Simulations studies of non-scaling FFAGs

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- Orbit correction

Operation of a nonscaling FFAG

Operation of a nonscaling FFAG (1)

scaling vs nonscaling

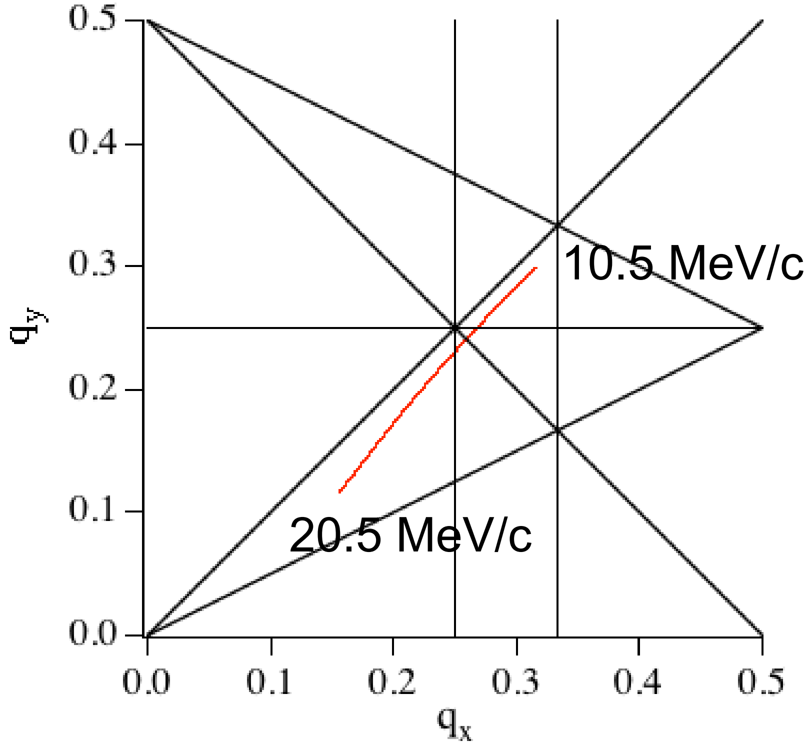
	Tune	Nonlinearity	Orbit shift
Scaling	Constant	Moderate	Moderate
Nonscaling	Move	Almost zero	Small
* Remark	Resonance	Dynamic aperture	Magnet size

- At the expense of tune excursion, a nonscaling FFAG minimize lattice magnets.
- For quick acceleration, tune excursion should not be a problem.

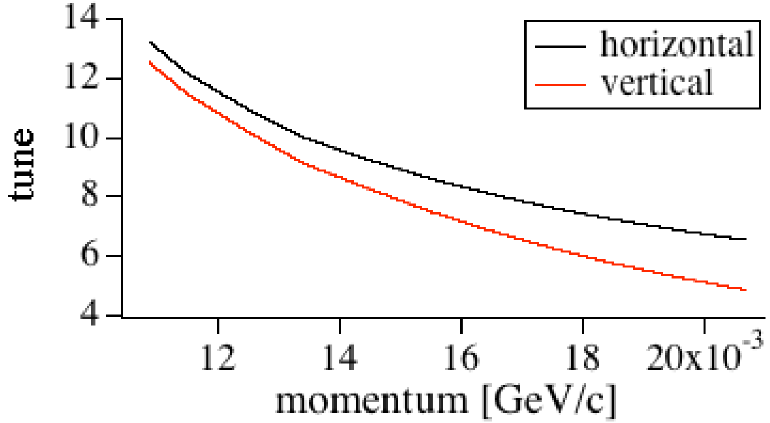
Operation of a nonscaling FFAG (2)

tune excursion

- Systematic integer and half-integer resonances are avoided by choosing “cell tune” below 0.5.
- Error driven integer and half-integer resonances have to be crossed several times.



Total tune vs. momentum in EMMA ring.



