Progress in Radiation Resistant Superconducting Coils

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NSCL/MSU

Targetry meeting 6/11/03

General radiation limits

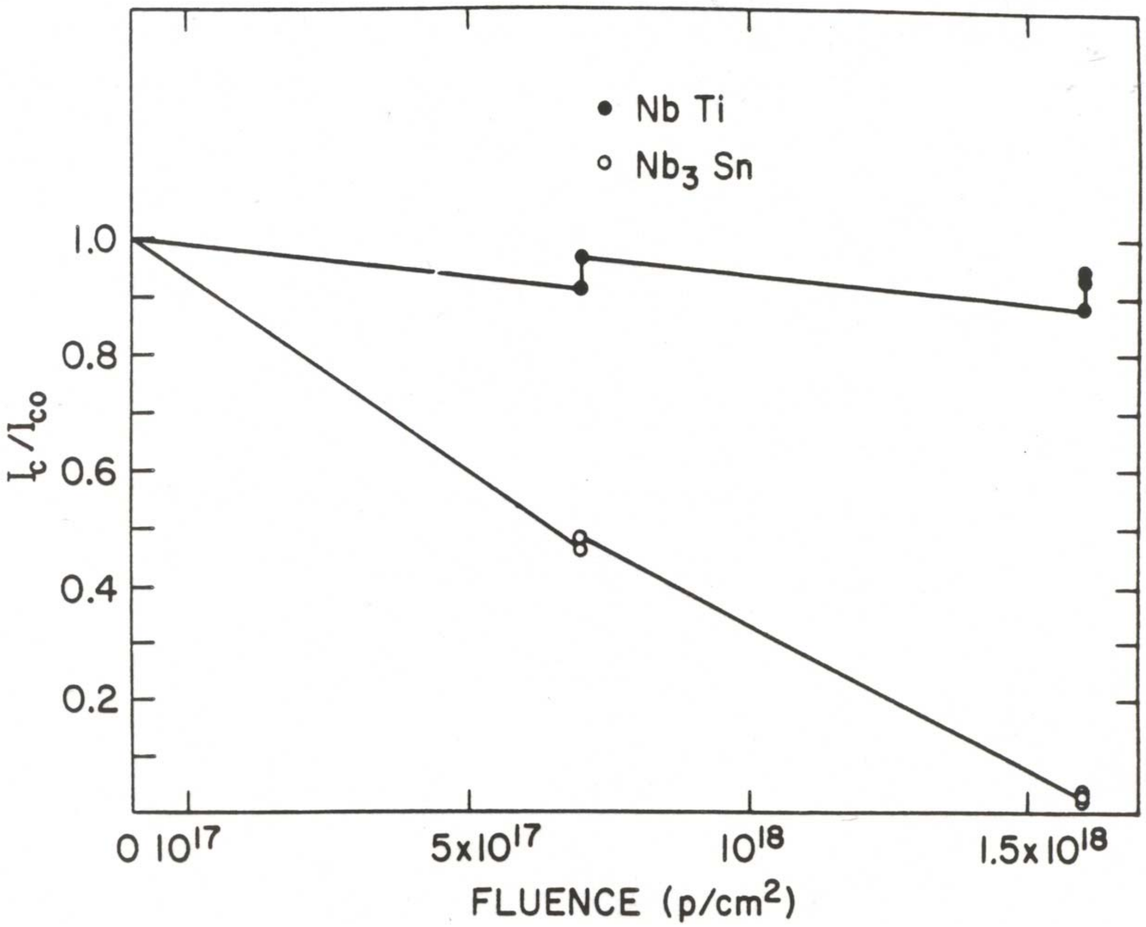
NbTi ~ 5 X 10^8 Gy

Nb_3Sn ~ 5 X 10^8 Gy plus

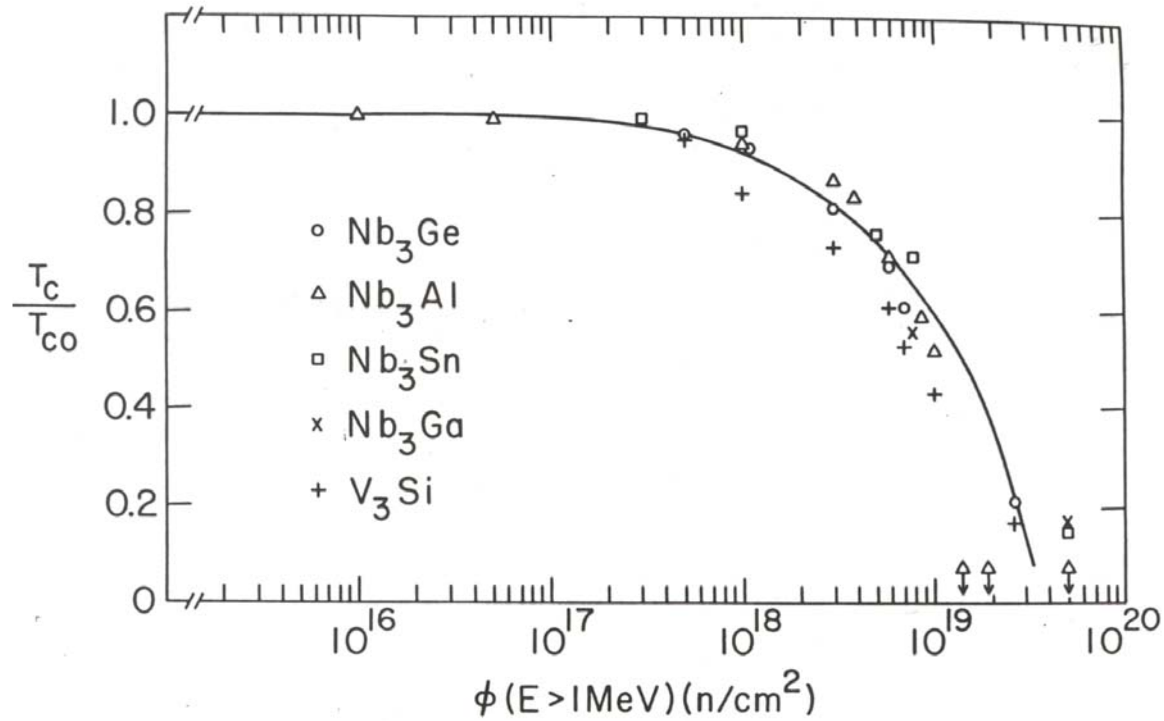
Copper > 10^{10} Gy

Ceramics > 10^9 Gy (Al_2O_3, MgO, etc)

Organics ~10^6 to 10^8 Gy



A comparison between the critical-current degradation of NbTi and Nb_3Sn for identical 30-GeV-proton irradiations and anneals. The critical currents were determined at 4 T. Anneals are for 273 K for the low-fluence point, and for 77 and 273 K for the high-fluence data. (After Snead 1978.)



1.0
0.8
0.6
0.4
0.2
0
Tc / Tco
o Nb3Ge
△ Nb3Al
□ Nb3Sn
x Nb3Ga
+ V3Si
10^16
10^17
10^18
10^19
10^20
φ(E>1MeV)(n/cm²)

Copper

The material itself good for at least 10^{11} Gy

Radiation causes increase in resistance - protection issue

Goal:

Make the superconductor the weak link

Electrical insulation:

External anodization

Good insulation

How do you clamp?

Other inorganic materials (MgO_2, spinel)

plasma spray for example

somewhat porous

How to clamp?

Require magnets that are reliable, long-lived and maintenance-free.

Resistive magnets with inorganic insulation and cement or inorganic “epoxy” fulfill these requirements, but low current density limit utility.

Two approaches:

1) Increase current density in resistive magnets
2) Develop superconducting versions

Anodized aluminum conductor has been used since the 1950s in small devices.

Hollow, water cooled aluminum conductor with anodic insulation only gives ~10% more than traditional copper with fiberglass insulation.

Try aluminum coated copper conductor and then anodize (Leonhardt PAC89)

Commercial vendor failed.

