Superconducting Magnets Research for a Viable US Fusion Program

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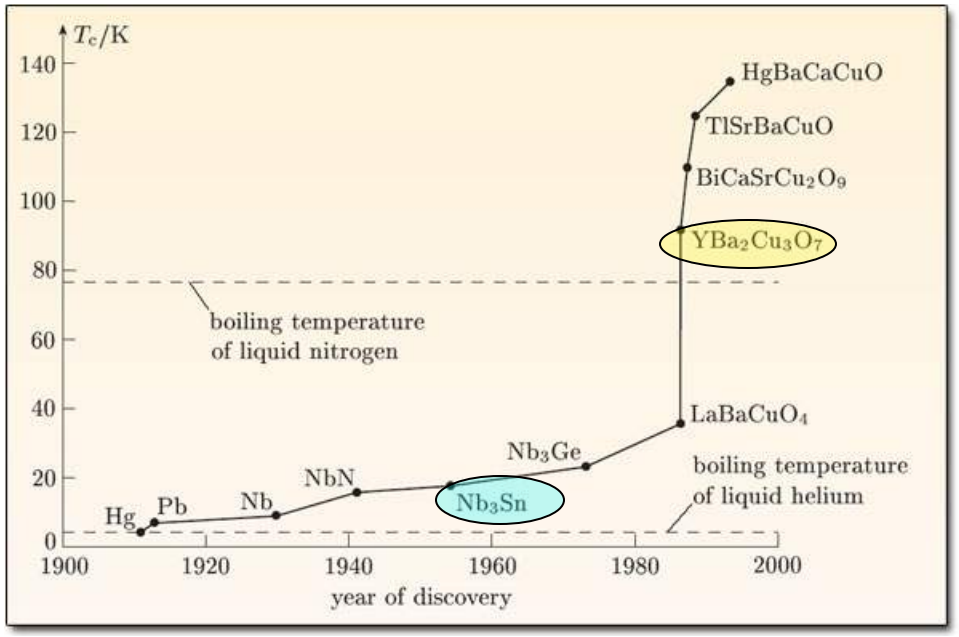
Magnet Technology *Enables* Magnetic Confinement Fusion

- Magnets are an *essential* component for magnetic fusion energy.
- Advances in magnet technology are needed to fulfill the strategic vision for integrated high-B physics (Whyte)
- The most exciting new development in magnet technology is the discovery and application of High Temperature Superconductors (HTS)
- The U.S. fusion program now has the opportunity to take a world-leading role in making high field superconducting magnets a reality.

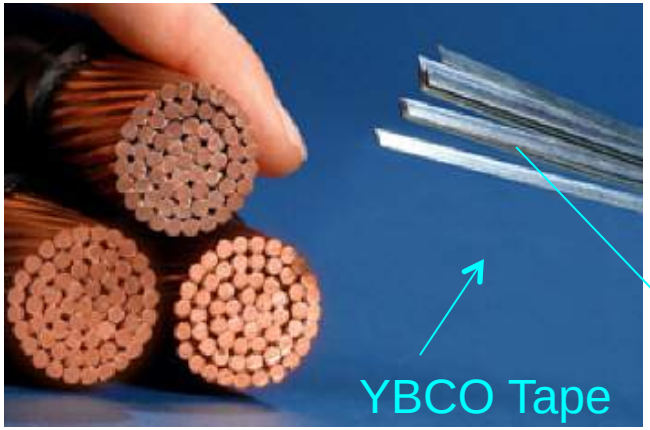


HTS Benefits for Magnetic Fusion Energy

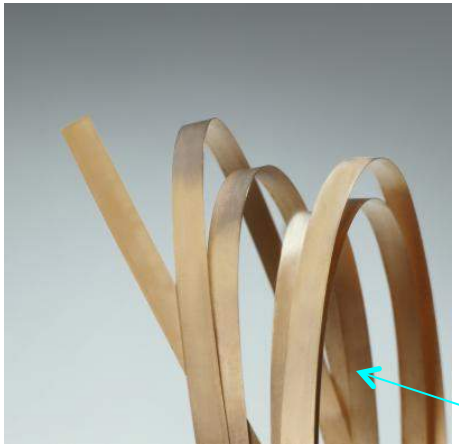
- HTS is a *'game changer'* opening up new opportunities for MFE: (Gap-8, ReNew Thrust 7)
  - high performance leading to very high plasma field (Gap-2)
    - Fusion Gain ~ B^3, Power Density ~ B^4 (Dennis Whyte)
  - increased magnet stability leading to high reliability and availability
  - acceptable cost by reducing machine size and volume
  - demountable magnets leading to improved maintainability (Gap-15)
- Flexible magnetic configurations including steady-state tokamaks, stellarators, and other 3-D configurations (Gap-6)
- Synergism with other DOE and scientific programs:
  - High Energy Physics
  - ARPA-E Electric Power Systems

