Massachusetts Institute of Technology

MIT Plasma Science & Fusion Center

The High Magnetic Field Tokamak Path to Fusion Energy*

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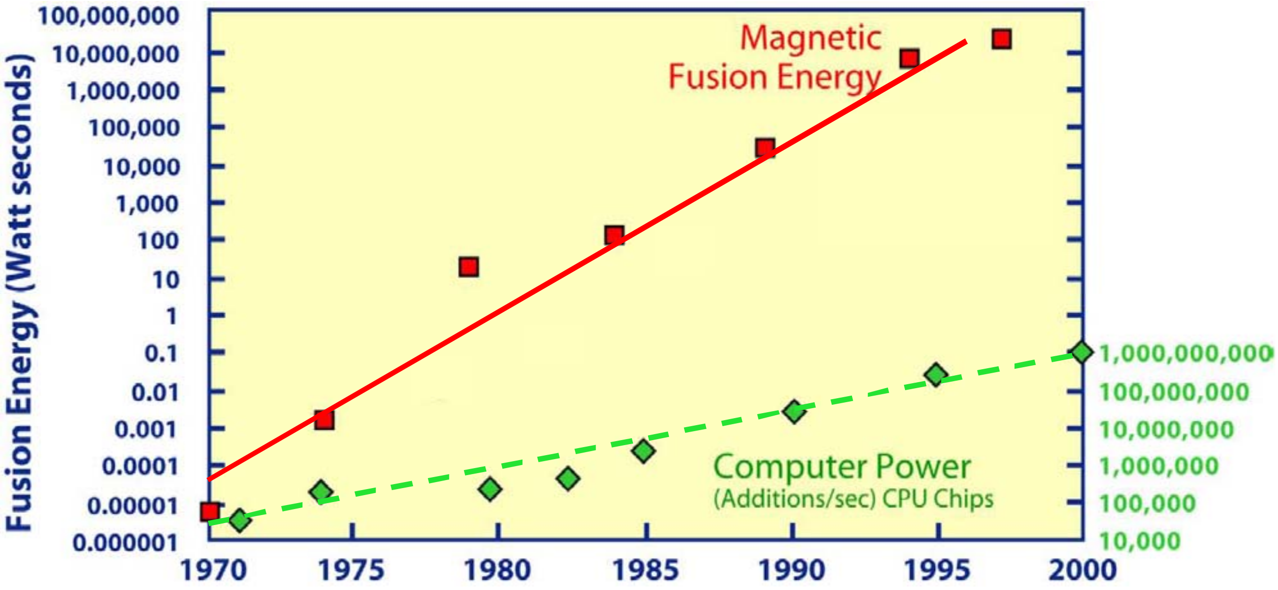
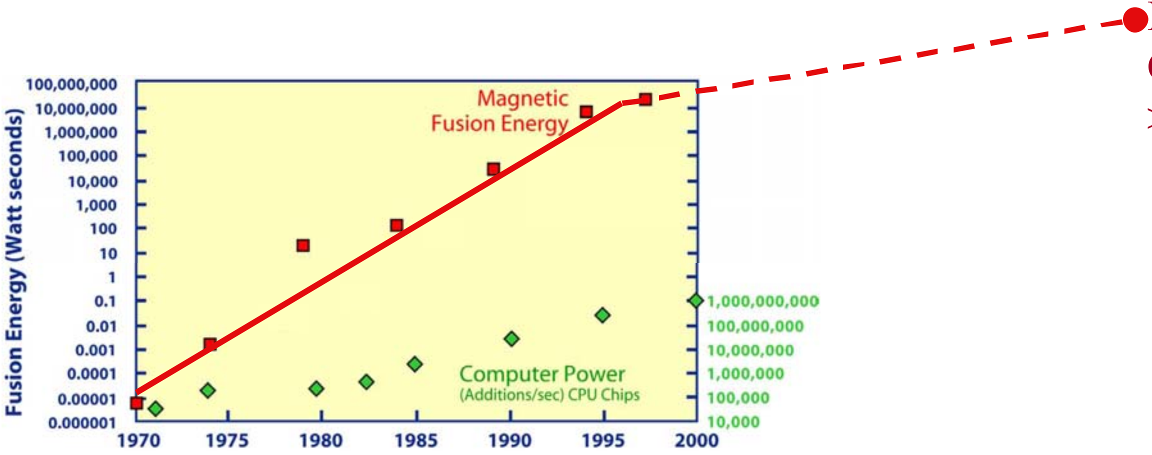
Fusion Energy Progress has been Truly Remarkable

- From 1970 to 1995, nτT, fusion power and fusion energy increased much faster than computing power (Moore’s law)
  - more than 12 orders of magnitude increase in fusion energy per pulse



Fusion Energy Development has Slowed

- From 1970 to 1995, nτT, power and energy increased much faster than computing power (Moore's law)
- Why the slowdown?
  - — research funding decreases
  - — unit size of devices being designed and built is very large

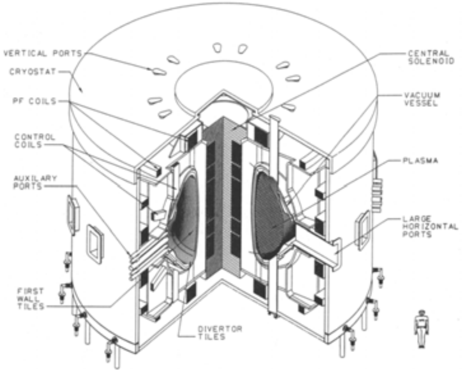


ITER
Q=10
>2030?

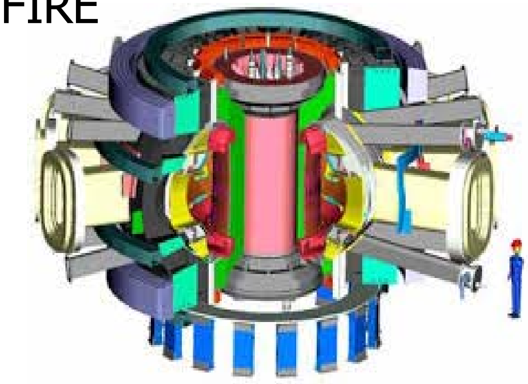
High-Field Tokamaks Long Recognized as an Expedient Approach to Study Burning Plasmas

- Compact copper-magnet designs, including Ignitor, Zephyr, CIT/BPX, FIRE
  - Demonstrate and study alpha-dominant heating regimes, in pulsed operation
  - Since the required magnetic fields were not achievable with conventional superconductors, deemed by some to be a “dead end”

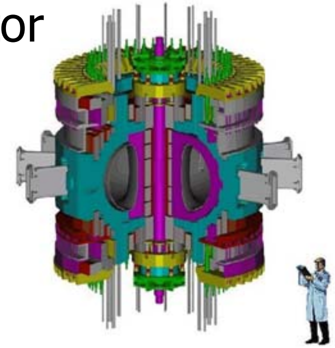
BPX



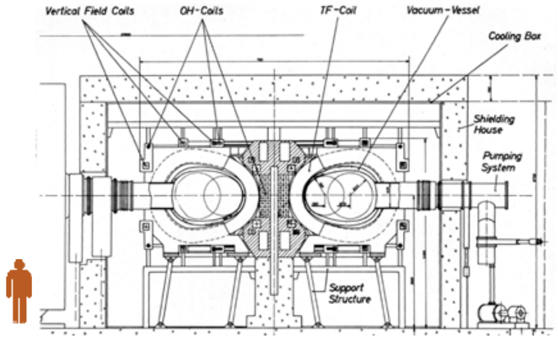
FIRE



Ignitor

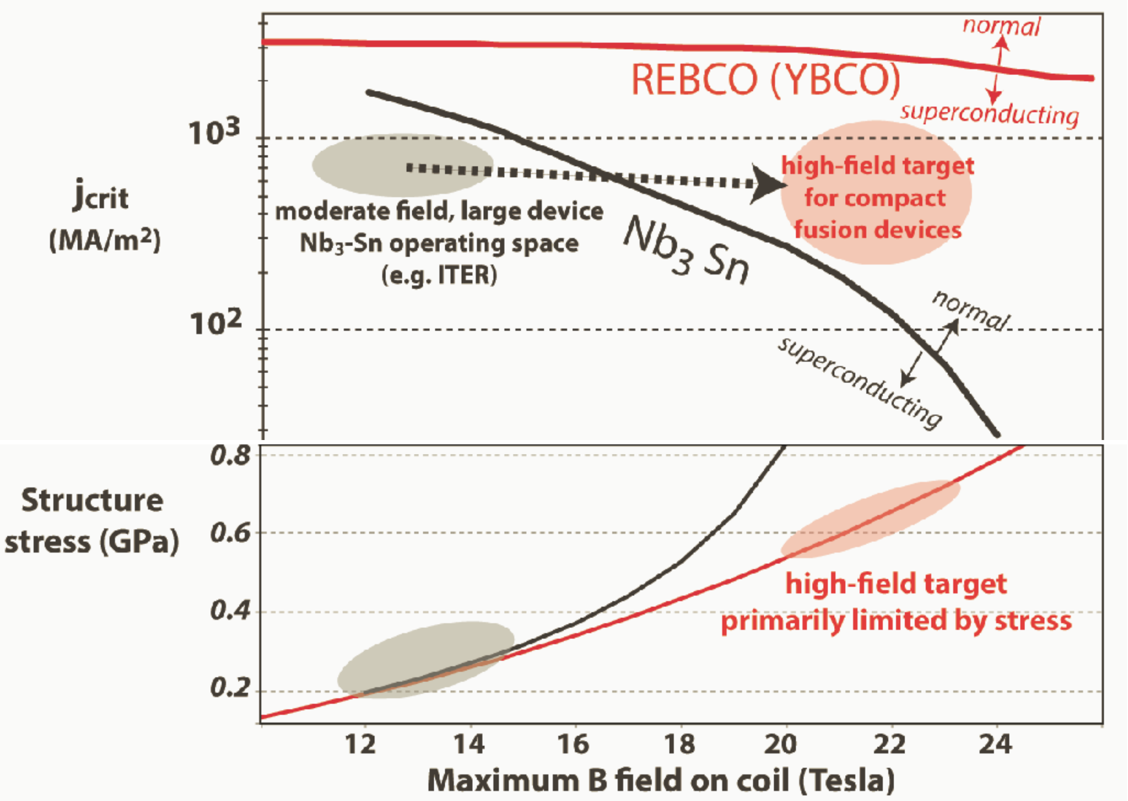


Zephyr



A Revolution in High Temperature Superconductors (HTS) in Last 5 Years

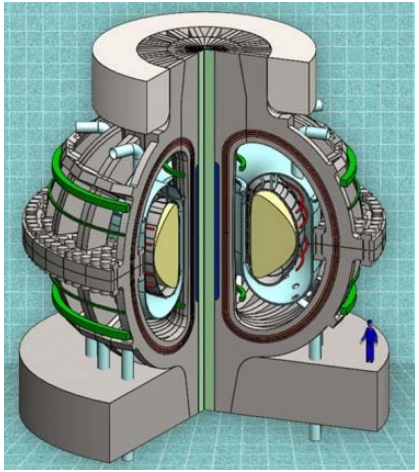
REBCO
(Rare-Earth
Barium Cu-Oxide)
remains
superconducting
at VERY
high B-field, and
above liquid He
temperatures