Operation of a nonscaling FFAG (3)
parameter range

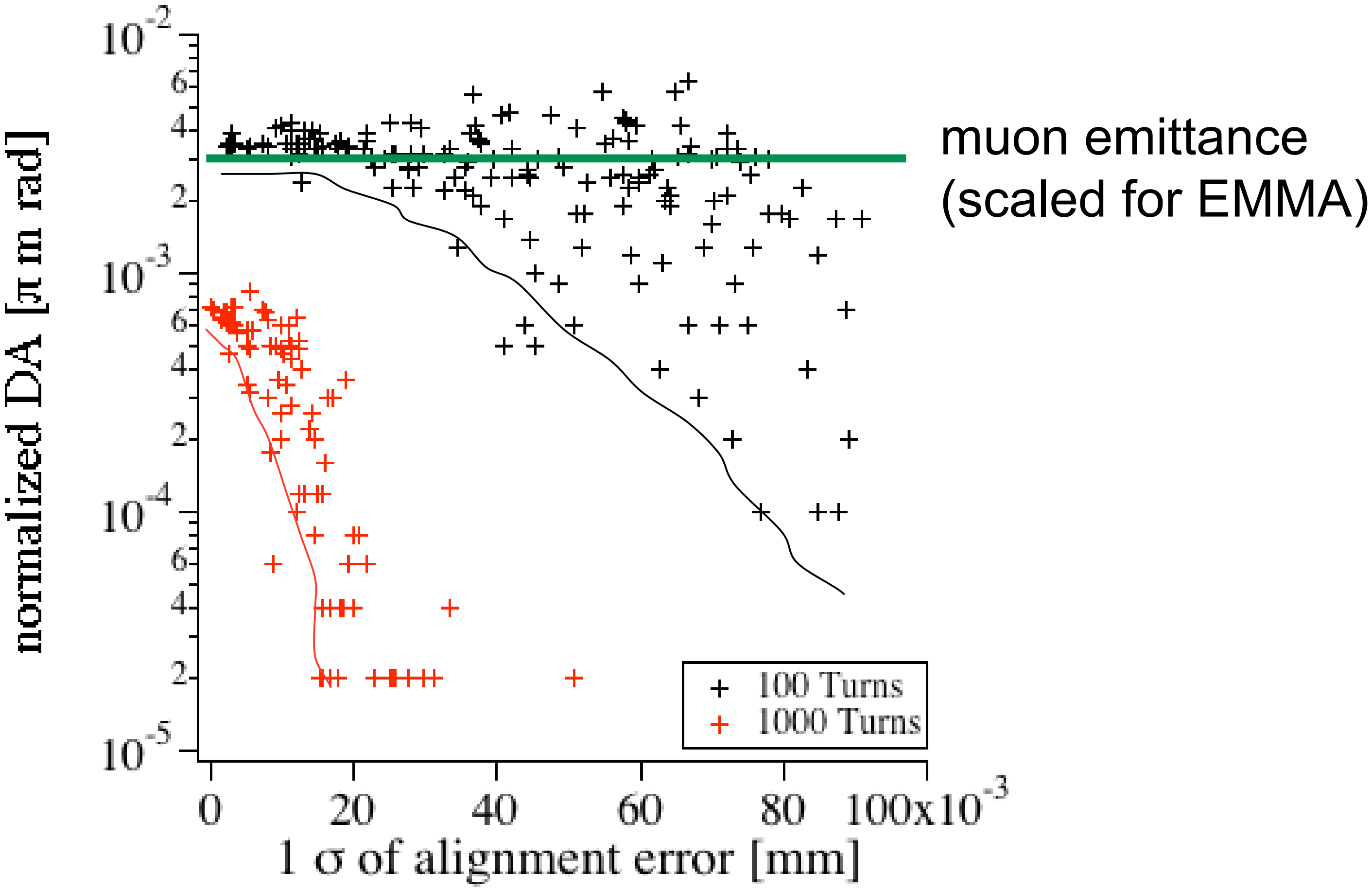
- How a nonscaling FFAG responds in different parameter space?

	Total turn: 1,000	100	10
Chromaticity correction: Off	A		C
On	B		D

Operation of a nonscaling FFAG (4)

A: *slow acceleration without chromaticity correction*

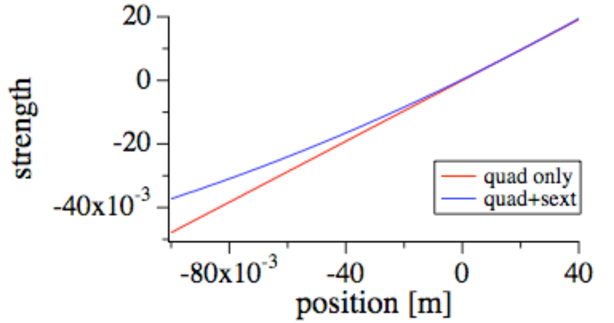
- Dynamic aperture becomes less with larger errors.
- In practice, no aperture with 1000 turns operation.

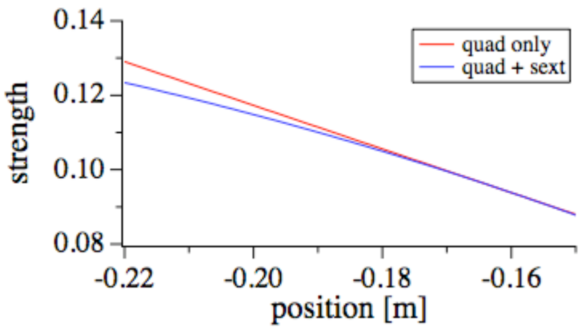


Operation of a nonscaling FFAG (5)

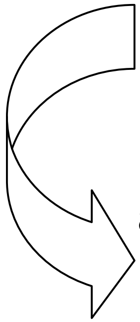
B: *slow acceleration with chromaticity correction*

- Sextupole (and octupole) make the tune almost flat.

