Superconducting Magnets Needs for the ILC

J. Tompkins, Fermilab
For the ILC RDR Magnet Systems Group
ILC RDR Layout

Machine configuration for RDR
Overview

- The ILC Reference Design Report was released in February, 2007
  - Effort on RDR began in January 2006, following the release of the Baseline Conceptual Design in December of 2005
  - For the RDR, an international team of scientists, engineers, and designers was assembled
    - **Area Systems** – e⁻ Source; e⁺ Source; Damping Rings; Ring to Main Linac (RTML); Main Linac; and, Beam Delivery System
    - **Technical Systems** - Vacuum systems; Magnet systems; Cryomodule; Cavity Package; RF Power; Instrumentation; Dumps and Collimators; Accelerator Physics
    - **Global Systems** - Commissioning, Operations & Reliability; Control System; Cryogenics; Conventional Facilities and Siting; Installation

- This talk discusses the ILC superconducting magnet needs based on the RDR
RDR Magnet Systems Group

• **Leaders:** R. Sugahara (Asia, KEK), J. Tompkins (Americas, FNAL), E. Bondarchuk (Europe, Efremov Inst.)

• **The International Team:**
  - Cherrill Spencer, SLAC
  - Vladimir Kashikhin, FNAL
  - Jin-Young Jung, LBNL
  - Ross Schlueter, LBNL
  - Brett Parker, BNL
  - Gianluca Sabbi, LBNL
  - Jim Clarke, Daresbury Lab
  - Mark Palmer, Cornell

  - Tom Mattison, UBC/SLAC
  - Paul Bellomo, SLAC
  - Mike Tartaglia, FNAL
  - David Warner, CSU
  - Nikolay Morozov, Dubna
  - Boris Kitaev, Efremov Inst.
  - Steve Marks, LBNL
  - Dave Plate, LBNL

• **Task:** determine the magnet requirements of each Area System and turn them into ‘designs’ with estimates of size, supports, current, cooling requirements, and costs
Approach

Developing magnet requirements/specifications

• Define ‘standard’ set of magnet input requirements; distribute to Area Systems Leaders; collect basic requirements data from Area Systems groups
  – Review input data from Area Systems
  – Iterate with Area Leaders: clarifications, magnet parameters, ‘stringing’ rules, etc.

• Reduce magnet lists to a manageable number of magnet styles
  – Iterate with Area Leaders on magnet styles decision
  – Coordinate – when possible – style development across Area Systems

• Develop conceptual designs for magnet styles
  – Focus on cost drivers – either large quantity or high complexity

• Develop associated requirements from conceptual design parameters
  – Power systems
  – Controls
  – Infrastructure – wall power, LCW, alcove space, cable trays, etc

• “Repeat as necessary” - Area Systems are evolving, major systems changes have taken place
### ILC Magnet Summary Table

**250Gev X 250Gev - 14 December 2006**

<table>
<thead>
<tr>
<th>Magnet Type</th>
<th>Grand Totals</th>
<th>Sources</th>
<th>Damping Rings</th>
<th>2 RTML</th>
<th>2 Linacs</th>
<th>2 BeamDel</th>
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<tr>
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<td>Quantity</td>
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<td>42</td>
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<td>0</td>
<td>42</td>
<td>0</td>
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<tr>
<td>Superconducting Magnets</td>
<td>43</td>
<td>2333</td>
<td>5</td>
<td>50</td>
<td>197</td>
<td>1</td>
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<tr>
<td>Overall Totals</td>
<td>135</td>
<td>13253</td>
<td>30</td>
<td>180</td>
<td>2185</td>
<td>17</td>
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</table>

### Overall Magnet Totals

**250Gev X 250Gev - 14 December 2006**

<table>
<thead>
<tr>
<th>Category</th>
<th>Styles</th>
<th>Totals</th>
</tr>
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<tbody>
<tr>
<td>Total Normal cond</td>
<td>92</td>
<td>10920</td>
</tr>
<tr>
<td>Total Superconducting</td>
<td>43</td>
<td>2333</td>
</tr>
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</table>

Note: this table is Cherrill Spencer's magnet summary - ILCMagnet
Count14Dec06NC_SC.xls - modified slightly for this talk
General Issues for All Magnets

- **Alignment** with respect to beam path
  - Preserve beam properties
  - Offset of quadrupoles from beam axis must be adjusted by moving beam (dipole correctors), or magnet
  - Sub-\( \mu \) accuracy achieved w/ mechanical movers in BDS

- **Stability**
  - Geometric – if magnet core is not mechanically stable its magnetic center will wander
  - Field stability/reproducibility
    - Over time (& thermal cycles for sc magnets)
    - With respect to changes in current/field – hysteresis, magnetization currents, etc.

