Scaling FFAG lattices for muon acceleration

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Nufact09 - July 2009

Motivations

Use the large **transverse acceptance** of scaling FFAG lattices

while using constant RF frequency acceleration to reach **high accelerating gradient**.

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Possible with **harmonic number jump** acceleration!

Outline

I. Reminder on harmonic number jump acceleration.

II. Harmonic number jump with RF cavities all around the ring.

1- Each cavity has to work at a different frequency: need for a double beam lattice.

2- Lattice example and tracking results.

3- Issue of the excursion: need dispersion suppressor!

III. Scaling FFAG lattice with reduced excursion areas.

1- Example of a FFAG dispersion suppressor.

2- Lattice example Lattice details and tracking results.

Reminder on harmonic number jump acceleration

To jump one harmonic every turn: $T_{i+1} - T_i = \frac{1}{f_{RF}}$

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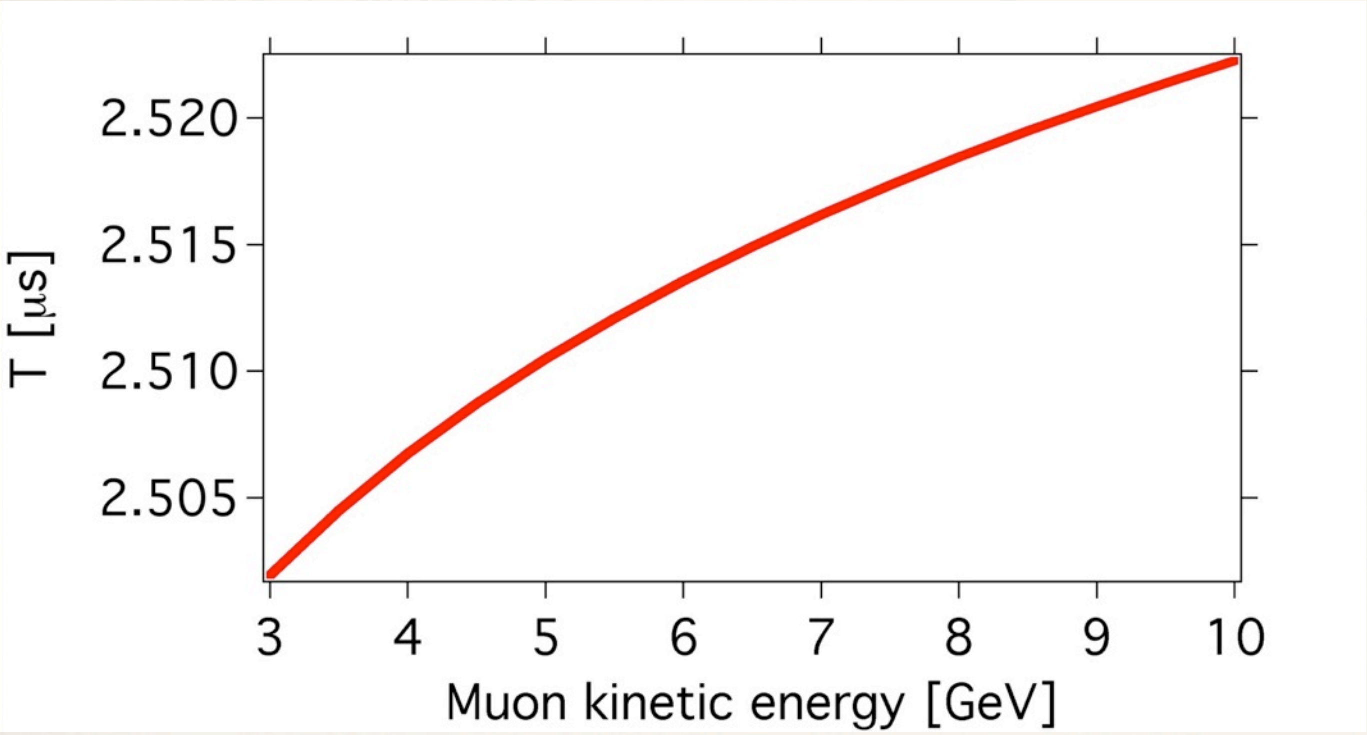


Figure 1 - Revolution time as a function of particle energy in the case of a 3 to 10 GeV scaling FFAG ring, with k = 145 and average radius = 120 m.

