Space charge effects in FFAGs

4 October 2017
Space charge workshop 2017
Shinji Machida
STFC/ISIS

Overview

1. Previous study on space charge effects in FFAGs
2. Short introduction on FFAGs in this study
3. Space charge issues on FFAGs
4. Simulation results
5. Summary

Previous study

PRL **97**, 104801 (2006) PHYSICAL REVIEW LETTERS week ending 8 SEPTEMBER 2006

Fundamental Limit of Nonscaling Fixed-Field Alternating-Gradient Accelerators

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(Received 14 March 2006; published 6 September 2006)

Systematic nonlinear space-charge resonances may cause substantial emittance growth in the non-scaling fixed-field alternating-gradient (FFAG) accelerators. To avoid systematic nonlinear space-charge resonances, the phase advance of each nonscaling FFAG cell must avoid $\pi/2$ and $\pi/3$. Using multi-particle numerical simulations, we empirically obtain a minimum tune ramp rate vs the systematic 4th order space-charge resonance strength. We also find that the emittance growth obeys a simple scaling property when the betatron tunes cross the linear half-integer and sum resonances.

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Previous study

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New Journal of Physics
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Emittance growth mechanisms for space-charge dominated beams in fixed field alternating gradient and proton driver rings

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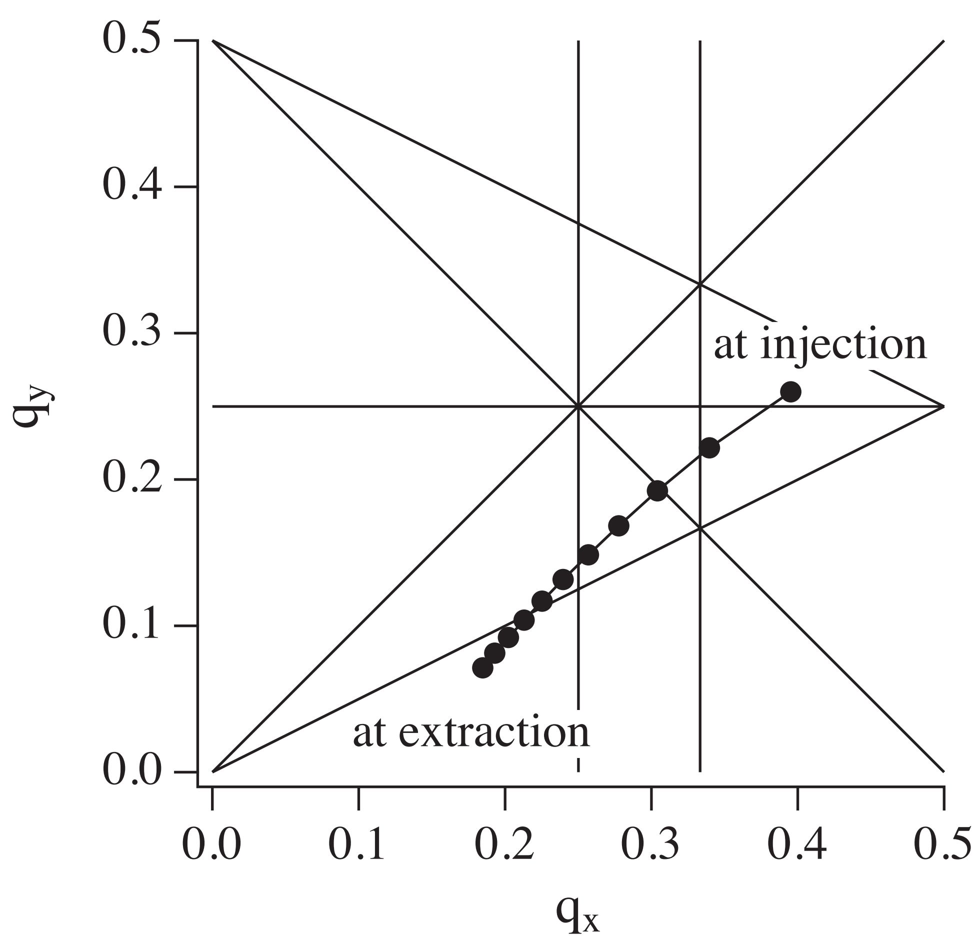
Previous study

FFAG considered here is so-called "linear non-scaling FFAG", in which (cell) tune moves a lot during acceleration, e.g. 0.30 to 0.05.

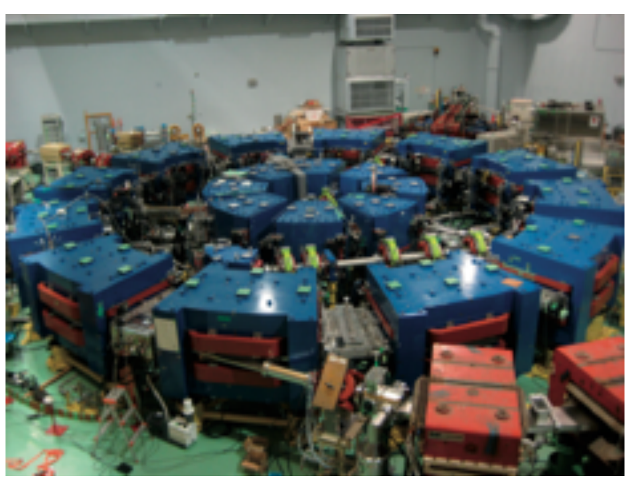
Resonance crossing (especially space charge driven) with slow acceleration is not possible.



