Radiation Heat Deposition in LHC IR Quadrupoles

I. Novitski, for HFM Group
Fermilab

Facility for Rare Isotope Beams

10 May - 14 May 2015

Outlines

- Thermal analyses and operation margin definition for NbTi and Nb_3Sn IRQ
- Thermal analysis experimental verification
- Nb_3Sn IRQ with low-Z mid-plane spacer
- Radiation-resistant materials for coil potting
- Nb_3Sn coil with Matrimid

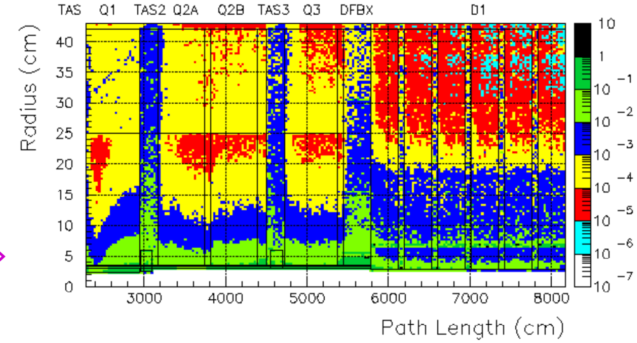
RESMM'15
WORKSHOP ON RADIATION EFFECTS IN SUPERCONDUCTING MAGNET MATERIALS

Thermal analysis of IR quads

Deposition studies to estimate the total radiation heat load to the system for adequate coil cooling and conductor quench margin.

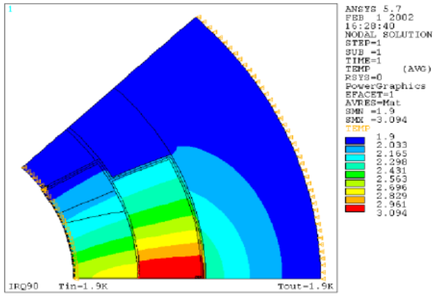
A continuous heat load due to the beam-induced deposition released in IR magnet coils

(pp collisions and beam loss in the IR vicinity, estimated by MARS Monte Carlo codes**)**



The beam induced energy deposition will cause the magnet coil temperature rise

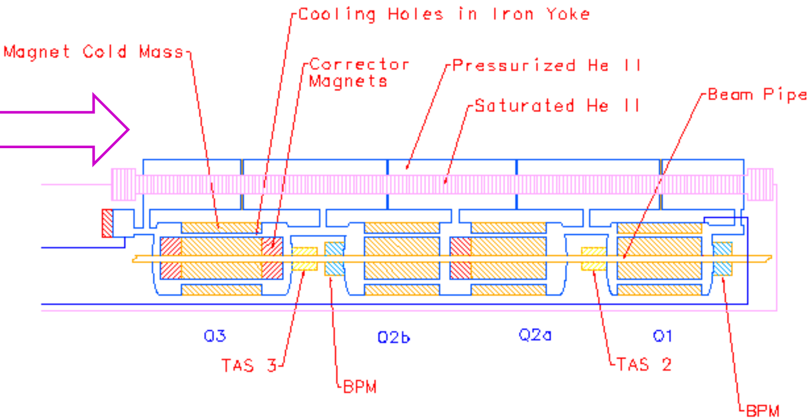
(estimated by ANSYS, FEA**)**



Heat will propagate from the coil (inner layer) through insulation to the helium channel around the beam tube, from the coil (outer layer) to the helium in space between collars or through the collars to the He around collar packs

Heat transfer through He to the heat exchanger located in the iron yoke hole

(Heat transfer analysis, analytical or code**).**



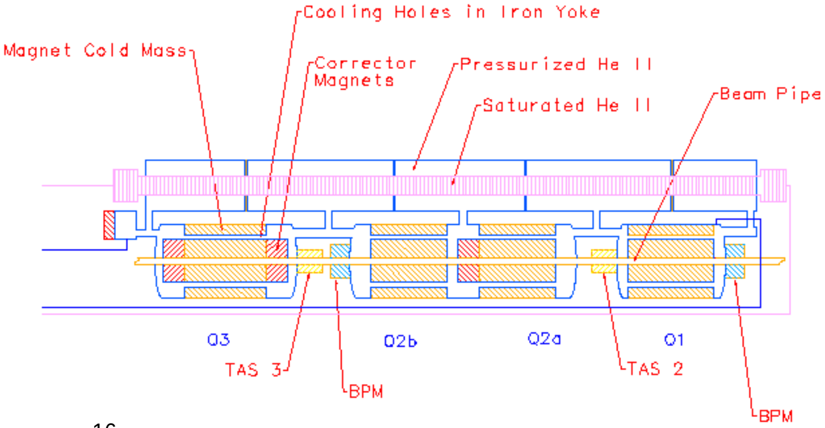
To prevent magnet quench, the cable turn temperature should be below the SC critical temperature

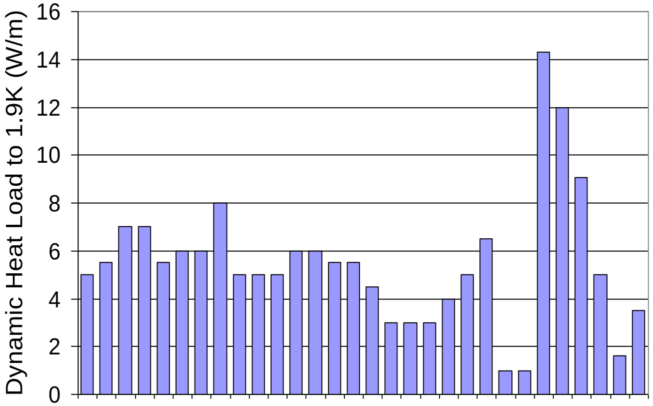
(delta Tc=F(conductor critical surface)**)**

IR Cooling

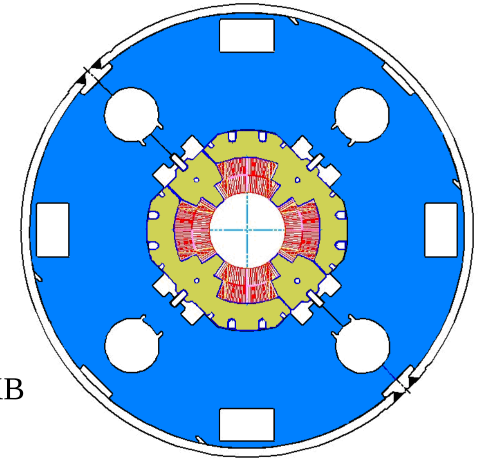
Cryogenic System

- Average dynamic heat load is 5 W/m, with a peak of ~15 W/m in Q1.
- Cryogenic system maintains the Q1 ‘hottest spot’ temperature within 70mK of system temperature at feed box.
- Channels are engineered into the coil insulation, collar packs, yoke laminations, and end volumes to provide adequate HeII conduction path to the heat exchanger.
- System performance was verified by small and large scale tests.

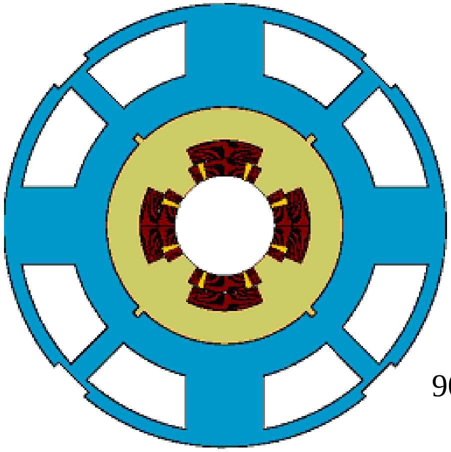




IRQ Magnet Design



70-mm NbTi MQXB cross-section.

