Advances in FFAG optics
lesson from evolution of synchrotrons

Shinji Machida
ASTeC/STFC/RAL

21 September 2009

http://www.astec.ac.uk/intbeams/users/machida/doc/nufact/ffag/machida20090921.pdf

Contents

- Introduction (3 slides)
  - Evolution of synchrotron
- Many family of focusing elements
- Insertion and matching
- Another way in scaling FFAG
- “Separated function” magnet
- Using second stability region
- Summary

Introduction (1)

synchrotron and FFAG optics

- First Alternating Gradient synchrotrons have
  - many identical cells: 20 (CPS), 24 (AGS).
  - all combined function magnet: no quadrupole.
- Footprint of those synchrotrons looks similar to FFAG.
  - high degree of symmetry.
  - magnet gives net orbit angle.

Introduction (2)

a lesson from evolution of synchrotron lattice

- AG synchrotron lattice evolves since then.
  - quadrupole (separated function magnets): straight section.
  - many family of focusing elements.
  - insertion and matching between sections.

- Superperiod is introduced.
  - different cell structure makes arc and insertion.

Introduction (3)

a possible reason

- High degree of symmetry is essential in linear nonscaling FFAG.
  - avoid structure resonances.

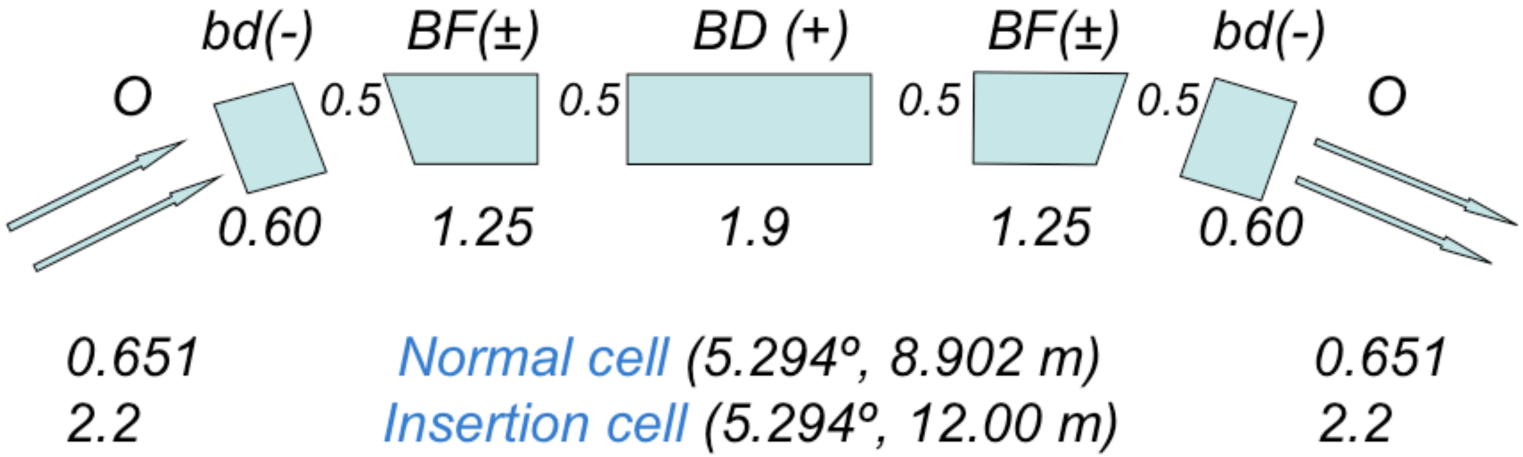
- However, if tune does not move much, operating tune can be optimized to avoid resonance crossing.
  - scaling FFAG.
  - nonlinear nonscaling FFAG with fixed tune.
- High degree of symmetry is not necessary in FFAG.

- Why FFAG still looks old shape?
  - in fact, FFAG lattices are evolving as well.

Many family of focusing elements (1)

early work

- Pumplet by Grahame Rees (nonlinear nonscaling)
  - zero chromaticity, constant tune, with non r^k field
  - isochronous ring



Insertion and matching (1)

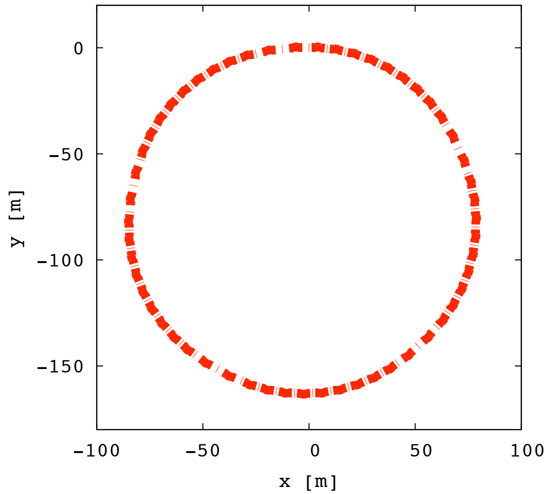
some examples

- 3-fold lattice by Phil Meads (scaling)
  - insertion with zero dispersion
- Muon FFAG by Al Garren (linear nonscaling)
  - insertion for injection, extraction and rf systems
- Pumplet by Grahame Rees (nonlinear nonscaling)
  - "bending" insertion with combined function magnets.
- Racetrack FFAG by Dejan Trbojevic (linear nonscaling)
  - insertion with quadrupole
- Muon FFAG by me (nonlinear nonscaling)
  - "bending" insertion with triplet
- Racetrack FFAG by Yoshiharu Mori (scaling)
  - insertion with large *k*
  - help harmonic number jump scheme

