High-temperature superconductors for fusion: Recent achievements and near-term challenges

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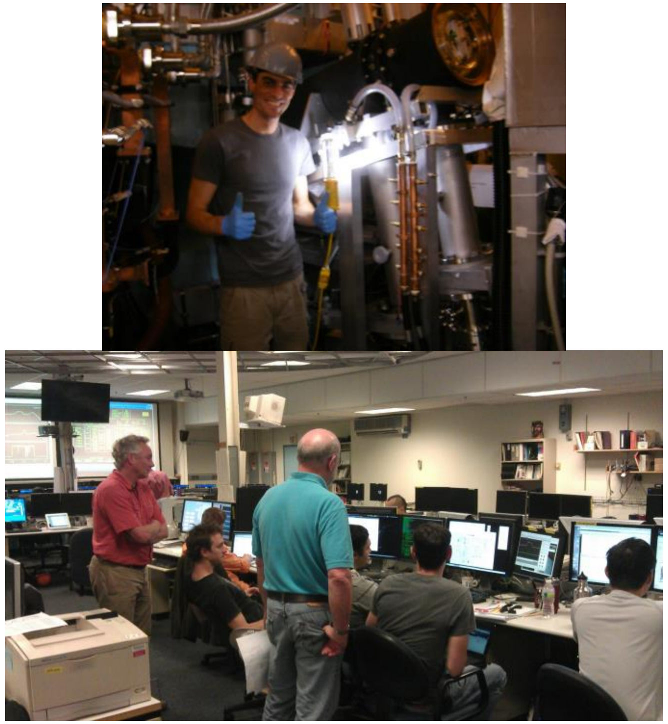
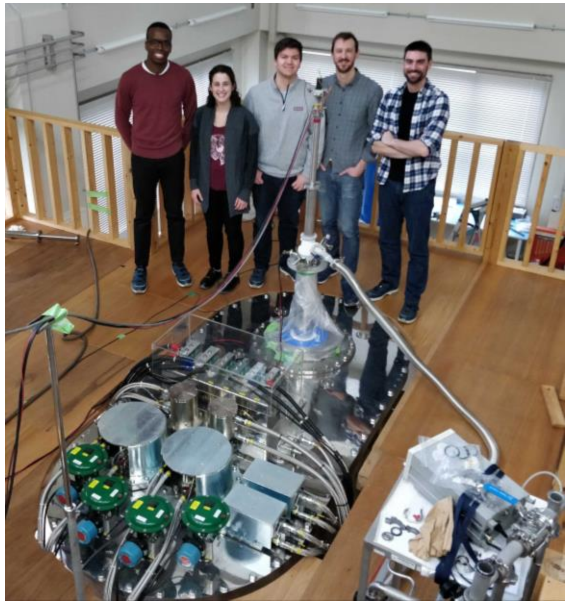
Commonwealth Fusion Systems

My road to fusion and HTS

Rowing (and injury…)



Accelerator-based diagnostics on C-Mod!



Globe-trotting HTS testing strike force

High field fusion

(aka why we care about HTS in the first place)

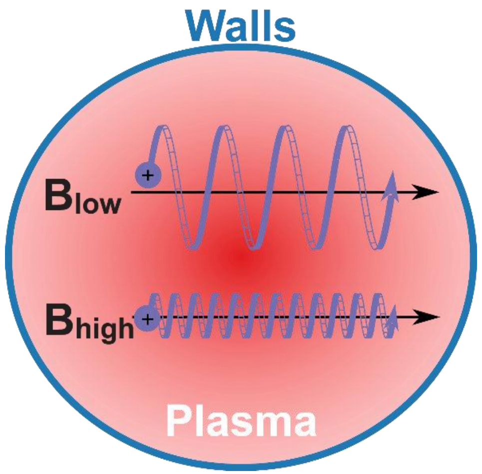
The magnetic field confining a tokamak plasma sets the performance

How well a plasma is insulated via the gyro-radius:

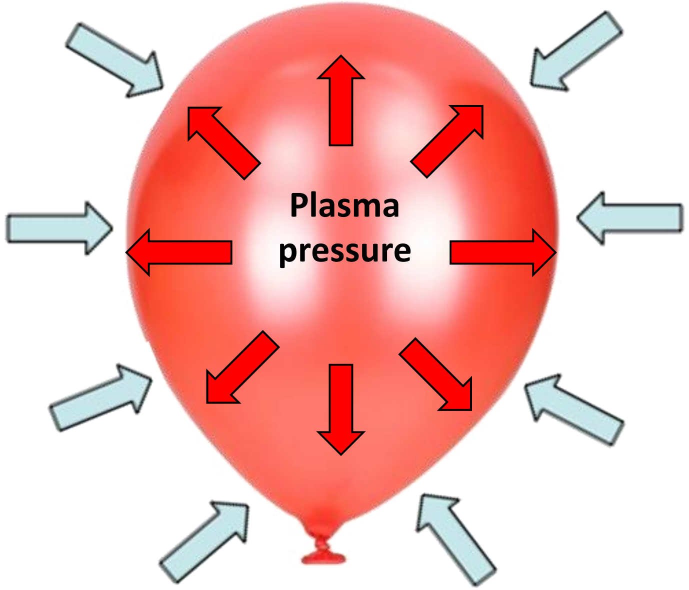
Make many of these fit inside the device → $r_{ion} \sim \frac{\sqrt{T}}{B}$

← Plasma temperature, set by fusion nuclear cross-section

← Magnetic field, set by device magnets



How stable the plasma is from MHD:



Magnetic pressure ~ B^2

How reactive the plasma is: Volumetric fusion rate ∝ (plasma pressure)^2 ∝B^4

ENERGY GAIN:
(science feasibility)

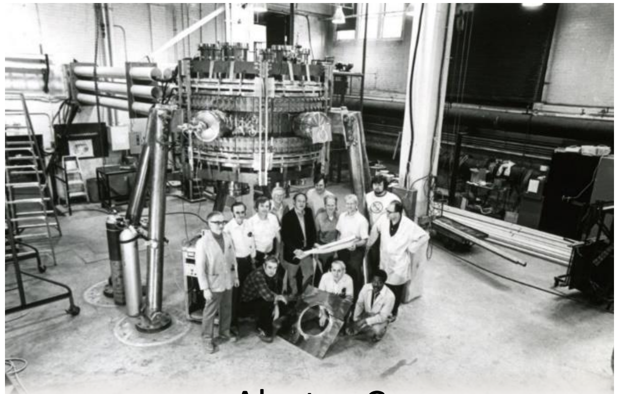
$$nT\,\tau_E \sim \frac{\beta_N H}{q_*^2} R^{1.3} B^3$$

POWER DENSITY:
(economics)

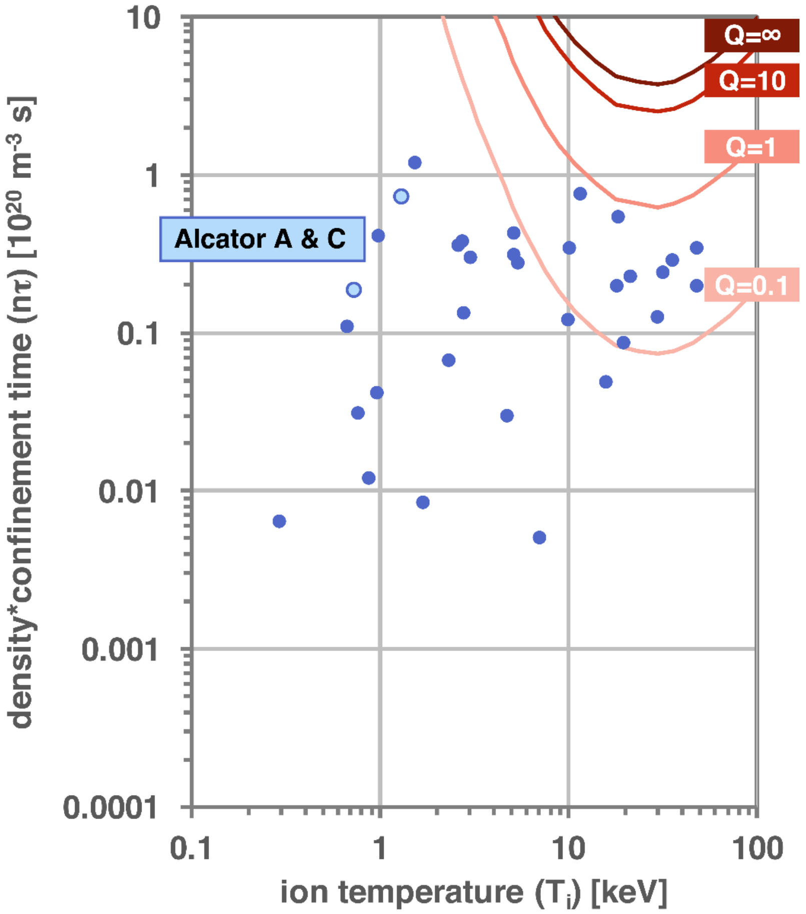
$$\frac{P_{fusion}}{S_{wall}} \sim \frac{\beta_N{}^2 \epsilon^2}{q_*^2} R B^4$$

We have achieved high performance in the past in small tokamaks using very high field copper magnets

Alcator A
MIT 1969
10 Tesla

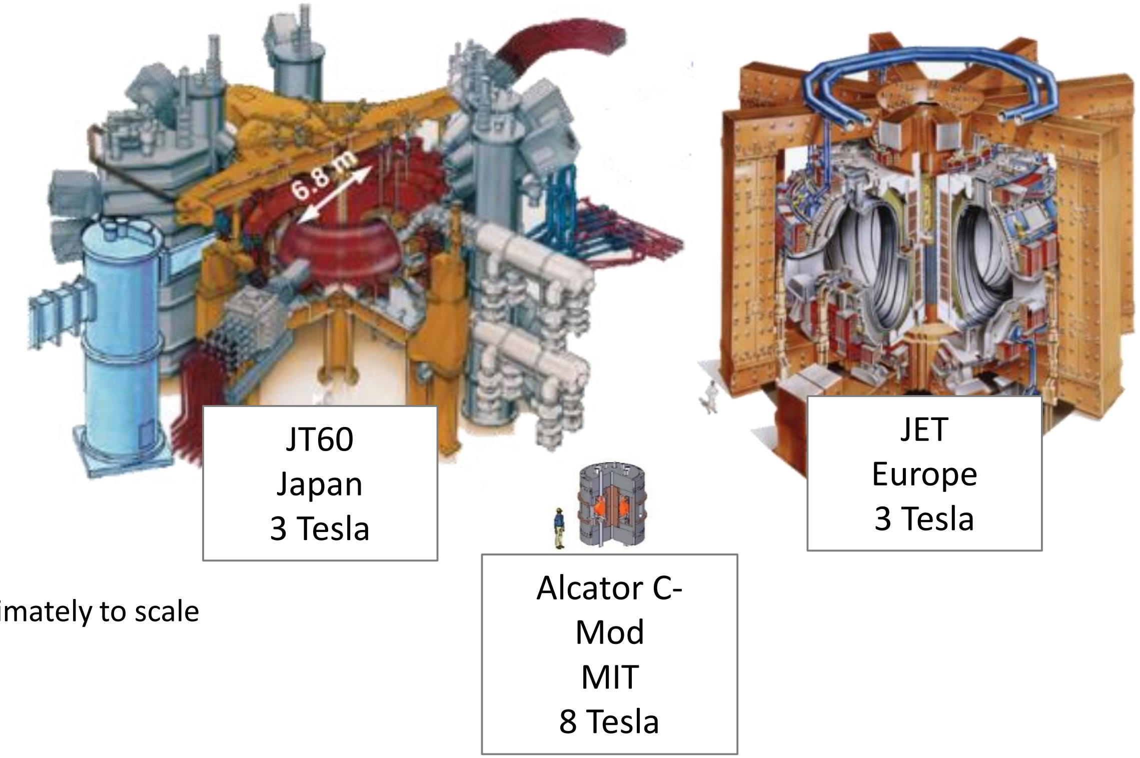


Alcator C
MIT 1978
12 Tesla

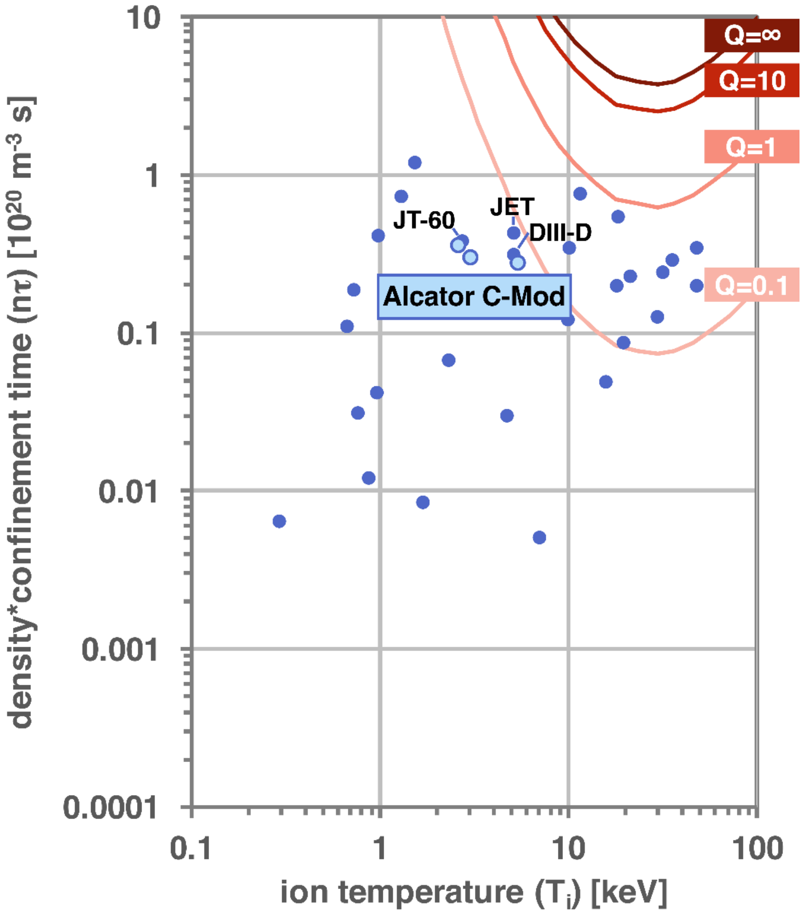


- These were enabled by a cutting edge technology at the time
  - High-field, cryogenically-cooled, high-strength copper magnets developed for magnetic science (MRI, NMR, etc)
- They were early, inexpensive, small, team-oriented, and quickly constructed on a university campus

