THE SPECIFICATION, DESIGN AND MEASUREMENT OF MAGNETS FOR THE ENERGY RECOVERY LINAC PROTOTYPE (ERLP) AT DARESBURY LABORATORY

Franz Bødker, Danfysik A/S, Jyllinge, Denmark
Neil Marks & Neil Thompson, ASTeC, CCLRC Daresbury Laboratory, Warrington WA4 4AD, UK

Abstract

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. A number of new ERLP beam transport system magnets have been procured for the project. The magnets have been designed, manufactured and measured by Danfysik following a stringent magnetic field specification produced by Daresbury Laboratory. In this paper we summarise the magnet specification. We then present details of the magnetic design of the magnets and finally discuss the measurement techniques used to demonstrate that the field quality of the magnets satisfied the specification.

INTRODUCTION

An energy recovery linac prototype is currently 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; a fairly long 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 which is predicted to induce a 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 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 [2]. 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 [3], who designed and constructed the magnets to match the stringent magnetic field requirements and dimension constraints specified by Daresbury Laboratory. The magnets have all been accepted on the basis of magnetic measurement data supplied by Danfysik that demonstrated that the field specification was satisfied for all magnet types.

THE MAGNET SPECIFICATION

The magnet specifications for the magnet types procured from Danfysik are summarised in Table 1 through Table 3. It is seen that the field strength requirements for all magnet types are modest, so air-cooled designs are appropriate. The only exceptions are the TBA dipoles where the increased current density in the coils makes water-cooling necessary. The aperture requirements are dominated by the uncertainty in the expected Twiss parameters from the photocathode gun, which necessitates a high contingency in aperture in the injector, and the fact that the return arc must transport with minimal loss a beam with a full energy spread induced by the FEL of around 4%. The field quality criteria are motivated by the facts that within the FEL wiggler beam motion must be limited to within 10% of beam radius and that steering back into the linac must be carefully controlled to maximise the efficiency of energy recovery.

Table 1. Specification for ERLP dipole magnets.

	Dipole A	**Dipole D**
Location	Injector line	TBA Arc
Length	0.2 m	0.5 m
Strength	0.08 T	0.27 T
$\int \Delta B_y/B_y(0).ds$	$\pm 1\times10^{-3}$	$\pm 1\times10^{-4}$
Good field (H×V)	± 41 × ± 33 mm	± 40 × ± 21 mm
Bend Angle	30°	60°
Full Gap	73 mm	52 mm

Table 2. Specification for ERLP quadrupole magnets.

	Quad A	**Quad D**	**Quad E**
Location	Injector	Inj/TBA	Dump
Length	0.15 m	0.15 m	0.15 m
Strength	1.1 T/m	1.82 T/m	1.1 T/m
$\int \Delta G_y/G_y(0).ds$	$\pm 1\times10^{-3}$	$\pm 1\times10^{-3}$	$\pm 5\times10^{-2}$
Good field (H&V)	± 33mm	± 42.5mm	± 100mm
Inscribed radius	36 mm	45 mm	102.5 mm

Table 3. Specification for ERLP sextupoles.

	Sextupole A
Location	TBA
Length	0.2 m
Strength	40 T/m^2
$\int \Delta G_s/G_s(0).ds$	$\pm 3\times10^{-3}$
Good field (H)	± 40 mm
Inscribed radius	45 mm

MAGNET DESIGN

Magnetic designs of the magnets were performed with the Opera-2D/ST and Opera-3D/TOSCA programs from Vector Fields [4]. The 2D code was used to design the pole profile and the magnet end termination was optimized with the 3D code.

Dipole A is of the traditional H-type with a simple racetrack coil. The pole is relatively wide to reduce the transverse field roll-off with additional Rose shims. This introduces a positive sextupole-like field component in the centre region of the magnet in order to negate the opposite effect from the end sections. With this simple design the relative variation of the field integral was reduced to $\pm0.2\times10^{-3}$ within the median plane and $\pm1\times10^{-3}$ in the good field region. The dimensions of this region are given in Table 1.

Dipole D is a 60º bend magnet of the C-type to allow straight-ahead vacuum ports for alignment purposes and extraction of synchrotron radiation for diagnostic purposes. The requirement of maximum $\pm1\times10^{-4}$ relative field integral deviation from the ideal linear variation (due to the variation of path length as a function of transverse entry coordinate) is a tight requirement. The field integral is evaluated along a number of trajectories within the good field region in the hard edge field boundary approximation. Rose shims are again used to minimize the deviation on the transverse variation of the integrated field. With this design the relative deviation of the field integral was reduced to $\pm0.8\times10^{-4}$ within the good field region in the median plan at 100% excitation. Figure 1 shows the 3D model of Dipole D.