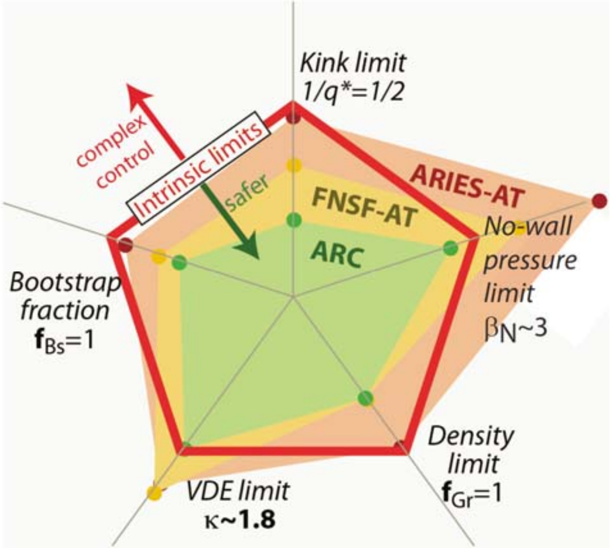


Industrial Maturity of High-B Superconductors Motivates Reconsideration

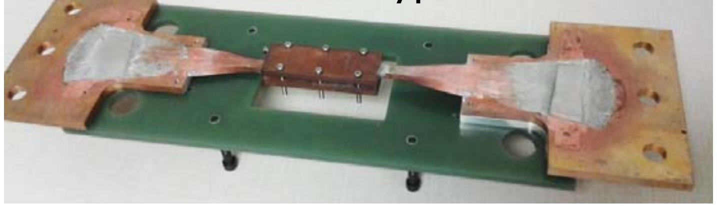
Possible game-changer for fusion energy

- Devices that produce net electricity could be built at smaller scale ⇒ sooner, lower cost
- Operating point would be more favorable for
  - Stability, control, sustainment, PMI, disruption-immunity
- Higher temperature operation opens new options for jointed coils
  - flexibility, maintainability





Prototype HTS Joint



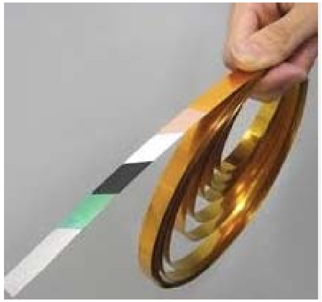
Recent Magnet Technology Advances Could Lead to Faster Development of Fusion Energy

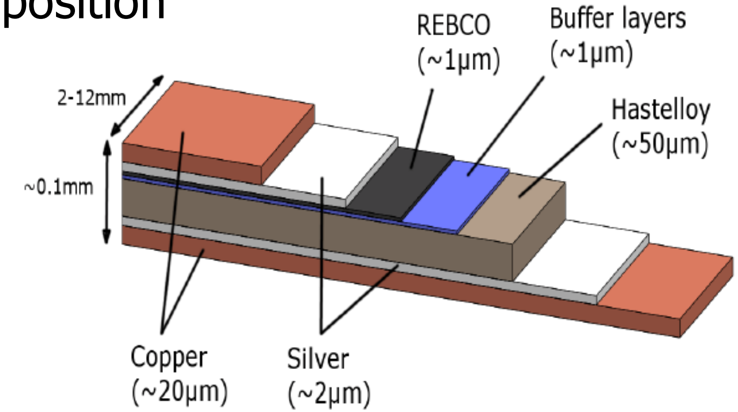
Outline

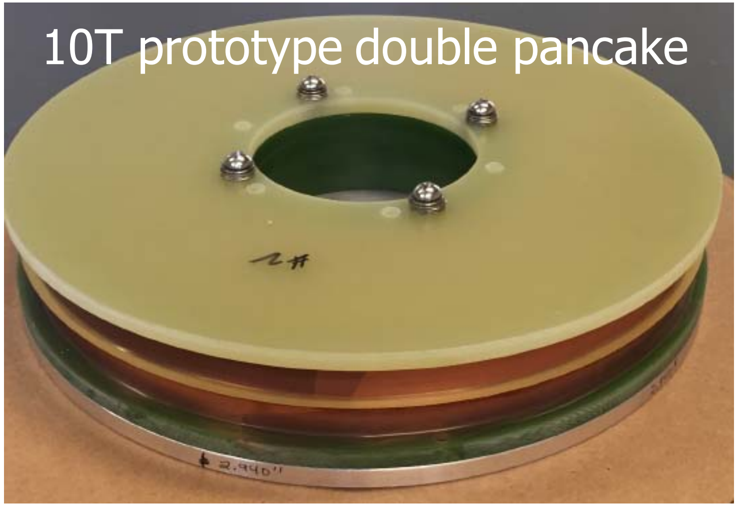
- — Superconducting Technology
- — Confinement and Stability: Core and Pedestal
- — Power Handling and Plasma-Wall Interactions
- — Next steps

REBCO: coated superconductors in robust tape form, commercially available

REBCO tape composition
(not to scale)





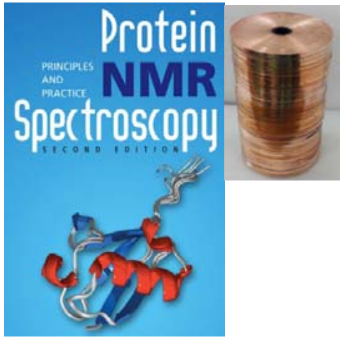

10T prototype double pancake

- Strong in tension due to hastelloy steel
- Flexible
- Outer Cu coating → simple solder low-resistance joint
- Stark contrast with Nb_3Sn superconductor strand & CIC!

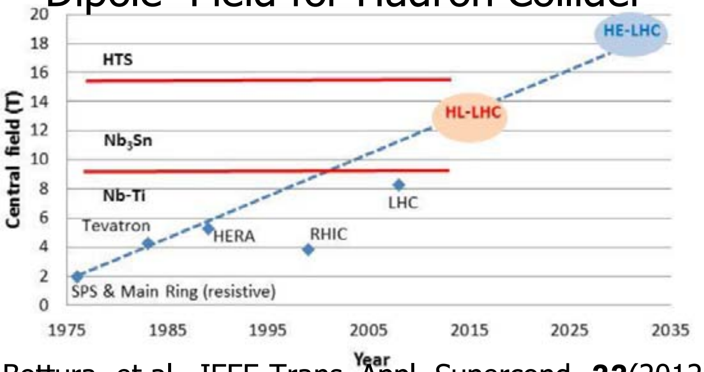
Other Applications of REBCO High-Field, High Temperature Superconductor

- Electrical Transmission
- Electrical Energy Storage
- NMR/MRI
- Possible upgrades to LHC

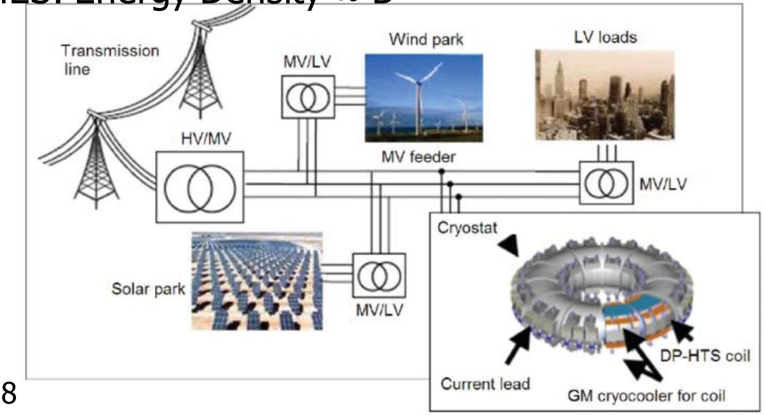
Higher B:
spatial resolving power ~B^3



Dipole Field for Hadron Collider*



SMES: Energy Density ∝ B^2

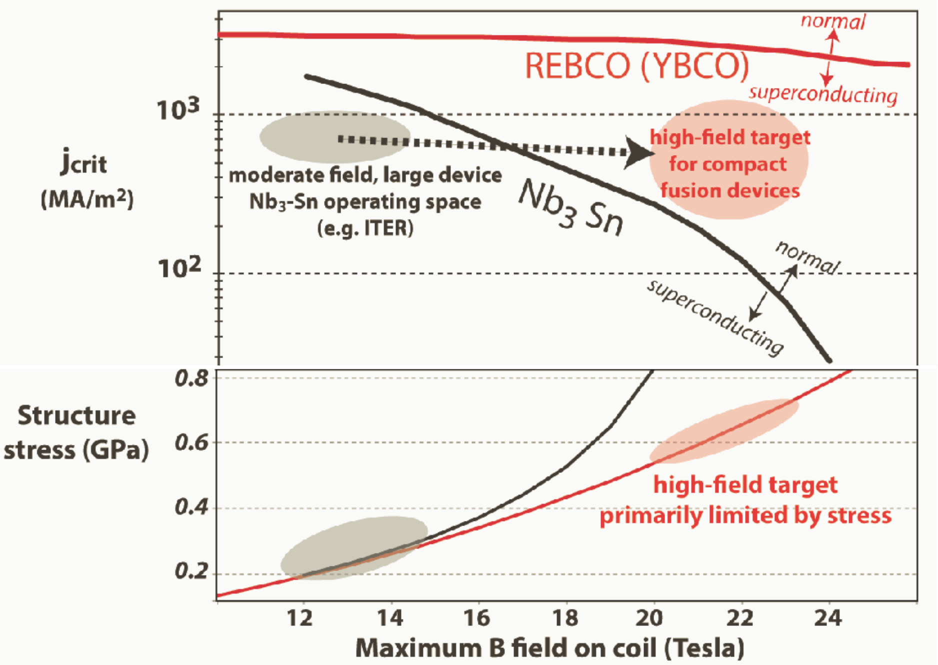


Small ST, Tokamak Energy, UK

*L. Bottura, et al., IEEE Trans. Appl. Supercond. **22**(2012)4002008

What limits B in an HTS Tokamak?

