Scaling FFAG for muon acceleration

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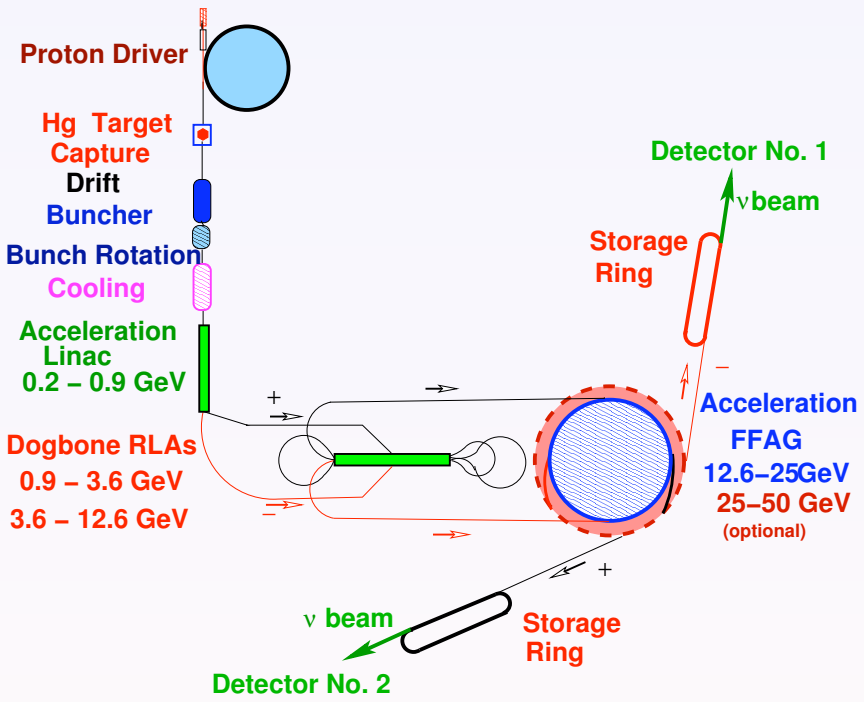
Neutrino factory

ISS scenario : Chris Prior nufact07

Neutrino Factory Overview

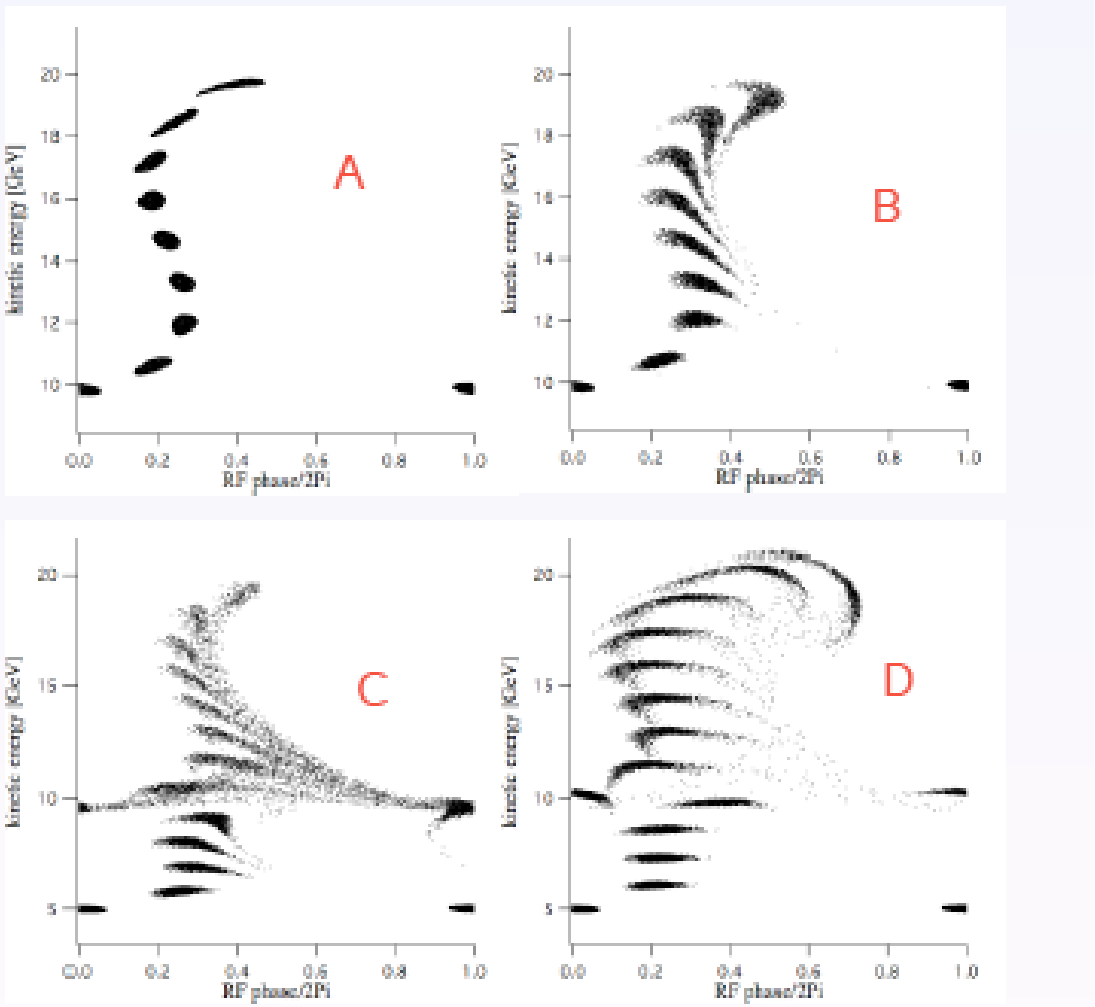
- Proton driver
  - primary beam on production target
- Target, capture, decay
  - create π, decay into μ
- Bunching, phase rotation
  - reduce ΔE of bunch
- Cooling
  - reduce transverse emittance
- Acceleration
  - from $\sim$ 130 MeV to 20–50 GeV
- Decay Ring
  - store for $\sim$ 500 turns
  - long ν production straight



