High intensity/power FFAG study

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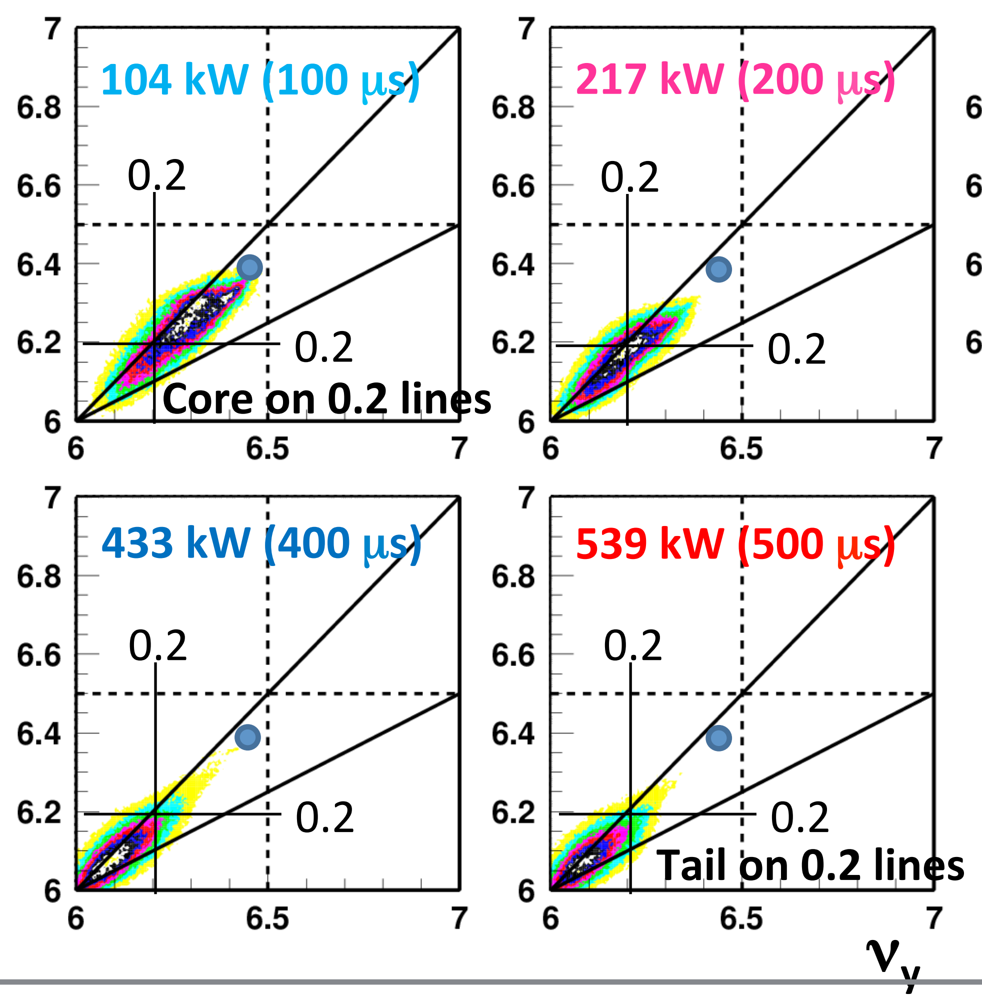
Overview

Overview

J-Parc Rapid Cycling Synchrotron (RCS) successfully achieved 1 MW with 3 GeV and 25 Hz.

Space charge tune spread is the limiting factor.



H. Hotchi
at 2013 SC workshop

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

n_t : # of particles

$\epsilon_{h,v}$: emittance

β, γ : energy

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Overview

- Beam power is
  - (repetition rate) x (# of particles) x (energy)

tune spread

- FFAG can (synchrotron cannot) easily
  - increase repetition rate to more than 25 Hz.
  - increase horizontal emittance to reduce space charge tune spread.
  - stack beams at the extraction energy to change the time structure of the output pulse.

- First assume the same energy machine as RCS
  - inject at 400 MeV and extract at 3 GeV.

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Overview

synchrotron

FFAG

	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**

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

FFAG can push the power up to ~10 MW.

Overview

Another parameter is injection energy.

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

Gain a factor of 3 by increasing from 400 MeV to 800 MeV.

	rep=25 Hz	50 Hz	100 Hz
Sqrt[eh/ev]=1	**3 MW**	6	12
2	4.5	9	18
3	6	12	**24 MW**

Overview

Neutron users do not want high repetition (< 25 Hz).

- Beam sharing with several target stations in the mean time (phase 1).
  - need development of high power target anyway.
  - ISIS users appreciate the facility with multiple targets although beam power is relatively low.

- Stack beams at the extraction energy (phase 2).
  - resume pulse structure back to 25 Hz or even lower.

Overview

Let us talk about the new ISIS with ~25 MW beam power!

ISIS at Rutherford Appleton Laboratory

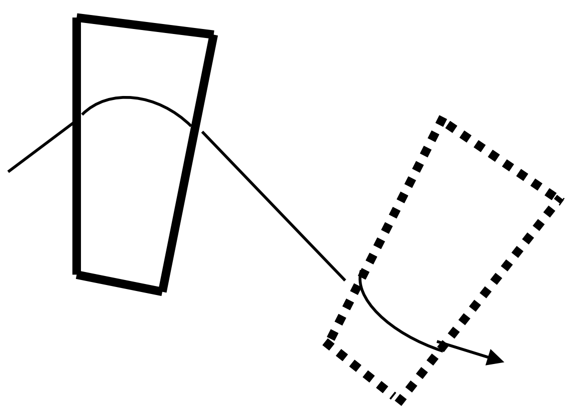
We are given an opportunity to discuss a machine in 20 years time.

- Two orders of magnitude higher than the present ISIS.
- 5 times higher than ESS (long pulse).

Lattice design with new idea

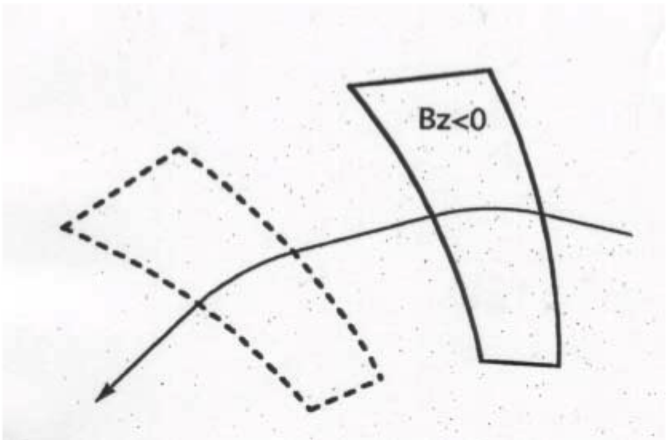
Radial or Spiral FFAG

radial sector

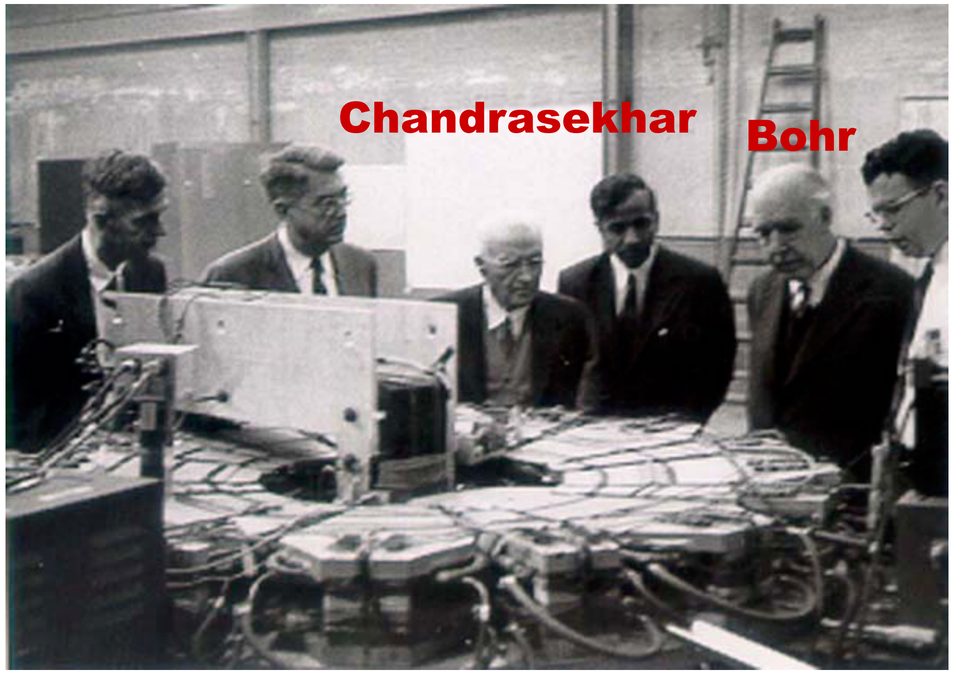


Alternating gradient focusing by focusing (normal bend) and defocusing (reserve bend)

