Compact IR Quadrupoles for Linear Colliders Based on Rutherford-type Cable

M. L. Lopes, V. S. Kashikhin, V. V. Kashikhin, A.V. Zlobin

Abstract— **The upcoming and disrupted beams in the interaction region (IR) of a linear collider are focused by doublets consisting of two small-aperture superconducting quadrupoles. These magnets need an effective compact magnetic shielding to minimize magnetic coupling between the two channels and sufficient temperature margin to withstand radiation-induced heat depositions in the coil. This paper presents conceptual designs of IR quadrupoles for linear colliders based on NbTi and Nb_3Sn Rutherford-type cables.**

***Index Terms*—Accelerator magnet, Rutherford-type cable, Superconducting quadrupole, Linear collider.**

I. 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 QD0 and QF1 and multipole correctors (see Fig.1). The two outgoing disrupted beams are channeled into extraction beam lines by two larger aperture SC quadrupoles QDEX1 and QFEX2 [1]. QD0 with its corrector and QDEX1 are placed in the same cryostat and installed inside the detector. The effect of the detector solenoid field on the incoming beams will be mitigated by a special solenoid with opposite field direction installed around QD0 and QDEX1 in the same cryostat [2]. The other two quadrupoles, QF1 with corrector and QFEX2, are placed in a separate cryostat outside the detector. It is expected that ILC IR magnet cooling be provided by superfluid helium at 2 K.

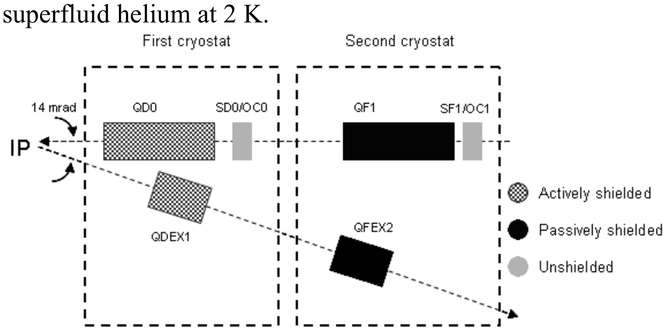

Fig. 1. ILC IR layout [1] (not in scale).

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The present baseline design of ILC IR quadrupoles is based on a NbTi round cable and direct wind technology. The quadrupoles QD0 and QDEX1 closest to the IP use active magnetic shields provided by external quadrupole coils. The other two quadrupoles can use passive iron shields. The magnet design and technology have been demonstrated by a series of short prototypes [3].

This approach has some attractive features, but it is not free from some disadvantages. The multilayer multi-turn coil design increases the magnet inductance and limits the accuracy of turn position control, complicates coil azimuthal pre-load, limits radial and azimuthal heat transfer, etc. Thermal analysis of IR quadrupoles with such low radial and azimuthal thermal conductivity in the ILC IR radiation environment showed that QFEX2 based on the baseline design has insufficient operation margin [4]. In addition, the direct wind technology was demonstrated at the present time only for NbTi superconductor.

This paper describes conceptual designs of compact IR quadrupoles based on shell-type coils and Rutherford-type cables which are suitable for linear colliders. This approach is being widely used in accelerator magnets. It meets all the requirements and is free from the mentioned above limitations. Moreover, it is compatible with both NbTi and Nb_3Sn magnet technologies.

II. MAGNETIC DESIGN AND PARAMETERS

The main design parameters of ILC IR quadrupoles can be found on the web [5]. They are summarized in Table I.

This paper focuses on QD0 and QDEX1 since these magnets have the most challenging parameters and requirements to their design. First of all, due to the proximity of QDEX1 and QD0, these magnets have to be shielded to minimize the magnetic coupling between them. However, the location of these magnets inside the detector solenoid and the limited radial space exclude the use of iron yoke for fringe field shielding. Active shielding is used instead. The solenoidal field is also added to the self field of the coil, which reduces the operation margin, and needs to be taken into consideration.