ns-FFAG chains

- Non-scaling FFAG rings
- advantages
  - small aperture
  - const. rf frequency (high frequency & field)
- problems (issues)
  - time of flight (path length) for large amplitude : cascade rings

Emittance mismatch

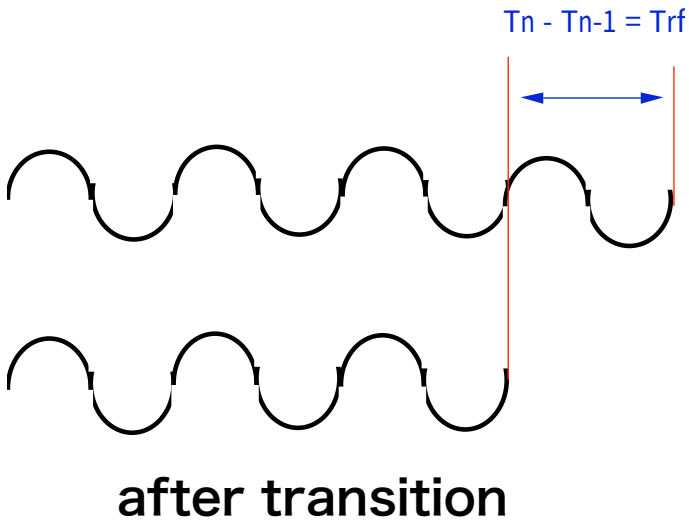


A: Zero emittance beam in 10-20 GeV FFAG
B: Finite transverse amplitude beam in 10-20 GeV FFAG
C: 30,000 π mm.mrad beam in two FFAGs
D: Correction with second harmonic RF

Emittance degradation in passing through a succession of ns-FFAGs

Harmonic Number Jump (HNJ) acceleration

- HNJ-acceleration (Kolomenski, Fujisawa, Ruggiero)
  - Difference of revolution period between n-th and (n-1)-th turn equals m(integer) times rf period.
- Tn - Tn-1 = Trf x m
  - Tn : revolution period for n-turn
  - Trf : rf period
  - m : integer (<0: before, >0: after transition)



