# Vertical Orbit Excursion FFAGs and Other Things

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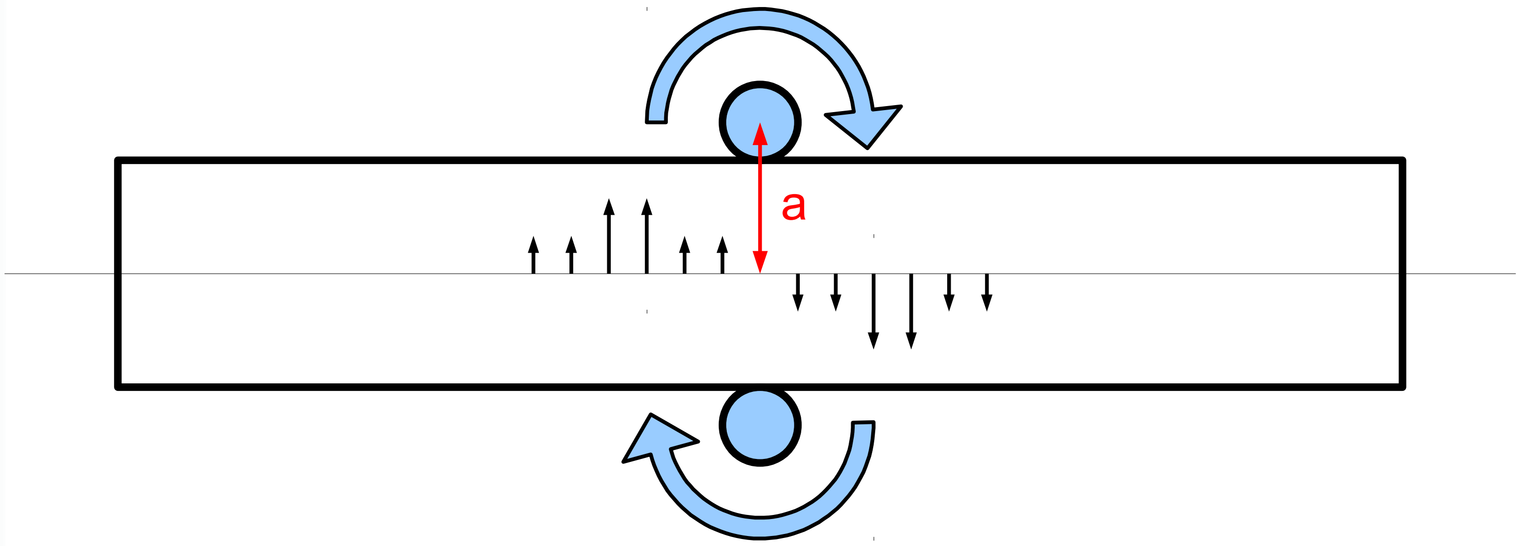
FFAG'11 workshop, Trinity College, Oxford, September 2011

# Horizontal SC magnet problem

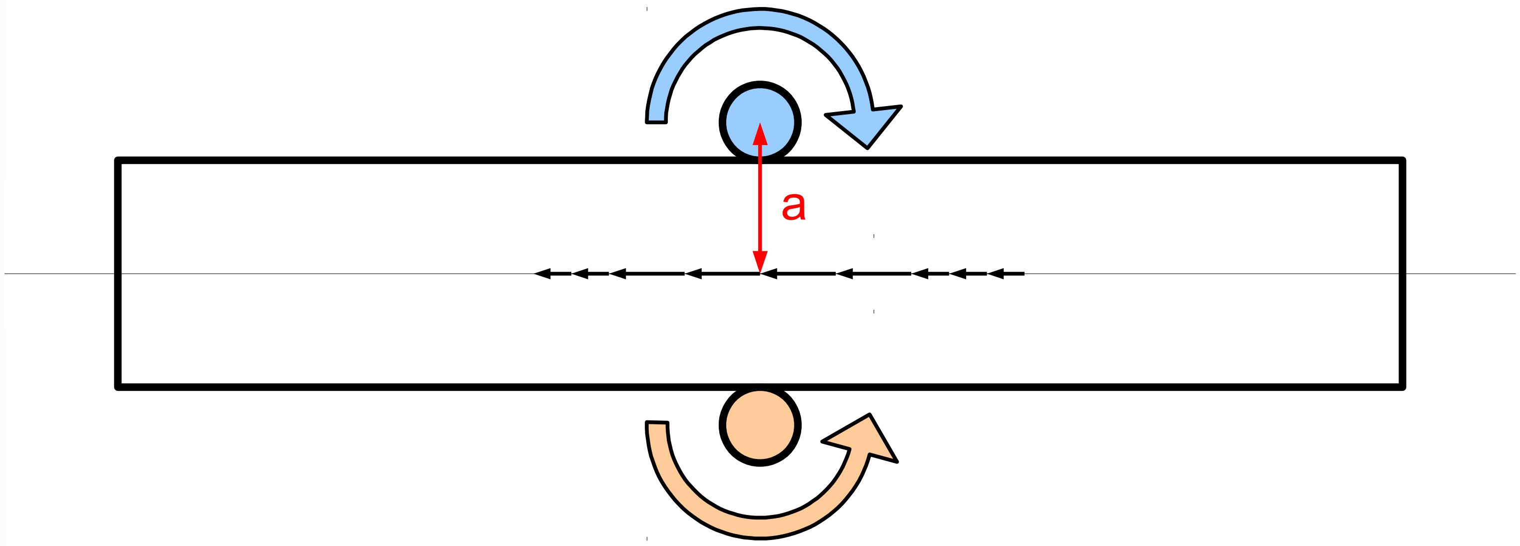
- Getting vertical B field requires same-direction current windings (nearby)




- By proportional to x/(a^2+x^2)

# Horizontal SC magnet variation

- Getting horizontal B field requires opposite current windings and is easier




- Bx proportional to a/(a^2+x^2)

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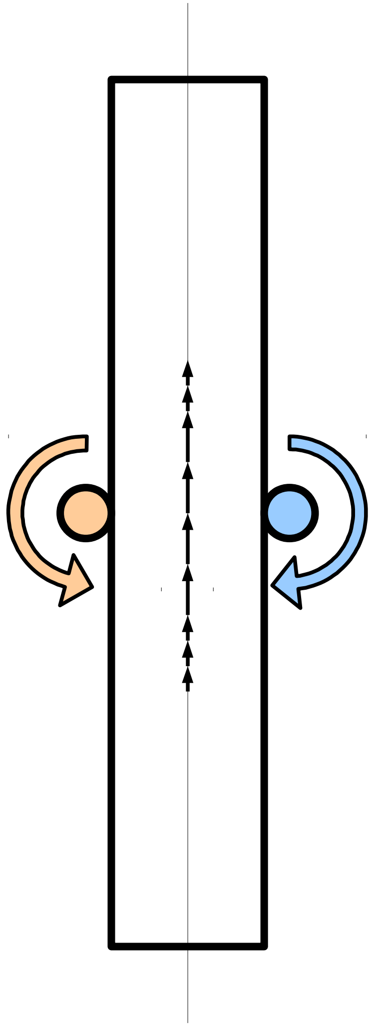
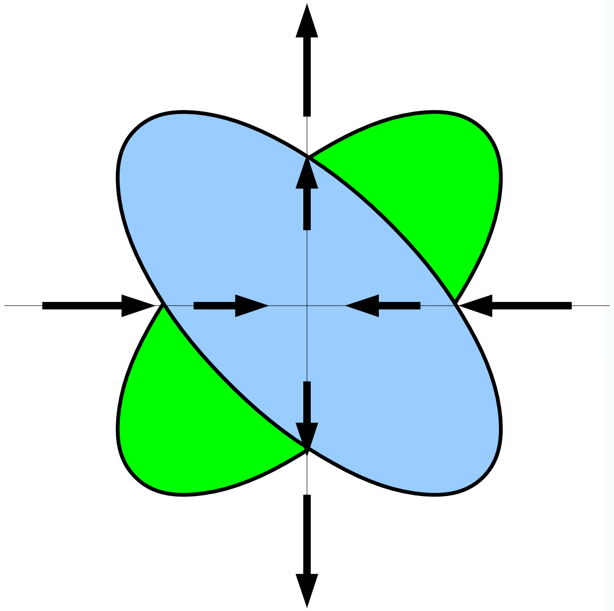
# Vertical SC magnet

- But now the field is in the wrong direction!
- That's OK, rotate the magnet
- The dipole field is there
- But what sort of focussing does this magnet give?



