Massachusetts Institute of Technology

PSFC

Plasma Science & Fusion Center

Accelerated Fusion Development Path Based on New Superconductor Technology

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FPA

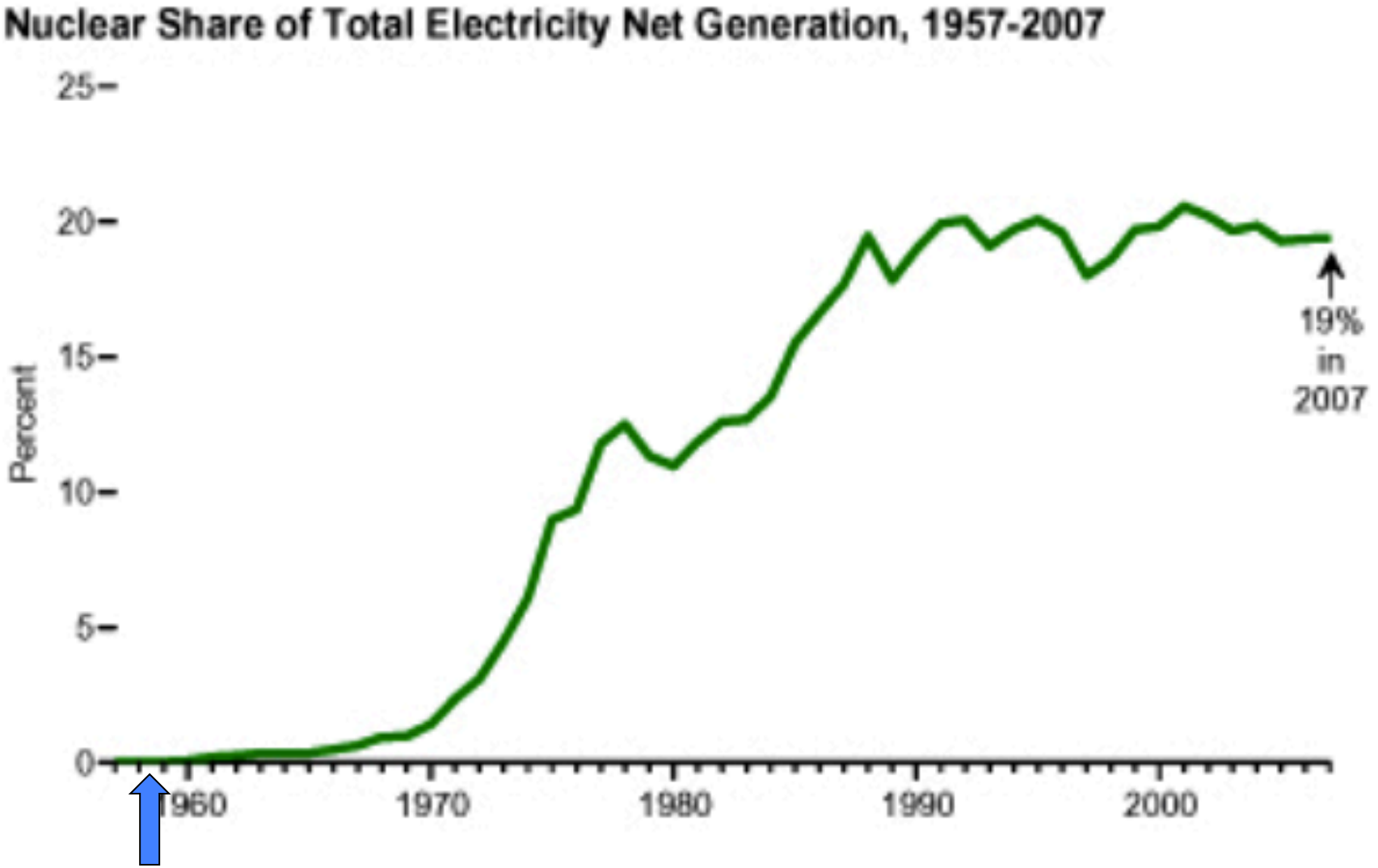
Washington DC December 2015

psfc.mit.edu

Thoughts on MFE development path

- **It is self-evident that if we could have many fusion-capable devices at small scale with modular design that this would accelerate fusion's science and energy development.**
- **The recent maturity of REBCO high-T, high-B superconductors place this within reach in the not-too-distant future.**
- **The established science basis for attractive compact high-field MFE devices (CIT, FIRE, etc.) is no longer a "dead-end"**
- **Demountable SC coils would provide transformative opportunities in modularized fusion magnet and nuclear engineering that are just starting to be explored.**

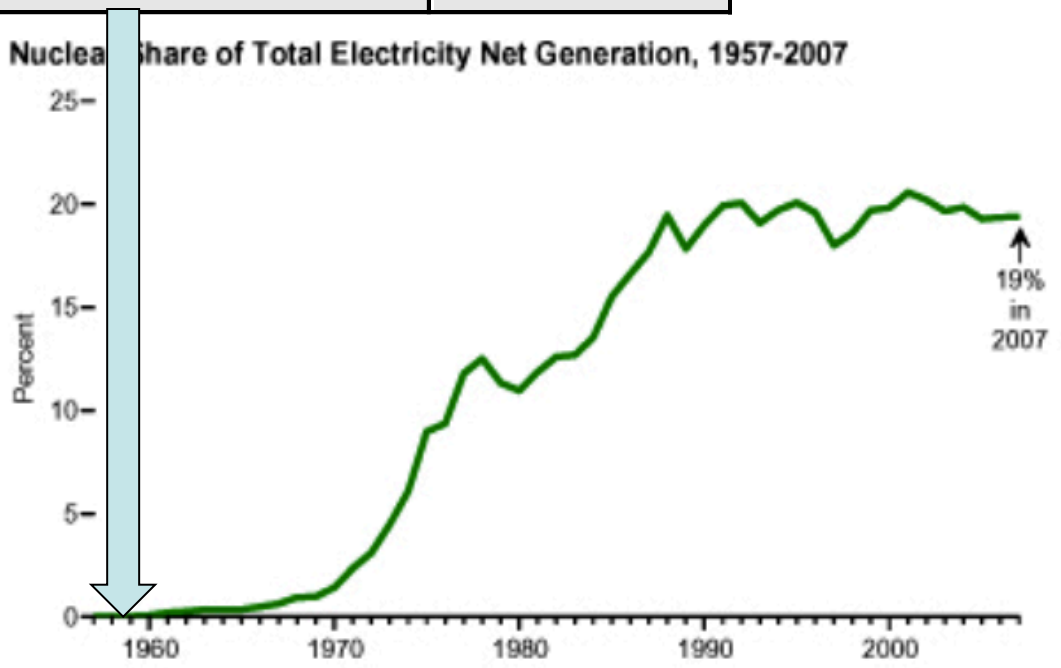
The history of fission proves that high power density, modular nuclear energy can be deployed at a very fast rate to provide carbon-free power