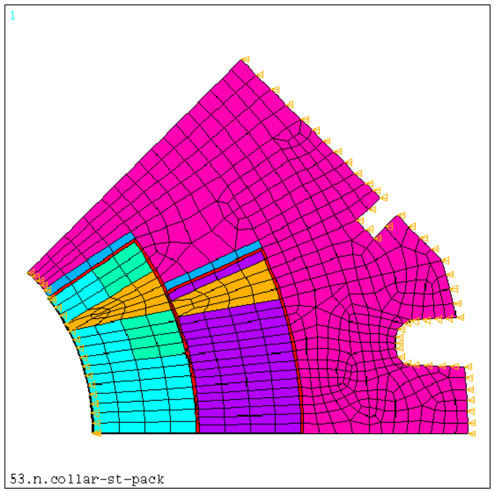


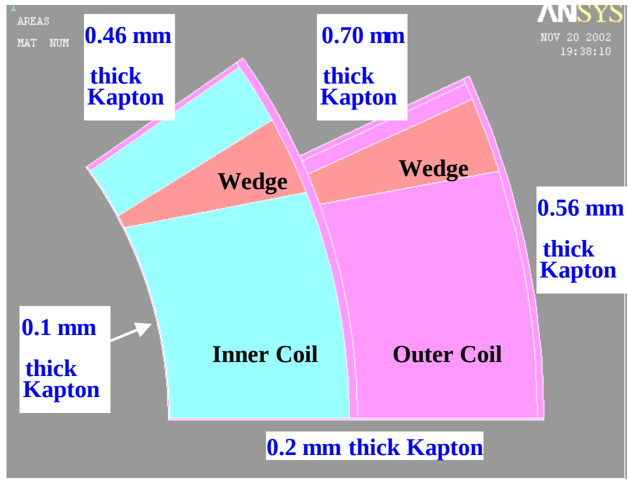
90-mm Nb3Sn quads cross-section.

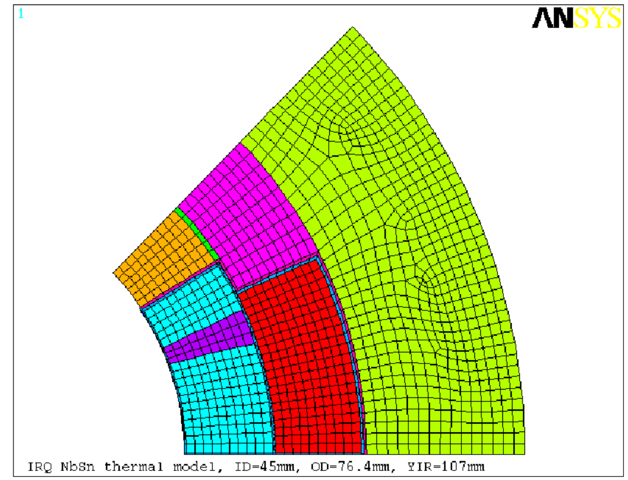
- For the consistent comparison of NbTi and Nb_3Sn IR quads the thermal analysis was performed for magnets with equivalent design and performance parameters.
- Both magnets were designed for maximum field gradient of ~250 T/m.
- NbTi quad coil: 70-mm bore, 15-mm wide graded cable, Kapton insulation.
- Nb_3Sn quad coil: 90-mm bore, 15-mm wide cable, S2-glass/epoxy insulation.
- Support structure: stainless steel collar, cold iron yoke, stainless steel shell.
- Cold mass (coil, collar and yoke) cooling: pressurized HeII at T=1.9 K.

RESMM'15
WORKSHOP ON RADIATION EFFECTS IN SUPERCONDUCTING MAGNET MATERIALS

NbTi MQXB: ANSYS Thermal Model

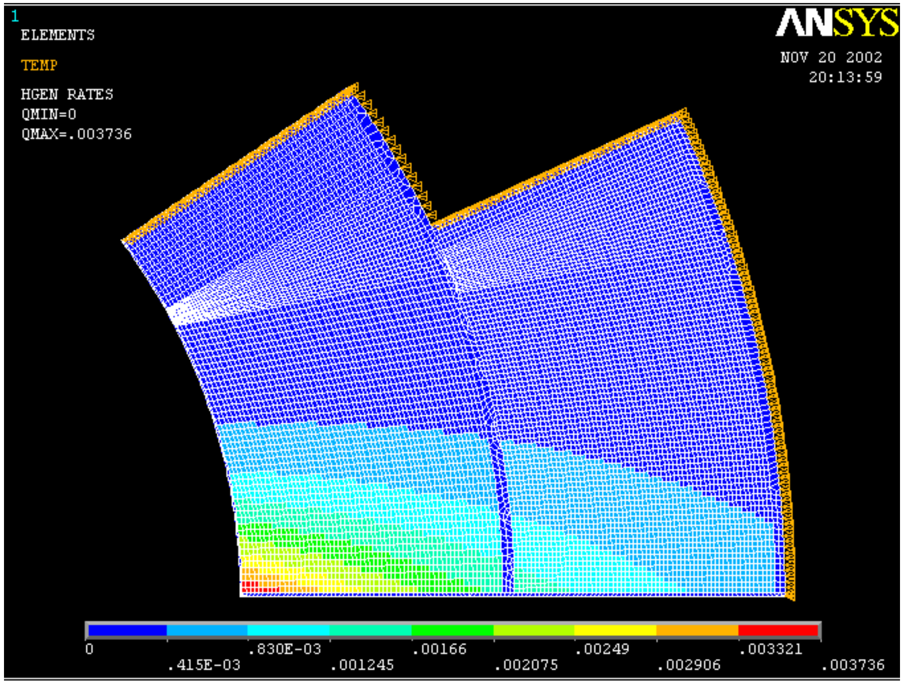






- Two-dimensional (octant symmetry) finite element thermal models of the collared-coil cross-section were developed using ANSYS code.
- It includes the inner and outer coil layers which consist of insulated cables and wedges, the ground insulation, and the stainless steel collars.
- The materials used in the modeled geometry are shown with different colors.

NbTi MQXB: Radiation Heat Depositions



Contour plot of the applied heat load.
There is strong dependence of radiation-induced heat depositions on radial and azimuthal coordinate.

The distribution of radiation-induced heat depositions in the coil was fitted by the function found from the analysis of the heat deposition distribution in MQXB calculated by MARS code:

$$P(r,\vartheta) = Po \cdot \exp\frac{-(r - Rin)}{Ro} \cdot \frac{\vartheta o}{\vartheta + \vartheta o}$$

where

r and θ are polar coordinates,

Rin is the coil inner radius,

Po is the energy deposition power on the coil inner surface,

Ro and θo are fitting parameters.

Can be done differently:

“Smoothing algorithm for histograms of one or more dimensions”, A. Van Ginneken

Material Properties & Cooling Conditions

RESMM'15
WORKSHOP ON RADIATION EFFECTS IN SUPERCONDUCTING MAGNET MATERIALS

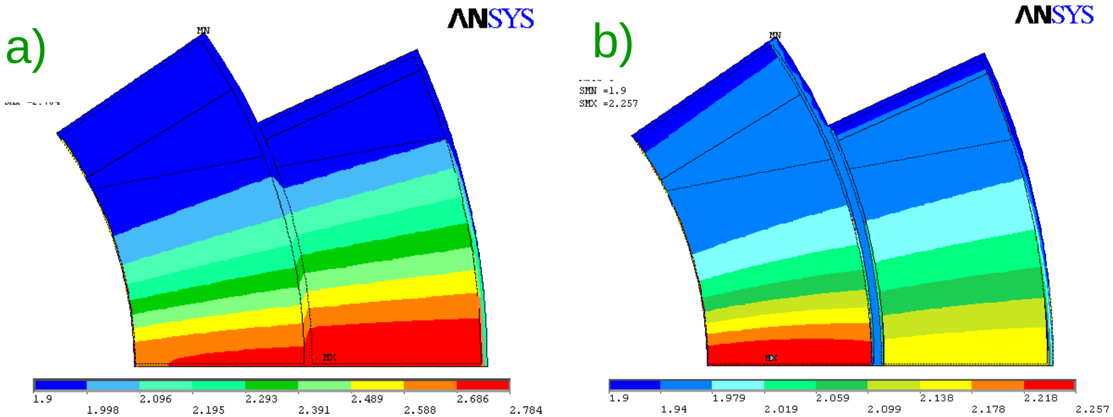
Material	Thermal Conductivity at 1.9 K (W/m/K)
NbTi Inner Coil Azimuthal	0.018
NbTi Outer CoilAzimuthal	0.016
NbTi Inner Coil Radial	4.54
NbTi Outer Coil Radial	6.45
Copper (wedges)	140
Kapton (insulation)	0.005
Stainless Steel (collar)	0.1
Nb3Sn Inner/Outer Coil Azimuthal	0.046
Nb3Sn Inner/Outer Coil Radial	10.0
Bronze (wedges, poles)	0.8
S2-glass/epoxy (cable insulation)	0.03

In this analysis it was assumed that the material properties are independent on temperature.

