Overview of the 13,000 Magnets in the International Linear Collider

Cherrill M. Spencer, Vladimir Kashikhin, Michael Tartaglia, John C. Tompkins, Mark Palmer, Brett Parker, Tom Mattison, and Ryuhei Sugahara

***Abstract*—The International Linear Collider has about 80 km of beamlines which require over 13,000 magnets for focusing and steering the beams. Approximately 18% are superconducting magnets and the rest "conventional" warm iron-dominated magnets with copper coils, totaling about 135 styles. Superconducting technology is primarily used for the magnets located in the linacs' RF cryomodules, but it is also required for the spin rotation solenoids, damping ring wigglers, positron source undulator and beam delivery octupoles, sextupoles and final doublet quadrupoles. A major criterion for ILC magnet design is to achieve very high availability in spite of the very large number of magnets. The "availability" goal of the ILC is 85% (or better) and the magnets have been budgeted to cause no more than 0.75% down time. Alignment and mechanical stability requirements in many areas are very challenging. In the Beam Delivery System, beam positions must be maintained at sub-micron levels to collide the beams at the interaction point. The ILC has 11 styles of kicker, pulsed or septum magnets. Some kickers need rise and fall times of a few ns and will require very powerful pulsers. Strategies for dealing with the major challenges confronting the ILC magnets will be described.**

***Index Terms*—Accelerator magnets, room temperature, superconducting.**

I. Introduction

THE International Linear Collider has about 80 km of beamlines which require magnets for focusing and steering the beams. There are over 13000 individual magnets powered by about 9500 power supplies through about 4000 Km of cables. Approximately 18% of the magnets are superconducting and the rest are "conventional" warm iron-dominated magnets with copper coils, of which about 60% are water-cooled. About 40% are low-current corrector magnets. The ILC comprises several sets of beam lines divided into areas, each with a particular purpose indicated in each area name, see Fig. 1. The complexity of the lattices results in 135 different magnet styles, 92 styles are room temperature magnets and 43 are superconducting, see Table I.

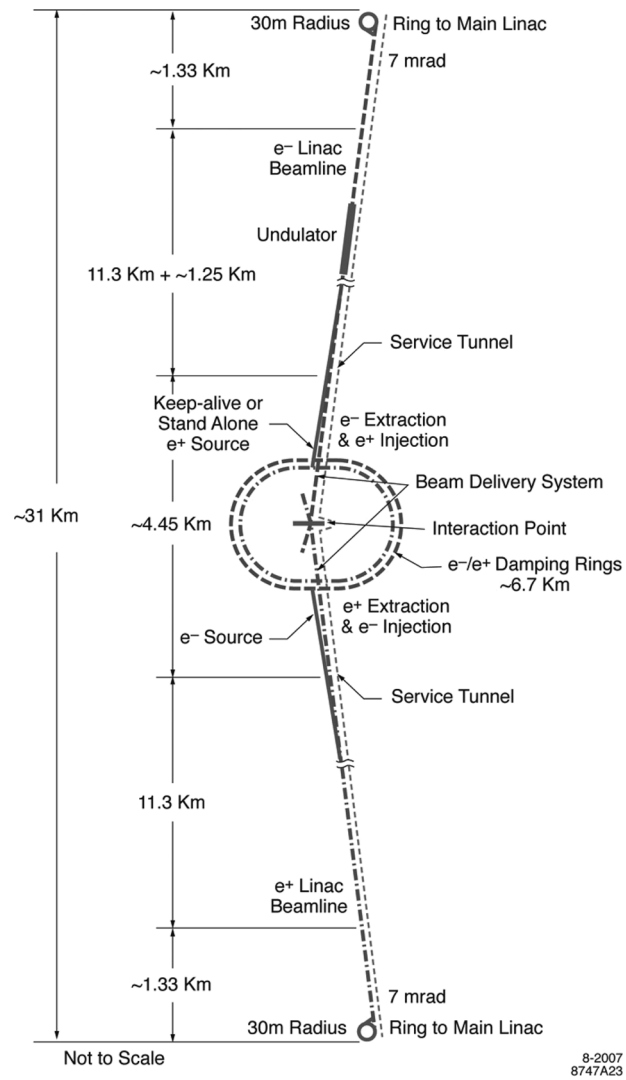

Fig. 1. Schematic layout of the International Linear Collider as proposed in its Reference Design Report. Beam line areas are noted by name.

