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DESIGN OF A BROADBAND MODULAR PERMANENT MAGNET ELECTRON ENERGY SPECTROMETER FOR FEBE

A. R. Bainbridge*, D. Angal-Kalinin, J. K. Jones, G. Marshall, H. L. Owen, T. H. Pacey, Y. M. Saveliev, B. J. A. Shepherd, ASTeC, STFC Daresbury Laboratory, Warrington, UK

Abstract

The FEBE experimental area on the CLARA accelerator at STFC Daresbury Laboratory will facilitate activities that combine a 250 MeV electron beam with a 100 TW class laser, including novel acceleration experiments up to 2 GeV. An innovative in-vacuum permanent magnet spectrometer dipole has been designed with modular construction to measure broadband electron energy spectra on a shot-by shot basis and is currently being procured. The modular construction of the dipole allows the total length to be tailored to the experiment, creating additional room for other diagnostics where the expected output energy is below 2 GeV. We discuss here the design, challenges, engineering and planned uses of this spectrometer.

INTRODUCTION

The Compact Linear Accelerator for Research Applications (CLARA) is a 250 MeV electron accelerator currently being commissioned at STFC Daresbury Laboratory, UK [1, 2]. Originally designed as a free-electron laser test facility, CLARA is being expanded with a separate experimental bunker known as the Full Energy Beam Exploitation (FEBE) facility to enable the facility to serve a variety of user experiments [3]. FEBE will allow users to conduct experiments combining a 250 MeV electron beam with up to 250 pC bunch charge with laser pulses of up to 100 TW power in a large target chamber, known as FEC1. A second chamber downstream (known as FEC2) will contain a suite of diagnostics that may be customized to meet the needs of the experiments being conducted.

The combination of an electron beam with a high-power laser in FEBE presents an opportunity to conduct novel acceleration experiments. The design of FEBE permits user experiments which aim to accelerate the electron beam via laser wake field techniques from 250 MeV up to 600 MeV, or to 2 GeV at a reduced repetition rate. Experiments involving acceleration to 6 GeV are theoretically possible but will require additional radiation shielding precautions and are not currently planned.

An effective way to measure the output of these experiments is to pass the beam through a dipole magnet acting as a spectrometer. To fulfil this goal we have designed an innovative in-vacuum Permanent Magnet (PM) spectrometer with modular construction that will facilitate shot by shot measurement of broadband energy spectra. The modular nature of the dipole will allow the length of the spectrometer to be tailored to the experiment, allowing additional diagnostics to be installed where energies below 2 GeV are anticipated.

* alex.bainbridge@stfc.ac.uk

SPECTROMETER OVERVIEW

The FEBE spectrometer follows the well tested principle of a long C-core dipole which allows electrons to exit through the open side of the yoke, a common technique in novel acceleration experiments [4, 5]. The FEBE dipole is configured to bend electrons down towards the floor to ensure radiation safety, and to allow a detector positioned beneath the magnet to be easily viewed from the side via slots in the sliding doors of the vacuum chamber.

There are several motivations for using an in-vacuum PM dipole as opposed to an electromagnetic system. FEC2 is a large chamber which holds several other diagnostics, and space in FEBE is limited, both of which make a magnet outside the vacuum impractical. Delivery of power and cooling to a strong DC electromagnet in vacuum is a significant challenge, and engineering the magnet and coils to function in a high vacuum environment is often impractical. A PM system allows for a more physically compact design than an electromagnet of equivalent strength, can easily be made vacuum compatible, and negates the power and cooling issues.

