Recent Progress Designing Compact Superconducting Final Focus Magnets for the ILC

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RECENT PROGRESS DESIGNING COMPACT SUPERCONDUCTING FINAL FOCUS MAGNETS FOR THE ILC*

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Abstract

QDO, the final focus (FF) magnet closest to the interaction point (IP) for the ILC 20 m crossing angle layout, must provide strong focusing yet be adjustable to accommodate collision energy changes for energy scans and low energy calibration running. But it must be compact to allow disrupted beam and Beamstrahlung coming from the IP to pass outside into an independent instrumented beam line to a high-power beam absorber. The QDO design builds upon BNL experience making direct wind superconducting magnets. We present test results for a QDO magnetic test prototype and introduce a new shielded magnet design, to replace the previous side-by-side design concept, that greatly simplifies the field correction scheme and holds promise of working for crossing angles as small as 14 mr.

PROGRESS BEFORE SNOWMASS'05

An initial compact superconducting magnet design for a 20 m crossing angle configuration for the NLC FF was developed shortly after Snowmass'02[1-4]. The design drew upon direct wind magnet experience the HERA-I1 and BEPC-II Luminosity upgrades[5,6]. Field strengths of the compact superconducting magnets are adjustable to accommodate energy and optics changes and the magnets fit within the original NLC permanent magnet solution space envelope.

The initial direct wind design was limited in that the inner coil layers used single-strand superconducting wire rather than seven-strand round cable used for the main HERA-II and BEPC-II magnets since we had never wound such small bend radius patterns before. But seven-strand cable has an advantage that less dead space is taken up by insulation and other materials so a higher effective engineering current density is possible with cable than single-strand coil windings.

Thanks to recent direct wind research and development, we now wind much tighter bend radius coil patterns using seven-strand cable[7,8]. This advance, along with a change from 4.5° supercritical liquid He to 1.9° superfluid He-II cooling, makes the side-by-side magnet scheme, shown in Figures 1 and 2 viable. Here the incoming and extraction beamline magnets start at the same L* and the required superconducting coil thicknesses are thin enough that the cold masses can be housed in separate cryostats. While starting the extraction beam line close to the IP is helpful in maximizing extraction line acceptance, the main benefit of the side-by-side configuration is for the extraction line where it permits local compensation of the external field generated outside QDO.

We wound and tested a short QDO prototype, QT, in order to demonstrate that we could meet the ILC QDO

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Figure 1. Plan View Schematic of Side-by-Side IR Layout (Obsolete). Disrupted beam from IP goes outside QDO into the extraction line.

Figure 2. Side-by-Side Magnet Layout Concept for 20 m Crossiong Angle (Obsolete). Same L* for extraction line enables partial compensation of QDO external field.
Figure 3. Winding the Short QDO Magnetic Test Prototype, QT, along with a 3D view of the coil configuration.

3 Serpentine Coil Sets Giving 6 Cable Layers

Start of winding for ILC QDO Prototype Test Magnet, QT, along with a 3D view of the coil configuration.

Compact quad design to provide 140 T/m with 20 mm crossing angle optics for ILC.

Figure 3. Winding the Short QDO Magnetic Test Prototype, QT, and CAD Model of Final Six Layer Quadrupole Coil Pattern. QT production is complete along with warm field harmonic measurements. Quench testing was performed in an existing BNL dewar at 4.3 to 3.0 K temperature, 1 to 10 A/s ramp rates and solenoidal background fields up to 6 T. design requirements of 20 mm clear full aperture and 140 T/m operating gradient in the presence of a 3 T solenoidal background field. Figure 3 shows the start of QT coil winding along with full final coil structure. QT was produced in three winding steps as Serpentine style dual-layer coil sets A, B and C, for a total of six cable layers[8]. Before winding was complete warm magnetic measurements were performed and the results were used to make minor pattern corrections to the final coil set C.

The chosen 380 mm QT coil length is a compromise between it being long enough to accurately measure central “body” harmonics separately from the field harmonic contribution of each end and it being short enough to fit inside an existing laboratory dewar test setup with an 8 T solenoid. We powered QT in the presence of a background solenoidal field to simulate the impact of the detector solenoid on QDO performance both in terms of total field on the conductor and the extra internal coil forces due to field interactions at the coil ends.