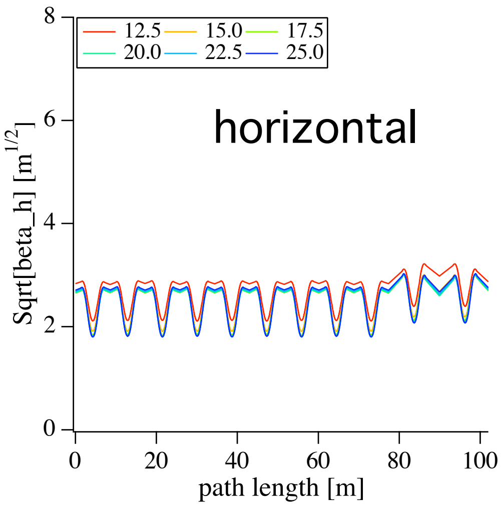
Insertion and matching (2)

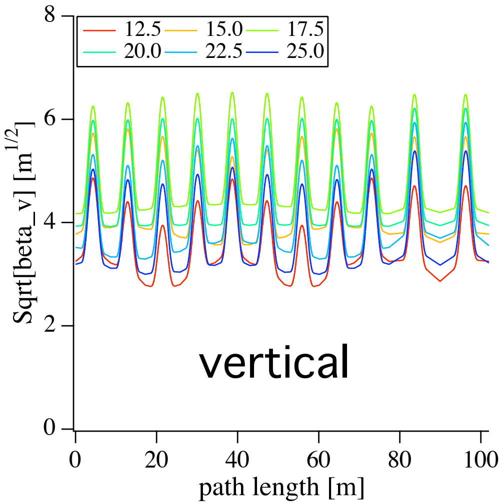
beta function in triplet

- One 7 m drift and two 5 m drift every 11 cells.
- 5 fold symmetry lattice.



- Modulation of beta function in different energy.





Insertion and matching (3)

difficulties

- Matching of lattice functions as well as dispersion for whole energy range cannot be perfect.
  - Approximation may be good enough, but introduce a slight mismatch.

- I name it "modular method". Insertion is introduce by matching between several modules.

Another way in scaling FFAG (1)

idea

- As long as magnetic fields have the shape of

$$B_z = B_{z,0}(\frac{r}{r_0})^k F(\theta)$$

$F(\theta)$ can be arbitrary. k should be constant.

- FFAG with long drift space can be designed with more complex function of $F(\theta)$.
  - FD, FDF are the simplest case.
  - In principle, all F and D can be different family.

Another way in scaling FFAG (2)
global method

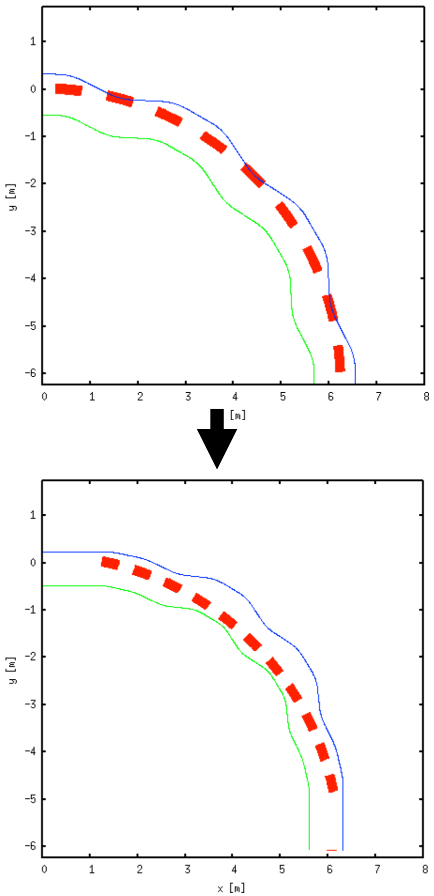
- I name it "Global method" (works only for a scaling FFAG)
  - Introduce a variety on azimuthal field distribution.

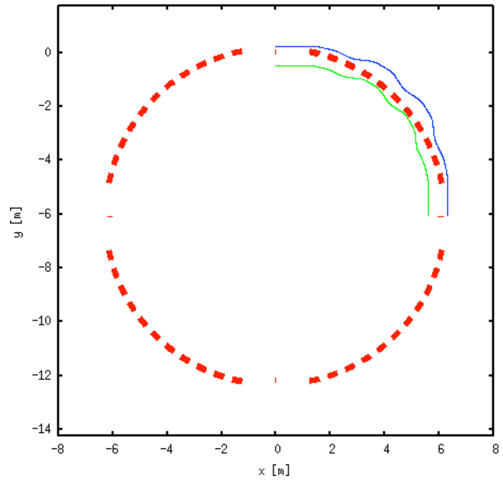
- No need to match section by section. Scaling property is assured.
  - tune is constant independent of momentum.
  - closed orbit is photographic enlargement.

