FFAGs for Proton Acceleration

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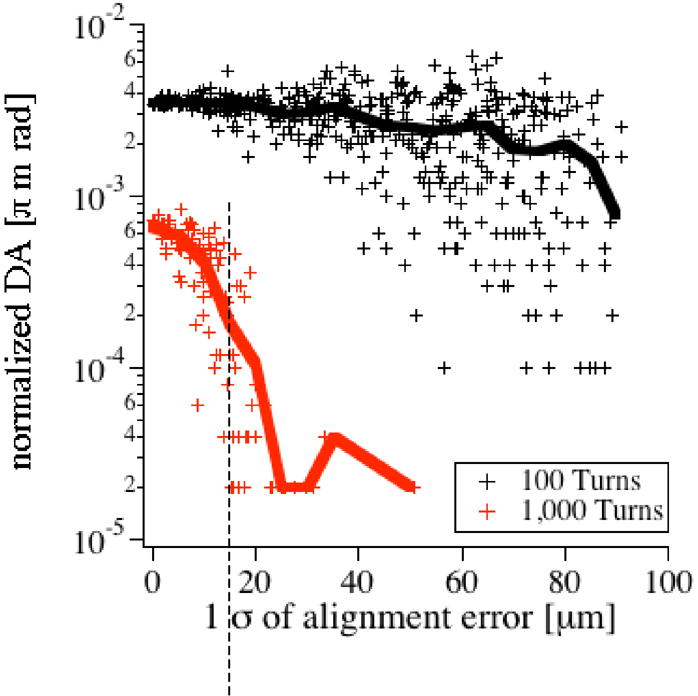
http://www.astec.ac.uk/intbeams/users/machida/doc/ffag/machida20080904.pdf & ppt

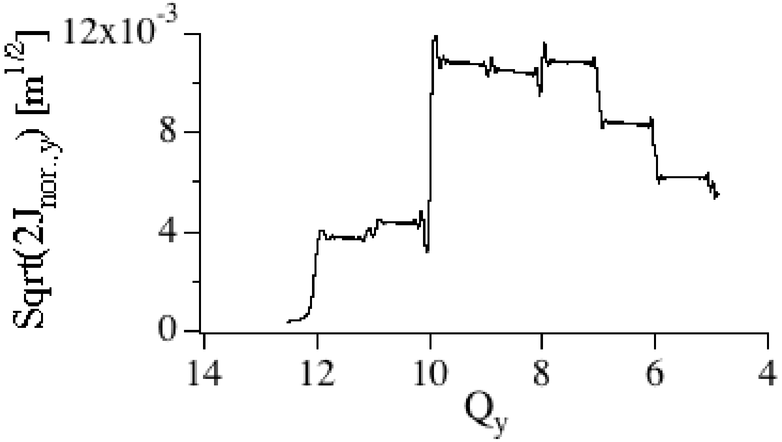
Background (1)

requirement of chromaticity correction

- Slow cycling FFAGs (NF proton driver, ADSR, particle therapy, etc.) must have chromaticity correction.



With practical alignment errors, there is almost no dynamic aperture.



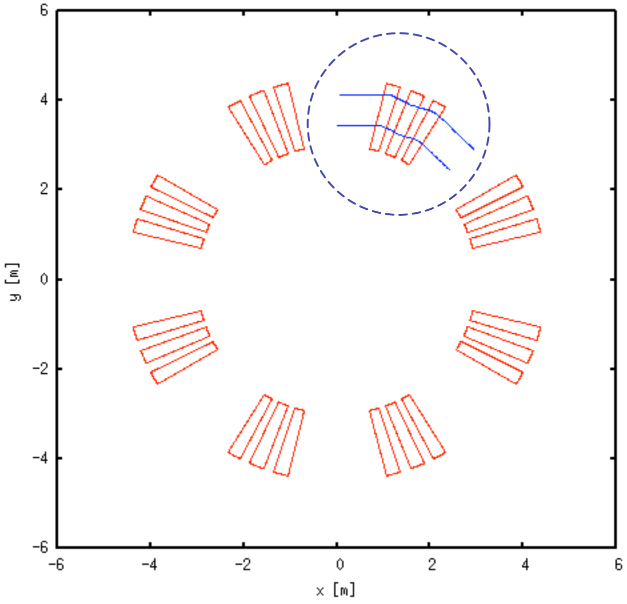
Dynamic aperture is limited by the amplitude growth at the integer resonance crossing.

Submitted to PRST-AB

Background (2)

scaling FFAG design

- Scaling FFAGs have full chromaticity correction.
- However, orbit excursion tends to be large.



