Permanent Magnets for the CEBAF 24GeV Upgrade

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Abstract

An upgrade of the CEBAF facility to double its present energy of 12GeV has been proposed. To provide double the number of linac passes using the existing five stacked arc beamlines, some beamlines are replaced by fixed-field accelerator (FFA) arcs, allowing multiple energies to pass through the same magnets. A solution is presented in which two of the existing electromagnetic beamlines are replaced with permanent magnet non-scaling FFA arcs, as demonstrated at CBETA. The two-stage design reduces peak magnetic field and synchrotron radiation loss compared to using a single stage. FFAs do not pulse their magnets, making permanent magnets a promising and power-efficient technology option. However, the magnetic field requirements are still at the high end of accelerator permanent magnets produced thus far (1.6T peak on beam), while the magnets must also be combined-function, having a gradient with a dipole offset. Designs using a novel oval aperture and open midplane within an adapted Halbach magnet are presented.

Energy Ranges

The CEBAF linac energy will be varied from 925 to 1090MeV to give a continuous energy range with different numbers of FFA turns. The injector will be upgraded from 123MeV to 650MeV. The total arc passes on each side of the machine is increased from 5 to 11.

Table 1: Energy Ranges of Electromagnetic and FFA Lines

Number of FFA Stages	E/M passes	FFA1 passes	FFA2 passes
None (current)	5	—	—
One	4	7	—
Two (4+4)	3	4	4
Two (5+3)	3	5	3
Energy ranges (GeV)			
None (current)	1.2–11	—	—
One	1.5–9.4	8.9–23	—
Two (4+4)	1.5–7.2	7.1–16	14–23
Two (5+3)	1.5–7.2	7.1–18	16–23

Arc Cell Constraints

An optimisation was performed to try and find arc cells with minimal maximum field on any energy's closed orbit centroid.

Table 2: Constraints on FFA Arc Cell Optimisation

Parameter	Value	Unit
Cell angle	2	° clockwise
Radius of curvature	80.6	m
⇒ Cell length	2.81347	m
Both drift lengths	0.1	m
⇒ Packing factor	0.929	
Maximum tune	0.425	cycles/cell
Minimum tune	0.025	in either plane

Arc Cell Lattices

The cell lattice is BF-O-BD-O using combined function magnets. Below is the cell for FFA2 in the two-FFA, 5+3 turn option, with the orbits exaggerated transversely by 64×.