⟹ Energy gain per turn must follow: $\Delta E_i = \frac{1}{f_{RF} \cdot \left[\frac{\Delta T}{\Delta E}\right]_{E_i}}$

HNJ with cavities distributed around the ring

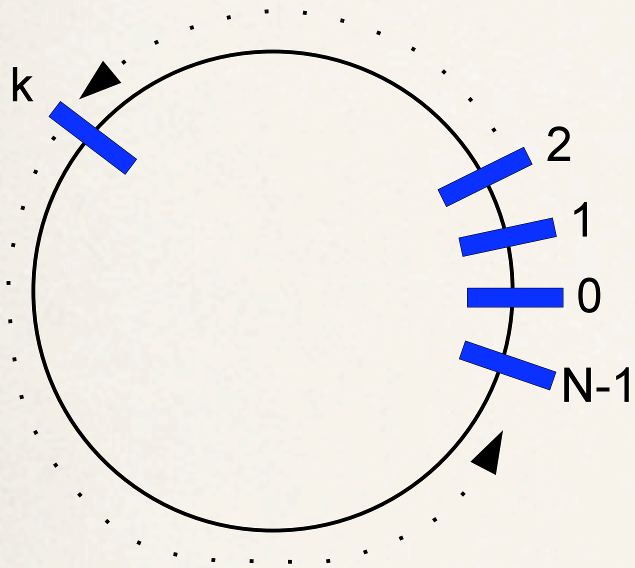


Figure 2 - N cavities homogeneously distributed around the ring.

Assuming that the initial number of harmonic h_0 is large we get(*):

$$f_k \approx f_0 (1 - \frac{1}{h_0} \cdot \frac{k}{N})$$

Every cavity working at a constant frequency f_k but the frequency has to be tuned to a slightly different value!

μ^+ and μ^- beams cannot be accelerated simultaneously if they circulated in opposite directions...

(*)look at the proceedings of PAC'09 for all details.

Need for a double beam lattice

A solution to circulate a particle and its antiparticle **in the same direction** in a scaling FFAG ring is to use a FD-symmetric lattice:

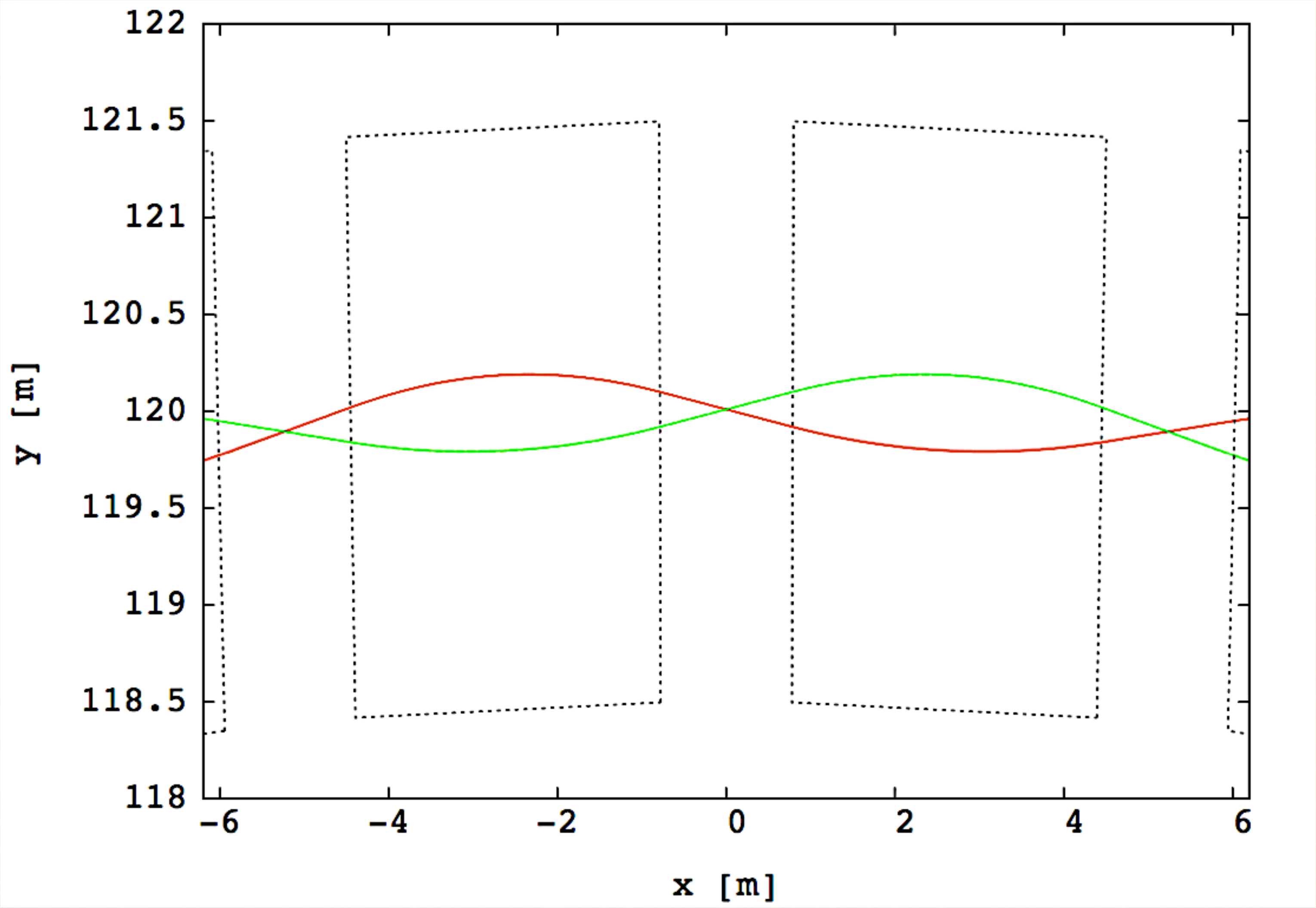


Figure 3 - Double beam FFAG lattice (k = 145). Closed orbits of μ+ and μ− circulating in the same direction. Results are obtained from Runge-Kutta stepwise tracking in hard-edge field.

3 to 10 GeV muon double beam FFAG

Table 1 - ring parameters

Mean radius	120 m
Number of cells	72
Field index k	145
Packing factor	0.7
B_{max} (at 10 GeV)	2.6 T
Horiz. phase adv. per cell	93.2 deg.
Verti. phase adv. per cell	30.2 deg.
Mean RF frequency	$\sim$ 400 MHz
RF peak voltage	1.6 GV/turn
Number of RF cavities	72

