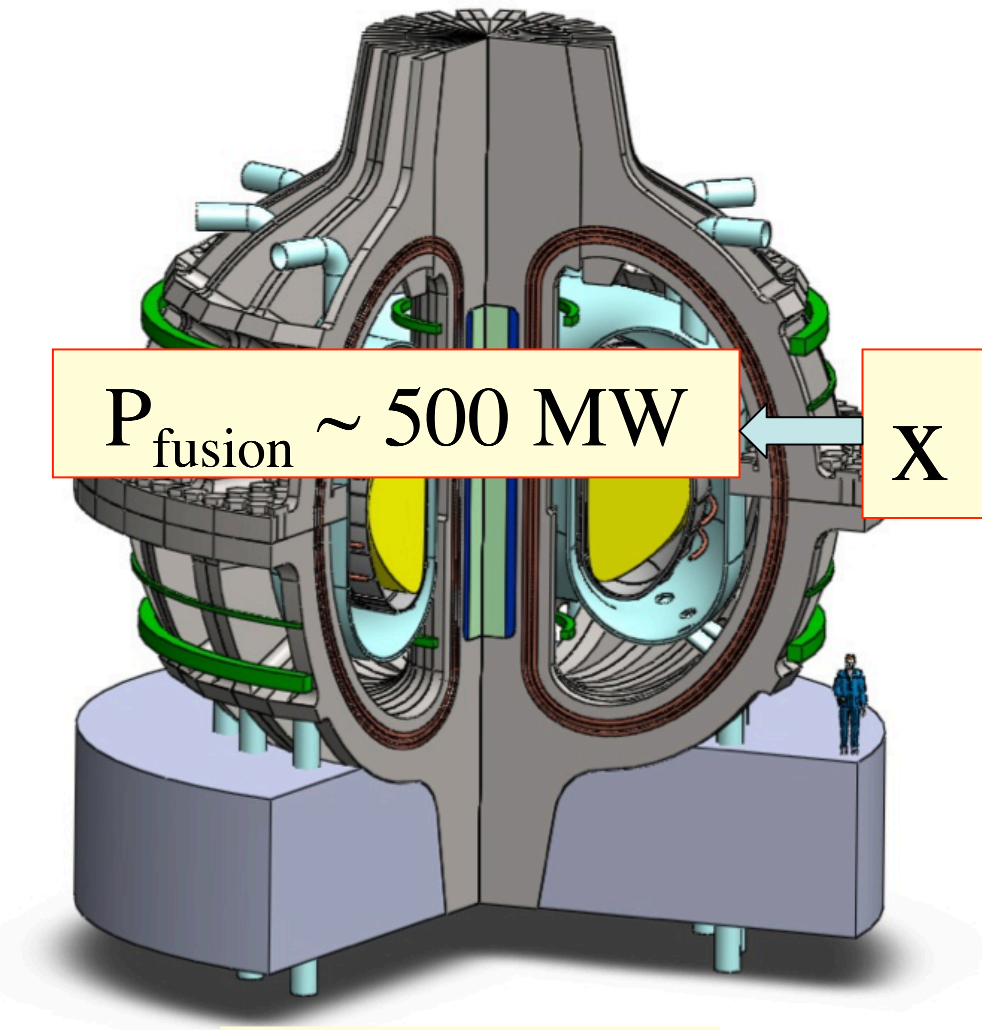
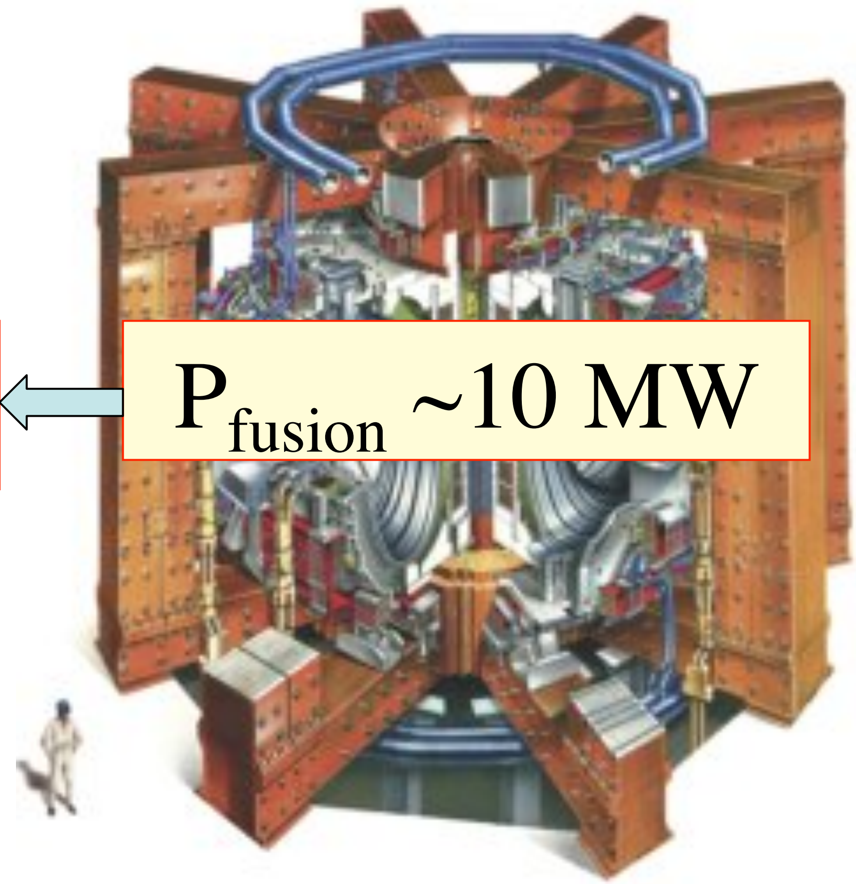
ARC conceptual design example of "smaller, sooner" fusion device using new superconductors

REBCO superconductor B = 9.2 T

Copper, B = 3.5 T



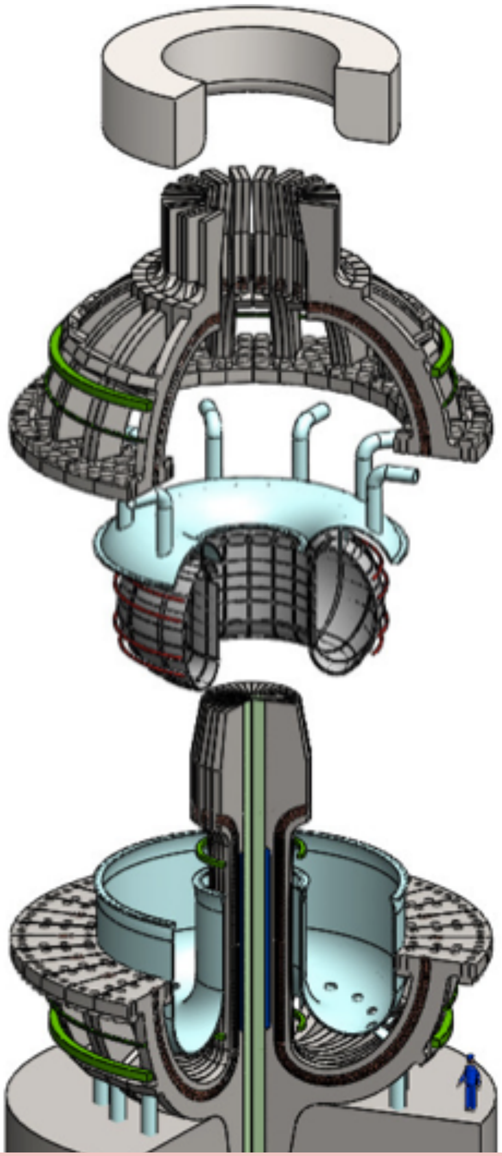


P_{fusion} ~ 500 MW ← x B^4 ← P_{fusion} ~10 MW

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



- Demountable magnetic field coils
- Single-unit vertical lift

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

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

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

Multiple, linked engineering design challenges to smaller, modular path

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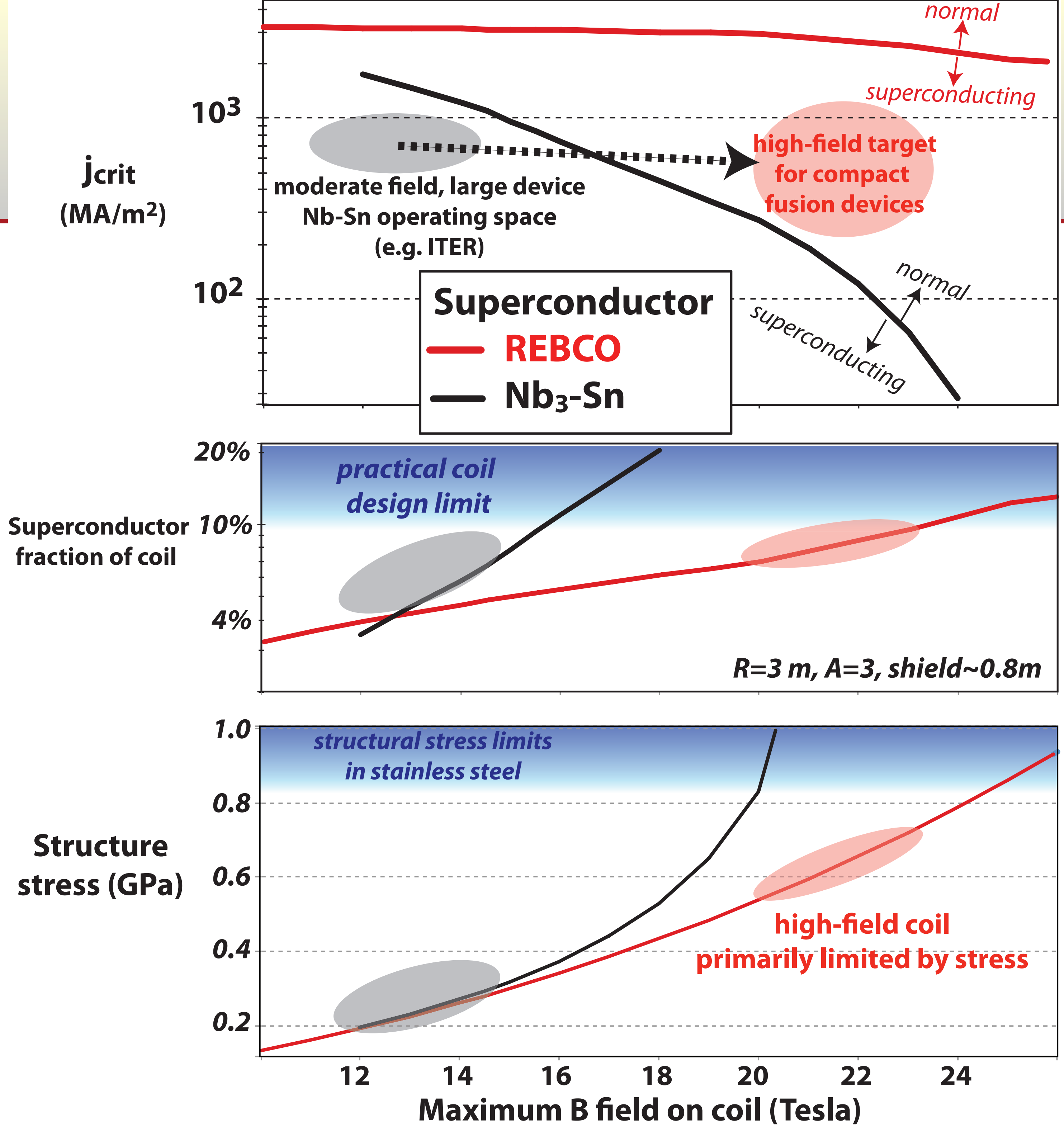
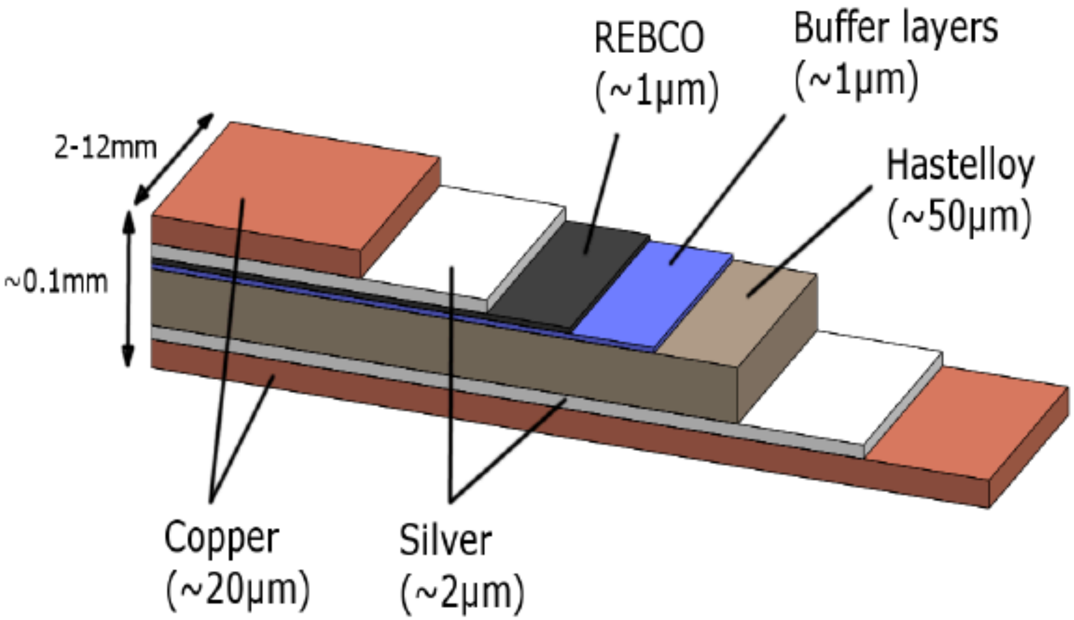
$B_{coil} > 20$ T	REBCO superconductors
SC	rm K
Demou	
Small r neutronics	anket
Internal components with small space + high power density	Additive manufacturing of single-unit VV/PFC with advanced cooling capability

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

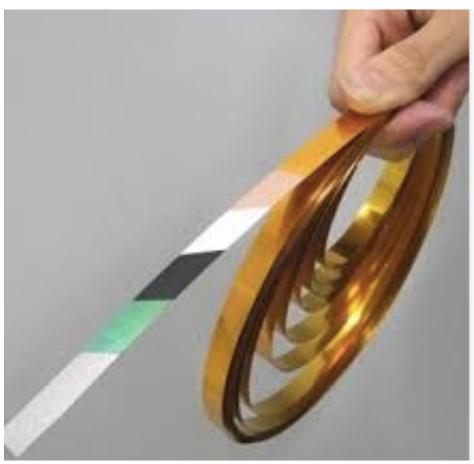
A revolution in superconductors in last 5 years: REBCO (Rare-Earth Barium Cu Oxide) remain superconducting at VERY high B-field and above liquid He temperatures



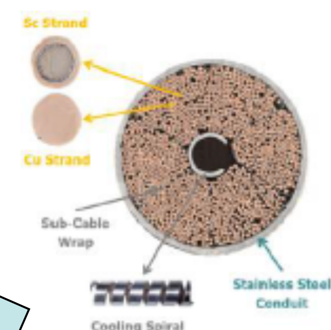
REBCO: coated superconductors in robust tape form, commercially available