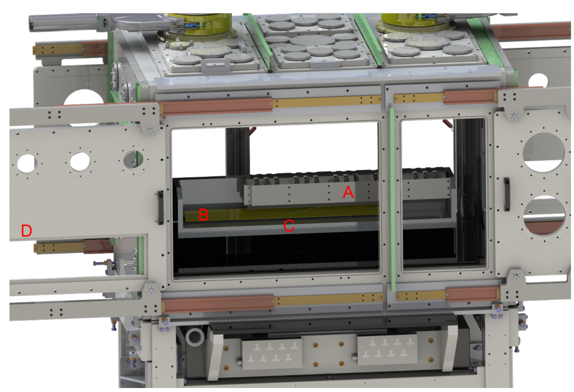

Figure 1: CAD image of the spectrometer inside FEC2. A: Spectrometer magnet in its full 5-section configuration. B: Scintillating screen viewing mirror. C: Support cradle with side to side movement. D: Camera viewing slot built into chamber door.

A PM system also readily enables modular construction, which this spectrometer takes full advantage of. The magnet will consist of identical sections with lengths of 200 mm, which locate into each-other using precision metal dowels. It is expected that a total magnet length of 1 m consisting of five sections will be used for GeV scale experiments. For initial experiments where energy gains are expected to be

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lower, or for experiments conducted at a high repetition rate where target energies will be limited to 600 MeV or below, a shortened version consisting of three segments at 600 mm will be used. This will allow additional room in FEC2 for other diagnostics to be installed. To employ the additional diagnostics, the spectrometer may be enabled or disabled by moving it sideways in and out of the beam path. The layout of FEC2 including the spectrometer design is shown in Fig. 1.

MAGNET DESIGN AND MODELLING

The magnetic modelling and particle ray tracing was performed in OPERA [6], and the magnet model is shown in Fig. 2. The magnet is analogous to a traditional C-dipole in which the PM material sits either side of the gap in place of the traditional coils. A steel pole plate between the PM and the beam defines field homogeneity across the gap, and has the additional benefits of shielding the NdFeB from direct electron impacts and acting as a clamping plate to remove the need for in-vacuum adhesives. The return leg of the yoke fixes the PM blocks in place and provides a return path for the flux. All steel components will be manufactured from AISI grade 1006 low-carbon magnet steel, which will have a few-micron thick nickel coating for vacuum compatibility and rust prevention.

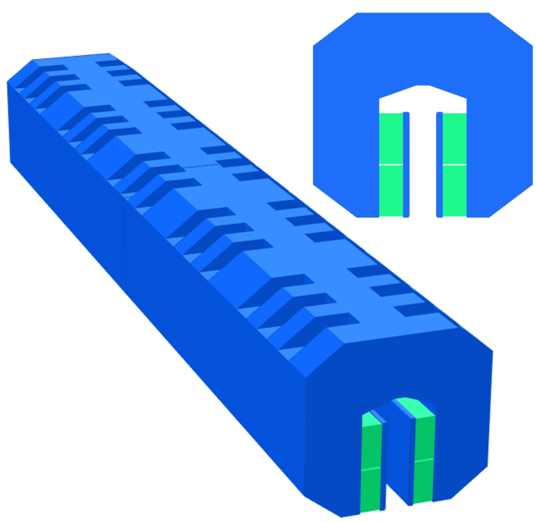

Figure 2: OPERA model of the FEBE spectrometer magnet, 3D and end on views. Blue: Steel Yoke. Green: NdFeB blocks. Aluminium lattice not shown.

Each 200 mm section contains 16 magnet blocks sized at 49 × 38.5 × 18 mm, magnetized along the 18 mm axis. The blocks are modelled as NdFeB with a typical B_r of 1.41 T and a minimum B_r of 1.37 T. The typical H_c is 1090 kA/m with a minimum H_c of 1035 kA/m. The NdFeB is encased in a UHV compatible metallic coating. The predicted magnetic flux densities through the magnet along the vertical centreline and unbent beam axis are shown in Figs. 3 and 4 for the 1 m and 600 mm versions, for all blocks at typical strength and all blocks at minimum strength. each section is built in halves that are bolted together in the cutouts visible in Fig. 2, and located by precision dowel pins.