- Need sufficient volume for superconductor, with given j_c constraints
  - — thin tape geometry advantageous
- Stay within structural stress limits
  - — Understanding of mechanical stress and limits is a mature engineering discipline
  - — Note that C-Mod successfully operates (1000's of cycles) at high fields (≤17 T at the coil), with demountable joints (copper)



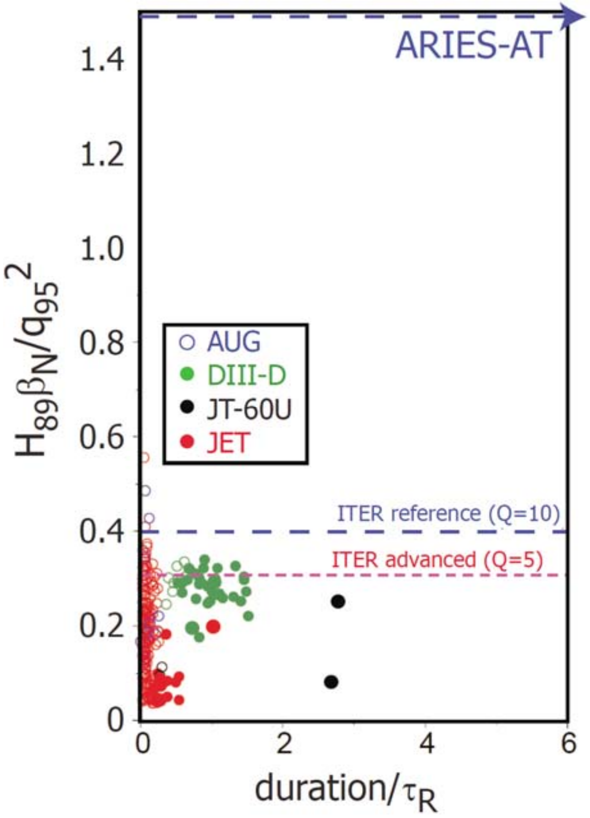
Smaller, modular fusion devices can accelerate fusion's development

	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
- ITER is an invaluable science experiment for burning plasmas, not an optimized size for modular fusion energy "pilots"
  - — ITER is a trial of one fusion concept, fission pilot tried four different cores!
- Small size and modularity are self-reinforcing: pilots of complex engineered systems should be no larger than necessary, yet sufficiently capable

Integrated steady-state parameters required for advanced tokamak reactors (@B≤6 T) not yet achieved

	DIII-D	**ARIES-AT**
B_0 (T)	2	5.8
q_{95}	6.3	3
H_{89}	2.7	2.5
β_N	3.7	5.4
$G = \beta_N H_{89}/q^2$	0.25	1.5
$f_{bootstrap}$	0.65	0.91
$n / n_{Greenwald}$	0.5	0.9



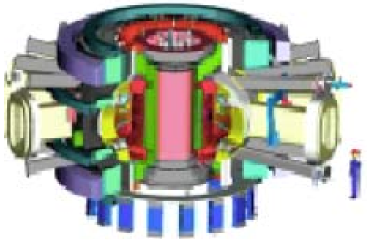
Najmabadi et al. FED ***80*** *(2006)*
Chan et al. NF (2011)

A.C.C. Sips, Plasma Phys.Control.Fusion, ***47****(2005)A19–A40*
Zarnstorff Demo workshop 2012

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**

Copper coil
pulse ~ 40 s



FIRE

R (m)	2.14
V (m³)	30
B_o (T)	10
Q_p	>10
Steady-state	No
Tritium breeding	No
$Q_{electric}$	0

Can this be made steady-state with High-B Superconductors?

Known physics scaling + Superconductor B_{peak} > 20 T → High-gain burning plasma: Compact Size & Steady-State

Gain

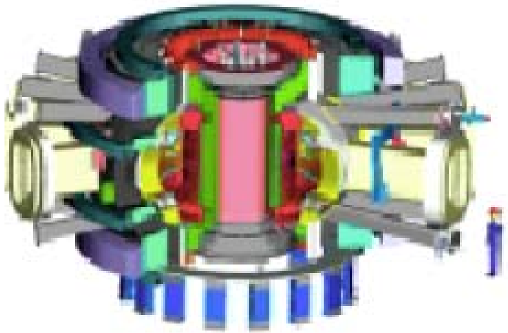
$$nT\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

$$V,\$ \propto R^3$$

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

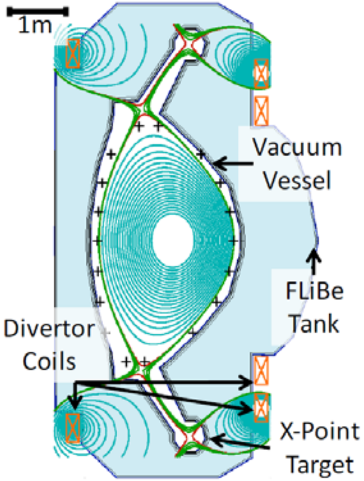
Power density

FIRE*
copper



	FIRE*	ARC
R (m)	2.14	3.2
B_o (T)	10	9.2
Q_p	>10	>10
Steady-state	No	Yes
Tritium breeding	No	Yes
$Q_{electric}$	0	~ 4

"ARC"**
REBCO superconductor

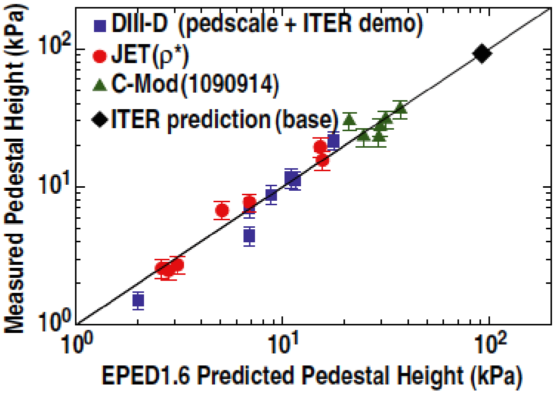


*D. Meade, Fus. Sci. Tech. **47**(2005)393

**B.N. Sorbom, et al., Fus. Eng. Des., 100(2015)378

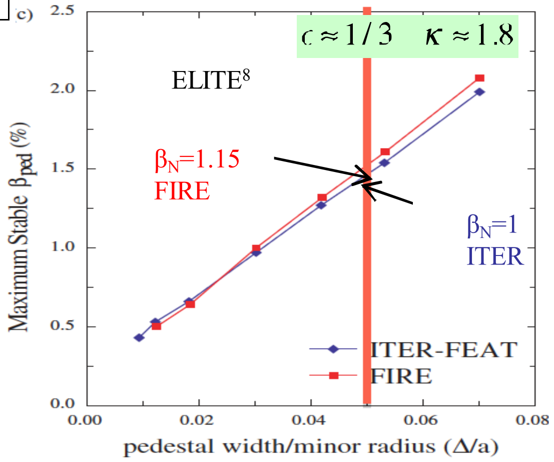
High B permits a pedestal with required pressure for fusion performance, away from Peeling-Balooning stability limits

- Reactor/FNSF pedestal is constrained:
  T~ 5 keV (D-T reactivity), n_{20}~ 1
  → p_{ped} ~ 0.15 MPa (~x1.5 $p_{ped, ITER}$)
- But the P-B limit, defined in β_N, cannot be violated due to PFC damage from ELMs.
- This greatly favors high B^2 to push the required pedestal away from the P-B limit, and to be consistent with non-disruptive high q_*



Snyder et al NF 2011

$$\beta_{N,Ped,\lim} \simeq 1.05\left(\frac{\Delta\psi_{ped}}{5\%}\right)^{3/4}$$

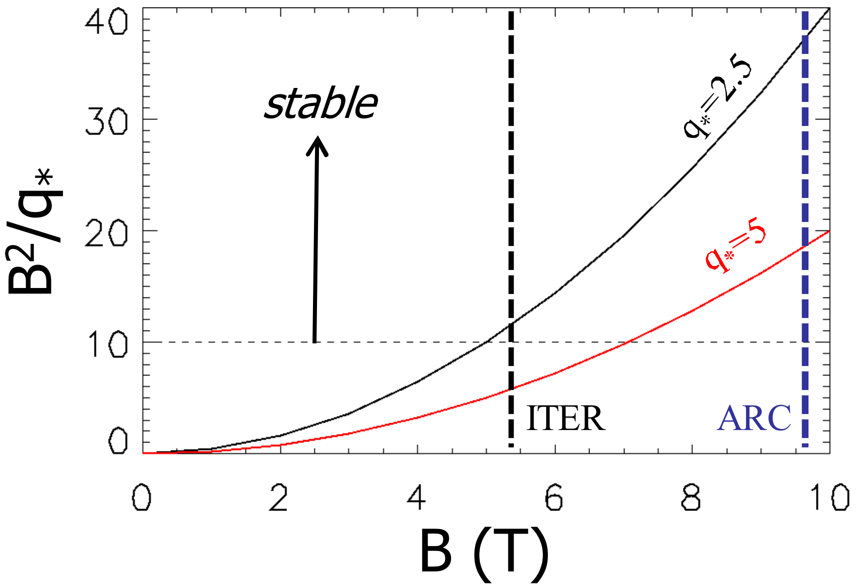


High B permits a pedestal with required pressure for fusion performance, away from P-B stability limits

- Example: take pedestal width, r/a~5%, fix aspect ratio and shaping of ITER, FIRE, ARC
  - this reduces to requirement for minimum B^2/q

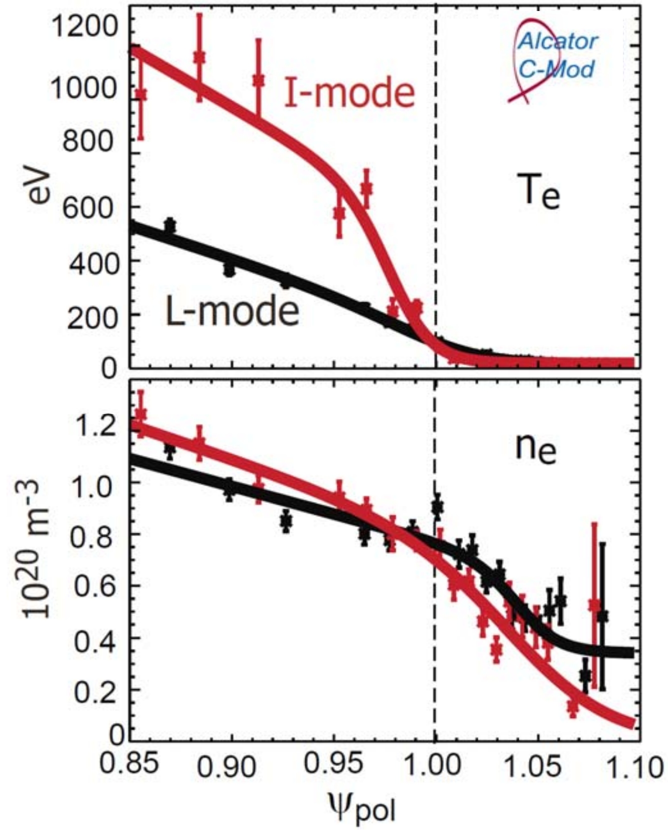
$$\beta_{N,ped,\lim} \propto \frac{p_{ped}}{p_B}\,\frac{5\epsilon}{q_*}\,\frac{\left(1+\kappa^2\right)}{2} \Rightarrow \frac{B^2}{q_*} > 10\left(\frac{p_{ped,MPa}}{0.15}\right)$$

- Key transport physics requirement…some transport regulation mechanism to hold pressure below limit (QH-mode, I-mode, etc.)