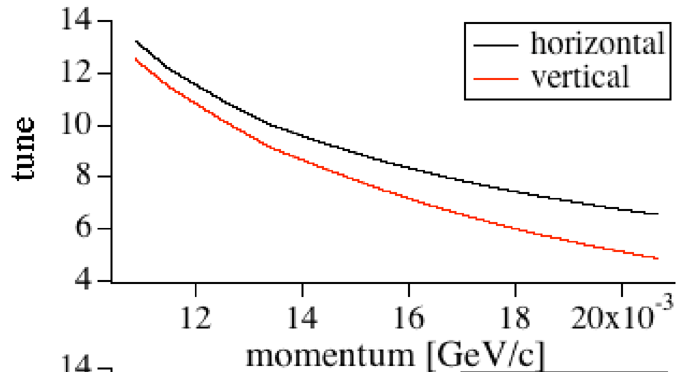


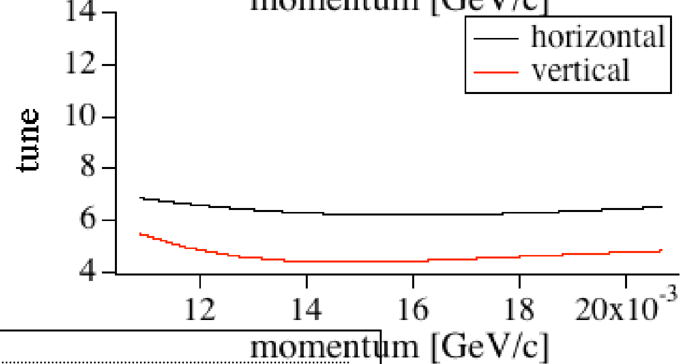


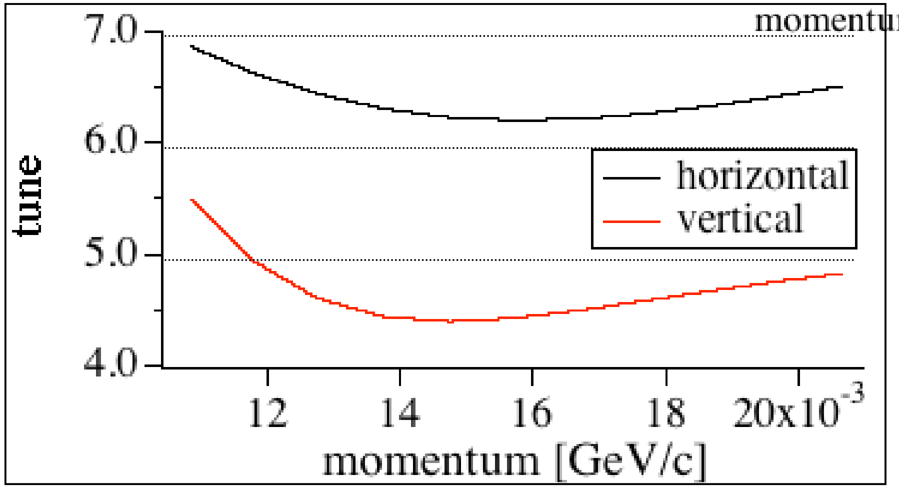
linear



+ sext and oct



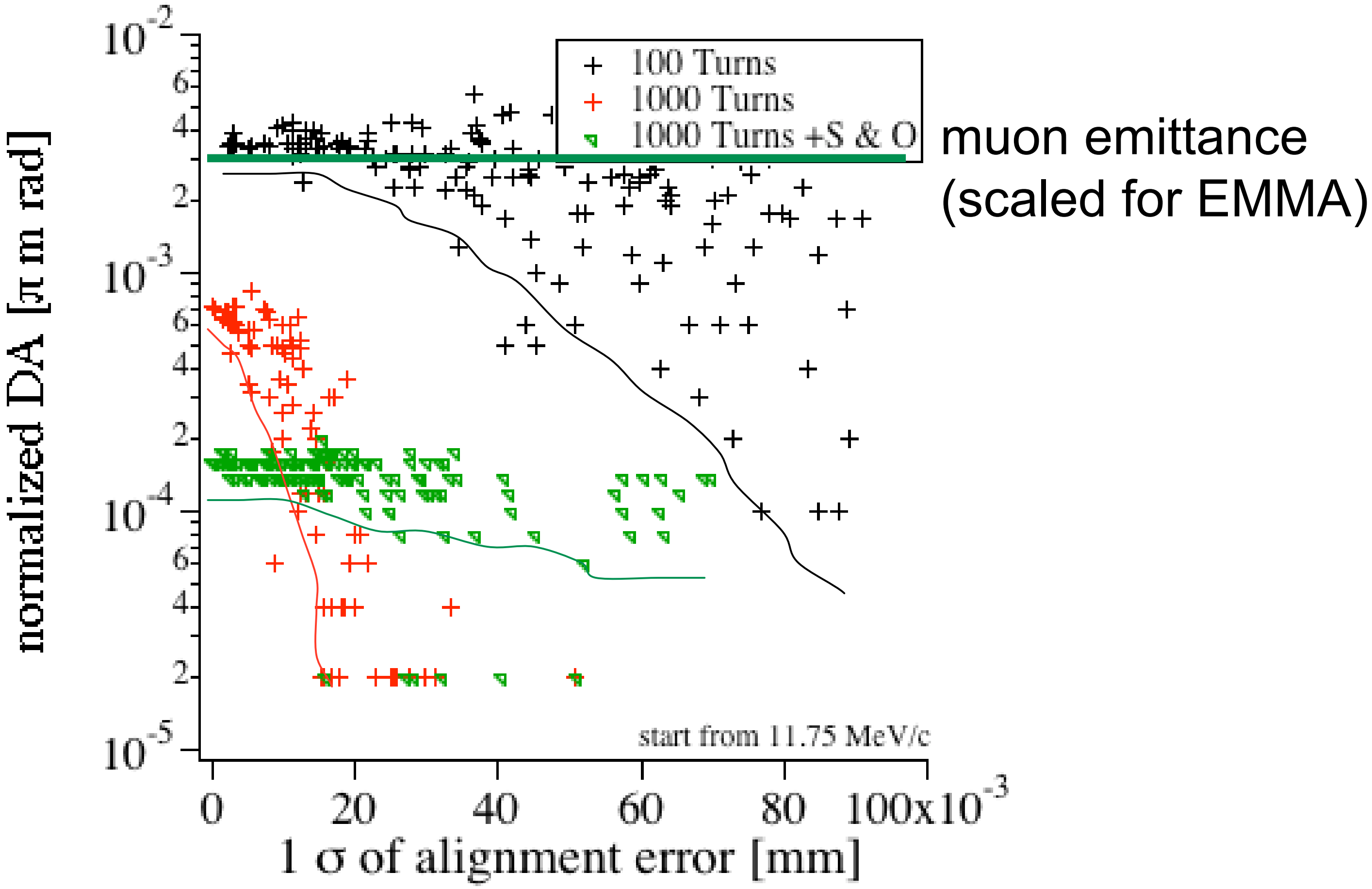




Operation of a nonscaling FFAG (6)

B: *slow acceleration with chromaticity correction*

- Dynamic aperture become less sensitive to errors.
- Absolute value of DA is reduced.



