CEBAF 20GeV FFA Upgrade

First attempts at permanent magnets

Comparison of 1 vs. 2 FFA loops

More-optimised magnet designs

CEBAF ~20GeV FFA Upgrade

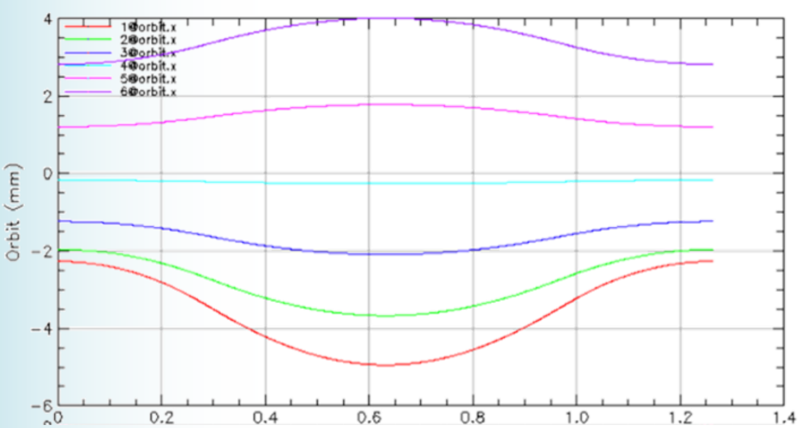
More in Ryan Bodenstein's talk

- CEBAF is currently a 5.5-turn racetrack RLA
  - 123MeV injector, 1090MeV North & South linacs
  - Maximum output energy 12GeV
  - Five stacked electromagnetic arcs on East & West
- Propose replacing one or two EM lines by multi-pass FFAs for extended energy reach
  - R=80.6m so 20GeV → 0.83T mean bending field
  - Non-scaling FFAs used for magnetic efficiency
  - Permanent magnets uses for power, cost savings

Parameters from IPAC'21 Paper

- Take parameters directly from the paper
- Note peak fields

20-24 GeV FFA CEBAF Energy Upgrade, S.A. Bogacz et al., Proc. IPAC'21



Element	Length [m]	Angle [°]	Dipole [T]	Gradient [T/m]
BF	0.625	0.5	0.681	250.91
O	0.05	0		
BD	0.5382	0.5	0.941	-233.13
O	0.05	0		

Table 1: Energy doubler FFA arc cell.

the 10-22 GeV beams are all confined to a region $-5\text{mm} < x < 4\text{mm}$. The orbits and optics of the unit cell for the

Magnet	Dipole at x=0 (T)	Gradient (T/m)	Xmin (mm)	Xmax (mm)	B(Xmin) (T)	B(Xmax) (T)
BF	0.681	250.91	-5	4	-0.574	1.685
BD	0.941	-233.13	-5	4	2.107	0.008

Permanent Magnet Design Rules

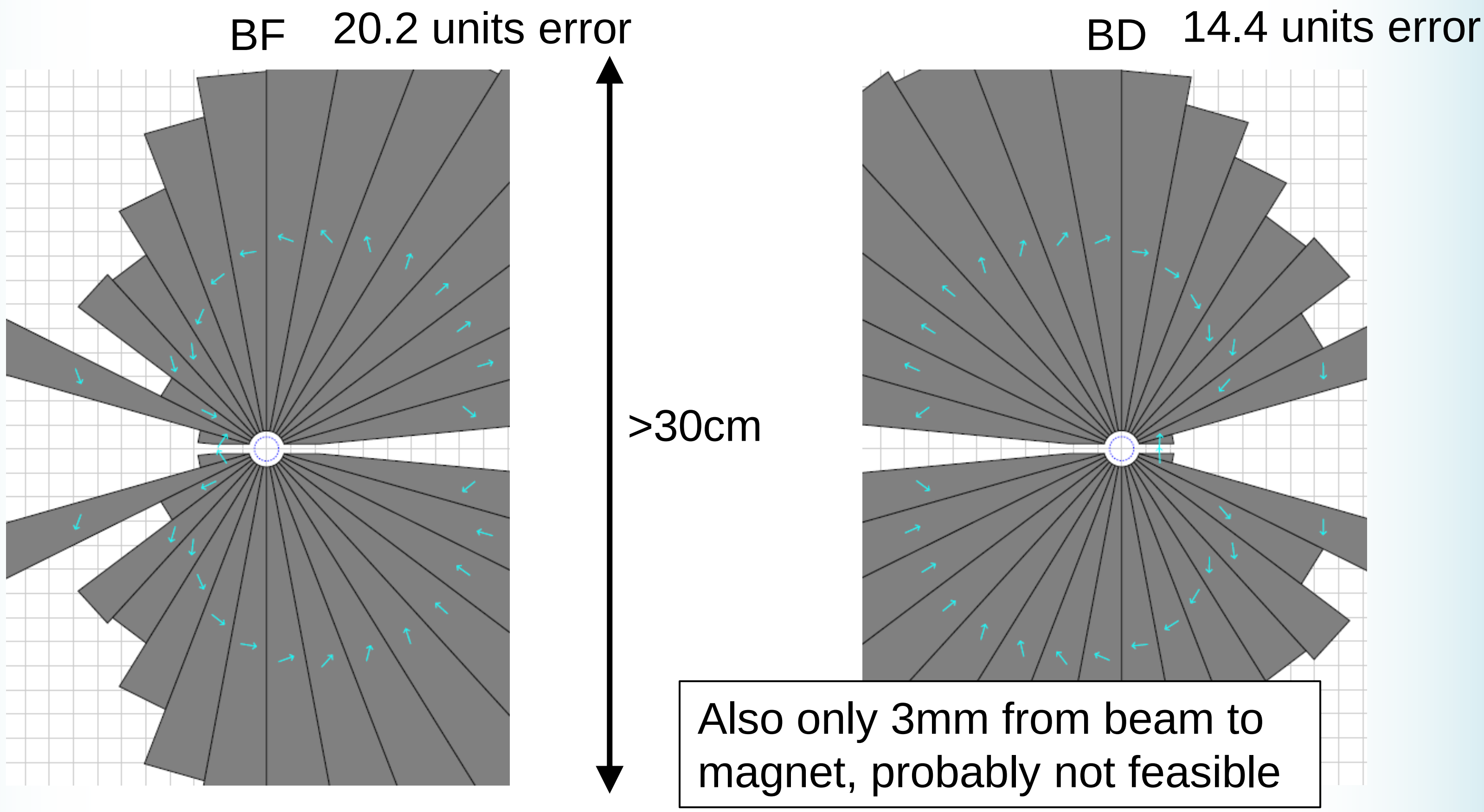
- Open midplane full height of 4mm ($y=\pm 2$mm)
  - Same as NSLS-IIU upgrade magnet (2020)
    - Which is also 250T/m
- Beam-centroid-to-magnet clearance of 5mm
  - Again, same as NSLSII-U, has R=5mm aperture
- $B_r=1.30$T material
  - E.g. AllStar N42EH grade
    - Intrinsic coercivity $H_{cj}=29.0$kOe (without radiation)
      - I.e. demagnetises totally at $\mu_0 H=-2.9$T (expect "knee" ~-2.7T)

Run HalbachArea Script

- https://stephenbrooks.org/ap/halbacharea/
- Good field region of 9mm full width means:
  - +/-4.5mm if re-centered in magnet
  - Try $R_{aperture}$=10mm to give >5mm clearance
- Does not converge, fields 25% wrong

Reduce to $R_{aperture}$=7.5mm

- Magnets converge but come out giant



Field Overshoot at High Gradient

- The 5mm clearance distance translates to a larger field increase for higher gradients
  - E.g. at 250.9T/m it corresponds to 1.255T
    - Makes 2.107T max field into 3.272T at "pole tip"
  - At 125.5T/m it corresponds to 0.627T
    - Now only becomes 2.689T at pole tip
- Not exact but gives idea of magnet difficulty
  - Lower gradient can make magnet smaller even though good field aperture becomes larger

* not scaling FFA laws

FFA scaling* laws

Scaling type (by factor a)	Length	Angle	Dipole	Gradient	Quad offset (=dipole/grad) & orbit excursion
Momentum (~energy)	1	1	a	a	1
Machine radius	a	1	a^{-1}	a^{-2}	a
FFA beta length (fixed bend radius, fixed cell tune)	a	a	1	a^{-2}	a^2
FFA arc-to-straight (=row 3/row 2)	1	a	a	1	a
FFA radius with fixed orbit excursion and field (row 2*row 1/sqrt(row 3))	$a^{1/2}$	$a^{-1/2}$	1	1	1

This one is the knob for changing gradients and orbit range: an engineering trade-off

Lattice Scaled to 50% Gradient

- Original

Magnet	Dipole at x=0 (T)	Gradient (T/m)	Xmin (mm)	Xmax (mm)	B(Xmin) (T)	B(Xmax) (T)
BF	0.681	250.91	-5	4	-0.574	1.685
BD	0.941	-233.13	-5	4	2.107	0.008

- 50% gradient, 2x beam excursion

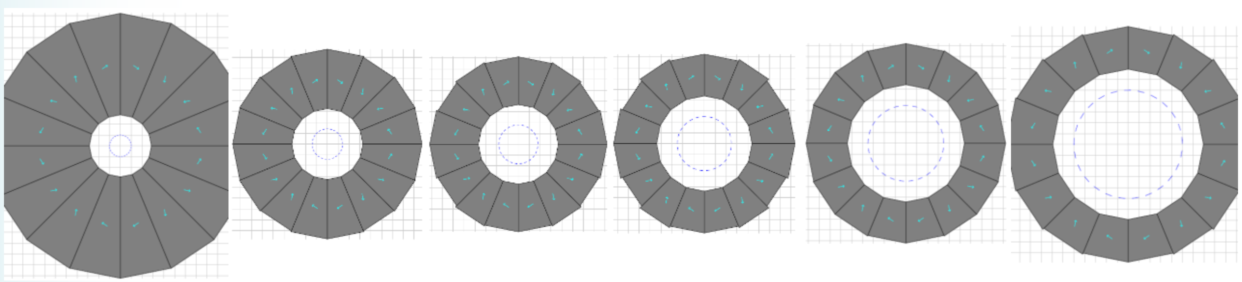
Magnet	Dipole at x=0 (T)	Gradient (T/m)	Xmin (mm)	Xmax (mm)	B(Xmin) (T)	B(Xmax) (T)
BF	0.681	125.46	-10	8	-0.574	1.685
BD	0.941	-116.57	-10	8	2.107	0.008

NB: length and bend angles of elements to be multiplied by sqrt(2)

Gradient Tradeoff Example

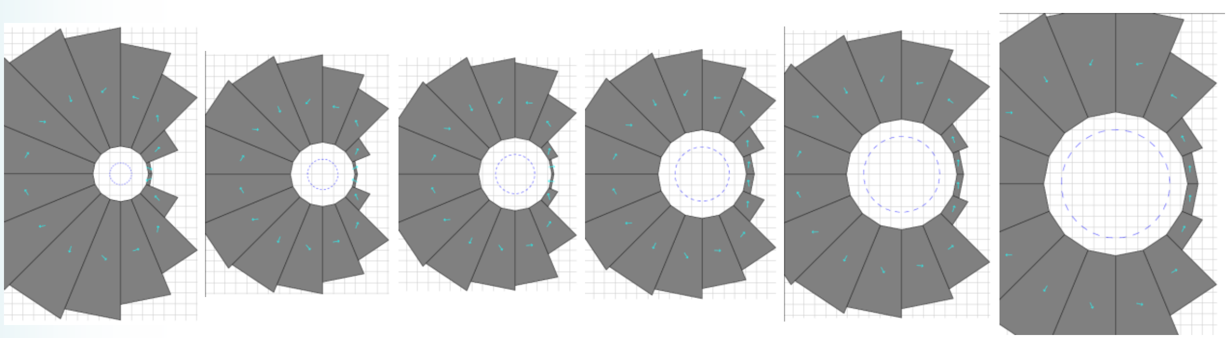
±10mm	±14mm	±18mm	±25mm	±35mm	±50mm
58T/m	41T/m	32T/m	23T/m	17T/m	12T/m

QF



(All using CBETA clearances)

BD



The gradient of the cell can be scaled, which results in orbits that are closer together but have the same magnetic field at each orbit. In other words, the dipole is constant but the gradient scales inversely with orbit separation.