Superconducting technology is primarily used for the magnets located in the RF cryomodules, but it is also required for some spin rotation solenoids, damping ring wigglers, the positron source undulator, some beam delivery octupoles and sextupoles and the four quadrupoles closest to the interaction point.

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TABLE I
QUANTITATIVE SUMMARY OF ILC MAGNET TYPES AND STYLES BY BEAM LINE AREA

Magnet Type	Grand Totals		Sources		Damping Rings		2 RTML Qty	2 Linacs Qty	2 BeamDel Qty
	Styles	Quantity	e-	e+	e-	e+			
Dipole	22	1356	25	157	134	134	716	0	190
Normal Conducting Quad	37	4182	93	871	823	823	1368	0	204
Sextupole	7	1050	0	32	504	504	0	0	10
Normal Conducting Solenoid	3	50	12	38	0	0	0	0	0
Normal Conducting Corrector	9	4047	0	871	540	540	2032	0	64
Pulsed/Kickers/Septa	11	227	0	19	46	46	52	0	64
NC Octupole/Muon Spoilers	3	8	0	0	0	0	0	0	8
Room Temp. Magnets	*92*	*10920*	*130*	*1988*	*2047*	*2047*	*4168*	*0*	*540*
Superconducting Quad	16	715	16	51	0	0	56	560	32
Superconducting Sextupole	4	12	0	0	0	0	0	0	12
Superconducting Octupole	3	14	0	0	0	0	0	0	14
Superconducting Corrector	14	1374	32	102	0	0	84	1120	36
Superconducting Solenoid	4	16	2	2	0	0	8	0	4
Superconducting Wiggler	1	160	0	0	80	80	0	0	0
Superconducting Undulator	1	42	0	42	0	0	0	0	0
Superconducting Magnets	*43*	*2333*	*50*	*197*	*80*	*80*	*148*	*1680*	*98*
Overall Totals	135	13253	180	2185	2127	2127	4316	1680	638

II. GENERAL TECHNICAL ISSUES AND SOLUTIONS

These 135 styles cover a remarkable range of magnetic strengths and purposes; the smallest are about 0.12 m long correcting dipoles, the longest is the 146 m long undulator; the most massive are the 5 m long muon spoilers that weigh about 913 tonnes each. Based on requirements provided by the beam area physicists the ILC Magnet System Group conceptually designed and costed 13,253 magnets, their supports and power supplies over the 15 months from September 2005 to December 2006. The ensuing details can be found in the ILC Reference Design Report [1].

About 75% of the ILC's numerous magnets have straightforward magnetic designs with easy to reach integrated strengths and typical field quality requirements, but they are not without some technical challenges.

A. High Availability and Low Cost

The availability goal of the ILC is better than 85% and the magnets have been budgeted to incur no more than 0.75% downtime. The availability "A" of a component is given as $\mathrm{A} = \mathrm{MTBF}/(\mathrm{MTBF} + \mathrm{MTTR})$, where MTBF is Mean Time Between Failures, and MTTR is Mean Time To Repair a magnet, turn it back on and restore the beam.

