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THE EFFECT OF VACUUM VESSEL PERMEABILITY ON THE FIELD QUALITY WITHIN DIPOLE AND QUADRUPOLE MAGNETS AT THE ENERGY RECOVERY LINAC PROTOTYPE (ERLP) AT DARESBURY LABORATORY

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The Energy Recovery Linac Prototype (ERLP) is currently under construction at Daresbury Laboratory in the UK and will serve as a test bed for the investigation of technologies and beam physics issues necessary for the development of Daresbury Laboratory’s Fourth Generation Light Source (4GLS) proposal. To assist with the material specification of the vacuum vessels, analyses have been done on the effect of vessel permeability on the magnetic field quality within quadrupole and dipole magnets. It is found that for dipoles where the specified maximum relative dipole field variation over the good field region is B/B_0 __ $\pm1\times10^{-4}$ or for quadrupoles where the specified maximum relative gradient variation is G/G_0 __ $\pm1\times10^{-3}$, the transverse size of the good field region decays unacceptably for relative permeability ${}_r >$ 1.006. However, for the dipoles where the specified maximum relative dipole field variation is B/B_0 _ $\pm1\times10^{-3}$, the decay of the good field region is more gradual and would safely permit a material with relative permeability ${}_r >$ 1.006 to be used for the vacuum vessels within these dipoles

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INTRODUCTION

An energy recovery linac prototype is funded and under construction at Daresbury Laboratory. This proof-of-concept facility will enable the R&D necessary for the 4th Generation Light Source (4GLS), a novel high intensity source for which the Conceptual Design Report was published this year [1].

The layout of ERLP is summarised as follows: a DC photocathode gun produces electrons at ~350keV; a superconducting booster cavity accelerates the beam to 8.35MeV; an injection line transports the beam through an isochronous dog-leg into the injection chicane; a superconducting linac accelerates to 35MeV; a 180° triple-bend achromat (TBA) transports the beam isochronously to the back straight; a 4-dipole chicane compresses the bunches to obtain the high peak current necessary for the FEL; a planar wiggler, supplied on loan from Jefferson Laboratory, is used for the FEL [2] which is predicted to induce a full energy spread in the beam of up to 4%; a 180° TBA, identical in design to the outward arc, transports the disrupted beam back to the injection straight; the linac recovers most of the beam energy by decelerating to 8.35MeV; a 3-dipole extraction chicane steers the decelerated beam to a dump line.

The beam transport magnets required for the injection and extraction chicanes and bunch compression chicane have been generously supplied on loan from Jefferson Laboratory where they were previously used in the IR-DEMO FEL project [3]. In addition a number of quadrupoles in the straights have been loaned by Jefferson Laboratory. All of the remaining magnets have been procured from Danfysik A/S, who designed and constructed the magnets to match the stringent magnetic field requirements and dimension contraints specified by Daresbury Laboratory [4].

THE MAGNET SPECIFICATION

The magnet specification for ERLP imposes stringent field quality requirements. These criteria are motivated by the facts that within the FEL wiggler electron beam motion must be limited to within 10% of electron beam radius and that steering back into the superconducting linac module must be carefully controlled to maximise the efficiency of energy recovery. This implies that the relative permeability of the vacuum vessels within the magnet apertures must be as close to unity as possible to minimise the disturbance to the field.

The preferred material for vacuum vessel manufacture is stainless steel of specification 316LN which has a relative permeability of $\mu_r < 1.006$. The letter L indicates a low carbon content and the N indicates added nitrogen. As well as a low permeability this material displays added hardness with respect to standard stainless steel which makes it particularly suitable for vacuum flanges.

During the procurement of the vacuum system the possibility was foreseen that some materials necessary for fabrication, for example seamless welded tubes in appropriate sizes and some flanges, might not be available in 316LN. Alternatively it was thought it might be possible to use higher permeability steel in places to reduce the facility cost. For these reasons it was decided to investigate the effect of vacuum vessels with permeability $\mu_r > 1.006$ (the value for 316LN) on the magnetic field quality within certain dipole and quadrupole magnets.

MODELLING

During the production of the magnet specification, prior to tender, a number of magnetic models had been produced in Opera 2D by Daresbury Laboratory. These had been used to assess the feasibility of achieving the requested field specification and to assess reasonable limits for the physical dimensions of the magnets. The latter information was required to assist with the engineering layout of the beam transport system. By the time the specification was released the magnet parameters had been amended slightly due to further accelerator physics work refining the aperture and field quality requirements. However, the original Opera 2D models were close enough to the final specification to be useful for assessing the effect of the vacuum vessel permeability on the transverse field quality.

The models were amended to include a vacuum vessel wall within the aperture of two types of dipole, Dipole A and Dipole D, and one type of quadrupole, Quadrupole D. The specifications of these magnets, as modelled, are summarised in Table 1. Linear magnetostatic solutions were calculated for each magnet type, varying the relative permeability of the vacumm vessel over the values μ_r = 1.000, 1.006, 1.040 and 1.080.