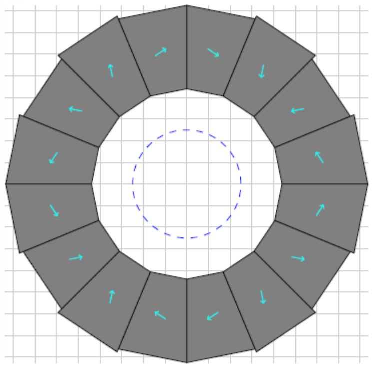
The clearance requirements create an area optimum.

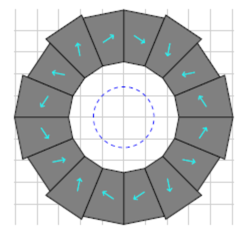
Clearance Tradeoff Example

CBETA clearances
~12+2+3mm
Beam-centroid-to-pipe, pipe, pipe-to-magnet

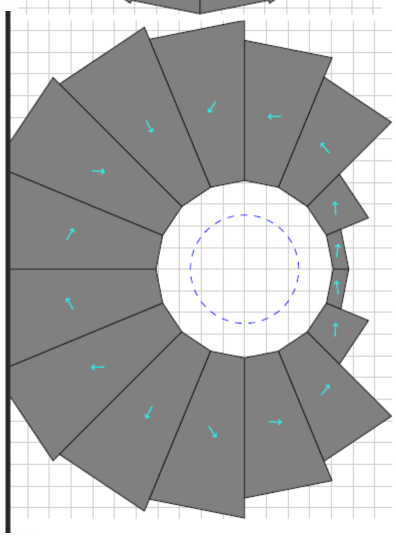
Reduced clearances
6+2+3mm
and re-optimise gradient

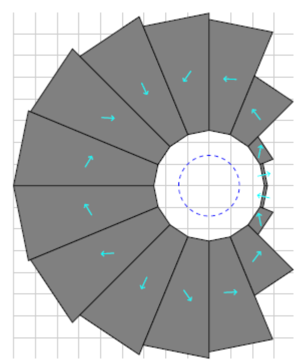
QF





BD

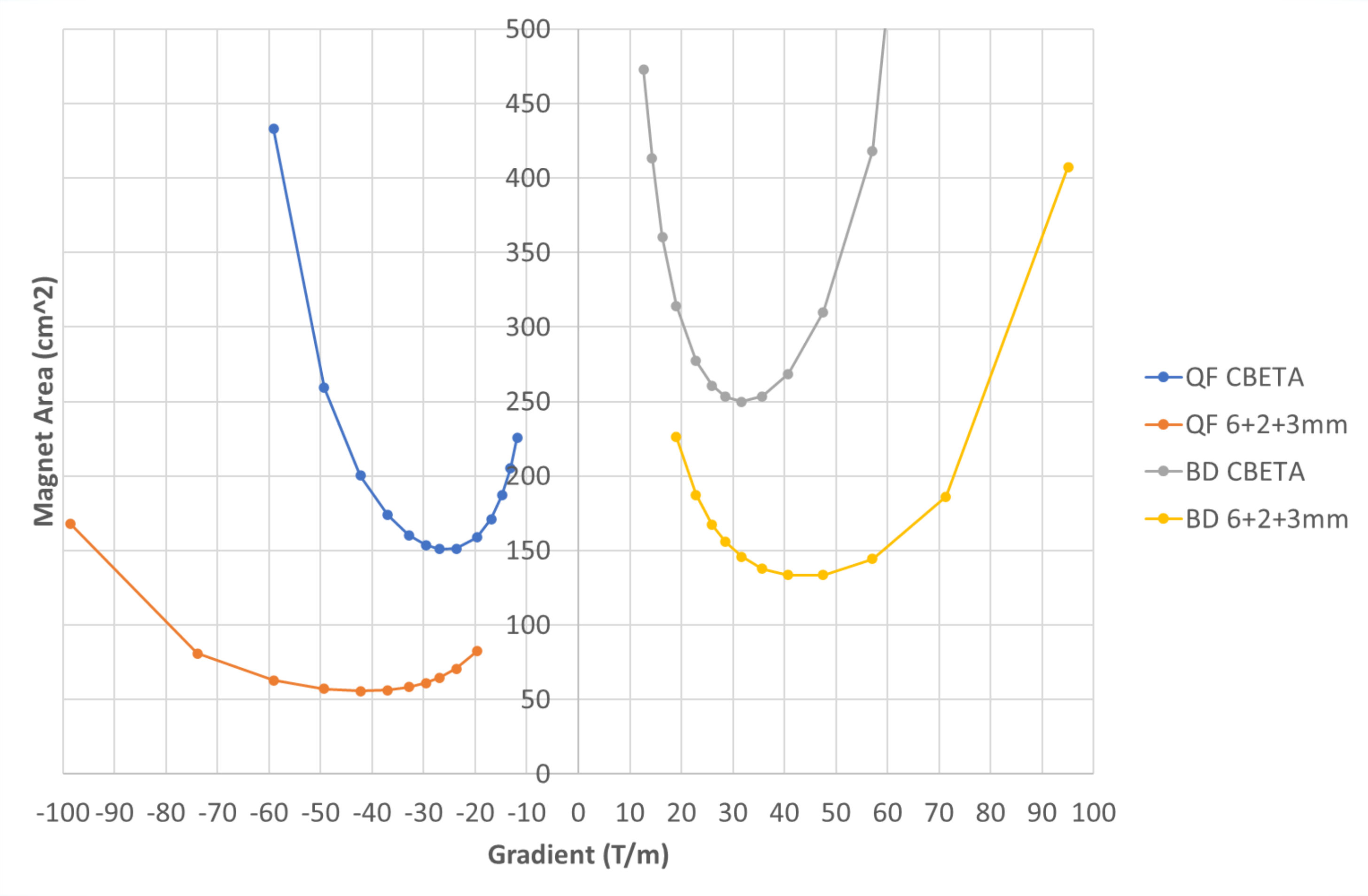




Smaller clearances allow even more efficient magnets by increasing the gradient to the new higher optimum.

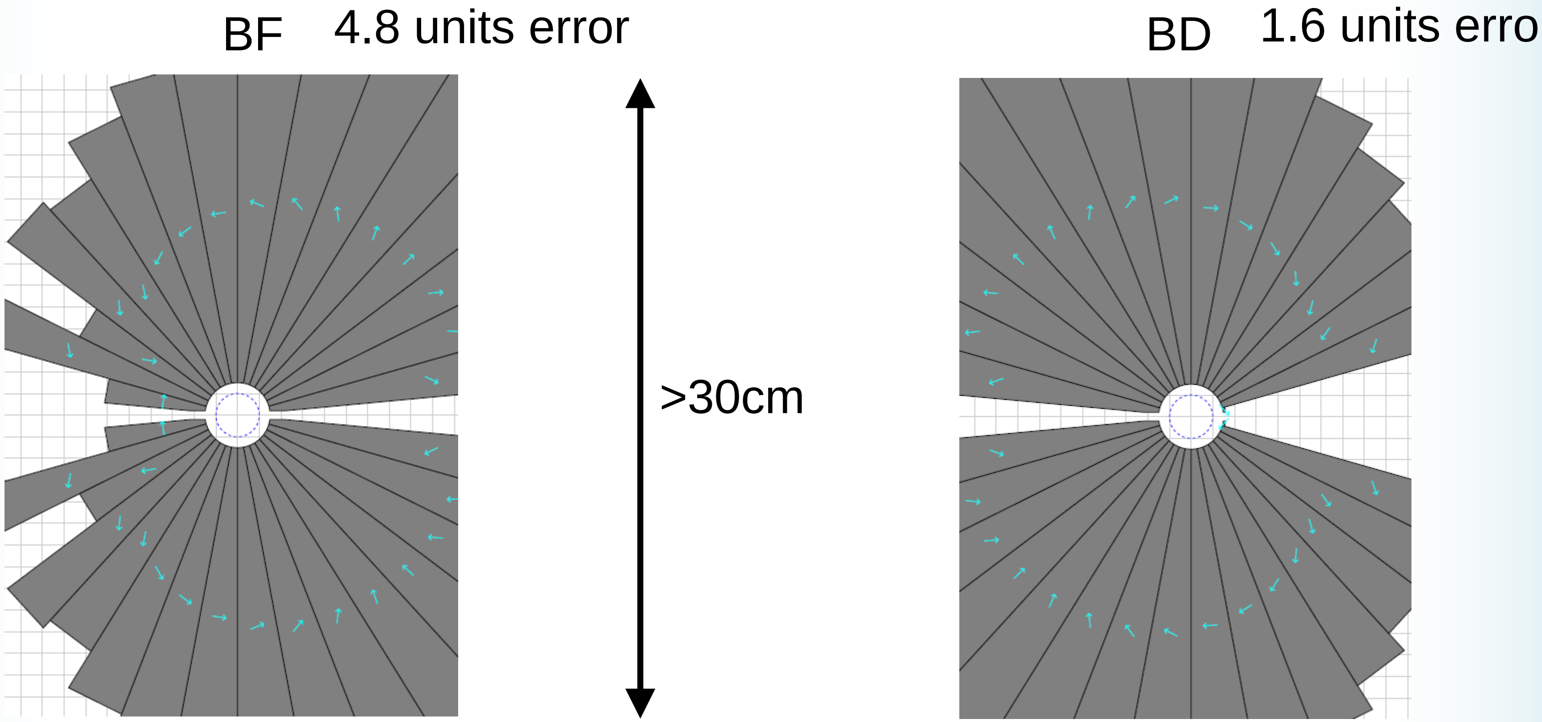
However, smaller clearances are harder to engineer and magnify relative errors from position misalignments.

Clearance vs. Gradient Example

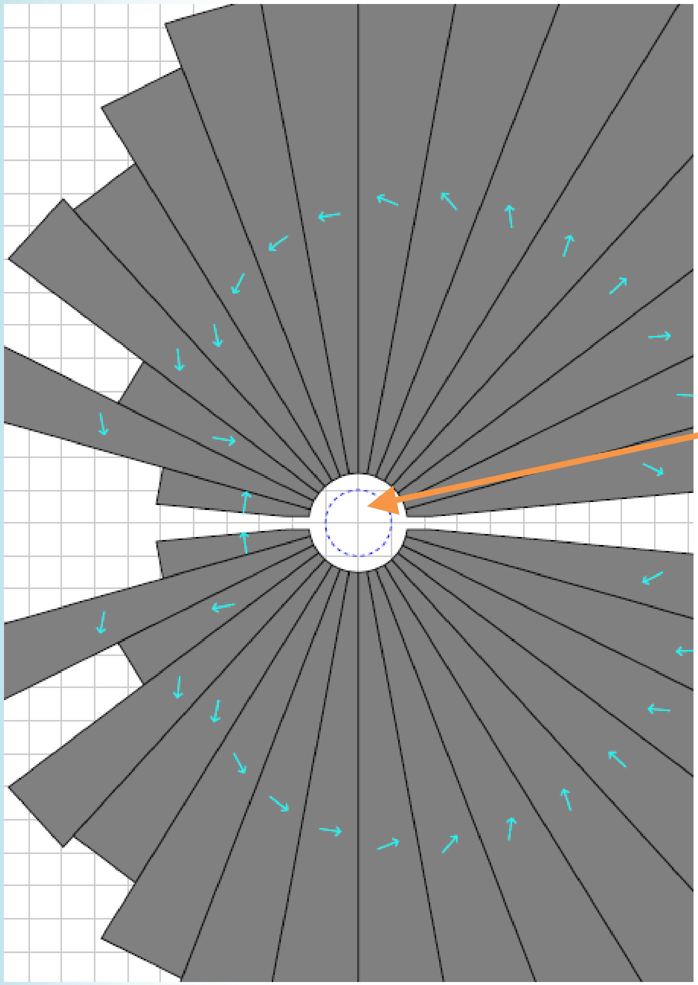


Using $R_{aperture}$=15mm (R_{field}=10mm)

- 50% gradient scaled magnet converges with the full 5mm clearance
  - But the magnets still come out giant!



