MAGNET DESIGN FOR THE SPLITTER/COMBINER REGIONS OF CBETA, THE CORNELL-BROOKHAVEN ENERGY-RECOVERY-LINAC TEST ACCELERATOR

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Abstract

The Cornell-Brookhaven Energy-Recovery-Linac Test Accelerator (CBETA) will provide a 150-MeV electron beam using four acceleration and four deceleration passes through the Cornell Main Linac Cryomodule housing six 1.3-GHz superconducting RF cavities. The return path of this 76-m-circumference accelerator will be provided by 106 fixed-field alternating-gradient (FFAG) cells which carry the four beams of 42, 78, 114 and 150 MeV. Here we describe magnet designs for the splitter and combiner regions which serve to match the on-axis linac beam to the off-axis beams in the FFAG cells, providing the path-length adjustment necessary to energy recovery for each of the four beams. The path lengths of the four beamlines in each of the splitter and combiner regions are designed to be adapted to 1-, 2-, 3-, and 4-pass staged operations. Design specifications and modeling for the 24 dipole and 32 quadrupole electromagnets in each region are presented. The CBETA project will serve as the first demonstration of multi-pass energy recovery using superconducting RF cavities with FFAG cell optics for the return loop.

INTRODUCTION

The Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE) and the Brookhaven National Laboratory have begun collaboration on the design, construction and commissioning of a four-pass 150- MeV electron accelerator based on a superconducting, six-cavity linac with energy recover, using 106 fixed-field alternating-gradient (FFAG) cells as the return loop [1–3]. Figure 1 shows the layout comprising the injector, the main linac cryomodule, the splitter section, the FFAG return loop, the combiner, and the beam dump section. The FFAG cells carry four beams of 42, 78, 114 and 150 MeV in a vacuum chamber with interior dimensions of 84x24 mm. The splitter and combiner regions, labeled SX and RX in Fig. 1 serve to adjust the path length of each beam for energy recovery. Figure 2 shows the splitter region SX. The 24 dipole magnets and 32 quadrupole magnets in each of the splitter and combiner sections must cover a wide range of excitations and accommodate an extruded aluminum vacuum chamber of inner dimensions 34x24 mm with 3-mm thick walls. Here we describe magnet model development for the dipole and quadrupole magnets in these sections.

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MAGNET PARAMETERS AND MODELING

The splitter and combiner optics designs [1] each specify 24 dipole magnets with fields ranging from about 1.5 kG to 9 kG and 32 quadrupole magnets with field gradients ranging from about 0.1 T/m to 4 T/m (see Fig. 3) to be accommodated on a girder of surface area approximately 4x2 m^2, imposing stringent constraints on the magnet geometries, limiting the horizontal extent to about 20 cm and the length to 20 cm for most of the magnets. Given the limited space for coil pockets, we have constrained the power supply voltage, current and dissipated-power parameters to ensure availability of commercially available units.

The chosen quadrupole poleface and yoke design derives from a large-aperture design developed at the Cornell Electron Storage Ring (CESR) in 2004 [4]. Figure 4 shows surface color contours of the field magnitude on the iron for the 4.0 T/m excitation. A model scaled to a 40-mm bore diameter, resulting in a 12.3-cm square outer cross section, was found to exhibit excellent linearity up to an excitation of 4.0 T/m with the central field and field integral nonuniformities shown in Fig. 5, as modeled with the Vector Fields Opera 18R2 software [5].

An H-magnet design was chosen for the dipoles in order to minimize stray fields given the close proximity of the four beamlines. The maximum field is restricted to 6 kG in order to limit flux leakage out of the central pole iron. This arises from the height of the magnet, bounded below by the need for space for the coil and the number of conductor turns required to permit use of an 80-A power supply. Figure 6 shows the resulting field and field integral uniformity.

Table 1 shows an overview of geometrical, electrical and cooling parameters of the dipole and quadrupole magnet designs. The 30-cm H-dipole is intended for use in the seven cases where the lattice specifies fields greater than 6 kG (see Fig. 3). The table also shows that the non-linearity in the field/current relationship between 4.5 kG and 5.937 kG is 1.1%. Modeling shows the dipole design to be linear at the 10^{-4} level for lower excitations. The linearity of the quadrupole design is modeled to a similar accuracy for the field gradients below 4.0 T/m, permitting this design to be used for all 64 quadrupoles in the splitter and combiner.