TABLE I DESIGN PARAMETERS OF ILC IR QUADRUPOLES

	QDO	QF1	QDEX1	QFEX2
Aperture, mm	28	28	38	60
Nominal gradient, T/m	142	80	100	23
Magnetic length, m	2.20	2.00	1.06	1.20

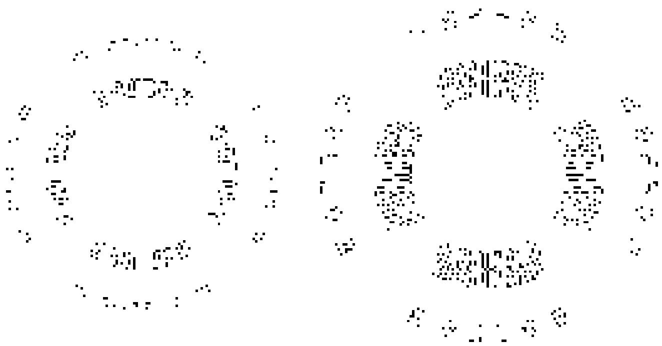

Fig. 2. Single (left) and double (right) layers quadrupole designs. The outer layer is the active shield.

Figure 2 shows the two compact designs of quadrupole coils with active magnetic shield for the ILC interaction region. The innermost single or double layer represents the main coil. The active shielding is provided by the outer single or double layer coil. Table II summarizes the design and performance parameters of these quadrupoles.

TABLE II QUADRUPOLE DESIGN PARAMETERS

	QD0		QDEX1	
Coil design	Single layer	Double layer	Single layer	Double layer
Superconductor type	Nb_3Sn	NbTi	Nb_3Sn	NbTi
Operation temperature, K	4.2	1.9	4.2	1.9
Coil ID, mm	28		38	
Magnet OD, mm	49.4	61	61.4	76.8
Coil cross-section, mm^2	37.1	81.9	52.1	97.1
B_{peak} (magnet body), T	5.84	4.86	6.0	5.0
I_{max} @ B_{peak}, A	9971	4728	9617	4578
G_{max}, T/m	302.7	284.5	226.2	215.6
G_{max}/G_{nom}	2.13	2.00	2.26	2.16
Inductance, mH/m	0.18	0.89	0.24	1.17
Stored energy at G_{nom}, kJ/m	1.9	2.4	2.2	2.6

The geometrical parameters of the cables used in the main and shielding coils are reported in Table III. The NbTi strand considered in this study had J_c(5 T, 4.2 K) = 2500 A/mm^2 and a Cu/Sc ratio of 1.3. The Nb_3Sn strand had J_c(12 T, 4.2 K) = 2500 A/mm^2 and a Cu/Sc ratio of 0.85. These are standard parameters for commercially available strands.

TABLE III CABLE PARAMETERS

	Main coil	Shielding coil
Number of strands	12	6
Strand diameter, mm	0.5	0.7
Cable width, mm	3.066	2.123
Average thickness, mm	0.893	1.249
Insulation thickness, mm	0.1	0.1

TABLE IV QD0 BASELINE DESIGN PARAMETERS

Nominal current, A	779
Stored energy at the nominal gradient, kJ/m	1.62
Inductance, mH/m	5.3
Coil cross-section, mm^2	42.6
Magnet OD, mm	70

The operation margin defined as G_{max}/G_{nom} is more than 2 for all the designs presented in Table II. The single-layer Nb_3Sn coil designs reduce the magnet OD by 20% and can operate at higher temperatures with a simpler and more effective cryogenic system.

Table IV summarizes the parameters simulated for the baseline ILC quadrupole design QD0 described in [2, 3, 5]. As can be seen from Tables II and IV, the OD of the baseline design is larger than that of the proposed double-layer and single-layer designs based on NbTi and Nb_3Sn cables respectively. The stored energy in the baseline design is smaller than in the designs presented in this paper. However, the inductance of the proposed designs is much smaller than that of the baseline magnet. This is an important factor when considering the magnet quench protection system.

The excess of maximum field gradient provided by these new quadrupoles can be translated in terms of their design margin. The design margin will take into account not only the usual problems during magnet construction, but also the external solenoidal field and the heat deposition due to the disrupted beam.