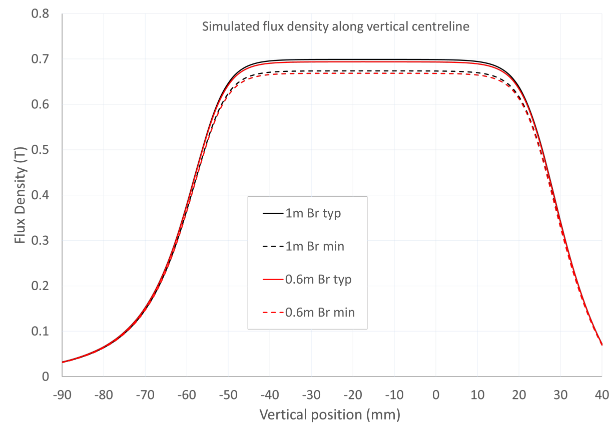

Figure 3: Simulated flux density along a vertical line at the longitudinal centre for 1 m long and 0.6 m long variants, for typical strength and minimum strength magnetic materials. The beam axis is at 0 mm and is bent in the negative direction. The scintillator will be located between −70 mm and −90 mm.

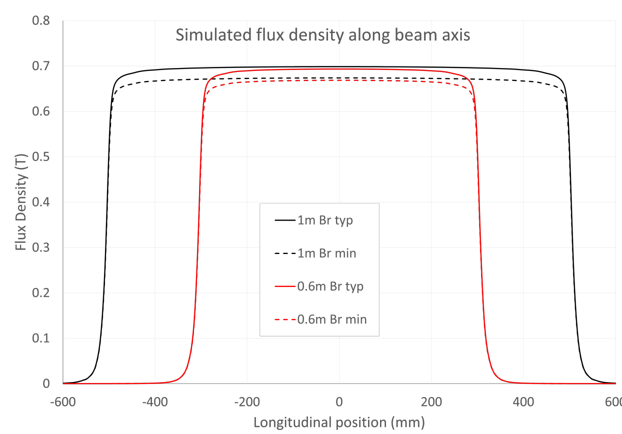

Figure 4: Simulated flux density along beam axis for 1 m long and 0.6 m long variants, for typical strength and minimum strength magnetic materials. The magnet is centered about 0 mm.

ELECTRON TRAJECTORIES

Ray tracing of electrons through the magnet demonstrates its utility at a wide variety of energies, confirming that the 5-section 1 m long version is suitable for energies up to 2 GeV, provided the screen extends slightly beyond the physical end of the magnet, and that the 3-section 600 mm version is valid up to 600 MeV. The magnet is also suitable for operating around the standard 250 MeV energy of the CLARA beam, however this can also be handled by a spectrometer at the end of the accelerator beyond the FEBE hutch.

Figure 5 shows the results of tracking electrons of 250 MeV, 500 MeV, 1 GeV and 2 GeV through two OPERA

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FEA models of the 5-section 1 m long variant, one with all PM blocks at typical strength and one with all PM blocks at minimum strength.

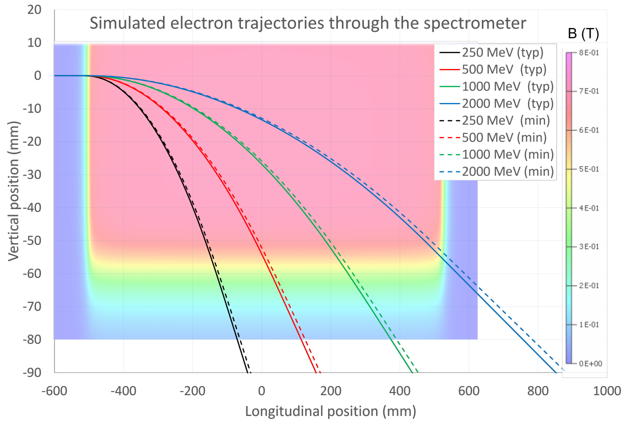

Figure 5: Simulated trajectories of electrons of different energies through the 1 m spectrometer, for typical strength and minimum strength versions. The magnet is centered about 0 mm. The field map overlaid is for the typical strength.