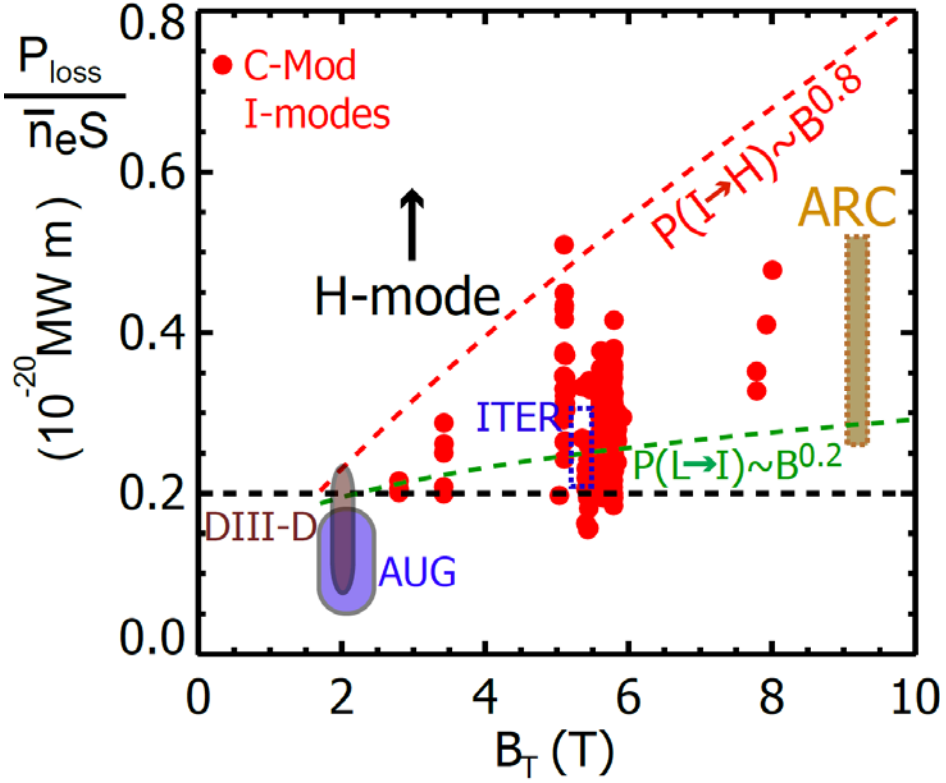
ARC designed with scaled I-mode profiles from C-Mod to assess I-mode viability in non-inductive burning plasma regime.

- Key transport physics requirement…some transport regulation mechanism to hold pressure below limit (QH-mode, I-mode, etc.)
- I-mode* is a naturally ELM-suppressed regime
  - — H-mode confinement, strong temperature pedestal
  - — Lack of density barrier helps to move pedestal further from P-B limit
  - — L-mode impurity confinement: no accumulation
- ARC pedestal below simple β_N limit



High Field Favors I-mode over H-mode

- Need to stay out of H-mode at high power
  - Run with $\boldsymbol{B} X \nabla \boldsymbol{B}$ away from x-point (~doubles H-mode threshold)
- How does high B (≥ 8 T) play into the access for I-mode and avoidance of unwanted ELMy H-mode?
  - Increase B, to further increase H-mode threshold ($P \sim B^{0.8}$)
    - I-mode threshold shows no, or at most weak scaling with B ($P \sim B^{0.2}$)



Doesn't Compact, High Field Make the Divertor Power Handling Problem Harder?

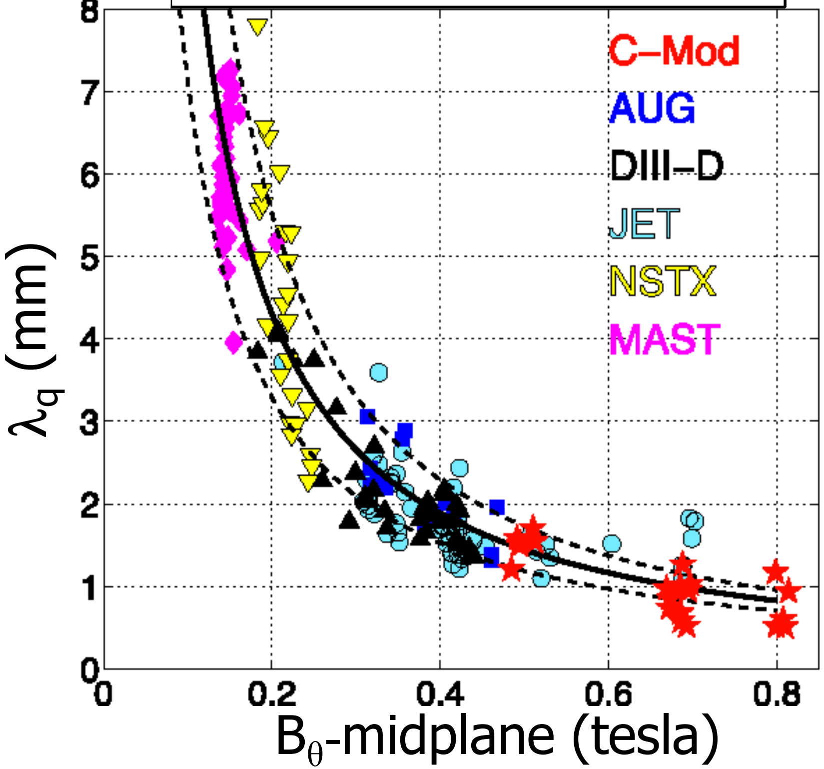
- Actually, the answer is no
- SOL power width, λ_q, independent of machine size ($\lambda_q \propto 1/B_\theta$)
  - — $q_\theta \equiv P_{SOL}/S_\theta$; $q_{||} \equiv q_\theta B/B_\theta$
  - — $S_\theta = \lambda_q \times 2\pi R \propto R/B_\theta$

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

For fixed P_{SOL}/S_{plasma}, $q_{||} \propto BR$

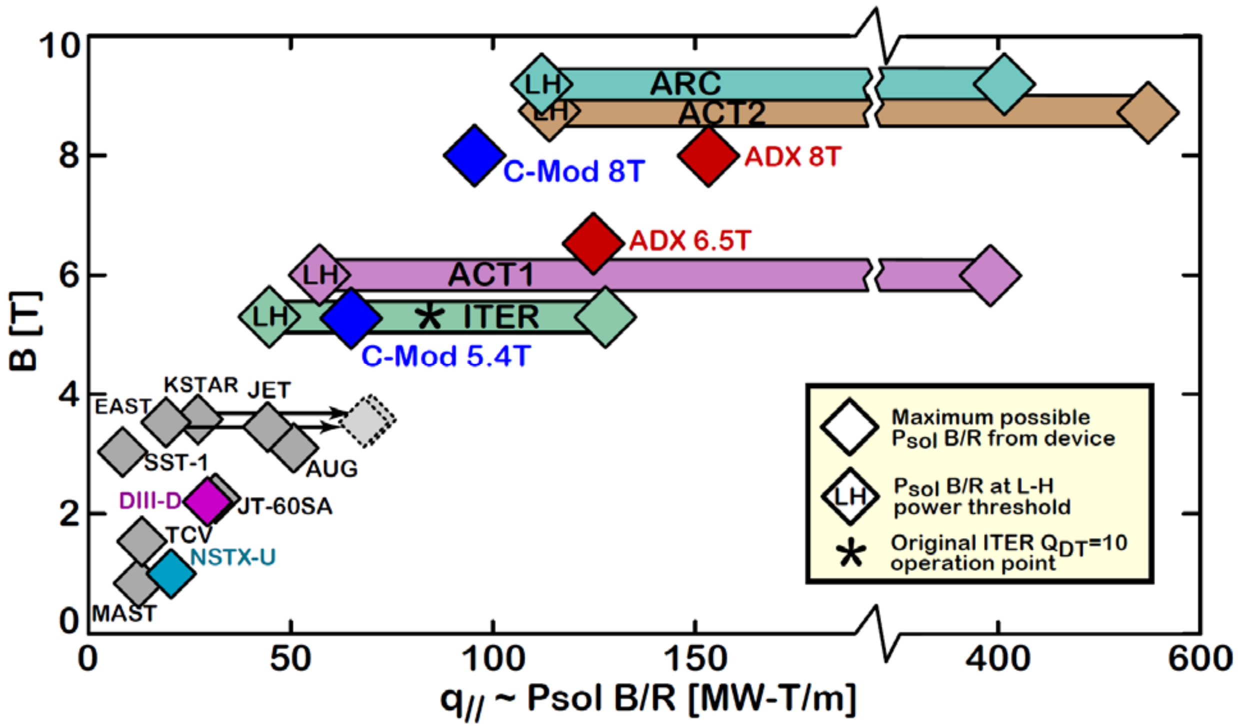
- ➢ Lawson criterion: $R \sim 1/B^{2.3}$
  - ➢ **$q_{//} \sim 1 / B^{1.3}$**