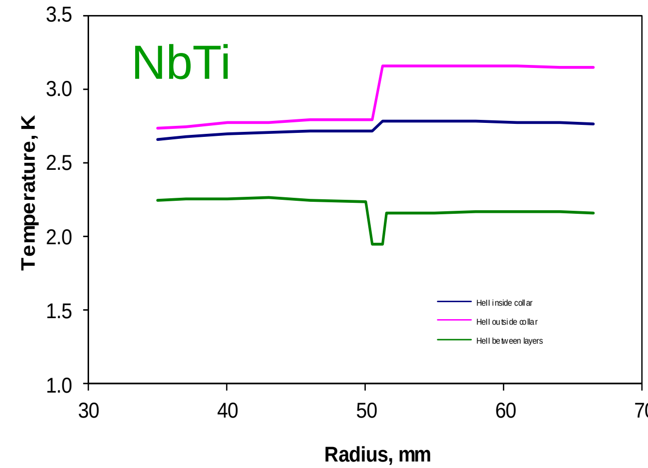
Coil cooling conditions:

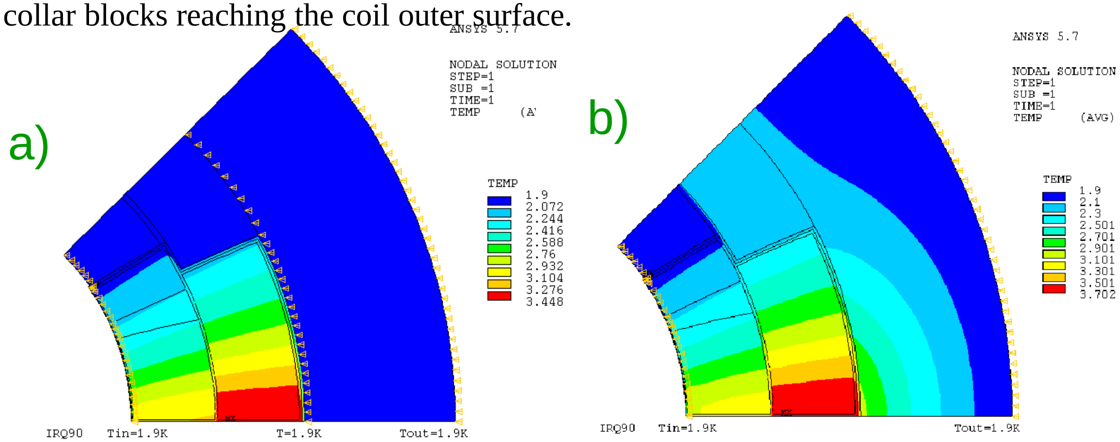
- constant HeII temperature of 1.9 K in the annular channel and on the outer surface of the coil (or collar)
- zero heat flux through the coil mid-plane
- constant heat transfer coefficient of 300 $W/m^2/K$ in the bore (Kapitza resistance)
- space between the turns inside the coil and between the coil layers is closed (filled) by cable insulation
- cooling channels between the coil layers was modeled by applying a temperature boundary condition of 1.95 K between the coil layers.

Temperature Profile

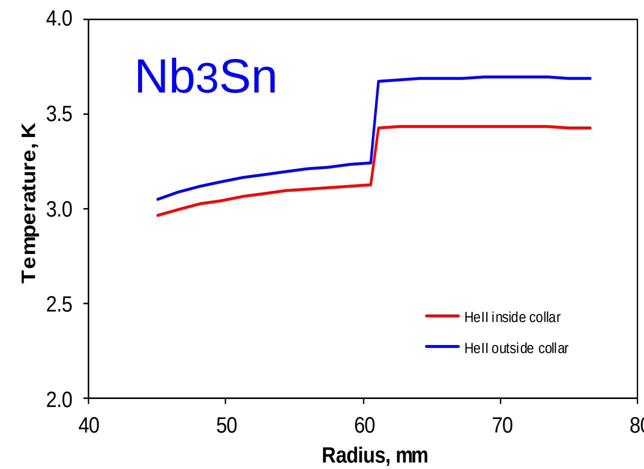


The calculated temperature profile in NbTi IRQ for two cases: a) without and b) with the inter-layer HeII channel. In both cases it is assumed that HeII penetrates inside the collar blocks reaching the coil outer surface.





The calculated temperature profile in Nb3Sn IRQ without the inter-layer channel for two cases: a) HeII penetrates between collars reaching the coil outer surface; and b) HeII does not penetrate inside collar blocks.



Calculated temperature profile along the coil mid-plane in IR quads

Operation Margin and Quench Limit

The **Magnet Operation Margin** (*MOM*) with respect to the radiation heat deposition in the coil could be defined as the **minimum** value **of Turn Operation Margins** (*TOM)* defined as

$$TOM_i = Pav_{c\_i} / Pav_{t\_i}$$

Pav_{c_i} is the turn quench limit

Pav_{t_i} is the average radiation heating power deposited in turn #i

The **Turn Quench Limit** could be calculated as

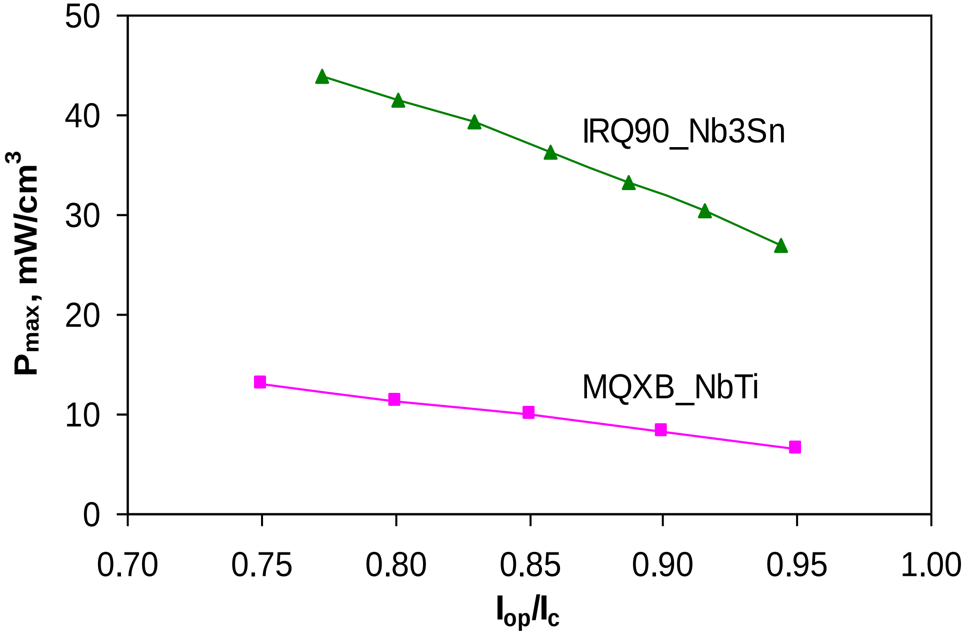
$$Pav_{c\_i} = dT_{c\_i} / k(P_{av\_i})$$

dT_{c_i} is turn critical temperature margin

$k(P_{av\_i})$ represents the turn cooling conditions in the coil.