Alcator C-Mod performs as well in many metrics as much larger tokamaks due to its high field

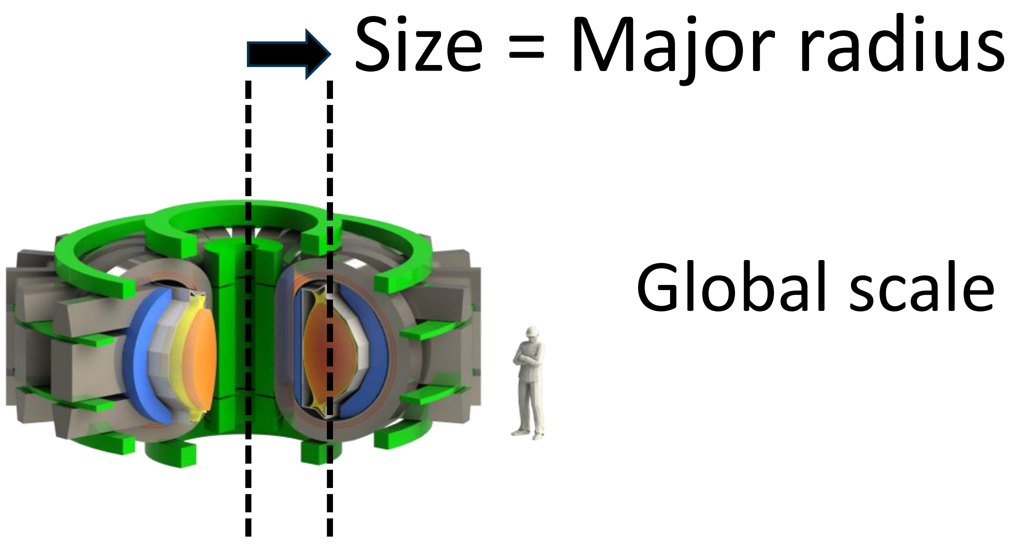


Approximately to scale



- Despite its size, C-Mod was a very high performance device
    - Operated in fusion-relevant regimes of plasma physics (e.g. thermonuclear temperatures, up to 100 million C)
    - And confirmed other benefits of high field (e.g. robust, quiescent plasmas)

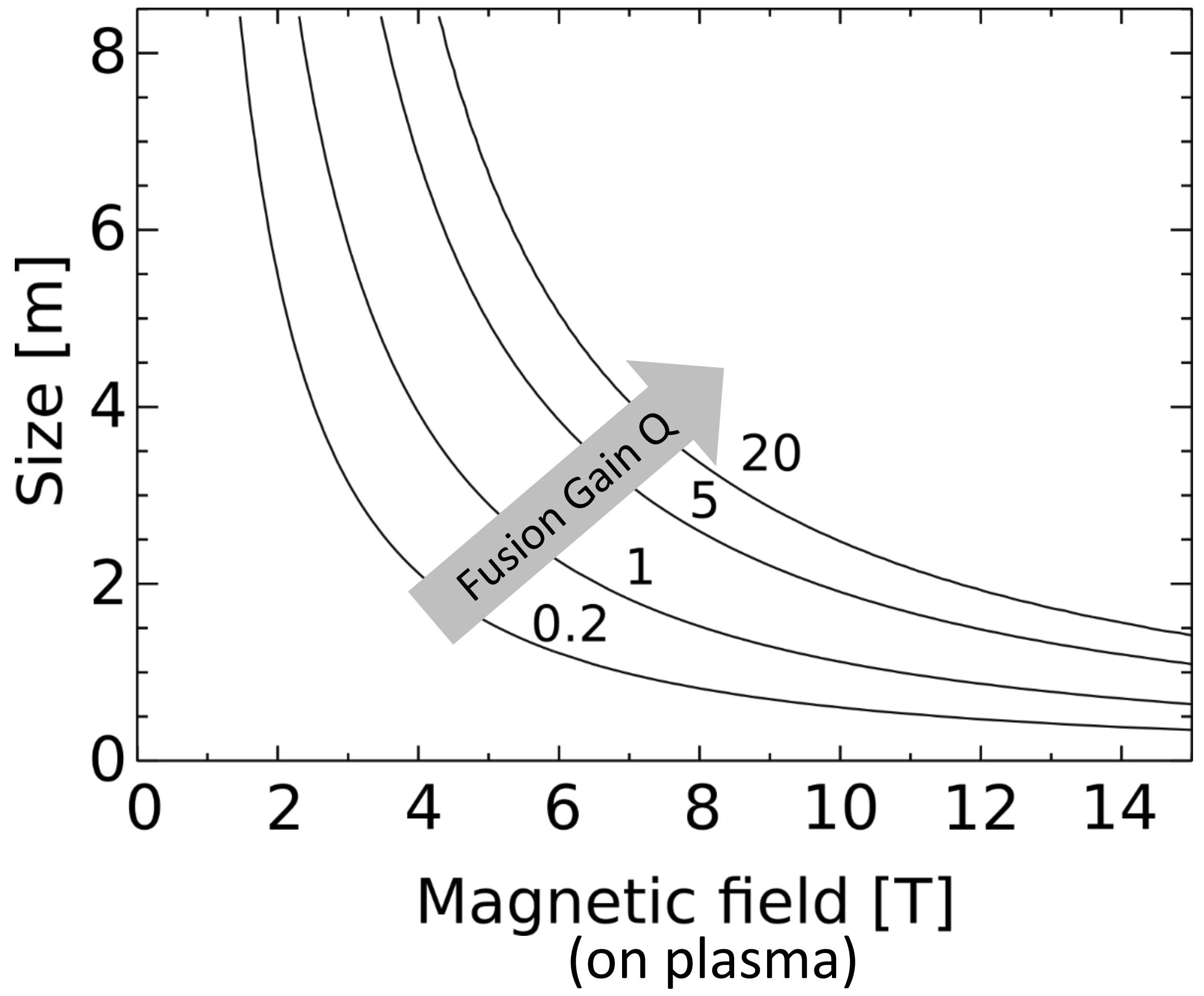
Magnetic field strength fundamentally sets size, cost, and time to build