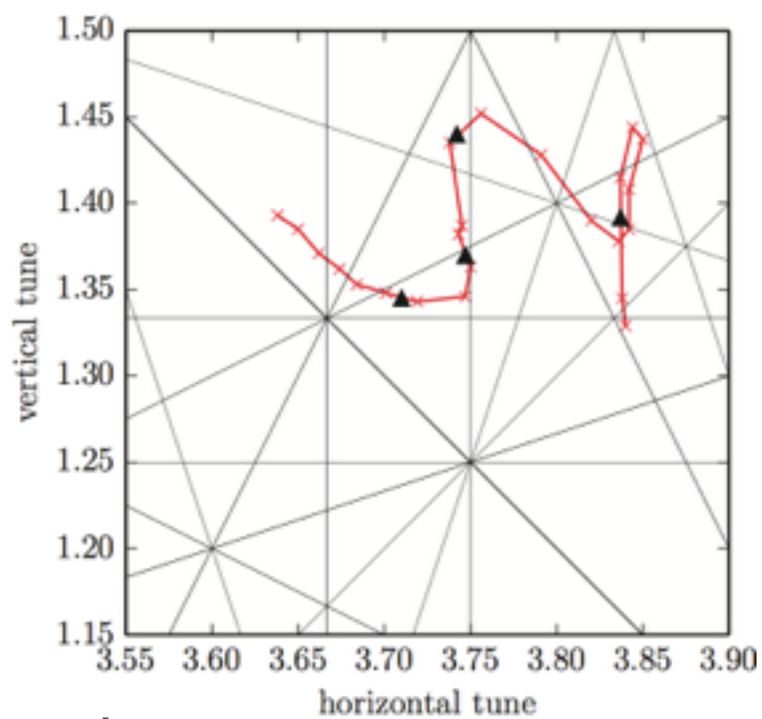
"Fundamental limit of nonscaling FFAG accelerators"

FFAG which we have studied

- Scaling or zero chromatic FFAG.
  - Transverse tune is (or supposed to be) constant during acceleration.
  - FFAG at Kyoto University for ADSR experiment.
  - Possible future upgrade of ISIS neutron and muon source.
- Operationally, it is similar to conventional synchrotron except potentially much higher repetition rate is possible.

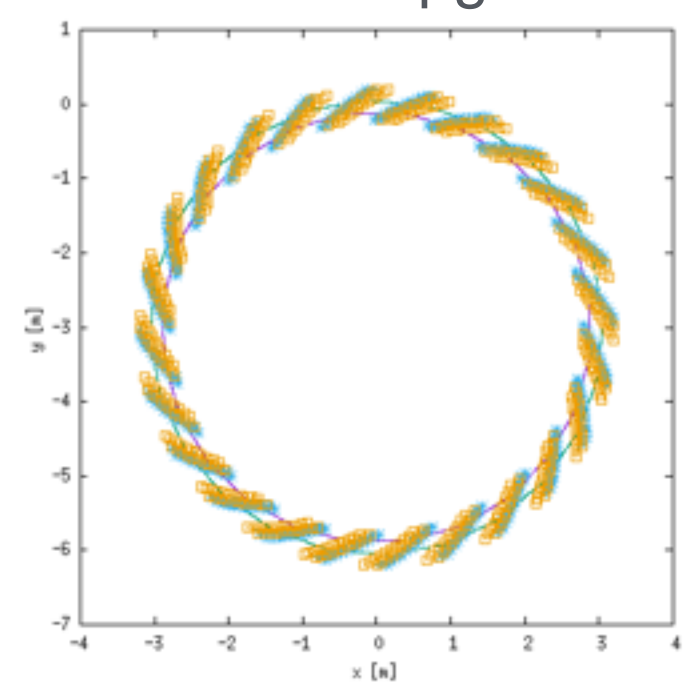


FFAG at Kyoto U.



Tune excursion

Future upgrade of ISIS



New configuration of neutron/muon source

short pulse option

If a short pulse is the requirement, a ring accumulator/accelerator has to be added.

SNS configuration	J-Parc (ISIS) configuration
full energy 1 GeV linac + accumulator ring	injector linac (400 MeV) + 3 GeV synchrotron
Full energy linac is long and costly both in construction and operation.	Repetition rate is limited (25 - 50 Hz).

New configuration
injector linac (200 ~ 400 MeV) + 1.2 GeV FFAG
• Modest energy linac and ring with high repetition rate (100 - 200 Hz). • Provide a variety of time structure of neutrons. • Best match with multiple target stations. • Muon benefits from high repetition rate. • Target is not ready for a few MW peak beam power yet.

1.2 GeV FFAG
parameter summary

beam power	**1.2 MW**
kinetic energy	**0.4 - 1.2 GeV**
mean radius at injection	**24 m**
number of cell	**24**
magnet longitudinal length (D, F)	**(0.63, 1.26) m**
packing factor	**0.35**
straight section	**4.08 m**
spiral angle	**60 degree**
k index	**20.97**
Bd/Bf	**-0.2862**
orbit excursion	**~ 1 m**
nominal cell tune (H, V)	**(0.21625, 0.21833)**
nominal ring tune (H, V)	**(5.19, 5.24)**
transition gamma	**4.7**

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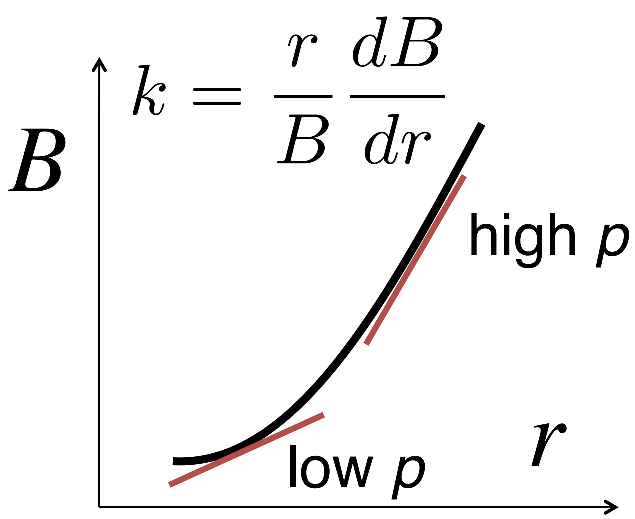
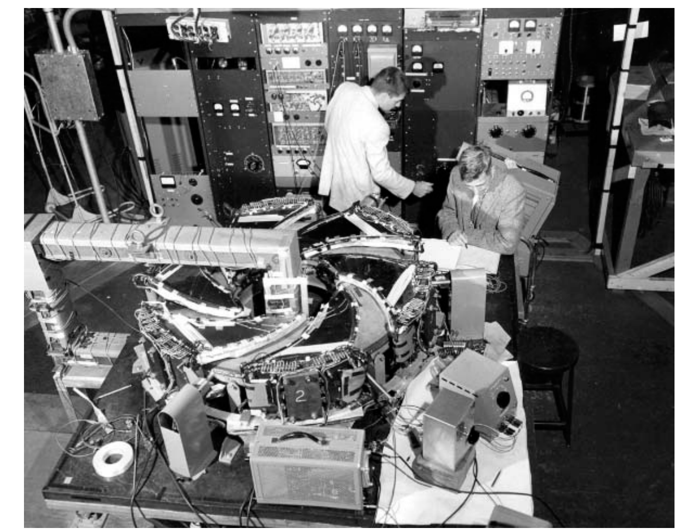
Differences from synchrotrons from beam dynamics points of view

- Intrinsic nonlinearity with multipole of all orders.
  - Field profile is r^k.