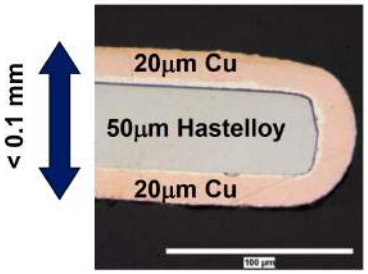
G-2	Demonstration of integrated, steady-state, high-performance (advanced) burning plasmas.
G-6	Sufficient understanding of alternative magnetic configurations that have the ability to operate in steady-state without off-normal plasma events.
G-8	The knowledge base required to model and build low and high-temperature superconducting magnet systems that provide robust, cost-effective magnets (at higher fields if required).
G-15	The knowledge base for efficient maintainability of in-vessel components to guarantee the availability goals of Demo are achievable.
ReNew Thrust 7: Exploit high-temperature superconductors and other magnet innova-tions to advance fusion research.	

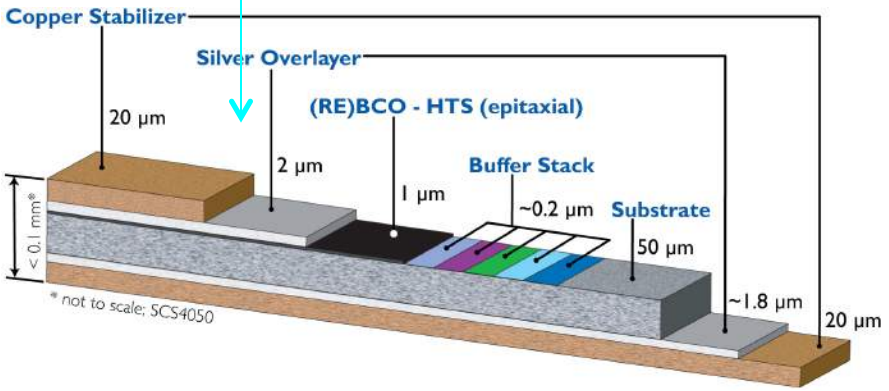
YBCO ($YBa_2Cu_3O_{7)}$ thin-film HTS is best present candidate for use in fusion magnets



- Tape is widely available now at a performance high enough to apply today
- Commercial suppliers in US, Japan, Russia, EU, and Korea