Eich, *et al.*, NF 53 (2013) 093031



Surface Power Handling is a Significant Challenge in all Reactor Concepts

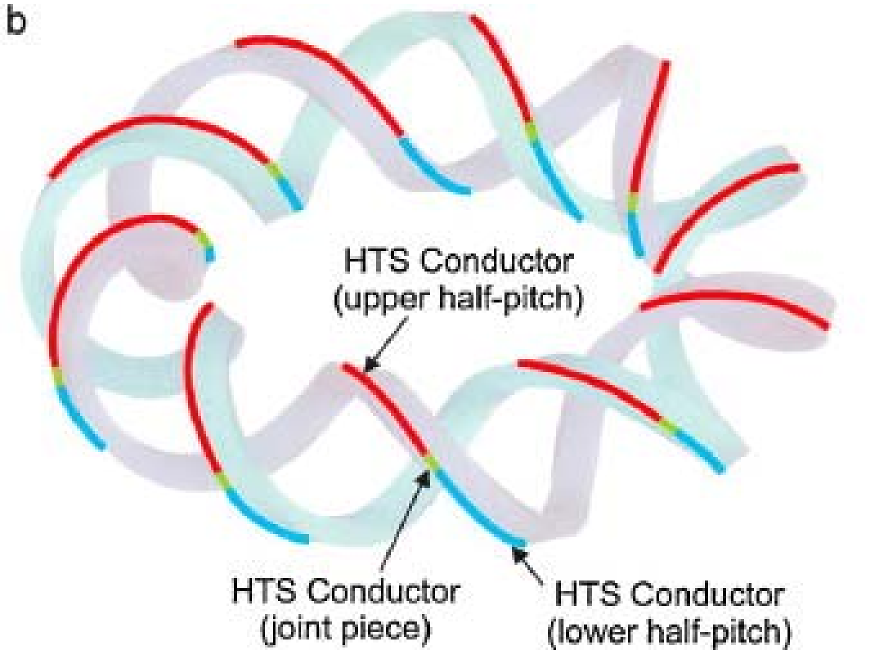
- Comparing ACT2 (R=9.8 m, $P_{SOL}/S=.4$ MW/m^2) and ARC (R=3.3m, $P_{SOL}/S=.7$ MW/m^2)
  - no significant difference in expected edge $q_{//}$



HTS could also be revolutionary for Stellarators

- High current density
  - — reduced coil pack size
- Strong, flexible
  - — simpler coil design
  - — does not require reacting after winding
- Slowly varying fields can simplify engineering requirements

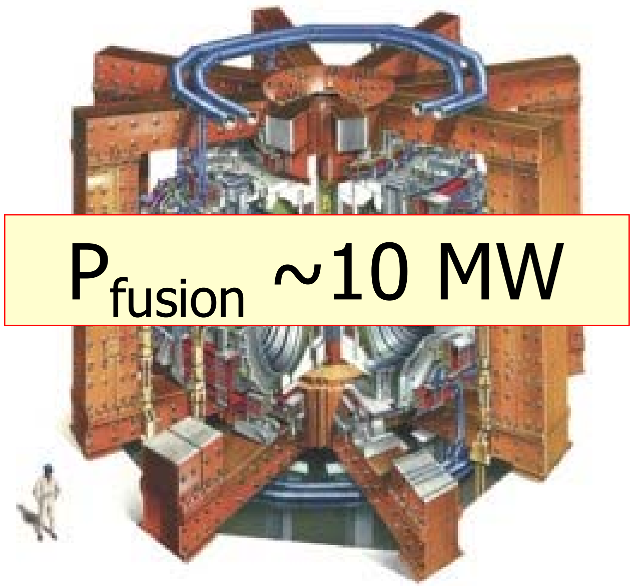
Modular HTS Option for FFHR-d1*



*A. Sagara, et al., Fusion Engineering and Design, **87**(2012)594

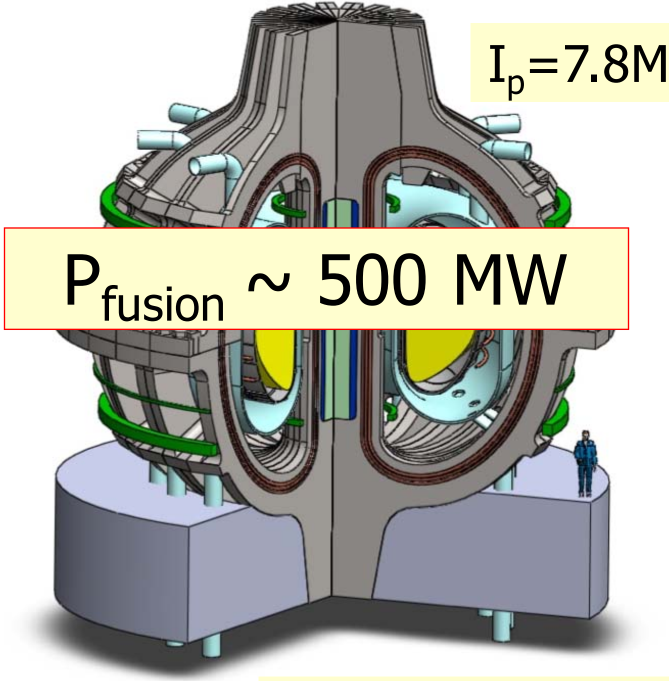
ARC* conceptual design example of “smaller, sooner” fusion device using new superconductors

Copper, B_0 = 3.5 T



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

REBCO superconductor, B_0 = 9.2 T



I_p=7.8MA

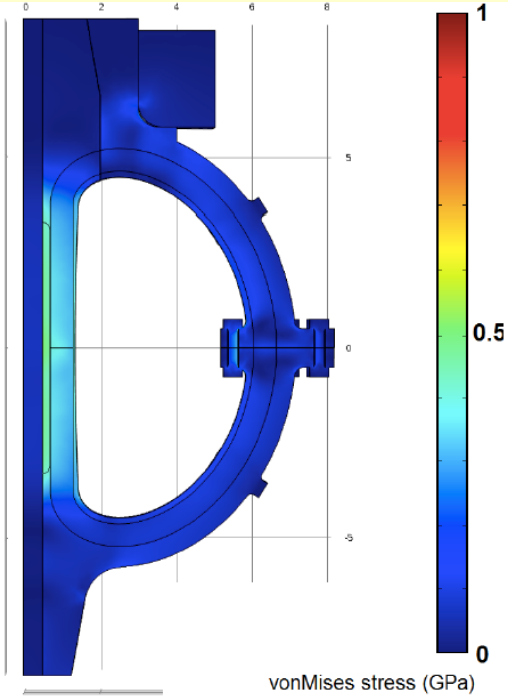
JET: R ~ 3 m
~4 years construction

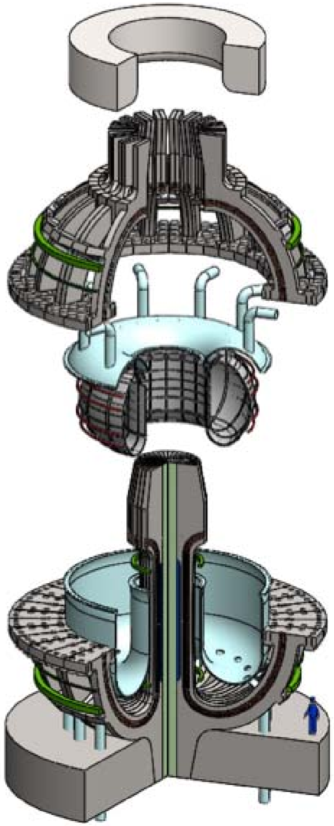
ARC*: R ~ 3.2 m

*B.N. Sorbom, et al., Fus. Eng. Des., 100(2015)378-405

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

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





- Demountable magnetic field coils
  - enabled by jointed conductor
- Employ liquid blanket
- Single-unit vertical lift

Small, modular design features generically attractive for any MFE choice:
ST, stellarator, liquid wall, etc.

Where are we now?

- Superconducting technology advance opens a new window for a faster path
  - HTS coils are a reality; not yet at scale needed for fusion
  - Jointed construction would yield significant improvements in flexibility, maintainability
    - R&D required
- Physics basis already largely demonstrated
  - Need improved surface power handling

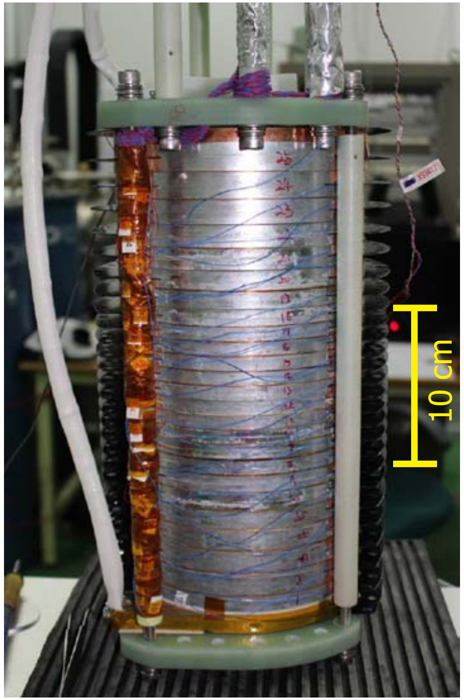
What can/should we do moving forward?

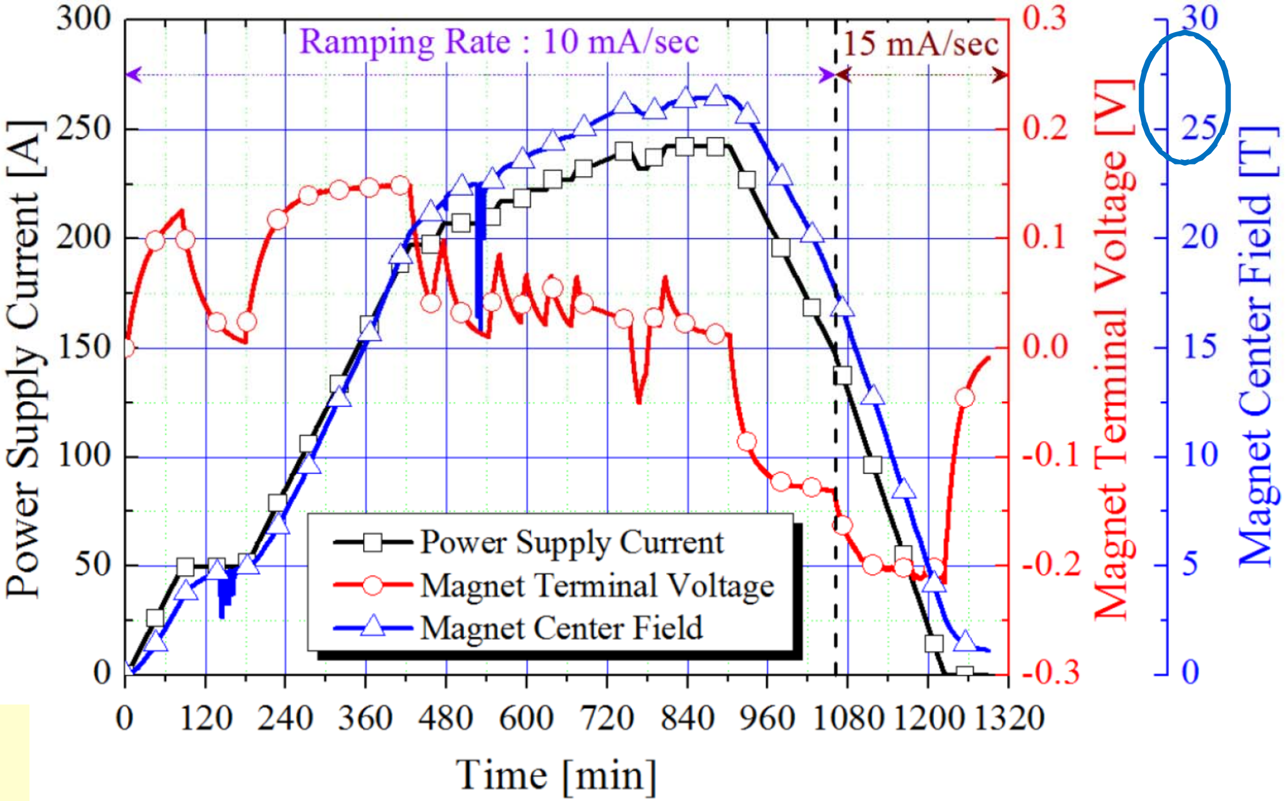
Fusion is needed, and soon: As a community we need to be continually looking for technology and science innovations to accelerate fusion's development.