400 keV radial sector



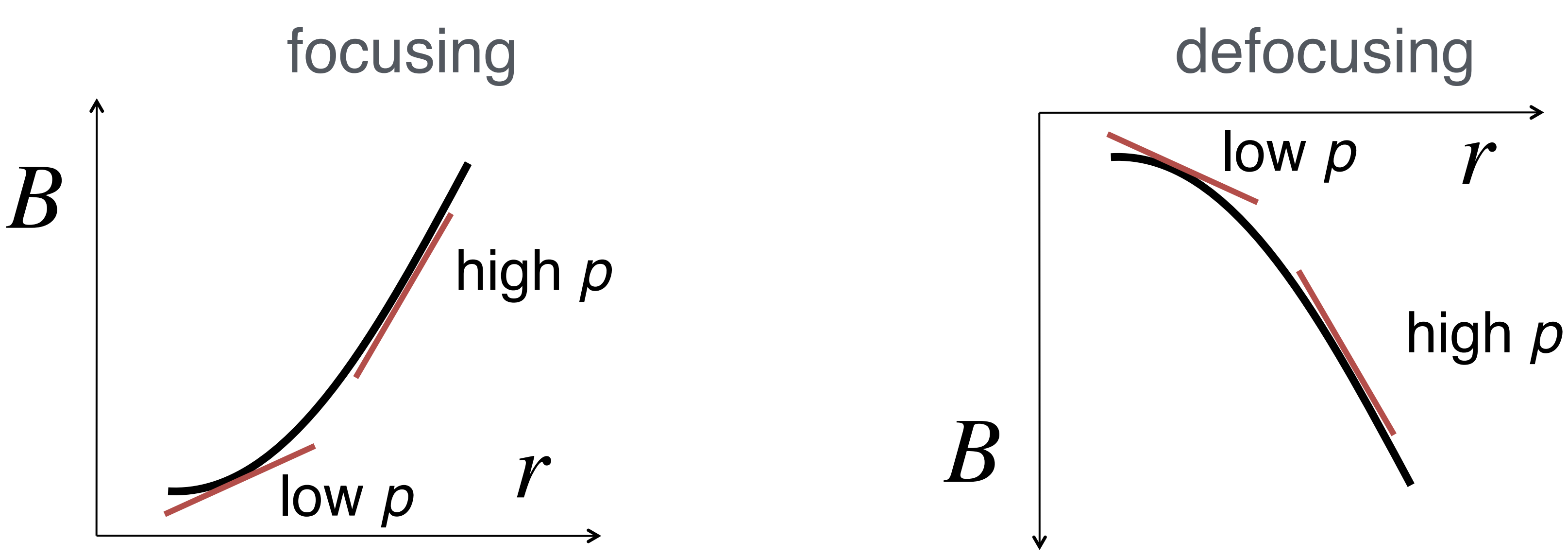
180 keV spiral sector

- Horizontal aperture is huge.
  - Horizontally large beam size can be accommodated.

- Longitudinal parameters have more flexibility.
  - synchrotron tune can be fixed.
  - Other parameters can be optimised.

Question 1

- Impact of intrinsic nonlinearities of scaling FFAG on the high intensity beams.
  - How the beams respond to space charge driven resonances and nonlinearities in magnets?
  - Do nonlinearities, especially octupole, reduce (or enhance) space charge tune shift?



Alternating gradient with field index of $k = \frac{r}{B}\frac{dB}{dr}$

Question 2

- Horizontal aperture is huge like cyclotrons. Horizontal beam size can be much larger than the vertical.
  - Does it help either by increasing horizontal emittance or decreasing horizontal tune to increase beta function?
  - How to deal with coupling resonance, 2Qh-2Qv=0 (Montague)?

$$\Delta Q_v = -\frac{n_t r_p}{\pi \epsilon_v (1 + \sqrt{\epsilon_h/\epsilon_v})\beta^2\gamma^3}\frac{1}{B_f}$$

	rep=25 Hz	50 Hz	100 Hz
Sqrt[eh/ev]=1	**1 MW**	2	4
2	1.5	3	6
3	2	4	**8 MW ?**

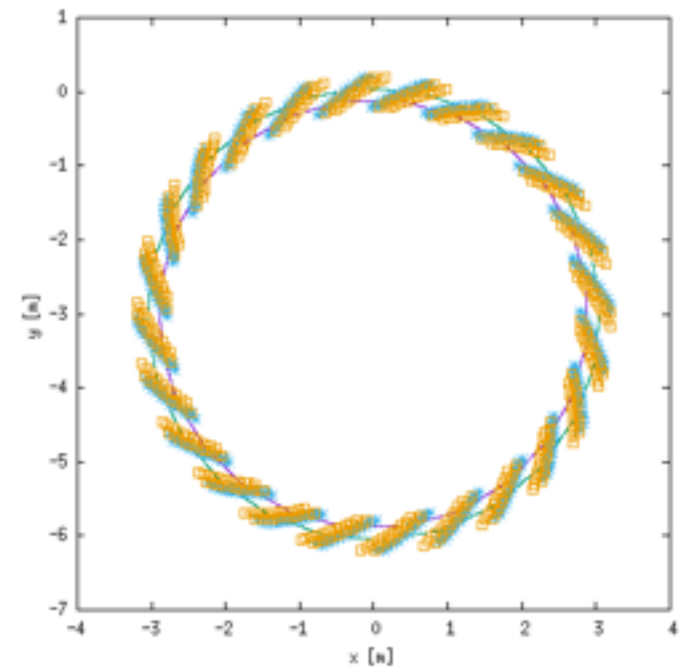
Simulation model

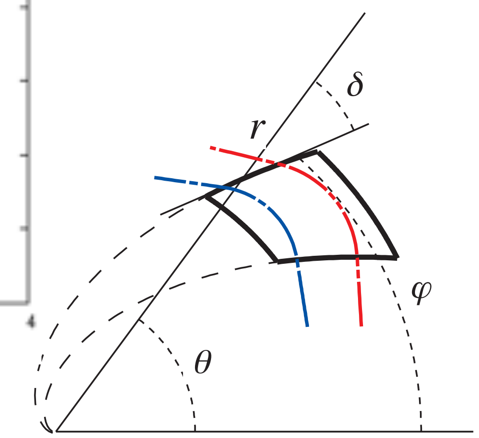
- Frozen space charge (Gaussian potential) with update of beam size every space charge kick.
- Transverse space charge kicks only, but with longitudinal position dependent line density.
- Synchrotron oscillation and acceleration (about 0.1 MeV per turn) are included.
- Runge-kutta integration to track particles.