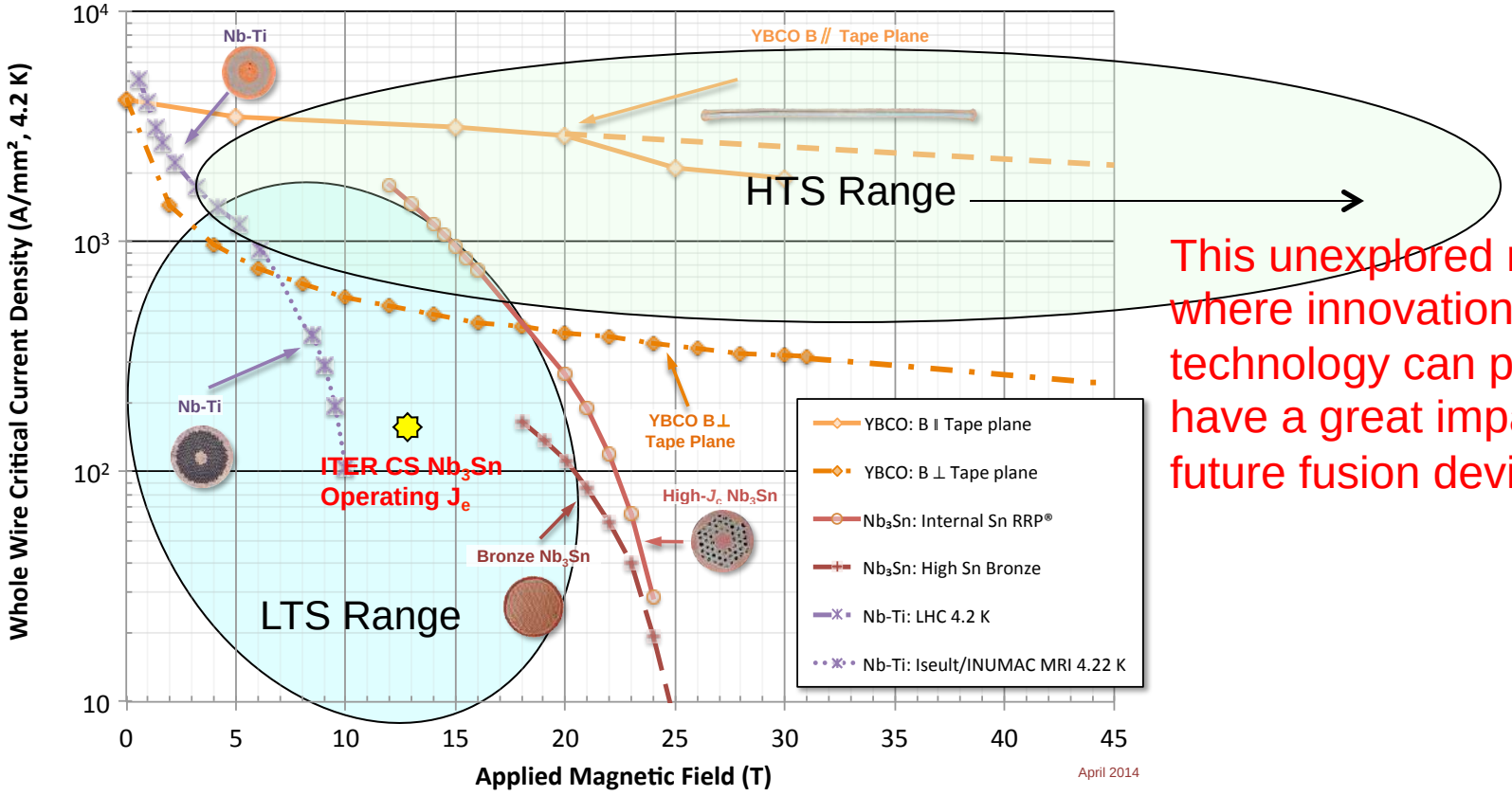




- YBCO tape is thin and flexible
- Nickel alloy substrate is very strong in tension

YBCO *High Temperature* Superconductor is an excellent *High Field* Superconductor

- Present day HTS performance is already good enough for use in fusion magnets and continues to advance rapidly.
- HTS provides high magnet stability and operating margins at T>20K.
- Reduces probability for spontaneous quench.
- Higher T operation increases refrigeration efficiency and nuclear heating handling.