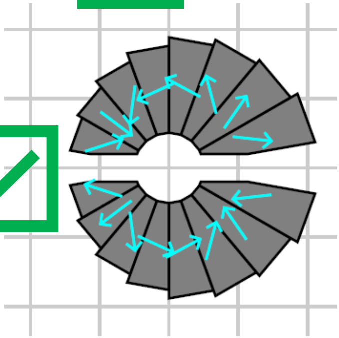
Need Some Ideas (idea #1)



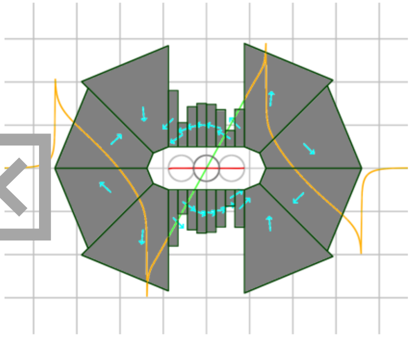
- Now that $R_{aperture}$=15mm…
- There's a lot of unused space above and below the beams
- Could use "oval aperture" idea from Dejan's hadron therapy gantry
  - While still having an open midplane

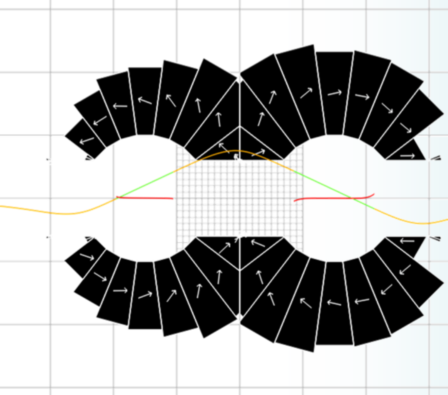
[IPAC'21] Halbach Magnet Variations

- Demonstrated (in accelerator)
  - Field tuning with iron rods
  - Combined-function magnets
- In development
  - Open midplane magnets



- Future research
  - Oval apertures
  - Multiple apertures



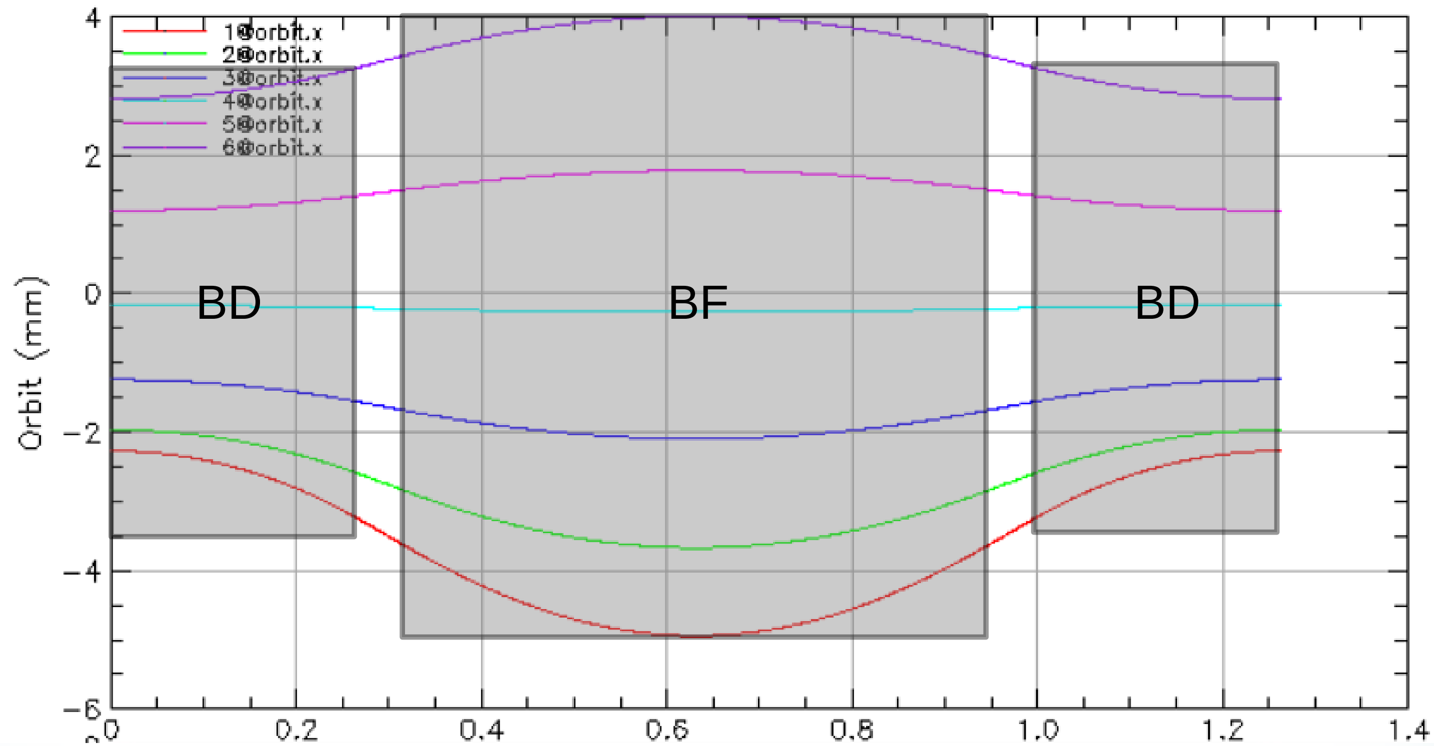


Unused Region in BD (idea #2)

From the orbit diagram it appears that while
the orbits in BF are -5mm < x < 4mm,
the orbits in BD are -3.5mm < x < 3.25mm.
Don't build magnet where you don't need it!

Element	Length [m]	Angle [°]	Dipole [T]	Gradient [T/m]
BF	0.625	0.5	0.681	250.91
O	0.05	0		
BD	0.5382	0.5	0.941	-233.13
O	0.05	0		

Table 1: Energy doubler FFA arc cell.



Trimming the BD Aperture Range

- 50% gradient, 2x beam excursion

Magnet	Dipole at x=0 (T)	Gradient (T/m)	Xmin (mm)	Xmax (mm)	B(Xmin) (T)	B(Xmax) (T)
BF	0.681	125.46	-10	8	-0.574	1.685
BD	0.941	-116.57	-10	8	2.107	0.008

- With reduced BD aperture range

Magnet	Dipole at x=0 (T)	Gradient (T/m)	Xmin (mm)	Xmax (mm)	B(Xmin) (T)	B(Xmax) (T)
BF	0.681	125.46	-10	8	-0.574	1.685
BD	0.941	-116.57	-7	6.5	1.757	0.183

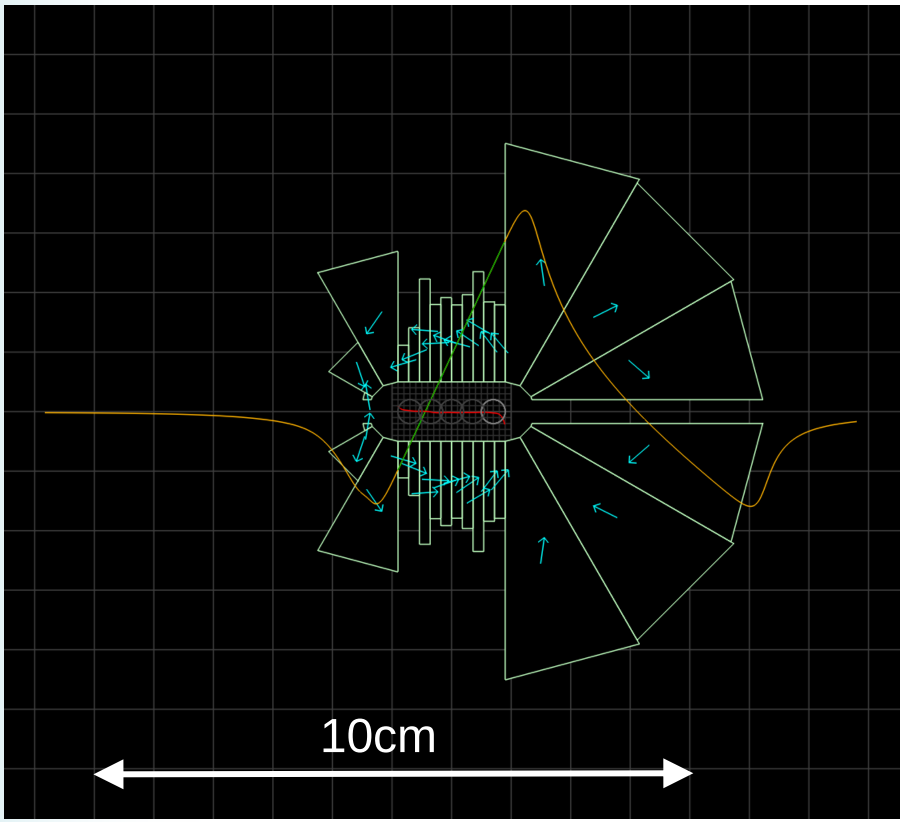
Peak fields better balanced between magnets (also minimises SR)

NB: length and bend angles of elements to be multiplied by sqrt(2)

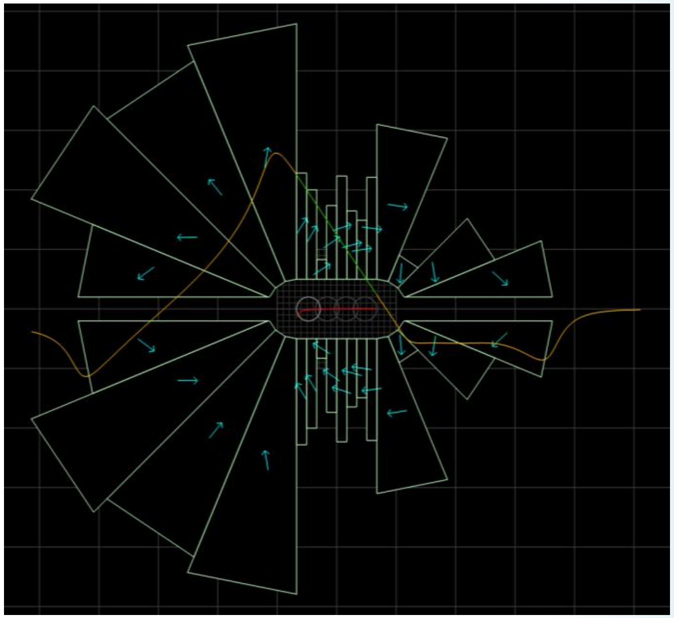
Finally!

- Small magnets, good field, full 5mm clearance

36.7cm^2 BF 27.8 units error

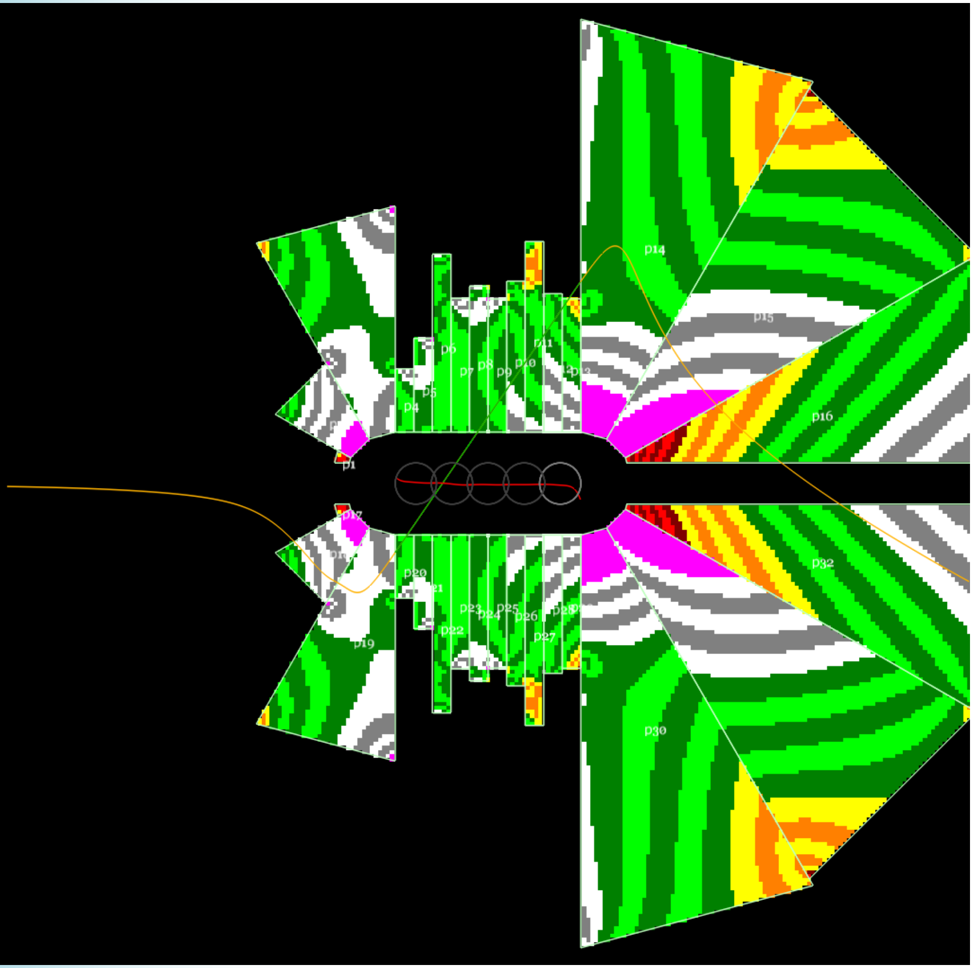


40.5cm^2 BD 24.1 units error

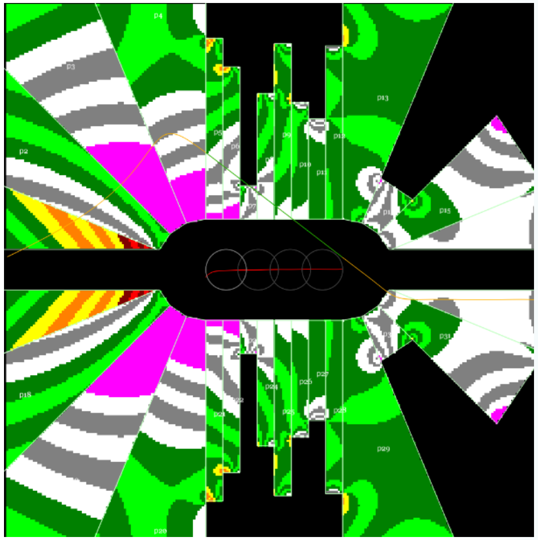


Demagnetisation?