1st fission "pilot" plant

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

	Shippingport: 1954 "Pilot" Fission Plant	ITER
P_{th} , P_e (MW)	200 , 50	500 , 0
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



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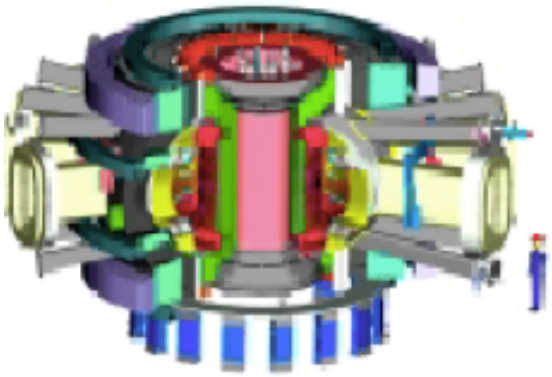
- Cost & time ∝ unit volume and mass
- ITER is an invaluable science experiment for burning plasmas but its large size, determined primarily by superconductor limits, is not optimized for modular fusion energy "pilots"
  - ITER is a trial of just one fusion concept, fission pilot tried four different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

Confinement strongly physics 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**

Copper coil
pulse ~ 10 s



FIRE

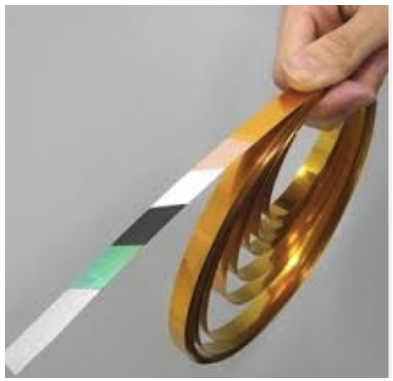
R (m)	2.14
V (m^3)	30
B_o (T)	10
Q_p	>10
Steady-state	No
Tritium breeding	No
$Q_{electric}$	0

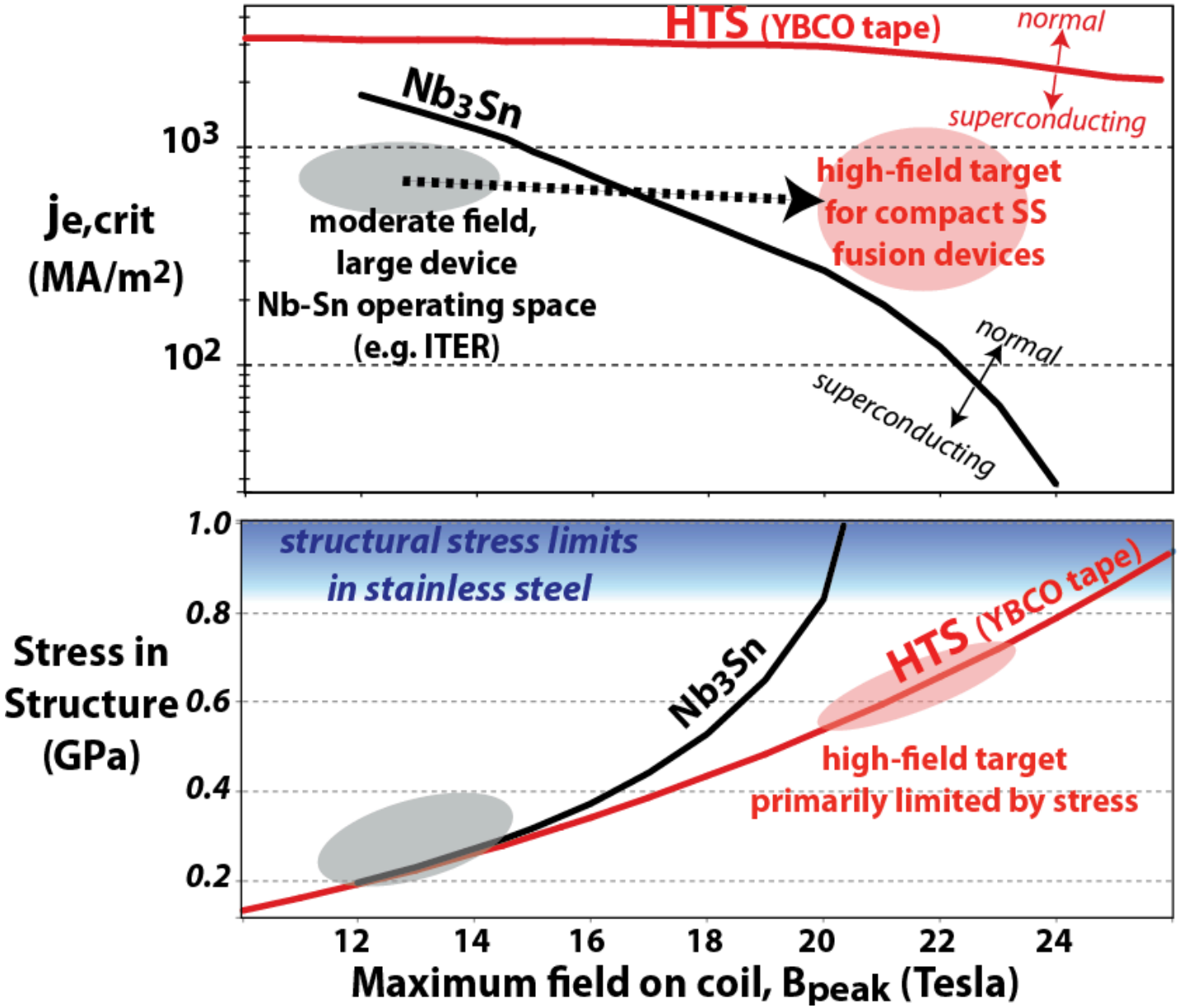
Continuous /w High-B Superconductors?