# “Scaling” VFFAG magnet

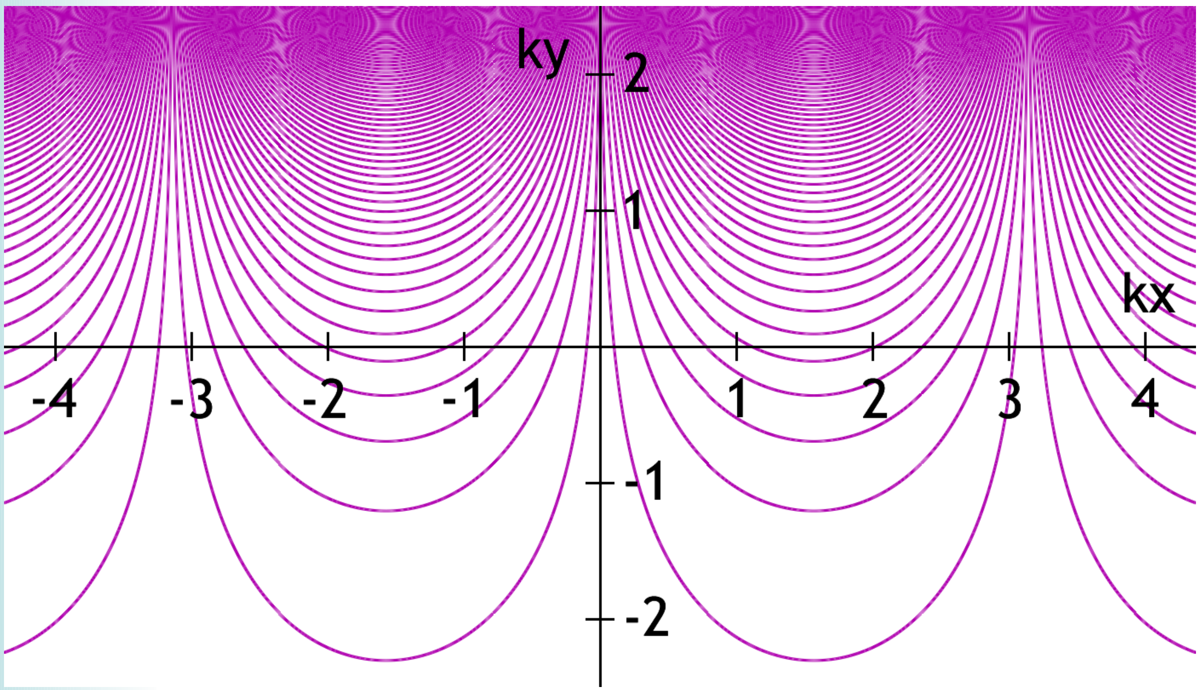
- Dipole field should increase moving up the magnet, so set By=exp(ky) on axis (x=0)
- Subtracting dipole component leaves the field of a skew quad:

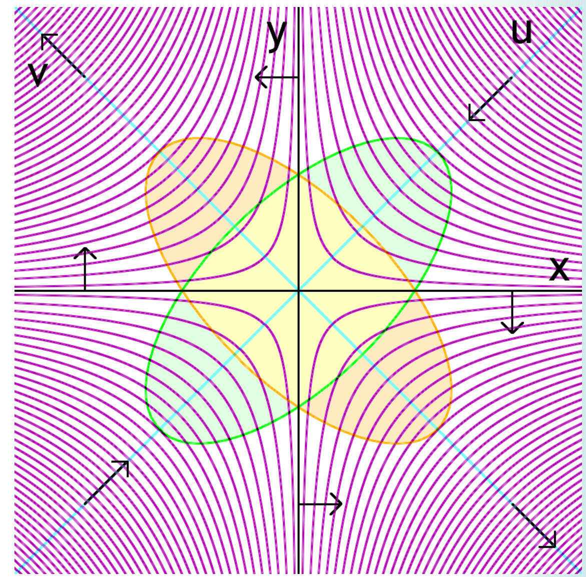


• Exponential is good because moving upwards just scales the field and all gradients
• Thus closed orbits at different momenta are exactly the same shape, just translated upwards
• VFFAG = Vertical orbit excursion FFAG

# Scaling VFFAG Field Formula

$$B_y = B_0 e^{ky} \cos kx \qquad B_x = -B_0 e^{ky} \sin kx$$

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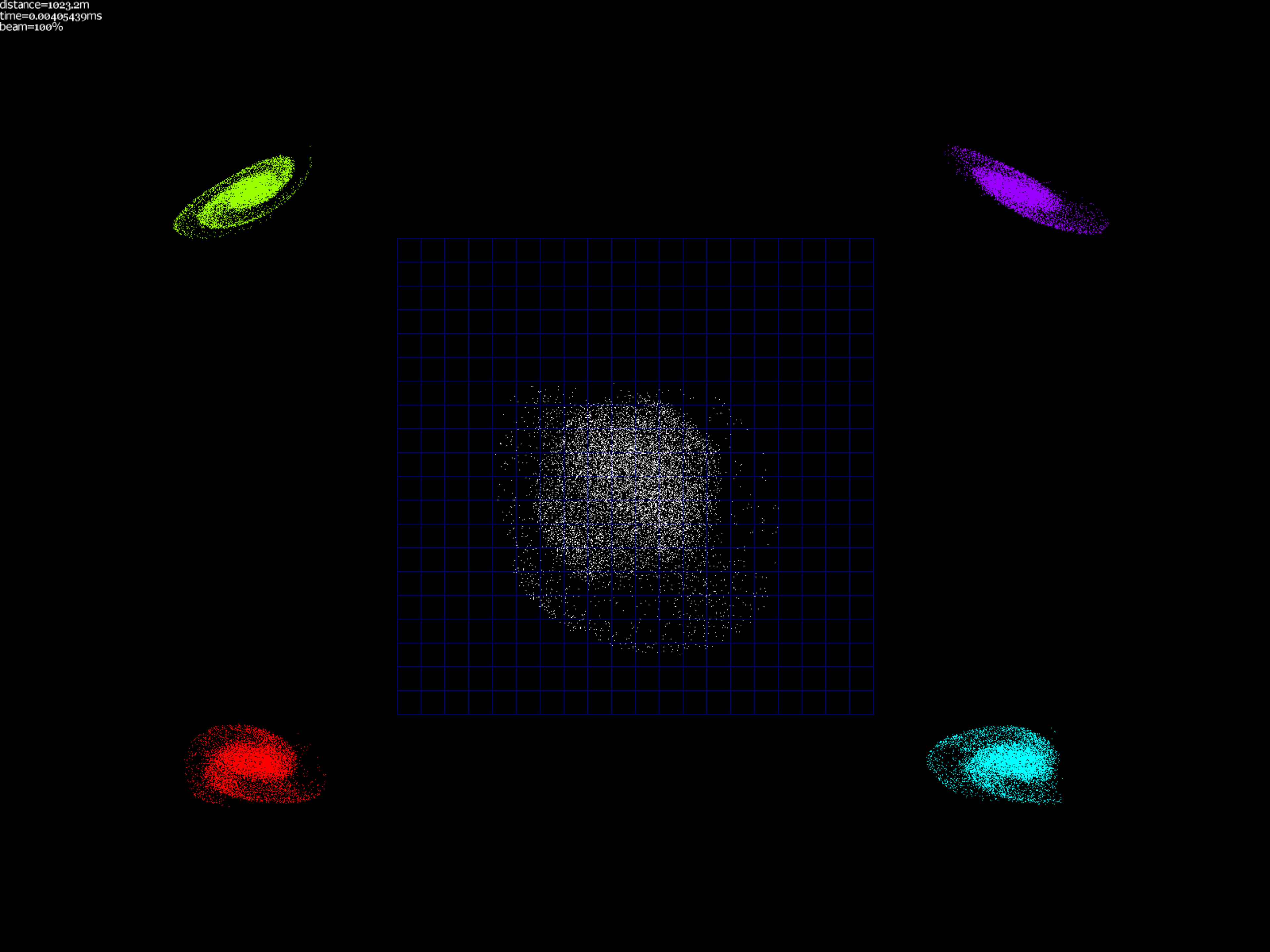
# FODO Scaling VFFAG Machine