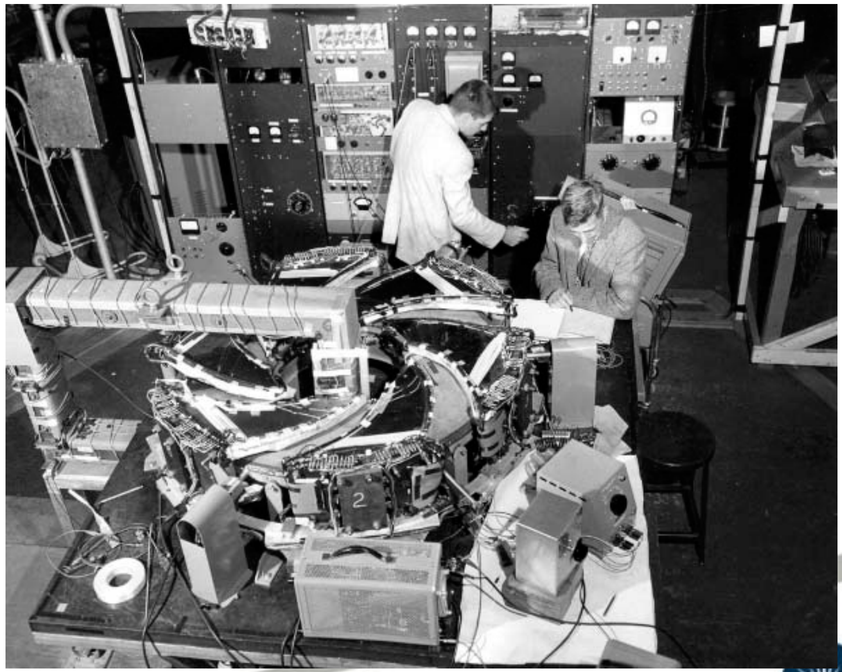
spiral sector



Alternating gradient focusing by focusing (normal bend) and defocusing (edge angle)



400 keV radial sector



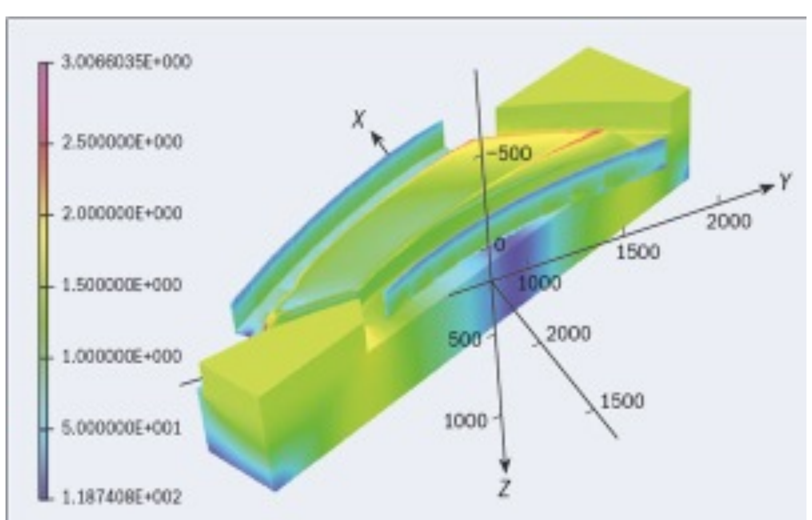
180 keV spiral sector

Radial or Spiral FFAG

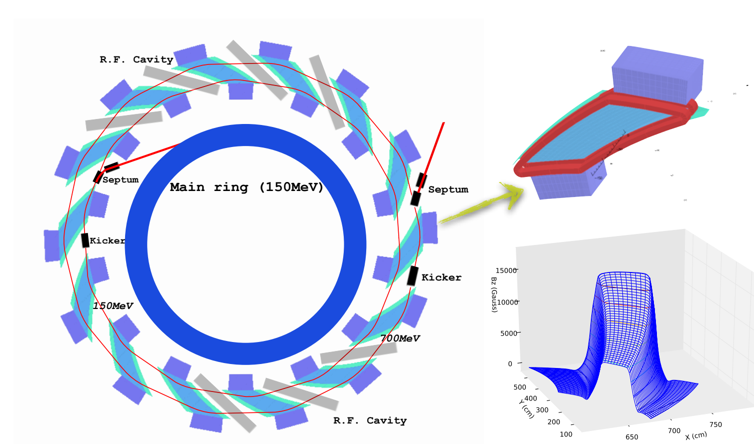
Advantage of spiral FFAG

- No reverse bending makes small footprint.
- Although Kyushu and KURRI are radial FFAGs, a few spiral *design* exists.
    1) RACCAM by Francois,
    2) 700 MeV design by QinBin,
    3) 300 MeV design by Okita-san.
- Not fancy like VFFAG, but more robust.

RACCAM, F. Meot

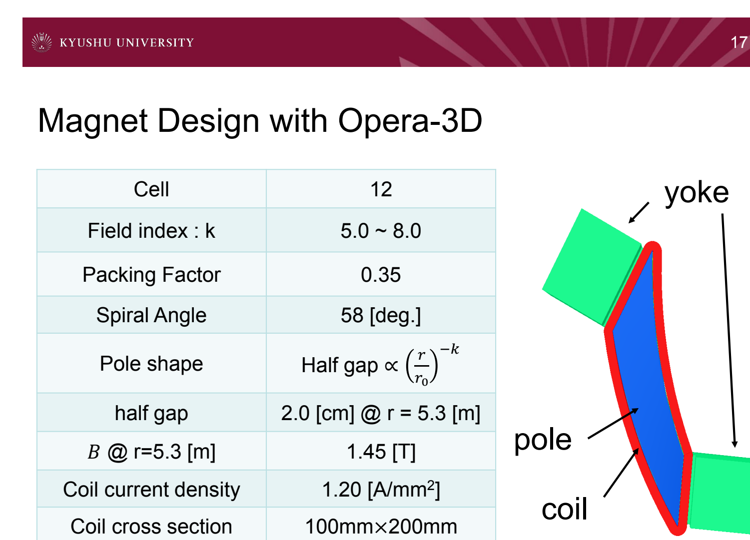


700 MeV, B. Qin



Schematic view of spiral FFAG ring (N=14)

300 MeV, H. Okita



Cell	12
Field index : k	5.0 ~ 8.0
Packing Factor	0.35
Spiral Angle	58 [deg.]
Pole shape	Half gap $\propto \left(\frac{r}{r_0}\right)^{-k}$
half gap	2.0 [cm] @ r = 5.3 [m]
B @ r=5.3 [m]	1.45 [T]
Coil current density	1.20 [A/mm^2]
Coil cross section	100mm×200mm

Cross sectionnal view of magnet

Radial or Spiral FFAG

Disadvantage

- Weaker focusing in vertical.
  - need large spiral angle.
  - long fringe field extent leads to less focusing.
- No knob for tune adjustment.

Tune is approximately (c.f. Symon, et. al., Phys Rev. 1956)

