Superconductivity, Superconductors, and Energy Needs

M.D. Sumption

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SuTC (Superconducting Technology Center)

Department of Materials Science & Engineering

The Ohio State University

CSMM [Center for Superconducting and Magnetic Materials]

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Overview

CSMM

SuTC

Industrial Collaborators

- Superconductor Wire Companies
- Magnet and subscale Device Companies
- System integrators

SuTC

- Coil performance
- AC loss
- Quench
- Conductor performance

CSMM

- Structure/properties
- Microstructure control
- Dopant control
- New Materials Development
- Improved Materials Properties
- Vortex pinning

Some Active Collaborations

Universities/Institutes

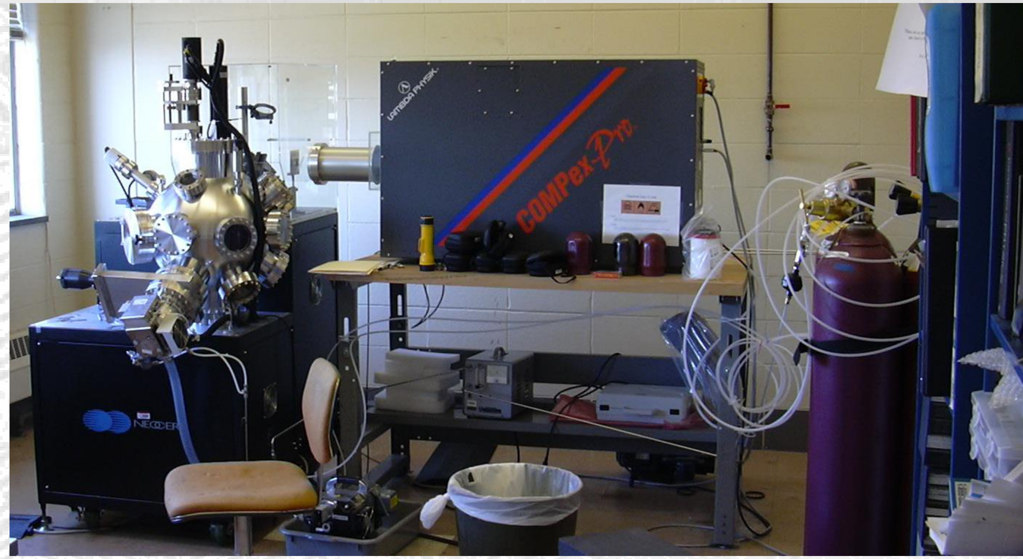
- U. of Wollongong (Australia)
- U. of Twente (Netherlands)
- U. of Geneva (Switzerland)
- U. of Cambridge (UK)
- IR&D (New Zealand)
- Southeast U. (China)
- AFRL (Ohio)

National Laboratories

- LBNL
- FNAL
- BNL

CSMM (Facilities-I)

Materials, Magnetic, transport, heat capacity studies



Pulsed Laser Deposition (above)

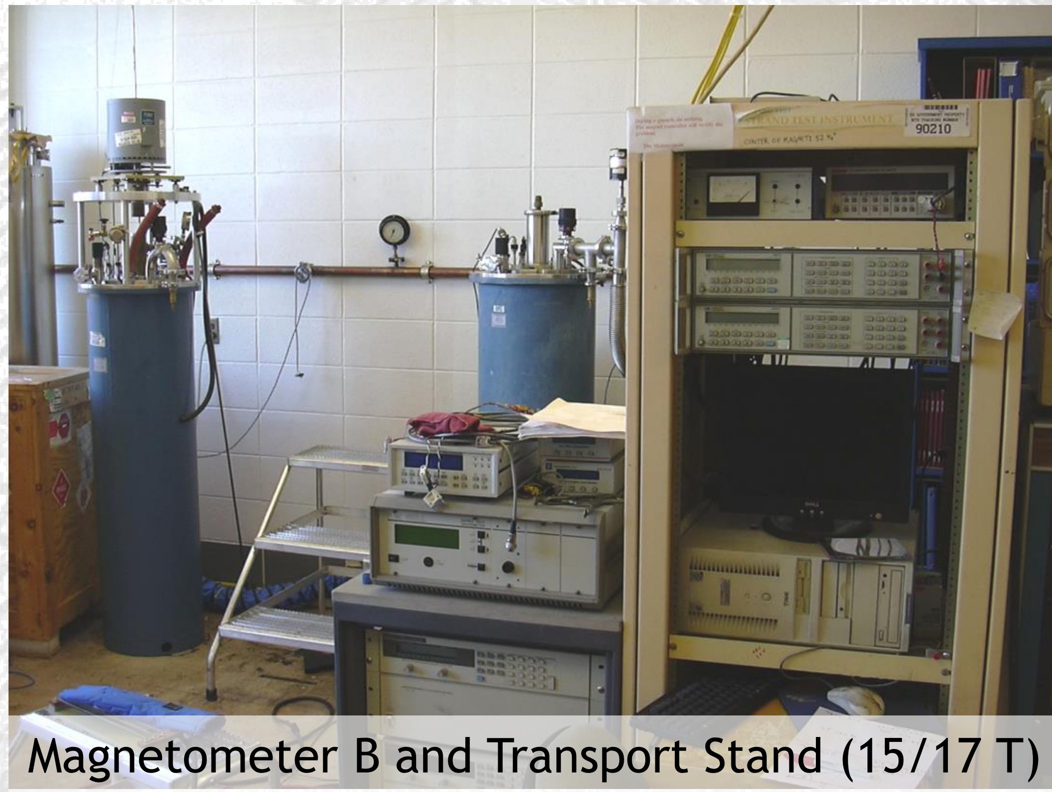
14 T PPMS with He re-liquifier (left)

Furnace (right)

1700 C/1500 psi

CSMM Facilities II-Transport Properties Lab

Magnetometer A



Magnetometer B and Transport Stand (15/17 T)

SuTC (Superconducting Technology Center)

Industrial Collaborators

Hyper Tech Research
Global R&D
SupraMagnetics
Supergenics
Rolls Royce
Siemens
Ceram Physics
Luvata
Superpower

Systems

MRI magnets

MRI Conductors

Fault current limiters

Adiabatic Demagnetization Refrigeration

Undulator Magnets

Motors/Generators

Fusion Magnets

Transformers

Power Cables

Areas of Study

Energy Loss (cyclic AC operation)

Energy Stability

Field Generation

Cooling

Power Transmission

SuTC (Facilities)

[Superconducting Technology Center]

Larger scale

Technology, coils, cables, AC loss

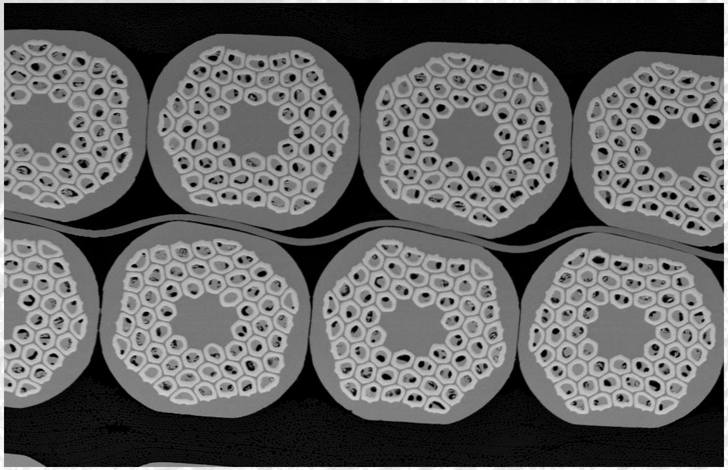
AC loss Measurement Facility

Large dewar/ coil

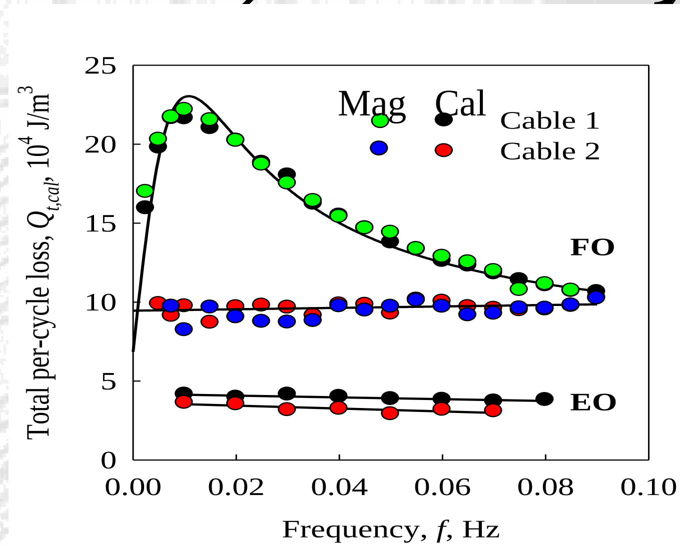
12 T dry magnet

Large magnet 4 K
cryocooler (4’ x 2’)

SuTC-Cables, AC loss, Stability

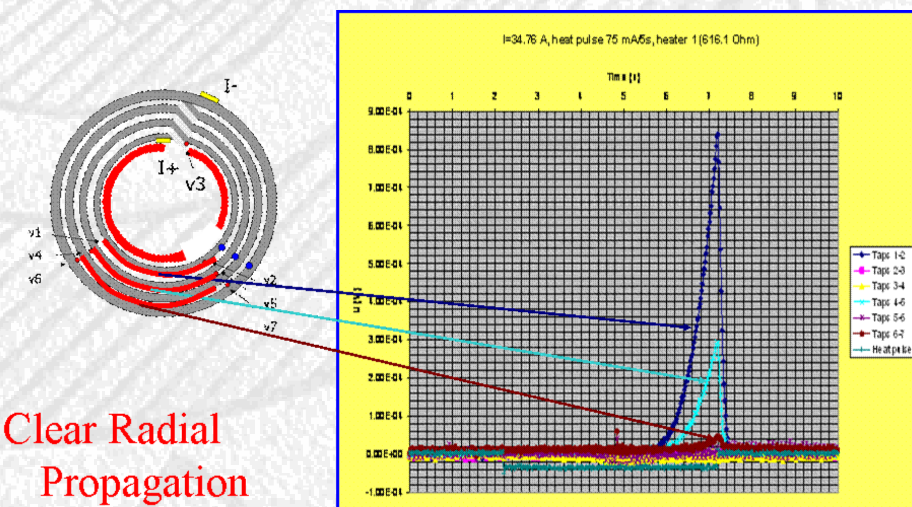


Nb$_3$Sn 20 kA cable (above)



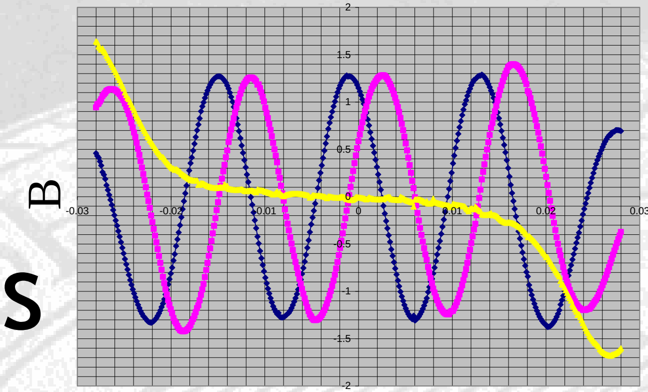
AC loss data and sample (above) quench propagation in YBCO (below)

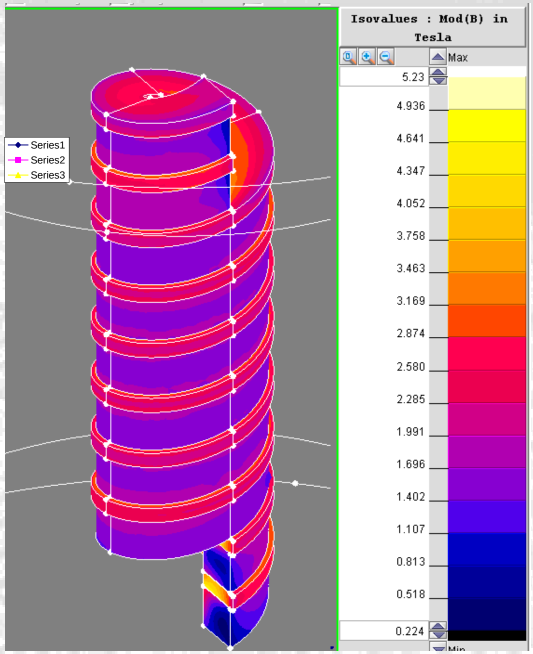
YBCO coil (Below)



