THE DEVELOPMENT OF A SUPERCONDUCTING UNDULATOR FOR THE ILC POSITRON SOURCE*

E. Baynham, T. Bradshaw, A. Brummitt, G. Burton, S. Carr, A. Lintern, J. Rochford
STFC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK
J.A. Clarke, O.B. Malyshev, D.J. Scott, B.J.A. Shepherd
STFC ASTeC Daresbury Laboratory, Daresbury, Warrington, Cheshire WA4 4AD, UK
I R Bailey, Lancaster University
N Ryder, Bristol University
G.A. Moortgat-Pick
Institute of Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, UK
Y.Ivanyushenkov
Argonne Advanced Photon Source, 9700 S, Cass Avenue, Argonne, IL 60439

Abstract

The ILC positron source relies upon the creation of a ~200 m long superconducting helical undulator, in order to generate the huge flux of gamma photons required. The proposed period for such a device is ~10 mm, generating field strength of ~1 T. The HeLiCal collaboration in the UK has undertaken an R&D programme to investigate the feasibility of making such a device. The collaboration's work has shown that it is feasible to build a device very close to this. More recently we have built and are currently testing a full scale 4 m long prototype. This design is now part of the baseline design for the ILC. A summary of the R&D programme, the 4m prototype design, manufacturing and latest test results are presented here.

INTRODUCTION

For a future TeV linear collider like the International Linear Collider (ILC) there is a desire to collide electron and positron beams with substantial polarisation [1]. Polarised positrons (and electrons) are produced when circularly polarised γ-radiation is incident on a thin target, producing Bethe-Heitler e^+e^- pairs. Polarised γ-radiation is produced by the passage of a high energy electron beam through a helical undulator [2]. This has been experimentally demonstrated in the E116 experiment at Stanford Linear Accelerator Center [3].

The HeLiCal group within the UK[4] have undertaken a research programme to develop an undulator capable of meeting the ILC requirements. The first stage of the project assessed the merits of using superconducting or permanent magnet technology [5][6]. Following this the group adopted the superconducting design based on NbTi technology (as the baseline option) [7]. This paper concentrates on the development of the baseline design; magnetic modelling, manufacturing R&D to develop the techniques necessary to build a real undulator, beam induced effects, and finally the design and test of the full scale prototype. The project has now reached maturation, with the manufacture of a full scale 4m long prototype, which is currently being tested at the Rutherford Appleton Laboratory. The parameters for this device have been adopted by the ILC reference design.

ILC UNDULATOR PARAMETERS

The current requirements for the ILC positron source undulator are presented in the ILC Reference Design Report [8]. They are summarized in Table 1. These values were developed following the work of the HeLiCal programme.

Table 1: ILC Undulator Parameters [8]

Electron Drive Beam Energy	150 GeV
Photon Energy (1st harmonic cutoff)	10.0 MeV
Photon Beam Power	131 kW
Undulator Type	helical
Undulator Period	11.5 mm
Undulator Strength, K	0.92
Field on-axis	0.86 T
Beam Aperture (diameter)	5.85 mm
Winding Bore	6.35 mm
Undulator Length	147 m

MAGNETIC MODELLING

This section presents a summary of the modelling work carried out for the program. All the Magnetic modelling used Vector Fields software [9].

Use of Iron in the Undulators

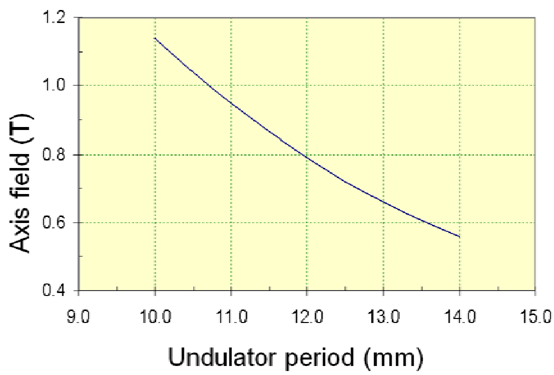

Figure 1: On-axis field required by the ILC undulator for a given period to produce 10MeV photons in the 1st Harmonic with a 150GeV electron drive beam.

