FFAG for pulsed neutron and muon source

10 September 2017

Shinji Machida

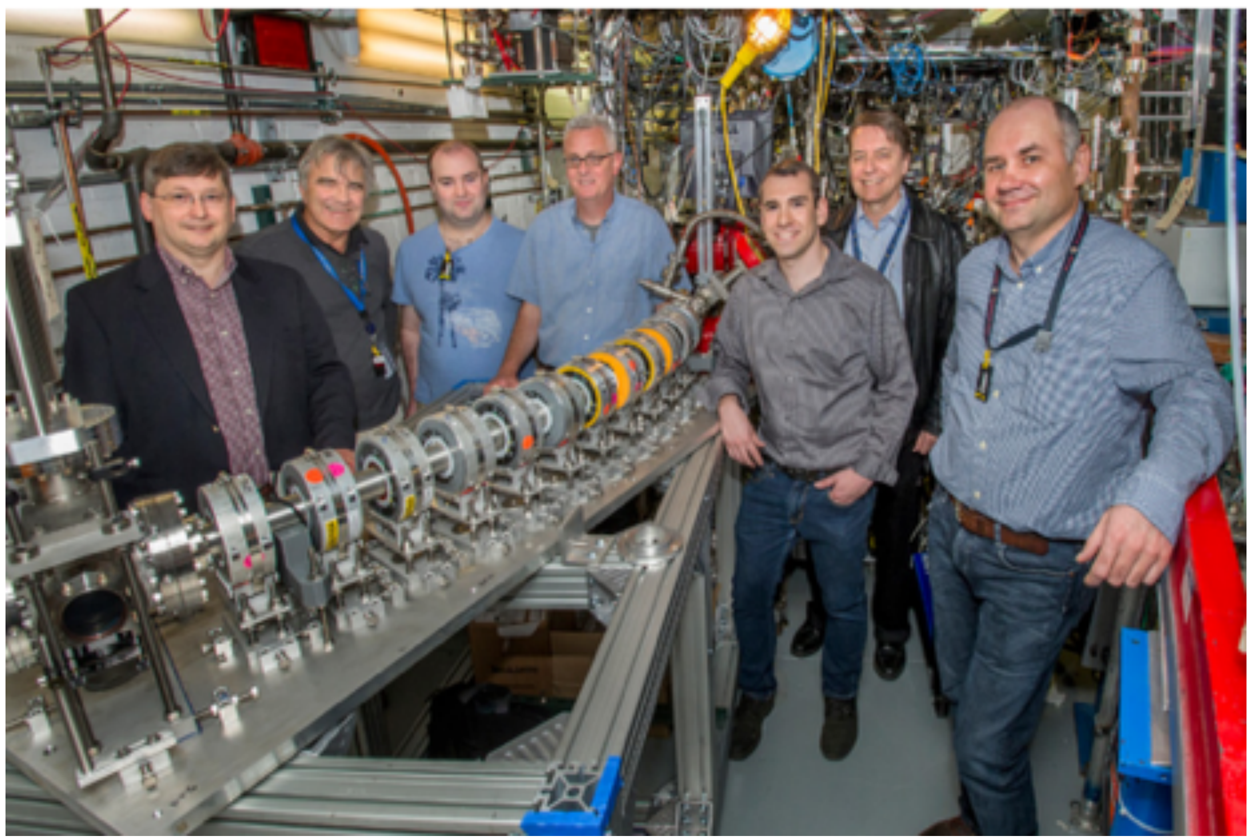
FFAG 2017 workshop

FFAG as a proton driver (7)

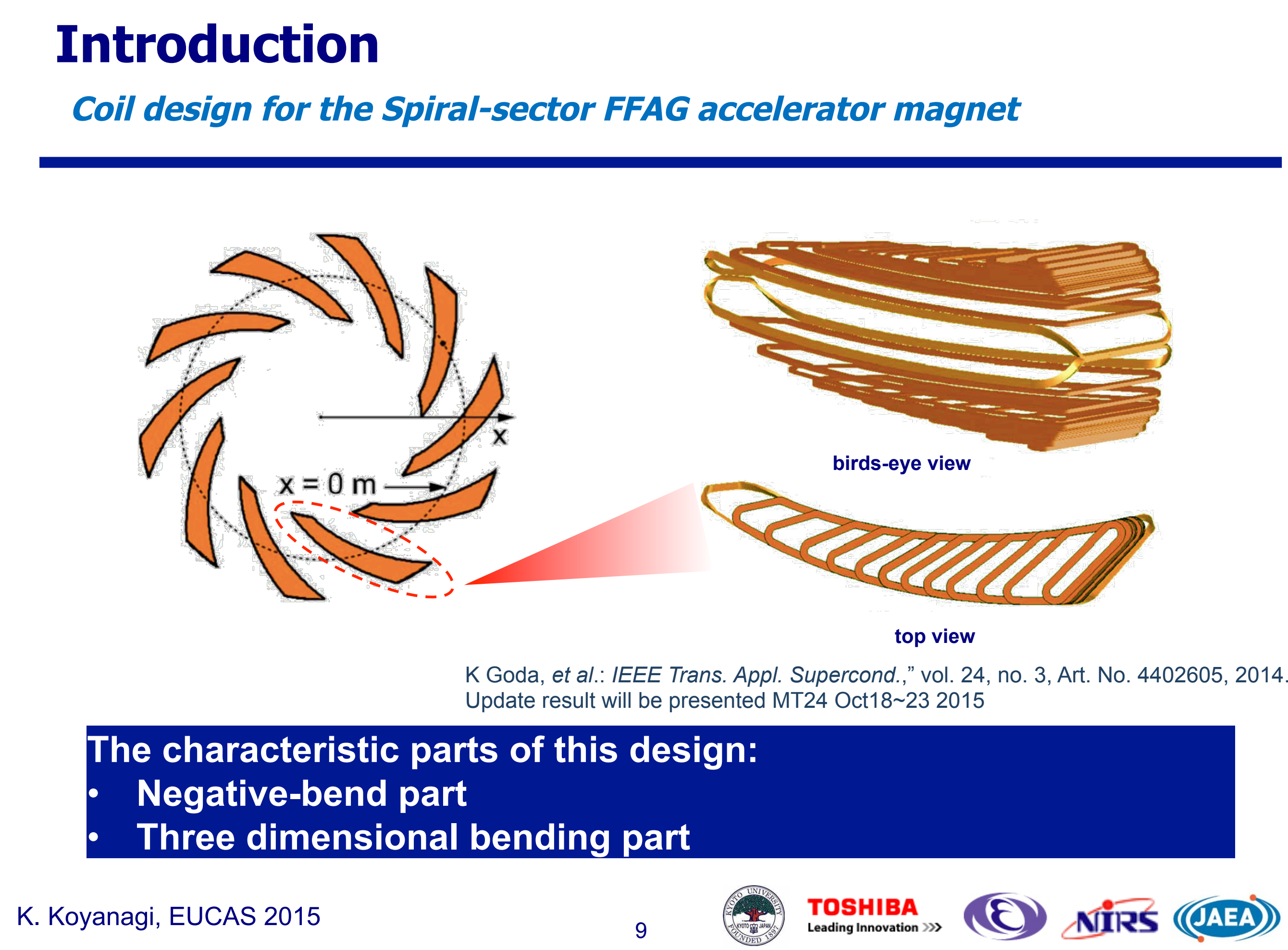
Energy efficient operation

Possibly permanent magnets or superconducting magnets reduce the operation cost considerably.

Congratulation!



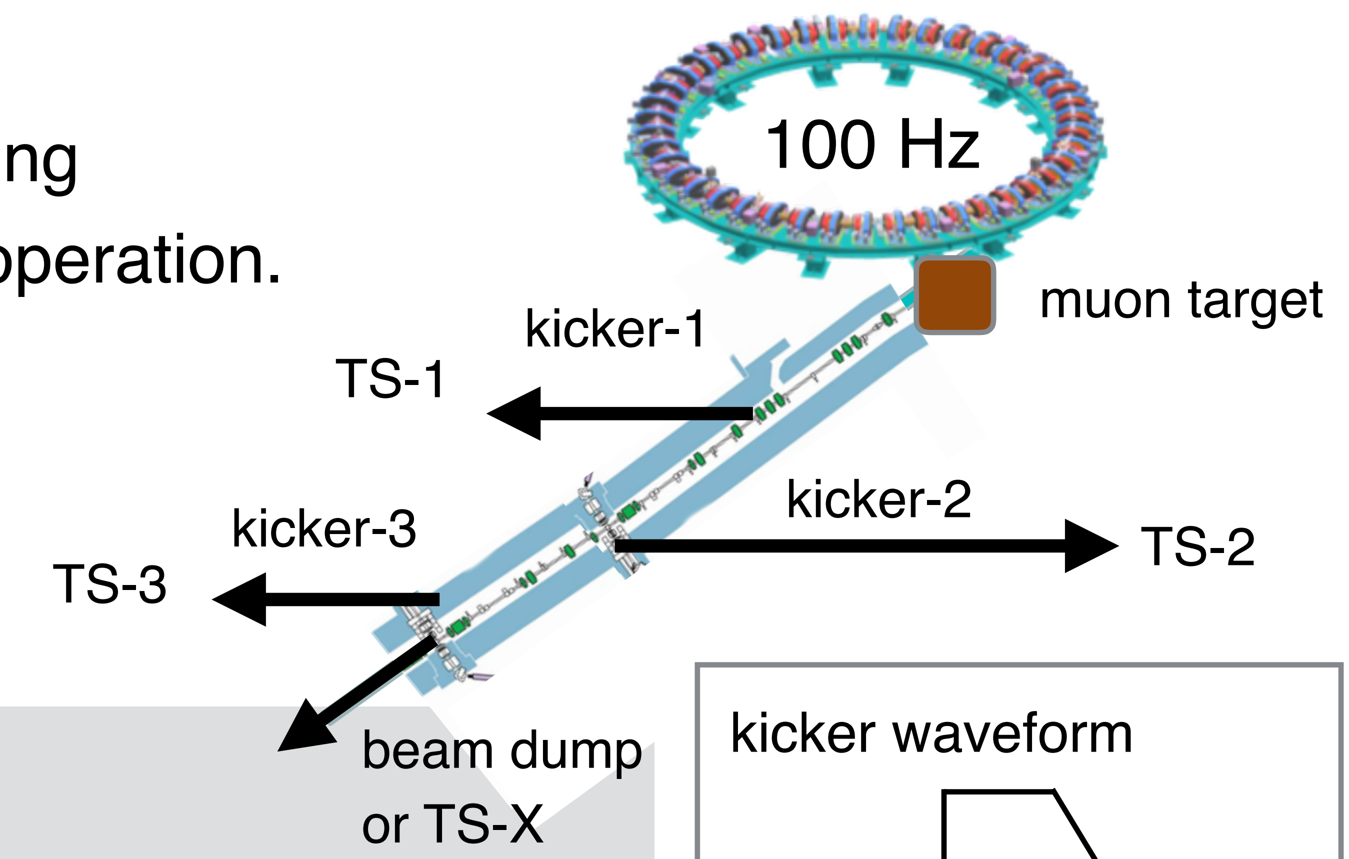
BNL *Features,* August 2017

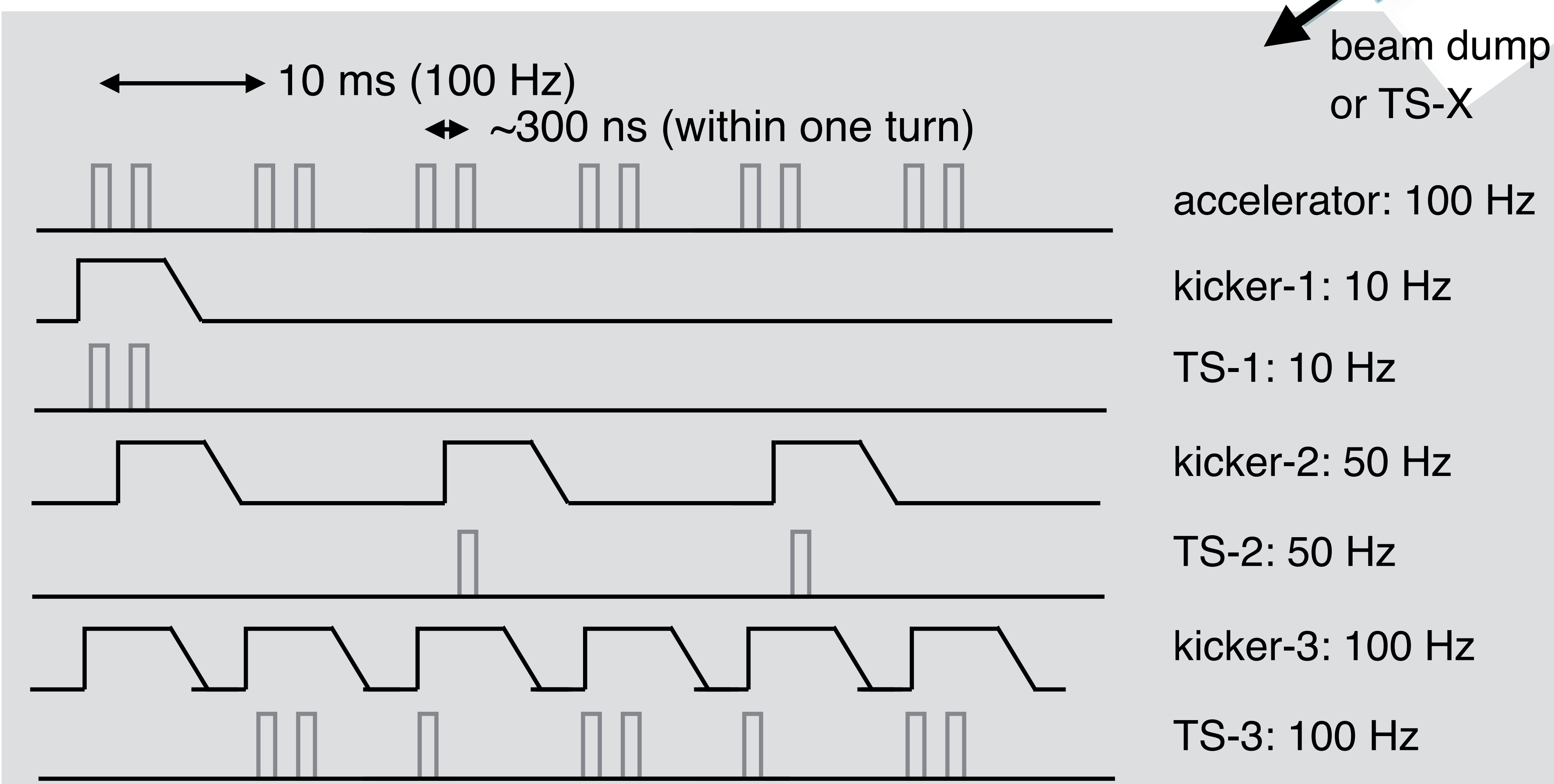


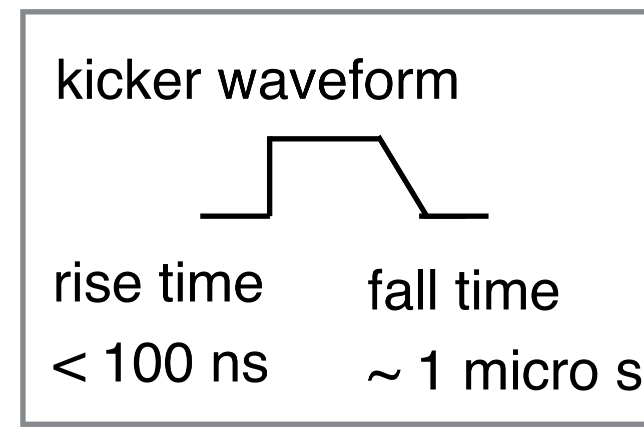
Ogitsu, et al, FFAG15'

Flexible operation

High repetition is good not only for increasing average beam power, but also for flexible operation.