Global scale

National lab scale

University/company scale

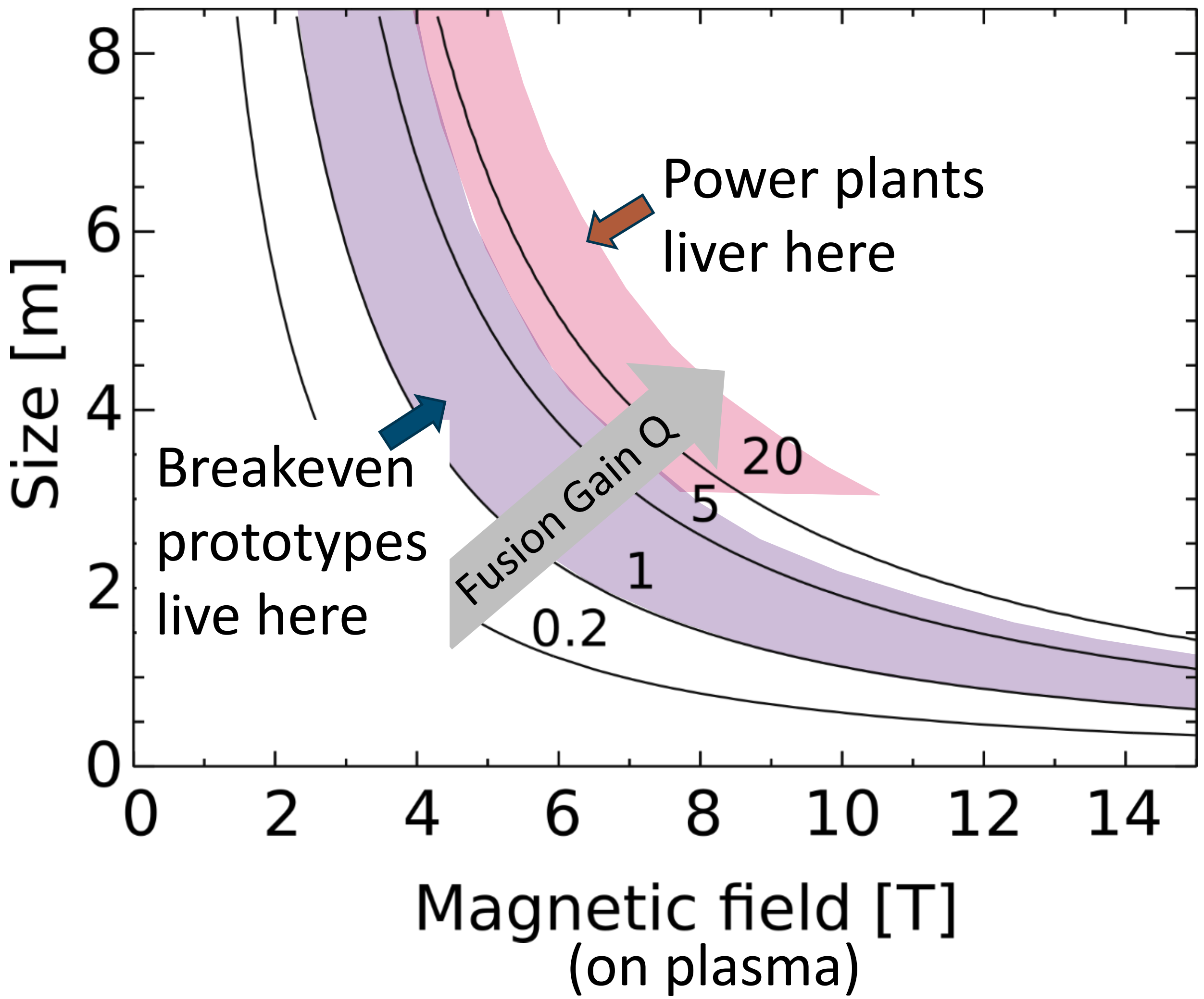


Magnetic field strength fundamentally sets size, cost, and time to build

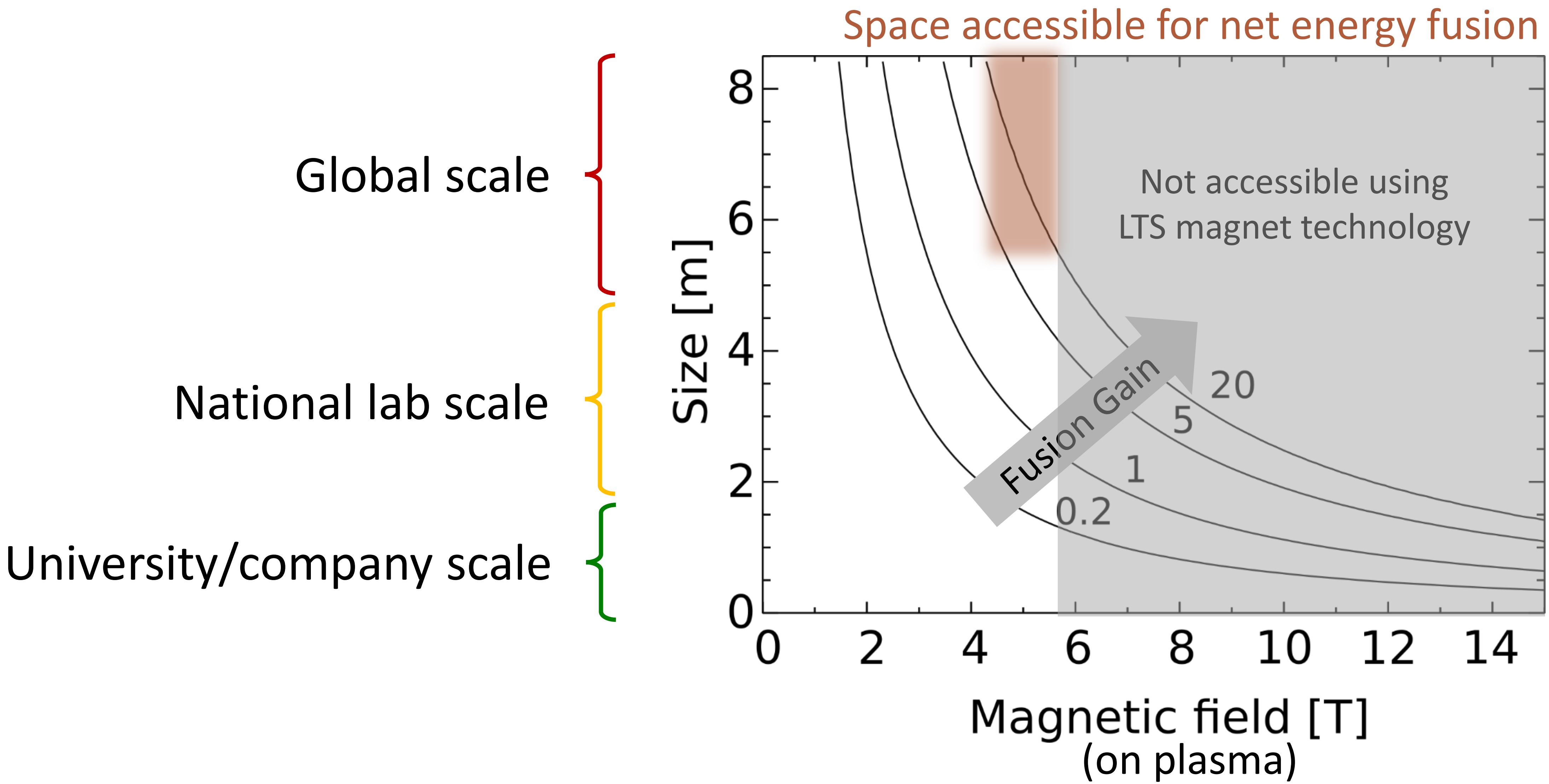
Global scale

National lab scale

University/company scale



Magnetic field strength fundamentally sets size, cost, and time to build

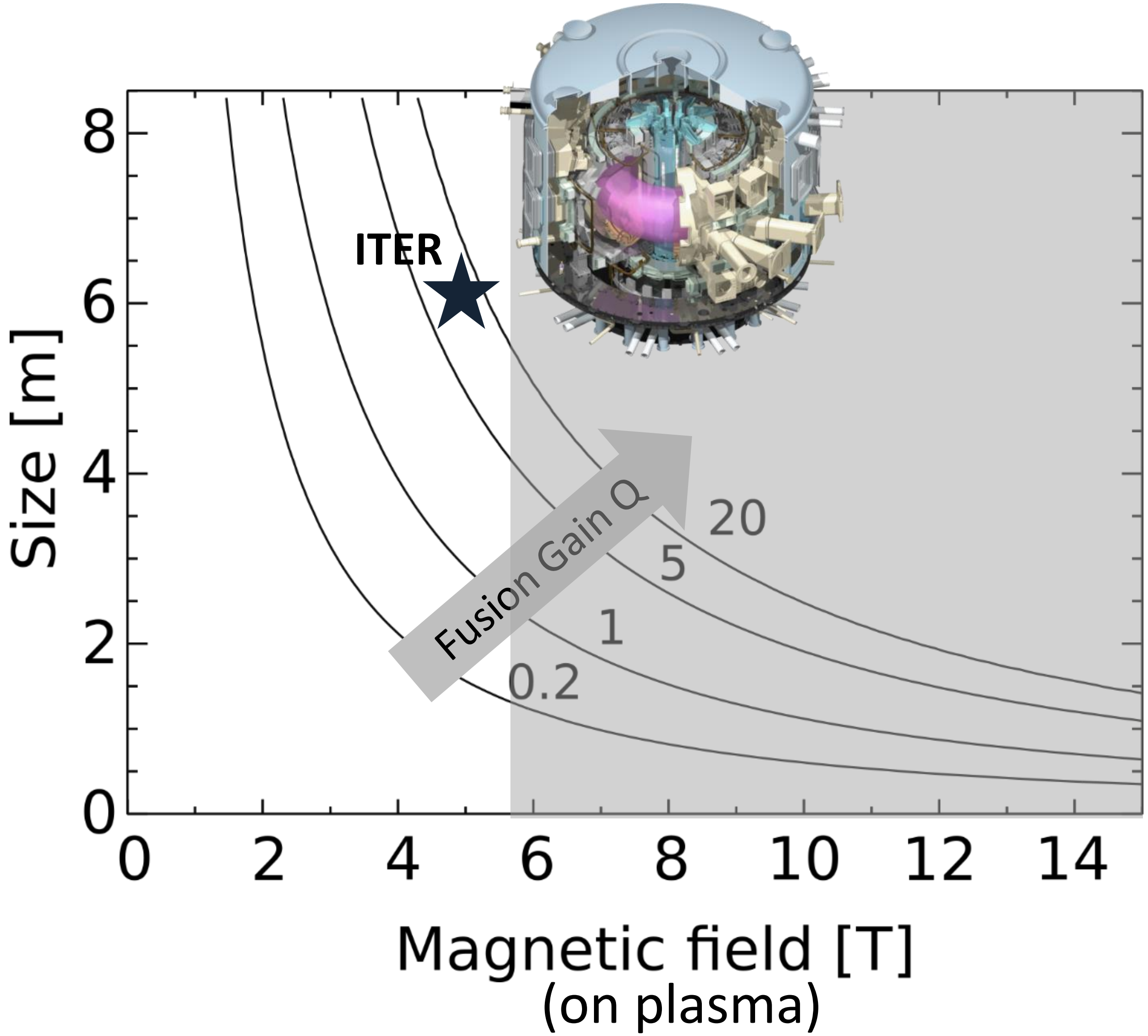


For ITER, this leaves little choice but to be large in scale

Global scale

National lab scale

University/company scale

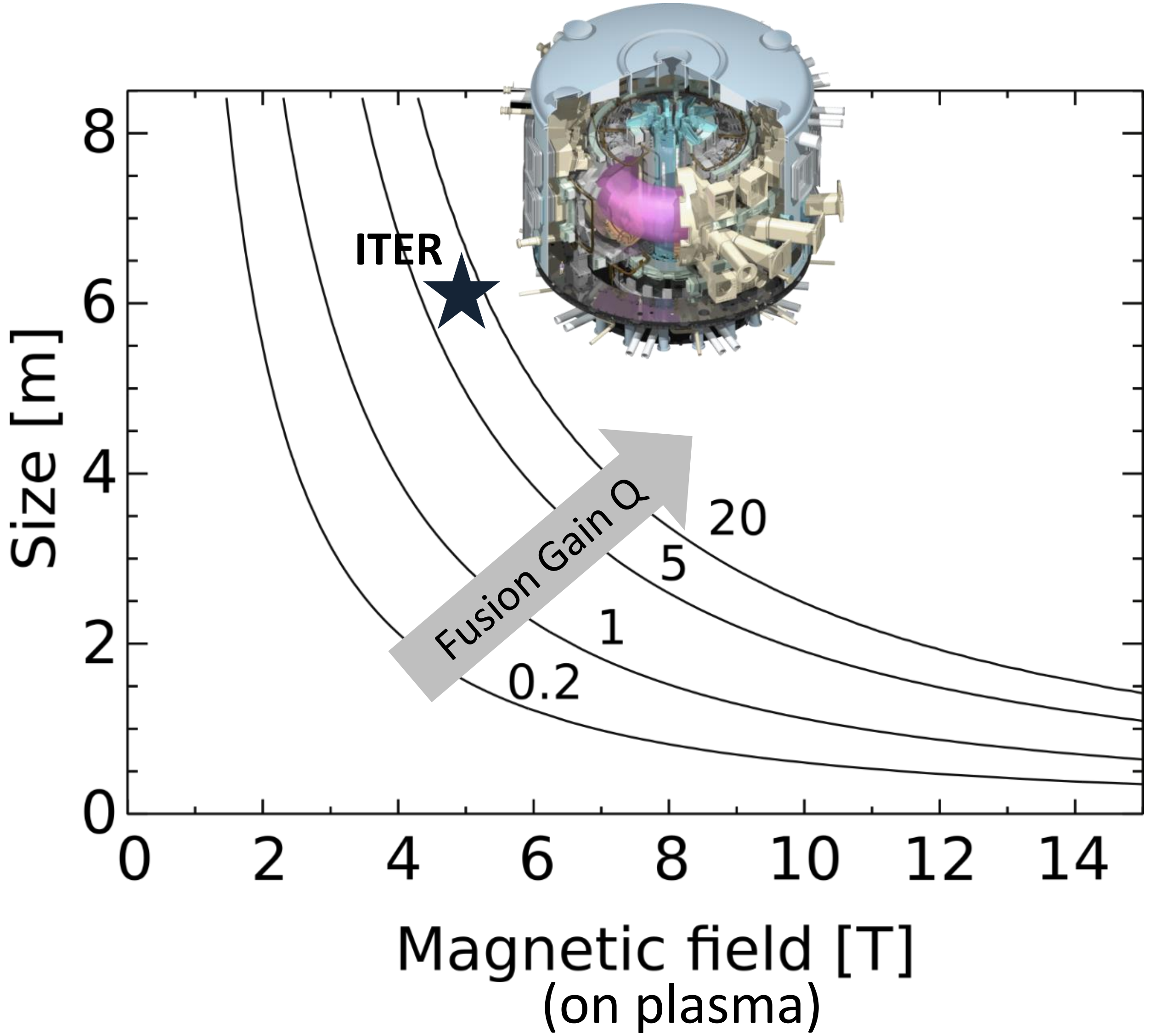


High-field HTS magnets opens a new SC path to much smaller size

Global scale

National lab scale

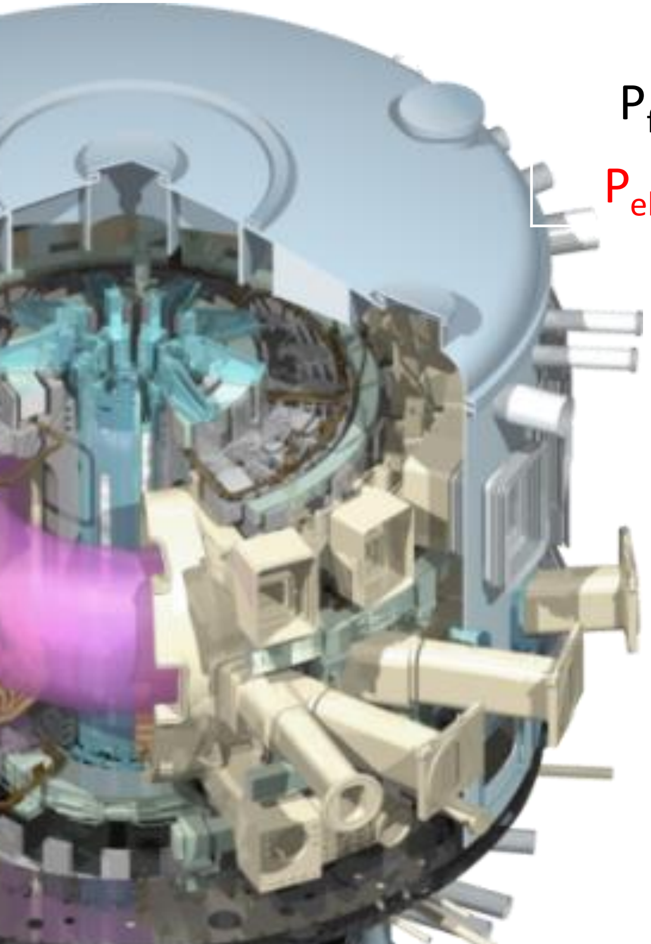
University/company scale



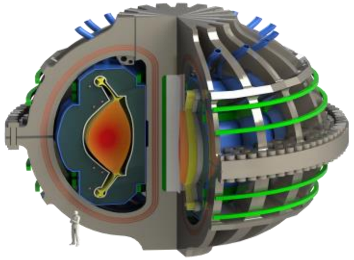
High field enables drastic reductions in size for 500 MW class tokamak fusion devices...

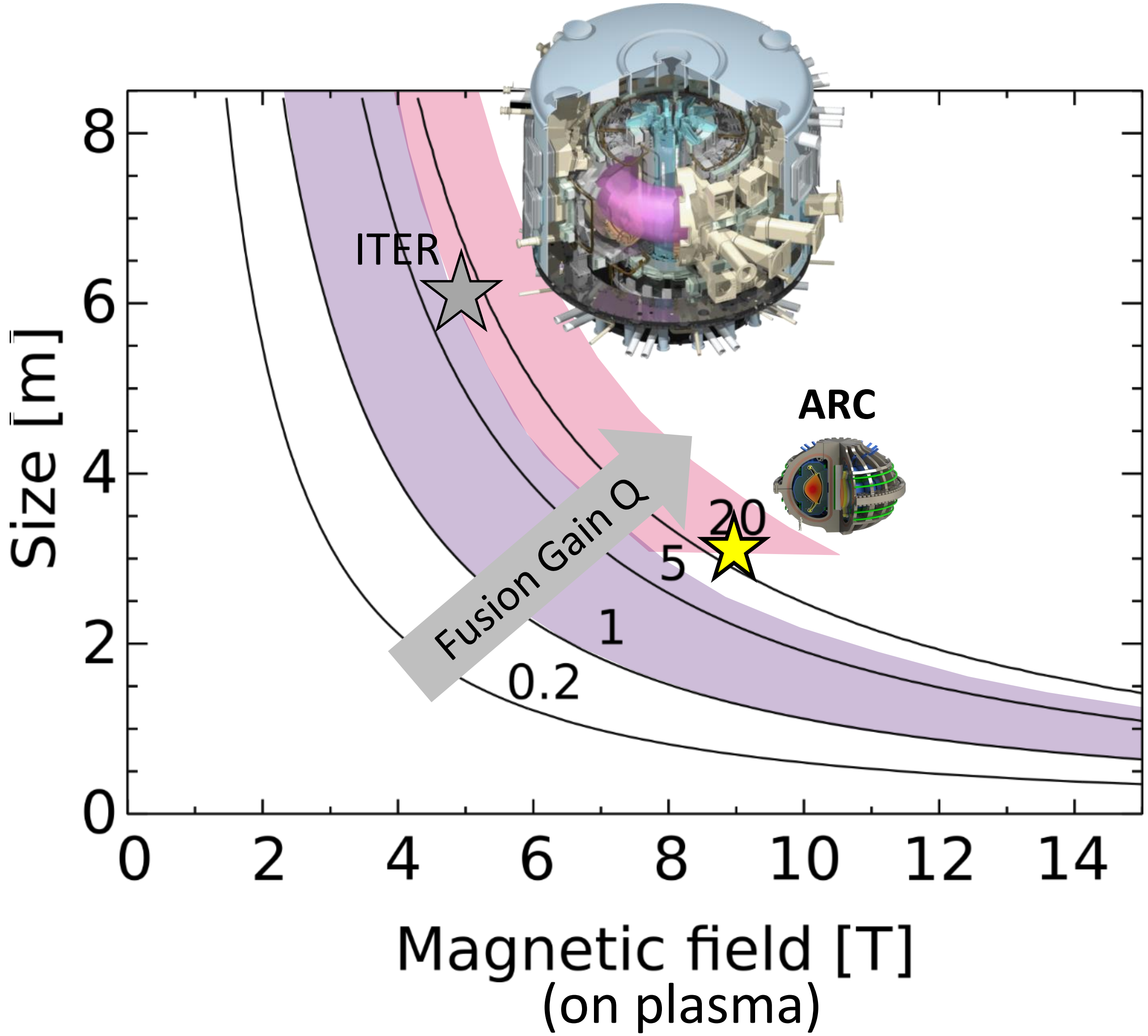
	ITER	ARC
R [m]	6.2	3.2
Magnet	LTS	HTS
B [T]	5.3	9.2
P_{fusion} [MW]	500	500
$P_{electric}$ [MW]	0	200

