Attempts to get Isochronous FFAG arcs for the CEBAF upgrade

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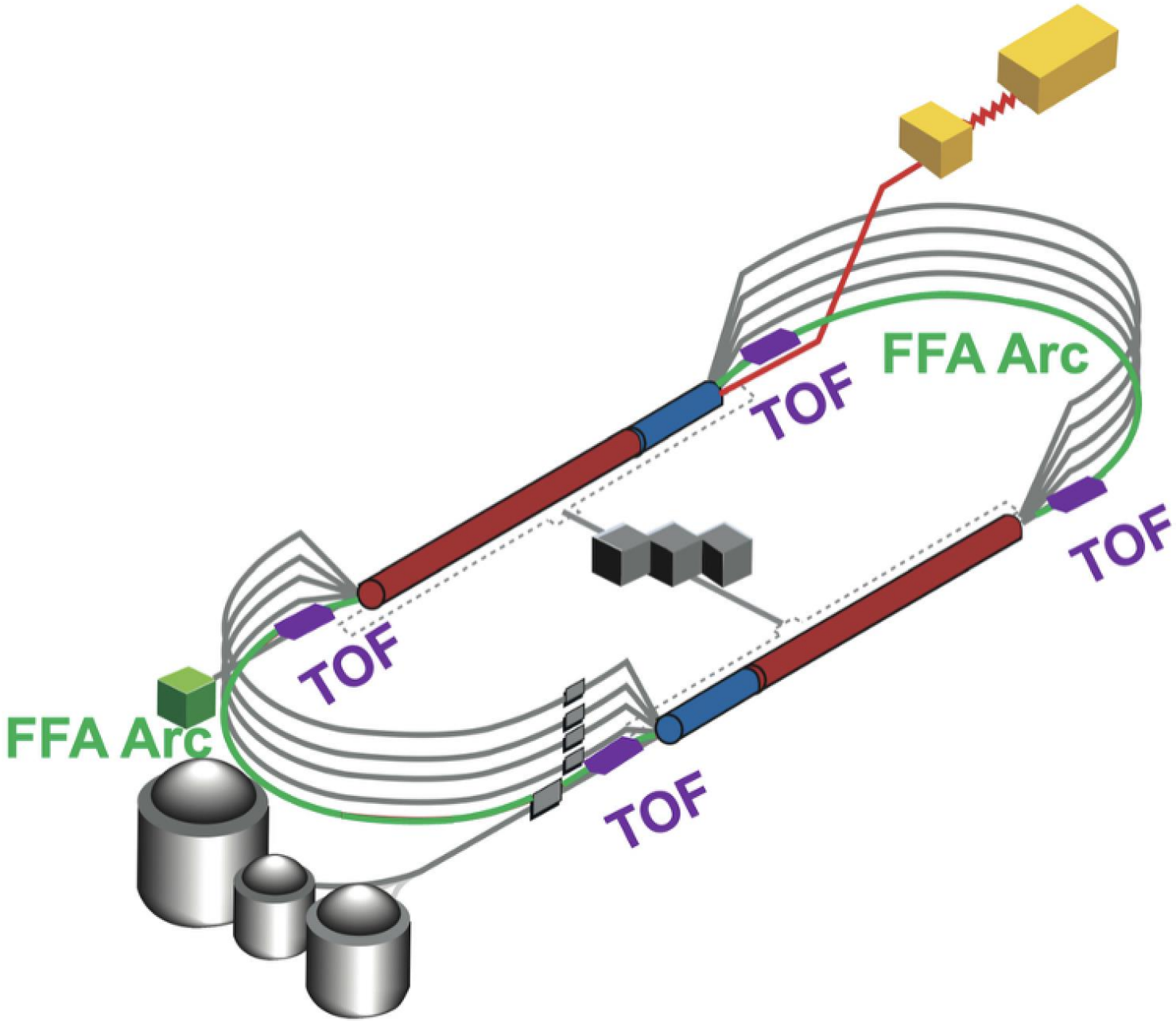
Abstract:
The Continuous Electron Beam Accelerator Facility (CEBAF) upgrade of the energy range from **12 GeV to 22 GeV with a single Fixed Field Alternating Gradient (FFAG) arcs** requires time-of-flight and adjusting the momentum compaction dependence on energy or M56 **with use of multiple splitters. To reduce these dependences and make required adjustments smaller and simpler a new approach towards isochronous FFAG arc design was introduced.** Both arcs in the CEBAF racetrack are made of 27 modules each containing eight variable combined function magnets. **The isochronous condition was established at the reference energy** by obtaining zero momentum compaction **due to dispersion function oscillations between positive and negative values in each module**. Orbits within the whole energy range between **9.6 and 22.6 GeV** oscillate around the central circular reference orbit following the dispersion function oscillations. This approach reduces the emittance of the electron beam (the H-function) and is applicable for the future electron ion colliders.


FFA Arc
TOF
FFA Arc
TOF
TOF
TOF

CEBAF upgrade - reducing M56 and time of flight in the FFA arcs

- The FFA arc is constructed by **using 27 modules** – assemblies **each having 8 combined function magnets**. The dispersion function oscillates between negative and positive values creating very small momentum compaction as the Momentum compaction α or the integral of the dispersion function is very small or zero:

$$\alpha = \frac{1}{C}\int_0^C \frac{D_x}{\rho} dx$$

  The essential idea is to make the 'isochronous' condition, or close to it, **reducing the time of flight and the momentum compaction through the whole energy range**. This would make the splitter corrections easier.

- The PTC results show stable orbits in 9.4-22.6 GeV

- The momentum compaction α is zero at the electron energy of 16 GeV. The M56 is obtained by multiplying α by the length of the 27 modules.

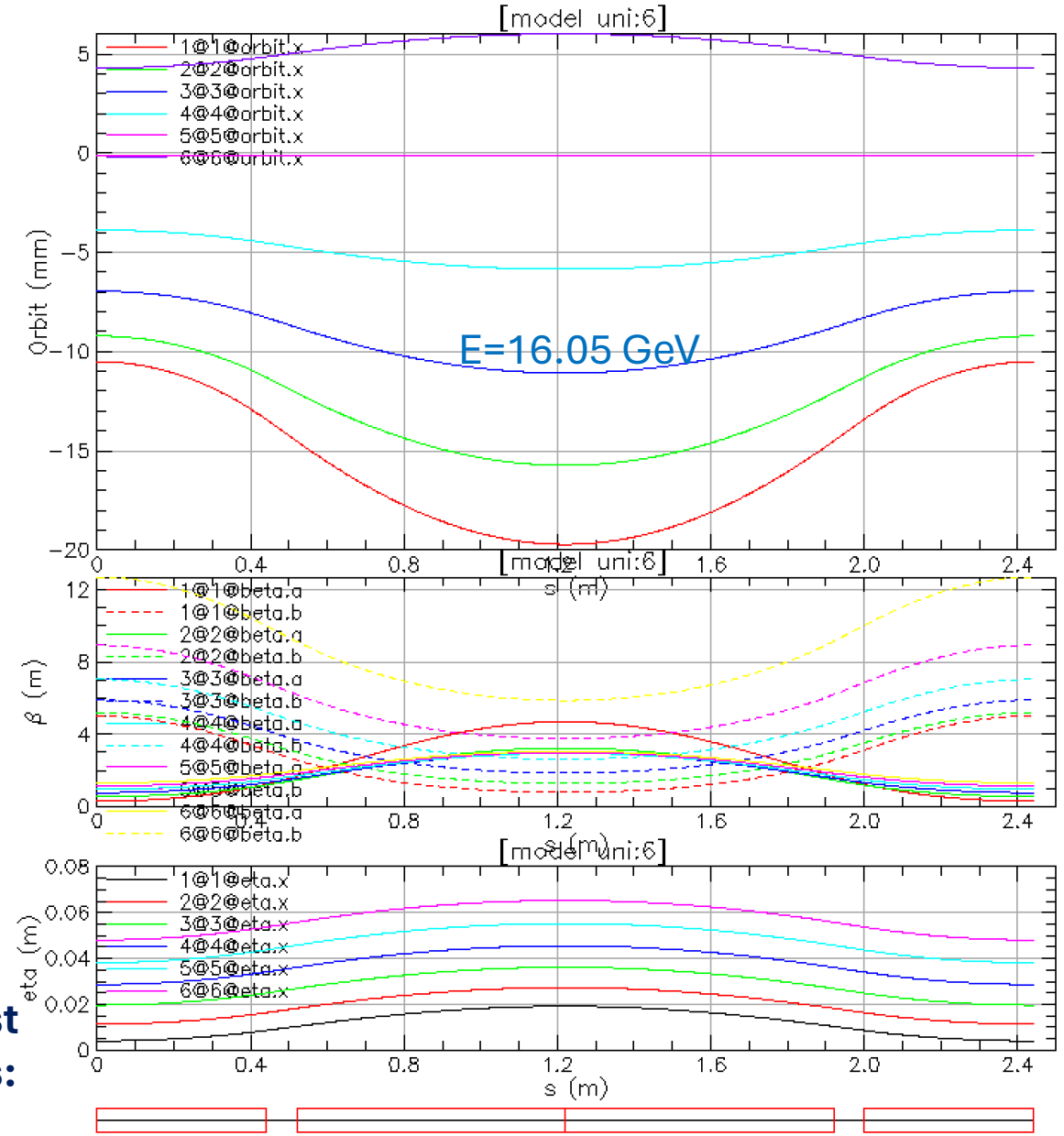
Lattice Functions in a Cell for the WEST-FFA arc