$$Q_x^2 = k + 1$$
$$Q_z^2 = -k + f^2 \tan^2 \zeta$$

where

k field index

ζ spiral angle

f field flutter

$$B = B_0 (r/r_0)^k \{1 + f \cos[N\theta - N \tan \zeta \ln(r/r_0)]\}$$

when # of cell N >> 1

$$\tan \zeta \approx \sqrt{k} \approx N$$

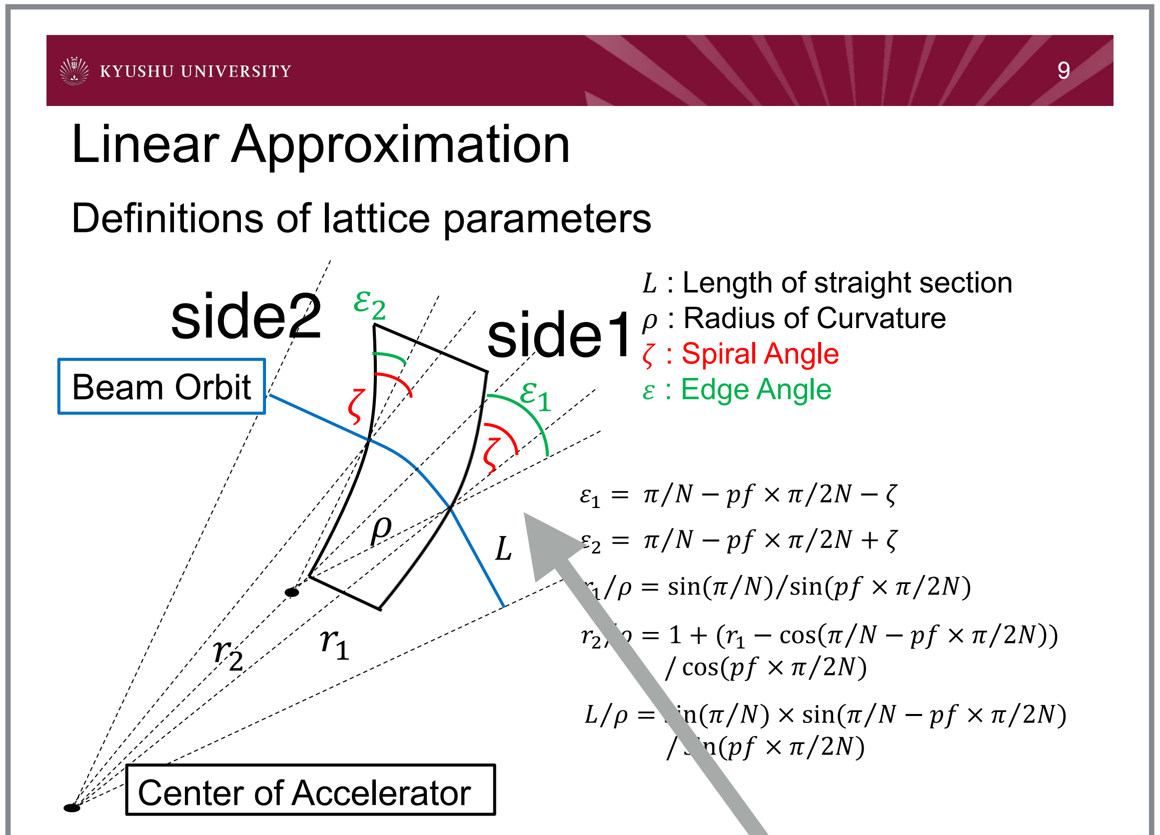
e.g. $N = 12 \ \ \zeta = 58^\circ$

⇔ $N = 36 \ \ \zeta = 78^\circ$

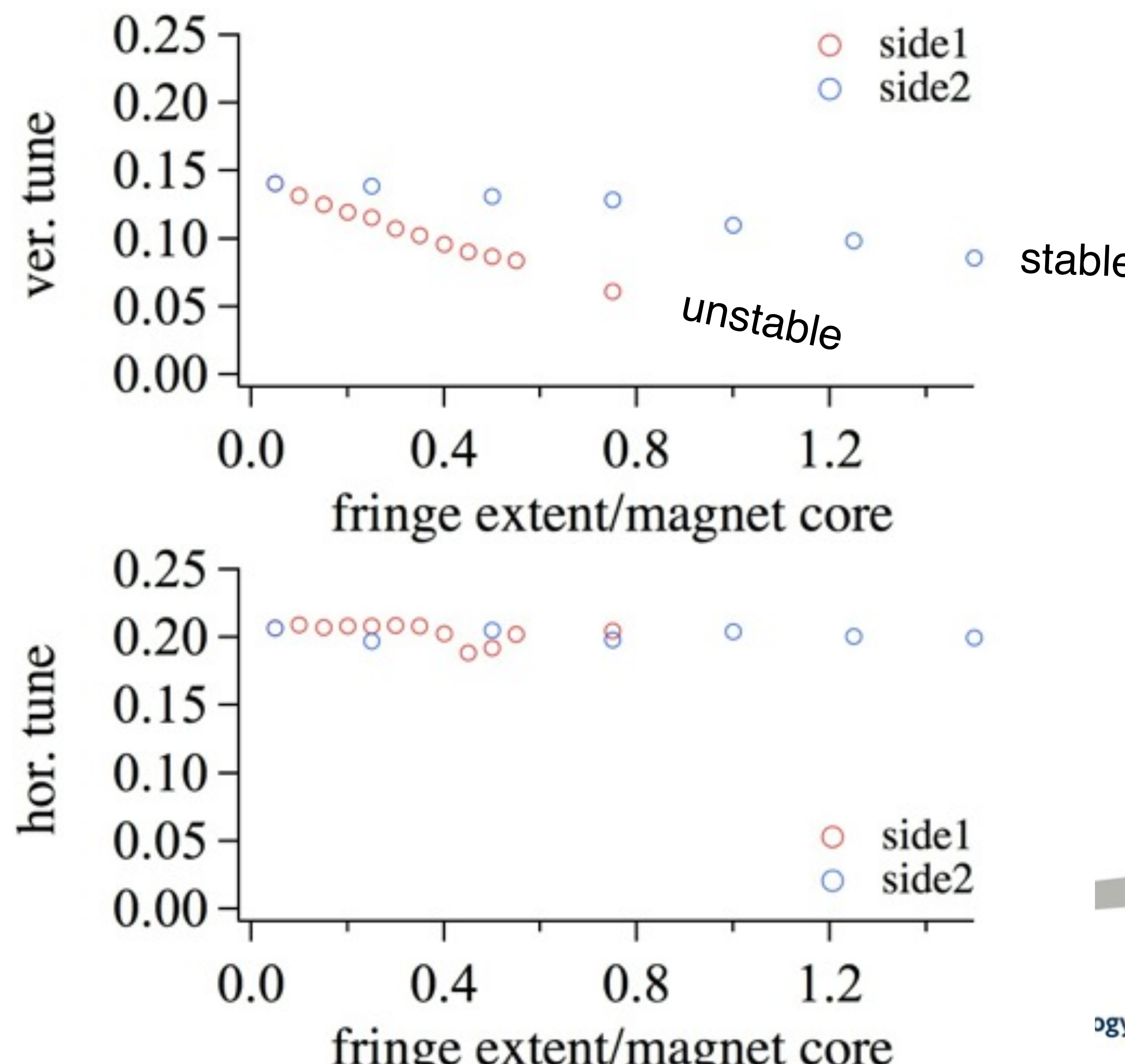
more difficult for high energy machine with large N.

Radial or Spiral FFAG

H. Okita, FFAG14



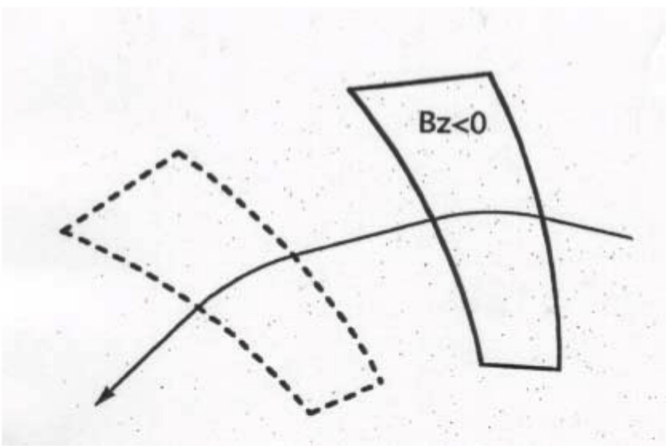
This side of the edge, side1, should have sharp fall off (extent/core<<1).

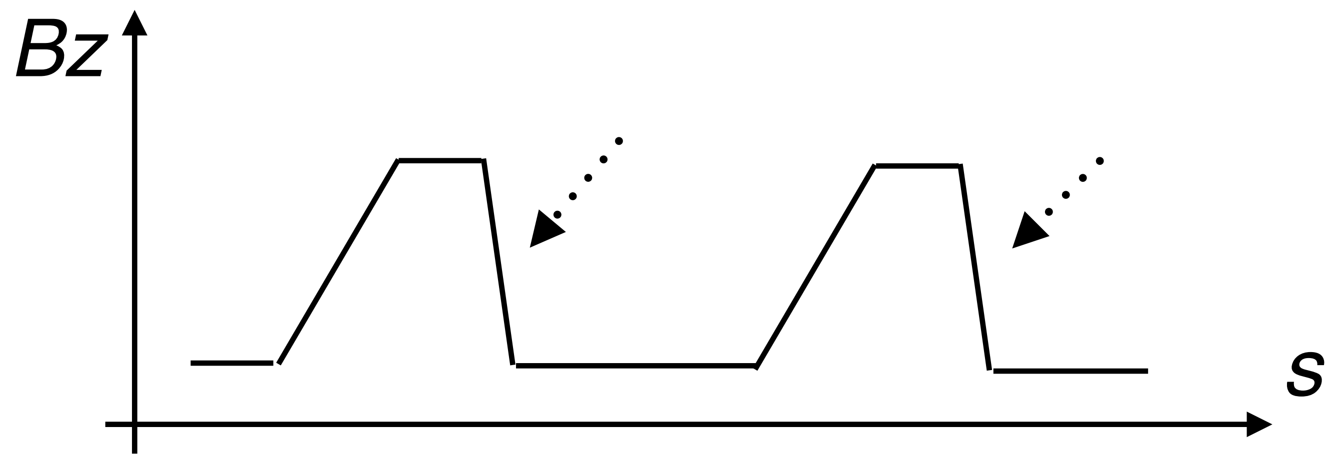


Vertical focusing comes mostly from the edge, side1 (ε_1).

Radial or Spiral FFAG

- Create shape edge, especially on one side.