Detailed studies of magnet failures at three high energy physics labs indicate that most failures are with conventional water-cooled magnets, which had MTBFs ranging from about 0.5 million to 12 million hours, based on tens of millions of integrated magnet-hours [2]. The ILC has about 7000 water-cooled magnets. Assuming an MTTR of 16 hours, Monte Carlo models of an operating ILC indicate that individual magnets must have an MTBF of well over 10 million hours in order to achieve the desired system availability [3]. This reliability level should be achievable, without incurring a significant increase in cost, by making meeting reliability requirements a key part of the design approach, by scrutinizing every aspect of magnet design, fabrication and operation in Failure Modes and Effects Analyses (FMEA) and by applying best modern magnet engineering practices. Already magnet manufacturers' advice is being sought, for e.g., via the Linear Collider Forum of America [4], on how to design in ease of fabrication. Magnets will be manufactured all over the world, so standards for materials and operating values (e.g. maximum allowed cooling water temperature rise) will be issued. Buying copper conductor and insulating tape, for e.g., for multiple magnet vendors will lead to larger quantity orders and will decrease the unit cost. Every magnet will be tested and measured at a well-equipped, high through-put on-site measurement facility.

B. Magnet Alignment

The magnets must be aligned very precisely with respect to the beams, especially at any quadrupole after the damping rings when the beam emittance is very small and to preserve it the beam must pass within a few micrometers of the magnetic center. Active correction of any offset between beam position and center will be effected by dipole correctors (in the linac quads) or 5-axis mechanical movers with a 50 nm minimum step (in the beam delivery system, BDS). The beam's position will be measured with high-precision beam position monitors (BPM). BPM positions are calibrated through a beam-based alignment process (called BBA) that demands the magnetic center of any BDS room temperature quad or sextupole not move by more than about 3 $\mu\mathrm{m}$ when its strength is reduced by 20% [5]. Prototype warm magnets will be built to check designs meet this requirement, which is affected by steel hysteresis.

C. Mechanical Stability and Reproducibility

Even though there will be active correction of some magnet positions, any movement of any magnet because of instability in its mechanical construction, or ambient temperature changes affecting the dimensions of its support or core must be minimized. The field obtained at a given current must also be stable with respect to the magnet powering history. The effect of persistent currents on the center behavior of superconducting quads is being investigated and more research will be done on prototypes.

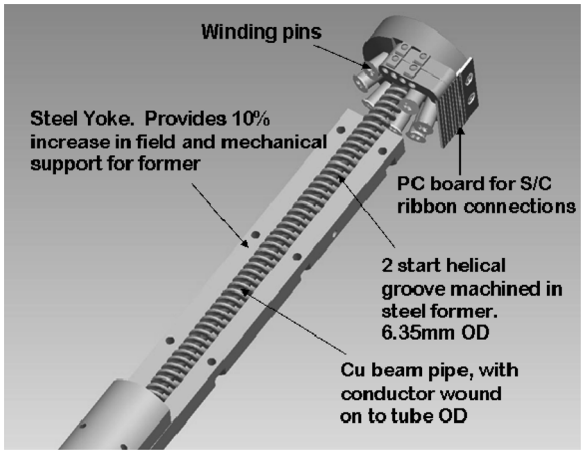

Fig. 2. Cut-away drawing of half of SC undulator module, 1.74 m long.

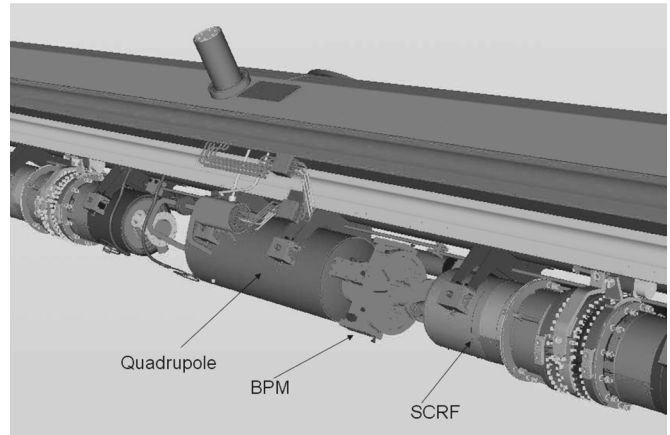

Fig. 3. Conceptual layout of main linac quad-corrector-BPM assembly at the center of an accelerator cryomodules, next to a SC RF cavity.

