Materials Issues for Magnets

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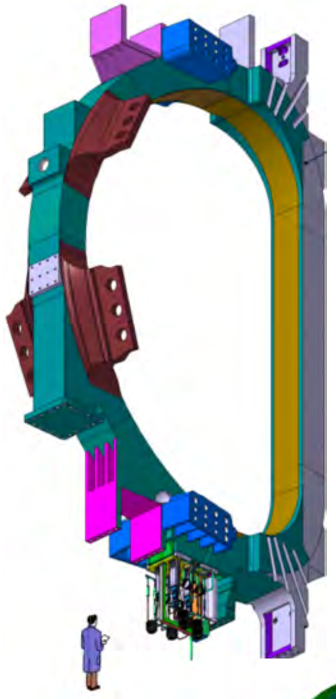
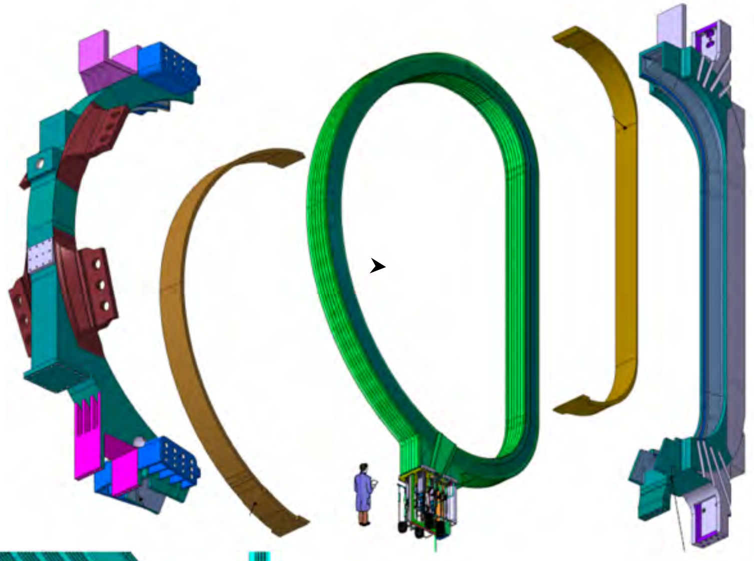
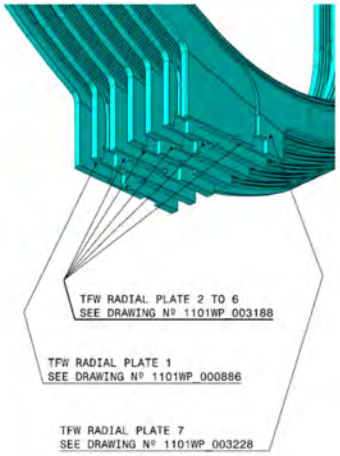
Outline