Meade, et al FED
Marmar APS 2015

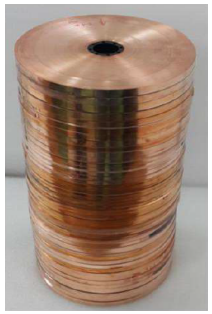
Last few years: A new generation of high-temperature, high-field superconductors is revolutionary for fusion energy

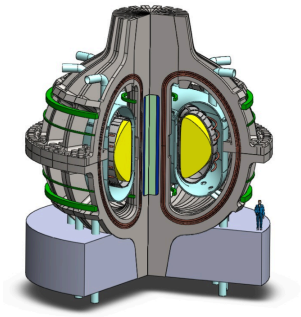
- Form of strong, flexible tapes → can form joints
- Critical T > 20 K
- Improves every year



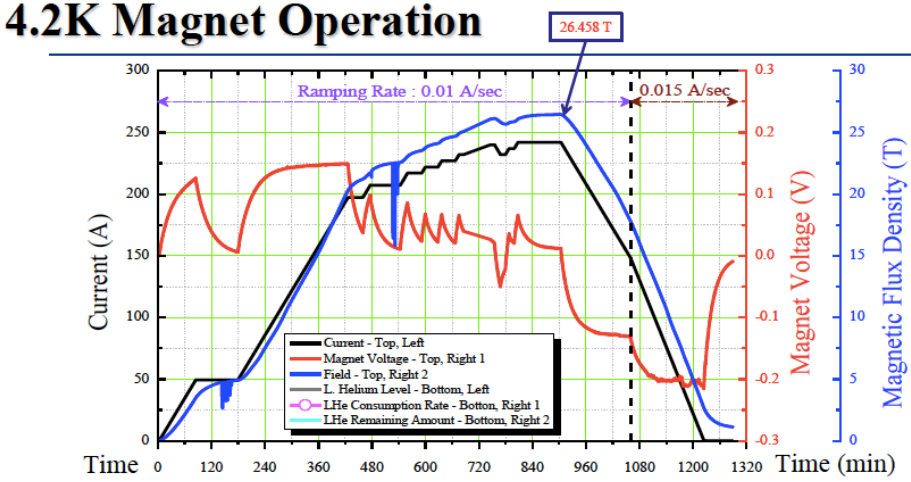


REBCO superconductor technology is primed for use in plasma and fusion science



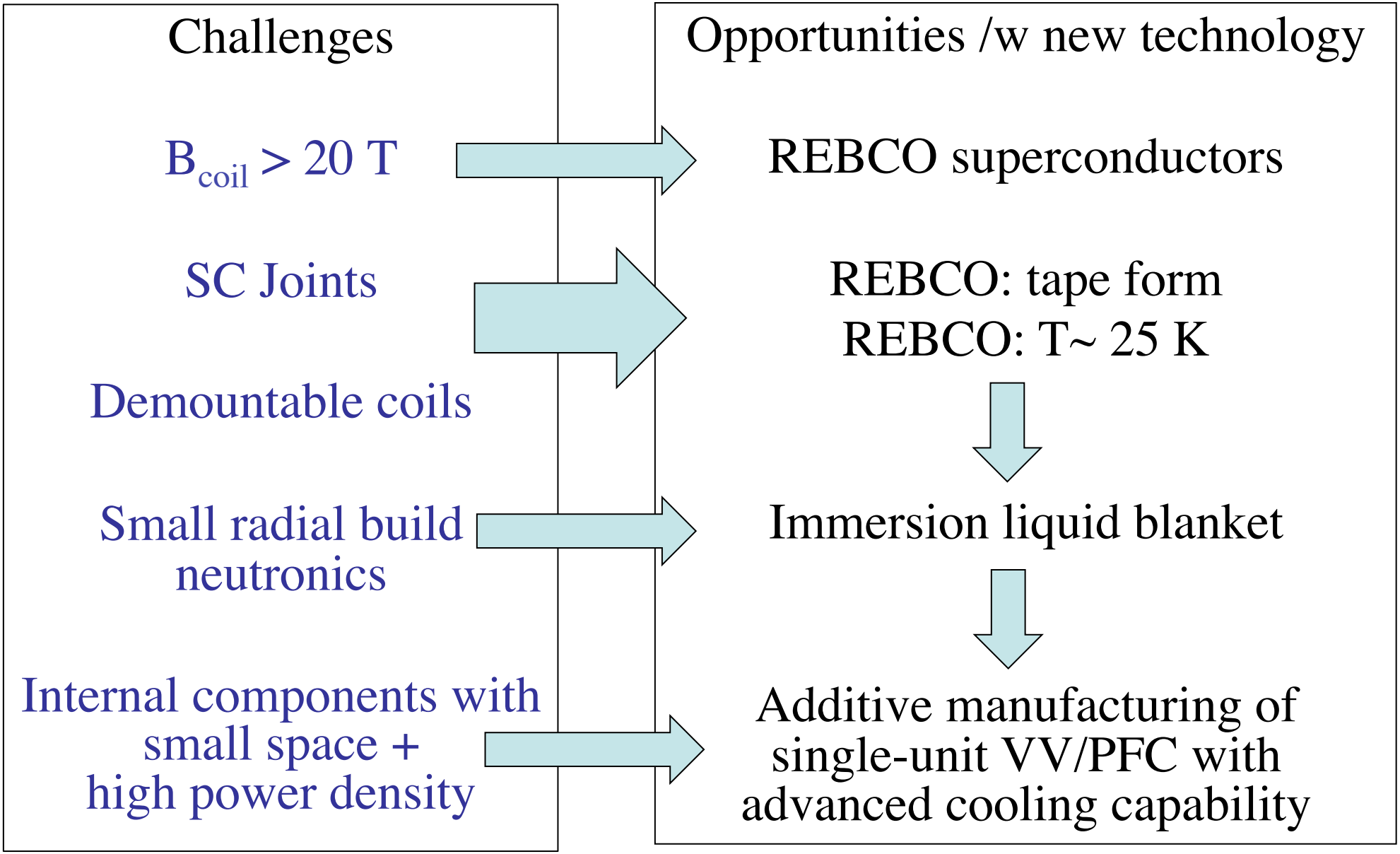


B_{coil}(T)	26.5	23
J_e (A/mm^2)	400	400-500
T (K)	4.2	25
Materials	REBCO, SS316L	
σ_{max} (MPa)	593	660
Diameter (m)	0.03	~ 6



S. Hahn et al. APL 2015

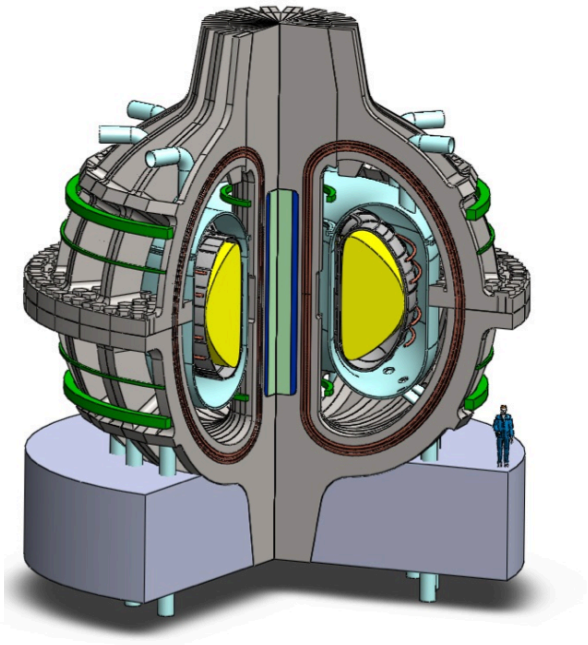
Multiple, linked engineering design challenges to smaller, modular path