HNJ Acceleration in scaling FFAG

- Revolution period for n-th turn

$$\left(\frac{T_n}{T_1}\right)=\left(\frac{C_n/v_n}{C_1/v_1}\right)$$

  - C: circumference, v: particle velocity

- Scaling FFAG

$$\frac{C_n}{C_1}=\left(\frac{p_n}{p_1}\right)^{\frac{1}{k+1}}$$

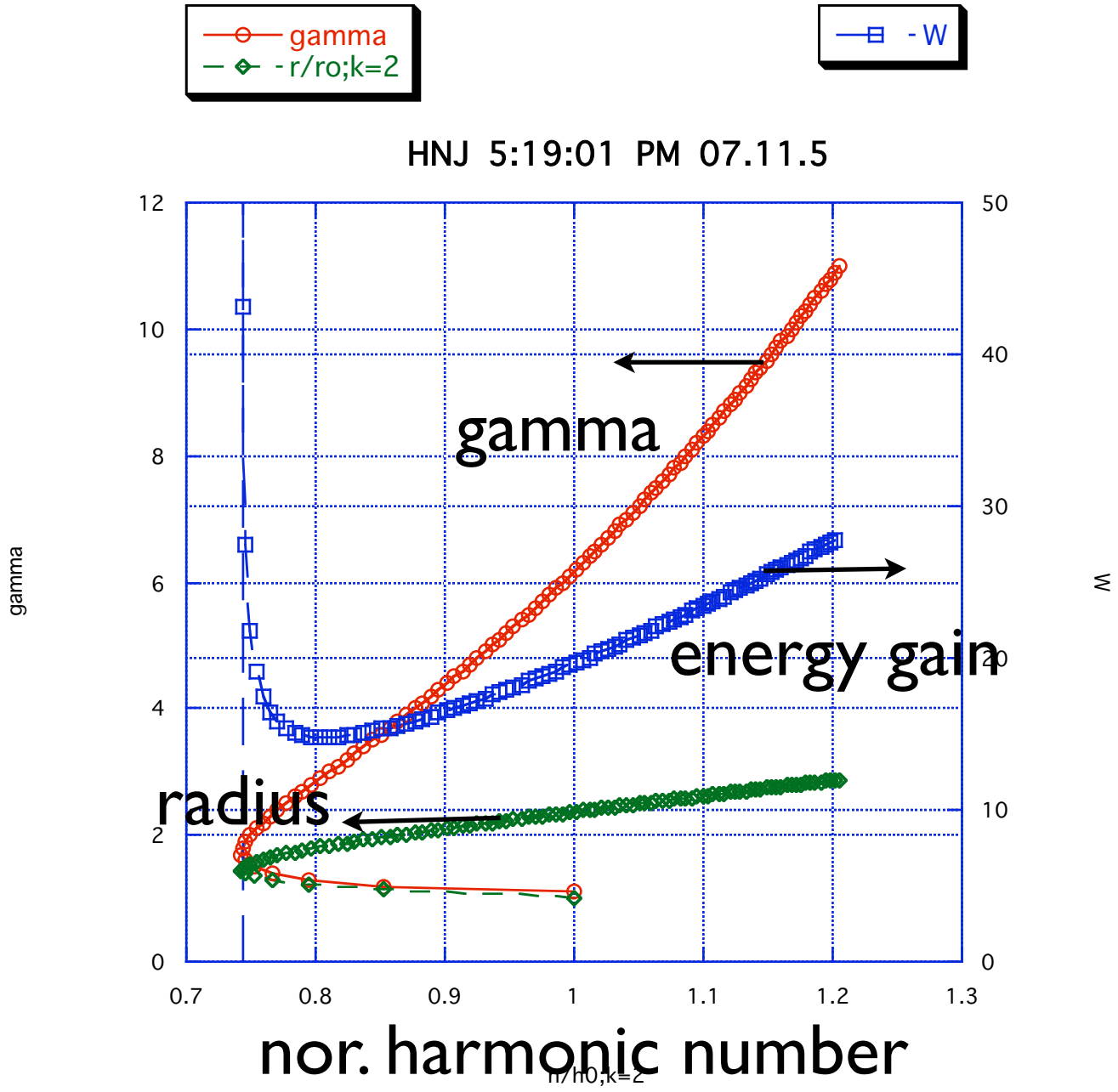
- For muon acceleration (v~c)

  - When k increases, or ring size decreases,
    - *No. of turns decreases.*
    - *Energy gain/turn increases.*
  - Need optimization!

$$\frac{C_n}{C_1}=\frac{h_n}{h_1},\quad p_n=p_1\left(\frac{h_n}{h_1}\right)^{k+1},\quad h_n=h_1+n\times m$$