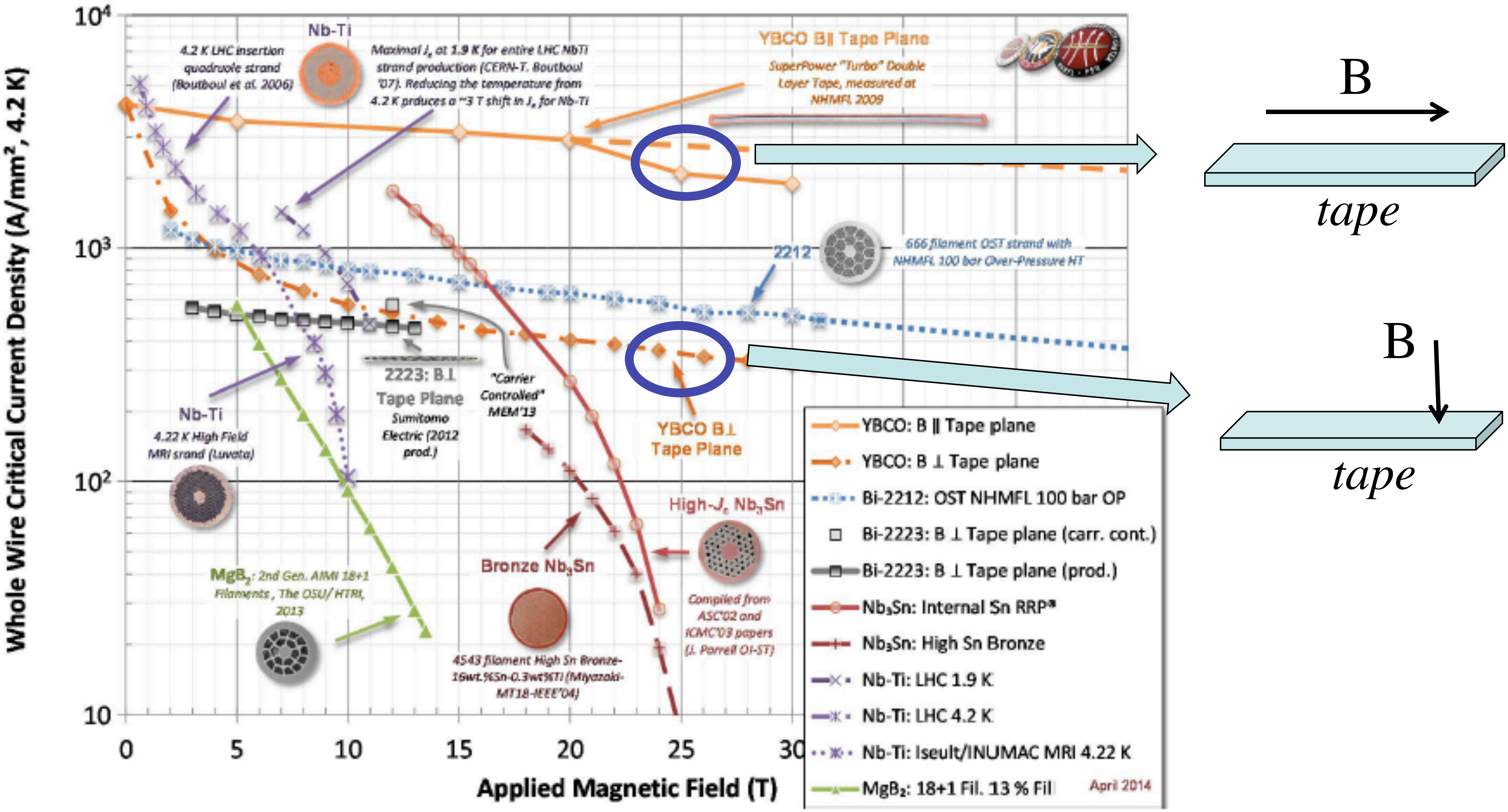
REBCO tape composition
(not to scale)



- 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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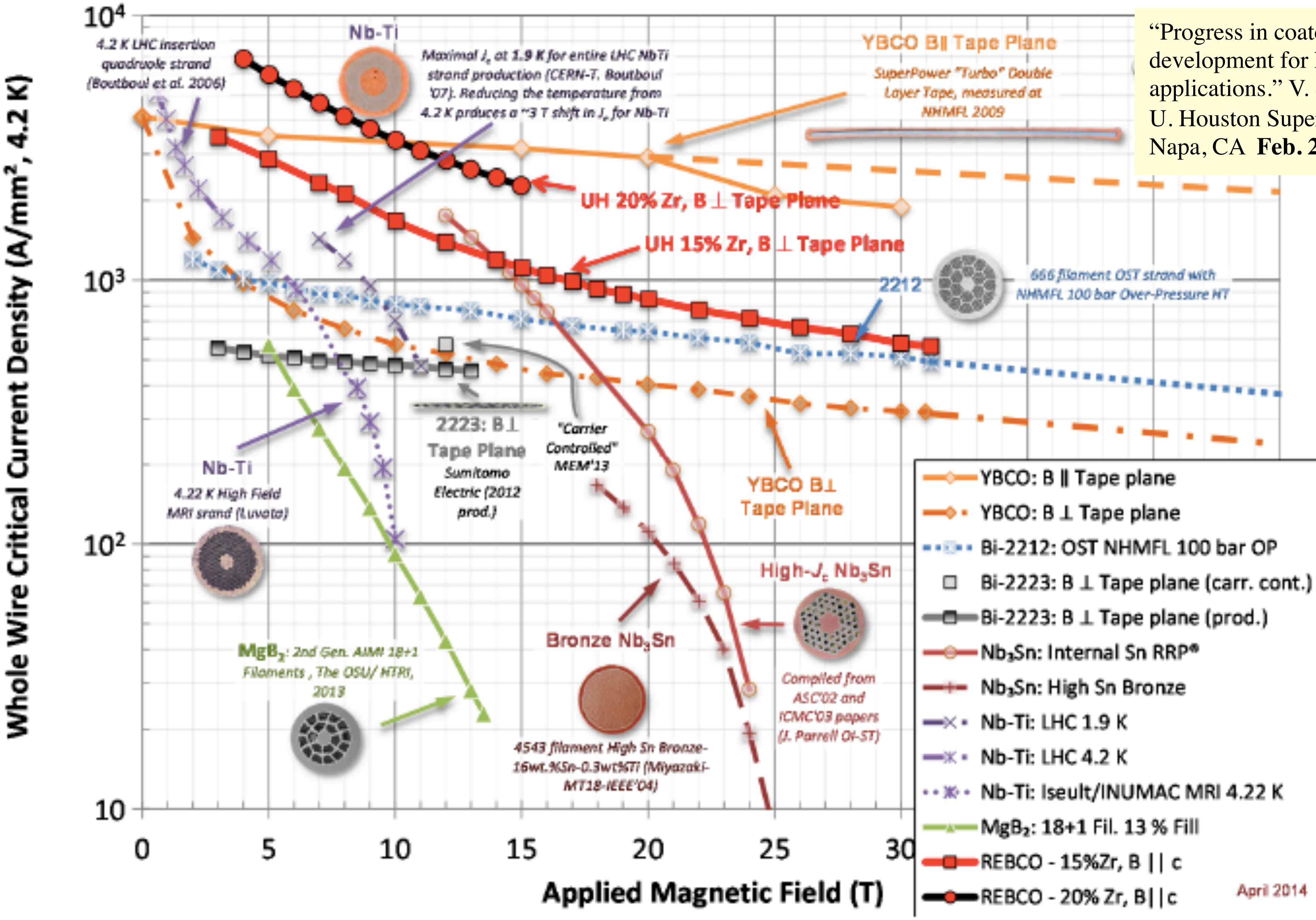
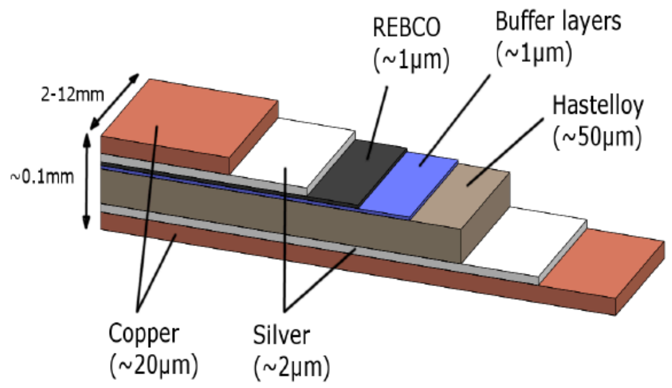
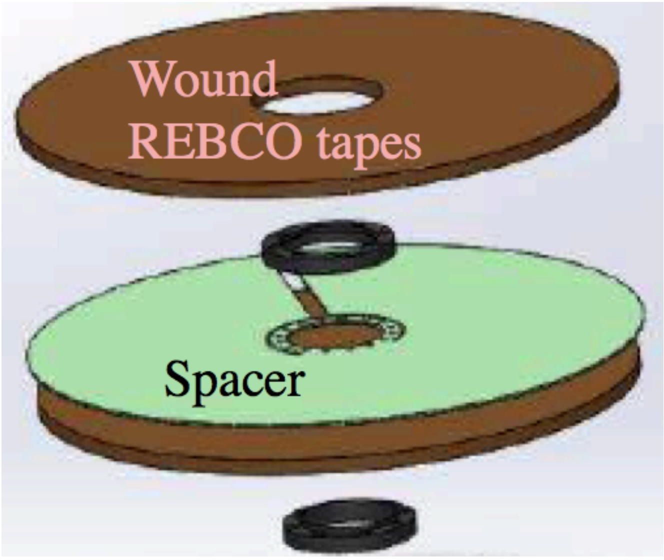


"Progress in coated conductor development for high magnetic field applications." V. Selvamanickam, et al. U. Houston Superconductor Workshop, Napa, CA **Feb. 2015**

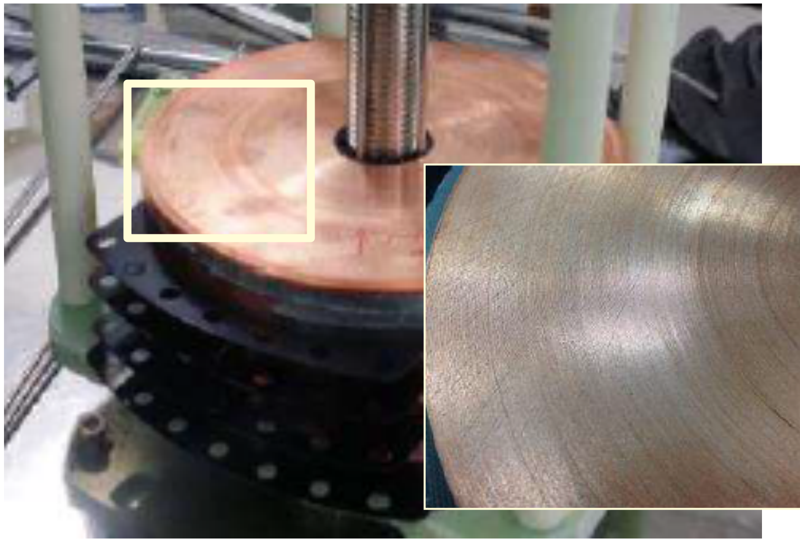
Making coils from REBCO: “No-insulator” tape winding highly attractive





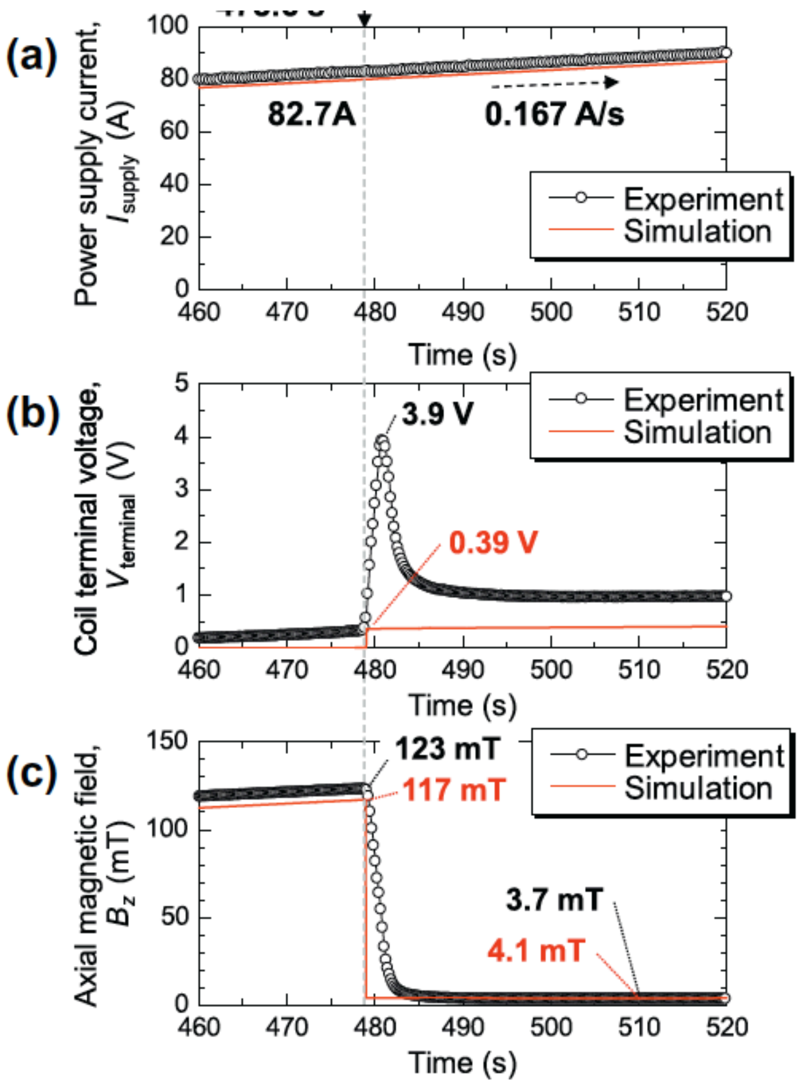
- Steel is “internal” insulator for each turn

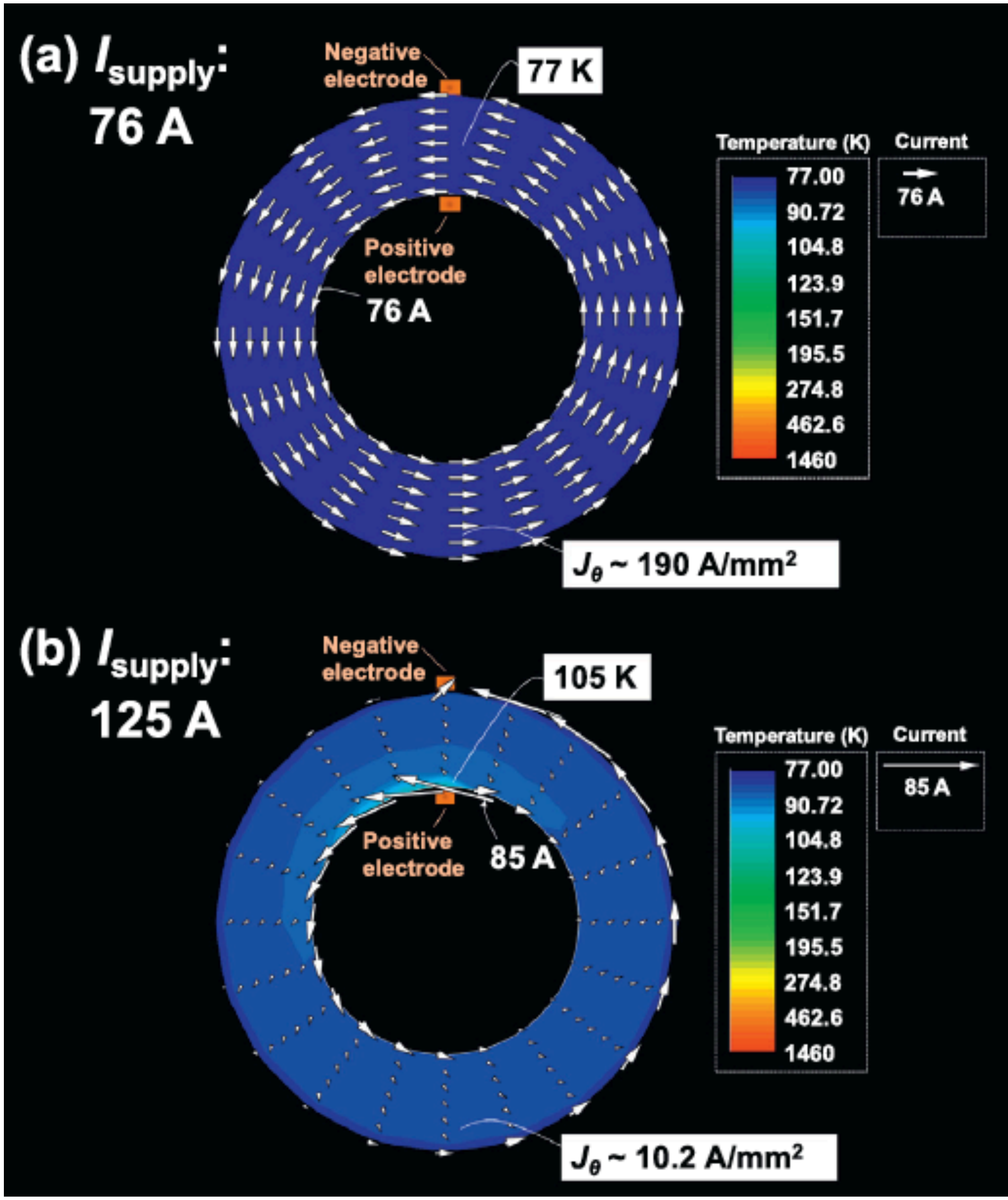
- Benefits
  - ➢ Simple
  - ➢ Improved mechanical strength
  - ➢ Radiation resistance (insulators weakest link)
  - ➢ Self-protecting in quenches