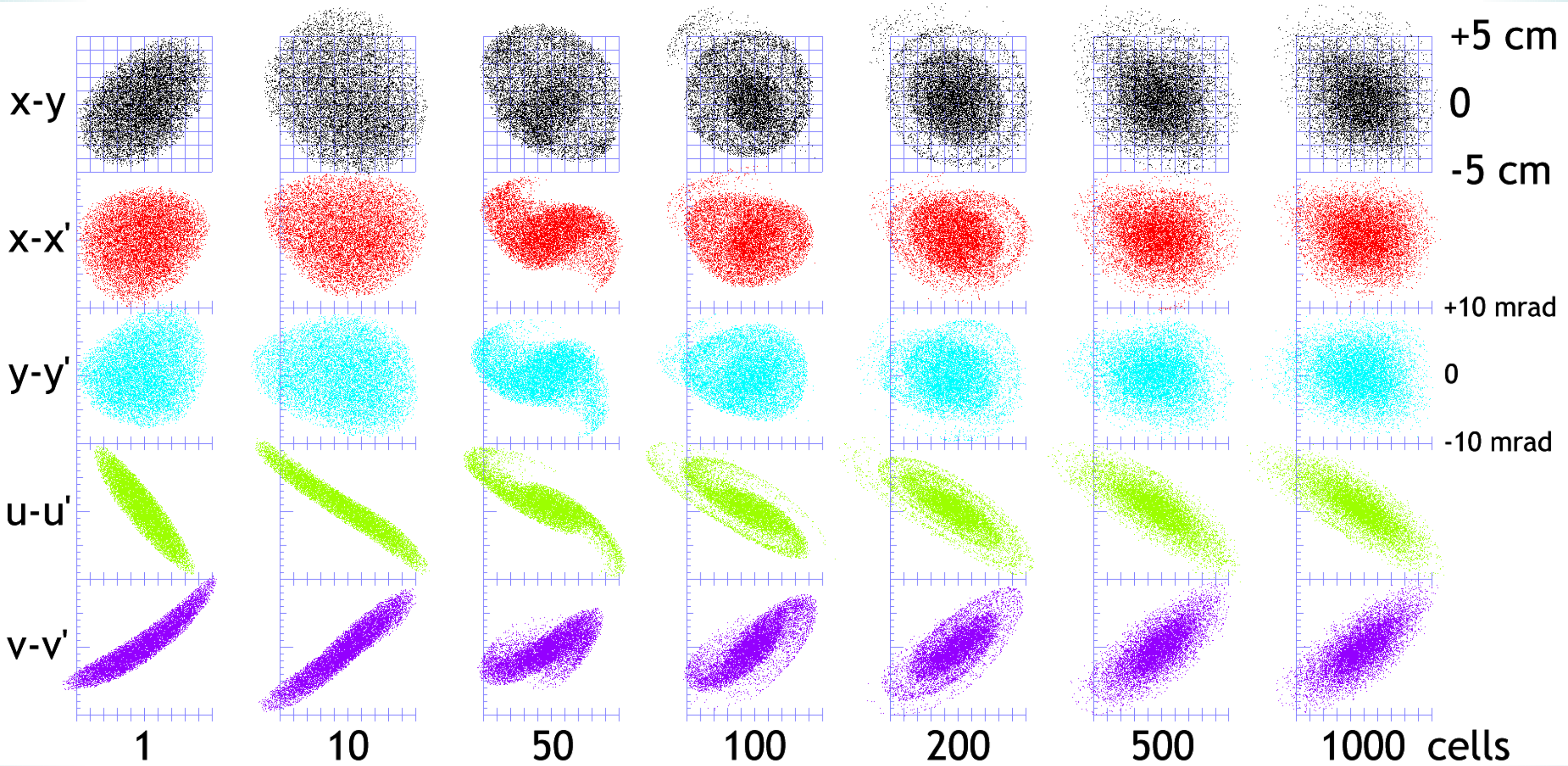
- Simulation

Table 1: Parameters of the FODO lattice.

| | |
|---|---|
| Energy range | 800 MeV–12 GeV |
| Orbit excursion | 43.5 cm (vertical) |
| $k$ | $5\,\mathrm{m}^{-1}$ |
| $B_0$ | 0.5 T |
| $B_{\mathrm{max}}$ | 4.41 T (beam centre) |
| | 4.96 T (beam top) |
| | 5.33 T (whole magnet) |
| Lattice | FODO |
| F length | 0.4 m |
| D length | 0.45 m |
| Drift length | 4 m |


distance=1023.2m
time=0.00405439ms
beam=100%

# Scaling VFFAG Tracking

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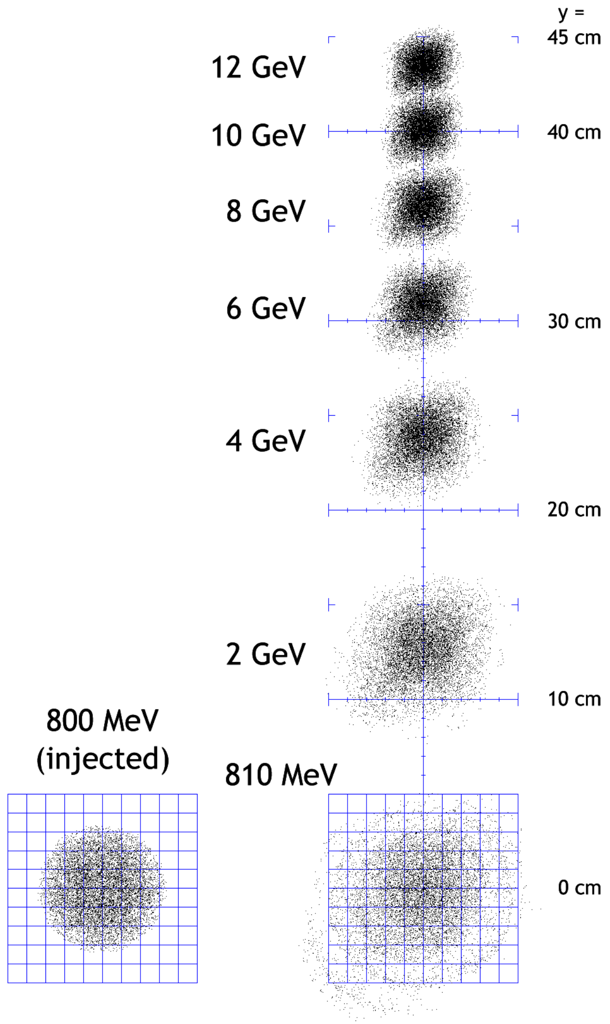
# VFFAG Acceleration