HNJ in scaling FFAG

k=2, gamma=1-10

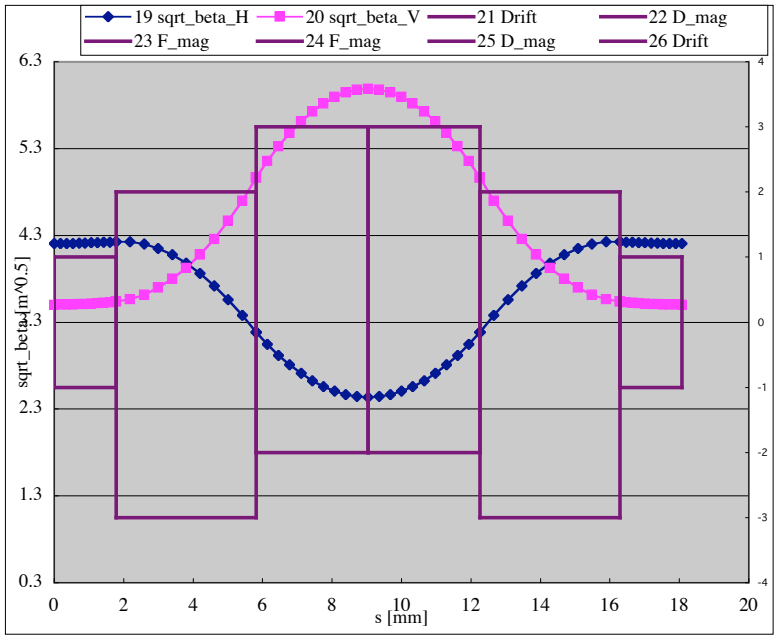


Scaling FFAG with HNJ

- Scaling FFAG with HNJ for low energy (5-10GeV) ring
- Advantages
  - Higher frequency (~200MHz) rf cavity : good matching -> Phase Rotation & non-scaling FFAG
  - energy gain/turn ~0.5-1GeV/turn, 5-10MV/cavity -->100-200 cavities/ring
  - Orbit shift is constant because orbit is scaled.
    - orbit shift ~ 5-8cm (n~10 turns)
    - ☑ *good for injection/extraction (only septa, no kicker)*
- Question
  - Acceleration of both Mu(+) and Mu(-) : If not possible, no hope for sacling FFAG to be a muon accelerator in neutrino factory.

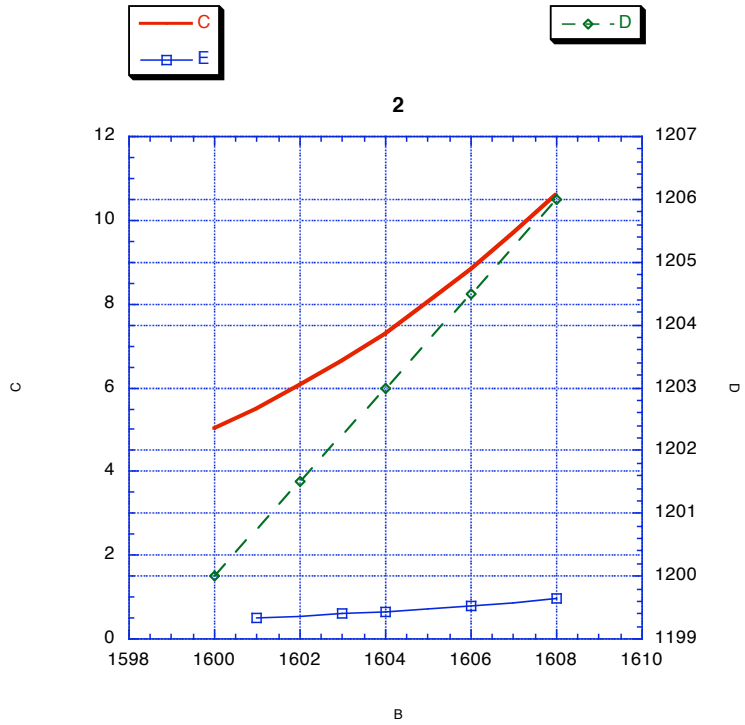
5-10GeV Scaling FFAG radial sector - FDF lattice

