Optimisation of a Permanent Magnet Multi-Energy FFA Arc for the CEBAF Energy Upgrade

S.J. Brooks {sbrooks@bnl.gov}, Brookhaven National Laboratory, Upton, NY, USA

Abstract

It is currently planned to increase the energy of the CEBAF recirculating linear accelerator to 20GeV or more by adding two new recirculating arcs that contain multiple new energy passes. The beam is continuous (CW), so no field ramping is desired, making this a fixed-field accelerator (FFA). The wide energy range requires a low dispersion lattice that can be created with high-gradient permanent magnets. One constraint is the existing tunnel radius in relation to the fields achievable by practically-sized permanent magnets. Thus, searching for the most efficient implementation in terms of magnet material volume is important. In this paper, a lattice cell search and optimisation is conducted that evaluates cells by the magnet volume per unit length, with the permanent magnet designs also produced via an automated code. The new lattice cells are compared to the previous manually designed cell.

Lattice Constraints

Option A is the baseline lattice with linear fields. Constant radius of curvature 80.6m was used to fit the CEBAF tunnel.

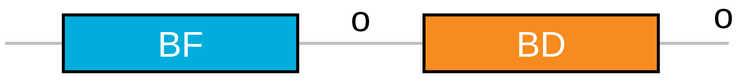


Table 1: Lattice Option Design Rules

Option	Energy (GeV) Min.	Energy (GeV) Max.	Cell tune (cycles) Min.	Cell tune (cycles) Max.
A	10.494	21.014	0.0363*	0.3943*
B	10.494	21.014	0.035	0.4
C	10.494	21.014	0.035	0.4
D	9	21	0.04	0.39
E	9	21	0.05	0.32

Option	Max. Dipole (T)	Gradient (T/m)	Sextupole (T/m^2)
A	1.2815*	43.44*	0
B	2	100	0
C	2	100	2000
D	2	100	400
E	2	100	400

* Point design values, rather than optimisation limits.