Coefficients $k(P_{av})$ for each turn in magnet coil are determined from the temperature profile calculated by FE analysis and the known distribution of heat deposition in the coil. In case of temperature-independent material properties these coefficients are constants, which depends only on magnet design and turn position in the coil. For the inner layer mid-plane turn these values are NbTi=0.207 K*cm3/mW, Nb_3Sn =0.165 K*cm3/mW.

IRQ Quench Limit



Calculated quench limit for Nb_3Sn IRQ and NbTi MQXB (inner-layer mid-plane turns) wrt the radiation heat depositions vs. the critical current margin at T_{op}=1.9 K.

Quench limit depends on superconductor *Ic(B,T)*, operation current (critical current margin), operation temperature and turn position in a coil.

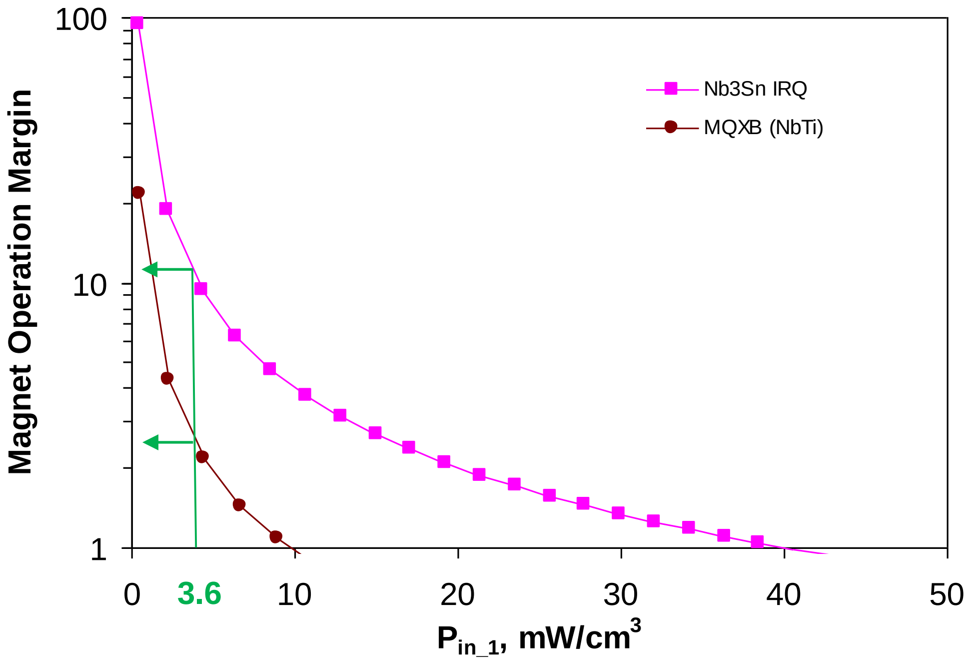
Quench limit at Iop/Ic=0.85 and Top=1.9 K

- 10 mW/cm^3 (NbTi MQXB)
- 36 mW/cm^3 (Nb_3Sn IRQ)

Nb3Sn IR quads provide more than factor of 3 larger quench limit with respect to the radiation-induced heat depositions than NbTi IR quads (MQXB).

The effect of critical current margin is relatively small.

IRQ Operation Margin Calculation



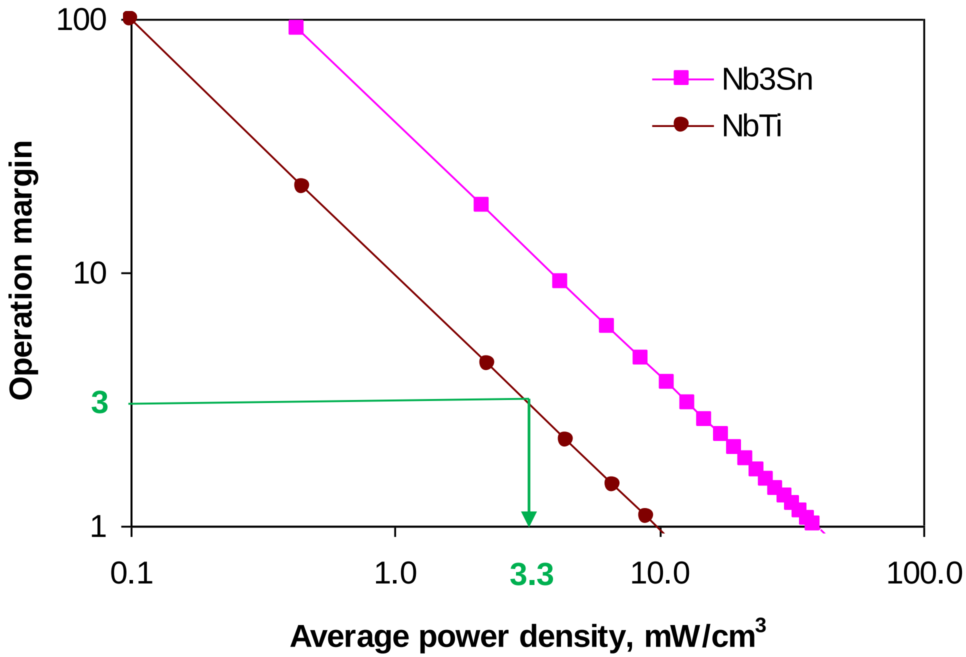
IRQ operation margin vs. the maximum energy deposition in the inner-layer mid-plane turn for the Nb3Sn IR quadrupoles and for the NbTi MQXB.

Energy deposition in the inner-layer mid-plane turn at the nominal LHC luminosity is 3.6 mW/cm^3.

NbTi MQXB quads at G_{nom}=205 T/m, T_{nom}=1.9 K and I_{op}/I_c=0.85 can operate at heat depositions in the coil a factor of ~2.5 higher than the nominal one.

Nb3Sn IR quads at G_{nom}=205 T/m, T_{nom}=1.9 K and I_{op}/I_c=0.85 can operate at heat load level a factor of 10 higher than the nominal one.

IRQ Operation Margin Calculation

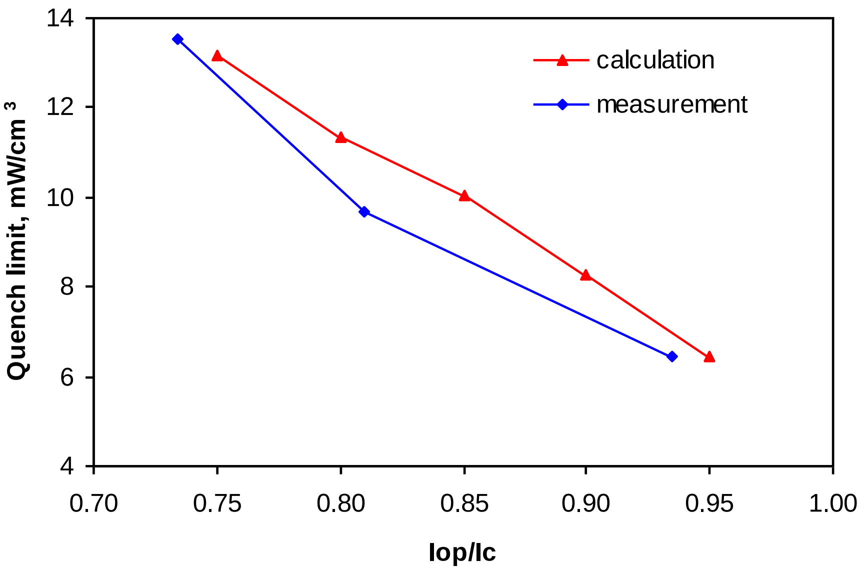


IRQ operation margin vs. the average energy deposition in the inner-layer mid-plane turn for the NbTi and Nb3Sn IR quads at 1.9K and I/Ic =0.80.