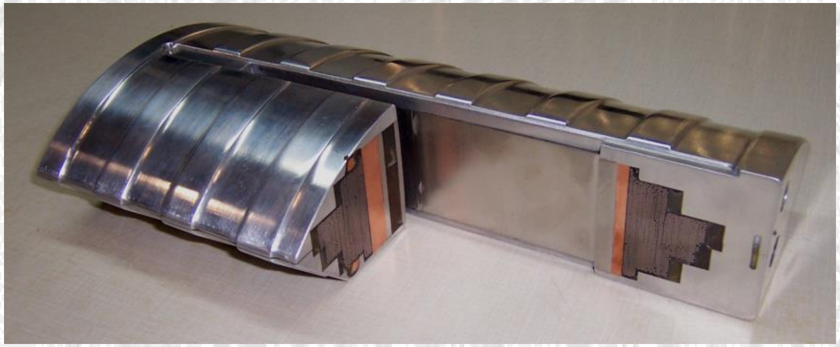
Clear Radial Propagation

SuTC-Magnets





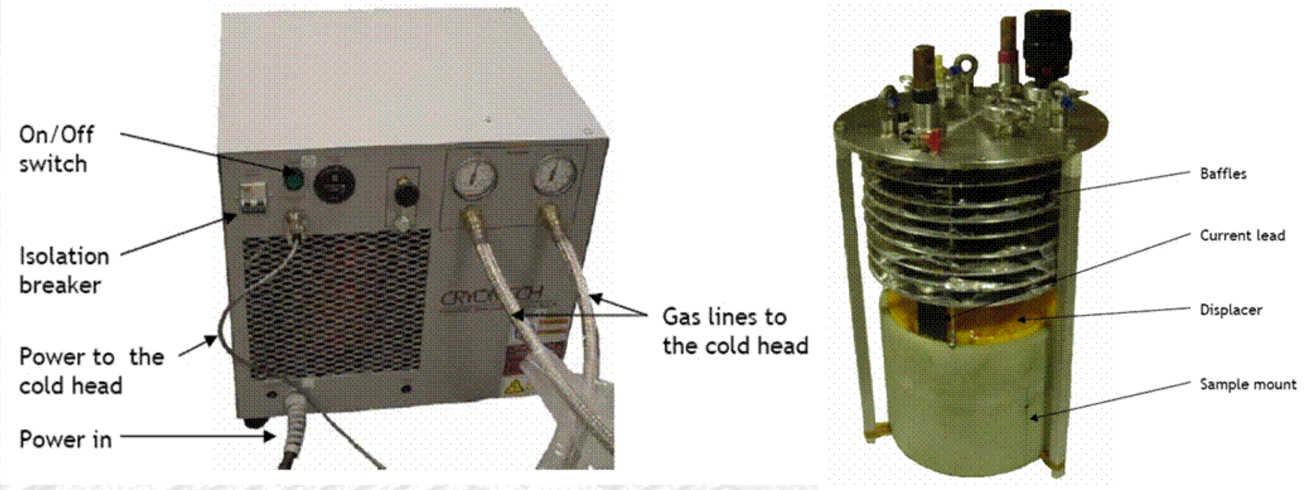
Small Scale Model Undulator for International Linear Collider



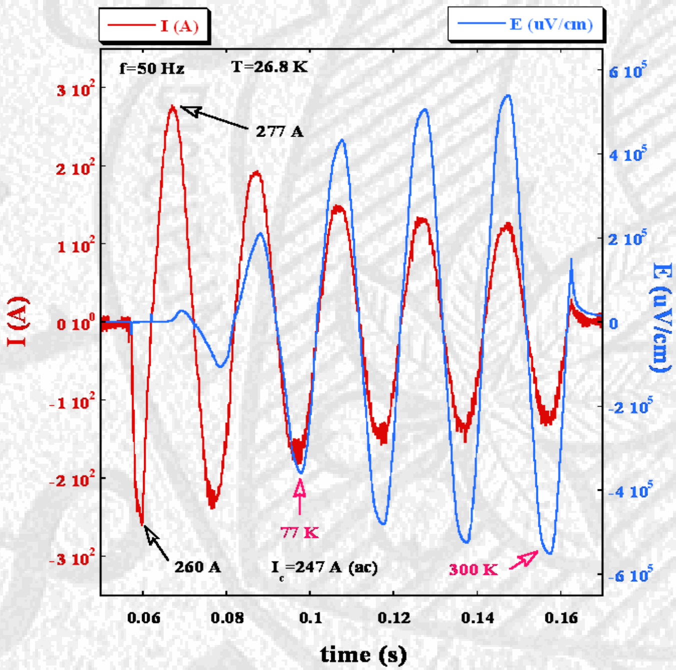
Rotor coil for NASA

MgB_2 small scale MRI model (left) and solenoid coil (right)

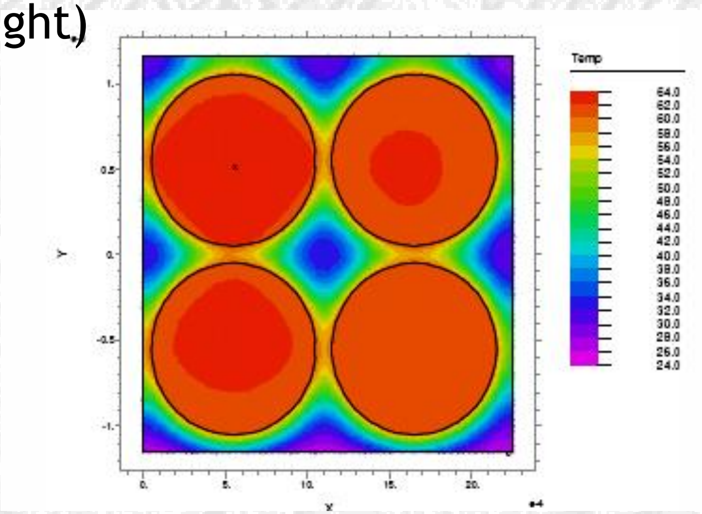
SuTC-Fault current limiters



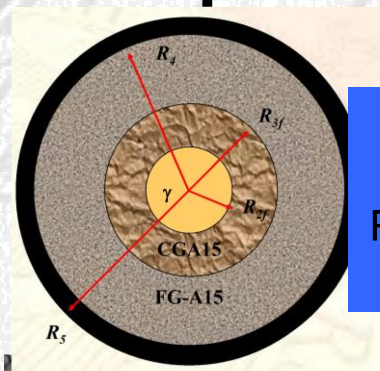
Right – cryocooler and element



Current limiting profile under increased voltage (left), temperature profile in cable (bottom) and cryostat assembly (right)

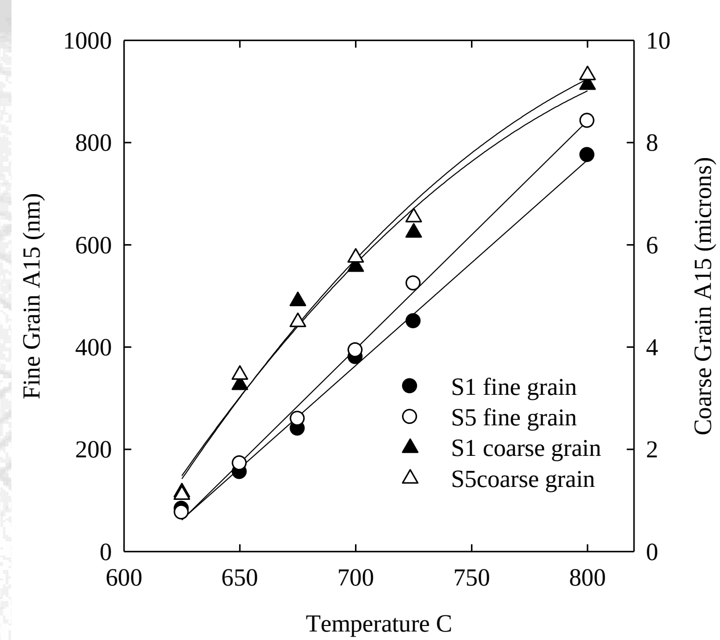


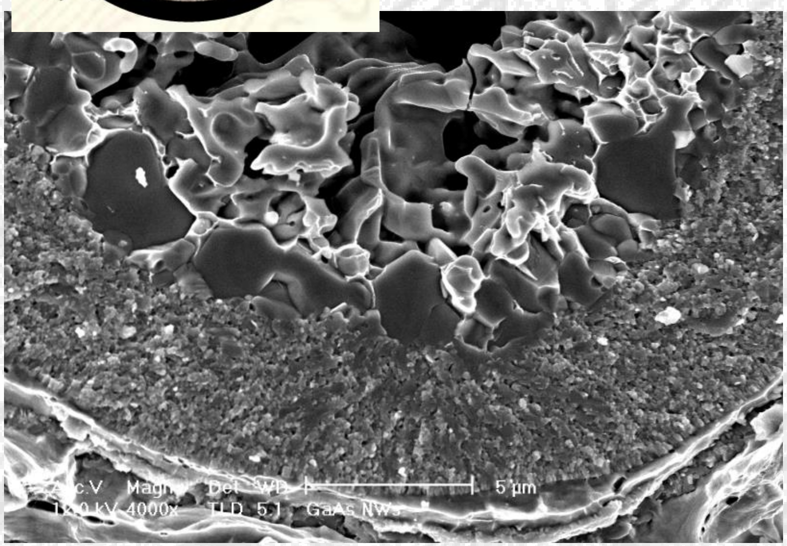
CSMM-Materials Development and optimization-Nb_3Sn

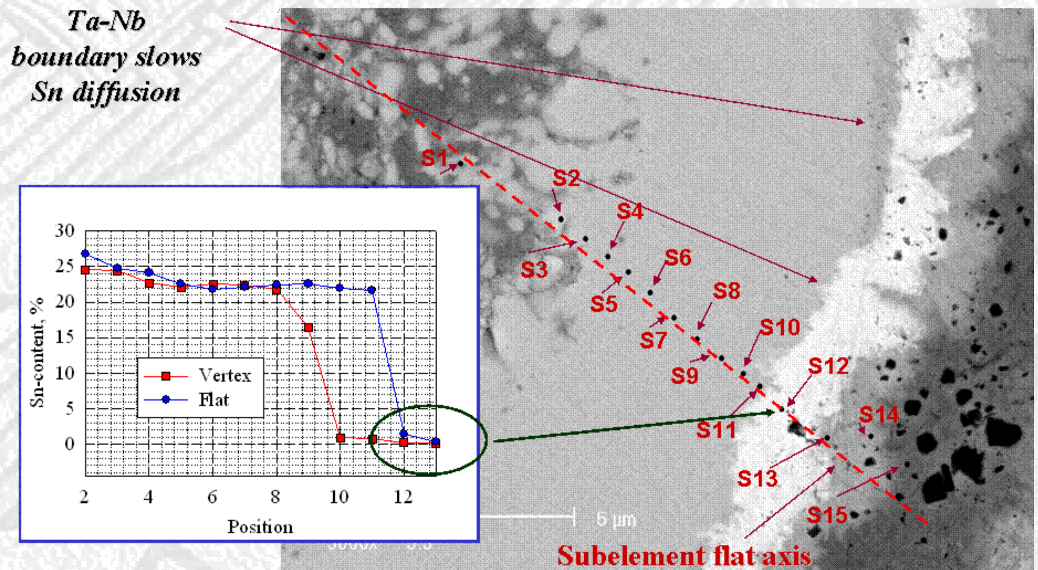


Tube-Nb-Sn Reaction model

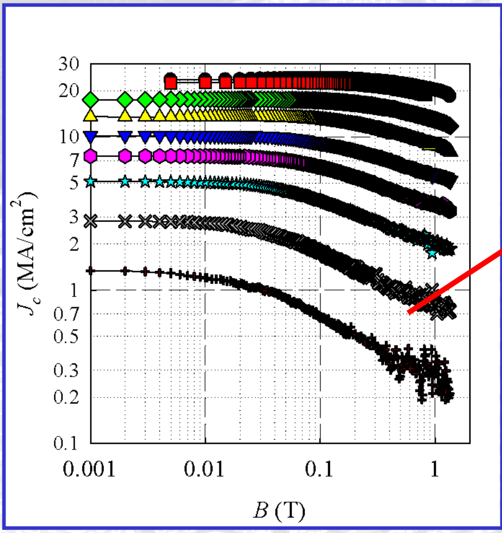
Grain size refinement, stoichiometry control