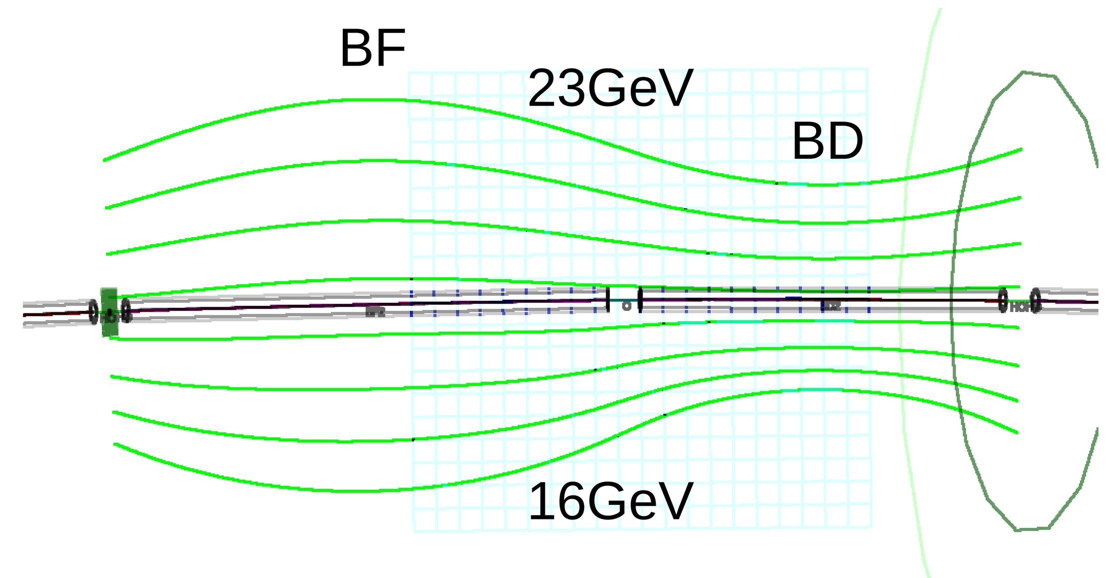


Table 3: Optimised Arc Cell Lattices for Different Options

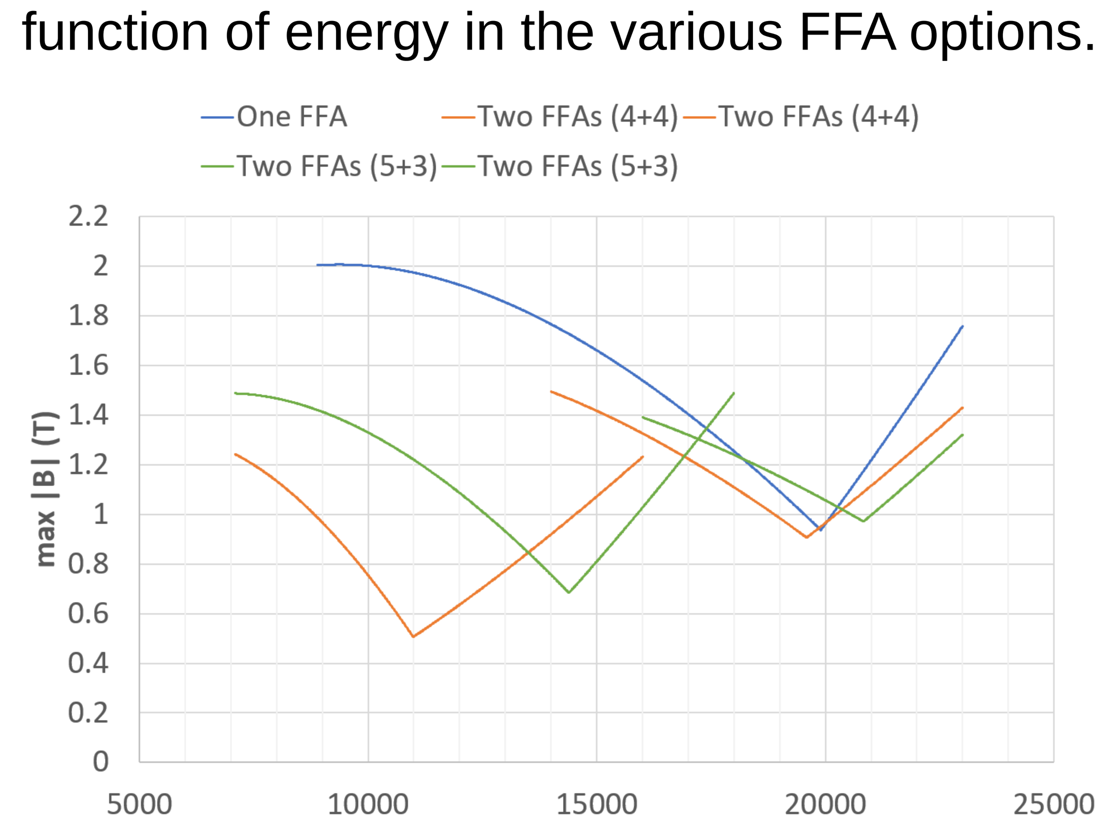
Parameter	One FFA	4+4 FFA1	4+4 FFA2	5+3 FFA1	5+3 FFA2	Unit
Reference energy	15.95	11.55	18.5	12.55	19.5	GeV
BF length	1.36109	2.09794	1.68482	1.57127	1.49155	m
BF angle	-0.05722	-1.73802	-1.14623	-0.65227	-0.98835	°
BF gradient	-48.649	-29.73	-65.616	-35.135	-80.781	T/m
BD length	1.25238	0.51553	0.92865	1.0422	1.12192	m
BD angle	-1.94278	-0.26198	-0.85377	-1.34773	-1.01165	°
BD gradient	43.393	93.393	86.787	42.943	76.276	T/m