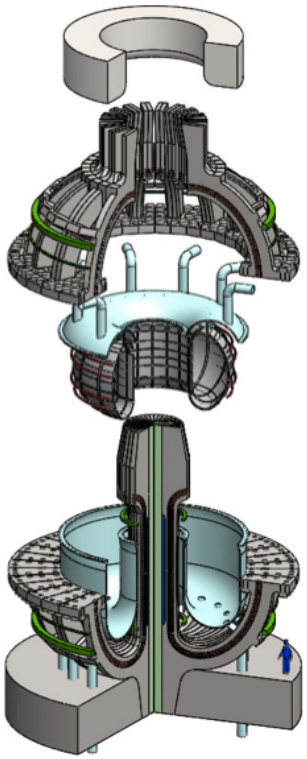


ARC is but a single example of the profound effects on engineering design by use of REBCO technology

Challenges	Opportunities /w new technology
$B_{coil} > 20$ T	REBCO superconductors
SC Joints	REBCO: tape form REBCO: T~ 25 K
Demountable coils	
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

Sorbom et al FED 2015





Peak field ~ 23 T
$B_0 \sim 9.2$ T
$V \sim 100$ m^3
$P_f \sim 500$ MW
$q_{95} > 5$

Modular close-fitting VV+PFC
FLiBe immersion liquid blanket
TBR ~ 1.15
> 10 year FPY coil lifetime

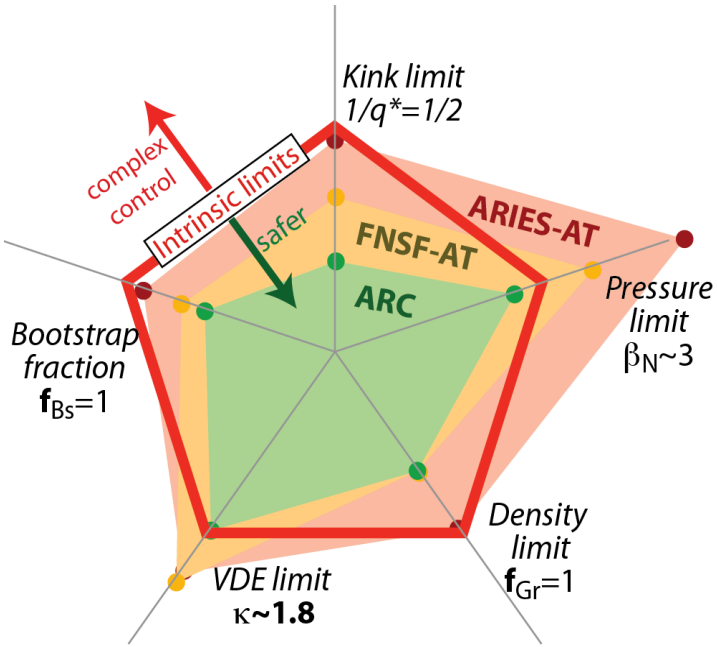
Power exhaust
Single-phase
Low-pressure
Divertor TBD

Access to high-B allows one to construct realistic integrated scenarios away from operational 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

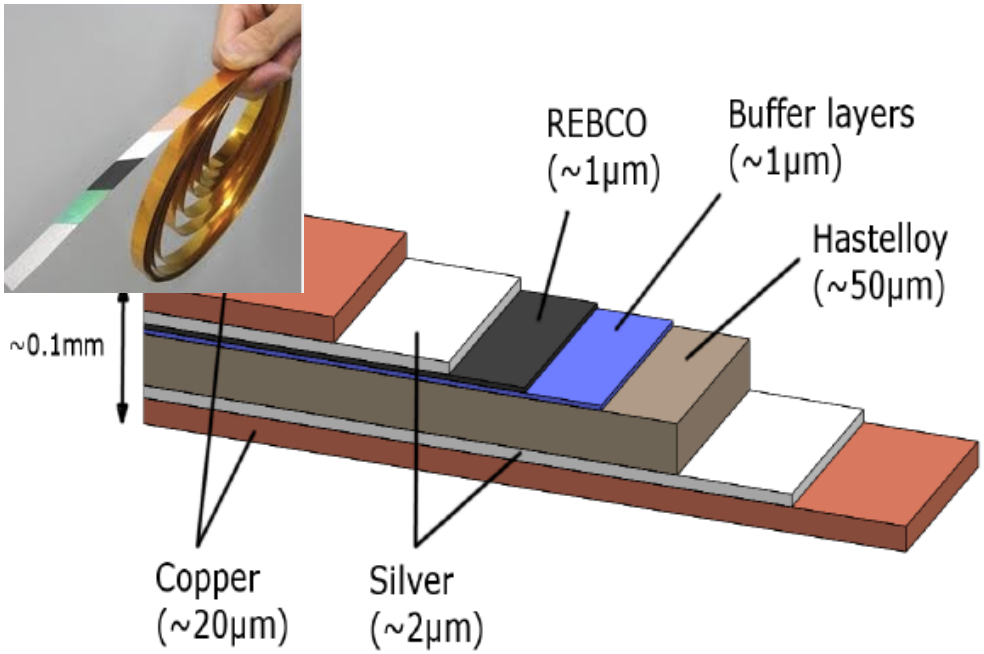
$$\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N^2 \epsilon^2}{q_*^2} R B^4$$