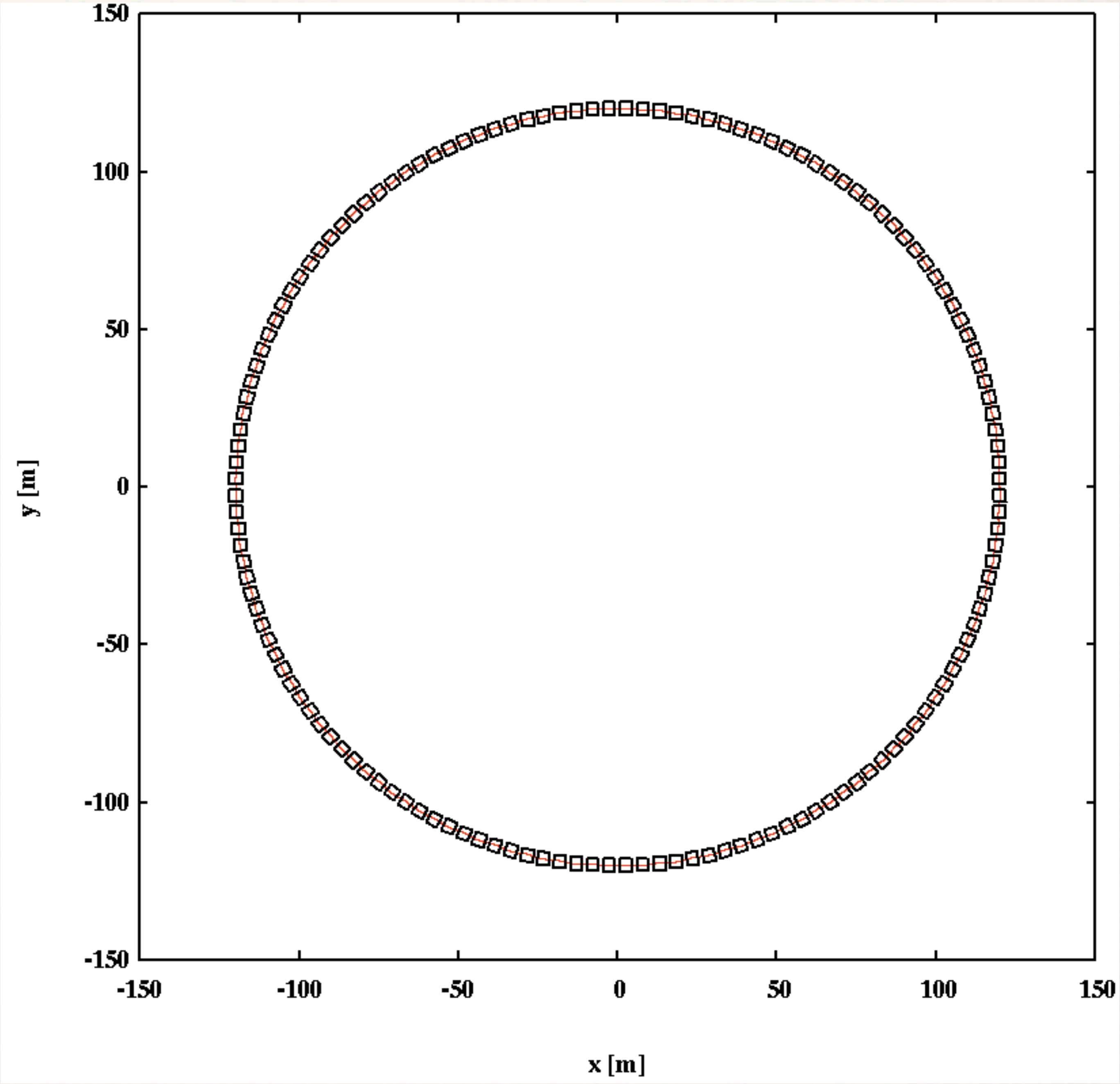


Figure 4 - Schematic view of a 3 to 10 GeV double beam muon FFAG ring.

1st example: 3 to 10 GeV muon double beam FFAG

4D tracking - 8 turns acceleration cycle with a constant RF peak voltage = 1.6 GV/turn:

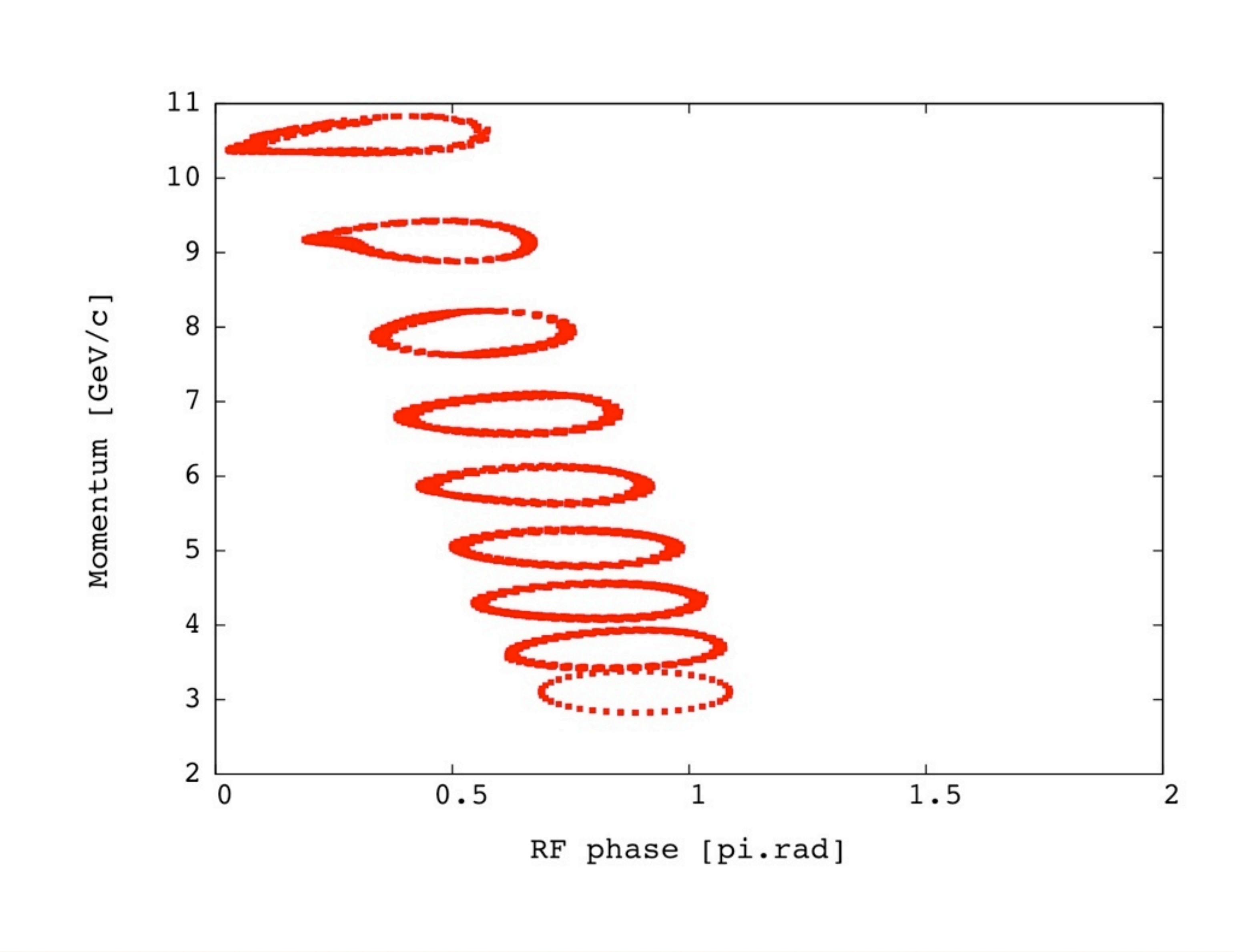


Figure 5 - 8 turns acceleration cycle plotted in the **longitudinal phase space**, at the location of the first cavity. Initial beam emittance is **0.21 eV.s x 10 000 π mm.mrad (normalized)**.

Issue of the excursion: need for dispersion suppressor insertions!

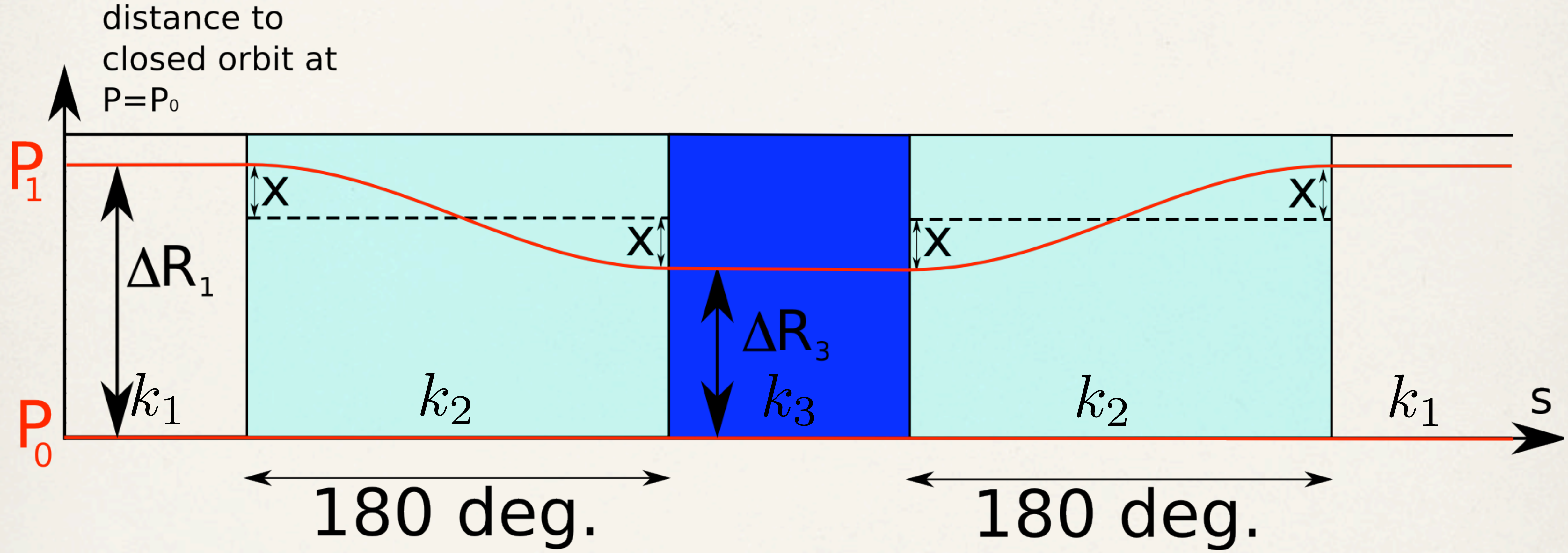
Harmonic jump condition: $$T_{i+1} - T_i = \frac{1}{f_{RF}}$$