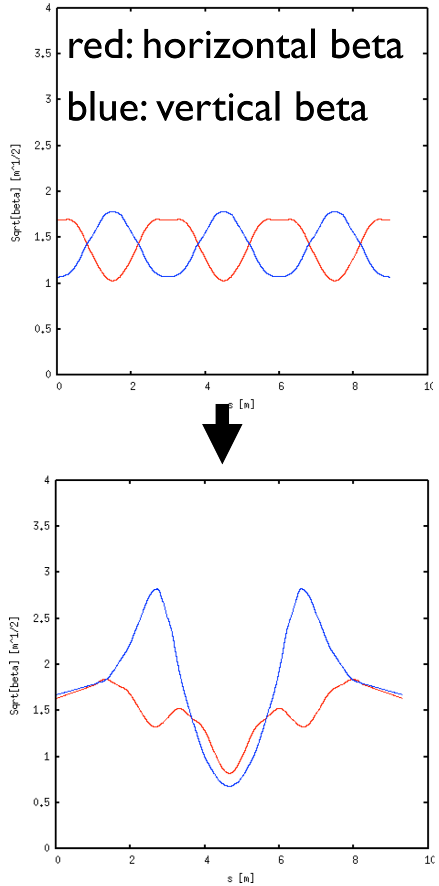
Another way in scaling FFAG (3)

inserting long straight drift

- O(FDF)(FDF)(FDF)O as one quadrant of a ring.







- Stable optics exist.
- However, beta functions are modulated.

Another way in scaling FFAG (4)

fitting example

- Fitting tool has to be developed.
  - Given initial configuration of lattice magnets, calculate closed orbit and optics functions.
  - If beta functions are larger than what we expected and/or phase advance is not what we want, change strength of magnets.
  - Repeat the above process until it converges.

- Command in s-code

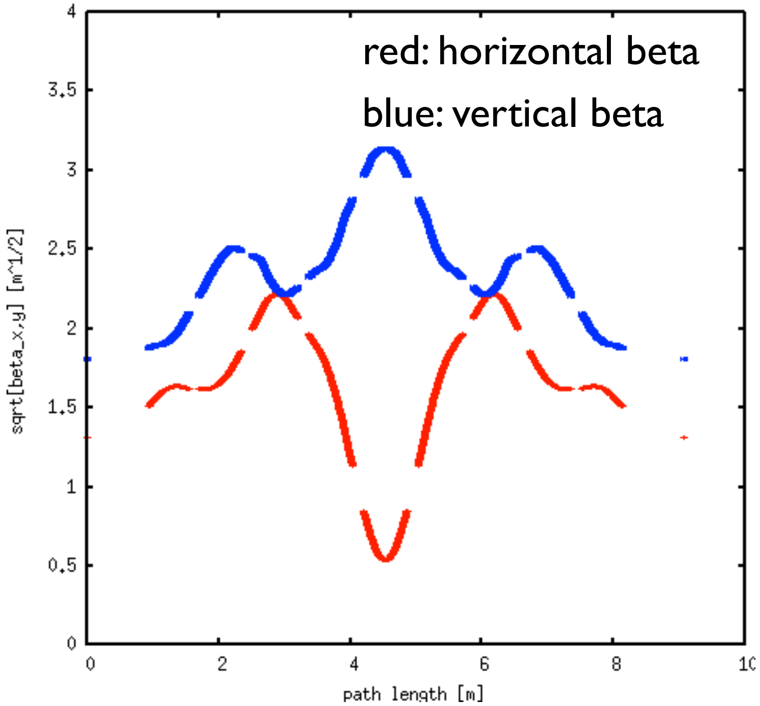
```
twissf1,    iring=13, &
          betaymax=2.D0, betazmax=4.D0, &
          pcinj=0.729D0, trpt, periodic, &
          dtimes=-0.010D0
```

Another way in scaling FFAG (5)

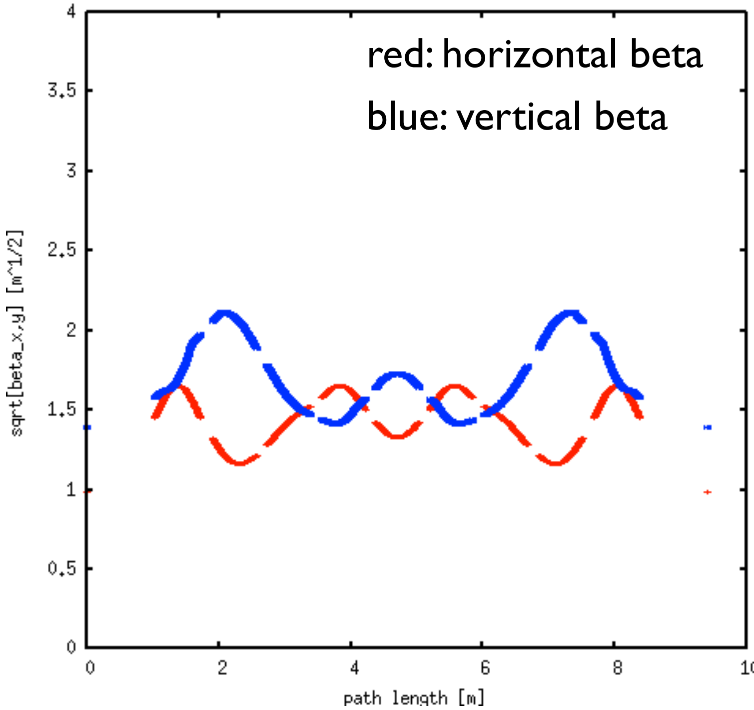
fitting example

- Example of minimizing (flattening) beta functions.
  - $O(F_3D_2F_2)(F_1D_1F_1)(F_2D_2F_3)O$ as one quadrant of a ring.