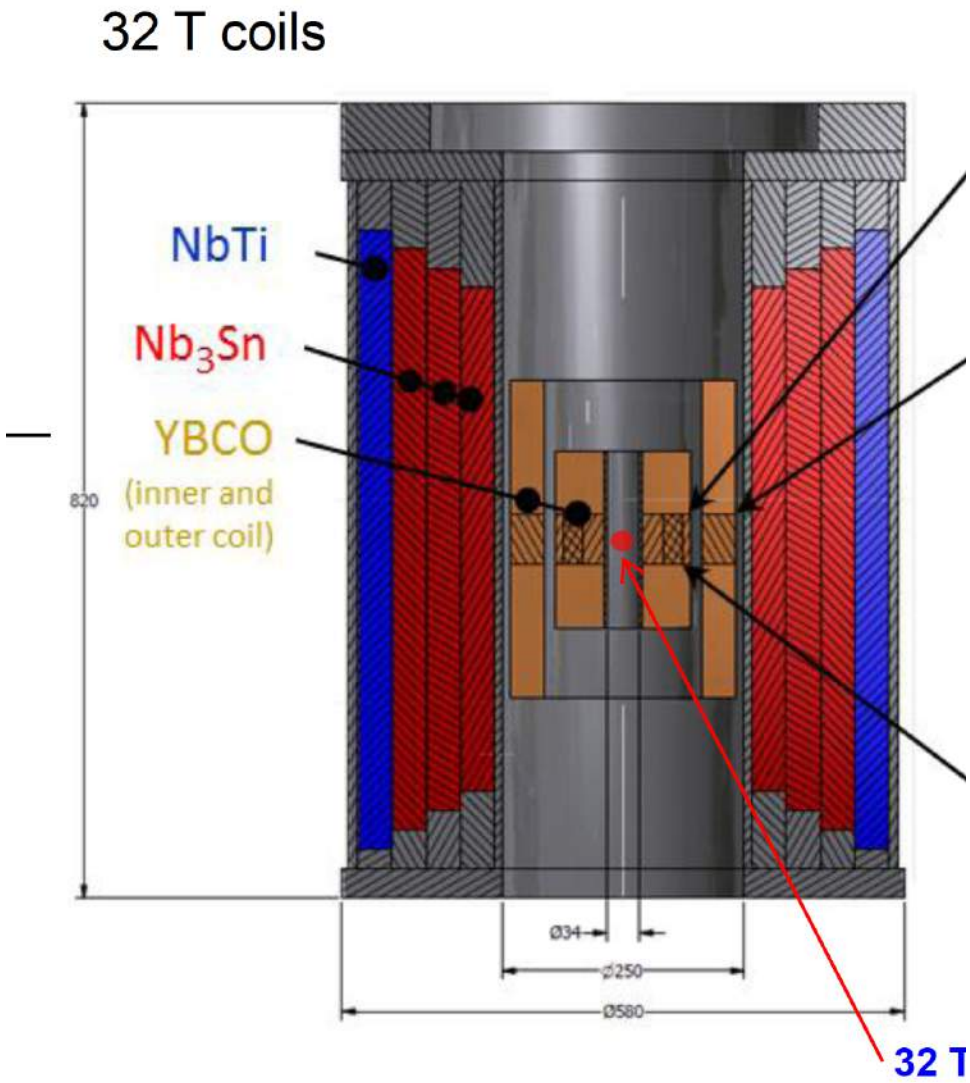


This unexplored range is where innovation in magnet technology can potentially have a great impact on future fusion devices.

http://magnet.fsu.edu/~lee/plot/plot.htm

Very High Field Magnet Technology is now being demonstrated at 32T

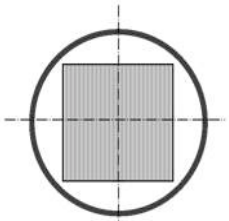
NHMFL is building a 32 T user magnet now

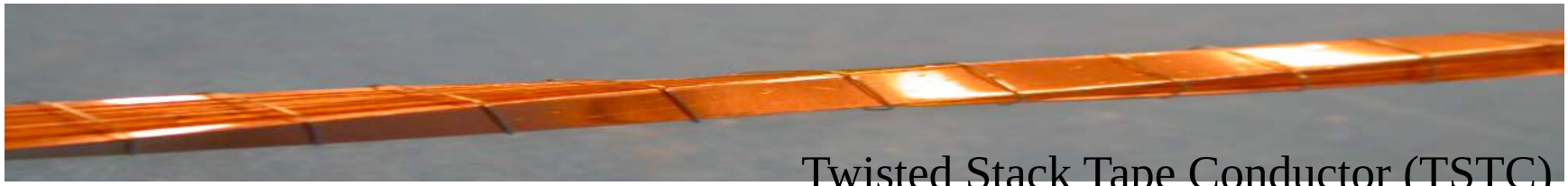


- HTS wire technology is already advanced enough to start building very high field magnets
  - Magnets such as this will demonstrate the YBCO performance in high field
- Fusion magnets, however, require a more advanced conductor concept.
- The US fusion magnets program can take advantage of these developments and should initiate a comprehensive fusion conductor development program.