ITER



ARC

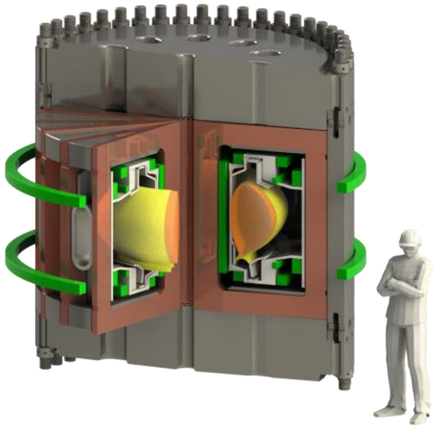




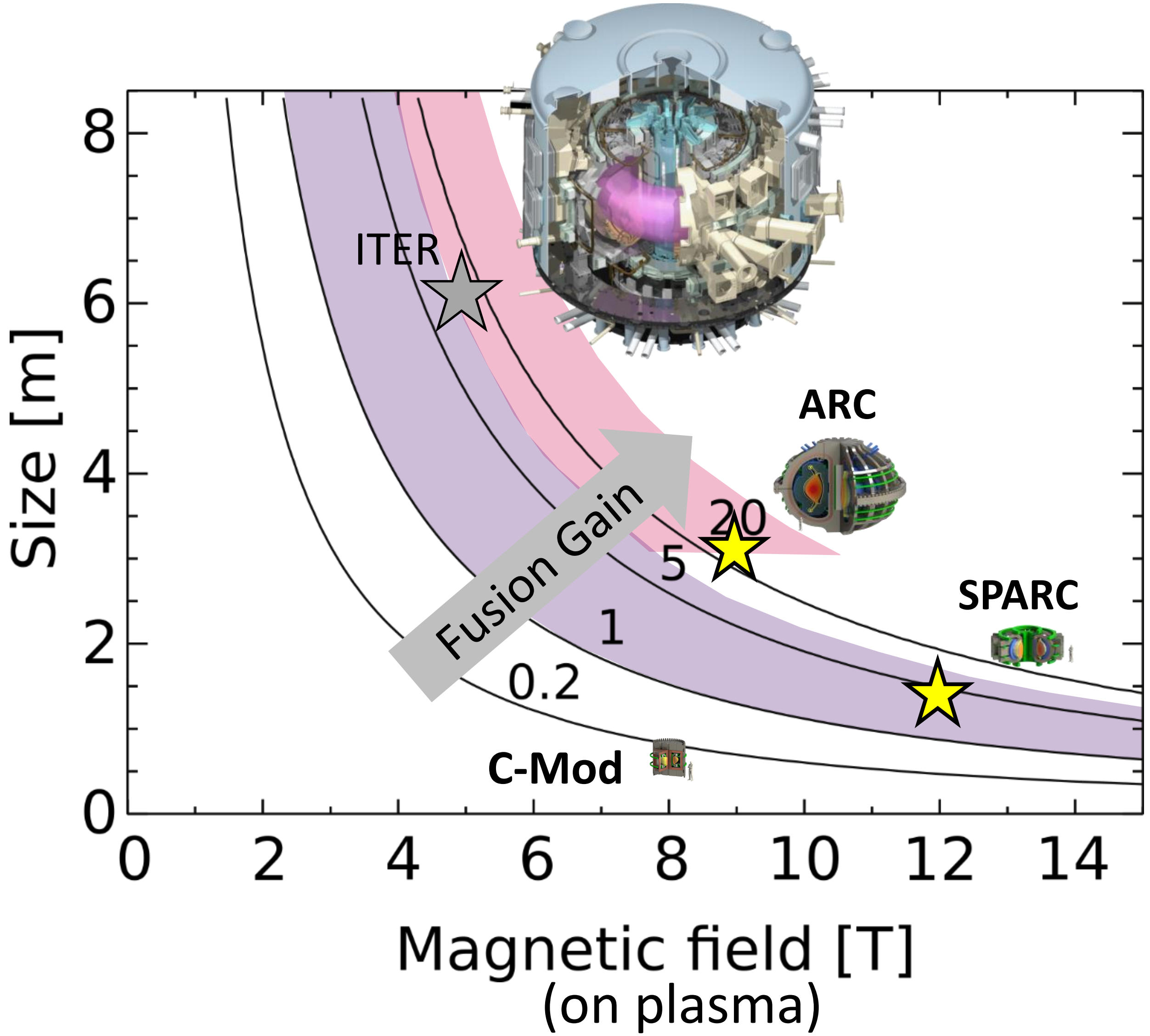
...and also enables extremely small proof of concept devices

If higher magnet fields enable ARC to rethink how fusion energy tokamaks are designed … why stop there?

SPARC will be a net-energy device but only be about 3x the size of Alcator C-Mod



Alcator C-Mod
(MIT PSFC)



High Temperature Superconductors

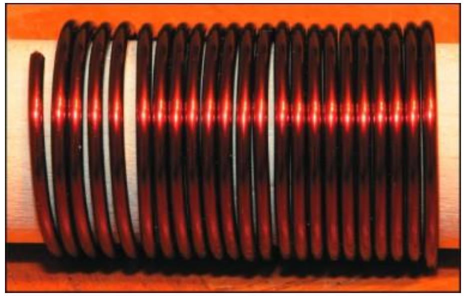
Intro to REBCO physics and challenges

Fusion has pushed to the limits of magnets since the beginning…

1950-1960s:

Copper wire

The pioneers

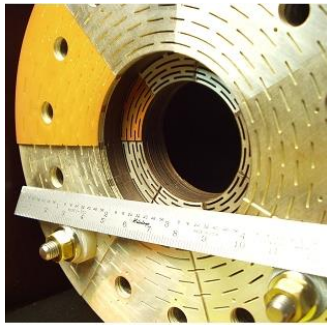


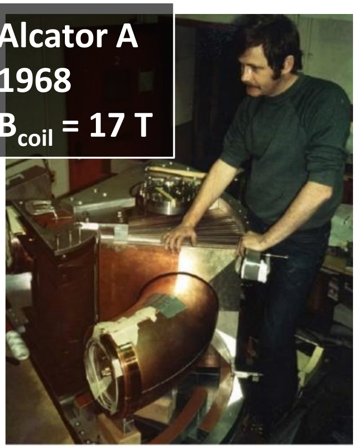
Stellarator A 1953
B_{coil} = 0.1 T

1960-1980s:

Cryogenic Bitter plates

The Alcators at MIT



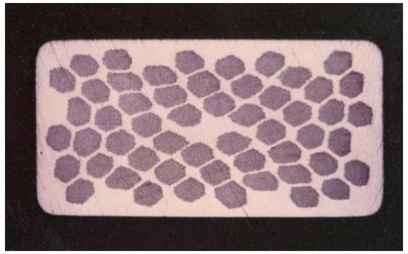


Alcator A
1968
B_{coil} = 17 T

1980-2000s:

NbTi superconductors

First SC fusion devices



Tore Supra 1988
B_{coil} = 9 T

1990s-2010s:

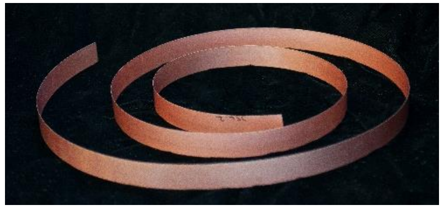
Nb_3Sn for higher field

Reactor-class devices

ITER 2015
B_{coil} = 13 T

2010-2020s:

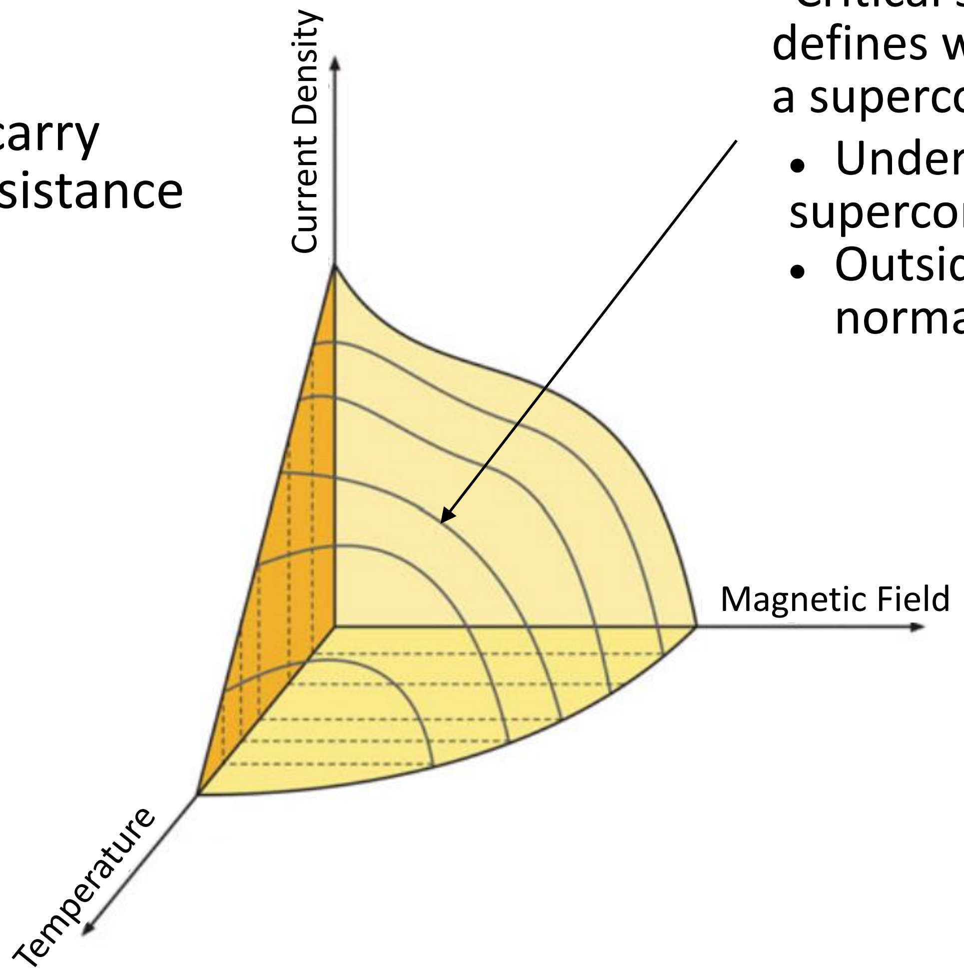
REBCO: very high magnetic fields



? ? ?
B_{coil} > 20 T

Superconducting Physics – The Critical Surface

Superconductors carry current with no resistance



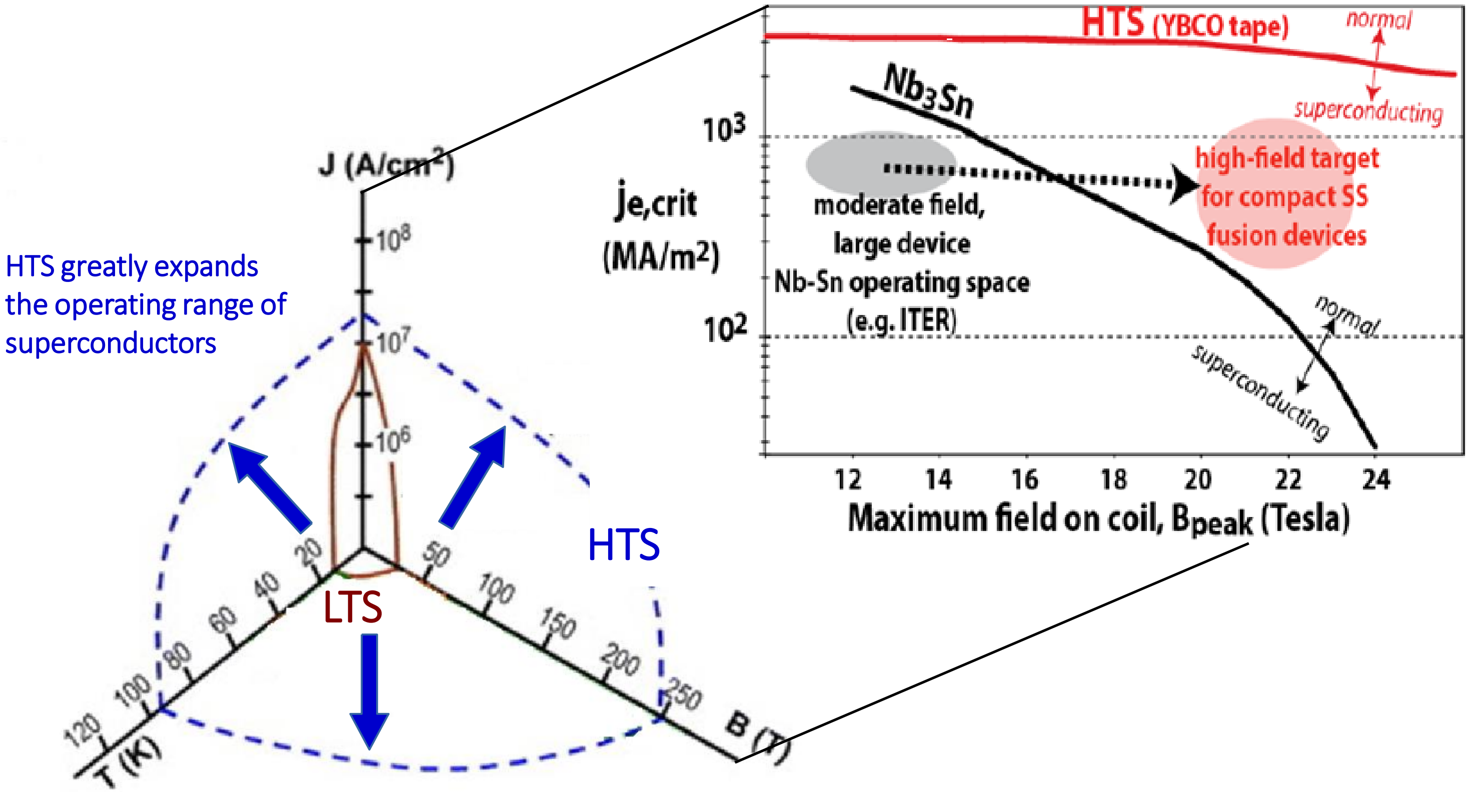
"Critical surface" which defines whether material is a superconductor or not

