# Vertical Orbit-Excursion FFAGs (VFFAGs)

a.k.a. FFAG Cyclotrons (Ohkawa, 1955) a.k.a. Helicoidal FFAGs (Leleux, 1959) a.k.a. Ring Cyclotrons (Teichmann, 1960-2)

I. Principle & Magnetic Fields
II. Proton Driver Study
III. Isochronous Machines
IV. Three-Lens Horizontal FFAGs
V. Proton Omni-Ring


Stephen Brooks, PASI 2013 & BNL seminar
stephen.brooks@stfc.ac.uk

# Vertical Orbit-Excursion FFAGs (VFFAGs) for applications

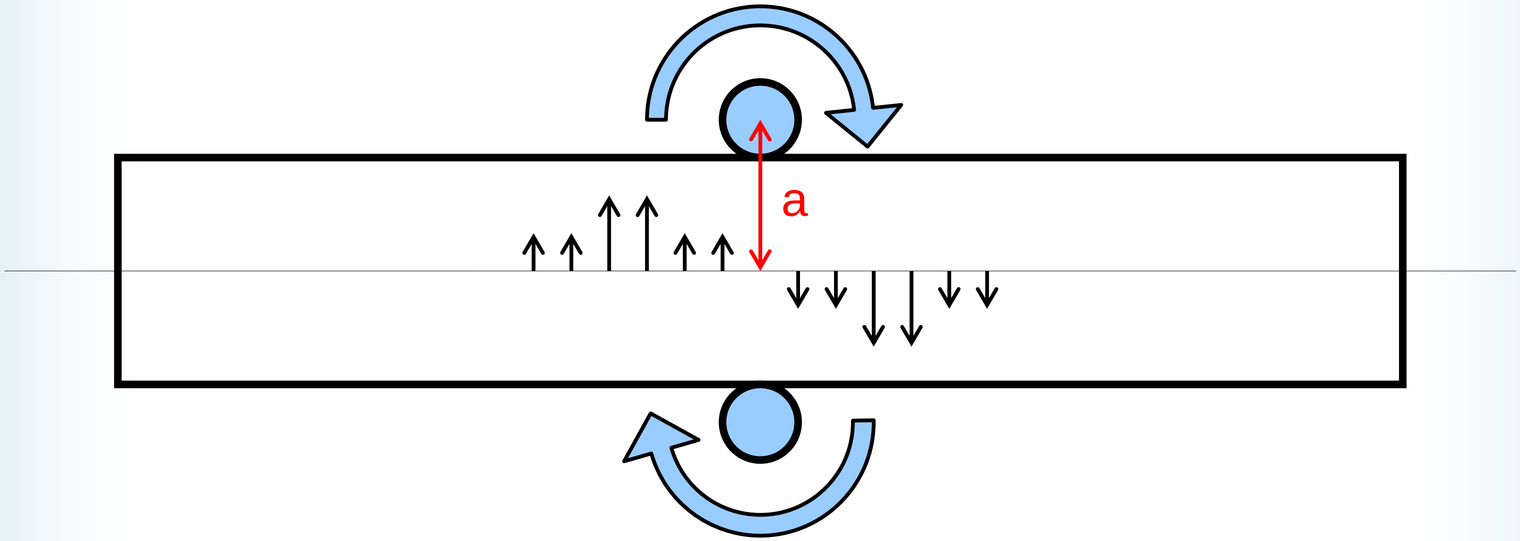
a.k.a. computers and superconducting magnets weren't much good in 1960 but now they are

I. Smaller Hadron Therapy Magnets
II. Neutrino Factory, ISIS Upgrade
III. Transmutation, Antimatter(?)
IV. Design by Artificial Intelligence
V. High Beam Dynamics R&D per £

# I. Principle & Magnetic Fields

# Horizontal SC magnet problem

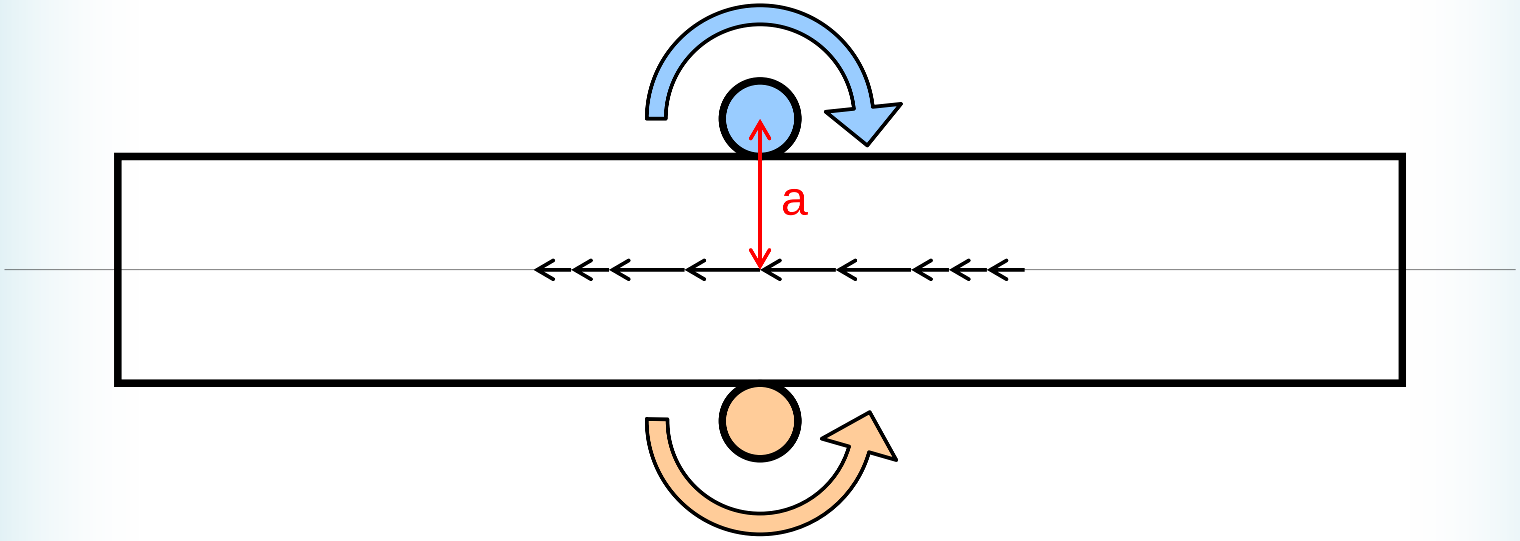
- Getting vertical B field requires same-direction current windings (nearby)




- $B_y$ proportional to $x/(a^2+x^2)$

# Horizontal SC magnet variation

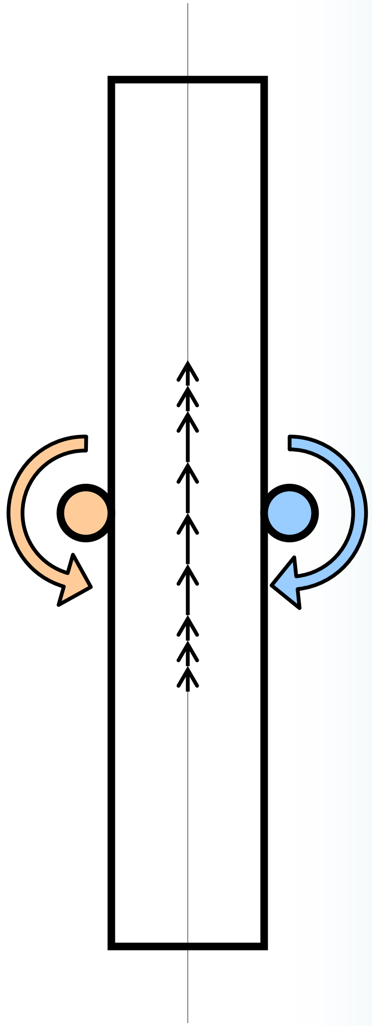
- Getting horizontal B field requires opposite current windings and is easier




- $B_x$ proportional to $a/(a^2+x^2)$

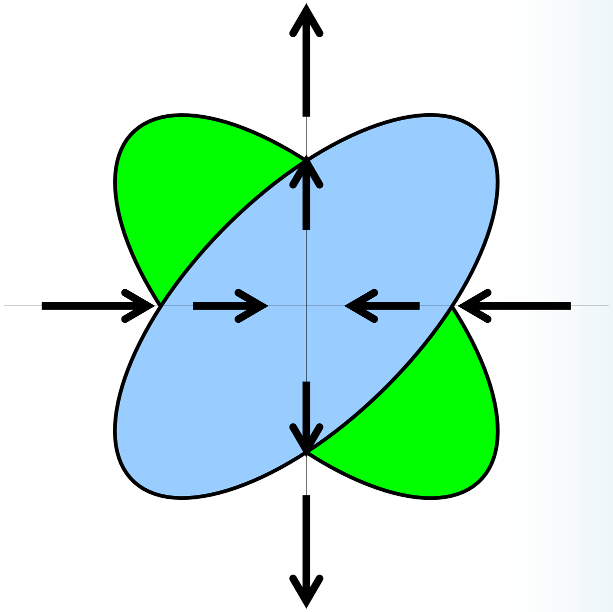
# Vertical SC magnet

- 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?



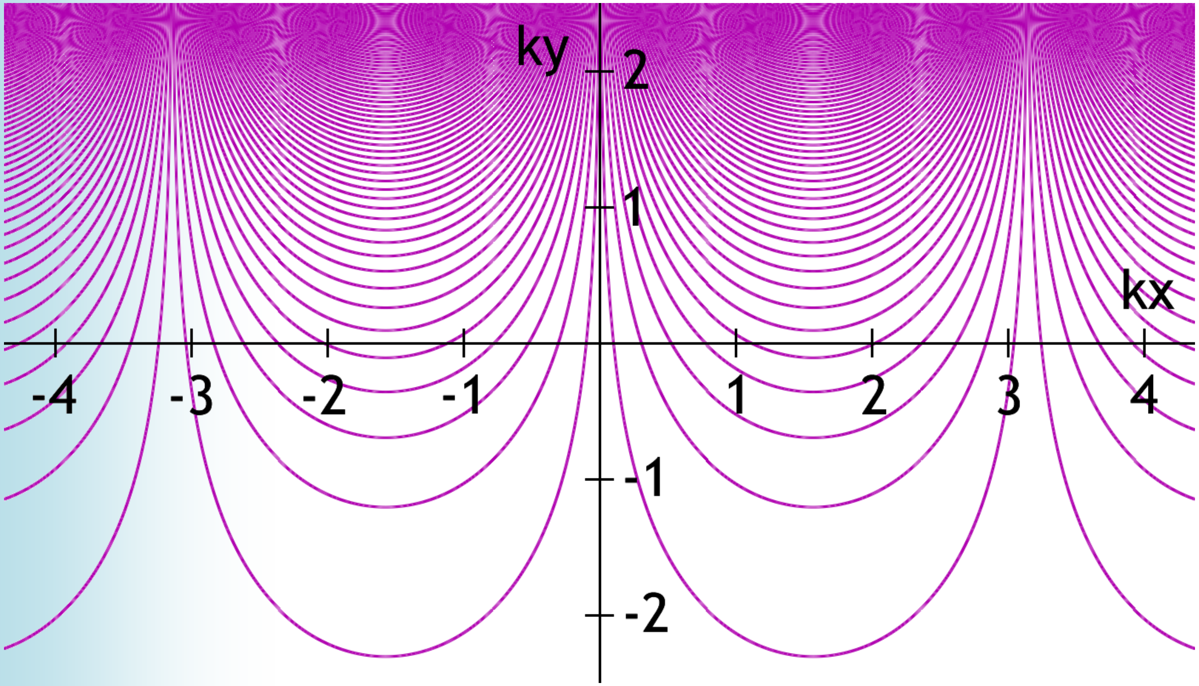
# "Scaling" VFFAG magnet

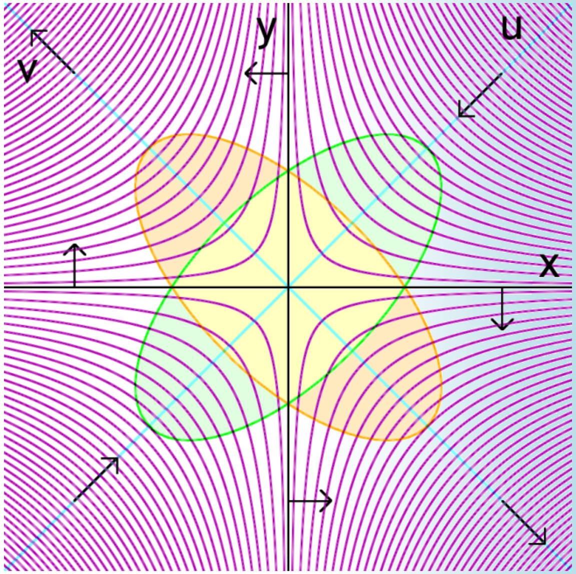
- Dipole field should increase moving up the magnet, so set $B_y = B_0 e^{ky}$ on axis (x=0)
- Subtracting dipole component leaves the field of a skew quad:
  - Exponential is good because moving upwards just scales the field and all gradients
  - Thus closed orbits at different momenta are exactly the same shape, just translated upwards
  - VFFAG = Vertical orbit excursion FFAG



# Scaling VFFAG Field & Scaling Law

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




$$y \mapsto y + \Delta y, \qquad (p, \mathbf{B}) \mapsto (p, \mathbf{B}) \mathrm{e}^{k\Delta y}$$

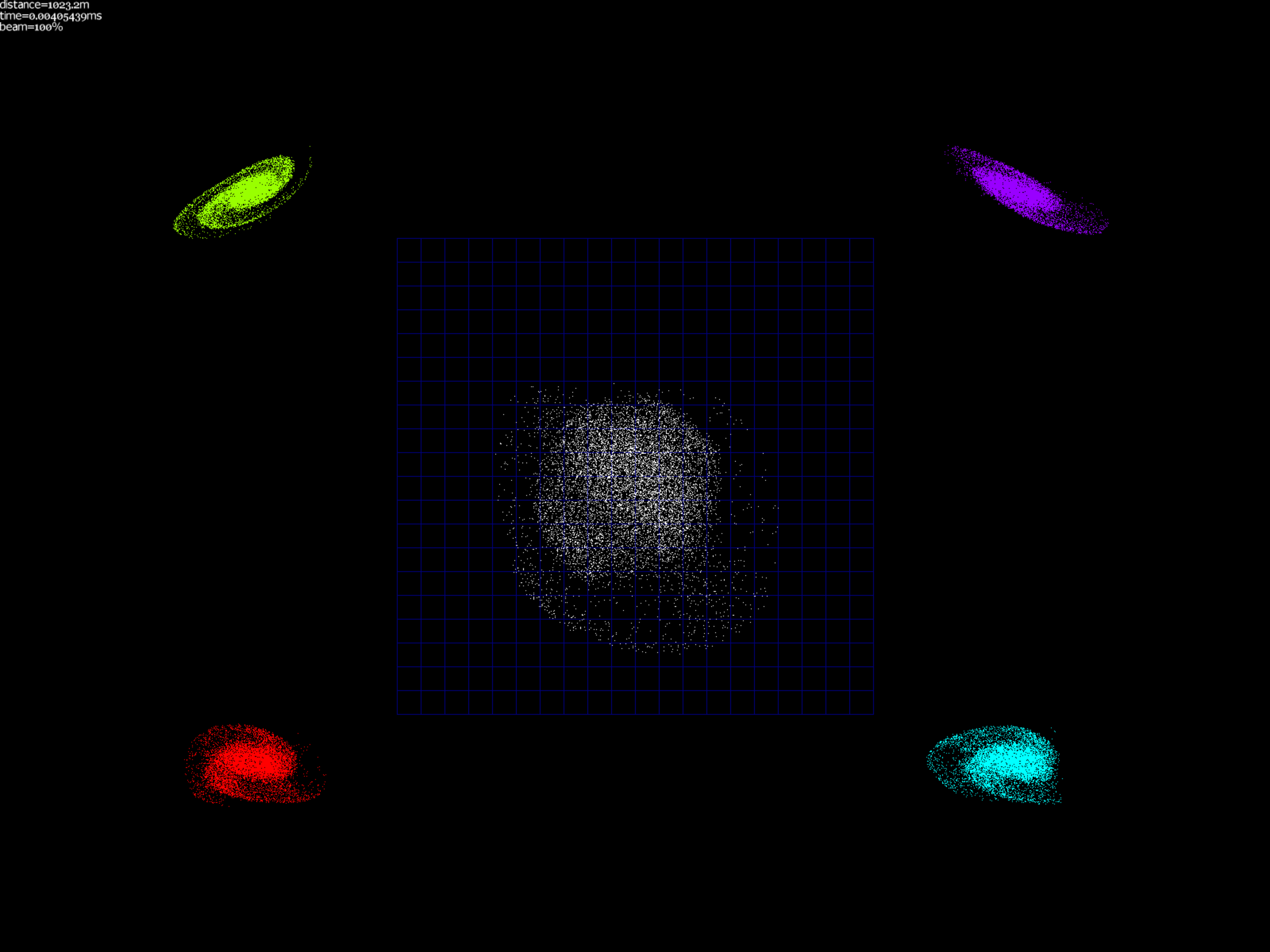
# FODO Scaling VFFAG Machine

- First VFFAG tracking simulation, for HB2010
  – 2D, zero space charge, nonlinear magnets
- 150mm.mrad $\varepsilon_{geom}$ input beam
- Proton-driver-like but nasty circumference factor! (C=17)

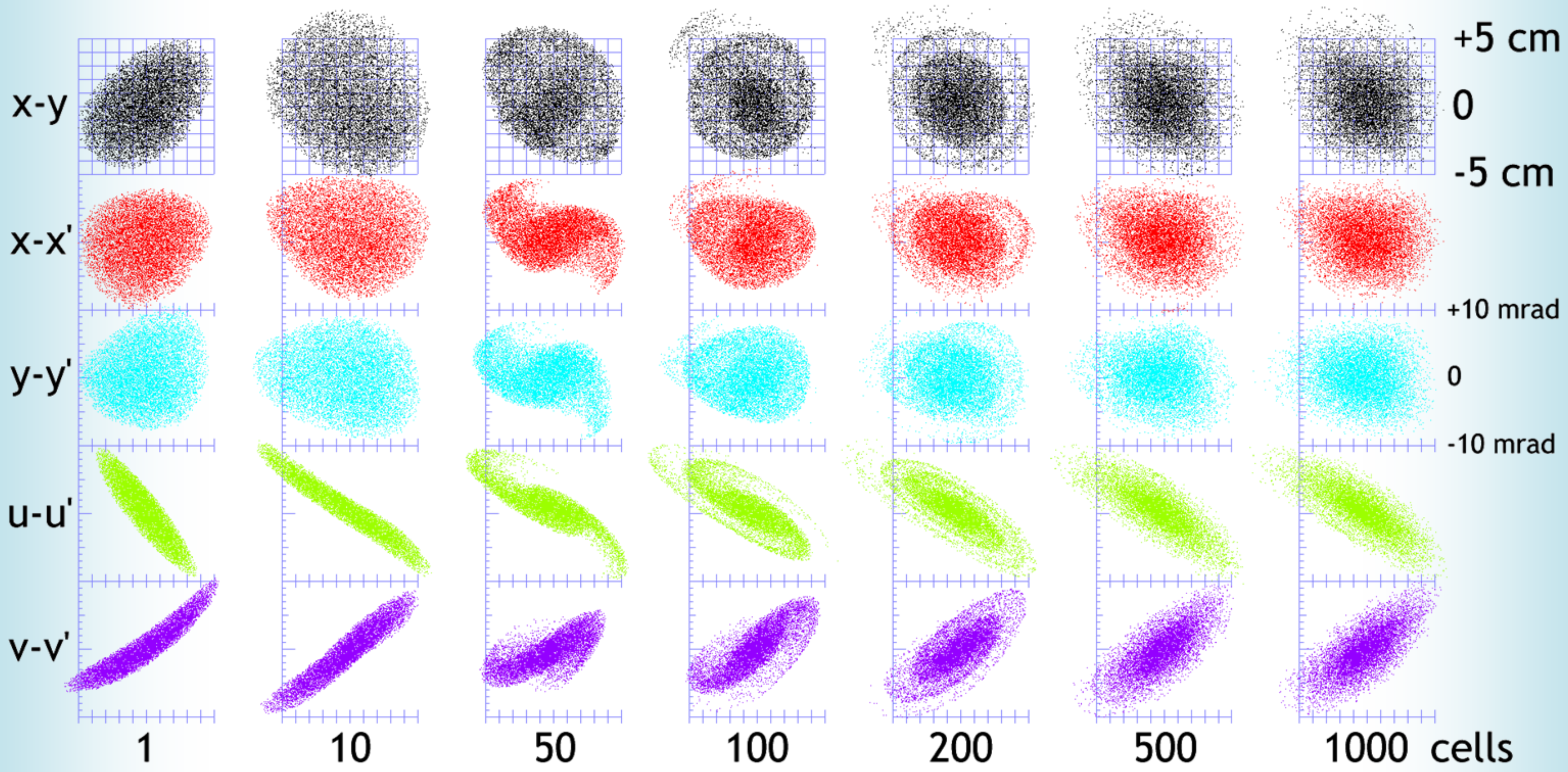
$$C = \langle|\boldsymbol{B}|\rangle / \langle B_y \rangle$$

Table 1: Parameters of the FODO lattice.

