Thermal analysis of a conduction-cooled superconducting quadrupole for ILC Main Linac with large temperature margin

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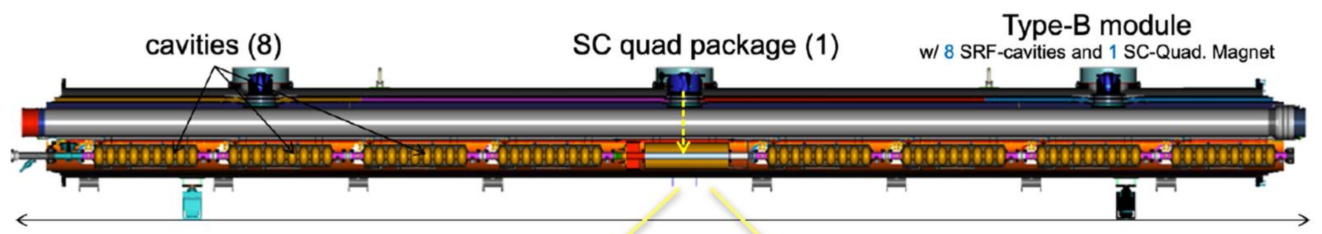
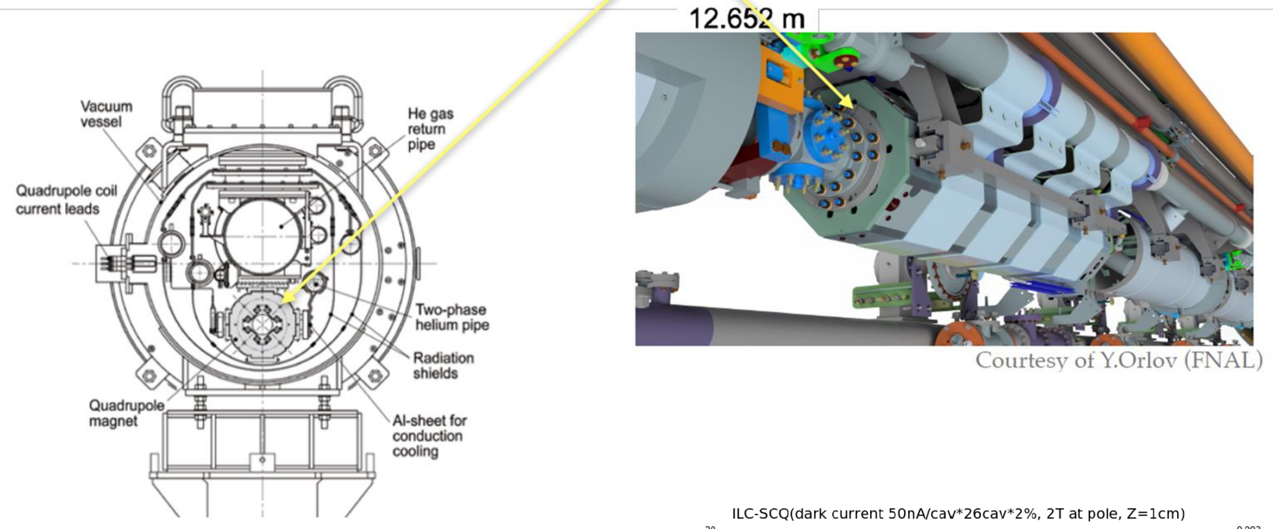
Abstract: The Main Linac of the International Linear Collider (ILC) includes superconducting quadrupole (SCQ) packages that are located between the superconducting RF cavities, with one SCQ within each of the Type-B cryomodules. This combined-functioned, splittable superconducting magnet focus and steer the electrons and positrons. The magnet is required to be cryogen free, and conductively cooled down via thermal links. This links should be connected to the outer surface of the transfer line that supplies liquid helium to the RF cavities. Additionally, to address the large heat deposition expected in the superconducting coils due to beam-induced dark currents, the use of Nb_3Sn strand is advocated for the coil, given their superior thermal margin related to NbTi.