- **Reliability**
  - MTBF for magnets \( \geq 10^7 \) hrs
  - Meeting reliability requirements must be a key component of design approach
  - R&D program/’lifetime’ studies

- **Stray Field**
  - Magnetic elements near SCRF cavities must meet stray field limits at cavity of \( \leq 1 \mu T \) (warm) and \( \leq 10 \mu T \) (cold)

- **Cost**
  - Design must be cost efficient while meeting lattice and reliability requirements
Overview of Superconducting Magnets

• There are 2333 superconducting magnets required for the ILC in the Reference Design
  – Roughly 60% are correction coils wound in the same cold mass as the main coils, or immediately adjacent to it

• Main Linac
  – Most of the SC magnets (~1680) are located in the RF cryomodules.
  – A package containing a focusing quadrupole (quad), steering dipole corrector(s) and a BPM in every third main linac cryomodule

• Damping Rings
  – Superconducting wigglers provide beam damping in the Damping Rings
ILC Superconducting Magnets, cont.

- **Positron Source**
  - Superconducting undulators in the e⁻ linac provide the photons needed to create positrons in the positron source
    1619 - THPMN071 “Status of R&D on a Superconducting Helical Undulator for the ILC Positron Source”, J. Rochford et al.

- **Beam Delivery System**
  - Perhaps the most challenging superconducting magnets are those just before the interaction point. They have strong gradient fields with layers of correcting coils, and must fit into as small a radius possible to not interfere with the detector.

- **Superconducting Solenoids**
  - In the ILC sources, there are superconducting solenoids for spin rotation and a few large aperture magnets that may be either conventional or superconducting, depending on detailed optimization of operating versus capital cost.
Main Linac Quadrupole & Correctors

• Overview
  – Located at the center of a cryomodule
    • Operated at 2K
    • Quadrupole, dipole correctors, and BPM in one assembly
  – Maximum integrated strength $\sim 36$ T
    • $\sim 54$ T/m maximum gradient
  – Beam based alignment
    • Decrease gradient by $\sim 20\%$, measure beam position in adjacent BPM while increasing field in steps
    • Critical requirement: quadrupole center must be stable to $\sim 1\mu$ over current/field range
  – Challenges
    • Center stability, reproducibility with field strength
      – Mechanical
      – Hysteric effects due to magnetization currents
    • Stray field at adjacent cavities
      – $< 10 \mu$T when cold, $< 1 \mu$T warm
Main Linac Quadrupoles and Dipole Correctors

300 mm pipe
Central support
Current leads
SCRF

Quadrupole and Corrector Package
## Specifications for Main Linac Quadrupole & Correctors

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tr>
<td>Integrated gradient, T/m</td>
<td>36</td>
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<tr>
<td>Aperture, mm</td>
<td>78</td>
</tr>
<tr>
<td>Effective length, mm</td>
<td>666</td>
</tr>
<tr>
<td>Peak gradient, T/m</td>
<td>54</td>
</tr>
<tr>
<td>Field non-linearity at 5 mm radius, %</td>
<td>0.05</td>
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<tr>
<td>Dipole trim coils</td>
<td>Vertical+Horizontal</td>
</tr>
<tr>
<td>Trim coils integrated strength, T-m</td>
<td>0.075</td>
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<tr>
<td>Quadrupole strength adjustment for BBA, %</td>
<td>-20</td>
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<tr>
<td>Magnetic center stability at BBA, um</td>
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<tr>
<td>Liquid Helium temperature, K</td>
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<tr>
<td>Quantity required</td>
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</table>
Quadrupole Programs