Fusion Magnets Require Very High Current Conductors

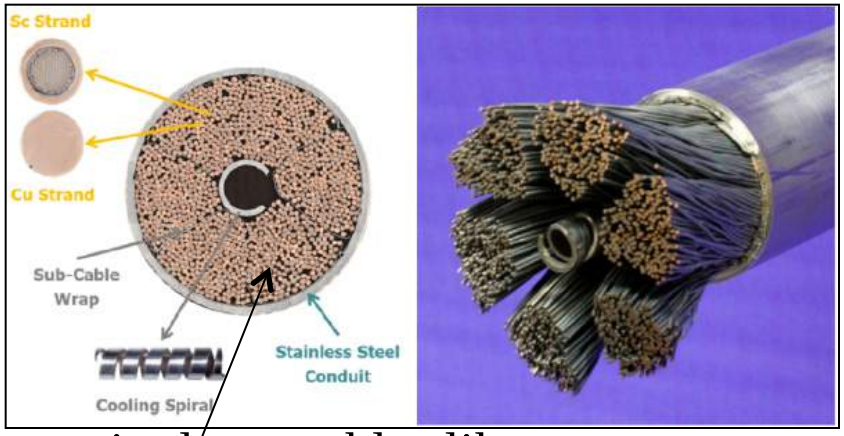
- The base program is developing the Twisted Stacked Tape Conductor to build up multi-tape cables to operate at 50 – 100 kA.
- Basic elemental conductor development
  - Basic cables made of 4 mm – 6 mm width YBCO tapes
  - Multi-tape conductor, twisted can be bundled into high current, multistage cables





Twisted Stack Tape Conductor (TSTC)

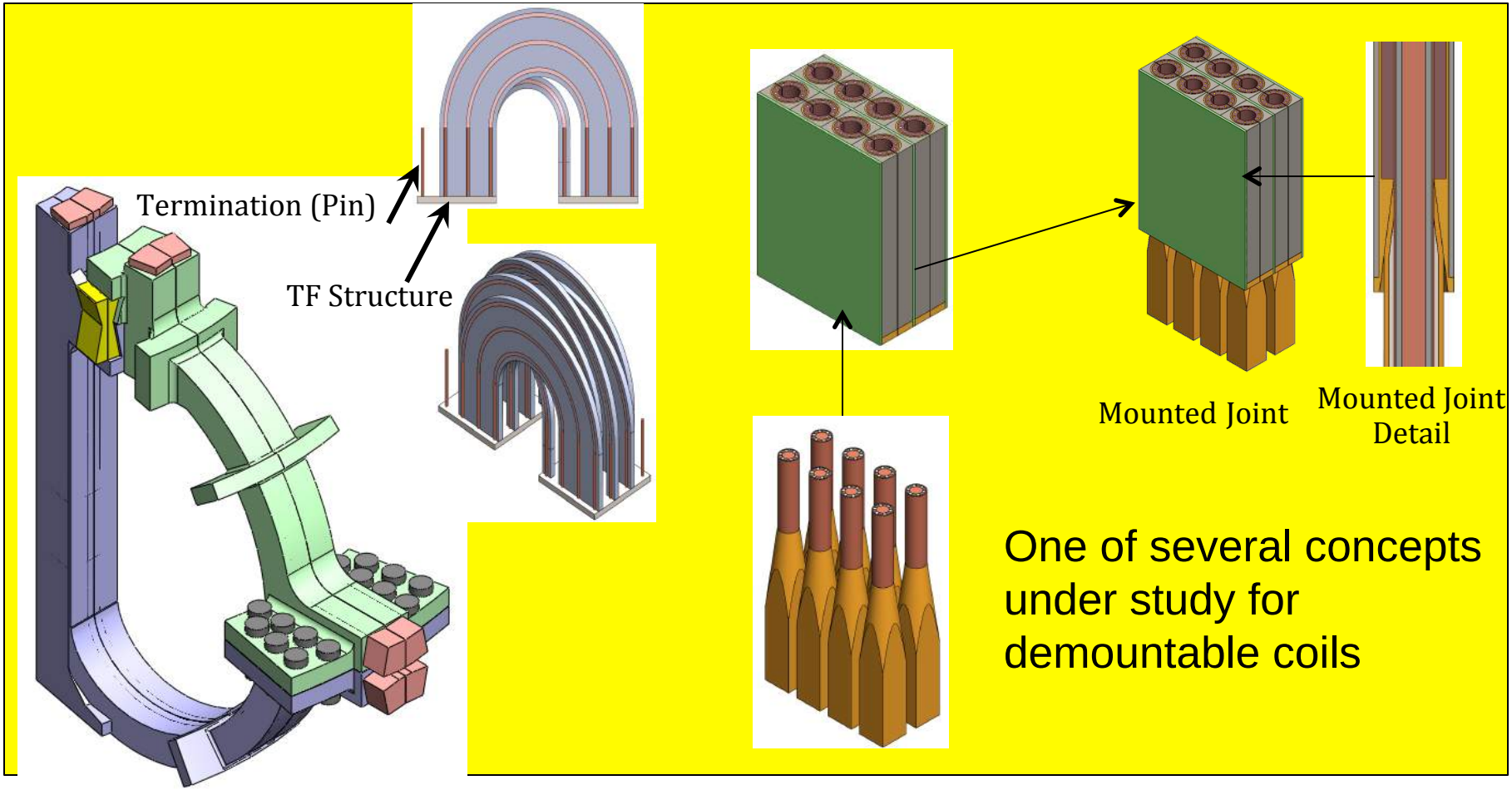
Multistage conductor:
3x3 cable and
12 sub-cable conductors