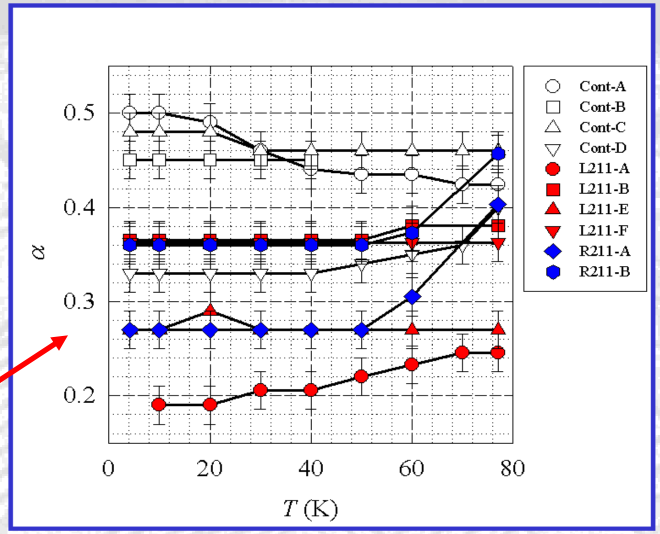


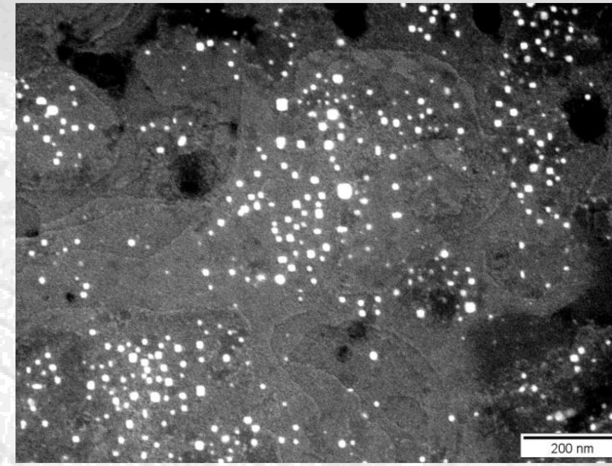




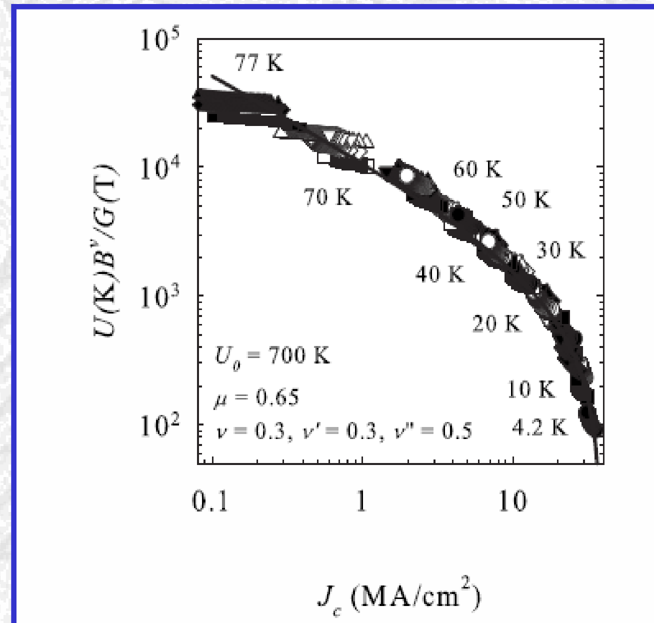
CSMM-YBCO

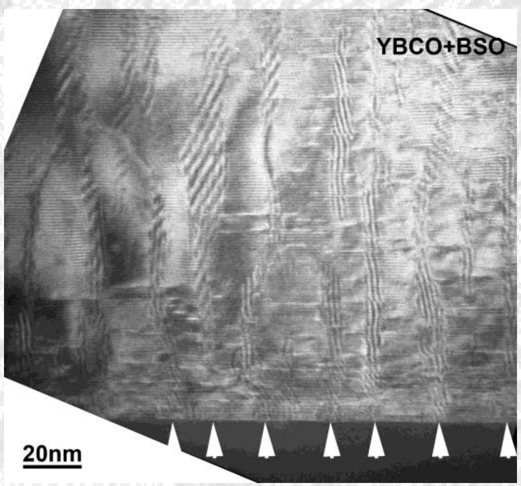






Random dispersions of 211



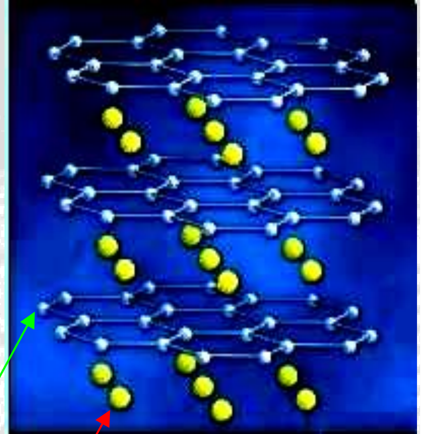


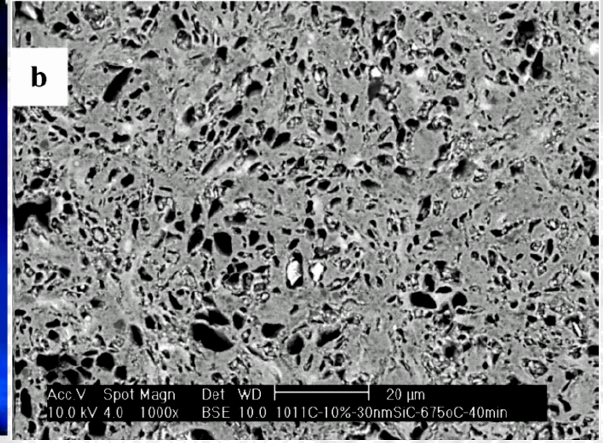
Columnar self-assembly of $BSnO_3$ precipitates (left) and patchy 211 layers (right)

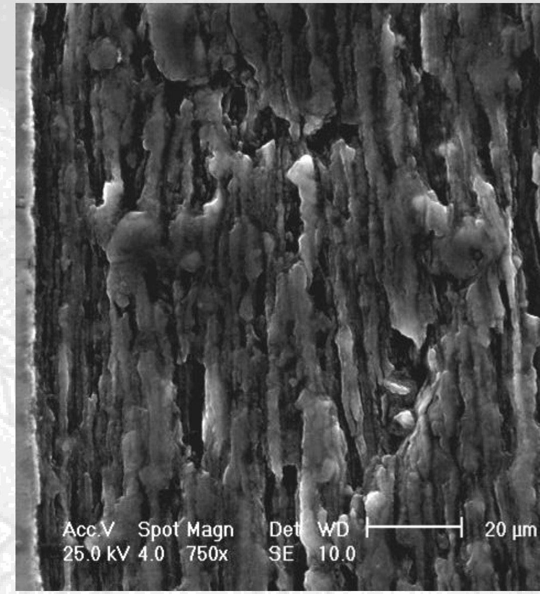
Sample	U_0, K	μ	ν	ν^* (10K)	ν^{**} (4K)	J_{c0}, MA/cm^2	C
			Ramp-rate derived data				
Cont-A	400±50	0.80±0.05	0.40±0.05	0.6±0.05	0.9±0.05	36±2	16±1
L211-A	600±50	0.60±0.05	0.10±0.05	0.10±0.05	--	43±2	16±1
R211-A	400±50	0.60±0.05	0.20±0.05	0.30±0.05	0.60±0.05	48±2	16±1
R211-B	500±50	0.75±0.05	0.40±0.05	0.60±0.05	0.80±0.05	40±2	16±1
			Magnetization decay data				
L211-A	700±50	0.65±0.05	0.30±0.05	0.30±0.05	0.50±0.05	39±2	16±1

MgB_2

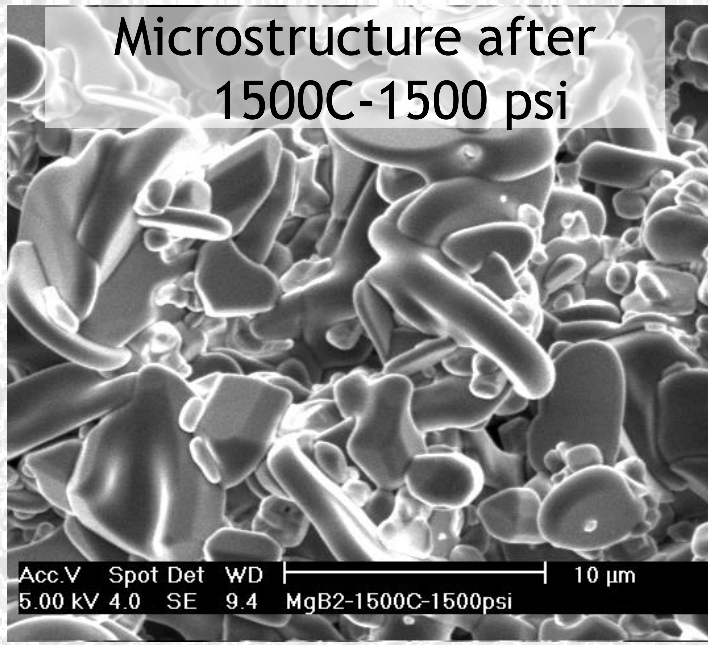
Doping in B or Mg site can substantially increase B_{c2} and B_{irr}

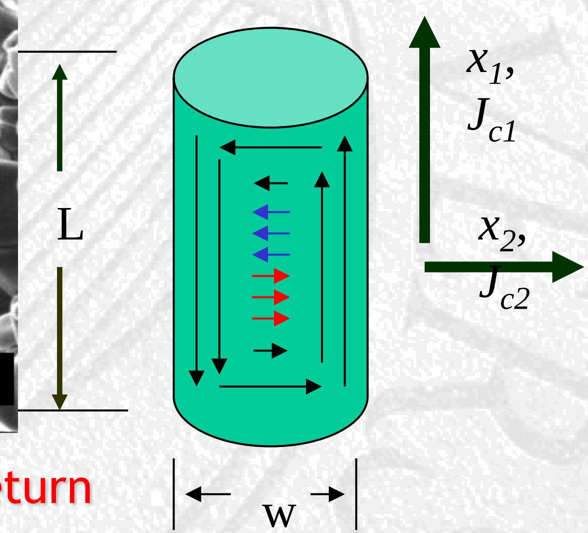






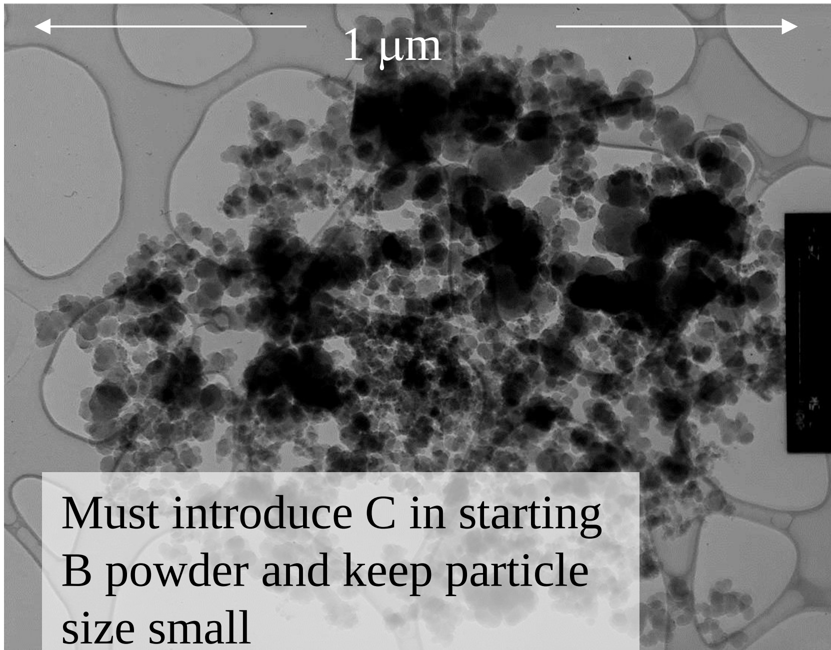
Sample Name	B_{irr}, T	B_{c2}, T
MB700	16.0	20.5
MBCSiC/700	~24.5	>33
MBCSiC/800	~25.5	>33
MBCSiC/900	~28.0	>33
MBC/700	~20.0	>33
MBC/700	~20.0	>33
MBacetone/800	~23.0	>33
MBZrB$_2$/700	24.0	28.6
MBNbB$_2$/700	20.5	25.5
MBNbB$_2$/800	18.5	22.8
MBNbB$_2$/900	18.0	21.6
MBTiB$_2$/700	19.0	22.5
MBTiB$_2$/800	18.0	22.6