- Increase the field flutter f has the same effect of ζ.

$$Q_x^2 = k + 1$$
$$Q_z^2 = -k + f^2 \tan^2 \zeta$$

$$B = B_0 (r/r_0)^k \{1 + f \cos[N\theta - N \tan\zeta \ln(r/r_0)]\}$$

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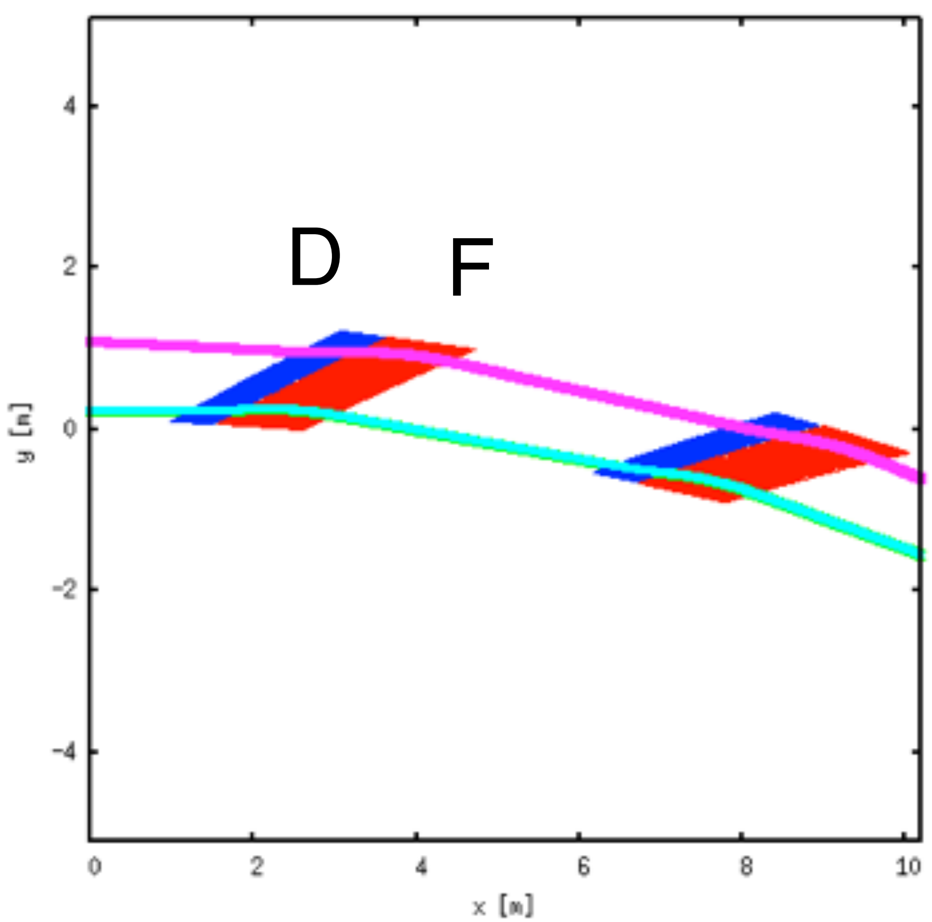
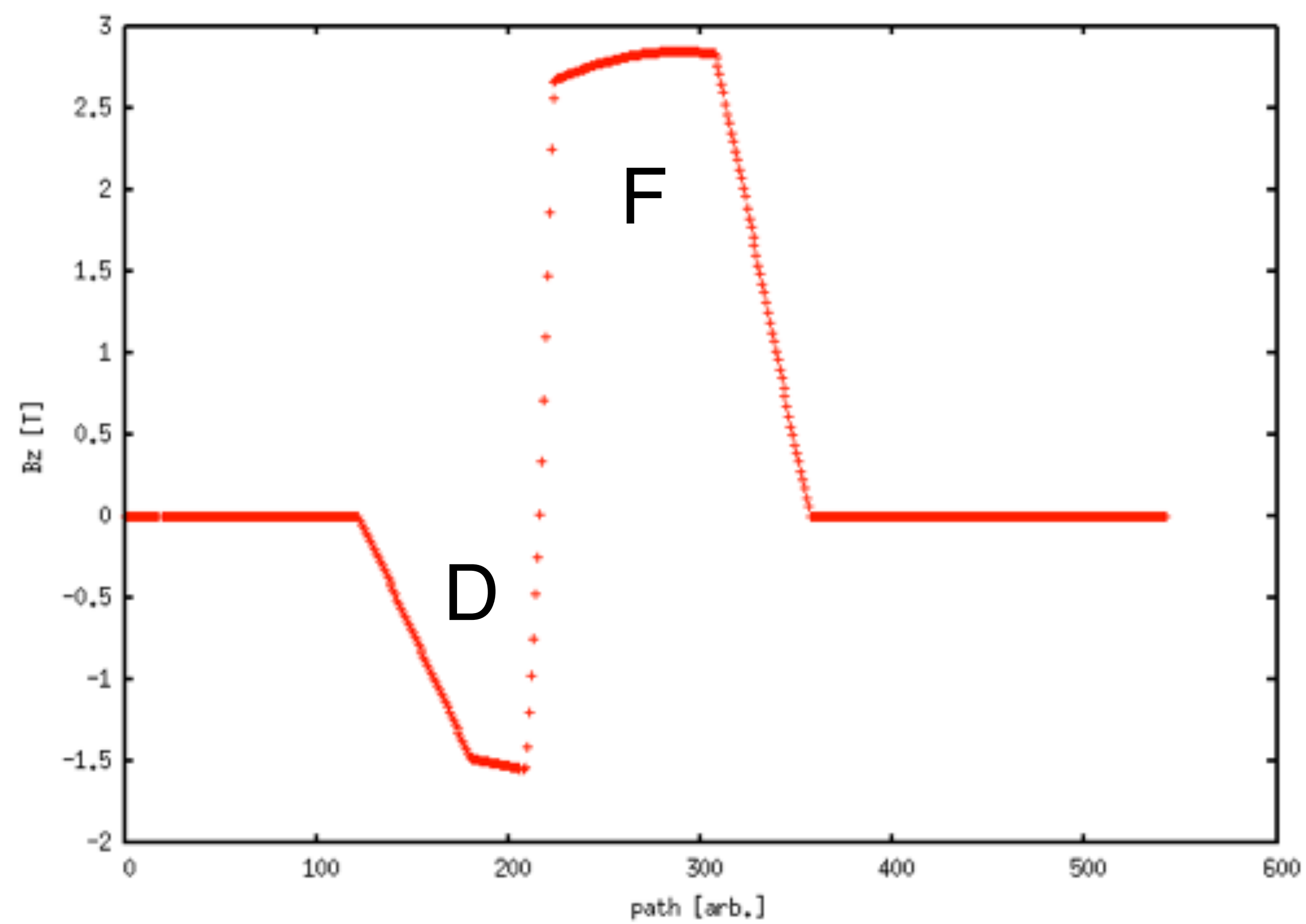
DF-Spiral FFAG

- New idea: *DF-Spiral*
  - Introduce (small) negative field on one side of the main spiral magnet.

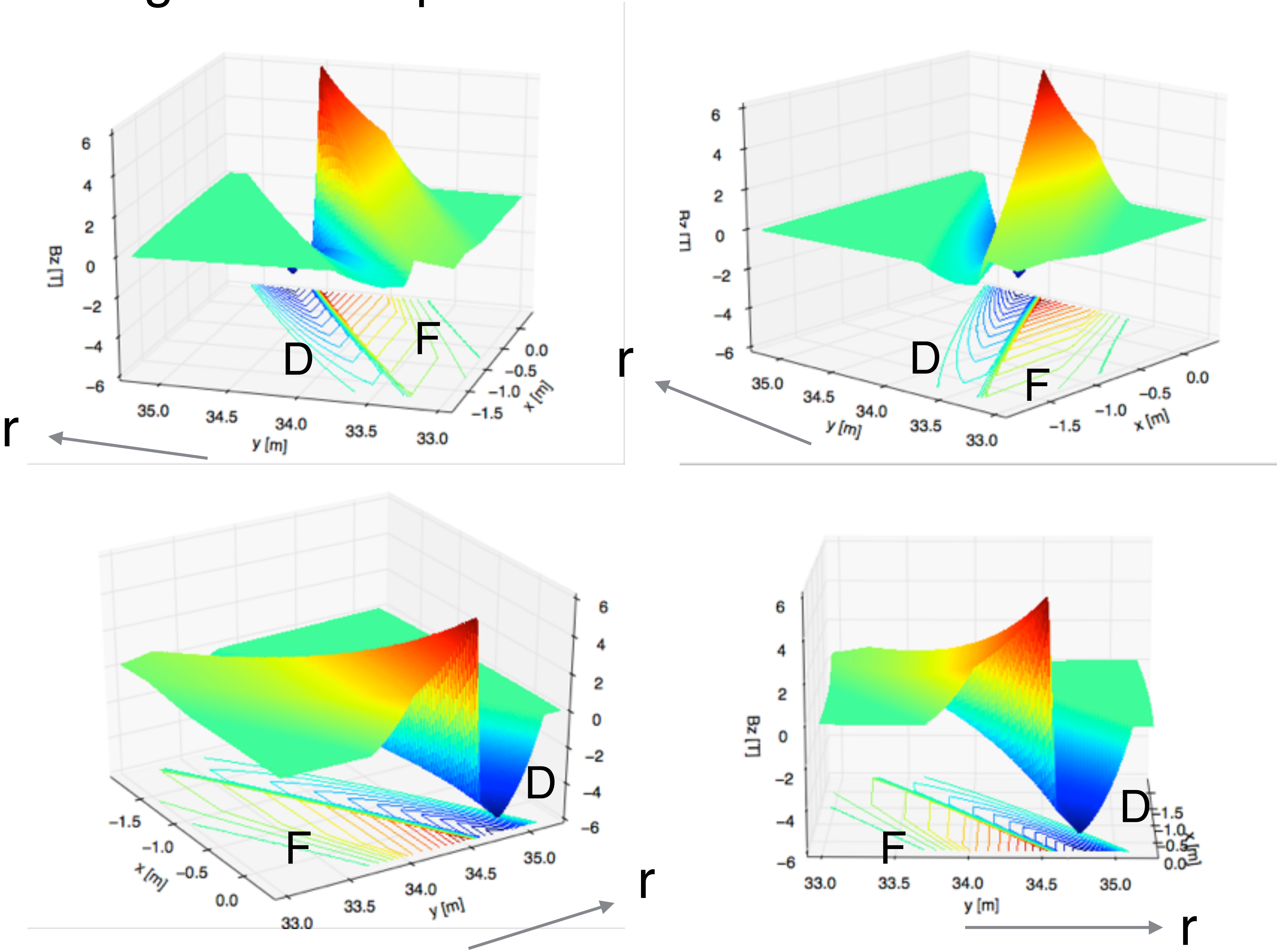




- Shape edge is created between D and F.
- Field flutter increases.
- Knob of F/D ratio like radial type.

