50 Tesla Muon Cooling Solenoids

D. J. Summers
Univ. of Mississippi - Oxford

Neutrino Factory
Muon Collider

Working Group 3: Accelerator Physics
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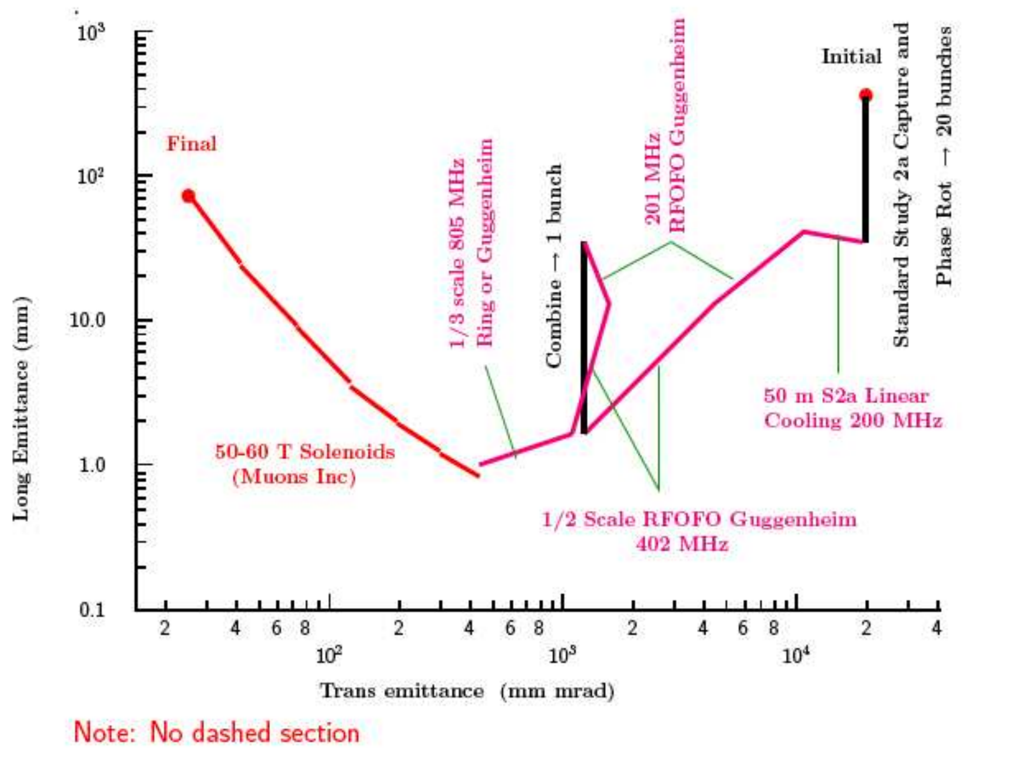
50T Solenoid Motivation

- **Five 50T plus one 60T Solenoids could provide the final cooling for a muon collider.** **And a second use for Neutrino Factory muons!**
- **Steve Kahn et al., EPAC06, "High Field Solenoid Magnets for Muon Cooling,"** http://accelconf.web.cern.ch/AccelConf/e06/Pre-Press/WEPLS108.pdf
- **Bob Palmer et al., "Collider Scheme with Bunch Merging,"** http://mice.iit.edu/mutac06/mutac06_palmer_bunchmergedcollider.pdf, **MUTAC Review, Fermilab, 16-17 March 2006.**



Five Existing BSCCO Solenoid Inserts

Location	BSCCO	ID/OD/Length	B	IEEE T.A.S.
Florida	Bi-2212	41/165/209mm	20+5=25T	13 (2003) 1396
Karlsruhe	Bi-2223	50/185/177mm	12+5=17T	15 (2005) 1484
MIT	Bi-2223	78/126/402mm	1.7T	15 (2005) 1299
Tohoku	Bi-2223	90/180/250mm	19T goal	15 (2005) 1512
MIT	Bi-2223	40/108/113mm	22.5+1.5=24T	67 (1995) 1923*

* Applied Physics Letters

- **Steve Kahn et al.,**
"High Field Solenoid Magnets for Muon Cooling,"
eConf,C060626,WEPLS108, EPAC2006.

