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Superconducting Magnet Design for Fixed-Field Alternating-Gradient (FFAG) Accelerator

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Abstract--The FFAG accelerator requires static fields that increase with radius along the accelerator midplane according to $B=B_0 (R/R_0)^{1/4}$. The field is generated by equally spaced magnets around the circumference and varies from a maximum of 4.1 T to a minimum of -1.9 T. The general coil design employs cryostable magnets wound with aluminum stabilized superconductor. Each magnet has resistive pole face windings outside of the cryostat to allow for field fine tuning after construction. A set of iron-free coil windings generate the required field distribution.

1. INTRODUCTION

Proposals have been made to build a Fixed-Field Alternating-Gradient (FFAG) [1] accelerator as a source of pulsed protons for a spallation neutron target [2],[3]. These accelerators are non-isochronous and accelerate using frequency modulated cavities. The magnets are DC-excited with a field strength that varies with radius as $B_0(R/R_0)^k$, where B_0 is the injection field, R_0 is the average injection radius (circumferential path length $/2\pi$), and k is a constant called the field index.

A typical layout of an FFAG accelerator is shown in Fig. 1, where the black rectangles on the circumference are sector magnets which provide a magnetic field variation along the circumferential particle orbit shown in Fig. 2. The negative fields deflect positive charged protons radially outwards and the positive fields deflect the particles radially inwards. The peak positive field is considerably stronger to provide a net bending radius which defines the average radius, R .

Fig. 1. LAYOUT OF RADIAL-SECTOR FFAG.

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Fig. 2. AZIMUTHAL PROFILE OF MAGNETIC FIELD ALONG THE PATH OF ONE CELL AT EXTRACTION ENERGY.

Beam is injected at the inside radius of the FFAG at low energy and is accelerated to higher energy rf cavities located between sector magnets. As the beam gains energy, the average radius increases until the extraction energy is reached at the outer radius. The parameters for a 1500-MeV FFAG including sector magnet fields are listed in Table 1.

TABLE I
 PARAMETERS FOR THE FFAG ACCELERATOR

Extraction Energy, MeV	1500
Extraction Radius, $\sqrt{ds}/2\pi$, m	28.14
Injection Energy, MeV	350
Injection Radius, $\sqrt{ds}/2\pi$, m	26.37
Field Index, k	13.4
Peak Positive Bending Field @ Extraction, T	4.1
Peak Negative Bending Field @ Extraction, T	1.9
Peak Positive Bending Field @ Injection, T	1.717
Peak Negative Bending Field @ Injection, T	0.796
Horizontal Tune	4.25
Vertical Tune	3.25
Horizontal Emittance, mmmr	650π
Vertical Emittance, mmmr	500π
Repetition Rate, Hz	250
Maximum RF Voltage, kV	400
Maximum RF Frequency (Extraction), MHz	1.565
Maximum RF Frequency (Injection), MHz	1.241

The use of superconducting magnets is a natural choice for generating this dc field because of the 4.1 T requirement. Because a large beam current with a high repetition rate is required to be accelerated by the FFAG, the use of low Z

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material, like aluminum, is desired to minimize induced radioactivity due to beam loss. The magnets, therefore, will be designed with high purity aluminum as stabilizer and high strength aluminum for structural purposes. The vacuum chamber will also be aluminum.

Normal conducting aluminum pole face windings will be placed between the vacuum jacket of the superconducting magnets and the vacuum chamber for the proton beam. These coils will be used for final adjustment of the magnetic field. The field excitation will be provided without the use of iron, although some iron might be provided for fringe field reduction.

II. MAGNET CONFIGURATION

The problem of magnet configuration design is solved in two steps; the first is choosing an arrangement of coils that, with the "proper" current in each one, will achieve the required, or target, field distribution. The second step is to find these "proper" currents. This step is reduced to solving the reverse problem of finding the currents in a set of coils that generate a specified field distribution.

Through a combination of intuition and trial and error, several configurations are attempted. Fig. 3 shows two symmetrical sets, above and below the orbital plane, of a 6-coil core configuration that provides the correct field pattern. Fig. 4 shows the target field over the radius at the plane of symmetry along with that achieved with the 6-coil configuration. Fig. 5 shows the target and achieved azimuthal fields at the extraction radius for the same coil configuration. The coil sizes and required excitation currents are listed in Table 2. A plan view wire schematic of the 6-coil configuration showing current directions and identifying different coil segments is shown in Fig. 6.