III. Specific Challenging Magnets

Every area of the ILC has its share of technically challenging magnets; the more challenging ones, all of which have R&D projects devoted them, will be briefly described here, in their order along the beams' path.

A. Positron Source Undulator

Positrons are created by the e- beam (at the 150 GeV point in the e- linac) passing through a superconducting helical undulator generating polarized synchrotron radiation ($\sim$10 MeV), which hits a conversion target to create longitudinally polarized positrons. The helical structure creates twice the synchrotron radiation power per period than that of a planar undulator, but the short periods demand very high fields which push the limits of the technology. The narrow apertures require very tight fabrication tolerances to maintain alignment. The cold bore (4 K) cannot tolerate more than a few watts of heating per module. It is impossible to use conventional vacuum pumps in the tiny aperture.

To overcome these challenges multiple R&D efforts are ongoing; in the past few years warm copper, pulsed copper and superconducting prototypes have been made, with the latter being most promising, see Fig. 2. [6] Even so the ideal undulator parameters are being modified to match the demonstrated prototypes.

B. Damping Ring Wigglers

The e+ & e- damping rings accept and reduce the incoming large emittance beams to required levels within the 200 ms interval between machine pulses yielding 25 ms damping times. 200 m of superconducting wigglers in each ring do the damping. Their main challenges are: they need a large aperture to accept the large incoming e+ beam; no liquid nitrogen is allowed in the DR tunnel; they deal with a large synchrotron radiation load and the low vacuum requirement means beam pipe has to be baked so a warm bore vacuum chamber insert will be used. A superferric design has been chosen, based on the Cornell CESR-c design [7]; modifications are being made to deal with the above issues and to provide simpler assembly procedures so as to reduce the cost estimate which was initially very high.

C. Damping Ring Kickers

Kicker magnets, which make fast time-dependent changes in the beam path, are used all over the ILC; there are 7 different styles and the DR ones have the most difficult requirements. They are stripline structures inside the vacuum chamber, driven by pulsed power supplies. Their pulses are required to last only 4–5 nanoseconds, whereas the state-of-the-art width is $\sim$20 ns, and the extremely fast pulsers must provide $+/-11$ kVolts. To inject and extract a train of $\sim$3000 bunches in the DR tens of kickers will be needed, each with 2 pulsers. To ensure their high availability there will be extra kickers and pulsers in place which will take over automatically if a pulser fails; and the pulsers will be accessible while beams are running so failed units can be quickly replaced. There are 3 kicker R&D projects on going to help solve these issues [8].

D. Main Linac Quadrupoles and Correctors

The two main linacs accelerate the e- and e+ beams from their injected energy of 15 GeV to the final beam energy of 250 GeV over a combined length of 23 km. This must be accomplished while preserving the small bunch emittances as described above. There are 560 SC quads in the 2 linacs to keep the beams weakly focused and 1120 SC dipole correctors. The weak quads run over a wide strength range up to 36 T and are superconducting only to avoid many warm-cold transitions; they are about 0.66 m long with a 90 mm bore diameter and sit in the middle of the SC accelerators' cryomodules. A quad, 2 dipole correctors and BPM are in one assembly, supported from above: Fig. 3.

As described in Sections II-B and II-C, the critical requirement for the quads is their magnetic center stability; during BBA it must not move by more than 5 μm. The stray field from the magnets at adjacent RF cavities must be less than 10 μT when cold. R&D programs for these quads are underway at FNAL [9] and KEK [10]. A first prototype made by CIEMAT initially for TESLA is about to be tested for its center stability at SLAC [11].