Location	BSCCO	ID/OD/Length	B
NFMCC	Bi-2223	50/448/750mm	50T

Proposed NHMFL 30 Tesla NMR Solenoid for Florida

- **IEEE Trans. Ap. Supercon. 16 (2006) 1523**
- **Uniform NMR 30 T → 1.3 GHz protein size**
- **Quenches: Passive resistor/diode shunts Active persistent switch/network of heaters**
- **Bi-2212 Oxford Superconductor wire or Bi-2223 American Superconductor tape**
- **Dispersed SS reinforcing + Stronger Silver alloyed with Mg, Sb, Ti, or Nb nanoparticles**

B	Temp	ID	OD	Length	Energy
30 T	4.2 K	100 mm	1100 mm	1750 mm	90 MJ

BSCCO	Strain	J_c	Nb_3Sn	NbTi
304 kg	0.275%	70%	1882 kg	1552 kg

Proposed NHMFL 30 Tesla NMR Solenoid for Florida

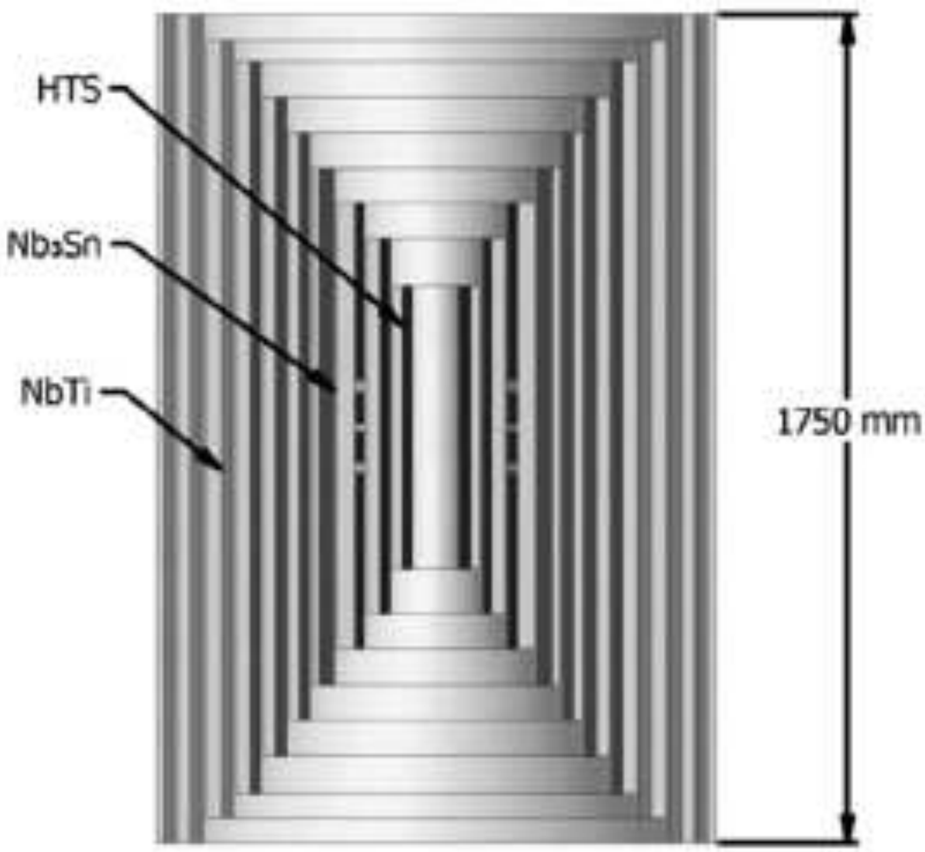


Fig. 2. Cross section of 30 T, 1.8 K magnet, showing coil windings and reinforcement, and a compensation coil set at intermediate diameter.

BSCCO Wire Critical Current Measurements at 4.2 K

			Critical Current			
			Bi-2223		Bi-2212	
Location	**B**	**IEEE T.A.S.**	$\parallel$	$\perp$	$\parallel$	$\perp$
Tsukuba	**28T**	**12 (2002) 1136**			**340**	
Florida	**45T**	**15 (2005) 2554**			**266**	
Florida	**33T**	**11 (2001) 3956**	**300**	**200**	**180**	**120**
Tsukuba	**30T**	**15 (2005) 2470**	**128**			
Oxford	**41T**	**5 (1994) 1313**				