Fusion magnets require large cables like the ITER TF conductor (~1000 round wires)

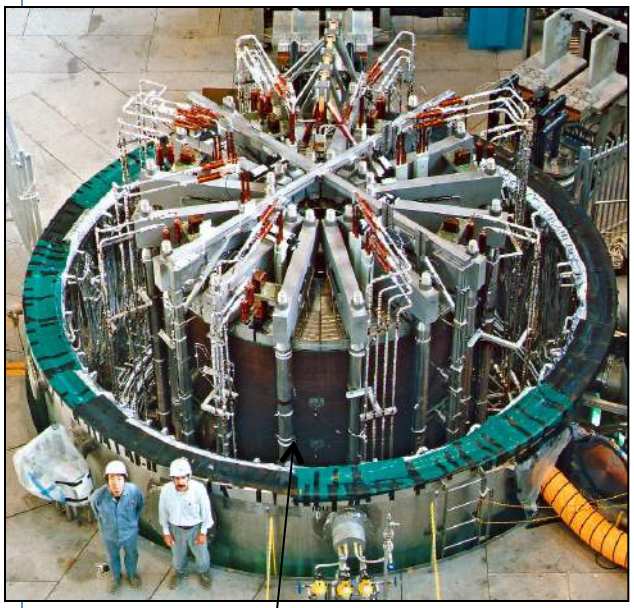
Magnets for FNSF and DEMO Should Be Demountable

- Demountability can improve maintainability and availability and make coil repair/ replacement possible.
- HTS makes this technology feasible
- But a development program for demountable joints is required



FESAC Should Recommend an Accelerated R&D Program for HTS Magnets

- **Start a program** to enable the development of HTS coils similar to ITER EDA magnet R&D
- **Design, fabricate, test components**:
  - Long conductor lengths in high fields
  - Full-size demountable joints
  - New structure concepts
  - Integration of conductor and structure
- **Relevant Scale Coil Fabrication**
- **Deliverables**
  - 5 Years: 50-100 kA conductors and demountable joints.
  - 10 years: Ready to build large size prototype coil operating at high field, and to begin design of an FNSF.
- Work collaboratively with **international partners**.
  - An HTS4Fusion working group has been formed with participants from US, Germany, England, Switzerland, Italy, Spain, Russia, Japan, and Korea representing 15 institutions.
- The ITER Central Solenoid Model Coil is an example of the relevant scale for a **prototype demonstration magnet.**



- **ITER CS Model Coil (EDA)**
- **13 T, 50 kA, 640 MJ, 2 T/s**
- **150 tons**
- **6 years including R&D, design, fabrication in industry**

R&D Elements

A structured research and development program consists of the following elements:

Most Critical Elements

1. High current conductors/cables made from YBCO tapes
2. Advanced magnet structural materials/structural configurations
3. Demountable joints for coils
4. Coil fabrication technology incorporating the unique features of elements 1-8.