- HTS High Field Magnet R&D for fusion:
  - Full scale models; Joint development
- Aggressive research to solve the power handling and sustainment challenges:
  - Existing, and new purpose-built facilities, to meet the challenges
- Combine in a net-electricity producing Pilot

Extra Slides

April 2015: New record of 26.4 Tesla with REBCO-only, “no-insulation” coil



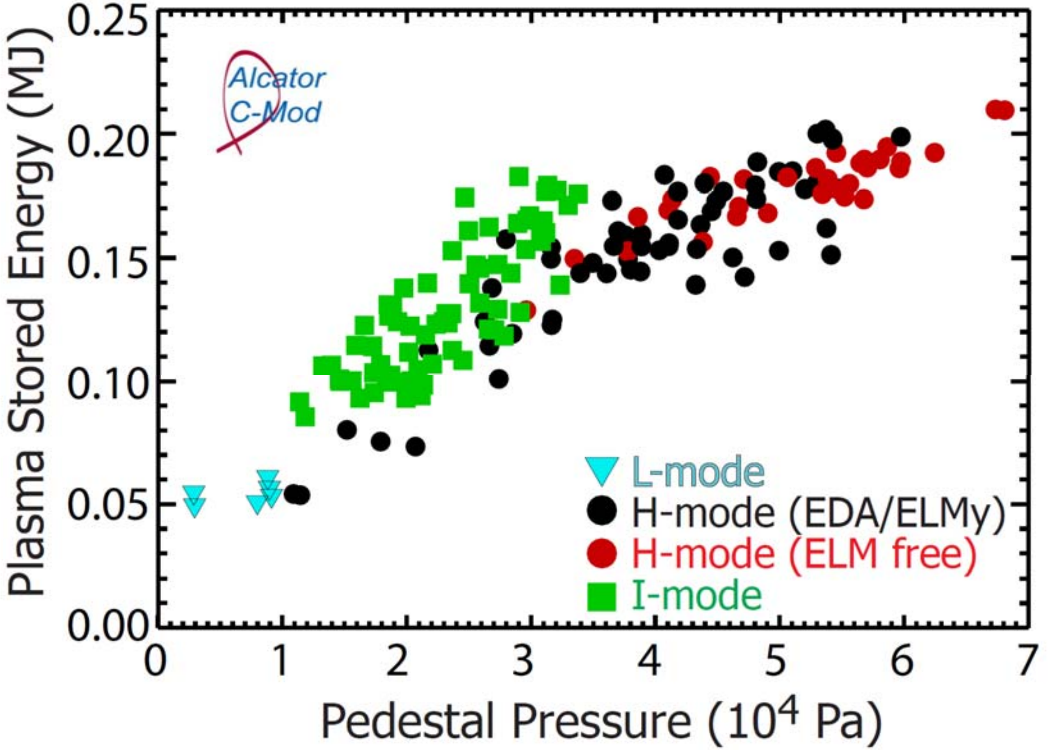


S. Hahn, J.M. Kim, et al.
NHMFL, FSU, SUNAM, MIT

L- and H-mode Confinement Tied to Pedestal Pressure
I-mode at least as good as H-mode, if not better

- Nearly universal curve for L-mode and H-mode
- Need to reduce or eliminate ELMs for divertor survivability
  - ELM-less regimes, with continuous pedestal regulation, below the peeling-ballooning stability limit, could be key
    - Possibilities include I-mode and QH-mode

C-Mod naturally operates ELM-suppressed



New technologies yield design advantages at high-B and small size:

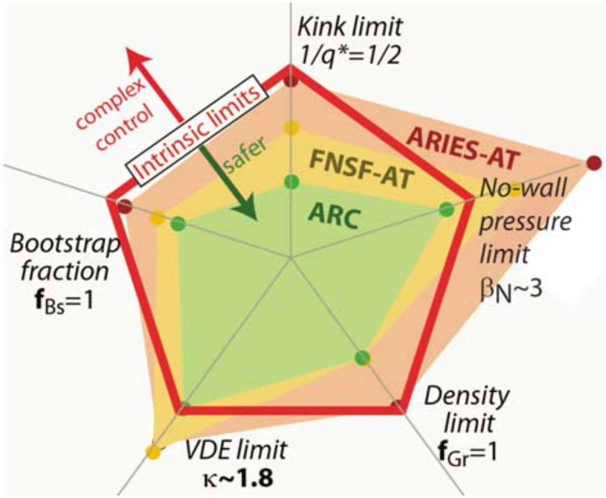
Robust, steady-state, far from disruptive limits

	DIII-D	ARIES-AT	ARC
B_0 (T)	2	5.8	9.2
q_{95}	6.3	3	7 .2
H_{89}	2.7	2.5	2.8
β_N	3.7	**5.4**	**2.6**
$G = \beta_N H_{89}/q^2$	0.25	**1.5**	**0.14**
$f_{bootstrap}$	0.65	**0.91**	**0.63**
$n / n_{Greenwald}$	0.5	**0.9**	**0.65**

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

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

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



New technologies yield design advantages at high-B and small size: Robust, steady-state, far from disruptive limits

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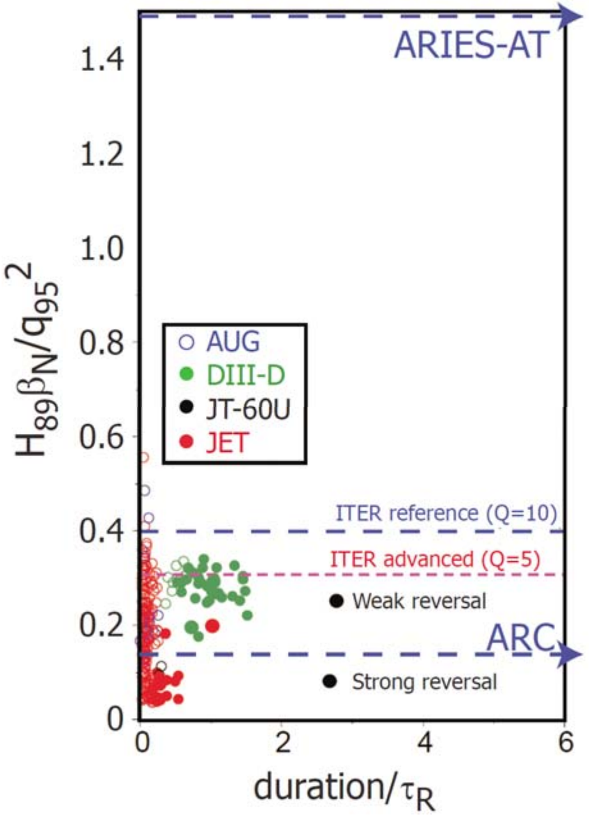
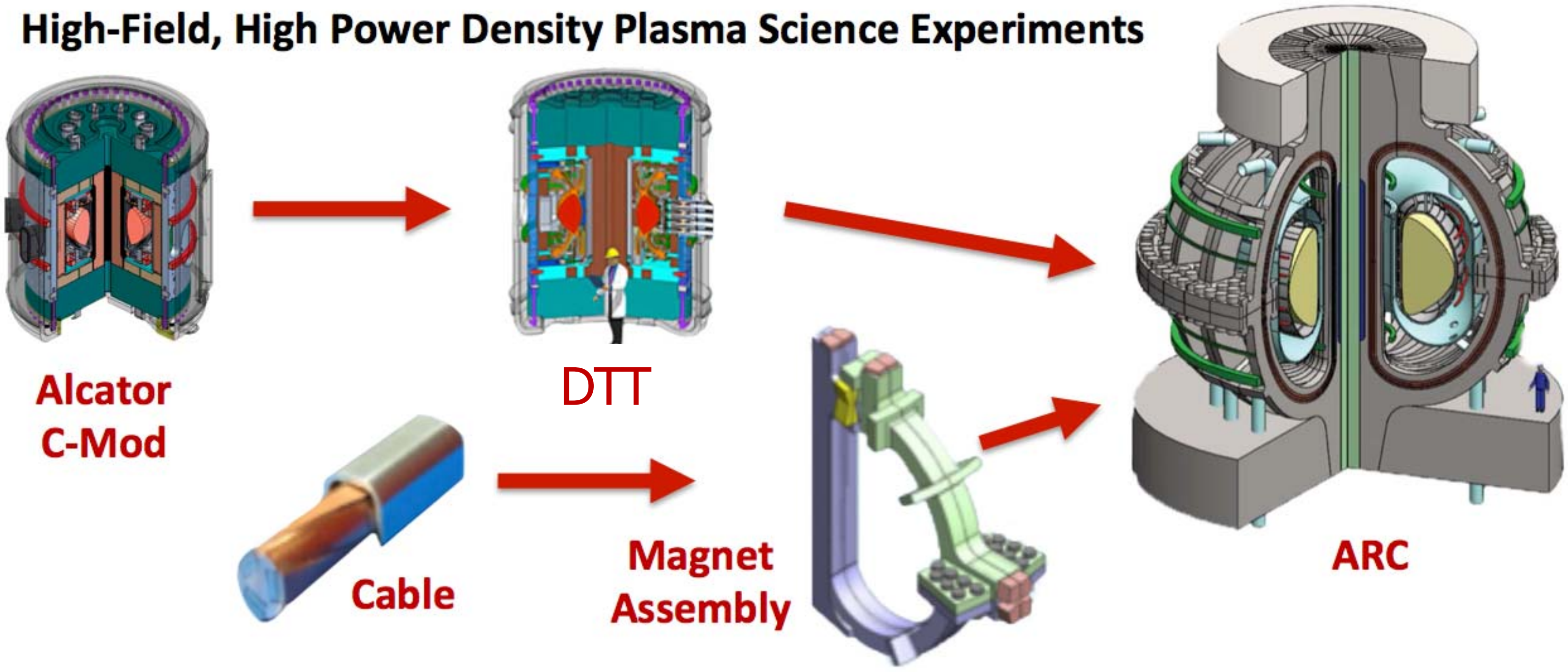