Superconductor Cost: $/kg

- **Estimates from 24T LHC Tripler Proposal**

http://accelconf.web.cern.ch/AccelConf/p05/PAPERS/MOPA008.PDF

http://www7.nationalacademies.org/bpa/EPP2010_Presentation_McIntyre.pdf

- **Nb/Ti: $100/kg today**

- **Nb_3Sn: $1000/kg today**

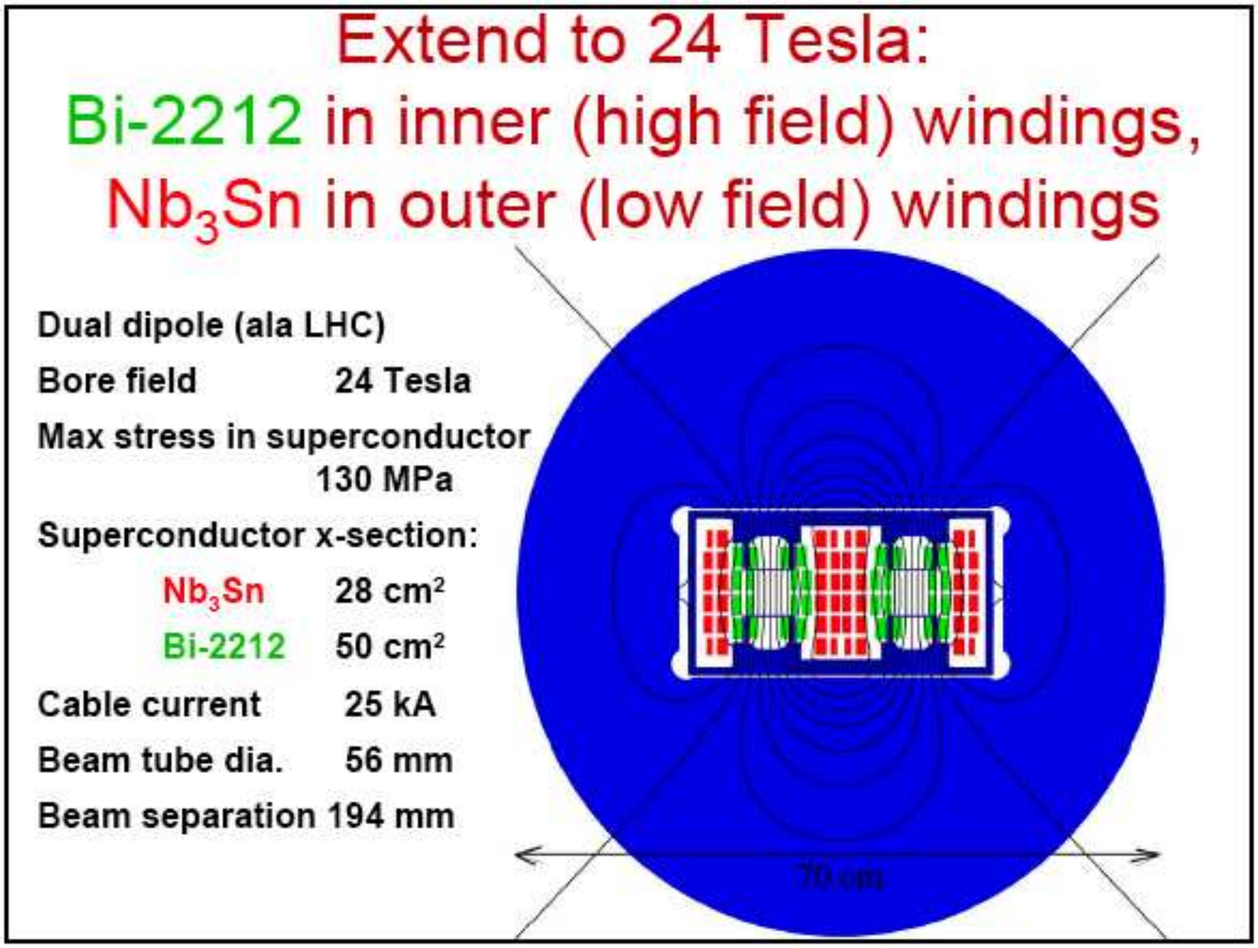
$300/kg goal for the ITER fusion project