- Under critical surface: superconducting
- Outside of critical surface: normal

For engineering magnets, HTS and LTS differ in two important ways: superconducting performance and physical form

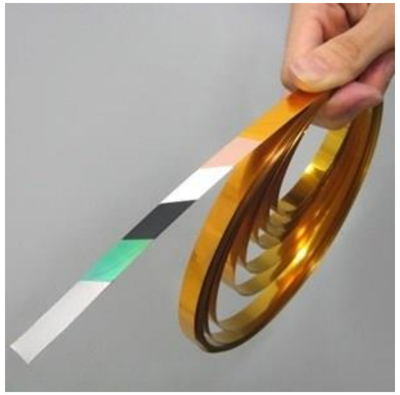
Superconducting performance

- HTS represent a quanum leap in performance:
  - Higher critical magnetic field (B)
  - Higher criticial temperature (T)
  - High engineering critical current (Je)

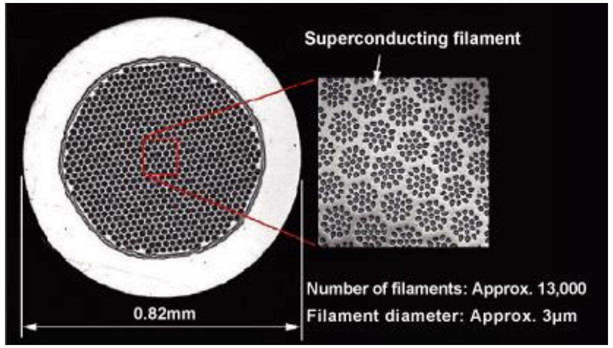


Physical form

HTS is manufactured in thin ribbon-like tapes

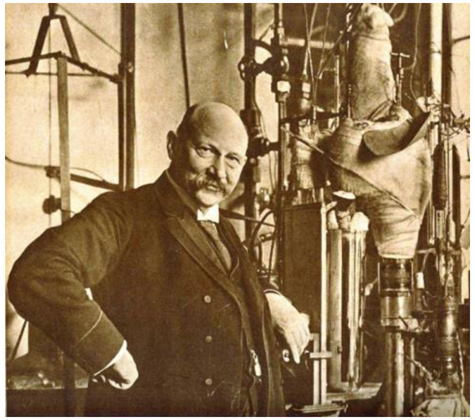


LTS is manufactured in thin strand wires



Low temp. superconductors (LTS) discovered in 1911, ready for engineering in 1960's; required 4K operation, low B-fields

- First superconducting material (Mercury) discovered in 1911 by K. Onnes
  - Required extremely low temperature and did not tolerate magnetic fields or high current ("critical surface" of superconductivity)
  - Many other materials found to superconduct but due to above limitations were impractical for real-world applications such as magnets

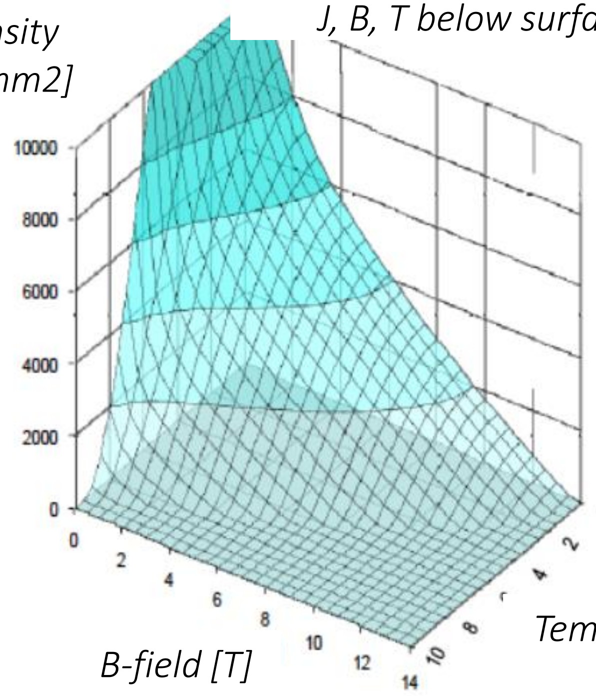


Kamerlingh Onnes

- NbTi and Nb3Sn (known as "low-temperature superconductors" or LTS) were discovered in the 1960's
  - Still required extremely low (~4 K) temperatures to operate but could tolerate moderate currents and fields
  - Development of NbTi and Nb3Sn in the 1970's and 80's led to use in MRI machines (NbTi) and in ITER coil development (Nb3Sn)
  - Developed for routine use in large-scale science facilities such as the particle accelerators, light sources, detectors, and magnet fusion devices

Critical surface for NbTi (superconducts only when J, B, T below surface)

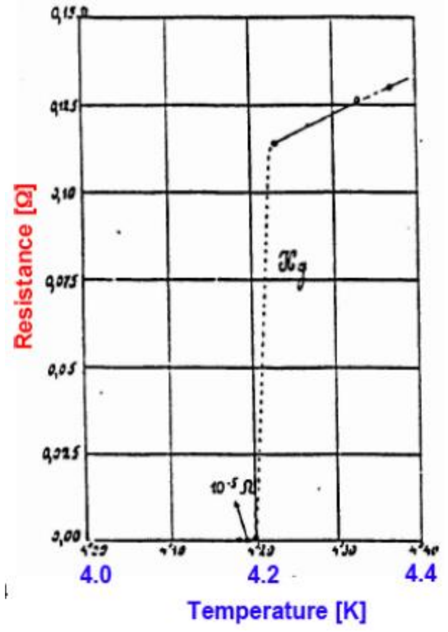
Current density [A/mm2]



B-field [T]

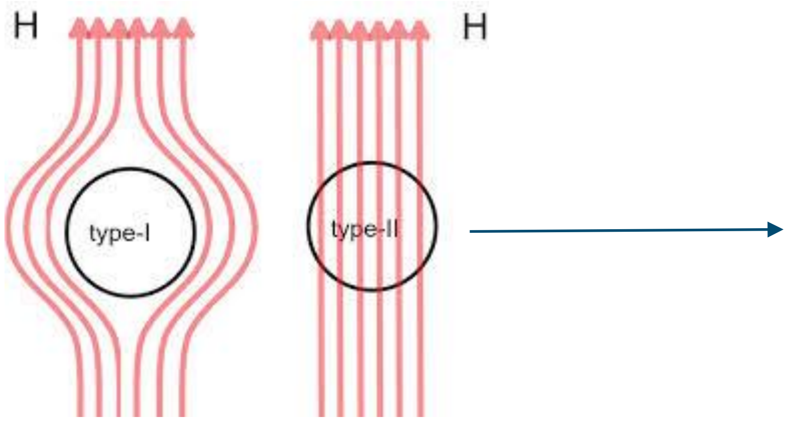
Temperature [K]

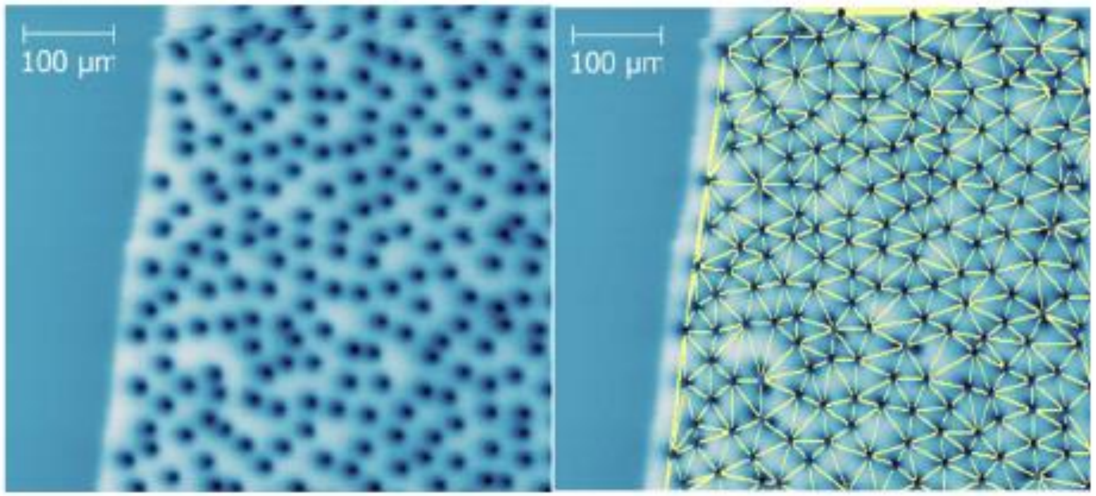
Resistance drops to zero @ 4.2K



Superconducting Physics – Type I vs. Type II

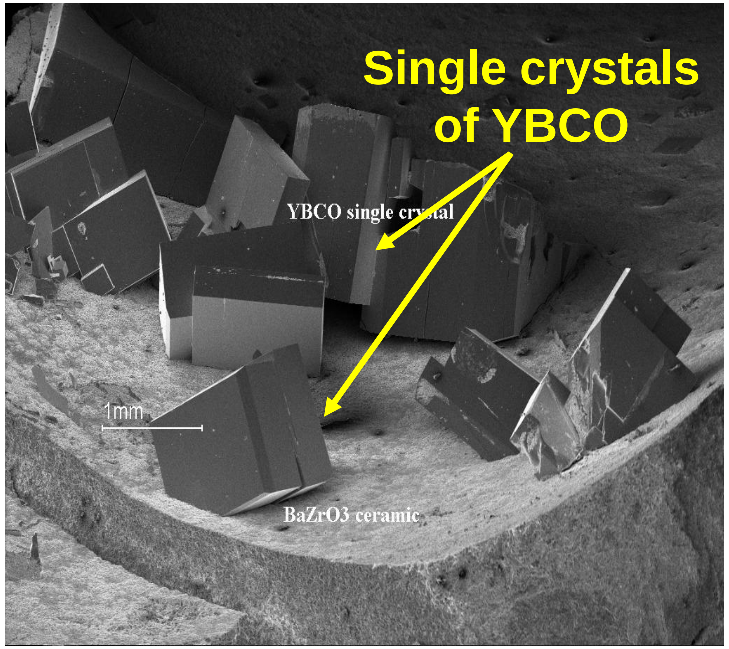
- One of the most distinctions between different superconductors is how they interact with applied magnetic fields.
- In a Type I superconductor, the Meissner Effect prevents magnetic flux lines from penetrating the superconducting material. These superconductors can only exist at very low applied fields.
- In a Type II superconductor, some magnetic flux lines are allowed to penetrate the superconductor, leaving a pattern of “normal cores” that allow higher applied fields (all practical superconductors, including both LTS and HTS are Type II).





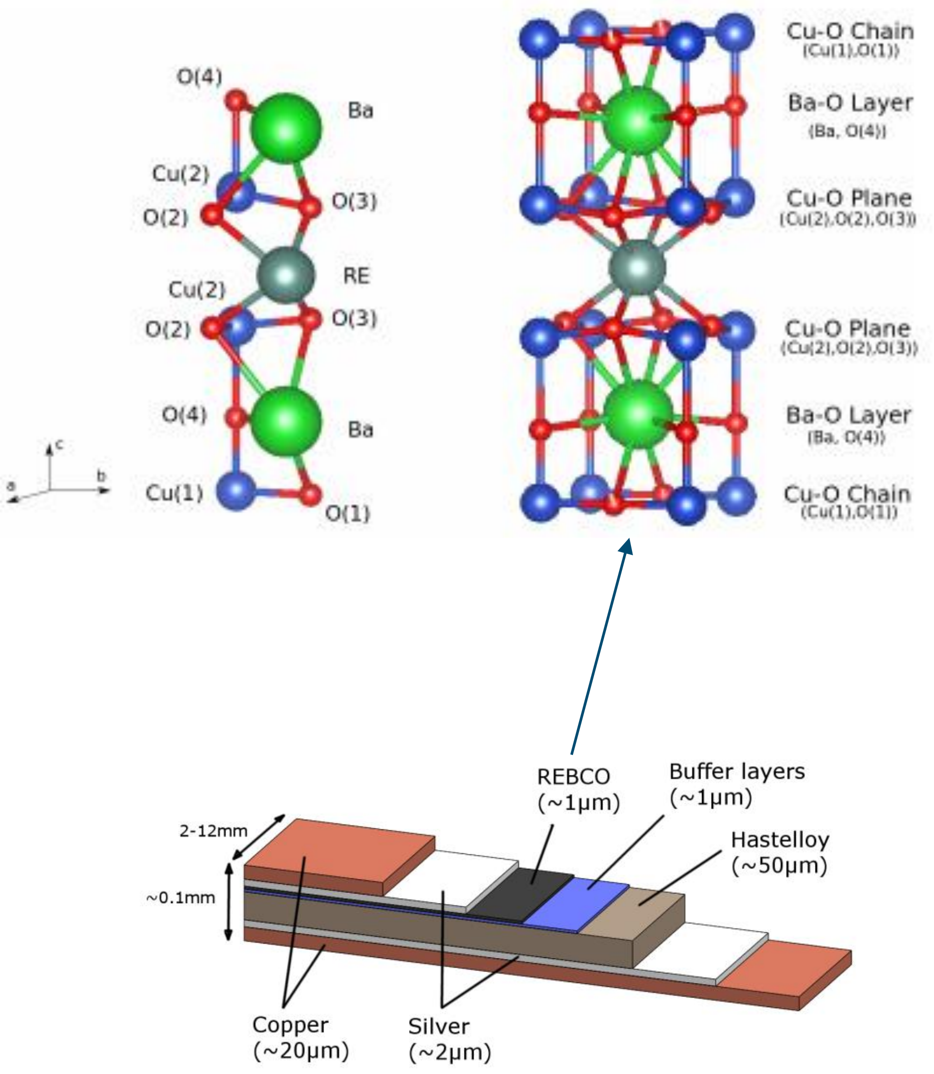
High temp. superconductors (HTS) were discovered in the 1980's with ability to achieve very high currents, B-fields

