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MAGNETIC MODELLING OF A SHORT-PERIOD SUPERCONDUCTING HELICAL UNDULATOR FOR THE ILC POSITRON SOURCE*

J. Rochford#, E. Baynham, T. Bradshaw, A. Brummitt, S. Carr, Y. Ivanyushenkov
CCLRC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK

J.A. Clarke+, O.B. Malyshev+, D.J. Scott+
CCLRC ASTeC Daresbury Laboratory, Daresbury, Warrington, Cheshire WA4 4AD, UK

I.R. Bailey+, P. Cooke, J.B. Dainton+, L. Malysheva+
Department of Physics, University of Liverpool, Oxford St., Liverpool, L69 7ZE, UK

D.P. Barber+
DESY-Hamburg, Notkestraße 85, 22607 Hamburg, Germany

G.A. Moortgat-Pick+
Institute of Particle Physics Phenomenology, University of Durham, Durham DH1 3LE, UK,
and CERN, CH-1211 Genève 23, Switzerland

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Abstract

A positron source utilising undulators is defined as the baseline option for the International Linear Collider (ILC). The ILC requires a short period undulator, as close to 10mm as possible, that is capable of producing 10 MeV photons. The HeLiCal collaboration within the UK has undertaken a programme to design, develop and produce a prototype undulator. Part of the programme is to perform a magnetic design of the prototype using FEA modelling. The modelling has addressed several issues including the effect of magnetic material for the undulator former, optimal winding geometry, the magnetic flux inside the superconductor and its variation with undulator period and the winding bore. This paper summarizes the results of both the 2d and the 3d magnetic simulations.

INTRODUCTION

The work presented here summarises the magnetic modelling carried out by the cryogenics group at the Rutherford Appleton Laboratory (RAL), as part of the HeLiCal collaboration within the UK [1]. The goal of the modelling is to define the shortest period undulator that can be reliably built using standard NbTi superconductor. The cryogenics group at RAL has previously developed a short prototype, superconducting helical undulator [2,3]. This was an air cored device (former permeability μ_r~1) developed to fulfil the requirements for the TESLA injection system. The modelling results presented here build on this earlier work. All the magnetic modelling was completed using OPERA 2d and 3d software from Vector Fields Ltd [4].

THE ILC UNDULATOR

The undulator required for the ILC is more ambitious than the previous TESLA design; it needs a higher central flux density and shorter period (see Table 1); with the goal of getting as close to 10mm as possible, more details are given in [5]. For shorter periods in Table 1 higher fields are required so the conductor needs to operate close to the limit of standard NbTi technology. The modelling presented here will demonstrate just how short a period can be attained.

Table 1: Axial field B_{axis} required by the ILC undulator for different periods

Electron energy: 150GeV	
First harmonic photon energy: 10MeV	
Period (mm)	**B_{axis} (T)**
10	1.14
11	0.95
12	0.79
13	0.66
14	0.56

EFFECT OF INCLUDING AN IRON FORMER

Some modelling results from the TESLA work are presented in Table 2, they show the effect of replacing the air core with an iron former; for a period, P=14mm, winding bore B=6mm, and a winding section; dr=4mm,

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[+] Cockcroft Institute, Daresbury Laboratory Warrington, Cheshire WA4 4AD,UK

[#] J.H.Rochford@rl.ac.uk

dz=4mm (refer to Fig 1). Notice the peak flux density in the conductor, B_{peak}, is 1.76T. However if the period is reduced to 10mm B_{peak} would rise to 3.3T for the same B_{axis}, of 0.8T. From Table 1 the ILC undulator requires a B_{axis} of 1.14T, for P=10mm. This creates an operating regime in which the NbTi superconductor can not work. However, Table 2 shows that if the former is changed to iron, B_{peak} increases but the current density to achieve the same B_{axis} is reduced. Overall, this gives a better operating margin for the superconductor, e.g. a B_{axis} of ~0.8T can now be achieved with a current density of 400Amm^{-2}. The iron poles effectively contribute ~0.5T to the central field. The effect is to reduce the operating point from 75% to 44%. The implications for the ILC helical undulator are clear if it is to use NbTi conductor it must have an iron former.

Table 2: The effect of including iron in the undulator former, for a copper to superconductor ratio (Cu:Sc) 1:1.