IR quads should have the operation margin of ~3 at the nominal operation conditions in accelerator.

Power of radiation heat deposition in the inner-layer mid-plane turns has to be limited by 3.3 and 13.3 mW/cm^3 in NbTi and Nb_3Sn quads respectively.

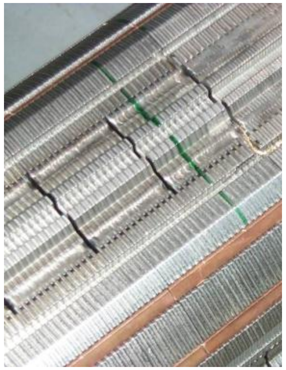
Measurement and Calculation Comparison for NbTi Quad

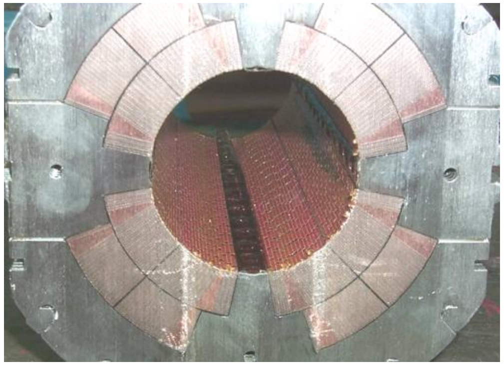


Measured and calculated values of quench limit of inner-layer mid-plane turns for NbTi quarupole model at 1.9 K.

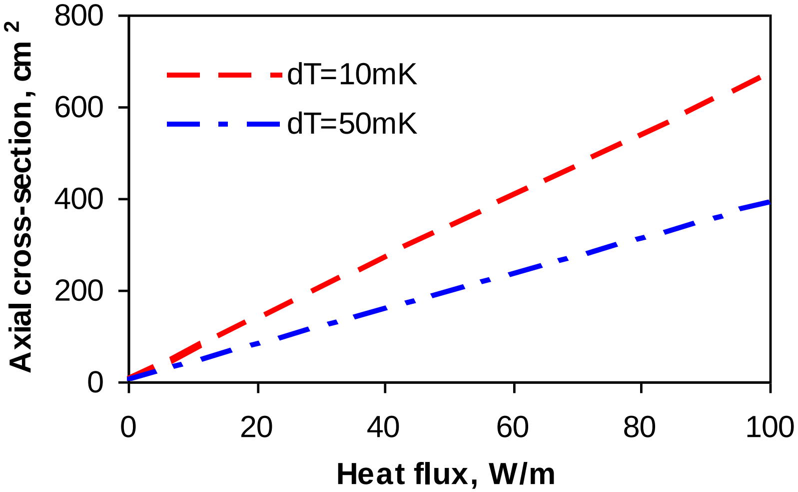
- A special 2-m long NbTi quadrupole model was designed to provide the level of AC losses in the coil comparable with the radiation heat deposition.
- The AC loss power was deposited in the coil inner layer with the maximum at high current ramp rates in the inner-layer mid-plane turns.
- There is a good correlation of measured and calculated data.
- At I_{op}/I_c=0.85 the calculated and measured values of quench limit for NbTi IR quad are 10 mW/cm^3 and 9-9.5 mW/cm^3.

Heat Transfer





Periodic radial channels in NbTi coil



Total cold mass axial heat transport cross-sectional area versus total cold mass heat flux.

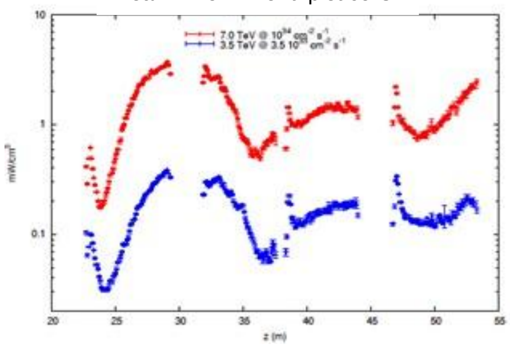
- Magnet quench limits and operation margins are valid if the He temperature does not increase with the heat load variations.
- In case of operation at 1.9 K the HeII temperature is determined by heat transfer inside the magnet cold mass.
- Radial heat transport out to the yoke holes is necessary.
- Radial channels spaced less than 0.5 m are necessary also for quench pressure venting to avoid collapse of the beam tube.
- Heat loads up to 400 W for the present cryogenic system is adequate.

RESMM'15 WORKSHOP ON RADIATION EFFECTS IN SUPERCONDUCTING MAGNET MATERIALS

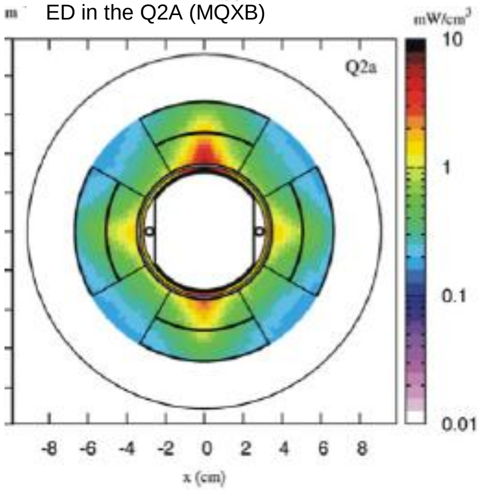
Quench Limit Calculation in MQXB with Network Model

Cable network model

Peak ED on inner triplet coils



ED in the Q2A (MQXB)



- The LHC inner triplet quadrupole magnet MQXB (Q2A) was analyzed with network model.
- Thermal model with all features of NbTi coil and implemented cable and coil insulation scheme, annular helium channel between coil and beam pipe as well as beam pipe and its insulation.
- Two heat load distribution calculated with FLUKA and interpolated into a coil heat load
- Temperature rise is below the quench limit, safety factor is 2.6 at nominal LHC condition (7 TeV, L=$10^{34}cm^{-2}s^{-1}$)

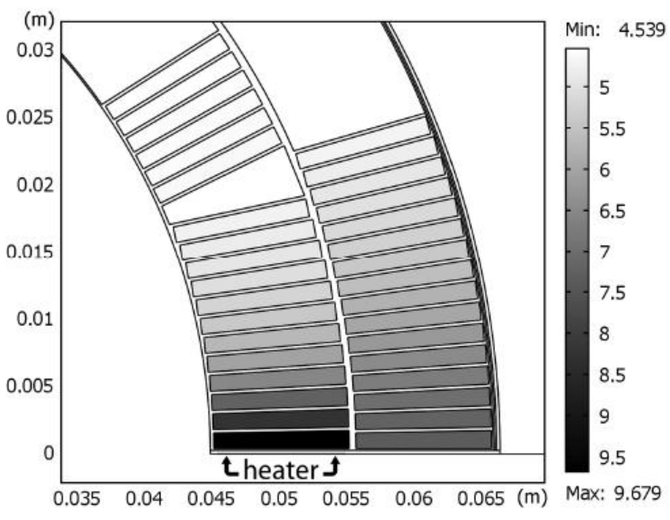
MQXB Quench Limit and Heat Load

Beam Energy (TeV)	Calculated Heat Load (mW/cm^3)	Quench Limit (mW/cm^3)
3.5	0.35	24*
7.0	3.5	9.1

QUENCH LIMIT CALCULATION FOR STEADY STATE HEAT DEPOSITS IN LHC INNER TRIPLET QUADRUPOLE MAGNETS
D. Bocian*, IFJ PAN, Cracow, Poland
F. Cerutti, B. Dehning, L. S. Esposito, A. Siemko, CERN, Geneva, Switzerland
Proceedings of IPAC2012, New Orleans, Louisiana, USA

Quench Margin in Nb_3Sn Quadrupole Magnet

COMSOL Model with temperature dependencies of thermal properties for all materials.