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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
• Moderate 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.

In summary, FFAG

- has advantage of both

  Cyclotron and **Synchrotron**

- has advantage of both

  AR (Accumulator Ring) and **RCS (Rapid Cycling Synchrotron)**

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However,

- There is **a problem** to go beyond GeV kinetic energy
  - Number of cell has to increase.
  - Bending angle per cell decrease.
  - Beam orbits are perpendicular to the magnet edge.
  - **Vertical focusing becomes weaker**.

- Solution
  - Relatively strong reverse bend magnets or,
    - Circumference becomes large.
  - Large spiral angle or,
    - Magnet becomes complicated.
  - **Both reverse bend and spiral angle** simultaneously.
    - **DFspiral design**.

PRL **119,** 064802 (2017) PHYSICAL REVIEW LETTERS week ending 11 AUGUST 2017

Scaling Fixed-Field Alternating-Gradient Accelerators with Reverse Bend and Spiral Edge Angle

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(Received 25 January 2017; published 10 August 2017)

A novel scaling type of fixed-field alternating-gradient (FFAG) accelerator is proposed that solves the major problems of conventional scaling FFAGs. This scaling FFAG accelerator combines reverse bending magnets of the radial sector type and a spiral edge angle of the spiral sector type to ensure sufficient vertical focusing without relying on extreme values of either parameter. This new concept makes it possible to design a scaling FFAG for high energy (above GeV range) applications such as a proton driver for a spallation neutron source and an accelerator driven subcritical reactor.

DOI: 10.1103/PhysRevLett.119.064802

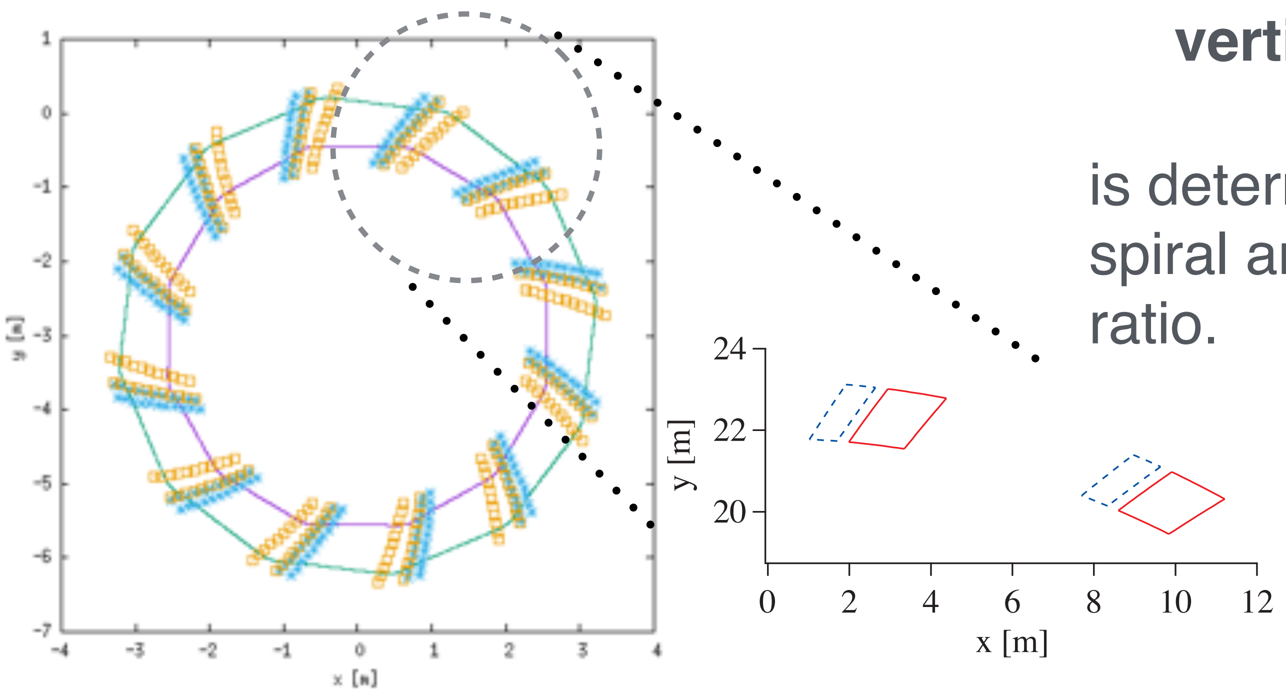
Particle accelerators were developed initially as a tool to explore particle physics at the energy frontier. Recently, however, many accelerators have been constructed for other fields of physics mostly with the aim of producing secondary

place until the late 1990s when the idea of a neutrino factory called for an accelerator that could rapidly accelerate muons before they had time to decay [8–10].

When FFAGs were invented, it was realized that an

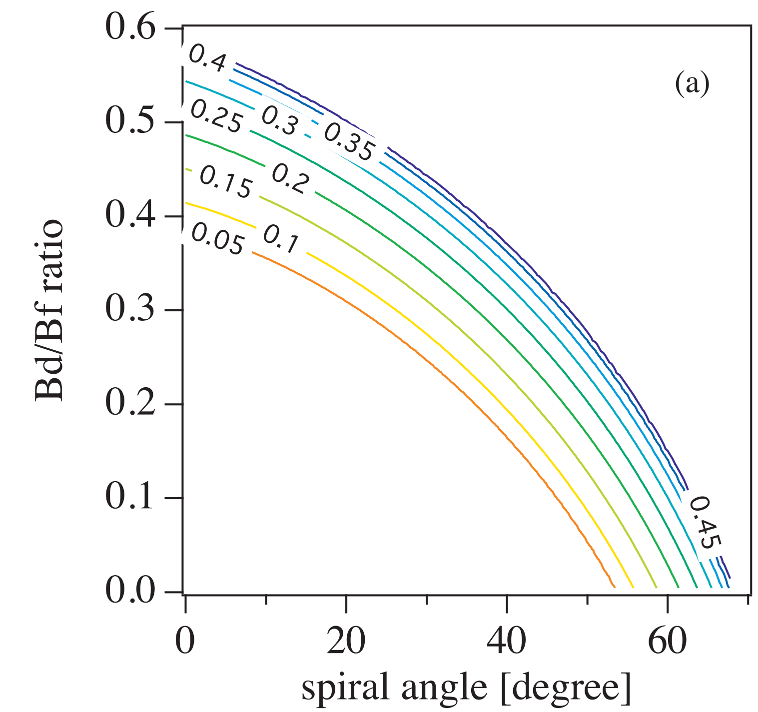
Vertical focusing by both

Spiral angle and reserve bending increase vertical focusing.



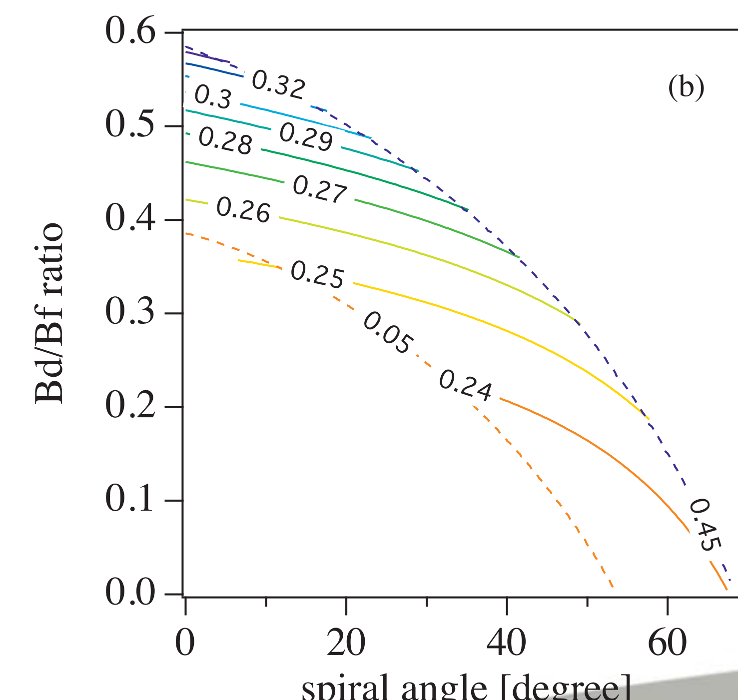
vertical cell tune

is determined by both spiral angle and Bd/Bf ratio.



horizontal cell tune

is determined mostly by Bd/Bf ratio.

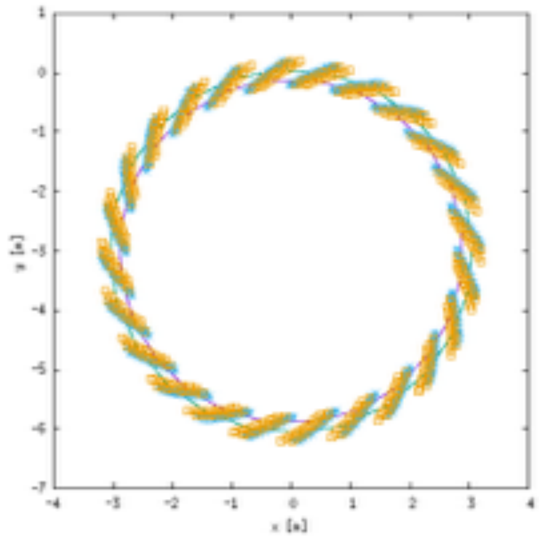


$$Q_x^2 \approx 1 + k + \frac{k^2 S^2}{N^2 b_0^2}$$

$$Q_z^2 \approx -k + \frac{k^2 S^2}{N^2 b_0^2} + \frac{\Phi^2}{b_0^2}\left(1 + 2\tan^2\delta\right)$$

$$S^2 = 2\sum_{m=1}^{\infty}\frac{|b_m|^2}{m^2} \qquad \Phi^2 = 4\sum_{m=1}^{\infty}|b_m|^2$$

$$B_z = B_{z0}\sum_{m=0}^{\infty} b_m \exp^{imN\theta}$$



1.2 GeV FFAG (8)

1.2 GeV FFAG
requirements

- Enough **space for injection/extraction, RF, collimations**, etc.
    - 4 ~ 5 m is minimum requirement.
- **Minimum orbit excursion** to reduce magnet size.
    - Inversely proportional to field index k (+1).
- **Simple magnet** to construct.
    - Not too large spiral angle.
- Adequate **dynamic aperture**.
    - Physical aperture is roughly 500 pi mm mrad.

1.2 GeV FFAG

parameter summary

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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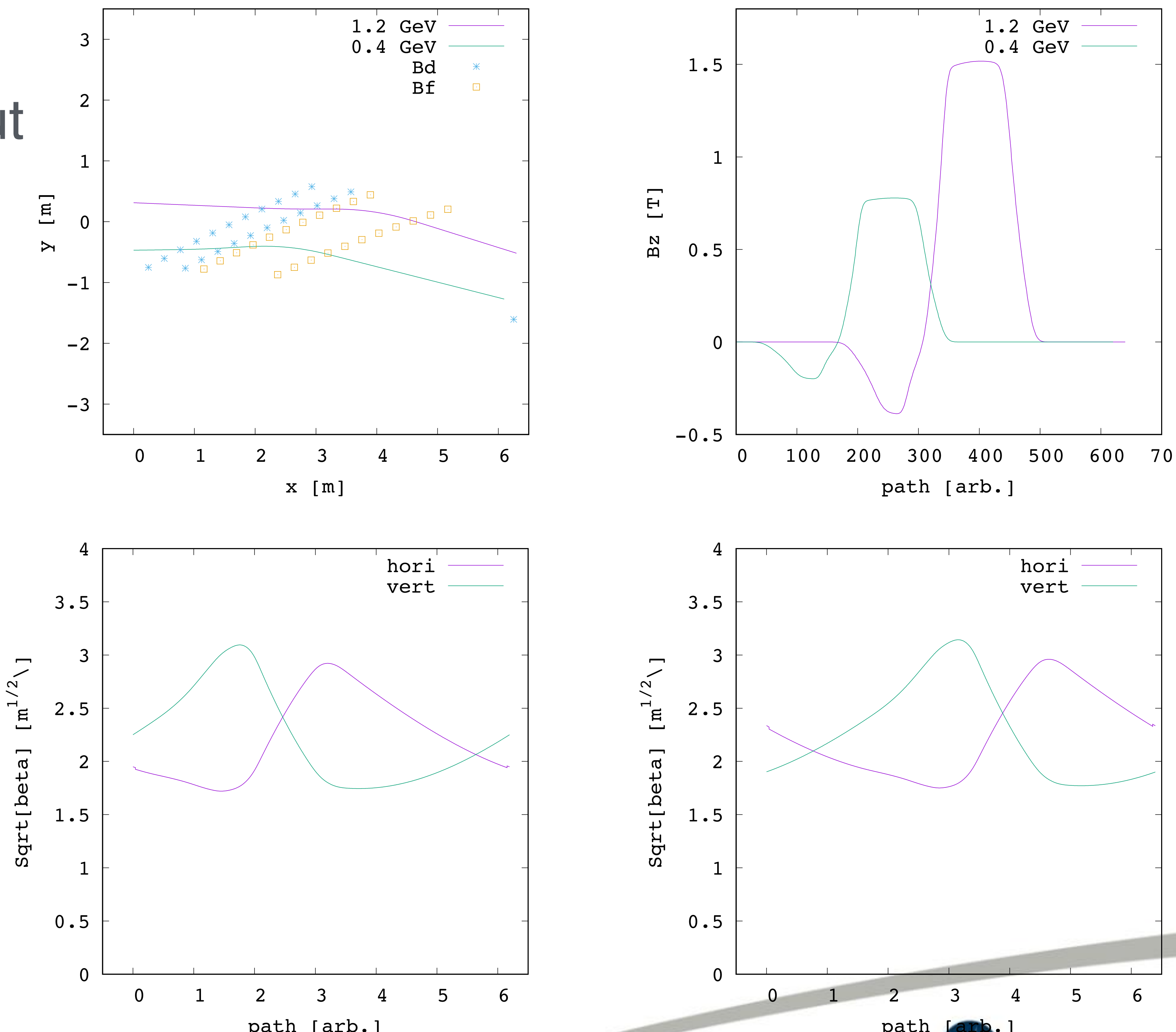
1.2 GeV FFAG

orbit and field strength

- Orbit excursion is about 1 m.
- Maximum magnetic field is just about 1.5 T.