QT field measurement results are summarized in Table 1. During QT production we learned to wind even Table 1. QT Measured Integral Field Quality. Harmonics are expressed in “units,” a part in ten-thousand, at a reference radius of 5 mm. Numbering convention: N=3 is sextupole. Values less than 0.01 omitted. ILC QDO design goal has all harmonics less than 10 units at this radius.

<table>
<thead>
<tr>
<th>Harmonic Number</th>
<th>Coils A+B+C</th>
<th>Normal</th>
<th>Skew</th>
</tr>
</thead>
<tbody>
<tr>
<td>T.F. (T/m/kA)</td>
<td>210.7</td>
<td>0.19</td>
<td>0.43</td>
</tr>
<tr>
<td>3</td>
<td>-0.03</td>
<td>0.43</td>
<td>1.49</td>
</tr>
<tr>
<td>5</td>
<td>-0.20</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.17</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-0.26</td>
<td>0.01</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Completed QT Prototype Being Prepared for Vertical Cold Testing. During production we learned to decrease turn spacing and bend radius for a 7% transfer function gain.

Figure 6. Completed QT Prototype Being Prepared for Vertical Cold Testing. During production we learned to decrease turn spacing and bend radius for a 7% transfer function gain.
testing by adding voltage tap and spot heater diagnostics and attaching QT's leads to current lead feedthroughs. QT was tested with a background field solenoid housed inside in a small laboratory test dewar. The solenoidal field profile is plotted in Figure 6. Testing was performed for various temperature (4.2 to 3.0 °K), ramp rate (1 to 10 A/s) and background field (0 to 6 T) combinations.

QT reached conductor short sample after a single training quench. At 10 A/s ramp rate QT quenched close to 85% (six-sevenths) of short sample due to well known lack of current sharing with center conductor. The 6-around-1 cable used for QT is not intended for fast ramping since the central conductor “drops out” due to its not being transposed with the outer 6 conductors. Slow ramp rate quench results are summarized in Table 2. QDO is specified to reach 140 T/m in a 3 T background field when cooled to 1.9 °K and QT exceeded this gradient by 13% at 3 T while at an elevated operating temperature of 4.3 °K. QT almost reached operating gradient in a 4 T, background field at 4.22 °K.

To test at lower temperature we lowered the helium dewar pressure via vacuum pumping. Unfortunately such pumping causes the helium level inside the dewar to drop significantly. Because QT had to be “long” to make accurate body harmonic measurements (enough straight section length to get harmonics of the central 254 mm via subtraction of rotating coil readings at two positions) the helium level fell below the current leads around 2.5 °K. The lowest test temperature we took quench data with simple pumping setup, i.e. no λ-plate, was 3.0 °K. In order to avoid running at excessively high current we increased background field to 6 T. Such an increased background field still gives large Lorentz forces in the coil ends but lets us remain below dangerous current levels where quench protection is an issue. At 3.0 °K and 6 T background, QT reached 137 T/m. When this result is scaled to 1.9 °K and 3 T background field QT should reach 232 T/m (1100 A). The nominal working point is at 60% of predicted short sample. In future work we plan to test a shorter ILC prototype that should enable data acquisition at lower temperature with the same test setup.

DEVELOPMENTS AFTER SNOWMASS’05

The proceeding discussion summarizes the compact superconducting magnet design status just before the Snowmass’05 meeting. During Snowmass many issues were discussed and in particular the detector groups wanted to know what the minimum crossing angle is for which the compact superconducting could still be used to retain the main advantages of the 20 mr layout, i.e. truly independent incoming and extraction beamlines for which upstream and downstream beam diagnostic sections could be provided. Referring to the side-by-side configuration shown in Figure 2, one approach to reducing the beamline separation is to eliminate space for the double cryostat and put both cold masses in a common cryostat. But the mutual external fields present at both beamlines increases very rapidly with decreasing separation. This forces us to use stronger correction coil windings which then generate their own stronger external fields which have to be compensated. The “cross talk” between the two beamlines increases dramatically with reduced separation and optimization of the correction/compensation scheme becomes more difficult.