In the same time: $$\frac{\Delta C_i}{\beta c} = T_{i+1} - T_i$$

In case of highly relativistic particles: $$\Delta R_i \approx \frac{c}{2\pi f_{RF}} = \frac{\lambda_{RF}}{2\pi}$$

$$average\ excursion = \lambda_{RF} \cdot \frac{N_{turns}}{2\pi}$$ ⟶ Need for excursion reduced areas!

Dispersion suppressor with FFAG magnets



$$with\ \frac{2}{k_2+1} = \frac{1}{k_1+1} + \frac{1}{k_3+1}$$

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

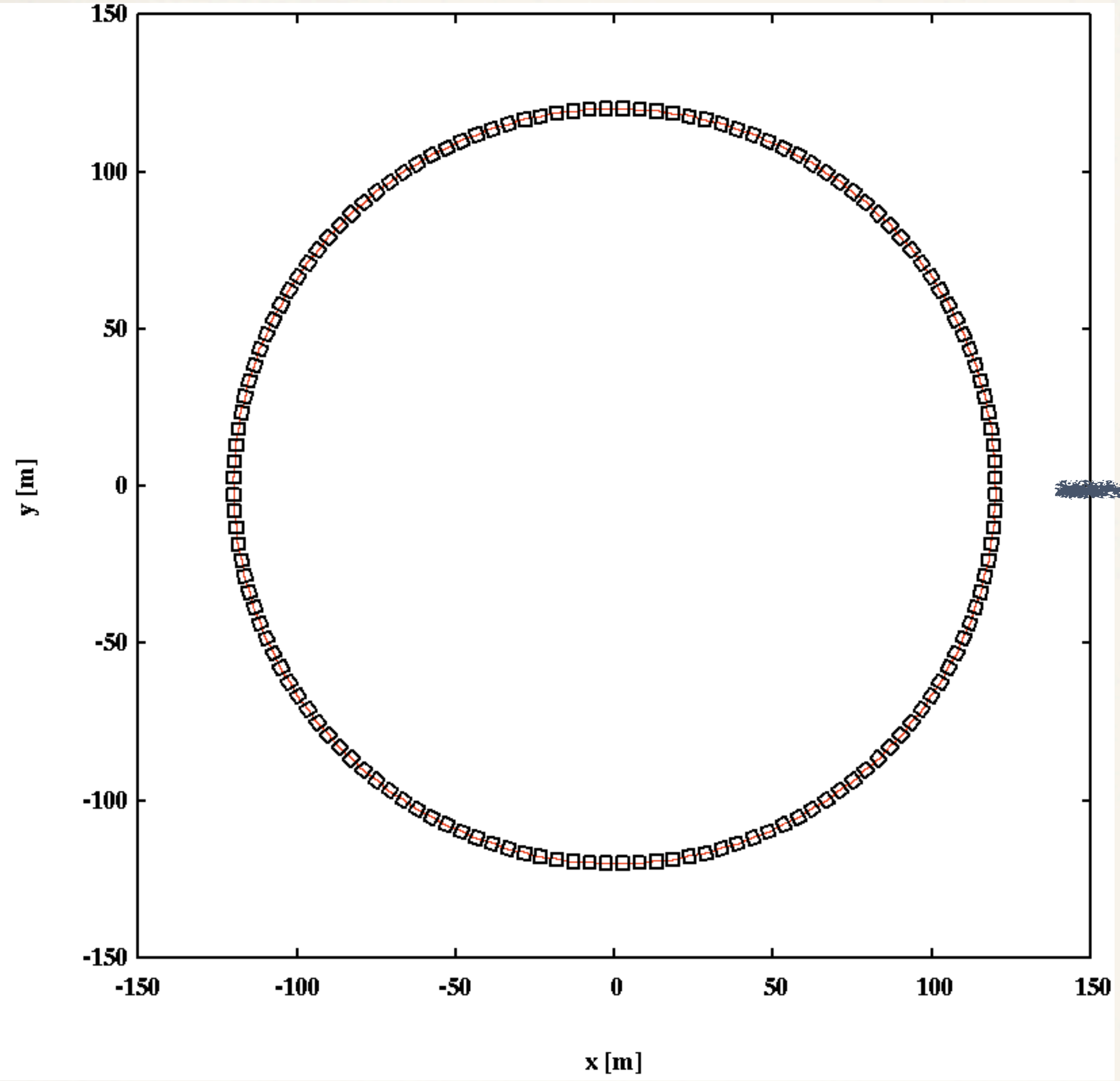


Figure 4 (slide #10)- Schematic view of a 3 to 10 GeV double beam muon FFAG ring.