Lattice Cells=98
L_{cell}= 2.440255 m

Magnet Properties:
Focusing Magnet QF
G_F= -71.60551 T/m
L_{QF}= 1.4 m
θ_F= -0.024771371 rad
B_F= -1.209916 T
B_{FMAX}=-1.6403 T

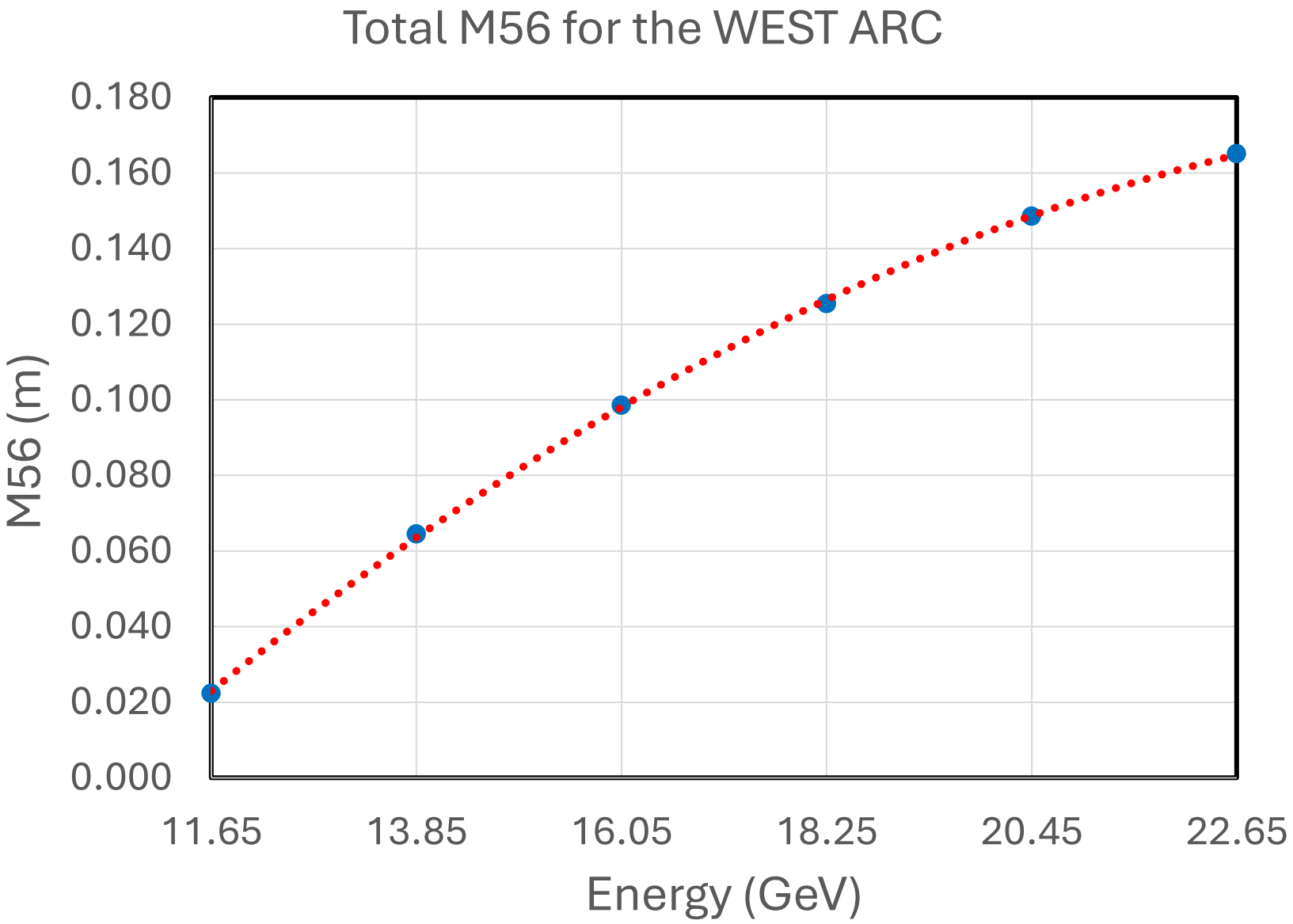
Defocusing Magnet BD
G_D= 89.643365 T/m
L_{BD}= 0.8802552 m
θ_D= -0.005504749 rad
B_D= -0.427624 T
B_{DMAX}=-1.631 T

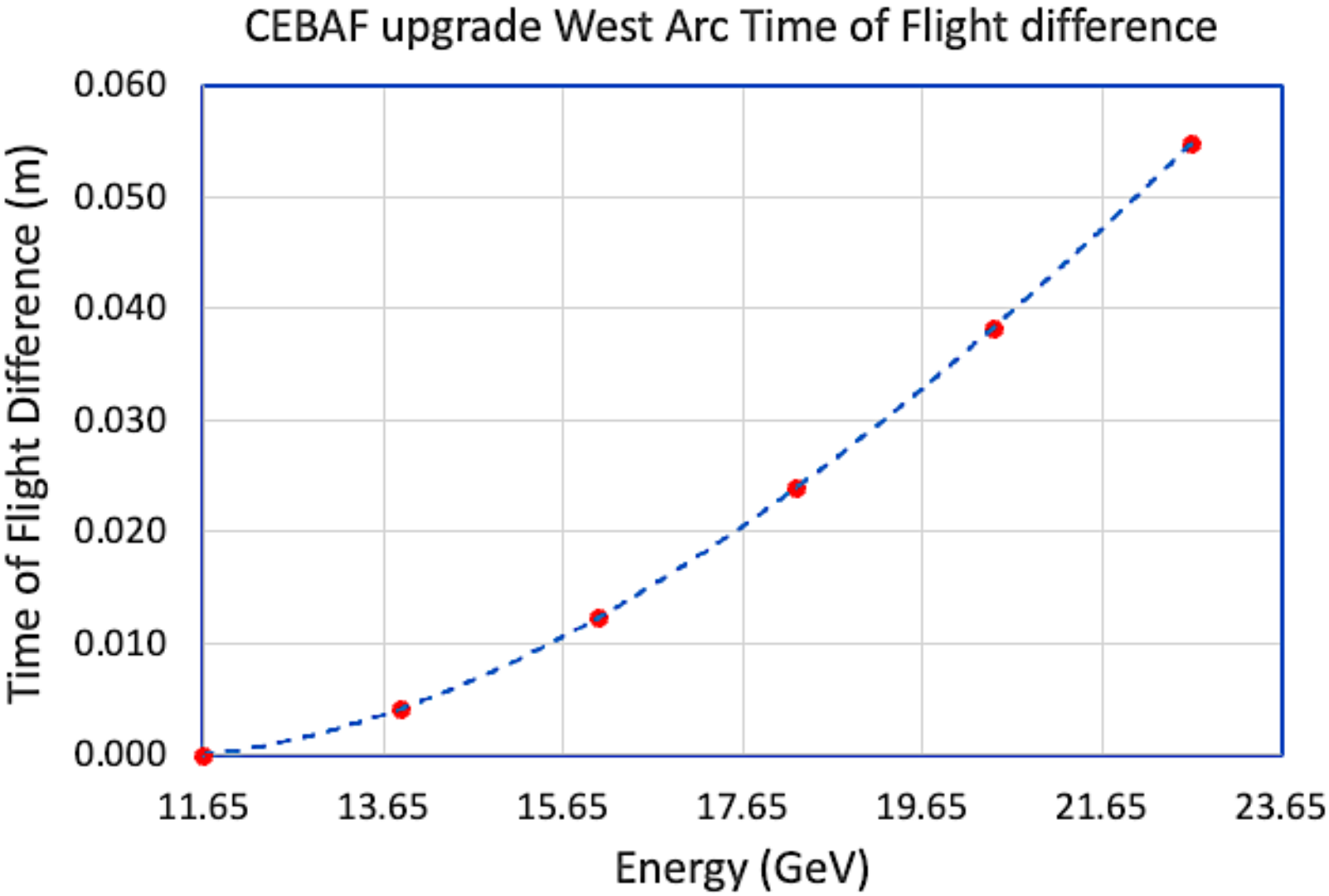
Total Synchrotron Radiation Lost In the West arc from five passes:
E_{Loss}=525.810 MeV