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

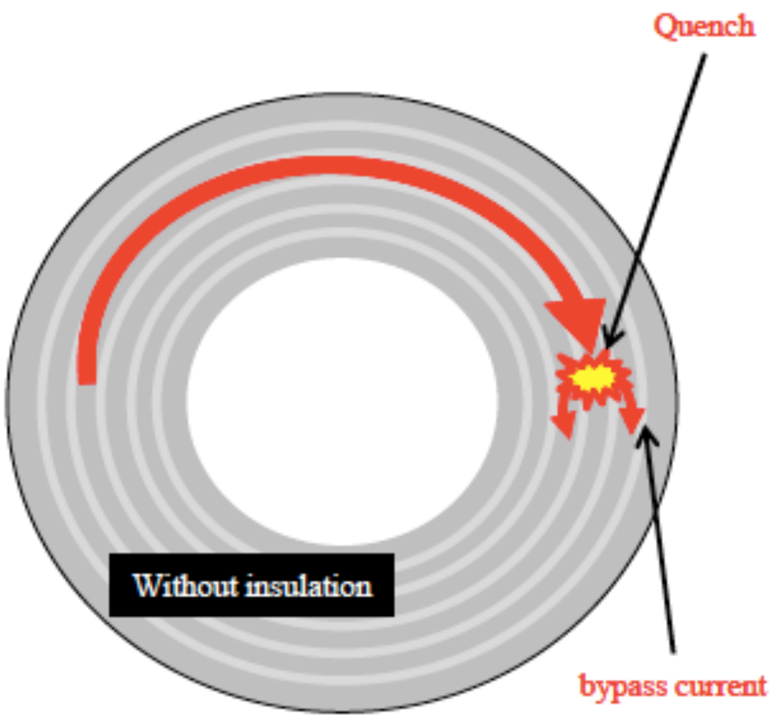
No-insulator coil self-heals via internal redistribution of j → "Single-turn mode" → Immediate drop in B, energy distributed in coil

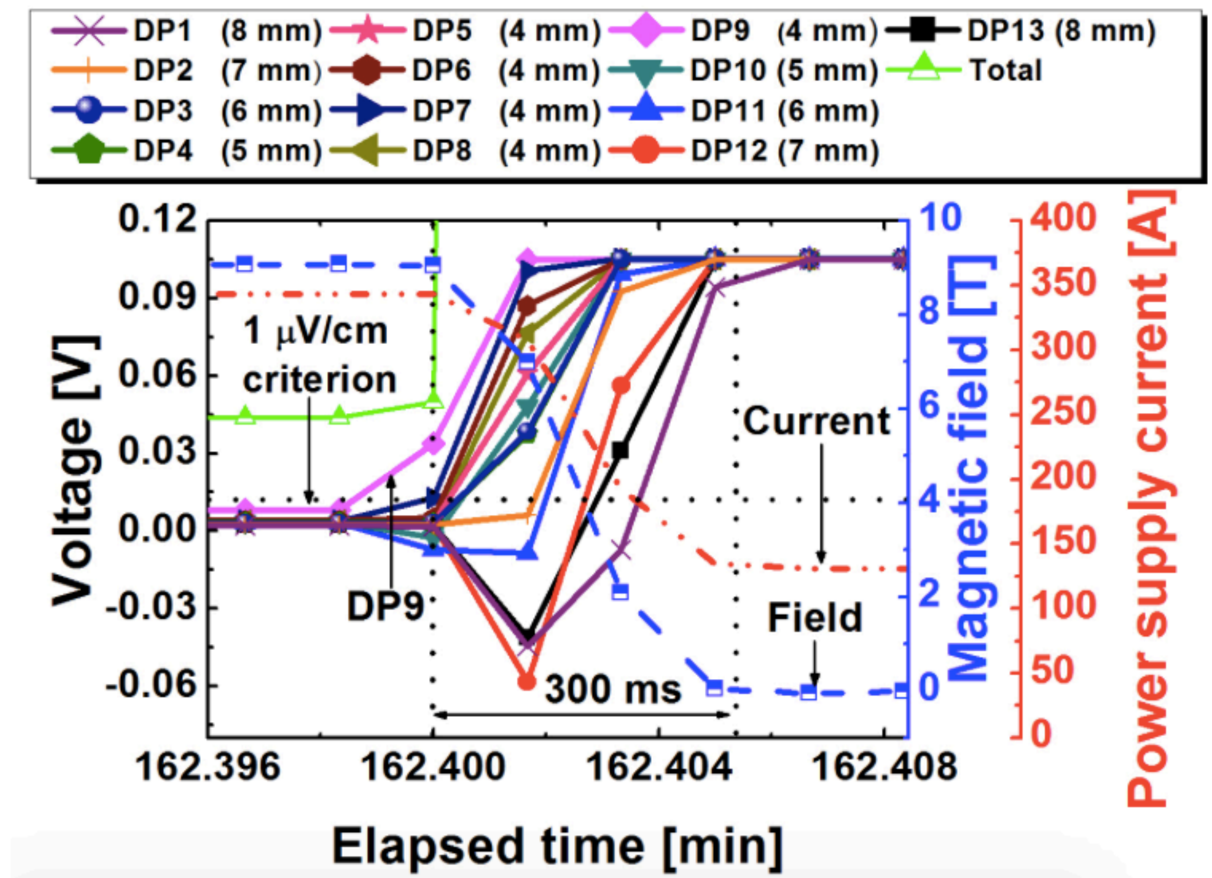




Yanagisawa et al. Physica Scripta C (2014) 40

"No-insulator" winding provides intrinsic quench protection in coil.





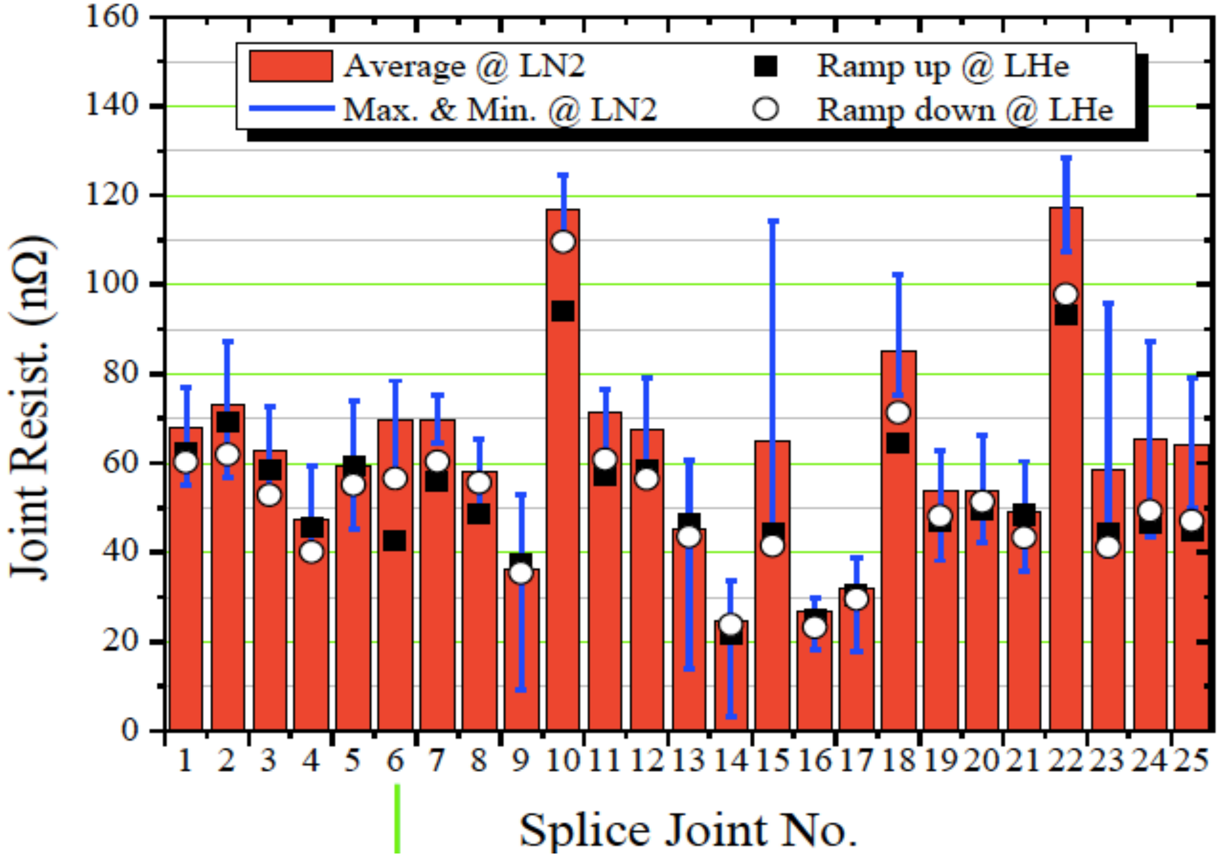
Quench at 9 Tesla: No damage to stacked double pancake coil (2014)

S. Hahn et al. Bitter Magnet Lab, MIT

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

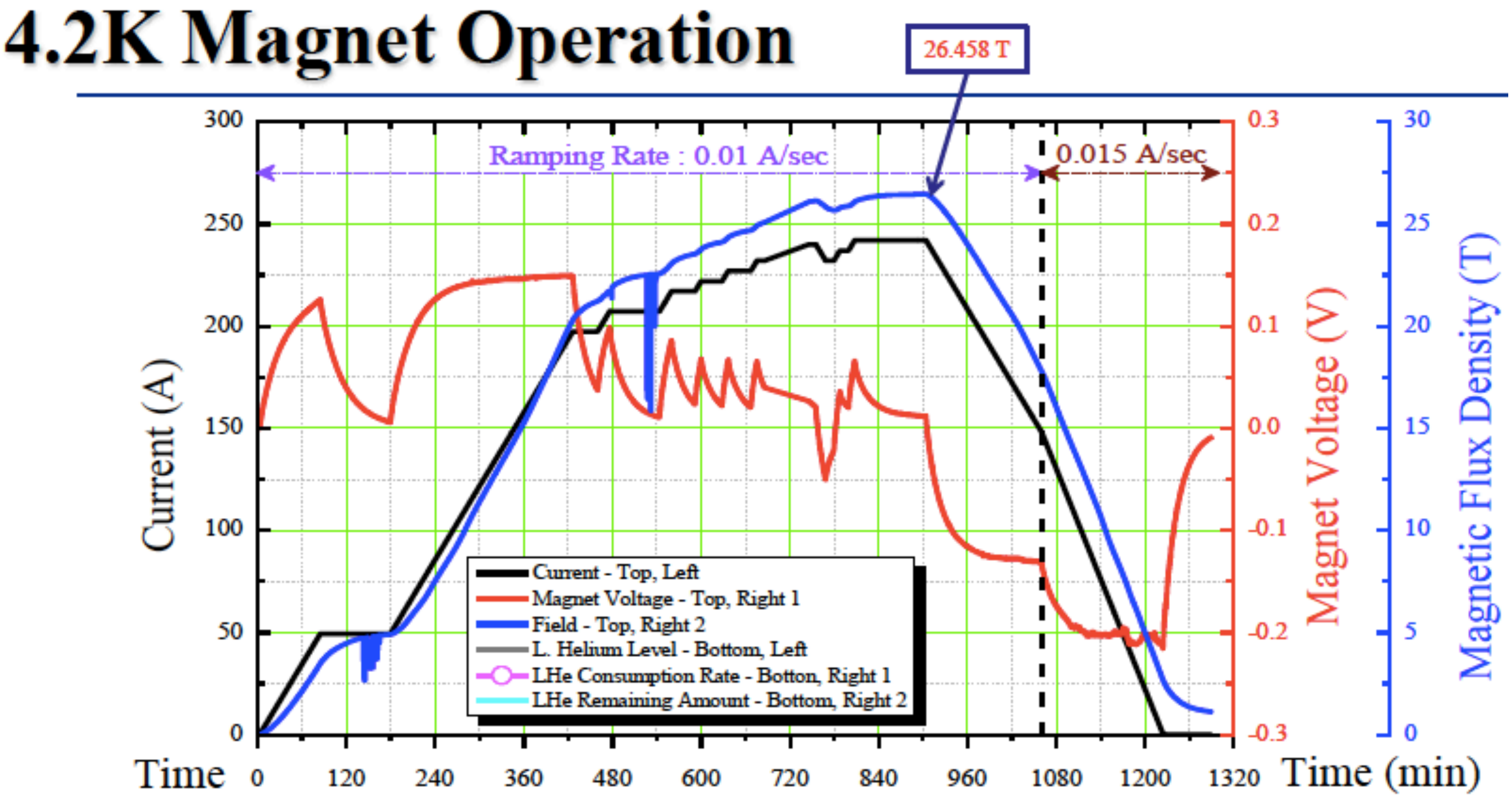
26 stacked coils

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



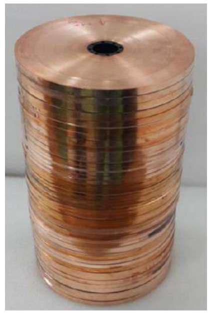
- Soldered joints!
- Mechanical attachment lowers resistance

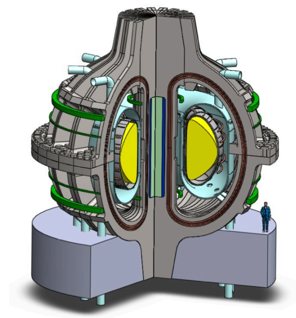
April 2015: New record of 26.5 Tesla with REBCO-only, "no-insulation" coil



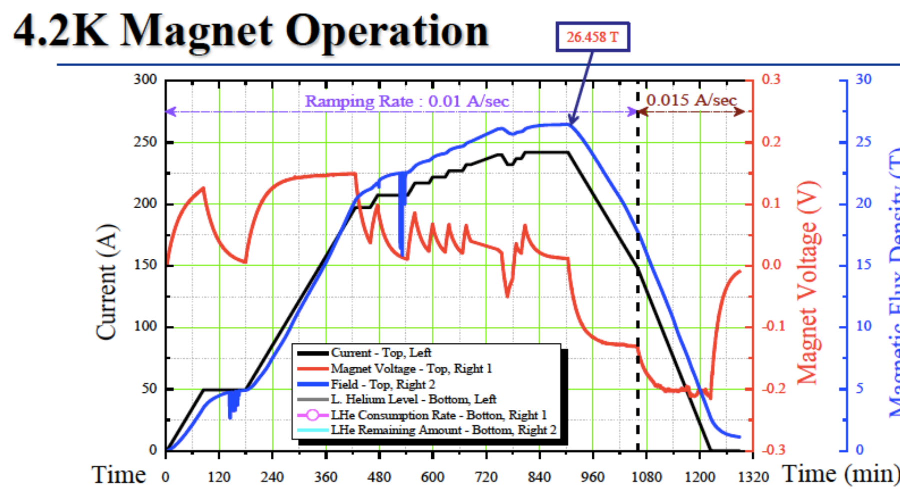
S. Hahn, J.M. Kim, et al.
NNFML, FSU, SUNAM, MIT