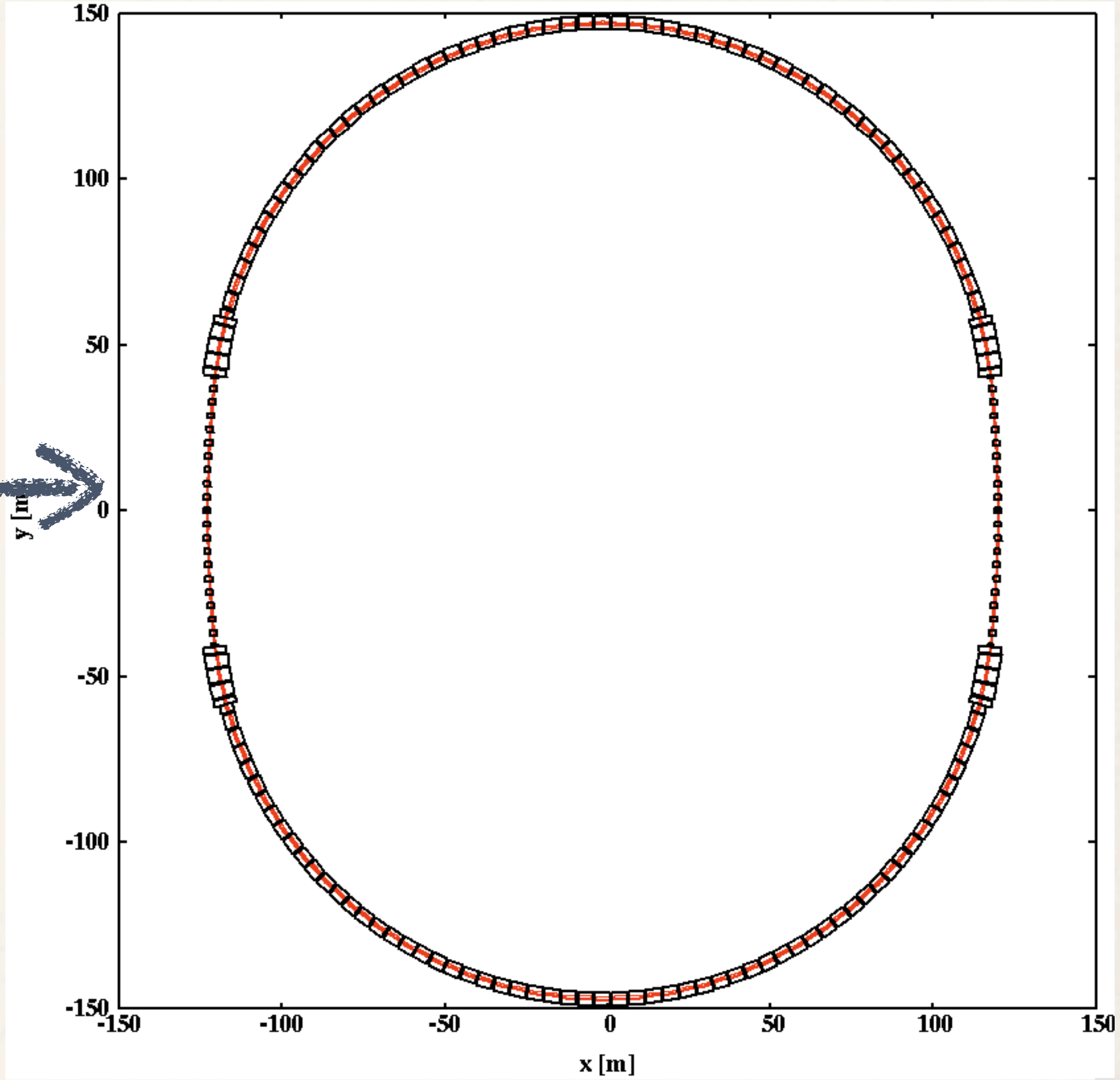


Figure 8 - Schematic view of a 3 to 10 GeV double beam muon FFAG ring with 2 excursion reduced insertions.