before fitting



after fitting

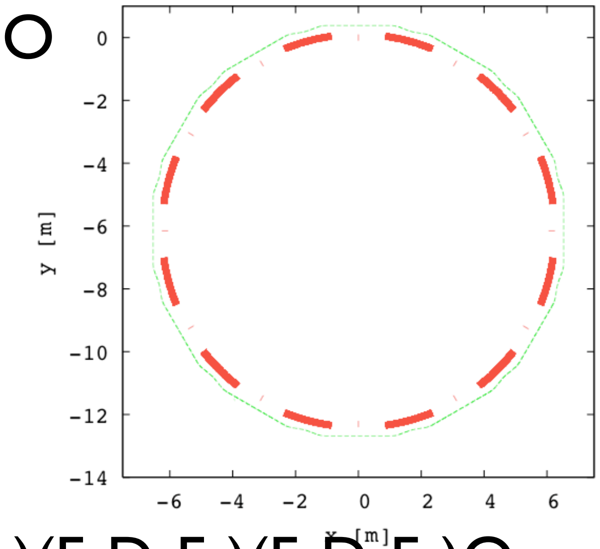


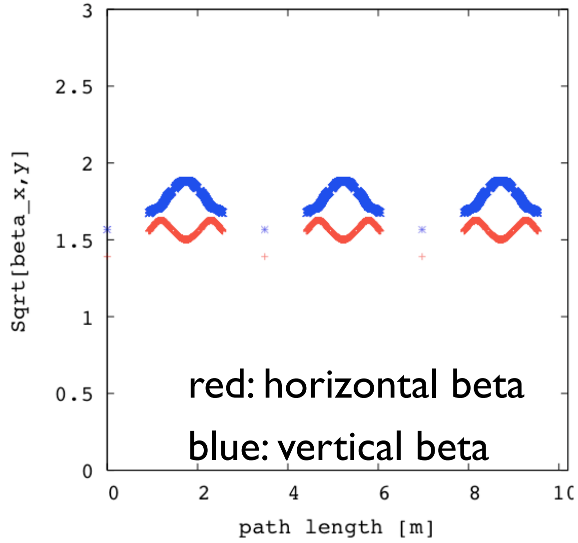
Another way in scaling FFAG (6)