Scaled-down REBCO coil matches most requirements for ARC design

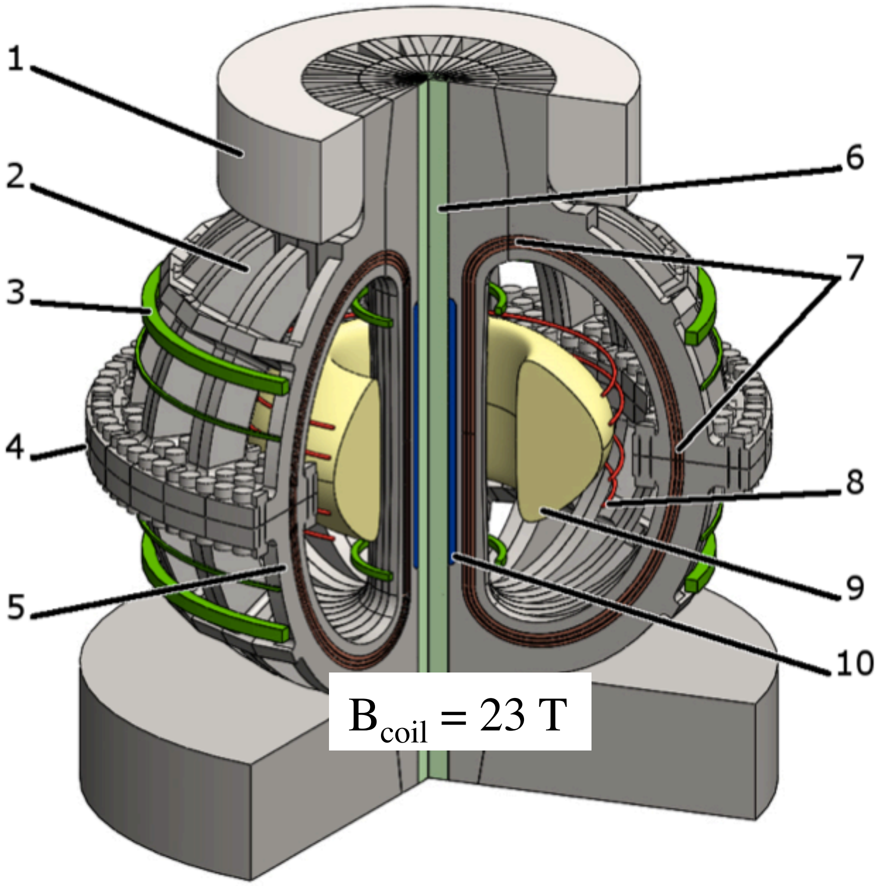




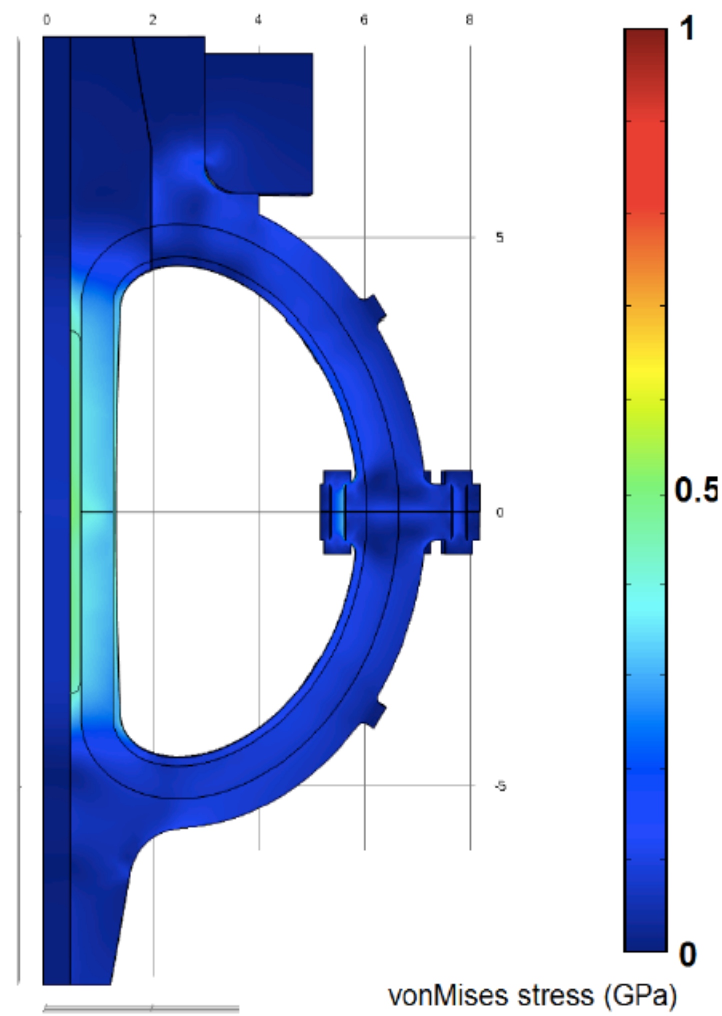
B_{coil}(T)	26.5	23
J_e (A/mm^2)	400	400-500
T (K)	4.2	25
Materials	REBCO, SS316L	
σ_{max} (MPa)	593	660
Diameter (m)	0.03	~ 6



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

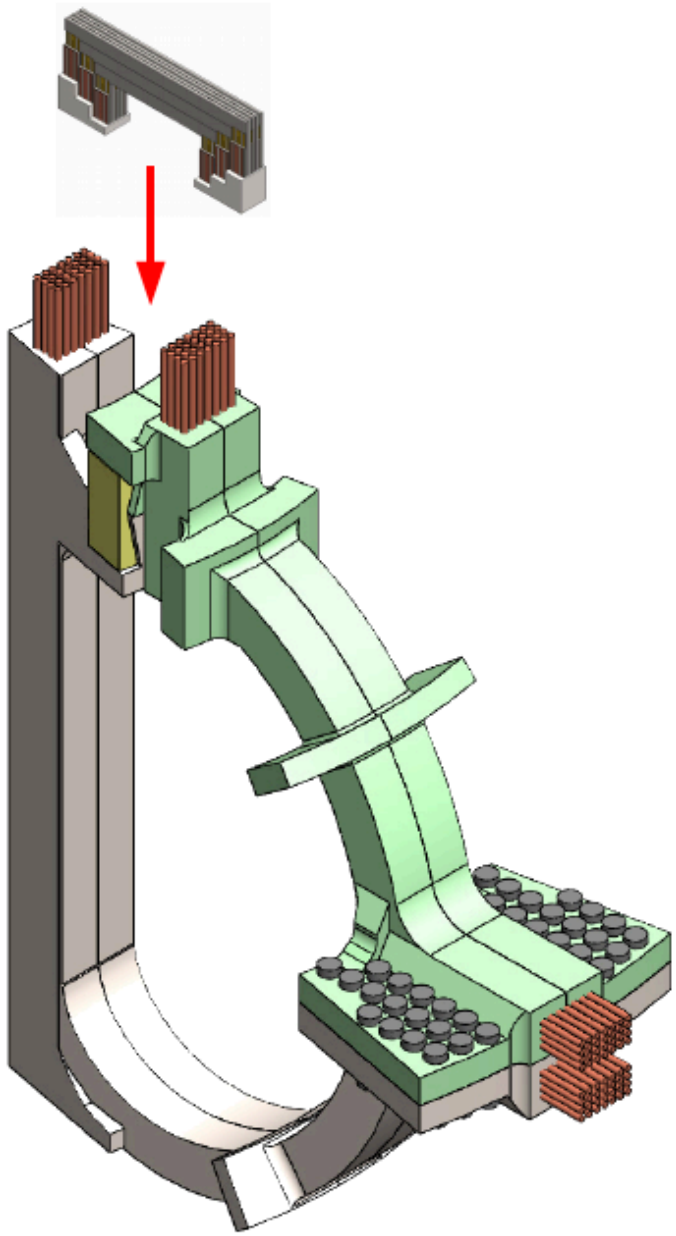


Peak stress ~ 0.67 Gpa
~65% of limit for 316SS LN



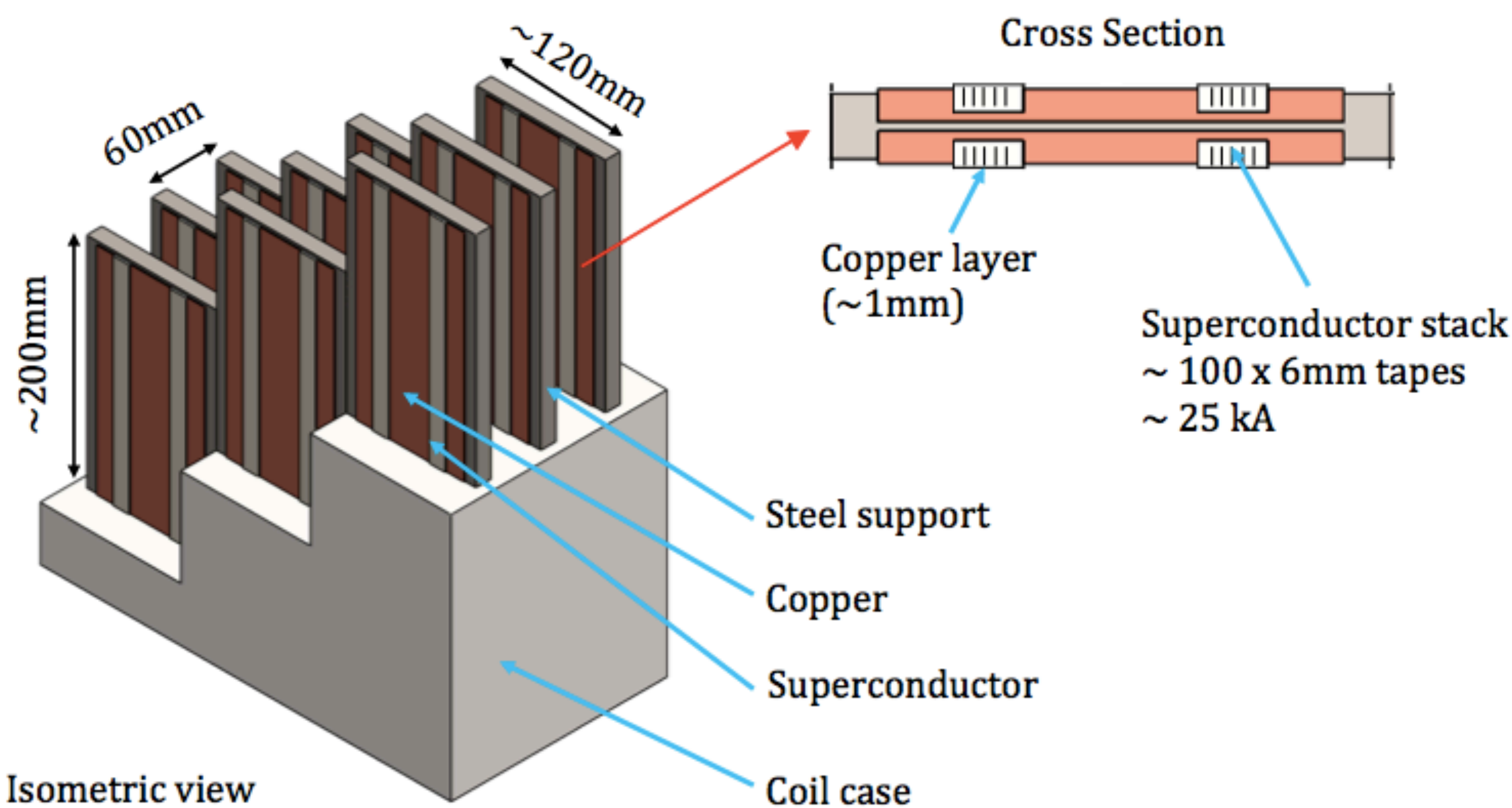
1. Support ring, 2. Top TF leg
4. Mechanical joint
6. Epoxy enforcement

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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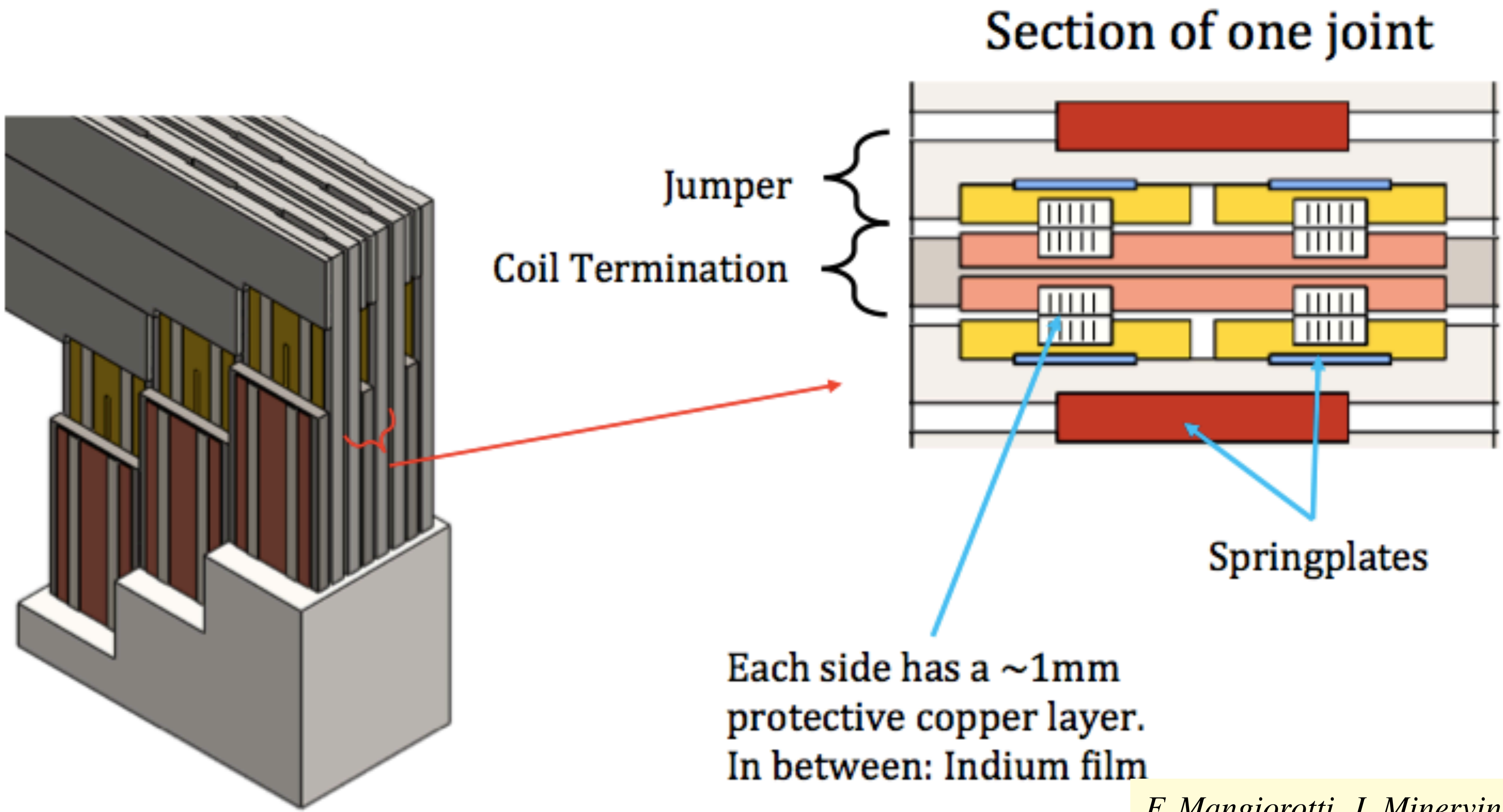
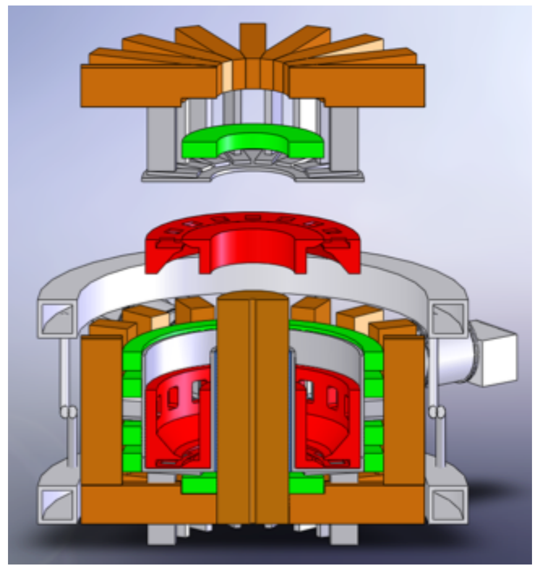