Operation of a nonscaling FFAG (7)

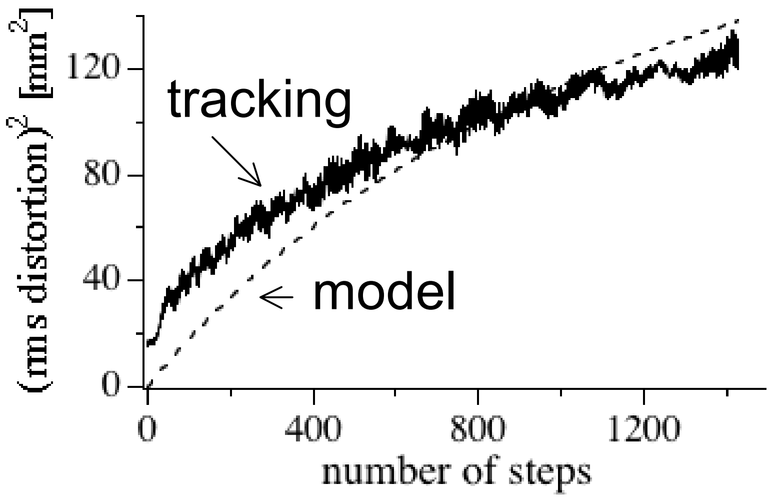
parameter range

- How a nonscaling FFAG responds in different parameter space?

	Total turn: 1,000	100	10
Chromaticity correction: Off	No aperture		C
On	Limited aperture: OK for some applications		D

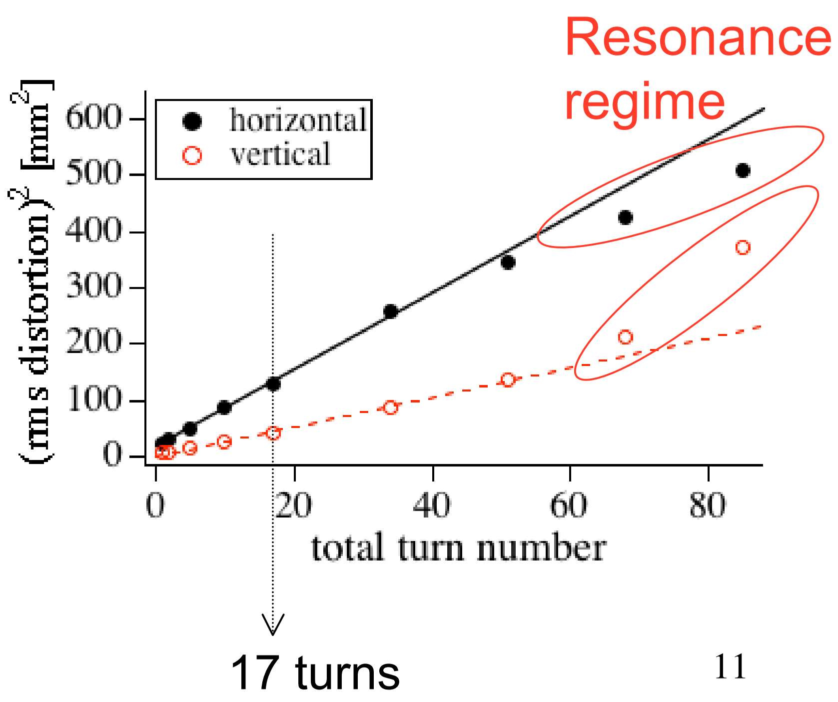
Operation of a nonscaling FFAG (8)
C: *fast acceleration without chromaticity correction*

- rms orbit distortion due to alignment errors agrees with random walk model.



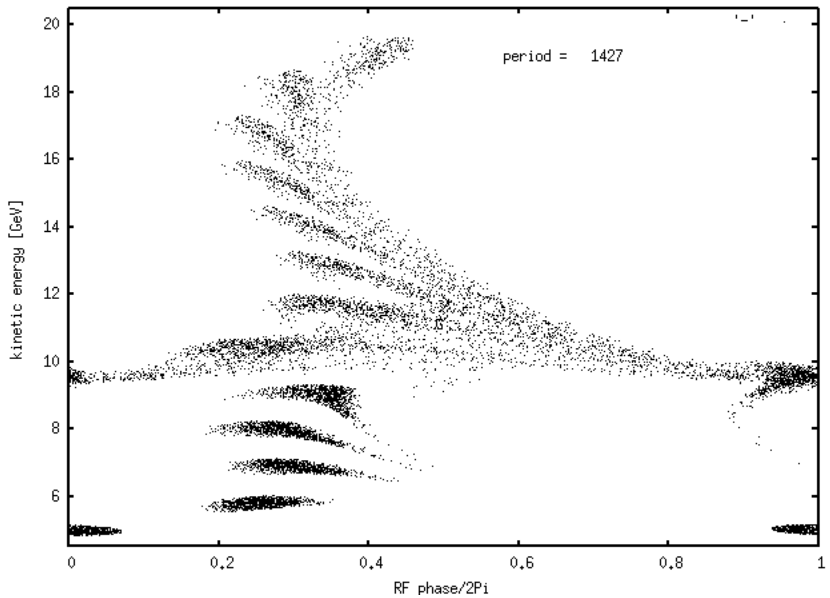
- Still enough aperture for muon.

