RADIATION AND THERMAL ANALYSIS OF SUPERCONDUCTING QUADRUPOLES IN THE INTERACTION REGION OF LINEAR COLLIDER*

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Abstract

Radiation heat deposition in the superconducting magnets of the Interaction Region (IR) of a linear collider can be a serious issue that limits the magnet operating margins and shortens the material lifetime. Radiation and thermal analyses of the IR quadrupoles in the incoming and extraction beam lines of the ILC are performed in order to determine the magnet limits. This paper presents an analysis of the radial, azimuthal and longitudinal distributions of heat deposition in the incoming and disrupted beam doublets. Operation margins of the magnets based on NbTi superconductor are calculated and compared.

INTRODUCTION

Compact FD doublets placed on each side of the ILC detector focus the upcoming electron and positron beams at the Interaction Point (IP). Each doublet consists of two small-aperture superconducting (SC) quadrupoles and multipole correctors (Fig.1). The two outgoing disrupted beams are channeled into extraction beam lines by two larger aperture SC quadrupoles labeled QDEX1 and QFEX2.
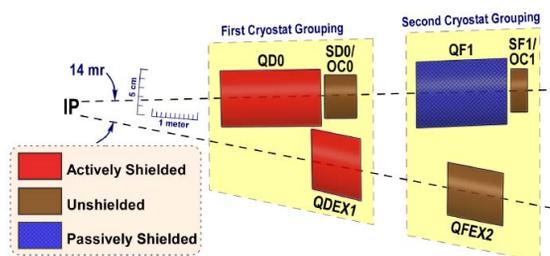

Figure 1: ILC IR layout [1].

The products of beam-beam interactions at the IP deposit energy in extraction line quadrupoles. This contributes to the dynamic heat load on the IR cryogenic system. The fraction of radiation heat, deposited in the coils, causes temperature rise and may lead to a magnet quench if the cooling is not sufficient. To prevent quenches, the coil temperature has to be kept below the SC critical temperature at the given field and current. Moreover, sufficient operating margin is required for the IR magnets to provide reliable machine operation.

Since the heat deposition is concentrated in the narrow region of the coil vertical and horizontal midplanes, the coil design should allow sufficient heat transfer in the

radial direction to maintain the target coil temperature and margin.

The baseline ILC IR magnets are based on the "direct-wind" technology [2] that implies multiple conductor layers interleaved with the insulation. It may not be an optimum concept in terms of the heat transfer as the multiple layers of insulation impede the radial heat transfer out of the coil. In order to improve the coil thermal characteristics, we propose a different solution based on the well-known Rutherford type cables. The design objective is to increase the effective thermal conductivity in the radial direction in order to maximize the heat transfer from the hot spot in the coil to the liquid helium bath.

This paper presents the magnet designs, an analysis of the radial, azimuthal and longitudinal distributions of heat deposition in the incoming and disrupted beam doublets and calculations of operation margins for NbTi magnets based on the Rutherford type cable.

IR MAGNET DESIGNS

The IR quadrupoles are designed to match the ILC RDR requirements [3]. Fig. 2 shows the two and four layer cross-sections of QD0 magnets with a 28-mm coil aperture and G=142 T/m operation gradient based on NbTi superconductor. The QDEX1 quadrupoles with a 38 mm aperture and G=98 T/m have the same design concept. Both designs utilize active shielding coils around the main coil to cancel the magnetic coupling with the extraction beam. The main and shielding coils are connected in series and powered from one power supply. The shielding coil is not as thick in the radial direction as the main coil, a feature that is beneficial for reducing the magnet outer diameter. The QF1 (G=80 T/m) and QFEX2 (G=31.3 T/m) magnets can have the same design as QD0 and QDEX1, respectively, with active shields or similar main coils and passive (iron) shield.
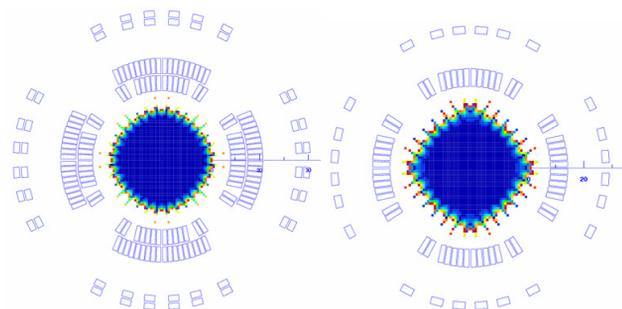

Figure 2: 4-layer and 2-layer QD0 magnet cross-sections.