F. Mangiorotti, J. Minervini
MIT Ph.D. thesis

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

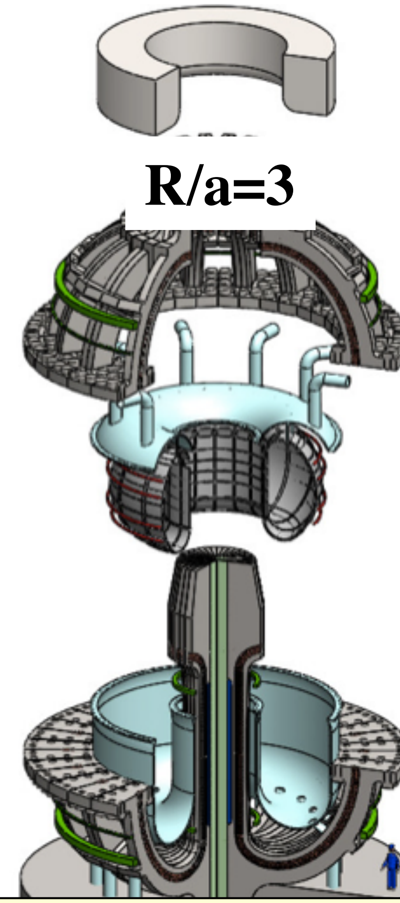
- Greatly reduces required cooling power (Carnot).
- Thermal stability due to higher heat capacity.
- Operation or ARC at T~25 K
  - ➢ Small power to joints
  - ➢ Liquid H or Ne for cooling options

R/a=3.5



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

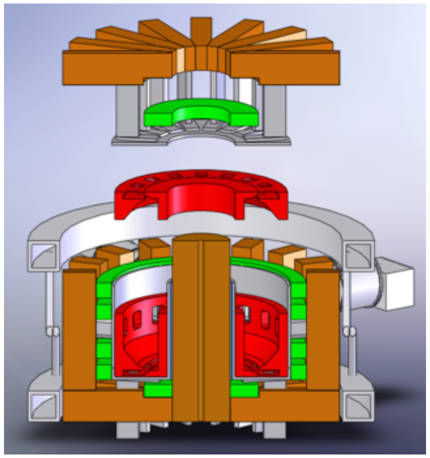
R/a=3



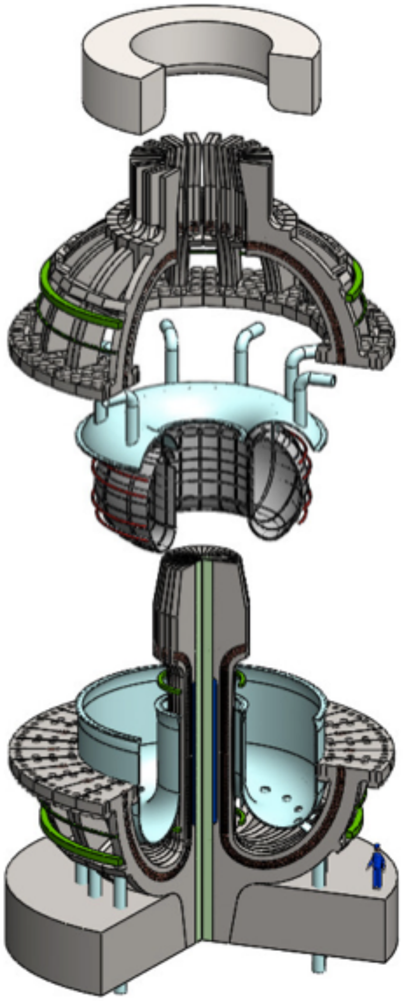
ARC: Resistive joints /w REBCO superconductors
Coil P_{coil}~ 1 MW

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



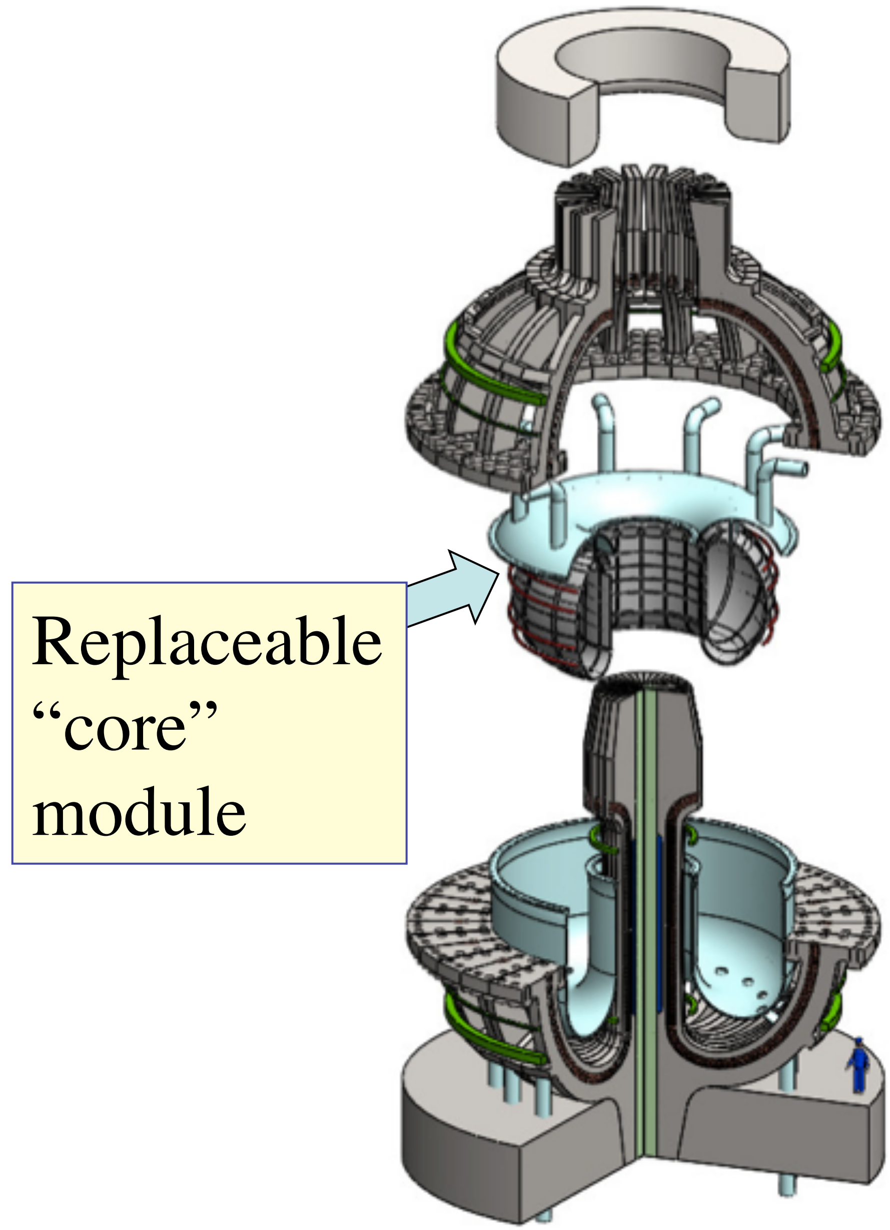
ARC

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

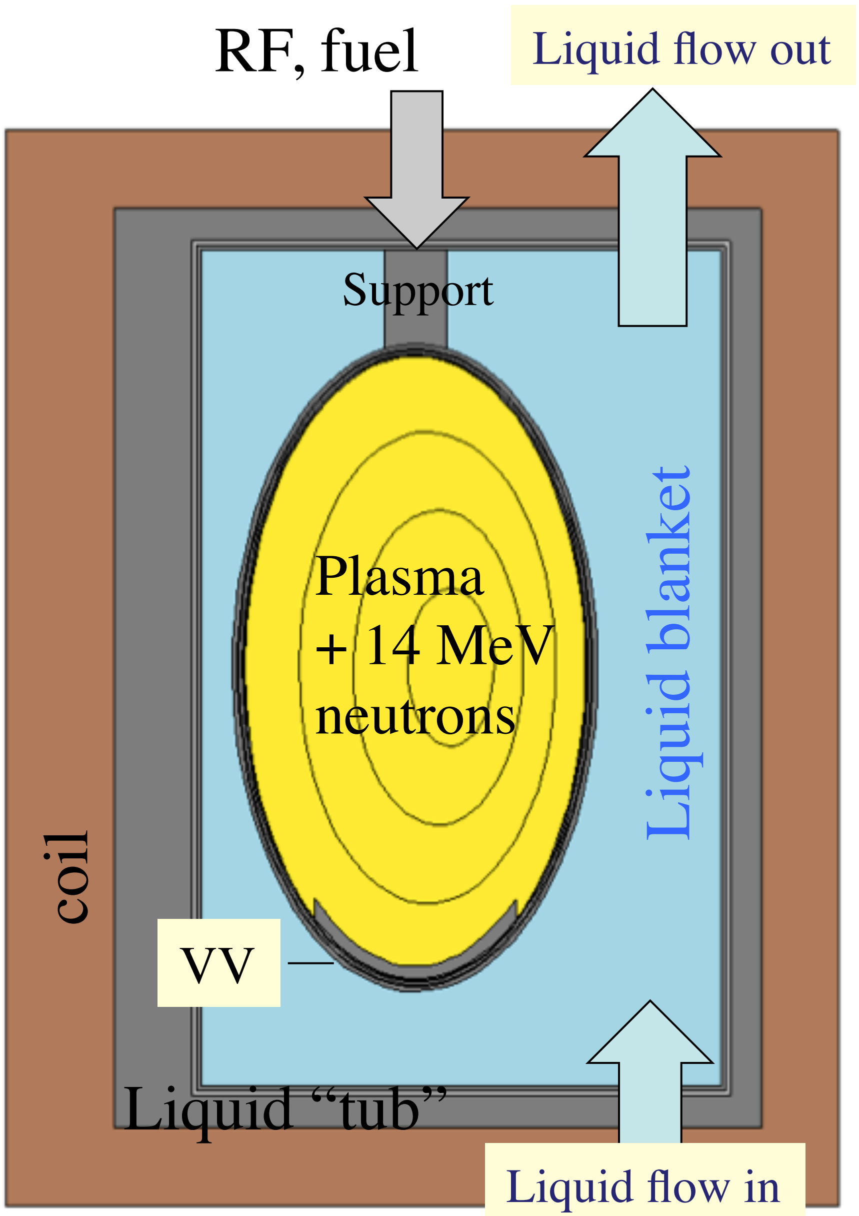
- **Fabrication + qualification done completely off-site**
  - **Vacuum**
  - **Heating**
  - **Cooling**