- Beta function is very modest, < **10 m**

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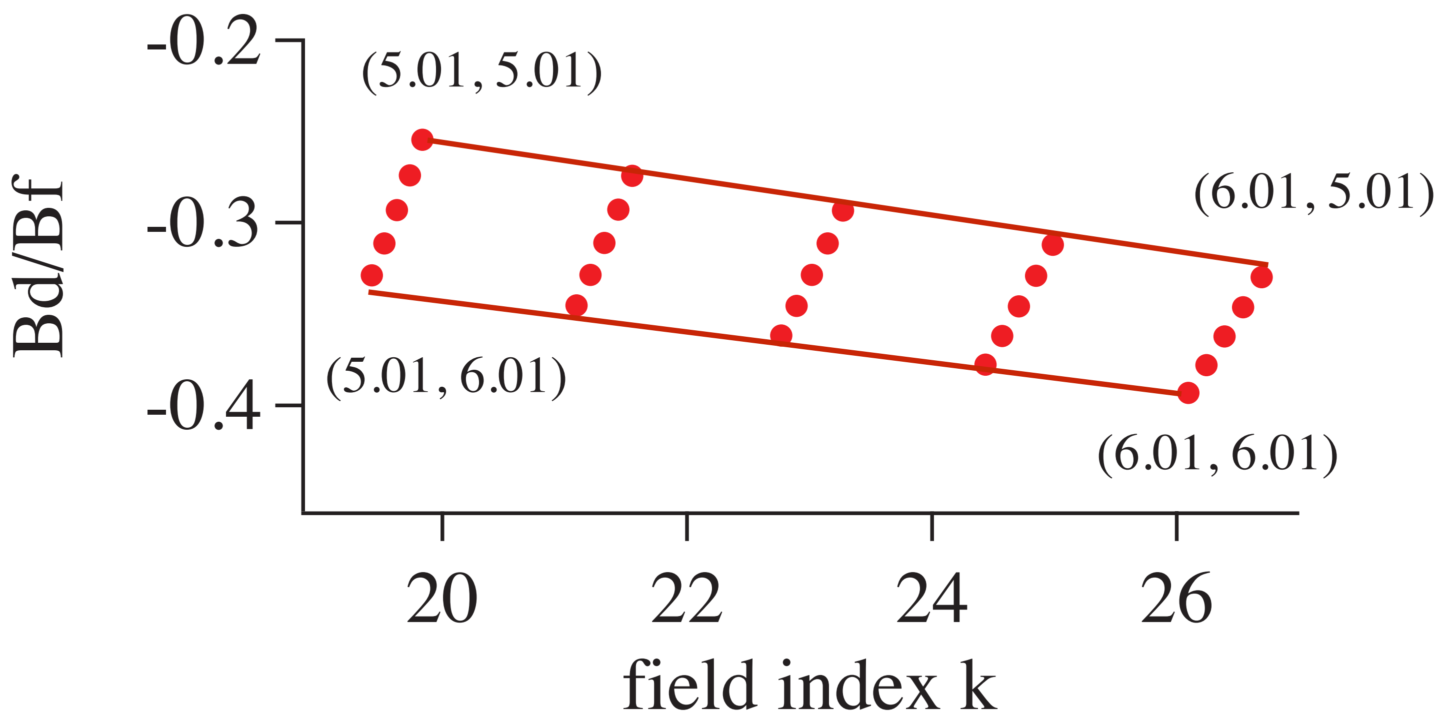
1.2 GeV FFAG

optics adjustment



$$k = \frac{r}{B_z} \frac{\partial B_z}{\partial r}$$

- Variable k of **19<k<27**
- PS capable of **-0.4<d/f<-0.2**

- Preparing knobs to adjust optics is **essential.**
  - We learnt from KURRI FFAG operation.
- DFspiral FFAG uses 1) **field index k** and 2) **Bd/Bf ratio** to adjust tune.
  - Adjusting Bd/Bf ratio is straightforward.
  - Magnet designer wants to know how much k has to be changed.

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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.

1.2 GeV FFAG

space charge tune shift

1.2 MW	1.2 GeV	1.0 mA	100 Hz	6.24 x 10^{13} ppp
			50 Hz	12.48 x 10^{13} ppp
1.0 MW*	3.0 GeV*	0.333 mA*	25 Hz*	8.33 x 10^{13} ppp*

When beam core emittance is **100 pi mm mrad**.

$$\Delta Q = -\frac{r_p n_t}{2\pi\beta^2\gamma^3\varepsilon}\frac{1}{B_f}$$

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

at 0.4 GeV $= -0.10\frac{1}{B_f}$ @100 Hz

$= -0.20\frac{1}{B_f}$ @50 Hz

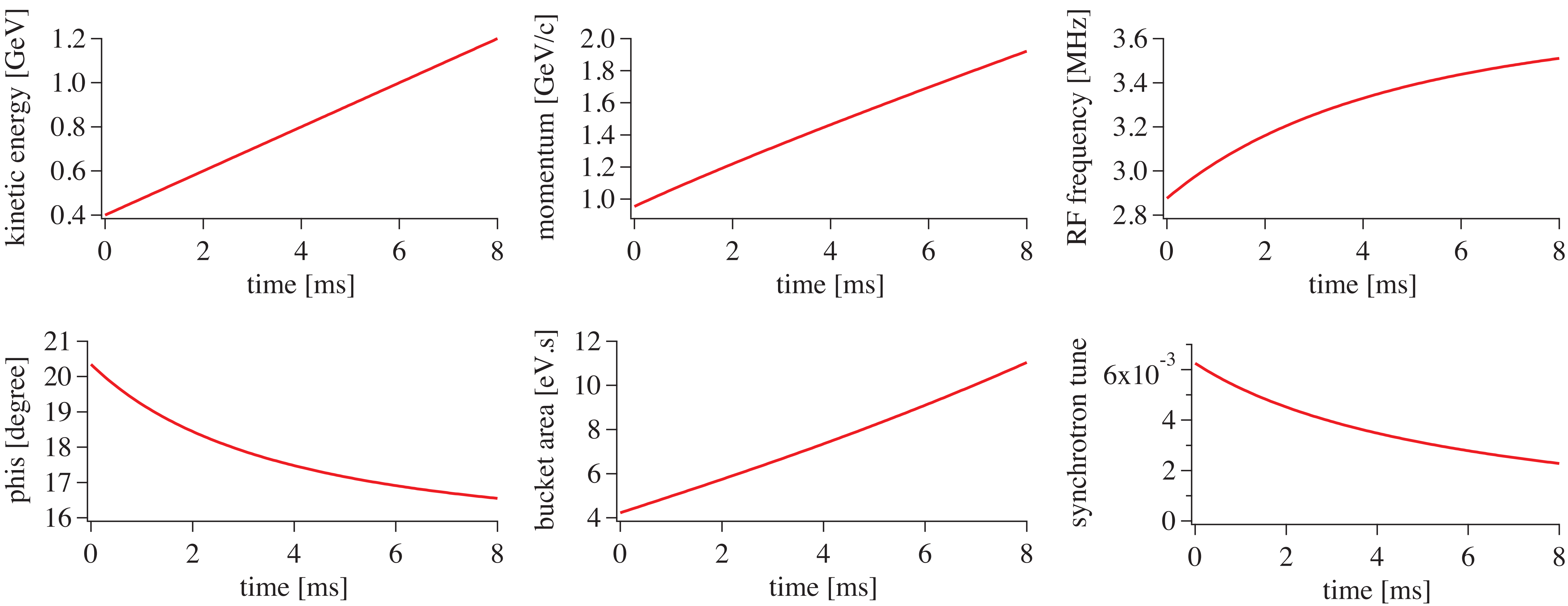
1.2 GeV FFAG

RF programme

- Let us take for example

$$\frac{dE}{dt} = \frac{1.2\ \mathrm{GeV} - 0.4\ \mathrm{GeV}}{8\ \mathrm{ms}\ \ (\sim 100\ Hz)} = 100\ \mathrm{keV}/1\ \mu s.$$

- With 200 kV RF cavity per turn and harmonic number of 2,



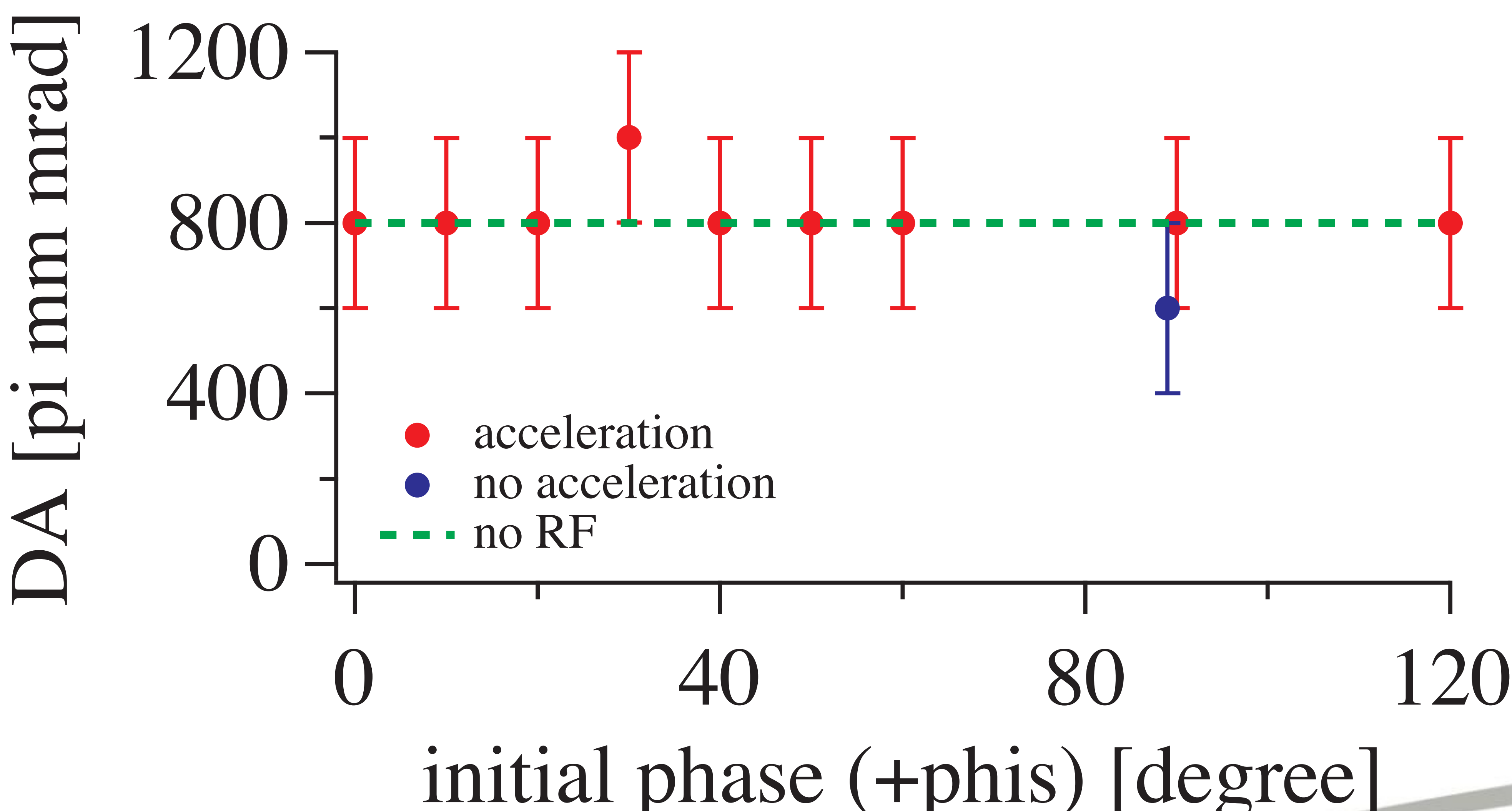
$$f_{rev} eV \sin\phi_s = \frac{dE}{dt} = \beta\frac{d\,(pc)}{dt} = e\,(\beta c)\,\rho\cancel{\frac{dB}{dt}}$$ can be any!

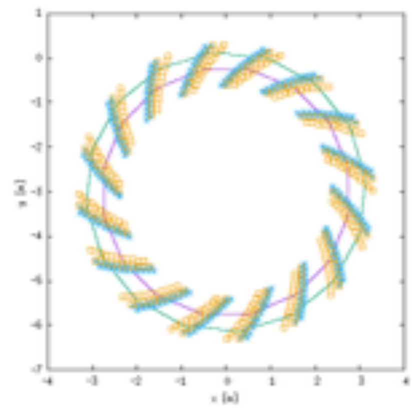
1.2 GeV FFAG

DA with full cycle

Dynamic aperture for the full cycle with acceleration in 6D.

- Effects of acceleration and synchrotron oscillation is within error bars.





Prototype ring (12)

Could be more challenging than 1.2 GeV FFAG!

Prototype ring
goals

- Prototype of future proton drivers in general.
- Show that FFAG design works as expected. Good agreement between simulation and measurement.
  - Demonstrate orbit correction and optics tunability by proper knobs.
    - This has not been considered enough (at least not in KURRI FFAG) as an accelerator in a user facility,
  - Demonstrate lossless operation with the aid of beam collimation.
  - Demonstrate lossless proton injection with tilted septum.
- Show that present hardware technology satisfies requirements from beam dynamics.
- Anything else?

Prototype ring
radius

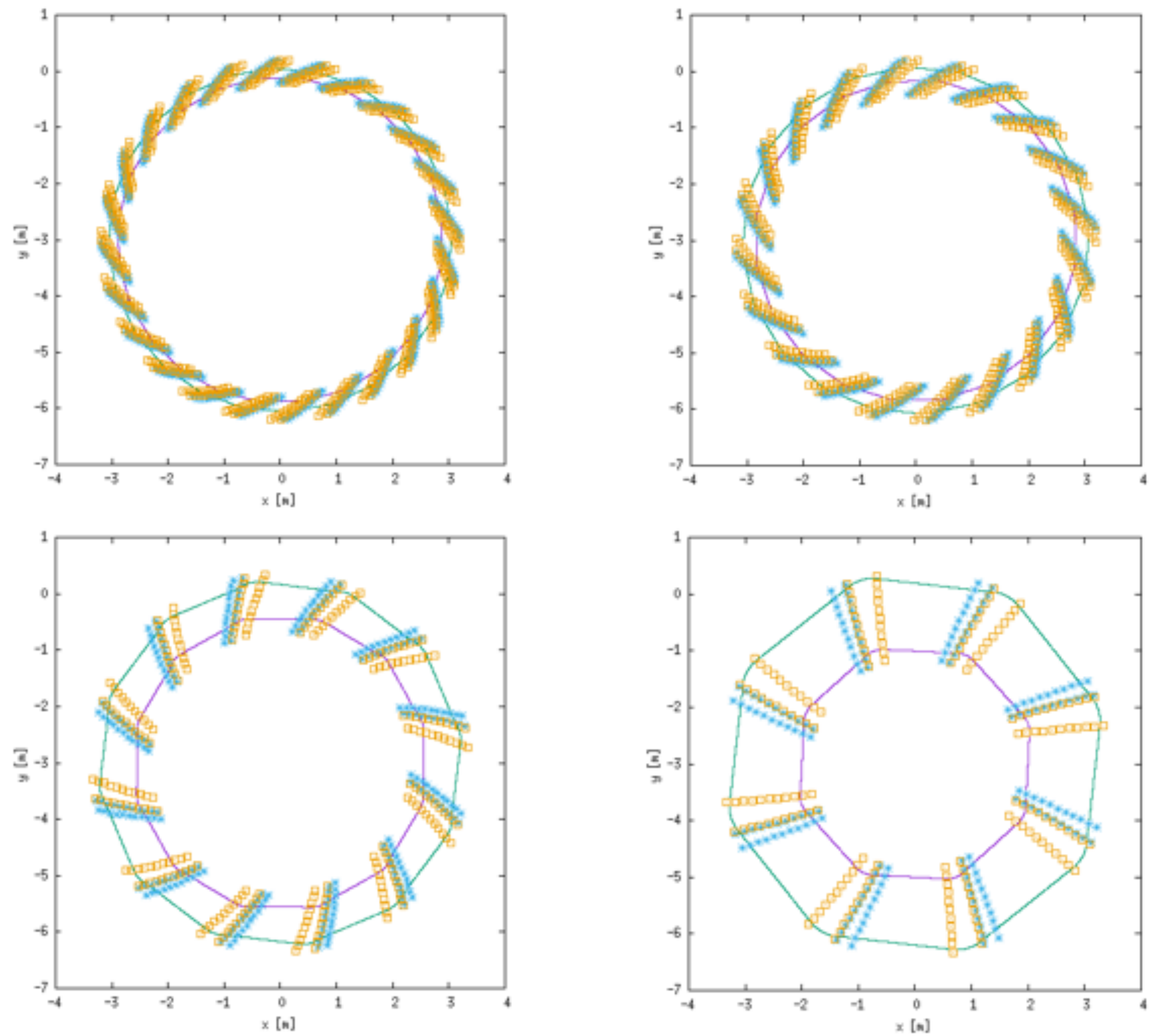
- How is the 1.2 GeV ring scaled down?