Lattice and beam model

Lattice

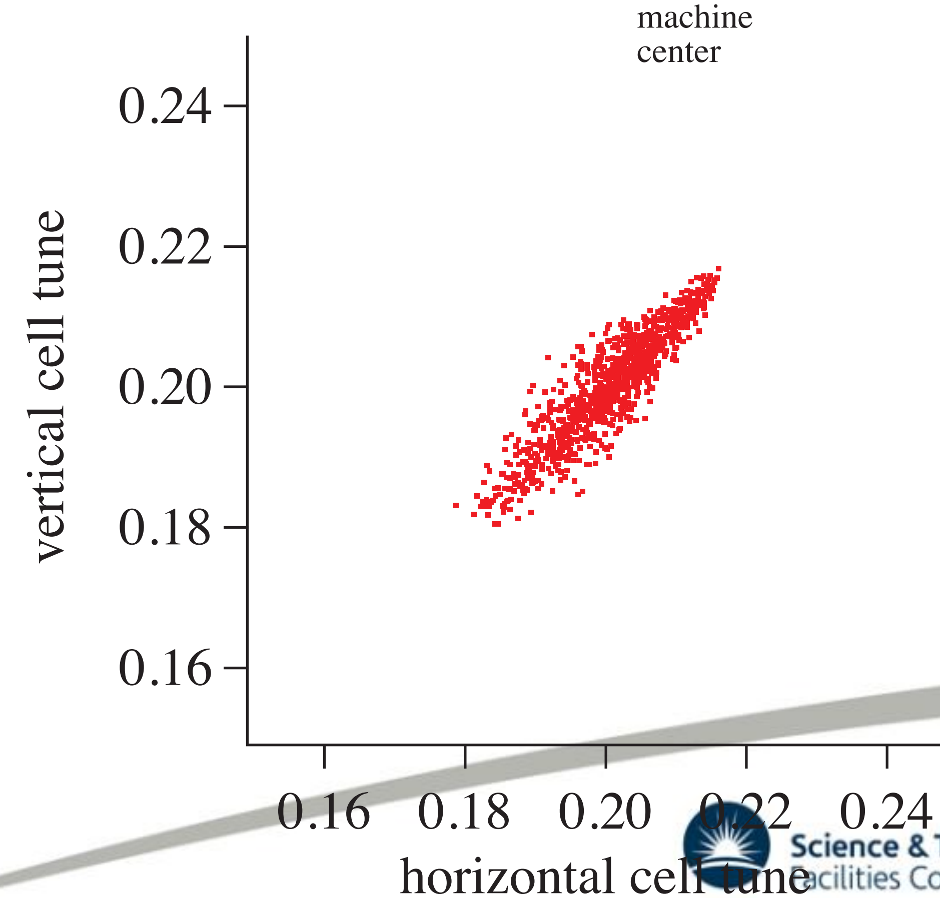
number of cell	24
k-value	21
spiral angle	60 degree
average radius	24 m