4 fold symmetry

- 12*O(FDF)O

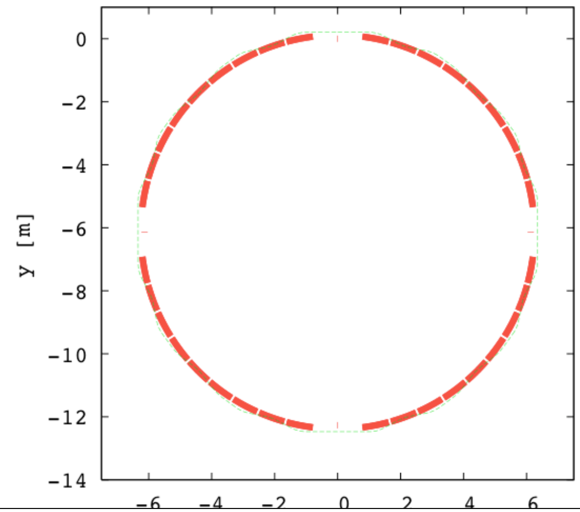
red: magnet
green: orbit

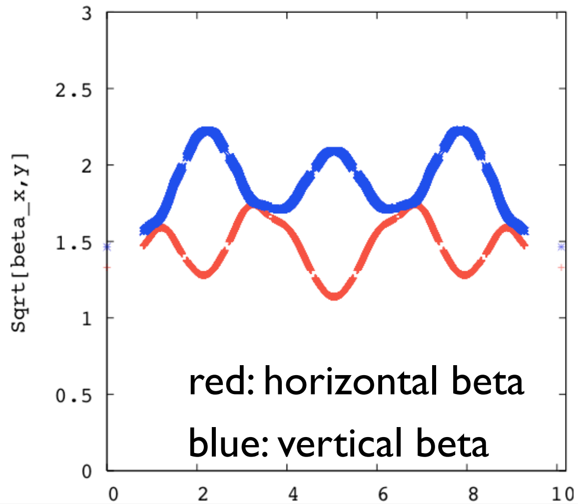




- 4*O($F_3D_2F_2$)($F_1D_1F_1$)($F_2D_2F_3$)O

red: magnet
green: orbit





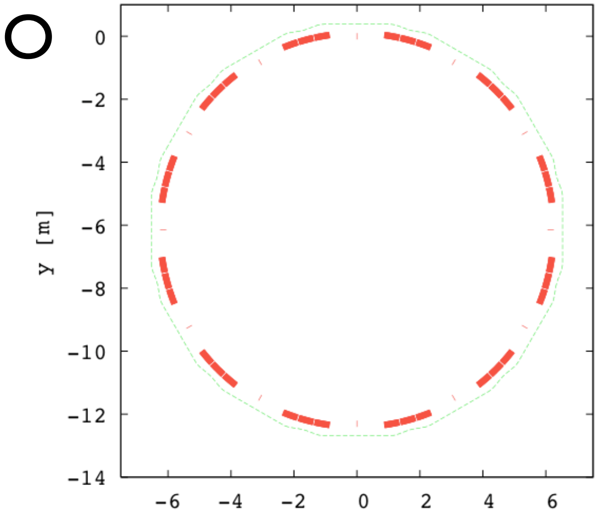
Another way in scaling FFAG (7)

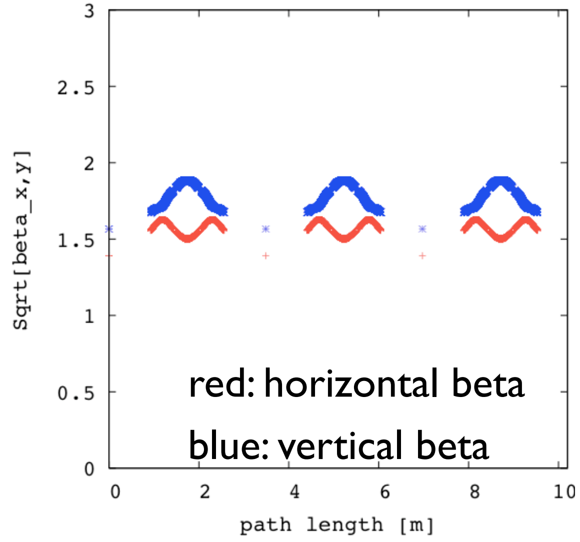
4 fold symmetry with shorter drift space

- 12*O(FDF)O

red: magnet

green: orbit

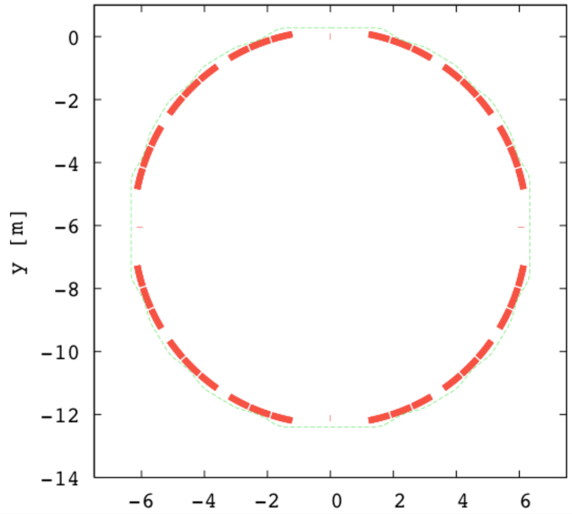


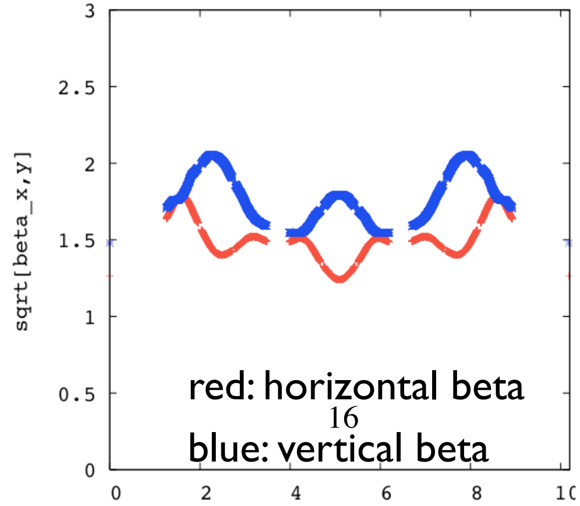


- $4*O(F_3D_2F_2)o(F_1D_1F_1)o(F_2D_2F_3)O$

red: magnet

green: orbit





Another way in scaling FFAG (8)

reduction of maximum fields

- Maximum field strength

superperiod	Bf_max [T]	Bd_max [T]	drift_max [m]
12 (original)	3.2	-2.2	1.96
6	2.7	-1.6	1.96
4	2.5	-1.5	1.96
4	3.4	-1.7	2.40

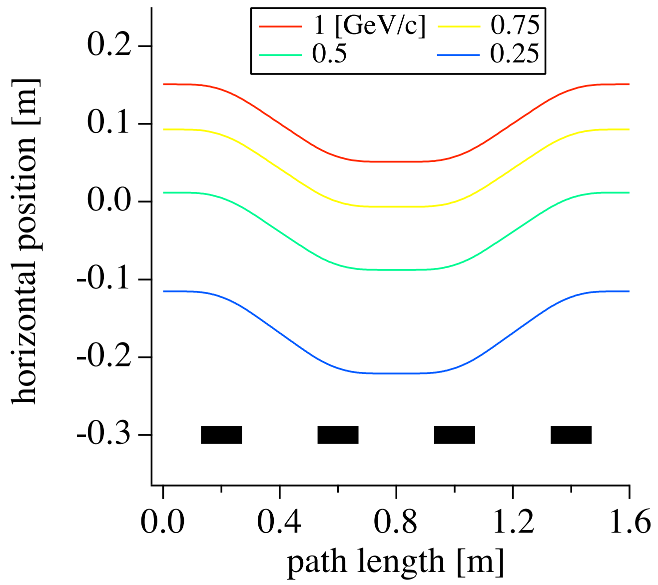
- Same drift length with lower magnetic field strength or longer drift length with same magnetic field strength.