DF-Spiral FFAG

Magnetic field profile

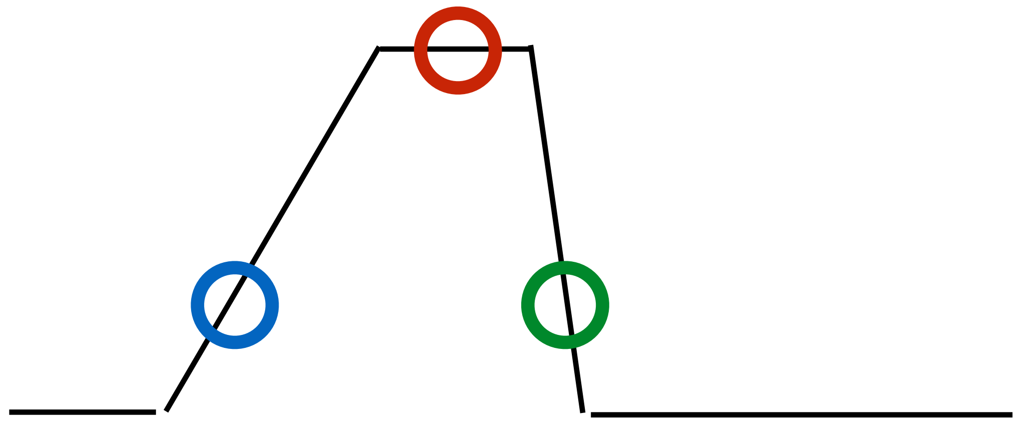


Field model

Field model

- Parameter search requires reasonably detailed field profile.
  - Spiral angle
  - Fringe field extent
- Linear optics model based in transfer matrix is not accurate.
- Tracking with TOSCA field map takes time.

- Reasonably accurate field model.
- Can be swapped easily with TOSCA field after initial parameter search.



Field model

$$B_z = \frac{\theta - (\theta_1 - \Delta\theta_1/2 + \tan\zeta \ln(r/r_0))}{\Delta\theta_1} B_{z0}(\frac{r}{r_0})^k$$

$$\theta_1 - \Delta\theta_1/2 + \tan\zeta \ln(r/r_0) < \theta < \theta_1 + \Delta\theta_1/2 + \tan\zeta \ln(r/r_0)$$

$$B_z = B_{z0}(\frac{r}{r_0})^k$$

$$\theta_1 + \Delta\theta_1/2 + \tan\zeta \ln(r/r_0) < \theta < \theta_2 - \Delta\theta_2/2 + \tan\zeta \ln(r/r_0)$$

$$B_z = \frac{(\theta_2 + \Delta\theta_2/2 + \tan\zeta \ln(r/r_0)) - \theta}{\Delta\theta_2} B_{z0}(\frac{r}{r_0})^k$$

$$\theta_2 - \Delta\theta_2/2 + \tan\zeta \ln(r/r_0) < \theta < \theta_2 + \Delta\theta_2/2 + \tan\zeta \ln(r/r_0)$$

Field model

Maxwell eqs in cylindrical coordinate system.

$$\frac{1}{r}\frac{\partial B_z}{\partial \theta} = \frac{\partial B_\theta}{\partial z}$$

$$\frac{\partial B_r}{\partial z} = \frac{\partial B_z}{\partial r}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(rB_\theta) = \frac{1}{r}\frac{\partial B_r}{\partial \theta}$$

Field model

Three components in BLUE region will be

$$B_z = \frac{\theta - (\theta_1 - \Delta\theta_1/2 + \tan\zeta \ln(r/r_0))}{\Delta\theta_1} B_{z0}(\frac{r}{r_0})^k$$

$$\frac{\partial B_\theta}{\partial z} = \frac{1}{r}\frac{\partial B_z}{\partial \theta} = \frac{1}{r\Delta\theta_1} B_{z0}(\frac{r}{r_0})^k$$

$$\therefore B_\theta = \frac{z}{r\Delta\theta_1} B_{z0}(\frac{r}{r_0})^k$$

$$\frac{\partial B_r}{\partial z} = \frac{\partial B_z}{\partial r} = \frac{k(\theta - (\theta_1 - \Delta\theta_1/2 + \tan\zeta \ln(r/r_0))) - \tan\zeta}{r\Delta\theta_1} B_{z0}(\frac{r}{r_0})^k$$

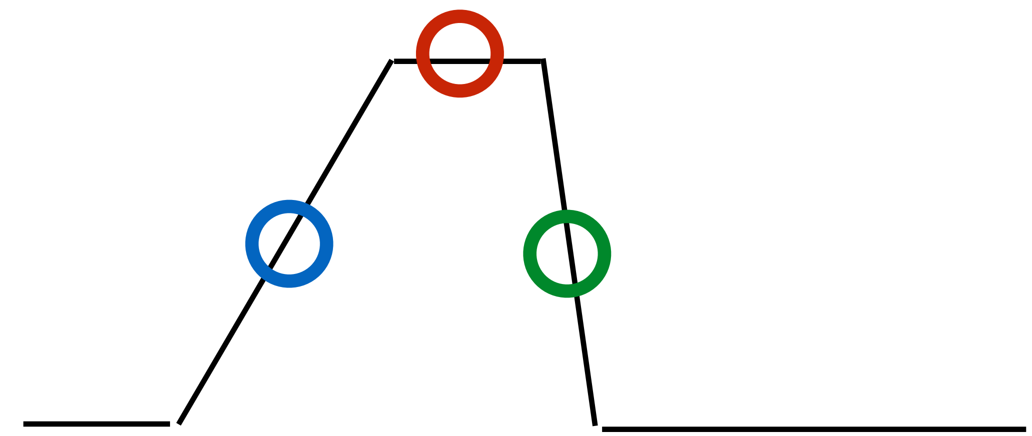
$$\therefore B_r = z\frac{k(\theta - (\theta_1 - \Delta\theta_1/2 + \tan\zeta \ln(r/r_0))) - \tan\zeta}{r\Delta\theta_1} B_{z0}(\frac{r}{r_0})^k$$

Field model

$$B_z = B_{z0}\left(\frac{r}{r_0}\right)^k$$

$$B_\theta = 0$$

$$B_r = z\frac{k}{r}B_{z0}\left(\frac{r}{r_0}\right)^k$$



$$B_z = \frac{(\theta_2 + \Delta\theta_2/2 + \tan\zeta \ln(r/r_0)) - \theta}{\Delta\theta_2} B_{z0}\left(\frac{r}{r_0}\right)^k$$

$$B_\theta = -\frac{z}{r\Delta\theta_2} B_{z0}\left(\frac{r}{r_0}\right)^k$$

$$B_r = z\frac{k((\theta_2 + \Delta\theta_2/2 + \tan\zeta \ln(r/r_0)) - \theta) + \tan\zeta}{r\Delta\theta_2} B_{z0}\left(\frac{r}{r_0}\right)^k$$