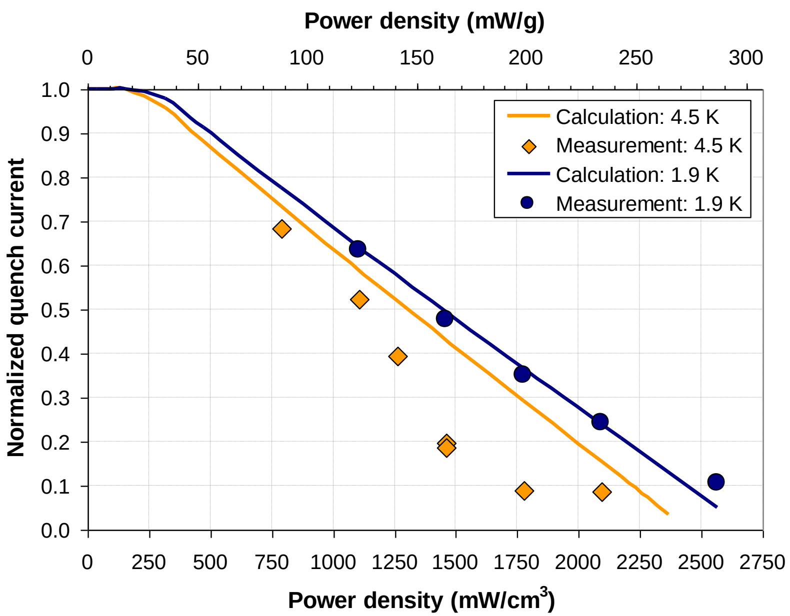
Temperature distribution inside the cable at the heater power of 20 W/m and T_0 = 4.5 K.

TQC02b Nb_3Sn Coils

- The heater experiments were performed in 90mm TQC02b magnet at 4.5K and 1.9K.
- Set heater current to a specific value, and then raising the magnet current to quench with a low ramp rate of 20 A/s to avoid additional coil heating by eddy currents.
- Good correlation between the calculated and measured quench currents at 1.9K.

Measurement and Calculation Comparison for Nb_3Sn Quadrupole

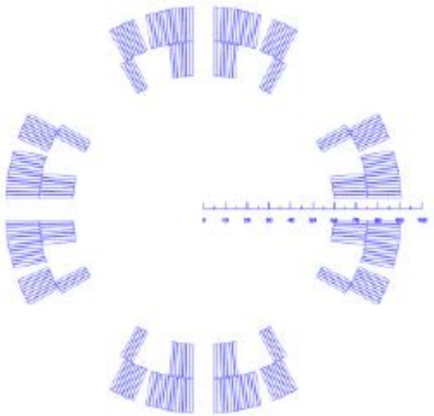
RESMM'15
WORKSHOP ON RADIATION EFFECTS IN SUPERCONDUCTING MAGNET MATERIALS



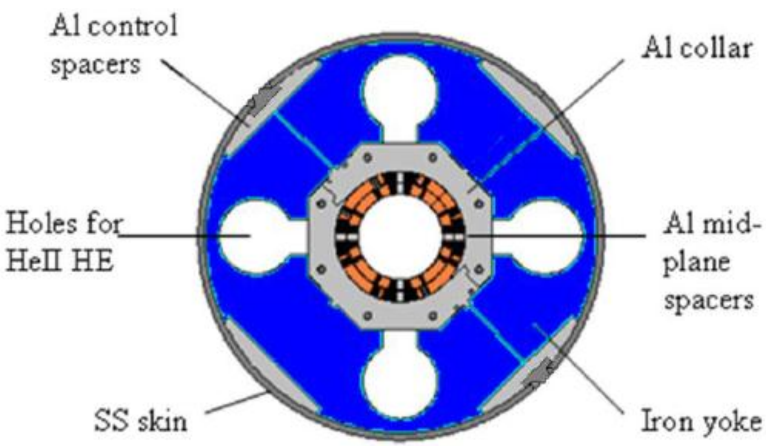
Calculated and measured normalized quench currents as functions of average power density distributed in the mid-plane cable of inner layer.

- The quench limit of Nb_3Sn quadrupoles was estimated using the experimentally verified thermal model.
- TQC models operating at 80% of their SSL can tolerate 165-185 mW/cm^3 of average radiation heat in the inner-layer midplane cables at 4.5 and 1.9 K respectively.
- The previous analysis put a quench limit of 40 mW/cm^3 for Nb_3Sn IR quadrupoles operating at 1.9 K and 80% of their SSL. It is more than a factor of 4 lower than the values quoted above.
- The higher quench limits calculated for TQC are explained by a factor of 2 thinner cable insulation, and by employing the real temperature dependencies of material properties in the model.

120 mm IRQ Magnet with low-Z material



Cross-sections of the coils with mid-plane spacers.



120mm Quadrupole cold mass cross-section.

- 130T/m at Jc(12T,4.2K)=2.5 kA/mm2 with 23% margin
- 2-layer Nb_3Sn coil with 120mm bore
- Rutherford-type cable with 40 strands of 0.7mm in diameter, bare cable width is 15.15mm.
- The cable insulation thickness is 0.1mm.
- 10mm thick AL mid-plane spacer, replaces ~4 turns next to each coil mid-plane where the radiation heat and dose reach their maximum.
- AL collar, two-piece iron yoke 550mm OD, SS skin.
- Cold mass is filled with pressurized HeII at T=1.9 K
- 105mm holes for heat exchanger.

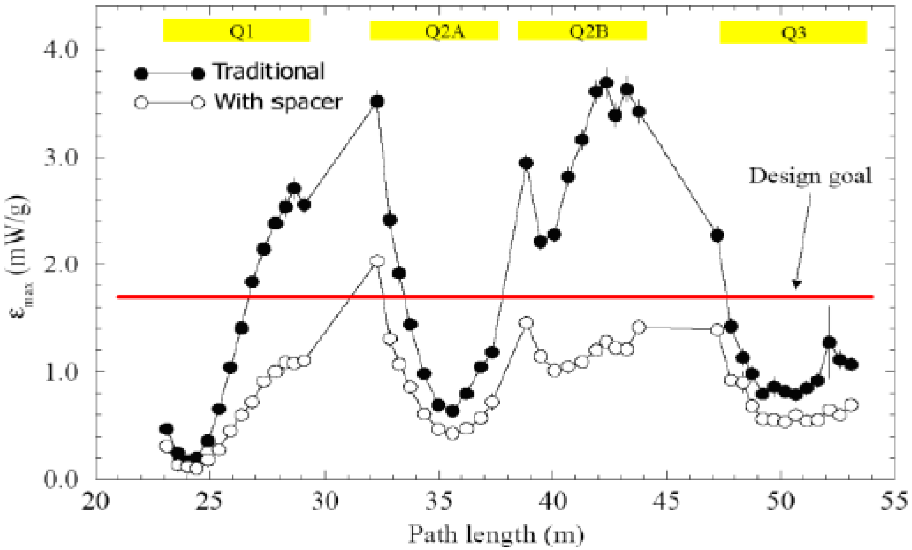
Dynamic Head Load

RESMM'15
WORKSHOP ON RADIATION EFFECTS IN SUPERCONDUCTING MAGNET MATERIALS

Radiation dynamic heat load in Q1(W)

Part	Magnet design		
	With spacer	Without spacer	Reference*
Coil	185	206	205
Collar	37	29	67
Yoke	79	72	42
Total	301	306	314

* Coil without mid-plane spacers with SS collar.



The peak power density in the coil inner layer of the quadrupole with and without Al spacers.

- The dynamic heat load in the coil with AL spacers is 11% lower than in the traditional coils.
- The power dissipation in the AL collar is also almost a factor of two lower than in the SS collar.
- More transparent for particles coil and AL collar increase the heat deposition in the iron yoke by a factor of two making the radial heat distribution more uniform.
- The total dynamic heat loads on the cryogenic system in the case with AL spacers and collar is 5% lower than in the traditional quadrupole design.