- 31 MeV to 250 MeV FFAG for PAMELA

- FDF triplet lattice
- Field index *k*: 5
- Bmax: 4.2 T at beam edge
- Orbit excursion: 0.7 m
- Tune: H: 0.337, V: 0.260

Background (3)

field index k vs. orbit excursion

- Orbit excursion is roughly proportional to *1/k*.

$$\frac{p}{p_0} = \left(1 + \frac{\Delta r}{r_0}\right)^{1+k} \cong \left[1 + \frac{\Delta r}{r_0}(1+k)\right]$$

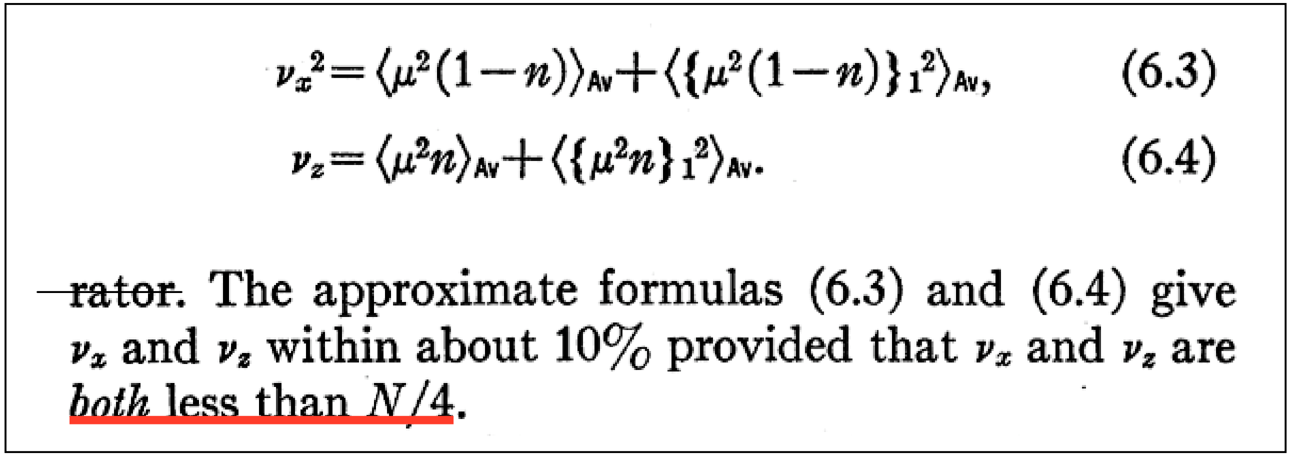
$$\frac{\Delta r}{r_0} \approx \frac{p/p_0 - 1}{k}$$

- Field index *k* should be as large as possible to reduce orbit excursion.

Background (4)

field index k vs. phase advance

- Physical Review by Symon, et. al. (1956)



$$\nu_x{}^2 = \langle \mu^2(1-n)\rangle_{\mathrm{Av}} + \langle\{\mu^2(1-n)\}_1{}^2\rangle_{\mathrm{Av}}, \qquad (6.3)$$

$$\nu_z = \langle \mu^2 n\rangle_{\mathrm{Av}} + \langle\{\mu^2 n\}_1{}^2\rangle_{\mathrm{Av}}. \qquad (6.4)$$

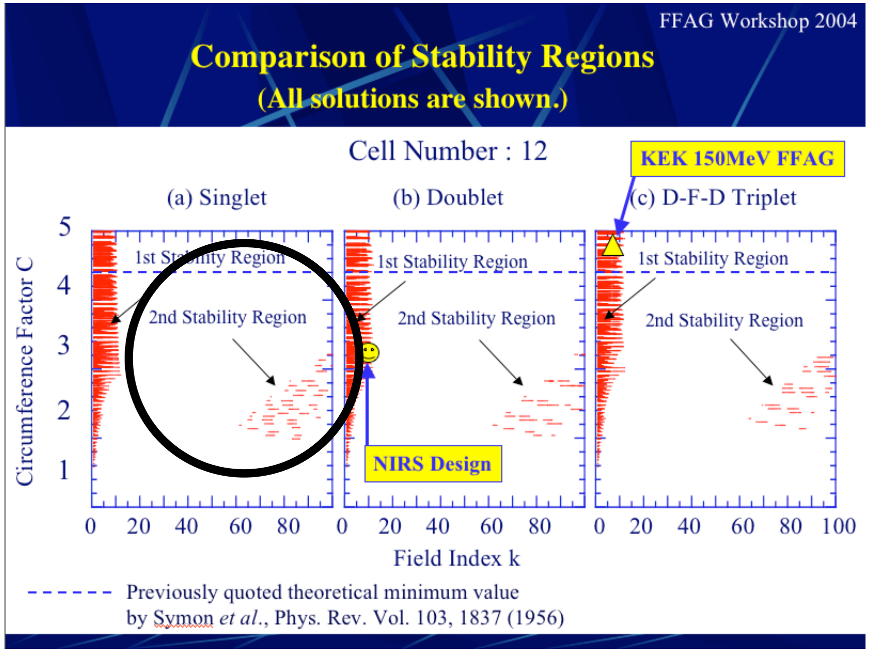
~~rator.~~ The approximate formulas (6.3) and (6.4) give ν_x and ν_z within about 10% provided that ν_x and ν_z are *both* less than $N/4$.