The quadrupole and the sextupole pole profiles were optimized in Opera-2D such that the unwanted higher harmonic field contribution was minimized for the central part of the magnet. The contributions from the end sections to the higher harmonics were minimized by introducing the usual 45º chamfer on the pole ends and the chamfer sizes were optimized with Opera-3D model calculations. The coils were modelled with a minimum degree of approximation to avoid any significant model errors on this account. The model of Quadrupole D is shown in Figure 2.

The harmonics were obtained from the model calculations by Fourier analysis of the potential on a circle with the good field radius (integrated potential in the 3D case). From these results the field and gradient errors were determined. It should be noted that the contribution of the n-harmonic term is n-1 times larger for the quadrupole gradient error compared to the field error:

$$dG_n / G = (n-1)dB_n / B \,.$$

The specifications on the gradient errors are therefore much tighter than similar field error requirements.

All magnets are solid magnets produced with tight mechanical tolerances.

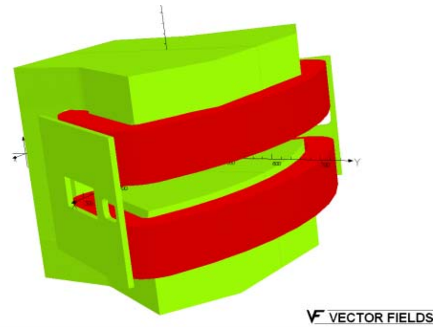

Figure 1. Opera-3D model of Dipole D.

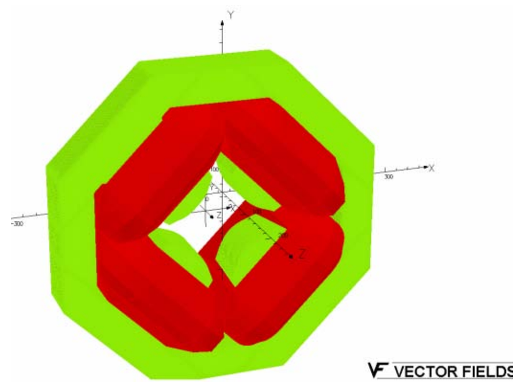

Figure 2. Opera-3D model of Quadrupole D

MAGNET TEST AND PERFORMANCE

The magnetic tests of the type A dipoles were performed with a Hall probe using the Danfysik System 695 *x-y-z* field mapper. With a centre field of only 0.08 T the drift of the Hall probe measurements is a significant concern. With a short term drift of 10μT the accumulated uncertainty on the relative integrated field is below $\pm0.3\times10^{-3}$ and thus acceptable for magnets with a specification level of $\pm1\times10^{-3}$. The average test results for the measured integrated field errors are given in Table 4 for all types of magnets.

Magnetic field integral evaluation based on Hall probe measurements is problematic for Dipole D due to the $\pm1\times10^{-4}$ requirement on the integrated field errors. The verification of the field integral deviation was therefore performed with an integrated coil (see Figure 3) which has significantly better performance. The integrating coil has 440 turns and an average width of 7 mm. It is fixed in the shape of the nominal trajectory in the hard edge approximation with the magnet bend radius of 477 mm and straight outside the effective field boundaries. By ramping up the magnet current with the integrating coil placed in the magnet the induced field integral is measured. At 100% excitation with a centre field of 0.27

T the field was found using a NMR probe to be stable with a standard deviation of 7 PPM.

As the field integral inherently has strong dependence on the horizontal position in bend magnets it is crucial for these type of measurements to have accurate position data. The position in the horizontal plane of the integrating coil was measured at each end of the magnet with linear encoders having a resolution of 0.005 mm and the coil position was found to be reproducible on this level. The absolute value of the field integral is best calibrated by comparison to Hall probe field mapping results. It was found that the relative stability on the measured integrated voltage was about $\pm 1 \cdot 10^{-4}$ corresponding to an uncertainty of ±0.1 mm on the effective magnetic length. Using this method the effective magnetic lengths were measured for all six magnets and using the field clamps the effective magnetic lengths were adjusted such that the spread was reduced to within ±0.2 mm. By measuring the relative variation of the field integral with the integrating coil in a number of positions the field integral deviation from the required linear variation was determined.