The field requirements of the ILC undulator are shown in Fig. 1. The initial goal was to investigate the shortest period that could be reliably delivered. The group had experience of modelling a 14mm period undulator for TESLA [10], so this was taken as a starting point. A number of models were generated to see what could be achieved with no iron in the magnet structure, as this complicates any further assembly; and additionally to identify the most efficient cross section for the winding, given standard NbTi wire. The models show that winding with minimal radial height to width ratio creates maximal field on-axis. However, taking into consideration the peak field in the conductor, a square shape is most effective. The peak field in the conductor is on the internal surface of the innermost layer of the winding, as shown in Fig. 2.

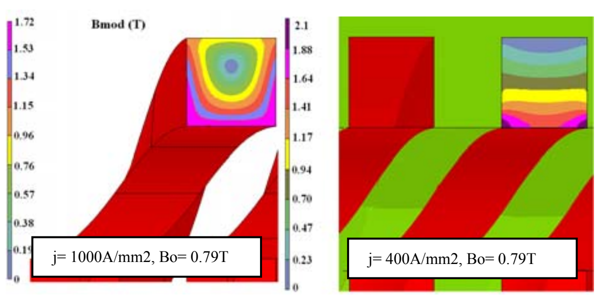

Figure 2: The peak field in conductor with and without no iron present, to deliver same bore field Bo.

It was found that it is not possible to generate the fields required by the ILC without including iron in the magnet structure. The models showed that to maintain the same on-axis field, the peak field in the conductor increases more rapidly as the undulator period is reduced. Table 1 shows the comparison for a (4x4) mm^2 winding cross section with a period of 14mm. For example, to generate an on-axis field of 0.8T the winding needs 1000 A/mm^2, (see Fig. 2); consequently the operating margin will vary from ~20%-30%, depending on the superconductor fraction in the wire, Table 2. However, if iron is included, the peak field goes up, but the magnet can now deliver the field with only 400A/mm^2 (see Fig. 2), and the operating margin on the conductor is now in the range of 50%-60%, Table 2. For the ILC the required field increases with decreasing period, so to get to shorter periods iron must be included in the structure. The models also show that the outer iron cylinder improves the relative operating margin by ~10%, whilst the iron pole (between the winding blocks) improves it by ~40% [11]. The vacuum chamber must be non-magnetic otherwise flux is shunted through it and the on-axis field is reduced.

Table 2: 3d Helical Undulator Models

Current density	J	400	1000*	A/mm^2
Air cored	B_{axis}	0.32	0.81*	T
	B_{peak}	0.7	1.76*	T
Operating point on	1.35:1	34.2	85.6*	%
load line for different	1:1	30.1	75.4*	%
C u/Sc ratios	0.75:1	27.2	68*	%
Iron former	B_{axis}	0.79*	1.35	T
and cylinder	B_{peak}	2.11*	3.06	T
Operating point on	1.35:1	47.9*	98.2	%
load line for different	1:1	43.9*	88.1	%
Cu/Sc ratios	0.75:1	41*	82.2	%

*Results shown in figs 2

Magnetic Optimisation

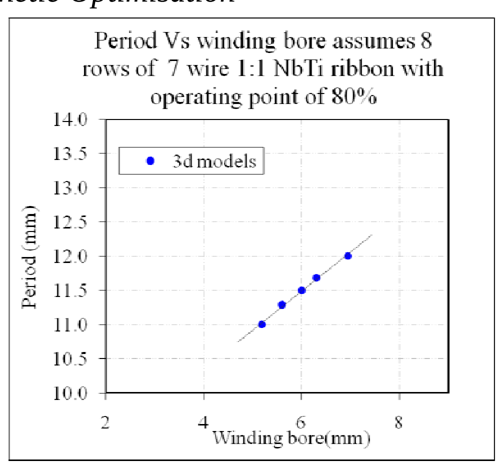

Figure 3: Optimisation of period and bore.

A critical area in the ILC design is the requirement for higher fields at shorter periods. There is a hidden effect here: the peak field in the winding also increases with reducing period, so as we progress to shorter periods we very quickly run out of conductor operating margin. Figure 3 summarises the 3d modeling results (more details can be found elsewhere [11]), showing the strong relationship between the period and winding bore size. These periods and bore combinations fulfil the ILC requirements, with a conductor operating point, at 80% of short sample. Note that operating points above the line are below 80% short sample, whilst those below the line are above 80% short sample. Allowing for a beam stay-clear of at least 4.5mm, and adding tolerances for manufacturing, alignment and a bore tube thickness of 0.25mm, a minimum practical winding bore was considered to be ~6mm. Based on this the shortest period attainable for the ILC with a Cu:SC fraction of 1:1 is ~11.5mm. In principle one can trade off some of the operating margin to reduce the period; in practice this would not take the period below 11mm and runs the risk of operating the magnet very close to it critical current. The operating margins calculated in this paper assume operation at 4.2K; again in principle one could operate a lower temperature, for example 1.8K, but again calculations show that the period is unlikely to get much smaller than 11mm.