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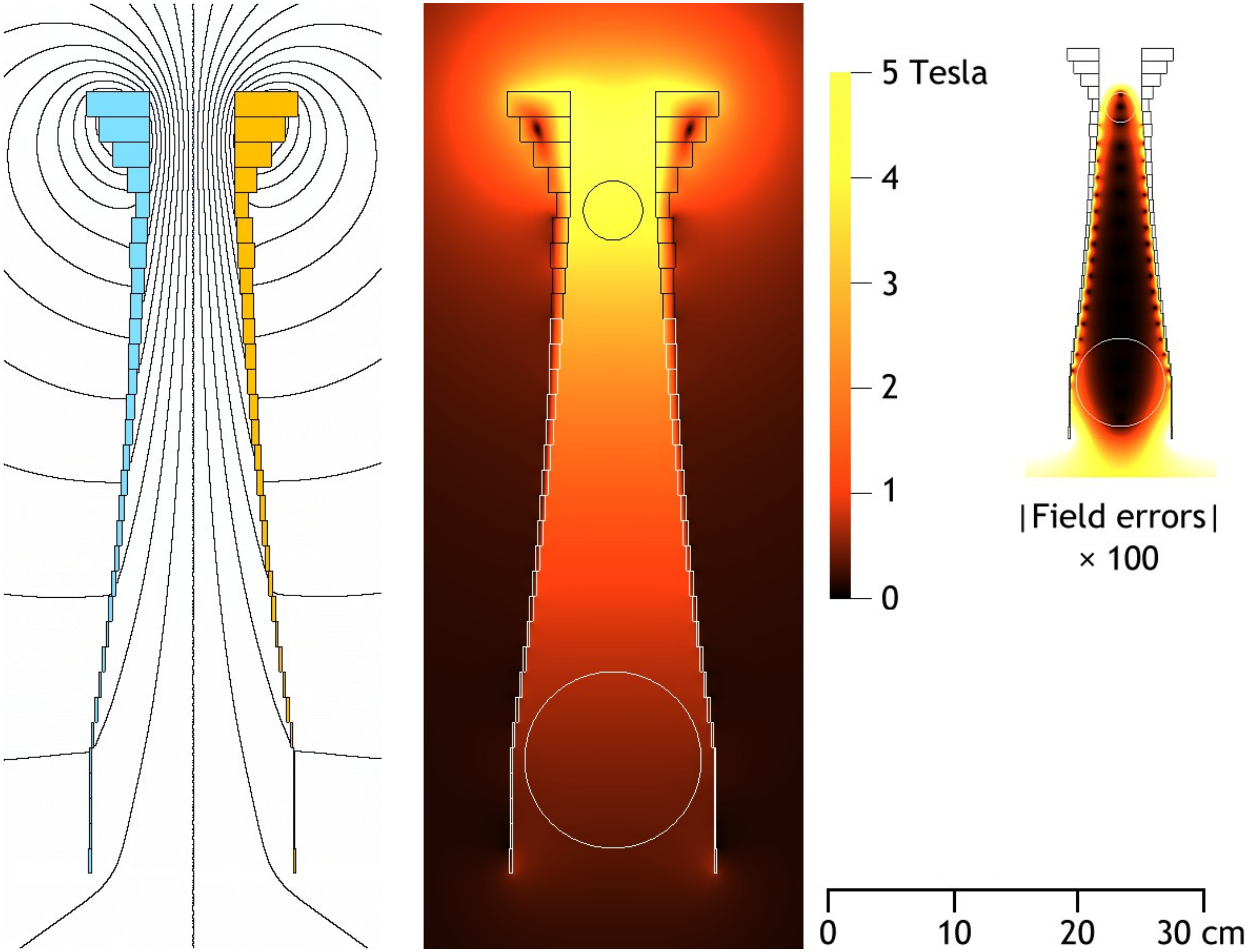
# Windings for Magnet

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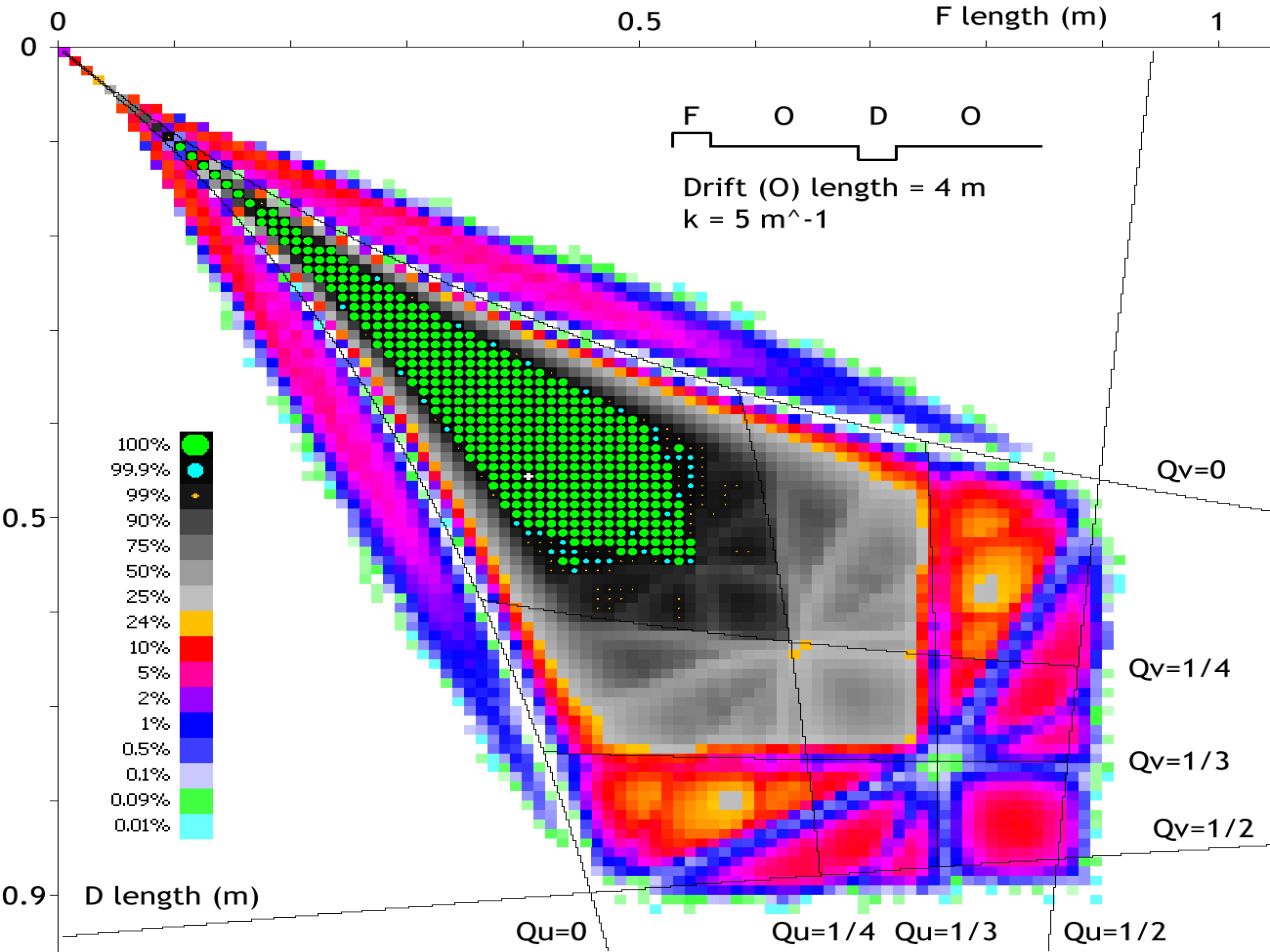
# Scaling (V)FFAG disease