- Distortion for different acceleration rate.
  - Circles are simulation results.
  - Lines are random walk model.



Operation of a nonscaling FFAG (9)
C: *fast acceleration without chromaticity correction*

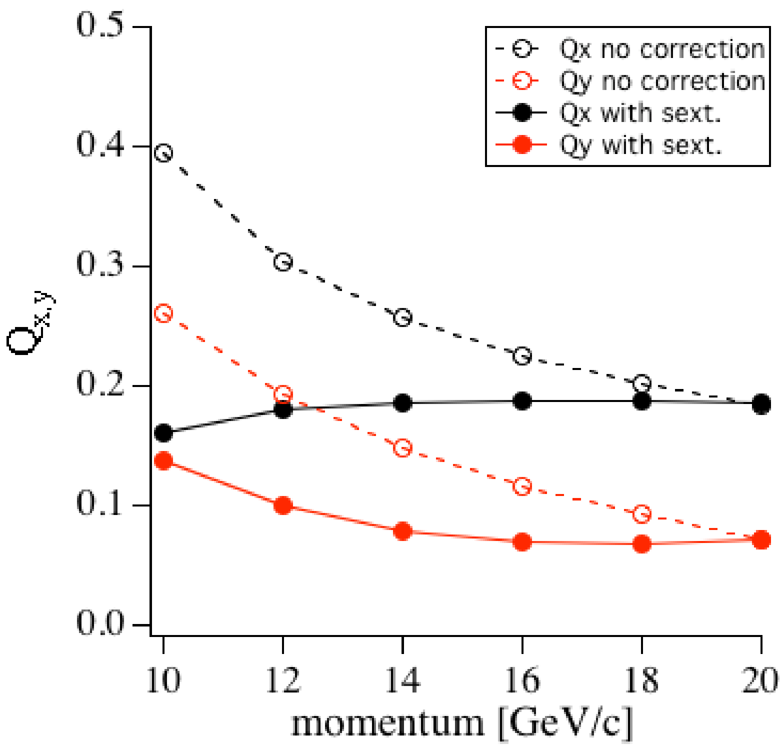
- "resonance" crossing itself is not a problem.
- However, no chromaticity correction causes another problem.
  - Longitudinal and transverse coupling.



Operation of a nonscaling FFAG (10)

D: *fast acceleration with chromaticity correction*

- Chromaticity correction eliminates the problem (Berg).
  - Reduction of dynamic aperture becomes a concern.
- Make a lattice with chromaticity correction.
  - 30 π mm acceptance is needed.

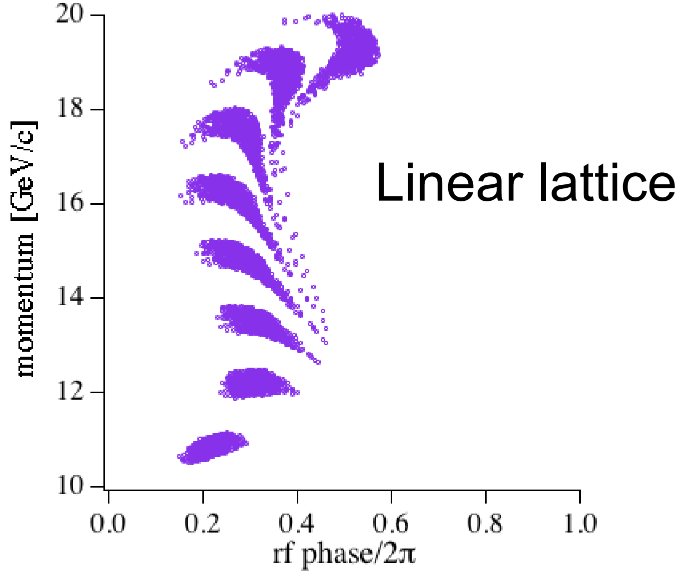


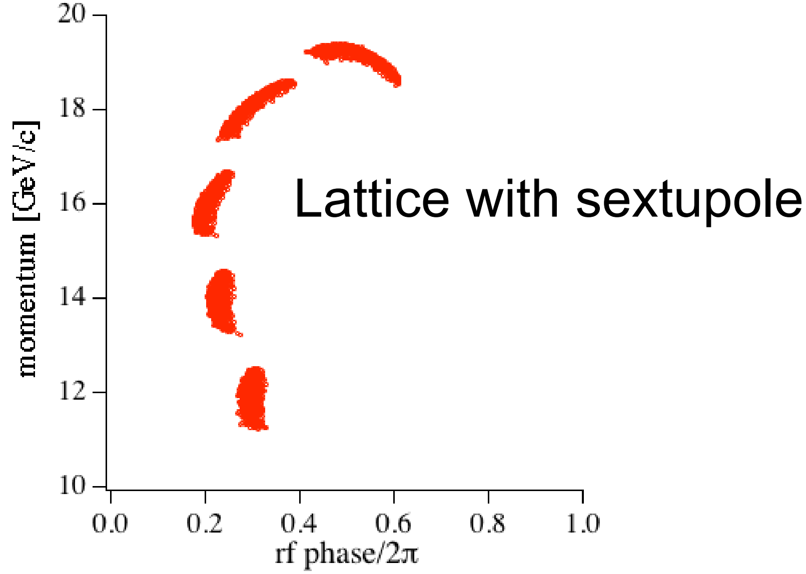
Dynamic aperture of 100 turns

Momentum [GeV/c]	Dynamic aperture [πmm]
10	18
12	9
14	6
16	9
18	15
20	18

Operation of a nonscaling FFAG (11)
D: *fast acceleration with chromaticity correction*