- Magnet components
- Radiation effects
- Advanced conductors

Magnet Components

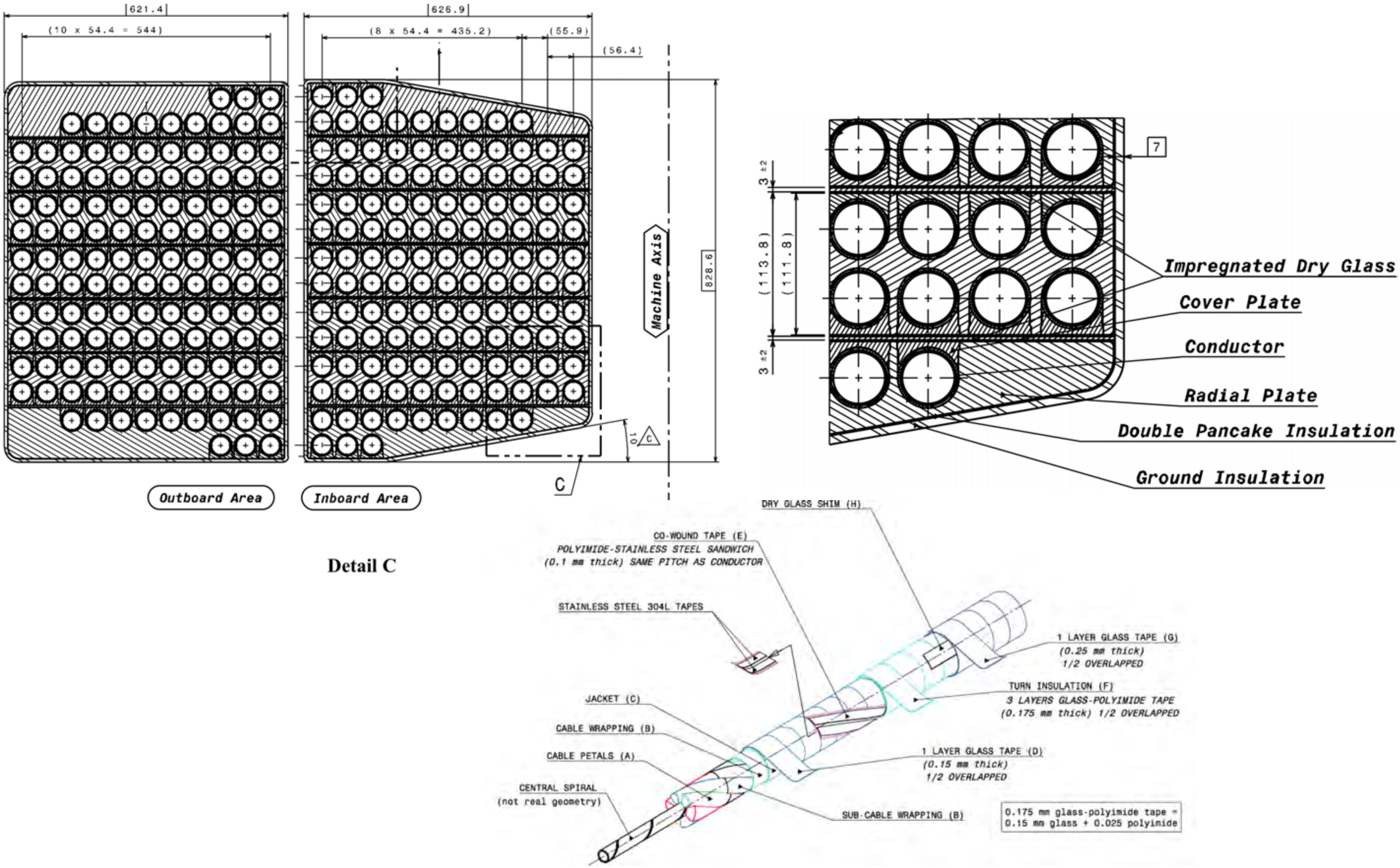




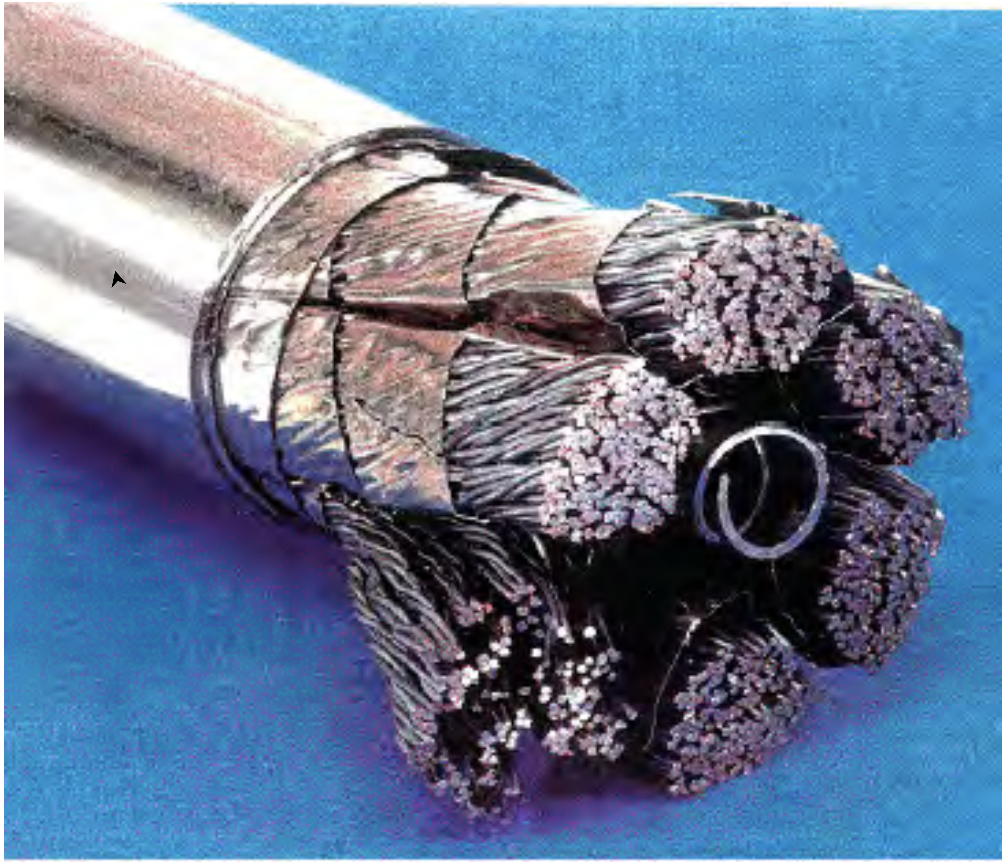


Dominated by SS Structure

Magnet Components

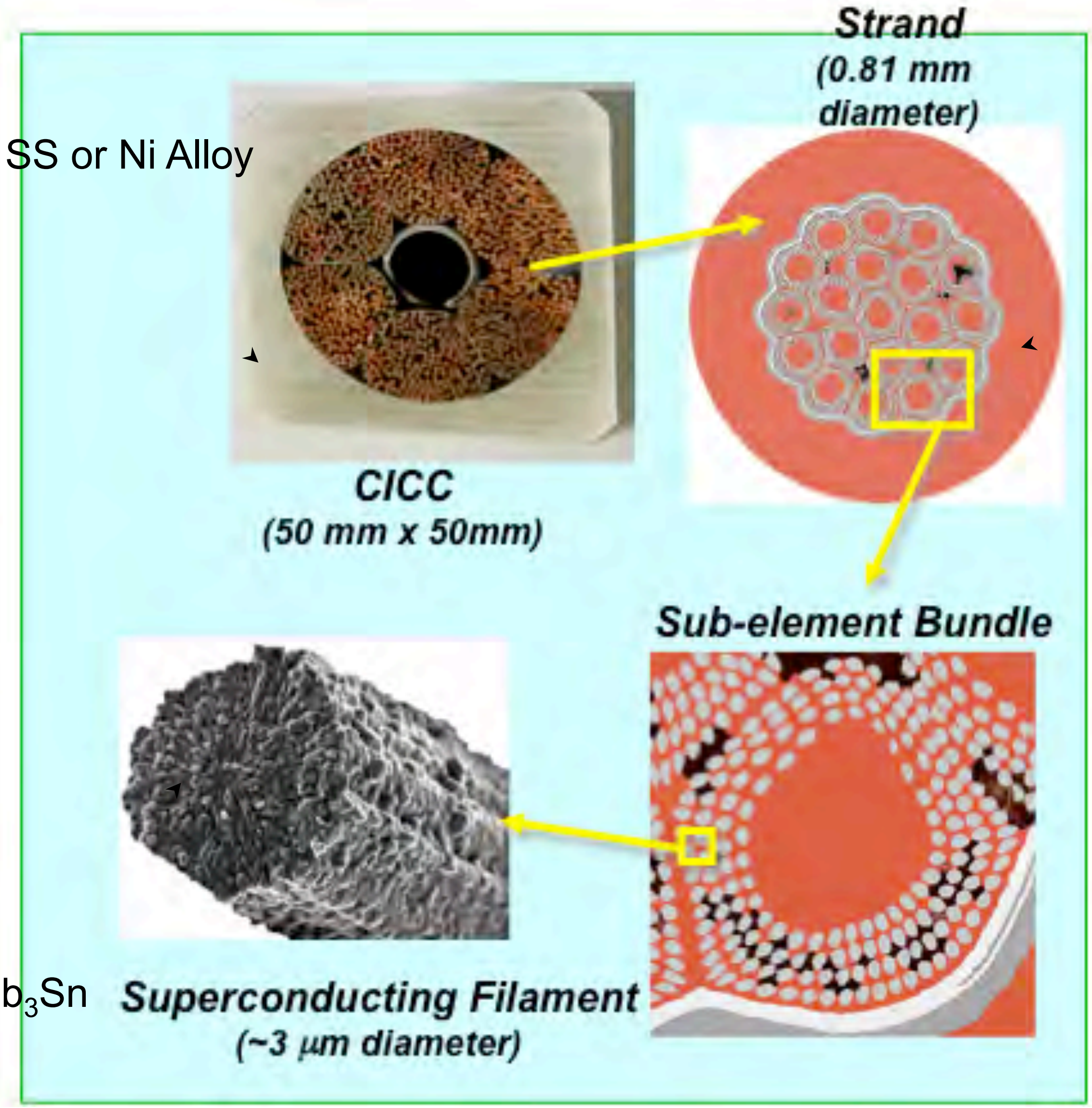


Conductor Components



Superconductor and Copper Cable

316 LN SS or Ni alloy jacket (conduit)



Jacket: SS or Ni Alloy

High RRR Copper

Nb_3Sn

Radiation Effects on Conductors

- Superconductor Material
- Copper Stabilizer Material
- Insulation Materials

Acknowledgements:

Newer data including for HTS materials from:

H.W. WEBER, TU Wien, Atomic Institute of the Austrian Universities, Vienna, Austria and colleagues.

Superconductor Materials

Low Temperature Superconductors (LTS)

- NbTi alloy typically for PF coils
- A15 Compounds: e.g. Nb_3Sn for TF Coils
  - With or without alloying (Ti or Ta additions)
  - (Nb_3Al and Nb_3Ge considered but not commercially **developed)**

High Temperature Superconductors (HTS)

- BSCCO compounds – considered not suitable for large scale fusion applications
- Rare Earth (ReBCO) Compounds: e.g. YBCO, GdBCO

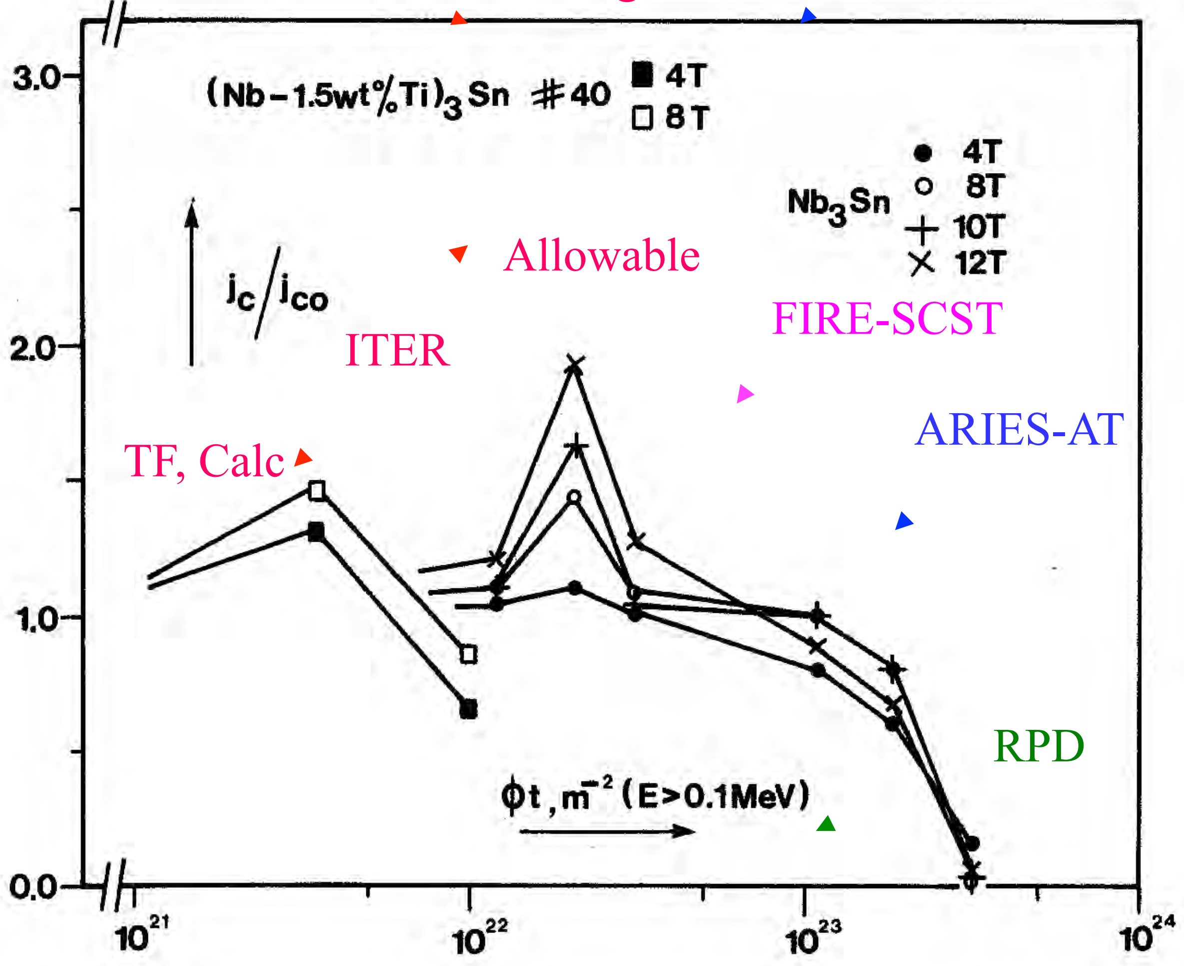
Superconductor Materials – LTS Nb_3Sn

- Significant (and later on drastic) effects on $\mathbf{T_c}$
  - caused by disorder

- Significant enhancements of $\mathbf{J_c}$ (followed by a precipitous drop)
  - increase caused by an increase of H_{c2} - mean-free-path-effect
  - drop caused by the T_c degradation