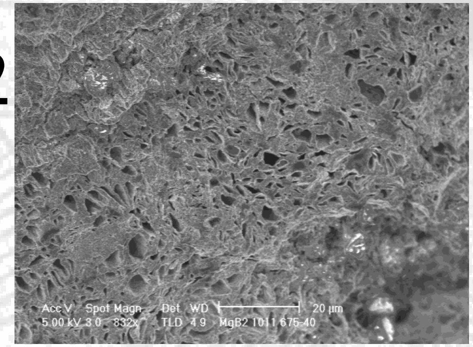
Different ways of probing B_{irr} return different apparent values because of the microstructure

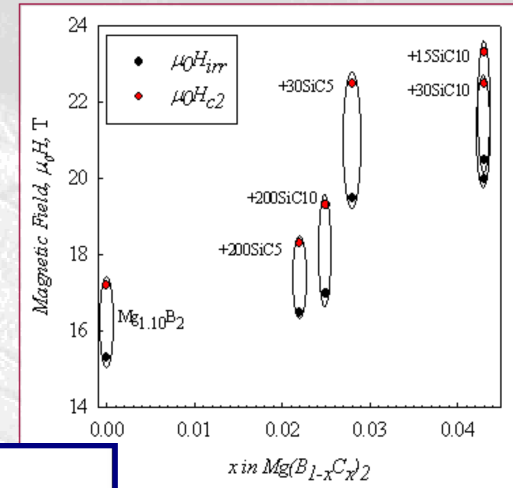
Challenges in MgB_2

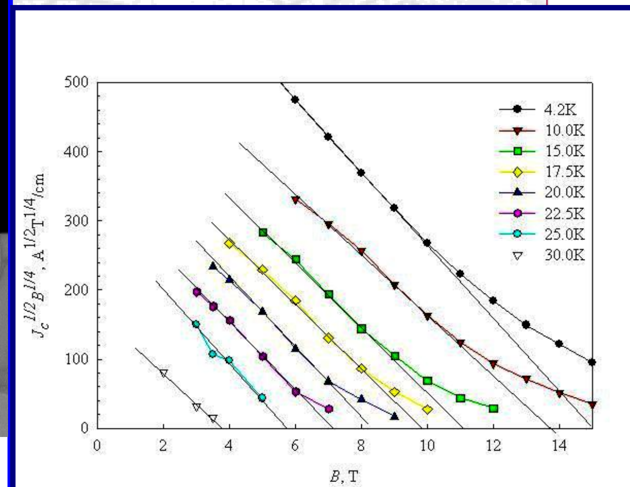


Must introduce C in starting B powder and keep particle size small

B, T







Present day MgB2

Homogenous C-doping

Connectivity improvement

Specimen Name	x-value in $Mg(B_{1-x}C_x)_2$	$k/10^4$, μΩcm-K	ρ_0, μΩcm	Connectivity Parameter, F	ResistiveDebye Temp. θ_R, K	Connectivity, $K^{\dagger}$, %
$Mg_{1.10}B_2$	--	8.38	3.9	7.79	902.7	**18.75**
+5SiC30	0.028	5.79	7.28	30.29	843.1	**4.82**
+10SiC30	0.043	4.41	9.77	18.40	753.1	**7.93**
+10SiC15	0.035	5.14	5.72	16.23	899.4	**9.00**
+5SiC200	0.022	6.35	6.68	27.04	858.5	**5.40**
+10SiC200	0.025	6.07	11.7	27.31	718.5	**5.35**

CSMM
Oxi-Pnictide

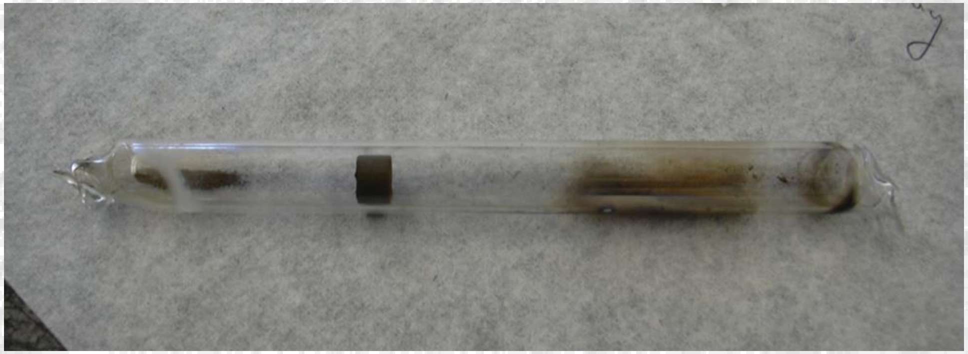
Now Developing new Oxypnictide bulk and wire materials and samples

$SmFeAsO_{1-x} F_x$

$T_c = 52$ K

$H_{c2}(0) > 120$ T

Dr. Maria Kanuchova – Institute of Experimental Physics (IEP), Slovak Academy of Sciences (SAV)



What are the Energy-Relevant Opportunities for Research in Superconductivity

In order to answer that, we must first ask: What are the Energy Applications of Superconductors?

Then, we can ask: What are the fundamental needs for development in superconducting materials?

Below remarks draw heavily from the BES workshop “Basic Research Needs for Superconductivity”, May 2006, available at http://www.sc.doe.gov/BES/reports/abstracts.html

What are the Energy Applications of Superconductors?

The answer to this question depends a great deal on performance and cost – but here is a common list

Power Transmission Cables

Transformers

Motors/Generators

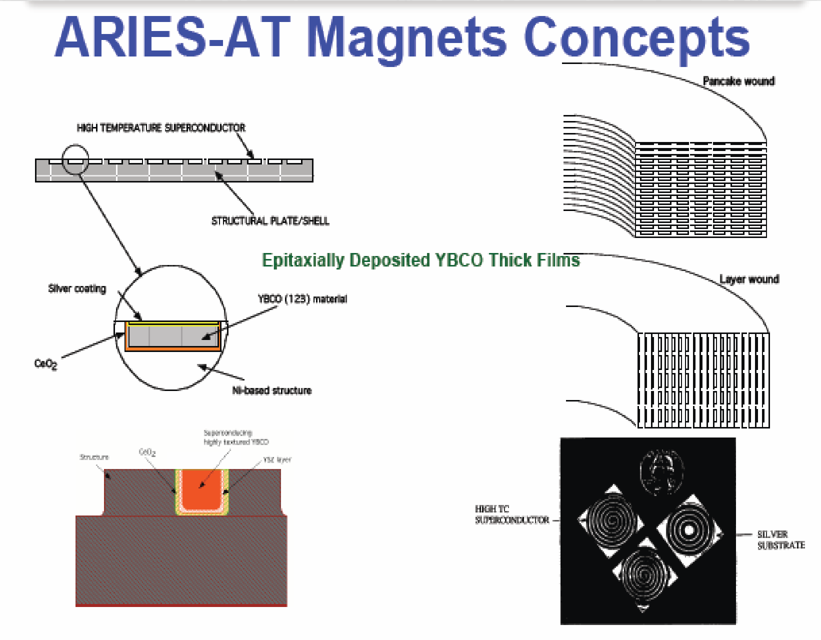
Fault Current Limiters

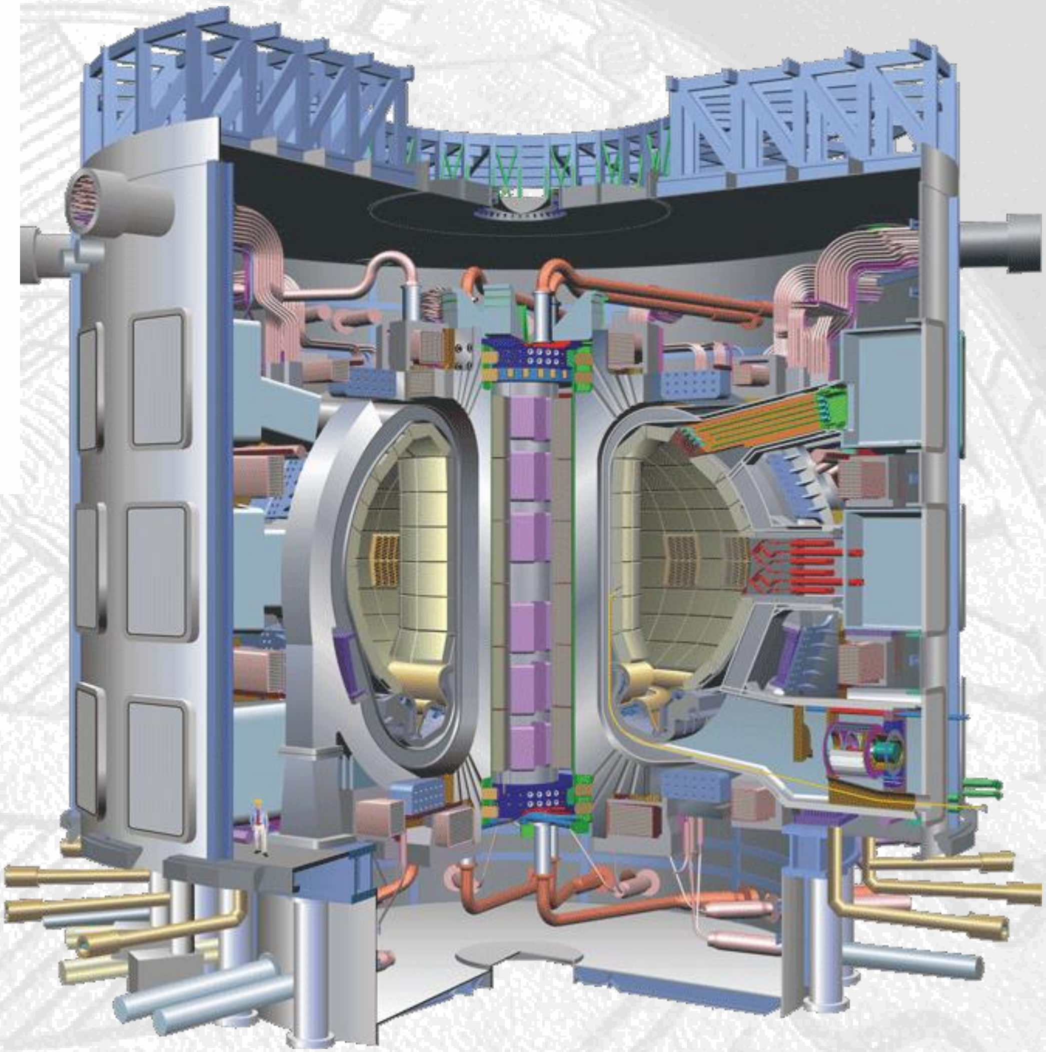
Fusion Reactors – both large scale and “mini”

Energy Storage (SMES)

Synergy with other aspects of Advanced/Alternative Energy (e.g., wind farms)?