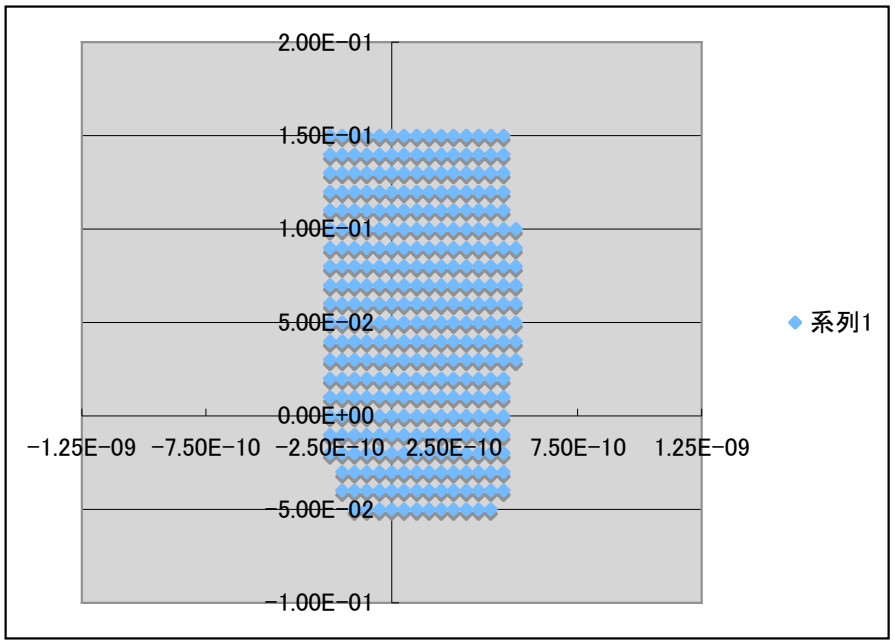
- Ring parameters
  - r=200m
  - N=70cells
  - Bmax ~F:1.6T ,D:1.5T
  - k=150
  - Orbit excursion
    62cm
  - Beam size(half) at 10GeV
    H: 7.4cm+1.2cm=8.6cm,V:6.1cm @s.s.
    H: 7.4cm+1.2cm=8.6cm,V:6.1cm @F-magnet
    H: 4.0cm+1.2cm=5.2cm,V:7.0cm @D-magnet

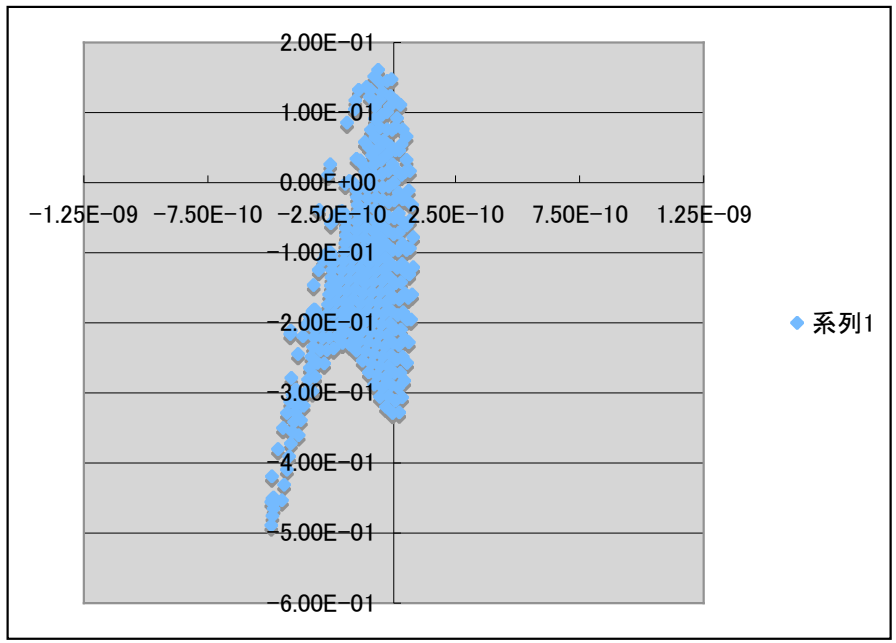


Radial FFAG 5-10GeV

- rf parameters
  - h=1200
  - f=400MHz
  - fai_s=2π/3
  - 1-cell cavity 15MV/cavity(15MV/m)