- Results typical for materials with *a high degree of order*

Reactor Fluence Levels vs. Nb_3Sn J_c/J_{co}



10^9 Rad, insulation limits design

$>10^{10}$ Rad, sc limits design

Allowable

ITER

TF, Calc

FIRE-SCST

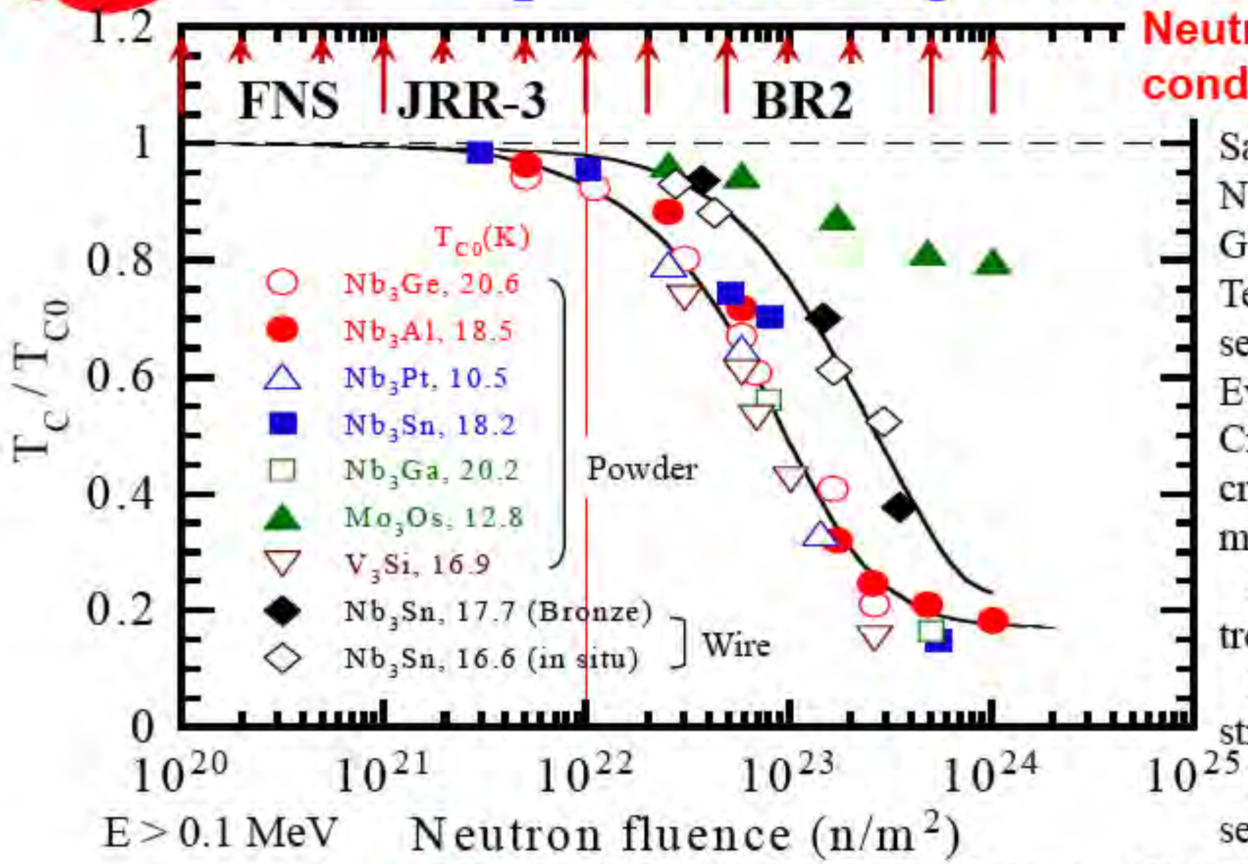
ARIES-AT

RPD

ITER – advanced Nb_3Sn should be within allowable

FIRE, ARIES-AT, RPD don't use Nb_3Sn – good thing

Critical Temperature of A15 Superconducting Materials



Neutron fluence: 13 conditions

Samples: Nb_3Sn, Nb_3Al, (NbTi), YBCO. GFRP, Cyanate ester. Temperature, Hall sensors.

Evaluated properties: Critical temperature, critical current, critical magnetic field.

Isochronal heat-treatment

Interlaminar shear strength

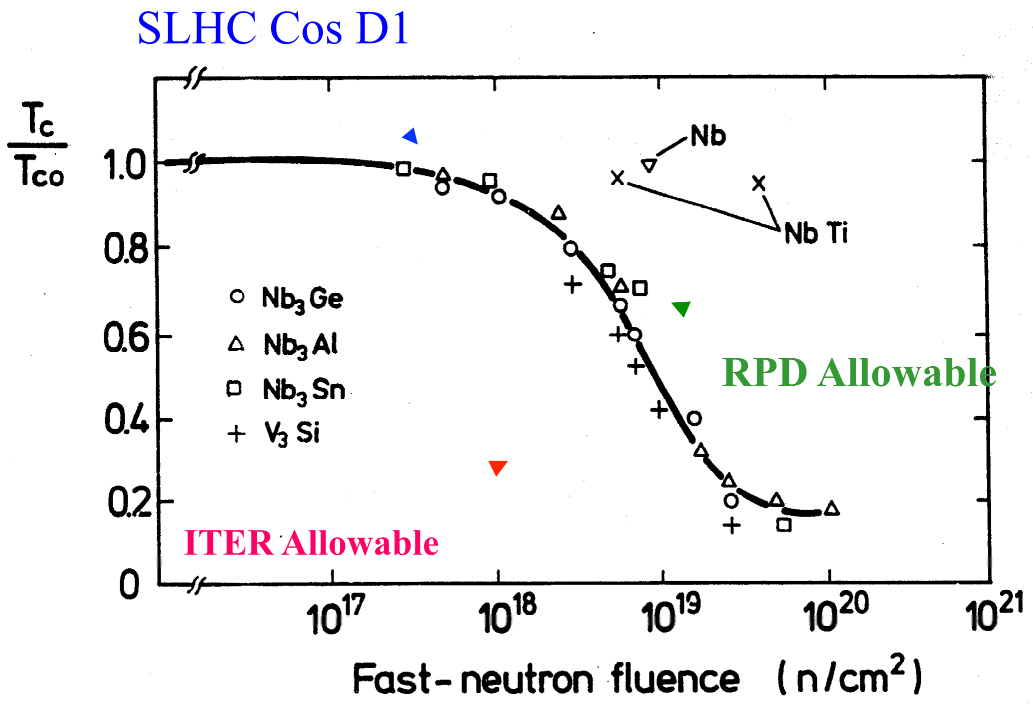
Performance of sensors

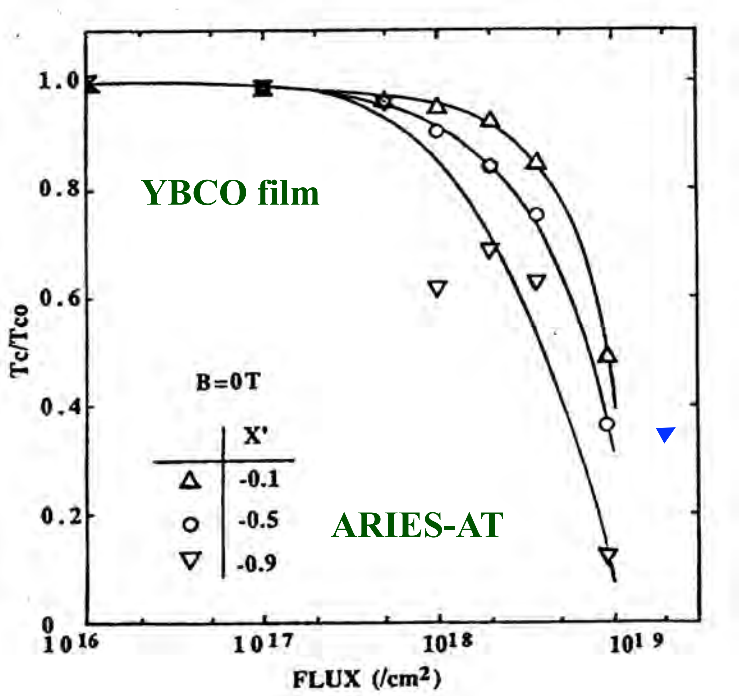
Powder: Brookhaven High Flux Beam Reactor. ~150 degree C.
A. R. Sweedler et. al., J. of Nuclear Materials 72 (1978) pp.50-69

Wire: Kyoto University Research Reactor. ~80 degree C.
T. Kuroda, et. al., J. of Atomic Energy Society Japan 37, pp.652-659 (1995)

Nishimura, NIFS

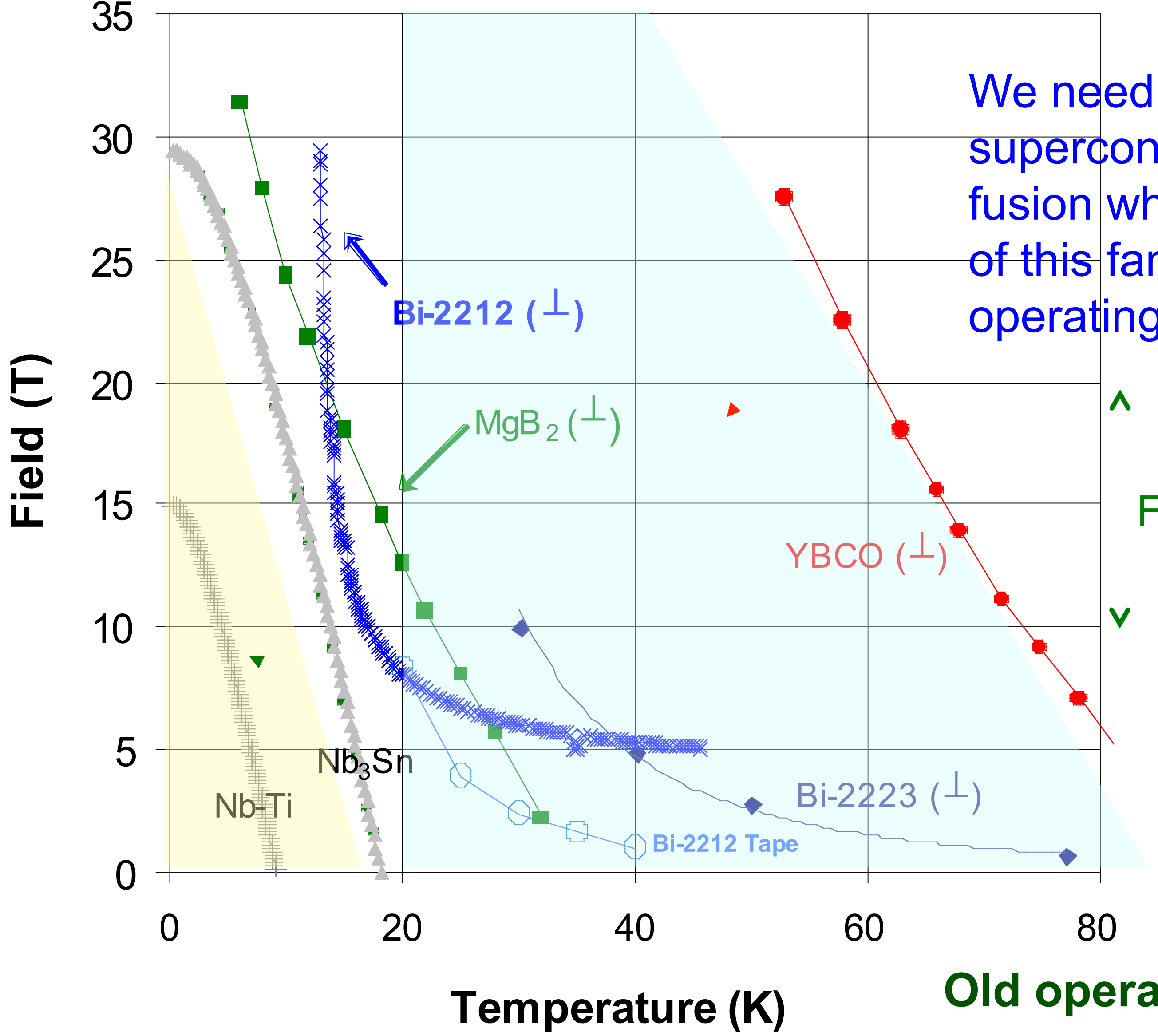
Neutron Degradation of T_c, A15's and YBCO