The magnet coils were also optimized for the field quality. The design target was to zero the b_6 and b_{10} geometrical harmonics at a reference radius equal to half of the quadrupole's aperture. The field quality was evaluated considering RMS errors of 50 microns for the radial and azimuthal positioning of the coil blocks. Table V summarizes the results for QD0. As can be seen, the standard deviations for all the harmonics are quite high due to the fact that the assumed geometrical errors are large compared to the transverse dimensions of these magnets. The effect of the expected field quality in the described magnets on the beam parameters needs to be carefully analyzed.

TABLE V FIELD HARMONICS ERRORS (QD0)

	a_n		b_n	
n	mean	sigma	mean	sigma
3	-0.63	9.33	0.08	9.89
4	-0.24	5.48	-0.34	6.03
5	-0.15	3.12	0.04	2.92
6	0.02	1.58	0.03	1.62
7	0.02	0.79	0.02	0.81
8	-0.01	0.40	-0.03	0.39
9	0.00	0.19	0.00	0.18
10	0.00	0.09	0.00	0.09

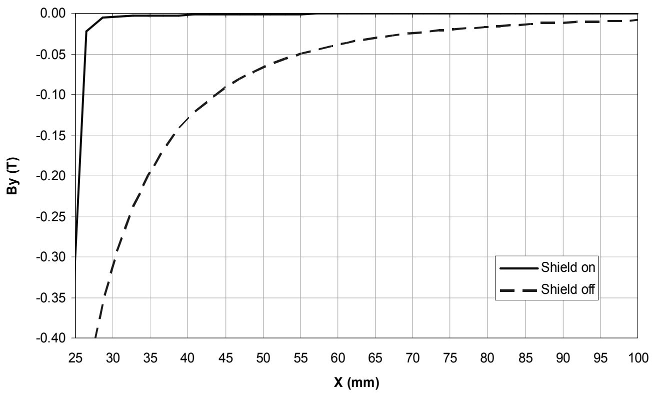

Fig. 3. The fringe field produced by QD0 at nominal gradient with active shield "on" and "off". X=0 corresponds to QD0 center.

III. Active Shield Optimization

QD0 and QDEX1 designs utilize active shielding coils around the main coils to reduce the magnetic coupling of the incoming and disrupted beam lines. The main and shielding coils are connected in series and powered from one power supply. The geometry of shielding coils in all the previously described designs was optimized to achieve the required field compensation outside the magnet and reduce the magnet transverse size. The active shield reduces the quadrupole strength of the main coil by about 19%. Figure 3 shows the effect of active shielding for the single layer QD0 quadrupole. Considering a minimum separation of 77 mm between QD0 and QDEX1, the QD0 shielding coil reduces the field on the QDEX1 axis from 18 mT (shield "off") to 0.2 mT (shield "on").

Figure 4 shows the distribution of the vertical field component B_y produced by QD0 along the QDEX1 axis Z (at x = 77 mm) with active shield for the three relative lengths of QD0 main and shielding coils. As can be seen, the level of field compensation significantly changes along the magnet axis near the coil ends. The integrated shielding effect depends on the lengths of the main and shielding coils.

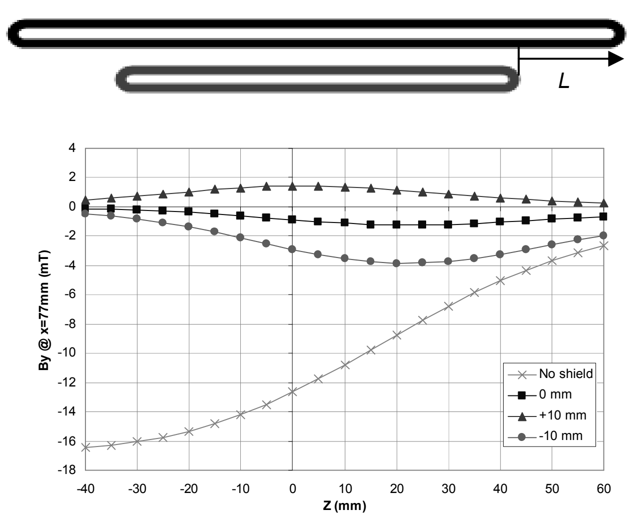

Fig. 4. Distribution of the vertical field component B_y produced by QD0 along QDEX1 axis (z). Z = 0 corresponds to the end of the main QD0 coil. L is the difference between the main coil and shielding coil end position.