Arc Cell Performance

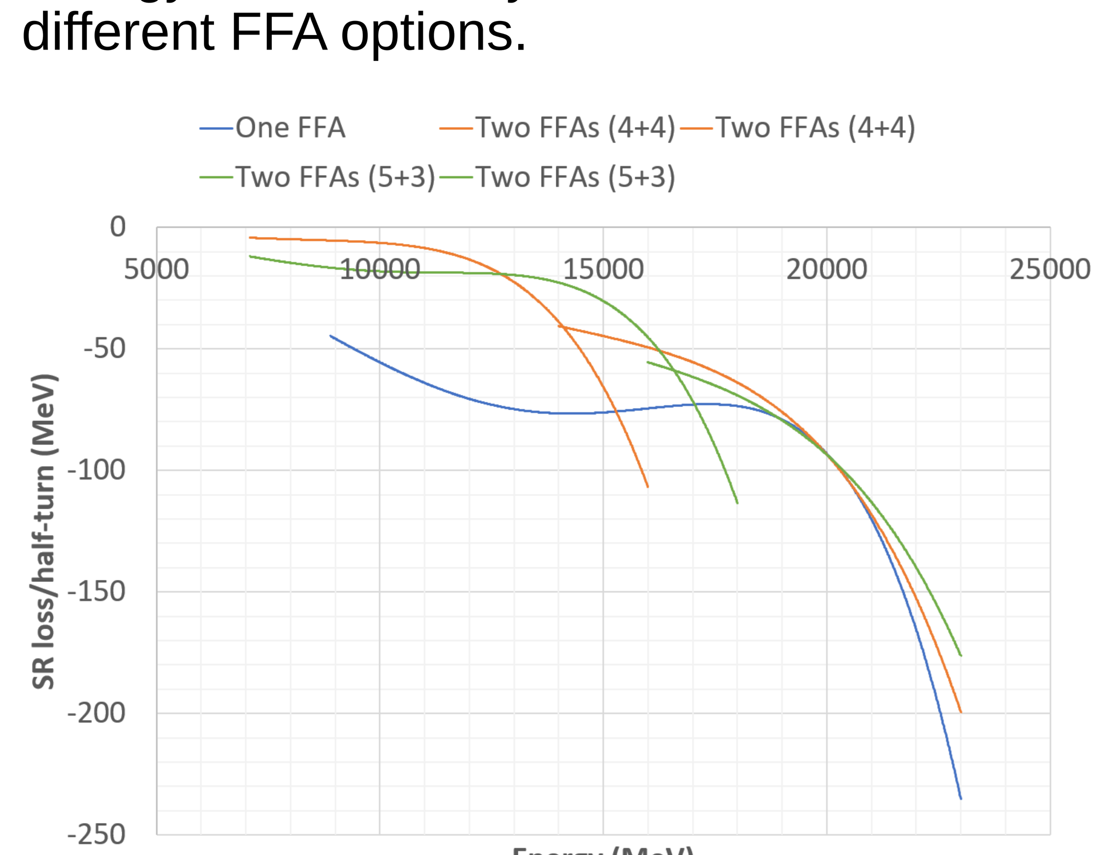
Table 4: FFA Cells Performance Comparison

Number of FFA Stages	Max Field (T)	SR Loss (MeV)	Final Energy (MeV)
One	2.007	1211.48	23418.52
Two (4+4)	1.495	964.44	23665.56
Two (5+3)	1.489	935.30	23694.70

Maximum field on beam centroid, as a function of energy in the various FFA options.



Energy lost to synchrotron radiation in different FFA options.



Permanent Magnets

Permanent magnets were designed for the two-FFA, 5+3 turn option with the highest performance. The magnet designs include open midplanes to allow synchrotron radiation to escape and use an oval-shaped modified Halbach design for greater efficiency with a horizontal orbit span.