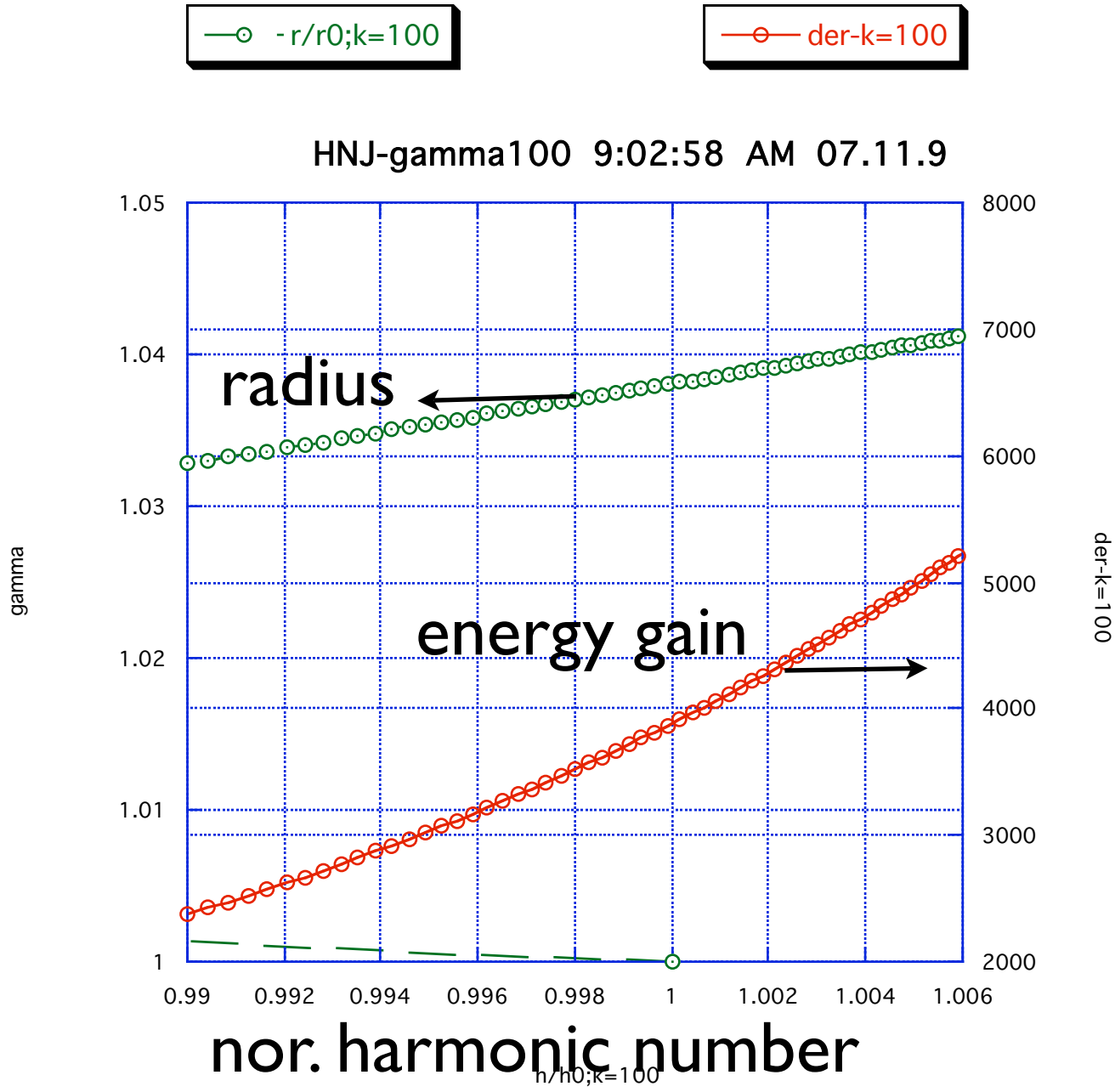




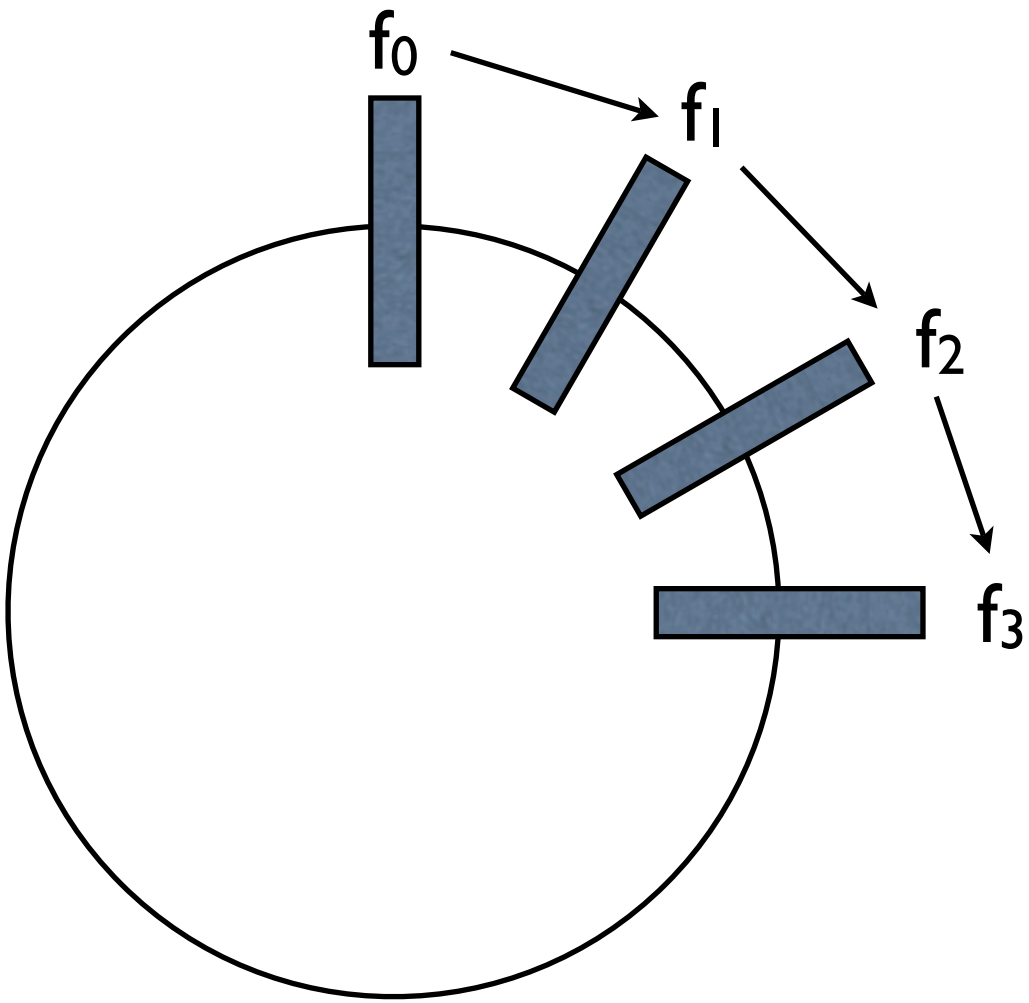


HNJ

k=100,gamma=50-100



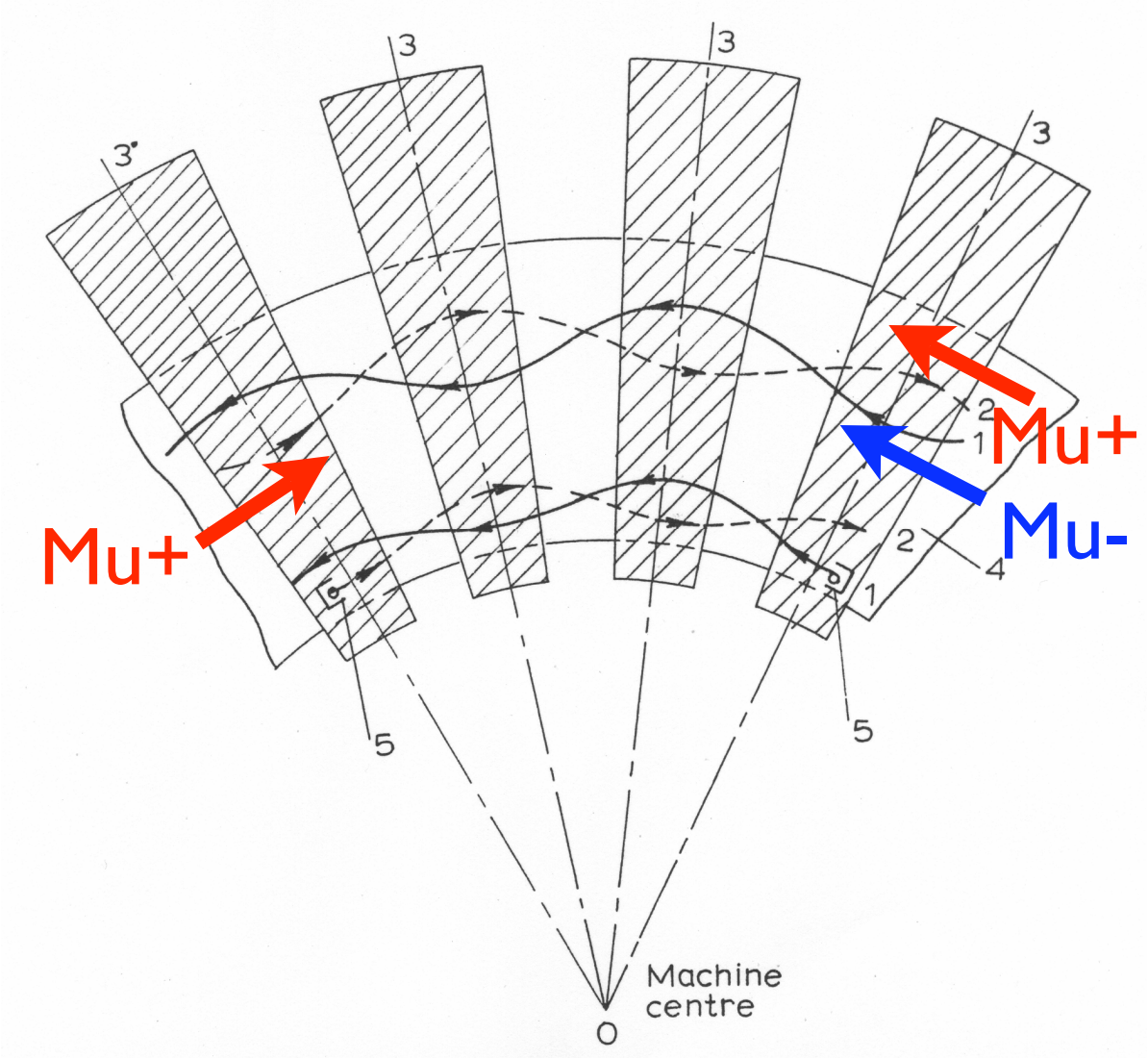
Multi rf system for HNJ acceleration



- Acceleration of Mu: need ~0.5MV/turn ---->multi rf system
- Frequency of each rf cavity for HNJ acceleration
  - monotonic change
    $f_0 > f_1 > f_2 > f_3 > \ldots$
- Question?
  - Mu(+) & Mu(-) acceleration