SUMMARY

We have presented a first-pass design study for the magnets required for the splitter and combiner regions of the Cornell-Brookhaven ERL Test Accelerator. Stringent

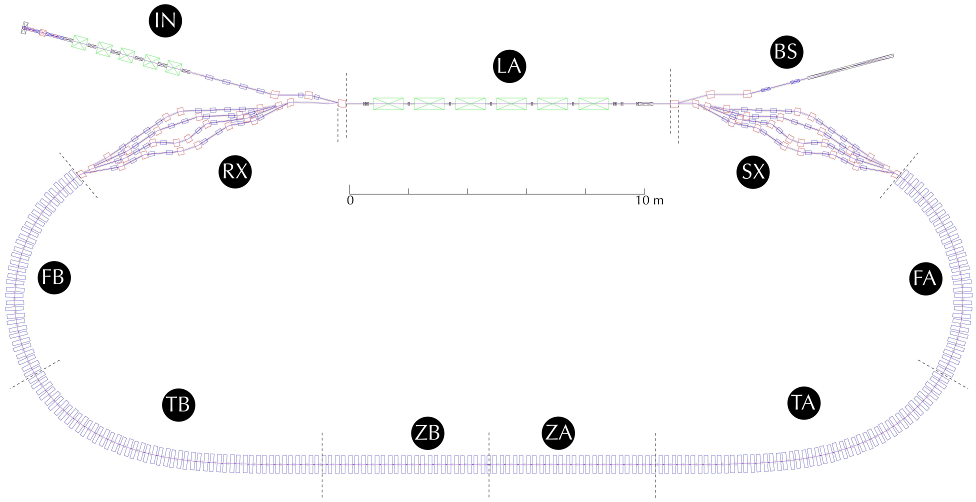

Figure 1: Layout of the 150- MeV, four-pass CBETA electron accelerator with energy recovery. The injector, main linac cryomodule, splitter, FFAG-based return loop, combiner, and dump sections are shown.

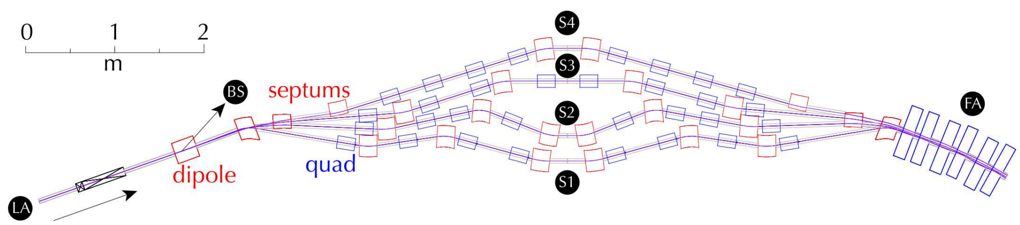

Figure 2: Layout of the splitter region

Table 1: Operational Parameters for the CBETA Splitter Dipole and Quadrupole Magnets: Electrical and thermal properties of the CBETA splitter/combiner magnets. The conductor for the dipole coils is 1/4" (6.35 mm) square with a 1/8" circular hole for water flow, as is commonly used in CESR magnets. Space constraints in the quadrupole coil pocket reduce the conductor cross section to 5-mm square with a 2.5-mm hole. The flow rate and temperature rise calculations assume that the CESR 85-degree cooling water source is used. A single water circuit suffices for each of the dipole and quadrupole coils.

Parameter	**H-Dipole 21x39x20**	**H-Dipole 21x39x20**	**H-Dipole 21x39x30**	**Quadrupole 12x12x15**
Gap or Bore (cm)	3.0	3.0	3.0	4.0
Steel height (cm)	39.0	39.0	39.0	12.3
Steel width (cm)	21.0	21.0	21.0	12.3
Steel length (cm)	20	20	30	15
Pole width (cm)	6.0	6.0	6.0	3.1
Field (G)/Gradient (G/cm)	5936	4500	5977	400
NI (Amp-turns)	7166	5375	7166	637
Turns per coil	5x20	5x20	5x20	2x4
Coil cross section (cm x cm)	3.4x13.7	3.4x13.7	3.4x13.7	1.0x2.0
Conductor straight length (cm)	20	20	30	15
Coil inner corner radius (cm)	1.0	1.0	1.0	1.53
Conductor length per turn, avg (cm)	65.1	65.1	85.1	41.2
R_{coil} (Ω)	0.0323	0.0323	0.0422	0.00263
Power supply current (A)	71.7	53.8	71.7	80.0
Current density (A/mm^2)	1.78	1.33	1.8	3.2
Voltage drop for two (four) coils (V)	4.6	1.7	6.1	0.8
Power/coil (W)	165	45	219	17
Water flow/coil @Δp=45 psi (Gal/min)	0.11	0.11	0.09	0.31
Coil temperature rise (°C)	6.0	3.4	8.9	0.2

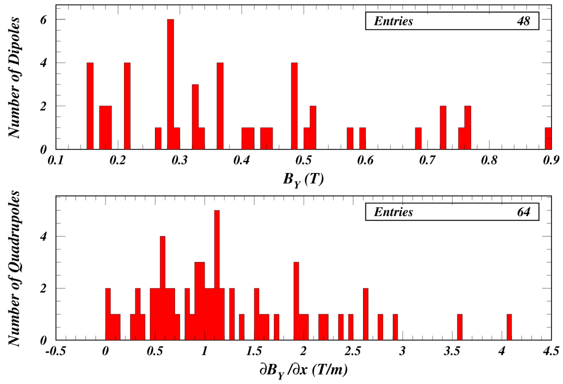

Figure 3: Distributions of required splitter/combiner dipole and quadrupole magnet field strengths