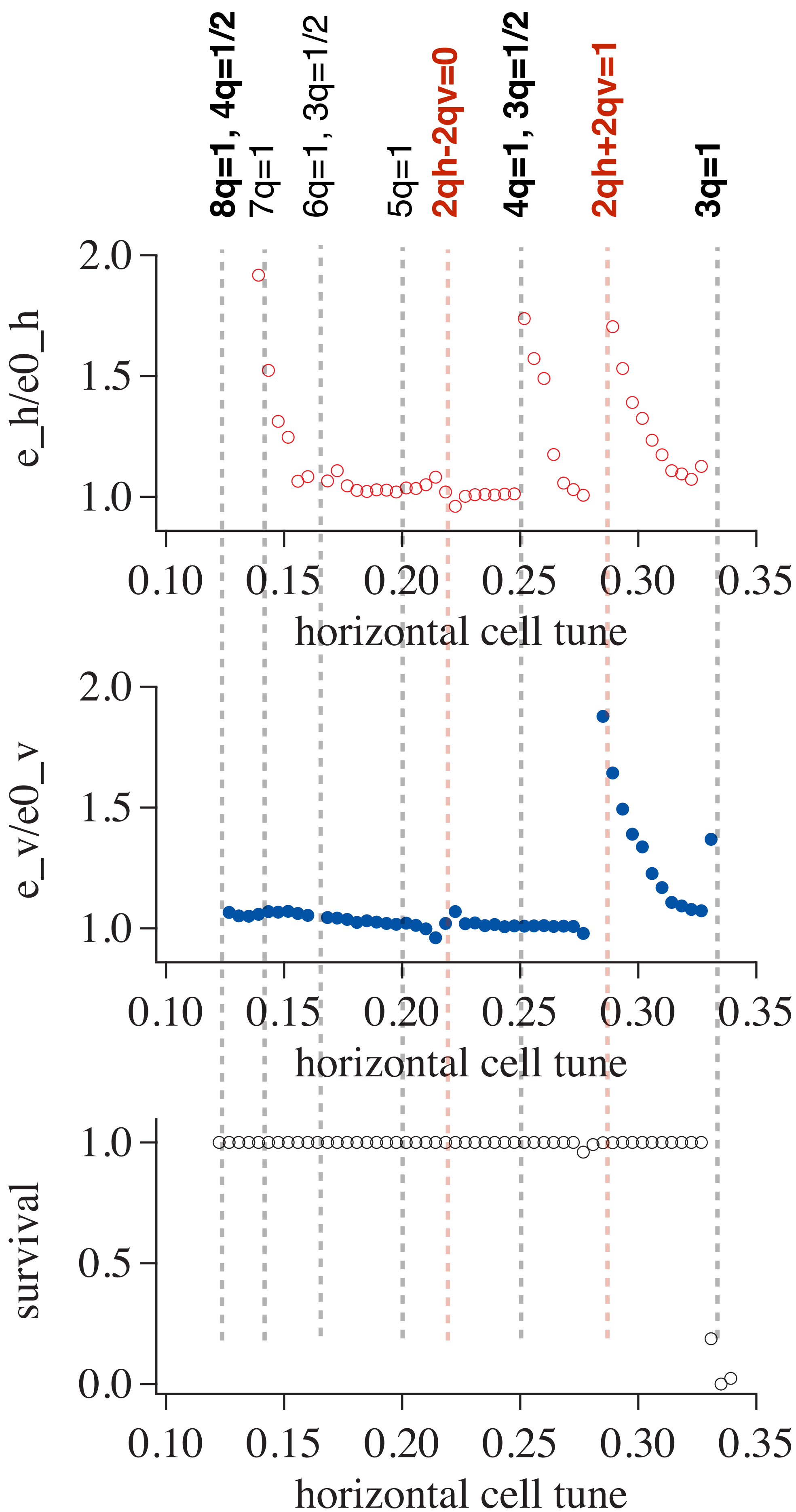




Beam

intensity	4.68 x 10^{13}
rms emittane	25 pi mm mrad
distribution	Gaussian
energy	0.4 - 1.2 GeV
incoherent tune shift	-0.8
per cell	-0.033





Result 1-1

resonance structure in tune space

Vertical tune is fixed at 0.21625 (5.19).

- Resonance driven by magnets

$$m\left(Q_0 - C_m \Delta Q\right) = k$$

Sacherer

- Resonances driven by space charge

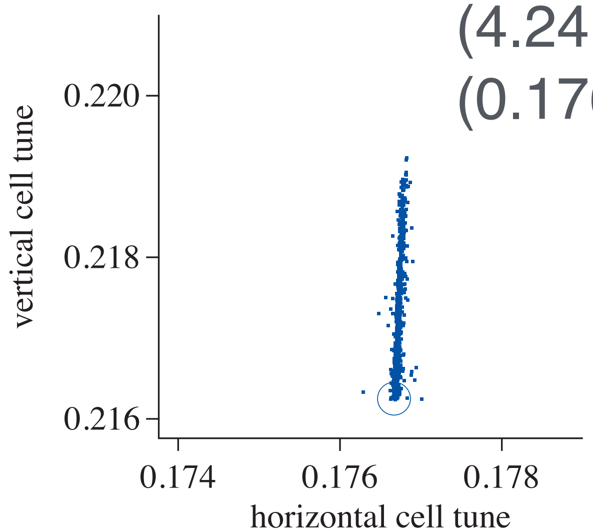
$$m\left(Q_0 - C_m \Delta Q\right) = \frac{k}{2}$$

Okamoto and Yokoya

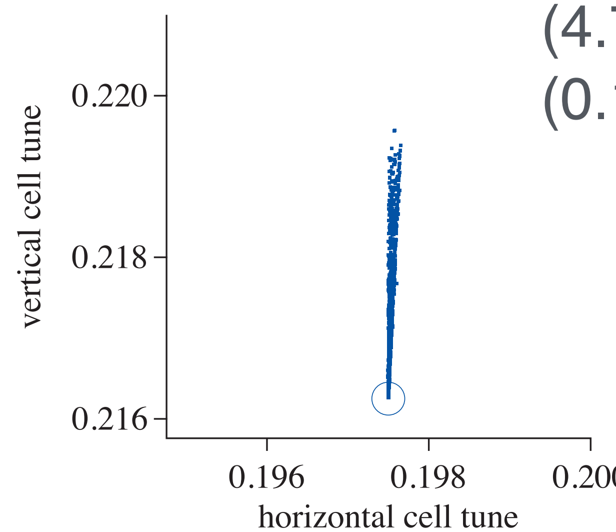
Lattice nonlinearities are relatively weak except sextupole (3q=1).

Result 1-2

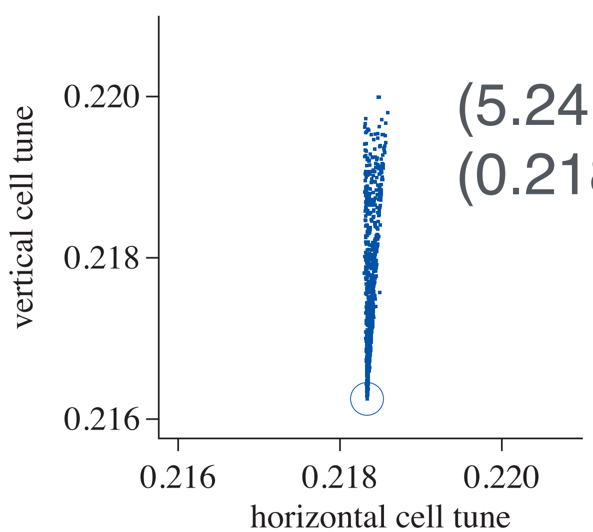
tune shift due to nonlinearities



(4.24, 5.19) or
(0.17667, 0.21625)



(4.74, 5.19) or
(0.19750, 0.21625)



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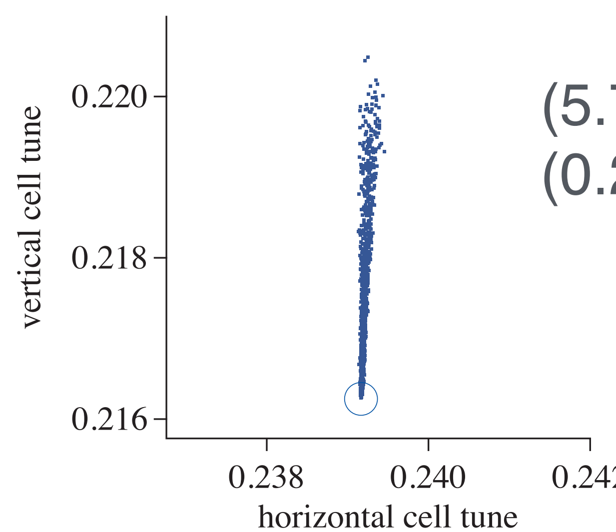

(5.74, 5.19) or
(0.22917, 0.21625)