- **DESY - Tesla & XFEL**
  - CIEMAT (Spain) built prototype for TTF
    - Tested at DESY
  - CIEMAT also design and building a new version for XFEL
- **ILC - SLAC**
  - Will study magnetic center stability of CIEMAT TTF quadrupole
- **ILC - Fermilab**
  - R&D Program to build superferric models
    - Study magnetization effects & stability
    - First model under way – test end of summer (?)
- **ILC - KEK**
  - Beginning program to build quadrupole with nested correctors
    - KEKB experience
CIEMAT Quadrupole w/ Dipole Windings

- CIEMAT (Spain) quadrupole prototype for Tesla/XFEL
- Tests at DESY revealed gradient dependence on corrector current

- Center stability study to be done at SLAC this summer

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>quadrupole gradient</td>
<td>63.5 T/m</td>
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<tr>
<td>quadrupole current</td>
<td>100 A</td>
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<tr>
<td>dipole field</td>
<td>0.11 T</td>
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<tr>
<td>dipole current</td>
<td>40 A</td>
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<tr>
<td>max. field at conductor</td>
<td>3.22 T</td>
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<tr>
<td>field length</td>
<td>0.52 m</td>
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<tr>
<td>alignment error (angle)</td>
<td>0.1 mrad rms</td>
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</table>
Fermilab Approach

- **Superferric quadrupole configuration**
  - four racetrack coils, cold iron core
- **Low peak current (100 A)**
  - reduce heat load from current leads (each quadrupole is powered separately)
- **NbTi wire with small filaments to reduce magnetization effects**
- **Racetrack coils and yoke configuration provide easy assembly/disassembly**
  - Coils wound into a stainless steel channel: mechanical rigidity and robust coil manufacturing technology
  - Low carbon steel iron yoke is laminated to use stamping as more economic process - all four poles and flux return combined in one solid lamination
- **Yoke has magnetic shields at both ends to reduce fringe fields**
- **Two dipole shell type trim coils mounted on beam pipe outer surface**
  - Trim coils with beam pipe could be installed/removed
Fermilab Design for a Superferric Quadrupole

From Vl. Kashikhin, FNAL

Cold mass: Length 680 mm
          OD    280 mm
2\textsuperscript{nd} Generation CIEMAT Design

\textbf{XFEL contribution (II)}

- Engineering design of a combined superferric magnet (2006).

\textbf{From F. Toral, CIEMAT}
ILC-Quadrupole R&D plan at KEK

- KEK will study the nested quadrupole with corrector coils for the ILC quadrupole.
  - KEK has the experience of the nested magnet for the final focus quadrupole in KEKB.
  - KEK plans to make the magnetic field measurement system for studying the effect of the coupled fields in the magnet.

- The cross section of the magnet is now being studied.
  - For designing the magnet, the magnet current will be less than 300 A.
  - For transporting the current to the magnet, HTC current leads will be used, and the ceramic feed-through at low temperature is the R&D component.

From N. Ohuchi, KEK
Damping Ring Wigglers

• The Damping Rings play a crucial role
  – they must accept the large emittances of the incoming e- and e+ beams and damp them to required levels within the 200 ms interval between machine pulses
• To achieve the short damping times required, 160 sc wigglers are required for the two rings.
• RDR design is based on Cornell CESR-c wiggler design
  – CESR-c: 1.3 meters
  – ILC RDR: 2.5 meters
  – Other parameters essentially the same
• Larger gap is considered
  – Simplify assembly
  – More space to handle ~10x increase in synchrotron radiation load
  – Field quality remains acceptable
DR Wiggler Design Overview

Modified CESR-c Wiggler

- $B_{\text{peak}} = 1.67 \, \text{T}$
- $\lambda = 40 \, \text{cm}$
- 5 periods + end poles
- Pole Width = 238 mm
- Pole Gap = 76 mm
- Beam Stay Clear = 50 mm
- Performed well in all BCD option DRs...too well?
- OCS v2: $DA_{\text{linear wiggler}} > PA > \text{wiggler map}$

From: J. Urban, M. Palmer - Cornell
DR Wiggler Design, cont.

Physics Design Optimization

- CESR-c wiggler optimized specifically for CESR-c conditions
  - gap, width, coil shape, pole cutout/shim

- Field quality greater than necessary for ILCDR

- Potential for cost savings?
  - Field quality
  - Total number

From: J. Urban, M. Palmer - Cornell

Wiggler models in Opera & Radia
DR Wiggler Design, cont.