- Assumption: Output energy of the Prototype ring is 30 MeV.
  - (Ext_energy, 30MeV)/(Inj_energy, 3MeV) = 10
  - Momentum ratio p(30MeV/3MeV) = 3.2
  - Momentum ratio of 1.2 GeV FFAG
    - p(1.2GeV/0.4GeV) = 2.0
    - p(1.2GeV/0.2GeV) = 3.0
  - Energy gain of a factor 10 is a good number to claim success!

- Radius should be scaled by momentum ratio p(1.2GeV/30MeV) = 8.0
  - Radius ratio r(1.2GeV/30MeV) = 8.0
  - R = 24m/8 = **3m**

Prototype ring
footprint

- Considered N=24 (option1), 20, 16, 12, 8 (option2)



Same packing factor

Bd: 10% + Bf: 20%

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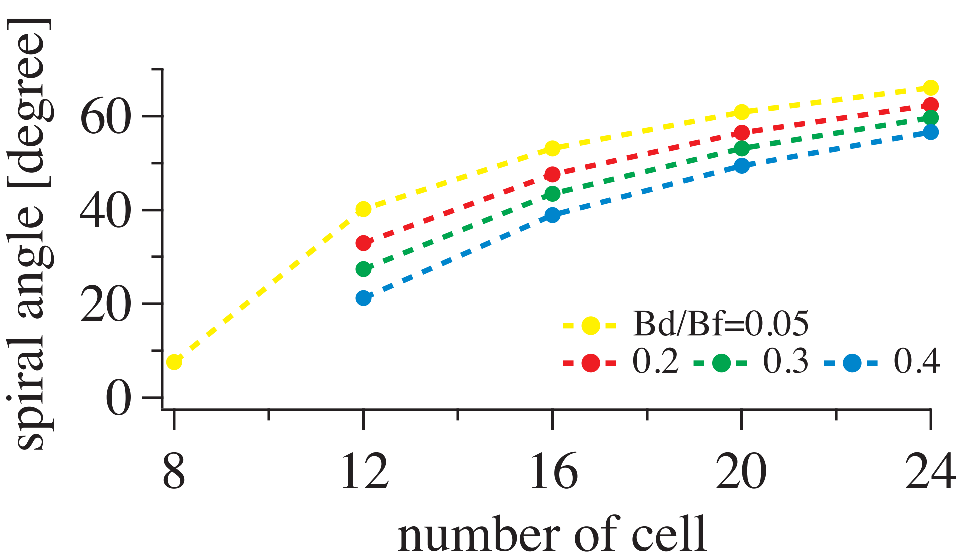
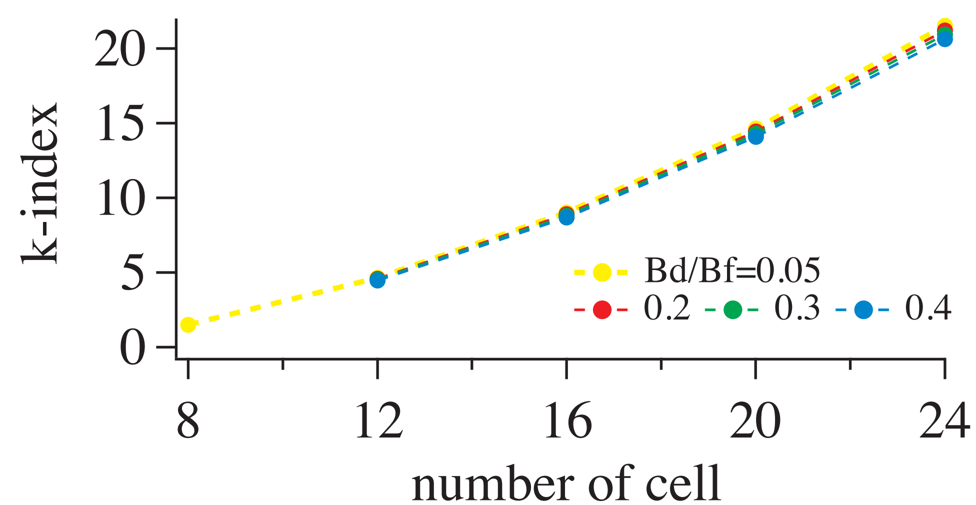
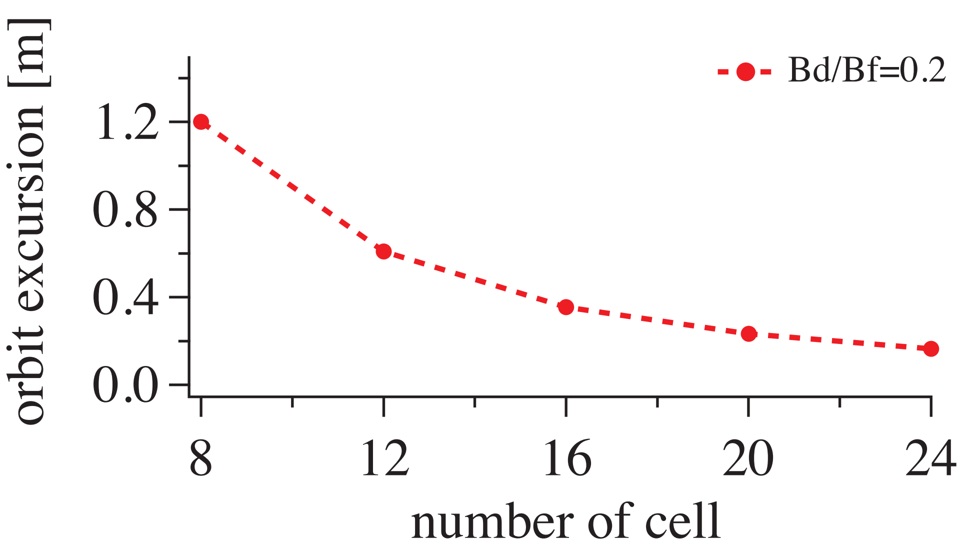
Prototype ring
number of cell

- Look at (the same) calculation as a function of N (number of cell).
  - For Bd/Bf at 0.05, 0.2, 0.3, 0.4 (Bd/Bf of 1.2 GeV is about 0.3)
  - Bd/Bf is a tuning knob and has to be variable around nominal value.







Prototype ring
parameter summary

kinetic energy	**3 - 30 MeV**
mean radius at injection	**3 m**
number of cell	**24**
magnet longitudinal length (D, F)	**(0.079, 0.158) m**
packing factor	**0.35**
straight section	**0.51 m**
spiral angle	**60 degree**
k index	**20.97**
Bd/Bf	**-0.2862**
orbit excursion	**~ 0.16 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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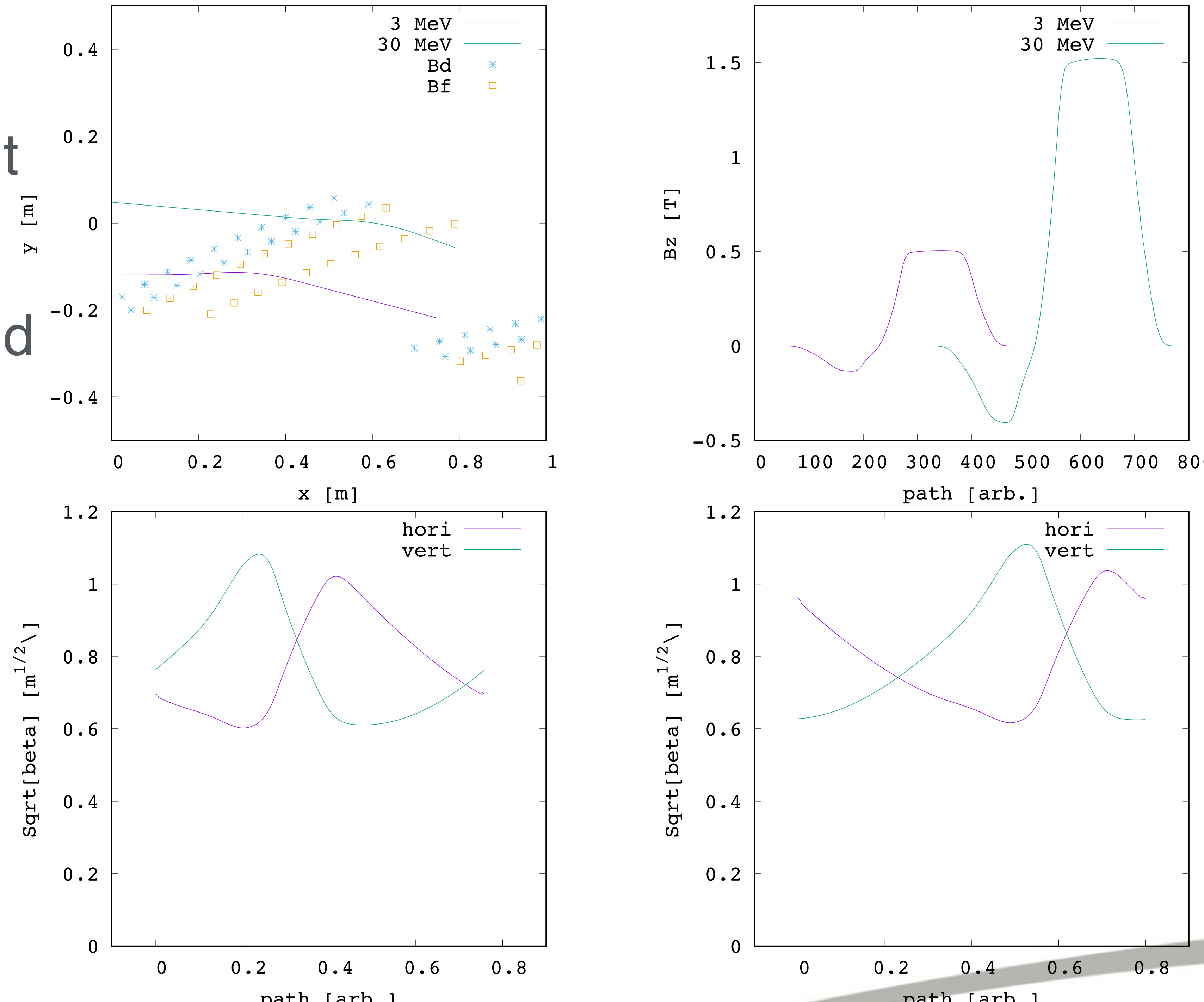
Prototype ring
orbit and field strength

- Orbit excursion is about 0.16 m.
- Maximum magnetic field is just about 1.5 T.
- Beta function is very modest, ~ 1.2 m maximum.



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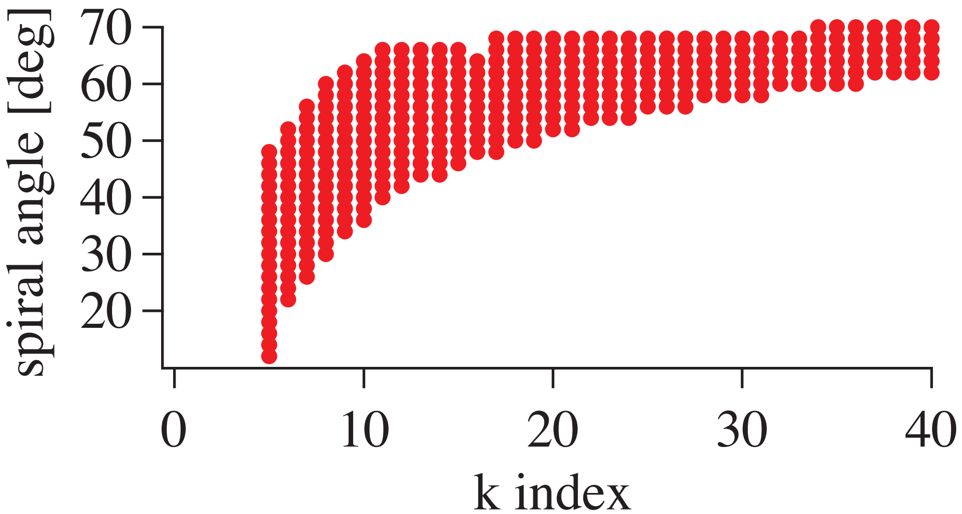
Prototype ring

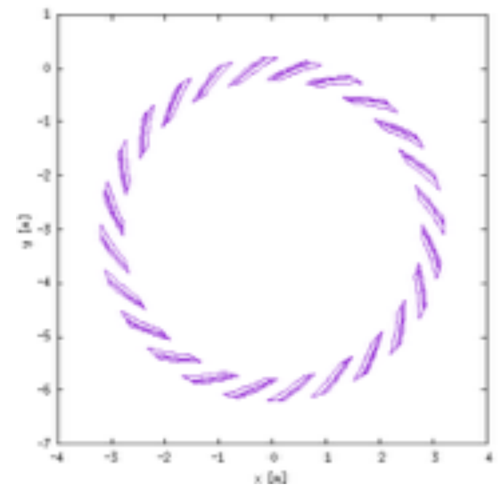
"superperiod"

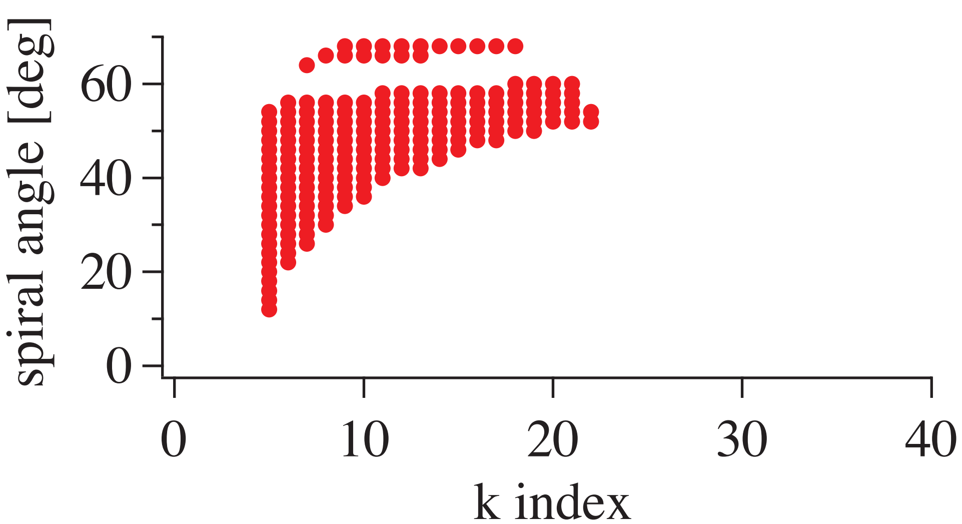
Long straight section can be made.