- **Tune shift, mostly in vertical, has positive sign with amplitude.**

Result 1-2

tune shift due to nonlinearities

(4.24, 5.19) or
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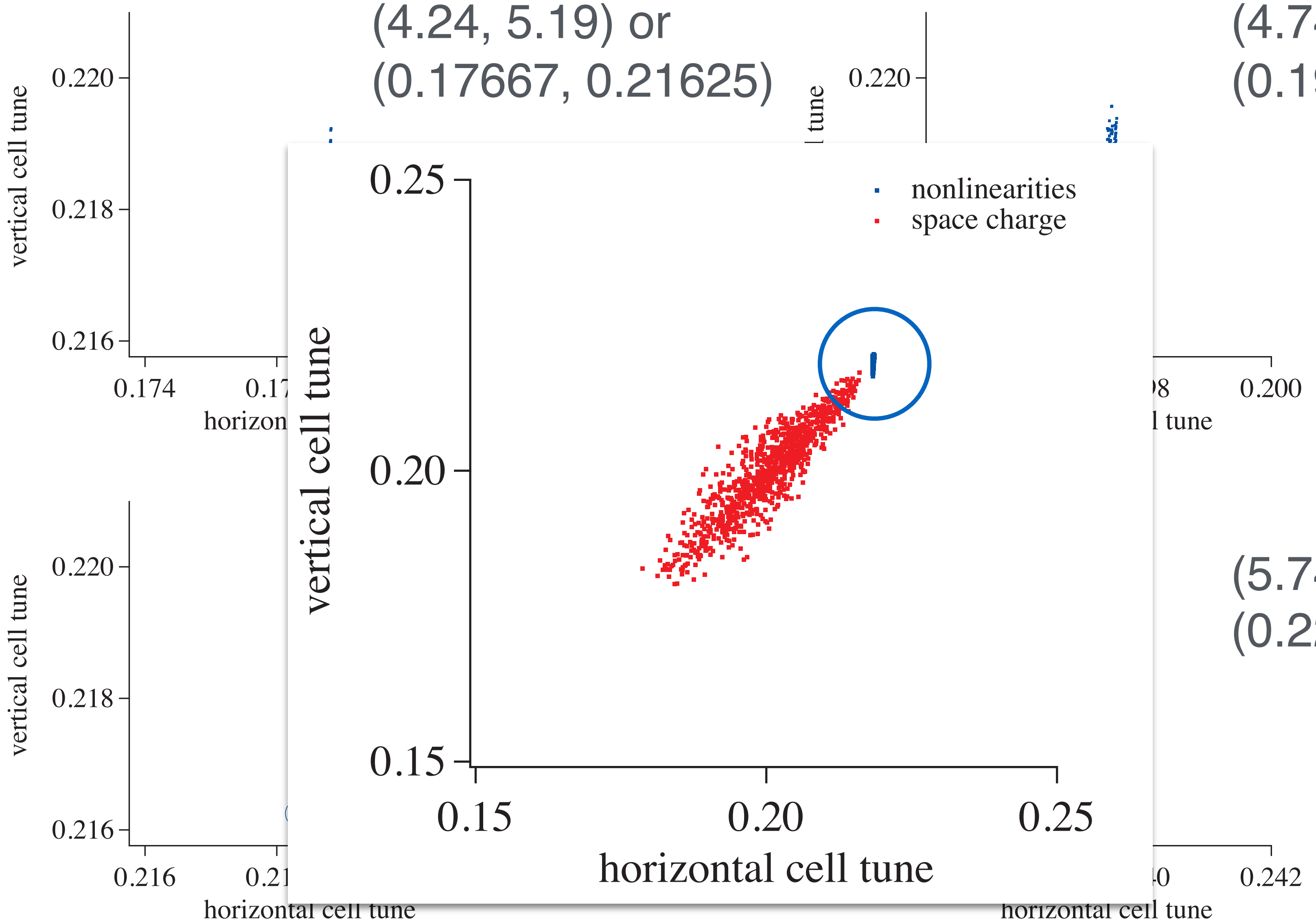


(5.74, 5.19) or
(0.22917, 0.21625)

- Tune shift, mostly in vertical, has positive sign with amplitude.
- **Order of magnitude smaller than space charge tune shift.**

Result 2-1

way to increase horizontal beam size

$$E_v = \frac{\lambda}{\pi\varepsilon_0 b\left(a+b\right)} y \quad \text{gives} \quad \Delta Q_v = \frac{r_p R N_t}{\pi b\left(a+b\right)\beta^2\gamma^3 B_f Q_v}$$

With assumption of $\beta_{h,v} \propto 1/Q_{h,v}$

$$\Delta Q_h = \frac{r_p N_t}{2\pi\epsilon_h\left(1+\sqrt{\frac{Q_h}{Q_v}\frac{\epsilon_v}{\epsilon_h}}\right)/2\left(\beta^2\gamma^3 B_f\right)}$$

$$\Delta Q_v = \frac{r_p N_t}{2\pi\epsilon_v\left(1+\sqrt{\frac{Q_v}{Q_h}\frac{\epsilon_h}{\epsilon_v}}\right)/2\left(\beta^2\gamma^3 B_f\right)}$$

Increase horizontal emittance (eh) or decrease horizontal tune (qh) to utilise horizontal aperture.