Results From Different Codes for M_{56} and Time of Flight of the WEST FFA arc

Energy(GeV)	L_arc*Alpha_C	M56	M56 (m) MADX-PTC	M56 (m) Bmad	Time of Flight Difference (m)	Time of Flight Difference (m)
22.65	0.16633	0.16509	0.16509	-0.16487	0.054853	0.0000000
20.45	0.14808	0.14858	0.14858	-0.14871	0.050772	0.0169059
18.25	0.12588	0.12542	0.12542	-0.12521	0.042509	0.030894
16.05	0.09863	0.09850	0.09853	-0.09836	0.030894	0.042509
13.85	0.064815	0.06450	0.06450	-0.06444	0.016560	0.050772
11.65	0.02228	0.02234	0.02234	-0.02227	0.0000000	0.054853


Total M56 for the WEST ARC
M56 (m)
0.180
0.160
0.140
0.120
0.100
0.080
0.060
0.040
0.020
0.000
11.65
13.85
16.05
18.25
20.45
22.65
Energy (GeV)

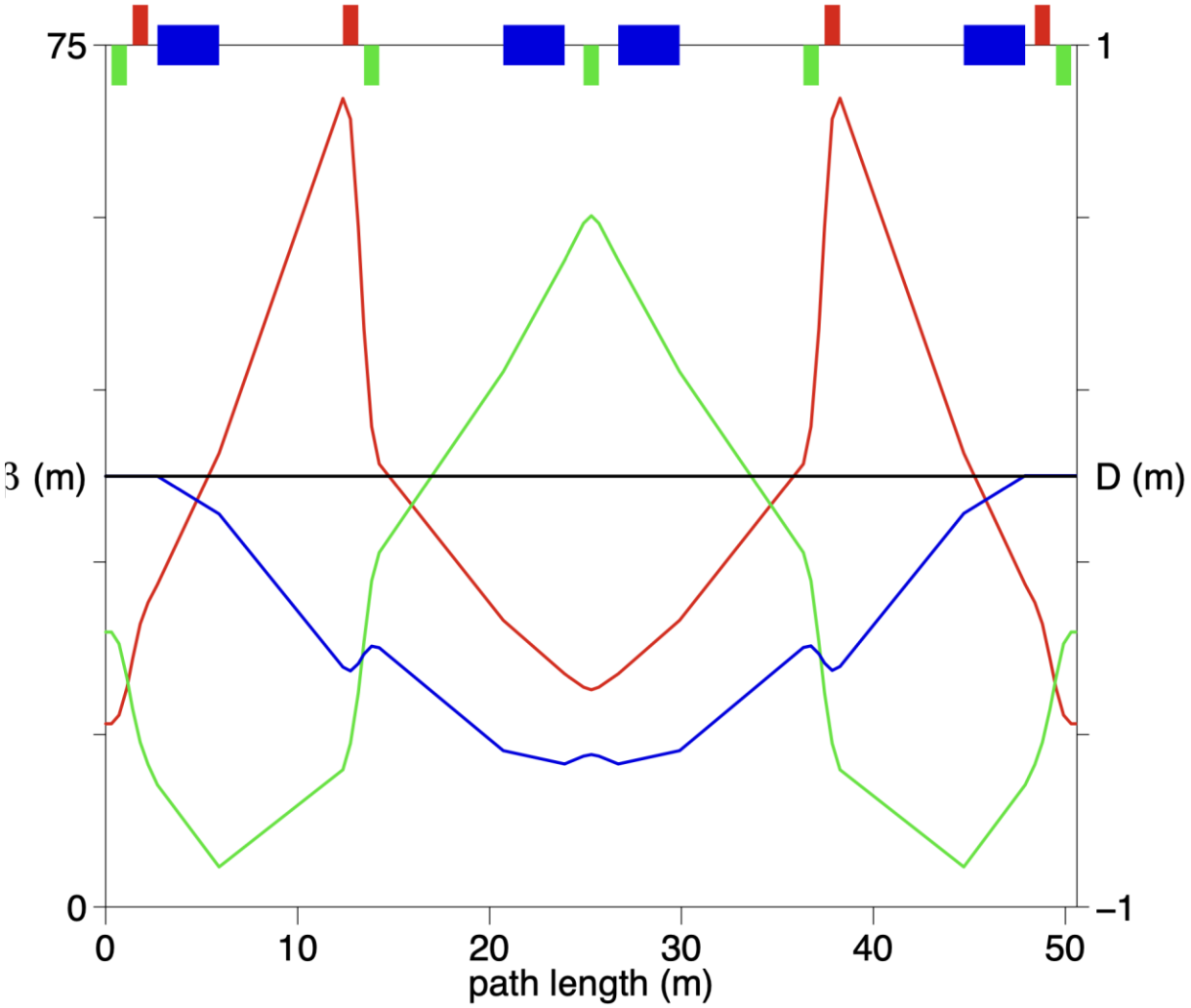

CEBAF upgrade West Arc Time of Flight difference
Time of Flight Difference (m)
0.060
0.050
0.040
0.030
0.020
0.010
0.000
11.65
13.65
15.65
17.65
19.65
21.65
23.65
Energy (GeV)

Initial Splitter Design – M56 and Geometry

α = -0.0013903 C= 50.6 M_{56}= 50.6m*(-0.0013903) = –0.0704 m

LS_{DIP} =18 m
BYD=1.3 T
LDIP =3.2 m
LQ = 0.8 m

GD1= -21.1
GF2=12.46
GD3=27.24
GD4=-26.36
GDA=-5.24



NON-ISOCHRONOUS & ISOCHRONOUS, NON-SCALING FFAG DESIGNS

Graham Rees : Cyclotrons and Their Applications 2007

Five magnets, of three, different types are used for the dFDFdO “pumplet” cell.

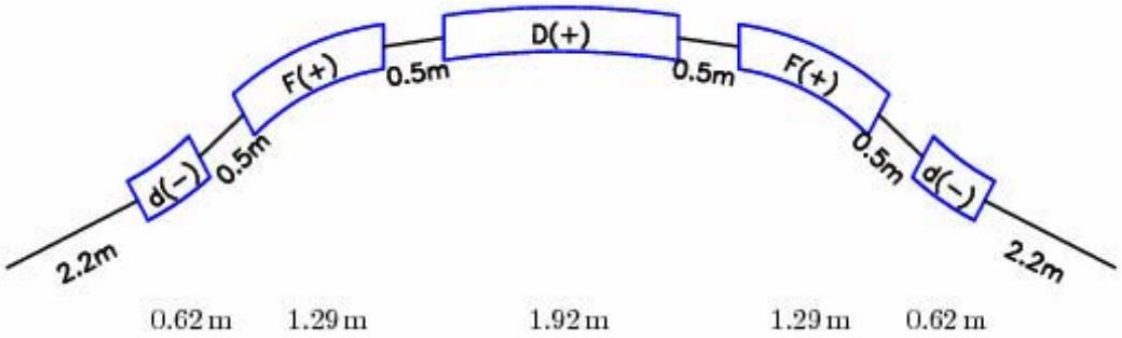


Figure 2: A single lattice cell of the 50 Hz, 4 MW, 3-10 GeV, NFFAG proton driver ring.

Non-linear, nearly isochronous motion occurs for orbits **whose lengths vary quadratically with momentum**, relative to the mid-range, γt = γ orbit. The bunch centroids pass by the crest of the cavity fields, once or three times, during the “gutter” acceleration around the stable region

Descriptions are given of some non-scaling, FFAG ring designs for the acceleration of proton or ion beams, and for the very rapid acceleration of muons to high energy