- All the scaling designs so far have the phase advance per cell < Pi.
  - FODO lattice does not have stable optics at more than Pi.
  - Exception is the second or higher stability region of the Hill's equation.
- Nonscaling FFAG is always < Pi to avoid Pi crossing.

Background (5)

use of higher order stability regions

- CERN Symposium paper by Kolomenski (1956)
  - *A circumference factor of about 2 should be possible if one does not work in the intersection of first stability regions, but in the intersection of the first and the second stability regions.*
- PRST-AB by Misu, et. al. (2004)



FFAG Workshop 2004

Comparison of Stability Regions

(All solutions are shown.)

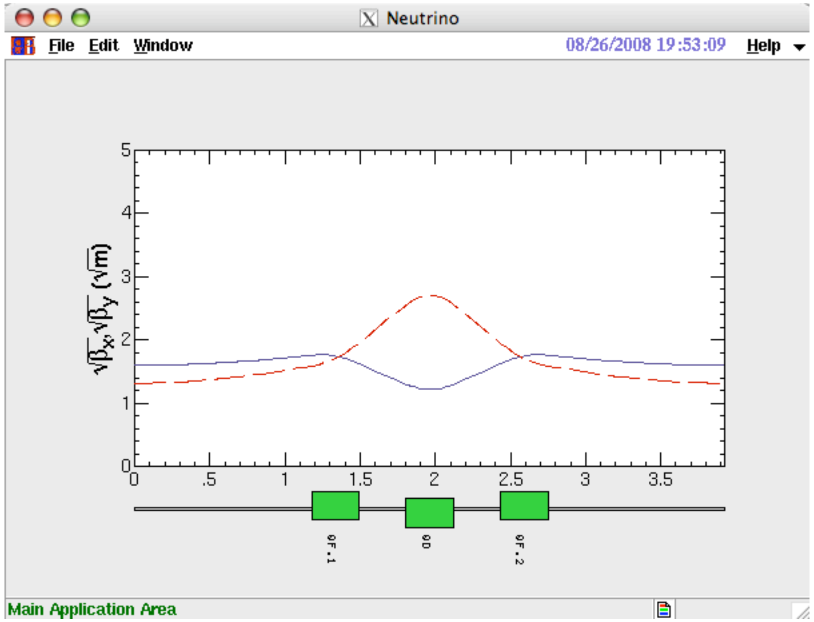
Previously quoted theoretical minimum value by Symon *et al.*, Phys. Rev. Vol. 103, 1837 (1956)

Lattice design (1)

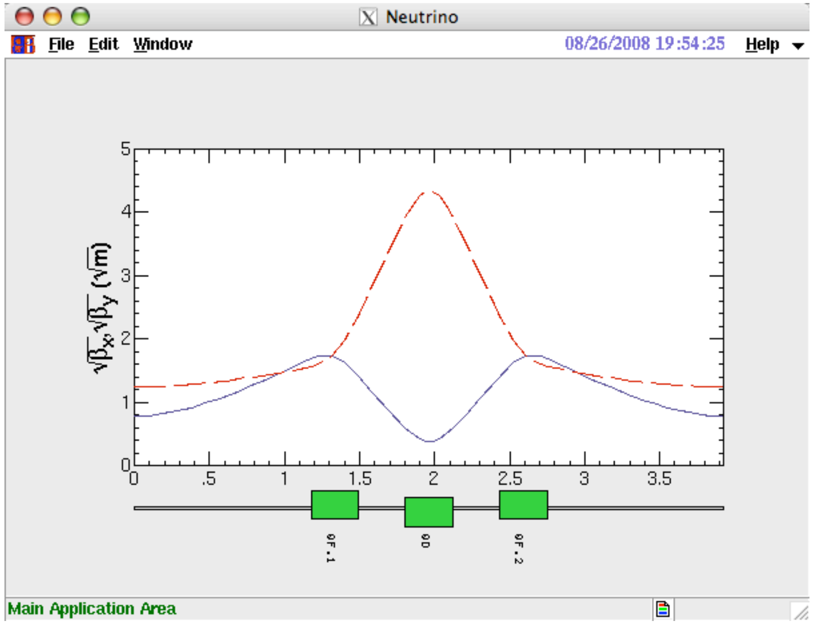
phase advance of triplet focusing

- Phase advance of triplet can be more than Pi (q=0.5) in the first stability region.