MANUFACTURING R&D

An extensive R&D programme was undertaken to develop fabrication techniques suitable for producing 2-m long sections of undulator. The issues of machining undulator formers with a precision of 50μm or better, incorporating a beam pipe into the former, developing winding and vacuum impregnation techniques were addressed.

Figure 4: Prototypes 1 to 4.

The techniques were developed by manufacturing a series of 5 short prototypes and testing them, Fig. 4.

Details of winding techniques are described in [6]. Prototypes 1- 4 were wound with a superconducting wire having a cu:sc=1.35:1, while the final prototype 5 and 5' used cu:sc=0.9:1, allowing for an increase in the operational current. The windings are wound with ribbon created from off the shelf conductor wound with a bespoke winding machine. After winding, all the prototypes were vacuum impregnated with epoxy resin. For prototypes 1-4 the end regions were loaded with glass micro spheres to reduce the volume of clear resin and reduce cracking. This was tested for prototypes 5 and 5'. Prototype 5 had no micro spheres in the resin, and showed visible cracking after cool down. It was re impregnated as prototype 5' with micro spheres and showed no cracking.

Prototypes 1 and 2 have a period of 14 mm and magnetic bore of 6 mm, and are wound onto aluminium formers. Prototypes 3 and 4 have a shorter period (12 mm), and differ only in the former material (aluminium and soft iron respectively). These were used to study the effect of magnetic material and to benchmark the magnetic modelling results. Prototypes 1-3 had the winding groove and bore machined from a single solid piece. The formers of the prototypes 4 and 5 were assembled by mounting a separate iron spring onto the copper bore tube. This technique has been adopted for the fabrication of 2-m long undulator sections. Prototype 5 is a 0.5m long version of the final geometry selected for the full scale prototype. It was used to check the final manufacturing technique and winding geometry, before building the 2m long sections required for full-scale undulator module. Note the diameter of the bore in the prototype is 4.8mm, due to lack of availability of 5.85mm bore tube at time of manufacture. The winding bore is always maintained at 6.35mm.

Prototype Measurement

Field profile for all the prototypes was measured using a Hall probe, moved by a stepper motor through the bore of the undulator. The radial component of magnetic field was measured in steps of 0.1 mm over the length of each magnet. Additionally, for some cases the field was measured in an orthogonal plane. Typically, for the prototypes the homogeneity of the field (peak-to-peak) was at the level of 1%, or slightly better. The field quality depends on the geometric tolerance of the former. A study of the data showed that there is 1% in peak field homogeneity for a machining variation of 50μm on the winding radius [12].

BEAM EFFECTS

A key component of the prototype is the design and specification of the beam pipe. A number of studies have been undertaken to address this area, a good description can be found in [6].

Vacuum Design

The vacuum pressure required by the ILC is 1.3×10^{-10} bar [13]. To achieve this in a long narrow beam pipe is not a trivial matter. Two main effects limit the vacuum, thermal desorption of molecules and photon desorption of molecules from the vessel wall. Generally the cold beam pipe will minimise the effect of the former, but the latter is stimulated by the emission of upstream photons. To minimise this we must include regular collimation over the final 150m length.

Synchrotron Radiation Heating

As mentioned, collimation is required to minimise photon induced desorption in the vacuum vessel. Another area of concern is the thermal power deposited by synchrotron radiation heating from the beam. Potentially this can quench the magnets, if not intercepted. This can also be minimised by careful selection and positioning of collimators. It has been shown [6] that the un-collimated beam produces a thermal load of ~19.4W/m for the ILC RDR configuration. By placing circular collimators, with an aperture diameter 4.4mm, every ~4m (entry and exit of module), the load can be reduced to a mean value of 0.022W/m for the ILC RDR configuration.

Wakefield Calculations

Wakefield heating influenced by the conductivity and geometry of the beam pipe has been addressed in the design. Key findings are summarised here; more details can be found elsewhere [6].