Near-term, *small-scale* research can pursue this exciting path for fusion energy

High-Field, High Power Density Plasma Science Experiments



Alcator C-Mod

DTT

Cable

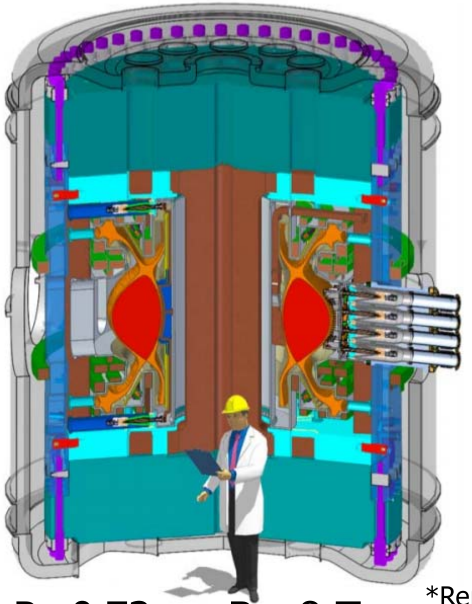
Magnet Assembly

ARC

High-Field Superconducting Magnet Development

Candidate High-Field Configurations Proposed for Divertor Test Tokamak

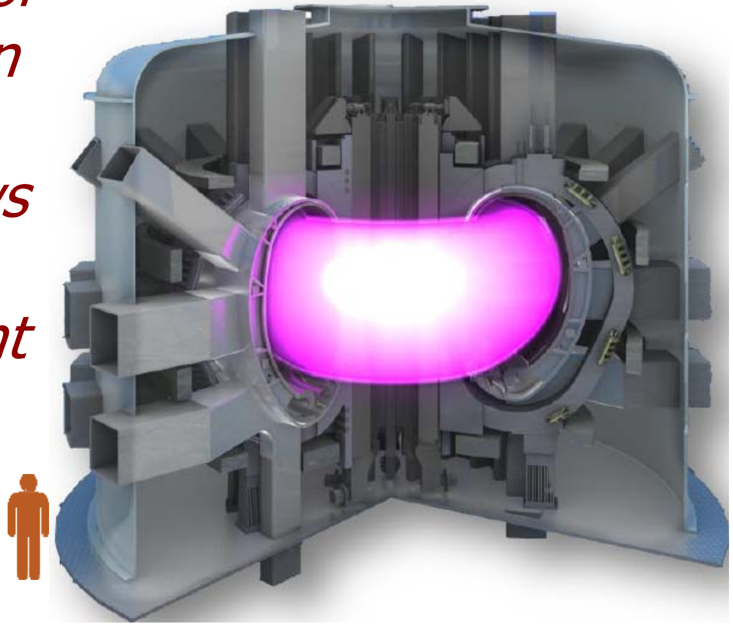
Advanced Divertor eXperiment



R=0.73 m, B_0=8 T
I_p=2 MA

*in-depth understanding of the science for projection to reactors needs a flexible facility that allows innovative divertor and plasma facing component options with rapid evaluation cycles**

ENEA DTT

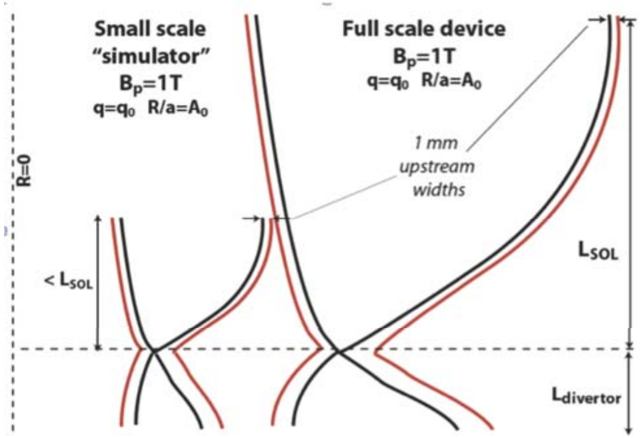


R=2.2 m, B_0=6 T
I_p=6 MA

*Report on Science Challenges and Research Opportunities in Plasma Materials Interactions, MAY, 2015: www.burningplasma.org/resources/ref/Workshops2015/PMI/PMI_fullreport_21Aug2015.pdf

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

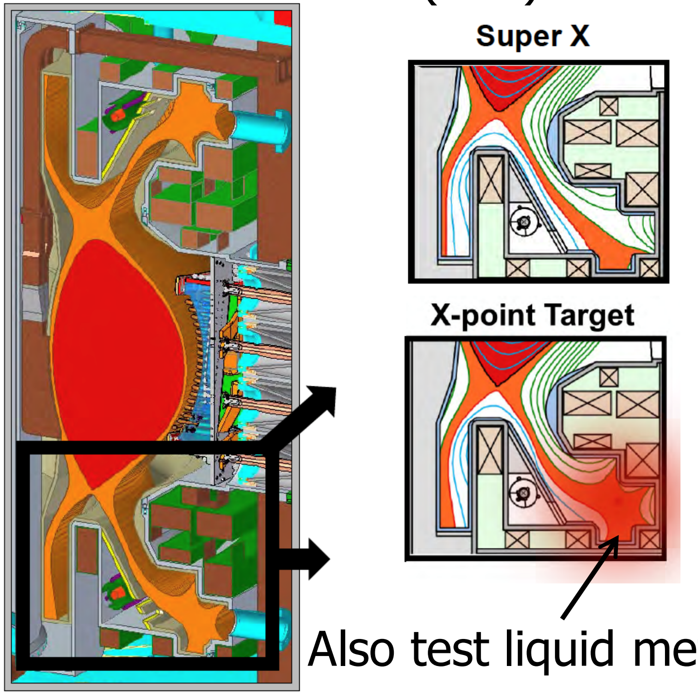
- Advanced divertor coils built into modular core as replaceable components
  - ➢ Exploit physics advances from expanded volume divertors



*D. Whyte, G04-02, Tues. AM

B. Labombard, et al., Nucl. Fusion, 55(2015)053020

Compact, High-Field, Divertor Test Tokamak (DTT)*



Also test liquid metals

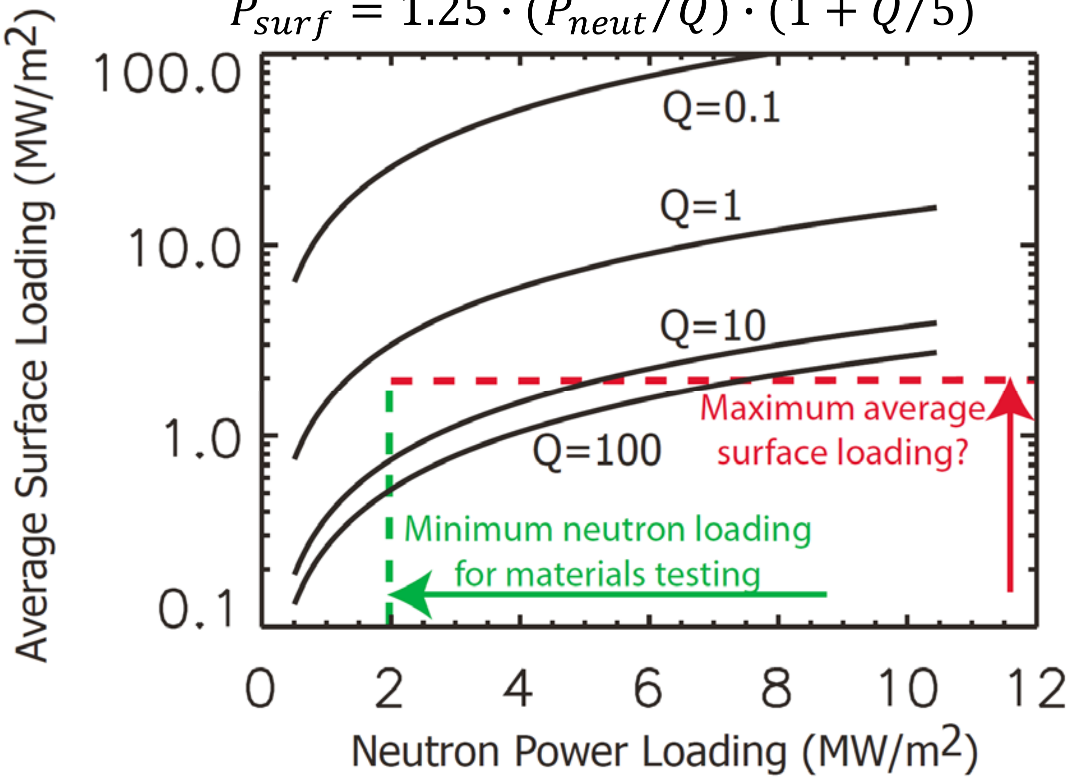
Related power handling issue: What about low Q approaches to an FNSF?

- Could envision relaxing confinement and other performance metrics, if mission is nuclear testing, rather than energy production
- However, must consider the surface power handling problem at the same time

Low Q (=P_{fus}/P_{aux}) for Nuclear Materials Testing?