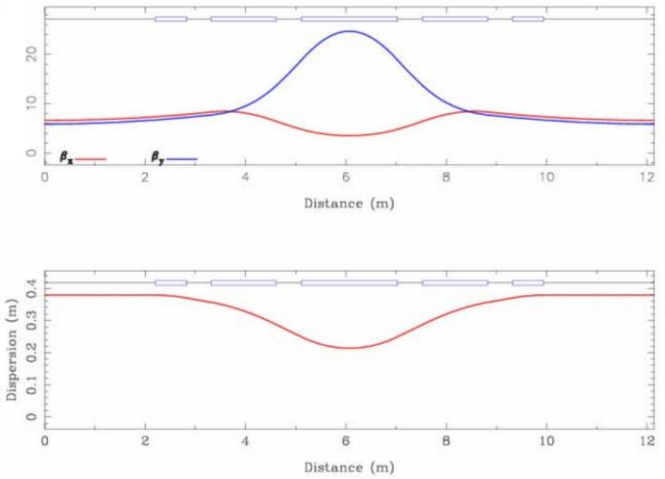
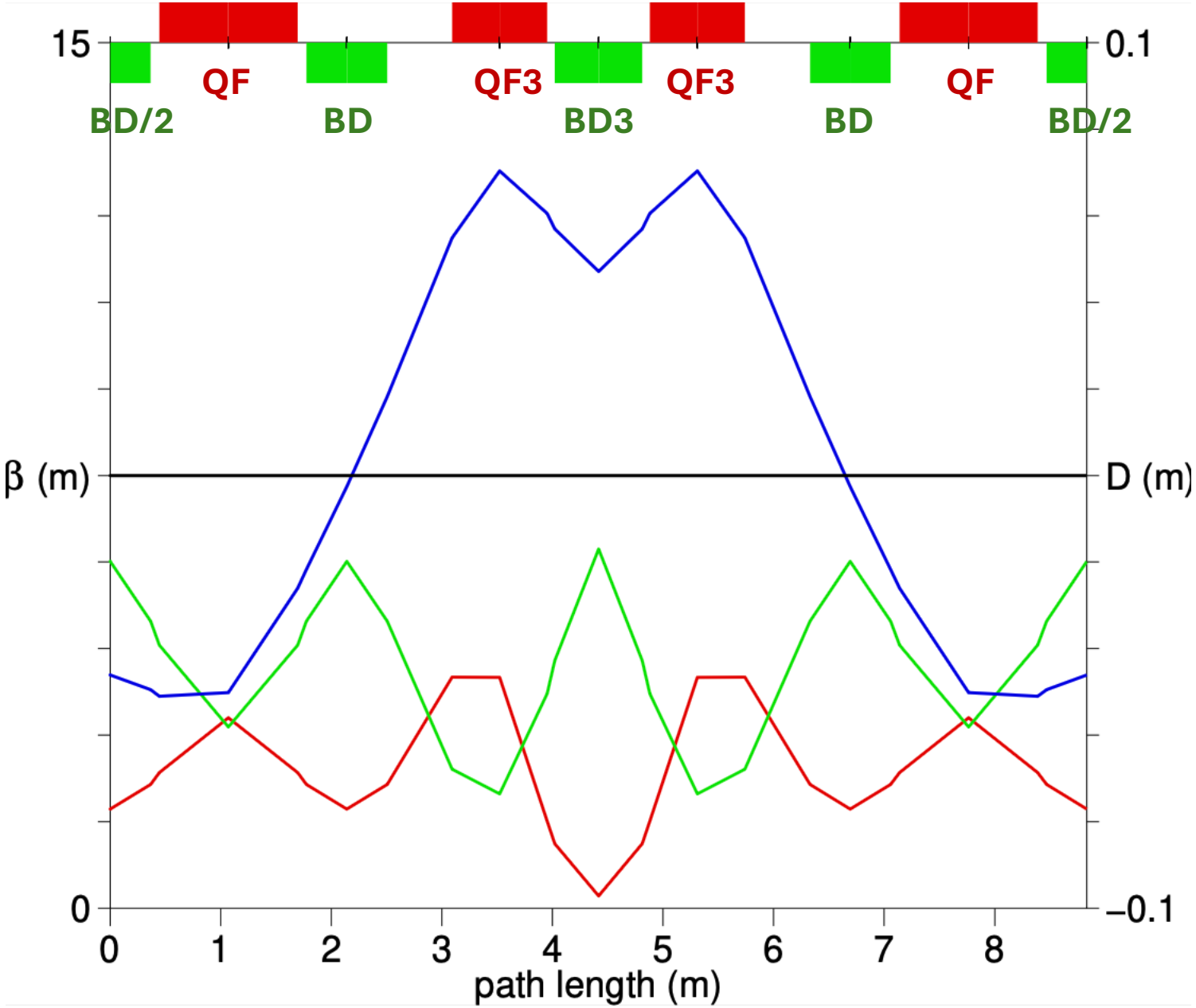


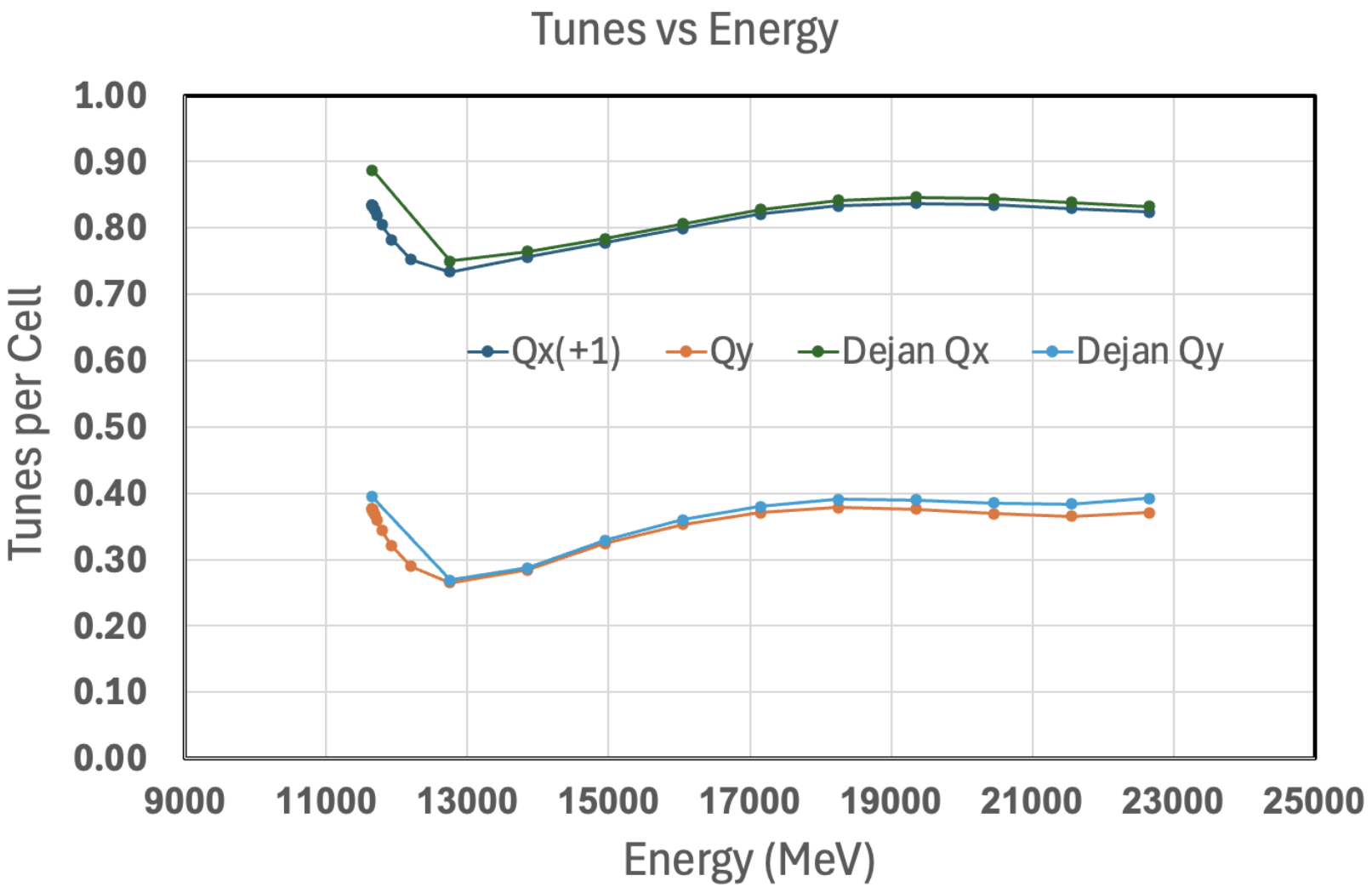
Figure 3: Small amplitude, betatron and dispersion functions for the NFFAG, 10 GeV orbit.