Fusion Reactors



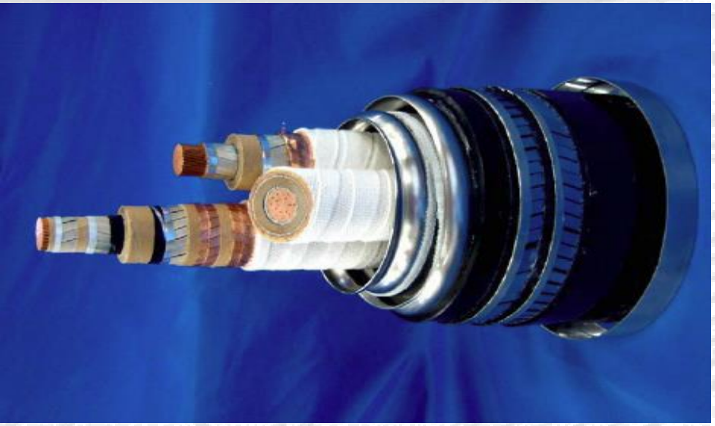


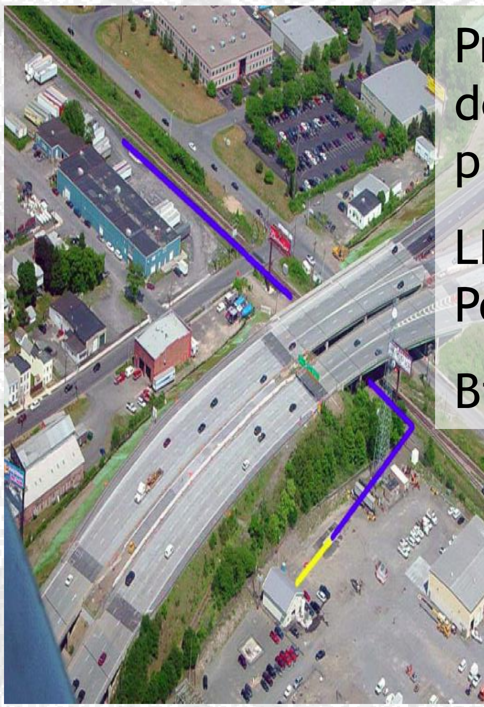
Present system ITER and follow-on DEMO, will use Nb_3Sn

Concept for ARIES is a compact fusion reactor using YBCO

--biggest limitation seems to be cost– enabling SC would be high current/high field/high Tc/low cost

Power Transmission and Distribution Cables





Presently three demonstration projects

LIPA (Long Island Power Authority)

Bixby (Columbus)

Present transmission/distribution relatively efficient – major benefit is power ***density***, especially in urban areas

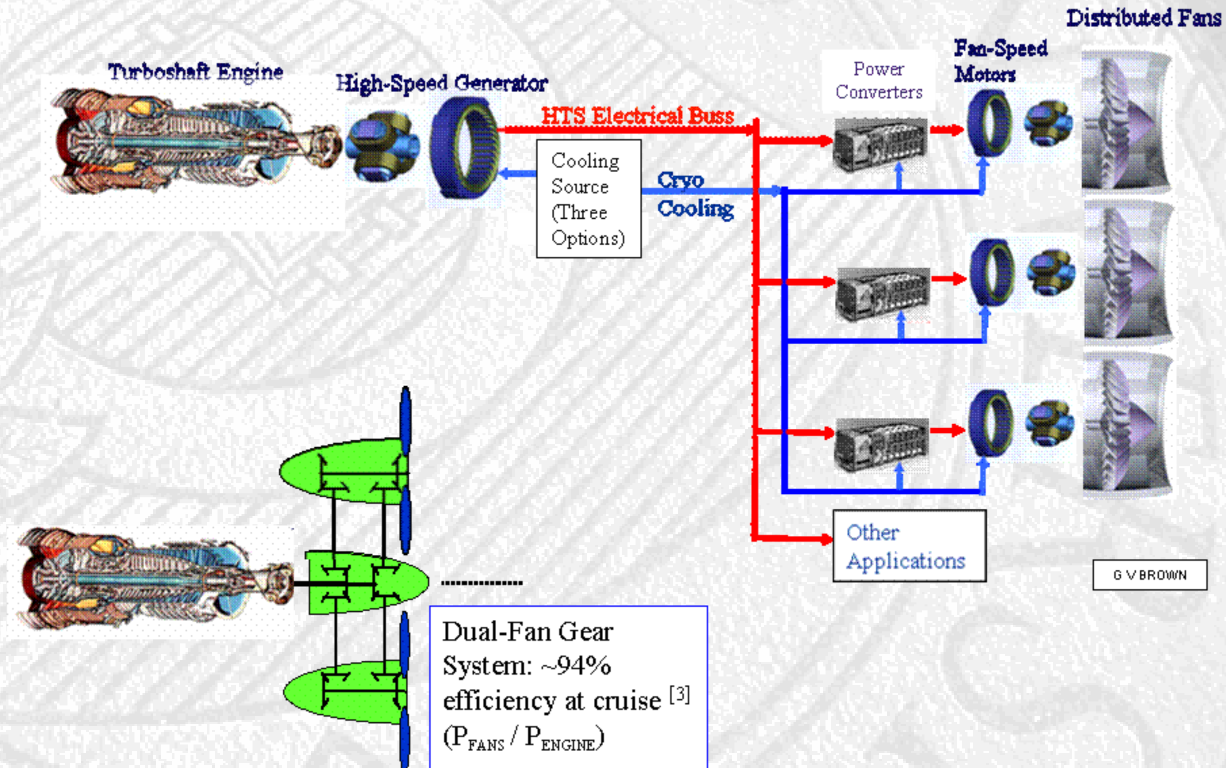
<u>YBCO only conductor under serious consideration – high performance and projected lower costs</u>

Motors/ Generators

While land based systems have been considered, motors/generators are typically quite efficient 97-99%, so the need is not for efficiency per se.

Where they can be helpful is in making higher power density systems – say for a new generation of all-electric turbo-electric aircraft

<u>MgB_2 – prefer round wire, new round wire SC also possible</u>



ORNL and WES developing XFRM; 138 kV rating, YBCO Conceptual design rework, HV cryogenic dielectric & ac loss testing, composite dewar development at ORNL

Transformers

YBCO has displaced BSSCO, new SC also possible

Transformer relatively efficient, reduced size/weight benefits

Energy Storage

Magnet Data

Power Discharge: 3 MW

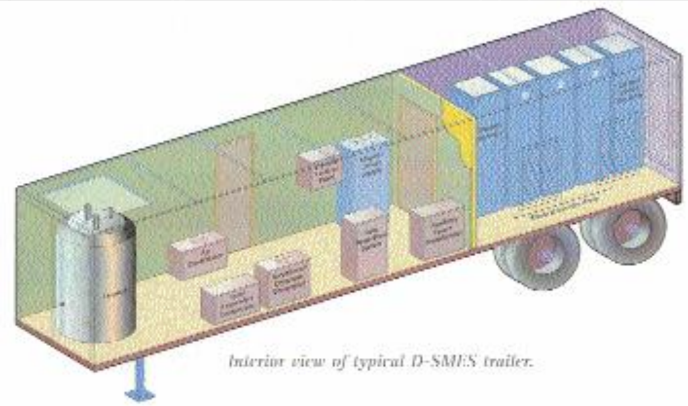
Energy Storage: 3 MJ

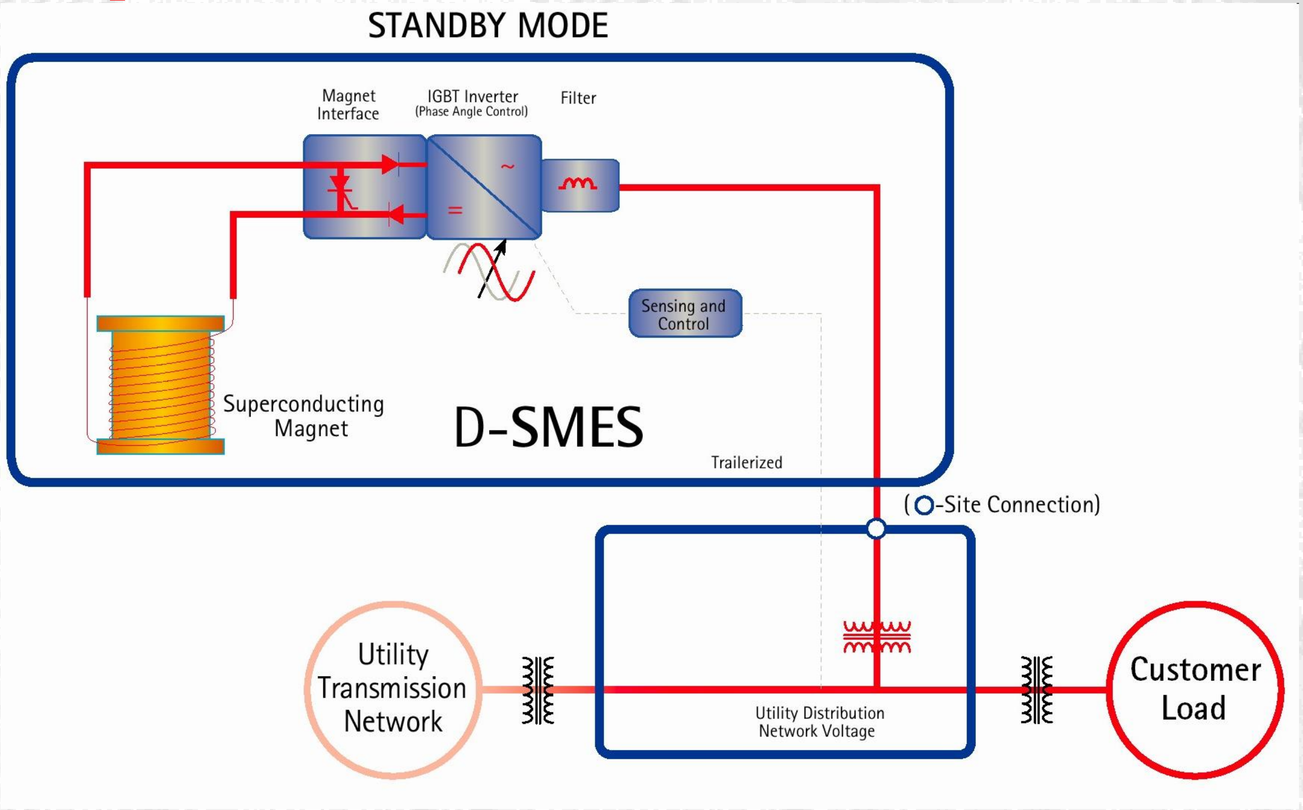
Recharge Time: <90 seconds

Typically used for industrial applications – AMSC pushing for utility applications

Presently use LTSC – but could transition to HTSC if costs lowered

Presently using NbTi – AC loss very important, also cost, T_c less so

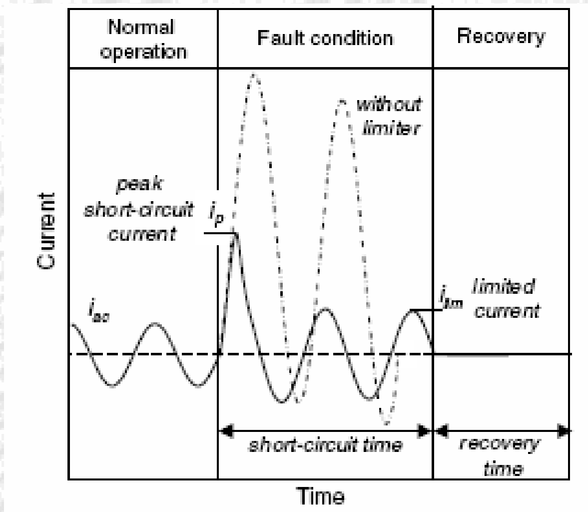

Interior view of typical D-SMES trailer.