- Need minimum 14 MeV neutron fluence for sensible materials testing: desire at least 2 MW/m² @ high availability; more would be better
- First wall power loading ($P_\alpha + P_{aux}$) increases dramatically as Q reduced below 10
  - Makes an already daunting PMI power handling problem look significantly worse

$$P_{surf} = 1.25 \cdot (P_{neut}/Q) \cdot (1 + Q/5)$$



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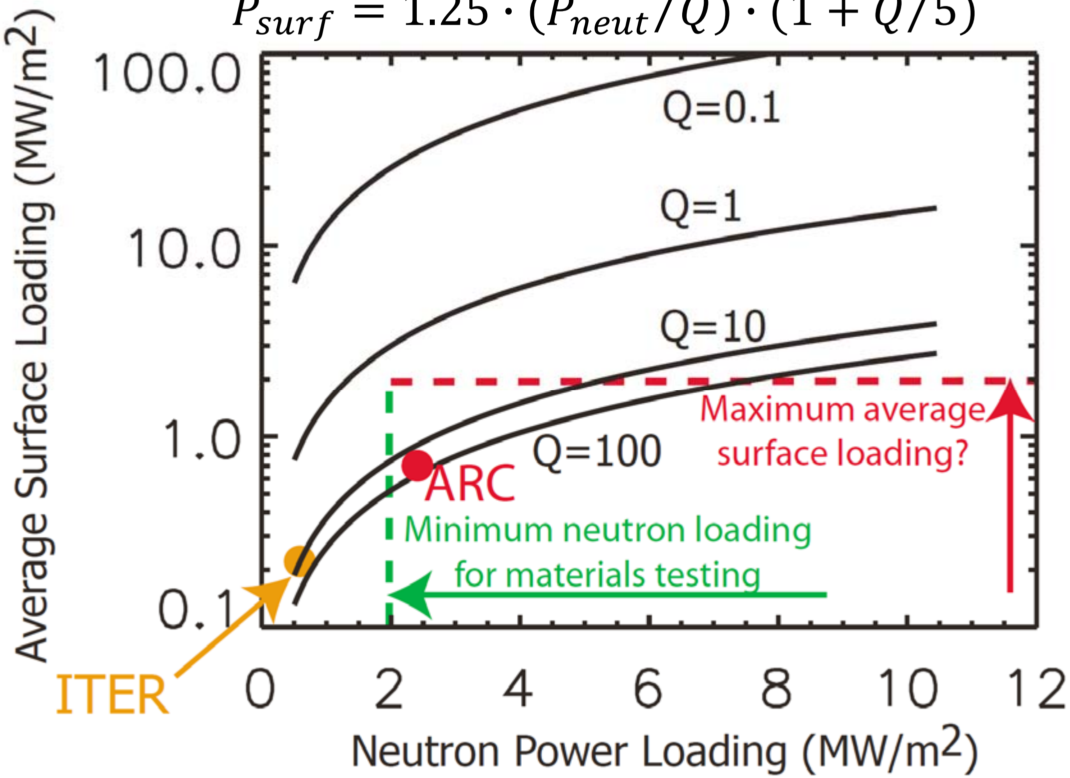
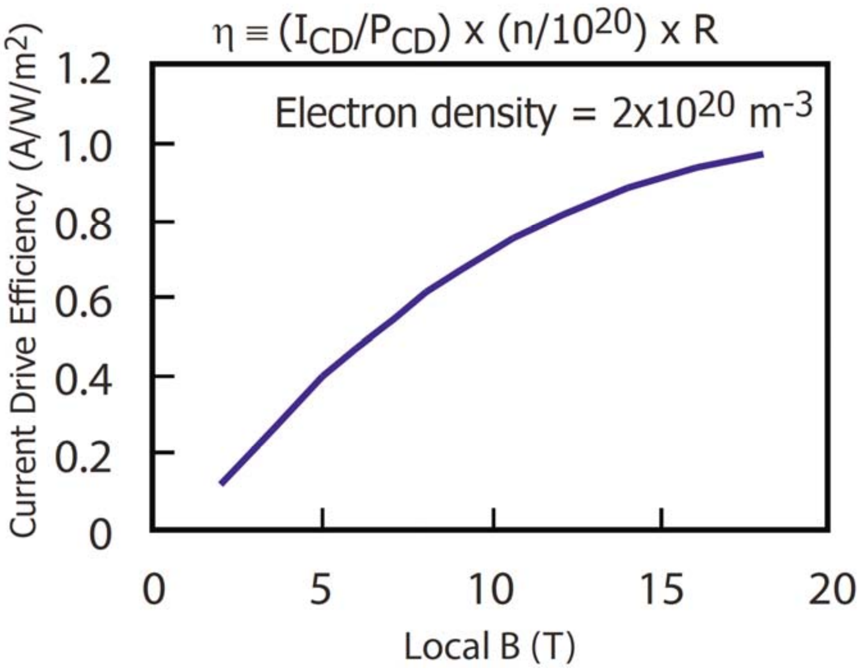


Disruptions Challenging for all High Performance Tokamaks; Compact, High B has Advantages

- Operating away from limits
  - Staying further away from limits (including density , q_{95}, elongation), and staying below the no-wall β_N limit, should significantly reduce disruption probability
- Runaway electron growth dramatically reduced
  - growth exponential with plasma current $(I_{runaway}/I_{seed} \propto e^{2.5*Ip})$
    - high-field, compact designs are at lower plasma current (ITER=15 MA, ARC= 7.8 MA): $e^{2.5*(15-7.8)} = 7x10^7$
- Disruption forces not obviously more difficult for compact, high-field
  - \+ IxB about the same; lever arms are smaller (lower stress)
  - \+ distances can be smaller for mitigation actuators (gas, pellets)
  - – But, quench times faster for compact devices

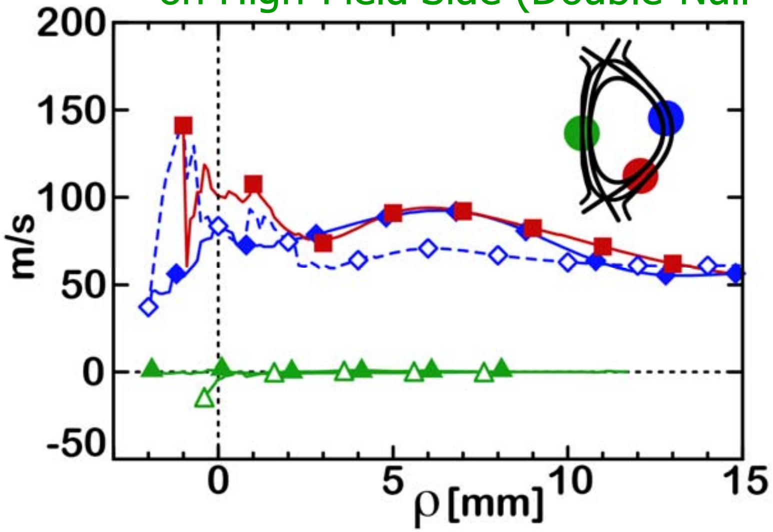
Must Sustain Plasma Current in Steady-State

- Bootstrap must provide substantial fraction
  - Note that $I_{boot} \propto \beta_{poloidal}$ not β_N
- Beam current-drive unlikely to be a solution for reactors
- ECCD works, but relatively low efficiency
- LHCD is higher efficiency at high B
  - Accessibility for lower $n_{||}$ at higher B ⇒ higher efficiency, and damping at higher Te (closer to core)
- Required power scales as I_P*R
  - compact, high-field wins on both counts

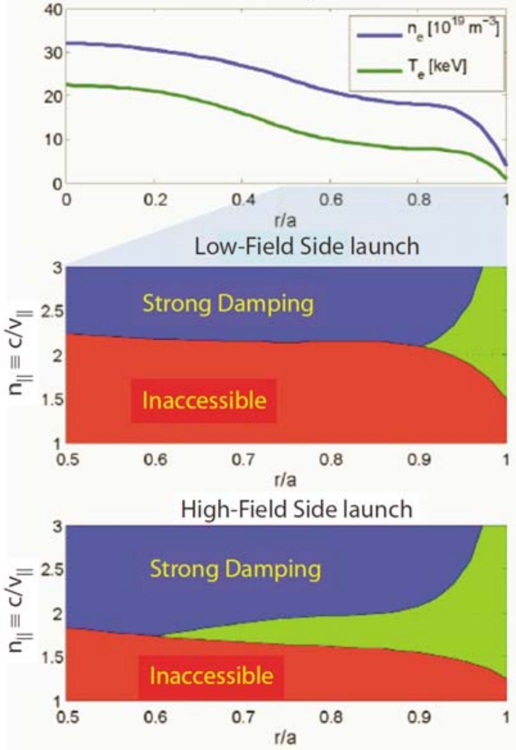


High-field → Synergistic gains in CD efficiency
High-field side launch → launcher protection from PMI, fast ions, REs

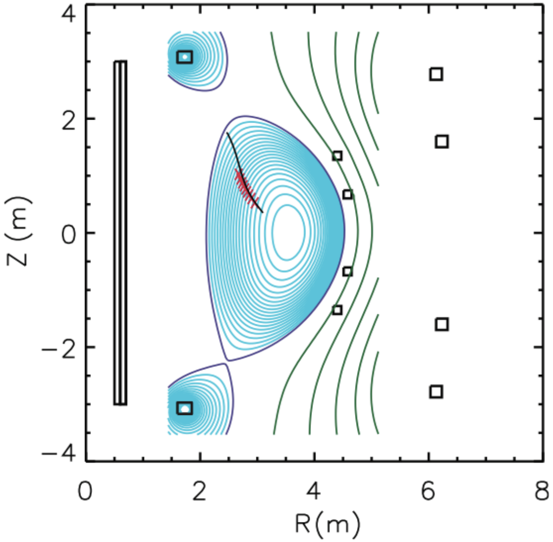
No fluctuation induced transport on High-Field Side (Double-Null



FNSF-AT (5.5T)



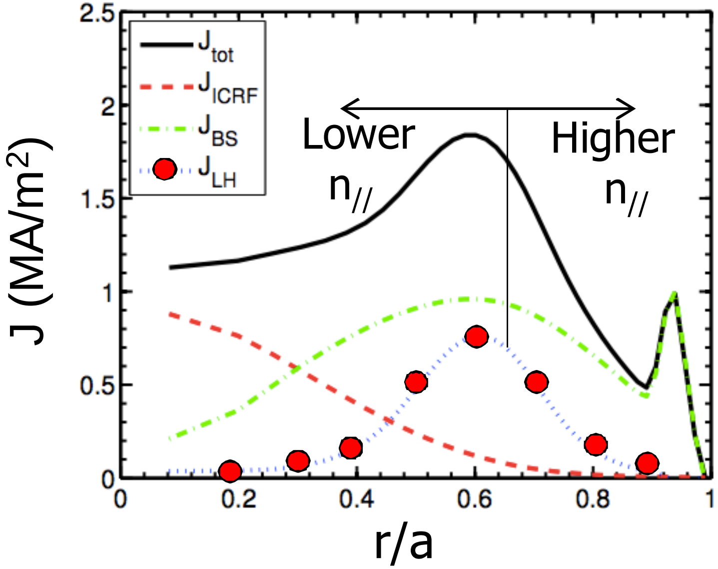
ARC (9.3T)



LHRF full-wave simulation: Strong single pass absorption at r/a~0.5

Optimized CD efficiency leads to significant control of AT current profile, below no-wall β_N limit

ARC simulation:



Control of the q profile: Key actuator for enhanced H factor