It is interesting to consider what occurs when the first extraction line magnet, labeled QDEX in Figure 2, is replaced by a bare beam pipe. The external field generated by QDEX is gone but so is the opportunity for local compensation of QDO’s external field unless we add an active shield coil.

As outlined in Figure 7 and shown implemented, for realistic QDO coil parameters in Figure 8, active shielding can have minimal impact on QDO performance when the average inner and outer coil radii, $a_1$ and $a_2$, are
\[ I(\phi) = I_0 \cos(m\phi) \]

**Quadrupole m=2**

\[ G^{\text{out}} = G^{\text{in}}(a/x_0)^4 \]

\[ B^{\text{out}} = -(G^{\text{in}}a)(a/x_0)^3 \]

For coils 1 & 2 to have external field shielded...

We need: \[ I_2 = (a_1/a_2)^2 I_1 \] for \[ G^{\text{net}} = G_1[1-(a_1/a_2)^4] \]

Figure 7. Criteria for Field Cancellation at Point \( x_0 \) Outside Two Concentric Nested Current Distributions. The case of quadrupole external field shielding is emphasized. For a pure quadrupole its external field can be eliminated while retaining a significant net inside gradient, \( G^{\text{net}} \), thanks to the forth power scaling with average coil radius.

sufficiently different. Our proposed QD0 active shield design brings only a 5\% increase in excitation current.

With reduced external field we can place the extraction beam pipe close to the outer shield. In Figure 9 we plot the external field seen by extracted beam with this new solution as a function of distance to the IP, \( Z_{IP} \), for QD0 \( L^* \) of 3.51 m but now done for a 14 mr crossing angle. Near the middle of QD0 the cancellation is nearly perfect while at each end there is a small residual field. The 2D approximation outlined above breaks down near the coil ends and the IP end separation is smallest yielding the largest residual field there.

We manufactured a shield coil for the QT prototype with the coil layout shown in Figure 10 that could just fit inside our test solenoid in order to test the active shielding

Figure 8. Actively Shielded QD0 Design Compatible with 14 mr Crossing Angle. The inner and outer coils are wound on separate support tubes (not shown) with 5 mm space left inside the outer support tube for He-II cooling. Running both coils at \( \approx 700 \) A gives 148 T/m from the inner coil and -8 T/m from outer for 140 T/m net gradient.

Figure 9. Field Seen Outside an Actively Shielded QD0 Magnet at Extraction Beamline.

Figure 10. Shield Coil Design for QT, the QD0 Magnetic Prototype. For 748 A, \( G_{in} \) is 157.5 T/m while \( G_{\text{corr}} \) is \(-17.5 \) T/m for net 140 T/m gradient. There is limited space for He-II between QD0 and the support tube that is produced by omitting the QD0 correction coil windings.
concept. Because this QT shield coil is pulled closer in, a greater number of shield turns are required.

Both layers of the QT shield coil are pictured during winding in Figure 11 and assembled with the original QT prototype in Figure 12. Due to the short time span between the end of Snowmass’05 and the present Nanobeam’05 conference, we produced the shield coil support tube using existing stock with wall thickness about 1 mm thicker than desired. The correction windings shown in Figure 10 were omitted in order to provide some space for helium cooling and not to delay production.

This QT active shield coil illustrates issues that arise with bringing the shield closer in to QDO than the amount budgeted in Figure 8 (i.e. if one tries to reduce the crossing angle below 14 mrad). An obvious impact of pulling the closer in similar to the QT shield design is that the current now has to rise to 748 A in order to reach 140 T/m which is a 13% increase compared to a bare QDO. The associated reduction in operating margin is troubling but is not the most important impact.

In Figure 10 we see that the space available for direct He-II cooling of such an inner coil package is quite tight. While superfluid helium can penetrate small gaps, the amount of heat that can be removed through a long cooling section depends critically on available space. Since QDO’s beam related energy deposition occurs primarily on its innermost structure, the annular space available for He-II in contact with the inner coils determines the temperature profile along QDO’s length.