$$q_{x,y}=\frac{\text{(phase advance per cell)}}{2\,\text{Pi}}$$



(qx,qy)=(0.25, 0.25)



(qx,qy)=(0.75, 0.25)

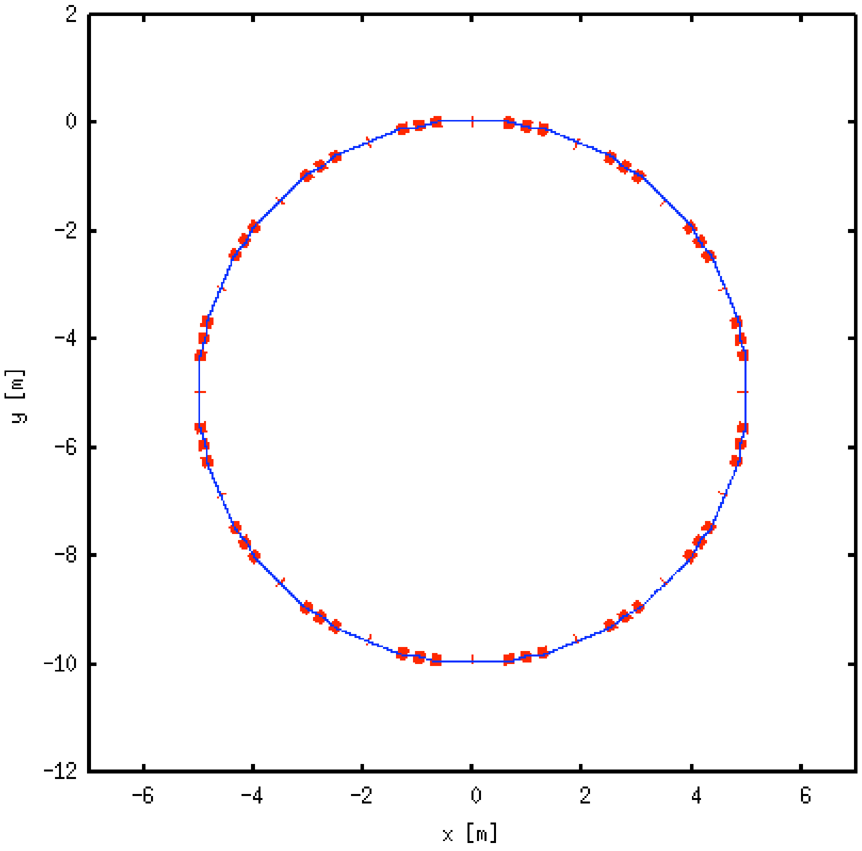
Horizontal phase gain of almost 0.50 at the centre QD.

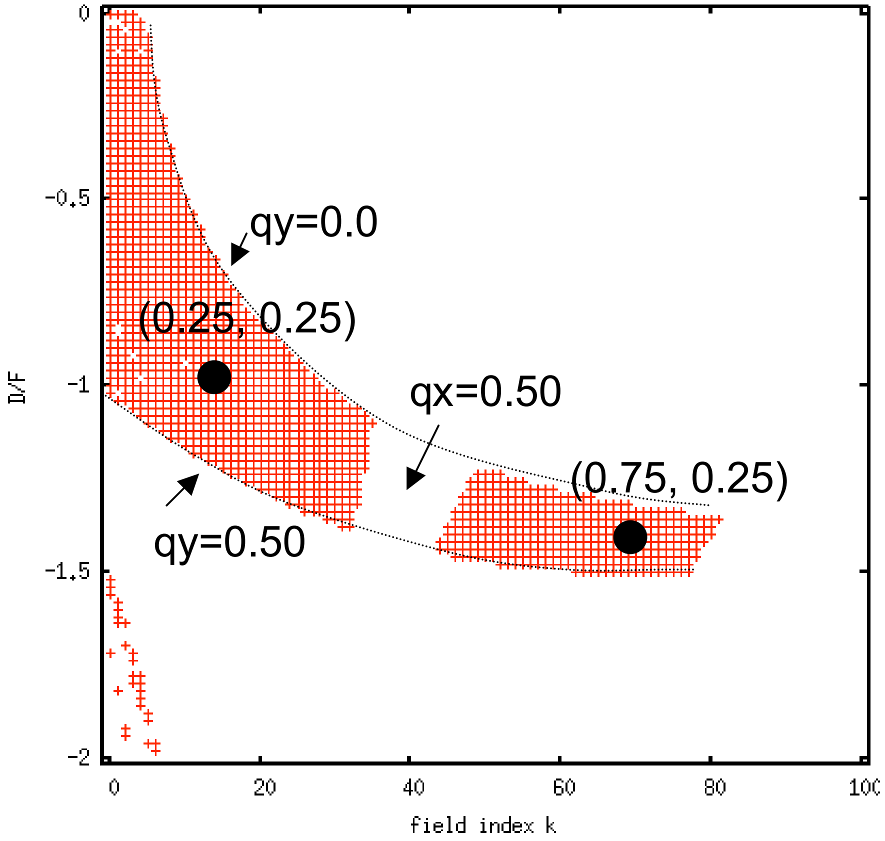
Lattice design (2)