- New family of Type II copper oxide ceramic superconductors were discovered in 1986 ("High temperature superconductors" or HTS)
- Demonstrated to superconduct at 93 K in 1987, breaking the liquid nitrogen temperature barrier of 77 K with Yittrium Barium Copper Oxide (YBCO)
- In addition to high temperature operation, this new material could also tolerate high currents and high magnetic fields unlike previous LTS materials
- Discovery was so momentous it led to standing-room-only "Woodstock of Physics" meeting at 1987 APS conference and a Nobel prize
- Unfortunately, fabrication process difficult for samples larger than a single crystal, requiring extremely precise grain boundary alignment via "texturing" of substrate
- Thus, high-temperature superconductors existed mostly as a bench-top scientific curiosity for two decades



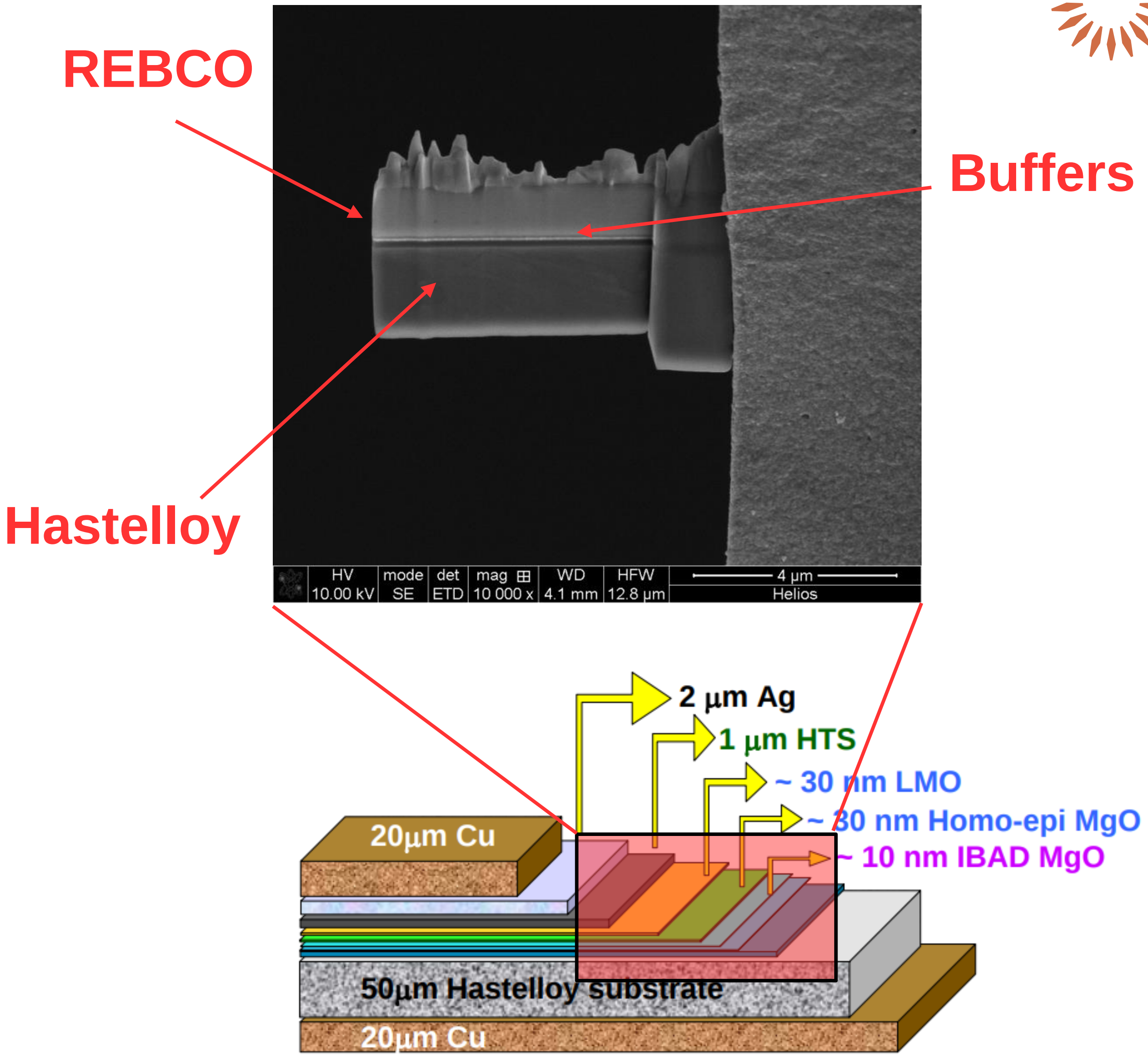
REBCO Physics – Atomic Structure

- REBCO is the general name for HTS cuprates, the "RE" stands for "Rare Earth" of which Yttrium was the first example (for YBCO)
- The exact stoichiometry and atomic structure determines how well the material superconducts (if at all) within a REBCO crystal
- Unit cells form a crystal lattice which is highly anisotropic (elongated c-axis) – this leads to anisotropic performance with respect to applied field direction
- When you see a REBCO "tape" only 1-2% of the cross sectional area is the superconducting layer!
- Much of the REBCO manufacturing process is devoted to putting down this layer correctly and protecting it



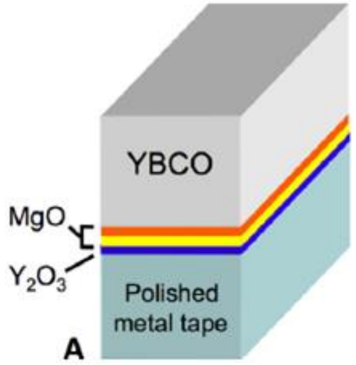
REBCO Manufacturing

- 30 years devoted to material science behind growing uniform thin (~1 um) films of HTS to produce a commercial product
- While tapes look simple from the outside, they are actually a very complicated composite structure which requires a lot of processing
- Multi-step process to make tape:
  - Prepare substrate
  - Texture with buffer layers
  - Deposit superconductor
  - Cap with silver
  - Apply copper stabilizer

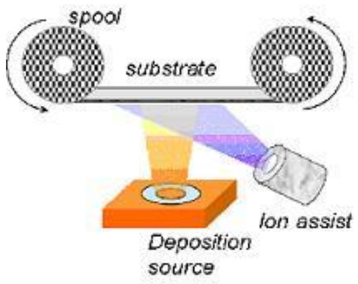


REBCO Manufacturing – Subtrate prep and buffer layer deposition

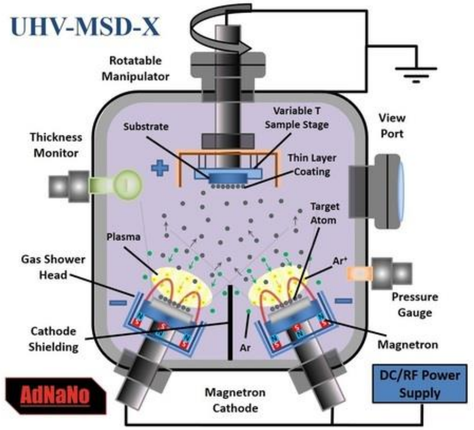
- First, substrate (steel or Hastelloy) is made smooth by electropolishing
- Then, several buffer layers are applied in order to:
  - Stop nickel from diffusing out from substrate
  - Provide a textured, grain-aligned lattice for REBCO to grow on
- Buffer layers deposited by:
  - Ion beam-assisted deposition (IBAD)
  - Sputtering
  - Rolling assisted biaxially textured substrates (RaBiTS)
  - Inclined substrate deposition (ISD)



Electropolishing



IBAD



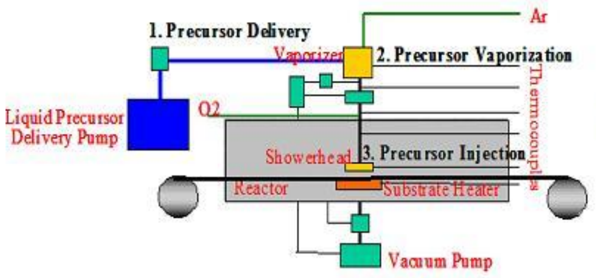
Sputtering

REBCO Manufacturing – REBCO layer deposition

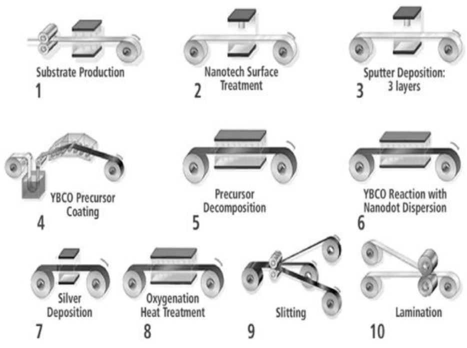
- Four main classes of superconductor deposition
  - Metal Oxide Chemical Vapor Deposition (MOCVD)
  - Reactive Co-evaporation (RCE)
  - Pulsed Laser Deposition (PLD)
  - Metal Oxide Deposition (MOD)

- Each main technique has variations (e.g. RCE-CDR, RCE-DR, and CE are all different forms of RCE)

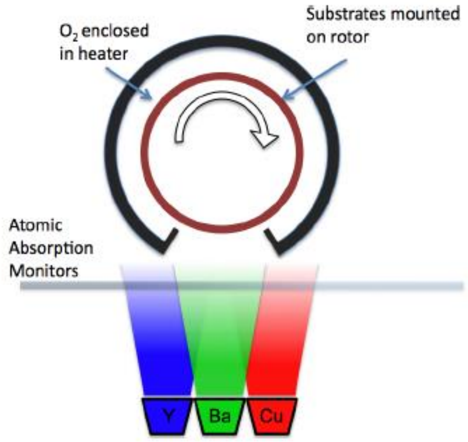
- MOCVD, RCE, and PLD have demonstrated high-field performance REBCO tape in high fields. MOD is still getting there



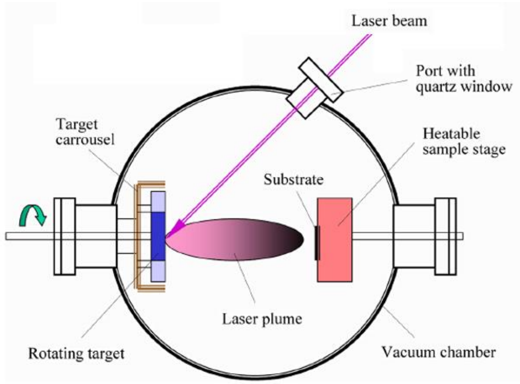
MOCVD



MOD



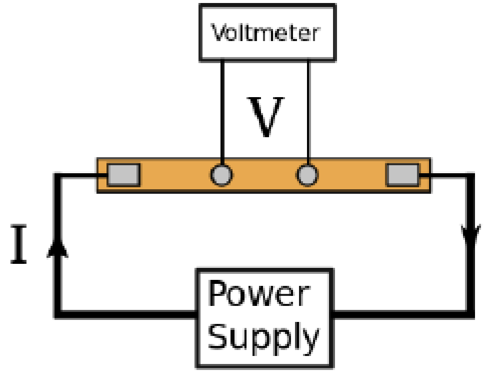
RCE

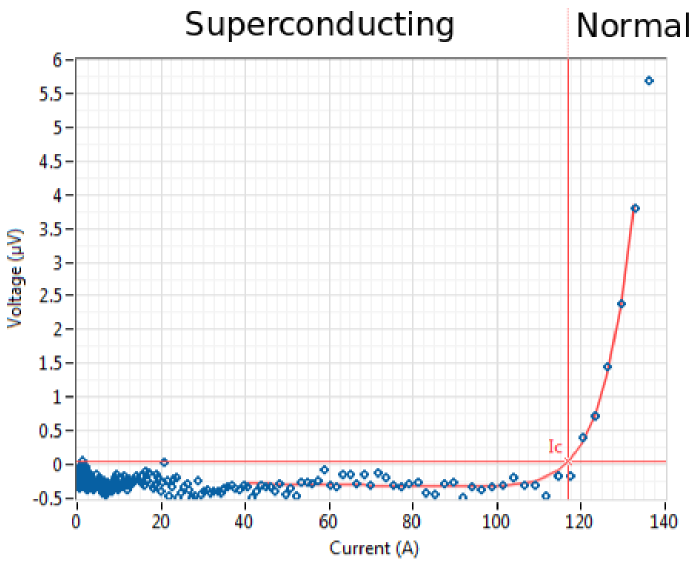


PLD

Critical current – how we assess HTS performance

- Critical current (I_c) is used as a metric to judge the "performance" of a superconducting tape – matters to us because magnet performance (i.e. field) increases with current
- Often expressed as a current *density*, i.e. current/area (J_e) – matters to us because higher Je means more room for structure, cooling, and quench protection in the magnet.
- The denominator matters for current density. J_e is typically used by engineers and takes into account the whole composite tape. J_c is typically used by scientists and just looks at the area of the superconducting layer.
- Critical current has complicated dependencies on tape chemistry, applied magnetic field (and the angle of that field to the tape), and operating temperature – **it is not just one number!**

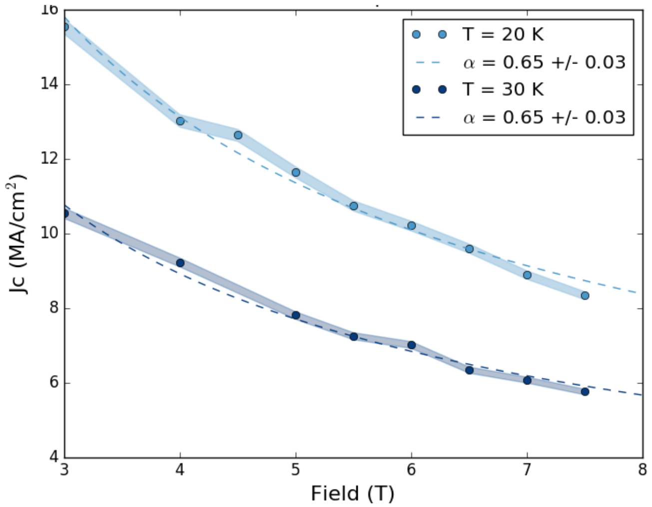


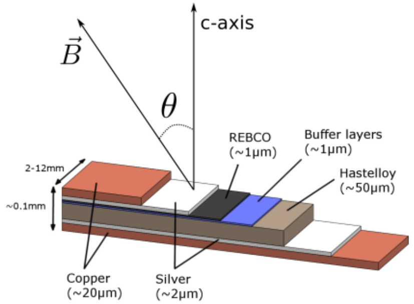


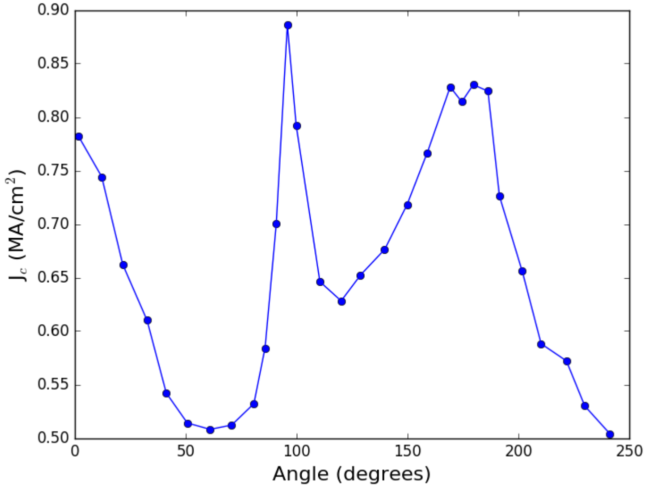
Critical current – we really care about performance at high field!