The outer radius shown in Figure 8 of the 14 mrad crossing angle compatible shield coil is only a few millimeters larger than that shown for QT in Figure 10 but includes 5 mm space inner helium cooling while QT has essentially none. Some of the outer radial space that could have been gained by pulling the QT shield closer in was instead lost due to doubling the shield coil thickness.

However even with its tight design space constraints, the shield coil was quite successful in reducing the QT external field. Magnetic measurements made with a rotating coil parallel to the QT axis and almost touching the shield coil outer surface show that the integrated external field is reduced by a factor of 22 when the QT and shield coils are powered in series. This result gives us confidence that active shielding should work very well for the proposed 14 mrad crossing angle shield configuration.

The field at the shield coil is already smaller and the cancellation is not as delicate as for QT. For QDO we foresee providing a small trim current across the shield coil for fine tuning capability, but our QT active shielding test result suggests that this precaution may not really be necessary. We will make further tests when a full length actively shielded QDO prototype is finally produced.

Figure 13 shows one possible realization of an actively shielded QDO for 14 mrad crossing with a tapered extraction beam pipe almost touching the shield coil at the IP end. Note that here the QDO coils and the extraction line beam pipe share a common He-II volume in a cold mass and are supported in a single cryostat. Important features, such as the IP end warm-to-cold beam pipe transition and connection to a helium supply line with control valves and current leads, are shown but may be modified as the design matures.

Preliminary designs have been worked out for all the compact superconducting magnets needed to implement the 14 mrad crossing angle IR. A schematic representation of the compact superconducting magnets on one side of the IR for 14 mrad crossing angle and L* of 3.51 m is shown in Figure 14. Note that with the proposed scheme the first extraction line magnet, QDEX1A, starts past QDO at 6 m. The actively shielded coil layout for QDEX1A is shown in Figure 15. It is important that the stray field from QDEX1A seen at the incoming beam...
location be small since too large a field, even with a zero net integral, could cause too much synchrotron radiation and impact luminosity by spoiling the beam's emittance. Fortunately even though QDEX1A has a larger average coil radius than QD0, so its fringe field ought to extend further out, it is weaker than QD0 and the beam separation is greater at QDEX1A, so residual stray field seen by the incoming beam, shown in Figure 16, is small.

With direct wind magnet production it is natural to co-wind different magnet coils in concentric layers (instead of longitudinal segmentation). For instance by making an octupole magnet, such as OC0, longer we can achieve its required integrated field strength with fewer coil layers and the resulting coil package is itself more efficient because the average coil radius is smaller. Thus we can combine the original space allocation for the SD0 sextupole with OC0 and co-wind them in the pattern shown in Figure 17.

The octupole, being the higher multipolarity, is most favorably wound first on the support tube since this dramatically reduces its field strength at the conductor inner surface. But then the sextupole radial start point goes outward and for a fixed number of coil layers the sextupole ends up being weaker. However, since the sextupole is now longer, the required integrated field strength is still attained without increasing the excitation integral sense and locally, to avoid large field excursions.
Table 3. Parameter Summary for the SDO, OCO and Correction Windings in Their Common Coil Package.

| Design of | \( L_{\text{tot}} \) (mm) | T.F. \( \theta \) cent | I.T.F. | \( L_{\text{mag}} \) (mm) | \( I_{\text{op}} \) (A) | B or Gradient | Unit | \( B \) \( \theta \) 30 mm | Ext. \( \theta \) 85 mm | \( |B| \) \( \theta \) 85 mm |
|-----------|-----------------|------------------|--------|-----------------|-----------------|-----------------|--------|-----------------|---------------|-----------------|
| octopole  | 716 + 20        | 1.90E+03         | 1.34E+03 | 798.0          | 79              | 1.50E+05        | T/mm  | 0.190           | 3.16E-06      | 0.5             |
| sextopole | 716 + 20        | 5.46E+00         | 5.92E+00 | 700.0          | 709             | 6.00E+03        | T/mm  | 0.260           | 1.24E-02      | 81              |
| skew sextopole | 716 + 20 | 3.83E+00         | 2.65E+00 | 695.2          | 79              | 3.00E+02        | T/mm  | 0.293           | 4.07E-02      | 12              |
| dipole (hor) | 716 + 20       | 1.16E+03         | 7.41E+04 | 655.0          | 84              | 1.00E+01        | T      | 0.100           | 5.31E+02      | 53              |
| dipole (ver) | 716 + 20       | 7.65E+04         | 4.99E+04 | 650.6          | 92              | 7.00E-02        | T      | 0.070           | 5.54E+02      | 63              |