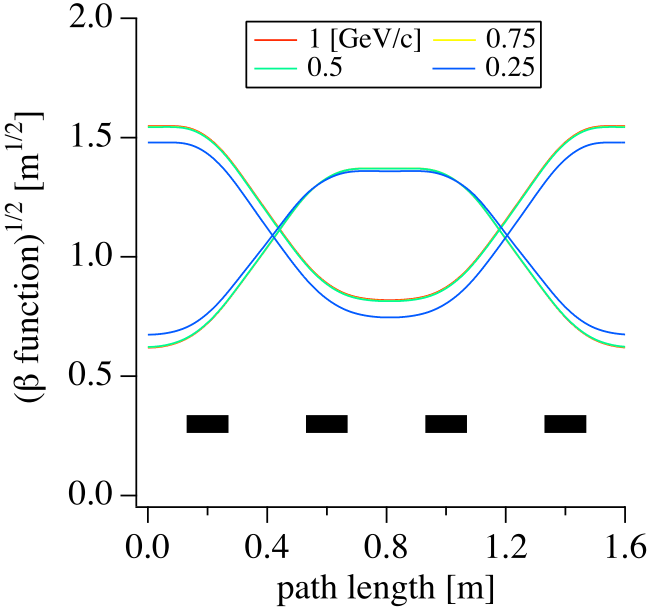
“Separated function” magnets (1)

idea

- In FFAG, focusing comes from gradient of net bending. Bending and focusing functions cannot be separated.

- However, FFAG straight beam line can be designed.
  – combination of F and D which gives zero net bending.

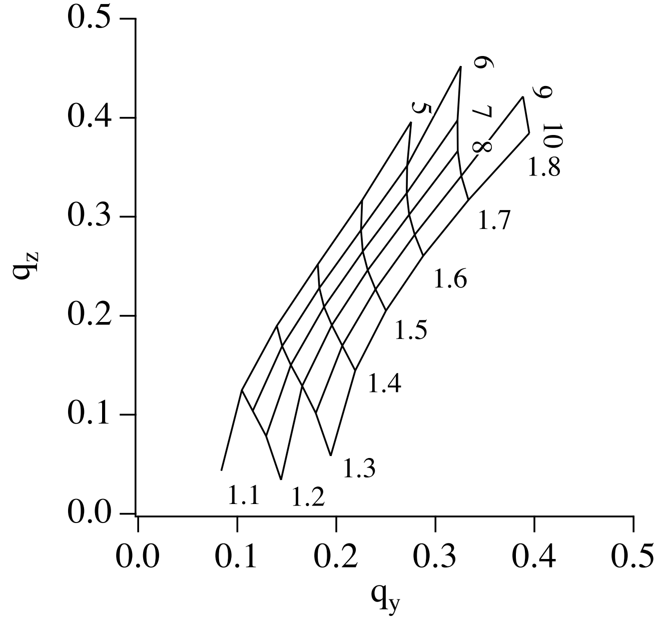




“Separated function” magnets (2)

phase advance

- Phase advance per cell is a function of
  - *k* value
  - F/D ratio



- I use a first few multipoles of

$$B_z = B_{z,0}(\frac{y}{y_0})^k F(\theta)$$

- With very larger *y0* and *k*, they are same as the ones of

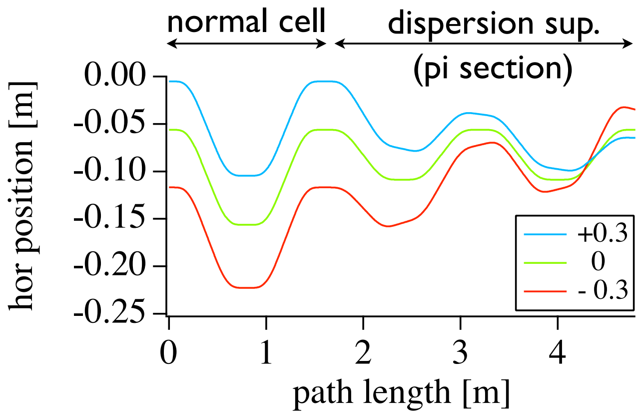
$$B_z = B_{z,0}\exp(\frac{ky}{y_0})F(\theta)$$