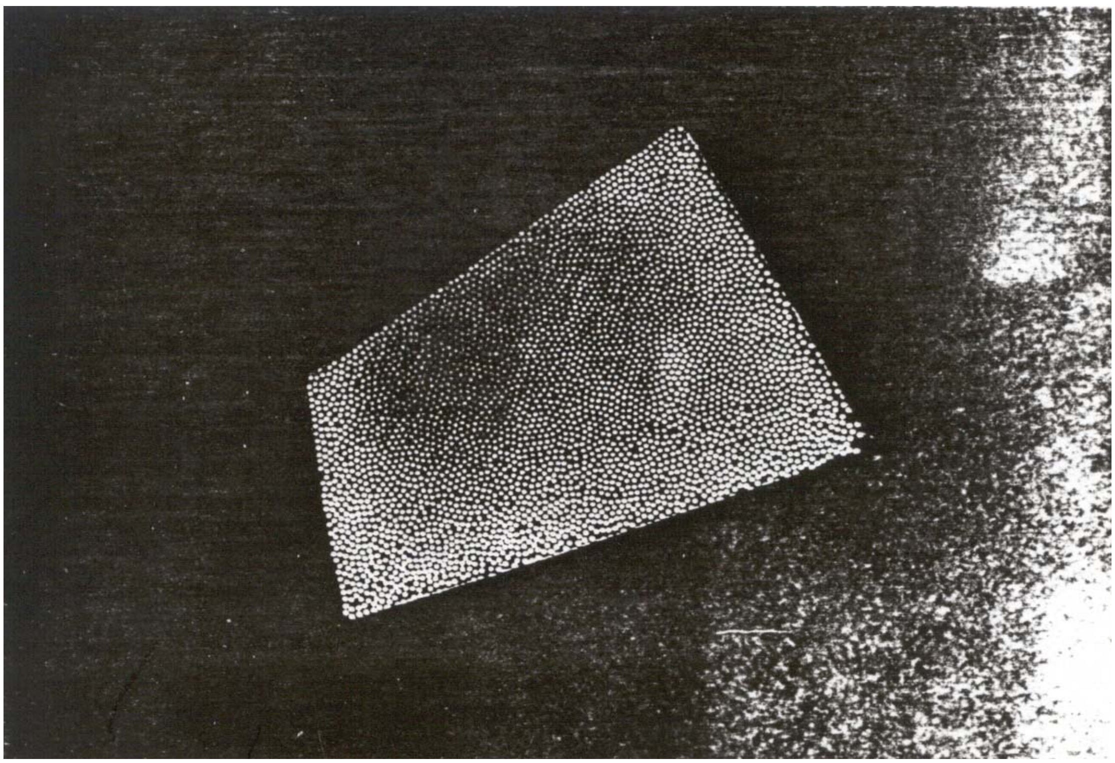
Potted coils with radiation resistant insulation and epoxy

Polyimids instead of Formvar

CTD-422 “epoxy”

High current density ($200\ A/mm^2$)

Is it tough enough for random winding procedures?



Material Solutions...
Composites • Insulation • Adhesives • Coatings
for cryogenic, high temperature
and other harsh environments

Mechanical Performance

Summary of Compression Test Results at 76 and 4 K

Resin System	76 K Compressive Strength (GPa)	76 K Compressive Modulus (GPa)	4 K Compressive Strength (GPa)	4 K Compressive Modulus (GPa)	76 K Dielectric Strength (kv/mm)
CTD-403	1.15	17.9	1.50	22.4	65.4 *
CTD-406	1.00	15.0	1.42	21.1	69.4 *
CTD-410	1.20	15.0	1.39	19.8	71.5 *
CTD-422	1.33	17.9	1.28	22.4	87.4 **
CTD-423	1.21	14.0	NA	NA	92.1**

* Nominal Specimen Thickness 0.9 mm; ** Nominal Specimen Thickness 0.5 mm

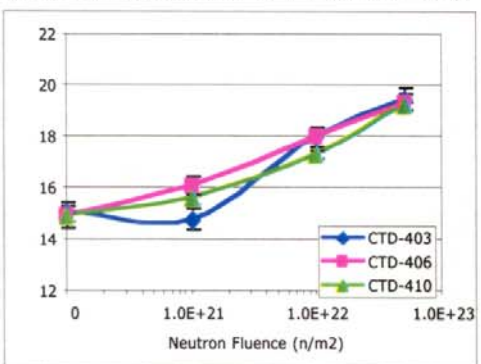
Summary of Shear Test Results at 76 and 4 K

Resin System	76 K Shear Strength (MPa)	76 K Flexural Modulus (GPa)	4 K Shear Strength (MPa)	4 K Flexural Modulus (GPa)
CTD-403	100.0	NA	109	NA
CTD-406	77.0	NA	107	NA
CTD-410	83.0	NA	90	NA
CTD-422	81.2	22.8	87.0	24.4
CTD-423	77.0	19.6	NA	NA

Performance after Radiation Exposure

Compressive Modulus (GPa)

Maximum Dose 5.0 x 10^{22} n/m^2 ≈ 6.4 x 10^{10} Rads



Compressive Strength (GPa)

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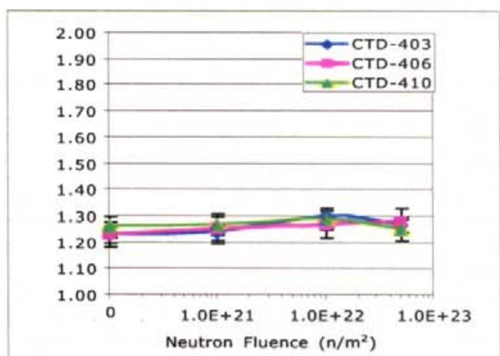