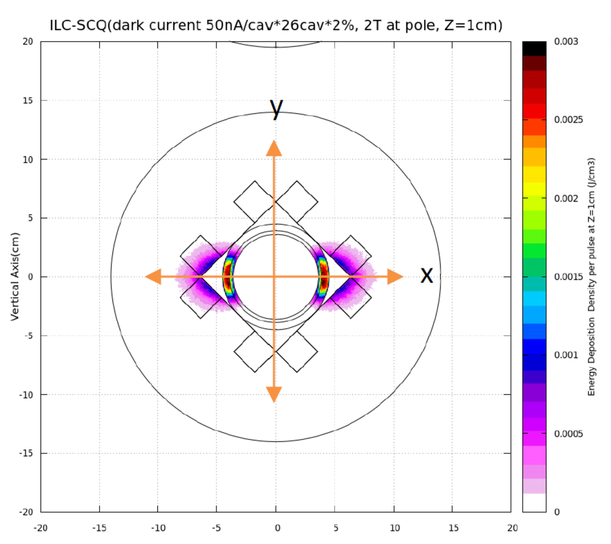
This poster depicts a numerical analysis of the thermal behaviour of the impregnated Nb_3Sn quadrupole coils and proposes a conduction-cooling strategy for these coils. The anisotropic behaviour of the coil has been thoroughly examined. A highly conductive casing for the coil has been designed and high purity aluminium sheets have been integrated to significantly improve thermal management.

Introduction





- ILC SC quadrupole package with an estimated high heat input (1,25 W) on each coil from beam dark currents. [1]
- **Nb_3Sn** single strand quadrupole coils with critical temperature of 13 K.



X-Y Cross-Section

Dark current deposition in quadrupole coils [1]

[1] A. Yamamoto et al., "*Dark Current Electrons and Irradiation Heating of Superconducting Magnets for High-Gradient SRF Linacs*", presented at TTC-2021, DESY (online), 20 Jan. 2020

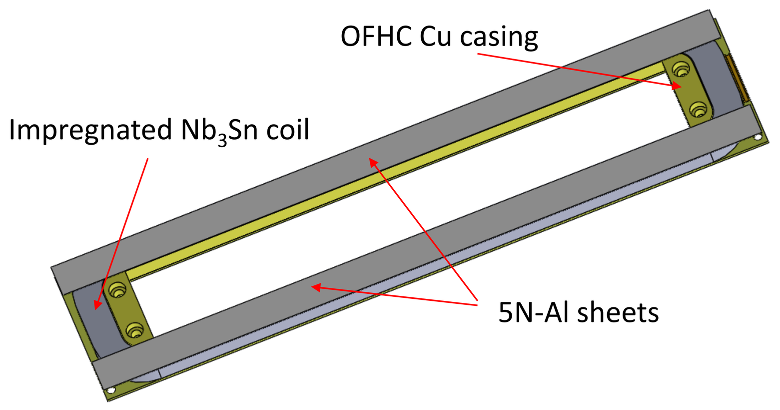
Materials

Highly conductive materials around the coil to extract dark current heat deposition.

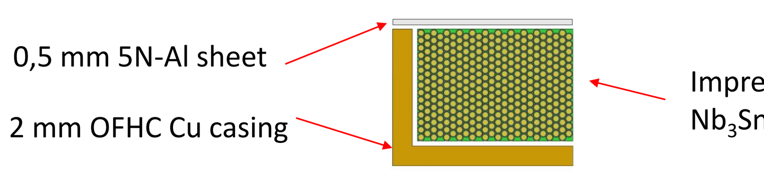
- OFHC Copper for the casing on the bottom and lateral of the coil.
- Al 5N Sheets on top of the coil.

Anisotropy of the impregnated, fiberglass insulated, Nb_3Sn Coil is considered in the thermal conductivity estimations:

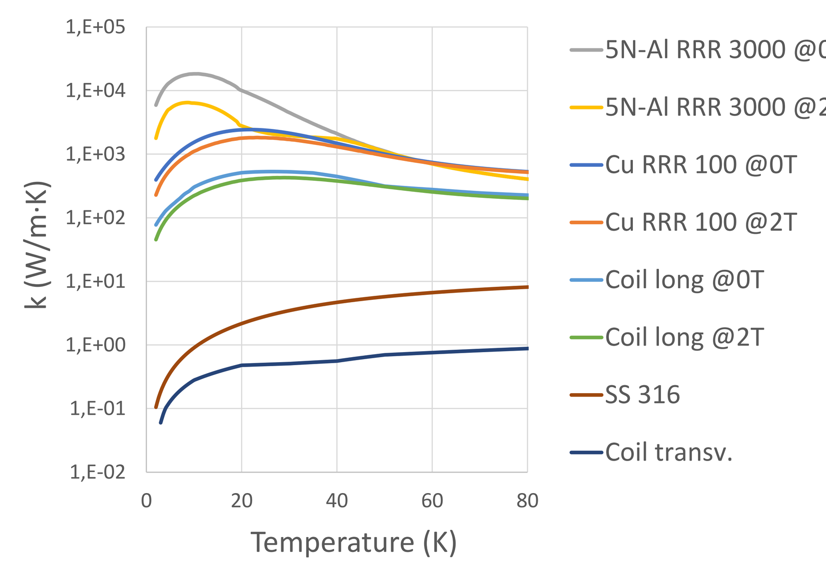
- Cross-section: Layers of **resin** in series with layers of copper. Cu as perfect conductor.
- Longitudinally: **Copper + bronze** + SC + charged resin + uncharged resin in parallel. SC and resin assumed non-conductor.