Fig. 3. 6-COIL ARRANGEMENT.

Fig. 4. FIELD AT PLANE OF SYMMETRY FOR THE 6-COIL DESIGN.

Fig. 5. FIELD AT OUTER RADIUS FOR THE 6-COIL DESIGN.

Fig. 6. WIRE SCHEMATIC OF THE 6-COIL ARRANGEMENT.

Normal conducting pole face windings would be placed between the beam vacuum chamber and outer cryostat wall of the sector magnets to fine tune the magnetic field and the beam.

The coordinates of the four corner points of the center line of each coil are listed in Table 2a. The x-coordinate is the radial direction in the FFAG and the z-coordinate is measured in meters perpendicular to the orbital plane. The y-coordinate is the distance along the beam orbit measured from the vertical plane of symmetry. Currents, in ampere-turns, along with current density, in amperes per square meter, and total ampere-meters of these coils are listed in Table 2b.

TABLE 2
COIL PARAMETERS.

a. COIL COORDINATES AND DIMENSIONS IN METERS.

coil #	X	Y	Z	X	Y	Z	W/H
1	28.8	.402	0.50	25.8	.360	1.10	0.40
	25.8	-.360	1.10	28.8	-.402	0.50	0.25
2	28.4	.124	0.25	26.0	.113	0.25	0.06
	26.0	-.113	0.25	28.4	-.124	0.25	0.10
3	29.0	.860	0.25	25.8	.766	0.45	0.20
	25.8	.540	0.45	29.0	.607	0.25	0.15
4	28.6	.420	0.25	27.8	.420	0.25	0.08
	27.8	.243	0.25	28.6	.250	0.25	0.10
5	29.0	-.860	0.25	25.8	-.766	0.45	0.20
	25.8	.540	0.45	29.0	.607	0.25	0.15
6	28.6	.420	0.25	27.8	.420	0.25	0.08
	27.8	.243	0.25	28.6	.250	0.25	0.10

b. COILS GROSS CURRENTS, CURRENT DENSITIES AND THEIR TOTAL AMPERE METERS.

coil #	Current (A turns)	J (kA/cm ²)	IS (Am)
1	-6.734E+06	6.73	5.147E+07
2	3.135E+05	5.22	1.653E+06
3	2.357E+06	7.86	1.662E+07
4	-5.234E+05	6.54	1.106E+06
5	2.357E+06	7.86	1.662E+07
6	-5.234E+05	6.54	1.106E+06

Positive current is counterclockwise.

III. MAGNET DESIGN

It is highly desirable to make the FFAG magnets cryogenically stable to avoid operation disruption and beam loss that would result from magnet quenches. The probability of these quenches in unstable magnets is higher in the FFAG accelerator because the energy deposited on a conductor section from an occasional stray beam might be large enough to induce a transition from the superconducting state to the normal one.

The FFAG coils will be wound with monolithic high purity aluminum (HPAL) stabilized conductor with NbTi strands as shown in Fig. 7. HPAL has the advantage of low resistivity at liquid helium temperature and tolerable magnetoresistivity in magnetic fields. The conductor will be cooled in a bath of liquid helium. The choice between normal and superfluid helium cooling will depend on the results of the stability analysis. The conductor will be embedded in a high strength aluminum (HSAL) support as shown in Fig. 8.

The windings will experience large magnetic forces resulting from their own fields and the interaction with other magnets. These magnetic forces have been calculated using the computer program EFFI [4]. Magnet supports will be designed to be strong enough to react to these forces and rigid enough to maintain the windings in their positions within an acceptable tolerance. The force between segments

S1 and S3 is 53.22 MN and is repulsive. The support structure will be inside the helium chamber to minimize refrigeration load. The proposed frame for the support structure will be made of thick HSAL plates. Each of the top and bottom segments of S1 and S3 have attractive forces of 8.14 MN. A box frame will be designed to hold the coils apart. Special frames will be designed for the injection and extraction beam locations.

Fig. 7. 5 KA HPAL STABILIZED CONDUCTOR

Fig. 8. CONDUCTOR EMBEDDED IN HSAL STRUCTURE

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