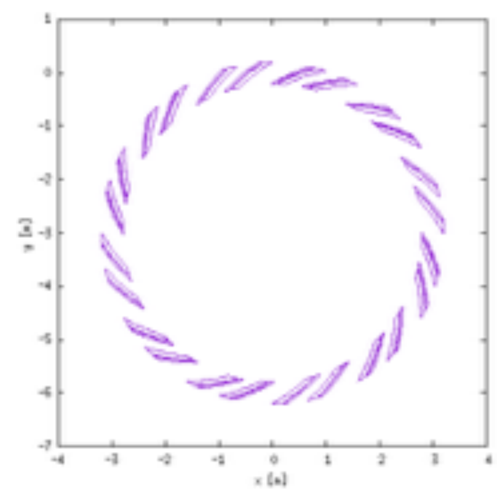
Instead of DFO x 24,

DFO_1DFO_2 x 12



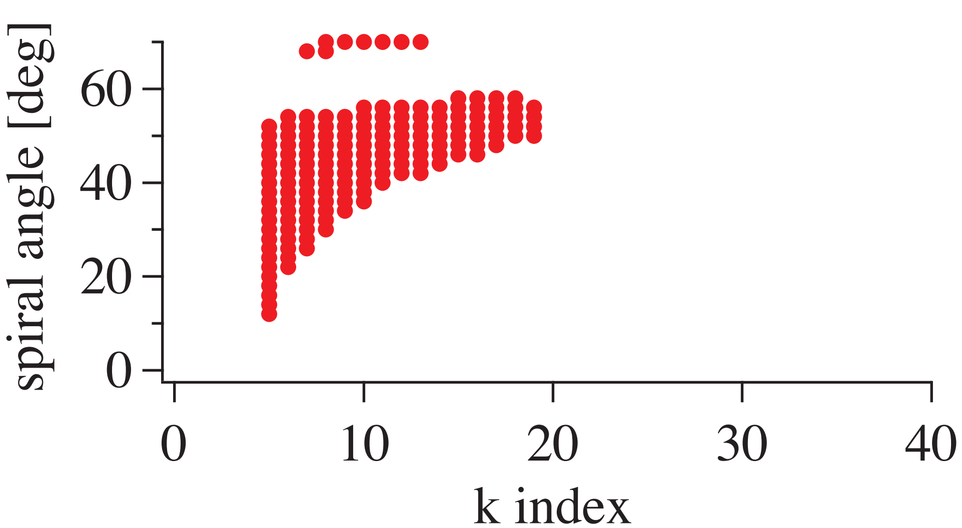


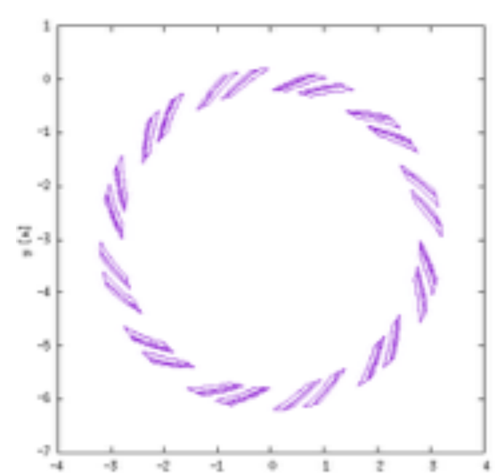




O_1=1.33 x O

O_2=0.67 x O





O_1=1.50 x O

O_2=0.50 x O

Prototype ring
normalised acceptance

- Physical acceptance will reduce by the same factor of 8.

$$\beta_{lat,3MeV} = \beta_{lat,0.4GeV}/8 \qquad \varepsilon_{un,3MeV} = \varepsilon_{un,0.4GeV}/8$$

$$\varepsilon_{un,0.4GeV} = \varepsilon_{nor}/\left(\beta\gamma\right)_{0.4GeV}$$

$$\varepsilon_{nor} = \varepsilon_{un,3MeV}\left(\beta\gamma\right)_{3MeV}$$

- Suppose normalised acceptance at 0.4 GeV is
$\varepsilon_{nor,ISIS-II} = 1000\ \pi\ \text{mm mrad}$

~0.08

$$\varepsilon_{nor,FETS} = \frac{(\beta\gamma)_{3MeV}}{(\beta\gamma)_{0.4GeV}}\varepsilon_{nor,ISIS-II}/8$$

$$= 10\ \pi\ \text{mm mrad}$$

A factor of 100 reduction!

Prototype ring

aperture consideration

	Half size [mm]	Physical [pi mm mrad]	Normalised [pi mm mrad]
Beam core	**+/- 32** ***1/8=4**	**100** ***1/8=12.5**	**1**
Collimator acceptance	+/- 45 *1/8=5.6	200 *1/8=25	**2**
Vacuum chamber acceptance	+/- (63 ~ 89) *1/8=7.9 ~ 11.1	400 ~ 800 *1/8=50 ~ 100	**4 ~ 8**
Magnet gap (VC+3mm)	**+/- (68 ~ 94)** ***1/8=10.9 ~ 14.1**		

c.f. Norm emittance of linac beam (**rms**) ~ 0.25 pi mm mrad.

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Prototype ring

space charge tune shift

When beam core emittance is 12.5 pi mm mrad

$$\Delta Q = -\frac{r_p n_t}{2\pi\beta^2\gamma^3\varepsilon}\frac{1}{B_f}$$

$$n_t = \frac{(-\Delta Q)\, 2\pi\beta^2\gamma^3\varepsilon}{r_p}\frac{B_f}{1}$$

with $\Delta Q\ B_f = -0.1$

$$= 3.29 \times 10^{10}$$

1 turn injection of 7 mA linac beam reaches tune shift of -0.1.

	linac current		
3 MeV	**50 mA**	1.305×10^{10} p/m	**2.46×10^{11} p/turn**
	7 mA	1.827×10^{10} p/m	**3.44×10^{10} p/turn**
	2 mA	5.22×10^{8} p/m	**9.84×10^{9} p/turn**
	1 mA	2.61×10^{8} p/m	**4.92×10^{9} p/turn**

Prototype ring

magnet gap

- Gap height of the magnet will be determined by
  - Beam dynamics
    - Dynamic aperture
    - Injection study
    - Space charge tune shift
  - Hardware tolerance
    - Ideal field profile
    - Fringe field shape

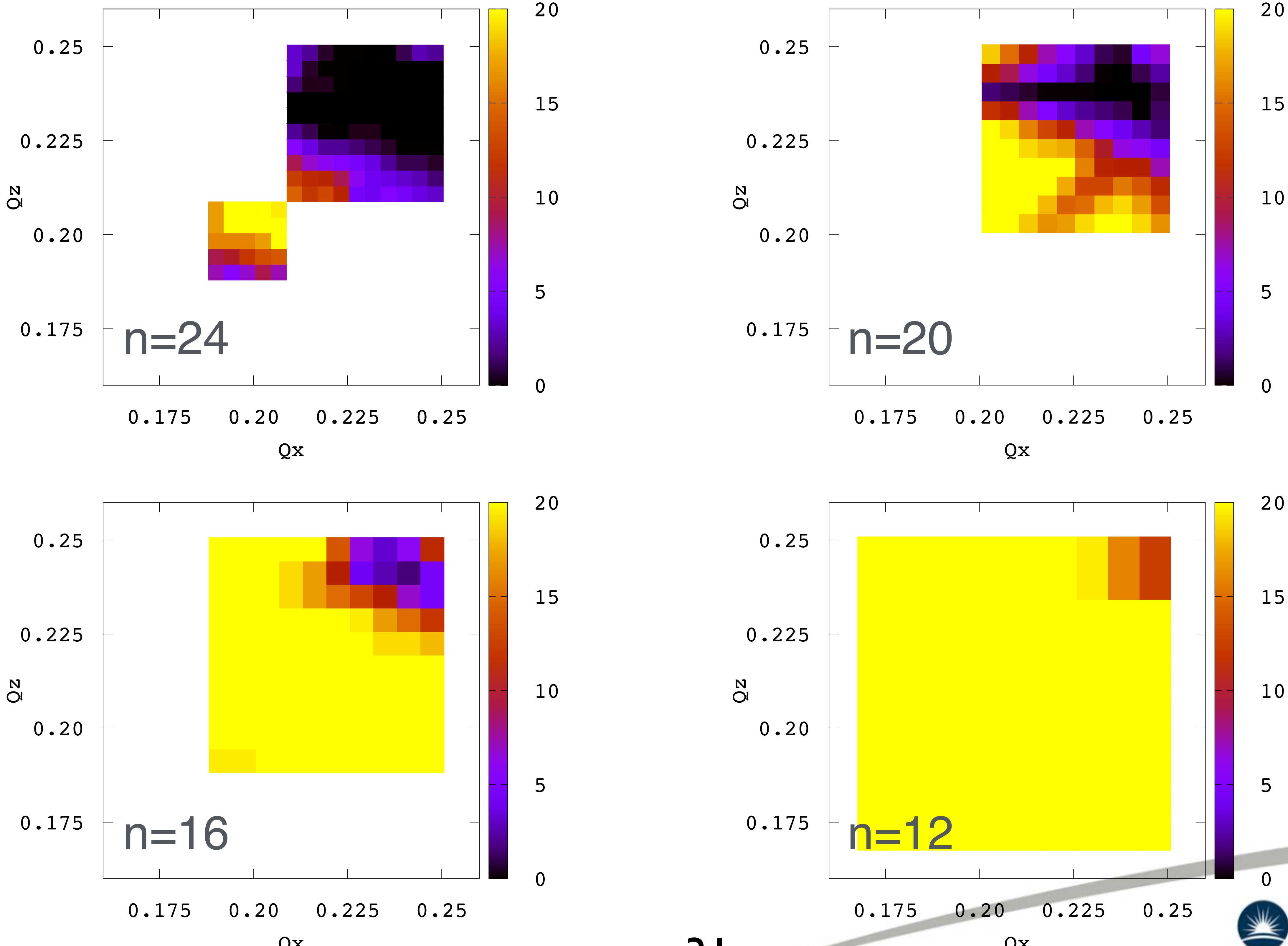
- Magnet will be **more challenging than that of 1.2 GeV FFAG**.
  - Large ratio of gap/length with the same k.

$$\left(\frac{r_0 + x}{r_0}\right)^k = 1 + \frac{k}{1! r_0}x + \frac{k(k-1)}{2! r_0^2}x^2 + \frac{k(k-1)(k-2)}{3! r_0^3}x^3 +$$

$$k \propto N^2$$

Prototype ring

dynamic aperture vs number of cells

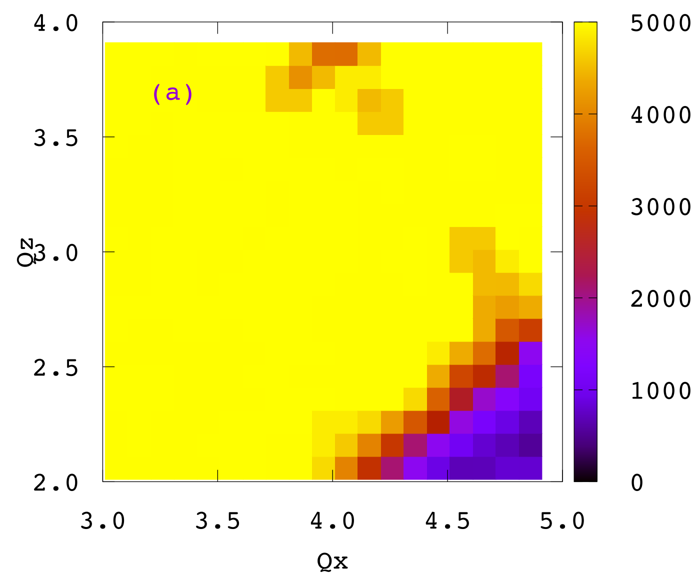


Prototype ring

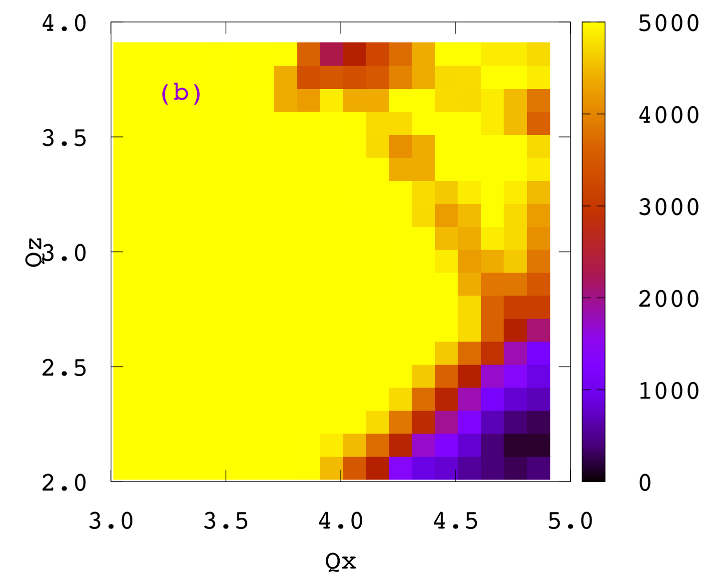
dynamic aperture of radial, spiral and DFspiral

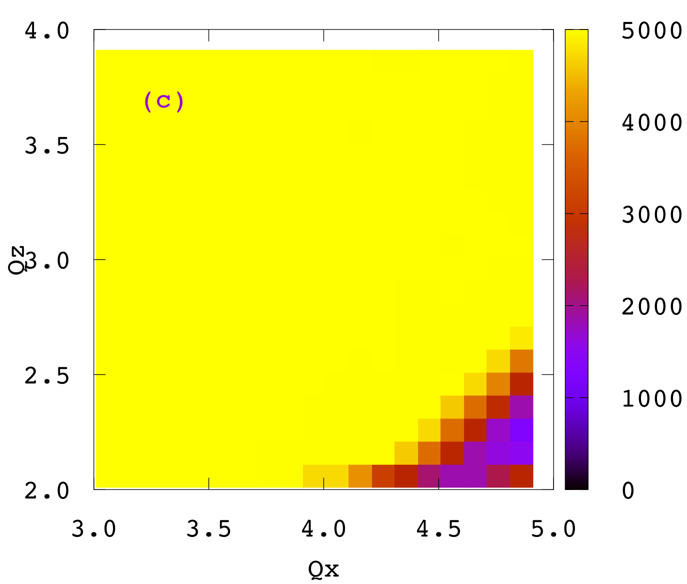
DFspiral

spiral=const



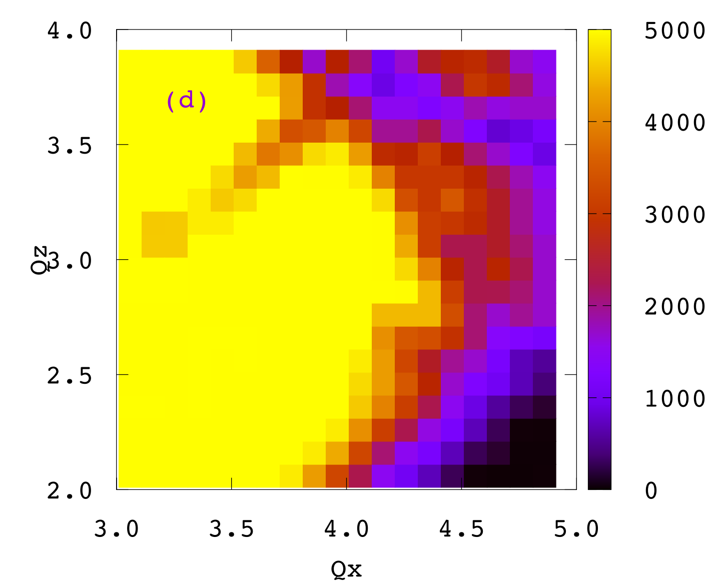
D/F=const





radial sector

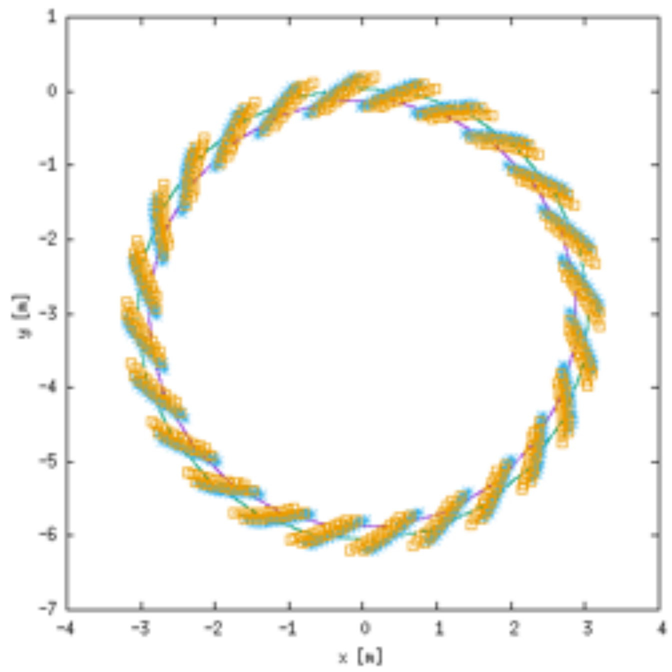
from PRL **119**, 064802 (2017)

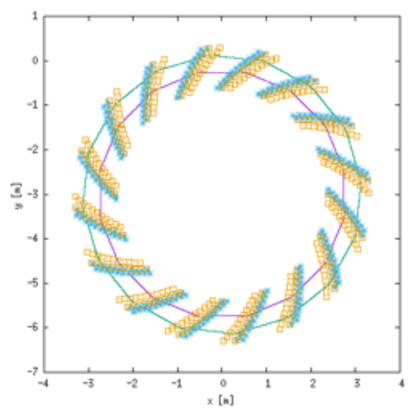


spiral sector

Remark

- Dynamic aperture is one of major issues.
  - Radial sector FFAG has some sort of cancelling of nonlinearity between F and D.
  - Spiral sector FFAG has strong nonlinearly in F without any counterpart of D.