Parameter search

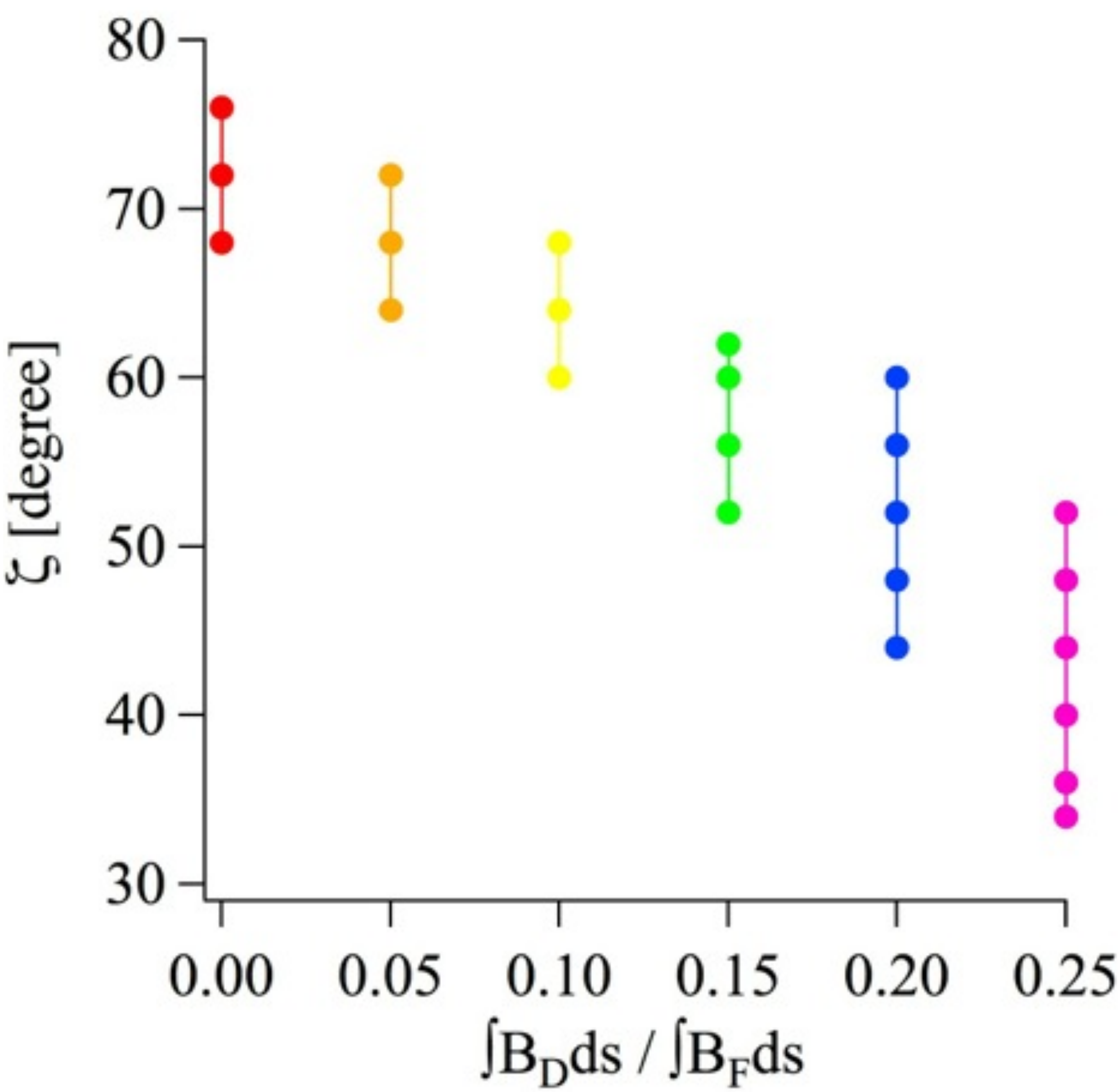
Parameter search

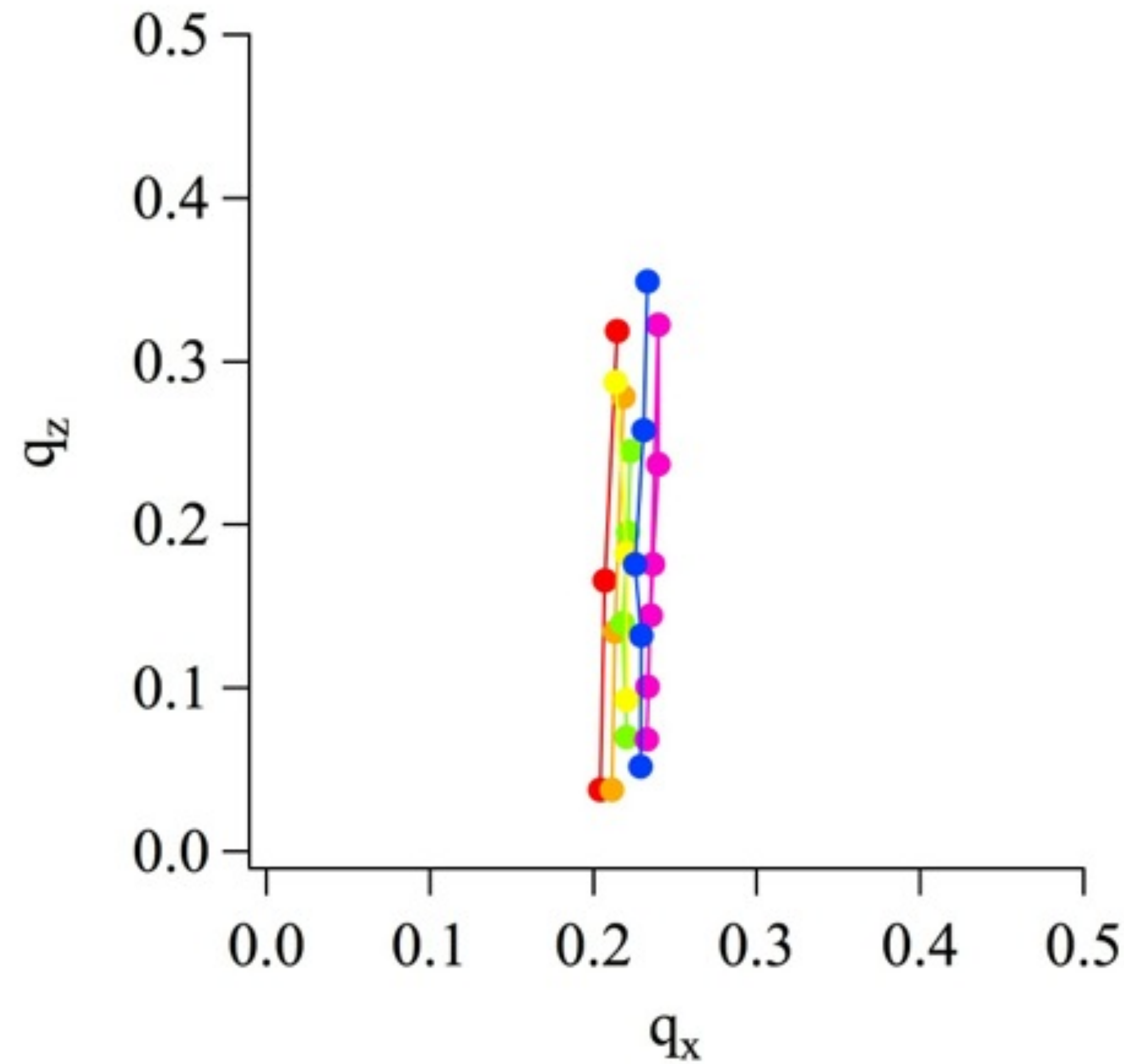
Some assumption

kinetic energy	0.4 to 3 GeV
# of cell	36
radius	~ 30 m
k value	50
packing factor	0.3 ~ 0.4
size of magnet	D:F=1:2

Parameter search

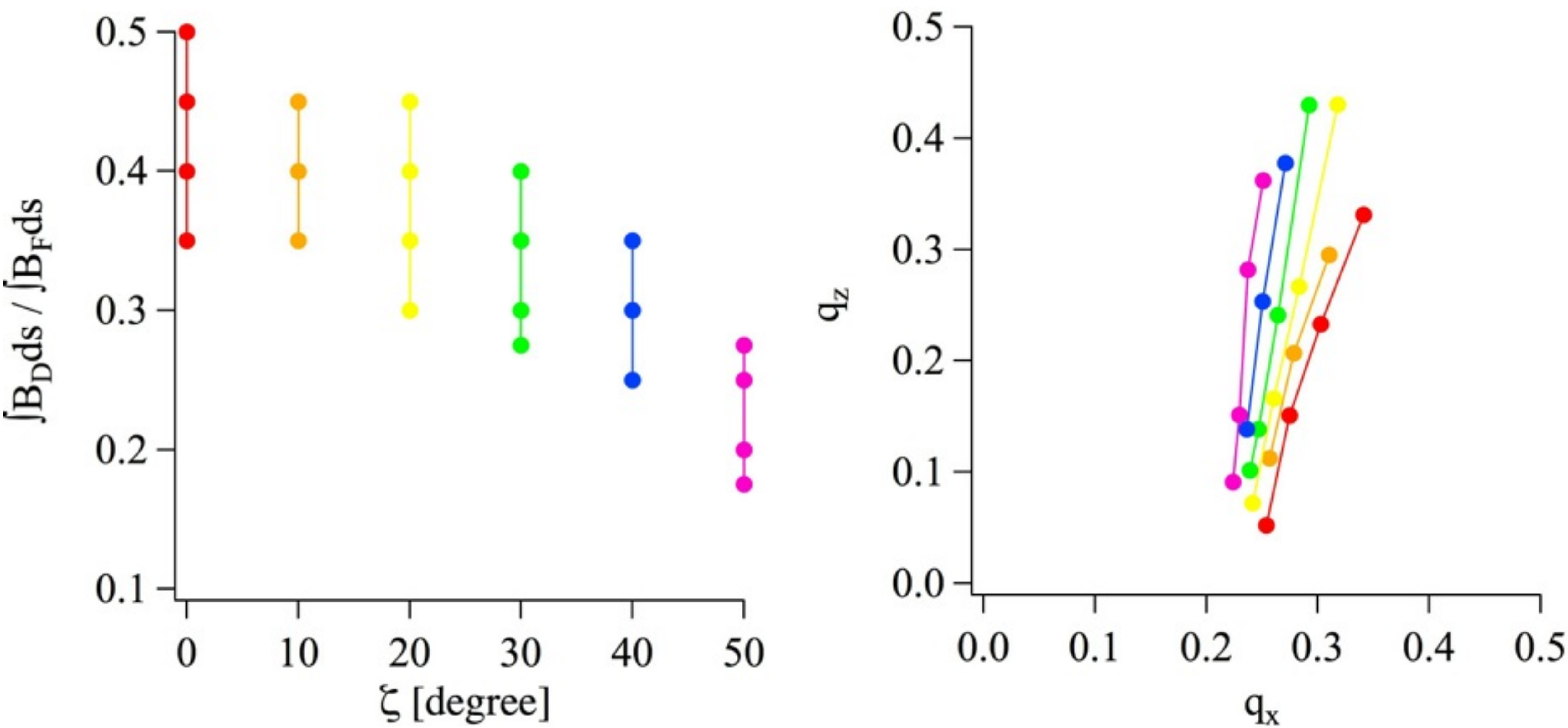
- BD/BF=0 means pure spiral sector FFAG.
- Introduction of reverse bend increases “field flutter”.
- “spiral angle” can be smaller to obtain the same tune.
- For fixed BD, spiral angle is a knob to adjust V tune.