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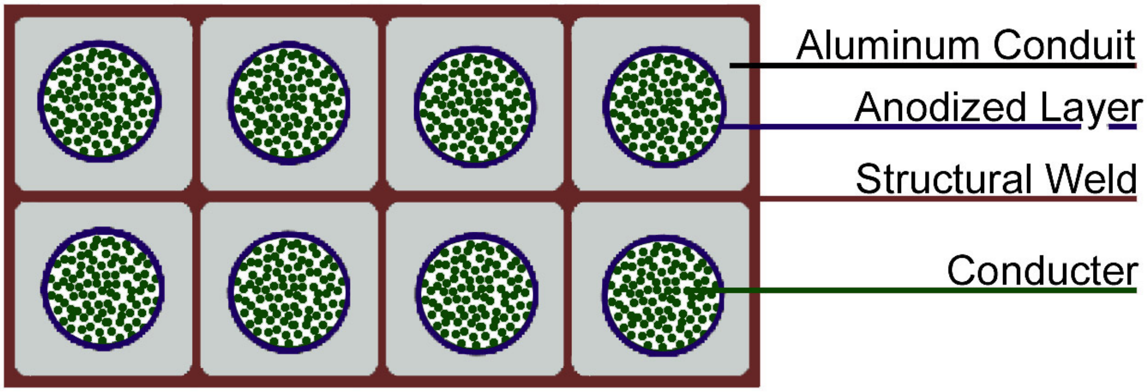
CICC

(Cable-in-Conduit-
Conductor)
high heat removal in the
circulating Lhe
Current densities of
>100 A/mm^2

High current operation
needed

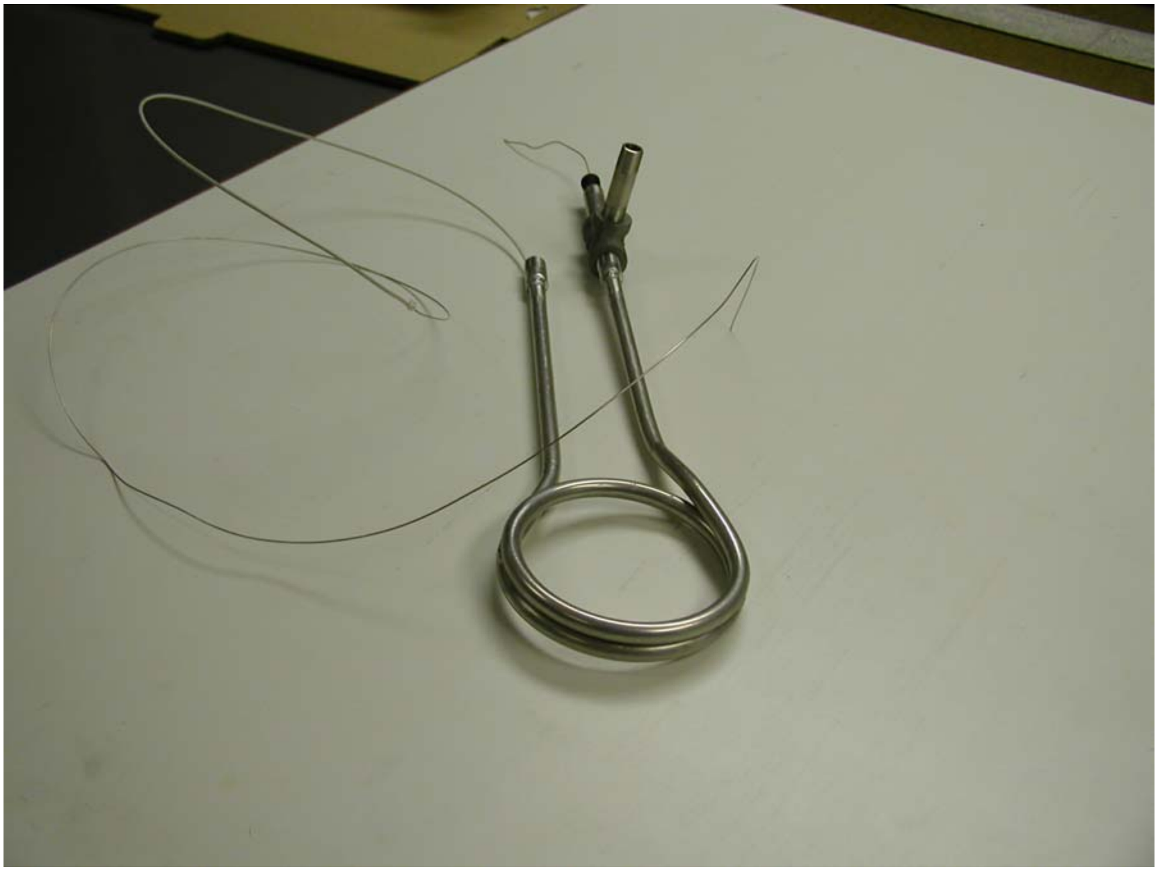


Schematic of an internally anodized CICC coil.

Anodic layer exaggerated for clarity.