Next step, schedule etc.

1.2 GeV FFAG
next step

- A set of basic parameters (lattice, magnet, RF) of DF-spiral FFAG is obtained.
- Next step
  - Single particle tracking with Zgoubi, OPAL and SCODE
    - Dynamic aperture
    - Acceleration
    - Error study
  - Injection study with CR's codes
  - Multi particle tracking with Zgoubi, OPAL and SCODE
    - Space charge
    - Beam loss and collimation
  - Developing tools

Physics design plan

2017	Basic lattice structure	Injection/ Extraction	Single particle dynamic aperture	Multi-particle space charge
April	DF-spiral, Pumplet			
May	others		OPAL, Zgoubi	
June			Scode	
July		proton or H- injection		OPAL, Zgoubi
August		kicker extraction		Scode
September		resonance extraction		
October				
November ←	2nd	iteration	starts	
December				
January				
February				
March				
2018 April ←		fix	parameters	

7 August, 2017

IOP New look for long-neglected a

physicsworld.com/cws/article/news/2017/aug/07/new-look-for-long-neglected-accelerator

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New look for long-neglected accelerator

Aug 7, 2017

Merging accelerators: an FFAG combines synchrotron and cyclotron methods

Smaller, potentially cheaper sources of high-intensity protons could become reality thanks to a novel type of fixed-field alternating-gradient (FFAG) accelerator designed by a physicist in the UK.

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Thank you for your attention

1.2 GeV FFAG

number of cell

Ring tune

$$Q_x^2 \approx 1 + k$$
$$Q_z^2 \approx -k + \frac{\Phi^2}{b_0^2}\left(1 + 2\tan^2\delta\right)$$

field index

$$k = \frac{r}{B_z}\frac{\partial B_z}{\partial r}$$

spiral angle δ

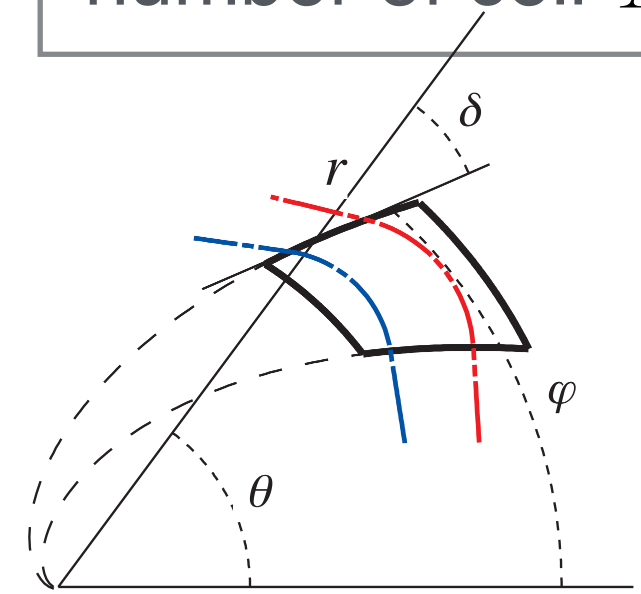
number of cell N

Cell tune

$$q_{x,z} \approx \sqrt{k}/N = \text{const (e.g. } 0.25).$$

Therefore

$$k \propto N^2$$



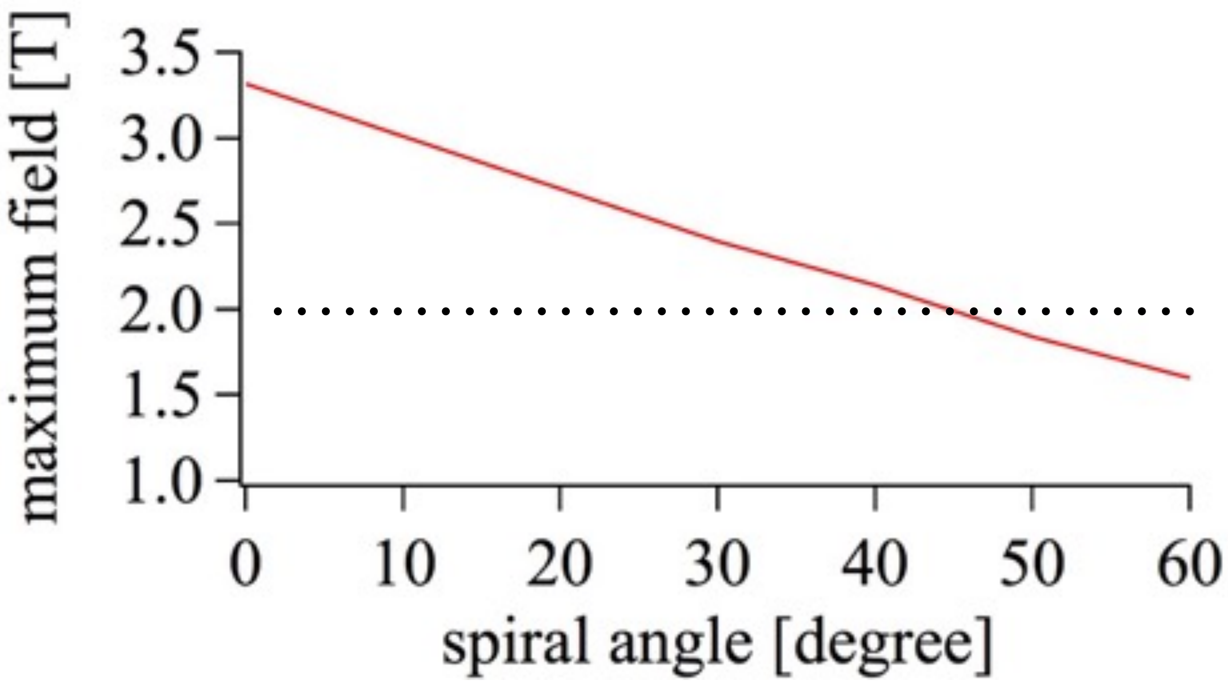
- In order to **increase field index *k*** to reduce orbit excursion, large N is preferable.
- However, large N means short straight section.

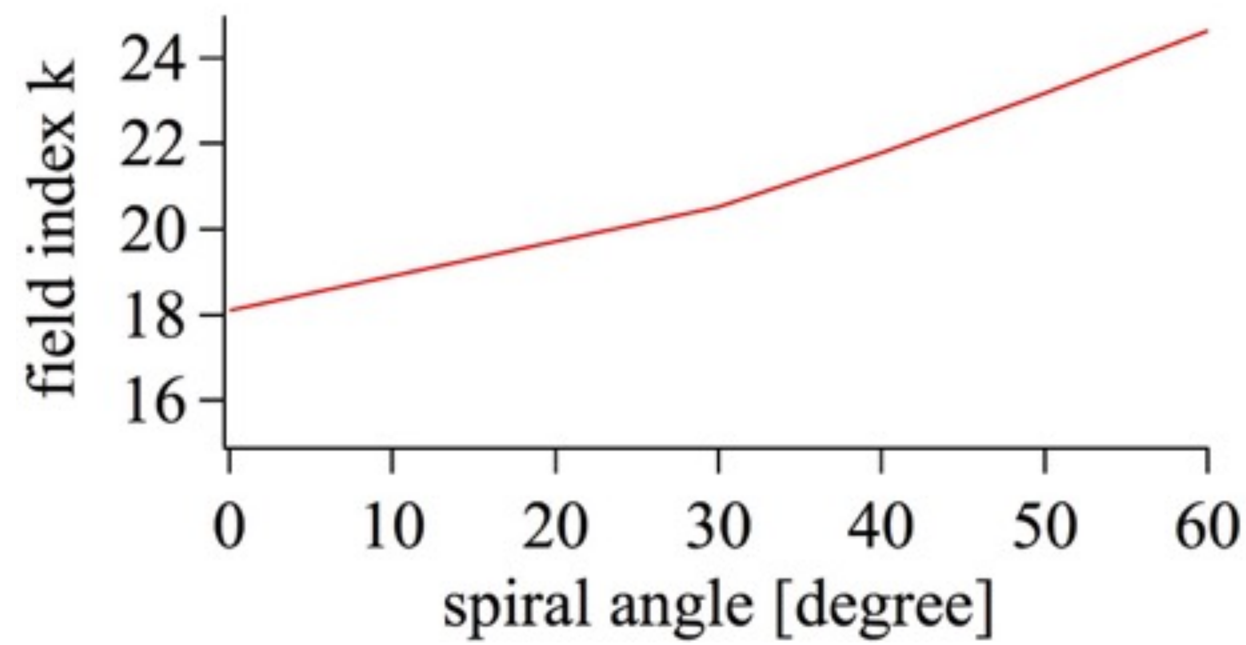
$L = 2\pi R/N - M$ where $R = 24$ m $M = 2$ m (minimum)

N	12	16	**20**	**24**	28	32
***L* [m]**	10.57	7.42	**5.54**	**4.28**	3.39	2.71

1.2 GeV FFAG
spiral angle

number of cell is fixed (n=24).





- The larger spiral angle, the less magnetic field.
- DFspiral design also helps to increase field index k so that less orbit excursion.

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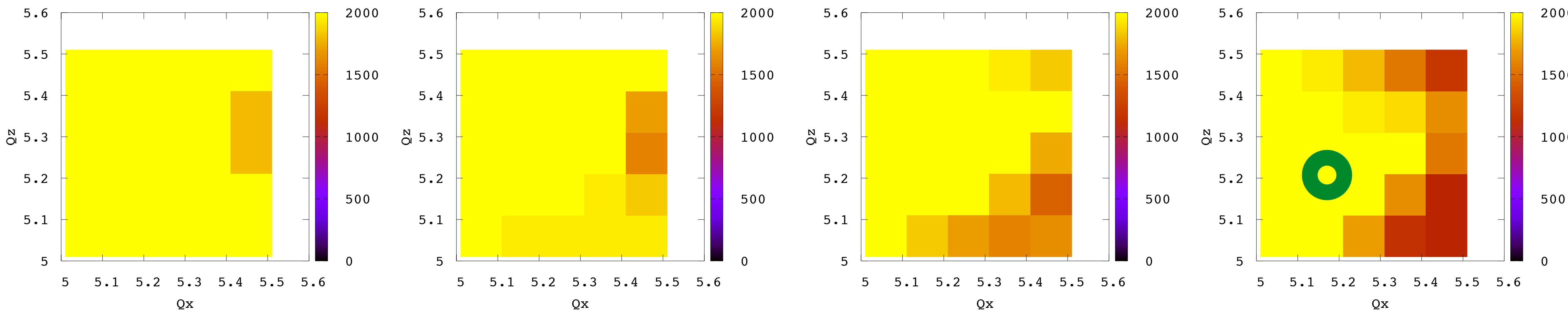
1.2 GeV FFAG

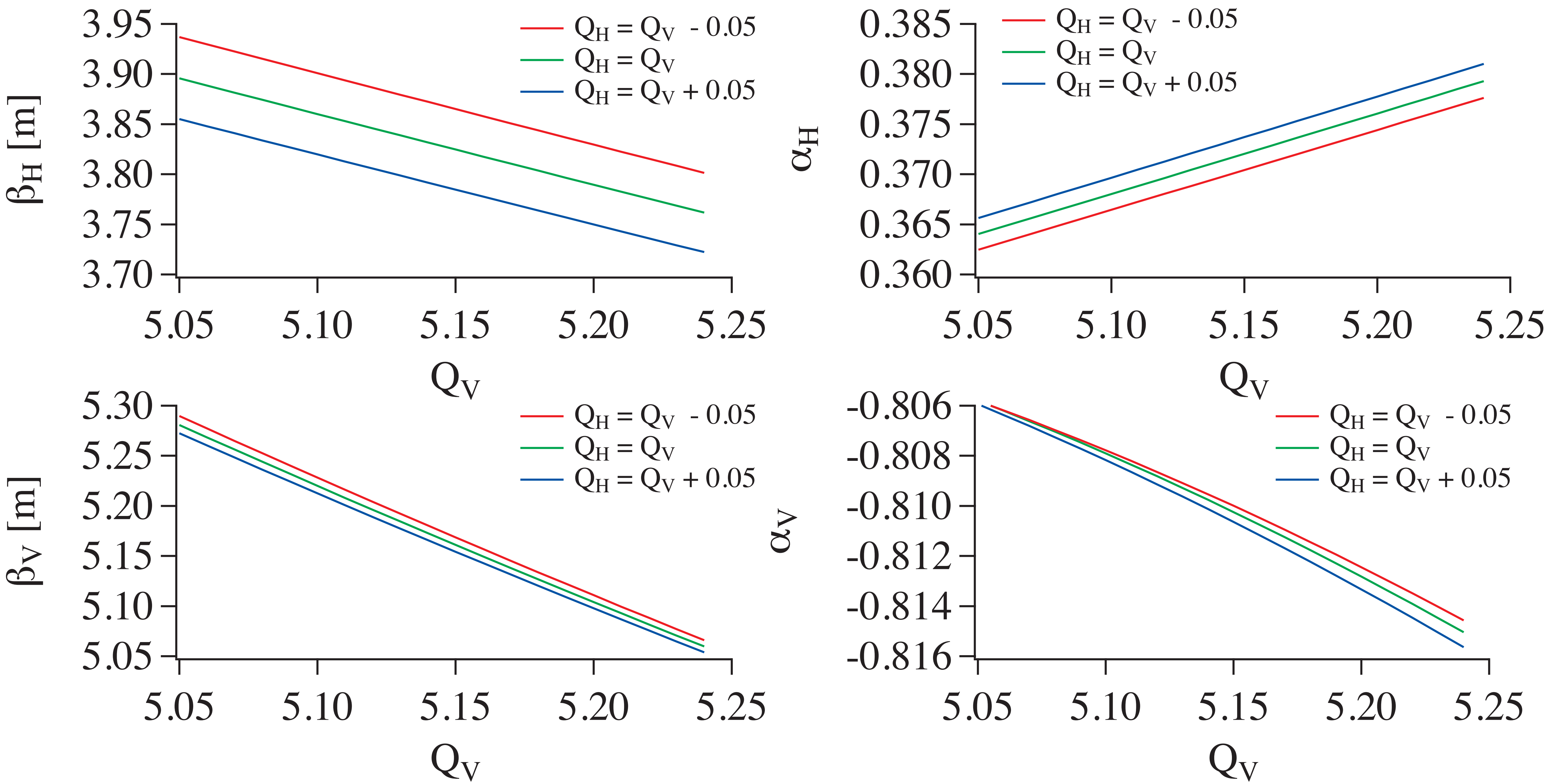
DA vs spiral angle



45 deg. | 50 deg. | 55 deg. | 60 deg.