- Above ~2 T, J_C vs. B field curves can be fit with a negative power law
- Power law coefficient (α) shows sensitivity of J_C to field, and lower α is better
- Power law coefficient is set by the physics of flux pinning – highly dependent on the quality and processing of the REBCO layer
- Angle refers to angle between the applied field and the tape (inconsistent in literature!)
- Features in angular J_c plots indicate the presence of correlated (directional) pinning sites, such as “natural” planar defects or “artificial” BZO nanorod inclusions

$$J_c \propto B^{-\alpha}$$



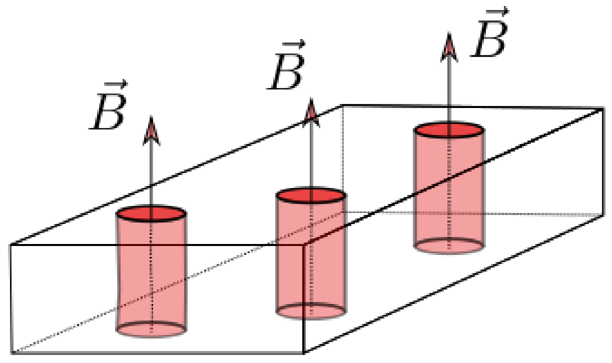


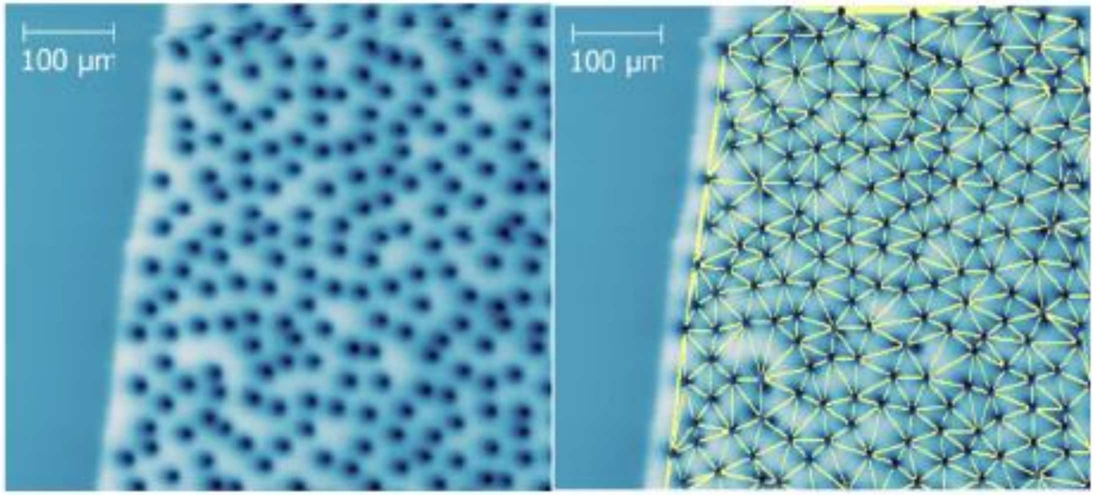


REBCO Physics – Flux Pinning

- All HTS are "Type II" superconductors and allow a certain amount of magnetic flux to pass through "normal cores"
- These normal cores are surrounded by vortex current loops which obey the right hand rule around the flux lines
- The physics of how these lines of flux are "pinned" into their normal cores determines the high-field performance of the superconductors

Magnetic field penetrates HTS at normal cores

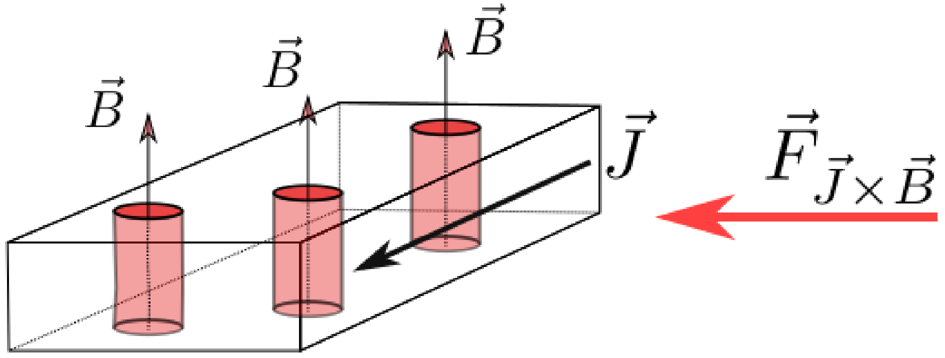




REBCO Physics – Flux Pinning

- When a current is passed through the superconductor, a Lorentz force is exerted on the flux lines in the normal cores

- If the flux lines move, changing field induces a voltage drop, destroying superconducting state

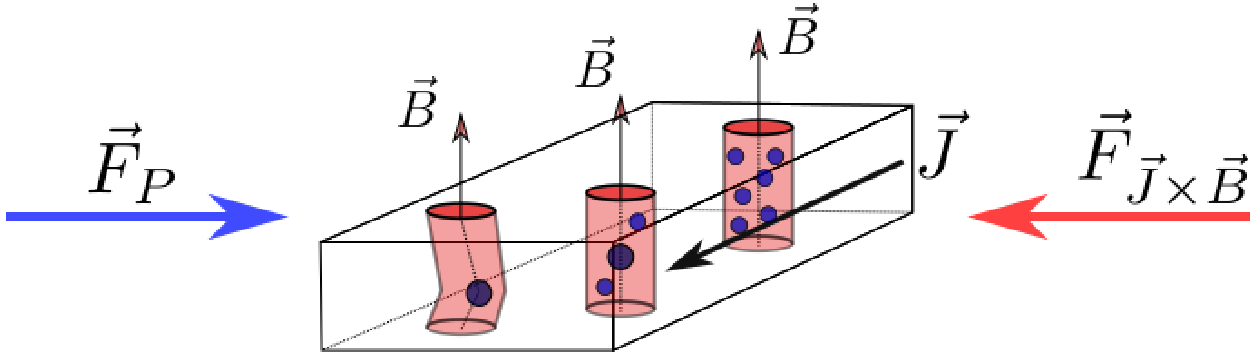


REBCO Physics – Flux Pinning

- When a current is passed through the superconductor, a Lorentz force is exerted on the flux lines in the normal cores

- If the flux lines move, changing field induces a voltage drop, destroying superconducting state

- The flux lines are held in place by pinning centers in the crystal lattice of the superconductor



Understanding HTS performance under extreme conditions is necessary

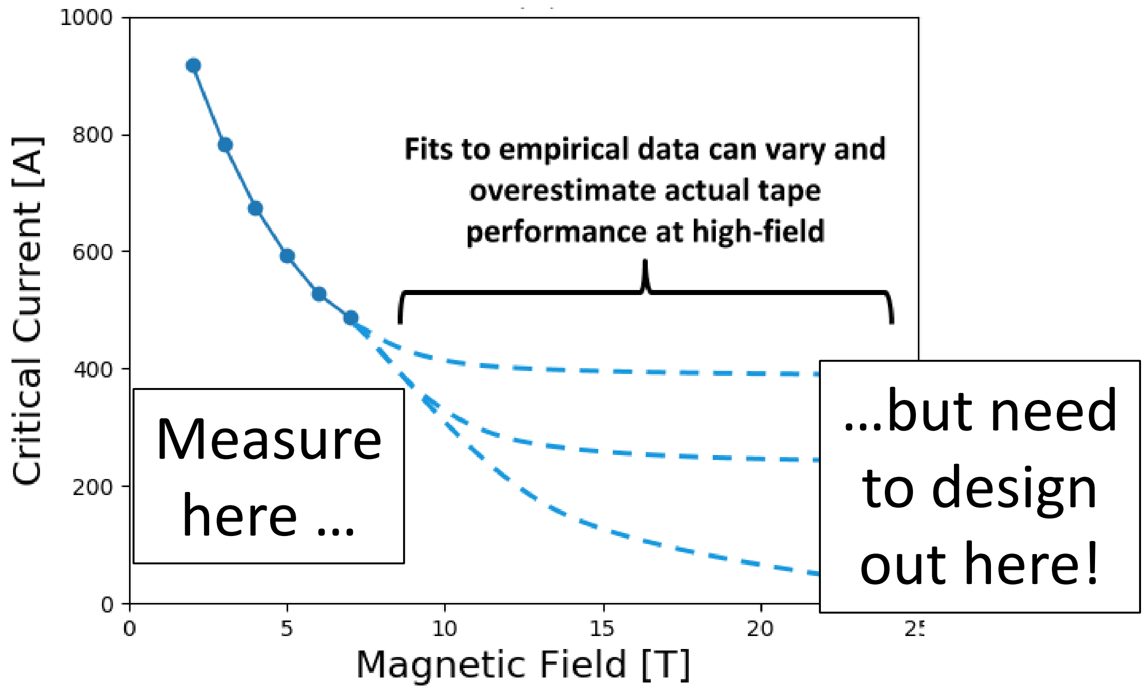
SPARC has two primary HTS characterization needs:

1. High **fidelity** I_c(B,T,A) characterization for design and analysis (i.e. can we build the magnet?)
2. High **throughput** I_c(B,T,A) characterization for QA/QC purposes (i.e. is the tape any good?)

Current measurement capability is limited:

- All measurement systems have limitations in one or more areas that restrict capability
  - Field/temperature/angle limitations
  - Throughput limitations
- Vast majority of existing data is a limited subset of Ic(B,T,A) space, i.e. Ic(B) at 4K and one angle

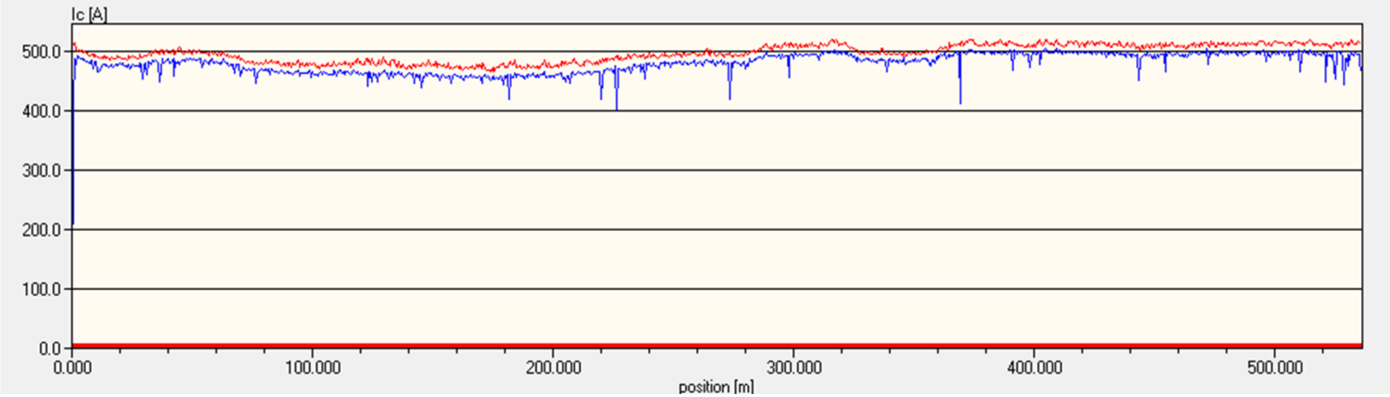
Example: Critical current at high magnetic field



An additional complication – the performance is often not uniform over a length of tape!