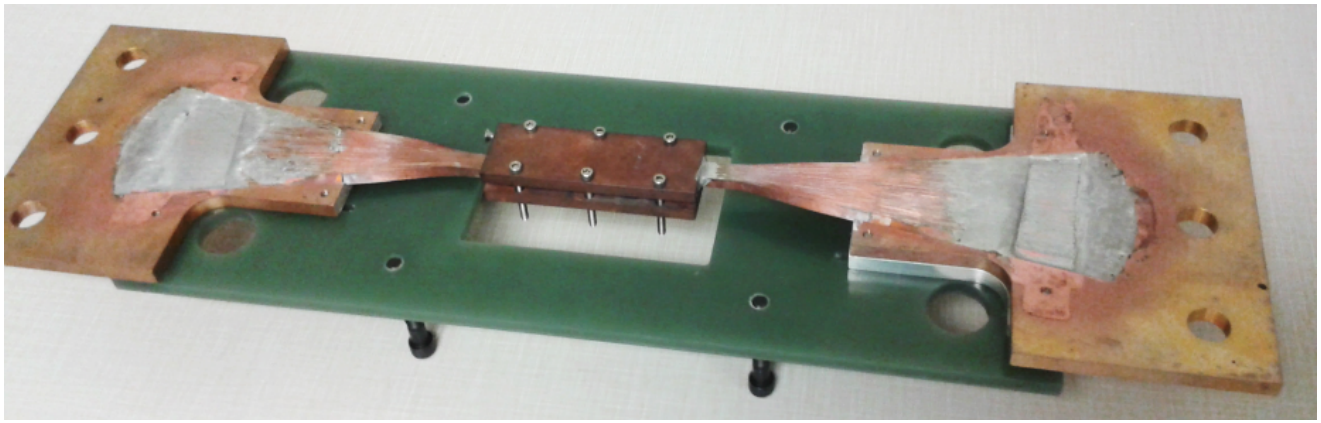
$$nT\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

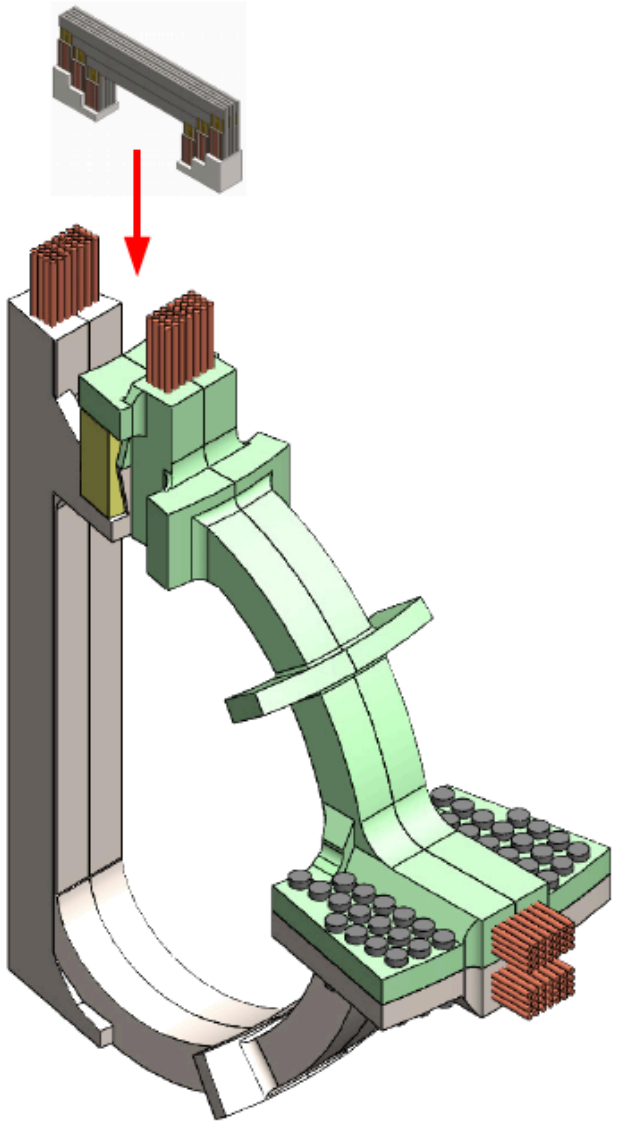


Garofalo, PoP 2006 056110
Najmabadi, FED 2006

First lab results show path to target of ~10 n-ohm joints…work on mechanical stability ongoing