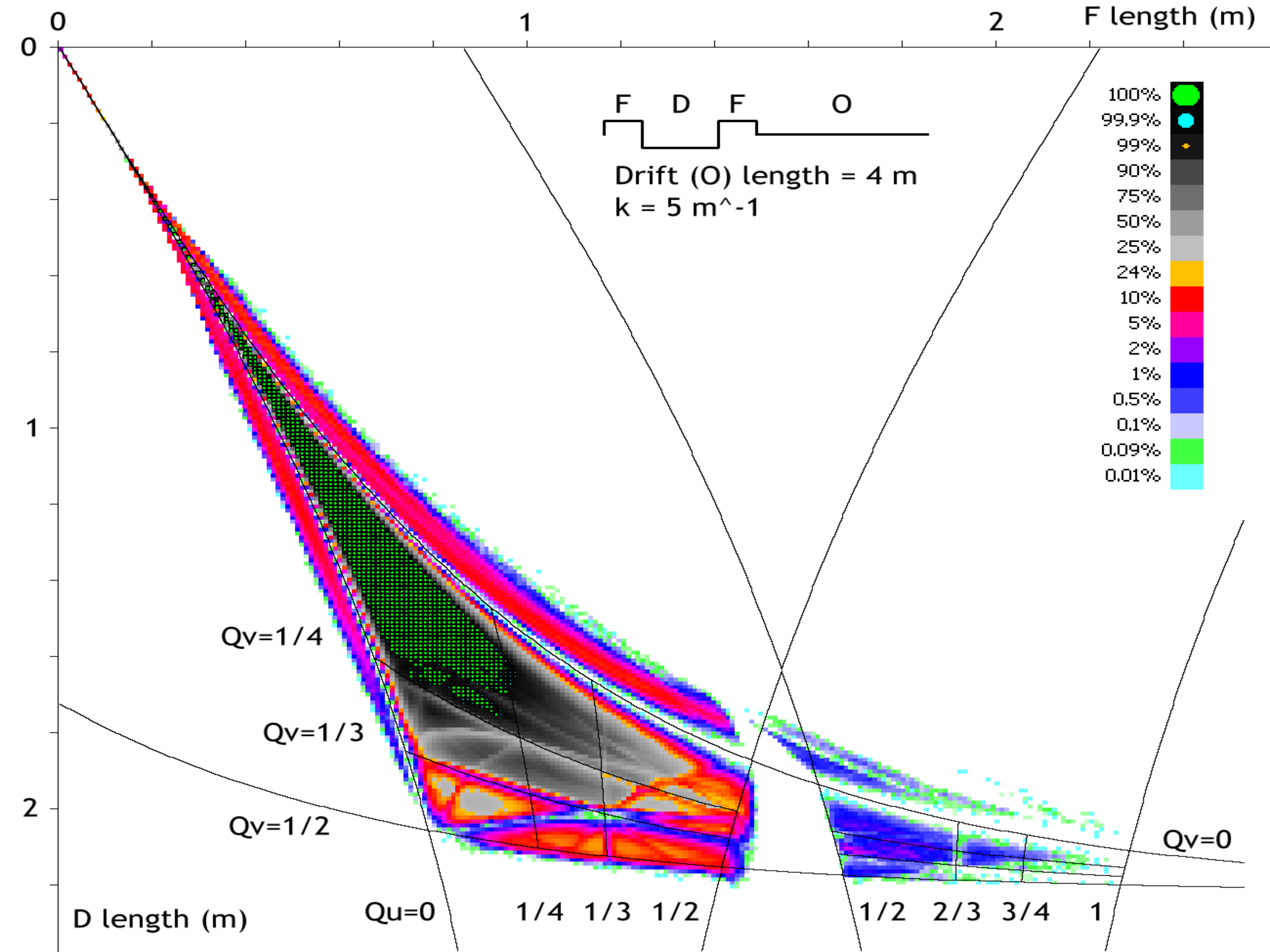
- This ring has unlimited energy range (until the maximum magnet field is reached)
- Constant tunes
- Space charge is probably a smaller term than intrinsic nonlinearities, need to check
- Unfortunately it is about 10x larger than ISIS instead of the desired 2x
  - Defocussing is locked to reverse bending, as in scaling FFAGs

# Search for “lopsided” lattices

- 10000 particles were tracked for 1km
- Survival rate plotted on axes of lengths of “F” and “D” type magnets
- This reveals both the lattice stability region and resonance stop-bands



0
0.5
F length (m)
1
0
0.5
0.9
D length (m)
F
O
D
O
Drift (O) length = 4 m
k = 5 m^-1
100%
99.9%
99%
90%
75%
50%
25%
24%
10%
5%
2%
1%
0.5%
0.1%
0.09%
0.01%
Qv=0
Qv=1/4
Qv=1/3
Qv=1/2
Qu=0
Qu=1/4
Qu=1/3
Qu=1/2