CEBAF upgrade - reducing M56 and time of flight in the FFA arcs

QF
QF3
BD
BD3



Muon1-S. Brooks code comparison to the PTC



Electron Orbits with Energies 9.6-22.6 GeV
E_{CENT}=16 GeV

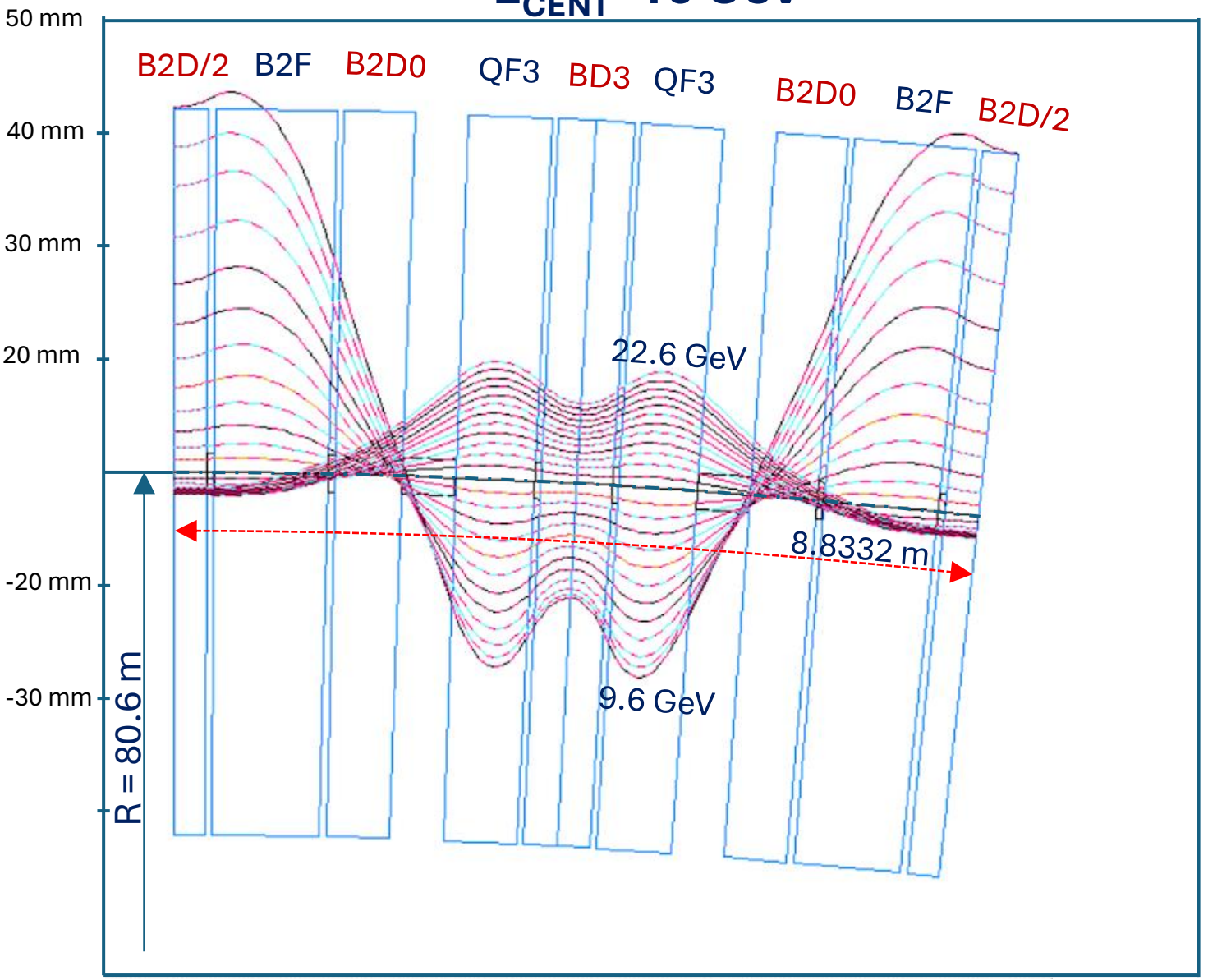
By = 0.81236 T
GFC= 49.264 T/m
GDC= -75.074 T/m
GF3= 118.996 T/m
GD3=-121.059 T/m

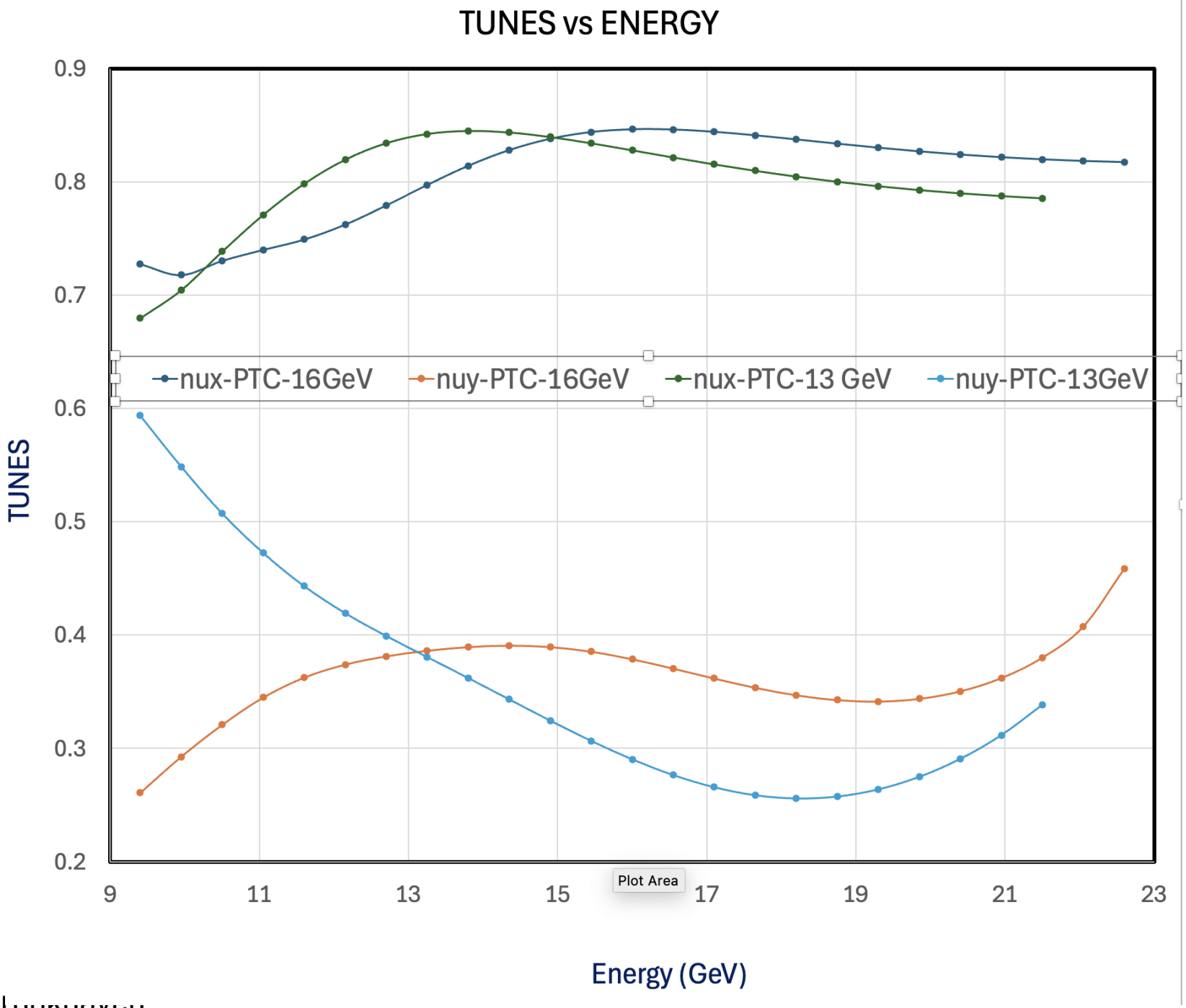
SEXF3= 818.
SEXD3=-1612.
SEXD0= 1422.
SEXD= 1722.
SEXF= -690.

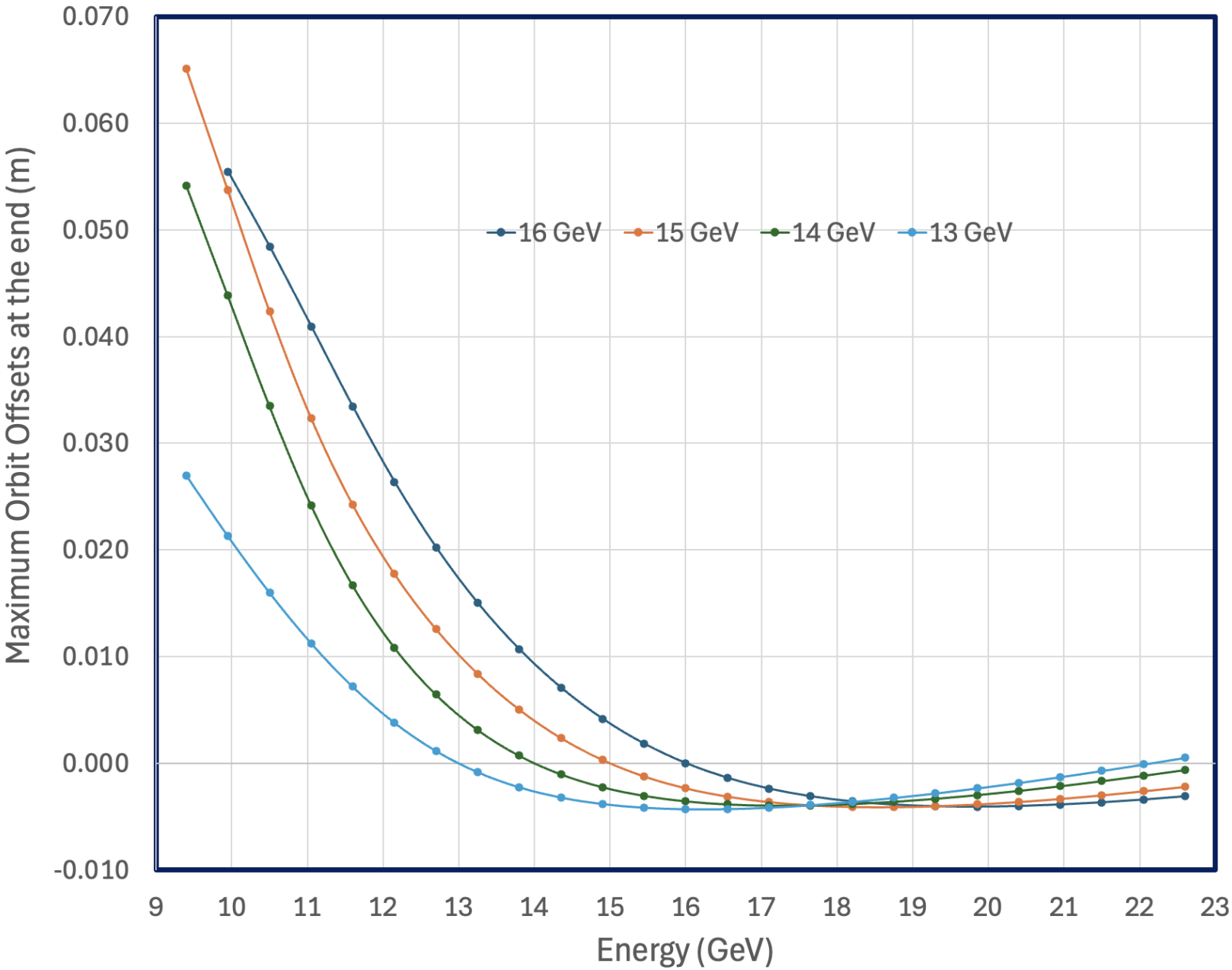
OCTF3= 3700.
OCTD3=-18490.
OCTD0= -4890.
OCTD =-14490.
OCTF = 4000.