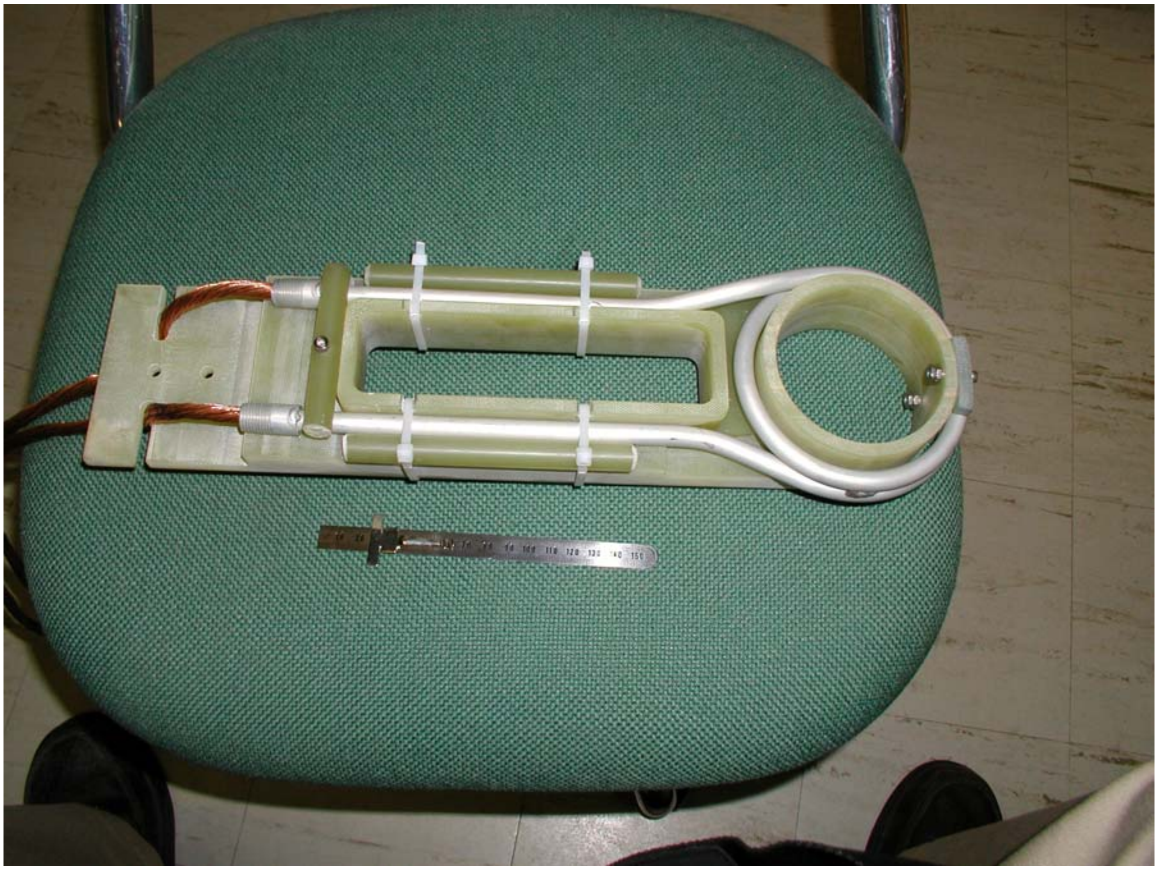
CICC coils get their strength from the cable, so major requirement is dielectric strength

Inorganic insulators such as Al_2O_3 and $MgAl_2O_4$ (spinel) have excellent radiation resistance ($>10^{11}$ Gy)