- 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**

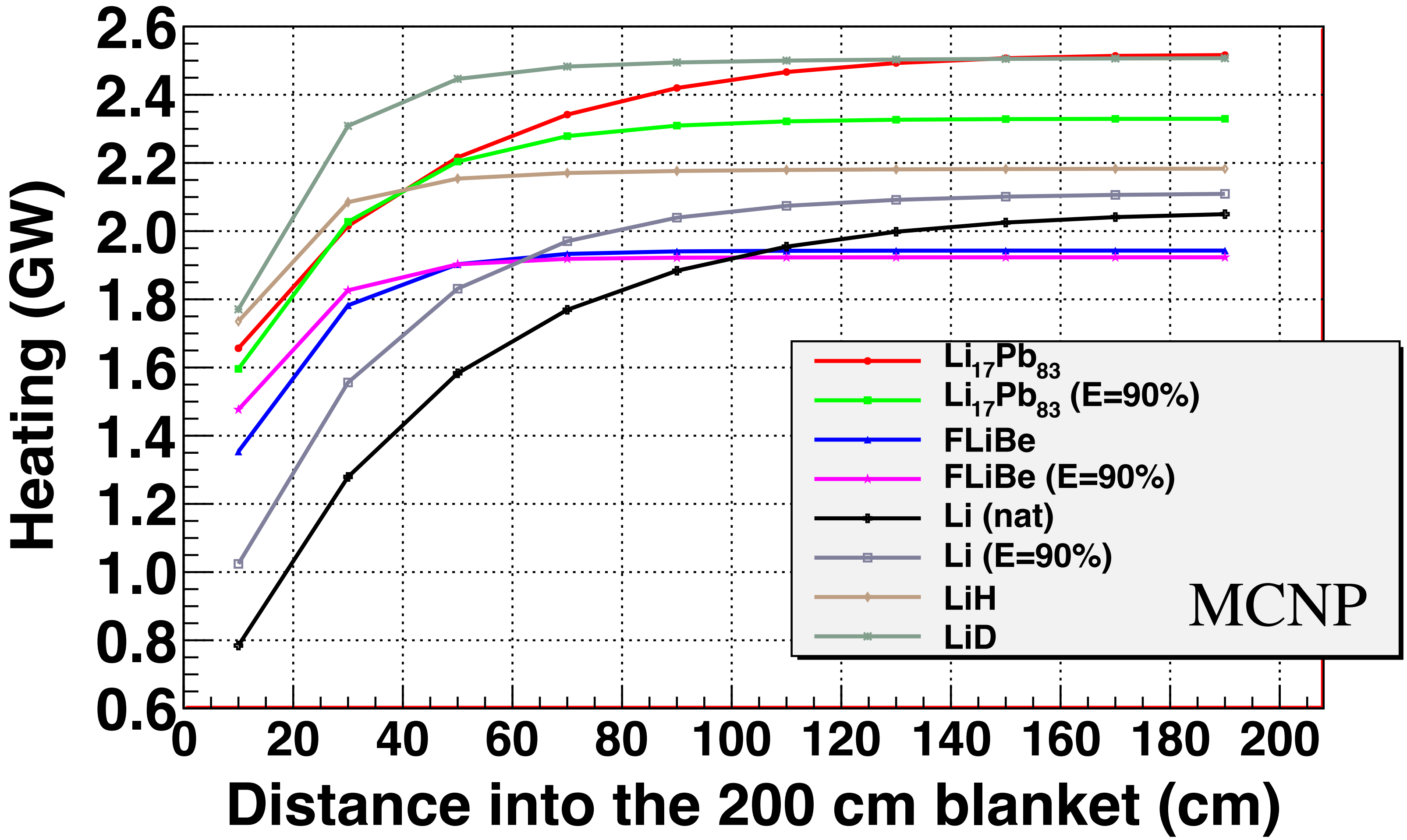


<u>Advantages</u>

- **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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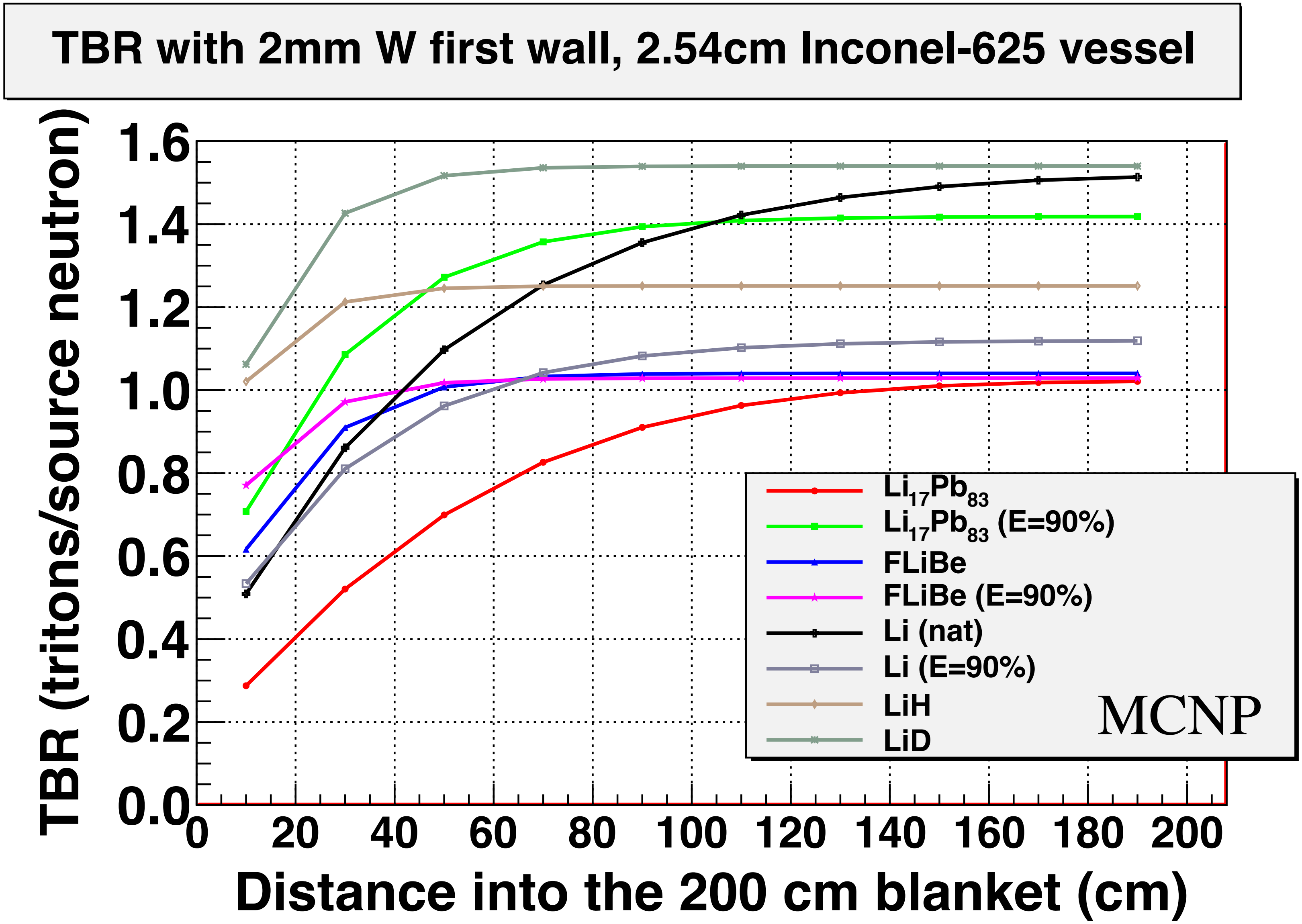
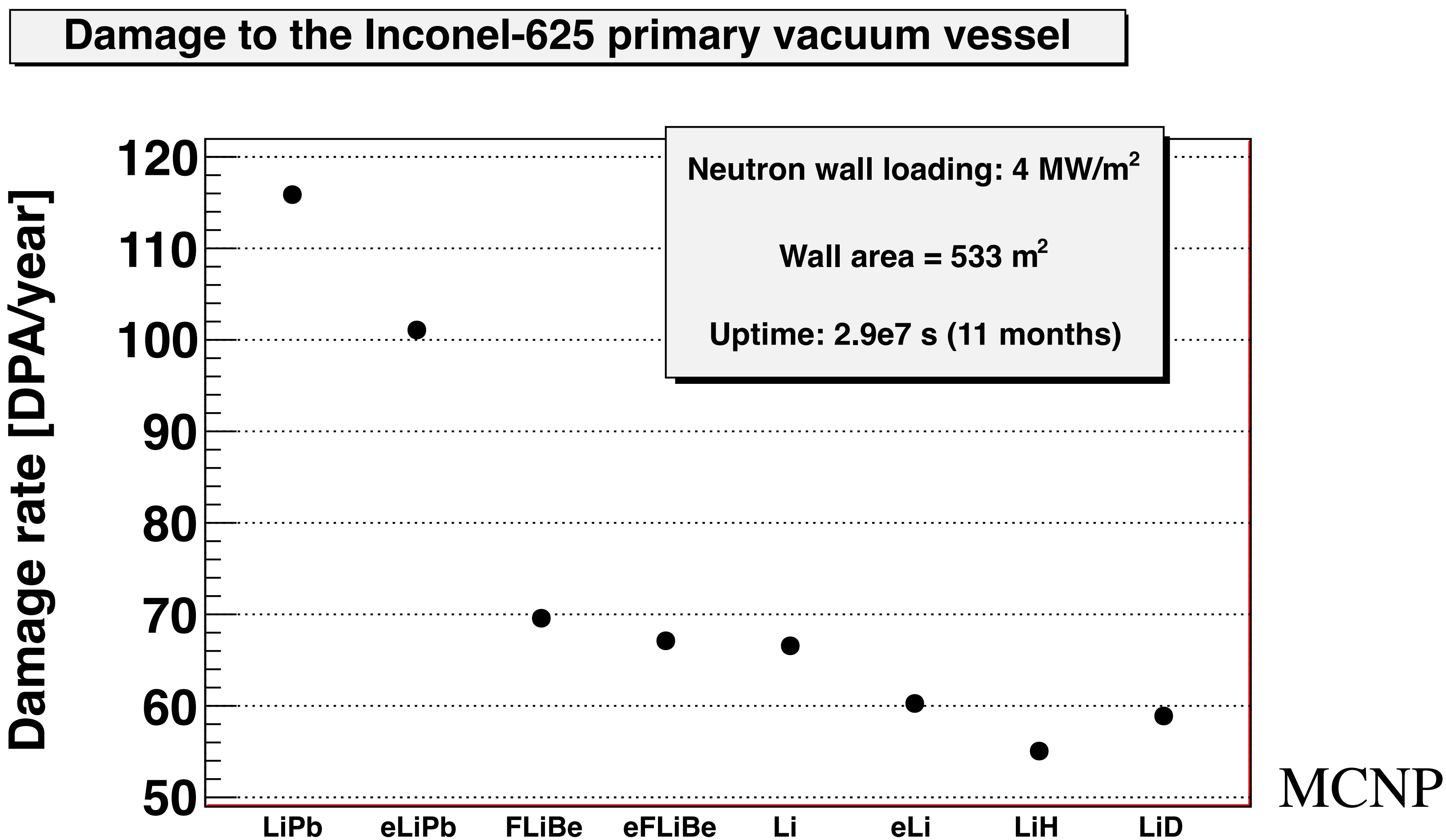


Immersion blanket: Solid, replaceable components (plasma-facing materials, vacuum vessel) receive minimized neutron damage immersed in low-Z fluid



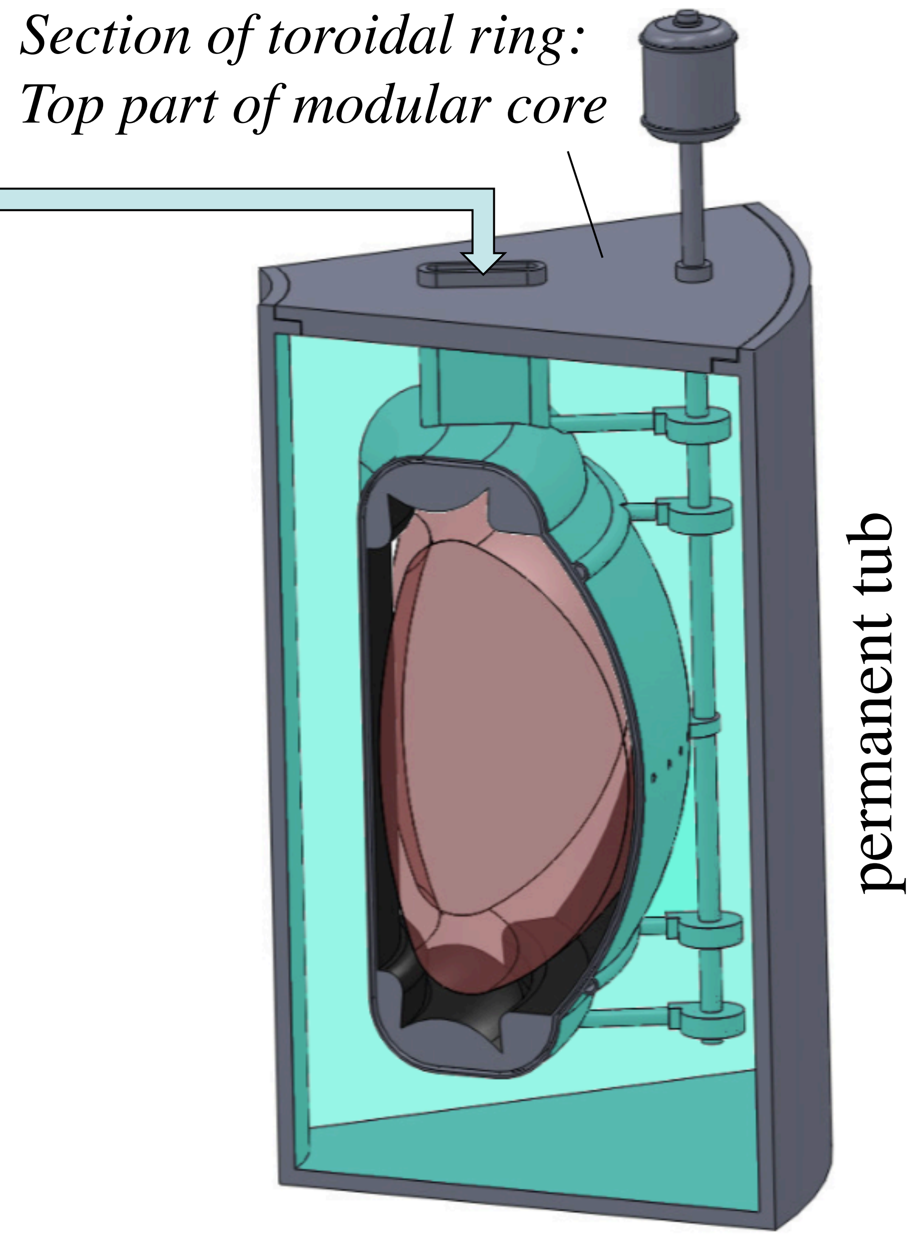
Z. Hartwig, C. Haakonsen MIT

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

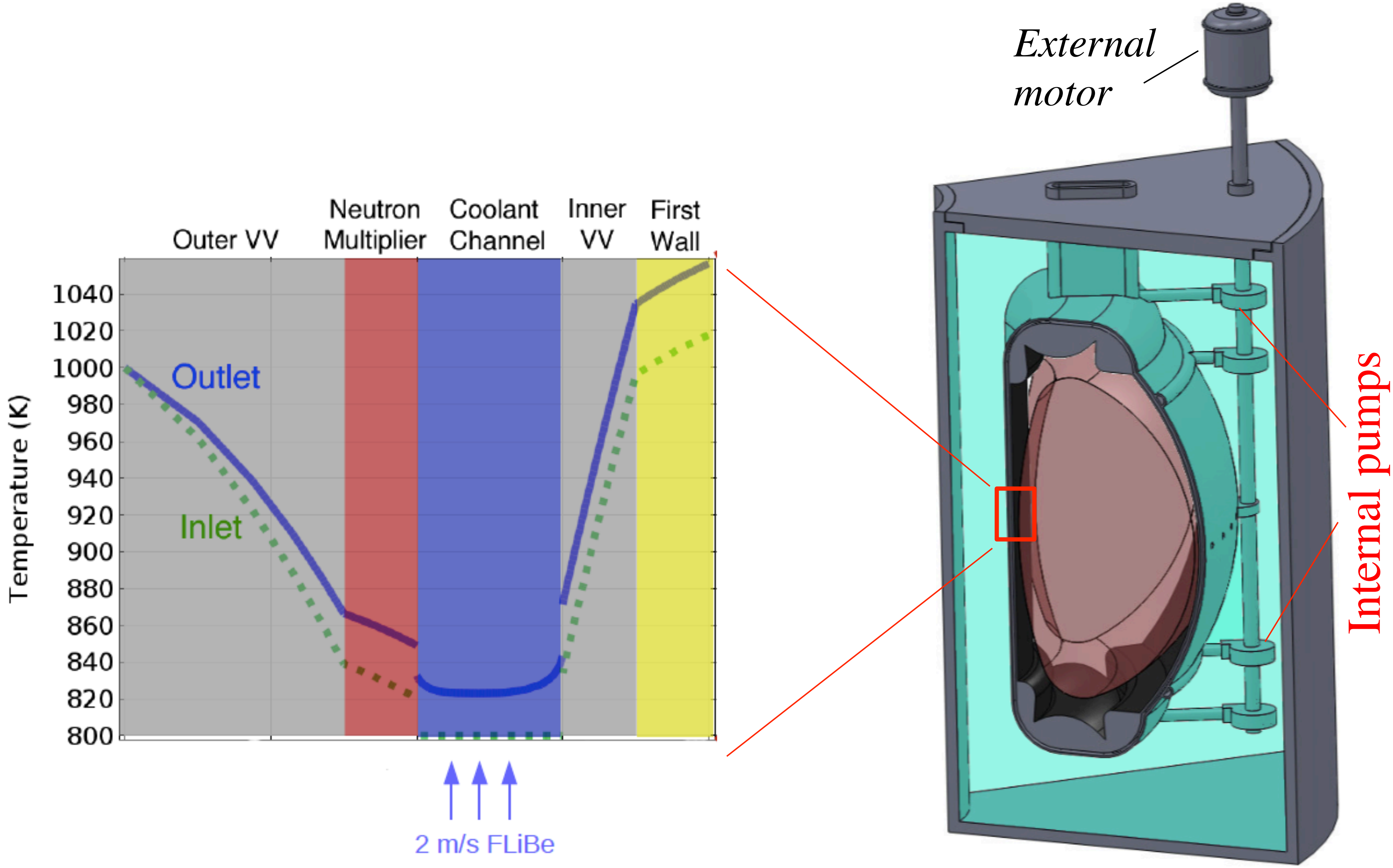
- Heating, pumping, diagnostics must wind through supports

- 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



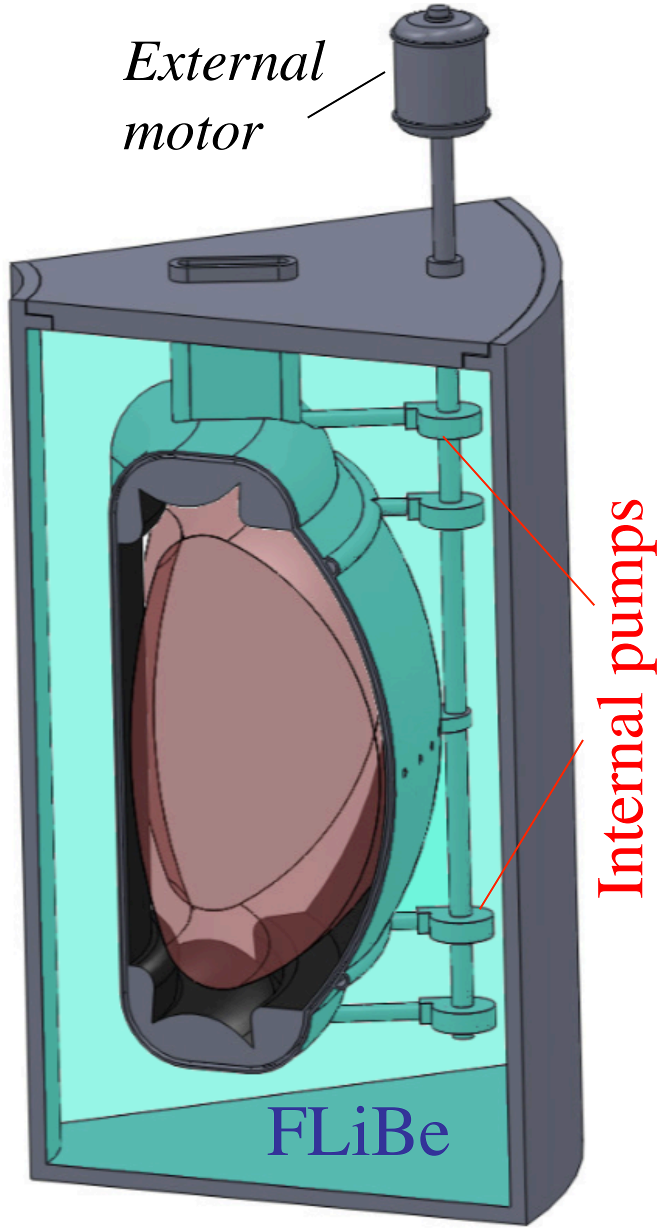
Immersion blanket: Very large heat sink in close proximity to internals provides fundamental improvement in heat exhaust