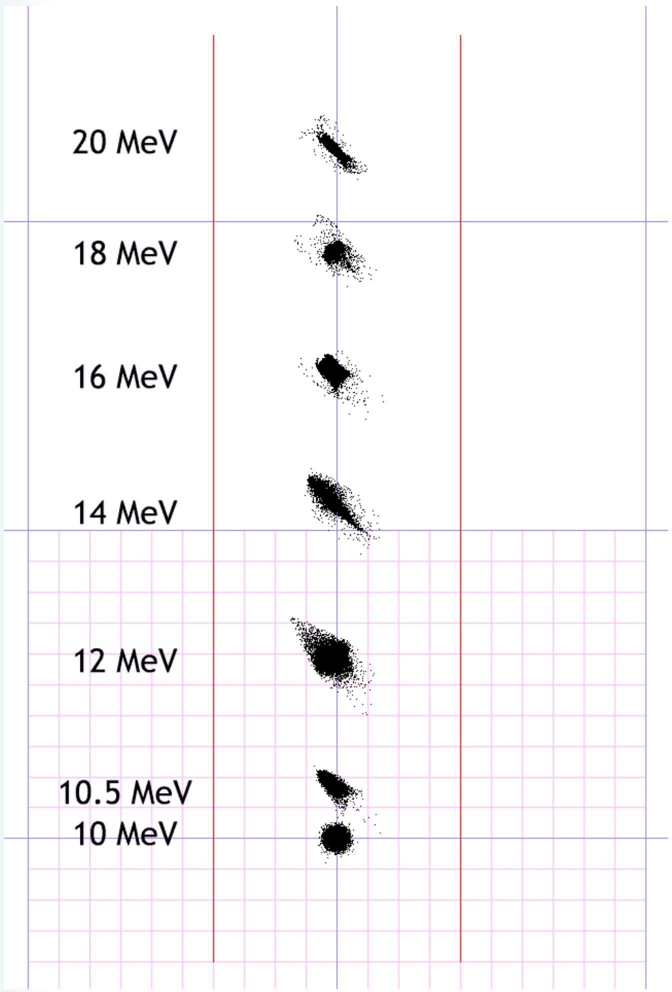


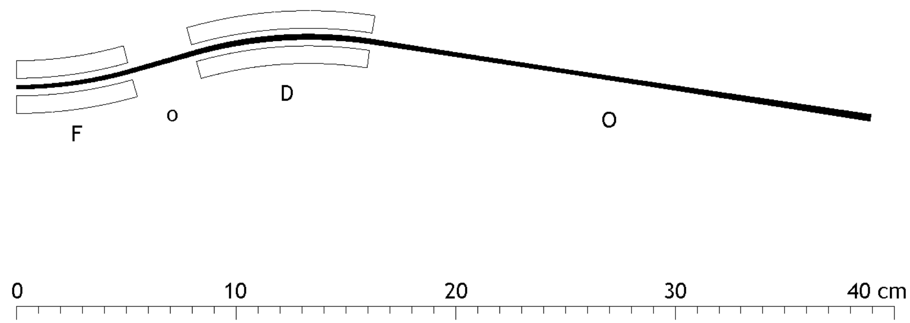
F length (m)
0
1
2
D length (m)
F
D
F
O
Drift (O) length = 4 m
k = 5 m^-1
100%
99.9%
99%
90%
75%
50%
25%
24%
10%
5%
2%
1%
0.5%
0.1%
0.09%
0.01%
Qv=1/4
Qv=1/3
Qv=1/2
Qv=0
Qu=0
1/4
1/3
1/2
1/2
2/3
3/4
1

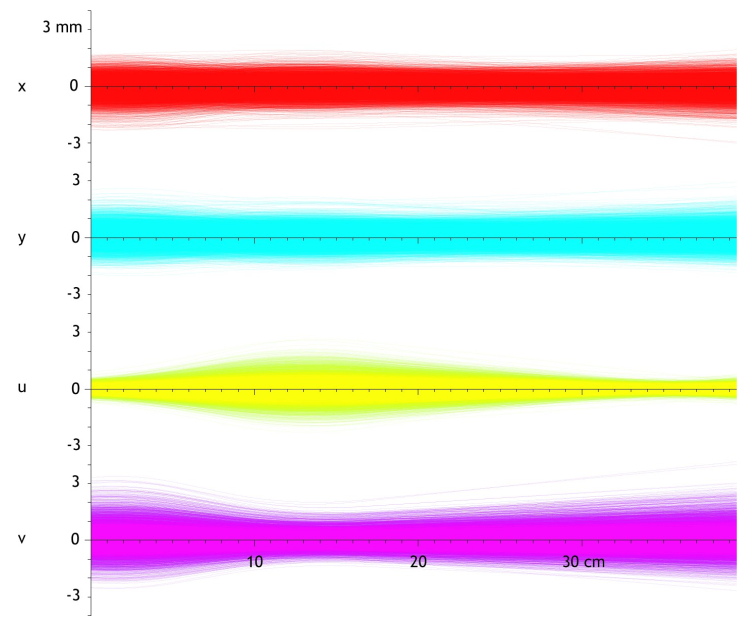
# Lattices can't be very lopsided

- Unfortunately in all cases the region of dynamic stability sticks very close to the F=D diagonal line
  – So pure exponential VFFAGs will always be big, with much reverse bending
- Another reason for choosing the non-scaling machine initially was to ensure msot magnets contribute to the bend
  – Thus, non-scaling VFFAG?  Interesting!

# Convert EMMA to VFFAG Study

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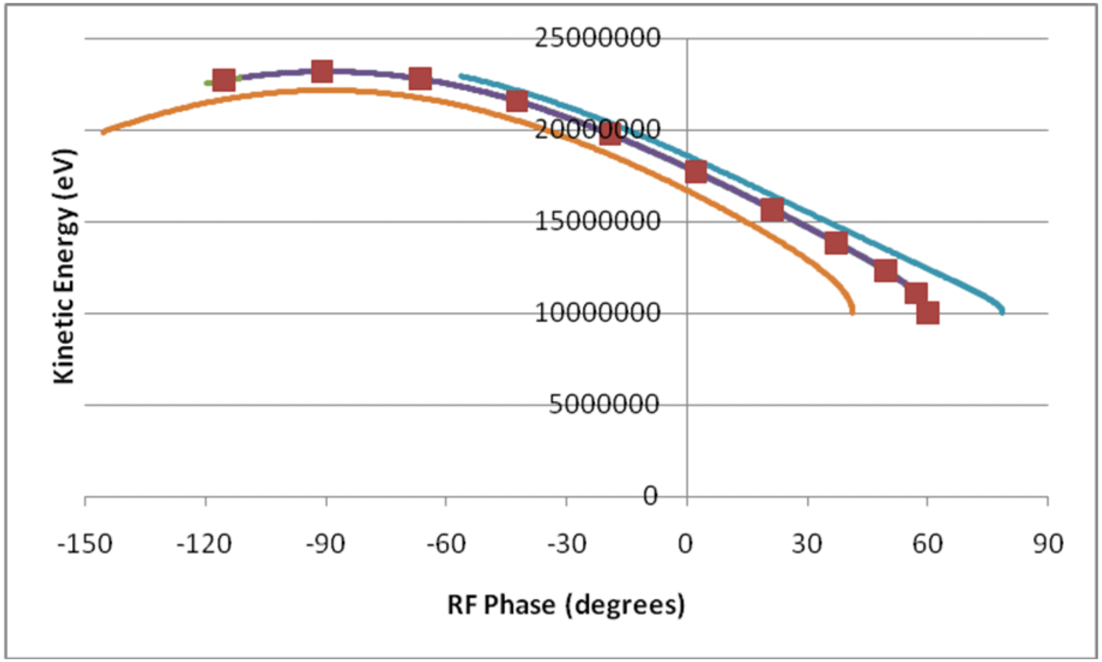
# “EMMA” VFFAG with 2.1MV RF