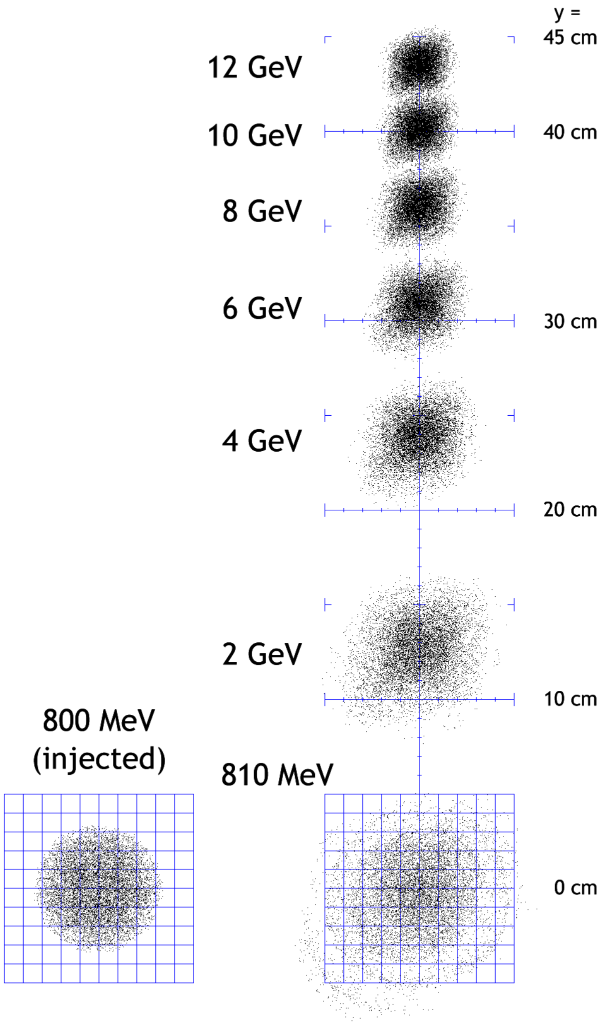
| | |
|---|---|
| Energy range | 800 MeV–12 GeV |
| Orbit excursion | 43.5 cm (vertical) |
| $k$ | $5\,\mathrm{m}^{-1}$ |
| $B_0$ | 0.5 T |
| $B_{\max}$ | 4.41 T (beam centre) |
| | 4.96 T (beam top) |
| | 5.33 T (whole magnet) |
| Lattice | FODO |
| F length | 0.4 m |
| D length | 0.45 m |
| Drift length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


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

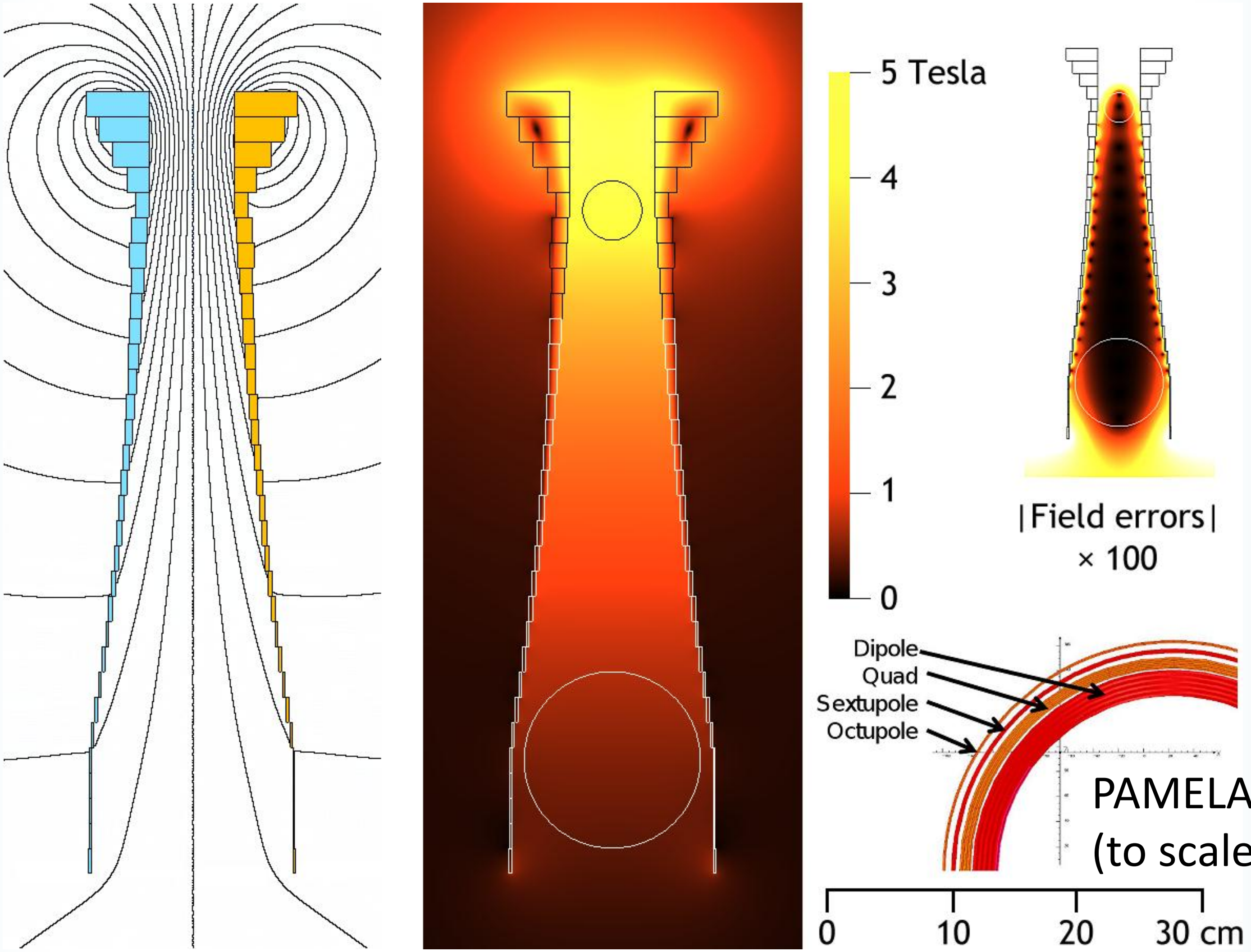
# Scaling VFFAG Tracking



# VFFAG Acceleration



# 2D Winding Model for Magnet



# Application: Hadron Therapy?

- Low intensity but high rep-rate
  - Fixed field is a plus, space charge not too bad
- Small beams
  - The VFFAG magnet can be a narrow vertical slot
  - Less stored energy, smaller windings required
- Fixed tune allows slower acceleration, less RF
- Disadvantage: we still have the FFAG extraction-from-an-orbit-that-moves problem

# II. Proton Driver Study

# Motivation: ISIS Energy Booster

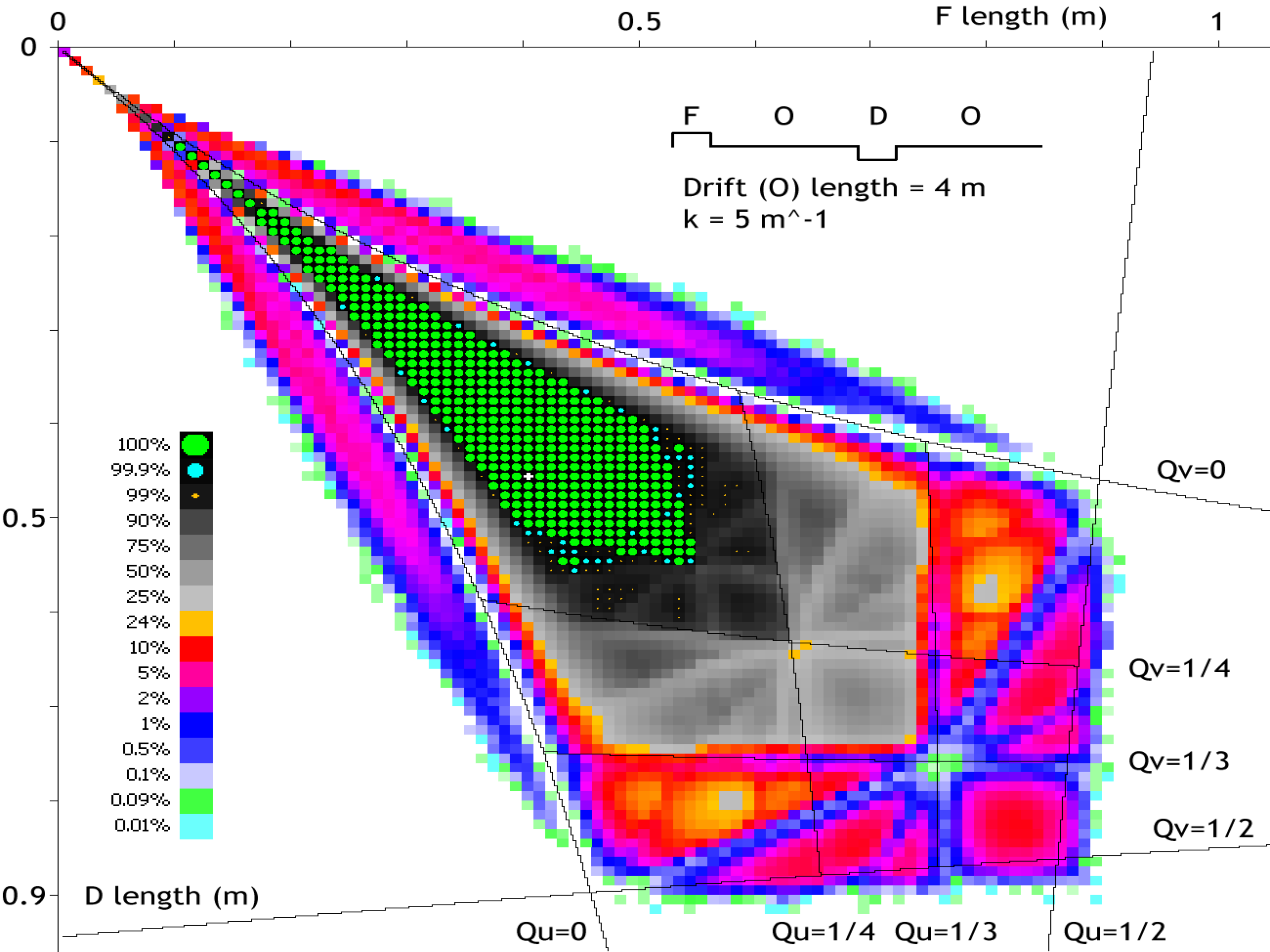
- FFAG of some sort (but with 2-4m drifts)
- Superconducting magnets
- Energy: 800MeV – 12GeV
- Ring radius 52m (2x ISIS) could do 2.5x,3x
- Mean dipole field in magnets 0.47 – 4.14T
- 30% RF packing factor, 20% magnets
- Warm 6.2 – 7.3MHz RF
- Harmonic number 8 (10,12 in larger ring)

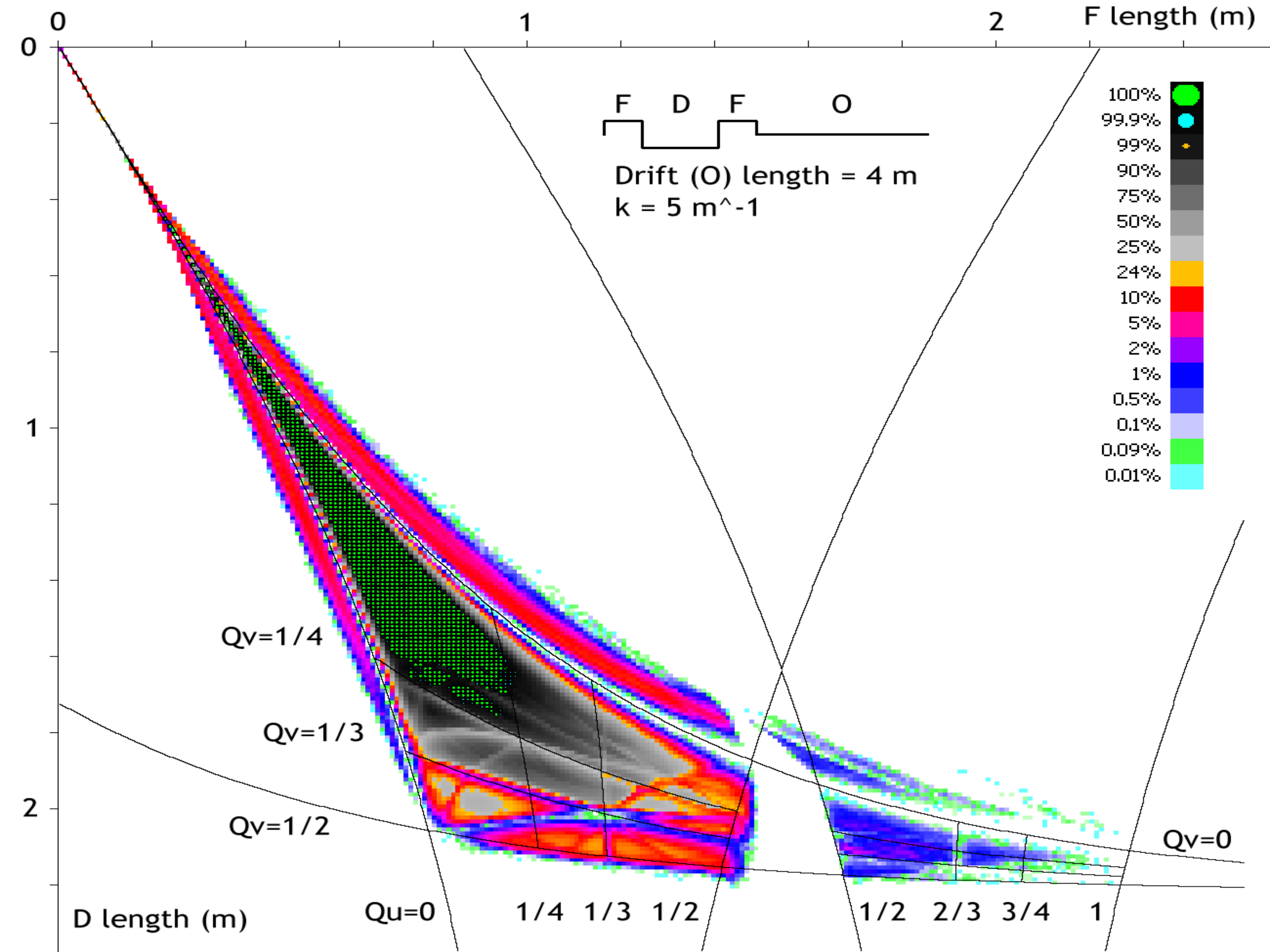
# Why 12GeV? (= 2.5MW at 208uA)

- Existing 2RF is 2x11kV in 1.9707m module
  - 11.16kV/m * 20ms * c = 67GeV
- Assume 30% ring RF packing factor
  - 67GeV * 30% = 20GeV
- Assume $\langle \cos\phi \rangle = 0.7$ ($\phi \sim 45°$)
  - 20GeV * 0.7 = 14GeV
- Finally, velocity goes from 0.84c to ~0.99c
  - 14GeV * 0.9 = 12.6GeV

# Scaling (V)FFAG disease

- Defocussing is locked to reverse bending, as in scaling FFAGs → large circumference factor
- Searched for "lopsided" scaling lattices with good dynamic aperture [HB2010]
  - 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

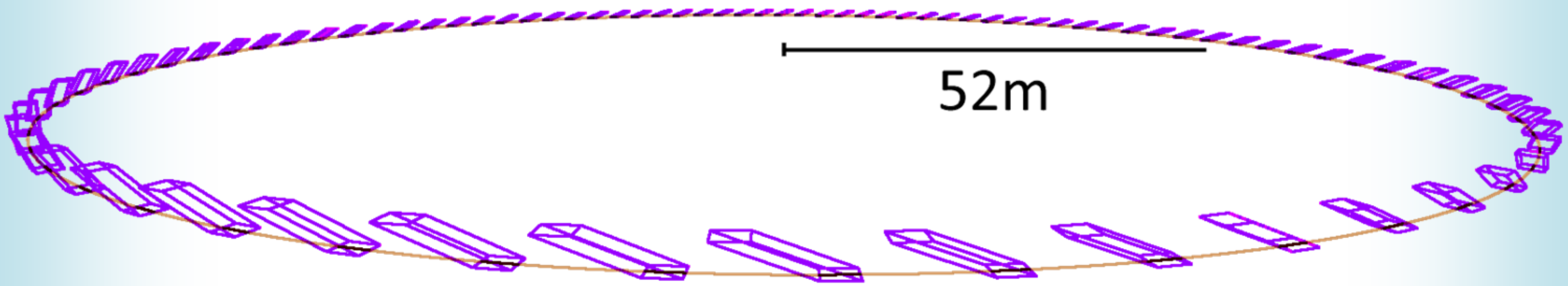

F length (m)
0
0.5
1
0.9
D length (m)
F O D O
Drift (O) length = 4 m
k = 5 m^-1
100%
99.9%
99%
90%
75%
50%
25%
24%
10%
5%
2%
1%
0.5%
0.1%
0.09%
0.01%
Qv=0
Qv=1/4
Qv=1/3
Qv=1/2
Qu=0
Qu=1/4
Qu=1/3
Qu=1/2


0
1
2
F length (m)
0
1
2
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
D length (m)

# Lattices can't be very lopsided

- Unfortunately in all cases the region of dynamic stability sticks very close to the F=D diagonal line
- The 2nd FDF stability region as used in PAMELA does not have enough dynamic aperture
- So basic scaling VFFAGs will always be big, with much reverse bending
  - Could edge focussing avoid reverse bends?

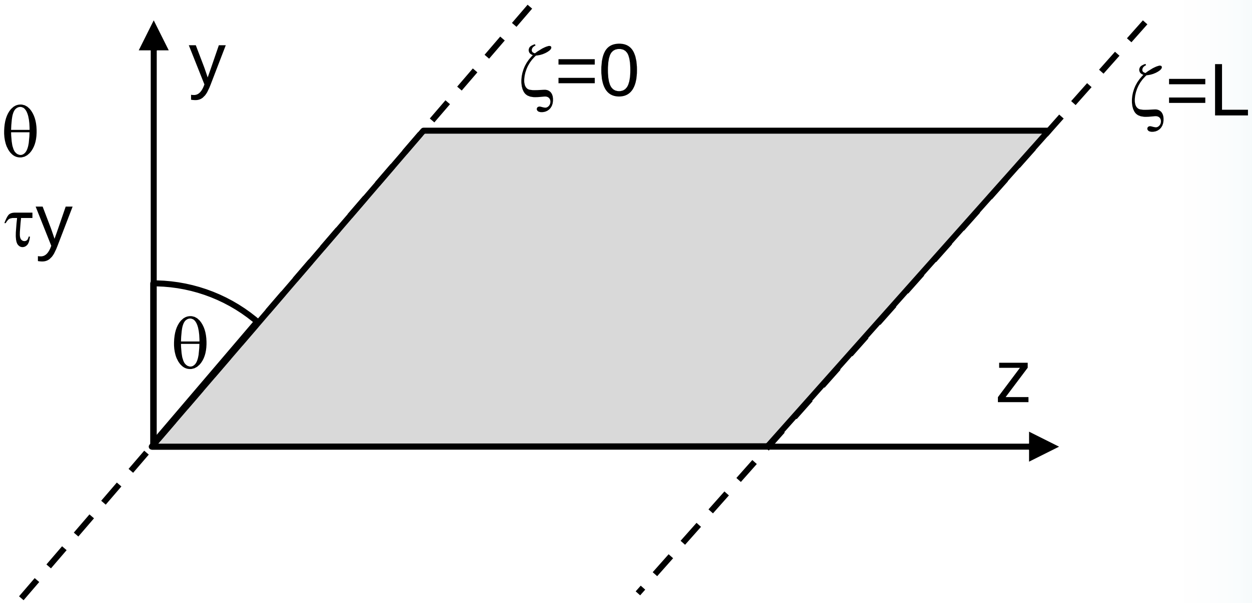
# [HB2012]



# VFFAG with Edge Focussing

$\tau = \tan\theta$

$\zeta = z - \tau y$




one wants a mid-plane field $B_y = B_0 e^{ky} f(\zeta)$ but to obey Maxwell's equation $(\nabla \times \mathbf{B})_x = 0$, this has to be modified to $(B_y, B_z) = B_0 e^{ky} \left( f(\zeta) - \frac{\tau}{k} f'(\zeta), \frac{1}{k} f'(\zeta) \right)$.

Scaling law: $y \mapsto y + \Delta y$, $\quad (p, \mathbf{B}) \mapsto (p, \mathbf{B}) e^{k\Delta y}$

$z \mapsto z + \tau \Delta y$

# Spiral Scaling VFFAG Magnet Field

- 5GeV design

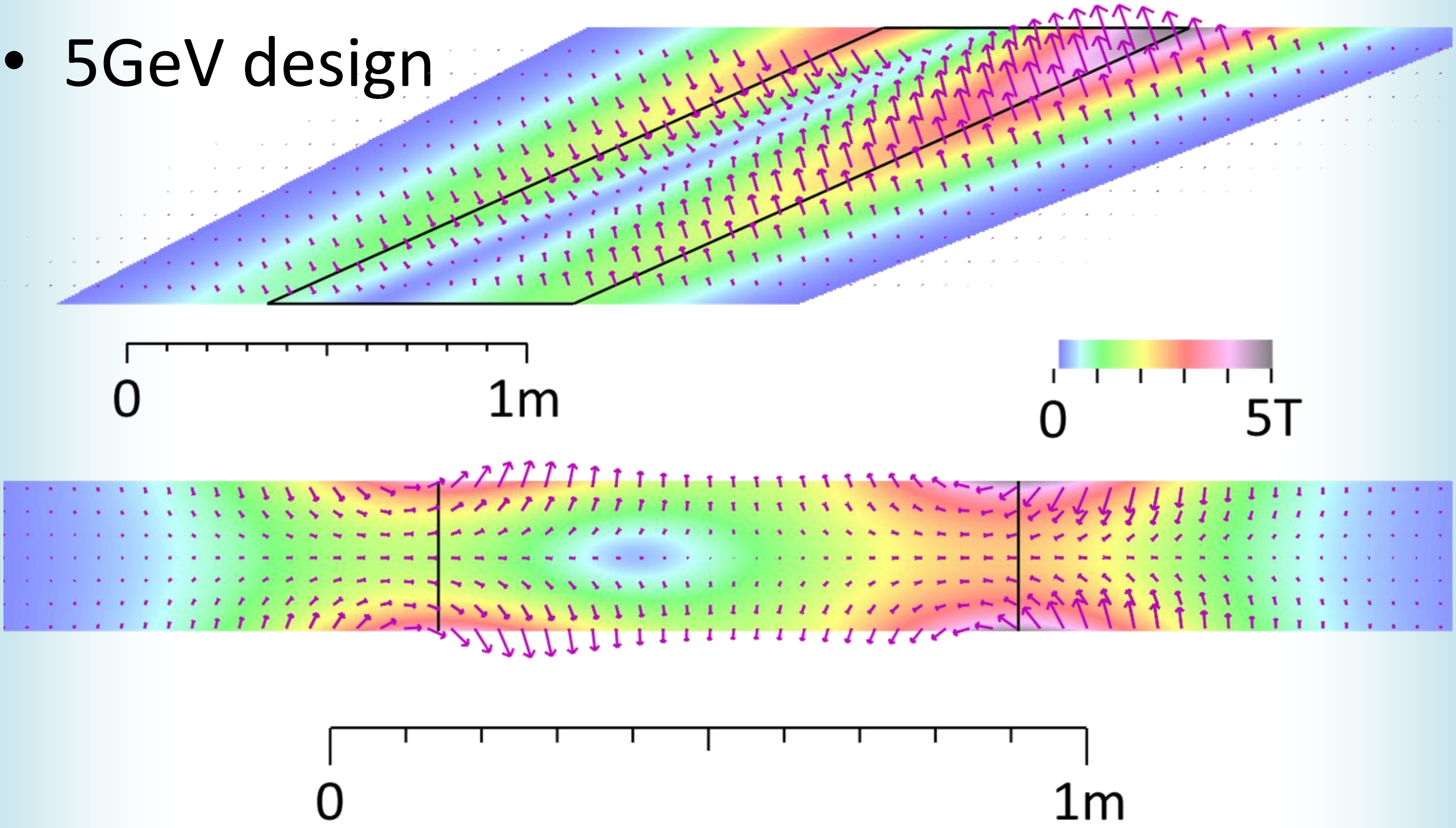
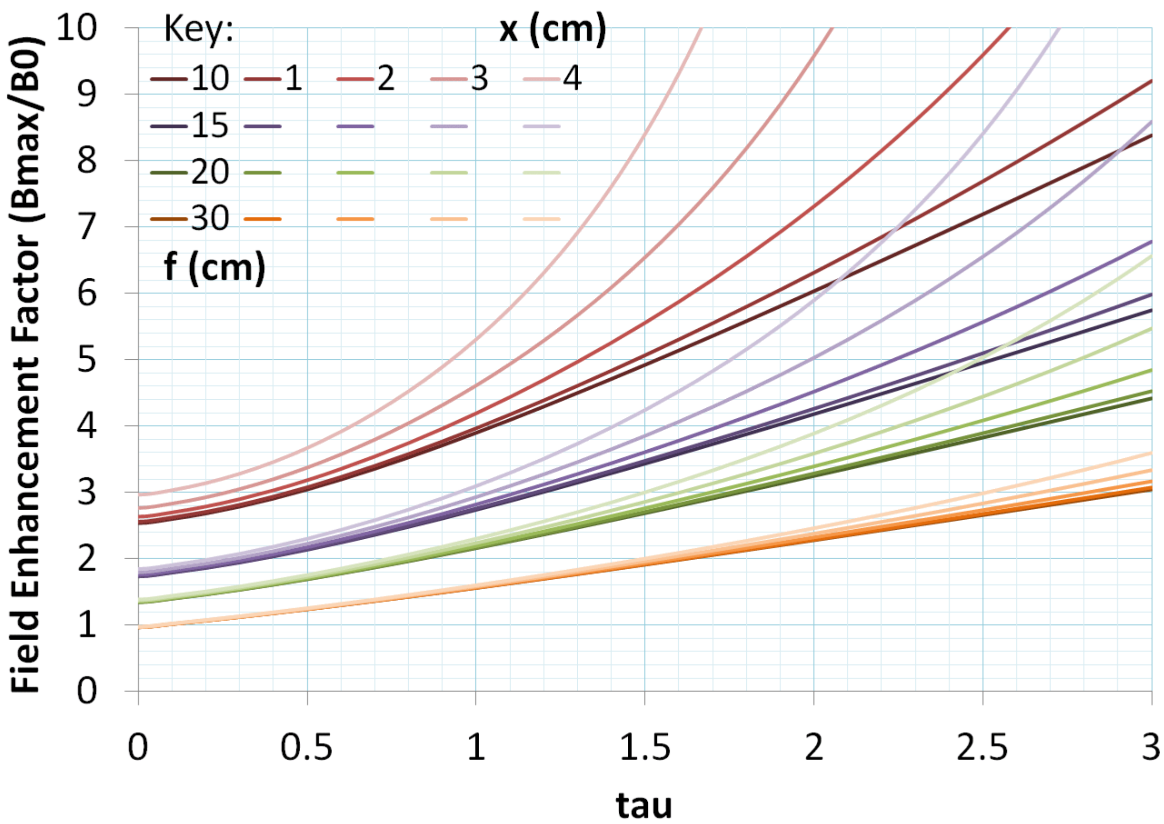