Fault Current Limiters

Use – to limit damage during transients on the power transmission or distribution grid

Can reduce blackouts, reduce system downtime, reduce damage during fault



2.25 MVA; 7.2 kV

Various designs, including resistive, inductive, and hybrid

Use SC as a fast acting switch to limit current in less than a cycle until the breaker can trip – typically five cycles

Conductor of choice – YBCO or MgB_2 based on cost and *n*-value, also AC losses

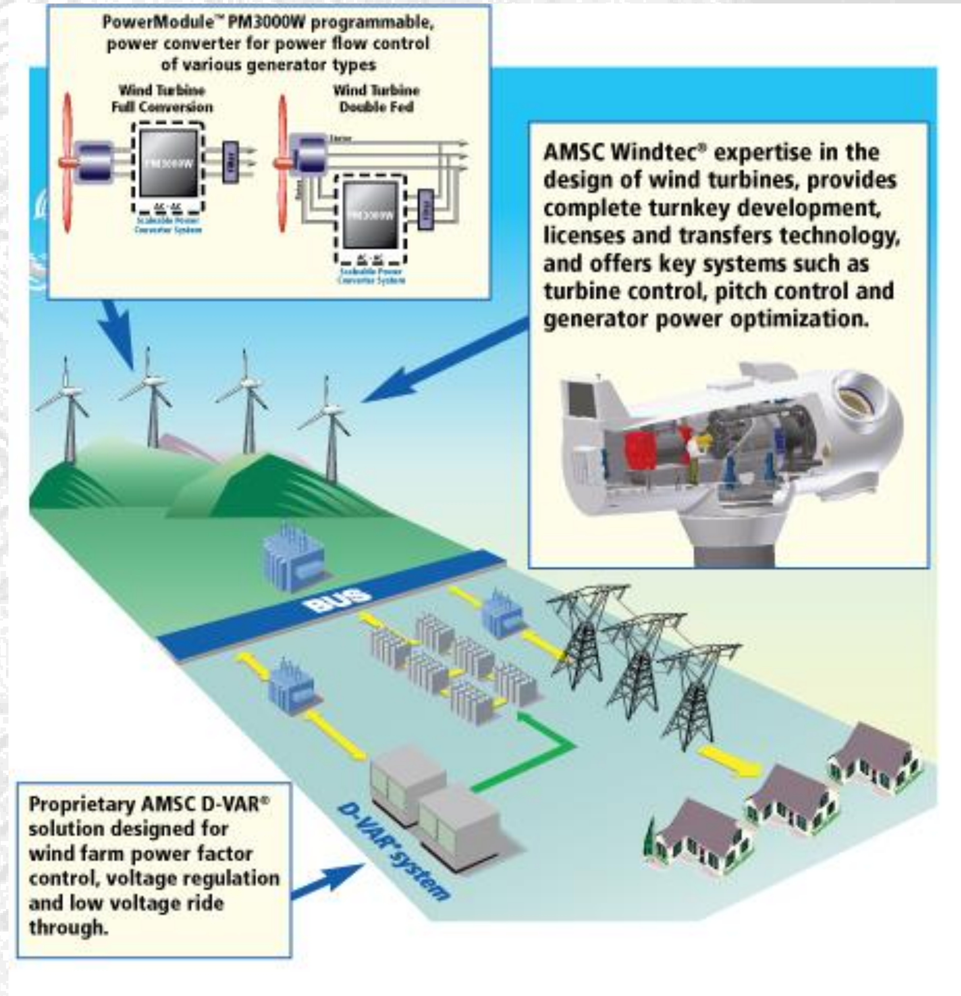
How does SC fit within Alternative Energy?

AMSC using SC to remove gearboxes at the top of windmills to reduce weight at the top of the pole

SC cables can collect and distribute power within a windfarm

SC transmission lines can be used to transport power from remote locations

FCLs can be used to reduce instabilities expected to result from the introduction of very distributed power generation, increasing connectivity



What are the Materials and Physics Issues for SC for Energy Applications?

T_c

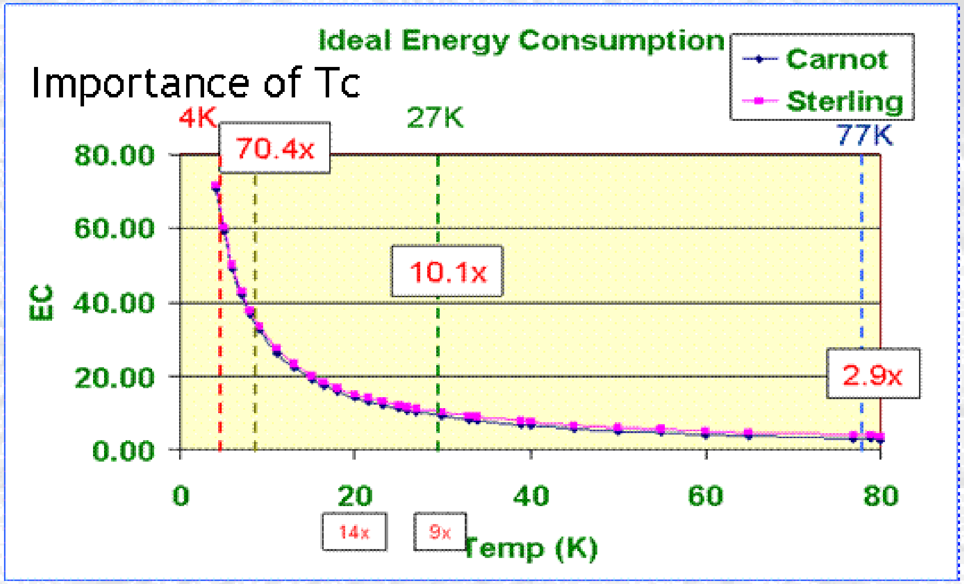
J_c (in field) 10^5 A/cm^2 min

Creep

Anisotropy

Weak links makes fabrication difficult and expensive

Cost



AC Loss -- Conductor geometry

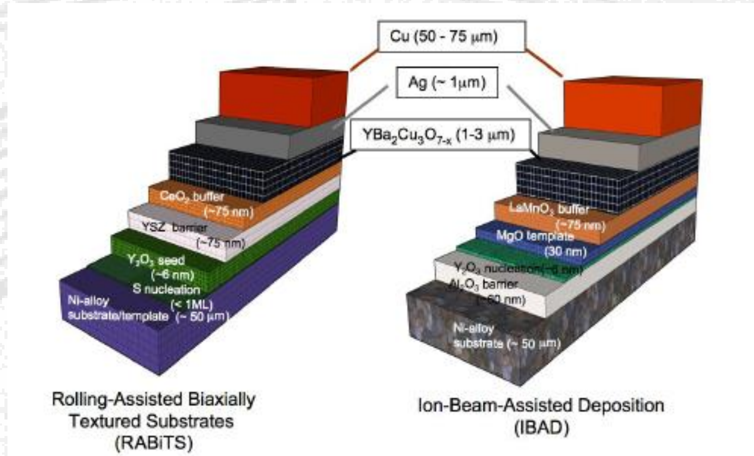
Compatibility

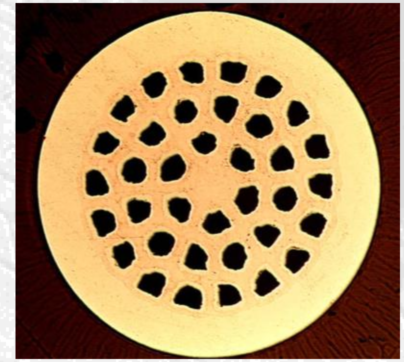
Presently Available Conductors

Bi2212 (HEP only) B2223 – too costly on basis of Ag alone – also γ ~ 200

YBCO – costs reduced?

$\gamma \sim 5\text{-}6$





MgB_2

MgB_2 – Low cost but low T -- specialty application in energy sector (FCL?)

"local" systems – no cryogen pumping

T_c=40 K, ξ~5 nm, γ ~6

Oxypnictides – similar to MgB_2 from a energy applications standpoint

Do we need a cheap room temperature superconductor?

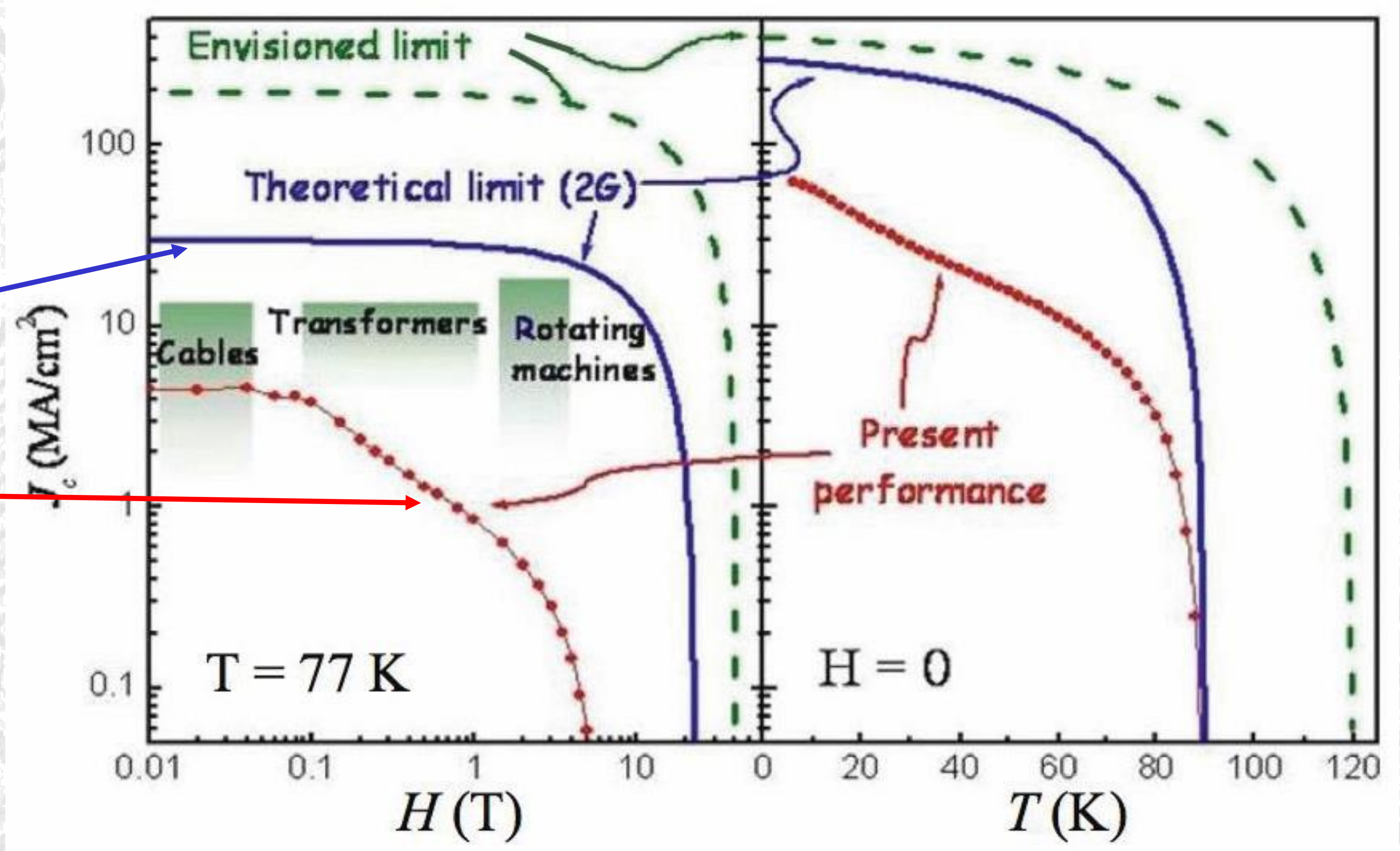
What exactly do we need – and what is worth pursuing for energy applications?

For the present HTS, the principal advantage over conventional devices is summarized as *smaller, lighter, and higher capacity* – *rather than* Energy savings per se.