stability diagram

- Example: FDF radial sector scaling FFAG

$$qx,y=\frac{\text{(phase advance per cell)}}{2\text{ Pi}}$$




qy=0.0

(0.25, 0.25)

qx=0.50

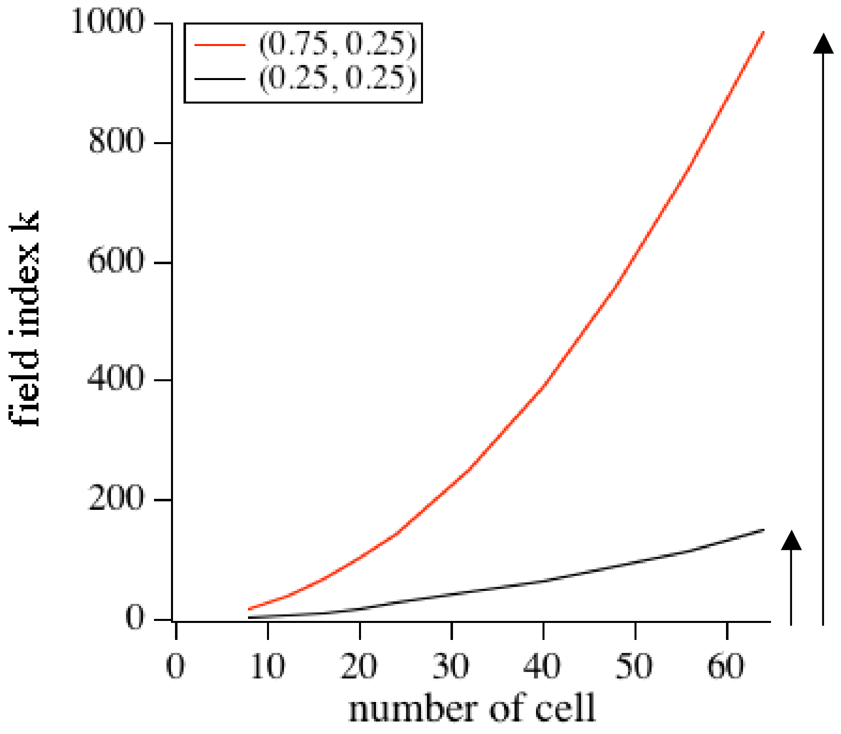
(0.75, 0.25)

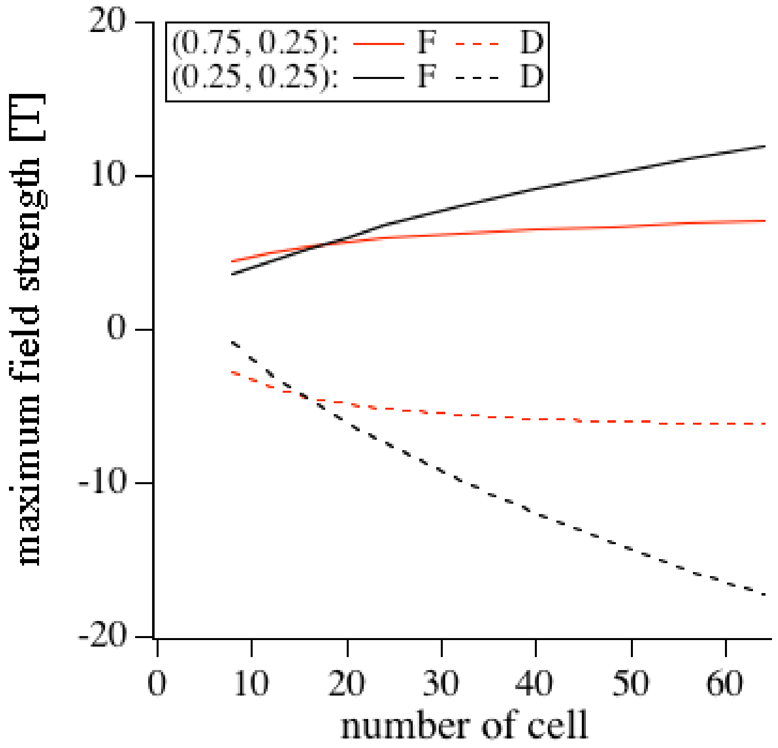
qy=0.50

Lattice design (3)

large field index and lower field

- Comparison between two designs.