TABLE I. Transverse Parameters for VFFAG Rings

| | | | |
|---|---|---|---|
| $E_{k,\mathrm{inj}}$ | 800 MeV | | |
| $E_{k,\mathrm{ext}}$ | 3 GeV | 5 GeV | 12 GeV |
| Mean radius | 52 m (2×ISIS) | | |
| Superperiods | 80 (superperiod is one cell) | | |
| Cell length | 4.0841 m | | |
| Drift length | 3.3174 m | | 3.1257 m |
| **Magnet Parameters** | | | |
| Magnet length | 0.7667 m | | 0.9584 m |
| $B_0$ | 0.5 T | | 0.4 T |
| $k$ | $2.01\,\mathrm{m}^{-1}$ | | $2.2\,\mathrm{m}^{-1}$ |
| $\tau = \tan\theta_{\mathrm{edge}}$ | 2.23 | | 2.535 |
| $\theta_{\mathrm{edge}}$ | 65.84° | | 68.47° |
| Fringe length | $f = 0.3\,\mathrm{m}$ in $B \propto \frac{1}{2} + \frac{1}{2}\tanh(z/f)$ | | |
| $B_{\mathrm{ext}}$ | 1.3069 T | 2.0036 T | 3.5274 T |
| $B_{\mathrm{fringe}}/B_{\mathrm{body}}$ | $2.6941_{x=4\,\mathrm{cm}}$ | | $2.6174_{x=2\,\mathrm{cm}}$ |
| $B_{\mathrm{max}}$ | 3.5210 T | 5.3979 T | 9.2326 T |
| **Beam Optics** | | | |
| $y_{\mathrm{ext}} - y_{\mathrm{inj}}$ | 0.4780 m | 0.6906 m | 0.9895 m |
| $\mu_u$ (per cell) | 71.30° | | 71.29° |
| $\mu_v$ | 28.65° | | 19.56° |
| $Q_u$ (ring) | 15.843 | | 15.843 |
| $Q_v$ | 6.367 | | 4.347 |

# Field Enhancement Factor

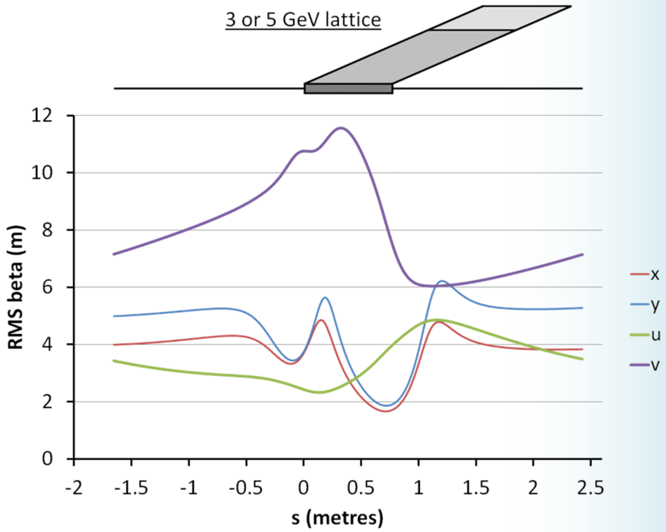
- For 3,5GeV designs with $k=2.01m^{-1}$

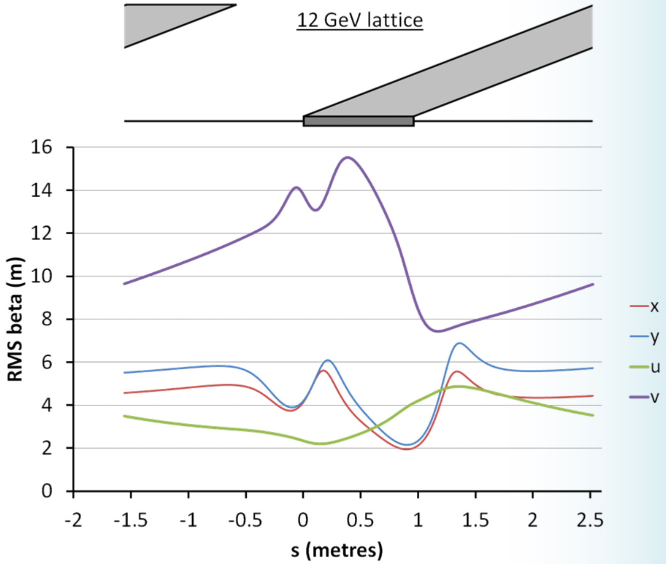


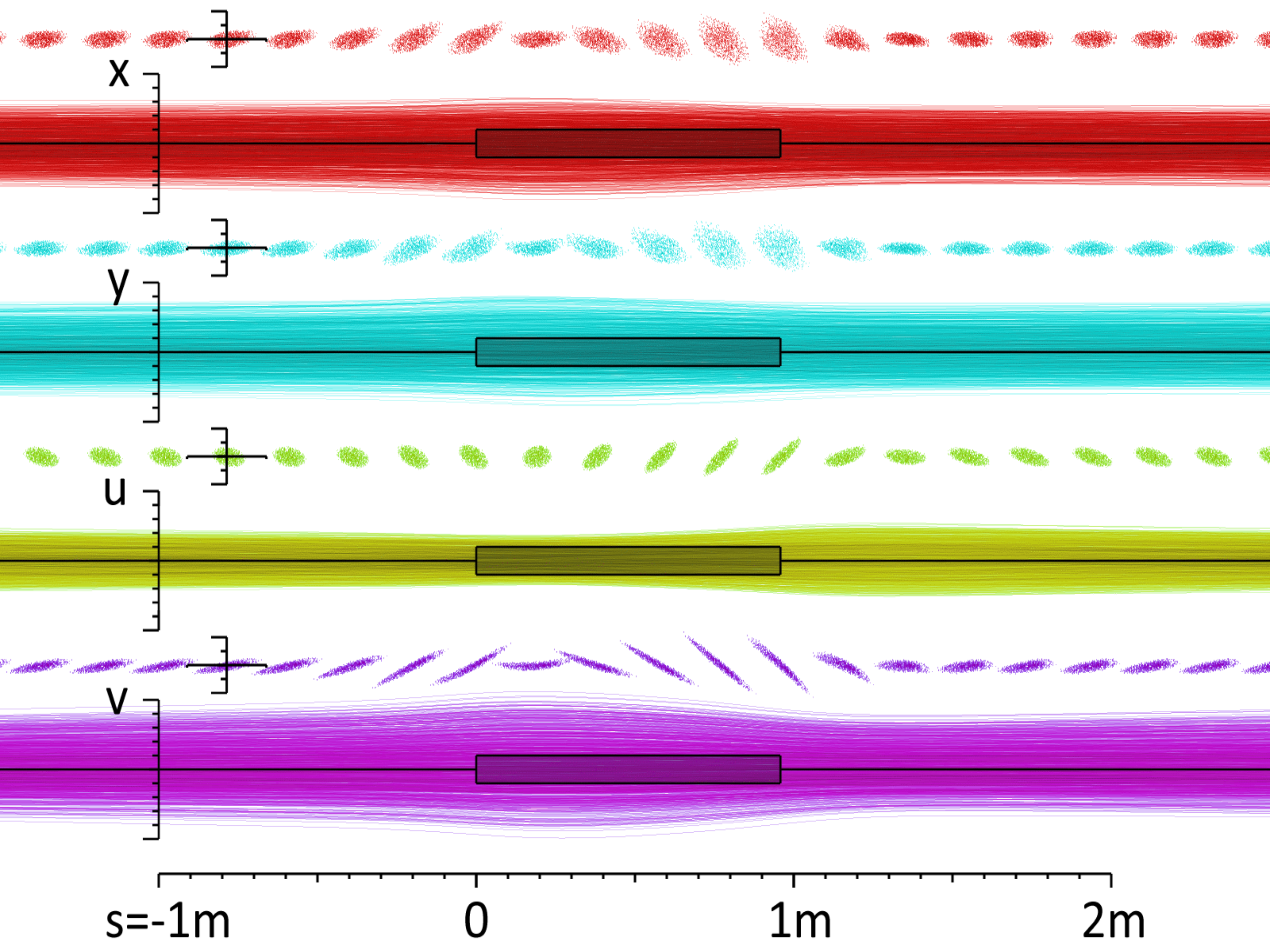
# Cell Beta Functions

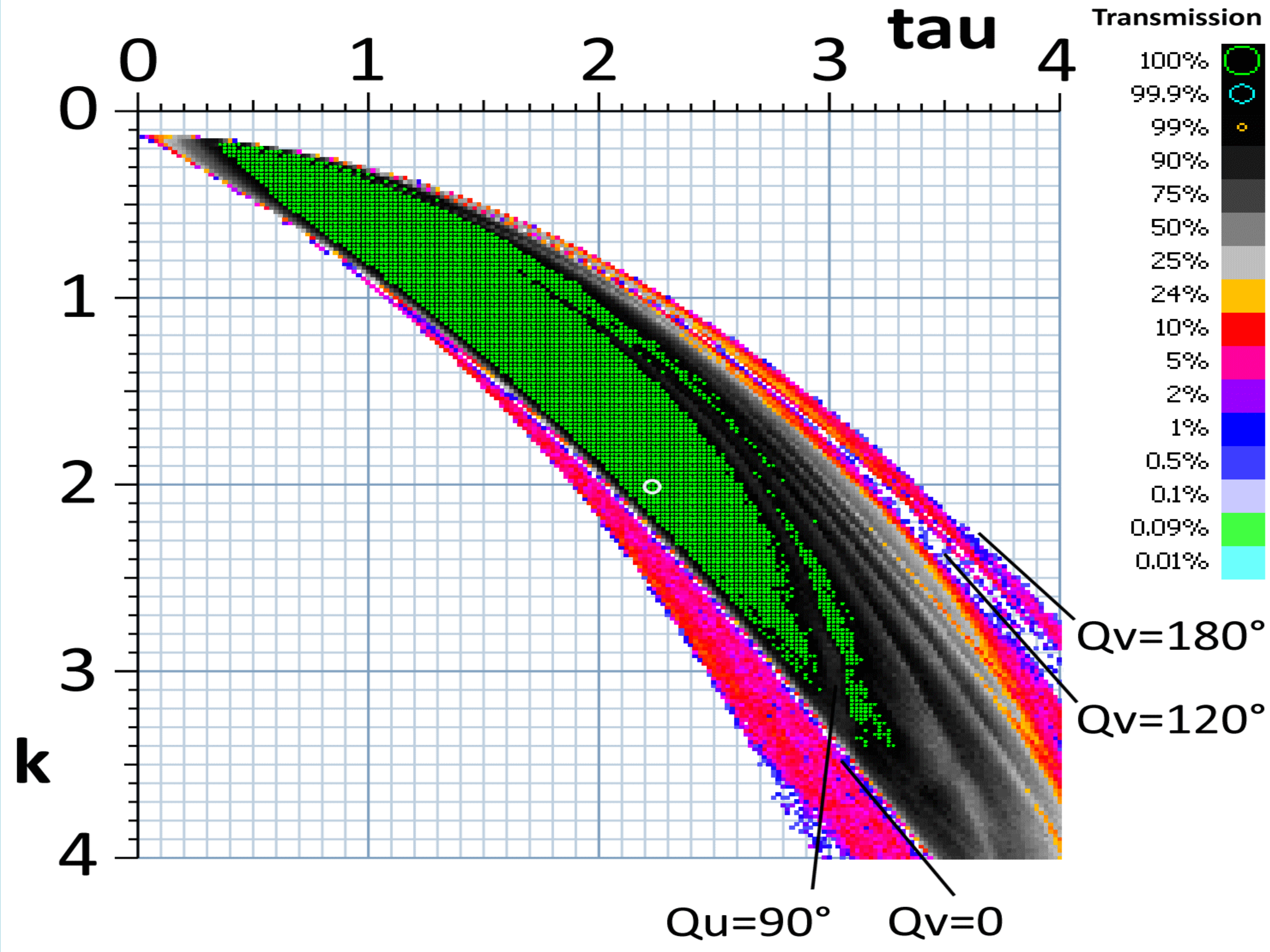
- Doublet focussing nature
  - Visible in u,v planes
- FfD
  - Doublet controlled by τ
  - Singlet controlled by k
- Ring tune sensitivity:

$$\frac{\partial Q_{u,v}}{\partial k} = \begin{bmatrix} -8.49 \\ -94.46 \end{bmatrix} \quad \text{and} \quad \frac{\partial Q_{u,v}}{\partial \tau} = \begin{bmatrix} 39.92 \\ 119.82 \end{bmatrix}$$



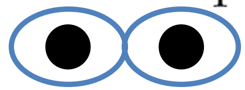



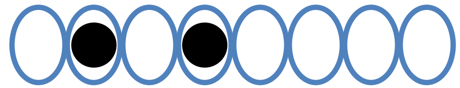

x
y
u
v
s=-1m
0
1m
2m



tau
0
1
2
3
4
k
0
1
2
3
4
Transmission
100%
99.9%
99%
90%
75%
50%
25%
24%
10%
5%
2%
1%
0.5%
0.1%
0.09%
0.01%
Qv=180°
Qv=120°
Qu=90°
Qv=0

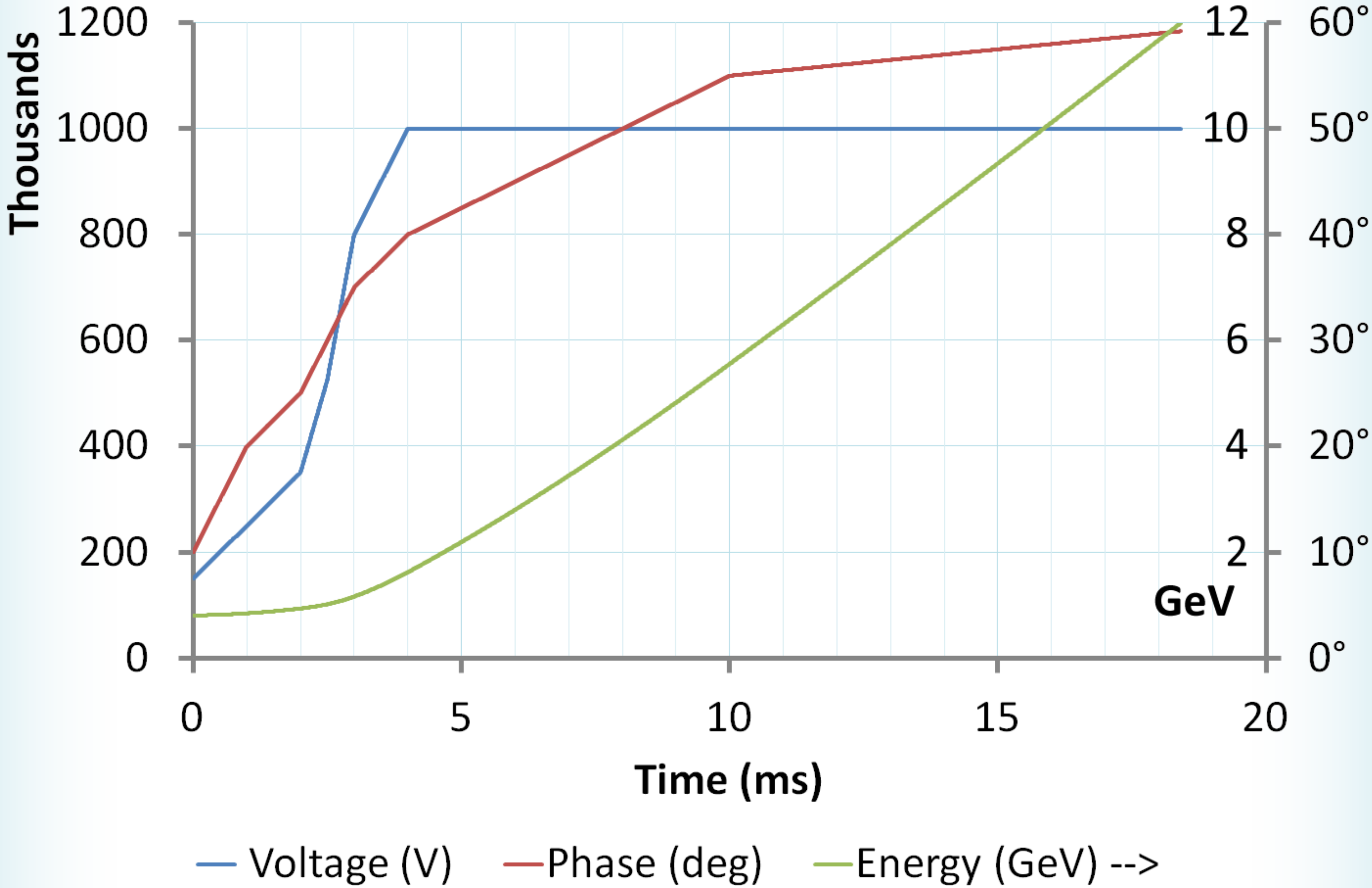
TABLE II. Longitudinal parameters for the 12 GeV VFFAG. Peak voltage per turn and phase are linearly interpolated from the times given.