- All A15's have same T_c/T_{co} degradation vs. fluence
  - 1-2 orders of magnitude more sensitive than NbTi
- YBCO films have faster T_c/T_{co} degradation than A15's

HTS make much higher magnetic fields accessible

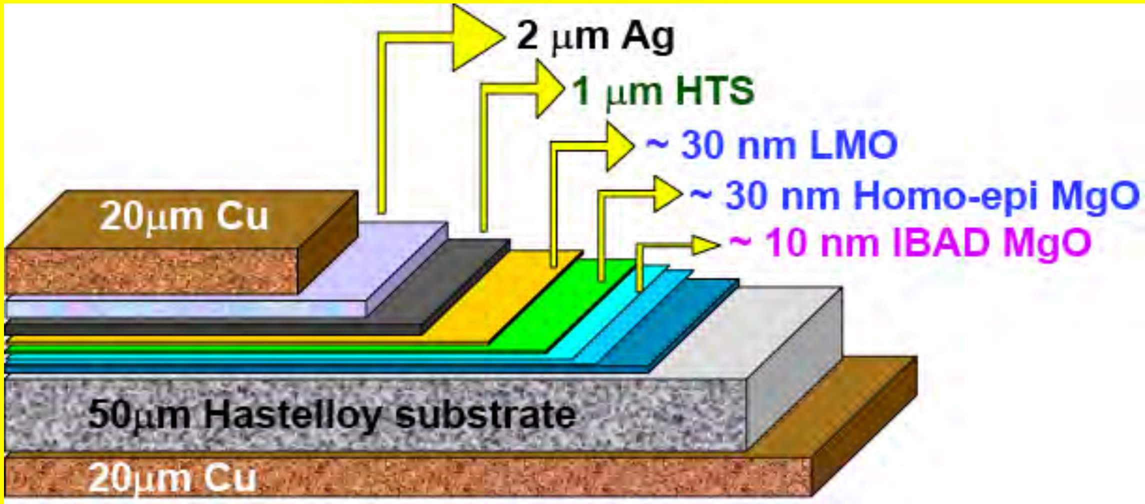


We need to develop superconducting magnets for fusion which take advantage of this fantastic new operating space

Fusion reactor range

Old operating space

YBCO Tape (2nd Generation-HTS)