BF



BD



Red areas show $\mu_0 H < -1.5T$, yellow $-1.5 < \mu_0 H < -1.0T$, etc. Stripes are 0.1T intervals.

Looks like worst reverse flux value is around -2.3T, knee is -2.7T, likely OK without radiation but not much margin.

B-H Curve and Demagnetisation

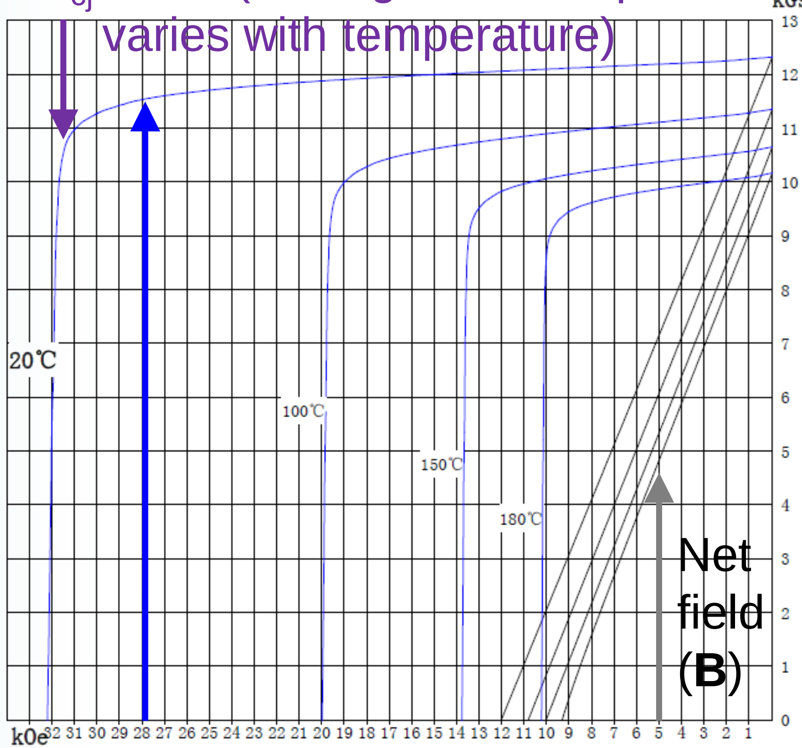
United Magnetics Co., Ltd

UMAG NIM-2000 HYSTERESIGRAPH TEST REPORT

CBETA material grade N35H

H_{cj} value (demagnetisation point, varies with temperature)

Magnetisation provided by material ($\mu_0\mathbf{M} = \mathbf{B} - \mu_0\mathbf{H}$)



External applied field ($\mu_0\mathbf{H}$) opposing magnetisation direction

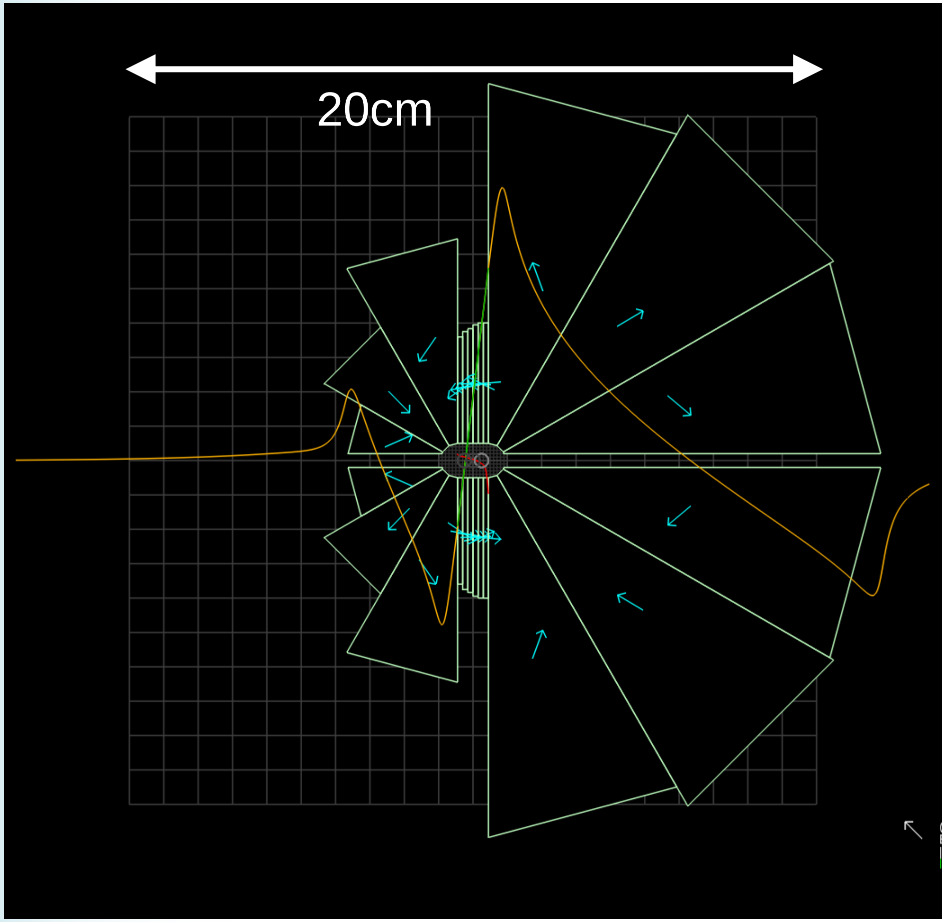
```
Spe. No.     : 005
Spe. Grade   : N35EH
Material     : NdFeB
Shape        : Cylinder
Size         : 10.00mm
Date         : 2013-9-22
Tester       : Alice
```

Temp ℃	Br kGs T	Hcb kOe kA/m	Hcj kOe kA/m	(BH)max MGsOe kJ/m^3	Hk kOe kA/m
20	12.33 1.233	12.07 960.4	32.25 2567	37.08 295.1	30.77 2449
100	11.36 1.136	10.87 864.7	20.03 1594	30.80 245.1	18.35 1460
150	10.66 1.066	10.07 801.2	13.81 1099	26.92 214.2	12.89 1026
180	10.18 1.018	9.356 744.6	10.27 817.2	24.42 194.3	9.739 775.1

Note: not N42EH, just example

Large opposing fields (negative **H** in the direction of **M**) can potentially demagnetise parts of the material in higher field magnets. Not observed or expected in CBETA (-H<1.3T). Depends on material grade H_{cj} value.

What about with 100% gradients?



- BF converges but is still rather large
- Probably should avoid super-high (>150T/m) gradients unless good reason
  - E.g. path length

Summary (IPAC'21 magnets)

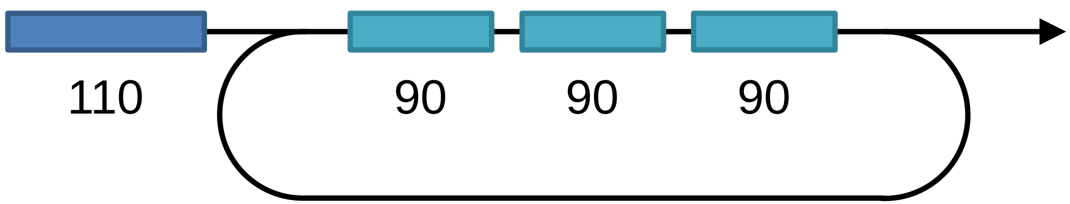
- Got a feasible magnet but had to employ several tricks:
  - Scaled lattice to 50% gradient (double orbit range)
  - Reduce circular aperture to vertically ±5mm oval
  - Trim BD good field range to cover only orbits
- Future work:
  - Is 50% (~120T/m) gradient the optimum?
  - Prediction of radiation dose limit (CBETA model)
- Are any design rules/assumptions wrong?

Existing 12GeV CEBAF Energies

Linac passes	Linac	Energy (MeV)	SR (MeV)	Line	E_Injector	E_Linac (MeV)	
0	injector	123.00	0.00	injector	123	1090	
1	North-1	1213.00	0.00	EM1E			
2	South-1	2303.00	0.04	EM1W			
3	North-2	3392.95	0.20	EM2E			
4	South-2	4482.76	0.61	EM2W			
5	North-3	5572.15	1.45	EM3E			
6	South-3	6660.70	2.95	EM3W			
7	North-4	7747.75	5.41	EM4E			
8	South-4	8832.34	9.13	EM4W			
9	North-5	9913.21	14.49	EM5E			
10	South-5	10988.71	21.88	EM5W	target (Halls A,B,C)		
11	North-6	12056.83		or target (Hall D)			
			Total				
			56.16777				

Upgraded CEBAF Injector Energy

- Avoid large energy ratios in linacs to >20GeV
- Three new RF modules of 90MeV each
  - Two passes through these with a single conventional return loop
- Use existing injector at 110MeV
- Total energy: 110+2*(3*90) = 650MeV



Energies with One FFA (4+7 turns)

Linac passes	Linac	Energy (MeV)	SR (MeV)	Line	E_Injector	E_Linac (MeV)		Low range:	Energy (M	SR (MeV)	E_Injector	E_Linac (MeV)		
0	injector	650.00	0.00	injector	650	1090			650.00	0.00	650	925		
1	North-1	1740.00	0.01	EM1E					1575.00	0.01		929.6626		
2	South-1	2829.99	0.10	EM1W					2499.99	0.06				
3	North-2	3919.89	0.35	EM2E					3424.93	0.21				
4	South-2	5009.54	0.95	EM2W					4349.73	0.54				
5	North-3	6098.59	2.08	EM3E					5274.19	1.16				
6	South-3	7186.51	4.00	EM3W					6198.03	2.21				
7	North-4	8272.51	7.03	EM4E					7120.81	3.86				
8	South-4	9355.48	11.50	EM4W					8041.95	6.28				
9	North-5	10433.99	59.33	FFA-1E					8960.68	45.36				
10	South-5	11464.66	67.26	FFA-1W					9840.32	54.00				
11	North-6	12487.40	72.91	FFA-2E					10711.32	61.68				
12	South-6	13504.49	75.93	FFA-2W					11574.64	67.98				
13	North-7	14518.57	76.55	FFA-3E					12431.66	72.65				
14	South-7	15532.02	75.35	FFA-3W					13284.02	75.48				
15	North-8	16546.67	73.48	FFA-4E					14133.53	76.57				
16	South-8	17563.19	72.80	FFA-4W					14981.96	76.17				
17	North-9	18580.39	75.89	FFA-5E					15830.79	74.80				
18	South-9	19594.50	86.04	FFA-5W					16680.99	73.28				
19	North-10	20598.47	107.42	FFA-6E					17532.71	72.78				
20	South-10	21581.04	143.72	FFA-6W					18384.93	74.84	Ratio			
21	North-11	22527.32	198.80	FFA-7E	or target (Hall D)				19235.10	81.48	2.51402	2.58427	for 8.9-23GeV FFA	
22	South-11	23418.52		target (Halls A,B,C)					20078.62					
			Total							Total				
			1211.476							921.3824				
	Half energ	11709.26												

Linacs adjusted 925-1090MeV for 50-100% energy tunability

Energies with Two FFAs (3+(4+4))