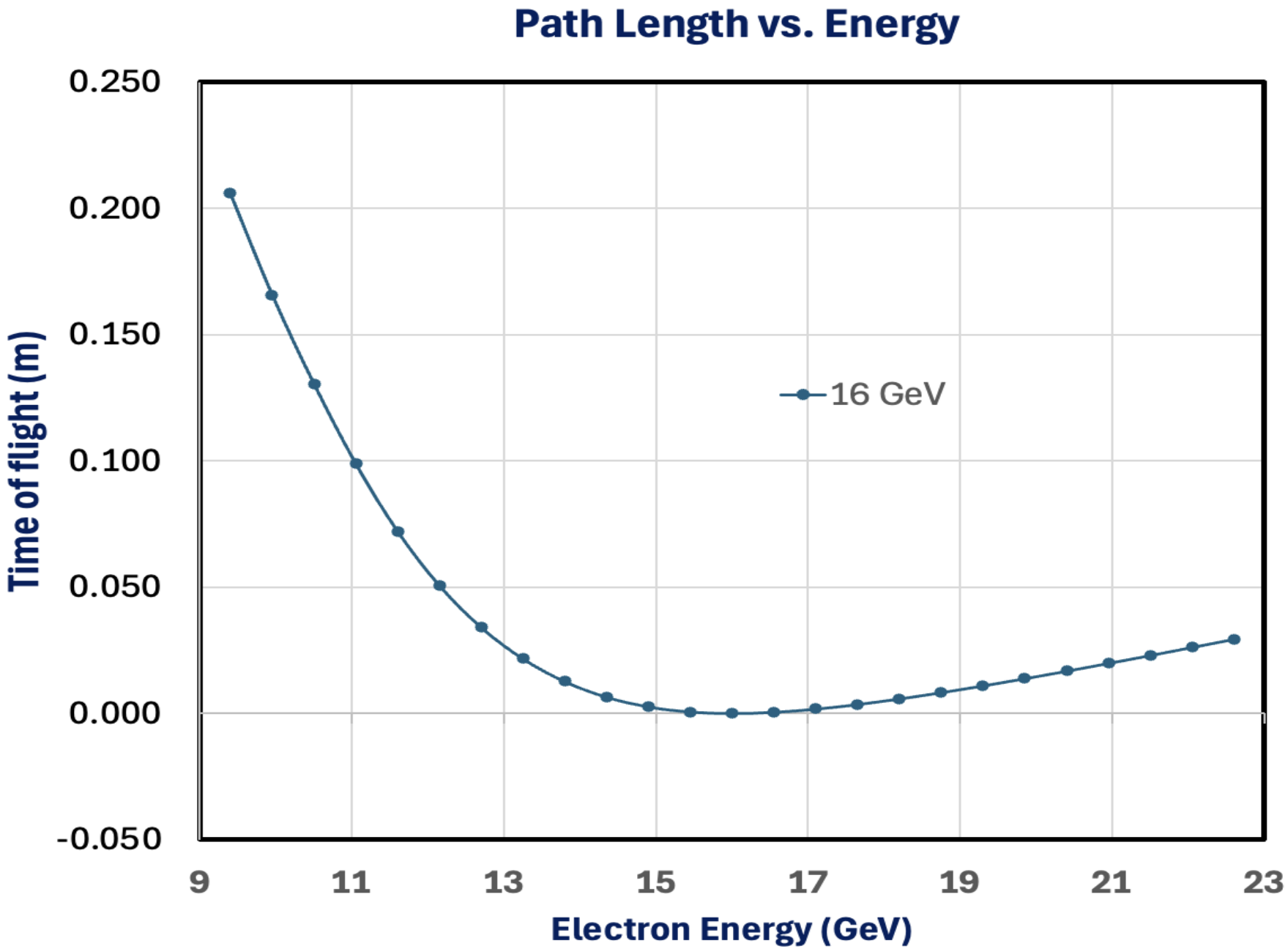
DECF3= 9750.
DECD3=-35000.
DECD0= -2000.
DECD = 35000.
DECF = -9350.

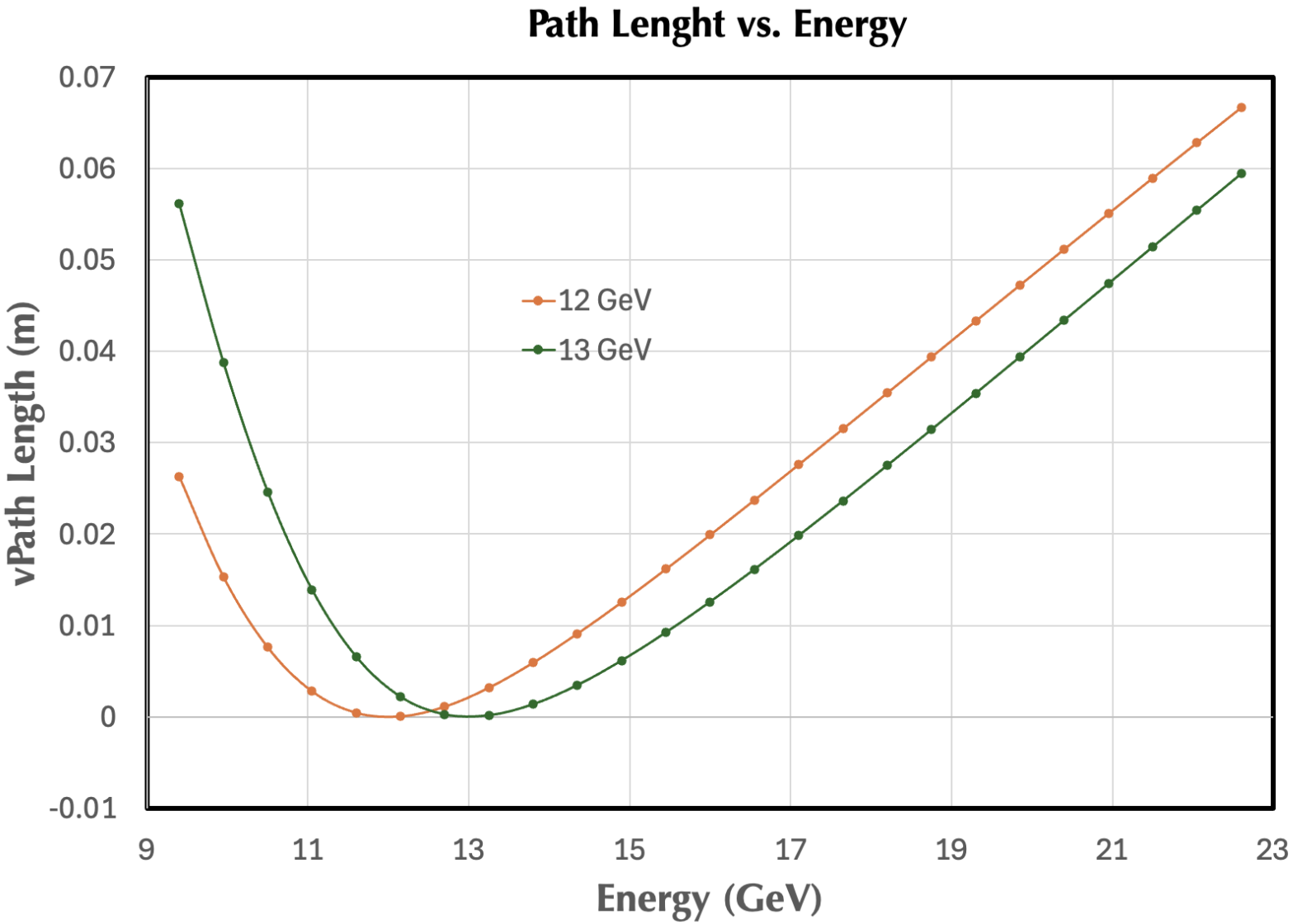
DDCF3= 31000.
DDCD3= -3900.
DDCD0= 4600.
DDCD =-42000.
DDCF = 30000.