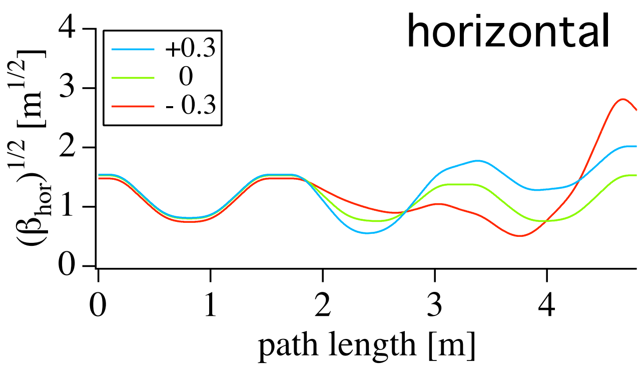
“Separated function” magnets (3)

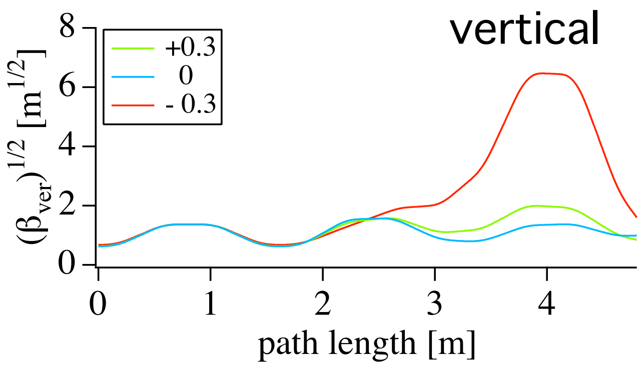
dispersion suppressor

- Dispersion suppressor can be made with combination of different *k*.

$$2k(\text{normal}) = k(\text{Disp. Sup.})$$







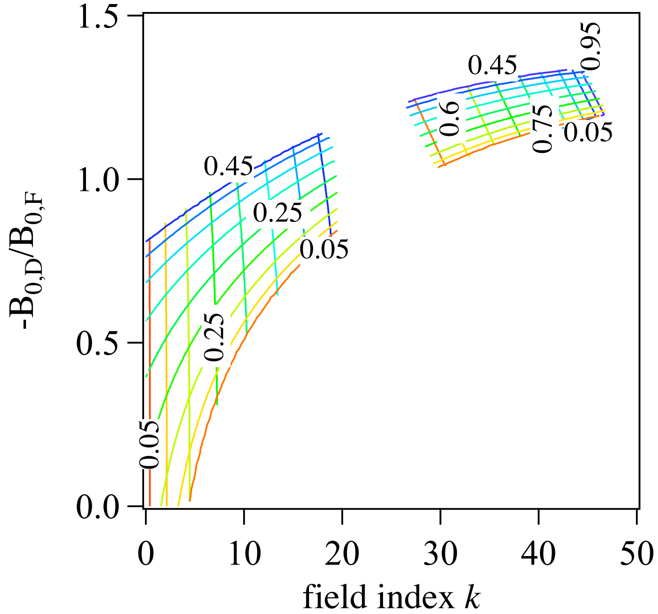
- Applications of the FFAG beam transport line
  – beam line between FFAG and gantry.
  – dump line of ADSR.

Using second stability region (1)

reduce orbit excursion

- No point to use second stability region in a synchrotron.
  - focusing strength and orbit shift (dispersion function) can be independently determined in synchrotron and linear nonscaling FFAG.

- In scaling and nonlinear nonscaling FFAG, field index *k* determines both focusing and orbit excursion.
  - large *k* is preferable to reduce orbit shift.
  - phase advance goes beyond 180 degrees.

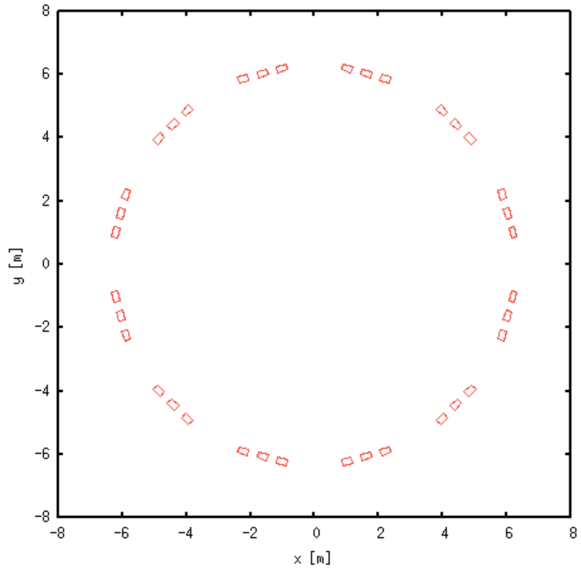


Using second stability region (2)

solutions to three major problems

- Beam blowup at resonance crossing can be avoided by almost constant tune.
- Magnets can be much smaller due to smaller orbit shift.
- Small number of cell gives enough room for injection, extraction and rf systems.