Result 2-1

way to increase horizontal beam size

When qh=qv

eh/ev	dqv	dqh
1	1	1
4	2/3	1/3
9	1/2	1/6
16	2/5	1/10

When eh=ev

qv/qh	dqv	dqh
1	1	1
4	2/3	4/3
9	1/2	3/2
16	2/5	8/5

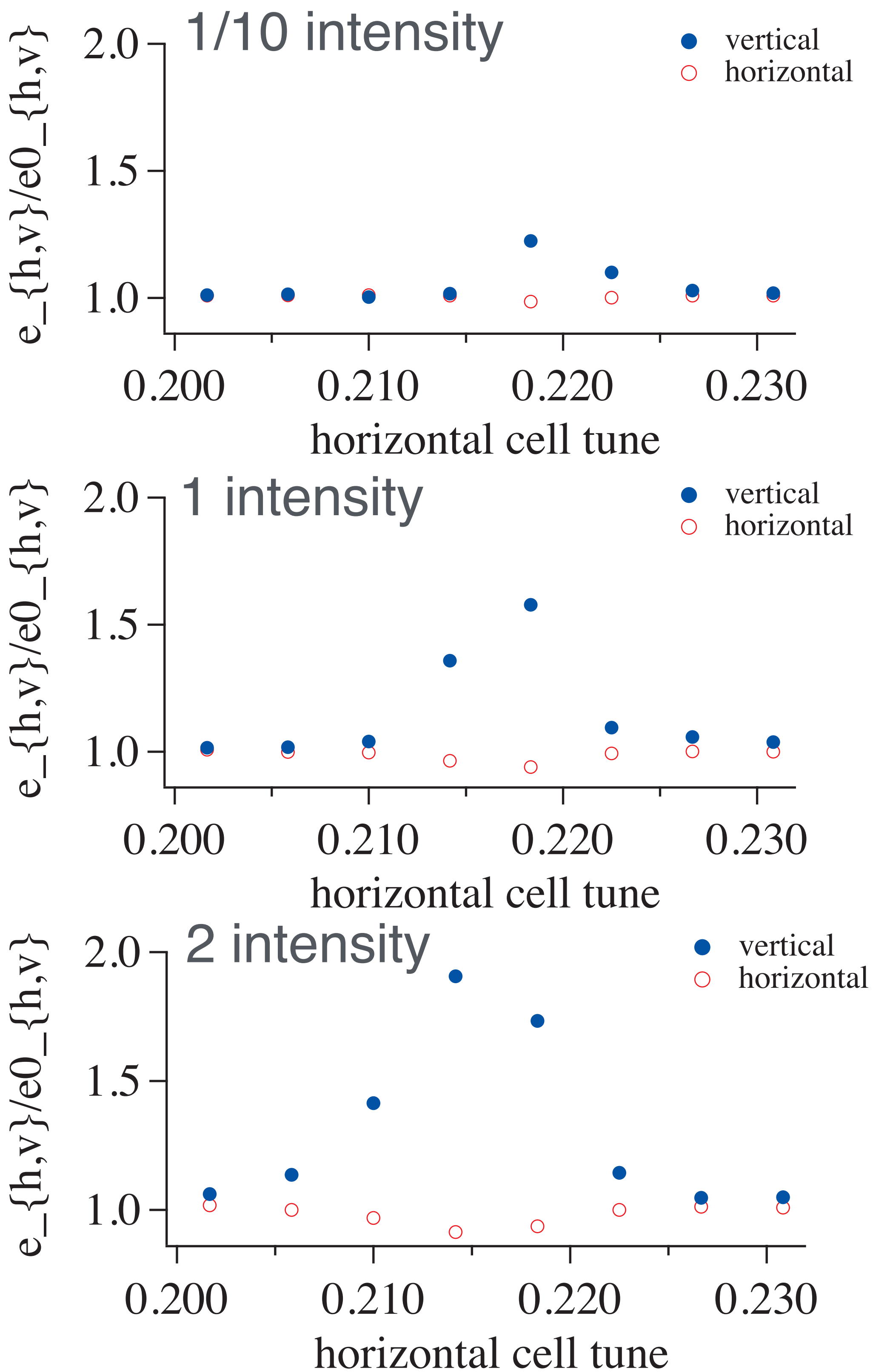
When qv/qh=eh/ev

qv/qh=eh/ev	dqv	dqh
1	1	1
2	2/3	2/3
4	2/5	2/5
9	2/17	2/17

Red > 1

Result 2-2

effects of coupling resonance



Vertical tune is fixed at 0.21625 (5.19).