Resistive Wakefield Heating

Wakefield heating in the vessel from resistive effects was calculated for different materials at 77K. The work finds that a copper tube is best to minimise this effect. It is shown that for a 5.8mm dia copper tube a power of 0.081-0.022W/m is dissipated. The range is given for different proposed ILC bunch fill patterns. The real vessel will run at ~4K, so the above is a worst case estimate. In addition to power dissipation, these wakefields can apply transverse kicks to the beam. In the current design it is estimated to be ~0.29eVμm^{-1}m^{-1}. This will have a very small effect, considering that the forward momentum of the beam is 150GeV and should be easily corrected

Geometric Wake Field Heating

Along with resistive wakefield effects, one must also consider the effect of wakefield's generated by the geometry of the beam pipe and photon collimators. A key area is shown to be the surface roughness of the copper tube. This can lead to a significant increase in the emittance of the beam. It is recommended that the internal surface of the beam pipe not exceed 100nm, which keeps the energy spread of the beam to an acceptable level. For the compete undulator (147m) the increase in energy spread remains below 10%.

In addition to the surface roughness, the effect of the beam pipe geometry on the beam was examined. The module has tapered transitions at the end to minimise any geometric effects. The calculations show that the existing design will increase the vertical beam emittance by 2.7% over the entire undulator under the pessimistic assumption that the tapers are misaligned transversely with a standard deviation of 300µm.

FULL SCALE UNDULATOR MODULE

Prototype Module

A key output from the HeliCal collaboration is the delivery of a full scale prototype module, capable of meeting the ILC positron source requirements [14]. A description of the module follows.

The module consists of two undulator sections immersed in liquid helium, held inside a rigid U-beam; this assembly forms the cold mass of the undulator. The U-beam maintains the sub assembly alignment and rigidity. The undulator axis is aligned to only ~+/-200µm in the U-beam. A revised alignment technique that will improve this considerably is presently under test. The cold mass sits inside a liquid He vessel, suspended by four tie rods.

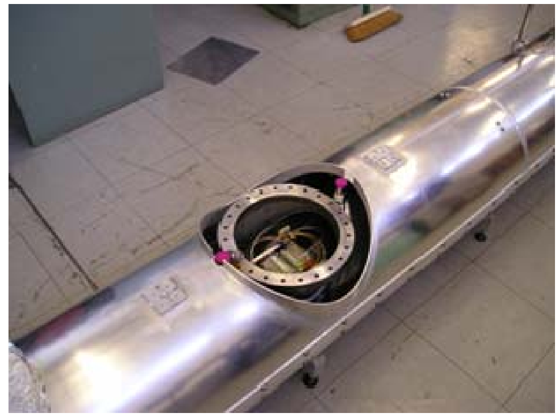

Figure 5: He vessel and magnets inside radiation shields.

The helium vessel is enclosed by a radiation shield held at a temperature of 50K, Fig. 5. It is a conduction cooled shield, linked to the 1st stage of the cryocooler.

The cryostat turret contains two pairs of HTS current leads and the condensing pot. The HTS leads allow independent powering of the magnet sections. The liquid helium condensing chamber is cooled down by the 2nd stage of the cryocooler, Fig. 6. The cryocooler and condensation stage create a thermal siphon, which recondenses the boiled off helium from the bath. Preliminary thermal calculations suggest that a closed-cycle cooling scheme can, in principle, be achieved. Current testing is underway to confirm if this is possible with beam heating effects.

Figure 6: The cryostat turret.

Magnet Testing

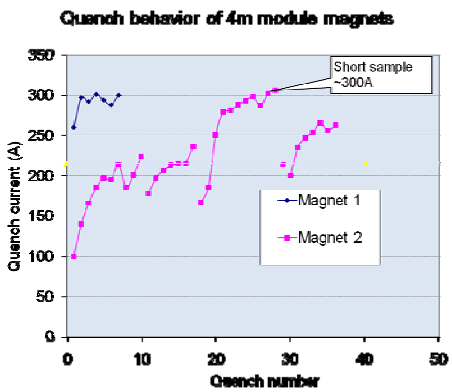

Figure 7: Results from the critical current testing of the magnets prior to integration in final vessel. Note the yellow line is the nominal current required by the ILC.

Each of the two magnet sections are a scaled up version of a 0.5m long undulator prototype, built and tested during the R&D phase. They were trialled in a dedicated test facility prior to assembly. The tests measured the field profile along the undulator axis and the quench current. From the quench testing, both magnets can deliver the nominal current required by the ILC, Fig. 7. The field profile data was used in conjunction with the numerical code SPECTRA[15] to examine the effects of the real undulator magnets on a 150GeV electron beam. The calculations showed that the expected radial deviation of the beam is <+/-20um over a single module. Figure 8 shows an example for magnet 2. The accuracy of the trajectories calculated is limited by the measurement data from the Hall probe as a small systematic error in every reading creates a significant trajectory effect. As a result these values are thought to be over pessimistic.