Quadrupole Coil assembly



Quadrupole coil assembly cross-section

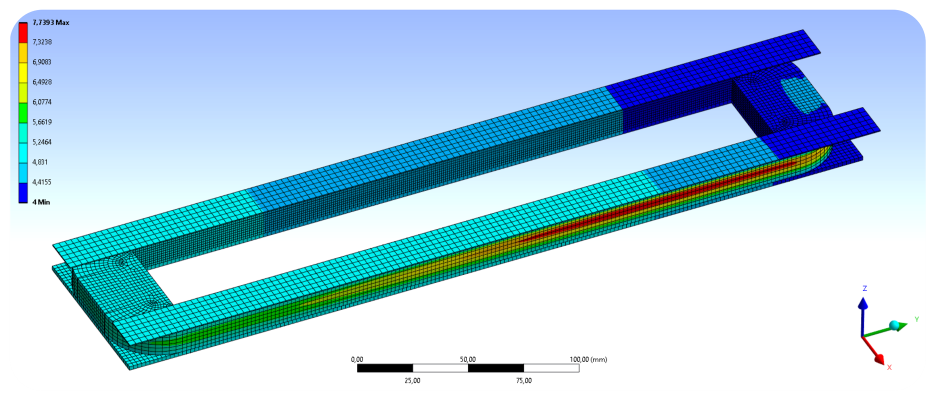


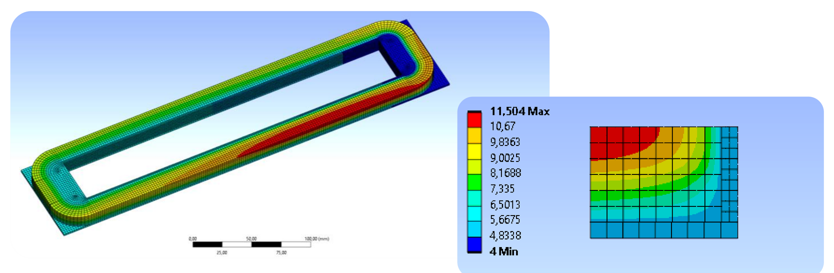
Thermal conductivities applied

FEM approach (ANSYS)

- 3-D evaluation of coil, Cu casing and Al sheet heat extraction.
- Steady state 1,25 W internally generated in 1/8 of the coil and 4 K in the extremity.

Maximum temperature in coil (K)		
	Analytical 1-D	FEM 3-D
Cu casing	13,4 K	11,5 K
+ Al sheets	9,2 K	7,7 K



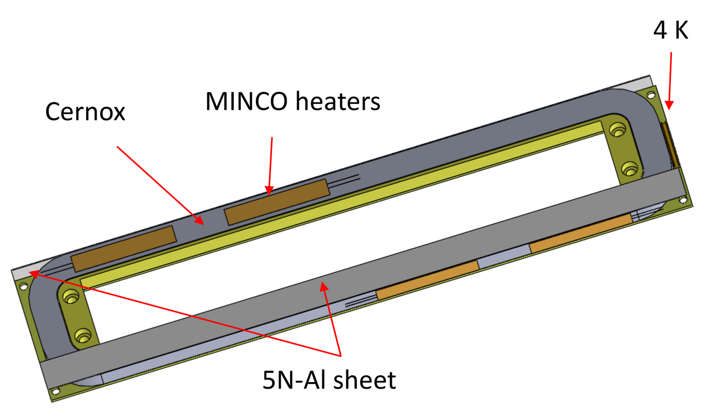


Steady-State Analysis with Cu Casing

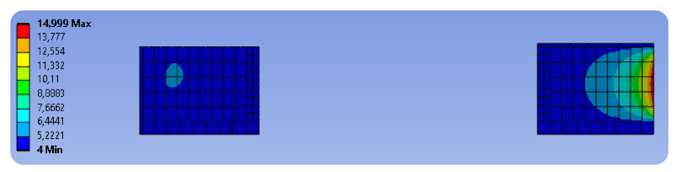
Improvement due to high purity 5N Al sheets on top of the coil

Test coil:

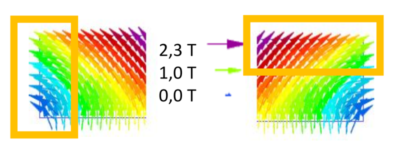
- Superficial heaters heating in regions of low and high magnetic field in the coil.