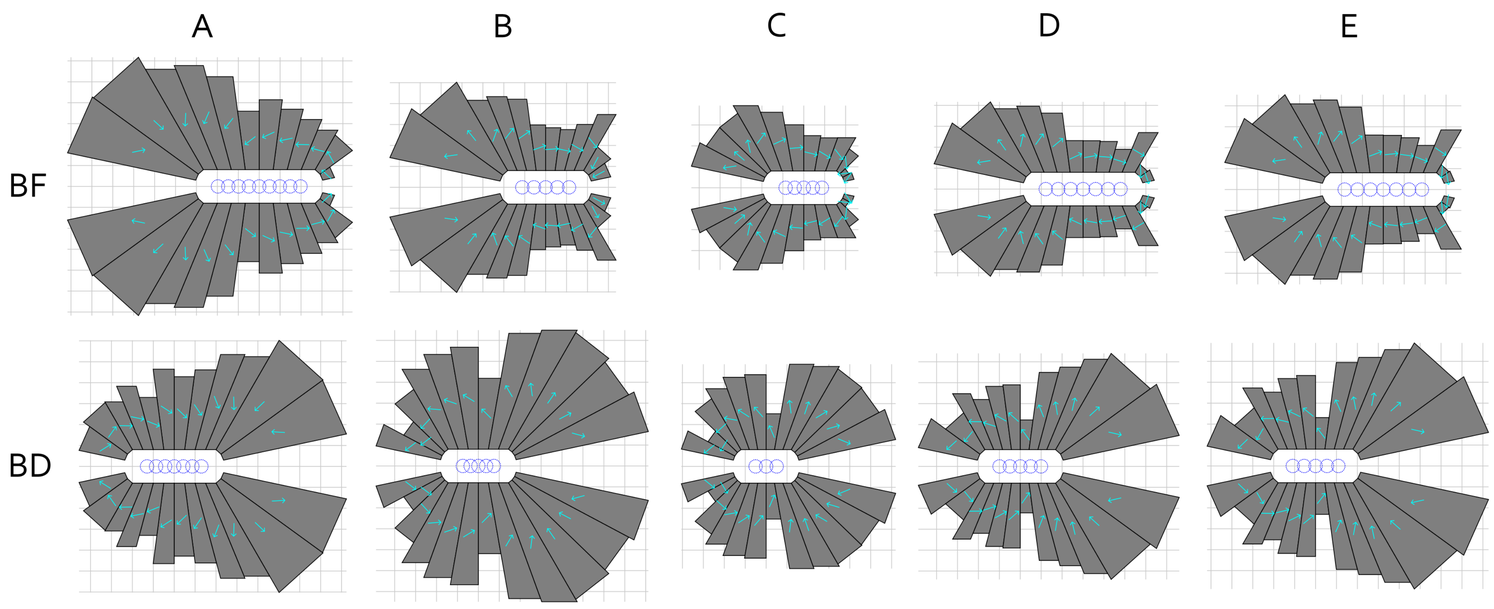
Magnet Constraints

Table 2: Permanent Magnet Design Rules

Parameter	Value
Number of wedges	24 (12 per side)
Midplane anglular gap	±12°
Vertical aperture	±8 mm
Minimum midplane gap	±3 mm
Material	NdFeB
Grade	N42EH
B_r (real)	1.28–1.33 T
B_{r1} (for $\mu_r = 1$ model)	1.248 T
$\mu_0 H_{cJ}$	2.9 T

Permanent Magnets

Grid is 1cm, arrows indicate magnetisation direction.



Lattice Results

Table 5: Lattice Results and Figures of Merit

Option	Cell tune (cycles) min.	Cell tune (cycles) max.	$\lvert B\rvert_{max}$ (T)	Orbit excursion (mm)	Path length change (mm)	Magnet areas (cm^2) Average	Magnet areas (cm^2) BD	Magnet areas (cm^2) BF
A	0.0363	0.3943	1.5346	44.968	1.233	84.69	87.43	94.41
B	0.0357	0.3994	1.6140	28.607	0.525	75.75	104.56	58.54
C	0.0352	0.3993	1.4922	23.602	0.344	44.29	59.32	34.04
D	0.0426	0.3898	1.4689	41.739	0.916	54.38	72.18	46.16
E	0.0500	0.3194	1.5438	42.966	0.910	64.24	86.07	53.86

Table 4: Lattice Magnetic Field Specifications

Option	Dipole (T) BD	Dipole (T) BF	Gradient (T/m) BD	Gradient (T/m) BF	Sextupole (T/m^2) BD	Sextupole (T/m^2) BF
A	-0.3828	-1.2815	43.44	-41.13	0	0
B	0.8629	0.8629	55.155	-69.369	0	0
C	0.9590	0.9590	59.960	-89.189	-1411.41	974.97
D	0.8228	0.8228	45.345	-48.549	-400	339.94
E	0.8148	0.8148	47.548	-50.951	-400	351.95

Table 3: Lattice Geometries

Option	Lengths (m) BD	Lengths (m) BF	Lengths (m) Drifts	Lengths (m) Cell	Angles (mrad) BD	Angles (mrad) BF	Angles (mrad) Cell
A	1.2448	1.6731	0.1162	3.1504	-7.11	-31.98	-39.09
B	1.1832	1.1892	0.09	2.5524	15.79	15.87	31.67
C	1.5195	1.4505	0.09	3.1500	20.00	19.09	39.08
D	1.4625	1.9760	0.09	3.6184	19.09	25.80	44.89
E	1.3814	1.7898	0.09	3.3512	18.11	23.47	41.58

Optimisation Method

Candidate lattice cells were tracked with the **Muon1** code and optimised with its built-in genetic algorithm. The optimiser started from random designs with no manually-set starting point, so the following scoring ranges were used to guide it towards viable designs.

1. If the first energy is unstable or has an unacceptable tune, the cell is scored by how far cos ϕ (calculated from the trace of the transfer matrix) deviates from the desired tune range limits, where ϕ is the phase advance.
2. If the first energy has correct tunes but later ones do not, the cell is scored by the percentage of the FFA energy range that is acceptable.
3. If all energies have correct tunes, the **HalbachArea** code is called to attempt magnet designs. If the magnet design fails, the cell is scored by peak field in the bore of the accelerator, with lower being better.
4. If all energies have correct tunes and magnets exist, the cell is scored by the average magnet area ($\Sigma_{\text{Elements e}}$ A_e L_e) / Σ_e L_e weighted by length through the cell, with lower being better.

Cell Tunes vs. Energy