Current. One consequence of co-winding different multipolarity coils with the same pattern length is that they naturally end up with different magnetic lengths. In Table 3 OCO and SDO show the same 716 mm coil pattern length but their respective magnetic lengths, 708 and 700 mm, differ.

The additional corrector windings shown in Figure 17, and parameterized in Table 3, are:

- skew-sextupole (specified to have 5% of main sextupole integrated strength for generating an effective sextupole field rotation)
- dipole and skew-dipole windings (used to shift the magnetic center).

These correction coil windings are useful because the SDO/OCO package is wound on a continuation of the QD0 coil support tube and it is not practical to move or rotate this package independently inside a cryostat.

In order to compare the stray field generated by these elements at the extraction beamline, we display in the last column of Table 3 the field contribution from each one when operated at maximum specified operating current and at the minimum beam separation. We see that even though the dipole and skew-dipole corrector fields are much weaker than the sextupole at the 10 mm beam pipe inner radius, if these correctors were to be run up to full current they would contribute almost as much as the sextupole to the external field seen at the extraction line because their external fields fall off much more slowly (combination of larger average radius and dipole's 1/r² dependence compared to sextupole's 1/r³). But note that even though the octopole field magnitude is one-quarter the sextupole field inside at 10 mm radius, the octopole contribution is negligible at the extraction beamline (octopole has smaller coil radius and 1/r³ dependence). Finally the skew-sextupole is 5% of the main sextupole inside the aperture but 15% of the main sextupole outside (skew-sextupole radius is larger and same r-dependence).

The SD1/OC1 coil package has the same coil cross section as SDO/OC0 but its stray field seen at the extraction line will be much smaller because:

- the beamline separation at SD1/OC1 is greater,
- and the passive shielding keeping QFEX2A stray field from the incoming beamline also works to keep SD1/OC1 stray field from reaching the extraction line.

Magnets which are beyond QDEXIA are comfortably outside the experimental detector solenoid where we can switch from active shielding via reverse polarity coils to passive shielding with magnetic materials. Unlike active shielding which reduces magnetic strength, passive shielding adds to the strength and works for all the field multipolarities that are present (i.e. on correction coils as well as the main magnets).

The cross section of a passively shielded magnet, QF1, is shown in Figure 18. For passive shielding we use a magnetic yoke shell that is placed at large enough radius

Figure 17. SDO/OC0 Common Coil Package. The SDO (sextupole) and OCO (octopole) coils are co-wound on a support tube and have the same physical length. First OCO is wound with 4 layers of single stand wire followed by 6 cable layers for SDO. A top this are skew-sextupole, dipole and skew-dipole correction coil windings.

Figure 18. A Passively Shielded QF1 Magnet that is Suitable for 80 T/m Operation. A thin cold magnetic yoke surrounds the QF1 coil (both containing stray field and increasing transfer function). This design has space inside the yoke for He-II cooling in contact with the inner coil.
Table 4. Incoming Beamline Magnet Package Summary.