1,25 W on high field region (T_{max} = 13,1 K)



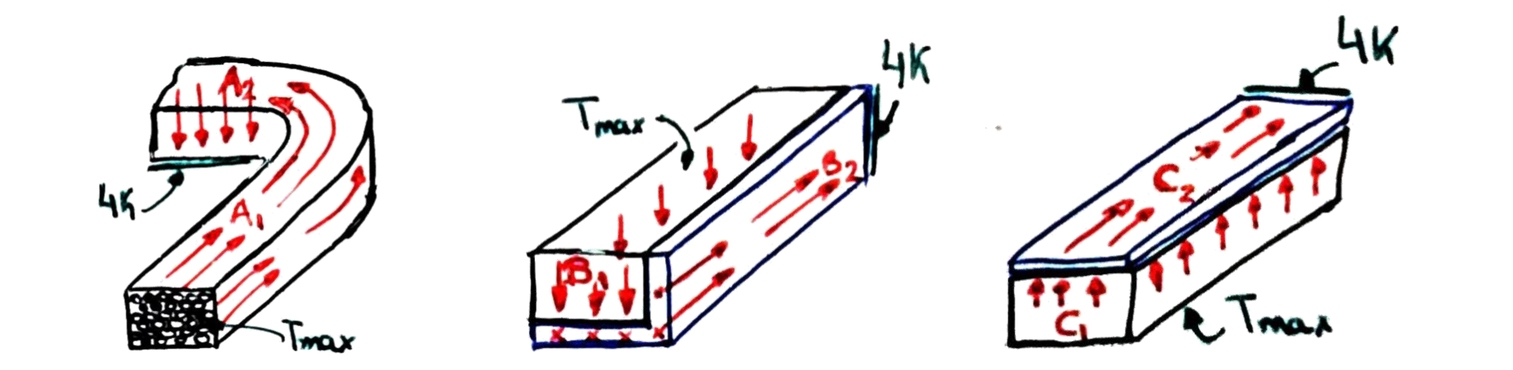
1,25 W on low field region (T_{max} = 15,0 K)



Magnetic field seen by the coil: Q@40T/m + D@0,10T

Analytical approach

1-D model analyzing the contribution of the three parallel thermal paths, evaluated with the conduction heat transfer equation and the equivalent circuit of the system:

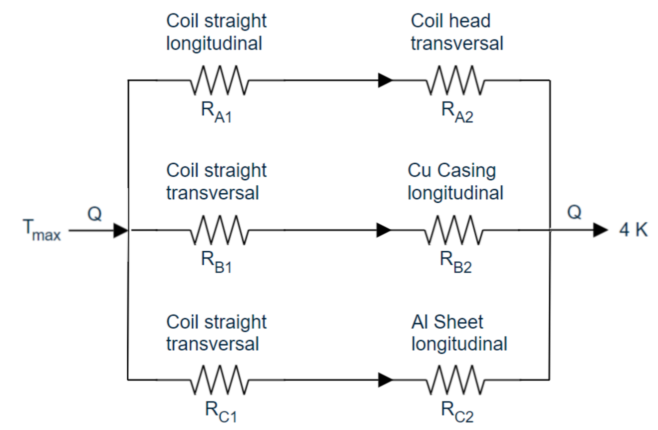


A. Longitudinally via strand + transversally via coil head.

B. Transversally via coil section + longitudinally via Cu Casing.

C. Transversally via coil section + longitudinally via Al sheet.

$$\dot{Q} = \frac{\Delta T}{R_k} = \Delta T \cdot \frac{k_m \cdot A}{L}$$



	A/L (m)	k_m (W/m·K)	R_k (K/W)		
R_{A1}	1e-3	256	3,9	R_A	22,8
R_{A2}	2e-1	0,25	18,9		
R_{B1}	3e-1	0,31	11,3	R_B	17,0
R_{B2}	3e-4	566	5,7		
R_{C1}	9e-1	0,32	3,6	R_C	7,3
R_{C2}	5e-5	5350	3,7		

Conclusions

- Analytical and FEM models offer a complete and complementary understanding of the coil assembly heat transfer.
- Impregnated bronze-route Nb_3Sn anisotropy and magnetoresistance influence the materials considerations for the calculations.
- Conduction through coil resin is the bottle neck of the heat transfer chain.
- A test coil configuration is identified to simulate the requirements of the quadrupole coil in the ILC SC magnet.
- Next steps:
  - Design and fabricate a test station. See poster Thu-Po-3.5.
  - Fabrication and test of the proposed test coil.

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