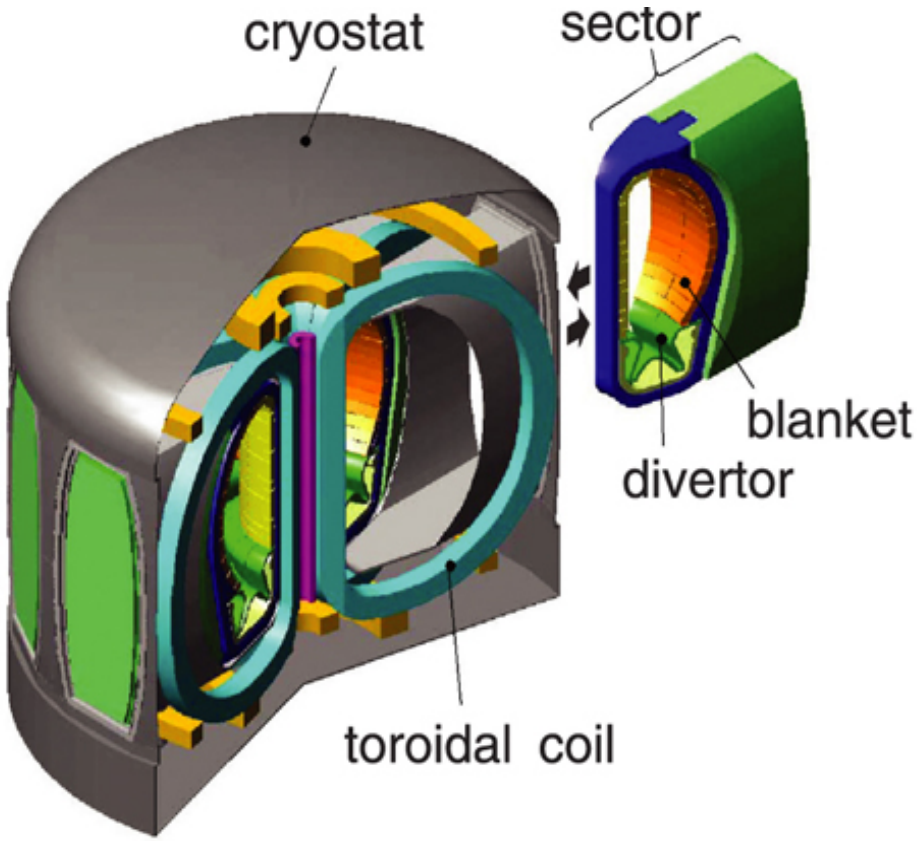


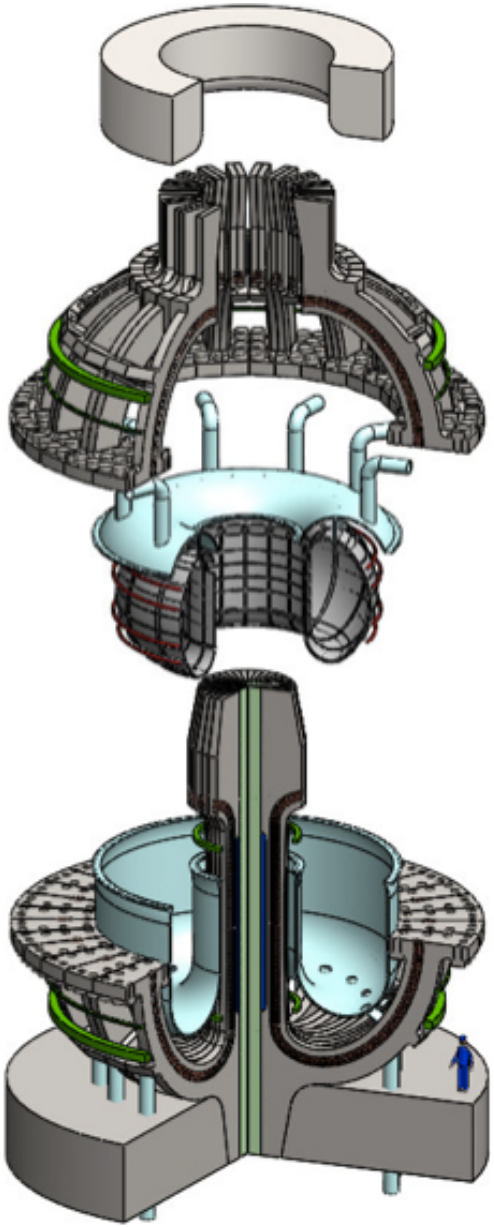




F. Mangiorotti, J. Minervini
MIT Ph.D. thesis

Demountable superconductor coils have a profound effect on modularity of fusion design

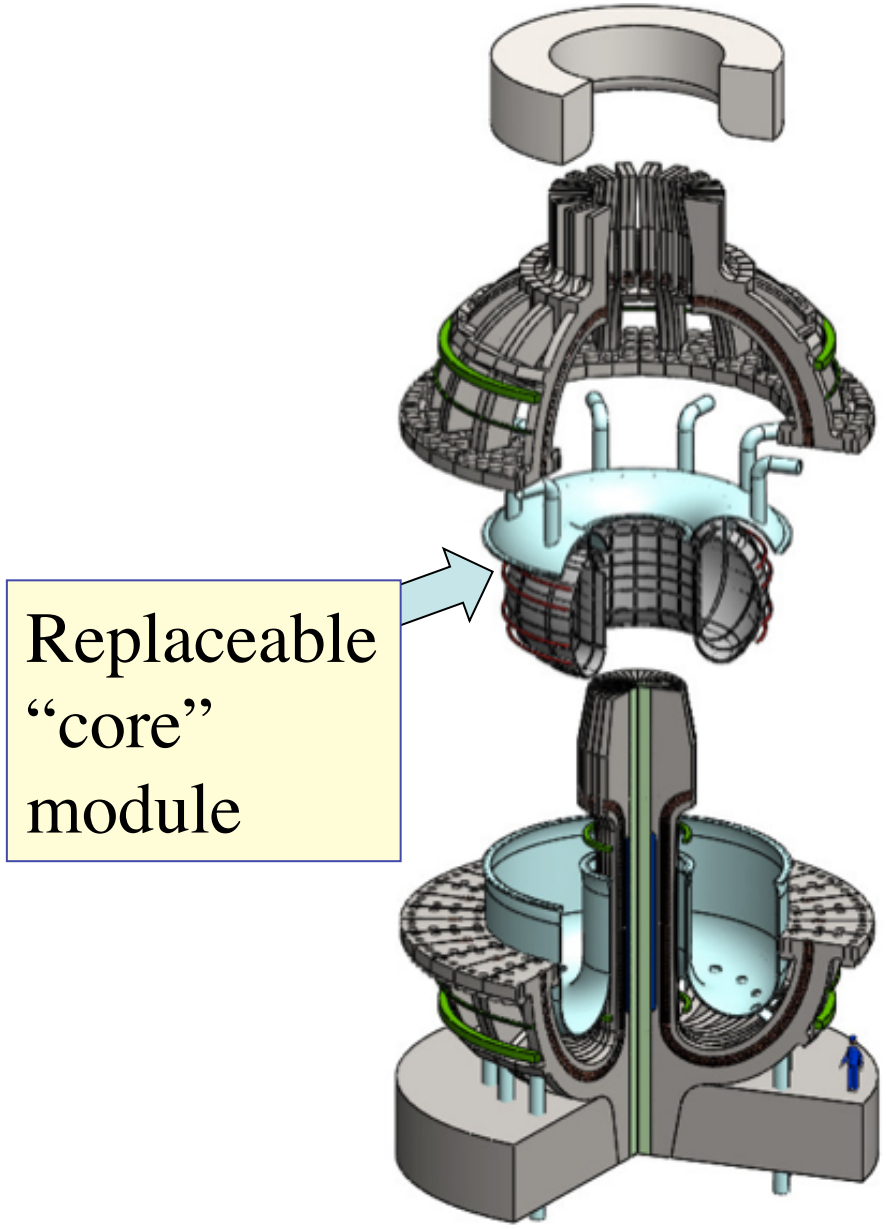




Demountable superconductor coils have a profound effect on modularity of fusion design

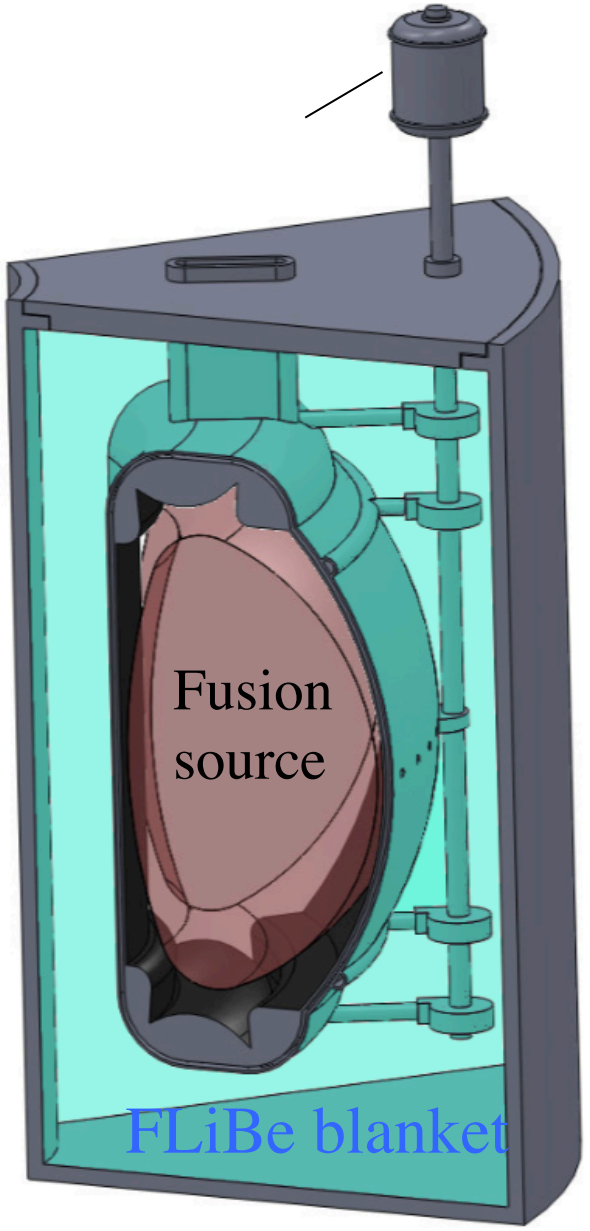
- Close-fitting VV+PFC is designed as a single integrated unit
  - Synergy with keeping design of small total mass and volume