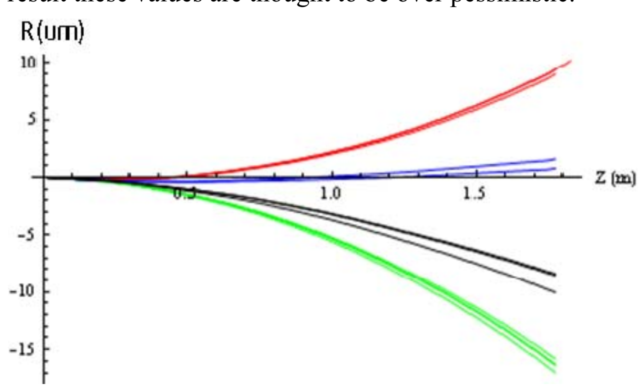

Figure 8: Calculated electron beam drift along magnet 2 the 4 different colours for equally spaced points (90^o) around the azimuth, calculated from measured field profiles, using SPECTRA. The same colour calculated for same field orientation measured with different hall probes.

CONCLUSION

A full-scale 4-m long superconducting helical undulator module has been built by the HeLiCal group. It has been demonstrated that all the components and design can meet the requirements of the ILC positron source. The integrated system has now been assembled and is currently being commissioned.

ACKNOWLEDGEMENT

The authors thank the members of the Magnets and Electrical Systems Group of CERN Accelerator Technology Department for their help in the manufacture of the superconducting wire ribbon.

REFERENCES

[1] G. Moortgat-Pick et al, “Polarized positrons and electrons at the linear collider”, Physics Reports 460 (2008) 131–243
[2] V.E. Balakin and A.A. Mikhailichenko, Preprint: INP 79-85, 1979.
[3] G.Alexander et.al, "Observation of Polarized Positrons from an Undulator-Based Source"Phys. Rev. Lett. 100, 210801, 2008
[4] http://www.astec.ac.uk/id_mag/ID-Mag_Helical.htm
[5] D.J.Scott et al, “Selection of the optimum magnet design for the International Linear Collider positron source helical undulator”, PRST-AB 10, 032401 (2007).
[6] D.J.Scott ,“An Investigation into the design of a helical undulator for the international linear collider positron source”, PhD thesis , University of Liverpool Feb 2008, Available: http://www.astec.ac.uk/id_mag/Polarisation%20Group/DuncanThesis
[7] Y. Ivanyushenkov, et.al, “Development of a superconducting helical undulator for a polarised positron source,” in Proceedings of the 21st Particle Accelerator Conference, (Knoxville), pp. 2295–2297, May 2005.
[8] International Linear Collider Reference Design Report, ILC-Report-2007-01, April,2007, Available : http://www.linearcollider.org
[9] http://www.vectorfields.com
[10] D. J. Scott, et.al "Design considerations for a helical undulator for the production of polarised positrons for TESLA" in Proceedings of the 9th European Particle Accelerator Conference, (Lucerne), pp. 458-459, July 2004.
[11] J. Rochford et al, “Magnetic Modelling of a Short Period Superconducting Helical Undulator for the ILC Positron Source”, Proceedings of EPAC 2006, Edinburgh, p.840
[12] Y. Ivanyushenkov et.al, "Status of R&D on a superconducting helical undulator fo rteh ILC positron source", Proceedings of PAC07, Albuquerque, New Mexico, USA, P.2865-2867. Available:http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/THPMN071.PDF
[13] O.B. Malyshev et.al "Vacuum Systems for the ILC helical undulator", J. Vac. Sci. Technol. A 25 (4) 2007 p791.
[14] Y. Ivanyushenkov et.al, "development of a full scale superconducting undulator for the ILC positron source", Proceedings of PAC07, Albuquerque, New Mexico, USA, P.2862-2864.Available:http://accelconf.web.cern.ch/AccelConf/p07/PAPERS/THPMN070.PDF
[15] T. Tanaka and H. Kitamura, "SPECTRA: A synchrotron radiation calculation code", J. Synchrotron Rad, vol. 8, pp. 1221-1228, 2001.