- The larger spiral angle, the smaller dynamic aperture (it is defined in 200 turns on above figures).
- Confirmed with Zgoubi by David.
- However, it is still huge in the most tune area.

1.2 GeV FFAG
for injection study



- About 5% variation over the tune range of 0.25.

1.2 GeV FFAG

2 planes multi-turn injection

Number of turns necessary to fill **6.24 x 10^{13}** particles with chopping factor of **0.5**.

	linac current			**ring inj.**
0.4 GeV	**50 mA**	1.46x10^9 p/m	2.20 x 10^{11} p/turn	**567 turns**
	100 mA	2.92x10^9 p/m	4.40 x 10^{11} p/turn	**283 turns**
	200 mA	5.84x10^9 p/m	8.81 x 10^{11} p/turn	**142 turns**

1.2 GeV FFAG

RF parameters

- Energy gain per time is

$$\frac{dE}{dt} = f_{rev} eV \sin\phi_s$$

- In synchrotron, this has to be synchronised with magnet ramping.

$$f_{rev} eV \sin\phi_s = \frac{dE}{dt} = \beta \frac{d(pc)}{dt} = e(\beta c)\rho \frac{dB}{dt}$$

or in more familiar form

$$V \sin\phi_s = 2\pi R\rho \frac{dB}{dt}$$ (from dB/dt)

and

$$f_{RF} = h f_{ref} = \frac{hc}{2\pi R}\frac{pc}{E}$$ (from B(t))

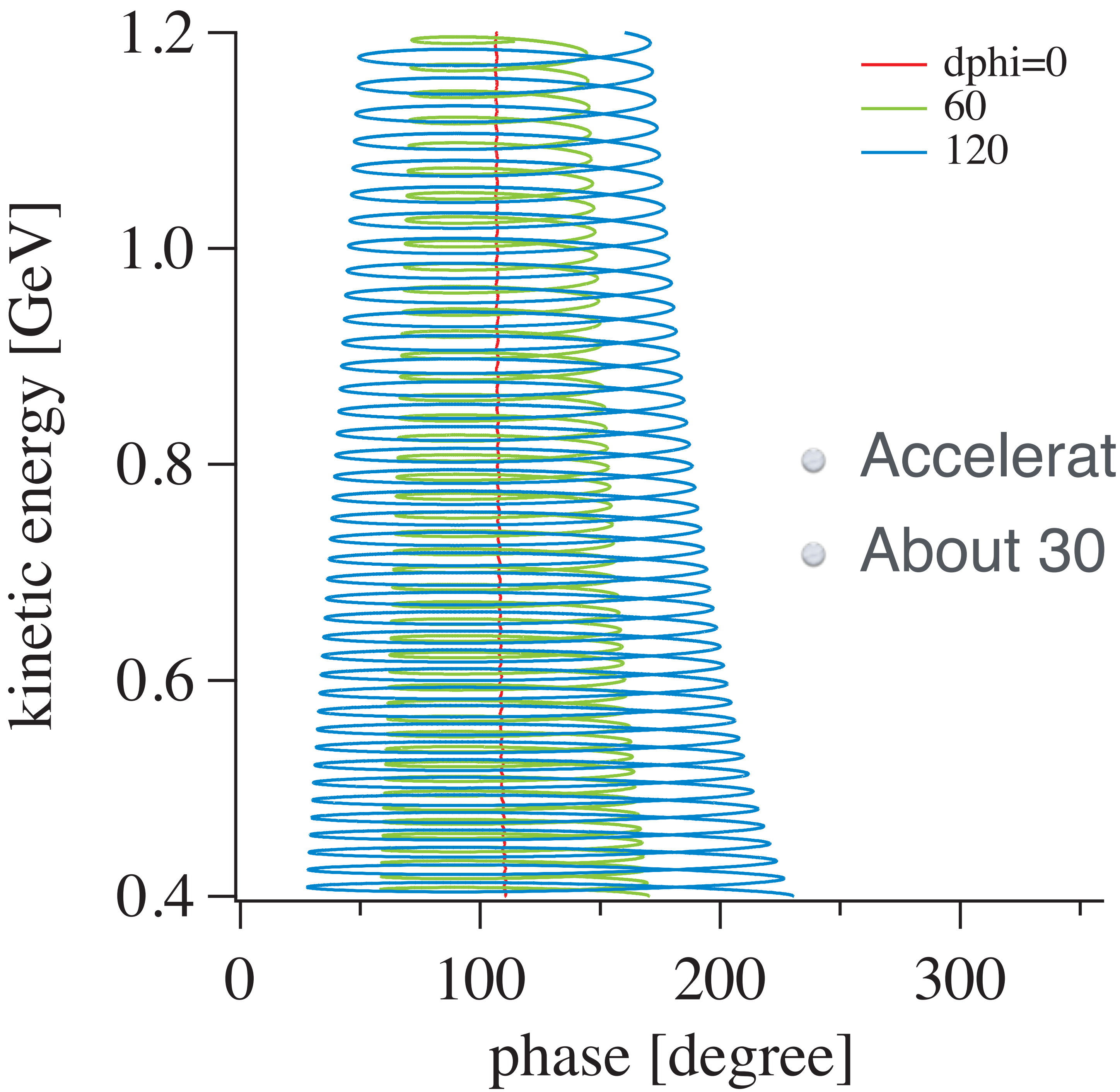
- In FFAG, **no constraint from dB/dt or B(t)**.

$$f_{rev} eV \sin\phi_s = \frac{dE}{dt} = \beta \frac{d(pc)}{dt} = \underline{\text{can be any.}}$$

$f_{RF}(t)$ determines p(t) and dp/dt, not the other way around. LLRF could be simpler.

1.2 GeV FFAG

synchrotron oscillation and acceleration



- Acceleration completes in 13300 turns.
- About 30 synchrotron oscillations.

1.2 GeV FFAG
optimisation

- dE/dt=const. is not necessarily the optimum RF programme.

- From hardware point of view
    - Minimise required RF voltage.
- From beam dynamics point of view, e.g.
    - Quick acceleration at low energy end.
    - Constant bucket helps?
    - Constant synchrotron tune helps?

- Optimisation study of RF programme is necessary.
    - More free parameters than synchrotrons.
    - Dual harmonic RF is an option as well.

Prototype ring
options

Two extreme design options

- Option 1 (SW): Simply scale down everything by a factor of 8.
  - A miniature of 1.2 GeV FFAG.
- Option 2 (HW): Emphasis on similar orbit excursion, ~1m.
  - Magnet size will be similar.
  - Vacuum and diagnostics size will be similar.
  - Then what k and *N* make the orbit excursion the same as 1.2 GeV FFAG?

$$\frac{\Delta r}{r} = \frac{1}{k+1}\frac{\Delta p}{p} \qquad \frac{k_{ISIS-II}+1}{k_{FETS}+1} = \frac{8}{1}$$

Therefore

$$k_{FETS}+1 = (21+1)/8 \qquad k_{FETS} = 1.75$$

Since

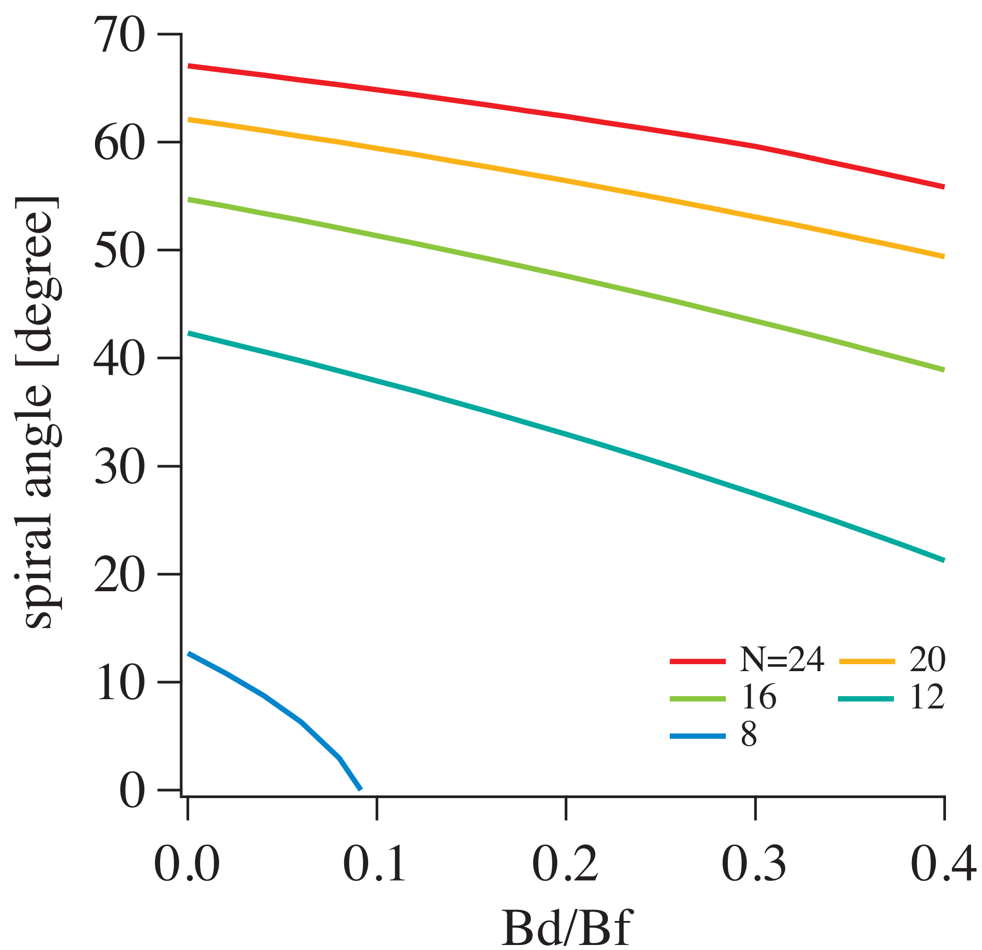
$$q = \sqrt{k}/N = \text{const.} \qquad \frac{N_{ISIS-II}}{N_{FETS}} = \sqrt{\frac{k_{ISIS-II}}{k_{FETS}}}$$

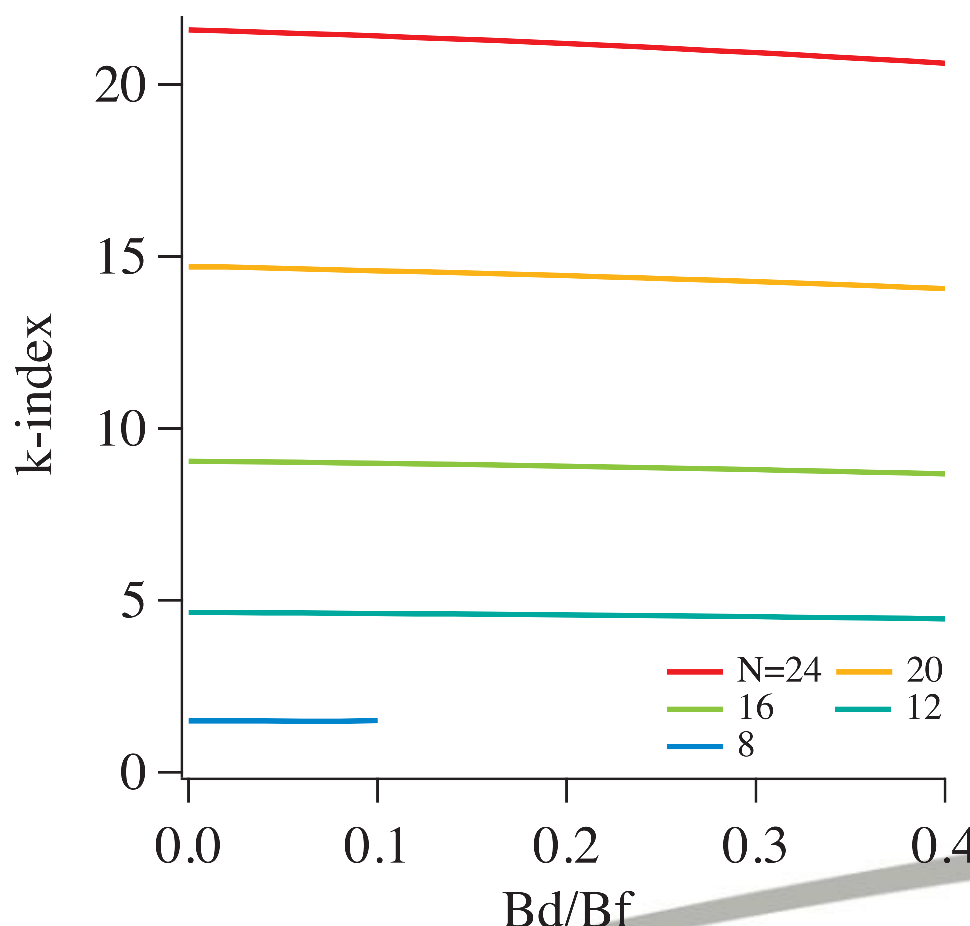
Finally

$$N_{FETS} = 7$$

Prototype ring
spiral angle and k-index

- Considered N=24 (option1), 20, 16, 12, 8 (option2)
    - Fix cell tune at the nominal value of 1.2 GeV FFAG (qh=5.19/24, qv=5.24/24).
    - Fix packing factor the same: Bf occupies 20% and Bd occupies 10% of circumference.