Linac passes	Linac	Energy (MeV)	SR (MeV)	Line	E_Injector	E_Linac (MeV)		Low range:	Energy (M	SR (MeV)	E_Injector	E_Linac (MeV)		
0	injector	650.00	0.00	injector	650	1090			650.00	0.00	650	925		
1	North-1	1740.00	0.01	EM1E					1575.00	0.01		929.6626		
2	South-1	2829.99	0.10	EM1W					2499.99	0.06				
3	North-2	3919.89	0.35	EM2E					3424.93	0.21				
4	South-2	5009.54	0.95	EM2W					4349.73	0.54				
5	North-3	6098.59	2.08	EM3E					5274.19	1.16				
6	South-3	7186.51	4.00	EM3W					6198.03	2.21				
7	North-4	8272.51	5.02	FFA1-1E					7120.81	4.28				
8	South-4	9357.49	5.70	FFA1-1W					8041.53	4.89				
9	North-5	10441.79	7.08	FFA1-2E					8961.64	5.42				
10	South-5	11524.71	10.51	FFA1-2W					9881.22	6.21				
11	North-6	12604.20	18.06	FFA1-3E					10800.02	7.91				
12	South-6	13676.14	32.61	FFA1-3W					11717.10	11.53				
13	North-7	14733.53	57.11	FFA1-4E					12630.58	18.35	Ratio FFA1			
14	South-7	15766.42	95.82	FFA1-4W					13537.22	30.20	2.214132	2.253521	for 7.1-16GeV	
15	North-8	16760.59	53.80	FFA2-1E					14432.02	42.31				
16	South-8	17796.80	61.90	FFA2-1W					15314.70	46.04				
17	North-9	18824.89	73.41	FFA2-2E					16193.66	50.39				
18	South-9	19841.48	90.13	FFA2-2W					17068.27	55.92				
19	North-10	20841.35	113.55	FFA2-3E					17937.35	63.24				
20	South-10	21817.80	145.47	FFA2-3W					18799.11	73.14	Ratio FFA2			
21	North-11	22762.33	186.76	FFA2-4E	or target (Hall D)				19650.96	86.54	1.57721	1.642857	for 14-23 GeV	
22	South-11	23665.56		target (Halls A,B,C)					20489.43					
			Total							Total				
			964.4367							510.5709				
	Half energ	11832.78												

Energies with Two FFAs (3+(5+3))

Linac passes	Linac	Energy (MeV)	SR (MeV)	Line	E_Injector	E_Linac (MeV)		Low range:	Energy (M	SR (MeV)	E_Injector	E_Linac (MeV)		
0	injector	650.00	0.00	injector	650	1090			650.00	0.00	650	925		
1	North-1	1740.00	0.01	EM1E					1575.00	0.01		929.6626		
2	South-1	2829.99	0.10	EM1W					2499.99	0.06				
3	North-2	3919.89	0.35	EM2E					3424.93	0.21				
4	South-2	5009.54	0.95	EM2W					4349.73	0.54				
5	North-3	6098.59	2.08	EM3E					5274.19	1.16				
6	South-3	7186.51	4.00	EM3W					6198.03	2.21				
7	North-4	8272.51	15.24	FFA1-1E					7120.81	12.04				
8	South-4	9347.27	17.33	FFA1-1W					8033.77	14.65				
9	North-5	10419.94	18.35	FFA1-2E					8944.13	16.66				
10	South-5	11491.59	18.63	FFA1-2W					9852.46	17.93				
11	North-6	12562.95	19.04	FFA1-3E					10759.53	18.49				
12	South-6	13633.91	21.16	FFA1-3W					11666.04	18.66				
13	North-7	14702.75	27.37	FFA1-4E					12572.38	19.05				
14	South-7	15765.38	40.98	FFA1-4W					13478.33	20.68				
15	North-8	16814.40	65.39	FFA1-5E					14382.65	24.90	Ratio FFA1			
16	South-8	17839.02	105.31	FFA1-5W					15282.75	33.58	2.505194	2.535211	for 7.1-18GeV	
17	North-9	18823.70	77.26	FFA2-1E					16174.17	56.46				
18	South-9	19836.45	90.88	FFA2-1W					17042.71	61.78				
19	North-10	20835.56	109.46	FFA2-2E					17905.94	68.34				
20	South-10	21816.10	134.44	FFA2-2W					18762.60	76.59	Ratio FFA2			
21	North-11	22771.66	166.95	FFA2-3E	or target (Hall D)				19611.01	87.40	1.407903	1.4375	for 16-23 GeV	
22	South-11	23694.70		target (Halls A,B,C)					20448.61					
			Total							Total				
			935.2956							551.3943				
	Half energ	11847.35												

Lattice Optimisation Rules

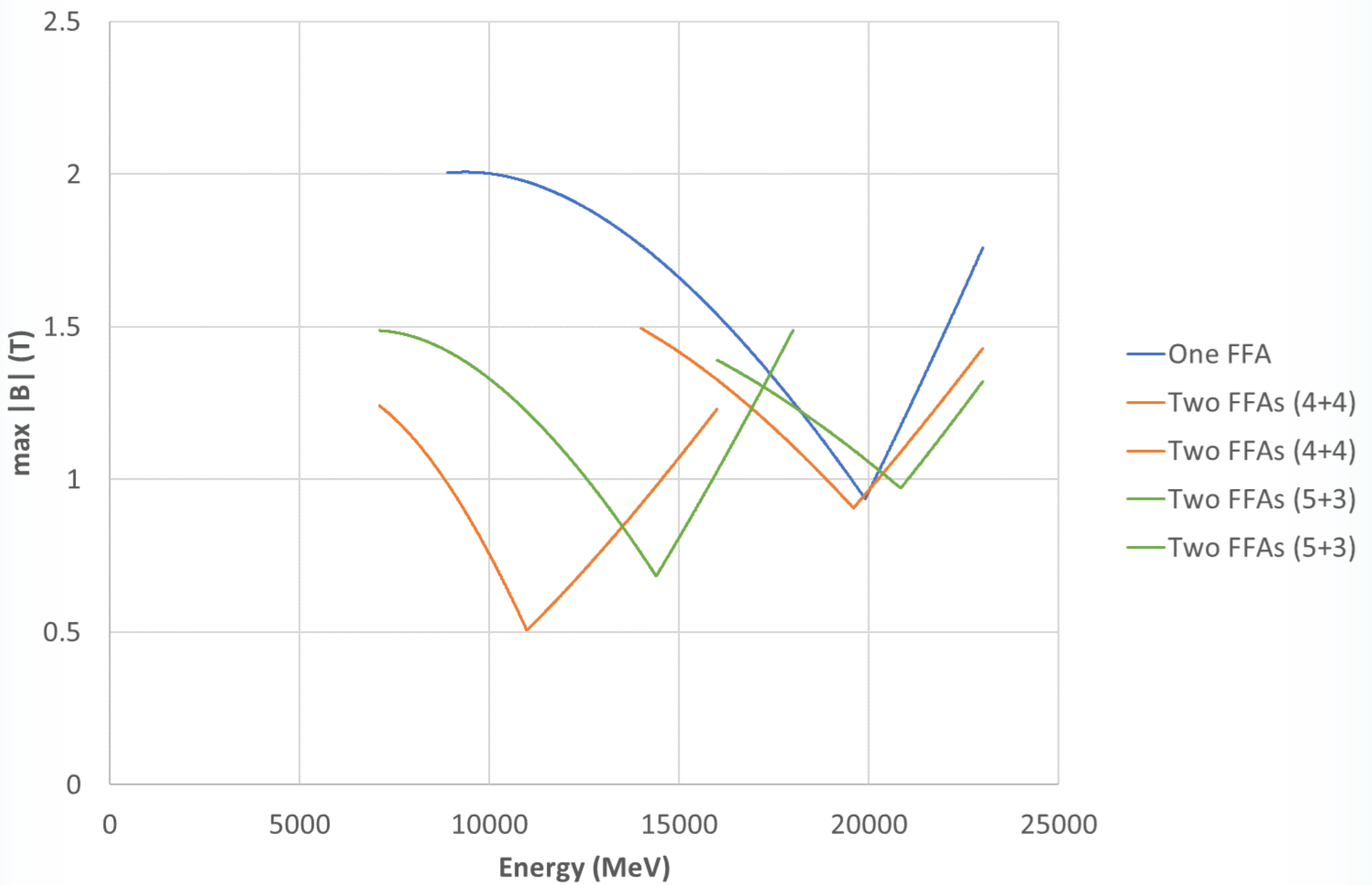
- Minimise maximum field on any beam orbit
- Cell angle = 2° clockwise (-2°)
- Overall radius of curvature = 80.6m
  - Ensures cell length of 2.81347m
- Both drifts are 10cm long
  - Packing factor 92.9%
- All cell tunes between 0.025-0.425, x,y planes
  - Wide range to compensate for energy adjustment

MAD-style Lattices

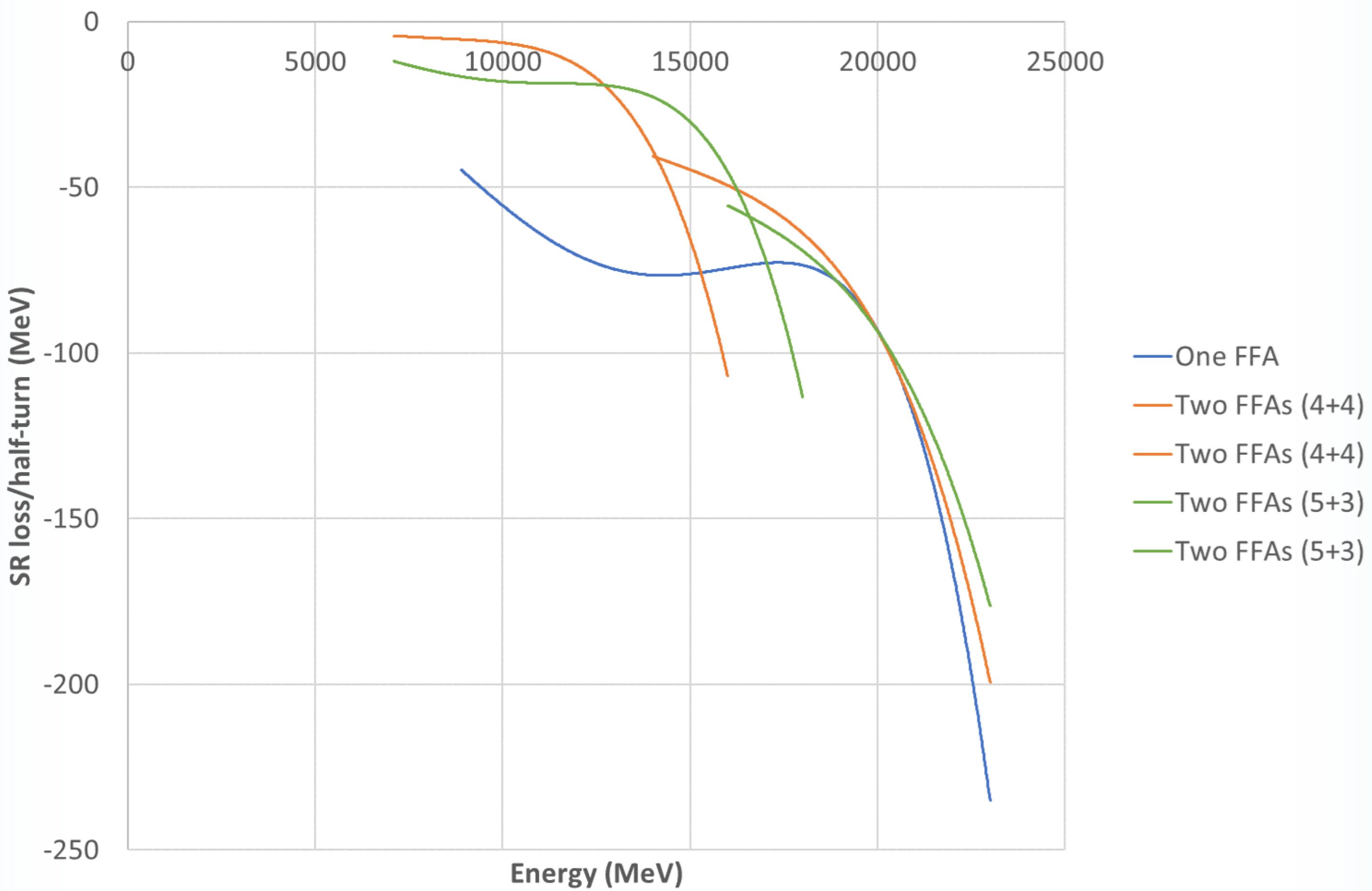
Parameter	One FFA	4+4 FFA1	4+4 FFA2	5+3 FFA1	5+3 FFA2	Units
Emin	8.9	7.1	14	7.1	16	GeV
Emax	23	16	23	18	23	GeV
Eref	15.95	11.55	18.5	12.55	19.5	GeV
BF length	1.36109	2.09794	1.68482	1.57127	1.49155	m
BF angle	-0.05722	-1.73802	-1.14623	-0.65227	-0.98835	degrees
BF quad	-48.649	-29.730	-65.616	-35.135	-80.781	T/m
BD length	1.25238	0.51553	0.92865	1.04220	1.12192	m
BD angle	-1.94278	-0.26198	-0.85377	-1.34773	-1.01165	degrees
BD quad	43.393	93.393	86.787	42.943	76.276	T/m