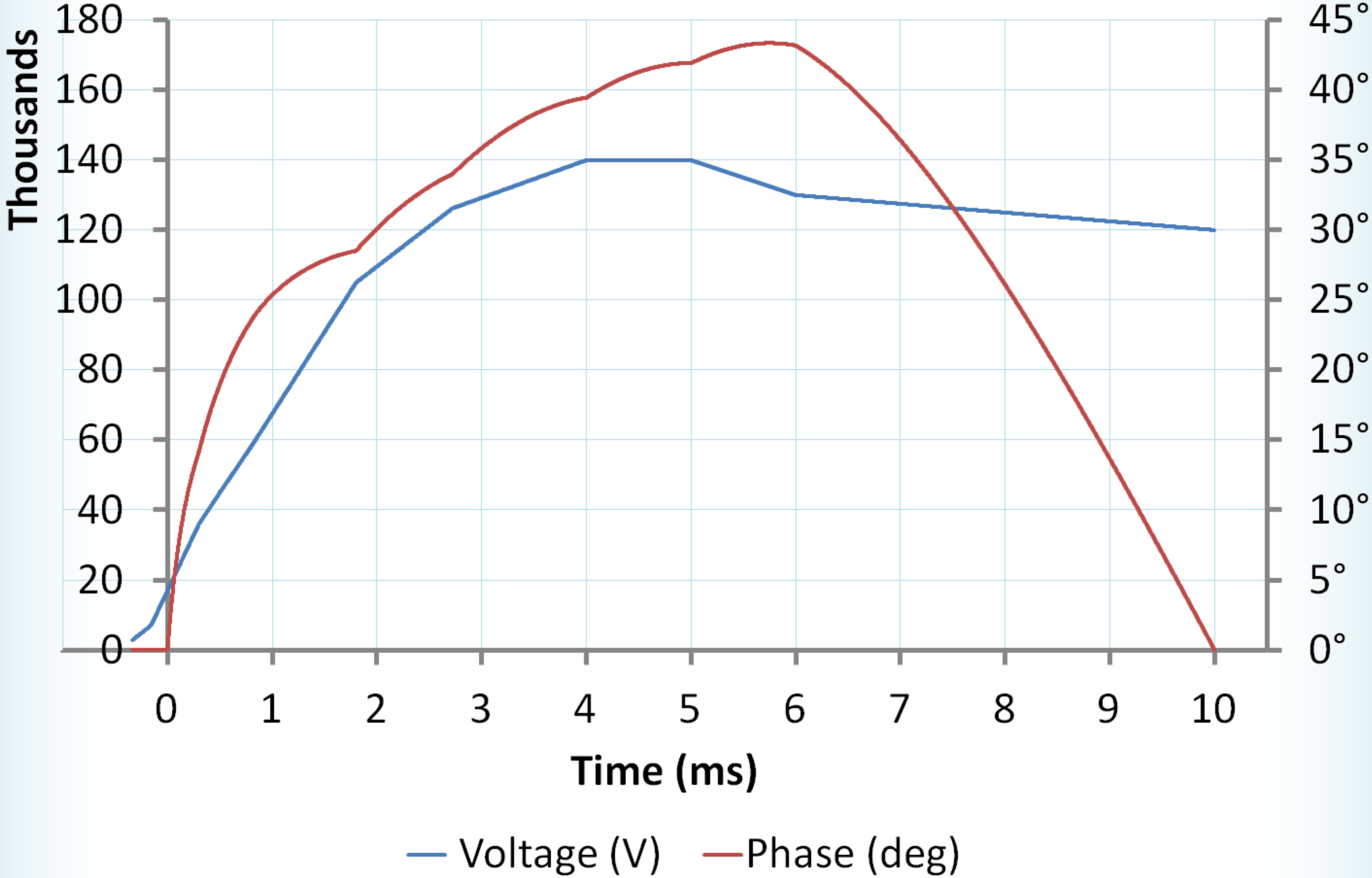


| | | |
|---|---|---|
| RF harmonic | $h = 8$ | |
| RF frequency | 6.179–7.321 MHz | |
| Cycle duration | 18.41 ms | |
| Rep. rate | 50 Hz | |
| **Time (ms)** | **Voltage (kV)** | **Phase** |
| 0 | 150 | 10° |
| 1 | 250 | 20° |
| 2 | 350 | 25° |
| 2.5 | 525 | 30° |
| 3 | 800 | 35° |
| 4 | 1000 | 40° |
| 10 | 1000 | 55° |
| *18.41 (extract)* | *1000* | *59.21°* |
| 20 | 1000 | 60° |

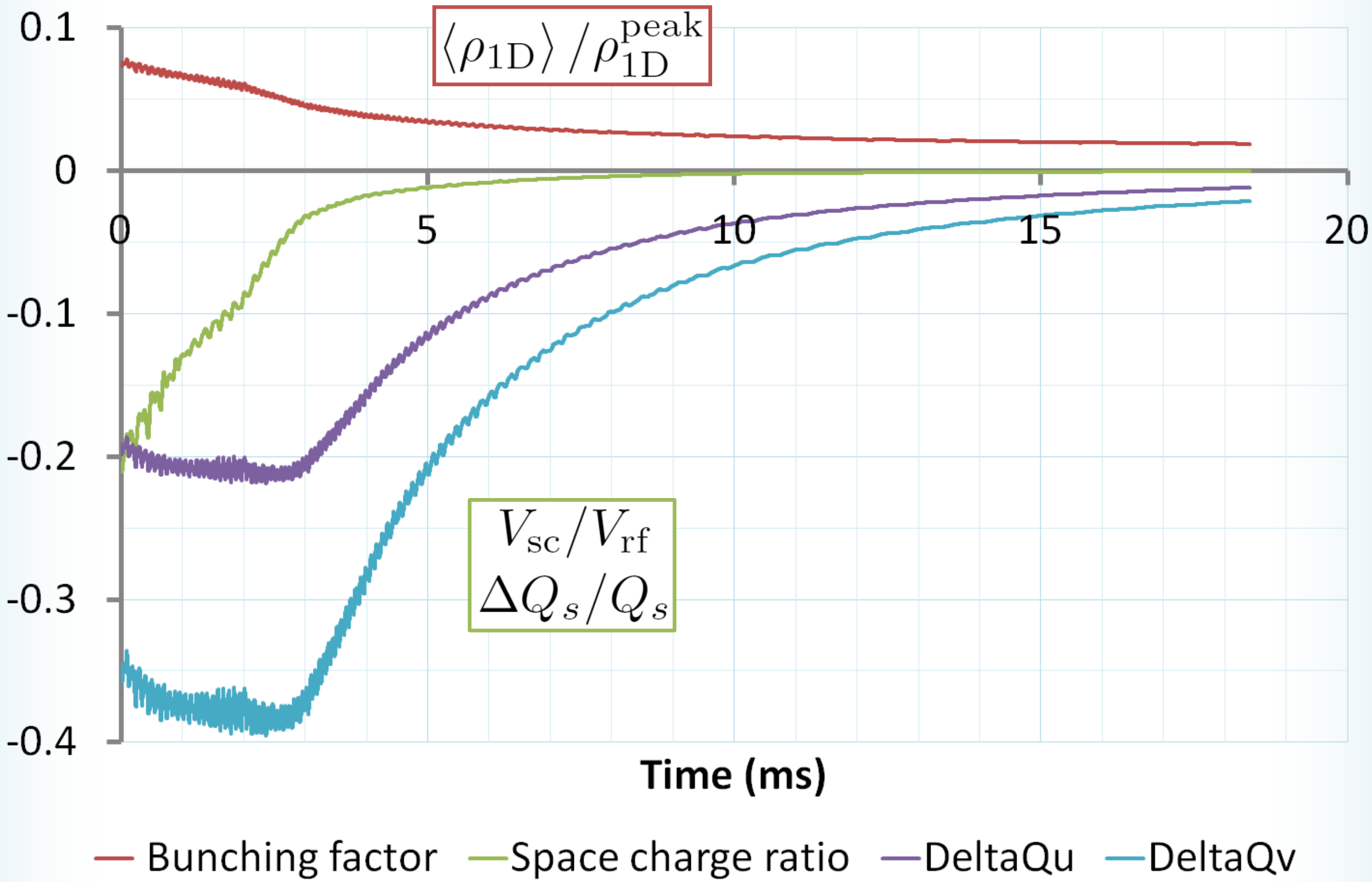
# 12GeV VFFAG RF Programme



# Compare with ISIS 1st harmonic RF



# Longitudinal Intensity Effects



# ISIS (1$^{st}$ harmonic) Intensity Effects

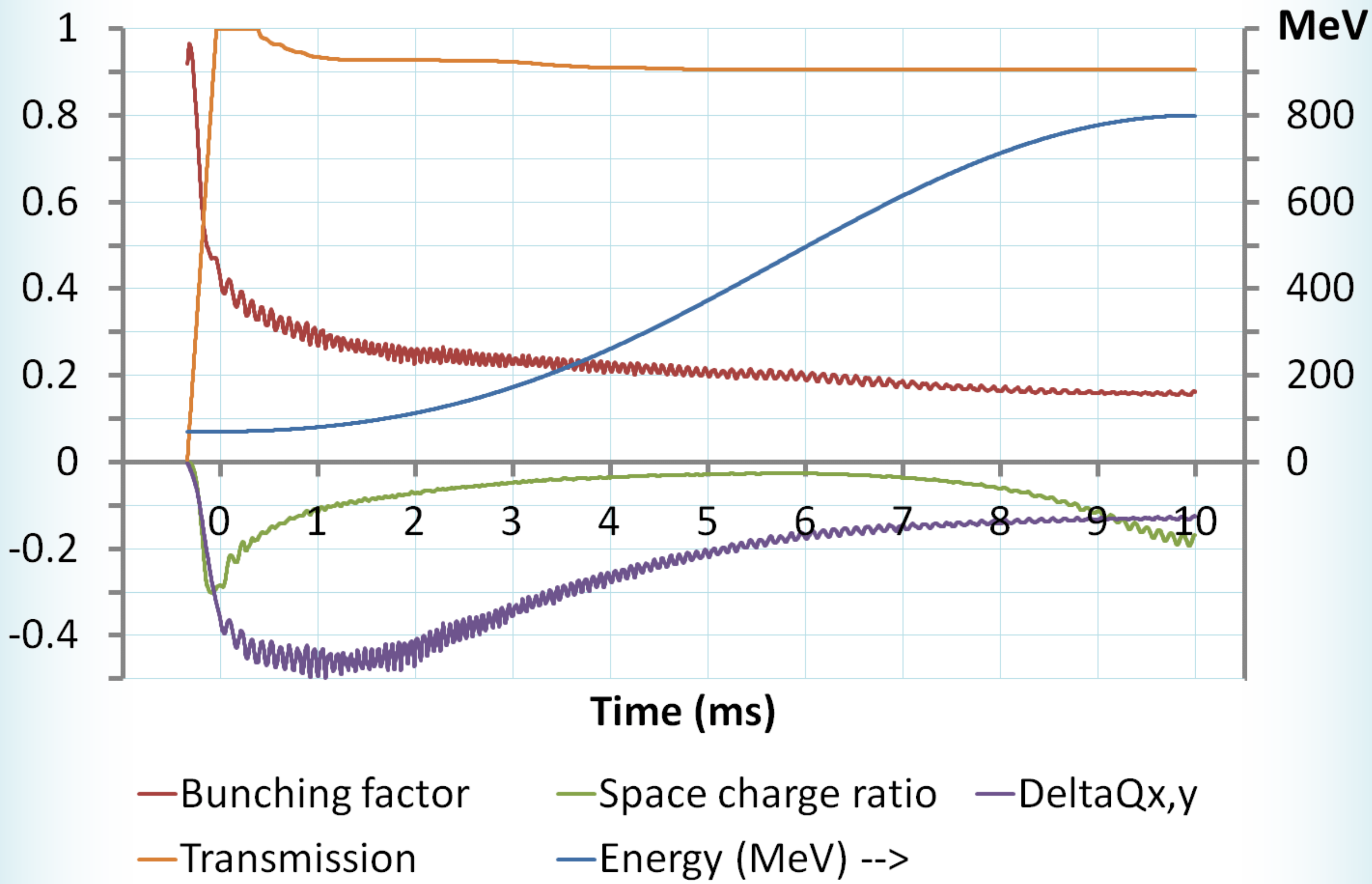
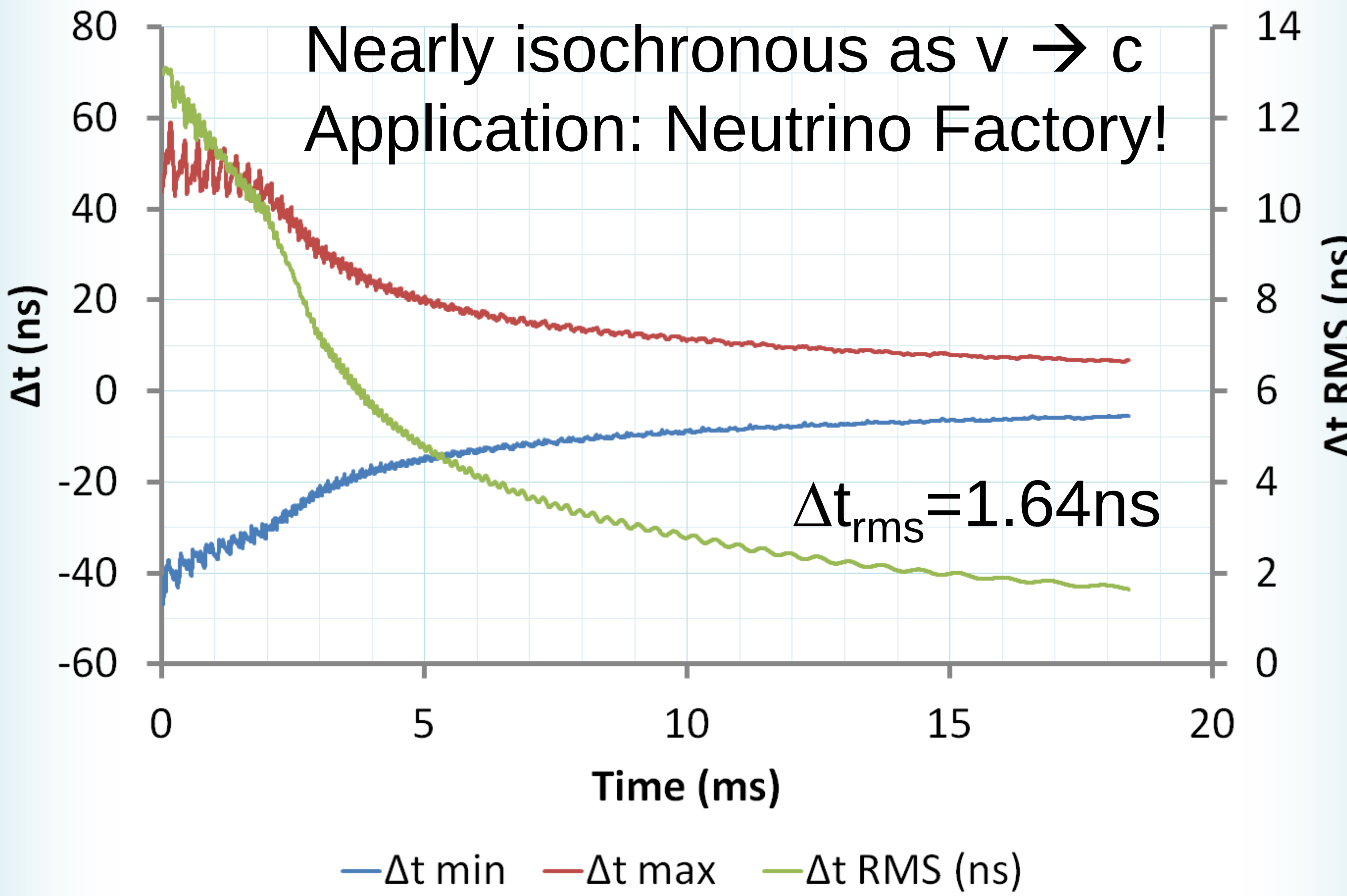


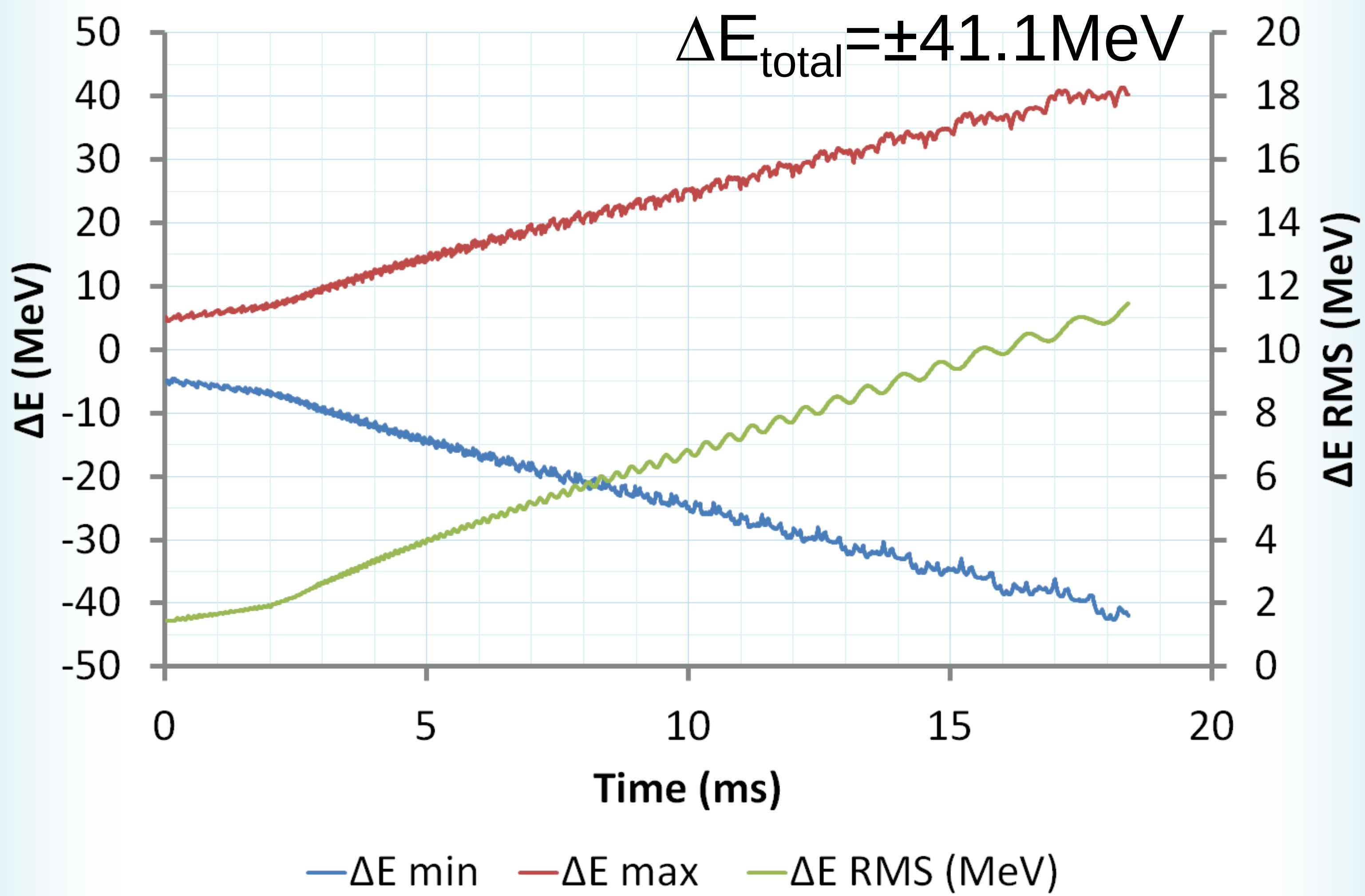
TABLE III. Intensity-dependent parameters for the ISIS single harmonic and 12 GeV VFFAG simulations run in series, for different numbers of protons injected into ISIS.

| **ISIS Protons In** | **2.50e13** | **2.75e13** | **3.00e13** |
|---|---|---|---|
| ISIS $\mu$A in | 200.3 | 220.3 | 240.3 |
| ISIS transmission | 90.54% | 87.95% | 85.98% |
| ISIS protons out | 2.26e13 | 2.42e13 | 2.58e13 |
| ISIS $\mu$A out | 181.3 | 193.7 | 206.6 |
| ISIS power (kW) | 145 | 155 | 165 |
| VFFAG transmission | | 100% | |
| VFFAG power (MW) | 2.18 | 2.32 | 2.48 |
| **ISIS Peak Intensities** | | | |
| Bunching factor | 0.154 | 0.150 | 0.151 |
| Space charge ratio | -0.301 | -0.305 | -0.311 |
| $\Delta Q_{x,y}$ | -0.499 | -0.544 | -0.580 |
| **VFFAG Peak Intensities** | | | |
| Bunching factor | 0.0188 | 0.0190 | 0.0190 |
| Space charge ratio | -0.211 | -0.257 | -0.278 |
| $\Delta Q_u$ | -0.219 | -0.240 | -0.254 |
| $\Delta Q_v$ | -0.395 | -0.434 | -0.458 |

# VFFAG Bunch Duration Evolution

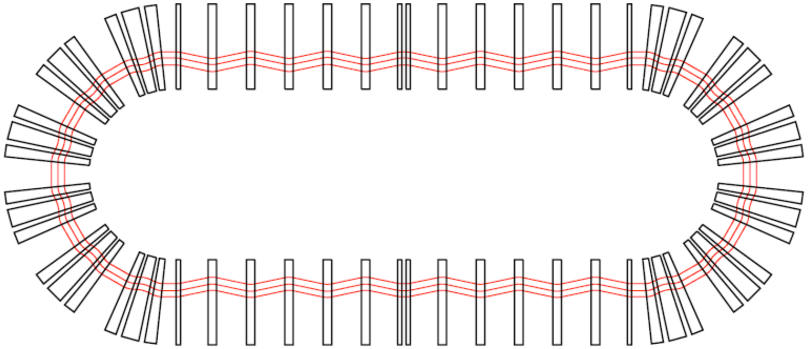


# VFFAG Bunch Energy Spread



# Proton Driver VFFAG Next Steps

- RF programme promising
  - But cavities won’t fit in diagonal-shaped drifts!
- Adapt Yoshi Mori’s idea of insertions in scaling FFAGs [Mori, FFAG11] to scaling VFFAGs



  - Arc section using magnets with edge focussing
  - Straight section using FODO lattice, long drifts
- Then 2+1/2.5D simulation with space charge

# III. Isochronous Machines

# Tilted Orbit Excursion

- Any angle θ is allowed, not just vertical!
  - Quadrupole field will rotate by θ/2
- Curved orbit excursion allows orbit radius ∝ velocity

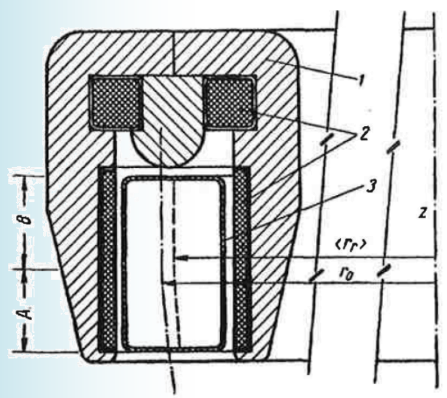
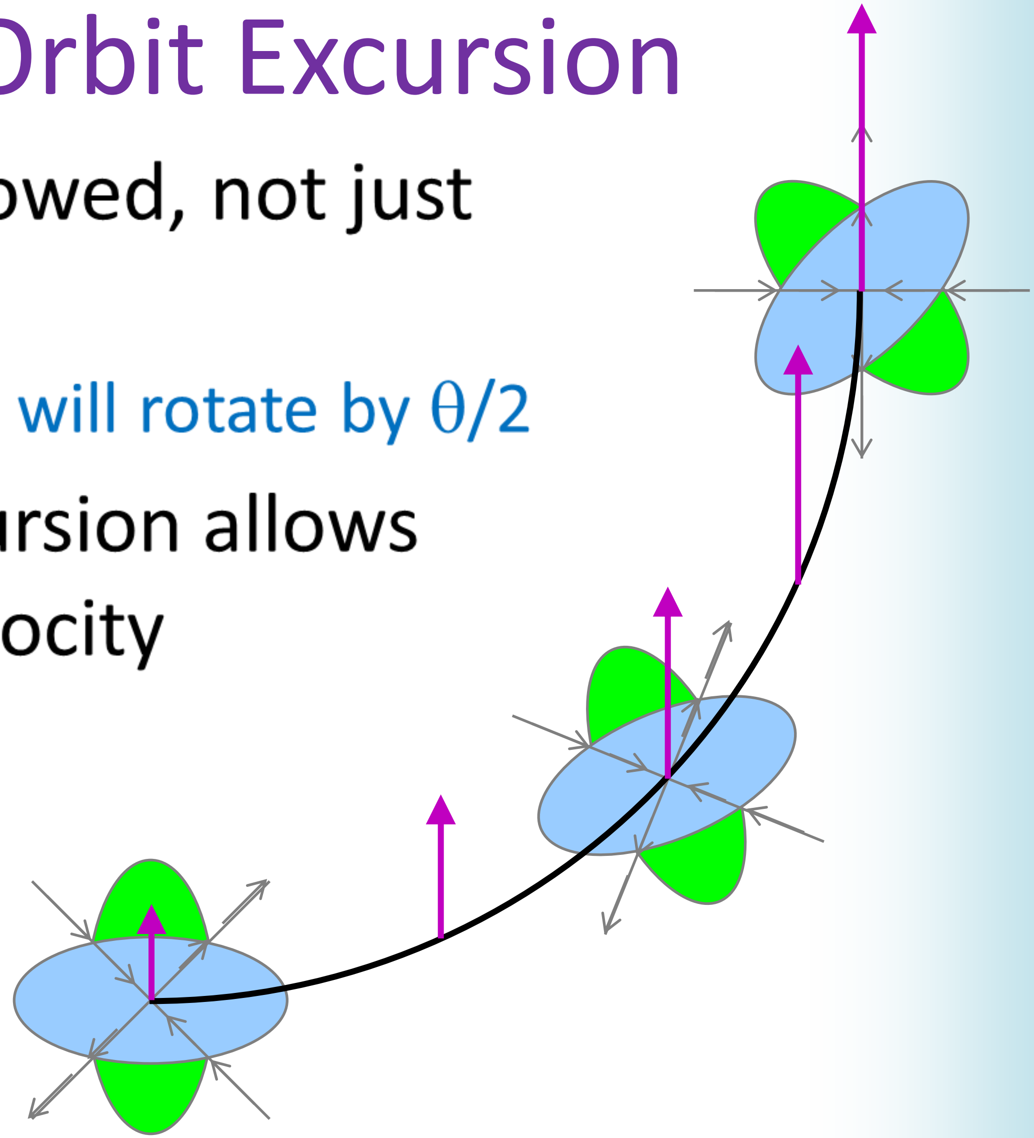



Fig. 1. Schematic section of accelerator with vertically increasing field: 1) ring magnet; 2) excitor windings for directing and focusing fields; 3) vacuum chamber; A) relativistic region; B) ultrarelativistic region.