2 μm Ag

1 μm HTS

~ 30 nm LMO

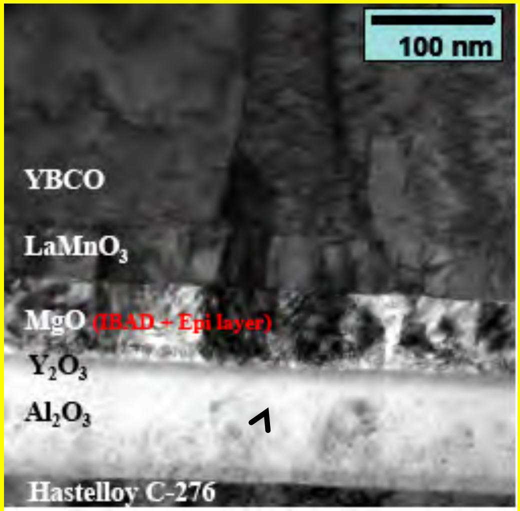
~ 30 nm Homo-epi MgO

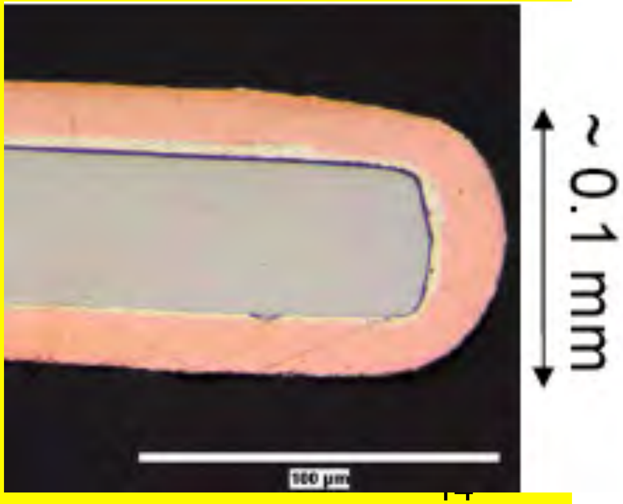
~ 10 nm IBAD MgO

20μm Cu

50μm Hastelloy substrate

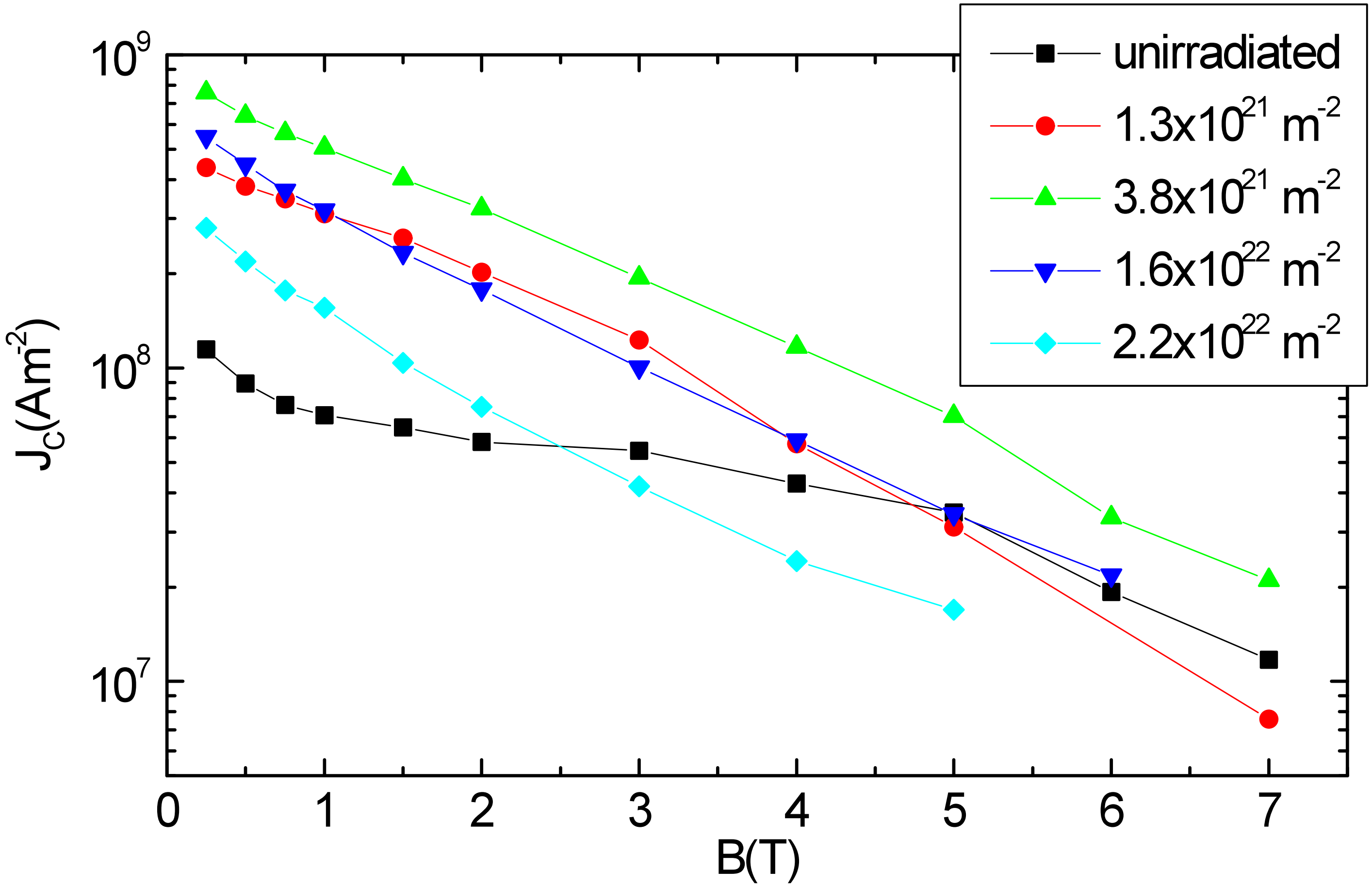
20μm Cu



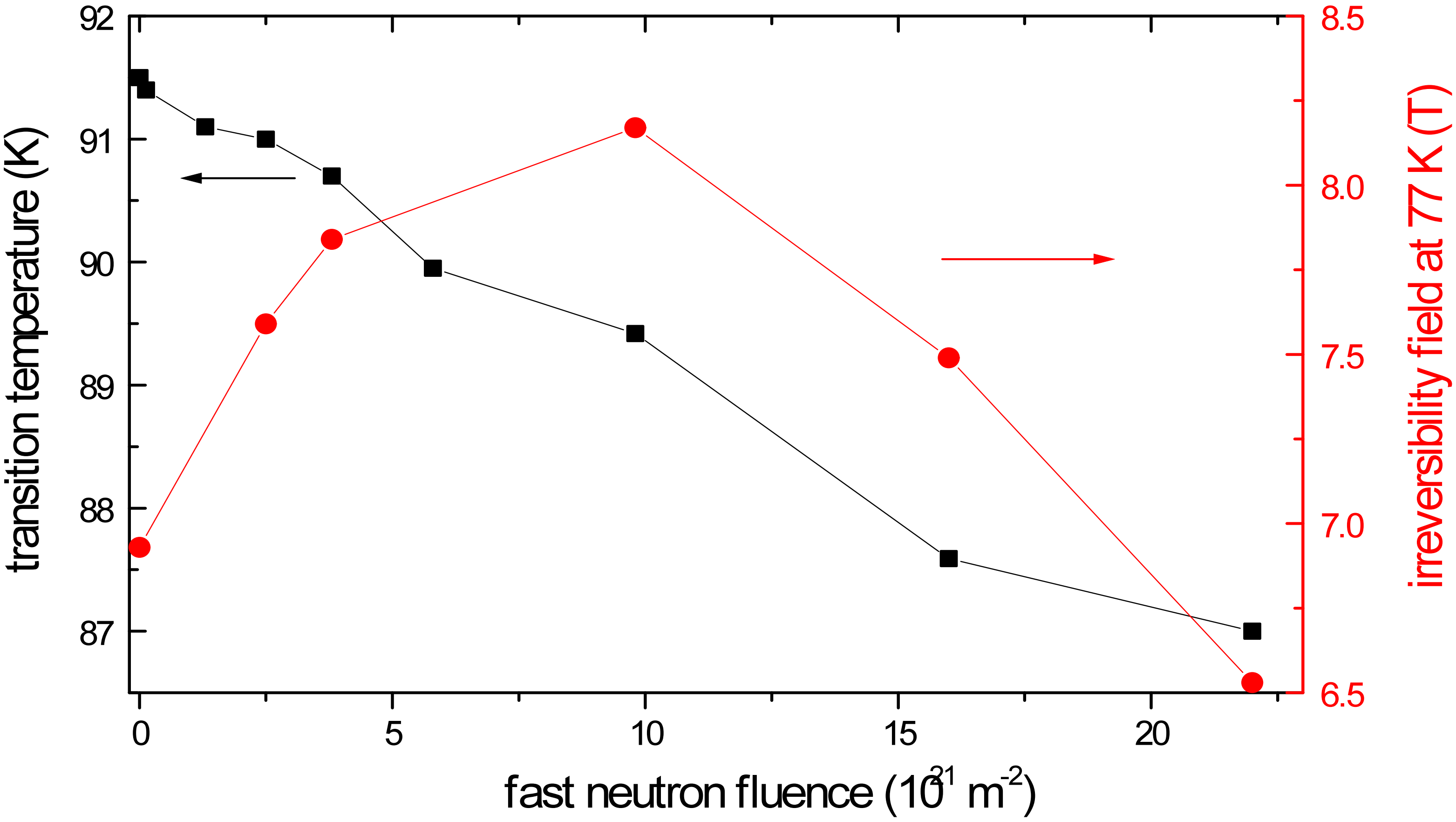


SuperPower Inc.
A Subsidiary of Intermagnetics General Corporation

Critical currents in YBCO bulk superconductors at 77 K

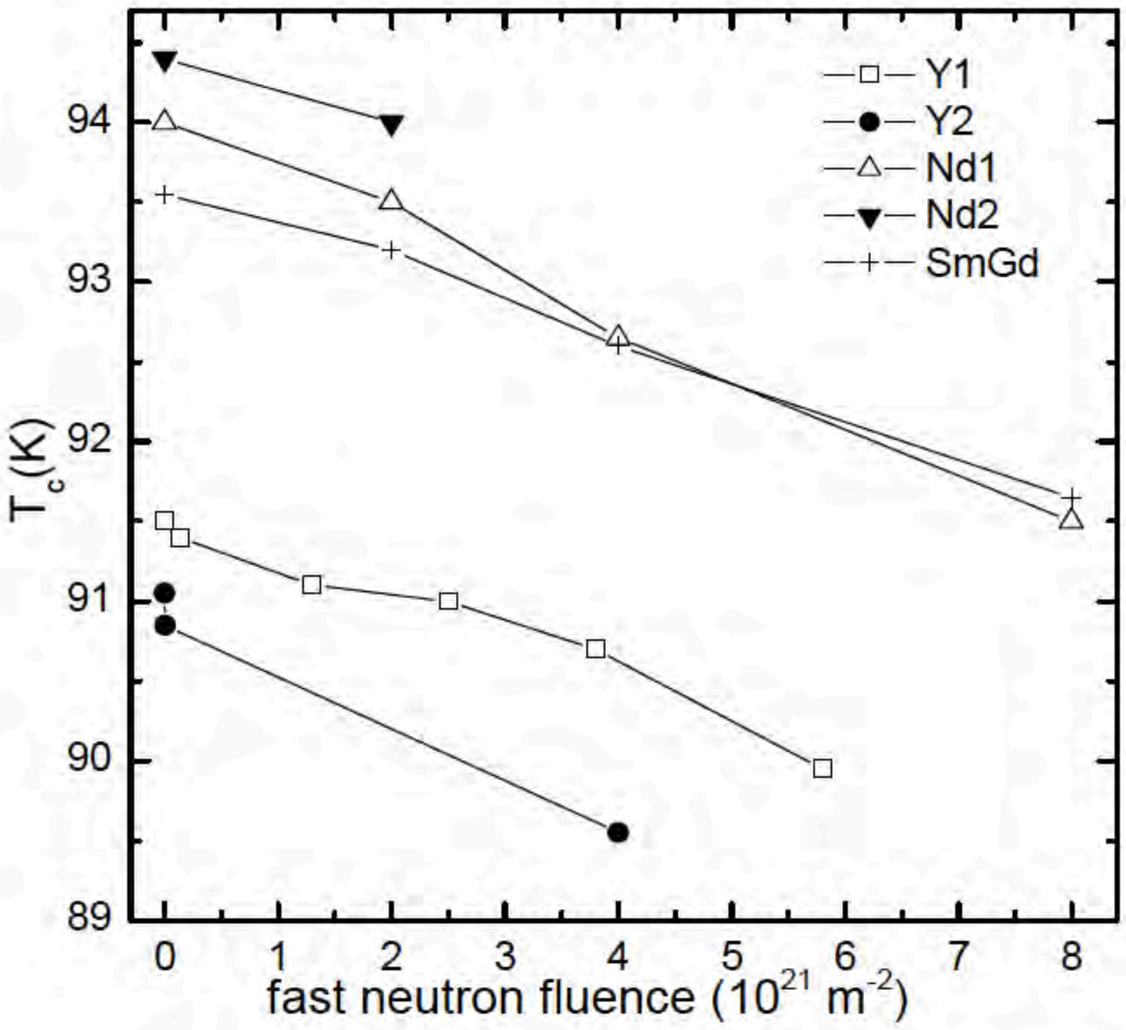


YBCO bulk



92
91
90
89
88
87
transition temperature (K)
8.5
8.0
7.5
7.0
6.5
irreversibility field at 77 K (T)
0
5
10
15
20
fast neutron fluence (10^{21} m^{-2})

YBCO Bulk

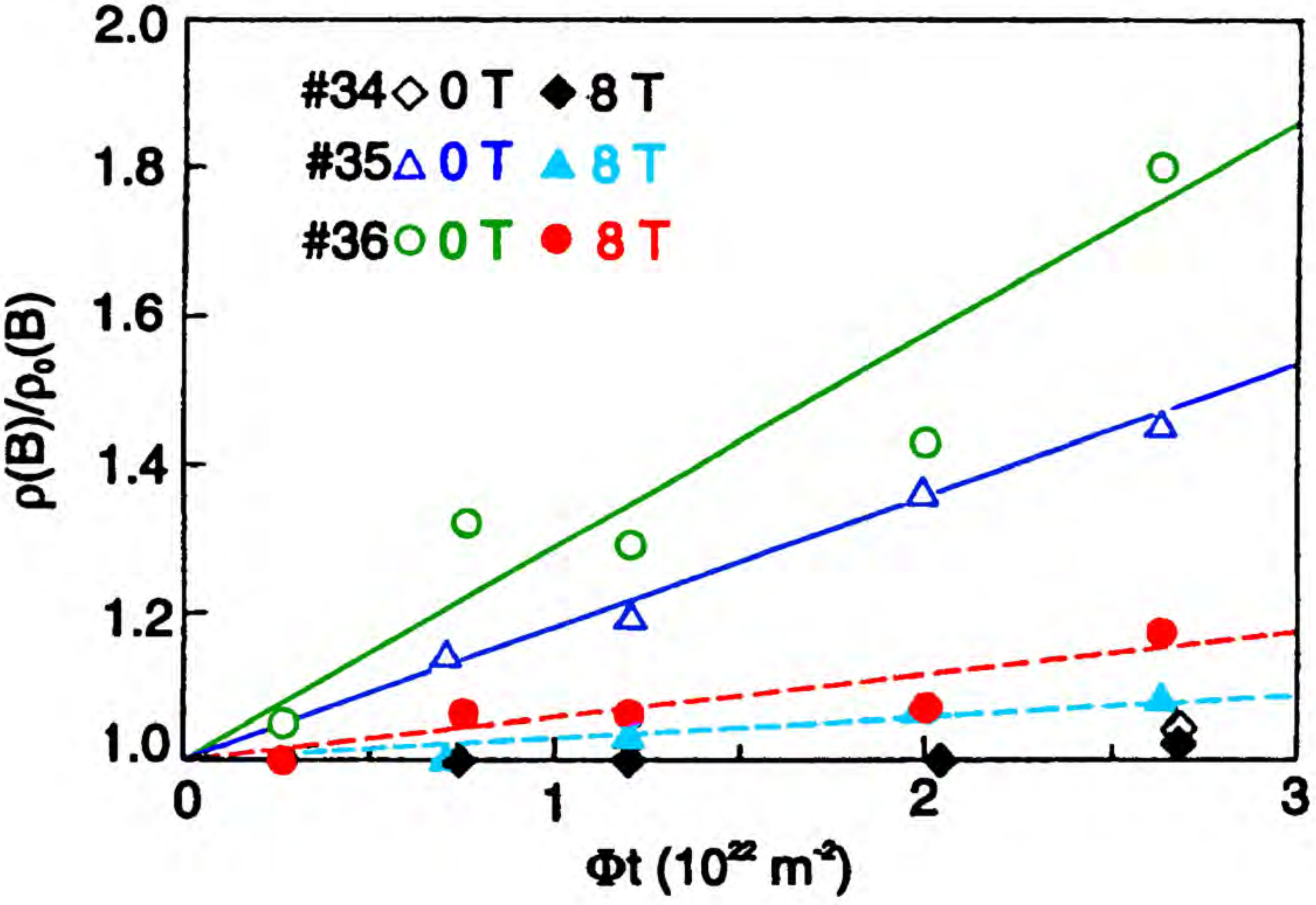


Y1
Y2
Nd1
Nd2
SmGd
T_c(K)
94
93
92
91
90
89
0
1
2
3
4
5
6
7
8
fast neutron fluence (10^{21} m^{-2})