- Dipoles calculated from length, angle and Eref

Max Field on Beams



SR Loss Per Half-Turn

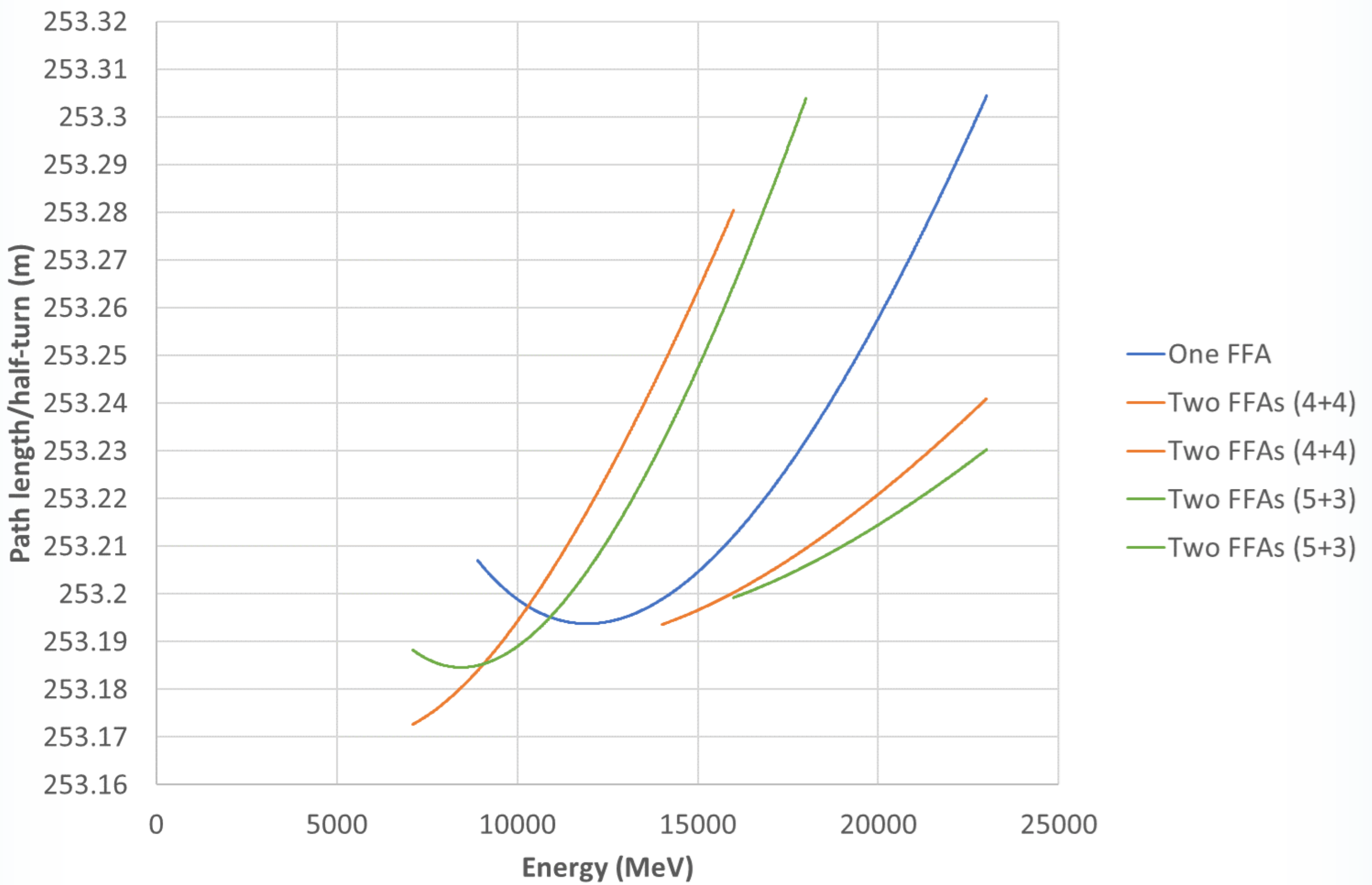


Performance Comparison

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

- Two FFAs should be considerably better from magnet point of view, particularly radiation hardness due to the decreased fields

Path Length



253.32
253.31
253.3
253.29
253.28
253.27
253.26
253.25
253.24
253.23
253.22
253.21
253.2
253.19
253.18
253.17
253.16
Path length/half-turn (m)
0
5000
10000
15000
20000
25000
Energy (MeV)
One FFA
Two FFAs (4+4)
Two FFAs (4+4)
Two FFAs (5+3)
Two FFAs (5+3)

Orbit Excursion

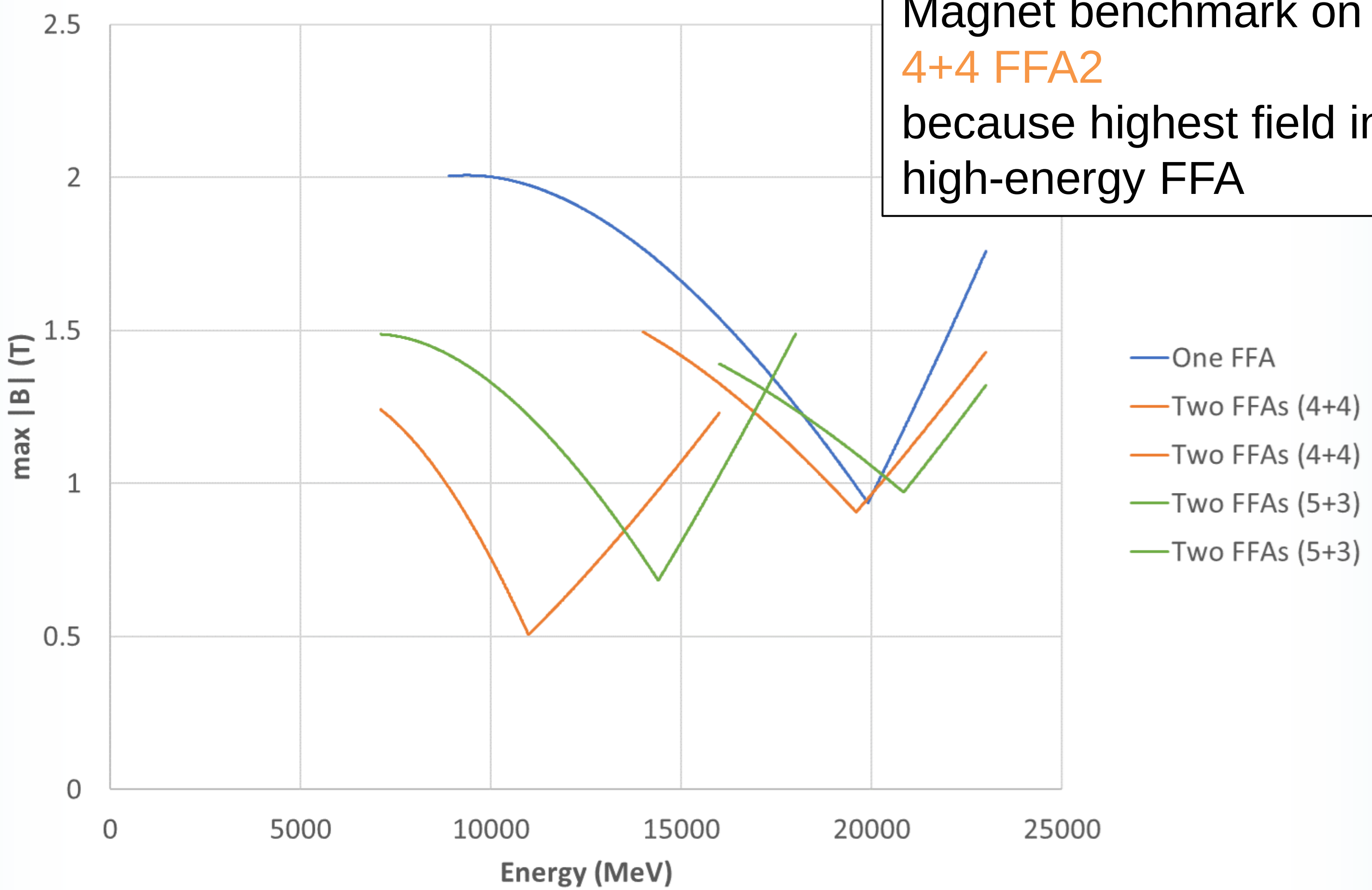
Lattice	Orbit range in BF (mm)	Orbit range in BD (mm)
One FFA	56.74	41.57
4+4 FFA1	42.61	27.89
4+4 FFA2	21.34	14.05
5+3 FFA1	54.79	39.07
5+3 FFA2	14.95	10.66

- Values given are full ranges (xmax-xmin)
  - CBETA would be 50mm in focussing magnet
- Generally the low energy FFA has a CBETA-like orbit excursion and FFA2 is much smaller
  - Could go below 2°/cell in FFA1 to reduce range

Summary (one vs. two FFAs)

- Using two FFAs reduced maximum field on beam from ~2.0T to 1.5T
  - Should lead to a substantial improvement in permanent magnet practicality
- Two FFA design has 22% less synchrotron radiation power loss than one FFA
- New lattices are baseline as of July 30th 2021
  - "5+3" is marginally better than "4+4"

Max Field on Beams

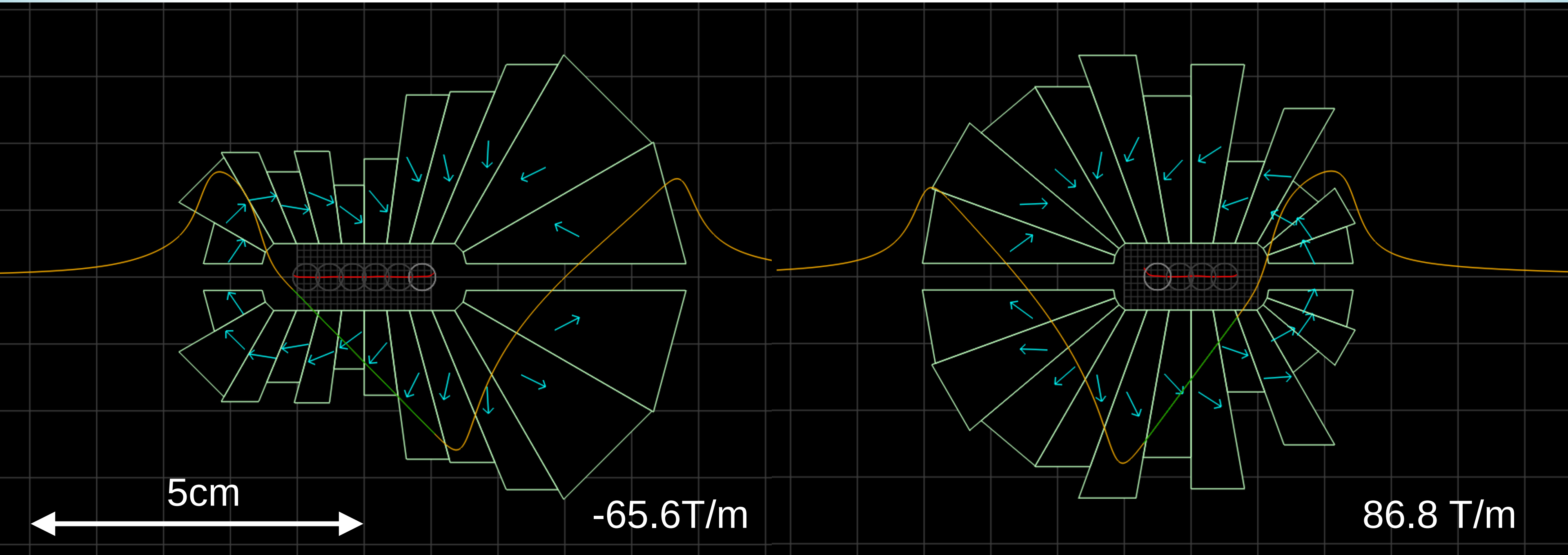


Magnet benchmark on
4+4 FFA2
because highest field in
high-energy FFA

Magnets for July 30th 4+4 FFA2

- Wanted to replace central rectangular pieces with wedges to avoid slipping
  - Reduce 32 to 24 pieces per magnet (CBETA=16)