← Teichmann (1962) also had idea

# Analysis without Weak Focussing

- Mean radius $r = \beta R$ where $R = c/2\pi f$
- Mean $B_y = p/qr = m\beta\gamma c/q\beta R = \gamma(mc/qR) = \gamma B_0$
- For optics to scale, $B'l/p$ = const. ($B'=dB_y/ds$)
  - $B'l/p = B'r\Theta/m\beta\gamma c = B'\beta R\Theta/m\beta\gamma c = (B'/\gamma)(R\Theta/mc)$
  - $B' \propto \gamma \propto B_y$, therefore $B_y = B_0 e^{s/S}$ and $s = S \ln \gamma$
  - ...for some scaling length $S=1/k$
- To fix strong focussing tune, $B_y$ must be exponential along the curved orbit excursion!

# Lower Velocity Bound

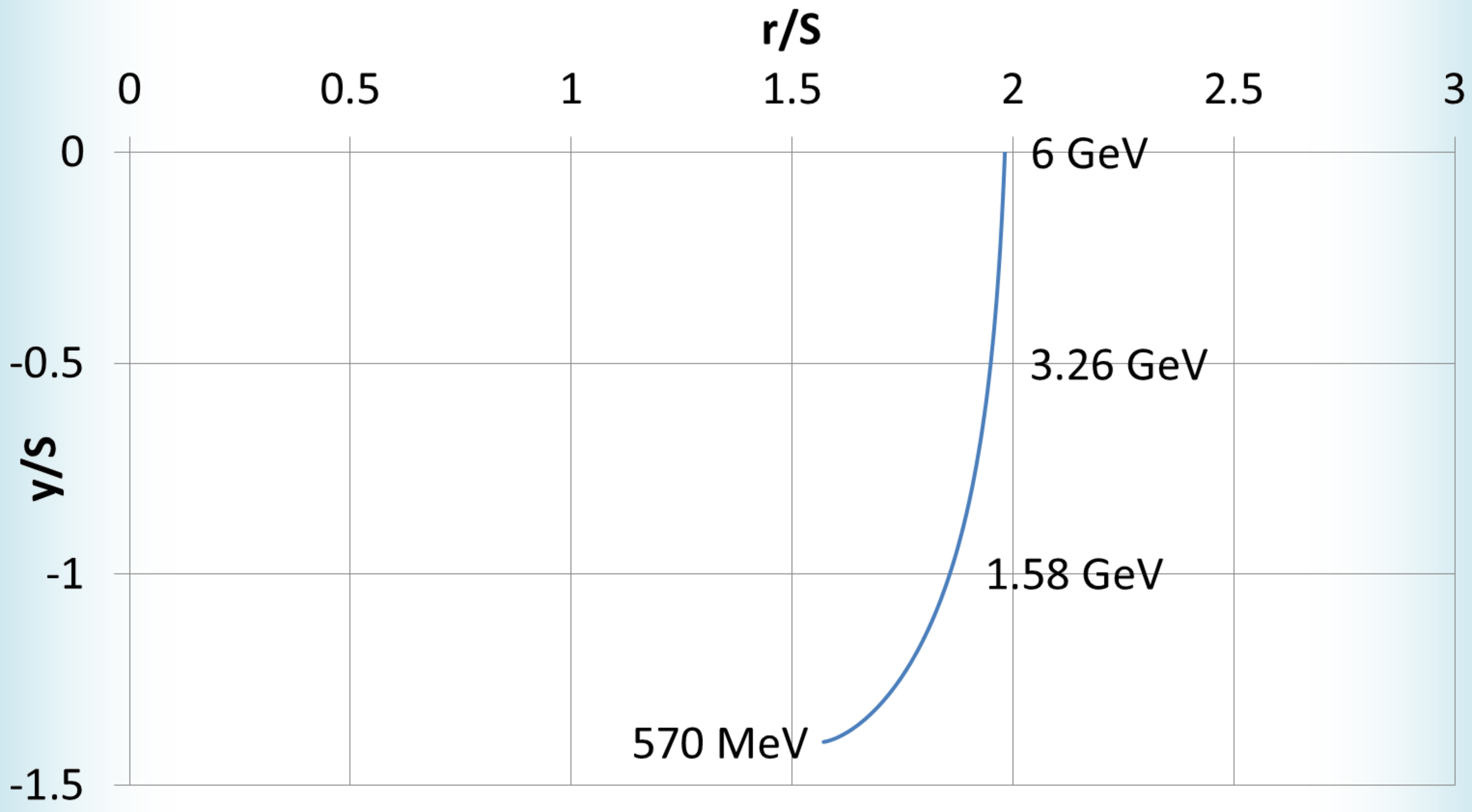
- Haven't yet used fact $\beta$, r are related to $\gamma$, s, $B_y$
- $r = \beta R = R\sqrt{1-\gamma^{-2}} = R\sqrt{1-e^{-2s/S}}$
- s is arc length so $dr/ds \leq 1$
  - Differentiate: $dr/ds = \frac{Re^{-2s/S}}{S\sqrt{1-e^{-2s/S}}} = \frac{R\gamma^{-2}}{S\beta} = (R/S)/\beta\gamma^2$
- Therefore $\beta\gamma^2 \geq R/S$ for scaling isoch. VFFAGs
  - Equality at horizontal excursion (minimum energy)
  - $dr/ds \rightarrow 0$ as $v \rightarrow c$ so asymptotically vertical
  - Compact machines require large R/S, high energy

# Lower Energy Bounds for Protons

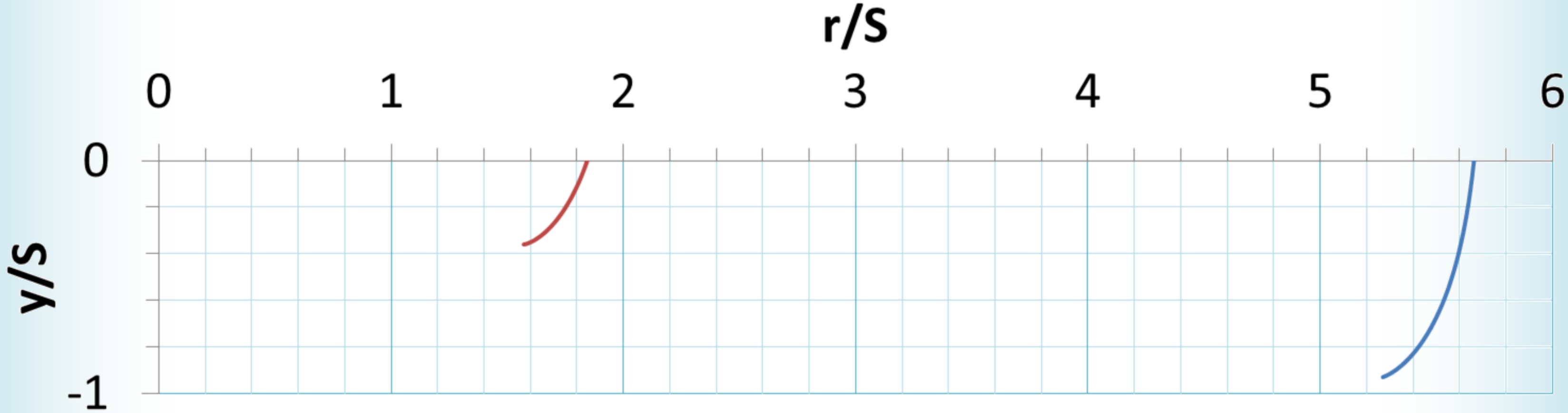
| Minimum Proton Energy | $\beta$ | Maximum R/S = $\beta\gamma^2$ |
|---|---|---|
| 100 MeV | 0.428 | 0.52 |
| 200 MeV | 0.566 | 0.83 |
| 500 MeV | 0.758 | 1.78 |
| 1 GeV | 0.875 | 3.73 |
| 2 GeV | 0.948 | 9.29 |

- For muons or especially electrons, things are much easier!
- Can’t join a cyclotron smoothly onto a *scaling* isochronous VFFAG with a different tune

# Orbit Excursion Shape (R/S=2)



# Staged Example




**R/S = 2**
1.49 GeV
580 MeV

**R/S = 5.7**
6 GeV
1.49 GeV

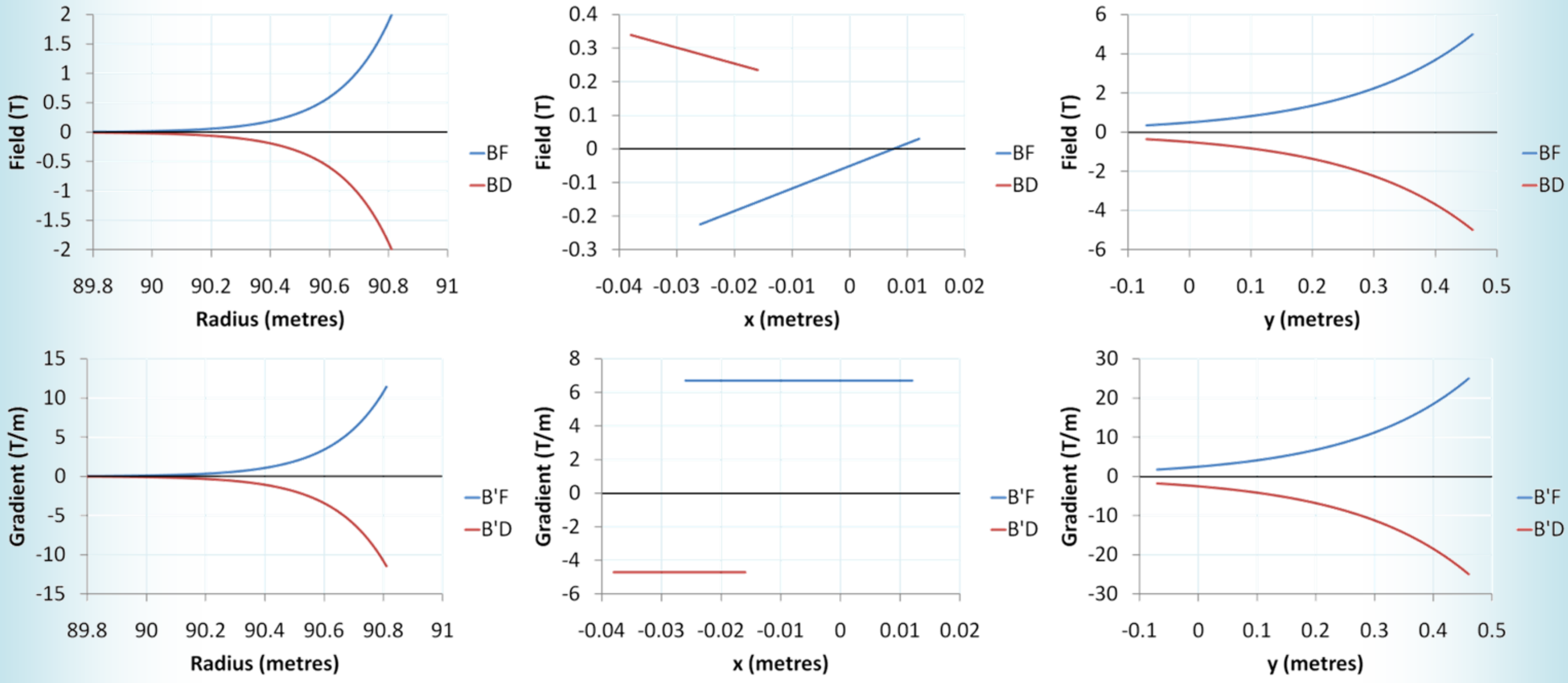
- If injector is PSI's 2.2mA 590MeV cyclotron, this two-VFFAG booster yields 13.2MW CW protons at 6GeV

# Prospects for Isochronous VFFAGs

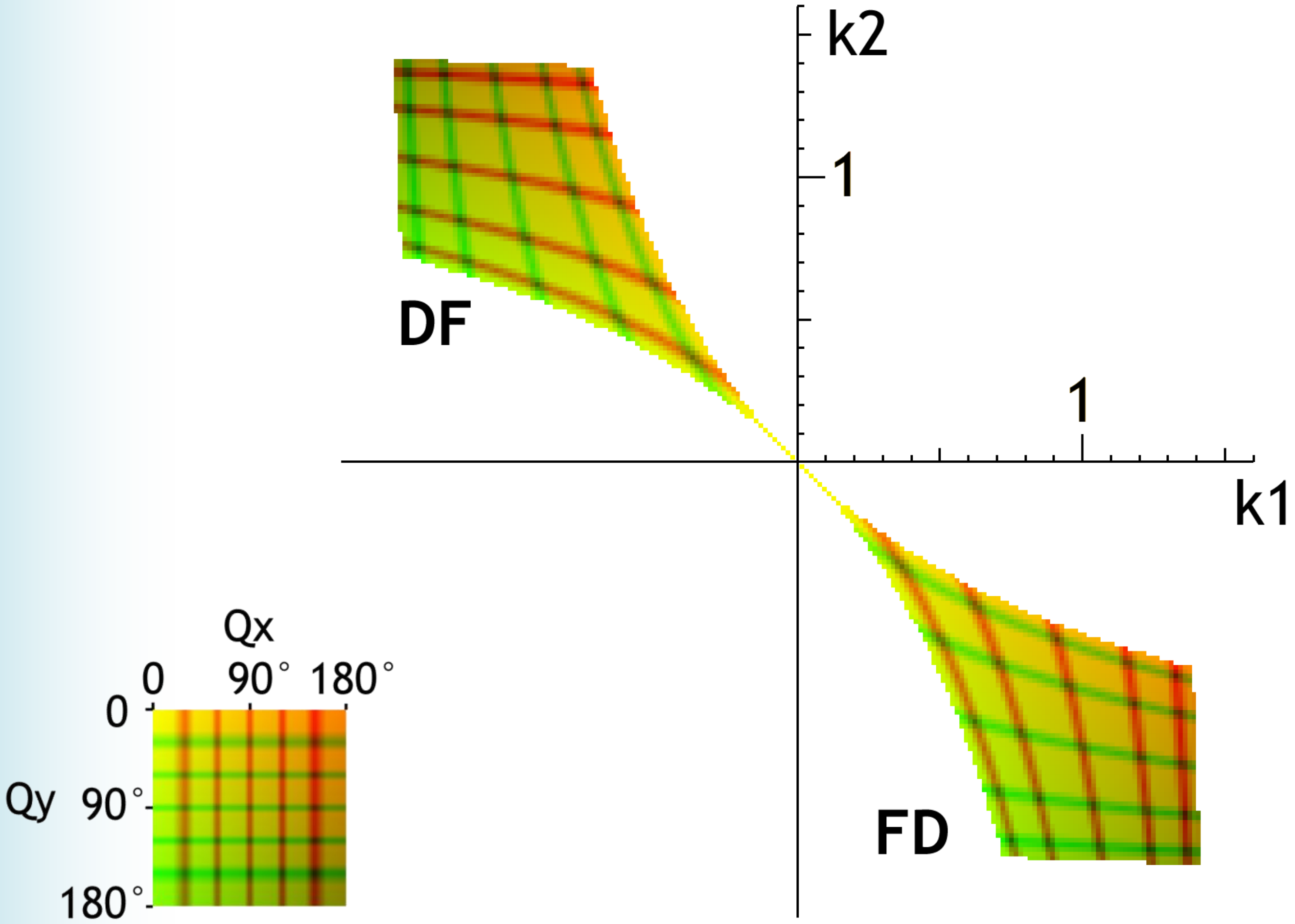
- I don’t see these beating cyclotrons at ≤ 1 GeV
  - …for protons.
  - Electrons: alternative to RCS?
  - Muons: alternative to non-scaling FFAGs?
- Protons at many GeV are potentially interesting for exotic particle factories
  - E.g. pbars, in terms of raw yield, though I believe most capture schemes assume a non-CW beam

# IV. Three-Lens Horizontal FFAGs

# Two Magnet Families Only

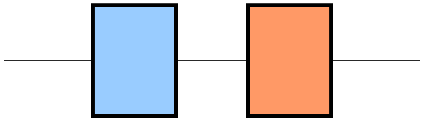


# Two-Lens Stability Diagram

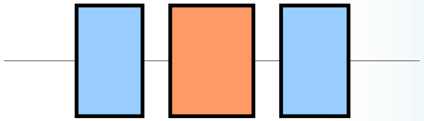


# Three-Lens Lattice Advantages

- Extended energy range non-scaling FFAGs
  - Allows gradient reversals e.g. FFD changing to FDD
- Fixed-tune non-scaling FFAGs
  - With at least three free gradients, you can satisfy
    - $dQ_x/dp = dQ_y/dp = 0$
  - …and not become a scaling FFAG!
- Two-lens:

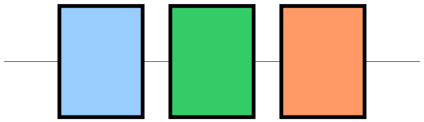


FODO or doublet

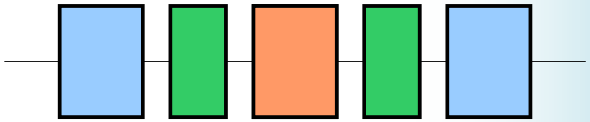


Triplet

- Three-lens:

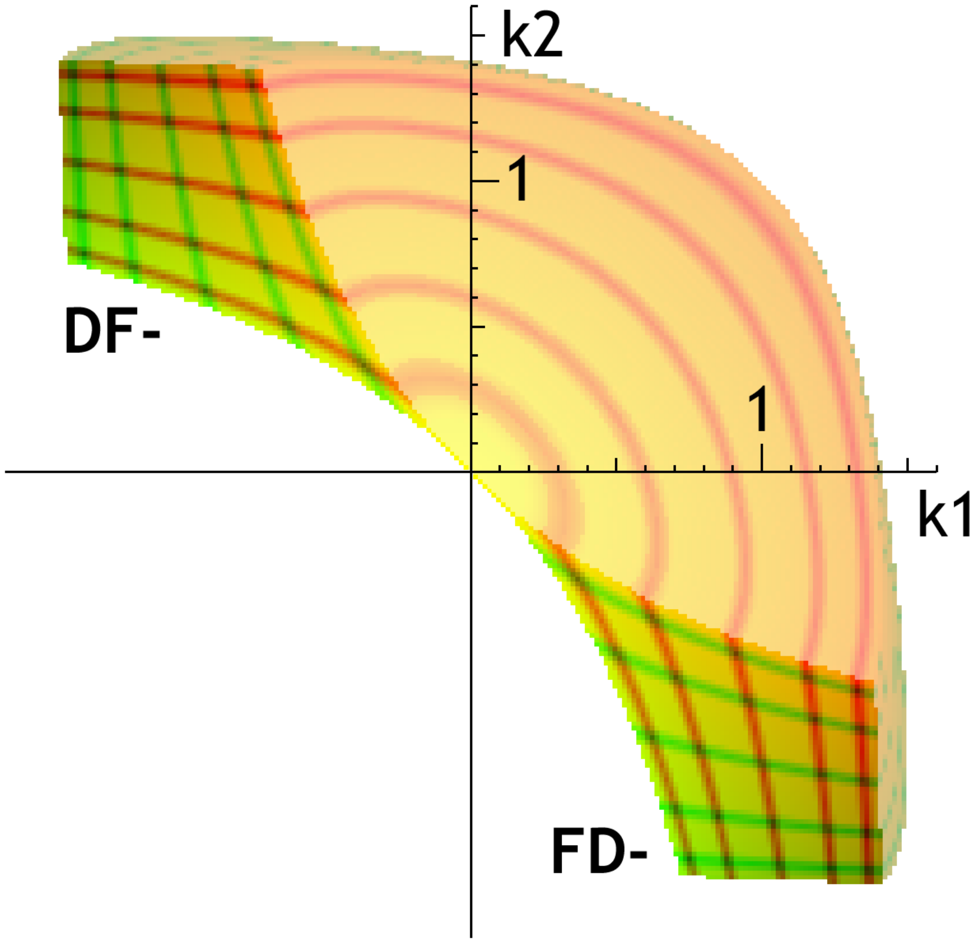


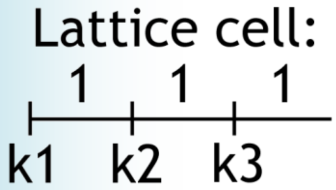
Three-lens FOGOHO



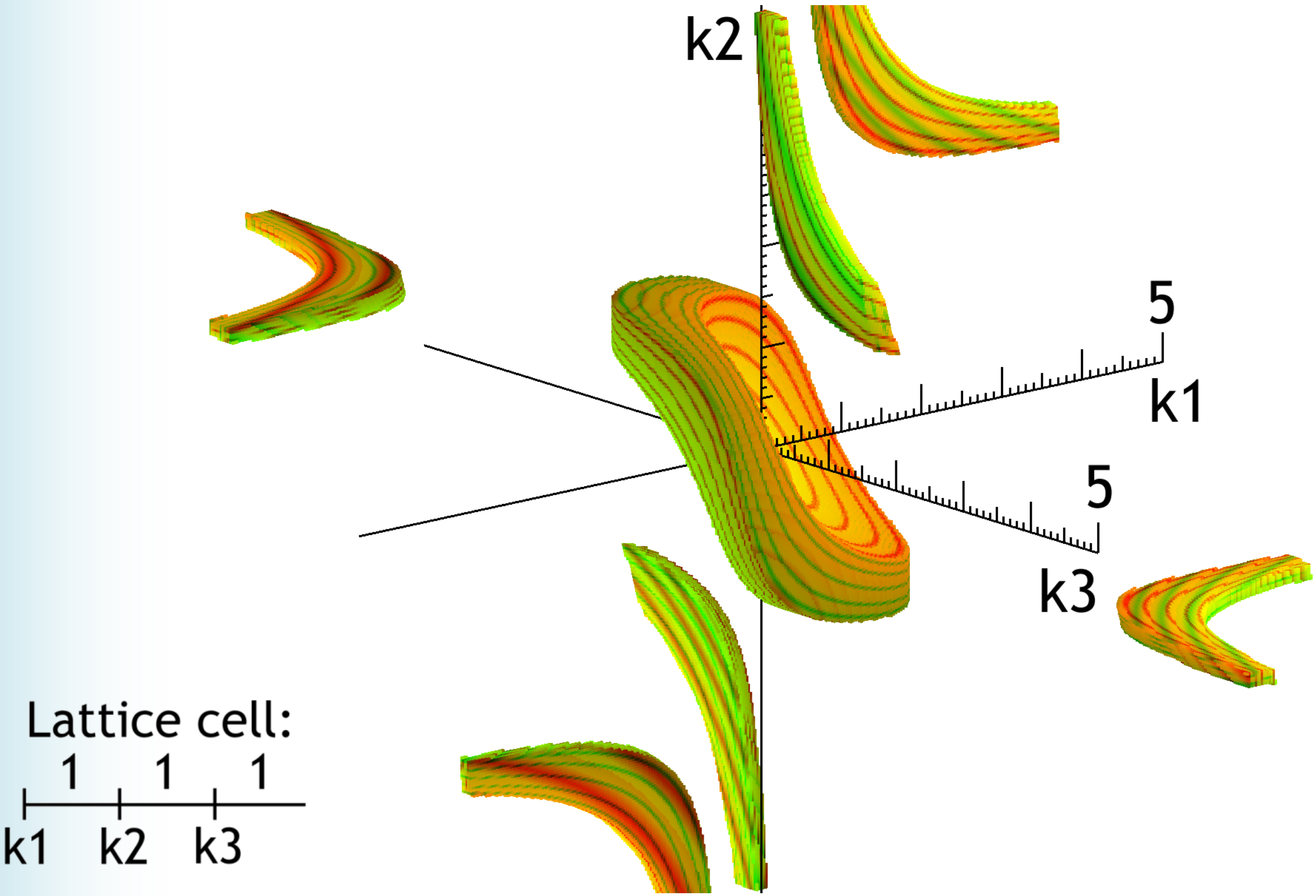
Grahame Rees's pumplet lattice

# 3D "Necktie" Diagram

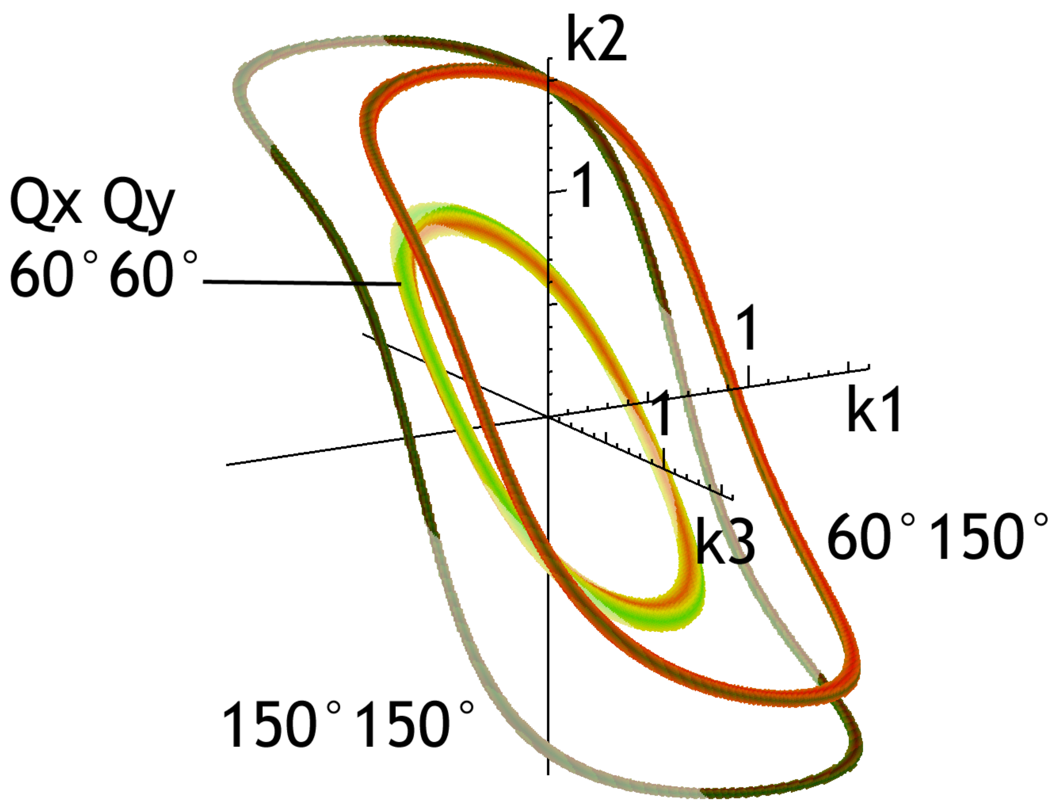


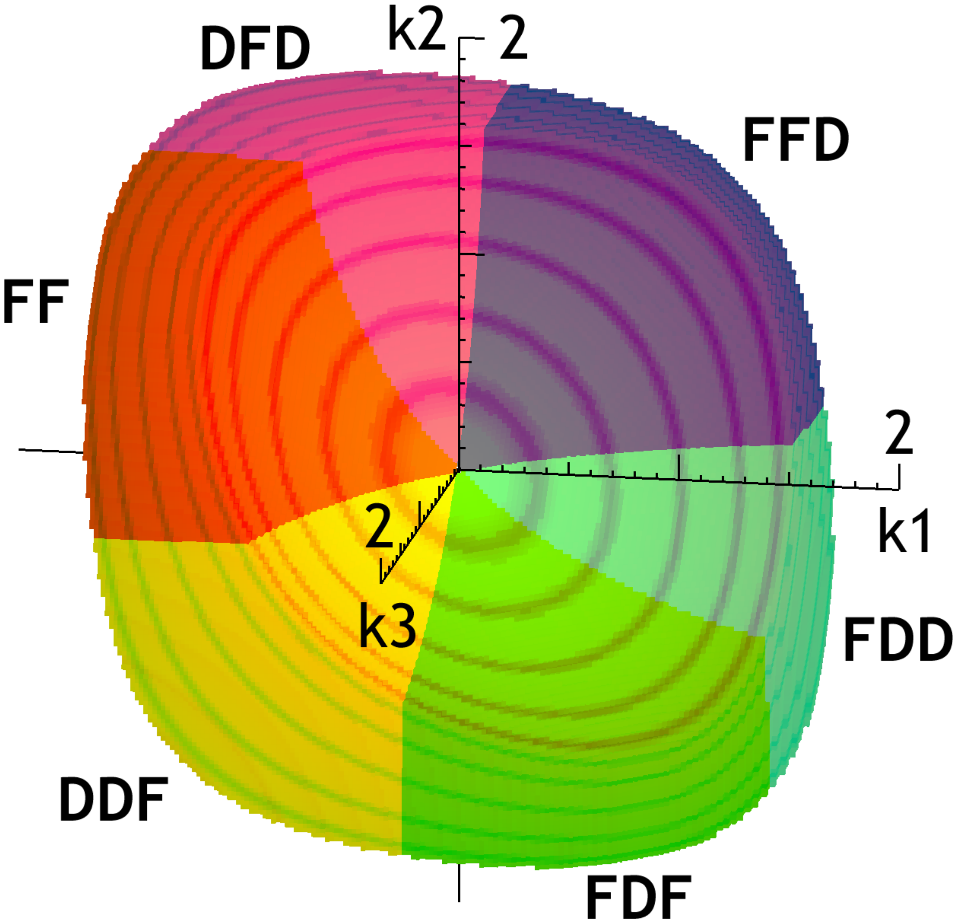
# Three-Lens Stability Regions



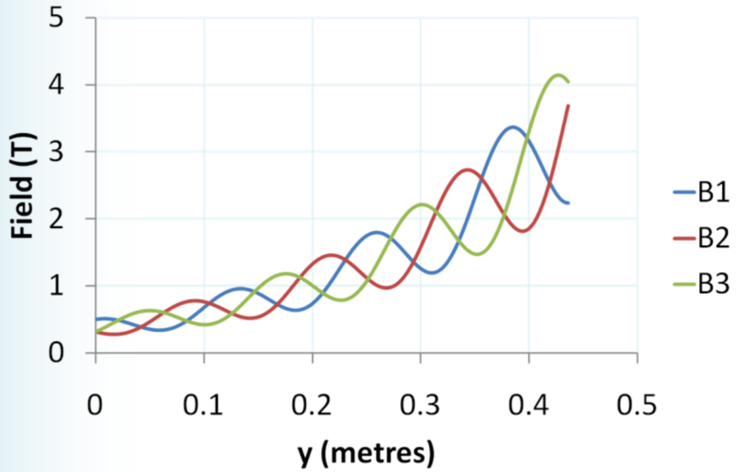
# Loci of Fixed Tune

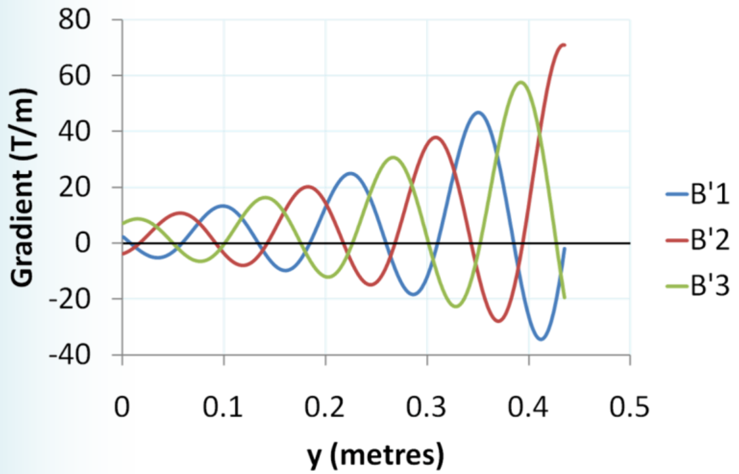


# Change in Nature of Lattice



# [IPAC11] attempt at 3-lens VFFAG




- Maybe somehow all magnets can bend the right way?

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

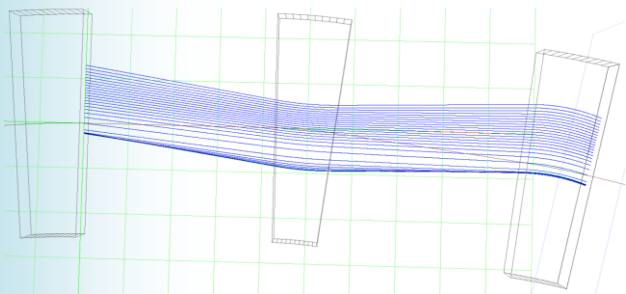
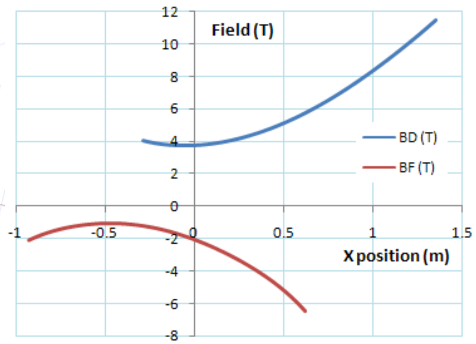
- Didn't work

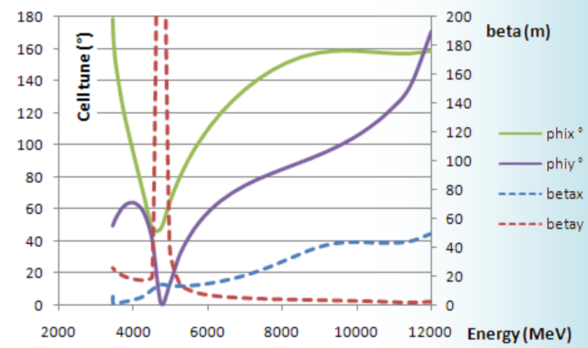
# [PAC09] Optimiser designed FFAG

- Before the VFFAG idea, I tried to make a non-scaling (horizontal) FFAG 12GeV proton driver
- Used the Muon1 optimiser (evolutionary algorithm) on field polynomials $B_{y,n}(x)$
  - Previously used on neutrino factory
    - http://stephenbrooks.org/muon1/ distributed project
- Scored 0-100 for percentage of energy range with stable closed orbits
- Didn't work

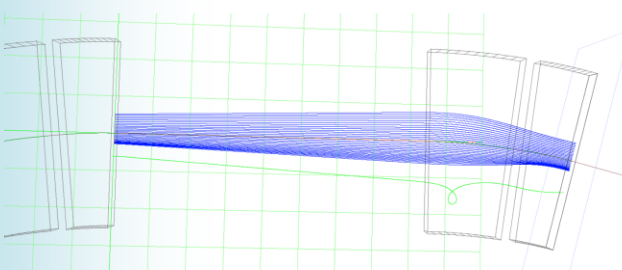
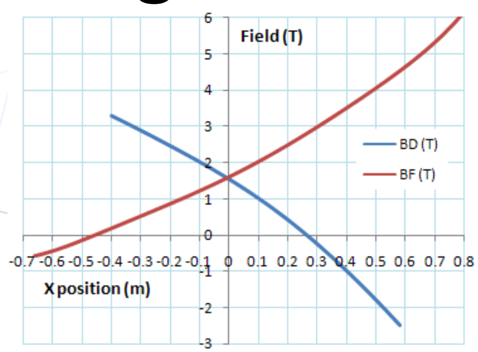
# FFAGs not working in more detail

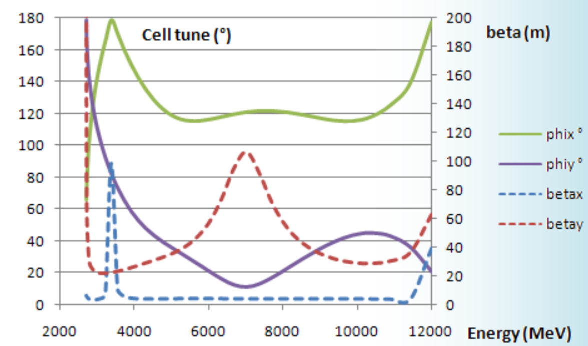
- FODO cell not working:



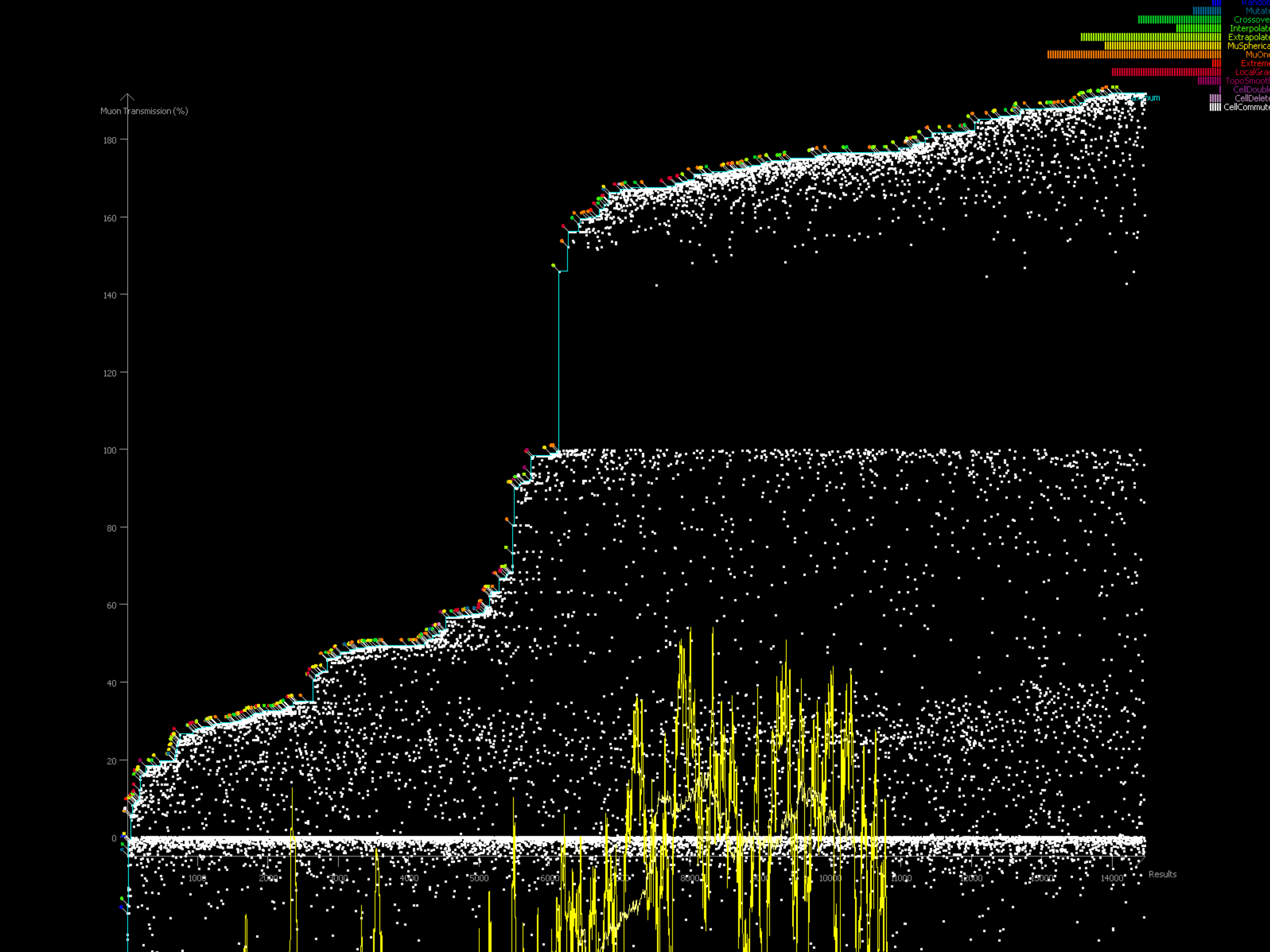

- Doublet not working:



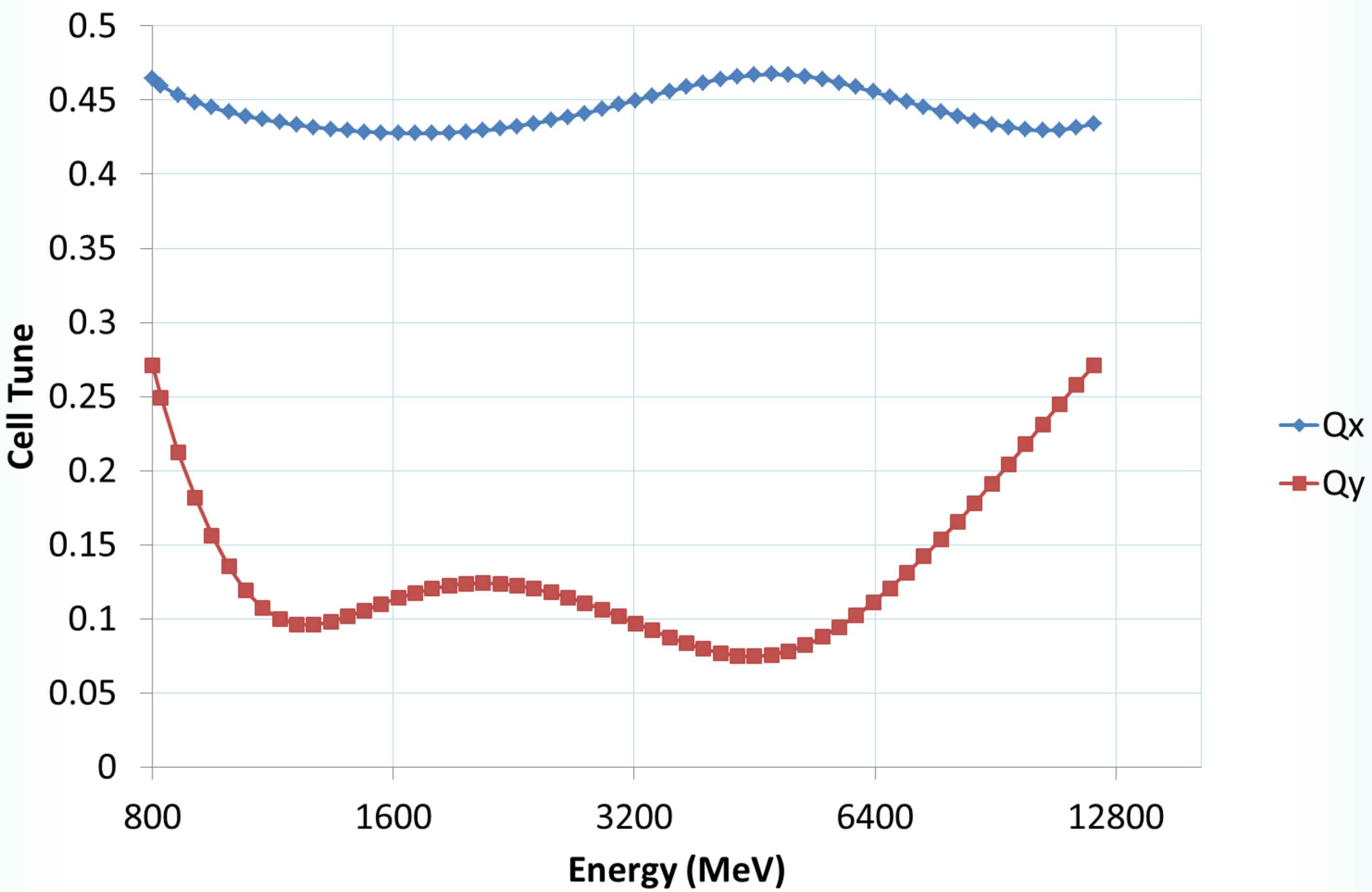
# (2013) Combine the two ideas

- Use the optimiser on a 3-lens horizontal FFAG
  - Just add a third magnet to the proton driver cell
- Score 0-100 for energy range with stable orbit
  - and because we're being optimistic,
- Score 100-200 for flat cell tunes
  - score = 200 – 100 ( $Q_{x,max} - Q_{x,min} + Q_{y,max} - Q_{y,min}$ )
  - Provided the full energy range is stable
- Final score: 196.601