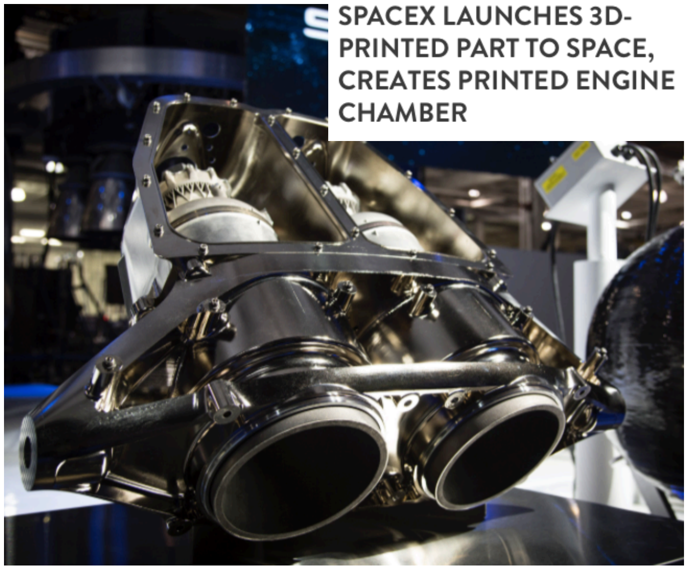
Immersion blanket: high-T molten salt FLiBe Single-phase, low-pressure flow with minimum MHD effects

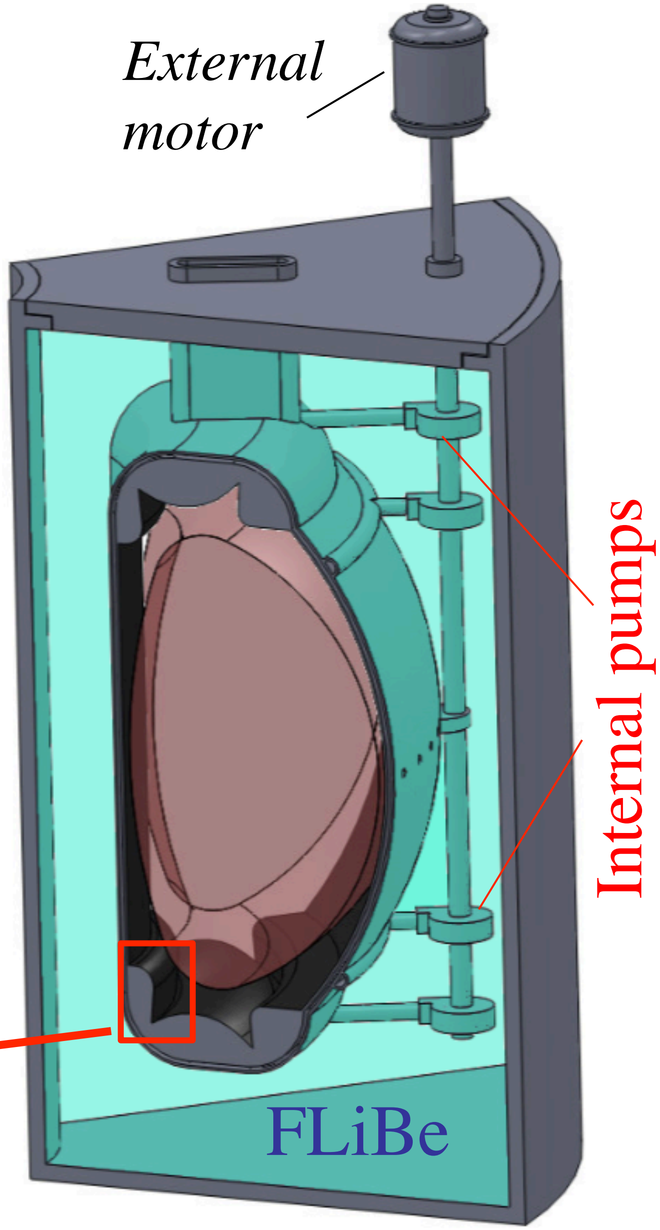
Property	FliBe [7]	Water
Melting Point (K)	732	273
Boiling Point (K)	1700	373
Density (kg/m³)	1940	1000
Specific Heat (kJ/kg/K)	2.4	4.2
Thermal Conductivity (W/m/K)	1	0.58
Viscosity (mPa-s)	6	1

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



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



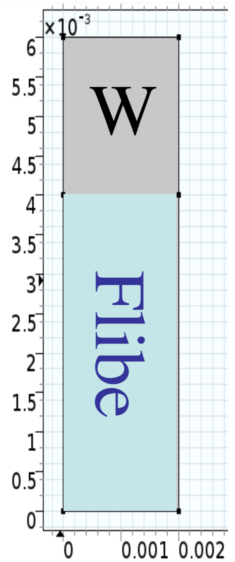


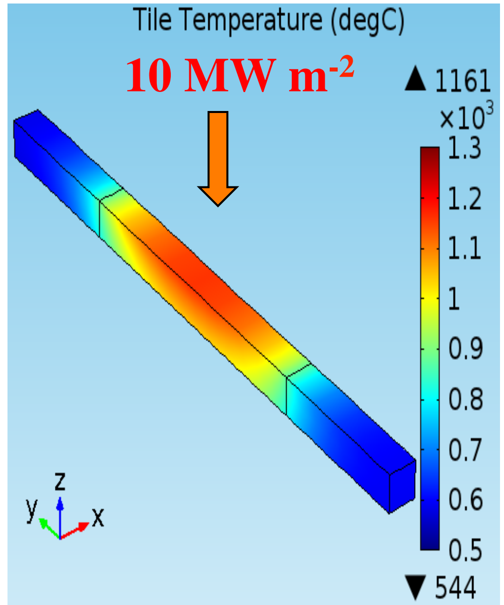
- TBR ~ 1.14
- High thermal efficiency ~ 0.4 - 0.5
- Shielding: 10 full-power coil lifetime
- Exploit FLiBe + Immersion blanket + Additive manufacturing to address high heat flux regions?

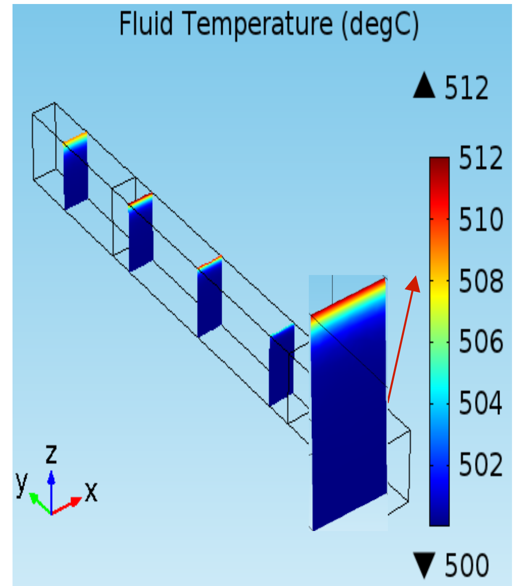
Preliminary study: Improved surface heat removal with FLiBe + 3-D printed cooling channels

Next major design study: ARC divertor & cooling

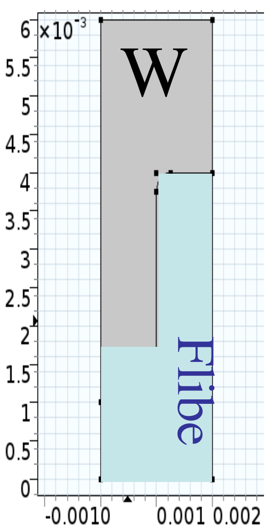
2 mm thick W tile

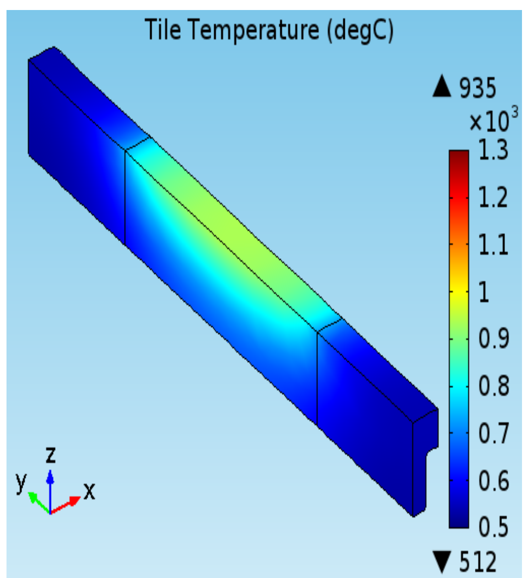


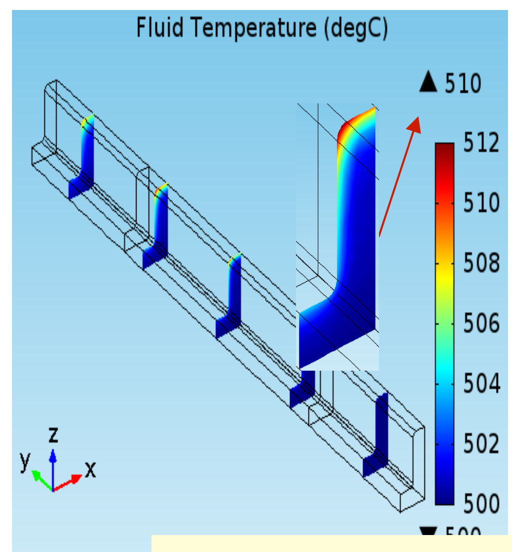




2 mm thick W tile + Internal Fin







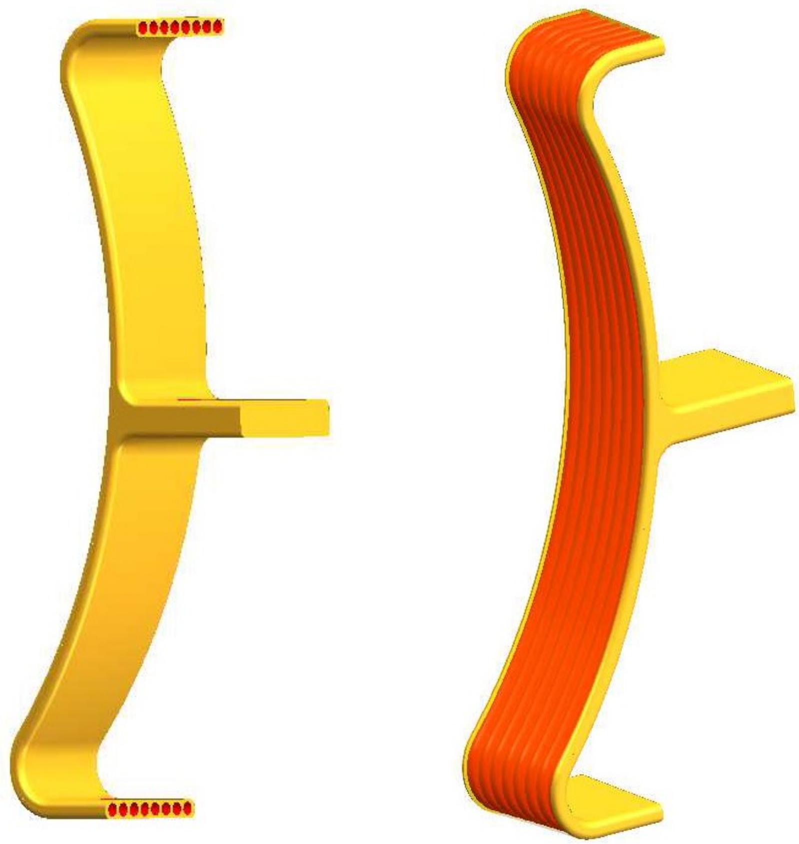
10 m/s

~ 1 bar pressure drop

L. Zhou, R. Vieira MIT

Strong benefits of 3D printing for actively cooled launchers too

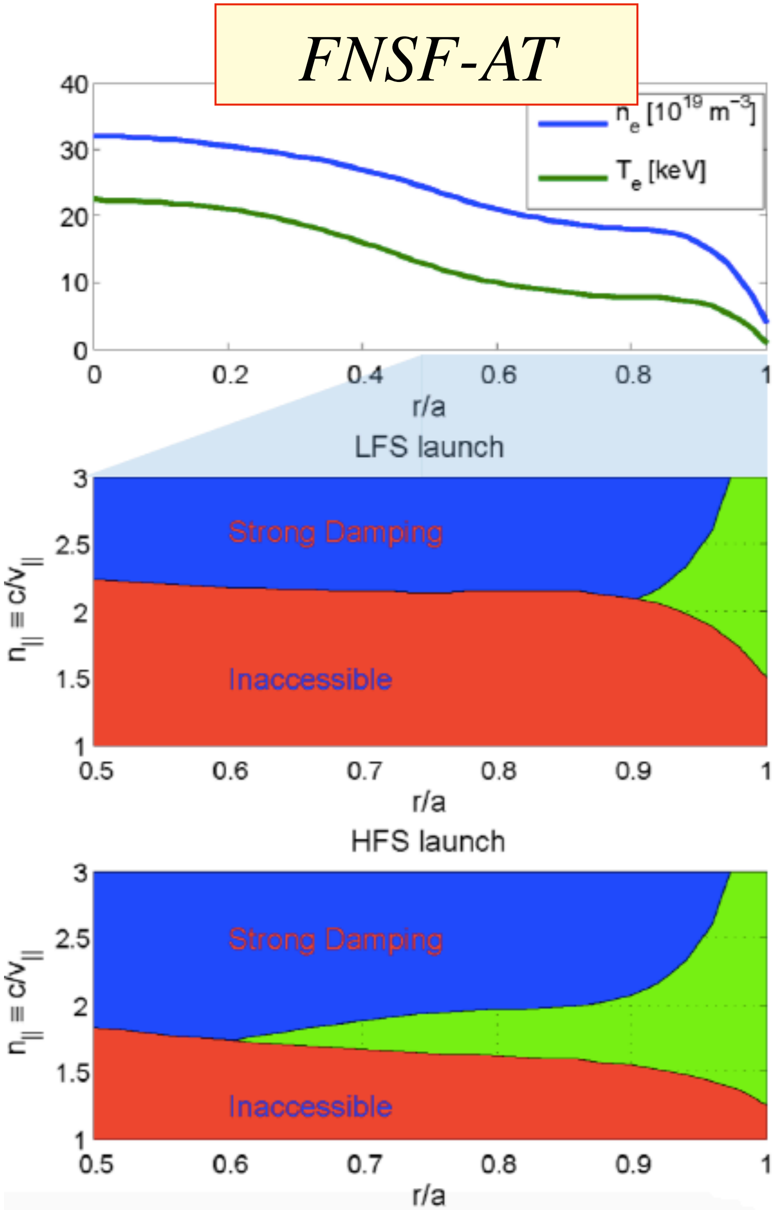
Example RF antennae strap
Integrated, near-surface cooling channels impossible /w standard manufacturing