- Reel-to-reel cryogenic test station continuously samples critical current using a non-contact method as tape is being produced

- The good news is that satisfactory tape uniformity is presently achievable in lengths up to 500 meters which is more than enough for the SPARC TF magnet



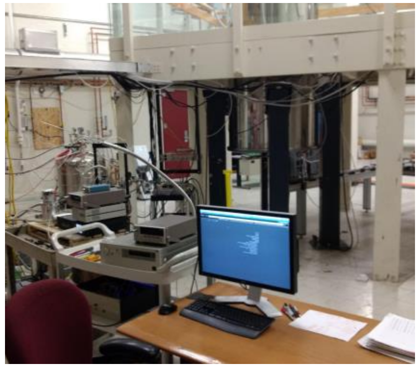
Critical current of tape (A)

Length of tape (m)

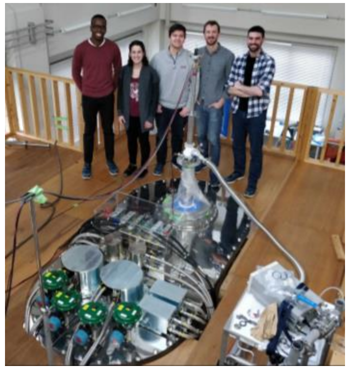
We are implementing a rigorous HTS QA and characterization tool chain

THEVA TapeStar
(CFS)
77K, SF

SuperCurrent
(RRI, HTS110, CFS)
15-77K, 0-12T, 0-240º



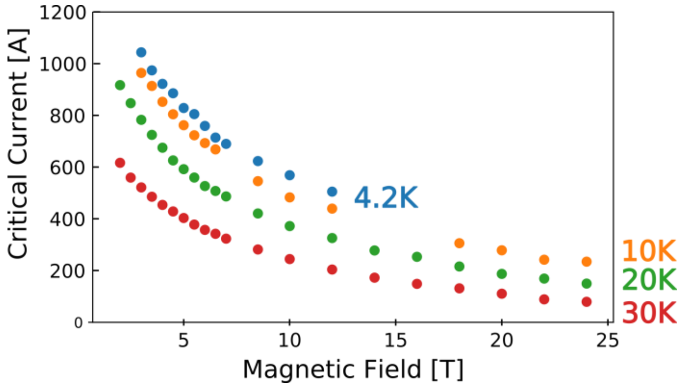
High-field Test Rig
(MIT PSFC)
20K, 16T, 0º

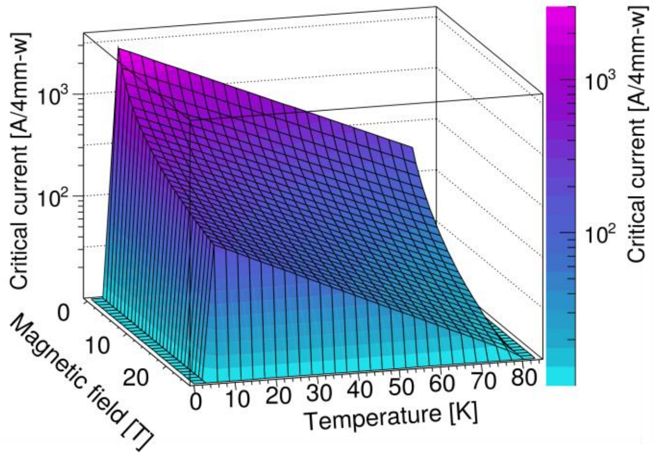


Tohoku Univ.
(Japan)
4-77K, 25T, 0-180º

CFS and MIT have assembled world-leading HTS measurement capabilities in-house and with external partners that are providing:

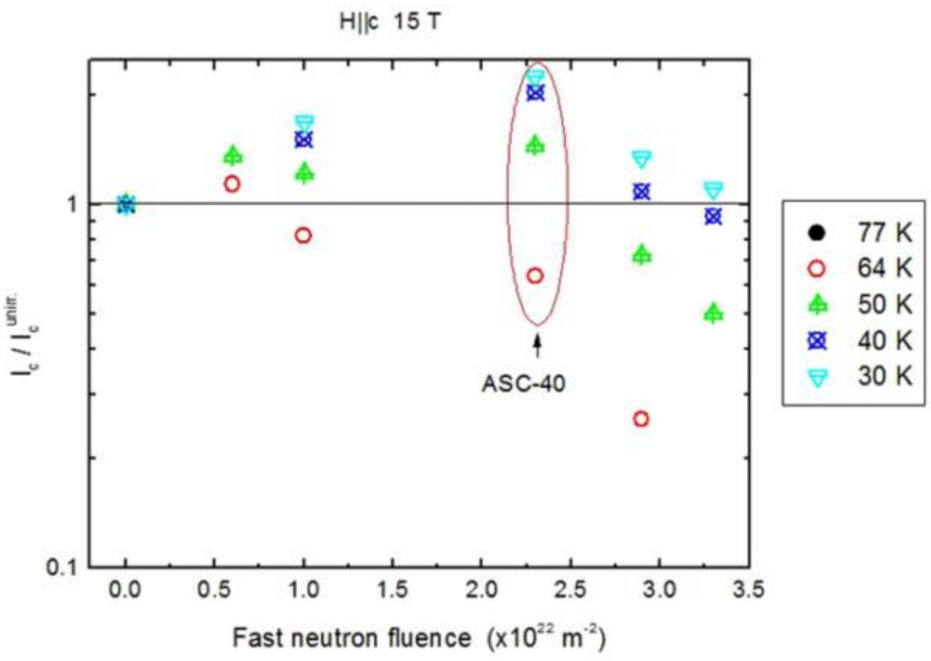
- High **throughput** methods to QA/QC 100's of km of HTS to rigorous SPARC magnet specifications
- High **fidelity** data sets over the entire magnet design space for magnet experiment and modeling
- Critical feedback loop to HTS manufacturers to improve HTS



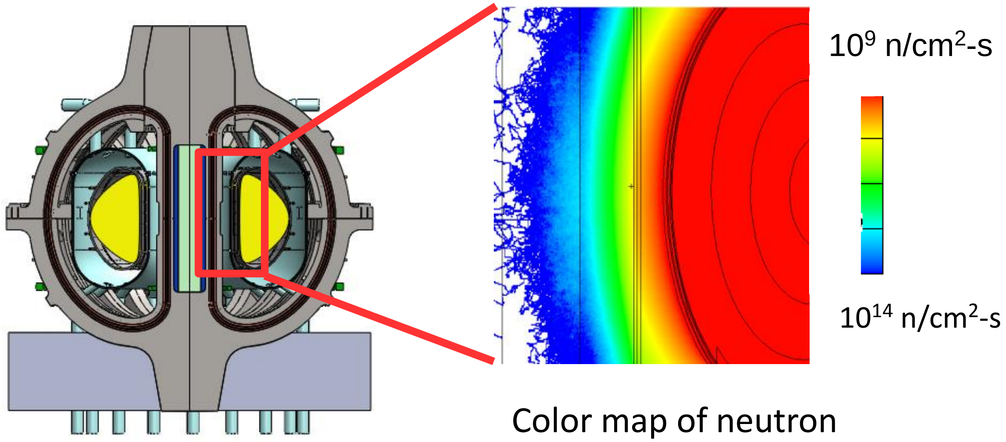


Challenges of using REBCO for fusion – radiation damage

- Neutron irradiation enhances then degrades critical current in superconductors via interaction with flux pinning sites
- Extensive fission irradiations carried out in the 1980's and 1990's with LTS to qualify for ITER-level neutron fluence
- Experimental data is sparse for HTS, but suggests conservative limit at ~3 x 10^{22} n/m^2 (3 x 10^{18} n/cm^2) [1]



- In a reactor, HTS tapes must survive for ~decades, which requires ~1m of shielding in the radial build.
  - The requirement to tolerate high fluence leads to larger device sizes due to shielding requirement
  - SPARC avoids this constraint by running pulsed plasmas and accumulating small total fluence
  - Ultimately radiation damage to REBCO is what sets the minimum size for a high-field tokamak



ARC Cross Section

Color map of neutron intensity from simulation

[1] Prokopec, R., et al. "Suitability of coated conductors for fusion magnets in view of their radiation response." Superconductor Science and Technology 28.1 (2014): 014005.

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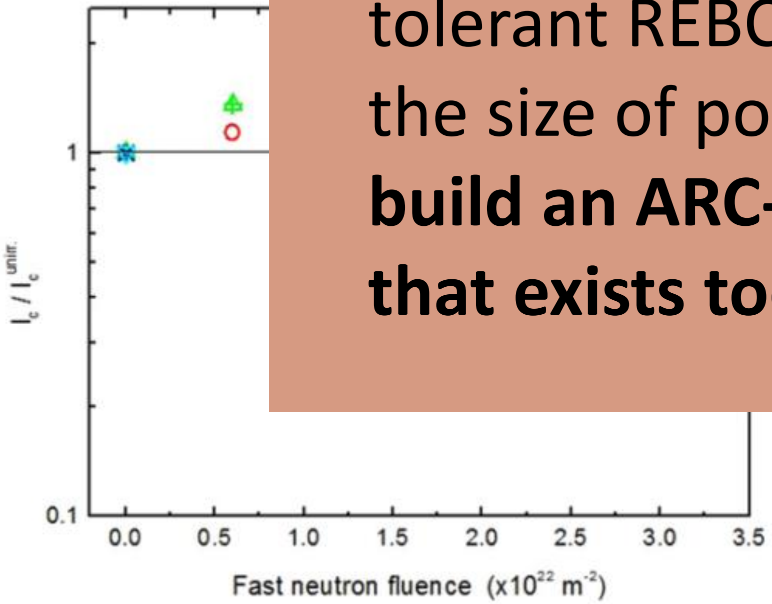
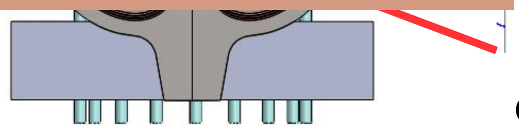
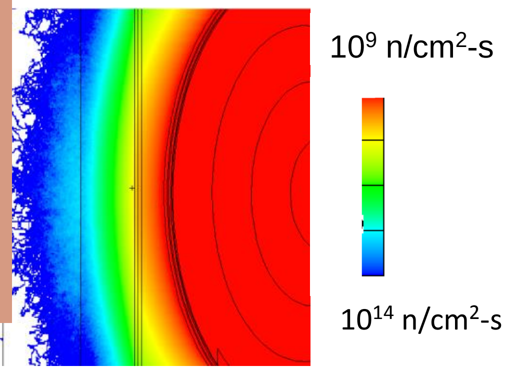
It is important to note: Radiation damage to REBCO is important to understand, but it is not a "showstopper"! More radiation-tolerant REBCO would allow us to reduce the size of power plants a bit **but we could build an ARC-sized plant based on REBCO that exists today.**





ARC Cross Section



Color map of neutron intensity from simulation

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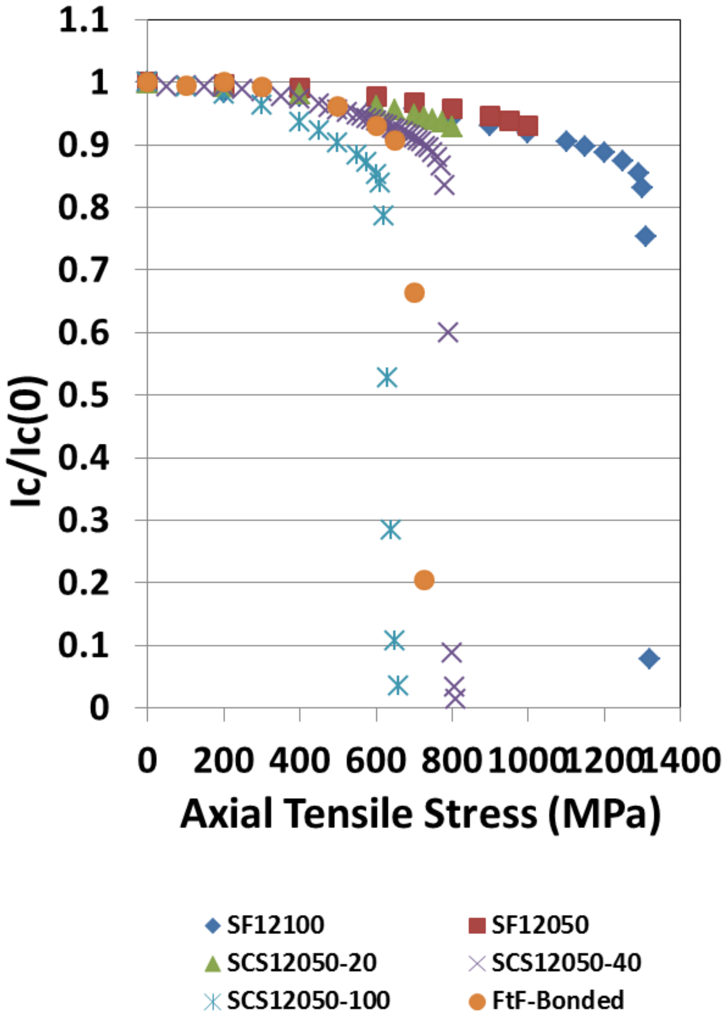
Challenges of using REBCO for fusion – strain damage

Cryogenic, axial tensile test station



5% critical current degradation occurs at 600-800 MPa and ~0.45% strain for most tape formulations

High-strength Hastelloy substrate allows tapes to tolerate high stresses before critical current degradation

Higher stress tolerance and Young's modulus improves ability to push magnet applications to higher field

Proportion of Cu stabilizer to Hastelloy can be adjusted to achieve higher maximum stress

Tokamak-scale conductors have been successfully tested at SULTAN for strain and JxB tolerance

High-current HTS cables were tested in the SULTAN facility (PSI, Switzerland) under a wide range of fields and temperatures to assess robustness to electromechanical loading

- Three separate 2-3 week tests in four months; each targeting explicit technical objectives
- Stacked tape cables with HTS from different manufacturers, different substrate thicknesses
- Ability to carry 10s of kA at 11 T field inside SULTAN, leading to SPARC-relevant JxB forces on tape stacks

SPARC SULTAN EM loading samples being instrumented and installed

The HTS industry is where we need it to be! Now it's time to build some fusion magnets.

- Although REBCO took 30 years to mature from the lab to industry, we are now in a place where:
  - The high-field performance is good enough for fusion
  - Performance uniformity is good enough for fusion
  - Radiation tolerance is good enough for fusion
  - Stress/strain tolerance is good enough fusion
  - The industry is on a trajectory to scale in time to meet fusion's volume needs
  - The industry is on a trajectory to reduce costs enough to make REBCO-based fusion magnets economically viable at power-plant scale
- All the pieces are there, the next step is to build some HTS fusion magnets!