Other essential elements

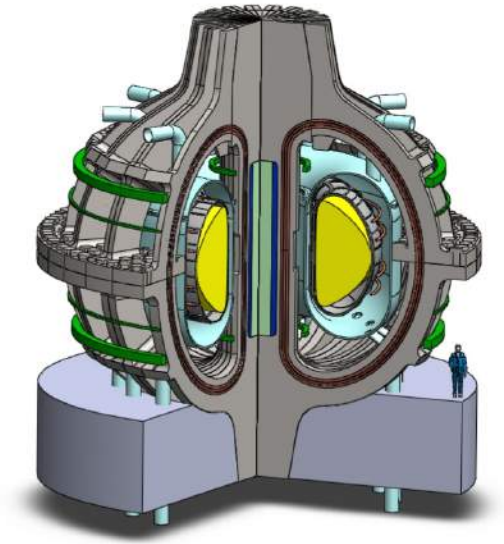
5. Cryogenic cooling methods for HTS magnets
6. Integration of conductor with structure, insulation, and cooling
7. Magnet quench detection/protection specific to HTS magnets
8. Advanced radiation tolerant insulating materials

- **Funding should start at ~$2 M/year and ramp to $5 M/year in 4 years.**
- **The prototype coil demonstration requires additional investment.**

[Note: Annual US HEP Magnet R&D (base + LARP + MAP) funding is ~33 x > FES magnet funding, and is distributed to 9 national labs + 40 university grants]

Summary

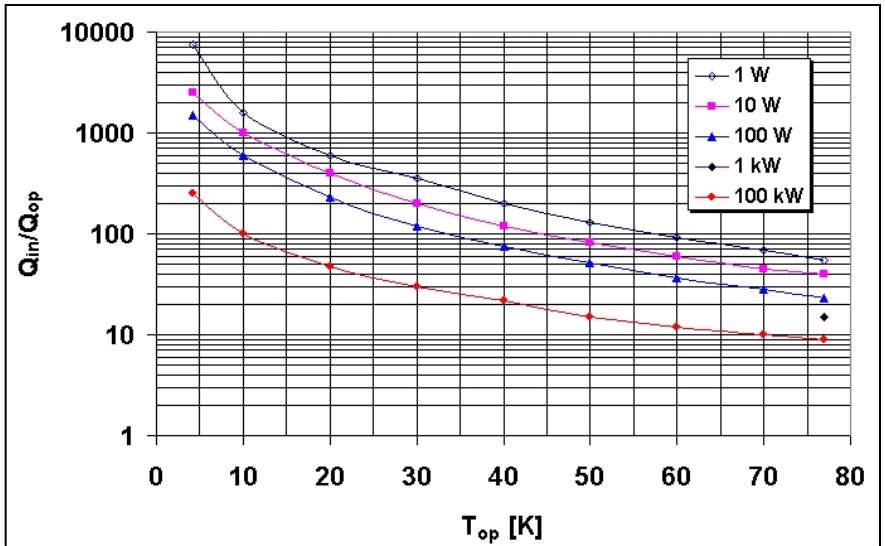
- Advanced superconducting technology is critical to development of a reliable and economic fusion reactor.
- HTS technology opens up new areas for fusion innovation.
- The US is uniquely positioned to take international leadership in this technology for advanced fusion reactors.
- We can't afford to wait 20-30 years. The time to start is now.
  - FNSF and Demo should not be built with 1990's ITER magnet technology.
- **FESAC should recommend initiation of a US program for high field HTS magnet technology.**



Backup

Advantages of HTS Operating at Elevated Temperature

- Increase in thermal conductivity (5-10 times)
- Increase in specific heat (10-100 times)
- Very high stability
  - (Disadvantage very slow quench propagation making projection more difficult)
- Less refrigeration wall power required (gain in fraction of Carnot Efficiency)



ITER Cryogenic Refrigeration Requirements

Heat Load (kW)	Temperature (K)	Q_{wall}/Q_{in}	Wall Power (MW)
65	4.5	180	11.7
1300	80	9	11.7

Structural materials exist today with sufficient strength and fracture toughness at cryogenic temperatures to build very large high field fusion magnets

Alloy		Test Temp K	Yield Strength MPa	Tensile Strength MPa	Elongation (in 13 mm) %	Reduction of Area %
Haynes 242 2.35 mm	As Rec'd	295	516	1104	56	49
		77	737	1518	64	50
		4	860	1675	55	45
	Aged	295	1098	1527	34	30
		77	1264	1863	28	23
		4	1340	1968	26	21
316 LN Mod 1.5 mm Strip	As Rec'd	295	372	700	54	59
		4	1132	1555	42	36
	Aged	295	396	733	51	58
		4	1168	1507	27*	24*
316 LN Mod 2 mm	As Rec'd	295	340	678	55**	59
		4	1081	1529	49**	34
	Aged	295	348	689	51**	59
		4	1099	1529	47**	40