Table 1: IRQ parameters

Parameter	Unit	QD0		QDEX1	
N layers	-	4	2	4	2
Coil aperture	mm	28		38	
Main cable size	mm	3.066x0.892			
Shield cable size	mm	2.123x1.249			
Cable insulation	mm	0.1			
Cu/nonCu ratio	-	1.3			
Conductor area	mm^2	426.0	193.5	503.9	271.0
B_{ref}	T	5			
$J_{cref}(B_{ref}, 4.2\ K)$	A/mm^2	2500			
T_{op}	K	1.9			
$B_{max}(T_{op})$	T	4.65	3.41	4.81	3.55
$I_{max}(T_{op})$	kA	4.52	5.83	4.38	5.66
$G_{max}(T_{op})$	T/m	272.1	176.8	206.3	133.1
L	mH/m	0.702	0.143	1.201	0.264
W at G_{max}	kJ/m	7.17	2.43	11.52	4.22

The magnet parameters are summarized in Table 1. The magnets are cooled by He II at 1.9 K through the channels between the beam tube and the coil inner surface and in the stainless steel collar containing the main coil. The shielding coil conductors are placed into the slots at the outer collar surface. Thus, there is only one layer of cable and ground insulation separating the conductor from the liquid helium in either design. In addition to high radial thermal conductivity, the coils have other advantages, including excellent turn position control, small number of turns and low inductance. The self-supporting Roman-arch structure allows mechanical and thermal decoupling of the beam pipe and coil.

RADIATION HEAT DEPOSITION

Earlier calculations have shown negligible heat deposition in the QD0 and QF1 quadrupoles of the incoming beam line [4]. For the extraction components, the sources of radiation are the disrupted beam, beamstrahlung photons, incoherent pairs, and radiative Bhabhas coming from the IP. The dominant source of heat load in the SC QDEX1 and QFEX2 quadrupoles is the disrupted beam, while contribution from incoherent pairs and radiative Bhabhas is ~0.2 W/m with beamstrahlung photons contributing even less. In our STRUCT/MARS15 simulations with these two 38-mm coil aperture quadrupoles, we assume a 30-mm aperture beam pipe with a 1.5-mm thick stainless steel wall. The nominal RDR parameters [3] are used in simulations.

In such a model, the load to QDEX1 is quite low, with losses concentrated in QFEX2 and upstream of this magnet. The total heat load to the 1.1-m long QFEX2 is 25 W for a 250-GeV beam. The losses practically vanish if the coil and beam pipe apertures are increased by 10 mm. The losses in these two extraction quadrupoles become substantially lower – even with a 30-mm aperture beam pipe – for a 500-GeV beam due to smaller divergence of the disrupted beam.

Based on the beam loss patterns calculated with the STRUCT code, full shower simulations in the QFEX2 quadrupole were performed with the MARS15 code. Two cases were considered for a 38-mm coil aperture magnet:

4-layer and 2-layer NbTi designs. Longitudinal distributions of power density are relatively uniform along the magnet length, with a broad maximum taking place at the non-IP end of QFEX2. Power density isocontours at that location are shown in Fig. 3. Power density is concentrated in the horizontal mid-plane, having an extremely strong radial gradient with a huge peak in the beam pipe. The peak power density in the SC coil is ~17 mW/g.

Derived from these results, 2D radial and azimuthal distribution of power density (mW/g) in the SC coils was approximated by the following function:

$$P(R,\varphi) = \left[12.8 \cdot e^{-8(R-R_{in})} + 4.0 \cdot e^{-2(R-R_{in})} \right] \cdot e^{-7\varphi}$$

where r and θ are polar coordinates and R_{in} is 1.9 cm. This formula is used in the thermal analysis below.
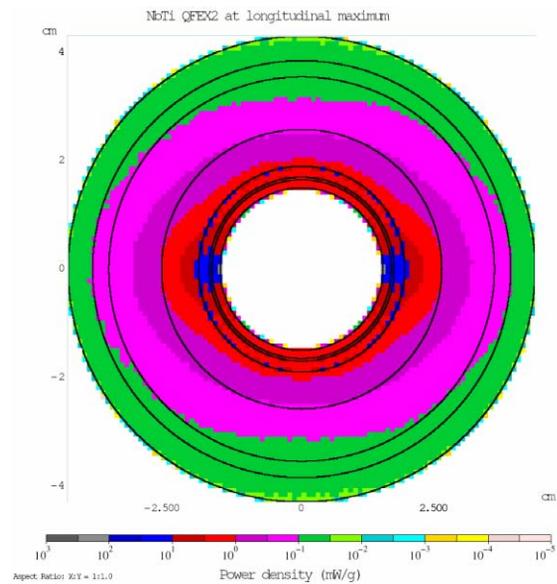

Figure 3: Power density isocontours in QFEX2 magnet.

THERMAL ANALYSIS

2D finite-element thermal models were developed using COMSOL Multiphysics code for both the 4-layer and 2-layer quadrupole designs. The models in Fig. 4 have octant symmetry and include all coils, interlayer and ground insulation, bronze pole spacers and wedges, and stainless steel collars between main and shielding coils.
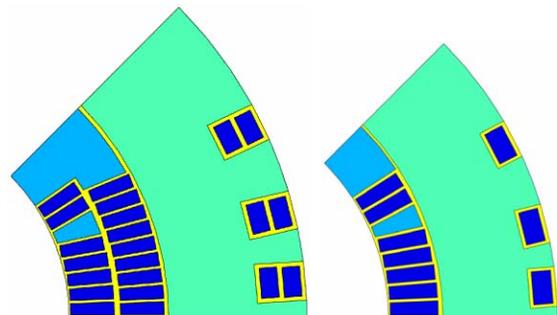

Figure 4: 2D finite element thermal model of NbTi IRQ.