Detection of electrons will be via a long screen made of scintillating tiles placed under the magnet, between 70 mm and 90 mm below the beam axis. This will by placed horizontally and viewed from beneath using a 45° in-vacuum mirror by cameras outside the vacuum chamber, looking through a long window slot in the chamber door.

Simulations have been performed to predict the energy spectra and divergence of electron bunches produced by novel acceleration experiments in FEC1. The propagation of these bunches has been modelled through to FEC2 up to the spectrometer screen. Between the chambers are four quadrupoles in a double-doublet that may be used to minimise beam beta functions on the screen. Figure 6 shows the expected distributions as seen on a detector 70 mm below the beam axis of three bunches with realistic energy distribution that have been laser-wakefield accelerated to energies of approximately 500 MeV, 1 GeV and 2 GeV.

MAGNETIC FORCES AND ENGINEERING

The modular construction of the magnet is designed to allow easy switching between configurations of different lengths, however as the flux is provided by PM blocks this will need to be done in the presence of a magnetic force. FEA models have been used to calculate the predicted forces between two modules as they are pushed together as a function of the separation between them, the results of which are shown in Fig. 7. This force is repulsive, and must be borne by an assembly frame that pushes the sections together, which is currently under design, before being borne by bolts and dowel pins that are inserted once they are in contact.

CONCLUSION AND OUTLOOK

A modular permanent-magnet in-vacuum spectrometer has been designed for the FEBE facility. This will be a versatile instrument that will measure the outcomes of novel acceleration experiments where a 250 MeV beam is accelerated by interaction with a 100 TW laser up to 2 GeV.

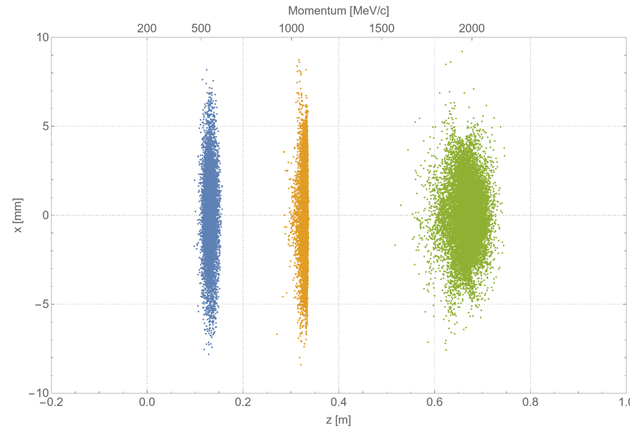

Figure 6: Expected distributions of three simulated laser-wakefield accelerated electron bunches on a scintillator 70 mm below the beam axis.

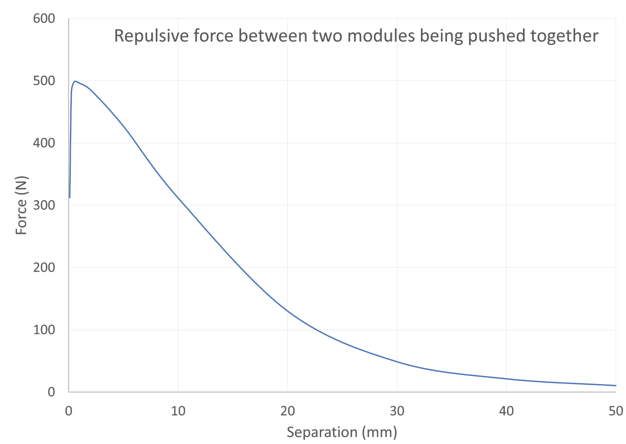

Figure 7: Magnetic forces calculated by FEA as a function of distance between two complete modules during assembly.

Magnetic modelling of the magnet has been completed, including field mapping, material variance models, magnetic forces and realistic particle tracking. These show that the magnet will be a versatile tool between 250 MeV and 2 GeV. The assembly procedure for the dipole is currently in development, as is procurement of components. The magnet will be assembled at STFC Daresbury Laboratory and measured in-house by 3D Hall probe mapping before installation to assist with the calibration of energy against screen impact point.

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