Gap Height

- Simplify construction & add flexibility
  - Larger gap
    - Simplifies support plate construction
  - Cost savings
- Larger gap possible
  - 76 → >98 mm @ 1.67 T

From: J. Urban, M. Palmer - Cornell

End-view of Wiggler Assembly

Thickness = 3 mm
Wigglers: Beyond the RDR

• Optimized and engineered design for ILC
  – 12 poles
  – Period: $\lambda$ 40cm $\Rightarrow$ 32cm
  – Field: $B$ 1.67T $\Rightarrow$ 1.95T
  – Gap: 76mm $\Rightarrow$ 86mm
  – Wiggler/cryostat engineering design
    • Vacuum chamber/cold bore interface
    • Simplify design and fabrication
  – Cost reduction
Undulators for the e\textsuperscript{+} Source

- Positrons are created by the e\textsuperscript{-} beam (at the 150 GeV point in the linac) passing through a helical wiggler generating synchrotron radiation (~10 MeV) which hits a conversion target
  - 2x synchrotron radiation power per period than that of a planar undulator
e\(^+\) Source Layout

(Stolen from V. Bharadwaj, Hamburg ILC/LCWS 2007)

FIGURE 2.3-1. Layout of the Positron Source in the ILC

FIGURE 2.3-2. Overall Layout of the Positron Source
Undulator Challenges
(from J. Clarke)

• High fields
  – Pushing the limits of technology
• Short Periods
  – Shorter periods imply higher fields
• Narrow apertures
  – Very tight tolerances - Alignment critical
• Cold bore (4K surface)
  – Cannot tolerate more than few W of heating per module
• Minimizing impact on electron beam
  – Must not degrade electron beam properties but have to remove energy from electrons
• Creating a vacuum
  – Impossible to use conventional pumps, need other solutions
Baseline Undulator Design
HeLiCal Collaboration

• HeLiCal collaboration
  – University of Liverpool, CCLRC, University of Durham, DESY, ASTeC
    • CCLRC (Council for the Central Laboratory of the Research Councils) ⇒ Science and Technology Facilities Council (2007)
    • Rutherford Appleton Laboratory
    • Daresbury Laboratory
    • ASTeC - Accelerator Science and Technology
Undulators for the e⁺ Source

Winding cross section: 45°4 mm²

20 periods of double-helix

314°
Undulator - Magnet Design Concept

- Steel Yoke. Provides 10% increase in field and mechanical support for former
- Winding pins
- PC board for S/C ribbon connections
- 2 start helical groove machined in steel former
- Cu beam pipe, with conductor wound on to tube OD
Prototype 5

- Same parameters as RDR Baseline undulator
- 11.5 mm period
- 6.35 mm winding diameter
- Peak on-axis field spec of 0.86T (10 MeV photons)
- Winding directly onto copper tube with iron pole and yoke
- New wire with more aggressive Cu:SC ratio of 0.9:1.0
**Plans for a 4m Undulator Module**

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<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
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<td>On axis field</td>
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<tr>
<td>Peak to peak variation</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Period</td>
<td>11.5 mm</td>
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<tr>
<td>Nominal Current</td>
<td>~250 A (80% of short sample)</td>
</tr>
<tr>
<td>SC wire</td>
<td>NbTi 0.4mm dia., SC:Cu ratio 0.9:1</td>
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<tr>
<td>Winding Cross Section</td>
<td>7 wires wide x 8 high</td>
</tr>
<tr>
<td>Number of magnets per module</td>
<td>2 (powered separately for tests)</td>
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<tr>
<td>Length of magnetic field</td>
<td>2 x 1.74 m</td>
</tr>
<tr>
<td>Number of modules req’d</td>
<td>42</td>
</tr>
</tbody>
</table>

- **Complete testing of Magnet 1** — August 2007
- **Complete testing of Magnet 2** — September 2007
- **Complete Magnet/Cryostat assembly** — November 2007
- **Complete Testing of 4m Module** — December 2007

From J. Clarke, Alison Birch/Steve Carr
Undulator Status

• One 11.5mm period SC undulator (prototype 5) built and tested
  – Period further reduced to RDR value of 11.5mm
  – New SC wire used (Cu:SC - 0.9:1)
  – Field strength measured greater than expected, possibly due to increase in SC content of wire
  – Best ever field quality results (well within spec)
  – Full length prototype will use these parameters