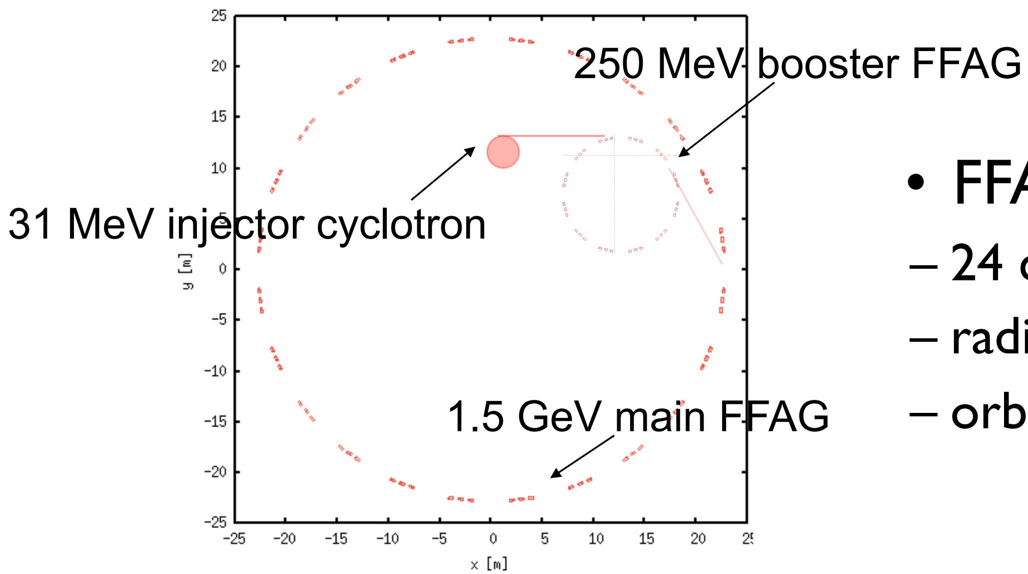
- In PAMELA design,
  - tune excursion is well within 0.5.
  - orbit shift is around 170 mm.
  - long straight is more than 1.5 m.



Using second stability region (3)

more examples

- Under the same design principle, higher momentum nonlinear nonscaling FFAG can be also designed.
  - 1.5 GeV proton FFAG for neutron production or ADSR.
  - 6 or 20 GeV proton FFAG as a proton driver of NF.



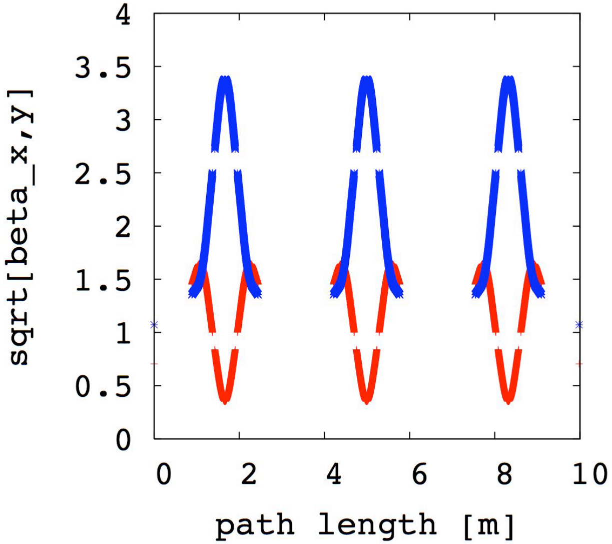
- FFAG for ADSR
  - 24 cells
  - radius is 22 m
  - orbit shift is 170 mm

Using second stability region (4)

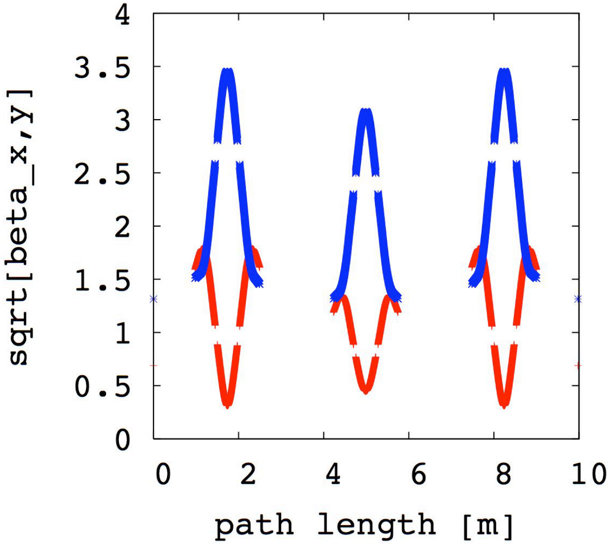
the ultimate FFAG

- Large *k* optics with long straight section.
  - should be the ultimate proton driver type FFAG.
  - perturbation on optics is larger with larger *k*.

12 cell symmetric lattice



additional 0.22 m every 3 cells



From scaling to nonscaing (1)

easy to build, make it cheaper

- In practice, exact scaling field profile is not necessary.
  - truncation of multiples.
  - rectangular magnets.
  - straight alignment.

- Nonscaling FFAG based with fixed tune (or phase advance.)

Summary

- FFAG optics is evolving in the same way as a synchrotron did.
  - quadrupole (separated function magnets): straight section.
  - many family of focusing elements: not one family of F and D.
  - insertion and matching between sections.
- Space for inject/extract, rf system and *flexibility* in general.

- In addition, use of the second stability region reduces orbit shift considerably.

- The third generation of FFAG (if nonscaling is the second generation) will includes all these ingredients.

Who is ready to make a proof of principle model?