- **Fabrication + qualification done completely off-site**

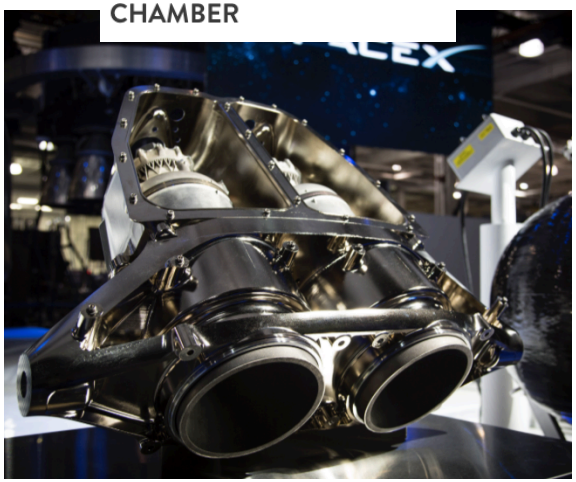


Modular core has a profound effect on fusion design: The liquid immersion "blanket" revolutionary to nuclear engineering of fusion

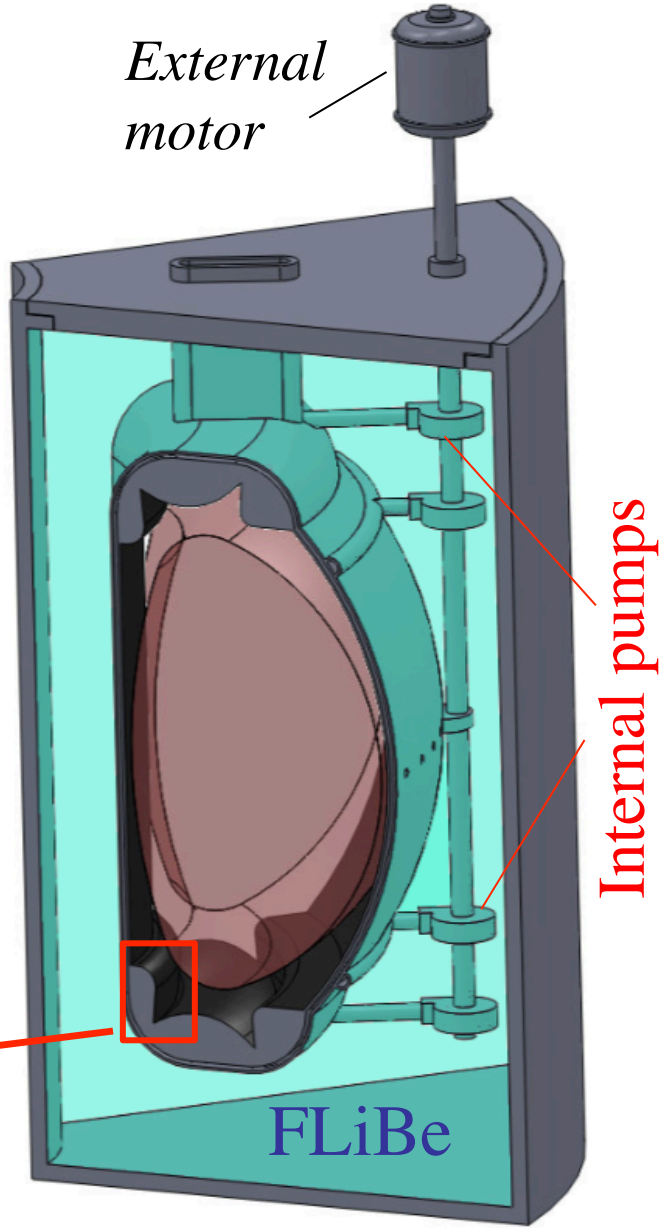
- Simple -- No gaps
- Energy & fuel extraction with liquid low-velocity flow
- No damage limits in blanket
- Solid replaceable components reduced by factor of 50.
  - VV + PFC damage rate reduced: 30-40 dpa/year
  - Built to be replaceable.



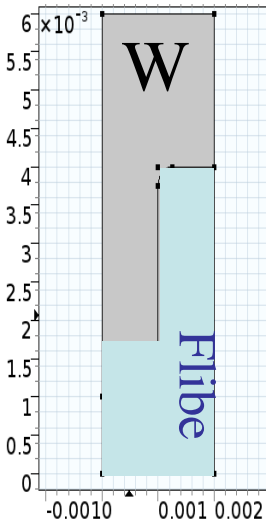
This magnet technology driven development path to fusion is ripe with near-term opportunities in science & industry