RESMM'15 WORKSHOP ON RADIATION EFFECTS IN SUPERCONDUCTING MAGNET MATERIALS

Coil Impregnation Materials

Studies to replace CTD101K epoxy as an impregnation material for Nb_3Sn coils with high radiation-resistant material like polyimide solutions started at Fermilab ten years ago.

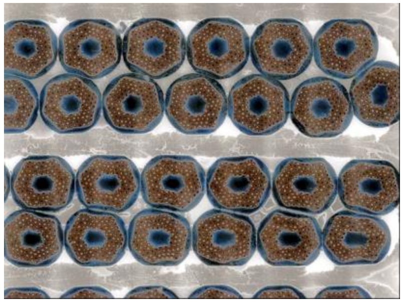
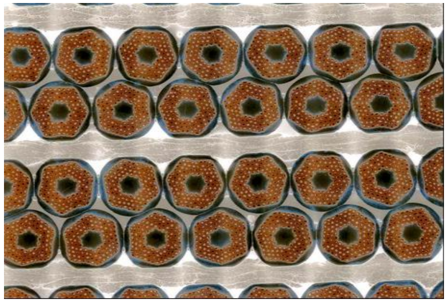
The studies concentrated on Matrimid®5292, a bismaleimide based material, which has an appropriate combination of viscosity and potlife, and provides excellent coil mechanical, electrical and thermal properties. A second good candidate is Cyanate Ester Blend (CTD425).

Features of Potting Materials

Material	CTD101K	Matrimid 5292	CTD425
Family	Epoxy	Bismaleimide	Cyanate Ester Blend
Initial Viscosity	100cP	10cP	70cP
Potting Temperature	60° C	125° C	60° C
Max Cure Temperature	135° C	200° C	150° C
Pot Life	24 hours	60 minutes	100 hours

Impregnation Quality Test

- Mechanical measurements of cables were performed on small stacks.
- Two stacks of each material were polished and observed under a microscope to assess the degree of fill around and within each turn (grey-filled material, white-voids).
- Impregnation quality of the stacks of the three materials is adequate, with the cyanate ester stack having slightly better fill than the other two.
- The quality of impregnation compares well with stacks and coils made in past tests.

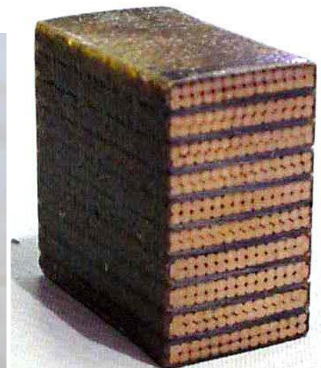

(a) (b) (c)

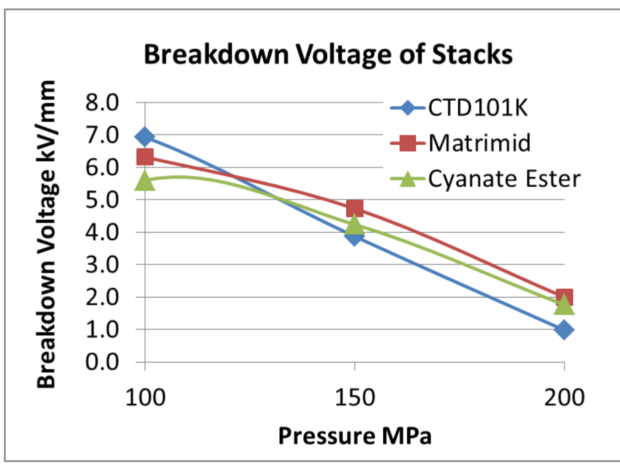
Sections of impregnated stacks. CTD101K (a) Matrimid 5292 (b) and Cyanate Ester CTD425 (c)

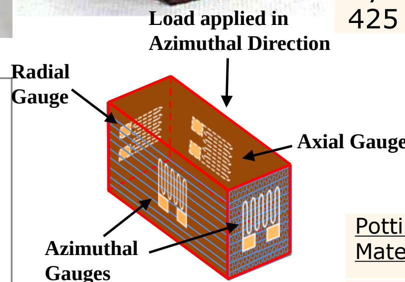
RESMM'15
WORKSHOP ON RADIATION EFFECTS IN SUPERCONDUCTING MAGNET MATERIALS

Material Properties

Breakdown Strength as a function of Pressure







Thermal contraction coefficients from room temperature to 77K (m/m)

Material	CTE azimuthal	CTE radial	CTE axial
Quartz Reference sample	0	0	0
Aluminum test sample	.0038	.0038	.0038
CTD-101K	.0032	.0022	.0019
Matrimid 5292	.0033	.0017	.0017
Cyanate Ester 425	.0029	N/A	.0018

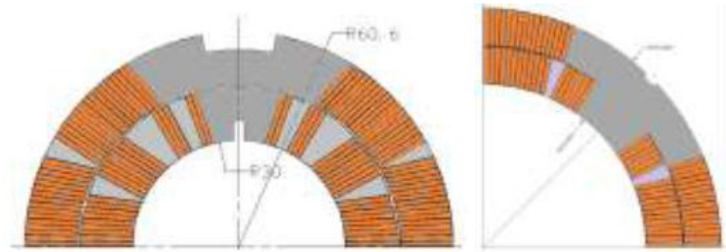
Young's Modulus of Elasticity and Poisson's Ratio of stacks pressed azimuthally and radially.

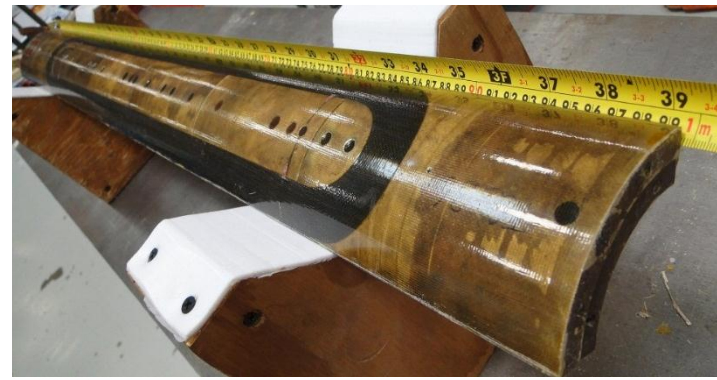
Potting Material	Stack Type (Pressing direction)	Parameter	Initial Pressing	Subsequent Pressings
CTD101K	Azimuthal	Young's Modulus Az	17	37
		Poissons ratio radial	.34	.37
		Poisson's ratio axial	.12	.20
	Radial	Young's Modulus Rad	30	33/46*
Matrimid 5292	Azimuthal	Young's Modulus Az	12	31
		Poissons ratio radial	.27	.39
		Poisson's ratio axial	.11	.14
	Radial	Young's Modulus Rad	22	21/51*

*33/46 and 21/51 represent Young's Modulus (between 0-100 MPa/between 30-100 MPa)

Coil Impregnation with Matrimid

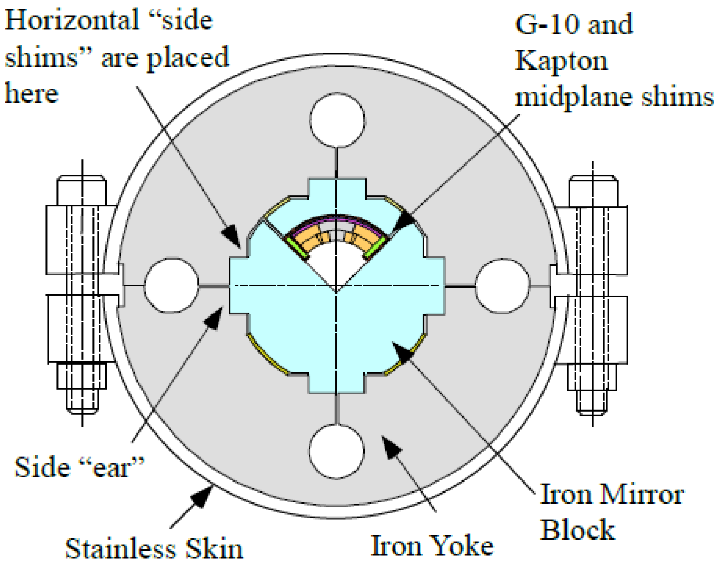
- Two Nb_3Sn coils, a 1 m long quadrupole coil and a 2 m long dipole coil, were impregnated with Matrimid.
- The impregnation temperature for Matrimid was 125 C and the potting time for the 1 m long quadrupole coil was 15 min.
- The potting time of the 2 m long dipole coil increased to ~45 min.
- After impregnation the coils were rested at 125 C and atmospheric pressure during 1 hour before ramping to cure temperature of 200 C.