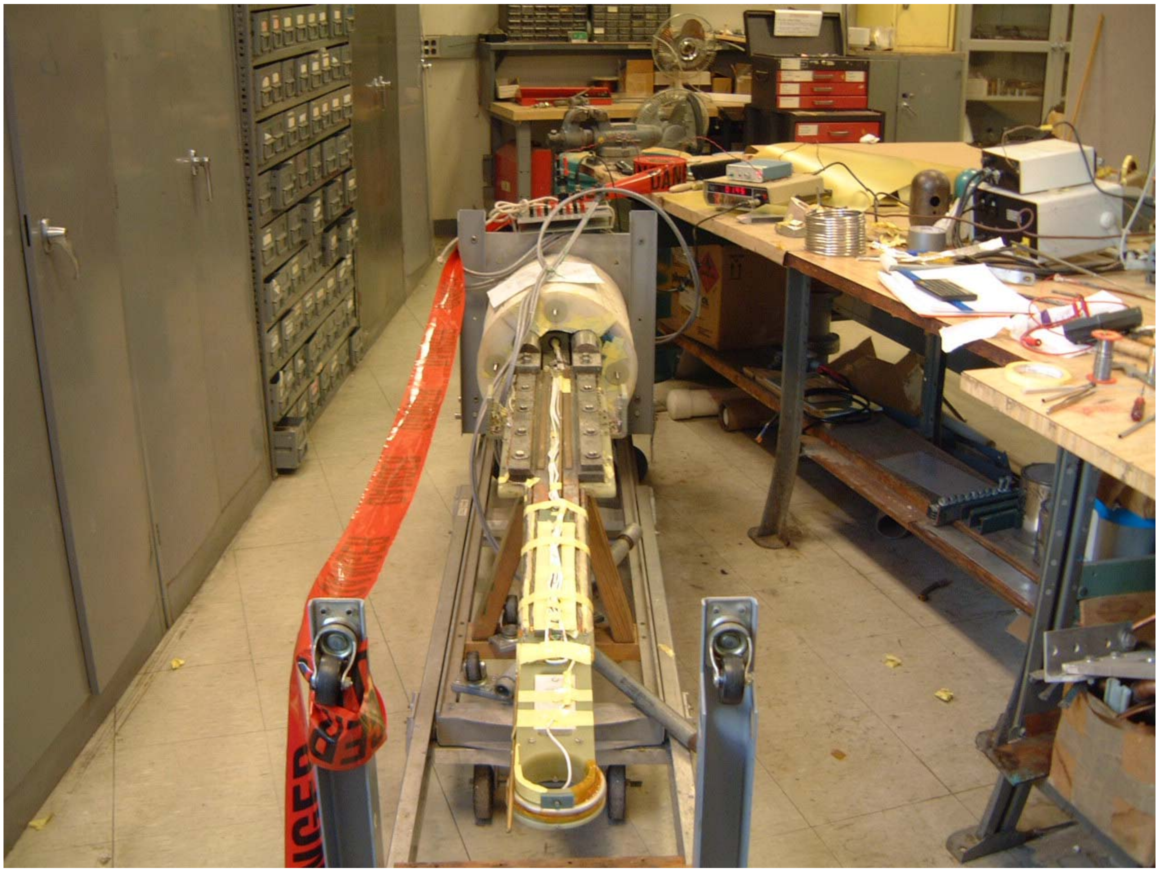


Anodizing Set Up

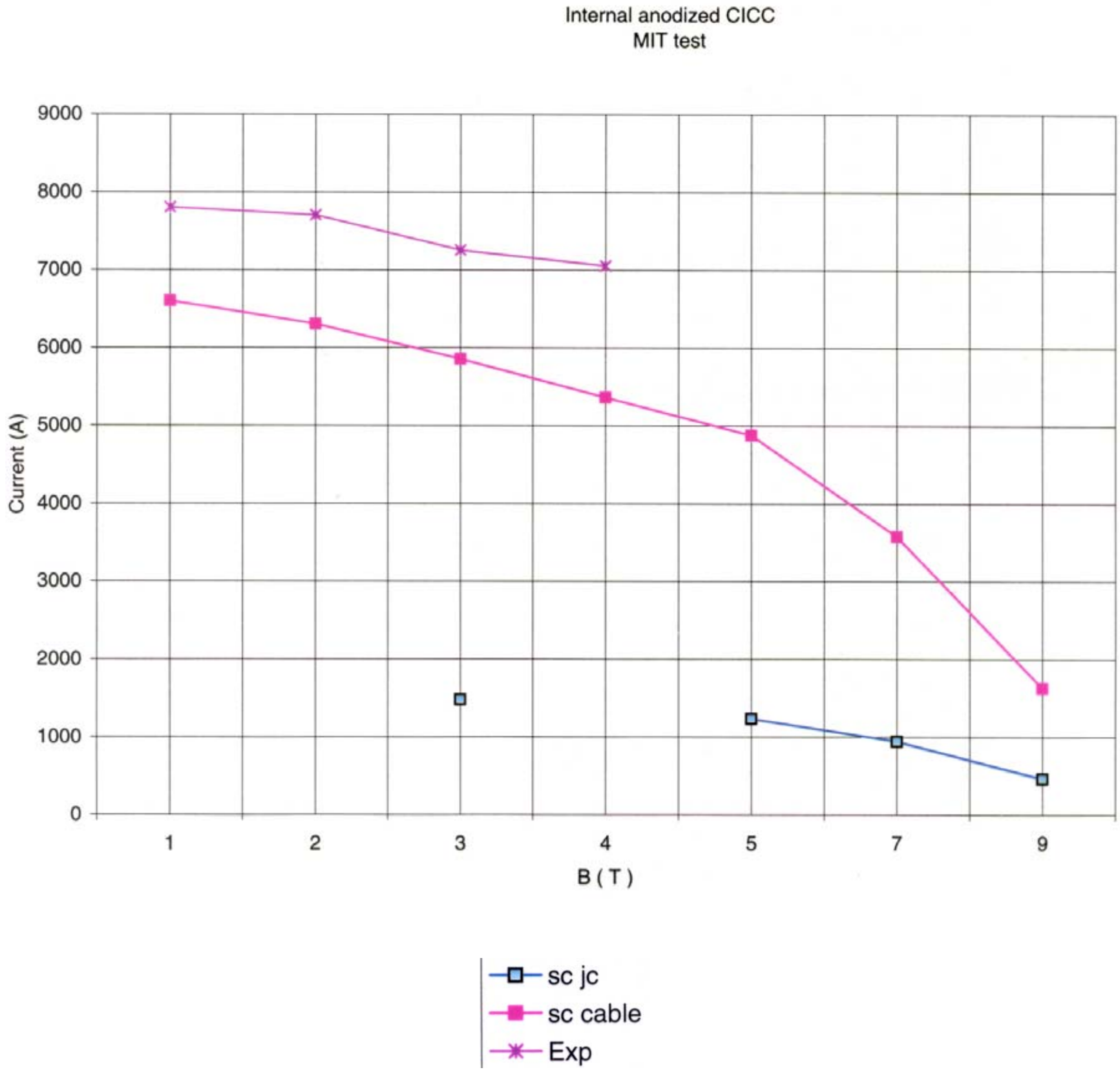
Polyvinyl alcohol film used as a slip-plane for cable insertion dissolves in hot water