E. Beam Delivery System Magnets

The ILC BDS is responsible for transporting the e+ e- beams from the exits of the high energy linacs, focusing them to the sizes required to meet the ILC luminosity goals, bringing them

into collision, and then transporting the spent beams to the main beam dumps. The corresponding beam lines have quite different magnetic requirements so the BDS has the most distinct styles of any area, 66, even though it has the second lowest magnet quantity, 638.

476 BDS magnets are conventional room temperature magnets, mostly with water-cooled hollow copper conductor coils and low carbon steel cores. BDS quads and sextupoles have straightforward designs which will be useable up to 500 GeV per beam. The post-interaction point (IP) extraction line magnets have large apertures, from 90 to 272 mm, to accommodate the disrupted beam and the photons emerging from the IP. To reduce their overall size and power consumption, HTS coils in local cryostats are being considered, to be used with regular warm steel cores.

As described in Sections II-B and II-C the main technical issues with BDS magnets are their positional and field strength stabilities. Thermal and mechanical disturbances will be minimized by stabilizing the BDS tunnel air temperature to $+/-0.5°\mathrm{C}$, the cooling water to $+/-0.1°\mathrm{C}$, and limiting high frequency vibrations due to local equipment to the order of 10 nm.

The magnets within $+/-10$ m of the IP are the most challenging of all the ILC magnets. The final focus region with a 14 mr crossing angle between the beams is quite complicated. The incoming and outgoing beams are in very close proximity: 49 mm apart if the first magnet (QD0) is 3.5 m from the IP. There is a massive detector with a strong field in the way! The last elements of the beam lines are captured with the detector and must move with it ('push-pull' for 2 detectors). The beams' stability is critical for collisions to occur, they must move <100 nm pulse to pulse if there's a working "fast-feedback system". There are significant radiation loads from e+ e- interactions and the disrupted beams to be dealt with. In the same cramped space higher order chromaticity correction elements are required and any magnet's field must not interfere with its neighbors' fields. On top of all these issues some gradients required are high: 140 T/m for QD0 and the particle physicists want as small a cryostat as possible to interfere with their detector's solid-angle.

Solutions have been identified for some of these challenges; others are still being worked on [12]. The magnets will be made using BNL's direct wind technology which allows them to be very compact [13]. The dipole correctors and higher order multipoles: sextupole, skew-sextupole, octupoles etc will be wound with common centers. Active shield coils to protect adjacent beam lines will be wound around the same center. Anti-solenoid coils to make local corrections to avoid luminosity loss due to overlapping solenoid and quadrupole focusing fields will be included.

Some schematic drawings of the magnets within 10 m on one side of the IP are given in Fig. 4. Enlarged details are shown on the left and right. The coils are around 50 mm in diameter and are in one 1.9 K cryostat.

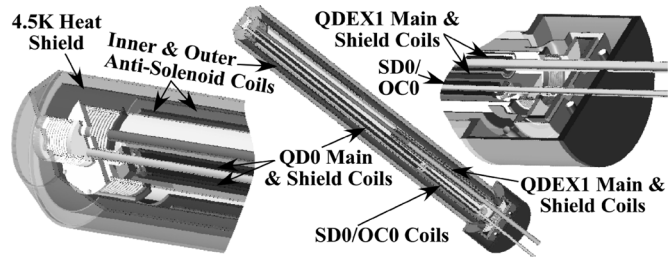

Fig. 4. The QD0 magnet grouping shown with a force-neutral anti-solenoid in a QD0 common cryostat. QDEX1 is 1st extraction line quadrupole. SD0: sextupole, OC0: octupole in incoming line.

IV. Conclusions

About 75% of the ILC's numerous magnets have straightforward magnetic designs with easy to reach integrated strengths and typical field quality requirements, their main challenges are to make them exceedingly reliable at a reasonable cost. The other 25% have a variety of other challenges as described here and several R&D projects are already working on these magnets.

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