	Current density					
	200	400	600	800	1000	A/mm^2
Air cored						
B_{axis}	0.16	0.32	0.49	0.65	0.81	T
B_{peak}	0.35	0.7	1.05	1.41	1.76	T
Cu/Sc	**Operating point of short sample**					
1:1	15.1	30.1	45.2	60.3	75.4	%
Iron former						
B_{axis}	0.53	0.79	0.97	1.15	1.35	T
B_{peak}	1.51	2.11	2.43	2.74	3.06	T
Cu/Sc	**Operating point of short sample**					
1:1	26.4	43.9	58.6	73.3	88.1	%

2D IRON MODELLING

A key lesson from the TESLA work is the steep field gradient at the iron-conductor interface; this makes it difficult to estimate the B_{peak}.

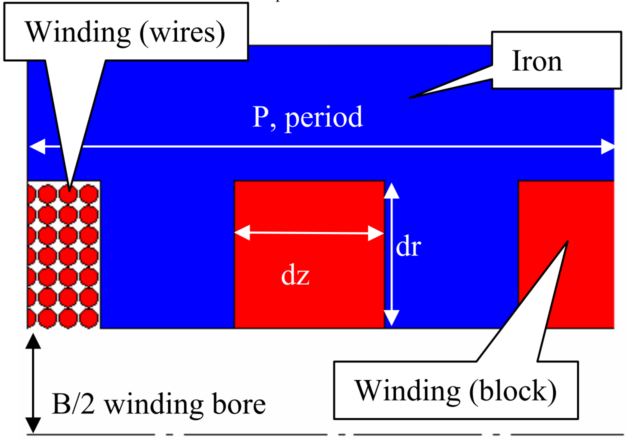

Figure 1: Diagram showing the 2d planar undulator models, the innermost winding has a high mesh density to model the peak field in individual wires accurately

This can be solved by using a very high mesh density in the 3d model. Unfortunately the helical undulator has no symmetry that can be exploited so the model size quickly becomes very large and inefficient. A more effective way to examine the parameter space of the helical undulator is to do the initial analysis with analogous planar undulators which can be modeled in 2d, these can be used to examine the effect of changing the period, bore and winding size. However care must be taken in translating the 2d planar results into an equivalent value for a 3d helical undulator. Because of the azimuthal winding, the on-axis field of a helical undulator is always greater than that of a comparable planar undulator, for a given current density. The effect of this is shown in Figure 2, which shows the comparative effects for P=14mm, B=6mm, dr=4mm, dz=4mm planar and helical undulators.

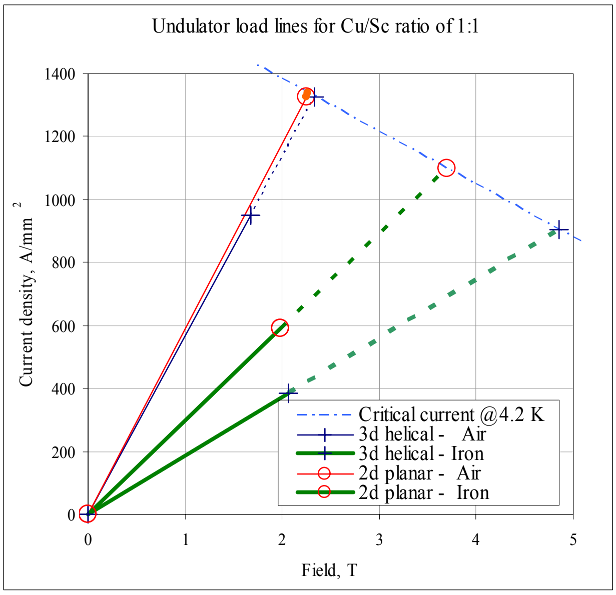

Figure 2: Load lines predicted for an analogous, 2d planar and 3d helical undulators, with and without iron. The blue dotted line is a theoretical fit to the conductor critical current based on data supplied by the manufacturer.

FORMER MATEIRAL

The first question addressed with the 2d model was to identify an optimum material for the iron poles. All previous models assumed US1010 mild steel because it is relatively cheap and has good machining properties. A series of models, each with different magnetic properties, were run for the same model; the 6 cases were:

1. High μ, high saturation level (Permendur)
2. High μ, lower saturation level (US steel 1010)
3. Low μ and a high saturation level (fictitious)
4. Low μ and a low saturation level (fictitious)

5. Linear, low µ, no saturation level (fictitious)
6. Linear, high µ , no saturation level (fictitious)

The last two have no saturation level and are non-physical, but were added for completeness. The results are shown in Table 3; the top row shows the comparable air cored case. All models are for; P=14mm, B=6mm, dr=4mm, dz=3.6mm. The results show that there is no benefit in using expensive high saturation and high µ material like Permendur over normal steel e.g. US 1010.