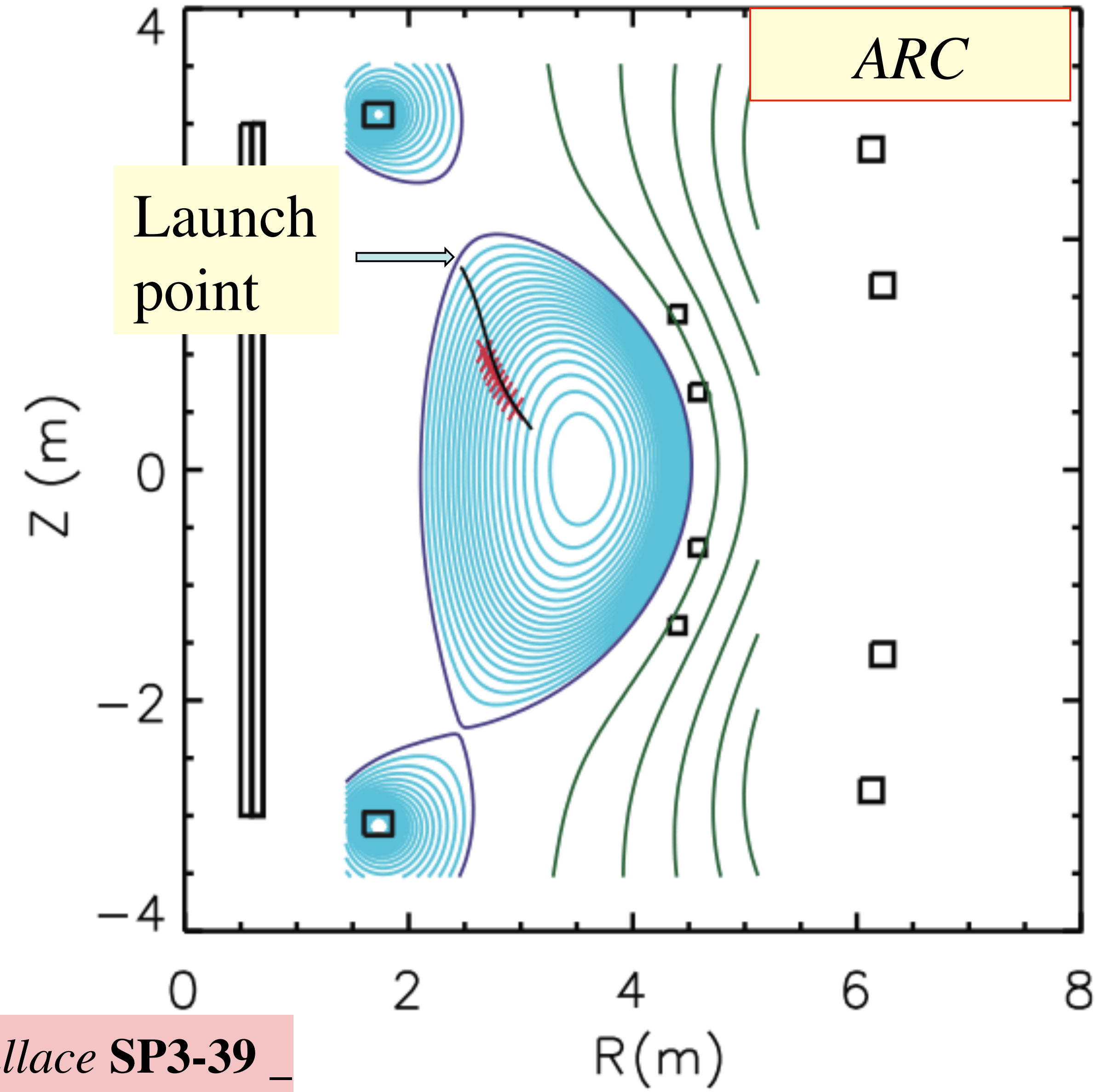


S. Wukitch
Tue pm
SO15

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** _

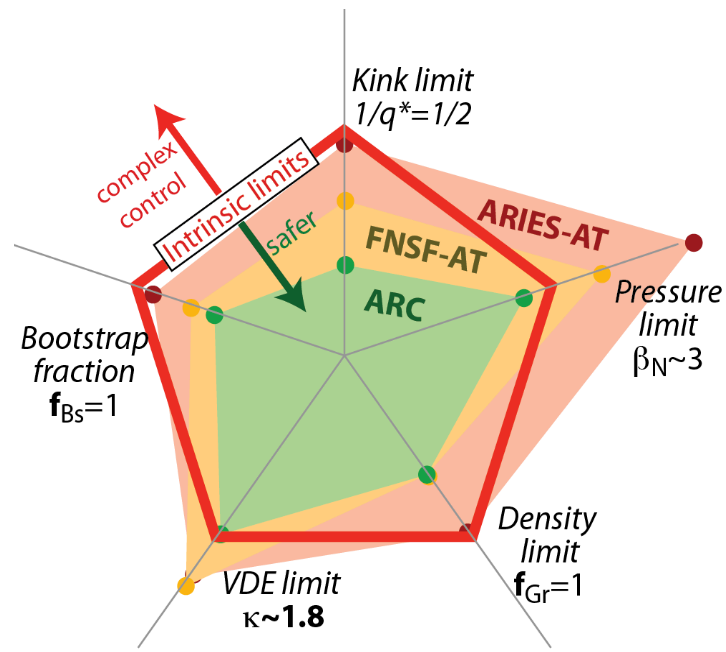
New technologies provide access to synergistic design advantages at high-B and small size:
Robust steady-state far from disruptive limits

	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

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

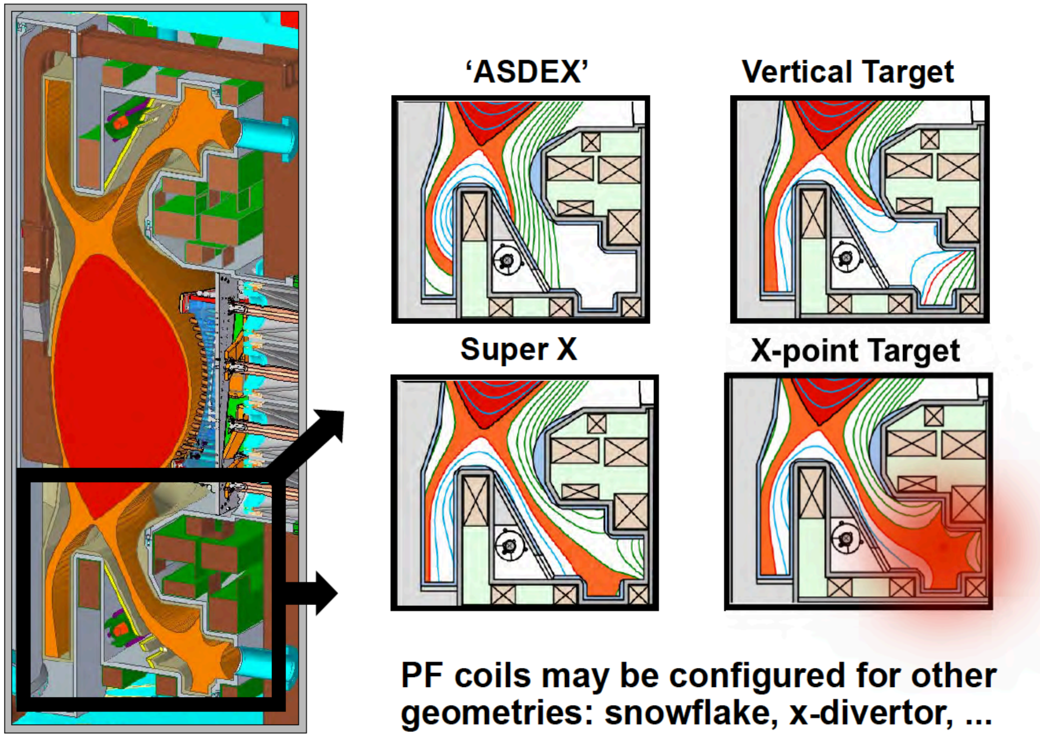
$$nT\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

- **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 → **$q_{//} \sim R\,B$**
  - ➢ Lawson criterion: $R \sim 1/B^{2.3}$
  - ➢ **$q_{//} \sim 1 / B^{1.3}$**
- Advanced divertor coils built into modular core as replaceable components
  - ➢ Exploit physics advances from expanded volume divertors

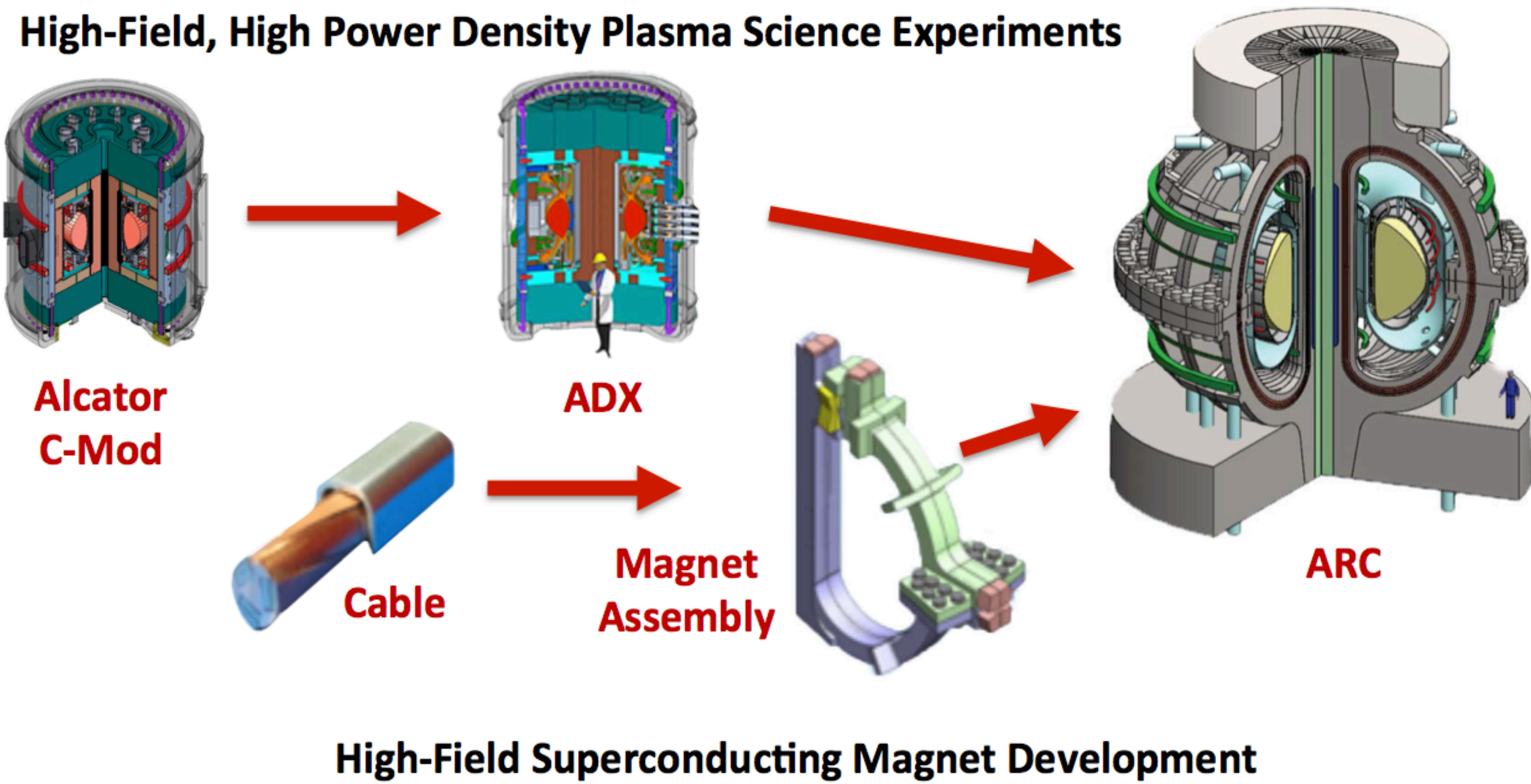


ADX presentations

LaBombard **SO10-3 Tue AM**

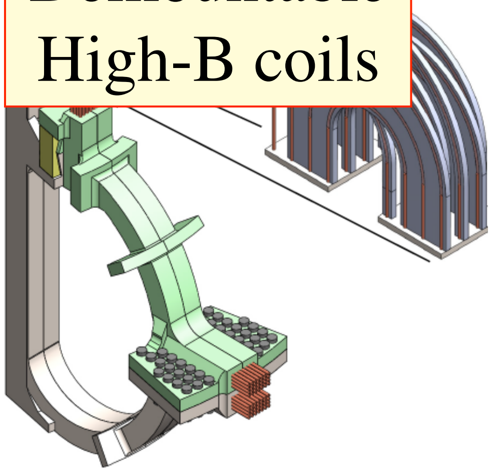
Posters**: SP3 Tue PM**

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

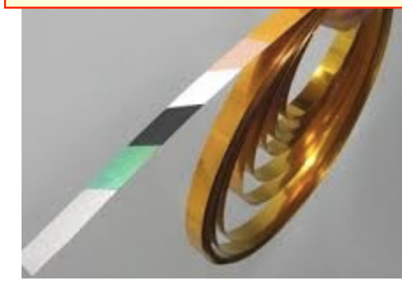


The disruptive innovation of high field, high-T superconductors

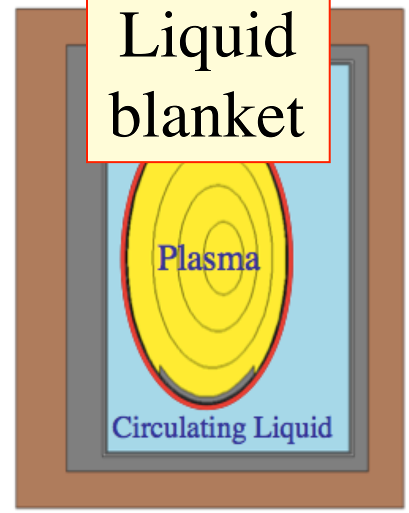
Demountable High-B coils



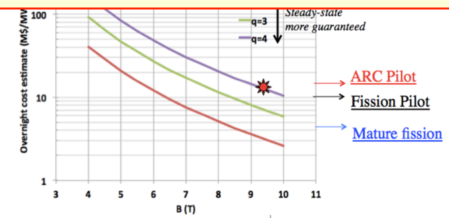
Superconductor

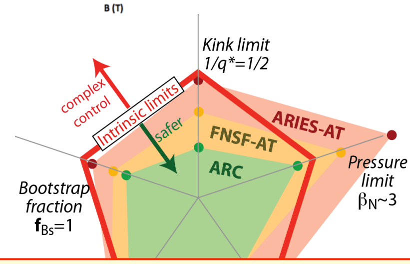


Liquid blanket



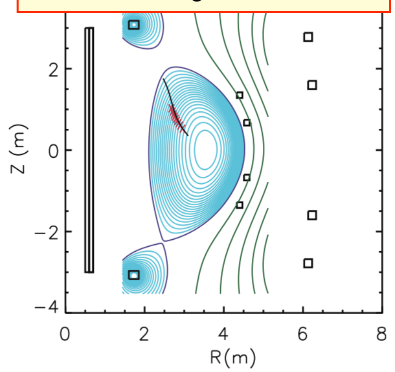
Smaller, sooner
Viable fusion energy



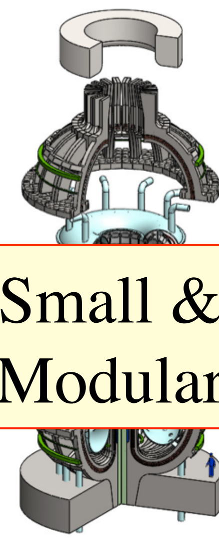


Operation robustness

Steady-state



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**