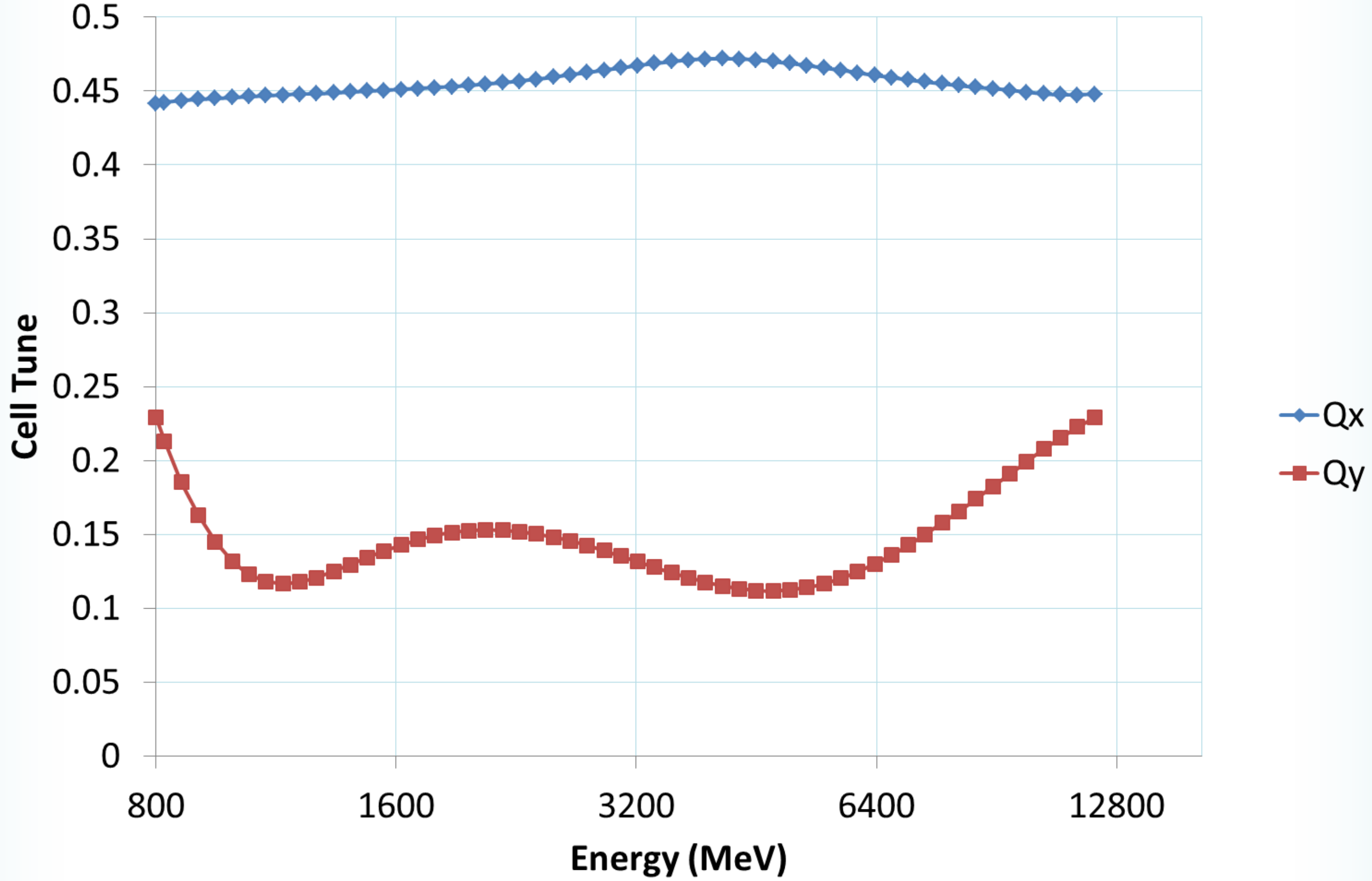


Muon Transmission (%)
180
160
140
120
100
80
60
40
20
0
1000
2000
3000
4000
5000
6000
8000
10000
11000
12000
13000
14000
Results
Mutat
Crossove
Interpolate
Extrapolate
MuSpherica
Extrem
LocalGra
TopoSmoot
CellDouble
CellDelete
CellCommute