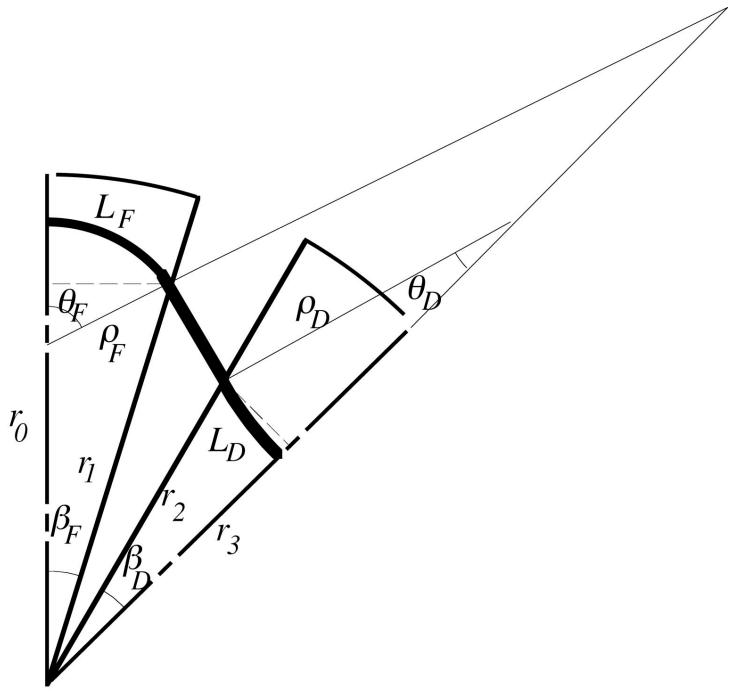
Scaling FODO

two beam accelerator



- Scaling FFAG ring with FODO lattice has opposite directional orbits for particles with same charge state. In other words, it has same orbits for particles with opposite charge state.
- Thus, HNJ acceleration for both Mu(+) and Mu(-) with mluti-rf cavity becomes possible.

two beams FODO



In addition to the singlet conditions,

$$\beta_F = \beta_D$$

and assume

$$\frac{\theta_F}{\theta_D} = \left(\frac{r_0}{r_3}\right)^{k+1}$$

- $Q_h^2 \sim 2k$, $Q_v^2 \sim \Phi^2 N^2/kS^2 \sim 2N^2/k$
- k=100, N=100 $Q_h \sim 14$, $Q_v \sim 14$
- r=100m, Δr=0.7m

Summary

- Two-beam singlet Scaling FFAG seems to be suitable for acceleration of Mu(+) and Mu(-) with HNJ at same condition.
- Issues
  - Proper acceleration field matching
  - Beam loading
  - Long-trans. coupling