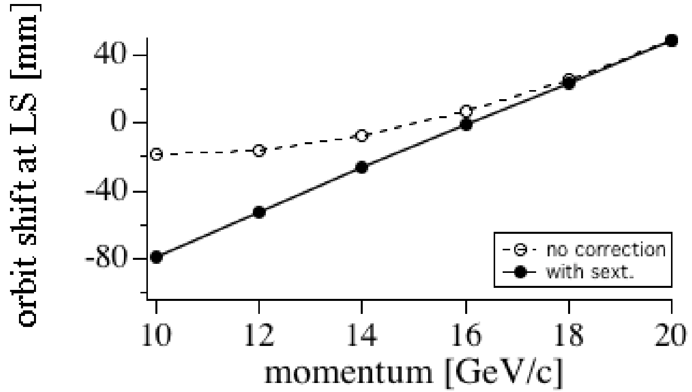
- Sextupole mitigates the phase slip problem.
- Muon beam with 30 π mm emittance is accelerated without beam loss.
  - Even though dynamic aperture of 100 turns does not give acceptance of 30 π mm.

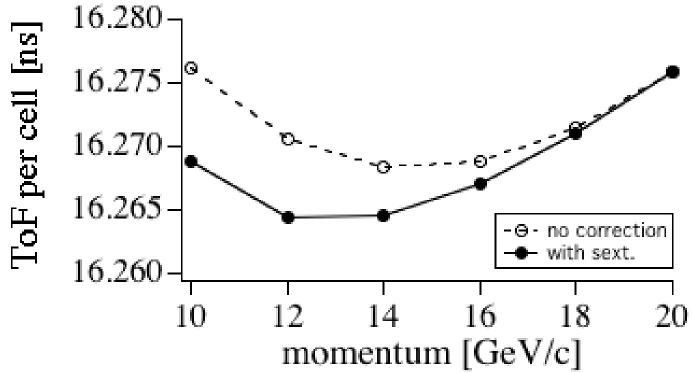




Operation of a nonscaling FFAG (12)
D: *fast acceleration with chromaticity correction*

- Orbit shift becomes as twice as much.
  - Need a bigger aperture magnet.
- Time of flight range increases 50%.
  - Need a higher voltage.
- Exchange of transverse emittance.
  - Can be cured by tune choice?





Operation of a nonscaling FFAG (13)
parameter range

- How a nonscaling FFAG responds in different parameter space?

	Total turn: 1,000	100	10
Chromaticity correction: Off	No aperture		Longitudinal-transverse coupling
On	Limited aperture: OK for some applications		Enough aperture

Orbit Correction

Orbit Correction (1)

Introduction

- Conventional Harmonic Correction will not work in a non-scaling FFAG with fast acceleration. This is due to the change in phase advance during acceleration.

$$\partial x_i \propto \theta_{corrector} Cos\left(\left(\varphi_{\mathbf{i}} - \varphi_{\mathbf{corr}}\right) - \upsilon\pi\right)$$

- Alternative correction methods:

  1. Optimisation algorithm over acceleration cycle utilising corrector magnets and injection orbit matching.
  2. Local correction of magnets : eliminate error source

Orbit Correction (2)

Optimisation algorithm (for vertical correction in EMMA)

- Calculate orbit distortion at each BPM using PTC tracking code
- Use differential algebra to find, to first order, dependence of distortion on initial phase space coordinates and corrector magnet strengths.
- Build up set of Taylor coefficients $A_{ij} = \frac{\partial y_i}{\partial \theta_j}$