Table 5: Magnet Parameters for the Two-FFA (5+3) Option

Magnet	Dipole (T) @ $x = 0$	Gradient (T/m)	x Aperture Range (mm)
FFA1 BF	-0.52616	-35.135	±27.39
FFA1 BD	-0.73168	42.943	±19.53
FFA2 BF	-0.80051	-40.390	±14.95
FFA2 BD	-1.06879	38.138	±10.66

Magnet cross-sections with 1cm grid. Blue arrows denote magnetisation direction.

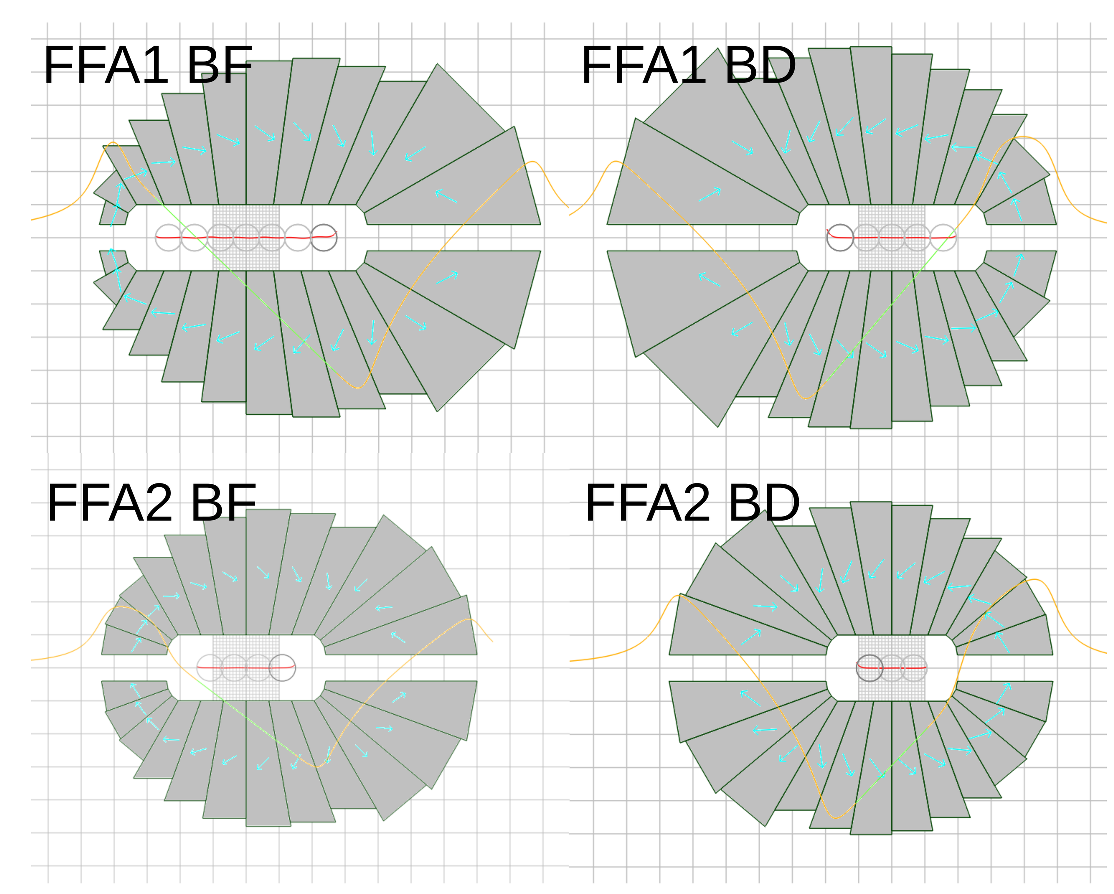
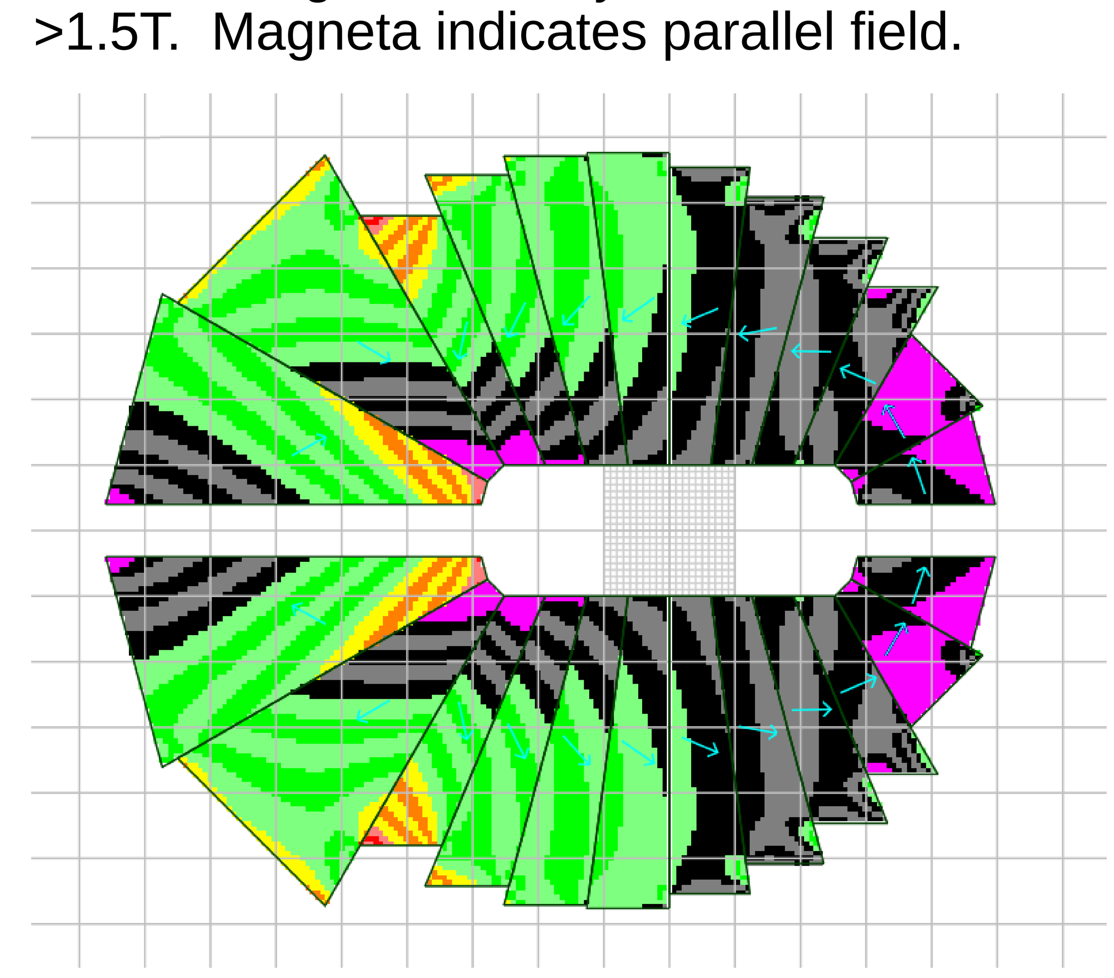


Table 6: Permanent Magnet Design Rules

Parameter	Value	Unit
Material	NdFeB	
Grade	N42EH	
Remnant field B_r	1.30	T
Central aperture gap	20	mm
Midplane slot gap	8	mm
Number of wedges	24 (12 per side)	
Wedge angles (FFA1,2)	30/7.5/30, 20/10/20	°

Sensitivity to demagnetisation in the FFA1 BD magnet, given by field antiparallel to the magnetisation direction, $-\mu_0 \mathbf{H} \cdot \mathbf{M} / |\mathbf{M}|$. Black is 0 to 0.5T, green ≤1T, yellow ≤1.5T and red >1.5T. Magneta indicates parallel field.



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