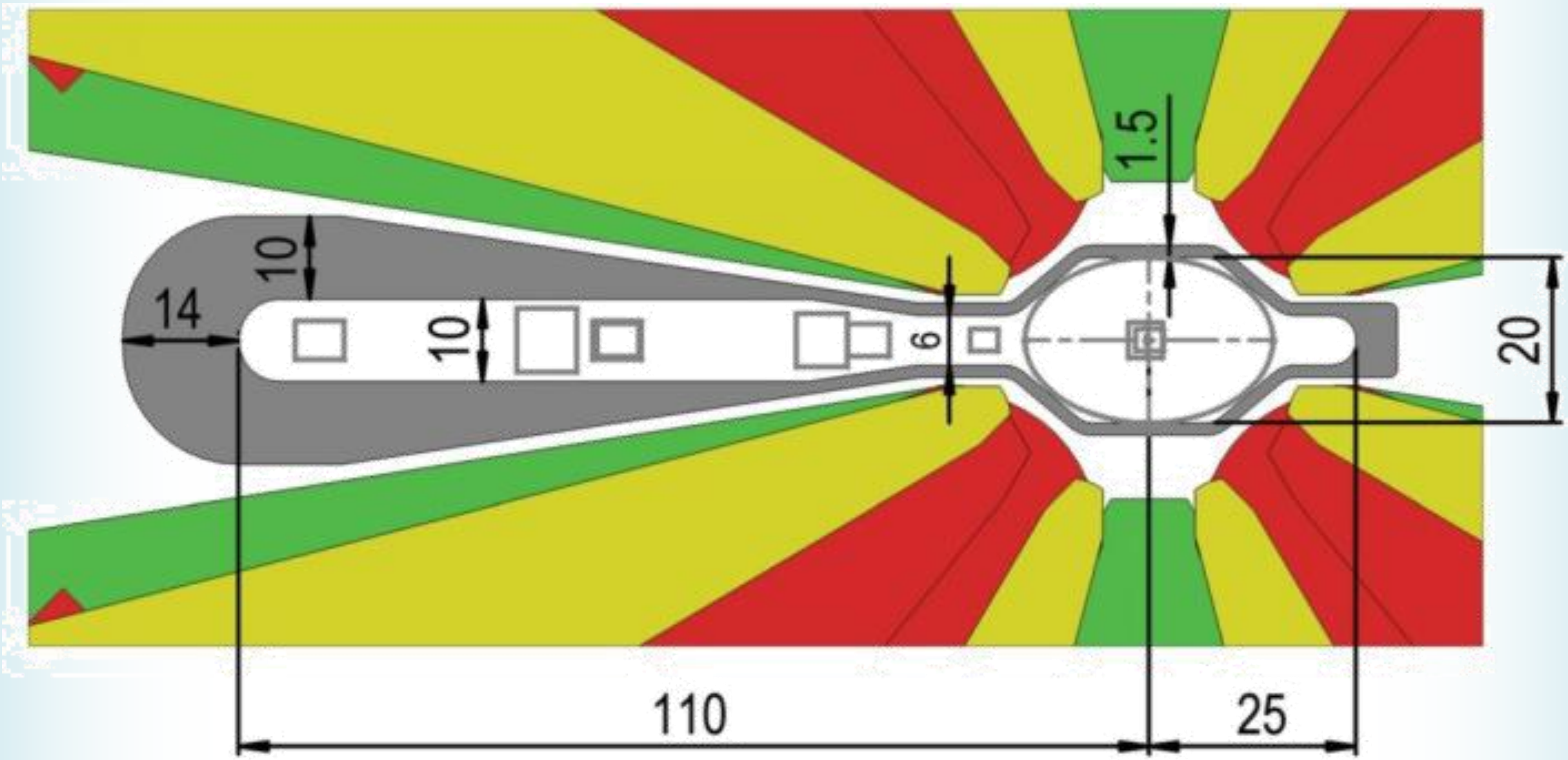
~25% less area than IPAC'21 magnets	CBETA magnets were from 38cm^2 to 78cm^2
27.8cm^2 BF 27.1 units error	27.4cm^2 BD 25.8 units error



Try Larger Clearances

- NSLS-IIU recently doubled their exit slot height from 4mm to 8mm (y=±4mm)
  - Allows vacuum chamber inside magnet
- Could try doing the same
  - Also double beam-to-magnet clearance from 5mm to 10mm (for 20mm full height central aperture)
- Rescale gradients on July 30th lattice to 50% to avoid field overshoot in larger clearance gap

ESRF Upgrade Chamber ~9mm Slot



Layout of the Vacuum System for a New ESRF Storage Ring,
M. Hahn et al., Proc. IPAC'14