Internally anodized coil in test fixture



Coil test fixture at MIT



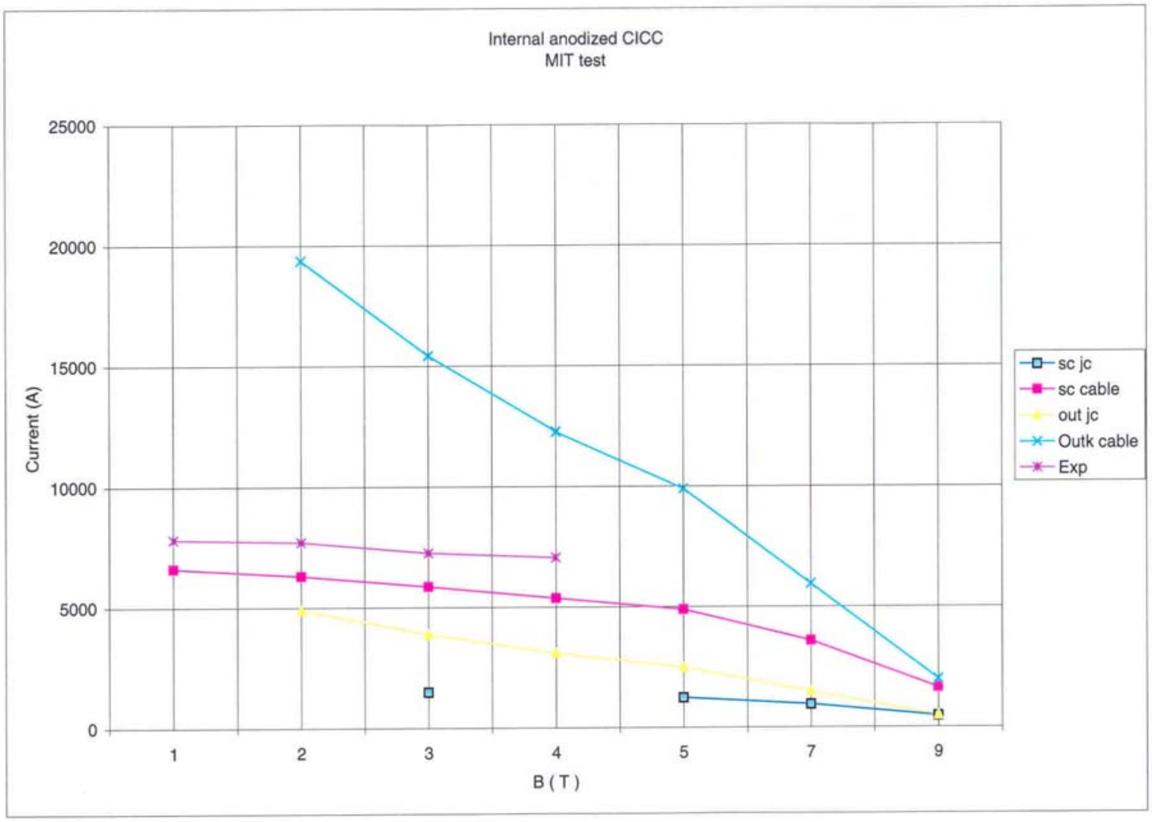
Measured currents in test coil

Note: Vendors specifications are guaranteed currents

MIT tests yield an engineering current density of 70 A/mm^2 at 4 T

Going to a lower Cu:SC and conductor optimized for 2-5T yields >100 A/mm^2

Power supply limit 10 kA means going to smaller cable



Using the upper line for low-field-optimized conduction increases critical currents without increasing fill-factor