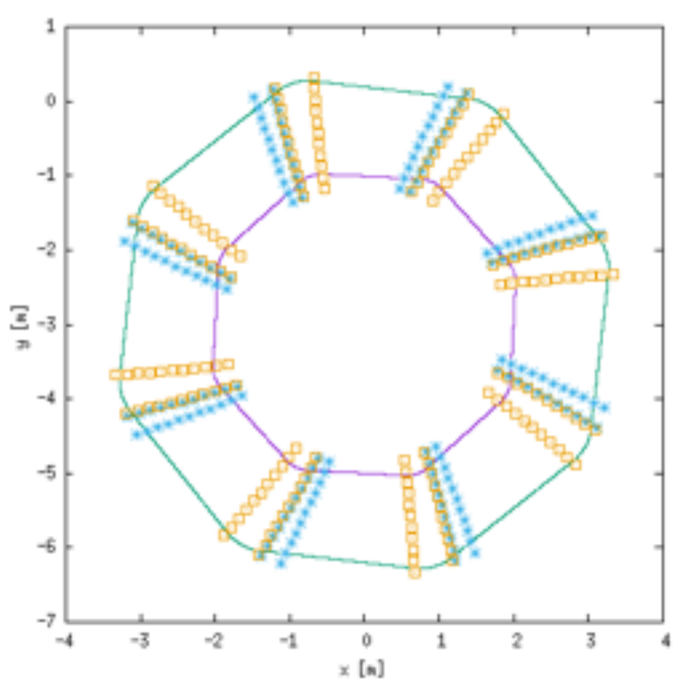


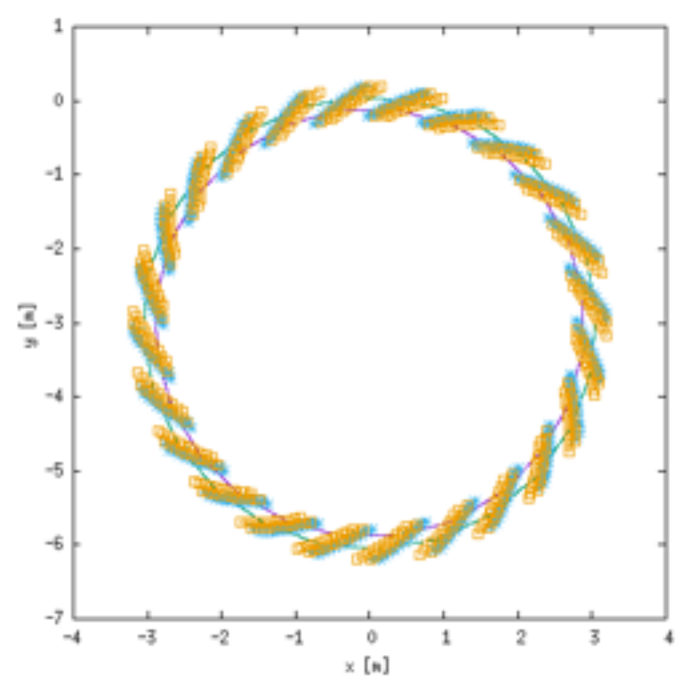


Prototype ring

summary so far

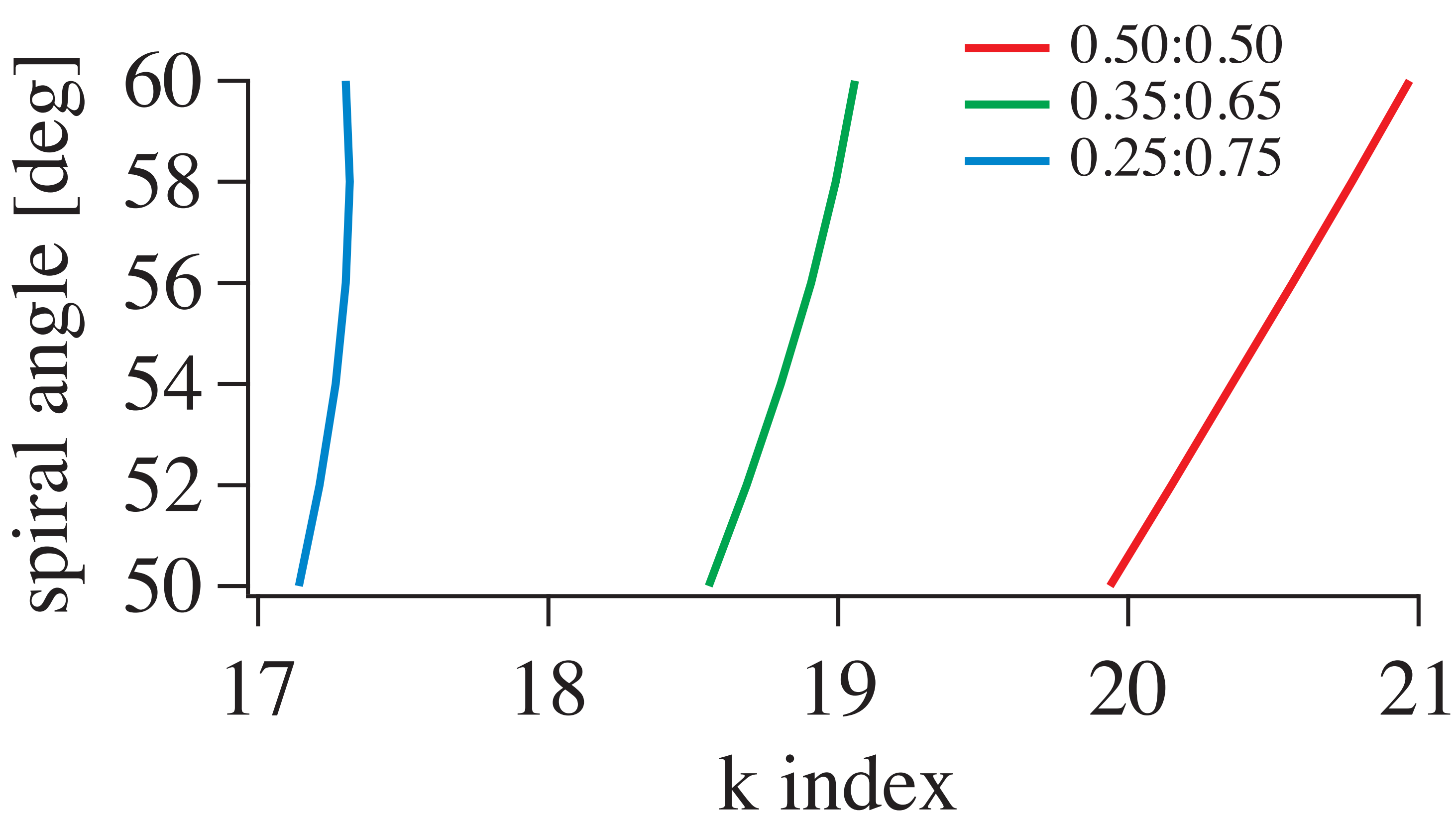
- N=8 lattice design has the similar orbit excursion and therefore dimension of HW (magnets, etc) will be similar to 1.2 GeV FFAG.
- On the other hand, both spiral angle and k-index have to be much smaller than that of 1.2 GeV FFAG. Therefore it may not fulfil a test of the DF-spiral concept (SW).
- I incline to the same number of cell as 1.2 GeV FFAG, namely N=24.





Prototype ring
optics adjustment

- Preparing knobs to adjust optics is **essential.**



$$Q_x^2 \approx 1 + k$$
$$Q_z^2 \approx -k + \frac{\Phi^2}{b_0^2}\left(1 + 2\tan^2\delta\right)$$

Prototype ring

summary so far

- N=8 lattice design has the similar orbit excursion and therefore dimension of magnets will be similar to 1.2 GeV FFAG.
- On the other hand, both spiral angle and k-index have to be much smaller than that of 1.2 GeV FFAG. Therefore it may not fulfil a test of the DF-spiral concept (SW).
- I incline to the same number of cell as 1.2 GeV FFAG, namely N=24.

- However, there is a caveat. Physical aperture scales as well although physical emittance increase inversely proportional to beta*gamma.

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Prototype ring

how much aperture is require for injection study?

- Suppose we want to test 2 planes injection with the total **50 turns**.
- Suppose we can reduce FETS linac current to **1 mA peak**.
- Accumulated total number of particles should be **2.46 x 10^{11} p**.

$$\varepsilon = \frac{r_p n_t}{(-\Delta Q)\, 2\pi \beta^2 \gamma^3} \frac{1}{B_f}$$

= 94 pi mm mrad (instead of 12.5 pi mm mrad)

- In terms of gap, it should be 2.7 times wider, namely +/- **21.6 ~ 30.4** mm.

	linac current		
3 MeV	**50 mA**	**1.305x10^{10} p/m**	**2.46 x 10^{11} p/turn**
	5 mA	**1.305x10^{9} p/m**	**2.46 x 10^{10} p/turn**
	1 mA	**2.61x10^{8} p/m**	**4.92 x 10^{9} p/turn**

Prototype ring

nonlinearity vs k (or N)

- Nonlinearity increases sharply with k.

$$\left(\frac{r_0 + x}{r_0}\right)^k = 1 + \frac{k}{1!r_0}x + \frac{k(k-1)}{2!r_0^2}x^2 + \frac{k(k-1)(k-2)}{3!r_0^3}x^3 +$$

- Choosing smaller N increases dynamic aperture.

$$k \propto N^2$$

Prototype ring

choice of N

Small number of cell (N=8)	Large number of cell (N=24)
(Hardware oriented)	**(Software oriented)**
• Size of hardware components is similar to 1.2 GeV FFAG. • Dynamic aperture is large, good for injection and space charge study.	• Parameters and dynamics are close to 1.2 GeV FFAG except size. • Small orbit excursion makes the hardware components small.
• Dynamics might be different from 1.2 GeV FFAG due to small spiral angle and k-index.	• Dynamic aperture is limited. • Simply scaled aperture is too small for injection and space charge study.

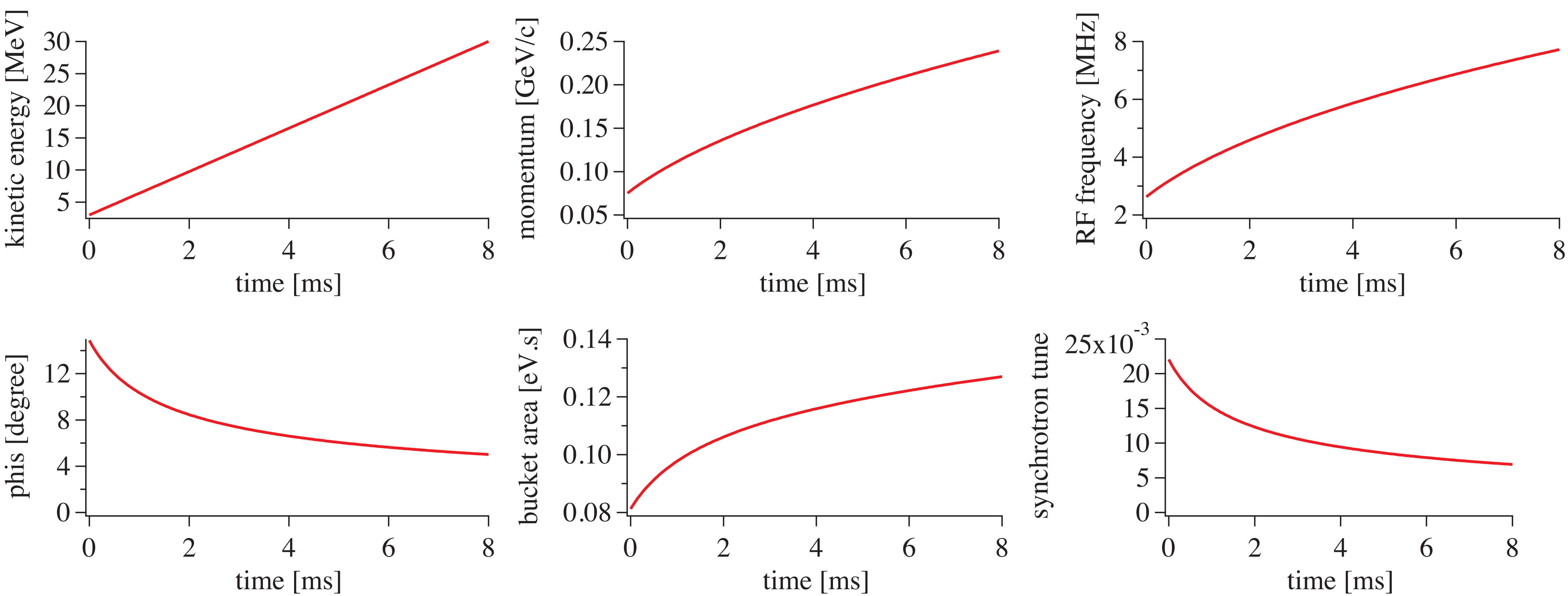
- My proposal is
  - Set **baseline lattice with N=24**, same as 1.2 GeV FFAG.
  - Study more details on dynamic aperture (Zgoubi, OPAL, SCODE).
  - Open up the gap as much as possible.
  - If still not enough, reduce number of cell N.

Prototype ring
RF programme

- Let us take for example

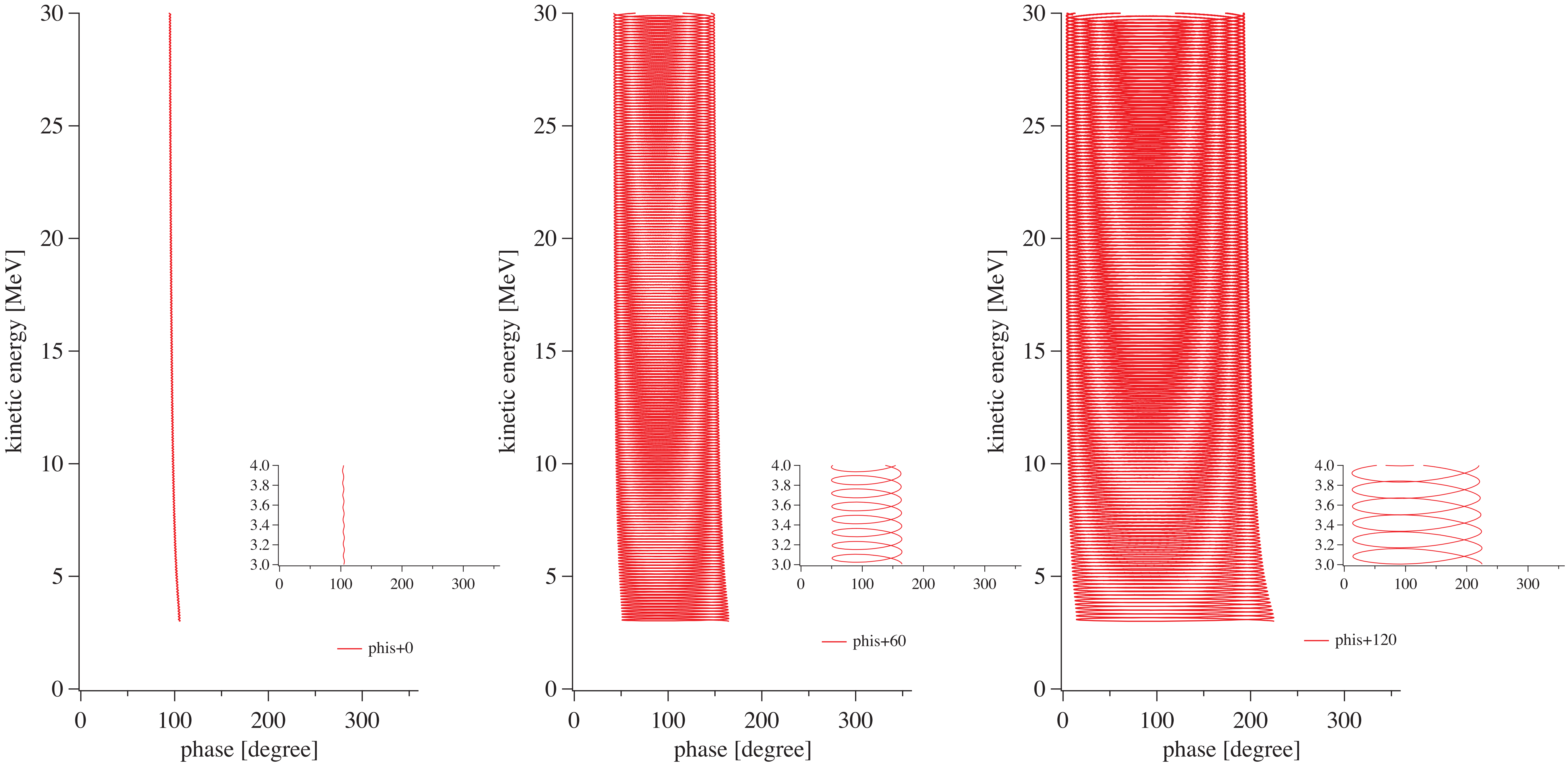
$$\frac{dE}{dt} = \frac{30\ \mathrm{MeV} - 3\ \mathrm{MeV}}{8\ \mathrm{ms}\ \ (\sim 100\ \ Hz)} = 3.375\ \mathrm{keV}/1\ \mu s.$$

- With 10 kV RF cavity per turn and harmonic number of 2,



Prototype ring

synchrotron oscillation and acceleration



- Acceleration completes in 22800 turns.