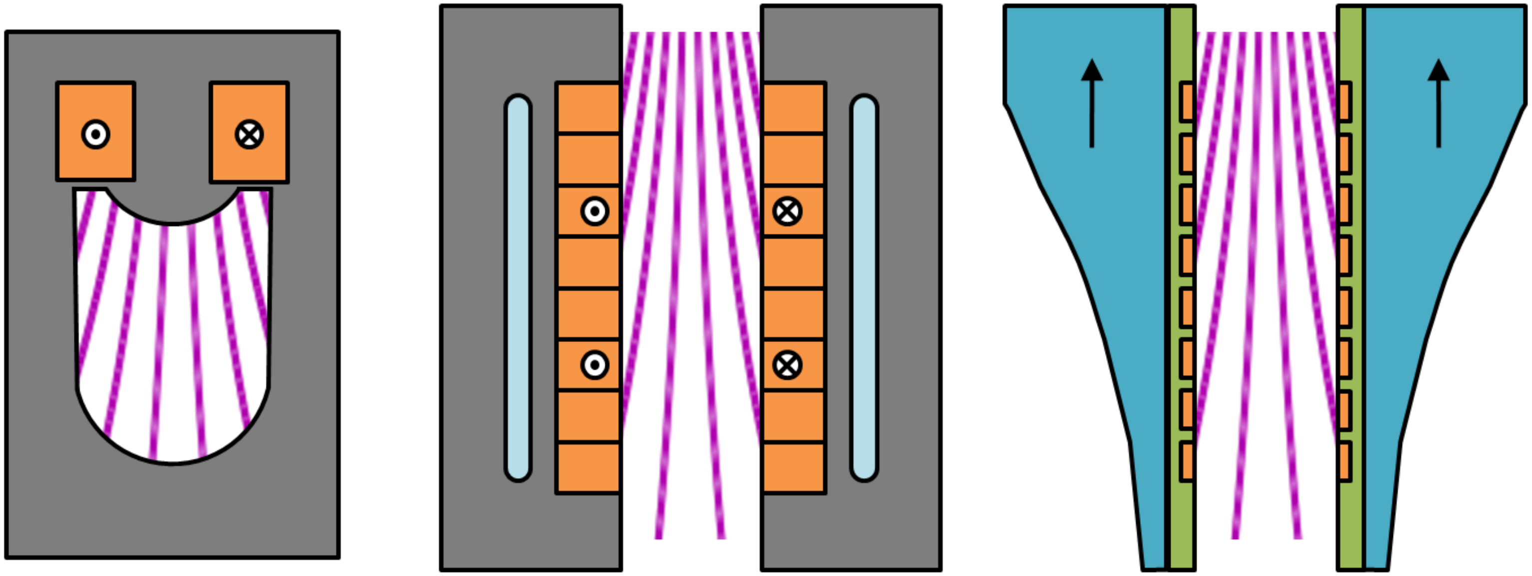
Below: RF acceleration of extremities (4 sigma) and centre of the ALICE bunch over 10 turns, assuming RF is synchronous at the 10MeV injection energy.




As the beam closed orbit has the same circumference at all energies in a scaling VFFAG, the time-of-flight for electrons in the ring simply scales as 1/velocity. Although this is further from isochronicity than the parabolic TOF dependence of the current EMMA model, the 1.3GHz RF can still accelerate the beam by at least a factor of two in energy before the phase slips too far.

In the plot above, a situation with 2.1MV of peak RF voltage per turn (less than the current 2.3MV installed in the ring [4]) accelerates a 10MeV electron starting 60 degrees ahead of the RF to a maximum energy of 23.17MeV before the RF becomes decelerating again.

# Normal Conducting Magnets?



:)

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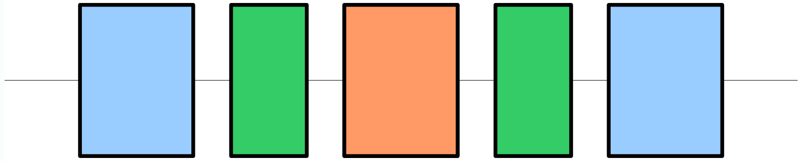
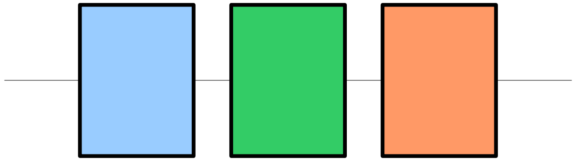
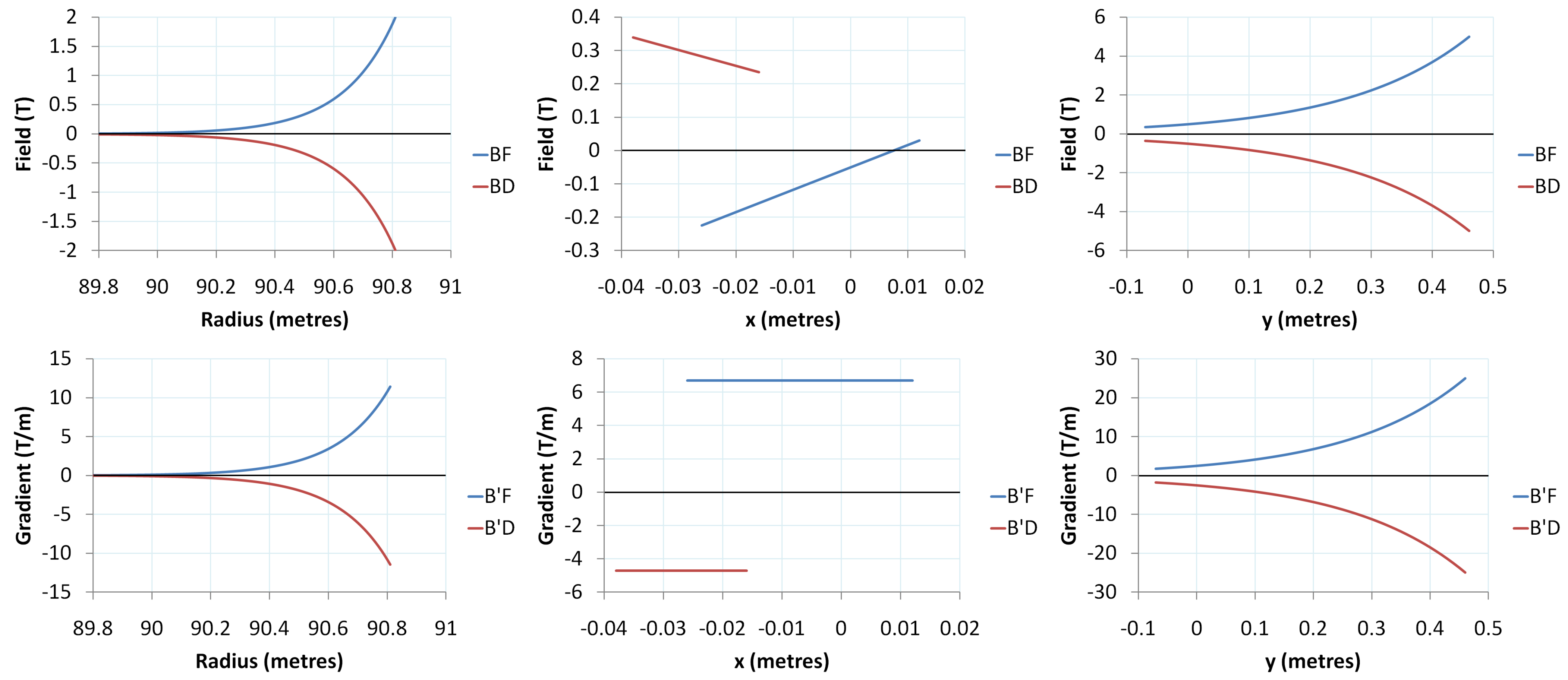
# Fixed tune non-scaling FFAGs

- In principle if you have at least three free magnet gradients, you can simultaneously satify the equations
- Sum of dipole = momentum * constant
- d(X tune)/dp = d(Y tune)/dp = 0
- Thus, Grahame's pumplet lattice
  - 1-2-3 configuration also possible





# Two Magnet Families Only



# FFAG Master Table

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Table 1: Classification of FFAGs and their characteristics. Uppercase 'Y' indicates property is always true, lowercase 'y' that it is achievable in some cases. '3+' means three or more lenses per cell are required.

| **Type of FFAG** | **Fixed tunes** | **Wide $E$ range** | **Isoch-ronous** | **Small ring** |
|---|---|---|---|---|
| Scaling | Y | Y | N | N |
| Non-scaling | 3+ | ? | y | y$^{\dagger}$ |
| Linear n.s. | N | N | y(quasi) | y |
| Vertical s. | Y | Y | N | N |
| V. n.s. | 3+ | ? | ? | ? |
| Linear v.n.s.$^{\ddagger}$ | ? | ? | ? | ? |
| Skew | y | ? | y$^{\dagger}$ | ? |

$^{\dagger}$Two 'y's may not be achievable simultaneously.