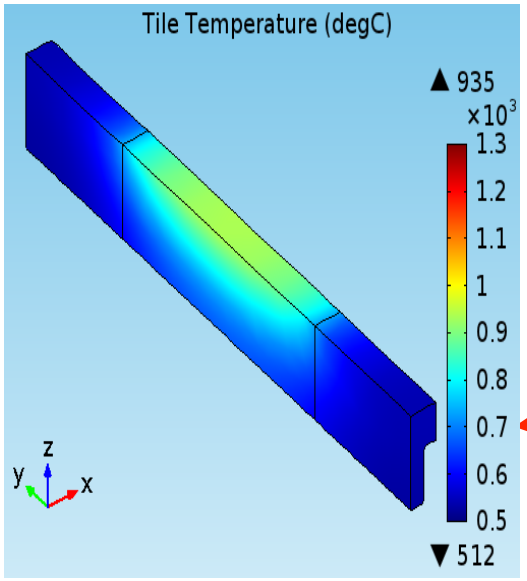


Advanced surface heat removal by combining high-T molten salts + 3-D printing



2 mm thick + Internal Fin

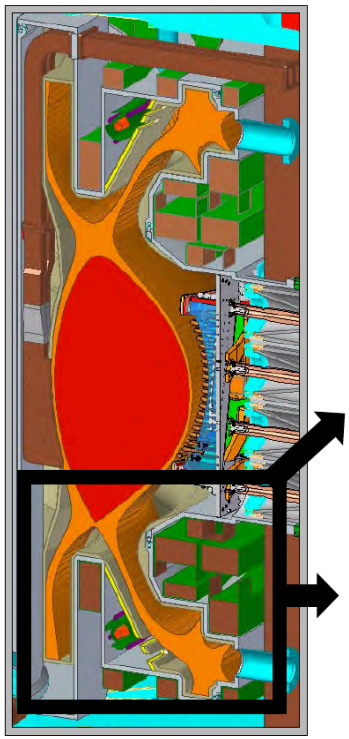


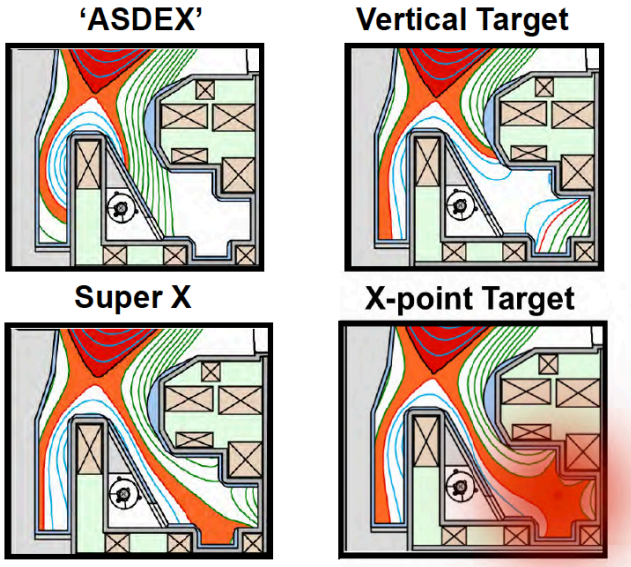


Modularity and small size should be enabling to solving critical issue of divertor heat exhaust

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

Divertor Test Tokamak: ADX

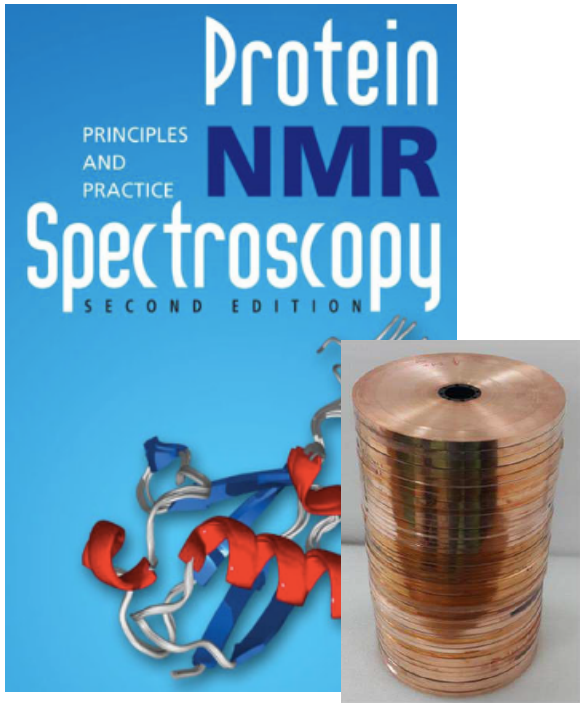




PF coils may be configured for other geometries: snowflake, x-divertor, ...

This magnet technology driven development path to fusion is ripe with near-term opportunities in science & industry

NMR / MRI resolution of biological system ~ B^3



10-fold improvement in protein, virus, etc. diagnosis

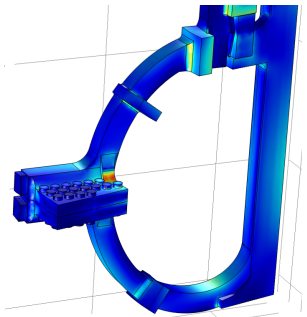
Higher imaging resolution

Modular/maintainable magnet

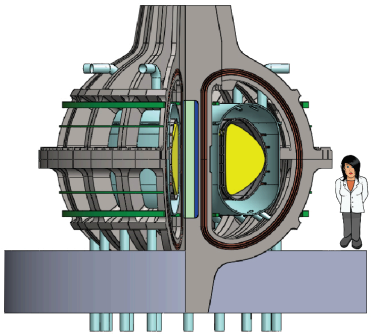
Eliminate need for scarce Helium

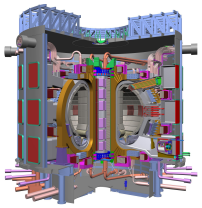
HTS Development pathway and R&D payoffs

High-B HTS demountable superconductor coils

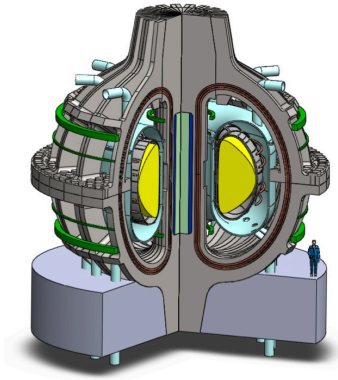


Small Energy Pilots

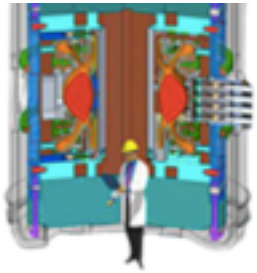


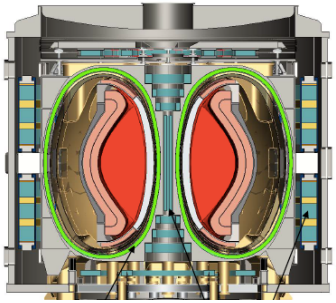


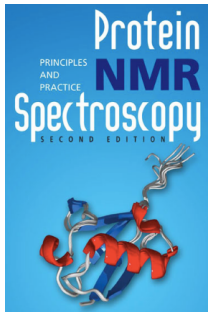
Fusion Electricity Pilots

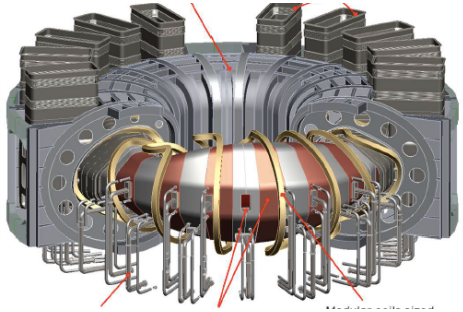


Divertor Test Tokamaks









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