- **Bi-2212: $2000/kg today**

$700/kg projection from 2 manufacturers
Note that silver costs $400/kg

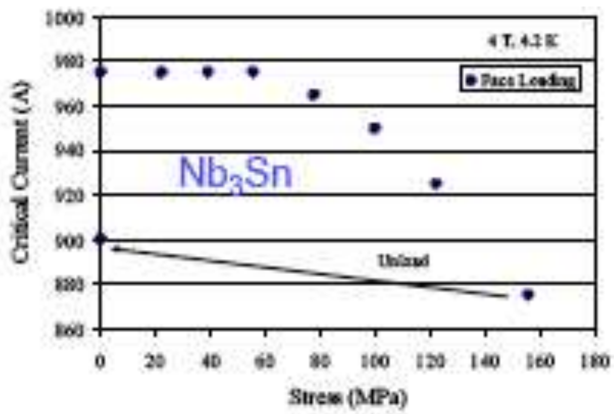
Maximum Allowed Superconductor Stress

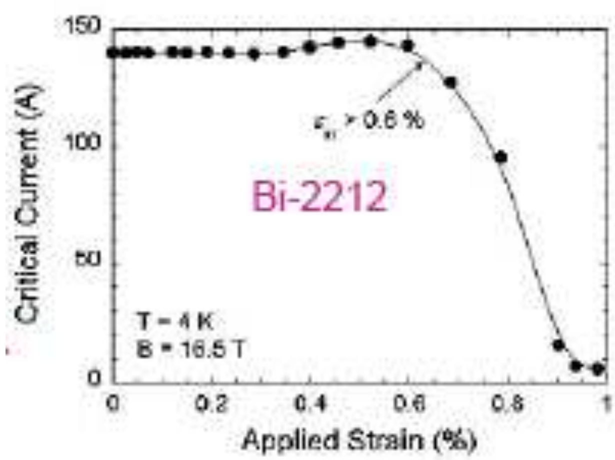
- **24T LHC Tripler Proposal uses 130 MPa**



- **24T Muon Collider open midplane ring option?**

Maximum Allowed Superconductor Stress





- **Reading List about BSCCO Stress**

IEEE Trans. Appl. Supercond. 9 (1999) 122
IEEE Trans. Appl. Supercond. 10 (2000) 1134
J. Appl. Phys. 88 (2000) 1178
IEEE Trans. Appl. Supercond. 11 (2001) 3577
Supercond. Sci. Technol. 17 (2004) 130

Stress Management

- **hoop stress = pressure × radius/thickness**

Radius acts as a lever to increase stress!

Coils/Hoops → Pancakes/Pillars at large r ??

- **Axial Force Buckling.**

Euler column instability for a cylinder.

$P_{cr} = n\pi^2 EI/\ell^2$, $\quad I = (\pi/4)(R^4 - r^4)$

- **Pre-Stress: LHC Tripler idea.**

Pump up Woods metal bladders, then freeze.

- **Pre-Stress solenoid layer to $S = -.004$.**

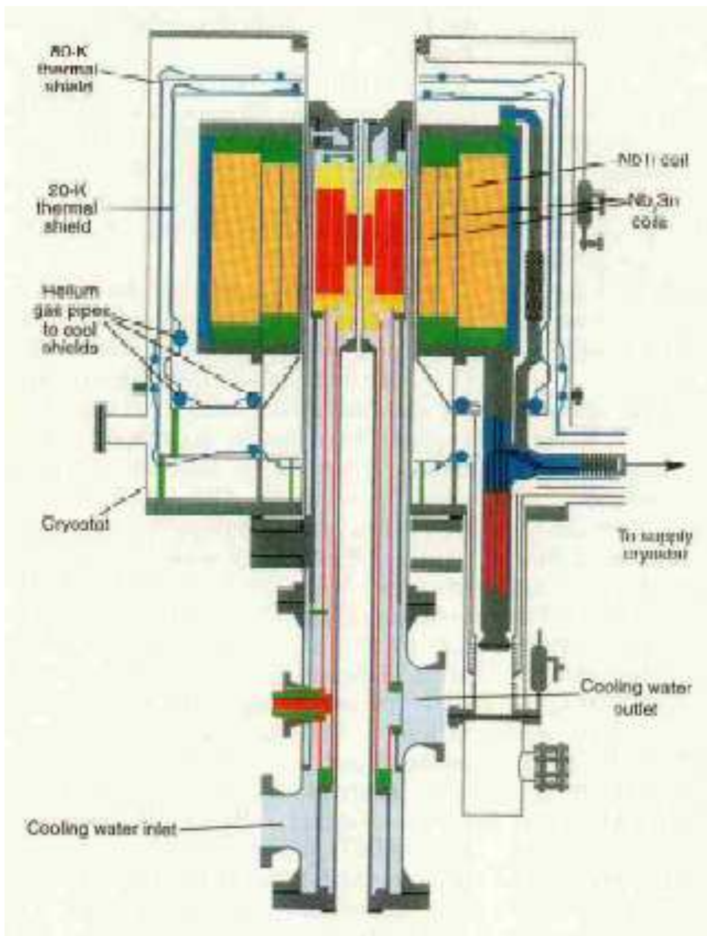
Turn B on, go to $S = .004$.