<table>
<thead>
<tr>
<th>Package Name</th>
<th>Multipole Type</th>
<th>Shield</th>
<th>Winding Type</th>
<th>Total # Layers</th>
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<tbody>
<tr>
<td>QDO</td>
<td>Main Quadrupole</td>
<td>Yes</td>
<td>Cable</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Dipole</td>
<td>No</td>
<td>Wire</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Skew-Dipole</td>
<td>Yes</td>
<td>Wire</td>
<td>1</td>
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<tr>
<td></td>
<td>Skew-Quadrupole</td>
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<td>Wire</td>
<td>1</td>
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<tr>
<td></td>
<td>Shield Quadrupole</td>
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<td>Cable</td>
<td>1</td>
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<tr>
<td>SD</td>
<td>Octupole</td>
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<td></td>
<td>Skew-Quadrupole</td>
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<td>Skew-Dipole</td>
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<td>Wire</td>
<td>1</td>
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<tr>
<td></td>
<td>Skew-Quadrupole</td>
<td>Yes</td>
<td>Wire</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Magnetic Yoke</td>
<td>---</td>
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</tbody>
</table>

Figure 19. Passively Shielded Designs for the Final Two Extraction Line Superconducting Magnets QDEX1B and QFE2A.

As we go further from the IP the extraction line aperture must grow in order to keep energy deposition manageable and therefore the quadrupole field strength drops from 50 T/m for QDEX1B to 40 T/m for QFE2A.

dipole correction coils (not shown in Figure 18) as QDO. For QFI its passive shielding has two additional benefits:
- external fields generated by the correctors are also shielded from the extraction beamline
- and the shield prevents outside stray fields from reaching the incoming beamline.

For completeness the designs for the remaining passively shielded extraction line magnets are shown in Figure 19. Summaries for all the coil packages are given in Tables 4 and 5. The extraction line QDEX1B and QFE2A magnets are similar to QFI; however, in order to reduce energy loss due to disrupted beam coming from the IP their apertures must be increased. Given the tight transverse separation between the incoming and extraction beamlines, shown in Figure 14 and the need not to saturate the QDEX1B and QFE2A magnetic yokes (avoid higher external field from saturated yokes), the
Table 6. Coil Package Physical Parameters for the 14 mr Crossing Angle Layout. $L_{p}$ is the coil pattern length, $R_{ip}$ the beam pipe inner radius (half-aperture) and $R_{outer}$ the outer package radius (for coil or yoke as appropriate).

<table>
<thead>
<tr>
<th>Package Name</th>
<th>$L_{p}$ (mm)</th>
<th>$R_{ip}$ (mm)</th>
<th>$R_{outer}$ (mm)</th>
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</thead>
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<tr>
<td>QD0</td>
<td>2220</td>
<td>10</td>
<td>36</td>
</tr>
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<td>SD0</td>
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<tr>
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<td>2020</td>
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</tr>
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<td>SF1</td>
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<td>QDEX1B</td>
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<tr>
<td>QFEX2A</td>
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</table>

QDEX1B and QFEX2A magnetic fields at their inner apertures are set to be less than 1.2 T.

Relevant physical parameters of the coil package and yoke sizes used for the 14 mr layout are given in Table 6. Note that these data are useful for deriving a lower limit for the crossing angle with the present design even if $L^{*}$ were to be increased by 1 m from 3.51 to 4.51 m.

With preliminary coil and yoke dimensions now in hand we are proceeding with a cryogenic design that integrates the 14 mr layout magnets in a common cryostat. Finally we plan to produce a full length prototype to be housed and supported in a full cryostat in order to be able to investigate vibration and active stabilization issues.

**REFERENCES**


**SUMMARY**

We have shown how to use BNL direct wind coil production techniques, originally developed for the HERA-II and BEPC-II Luminosity Upgrades, for making compact superconducting ILC FF magnets compatible with $L^{*}$ of 3.51 m and 14 mr total crossing angle. Some critical milestones were:

- learning to wind small bend radius cable coil patterns on small diameter coil support tubes (increased engineering current density)
- adoption of He-II cooling (better performance)
- and the development of active and passive external field shielding configurations (to eliminate beamline magnet field cross talk).

A short actively shielded QD0 prototype, QT, was produced and tested and QT performance exceeded ILC field quality and quench performance requirements. Even with the somewhat compromised shield design that had to be adopted to fit test dewar space limits, the QT active shield performed very well and reduced QT's integrated external field on contact by 22 fold.

In future work we will integrate heating elements directly into the body of a test coil prototype in order to directly measure the energy required to quench compact superconducting magnets under ILC operating conditions.