TUNES vs ENERGY
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
TUNES
nux-PTC-16GeV
nuy-PTC-16GeV
nux-PTC-13 GeV
nuy-PTC-13GeV
Plot Area
9
11
13
15
17
19
21
23
Energy (GeV)


Maximum Orbit Offsets at the Cell End
Maximum Orbit Offsets at the end (m)
0.070
0.060
0.050
0.040
0.030
0.020
0.010
0.000
-0.010
16 GeV
15 GeV
14 GeV
13 GeV
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Energy (GeV)


Path Length vs. Energy
0.250
0.200
0.150
0.100
0.050
0.000
-0.050
Time of flight (m)
16 GeV
9
11
13
15
17
19
21
23
Electron Energy (GeV)


Path Lenght vs. Energy
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
vPath Length (m)
12 GeV
13 GeV
9
11
13
15
17
19
21
23
Energy (GeV)

Electron Orbits with Energies 9.6-22.6 GeV

E_{CENT}=13 GeV

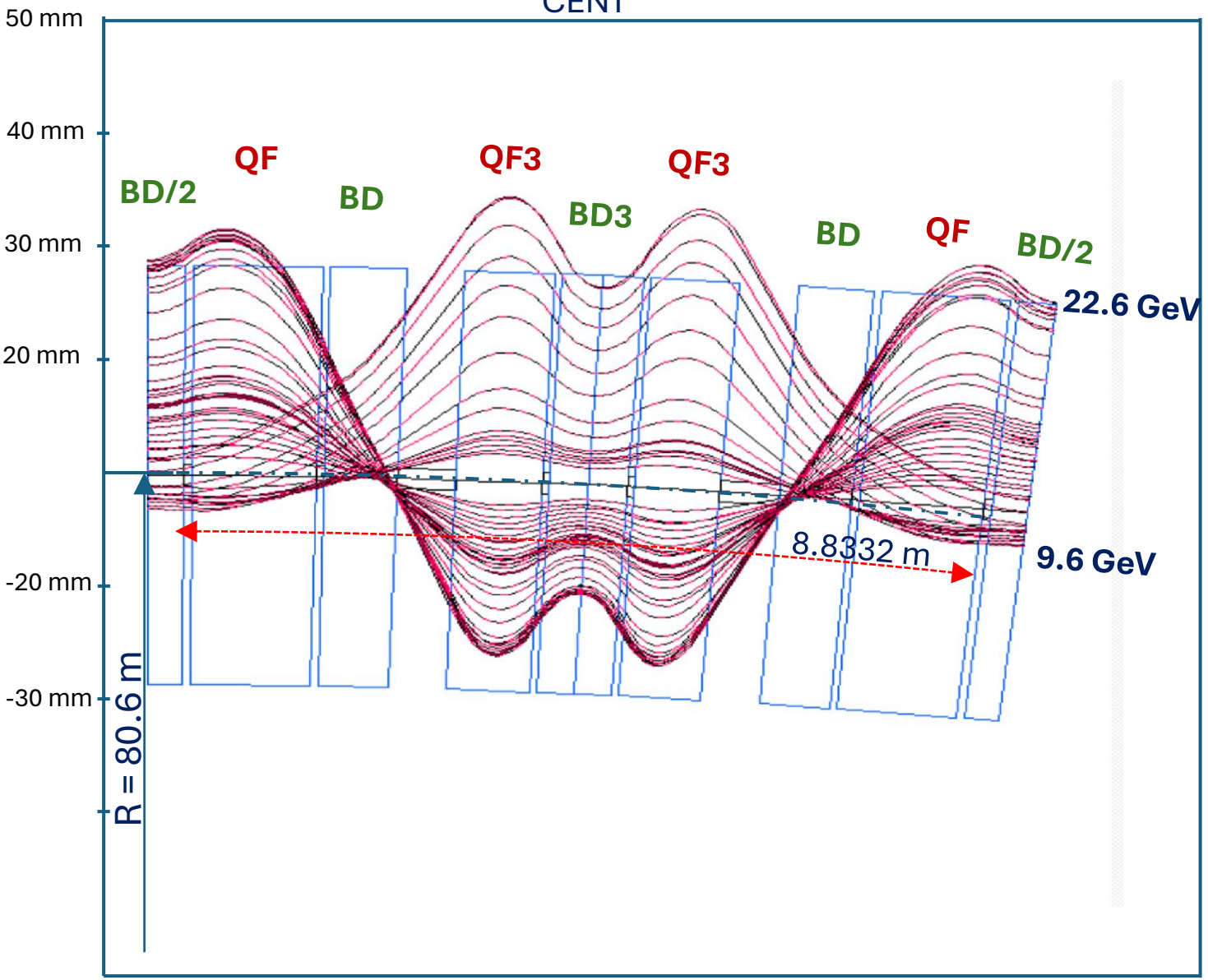
By = 0.609272 T
GFC= 36.948 T/m
GDC= -56.306T/m
GF3= 89.2469 T/m
GD3= -90.7946 T/m

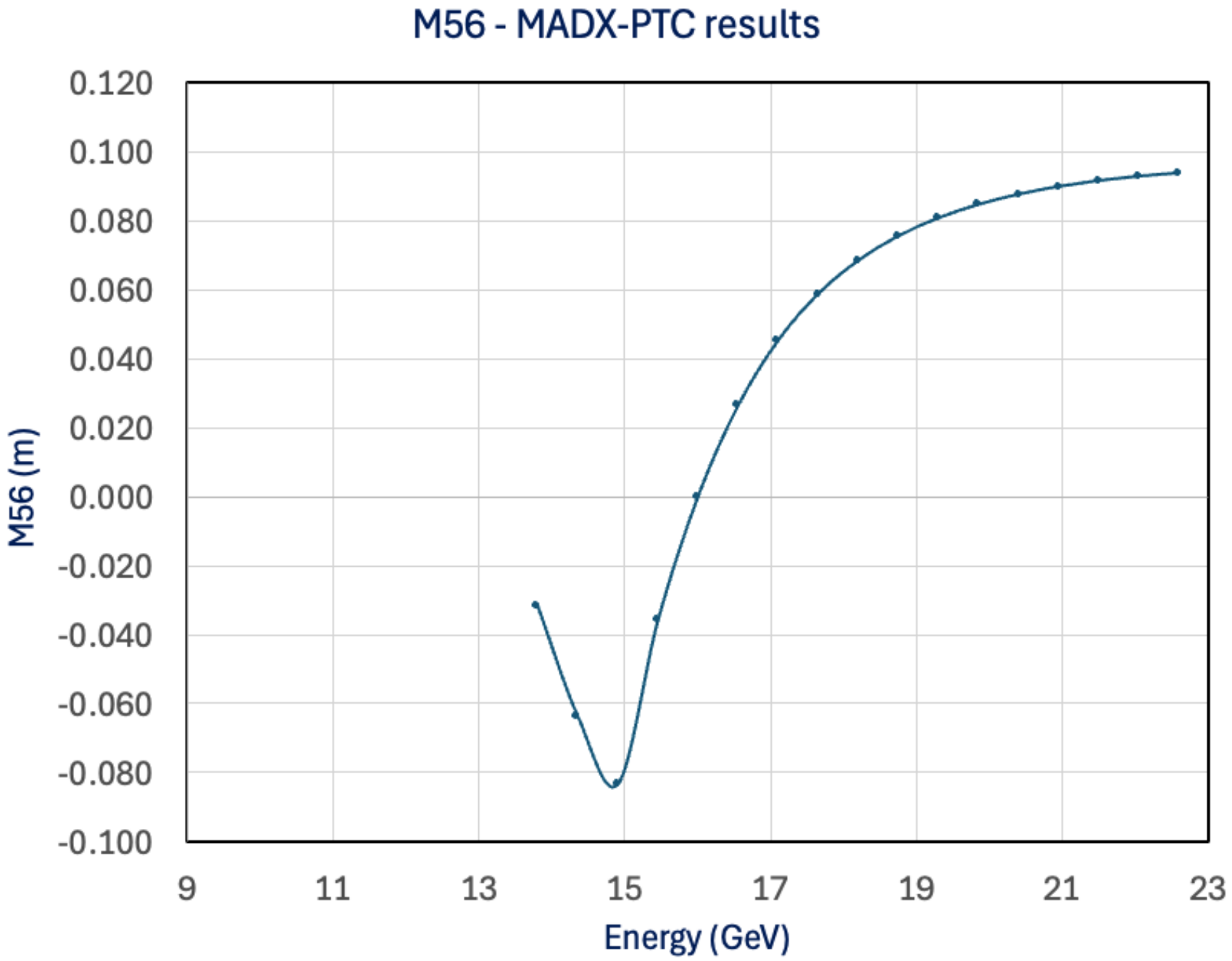
```
SEXF3   =    675.0D0;
SEXD3   =  -1142.0D0;
SEXD0   =   1122.0D0;
SEXD    =   1232.0D0;
SEXF    =   -550.0D0;

OCTF3   =   3500.0D0;
OCTD3   = -17490.0D0;
OCTD0   =  -4790.0D0;
OCTD    = -13490.0D0;
OCTF    =   3000.0D0;

DECF3   =   7050.0D0;
DECD3   = -30000.0D0;
DECD0   =  -2000.0D0;
DECD    =  32000.0D0;
DECF    =  -8050.0D0;

DDCF3   =  31000.0D0;
DDCD3   = -39000.0D0;
DDCD0   =   4600.0D0;
DDCD    = -42000.0D0;
DDCF    =  30000.0D0;
```