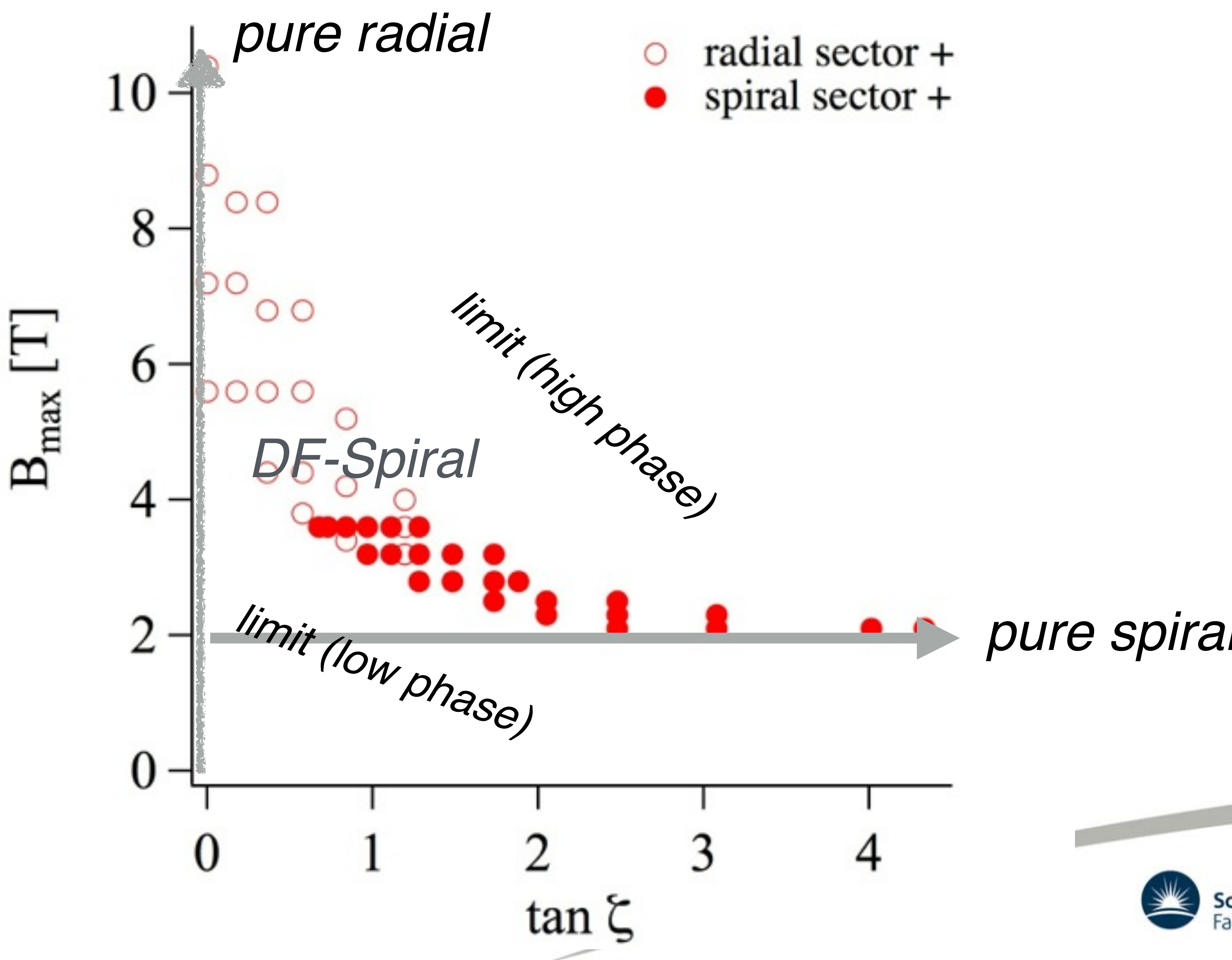
Parameter search

- Z=0 means pure radial sector FFAG.
- BD/BF field can be lower to obtain the same tune with the introduction of “spiral angle”.
- For fixed Z, BD is a knob to adjust V tune.



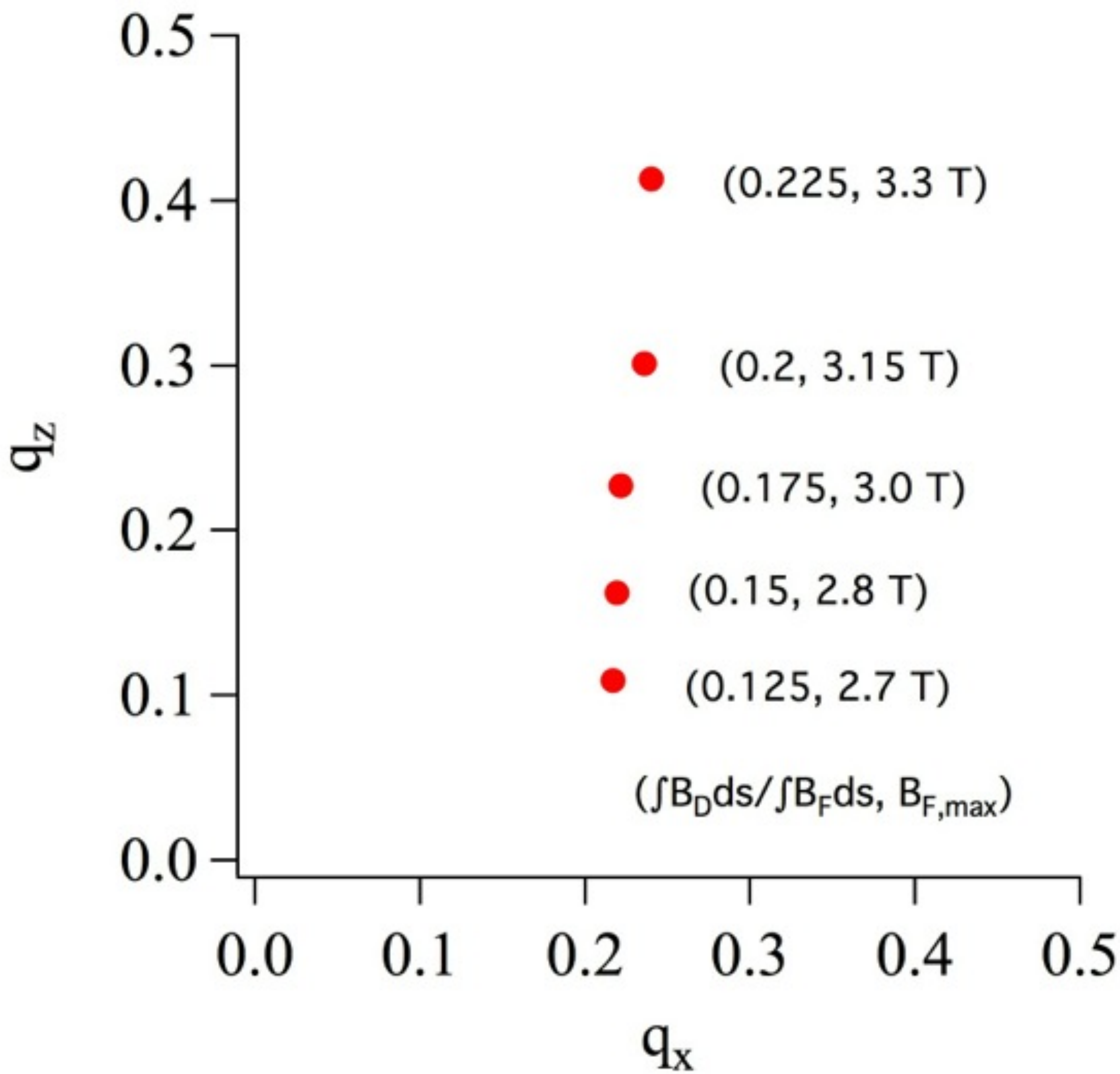
Parameter search

Practically, the best parameter is obtained with the balance between Bmax field and spiral angle.