Problems with anodized insulation:

Need to bend before anodizing

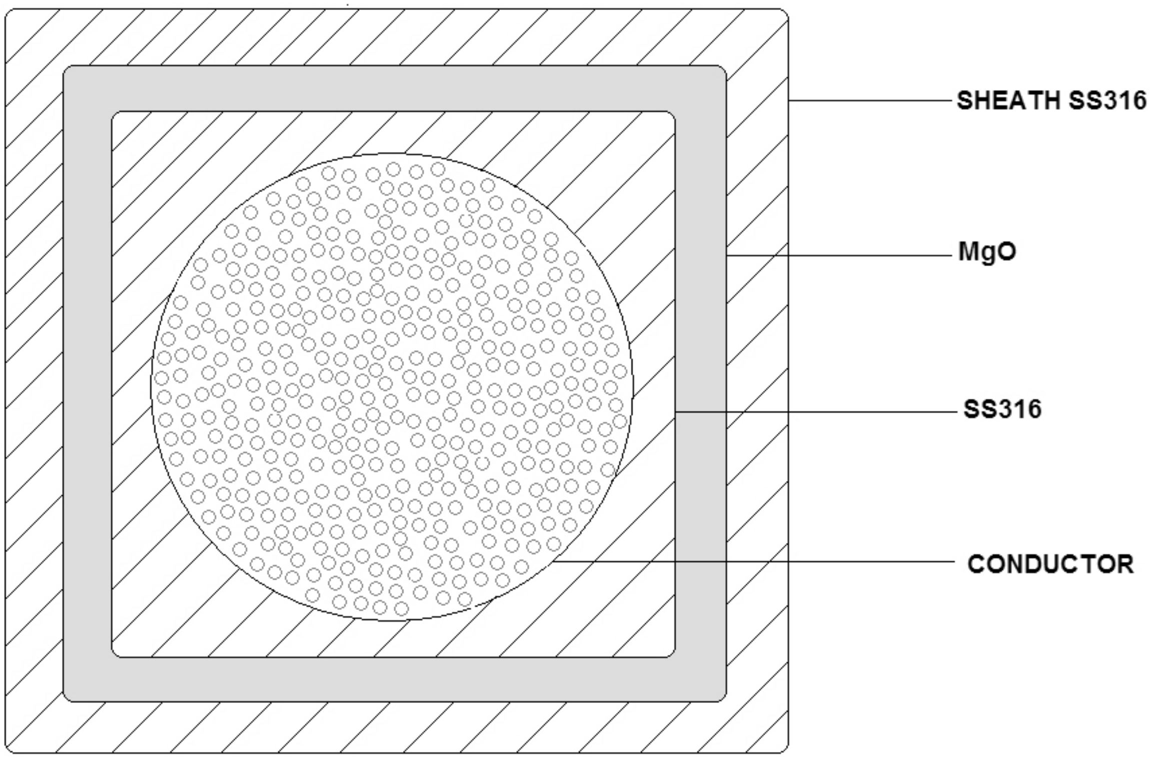
(some bending possible)

Difficult to insert conductor

Won't work with Nb_3Sn in aluminum conductor (melts).

1 hour of anodizing = **18μm** thick layer
Holds 500 VAC

Bend 9.5 mm diameter conduit over 250 mm radius reduces to 100 VDC


SHEATH SS316
MgO
SS316
CONDUCTOR

Metal oxide insulated CICC

Develop different insulations: MgO, Al_2O_3 and spinel (MgAl oxide)

Will probably work with Nb_3Sn in wind-and-react construction

Flexible

Long lengths possible

Development underway with Tyco Controls of Canada

MICICC example:

KSTAR:
25.7 X 25.7 mm^2 CICC
35.2 kA @7.5 T
= 53 A/mm^2 per CICC

add 1 mm MgO and 1 mm SS
= 40 A/mm^2 but includes insulation

ITER CS Model Coil

50.9 X 50.9 CICC

43 kA @ 13 T

= 16.6 A/mm^2

with MgO and SS

= 14.3 A/mm^2 with insulation

Stress?

Another possibility:
HTS coils

Radiation reduces Tc, but increases Ic

Operate at 20-40 K

Reduced load on helium system

Development underway at BNL

Summary

Internal anodized CICC looks promising

Radiation resistant epoxies for lesser radiation environments

Metal oxide CICC another possibility, especially for Nb_3Sn