• Full length prototype construction started
  – 4m prototype design complete
  – Fabrication has commenced
Cornell Alternative Design
(Mikhailichenko & Tigner)

Fig. 2: Details of design. 1–Iron yoke, 2–Copper collar, 3, 4–trimming Iron nuts. Inner diameter of Copper vacuum chamber is 8mm clear.
Beam Delivery System Final Focus Magnets

• The final focus region is quite complicated
  – Incoming and outgoing beams are in very close proximity
  – There is a massive detector in the way
  – The last elements of the beamline are captured with the detector and must move with it
    • ‘Push-pull’ for the 2 detector scenario
  – Beam stability critical for collisions to occur
    • Mechanical and magnetic stability of the final focus elements
  – Significant radiation loads from interactions and the disrupted beams
Final Focus Overview

- Brett Parker and colleagues (BNL) – have been working with the BDS group on final focus magnet designs and on integration issues with the detector groups (Brett actually began this work during NLC days…)
  - Compact magnet designs required due to very tight transverse space limitations caused by incoming and disrupted beam separation
  - Magnets must be shielded from the detector field
  - Adjacent beam lines must be shielded from each other
  - Higher order correction elements required
BSD Superconducting Magnets

Note: early conceptual view of detector-beam line interface
Details are not up to date or necessarily realistic
BDS – BNL Layout for Final Focus Magnets

Key:  
- Red: Actively Shielded  
- Brown: Unshielded  
- Blue: Passively Shielded

ILC International Linear Collider

Fermilab
Individual magnetic elements in each of the coil groups in a cryostat from the RDR design

QD0 Group moves with detector

QF1 Group is fixed in beam line

<table>
<thead>
<tr>
<th></th>
<th>QD0 Group</th>
<th>QF1 Group 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>QD0</td>
<td>QF1</td>
<td></td>
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<tr>
<td>Main Quadrupole</td>
<td>Quadrupole</td>
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</tr>
<tr>
<td>Dipole</td>
<td>Dipole</td>
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<tr>
<td>Skew Dipole</td>
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<td>Skew Quadrupole</td>
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<td>Shield Quadrupole</td>
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<tr>
<td>SD0</td>
<td>SF1</td>
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<td>Dipole</td>
<td>Dipole</td>
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</tr>
<tr>
<td>Shield Quadrupole</td>
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</tbody>
</table>
Other BDS Superconducting Magnets

• Detector Integrated Dipole
  – Compensate for beam at an angle to solenoid axis
    (not ‘formally’ a BDS magnet, part of detector)

• Compact Tail Folding Octupoles

Uses ‘6 around 1’ cable, with strands run in series
75A max operating current
Reduces lead heating
Allows for conducting cooling (cryocoolers)

From Brett Parker, BNL
Other Superconducting Magnets

- **Superconducting Solenoids**
  - Large aperture, high field strength solenoids are needed in several Areas:
    - e⁺, e⁻ Sources, RTML, BDS
    - Roughly 16 solenoids of 4 different “styles”
  - Some of the solenoids may have either conventional or superconducting technology solutions to be resolved by
    - Understanding of heat loads
    - Length vs. field tradeoffs
    - Operational cost (kwh & cooling) vs. capital cost & cryogenic operation
  - More work to be done
    - More detailed designs
    - Heat loads, backgrounds, etc.
    - Magnet engineers, designer/drafters…
Summary

- ILC magnets are mostly lower field conventional magnets, but there are a significant number of superconducting magnets required.
- The largest number of superconducting magnets in the Main Linac: there is an sc quadrupole plus dipole correctors in every third cryomodule.
  - Plus quads & correctors associated with SCRF accelerating sections in other areas.
- Superconducting magnets play important roles in the ILC.
  - Positron Source – sc undulators provide γ’s which create positrons.
  - Damping Rings – sc wigglers damp the beams within required 200 msec.
  - BDS – compact, nested sc magnets provide the final beam focusing.
- Much has already been accomplished in these sc magnet systems:
  - R&D is under way - undulators, Final Focus components, wigglers.
  - Successful prototypes have been built and tested.
  - Designs are maturing and adapting to changing requirements.