Table 1. Parameters of ERLP magnet Opera 2D models.

	Dipole A	**Dipole D**
Location in ERLP	Injector line	TBA Arc
Strength	0.08 T	0.27 T
$\Delta B/B_0$	$\pm 1\times10^{-3}$	$\pm 1\times10^{-4}$
Good field (H×V)	± 33 × ±33 mm	± 33 × ± 21 mm
Full Gap	80 mm	50 mm
	Quad D	
Location	Injector line/TBA	
Strength	1.82 T/m	
$\Delta G/G_0$	$\pm 1\times10^{-3}$	
Good field (H&V)	± 42 mm	
Inscribed radius	45 mm	

Dipole A Results

The results of the modelling over different relative permeabilities are summarised in Figure 1. The good field width has been normalised with respect to its value for unit permeability to allow these results to be useful in a general context. It is seen that the width of the good field region, defined here as the region in which $\Delta B/B_0 \leq \pm1\times10^{-3}$, reduces to 89% of its maximum value (i.e. at unit permeability) as the permeability reaches $\mu_r = 1.08$. The criteria was set for this magnet type that reduction in good field width below 95% of maximum value was unacceptable. Applying this criteria implies that for the vacuum vessels within Dipole A the vessel permeability must not exceed ~1.02. Hence the use of 316LN stainless steel is not compulsory for the vessels within these magnets.

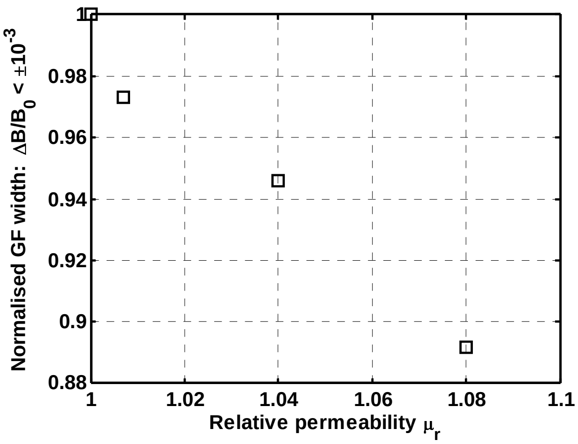

Figure 1: Summary of results for Dipole A. The good field (GF) width is normalised with respect to its value at unit relative permeability.

Dipole D Results

A summary of the modelling results for Dipole D is shown in Figure 2. Examples of the Opera 2D output are shown in Figure 3. For this magnet the good field region is specified as the region in which $\Delta B/B_0 \leq \pm1\times10^{-4}$. It is seen that in this case, compared to Dipole A, the good field width decays much more rapidly. Even at the relative permeability of 316LN the good field width is only 65% of its maximum width and for a permeability of $\mu_r = 1.08$ the good field width is only a quarter of its maximum width. The recommendations were made that the vacuum vessels must be constructed from 316LN stainless steel, and that the reduction of good field width due to this effect must be studied later once 3D models of the magnets had been produced which would allow assessment of the integrated field quality.

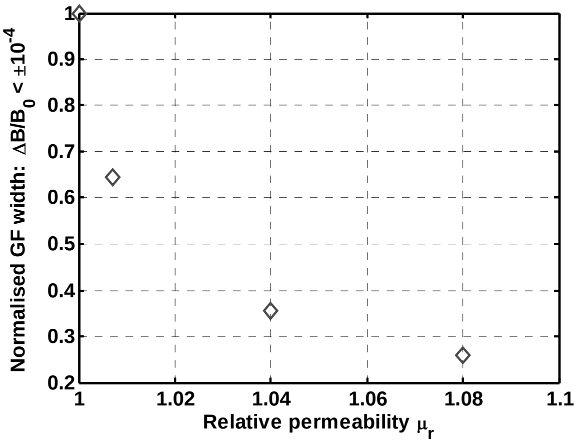

Figure 2: Summary of results for Dipole D. The good field (GF) width is normalised with respect to its value at unit relative permeability.