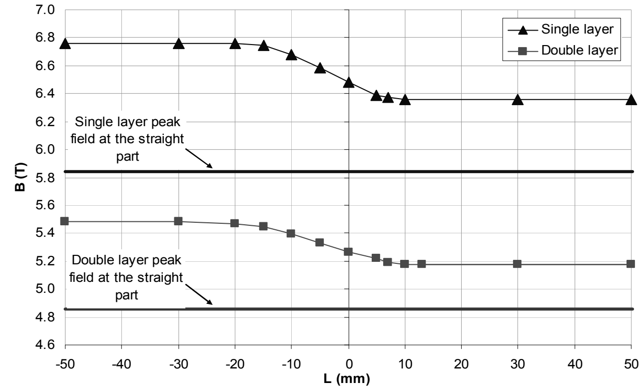

Fig. 5. Peak field in QD0 vs. the outer layer additional length *L* (defined in Fig.4) for the single-layer Nb_3Sn design and the double-layer NbTi design.

The average fringe field (the field integrated along the axis and normalized by the magnet length) on QDEX1 axis from QD0 without shielding reaches 22 mT. With shielding for the same lengths of the main and shielding coils (L=0) it reduces to 0.7 mT. As can be seen from the data in Figure 4, it can be further reduced by slightly increasing the shielding coil length (the optimum is between 0 and +10 mm).

It is well known that the peak field in unshielded superconducting magnets is located in the coil ends. Figure 5 shows the peak field in the coil ends as function of the shielding coil additional length L for the single-layer Nb_3Sn design and the double-layer NbTi design. The horizontal lines represent the peak field in the magnet straight section for both designs. The peak field in the coil ends is always higher than the peak field in the magnet body. With the optimal shielding coil length (L ~ +5 mm) the end peak field reduces by ~5% for both designs. The high peak field in coil ends reduces the maximum gradient by 4% with the optimal shield length for both double and single layer designs.

IV. Detector Solenoid Effect

QD0 and QDEX1 quadrupoles will be placed in a cryostat inside the detector solenoid. The external field will reduce the safety margin on these magnets. Figure 6 shows the reduction of the maximum gradient as function of the external fields. As can be seen, a reduction of the maximum gradient up to 22% could be observed in the external field up to 3 T.

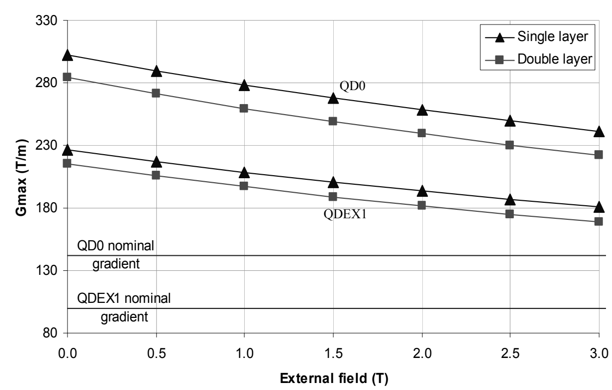

Fig. 6. Maximum gradient vs. the external field for the single-layer Nb_3Sn quadrupole operating at 4.2 K and for the double-layer NbTi quadrupole operating at 1.9 K.

The field produced by the detector solenoid in the area of focusing quadrupoles needs to be reduced in order to minimize its negative effect on the incoming beam. This is planned to be done with the help of a short anti-solenoid placed around the QD0 and QDEX1. The anti-solenoid will also increase the operation margin of focusing quadrupoles by reducing the detector solenoid contribution to the maximum field in the quadrupole coils.