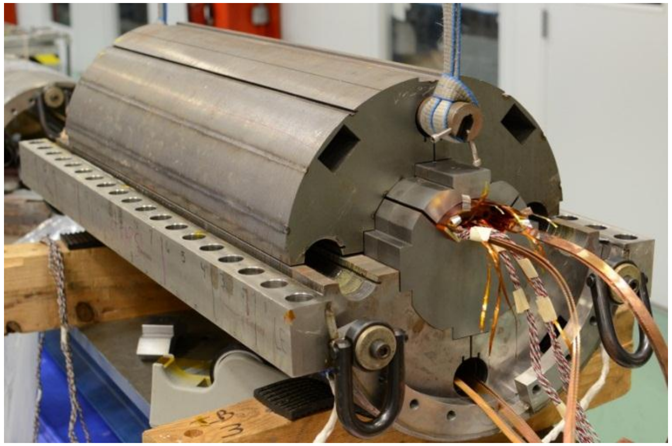




TQM05 Mirror Magnet

- 1m long quadrupole coil potted with Matrimid.
- The final azimuthal coil pre-stress of TQM05 at room temperature was 144 MPa.
- The quadrupole mirror TQM05 was tested at FNAL Vertical Magnet Test Facility.
- The magnet was tested in two thermal cycles with quench training, studies of ramp rate dependence both at 4.5 and 1.9 K, as well as measurements of temperature dependence of magnet quench current.

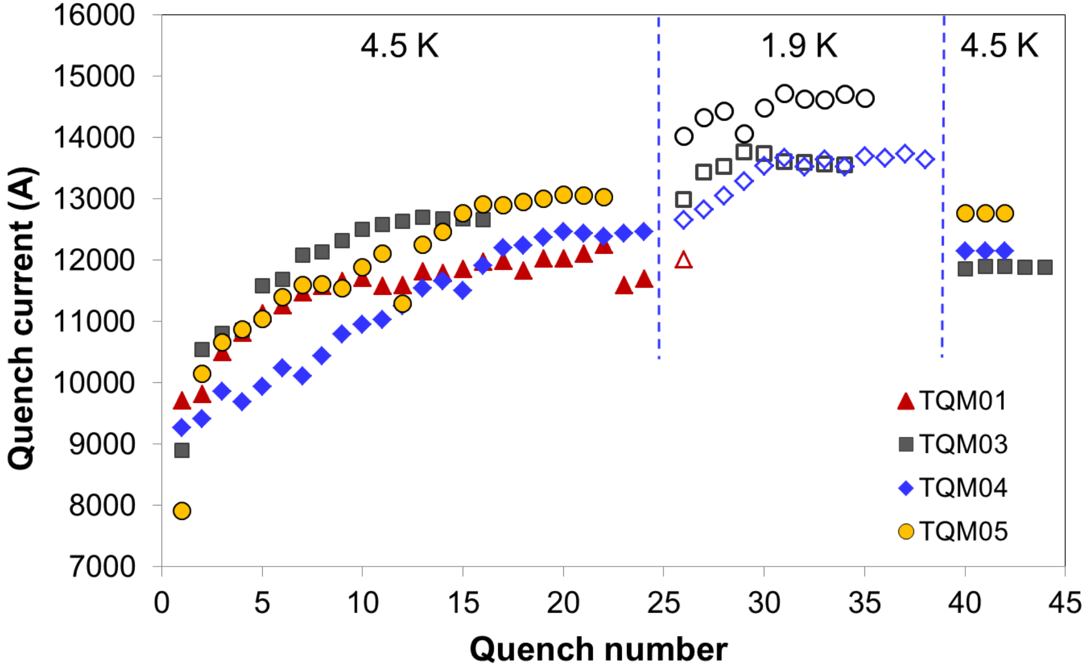




RESMM'15
WORKSHOP ON RADIATION EFFECTS IN SUPERCONDUCTING MAGNET MATERIALS

Quench History

Quench plot of Matrimid mirror coil vs CTD101K coils



Matrimid could be considered as a potting material for the Nb_3Sn accelerator magnets operating in severe radiation environments.

- Similar quench performance for all coils
- 98% of SSL reached at different temperatures
- Training quenches initiated in the pole-turns
- Final 4.5 K quench plateau established at 96% of SSL
- Results compare favorably with similar coils made with CTD101K

References

A.V. Zlobin et al., “Large-Aperture Nb3Sn Quadrupoles for 2nd generation LHC IRs”, *Proc. of EPAC’2002*, Paris, 2002, p. 2451.

D. Chichili et al., "Investigation of alternative materials for impregnation of Nb_3Sn magnets," *IEEE Trans. on Appl. Supercond.*, Vol.13, N 2, 2003, p. 1792.

N. Mokhov et al., “Energy Deposition Limits in a Nb3Sn Separation Dipole Placed in Front of the LHC High-Luminosity Inner Triplet”, Proc. of PAC2003, Portland, OR, p. 1733 (2003).

Novitski, I. and Zlobin, A. V., “Thermal Analysis of SC Quadrupoles in Accelerator Interaction Regions,” *IEEE Trans. Appl. Supercond.*, vol. 17, no. 2, Jun. 2007, pp. 1059-1062.

Zlobin, A. V., et al., “Nb_3Sn Quadrupoles in the LHC IR Phase I Upgrade,” *Proc. 2008 European Particle Accel. Conf.,* pp. 2491-2493.

V.V. Kashikhin et al., “Quench Margin Measurement in Nb3Sn Quadrupole Magnets”, IEEE Transactions on Applied Superconductivity, Vol. 19, Issue 3, June 2009, Page(s): 2454 – 2457.

V.V. Kashikhin et al., “Performance of Nb3Sn Quadrupole Magnets under Localized Thermal Load”, CEC/ICMC’2009, Tucson, AZ, 2009.

Zlobin, A. V., et al., “Testing of Nb_3Sn Quadrupole Coils Using Magnetic Mirror Structure,” presented at CEC/ICMC 2009, Tucson, AZ, 2009.

Zlobin, A. V., et al.,”120-mm Superconducting Quadrupole for Interaction Regions of Hadron Colliders”, Proceedings of IPAC, 2010, Kyoto, Japan.

D. Bocian et al., “Quench Limit Calculation for Steady State Heat Deposits in LHC Inner Triplet Quadrupole Magnets”, Proceedings of IPAC, 2012, New Orleans, Louisiana, USA

R. Bossert, et al., “Fabrication and test of 90-mm Nb_3Sn quadrupole coil impregnated with MATRIMID – bismaleimide based material*”,* in *IEEE Trans. on Appl. Supercond.*, Vol. 23, N 3, 2013, p. 400-405.

Zlobin, A. V., et al., “Test results of a Nb3Sn quadrupole coil impregnated with radiation-resistant Matrimid 5292”, Proceedings of IPAC, 2013, Shanghai, China.

R. Bossert, et al., “Recent Progress and Tests of Radiation Resistant Impregnation Materials for Nb3Sn Coils”, CEC/ICMC-2013 , Anchorage, Alaska, USA