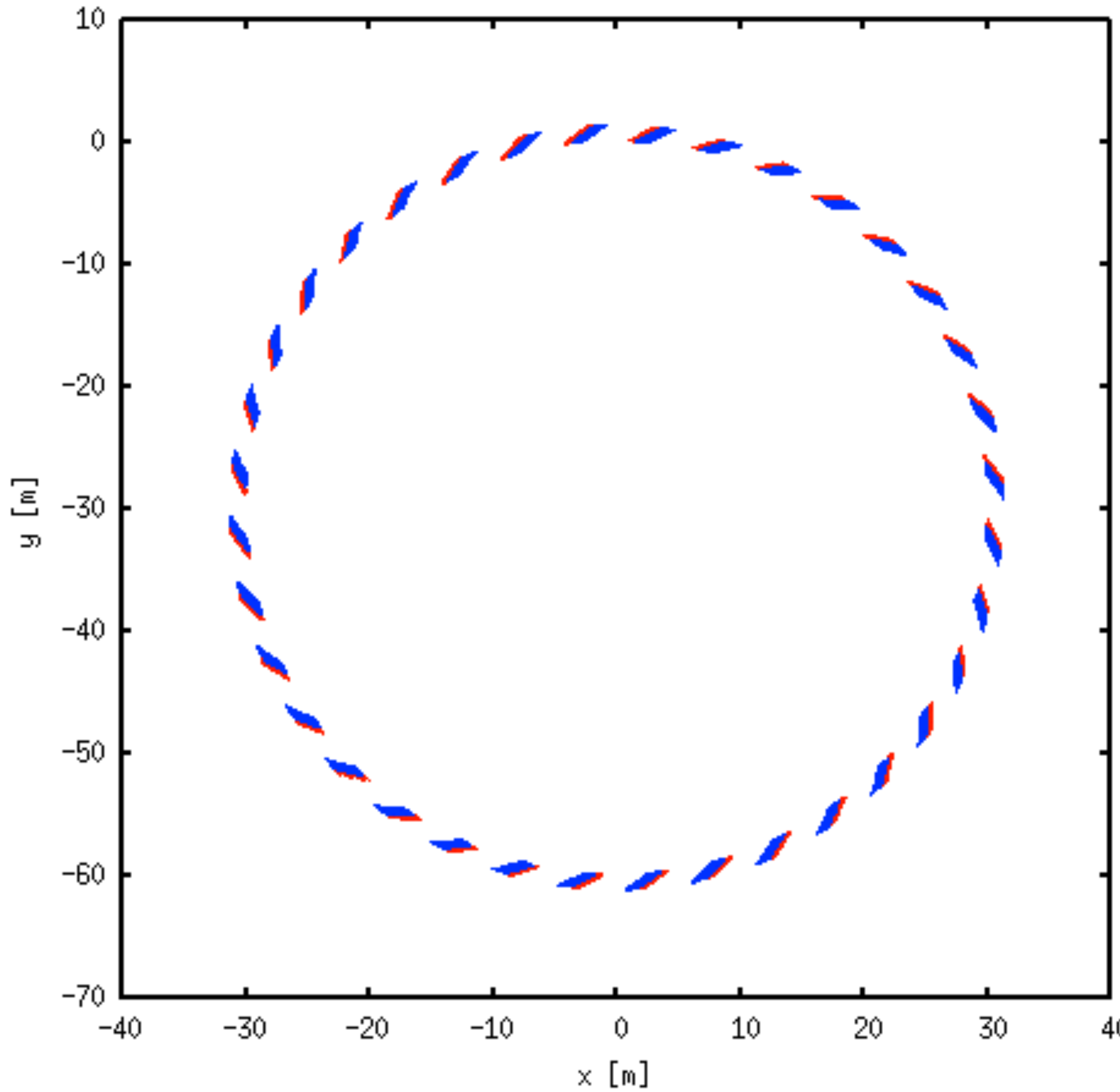
Parameter search

- spiral angle=58 degree.
- max B field is 3.0 (3.3) T.



Parameter search

Type	DF-Spiral
Kinetic energy	0.4 - 3 GeV
Pex/Pin	~ 4
Cell number	36
Packing f	0.31
Spiral angle	58
Field index	30
Orbit excursion	0.82 m
Rex/Rin	31.0 / 30.2 m
Bmax@orbit	3.0 (3.3) T
Straight	3.6 m



Key area of R&Ds

Magnets

- Superconducting magnets is a preferred option.
  - not because of high fields to make the machine compact,
  - but because reducing the operational cost.
- superferric magnets with up to 4 T is the best.

- Flexibility with trim coils.

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RF cavity

- High gradient RF with wider horizontal aperture (~ 1 m).
- Strong beam loading and its compensation.

Summary

Summary

- Showed FFAG option to achieve 25 MW beam power.
- DF-Spiral sector is the best mix of radial and spiral sector FFAGs.
- No reason to go back to pure radial or pure spiral sector.
- Patent under preparation.
- Simple but reasonably accurate field model was developed.

- Superferric magnet and high beam loading RF system are key R&D items.

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Backup

Before start

- Overview: Design principle (based on RCS 1 MW)
- Lattice design (spiral+ with D magnets)
- Tool development (TOSCA like field)

- Plan of experiments at KURRI and FETS
- Plan of Simulation with space charge
- R&D items (hardware, superferric magnets)

Field model

$$B_z = \frac{\theta - (\theta_1 - \Delta\theta_1/2 + \tan\zeta \ln(r/r_0))}{\Delta\theta_1} B_{z0}(\frac{r}{r_0})^k$$

$$B_z = B_{z0}(\frac{r}{r_0})^k$$

$$B_r = z\frac{k}{r} B_{z0}(\frac{r}{r_0})^k$$

$$B_\theta = \frac{z}{r\Delta\theta_1} B_{z0}(\frac{r}{r_0})^k$$

$$B_r = z\frac{k(\theta - (\theta_1 - \Delta\theta_1/2 + \tan\zeta \ln(r/r_0))) - \tan\zeta}{r\Delta\theta_1} B_{z0}(\frac{r}{r_0})^k$$

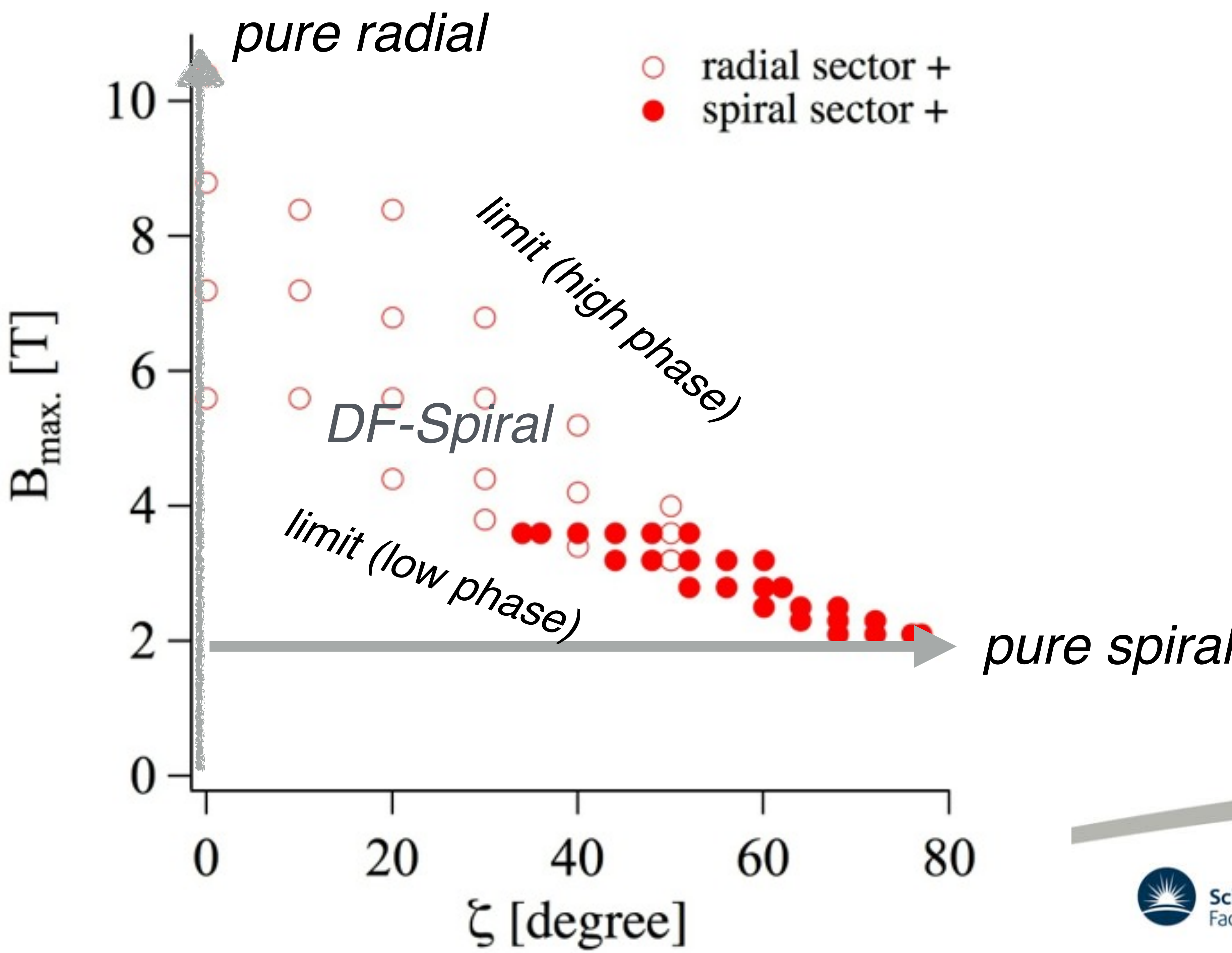
$$B_z = \frac{(\theta_2 + \Delta\theta_2/2 + \tan\zeta \ln(r/r_0)) - \theta}{\Delta\theta_2} B_{z0}(\frac{r}{r_0})^k$$

$$B_\theta = -\frac{z}{r\Delta\theta_2} B_{z0}(\frac{r}{r_0})^k$$

$$B_r = z\frac{k((\theta_2 + \Delta\theta_2/2 + \tan\zeta \ln(r/r_0)) - \theta) + \tan\zeta}{r\Delta\theta_2} B_{z0}(\frac{r}{r_0})^k$$

Parameter search

Practically, the best parameter is obtained with the balance between Bmax field and spiral angle.



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