V. Temperature Margin

Using the critical surface parameterizations for NbTi and Nb_3Sn superconductors [6]-[8], the magnet temperature margins were calculated for QD0 and QDEX1 based on both single-layer and double-layer designs, NbTi and Nb_3Sn coils, for two possible operation temperatures, 1.9 K and 4.2 K. Figures 7 and 8 show the magnet temperature margin with respect to the operation temperature as function of the maximum gradient for QD0 and QDEX1, respectively. As can be seen, the single-layer Nb_3Sn quadrupoles can operate at both temperatures with an operation margin more than 2. The double-layer NbTi quadrupoles can also operate at both temperatures; however, the operation margin at 4.2 K reduces to 1.5 for QD0 and 1.6 for QDEX1. It may not be sufficient for the reliable operation of these magnets in accelerator.

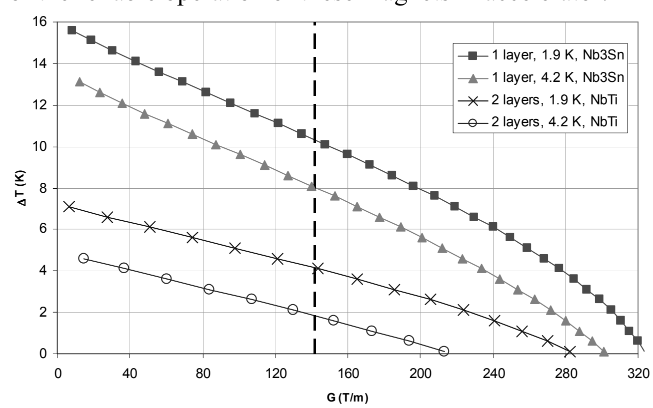

Fig. 7. Magnet temperature margin with respect to the operation temperature as function of the field gradient for QD0. The vertical dashed line represents the nominal QD0 gradient.

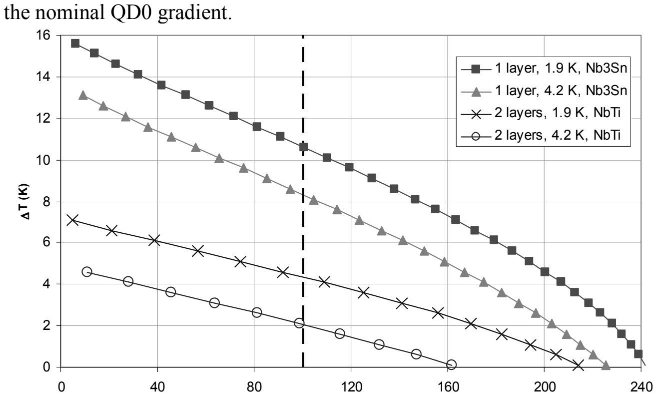

Fig. 8. Magnet temperature margin with respect to the operation temperature as function of the field gradient for QDEX1. The vertical dashed line represents the nominal QDEX1 gradient.

VI. Conclusion

Conceptual designs of ILC IR quadrupoles QD0 and QDEX1 based on Rutherford cable and active shield have been developed and studied. Magnet design parameters meet the ILC IR specifications.

It was shown that the design approach based on Rutherford cable has several advantages. Coils built with the Rutherford cable have a high packing factor which allows higher efficiency and more compact magnet design. The good turn positioning in the coils, the turn radial and azimuthal pre-load and support during operation provide stable field quality and alignment in current and thermal cycles during long-term operation. Low coil inductance helps to protect the magnet during a quench. Due to the self support of turns in the coils based on Rutherford cable, the beam pipe and the coil are thermally decoupled, which reduces coil heating from the heat deposited in the beam pipe. High radial thermal conductivity increases the magnet operation margin with respect to the radiation heat deposition in the coil.

The described design approach is compatible with both NbTi and Nb_3Sn superconductors presently used in accelerator magnets. In particular, the use of Nb_3Sn cable with higher critical temperature, critical field and current density allows reducing the coil volume by 15%, the magnet size by 40% and opens the possibility of operating the IR magnets at 4.2 K.

The effect of an active shield length on B_{max} in the coil and the QD0 fringe field variation along the QDEX1 axis were studied. The optimal length of active shield coil with respect to the main coil was determined.

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