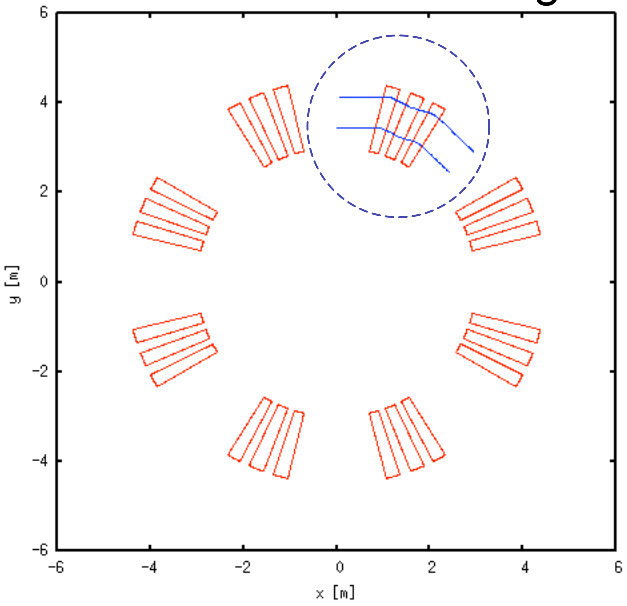
- Field index k is about 5 times larger.

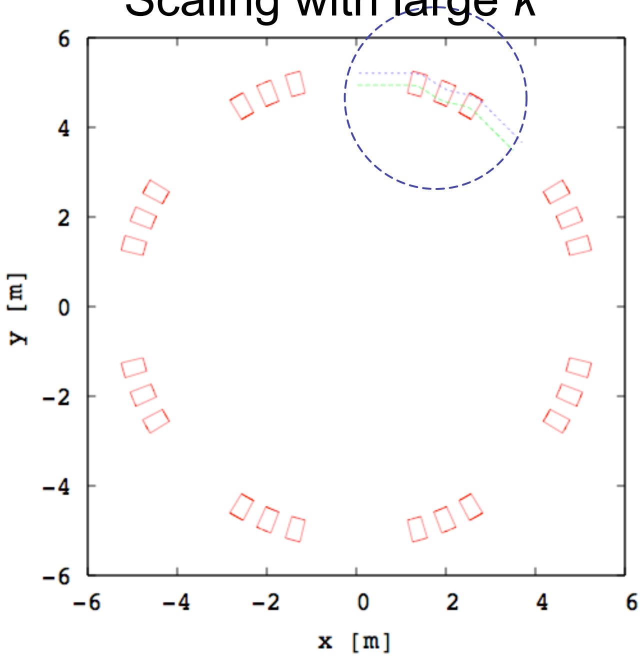
- Length of F and D can be the same because more focusing strength is needed.

Lattice design (4)

reduction of orbit excursion

- Footprint of 8 cell FDF example


Conventional scaling

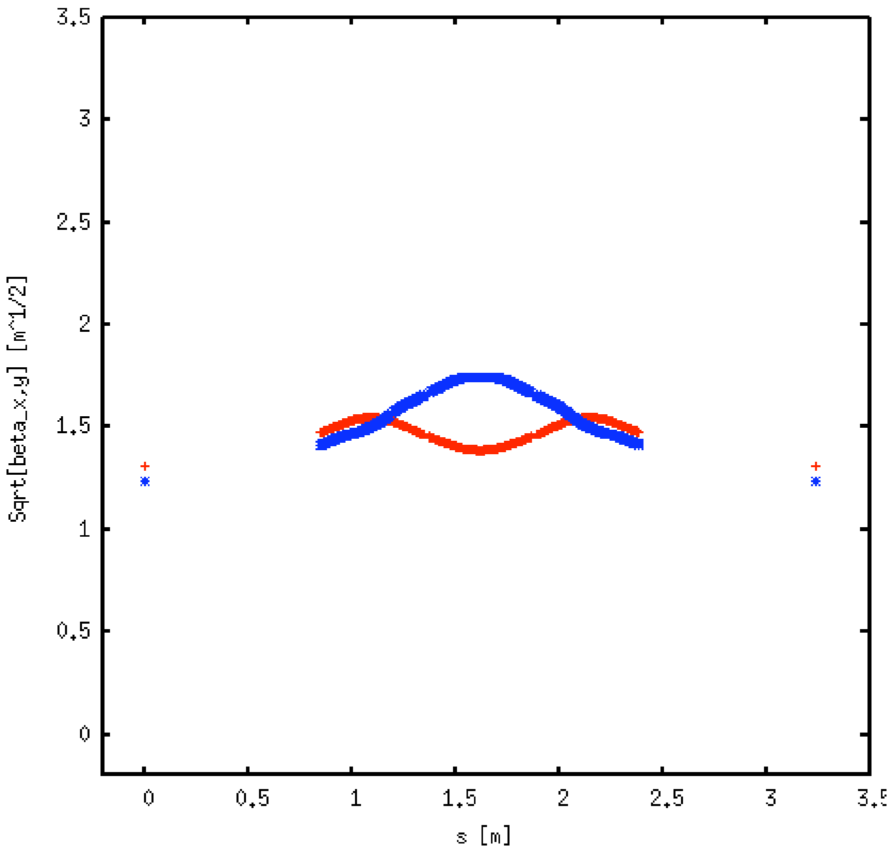

Scaling with large *k*

(Two optics have slightly different parameters other than “*k*”.)