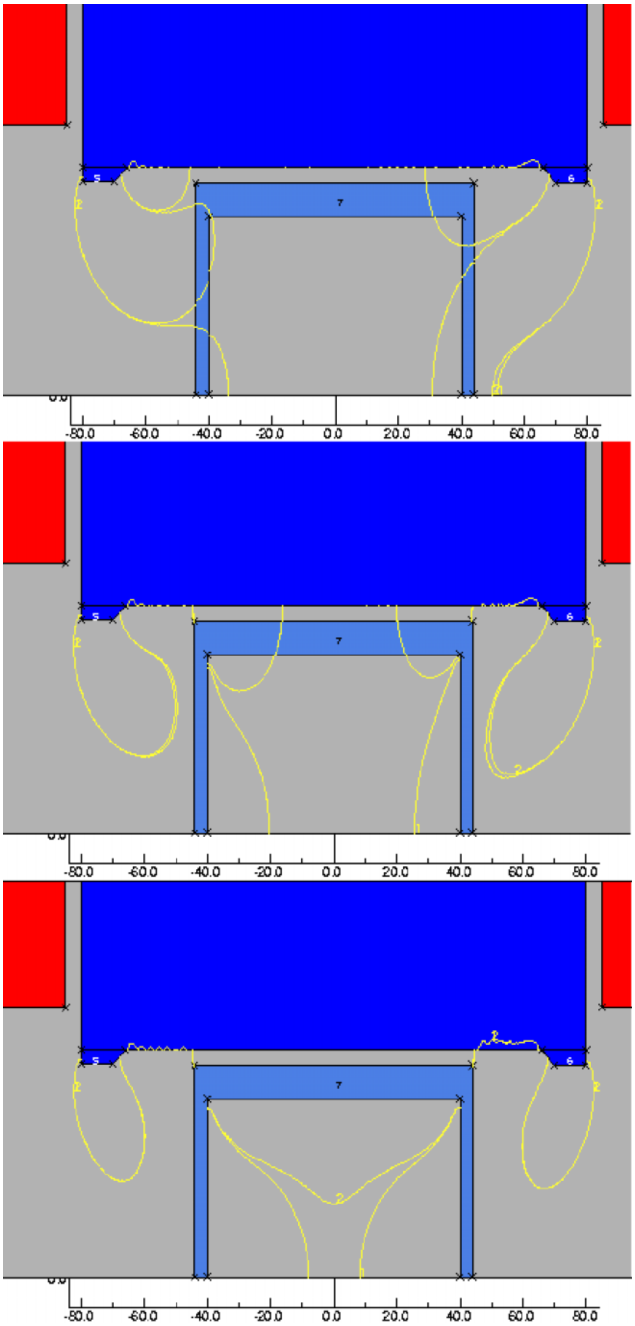

Figure 3: Opera models for Dipole D with the relative permeability of the vaccum vessel varying from $\mu_r = 1.000$ (top) to $\mu_r = 1.006$ (middle) to $\mu_r = 1.080$ (bottom). The contours are lines of $\Delta B/B_0 = \pm 1\times 10^{-4}$.

Quadrupole D Results

The results for the Quadrupole D are shown in Figure 4. They indicate that the use of 316LN would be advisable. The good gradient width, defined as the region in which $\Delta G/G_0 \leq \pm 1\times 10^{-3}$, where $G=dB_y/dx$, is seen to reduce rapidly as the relative permeability increases.

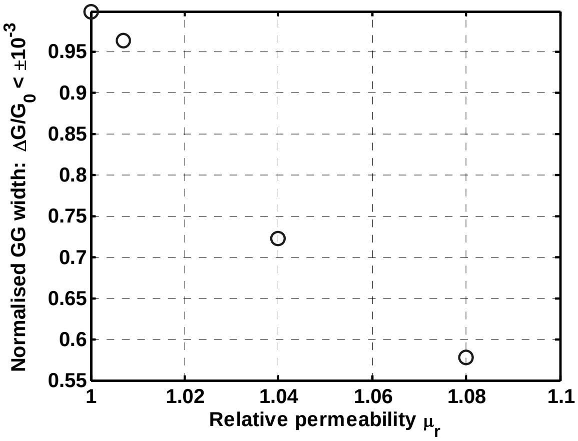

Figure 4. Summary of results for Quadrupole D. The good gradient (GG) width is normalised with respect to its value at unit relative permeability.

CONCLUSION

The effect of vacuum vessel permeability on the field quality within three different magnet types on the ERLP has been investigated. This has been done using preliminary Opera 2D models of these magnets. These models differ from the final magnet designs produced by Danfysik A/S, because the final specification was amended after this work was done and the Danfysik designs satisfy *integrated* good field and gradient specifications. However, the models used here are close enough to the final magnet designs to allow a quantitative analysis of the problem. It has been found that for the dipole type where the specified maximum relative dipole field variation over the good field region is $\Delta B/B_0 \leq \pm 1\times 10^{-4}$ or for the quadrupole type where the specified maximum relative gradient variation is $\Delta G/G_0 \leq \pm 1\times 10^{-3}$, the transverse size of the good field region decays unacceptably for relative permeability $\mu_r > 1.006$. In these cases it is recommended that the lowest permeability stainless steel, 316LN, is used for vacuum vessels within these magnets. However, for the dipole type where the specified maximum relative dipole field variation is $\Delta B/B_0 \leq \pm 1\times 10^{-3}$, the decay of the good field region is more gradual and would safely permit a material with relative permeability $\mu_r > 1.006$ to be used for the vacuum vessel within these dipoles.

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