YBCO performance and Machine Needs

De-pairing J_c, YBCO

Actual YBCO J_c



Dashed green line is de-pairing *Jc for* a hypothetical next-generation superconducting wire with *Tc* = 120 K

Opportunities in Existing Materials (Related to Energy)

Increase in pinning in YBCO

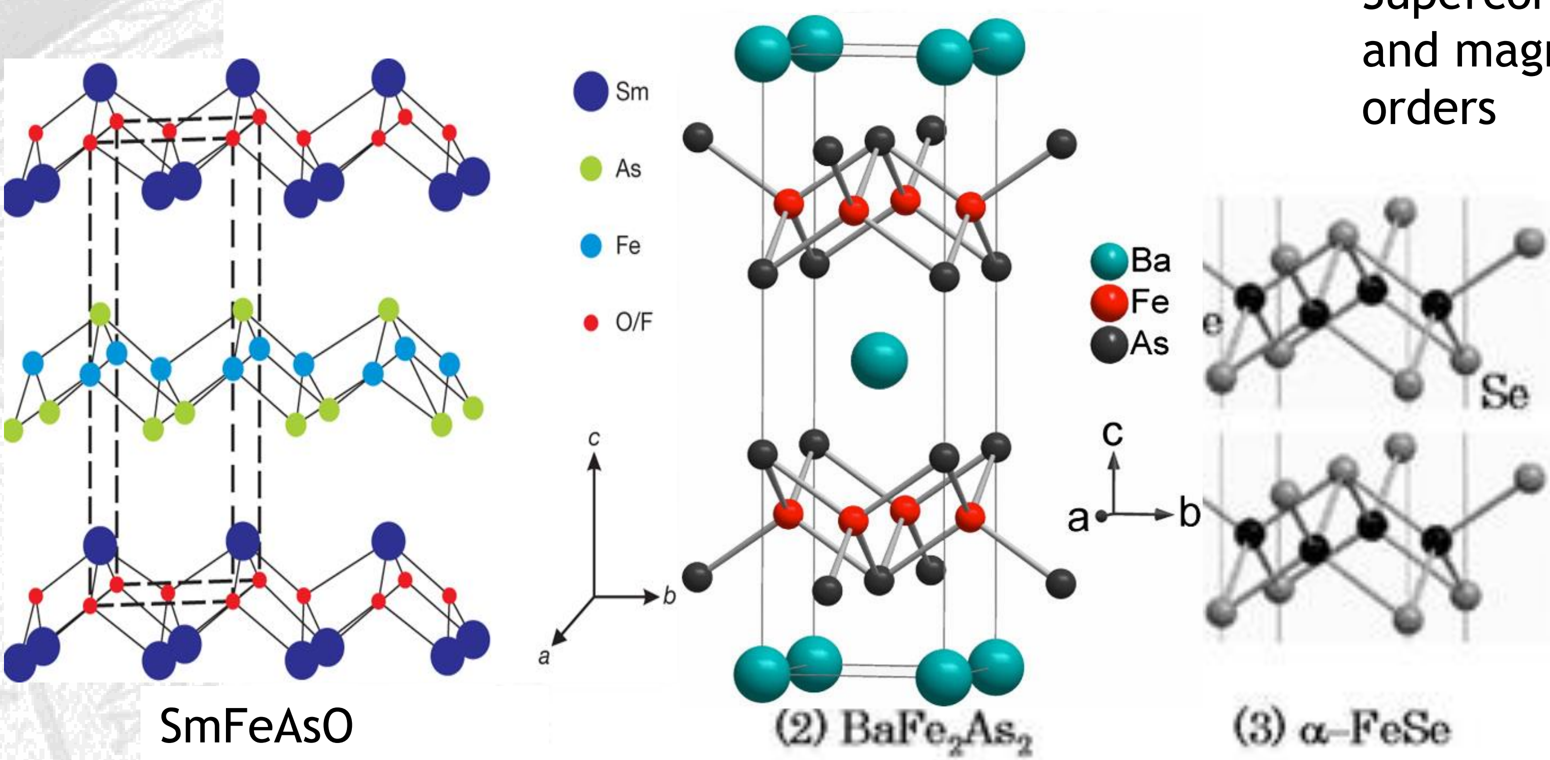
Decrease in cost of YBCO

Increase in connectivity/Homogeneity of MgB_2

But – What about new superconductors?

What about the new Oxipnictides?

Superconducting and magnetic orders



SmFeAsO

Class	REFeAsO: 1111	$AEFe_2As_2$: 122
T_c (up to):	55 K	38 K
	γ =5–10	γ =1-2
	G_i SmFeAsO ~ 10^{-2}	$G_i \sim 10^{-4}$

G_i $YBa_2Cu_3O_7 \sim 10^{-2}$

G_i $MgB_2 \sim 10^{-4}$

122: $Ba(Fe_{0.9}Co_{0.1})_2As_2$

Electron doped **LTS-Like**

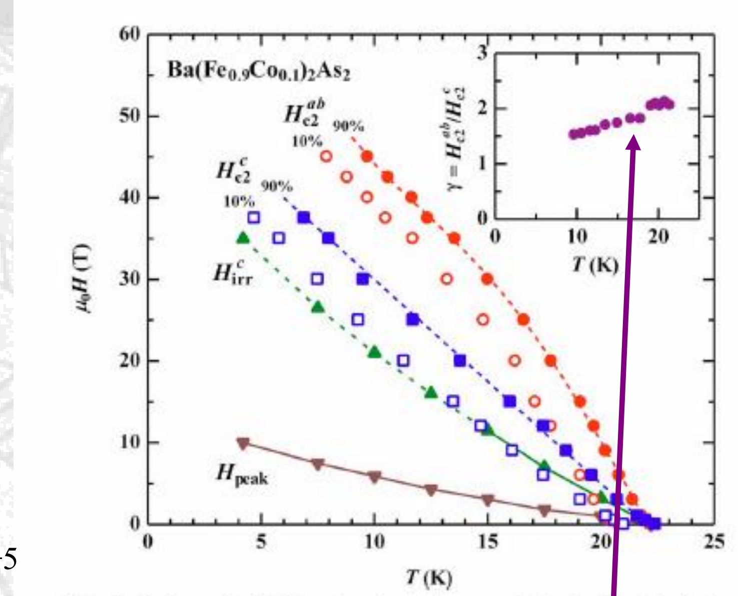
Yamamoto, J. Jaroszynski, C. Tarantini, et al., APPLIED PHYSICS LETTERS **94**, 062511 2009

Tc = 22 K

Reasonably high Jc in single crystals – suggests intrinsic pins

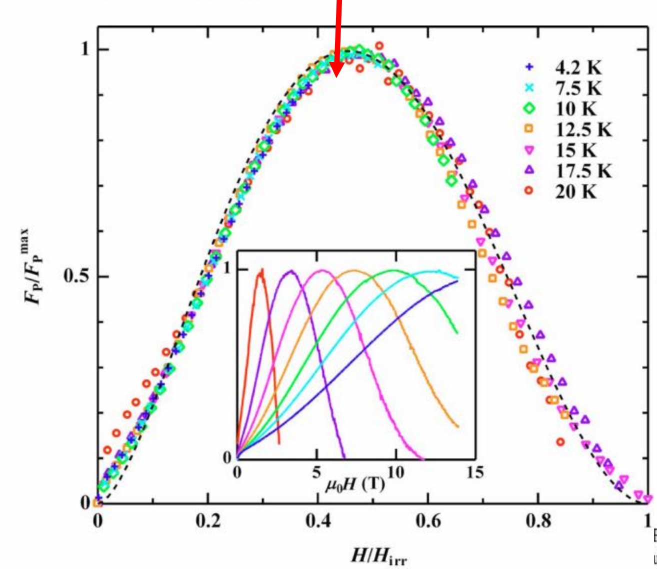
Lack of broadening with field

$G_i = 6.8 \times 10^{-5}$



062511-2 Yamamoto *et al.*

Appl. Phys. Lett. **94**, 062511 (2009)



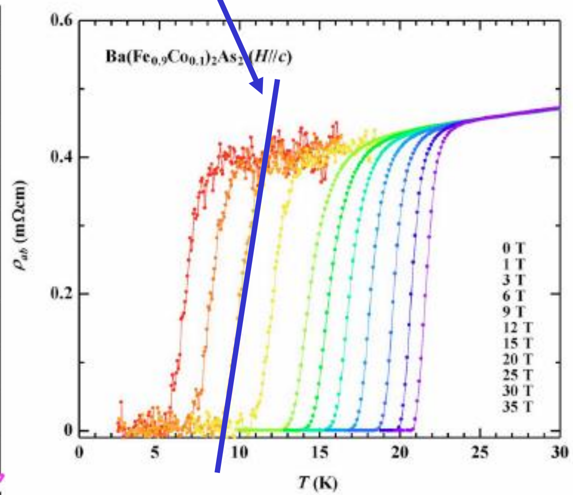


FIG. 4. (Color online) In-plane resistivity ρ_{ab} as a function of temperatures under magnetic field of $\mu_0 H$=0, 1, 3, 6, 9, 12, 15, 20, 25, 30, and 35 T. High field measurements above 15 T was performed using 45 T hybrid magnet.

Point pinning (Co disorder?)

Reasonably low anisotropy – suggests 3D behavior in spite of layered structure

ξ_{ab}=2.44 nm and

ξ_c =1.22 nm

Single crystals possible

Seem to lack weak links

Likely 2 band

1111: $SmFeAsO_{1-x}F_x$

T_c = 52 K
$H_{c2(0)}$ > 120 T
ξc=0.38 nm

J. Jaroszynski, Scott C. Riggs, F. Hunte, A. Gurevich, D. C. Larbalestier, and G. S. Boebinger et al., PHYSICAL REVIEW B **78**, 064511 2008