Copper Stabilizer

- Experiments on copper
- Irradiation *must* be done at low temperature (~ 5 K)
  - (no facilities for irradiation at cryogenic temperatures today)

Copper Stabilizer



Insulation Materials

- Presently employed glass-fiber reinforced epoxies degrade at the ITER fluence level
- Novel cyanate esters may not withstand the DEMO fluence level!
- New research efforts needed

Insulation Materials

(Data Required After Irradiation)

- Tensile Strength
- Compression Strength
- Shear Strength

– *INTRA*laminar Shear: Crck propogation

– *INTER*laminar Shear

- Pulsed Operation::

– Fatigue

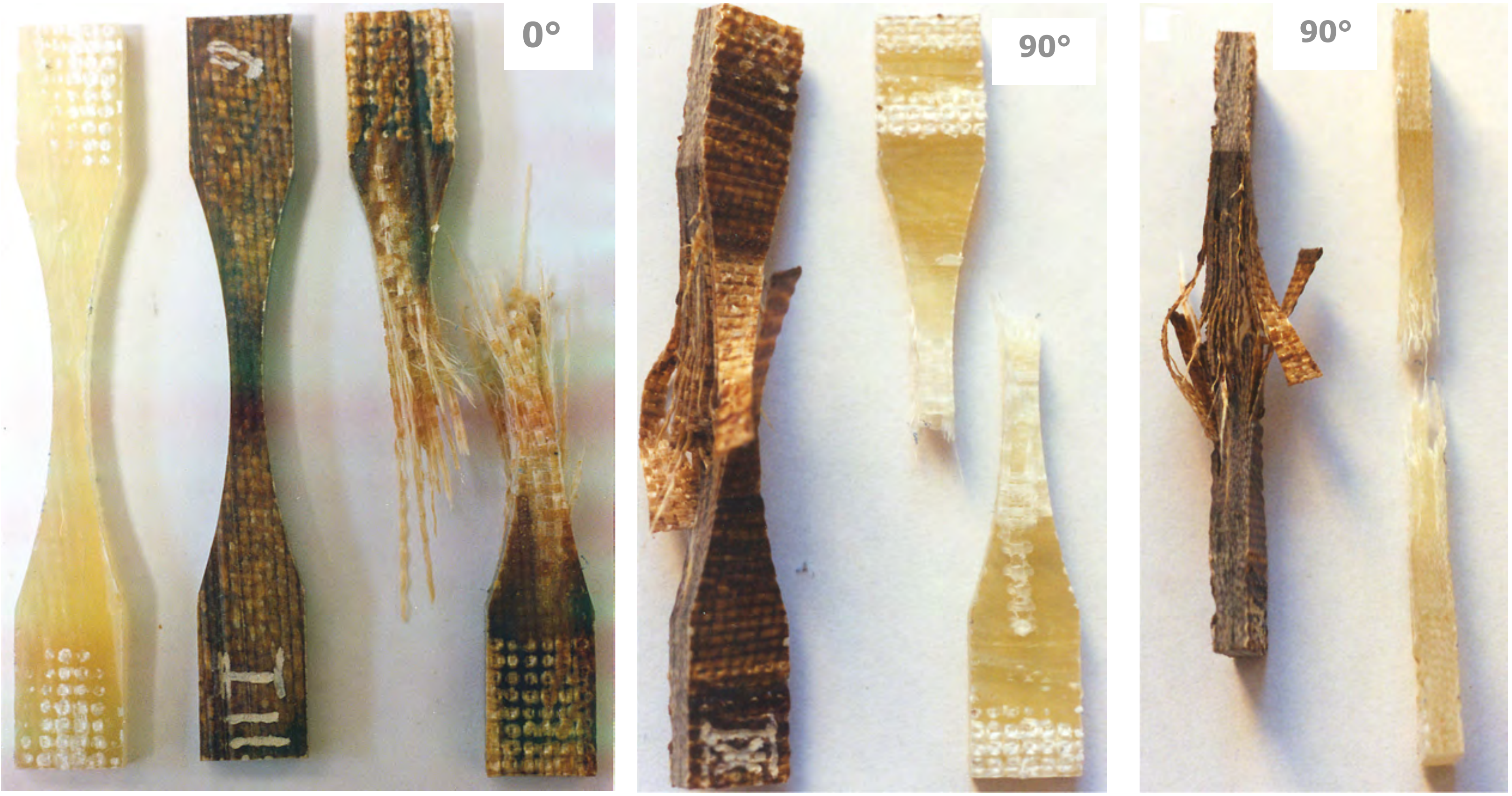
- Additional Property Changes:

– Swelling

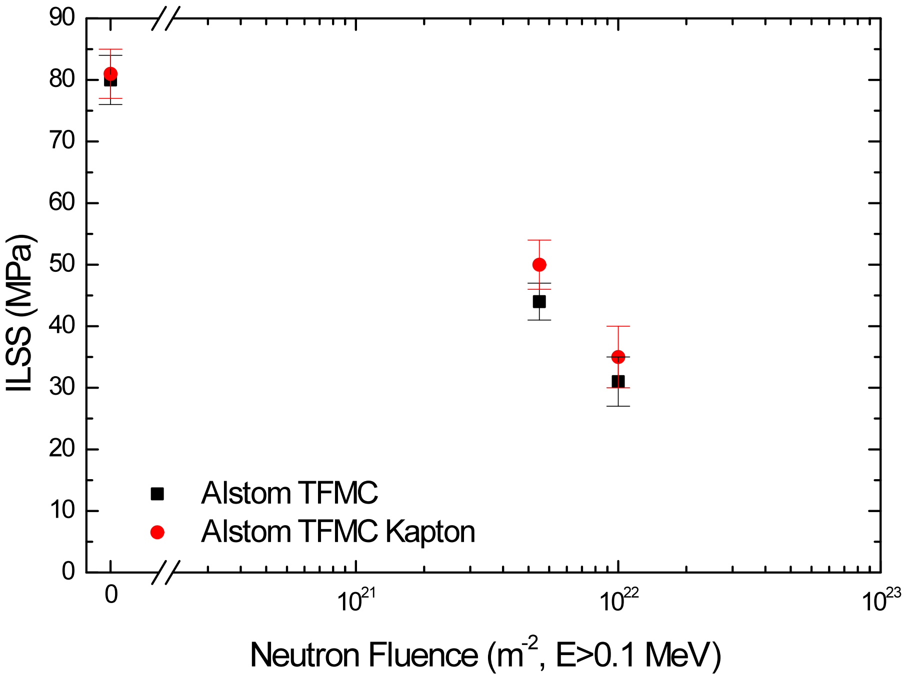
– Weight Loss

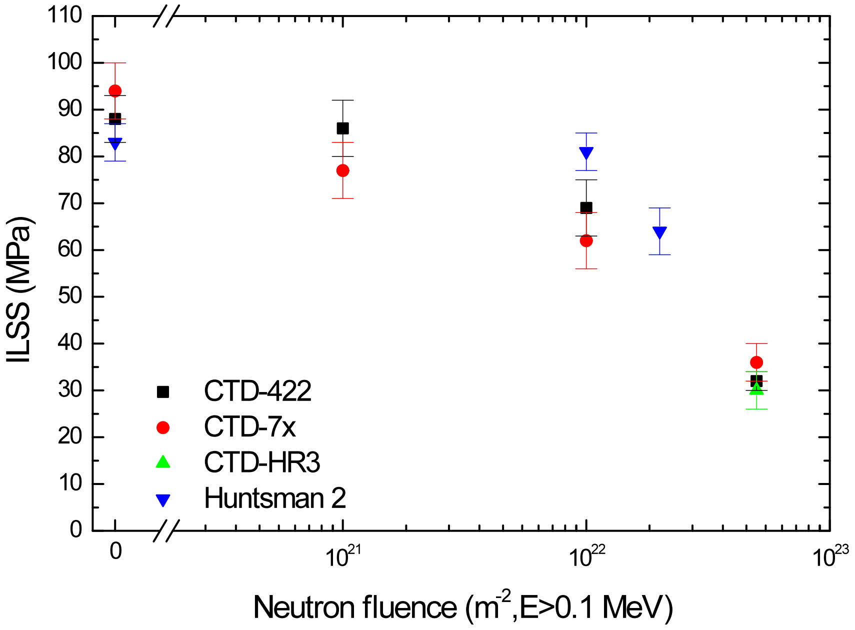
- Dielectric Strength

Tensile Tests of Unirradiated and Irradiated ALSTOM ITER Samples

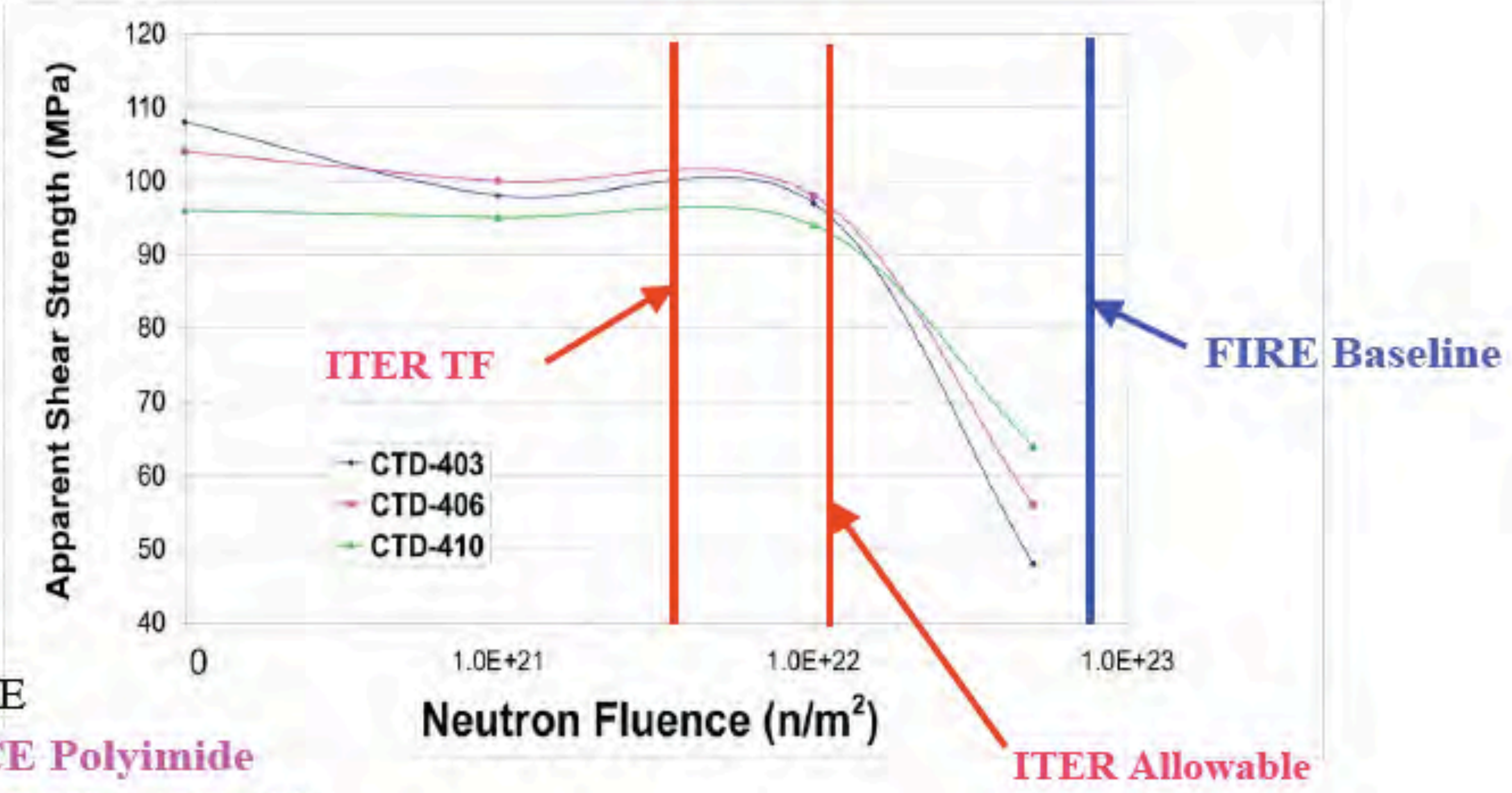


Fracture at 77 K before and after irradiation
to fast neutron fluence of 1x 10^{22} m^{-2} (E>0.1 MeV)


ILSS (MPa)
Neutron Fluence (m^{-2}, E>0.1 MeV)
0
10
20
30
40
50
60
70
80
90
0
10^{21}
10^{22}
10^{23}
■ Alstom TFMC
● Alstom TFMC Kapton


ILSS (MPa)
Neutron fluence (m^{-2},E>0.1 MeV)
0
10
20
30
40
50
60
70
80
90
100
110
0
10^{21}
10^{22}
10^{23}
■ CTD-422
● CTD-7x
▲ CTD-HR3
▼ Huntsman 2

Shear Strength vs. Neutron Fluence Imide & Cyanate Ester Hybrids



ITER TF

FIRE Baseline

ITER Allowable

CTD-403-CE

CTD-406-CE Polyimide

CTD-407-CE Bismaleimide

Preliminary Radiation Results for Cyanate Ester Hybrids

Gas Evolution Rates of Epoxy Resins

Resin/Hardener	MNA (anhydride) (cm^3/g-MGy)	MTHPA (anhydride) (cm^3/g-MGy)	DDM (aromatic amine) (cm^3/g-MGy)	DETD (aromatic amine) (cm^3/g-MGy)
DGEBA	1.35	1.38	0.32	0.57
	1.23	1.27		0.58
DGEBF		1.08		0.58
		1.03		
TGPAP		1.19		
		1.1		

Prepreg/Film	Hardener	Gas Evolution Rate (cm3/g-MGy)
TGDM	Anhydride	0.4
Bismaleimide (CTD-220P)		0.32
Polyimide (Kapton)		0.09

Most options the same to within x 2

Aromatics, imides better; no CE data

Kapton best

ρ~ 1.2 g/cc

Φ~0.22 Mgy

Φ_{TF}~2.9 Mgy

Φ_{CS}~223 Gy

R~O(1) (cm^3/g-MGy)

V_{gas}, lifetime,

TF ~2.4 cc/cc

V_{gas}, lifetime,

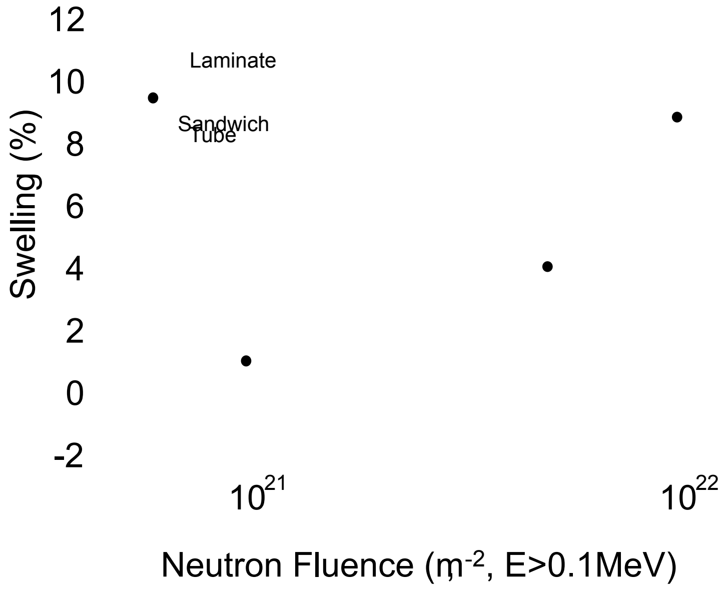
CS ~182 cc/m^3

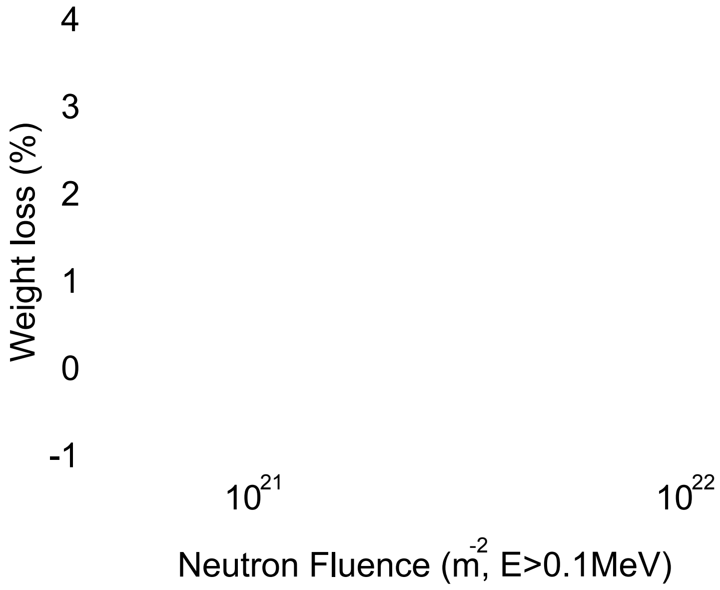
Vgas,TF large

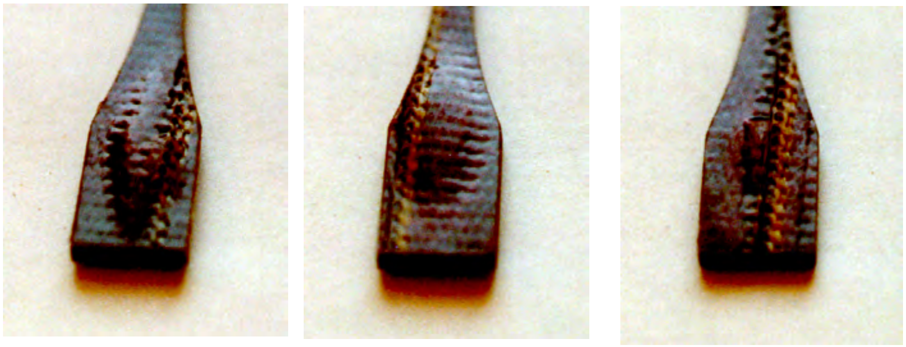
Vgas,CS small

Additional Characterizations

SWELLING AND WEIGHT LOSS (Graphs are for DGEBA)







Formation of bubbles inside the laminate after irradiation @ $1x10^{22}$ m^{-2} (E>0.1 MeV)

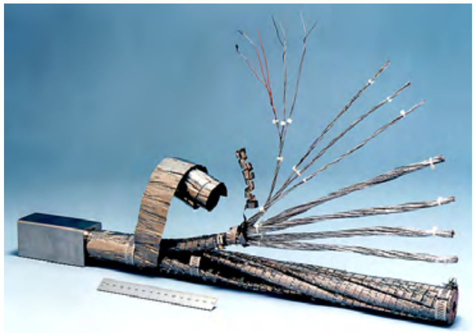
High Performance Electrical Insulator Needed for Extended High Q Operation

	Insulation	Superconductor
Near-term	10^7 Gy x 50 MPa	1,000 A/mm^2 (12 T, 4.2 K), 3 x 10^{21} n^o/m^2
Long-term	10^9 Gy x 500 MPa	1,000 A/mm^2 (12 T, 77 K), 1.5 x 10^{23} n^o/m^2

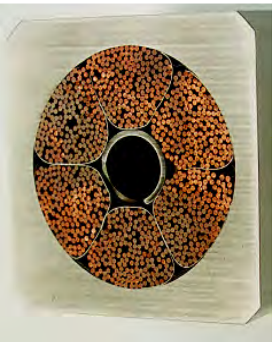
1. Better insulations being developed
2. Strong influence of structural concept
3. Superconductors can be weak link