Allows double the stress in the BSCCO.

Low SS Elastic Modulus a paper tiger ??

Florida 45 Tesla Hybrid Magnet

- Physics Today (Dec 1994) 21
- D=32mm bore, 24 MW, Cu/Nb_3Sn/NbTi



Possible Near Term Goal

- **1T BSCCO Insert Coil in Florida's 45T**

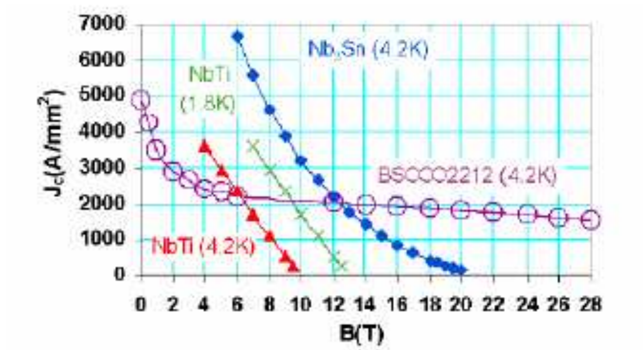


Fig 1: Critical current as a function of field for NbTi, Nb_3Sn and BSCCO 2212.

http://accelconf.web.cern.ch/AccelConf/e06/Pre-Press/WEPLS108.pdf

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 15, NO. 2, JUNE 2005

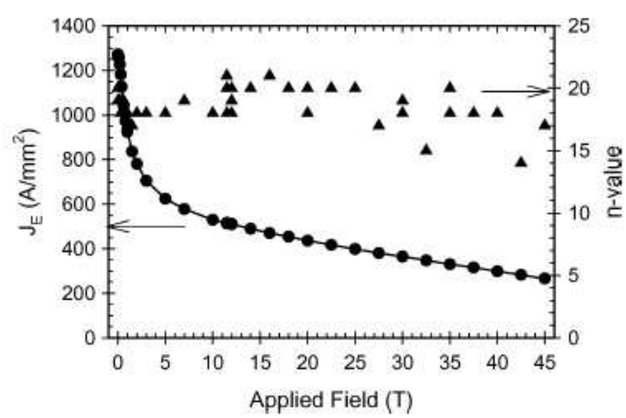


Fig. 6. J_E and n-value as function of applied field up to 45 T at 4.2 K in the 0.8 mm wire.

IEEE Trans. Appl. Supercond. 15 (2005) 2554

J. Schwartz, H. J. Schneider-Muntau, U. P. Trociewitz, and H. W. Weijers, "Transport critical current measurements to 45 T and upper critical fields of $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O_x$," *Phys. Rev. Lett.*, to be published.

1 Tesla Insert Coil Sketch

- $B = \mu_0 I = 1$**T, I = 800 000 Amp-turns**
200 Amps, mm^2 wire, 4 layers, 1000 turns/m

- $\mathbf{F}_r/\mathbf{A} = I \times B =$ **800 000** $\times$ **46 T = 37 MPa**

- **hoop stress = pressure $\times$ radius/thickness**
2mm of 316L Stainless Steel at r = 12 mm
hoop stress = 37$\times$12/2 = 222 MPa
Yield Strength of 316L = 292 MPa
S = (F/A)/E = 222/200 000 = .0011 $\ll$ .004

- **Limit: Strength not Modulus of Elasticity!**
Small r probably dictates wind and react.

- **r = 0 $\rightarrow$ 8mm LHe Bore**
r = 8 $\rightarrow$ 12 mm BSCCO or YBCO
r = 12 $\rightarrow$ 14 mm 316L Stainless Steel
r = 14 $\rightarrow$ 15 mm Vacuum
r = 15 $\rightarrow$ 16 mm 316L Stainless Steel