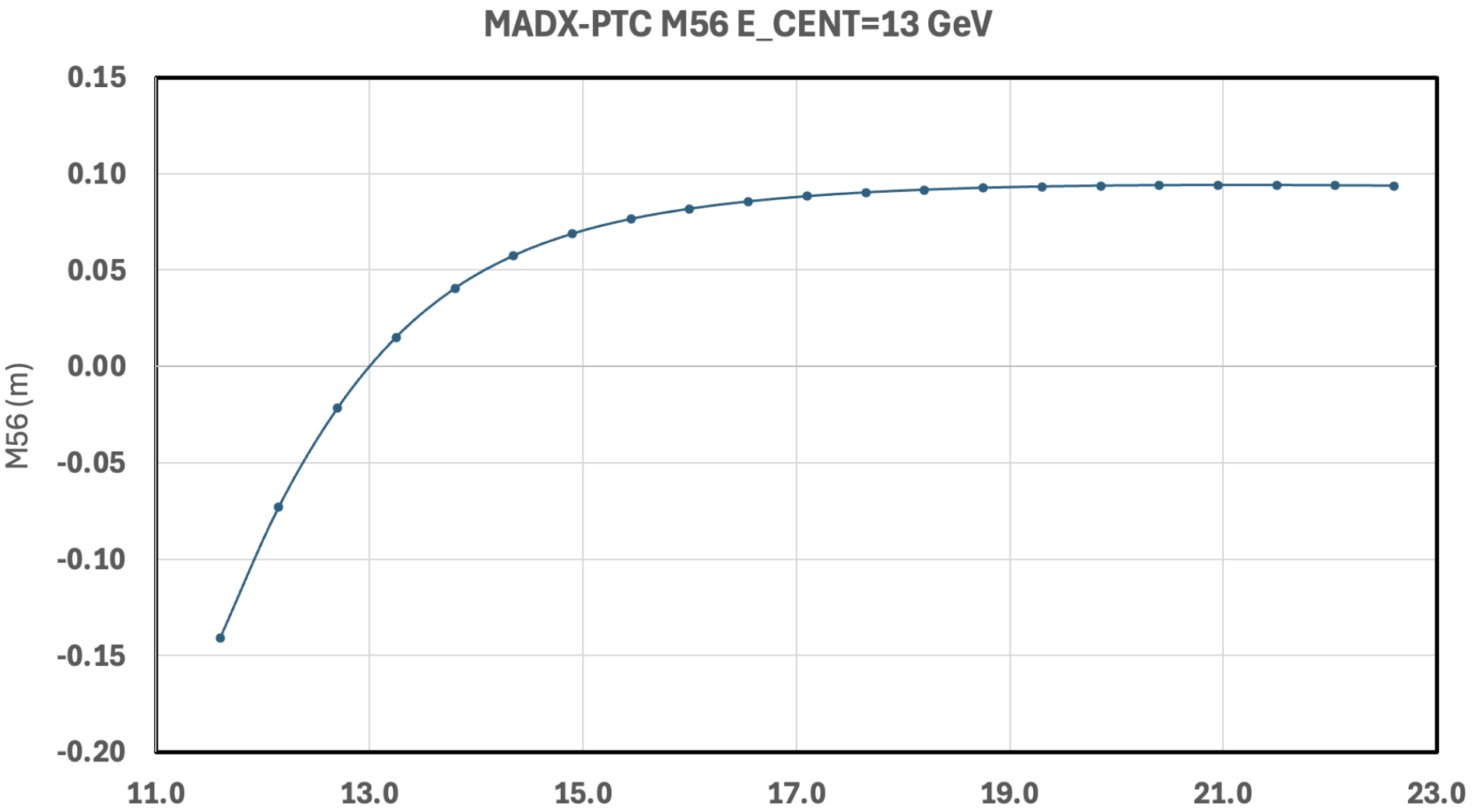



M56 - MADX-PTC results
0.120
0.100
0.080
0.060
0.040
0.020
0.000
-0.020
-0.040
-0.060
-0.080
-0.100
M56 (m)
9
11
13
15
17
19
21
23
Energy (GeV)

CEBAF upgrade - reducing M56 and time of flight in the FFA arcs

dp/p	Energy (GeV)	alpha	M56	Gamma_t	nux	nuy	x_min	x_max	delta_C
0.4125000	22.6	0.0003929	0.0937081	50.44896	0.813420	0.29075	−0.00309	0.01815	0.02947
0.3781250	22.05	0.0003890	0.0927789	50.70097	0.81605	0.28907	−0.00340	0.01692	0.02614
0.3437500	21.5	0.0003837	0.0915066	51.05222	0.81895	0.29053	−0.00367	0.01565	0.02294
0.3093750	20.95	0.0003765	0.0898059	51.53335	0.82211	0.29491	−0.00387	0.01436	0.01980
0.2750000	20.40	0.0003671	0.0875601	52.19007	0.82552	0.30193	−0.00402	0.01303	0.01674
0.2406250	19.85	0.0003547	0.0846040	53.09401	0.82912	0.31122	−0.00408	0.01166	0.01376
0.2062500	19.30	0.0003384	0.0806980	54.36378	0.83281	0.32232	−0.00404	0.01024	0.01091
0.1718750	18.75	0.0003165	0.0754860	56.20925	0.83640	0.33470	−0.00389	0.00876	0.00821
0.1375000	18.20	0.0002870	0.0683849	59.03477	0.83961	0.34772	−0.00359	0.00722	0.00573
0.1031250	17.65	0.0002463	0.0587390	63.72025	0.84206	0.36061	−0.00311	0.00559	0.00353
0.0687500	17.1	0.0001897	0.0452380	72.60878	0.84323	0.37246	−0.00239	0.00386	0.00178
0.0343750	16.55	0.0001104	0.0263262	95.18018	0.84252	0.38227	−0.00138	0.00200	0.00048
0.0	16.00	5.8777e−09	1.402e−06	13043.58	0.83929	0.38903	0.0	0.0	0.0
−0.034375	15.45	−0.000151	−0.0359124	i81.4927	0.83311	0.39197	0.001819	−0.00216	0.00059
−0.068750	14.90	−0.000350	−0.0834255	i53.4677	0.82390	0.39078	0.004158	0.00460	0.00260
−0.103125	14.35	−0.000267	−0.0636619	i40.6670	0.81214	0.38556	0.007091	0.00784	0.00645
−0.137500	13.80	−0.000133	−0.0317265	i86.7022	0.84838	0.61617	−0.009730	−0.00360	0.01262

CEBAF upgrade - reducing M56 and time of flight in the FFA arcs



MADX-PTC- reducing M56 and time of flight in the FFA arcs

ENERGY (GeV)	Δp/p	α_C	M56
22.6	0.73846148	0.00039276	0.093671929
22.05	0.6961538	0.00039357	0.093865046
21.5	0.65384611	0.00039409	0.093988818
20.95	0.61153843	0.00039412	0.093997115
20.4	0.56923074	0.00039386	0.093934855
19.85	0.52692306	0.00039286	0.093696768
19.3	0.48461537	0.00039105	0.093265073
18.75	0.44230768	0.00038821	0.092586305
18.2	0.40000000	0.00038403	0.0915901
17.650001	0.35769232	0.00037812	0.09018063
17.100001	0.31538463	0.00036991	0.088222117
16.550001	0.27307695	0.00035855	0.085513805
16.000001	0.23076926	0.00034276	0.081746338
15.450001	0.18846158	0.00032045	0.076426409
14.900001	0.14615389	0.00028827	0.068752262
14.350001	0.10384621	0.0002408	0.057430253
13.800001	0.06153853	0.0001697	0.040472505
13.250001	0.01923084	6.35E-05	0.015139193
12.700001	-0.0230768	-9.11E-05	-0.02171565
12.150001	-0.0653845	-0.0003059	-0.07294797
11.600001	-0.1076922	-0.0005909	-0.14091781