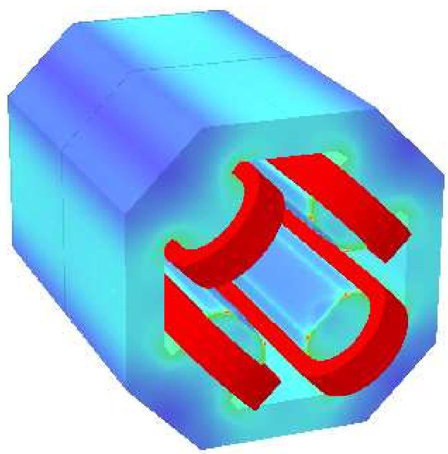

Figure 4: Color contours of the modeled field magnitude in the iron of the quadrupole magnet at 4.0 T/m excitation. The field ranges from 95 G (blue) to 970 G (red).

space and cooling constraints and a wide range of field strengths have been accommodated by a design featuring a single transverse cross section for all dipoles and for all quadrupoles. Modeling has shown that the per-mil field uniformity specifications are satisfied. This feasibility study will serve as the basis for near-term value engineering development.

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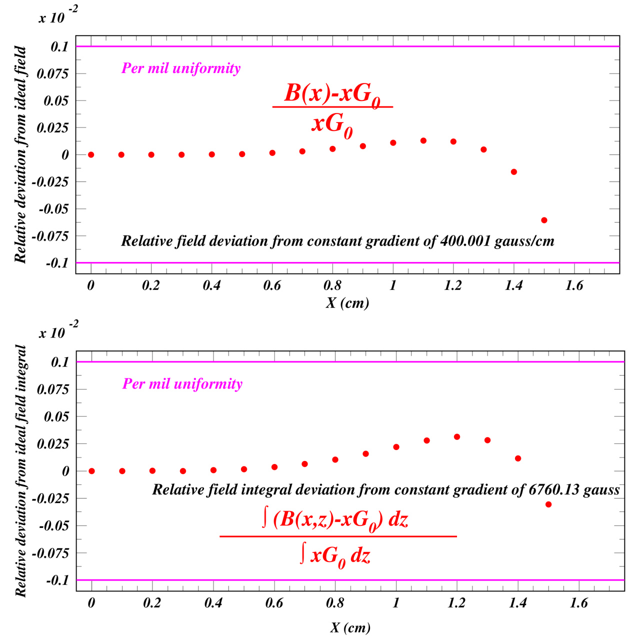

Figure 5: Uniformity of the 4.0 T/m quadrupole field. The upper plot shows the relative deviation of the field from a linear field with gradient equal to the central gradient at the longitudinal center of the magnet. The lower plot shows the relative deviation of the field integral from that of the perfectly uniform case. The 10^{-3} specification is satisfied over 30 mm of the 34-mm width of the vacuum chamber.

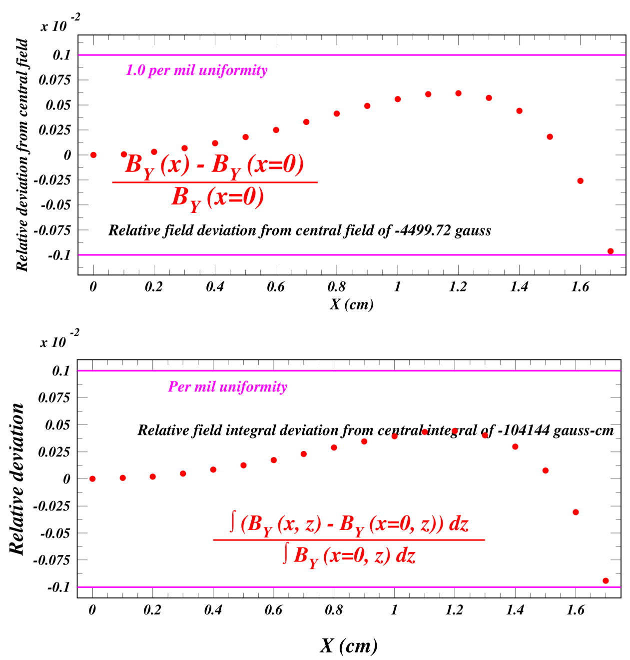

Figure 6: Modeled field uniformity for the 4.5 kG H-dipole magnet design. The upper plot shows the relative deviation of the field from the central field value in the middle of the magnet. The lower plot shows the relative deviation of the field integral from the ideal case.The per-mil specification is satisfied over the full 34-mm-wide interior dimension of the vacuum chamber.