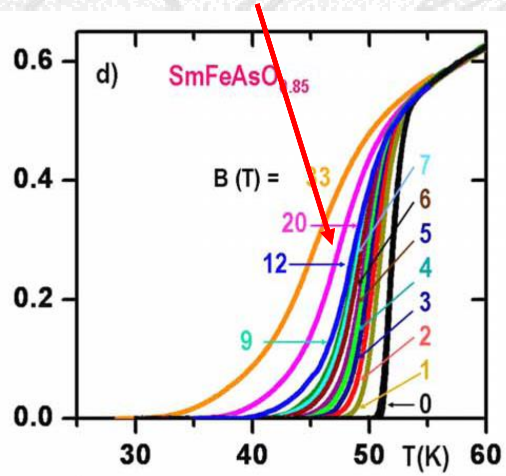
YBCO-Like

Single crystals difficult and small

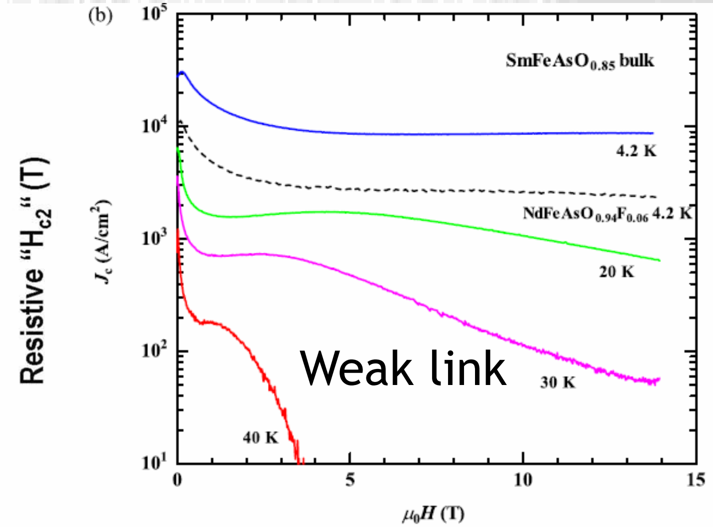
weak links present

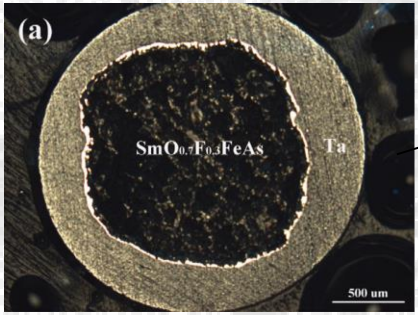
Likely 2 band

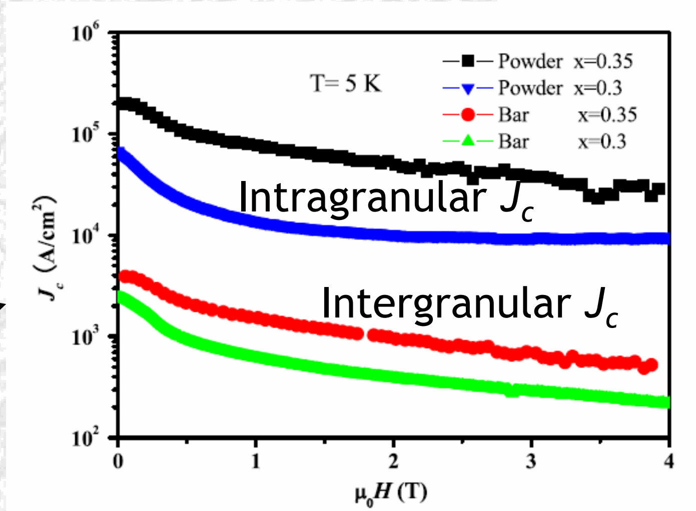
Significant broadening with field

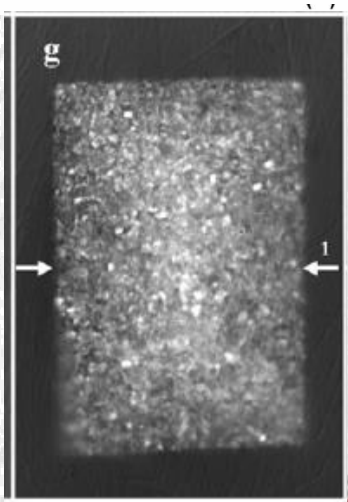


A Yamamoto1, A A Polyanskii1, J Jiang1, et al. Supercond. Sci. Technol. **21** (2008) 095008 (11pp)









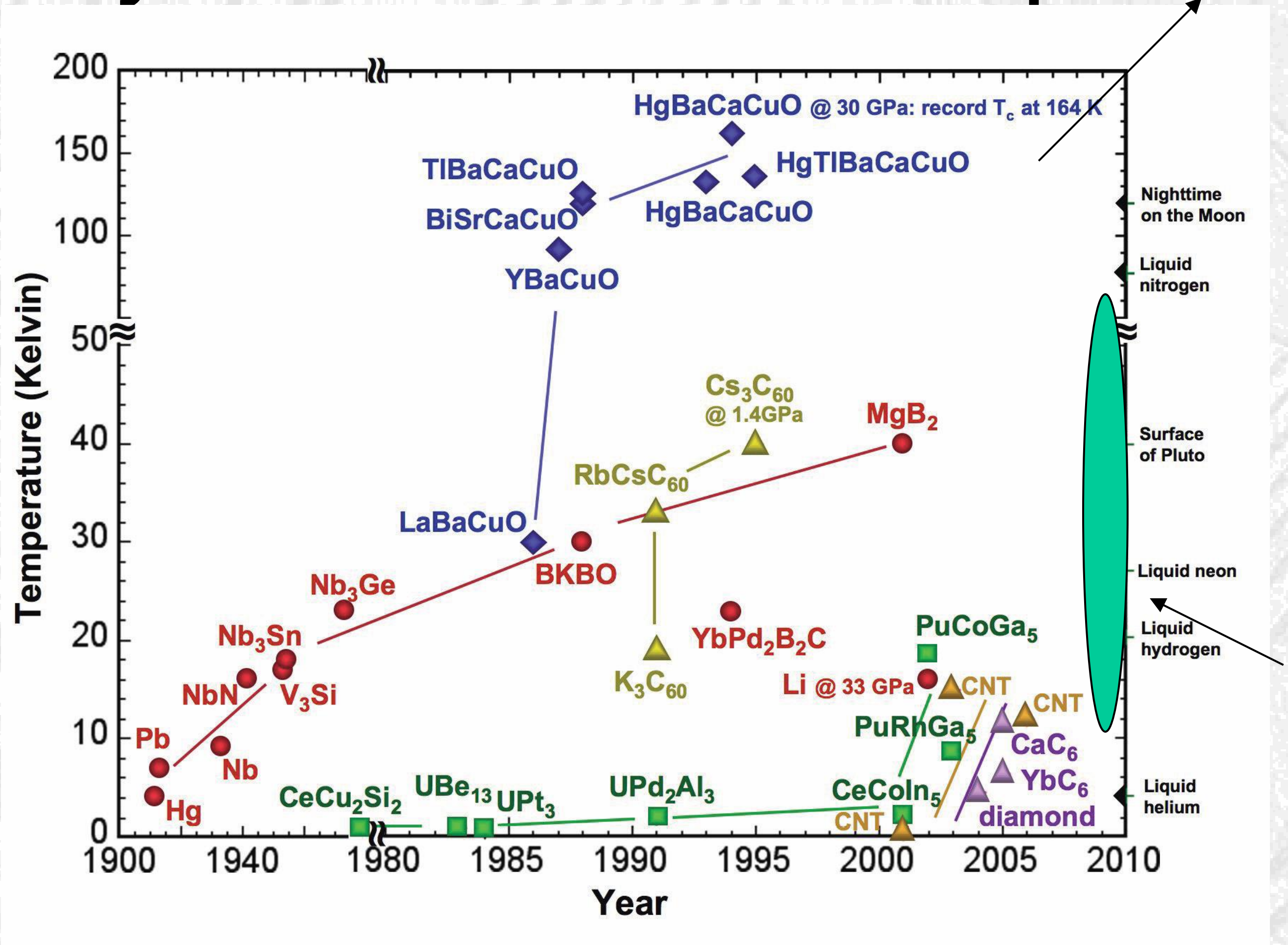
Oxi-pnictides?

<u>1111:</u> T_cs of 50+ are interesting, but YBCO-like properties (weak link/anisotropy) must be suppressed if this is to be useful. Unlikely to beat out MgB_2 (low cost, no weak links) for energy applications

<u>122:</u> Could prove very interesting at low temperatures for high field applications – not likely for energy applications

But – higher temperature, not too anisotropic variants could be very interesting.

What about new SC and higher T_c – maybe even room temperature SC?



What about up here?

oxipnictides

A Wish List for a *Transformational* SC

- T_c ~ 400 K (to operate at RT)
- $J_c > 10^7 A/cm^2$ (OK so we would live with 10^6
- Chemical Stability
- 3D and isotropic
- Lack of second phases
- Large superfluid density (see item 2)

- No WEAK links
- Capable of Round Wire or Tape
- Even better
- Ductile (unlikely)

Adapted from Jochen Mannhart, Road to Room T SC

What about "Room Temperature" Superconductors?

What do we actually want?

A higher Tc means a decreased coherence length   M. Beasley

$$\xi = hv_F / kT_{c0} \propto \frac{v_F}{T_{c0}}$$

But this can lead to weak link effects (i.e., grain boundary problems – or other defects usually to small to be a problem)

Decreasing coherence length increases Bc2

$$H_{c2}(0) = \frac{\phi_0}{2\pi\xi^2} \propto \frac{T_c^2}{E_F}$$

$$J_d = \frac{c\phi_0}{12\sqrt{3}\pi^2\lambda^2\xi}\left(1 - \frac{T}{T_c}\right)^{3/2}$$

A. Gurevich

$T = 300K$, $T_c = 350$ K,

$J_d(300) = 40$ MA/cm^2

for the parameters of YBCO

$$J_c^{GL} \propto \frac{nT_{c0}}{v_F}$$

We must have a high density of carriers too

Intrinsic phase separation

As the size of the Cooper pair $\xi \sim \hbar v_F / 2\pi k_B T_c$ drops below 2-3 nm, any "typical" lattice defects locally suppress $\Delta(r)$

If ξ becomes too small SC may become too "spotty" to be useful

Limitations due to vortex lattice melting and fluctuations made worse by anisotropy

Weak pinning: J_c = 0 in the vortex liquid phase $B > B_m$

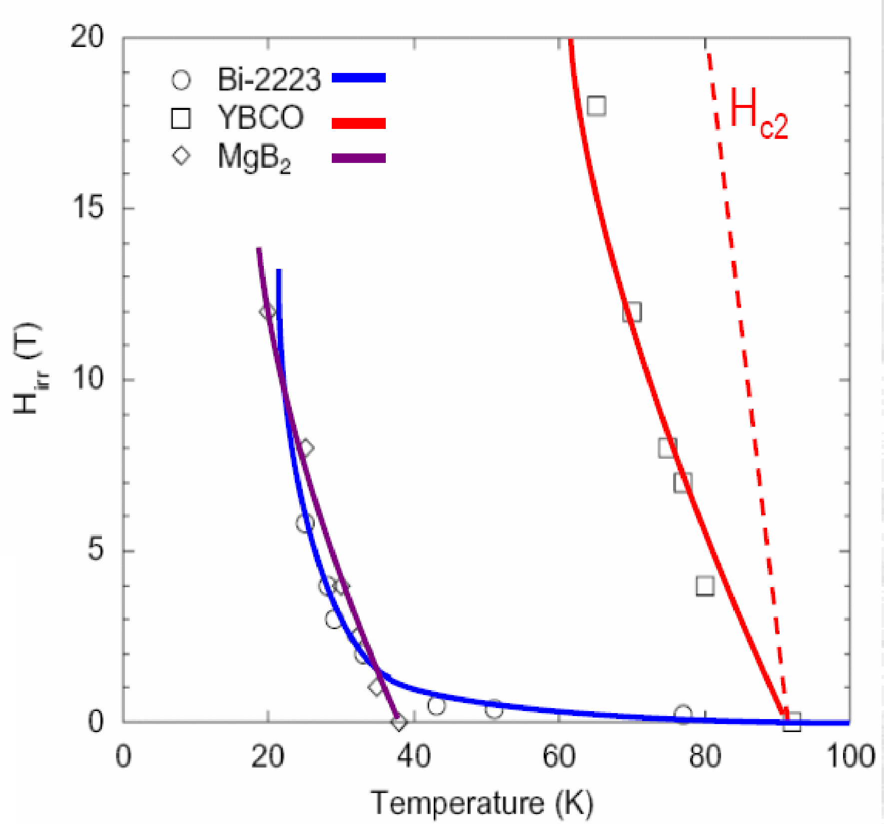
$$B_m \propto \frac{2\pi\, c_L{}^4 \Phi_0^4 \xi_{ab}^2}{(kT)^2 \lambda_{ab}^4 \gamma^2} B_{c2}$$

Also, must avoid large thermal fluctuation effects

Thermal Depinning

$J_c(T)$ rapidly drops above the depinning temperature

$$T^* \cong \frac{T_c}{1+\gamma}, \qquad \gamma \cong \frac{\Gamma T_c}{r_0 \varepsilon_0}$$



Anisotropic RT SC less useful than lower Tc but isotropic SC

So ..

- A viable RTS would be nice, but a **well behaved, isotropic superconductor with Tc > 95 K -150 K would be immensely useful**

Materials Based Limitations

- SC materials should have good connectivity (no increase in density with reaction)
- Competing orders (YBCO) or tendency to form non-SC tramp phases (Bi2223 & 2212) undesirable
- No obvious drawback (poisinous, radioactive)
- NO WEAK LINK (i.e., round wire OR flat tape)
- Easy to make and inexpensive

Recent and Existing Programs

DOE ERFC (New Superconductors or New Materials/Physics)

Brookhaven National, Laboratory, Center for Emergent, Superconductivity, Davis, J.C. Seamus By understanding the fundamental physics of superconductivity, discover new high-temperature superconductors and improve the performance of known superconductors.

Various Stimulus based programs (ARPA-E)

Other Advanced Energy

Conclusion

For Energy Applications of Superconductors

National Lab/Industry

Demonstration Projects, Device Engineering

At the University/National Lab

Improvements in existing conductors YBCO (pinning, Cost, AC Loss) and MgB_2 (Connectivity, Homogeneity)

New Conductors: Need isotropic, T_c = 100 K +, no weak links, inexpensive