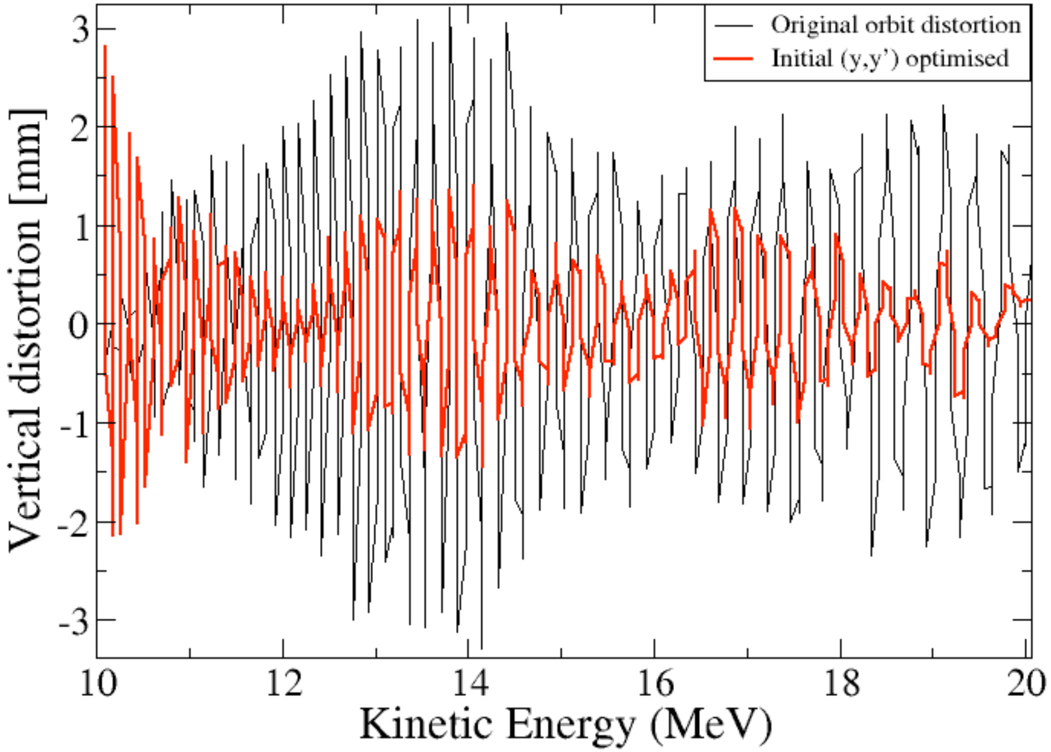
$$A \cdot \theta = -y_{BPM}$$

- Use a least squares method to find optimal θ.

The target is the orbit distortion measured at each BPM, turn-by-turn.

Orbit Correction (3)

Optimisation algorithm – phase space matching

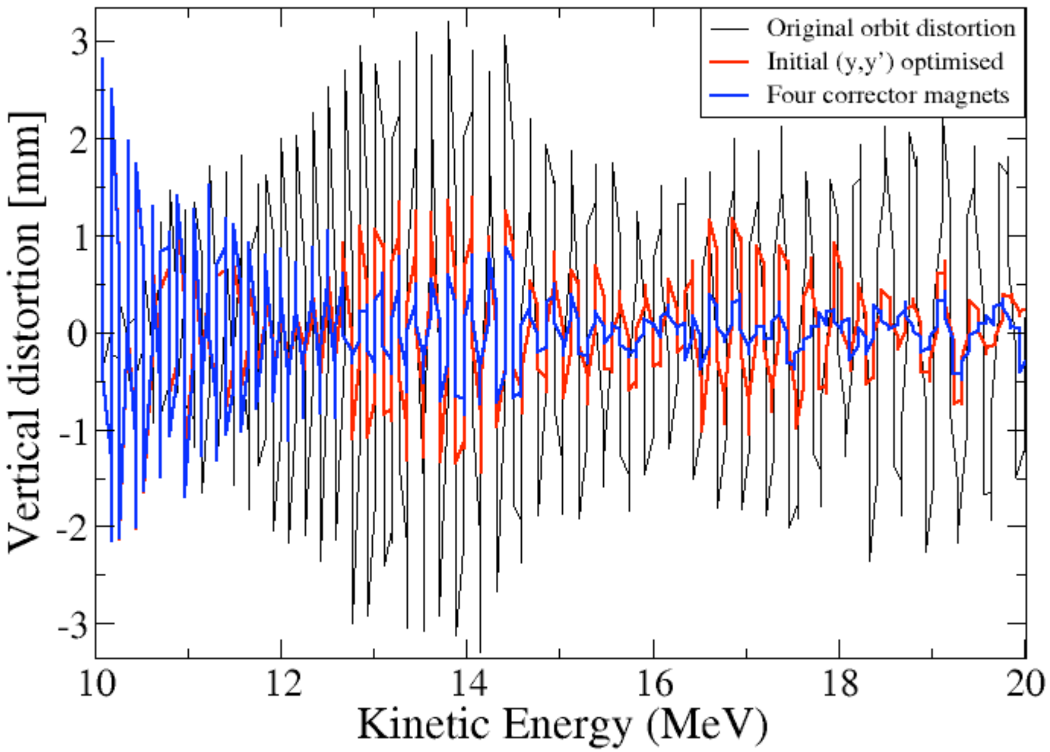


• Consider alternative target criteria in least squares fit, e.g. keep vertical distortion below a certain value everywhere, taking into account vacuum vessel size

Example from EMMA

Orbit Correction (4)