The boundary condition is set to T_{op} at the inner and outer surface of the coil pack. Different materials used in the thermal models are distinguished by different colors. The NbTi cable is insulated with Kapton tape. The coil wedges are made of bronze or G10 material and the collar supporting the main and shield coils is made of stainless steel. Thermal conductivities of the main structural materials were parameterized in the relevant temperature range after [5]. The thermal properties of Kapton were parameterized according to [6].

The calculated 2D temperature profiles for 4-layer and 2-layer QFEX2 magnets are shown in Fig. 5. The peak temperature in the 4-layer design of 3.6 K is in the second layer of the main coil. The peak temperature in the 2-layer design is 3.4 K in the main coil.
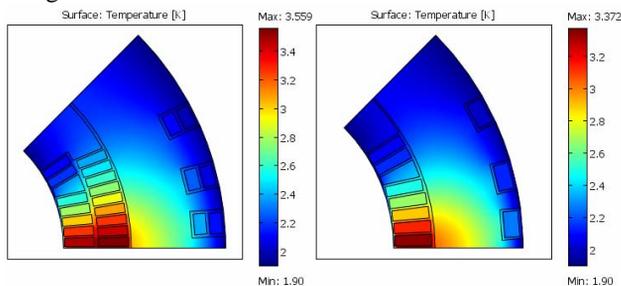

Figure 5: The calculated temperature profile in the 4-layer and 2-layer IR quadrupole magnets.

OPERATING MARGINS

Using the critical surface parameterization for NbTi superconductor and the calculated temperature profiles, the coil temperature margin was calculated for both designs. It was found that the magnet operating margin of IR quads with respect to the radiation heat deposition, localized in the coil mid-planes, is determined by the operating margin of the inner-layer mid-plane turns. Fig. 6 shows the temperature margin of QFEX02 magnet versus the operating gradient. Thus, at the nominal gradient of 31.3 T/m, the hottest SC QFEX2 magnets have temperature margins of almost a factor of 4. One can also notice that there is no significant advantage of the 4-layer design with respect to the 2-layer design at that gradient. However, the 4-layer design has significantly larger margin at higher gradients with respect to the 2-layer design and consequently may be used to reduce the magnet length and thus the total heat deposition in the IR system.

For comparison, the operating margin of the QFEX2 magnet based on the direct-wind technology [2] was also calculated. That magnet featured six layers of strands in the main coil separated by Kapton insulation. As one would expect, it has higher peak temperature, localized in the middle of the coil because of poorer radial heat transfer with respect to the designs based on the Rutherford type cables. Consequently, the temperature margin for that magnet is less than a factor of two as illustrated in Fig. 6. As was pointed out earlier, the operating margin cannot be significantly affected by changing the coil thickness at that gradient level. Thus,

the only way to increase the temperature margin in the direct-wind magnet is to incorporate radial cooling channels of sufficient size or increase the coil aperture.
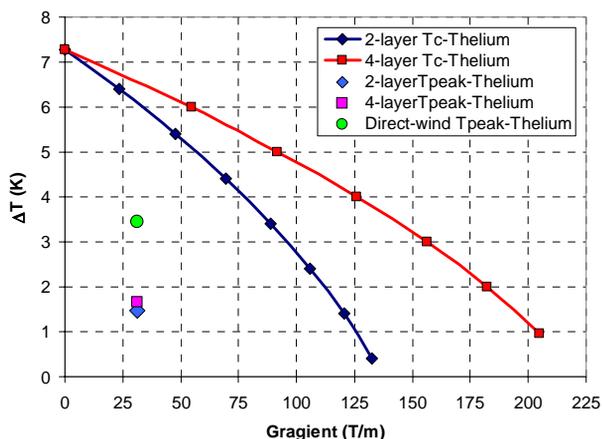

Figure 6: Temperature margin.

CONCLUSION

The radiation and thermal analysis of the ILC IR quadrupoles based on Rutherford type cables was performed. It was found that the peak radiation heat deposition takes place in the second extraction quadrupole QFEX2. The maximum power density in the coil is ~17mW/g. This is rather high, comparing to the proton machines (LHC). However, the fast radial decay of the heat deposition together with the high thermal conductivity of the Rutherford type cable limits the coil temperatures to a moderate level. It was determined that both 2-layer and 4-layer QFEX2 magnet designs have thermal margins of a factor of ~4 at the nominal gradient of 31.3 T/m. Because of the large margins, these magnets can easily accommodate possible changes in the IR optics and heat deposition levels.

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