* Failed at Gage Marks

** Elongation in 25 mm Gage length

YS: 1100-1500 MPa
UTS: 1500-1900 MPa

2/3 YS: 733-1000 MPa
½ UTS: 1000-950 MPa

Nitronic 50

TABLE 2. Tensile Test Average Results

Heat No. and Material ID	Test Temp. (K)	Specimen Orientation	No. of tests	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)	Reduction of Area (%)
A11371 Slab	295*	L	1	482	779	46	73
A11399 Slab	295*	L	1	526	803	47	75
G16529 Slab	295	L	4	408	766	40	68
G16529 Head	295	L	4	357	746	49	72
A11371 Slab	4	L	1	1540	1862	8	11
A11371 Slab	4	T	1	1525	1837	11	12
A11399 Slab	4	L	1	1620	1893	12	16
A11399 Slab	4	T	1	1395	1738	9	11
G16529 Slab	4	L	6	1326	1742	26	42
G16529 Head	4	45°	6	1264	1695	30	36

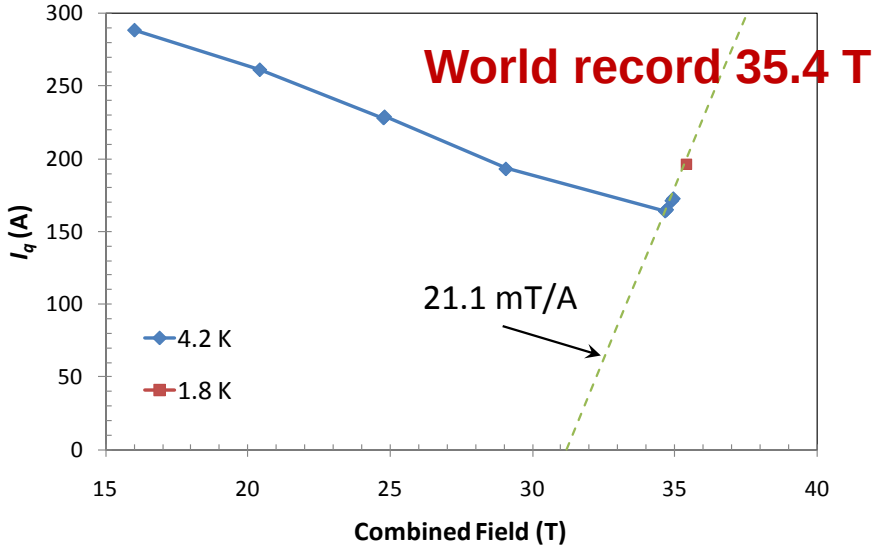
Alloy	Condition	Yield Strength MPa	Toughness Kic(J) MPa*m^0.5
242 2.35 mm	AR	860	>200
	Aged	1340	142
316LN 1.5 mm	AR	1132	>170
	Aged	1168	164
316LN 2 mm	AR	1080	193
	Aged	1099	182
316LN 3 mm	AR	1284	159
	Aged	1202	90

REBCO Layer Wound High Field Coil delivers World Record 35.4 T field

Conductor insulation facility

Whittington *et al.* Patent disclosed (2013)

- Wet layer-wound, epoxy filled
- no splices
- thin walled polyester heat- shrink tube insulated conductor (patent)



Trociewitz *et al.* APL 99 ,202506 (2011)
Patent Hilton *et al.* on insulation US 8,530,390 B2 (2013)
Patent Trociewitz *et al.* on terminals US 8,588,876 B1 (2013)

Fusion Magnet Development has Important Scientific and Commercial Spin-Offs

World's Highest Field Superconducting Cyclotron for Proton Beam Radiotherapy for Cancer Treatment (Gantry-Mounted) – Commercial start-up funded by investor capital. Licenses MIT IP.

Magnetized Dustly Plasma Experiment (MDPX) being commissioned at Auburn University (Funded by NSF MRE)