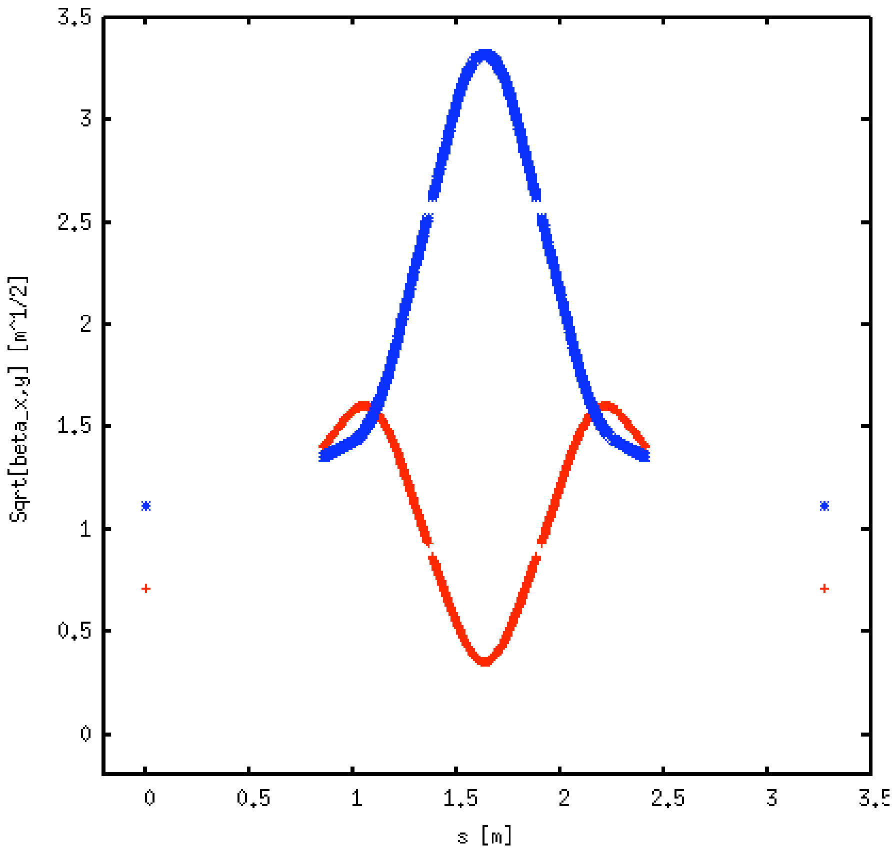
Lattice design (5)

lattice functions

- Vertical beam size becomes about twice as much.
  - Red: horizontal, Blue: vertical



(qx,qy)=(0.25, 0.25)

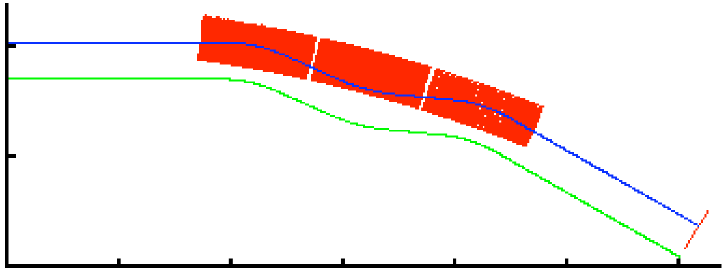


(qx,qy)=(0.75, 0.25)

Lattice design (6)

example 1: 250 MeV FFAG for proton therapy

- Constraints
  - Bmax = 4 T
  - p_ext/p_inj=3
  - Packing factor of magnets is 0.4

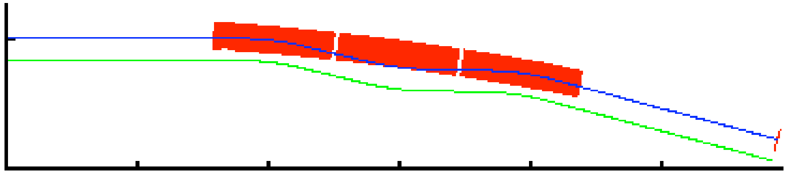


# of cell	Radius [m]	Orbit Ex. [m]	Long St. [m]	W/L of mag.
8	5.376	0.293	2.533	0.868
12	**6.251**	**0.168**	**1.964**	**0.642**
16	6.751	0.108	1.591	0.508
20	7.126	0.075	1.343	0.418