$^{\ddagger}$Linear field VFFAG suggested by D.J. Kelliher.

# 3D "Necktie" Diagram

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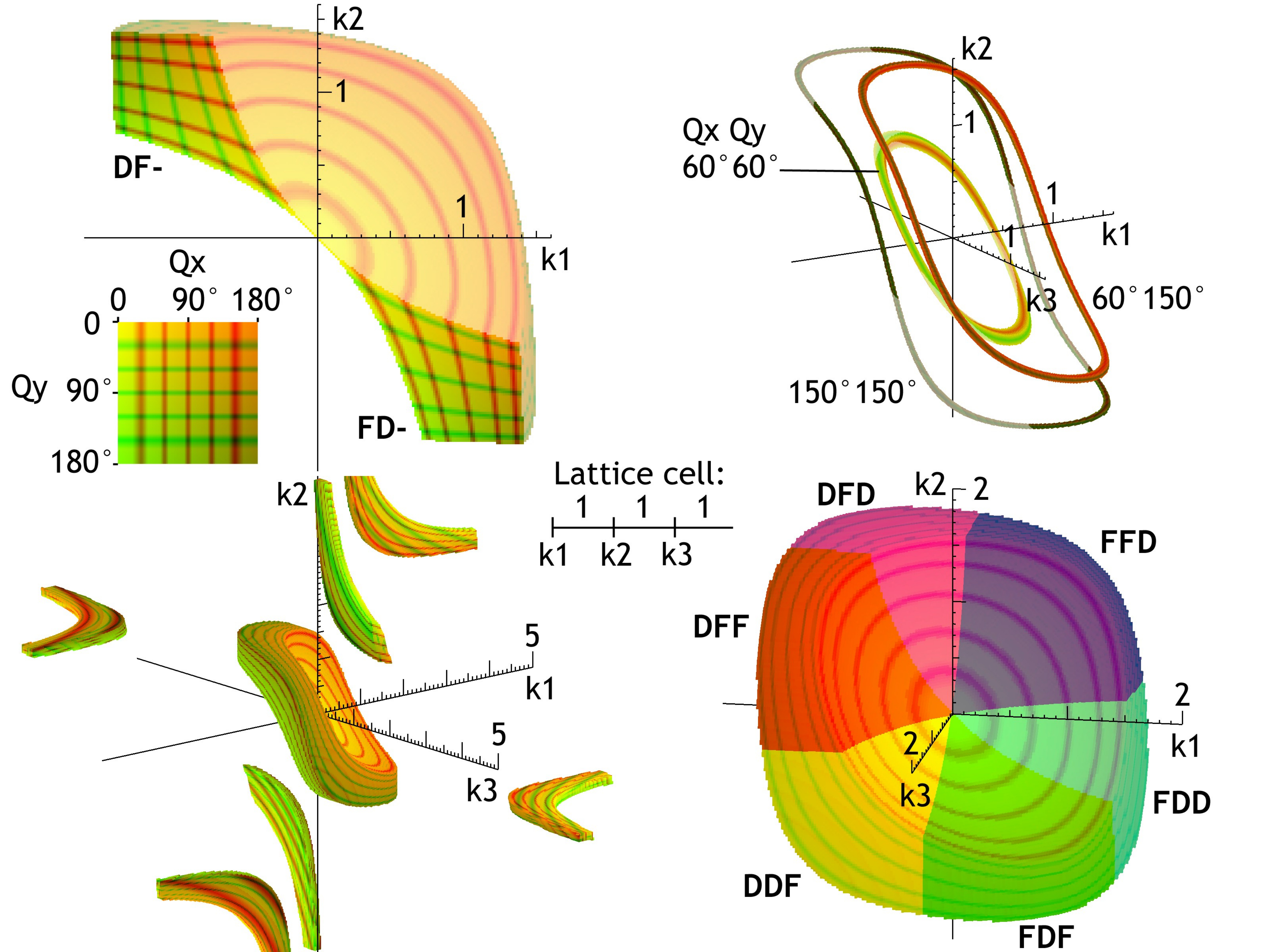
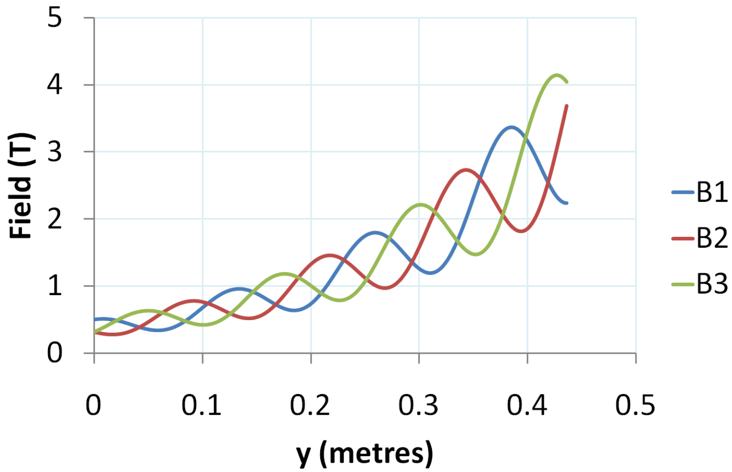
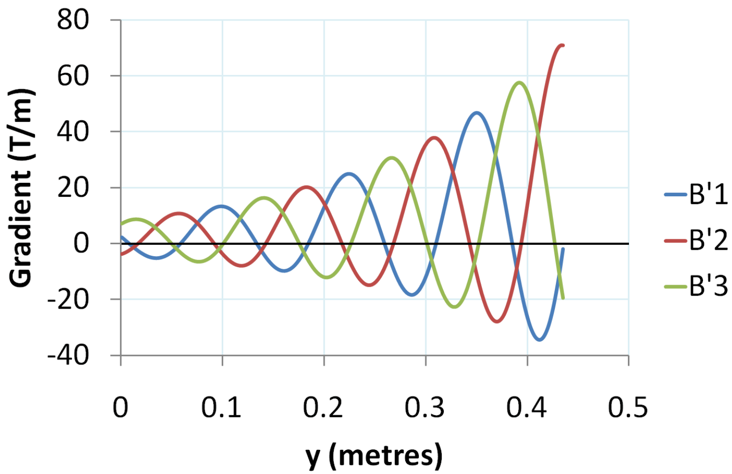


k2
1
DF-
1
k1
Qx
0
90°
180°
0
Qy
90°
180°
FD-
Qx Qy
60°60°
k2
1
1
1
k1
k3
60°150°
150°150°
Lattice cell:
1
1
1
k1
k2
k3
k2
5
k1
5
k3
DFD
k2
2
FFD
DFF
2
k1
2
k3
FDD
DDF
FDF

# Three Magnet Families?




$$B_{y,n}(0,y) = B_0 \mathrm{e}^{ky}(1 + a\cos(wy + \varphi_n))$$

# References

- Stephen Brooks
  - HB2010 *"Vertical Orbit Excursion FFAGs"*
  - IPAC'11 *"Three-Lens Lattices for Extending the Energy Range of Non-scaling FFAGs"*
  - http://stephenbrooks.org/ral/report/ (EMMA)
- *"Theory of the ring cyclotron"*, A.P. Fateev, J. Nucl. Energy, Part C Plasma Phys. **4** p.64 (1962). http://iopscience.iop.org/0368-3281/4/1/110