$$\Theta = \frac{3}{2}\left(\sqrt{\epsilon_r} - 1\right) \Delta Q_h$$

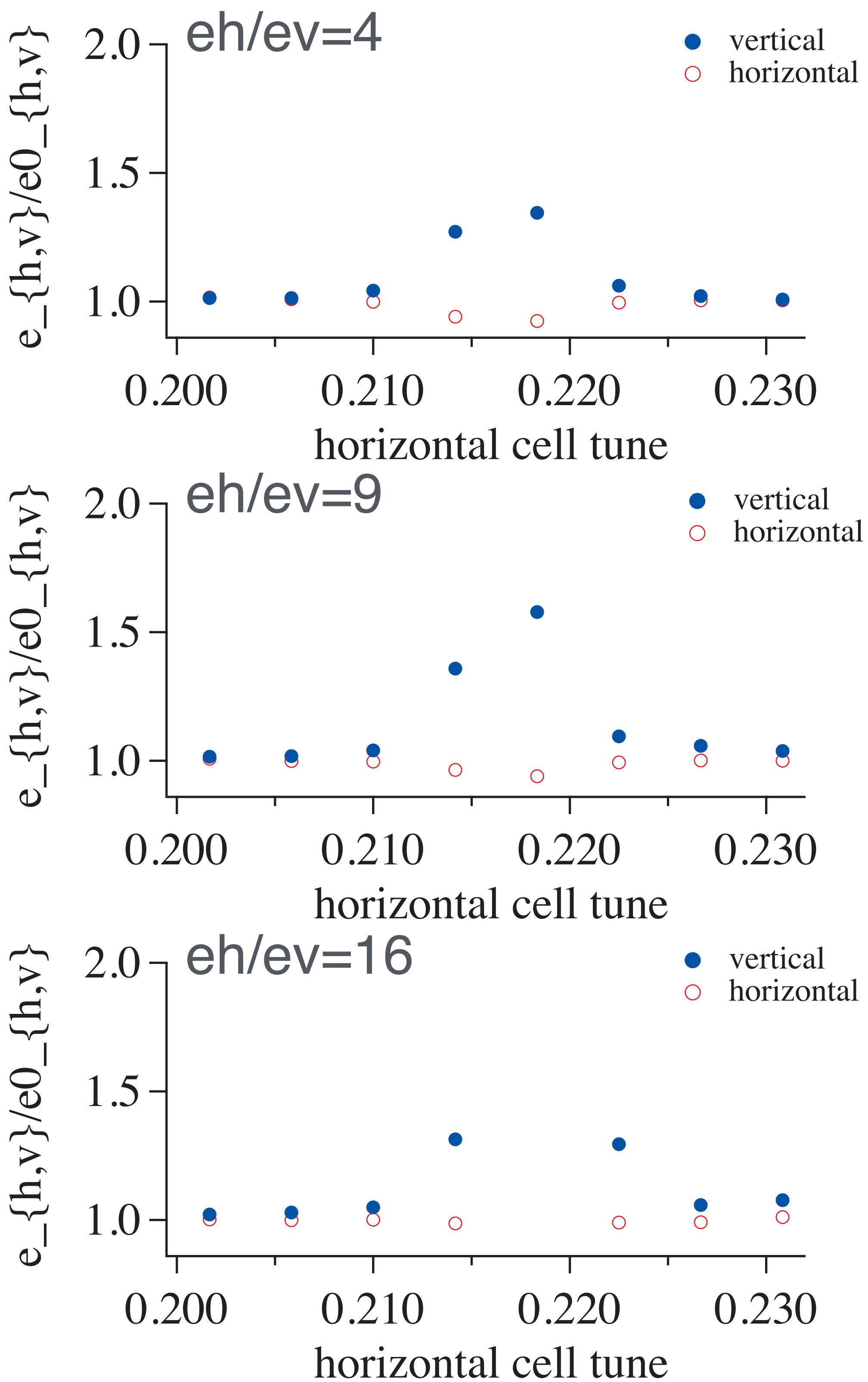
Hofmann and Franchetti

eh/ev	sqrt(r)-1	dqh	width
9	2	1/10	1/5
9	2	1	2
9	2	2	4

Qualitatively agrees, but not in absolute value.

Result 2-2

effects of coupling resonance



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$$\Theta = \frac{3}{2}\left(\sqrt{\epsilon_r} - 1\right)\Delta Q_h$$

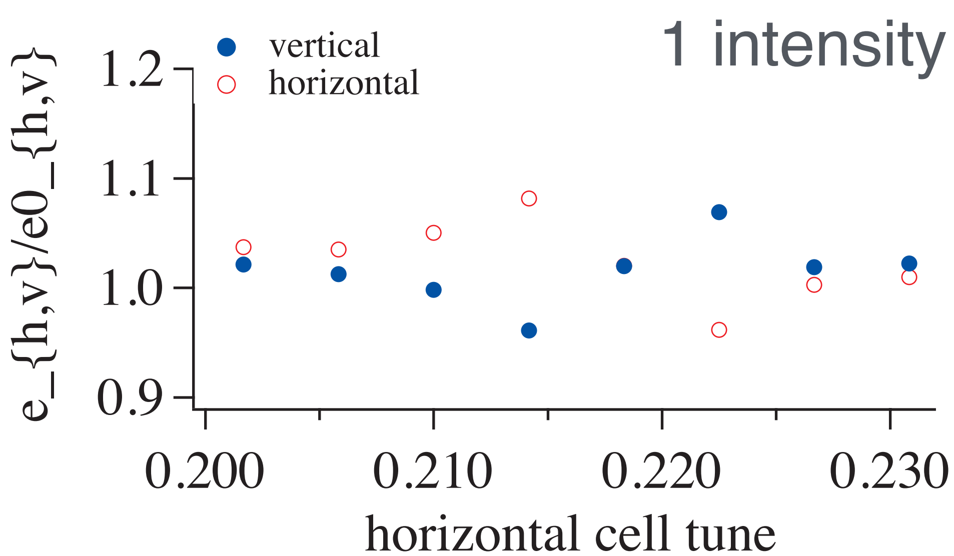
Hofmann and Franchetti

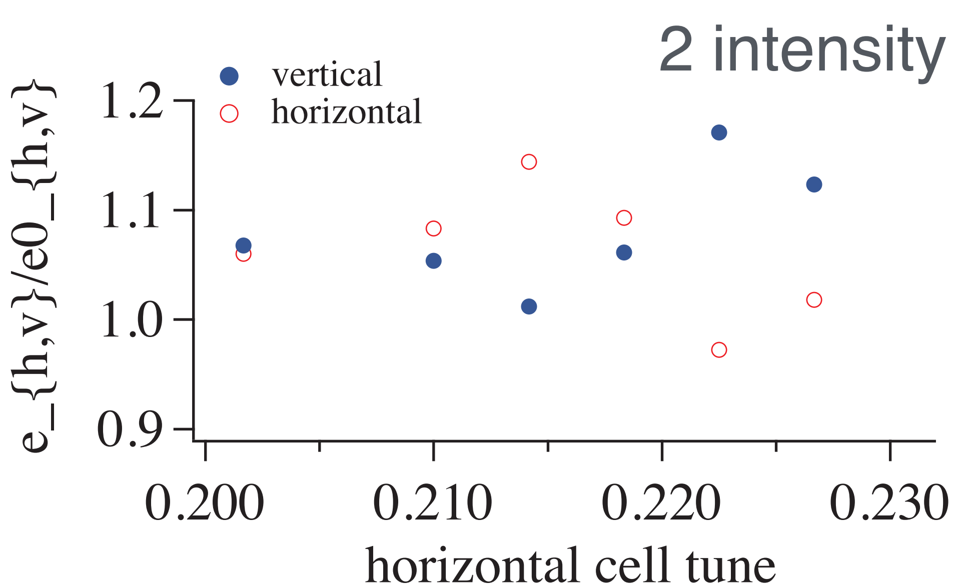
eh/ev	sqrt(r)-1	dqh	width
4	1	2	2
9	2	1	2
16	3	3/5	9/5

Qualitatively agrees, but not in absolute value.

Result 2-2

effects of coupling resonance





Range of emittance exchange with initially equal emittance is similar to unequal emittance case.

Question to Ingo and Giuliano:

Am I looking at something different from what you defined as resonance width?

Summary

- First attempt in scaling (zero chromatic) FFAGs to study
  - How do the intrinsic nonlinearities affect dynamics in tune space?
  - Can we fully utilise large physical aperture in horizontal plane?

- Resonance due to nonlinearities are relatively weak (except sextupole) than due to space charge driven ones.
- Amplitude dependent tune shift due to nonlinearities are much smaller than space charge tune shift. It does not help.
- On a coupling resonance, 2qh-2qv=0, scaling law derived for synchrotrons works qualitatively.
- With a proper selection of bare tune, unequal emittance (eh>>ev) can be used to reduce space charge tune shift.

Thank you for your attention.

1.2 GeV FFAG

aperture

	Normalised [pi mm mrad]	Physical [pi mm mrad]	Half size [mm]
Beam core	**100**	**100** 100-150*	**+/- 32**
Collimator acceptance	200	200 216-324*	+/- 45
Vacuum chamber acceptance	400 ~ 800	400 ~ 800 486*	+/- (63 ~ 89)
Magnet gap (VC+5mm)			**+/- (68 ~ 94)**

* Value at J-PARC RCS with 0.4 GeV injection.

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