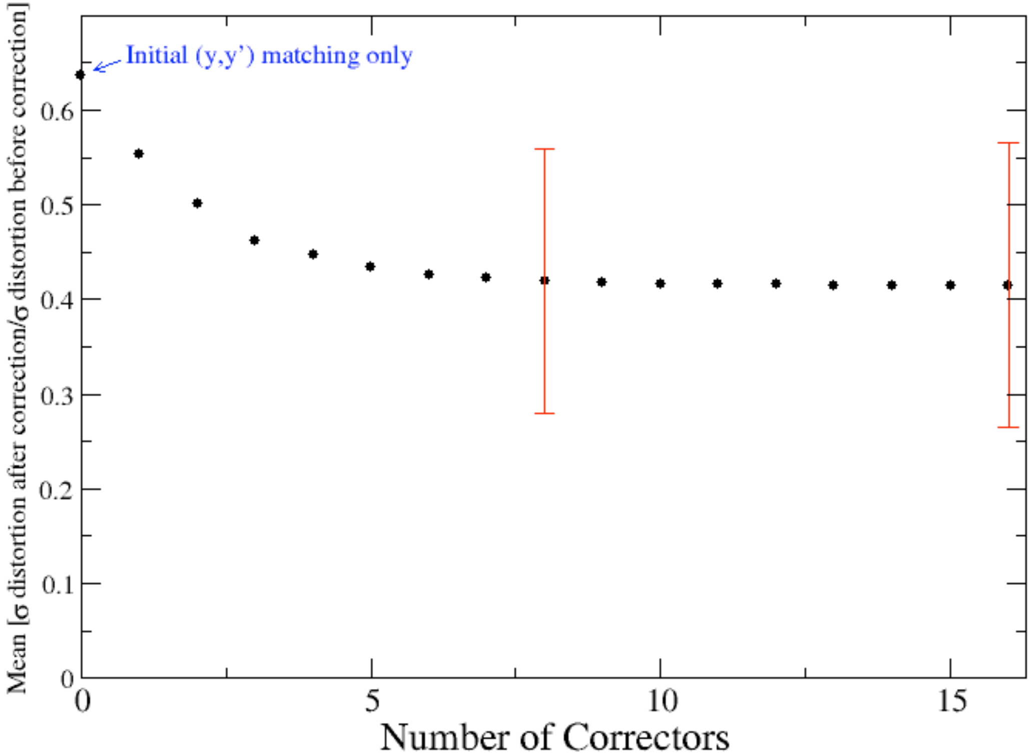
Optimisation algorithm – Corrector magnets



- Four corrector magnets in addition to matched initial phase space variables result in a further improvement in orbit distortion.

Example from EMMA

Orbit Correction (5)
Optimisation algorithm – Corrector magnets



- 100 misalignment seeds included in study
- In the case of EMMA, four corrector magnets provide almost all the orbit distortion reduction.

Example from EMMA

Orbit Correction (6)

Local Correction

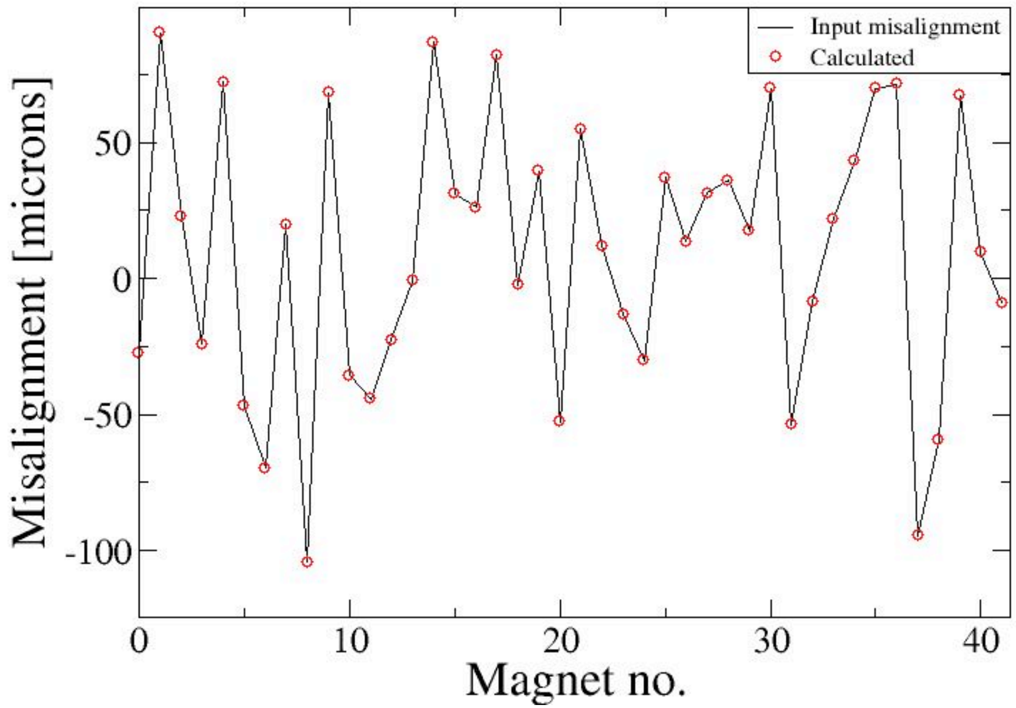
- Horizontal sliders in EMMA allow local correction of misalignments
- Include misalignment of BPMs, Δx_{BPM}
- Note dependence on kinetic energy of response matrix R_{ij}
- Assuming NBPM=NQUAD, the BPM measurements made at two energies would allow the simultaneous equations to be solved
- Assume ideal BPM readings known, $m_{co}(E)$

$$m_i(E) = m_{co}(E) - \Delta x_{BPM} + \sum_{j=1}^{N_q} R_{ij}(E)\Delta x_j$$

Orbit Correction (7)

Local Correction – Mathematica simulation

- In this ideal case, calculation of misalignments and BPM offsets is exact.
- In reality, statistical errors on BPMs and other error sources will reduce accuracy.



Conclusions

1. Chromaticity correction will be necessary for many FFAG applications.

- In the slow acceleration case it is needed to avoid resonance crossing.
- In the fast acceleration case it cures longitudinal-transverse coupling.

2. Correction scheme has been established for a nsFFAG since conventional harmonic correction will not work

- An algorithm that calculates optimal initial phase space matching and corrector magnet strengths has been developed
- A method to calculate and correct misalignments for local correction of magnets was described.