- gamma transition = 6.3

Lattice design (7)

example 2: 1.5 GeV FFAG for ADSR



- Constraints
  - Bmax = 4 T
  - p_ext/p_inj=3
  - Packing factor of magnets is 0.4

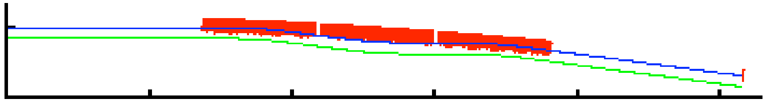
# of cell	Radius [m]	Orbit Ex. [m]	Long St. [m]	W/L of mag.
20	21.996	0.231	4.146	0.418
24	**22.767**	**0.171**	**3.576**	**0.358**
32	24.118	0.105	2.841	0.276
40	25.083	0.070	2.364	0.223

- gamma transition = 12

Lattice design (8)

example 3: 6 GeV FFAG as proton driver (low energy version)

- Constraints
  - Bmax = 4 T
  - p_ext/p_inj=3
  - Packing factor of magnets is 0.4



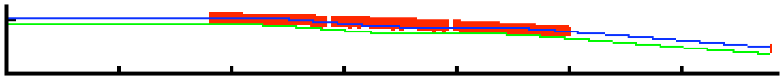
# of cell	Radius [m]	Orbit Ex. [m]	Long St. [m]	W/L of mag.
40	76.619	0.215	7.221	0.223
48	**79.095**	**0.155**	**6.212**	**0.187**
56	81.688	0.119	5.499	0.162
64	83.220	0.093	4.902	0.142

- gamma transition = 23

Lattice design (9)

example 4: 20 GeV FFAG as proton driver (high energy version)

- Constraints
  - Bmax = 6 T
  - p_ext/p_inj=3
  - Packing factor of magnets is 0.4



# of cell	Radius [m]	Orbit Ex. [m]	Long St. [m]	W/L of mag.
64	168.811	0.188	9.944	0.142
80	**172.636**	**0.124**	**8.135**	**0.114**
96	176.462	0.088	6.930	0.095
128	184.114	0.052	5.423	0.071

- gamma transition = 39

Issues (1)

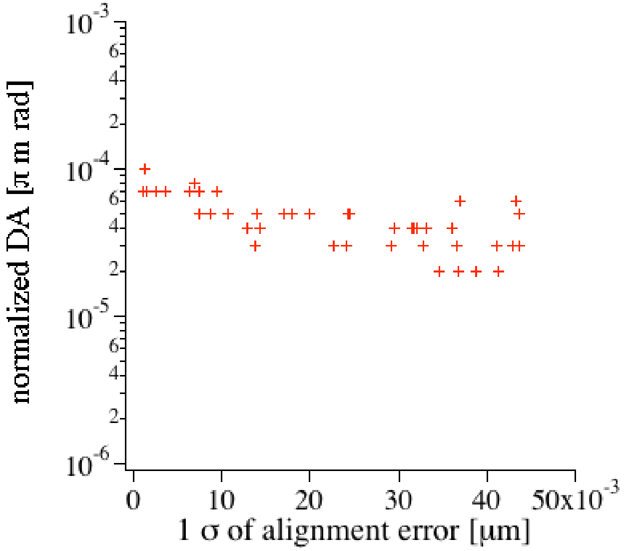
superconducting magnet

- Is it possible to make a magnet with large field index?
  - Holger Witte gave an answer for the simplified magnet (to be described later).

Issues (2)

dynamic aperture and stability against errors

- Simulation study shows the normalized acceptance is about 60 π mm mrad.
- This becomes smaller with errors (alignment), but reduction is moderate, nothing like linear nonscaling results.



- Gradient (field index *k*) error should be looked at later.

Further “improvement”

make it nonscaling

- Instead of using scaling magnet, only keep lower order multipoles.
- Instead of a wedged shape magnet, use a rectangular magnet.

This makes the fabrication of superconducting magnet simpler.

- Tune is no longer constant, but the deviation is small and total tune is still within an integer.
- The concept is applied to PAMELA.
  - See Suzie Sheehy’s talk.

Summary

- FDF triplet scaling FFAG can increase field index considerably.
- This design solves the following three major problems.
  - Beam blowup at resonance crossing in a linear nonscaling FFAG.
  - Large magnet of a scaling FFAG due to small field index.
  - No space for inj./ext. because of short cell length in NS and S.

- Magnet can be simplified by taking lower order multipoles only and with rectangular shape.

- Unfortunately, it does not have enough aperture for muon beams.
  - The ultimate FFAG *except* for muon acceleration.