High Current Conductors Required for Fusion Magnets

Typical Large Scale Cable-in-Conduit Conductor (CICC)



40 kA at 13 T, 4.5 K

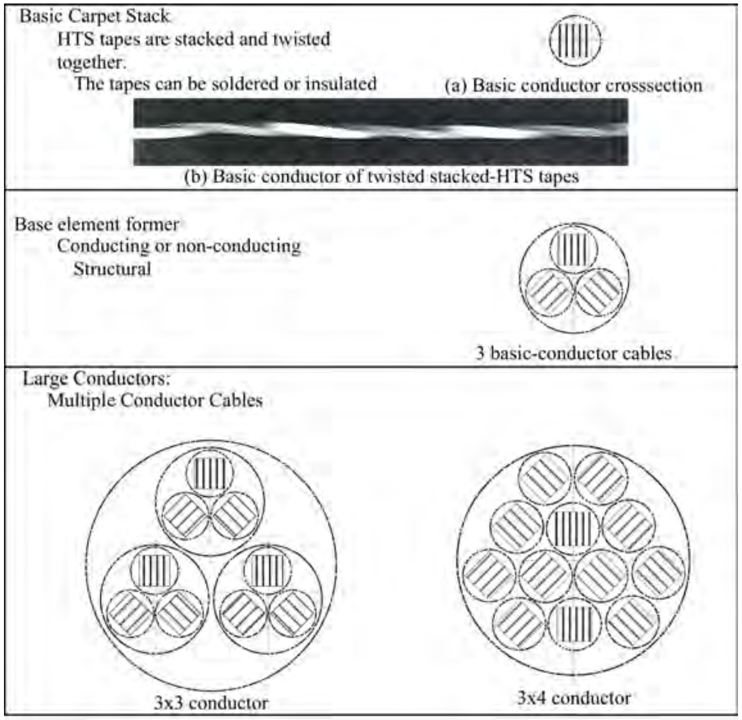


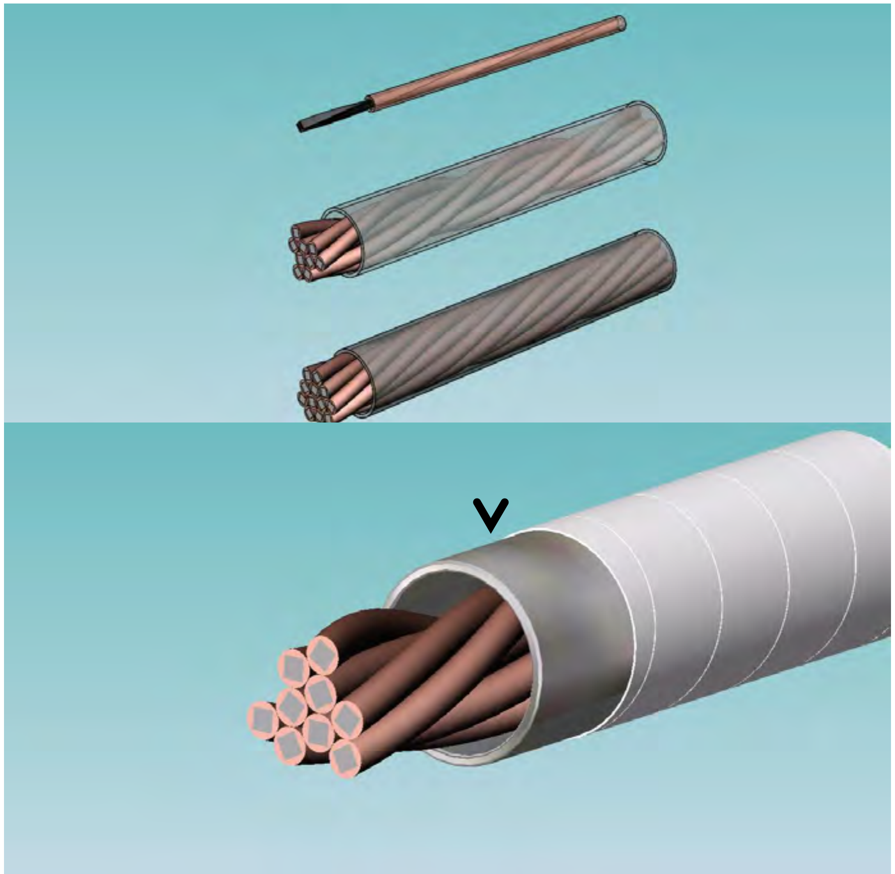
- High Currents Required to Limit Coil Inductance and Dump Voltage for Quench Protection

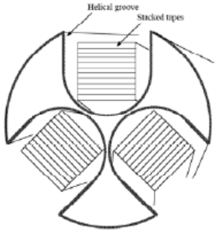
ITER TF coils (N*I = 9.1 MA, L = 0.349 H)

Conductor current	Number of turns	Inductance ratio L/L_{ITER}	Discharge voltage (τ_D = 12 s)	Discharge time constant (U_D = 10 kV)
68 kA	134	1	3.5 kV	4 s
30 kA	304	5	17.5 kV	21 s
10 kA	910	45	158 kV	190 s

Twisted Stacked Conductor Concept With YBCO HTS Flat Tapes

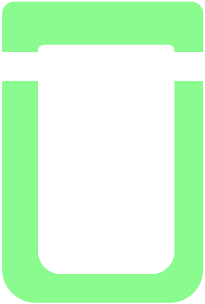


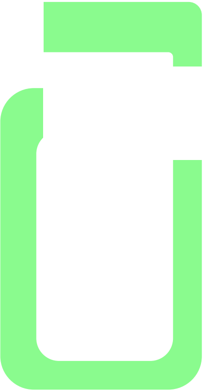


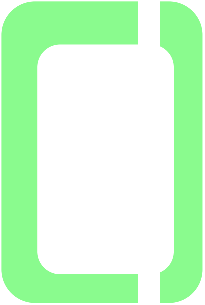


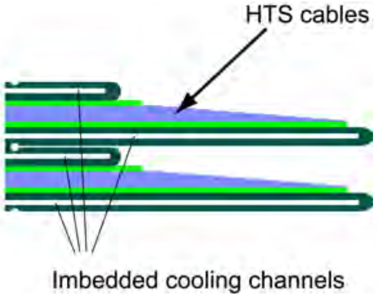
Supercon, Inc.
Phase I SBIR

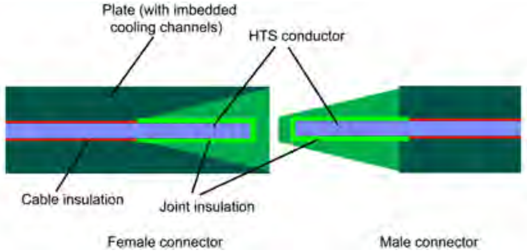
HTS Conductors Could Make Demountable Joints Possible

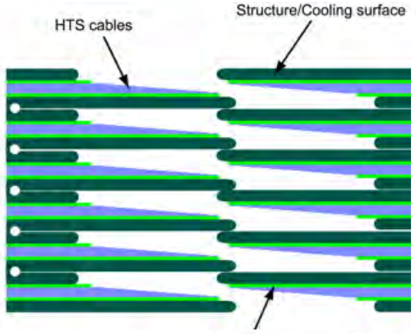

Case A

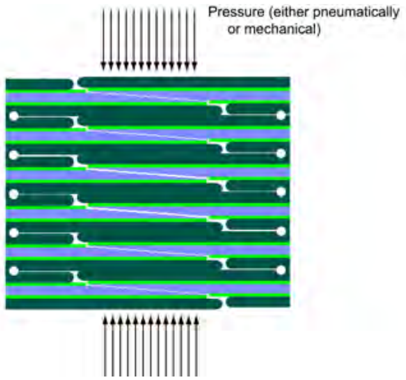

Case B

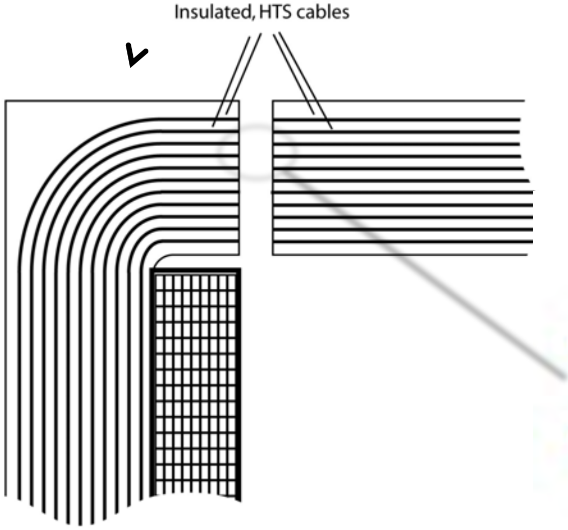

Case C

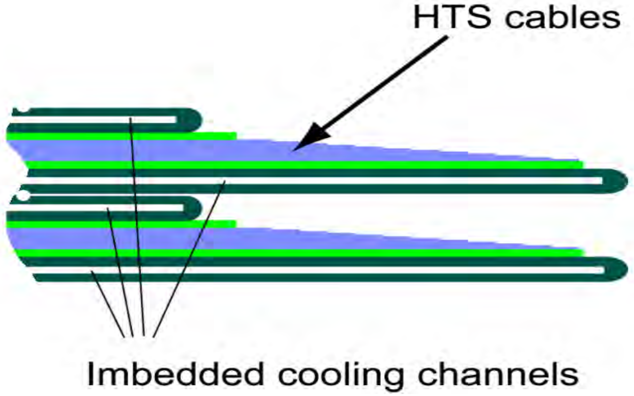












Summary

- Demo and commercial fusion reactors will not be built with 1990‘s ITER technology
  - *We can‘t afford to wait 20-30 years and then try to catch up*
- Advanced superconducting technology is critical to development of a reliable and economical fusion reactor
  - *Need intensive HTS high current, high field conductor development*
- Significant further R&D of radiation tolerant insulation systems must be pursued
- Can radiation resistance of superconductors be improved?
- New facilities are required including ability to irradiate at cryogenic temperatures
  - *Ideally perform mechanical tests at low temperature*