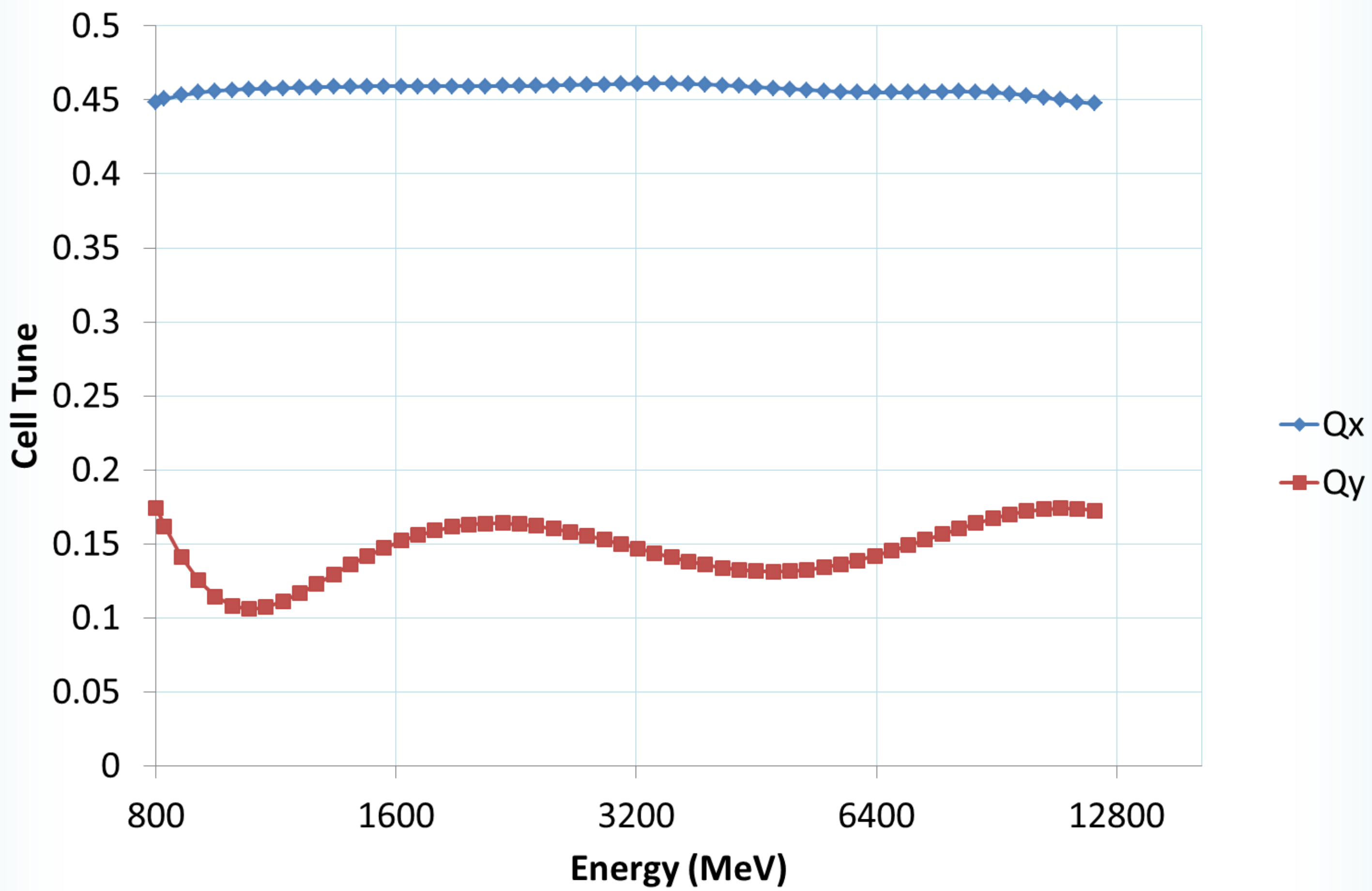
# Tune Variation, score = 176.379



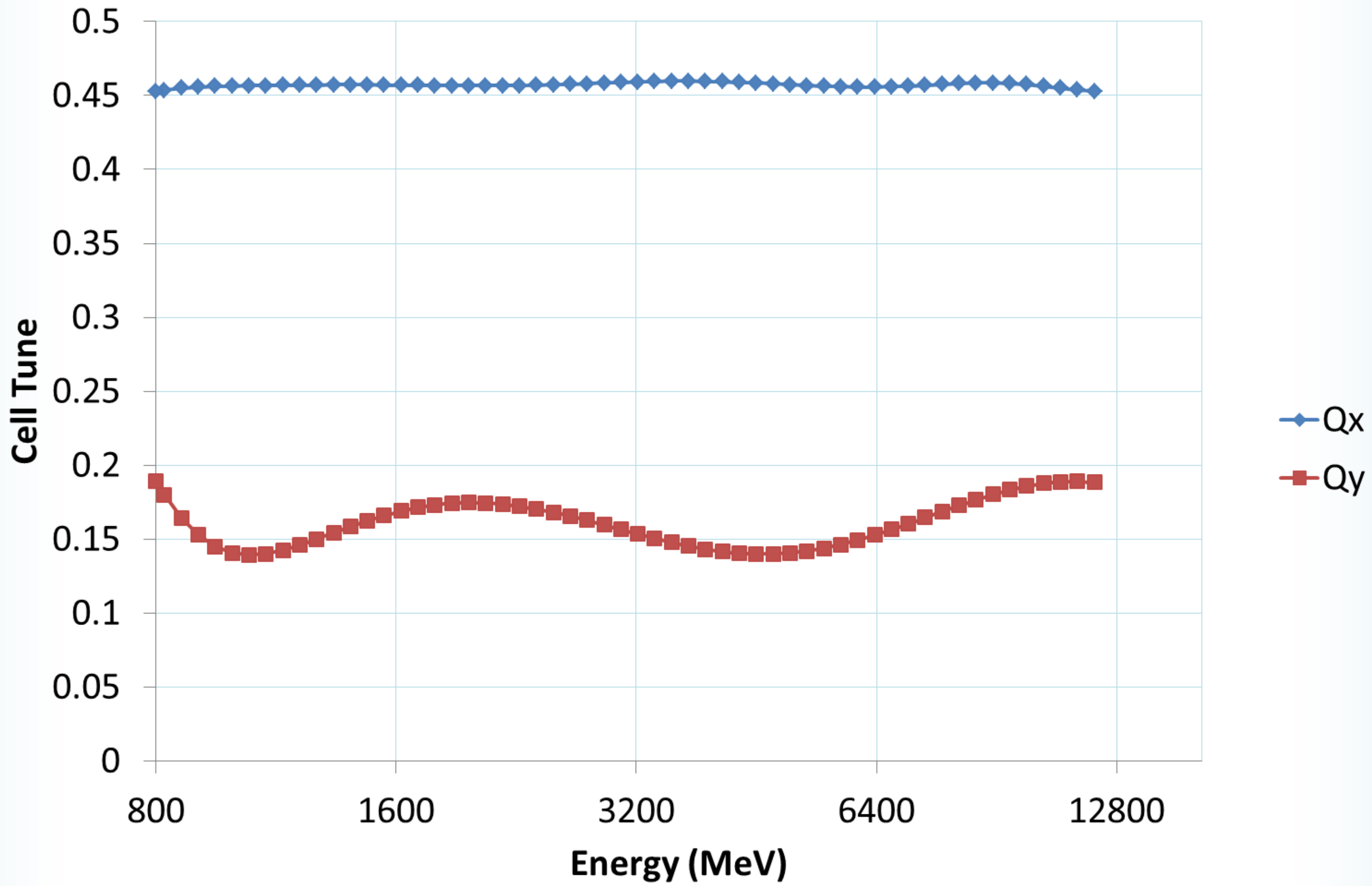
# Tune Variation, score = 185.216



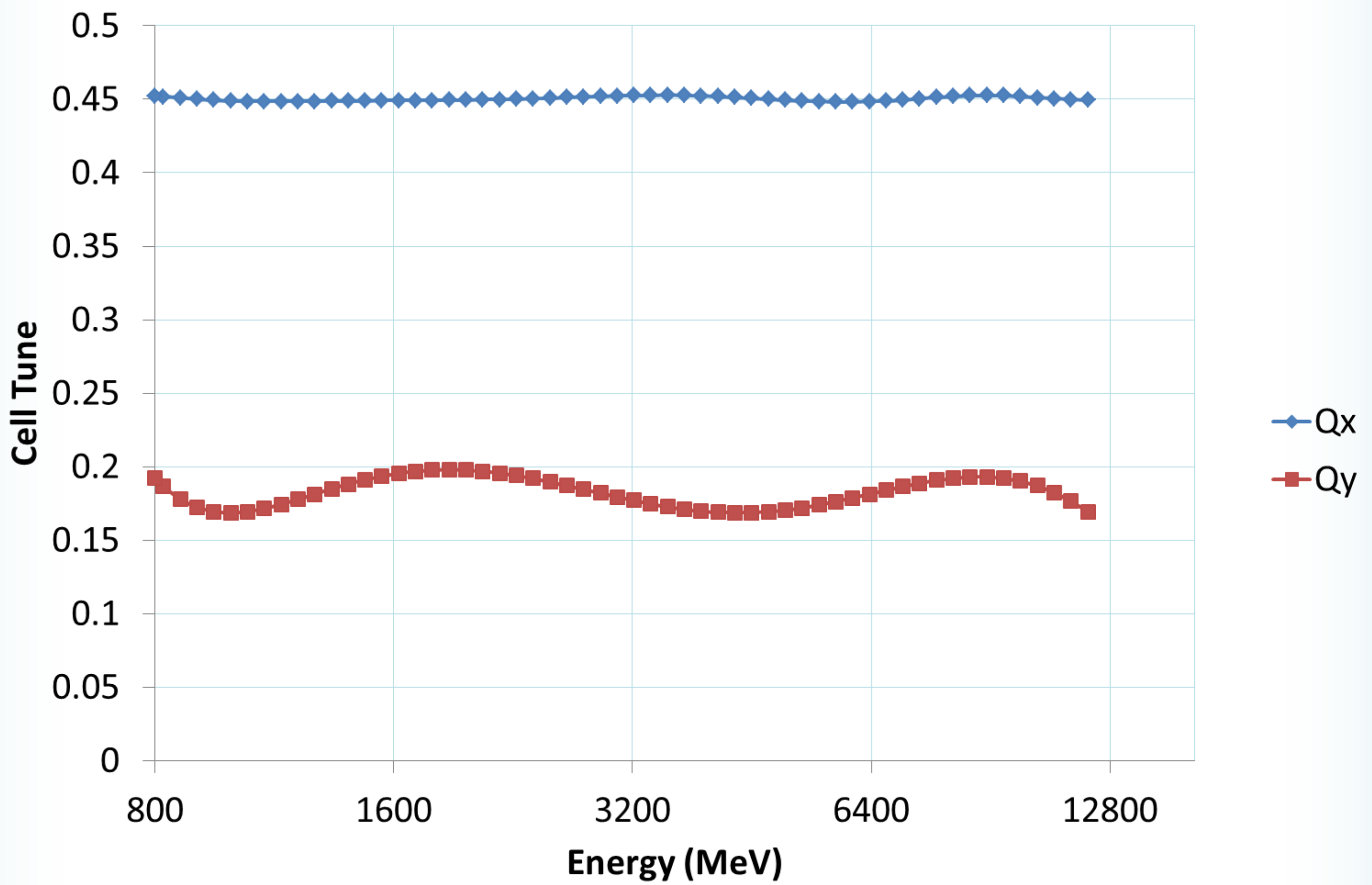
# Tune Variation, score = 191.844

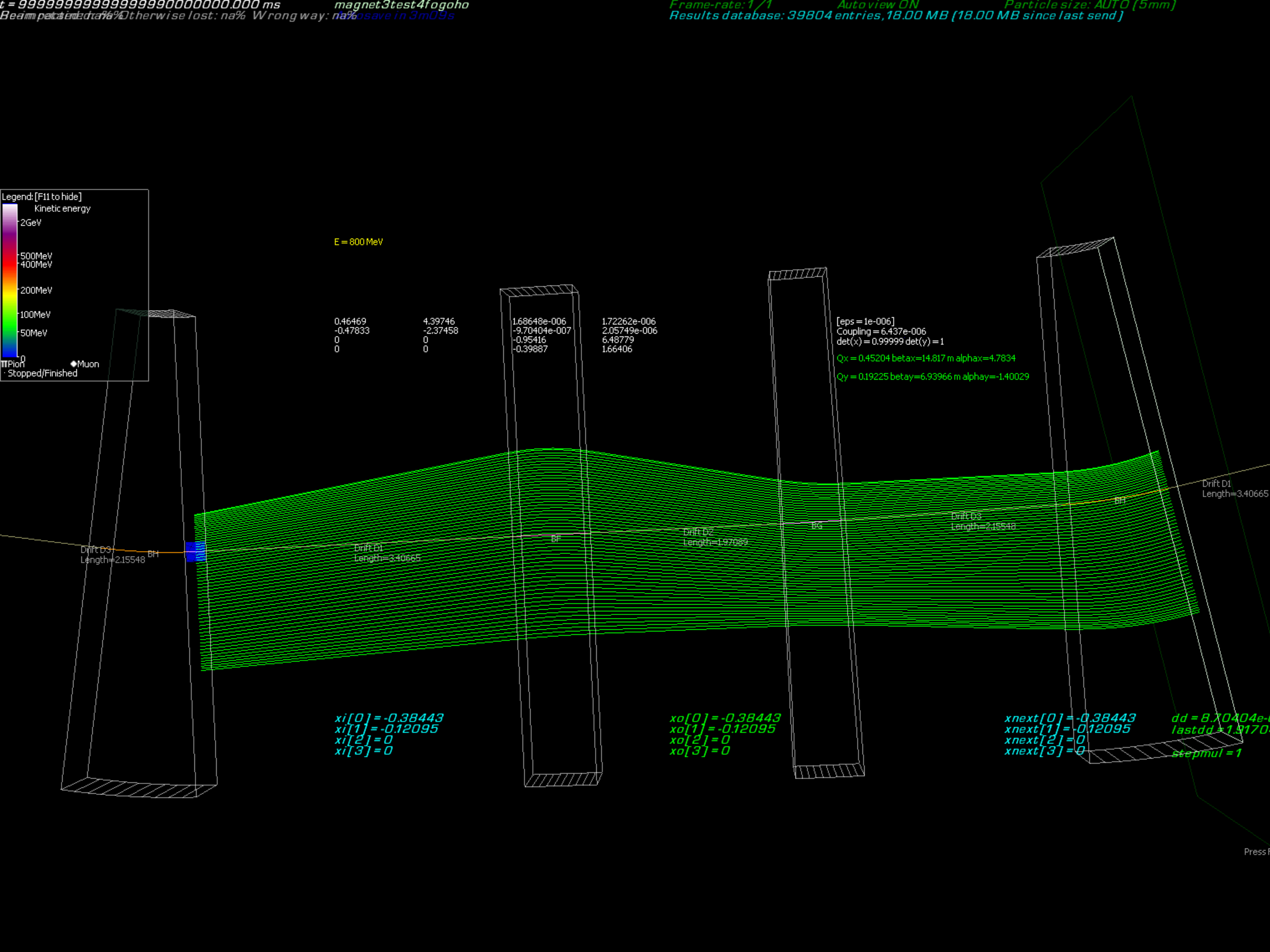


# Tune Variation, score = 194.263

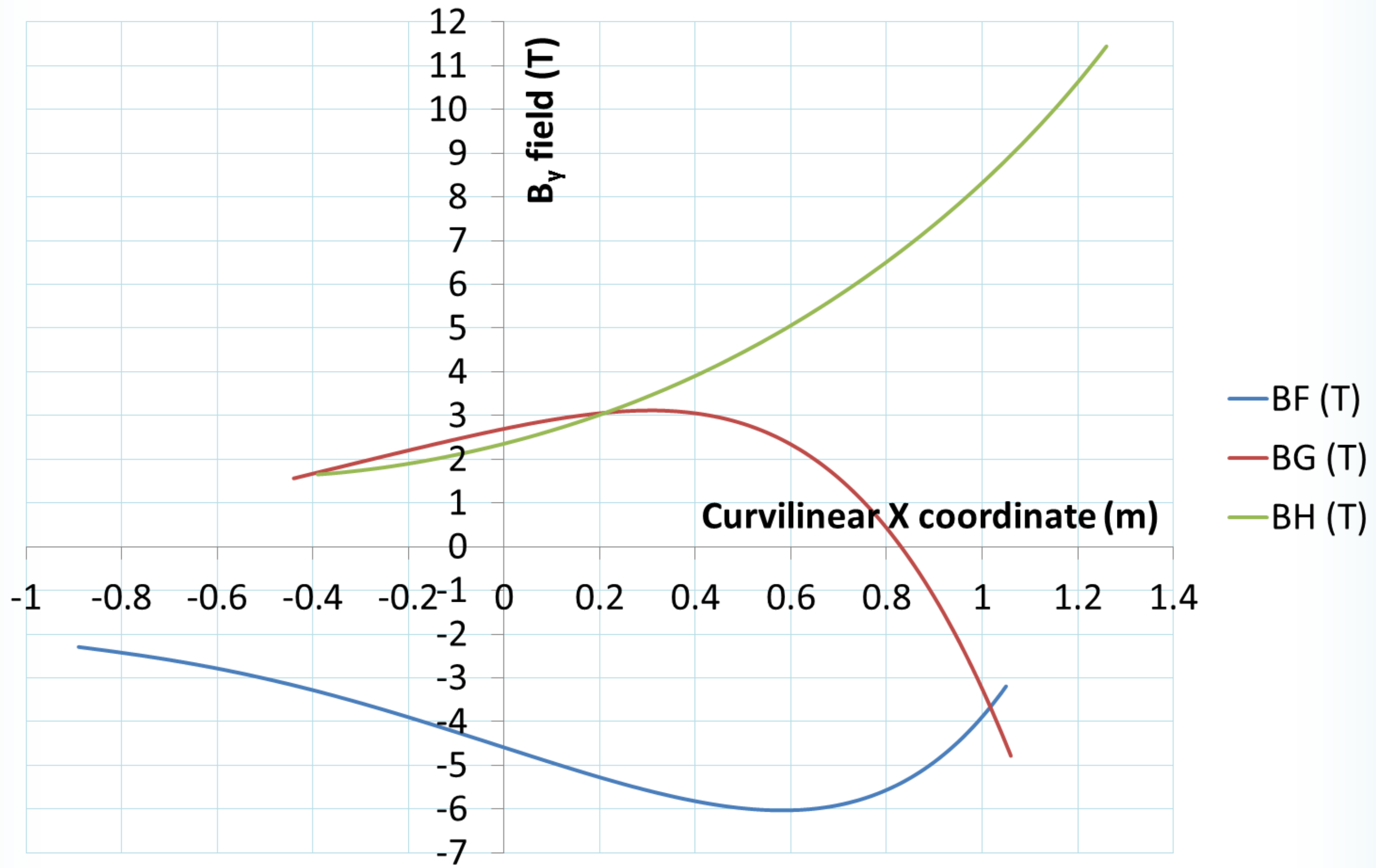


# Tune Variation, score = 196.601

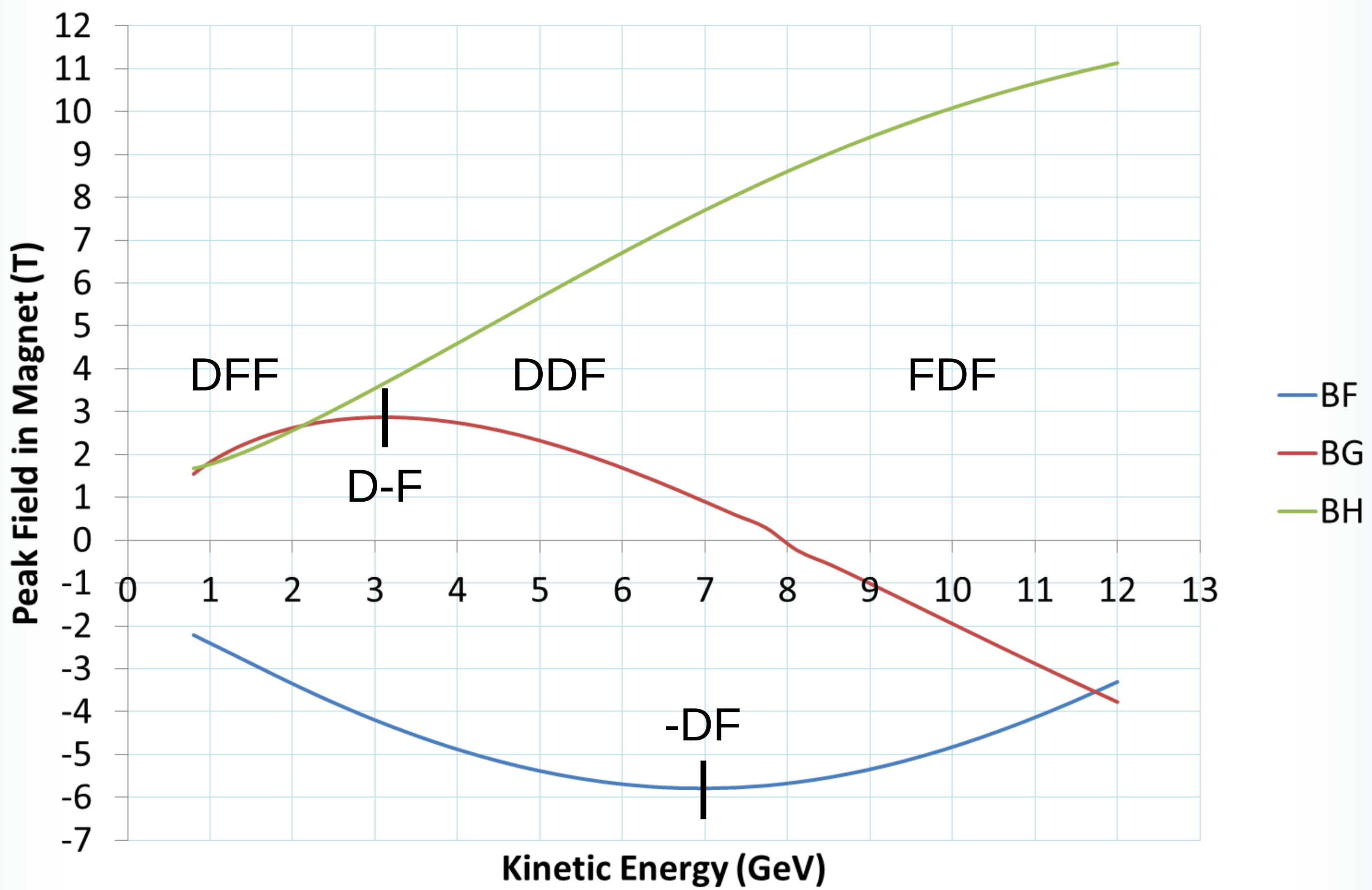



t = 9999999999999999990000000.000 ms
magnet3test4fogoho
Frame-rate: 1/1
Autoview ON
Particle size: AUTO (5mm)
Results database: 39804 entries, 18.00 MB (18.00 MB since last send)
Legend: [F11 to hide]
Kinetic energy
2GeV
500MeV
400MeV
200MeV
100MeV
50MeV
0
Pion
Muon
· Stopped/Finished
E = 800 MeV
0.46469
-0.47833
0
0
4.39746
-2.37458
0
0
1.68648e-006
-9.70404e-007
-0.95416
-0.39887
1.72262e-006
2.05749e-006
6.48779
1.66406
[eps = 1e-006]
Coupling = 6.437e-006
det(x) = 0.99999 det(y) = 1
Qx = 0.45204 betax=14.817 m alphax=4.7834
Qy = 0.19225 betay=6.93966 m alphay=-1.40029
Drift D3
Length=2.15548
BH
Drift D1
Length=3.40665
BF
Drift D2
Length=1.97089
BG
Drift D3
Length=2.15548
BH
Drift D1
Length=3.40665
xi[0] = -0.38443
xi[1] = -0.12095
xi[2] = 0
xi[3] = 0
xo[0] = -0.38443
xo[1] = -0.12095
xo[2] = 0
xo[3] = 0
xnext[0] = -0.38443
xnext[1] = -0.12095
xnext[2] = 0
xnext[3] = 0
stepmul = 1

# Magnet Field Profiles



# Magnetic Lattice with Energy



# Well that was fun but so what?

- Door opened to non-scaling FFAGs with wide momentum range and properly fixed tunes
  - Either via global optimisation
    - Could apply to FFAG gantry or insertion problems
  - Or Grahame Rees's integration technique using the chromaticity (solve $dQ_{x,y}/dp = 0$ for $B''_n$)
- This "proton driver" design needs more magnets bending the right way at 12GeV
  - Advance the pseudophase?

# V. Proton Omni-Ring

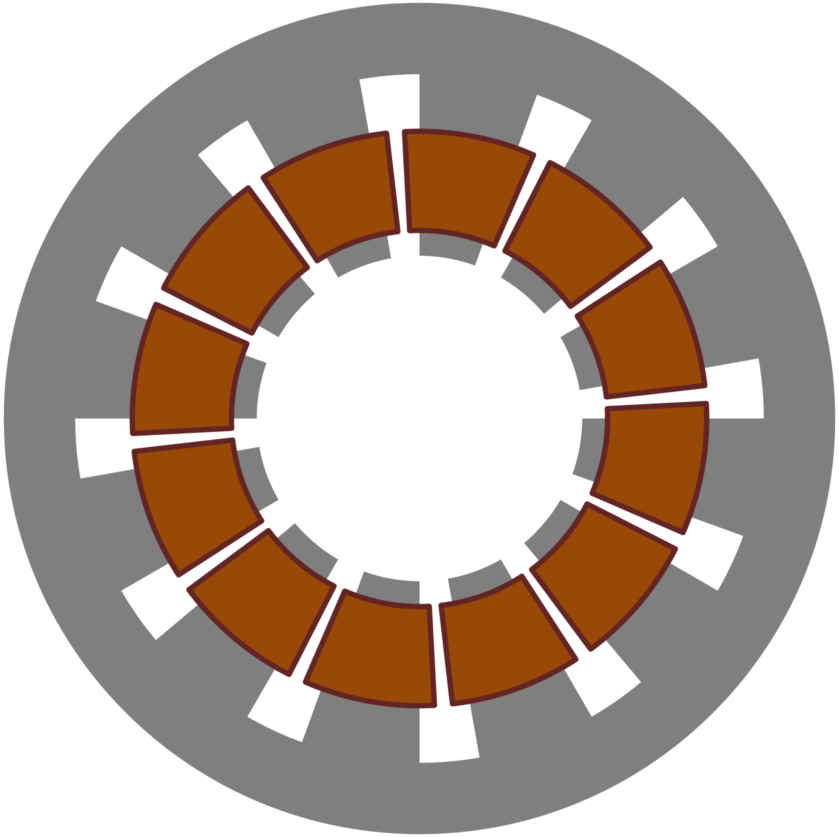
# Configurable Proton R&D Ring

- Magnets with independently-powered coils can provide nearly arbitrary combinations of multipoles up to a certain order
- May be used to make a general-purpose FFAG and synchrotron test ring for beam dynamics studies, if apertures reasonably large
  - Good fit for FETS, 3MeV, $H^-$, space in R9 (RAL)
- Normal-conducting, simulated with Poisson

# Possible Parameters

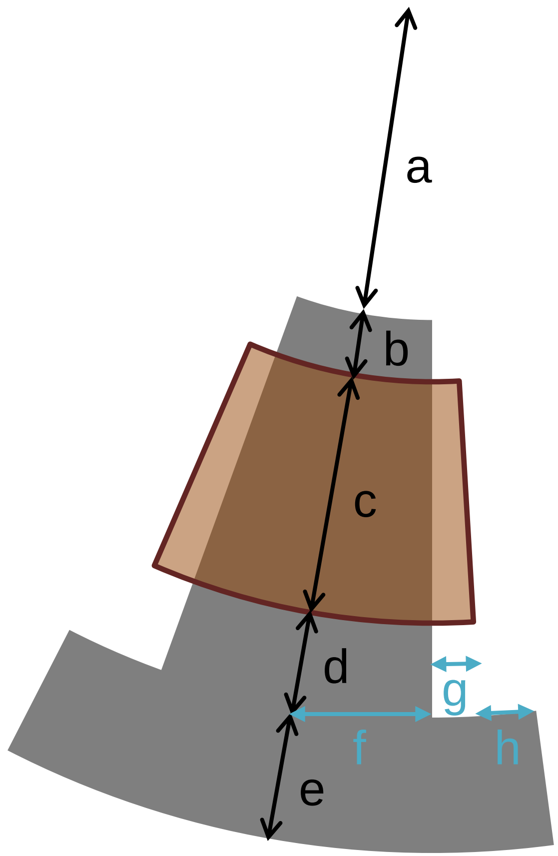
- Note: 3MeV = 75.1 MeV/c for protons/$H^-$
  - 4x as hard to bend as EMMA electrons already
- 0.2T dipole at 40% packing → 6.3m diameter
  - Compare EMMA at 5.3m
  - 24 magnets → 33cm magnet, 49cm drift per cell
  - Fits in R9, can branch off from >3MeV linac test stand (CH structure tanks etc.)
- Test: space charge, injection, FFAGs, halo…

# Omni-Ring Magnet



- Dodecapole with separately-powered coils
- Calibrated to produce multipole fields

# Geometry Parameters (1/12 magnet)

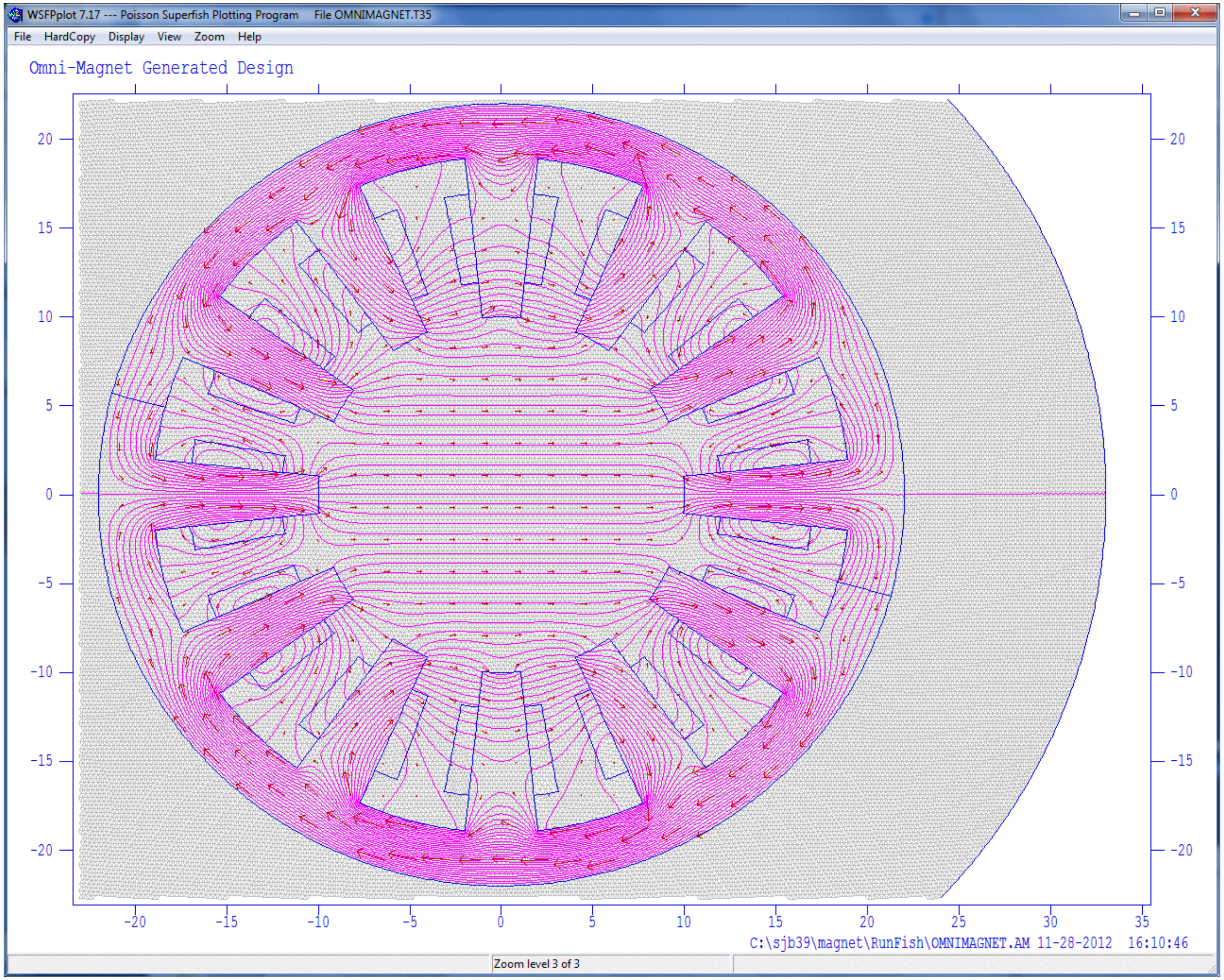



- Aperture = 2a, coil thickness = c, yoke = e, etc.
- f=pole fraction, g=coil fraction, f+g+h=1

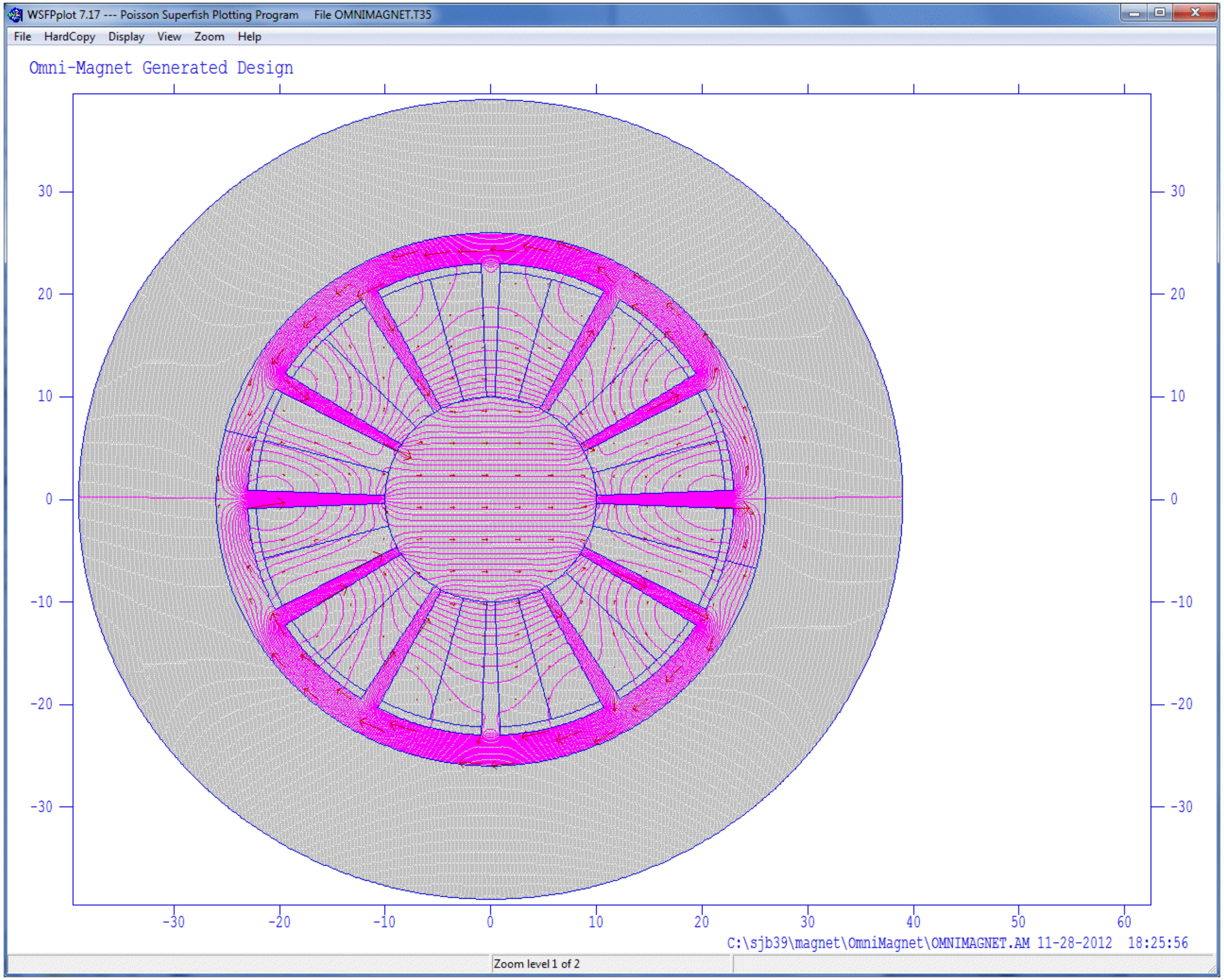
# Compare ISIS EPB2 magnet "Q11"

- 235A in 10x10mm coils
  - **2.35A/mm²** in coil+water+insulator overall
- 5.4kW total power (water-cooled copper)
- 105mm radius physical aperture
  - 80mm radius good field ±0.5%
- 3.76T/m * 105mm = 0.395T pole tip field
  - Spec says up to 1.4T flux in return arms

# Before Optimisation (0.0158 T)

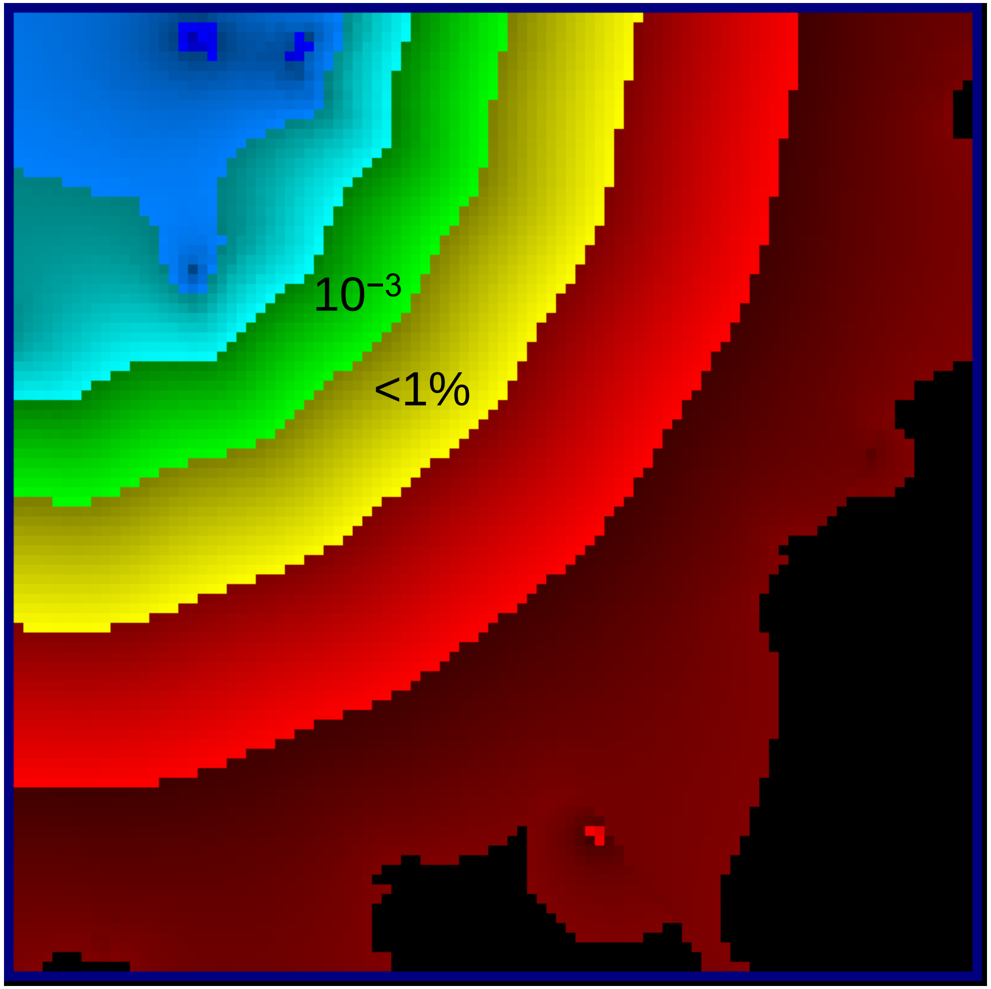


# After Optimisation (0.1141 T)



# Field Quality (Dipole case)

10cm aperture




Currents just from cos(θ) rule

# Magnet Practicalities

- Neil Marks used this idea for the corrector magnets of SRS at Daresbury Laboratory (UK)!
  - Could actually be used on ISIS too

[PAC1981]

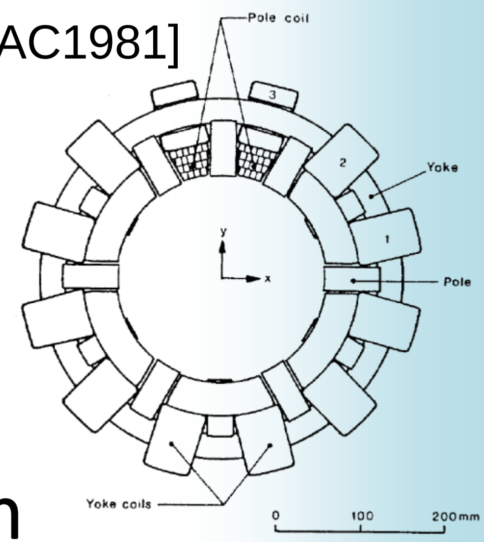



Fig.1 Cross-section of the multipole magnet

- Can it be done cheaply/practically?
  - Needs many-channel power supply
  - Maybe current density can go higher?
- Calibration is an interesting problem
  - Use standardised test rig for all magnets
  - Integrate magnet field sensors into poles?

# Other Ideas & Issues

- Ring can test chopping, injection painting, variable space charge levels, arbitrary tune settings, magnet nonlinearities
- Could do sequential single-turn extractions
  - Beam “movie”
  - Purpose-built halo diagnostic in extraction line?
- “Optical bench” positioning setup, bellows??
- Realisation of cheap ring at 3MeV hinges on whether $H^-$ stripping possible (foils too thin?)

# The End: FFAG Master Table

2013 Update

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† | y† |
| Linear n.s. | N | N | y(quasi) | y |
| Vertical s. | Y | Y | N | N …but spiral better |
| V. n.s. | 3+ | ? | ? | ? |
| Linear v.n.s.‡ | ? | ? | ? | ? |
| Skew | y | y | y ✓ | ? |

† Two 'y's may not be achievable simultaneously.

‡ Linear field VFFAG suggested by D.J. Kelliher.



Stephen Brooks, PASI 2013 & BNL seminar
stephen.brooks@stfc.ac.uk