Table 3: Effect of changing the pole material

Case	**Current density (A/mm2)**	**Peak field (T)**		**Op point Cu:Sc 1:1**
		Conductor	**Iron**	
Air core	1283	2.14	0.00	94
1	547	2.06	3.60	51
2	589	2.00	3.43	53
3	617	1.97	3.31	54
4	1083	1.81	2.28	79
5	295	2.53	7.20	42
6	340	2.43	7.01	43

FORMER GEOMETERY

In this section the results of the modelling to study the effect of undulator geometry, period, bore and winding section are presented. Figure 3 shows the 2d results, it emphasises the strong relationship between the period and the winding bore; this is modified locally by the winding section. On the basis of this relationship a selection of 3d models were analysed.

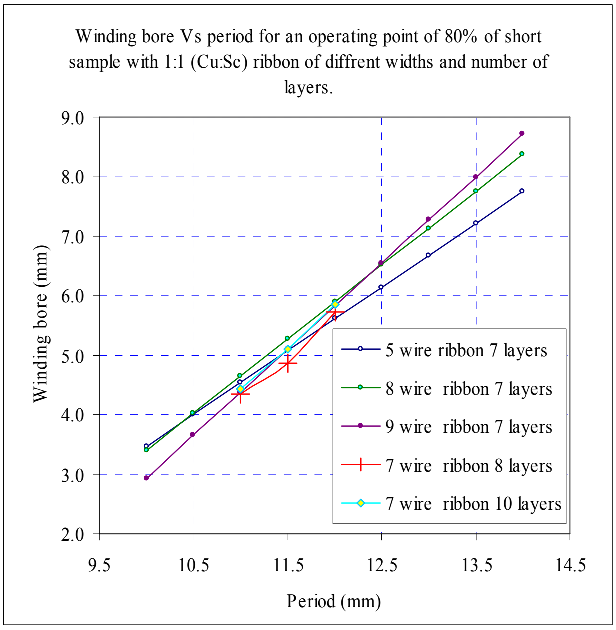

Figure 3: Some 2d results for the different configurations. The results are normalised for an operating point 80% of short sample.

The 3d results are shown in Figure 4 with the 2d results included for comparison (note the different slopes). The 3d results show which periods and bore combinations fulfil the ILC requirements, with a conductor operating point, at 80% of short sample. It is worth noting, that operating points above the line are below 80% short sample, whilst those are below the line are above 80% short sample. Allowing for a beam stay clear of 4.0mm and adding tolerances for manufacturing, alignment and a bore tube of wall thickness 0.25mm a minimum practical winding bore is considered to be 5.6mm. Based on this alone the shortest period attainable is ~11.5mm. However, in practice other manufacturing constraints need to be considered which may modify this figure.

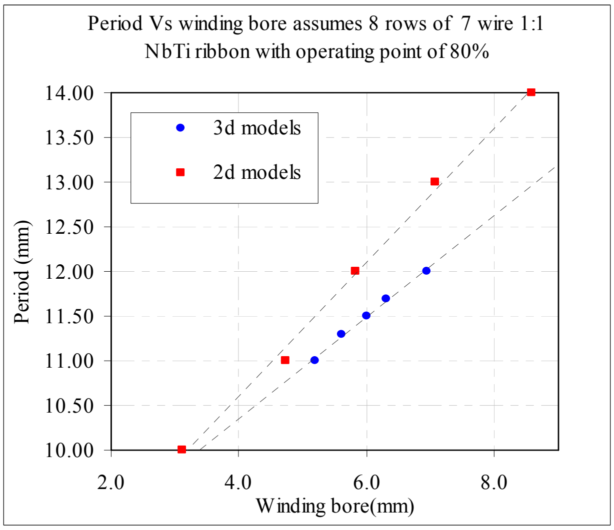

Figure 4: A comparison of 3d results and 2d results.

CONCLUSION

A helical undulator has been modelled in 2d and 3d for the ILC and the results corroborate each other. On the basis of the 3d results it is shown that for a beam stay clear of 4mm, and using NbTi wire with 1:1 copper to superconductor ratio, operating at 80% of short sample, it is unlikely that a period of less than 11.5mm will be possible without increasing the photon energy of the undulator first harmonic.

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[5] Y. Ivanushenkov et al., “Development of a Superconducting Helical Undulator for the ILC positron Source”, these proc