For the six magnets the relative field integral deviation was found to be on average $\pm 1.0\times10^{-4}$ which is only slightly larger than the design value of $\pm 0.8\times10^{-4}$. The measuring uncertainty on the relative field integral variation in the median plane was estimated from five consecutive measurements which gave a relative standard deviation of $\pm 0.3\times10^{-4}$.

The integrated harmonic content of the quadrupoles and the sextupole were measured with a Danfysik System 692 harmonic coil measuring bench. Both the bench and harmonic coils are produced at Danfysik. The quads were measured with harmonic coils made to allow compensated measurements [5] with high suppression of the quadrupole for precise measurements of the higher harmonic error terms. Different measuring coils were used for each of the three magnets such that all magnets were measured at the required good field radius or at a slightly larger radius to minimize the measuring uncertainties. By repeating the measurements the repeatability was evaluated and the integrated field error $\int \Delta B_y / B_y(R_0).ds$ at the good field radius of R_0 for each of the harmonics was determined to be $\pm 2\times10^{-5}$ or better. For the sum of the higher harmonic error terms the uncertainty accumulated to $\pm 1\times10^{-4}$ for all three types of quadrupoles.

Table 4 summarises the integrated field error specification compared with integrated field error from the 3D design and average test result at 100% excitation. The test results demonstrate that the field quality of all magnet types exceeds the specification. The one exception is the Quad A magnet which is slightly out of specification. Shimming work was proposed by Danfysik A/S which was expected to bring the magnets within specification, but Daresbury Laboratory decided to accept the magnets without correction after further beam dynamics simulations using the measured magnetic data.

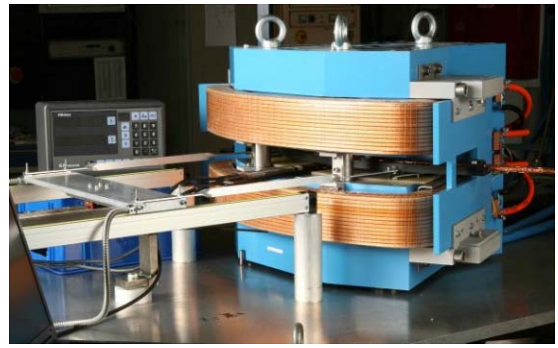

Figure 3. Test stand for field integral measurements on one of the Dipole D magnets.

Table 4. Integrated field error specification compared with integrated field error from the 3D design and average test result at 100% excitation.

	Field/Gradient Specification	**Simulated Opera 3D**	**Measured**
Dipole A	$\pm 1.0\times10^{-3}$	$\pm 0.2 \times10^{-3}$	$\pm 0.7 \times10^{-3}$
Dipole D	$\pm 1.0\times10^{-4}$	$\pm 0.8 \times10^{-4}$	$\pm 1.0 \times10^{-4}$
Quad A	$\pm 1.0\times10^{-3}$	$\pm 0.4 \times10^{-3}$	$\pm 1.7 \times10^{-3}$
Quad D	$\pm 1.0\times10^{-3}$	$\pm 0.4 \times10^{-3}$	$\pm 0.8 \times10^{-3}$
Quad E	$\pm 5.0\times10^{-2}$	$\pm 0.7 \times10^{-2}$	$\pm 1.2 \times10^{-2}$
Sext. A	$\pm 3.0\times10^{-3}$	$\pm 0.3 \times10^{-3}$	$\pm 2.1 \times10^{-3}$

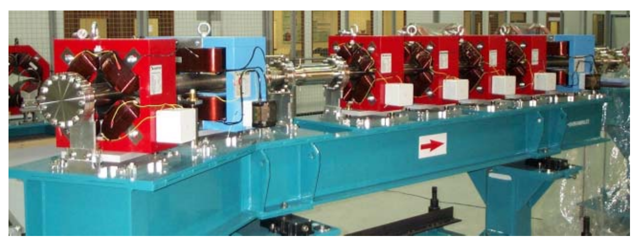

Figure 4. A completed ERLP girder assembly which forms a section of the injector line. The dipoles are Dipole A design and the quadrupoles are Quadrupole D design.

CONCLUSION

In this paper the magnet specification for the new magnets required for the ERLP at Daresbury Laboratory has been presented. The magnetic design and construction of the magnets has been done by Danfysik A/S. The techniques used for the magnetic measurement of the magnets have been discussed and it has been shown that the magnetic performance satisfies the stringent field specification. All magnets are on-site at Daresbury Laboratory where construction of the ERLP continues.

REFERENCES

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