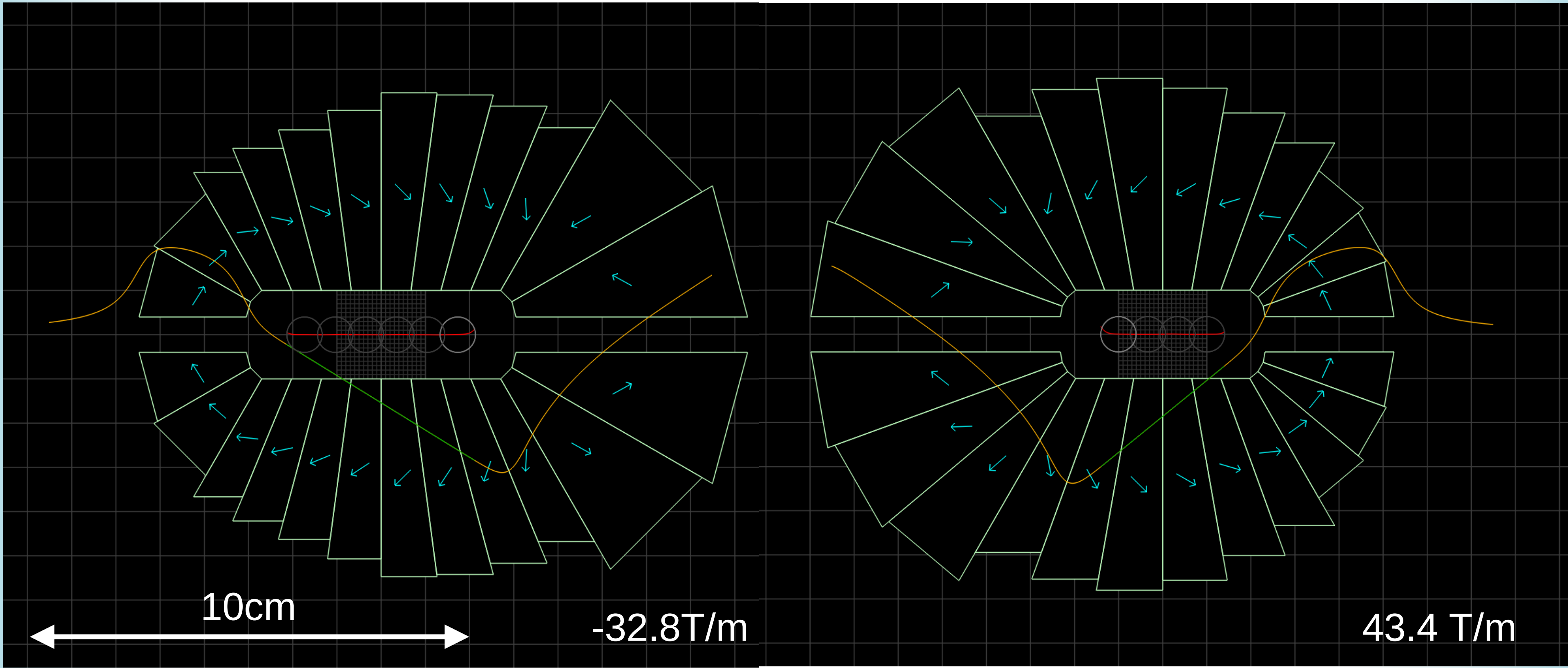
Magnets: 4+4 FFA2, 50% gradient

- Should be very similar, but 2x the size and 4x the area

CBETA magnets were from 38cm^2 to 78cm^2

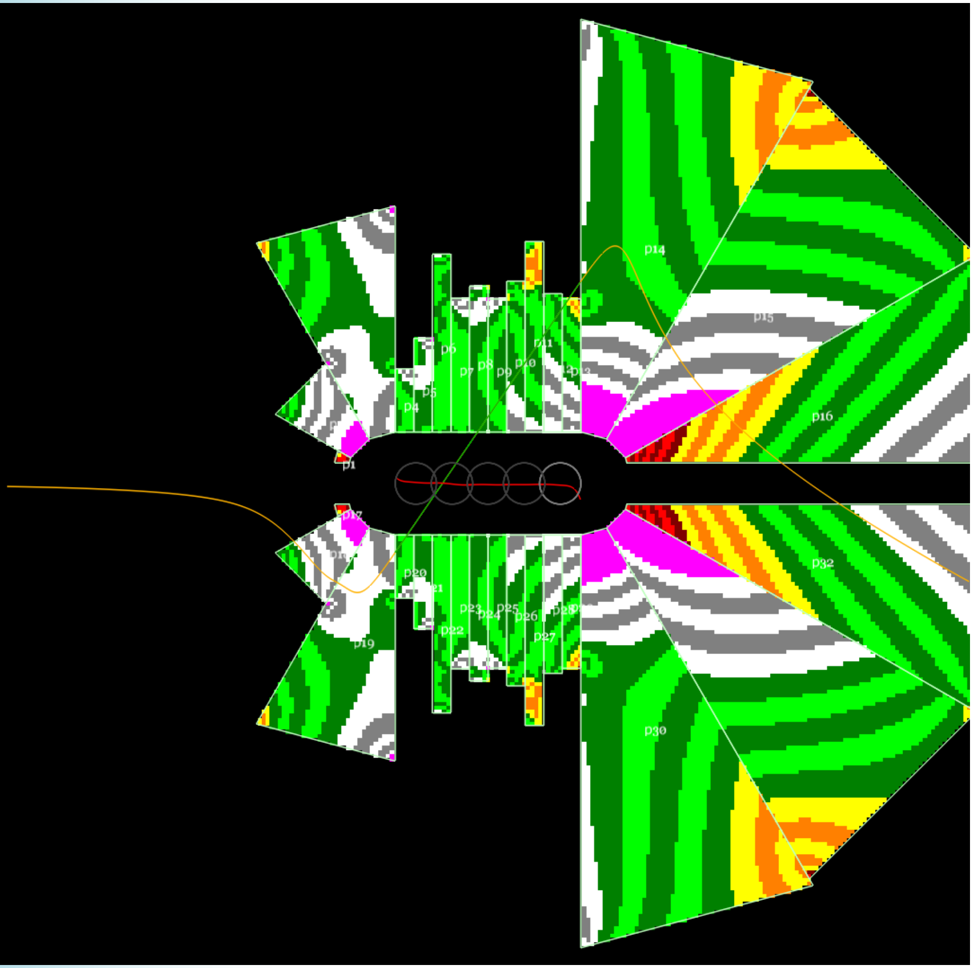
100.4cm^2 BF 32.5 units error

105.8cm^2 BD 27.1 units error

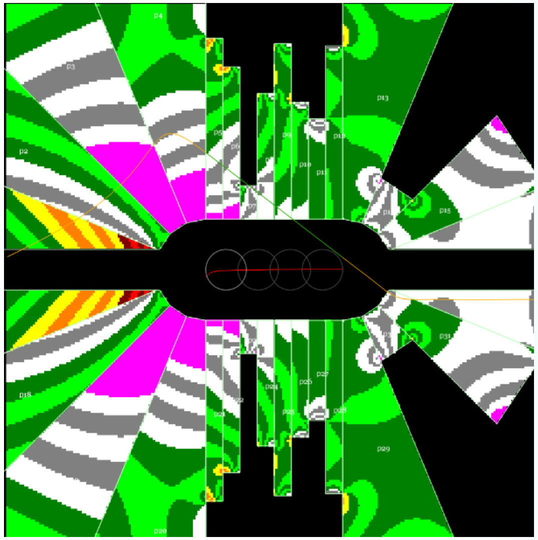


Demagnetisation in IPAC'21 magnets

BF



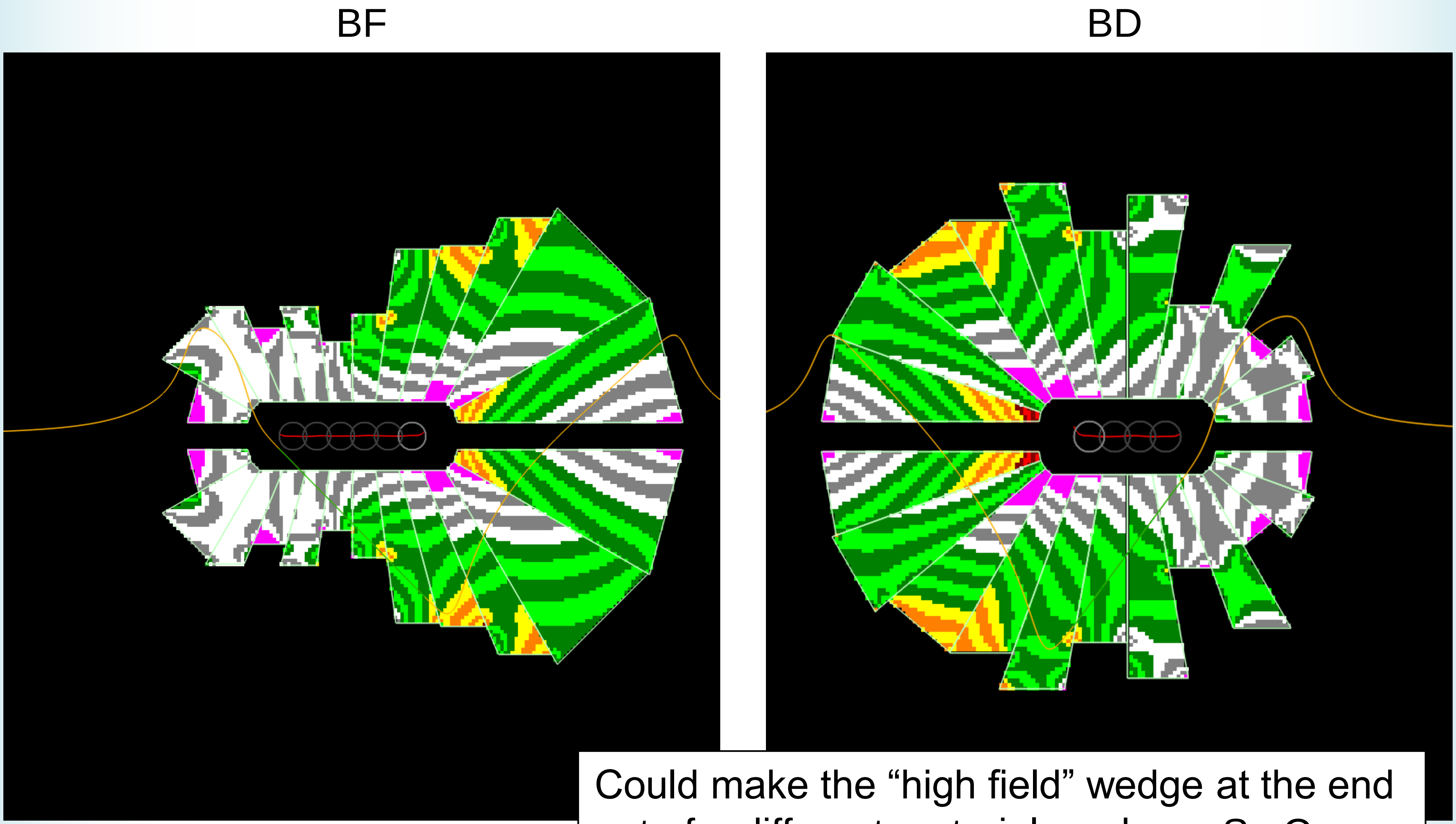
BD



Red areas show $\mu_0 H < -1.5T$, yellow $-1.5 < \mu_0 H < -1.0T$, etc. Stripes are 0.1T intervals.

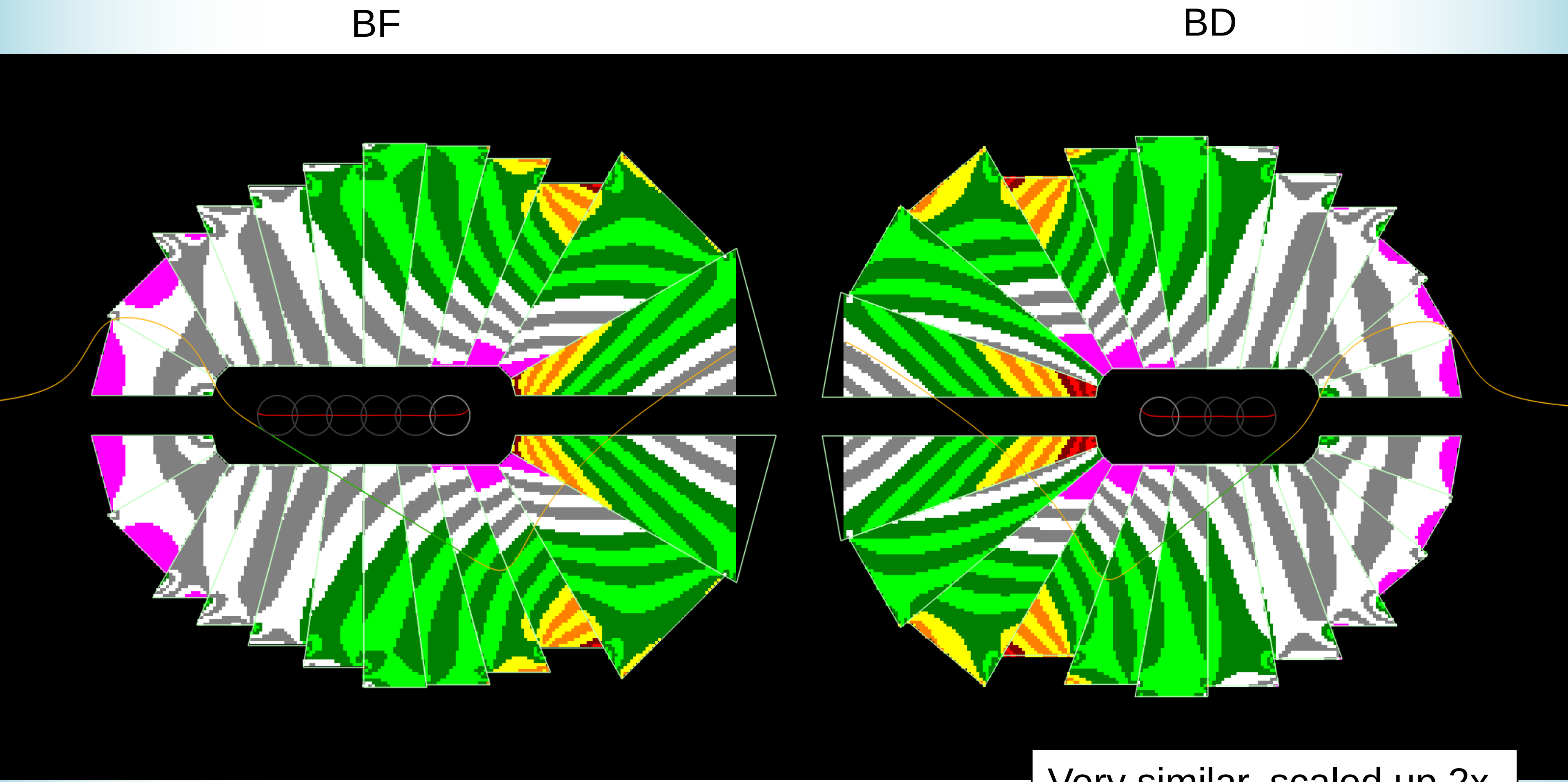
Looks like worst reverse flux value is around -2.3T, knee is -2.7T, likely OK without radiation but not much margin.

Demagnetisation in new magnets



Could make the “high field” wedge at the end out of a different material grade, or SmCo

50% gradient / large clearance

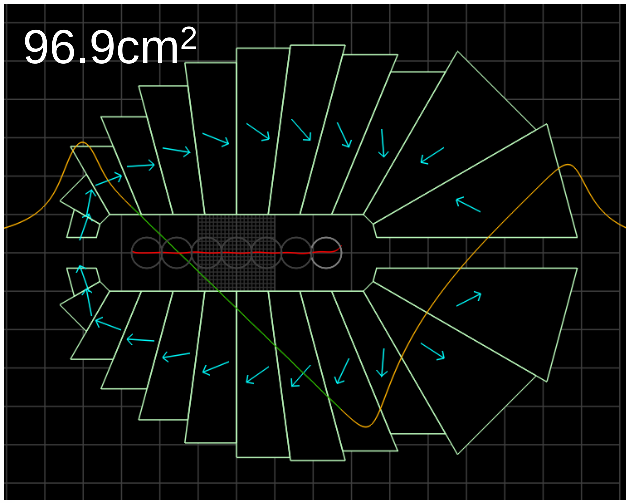


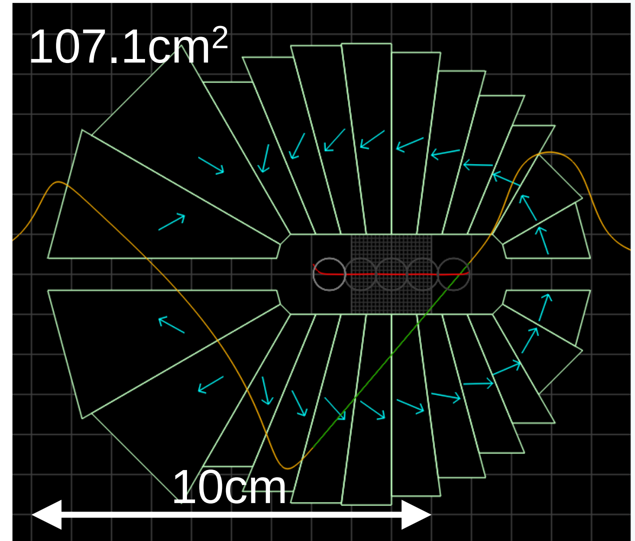
Very similar, scaled up 2x

All Magnets for 5+3 FFA1 and FFA2

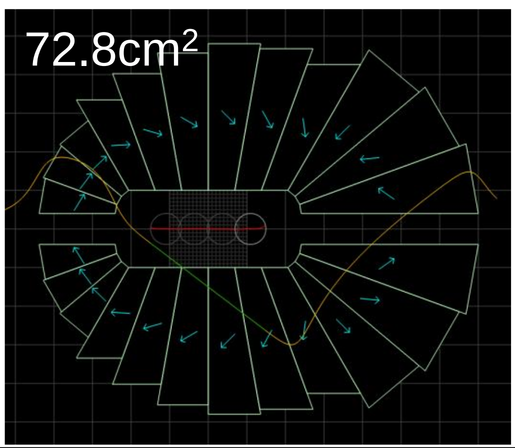
BF BD

FFA1

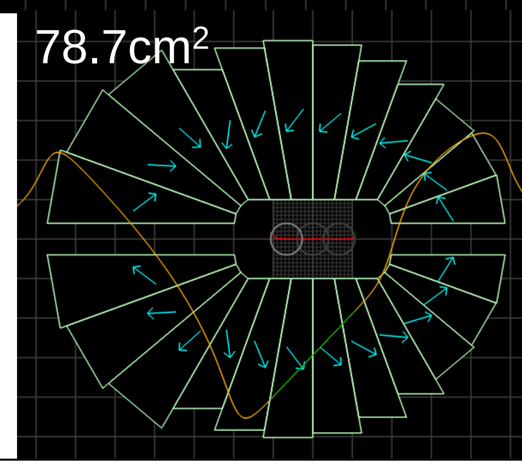




FFA2



All gradients between 35T/m and 43T/m



FFA2 magnets scaled to 50% gradient, FFA1 at 100% (aperture already large)

Summary (updated magnets)

- Reduced peak field allows larger apertures
  - Easier to fit vacuum chamber and beam through
    - The 10mm-to-magnet should give 7-8mm to pipe
- What height should the synchrotron radiation slot be?
  - E.g. 8mm full height minus both sides of chamber
  - When known, can optimise lattice gradient
    - Scaling law independent of maximum field, SR etc.
- LDRD funding from Oct 2021 → prototypes