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

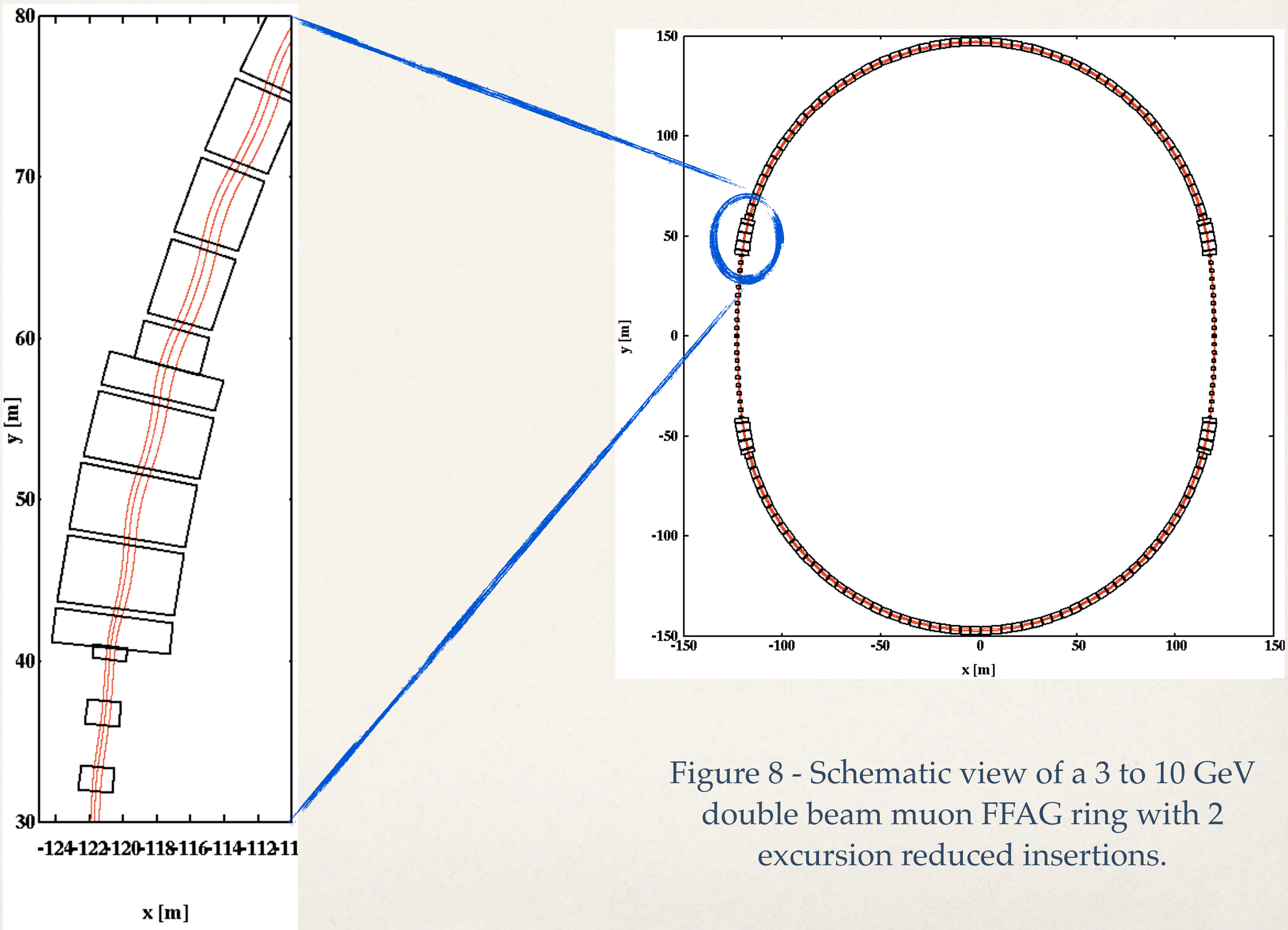


Figure 8 - Schematic view of a 3 to 10 GeV double beam muon FFAG ring with 2 excursion reduced insertions.

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

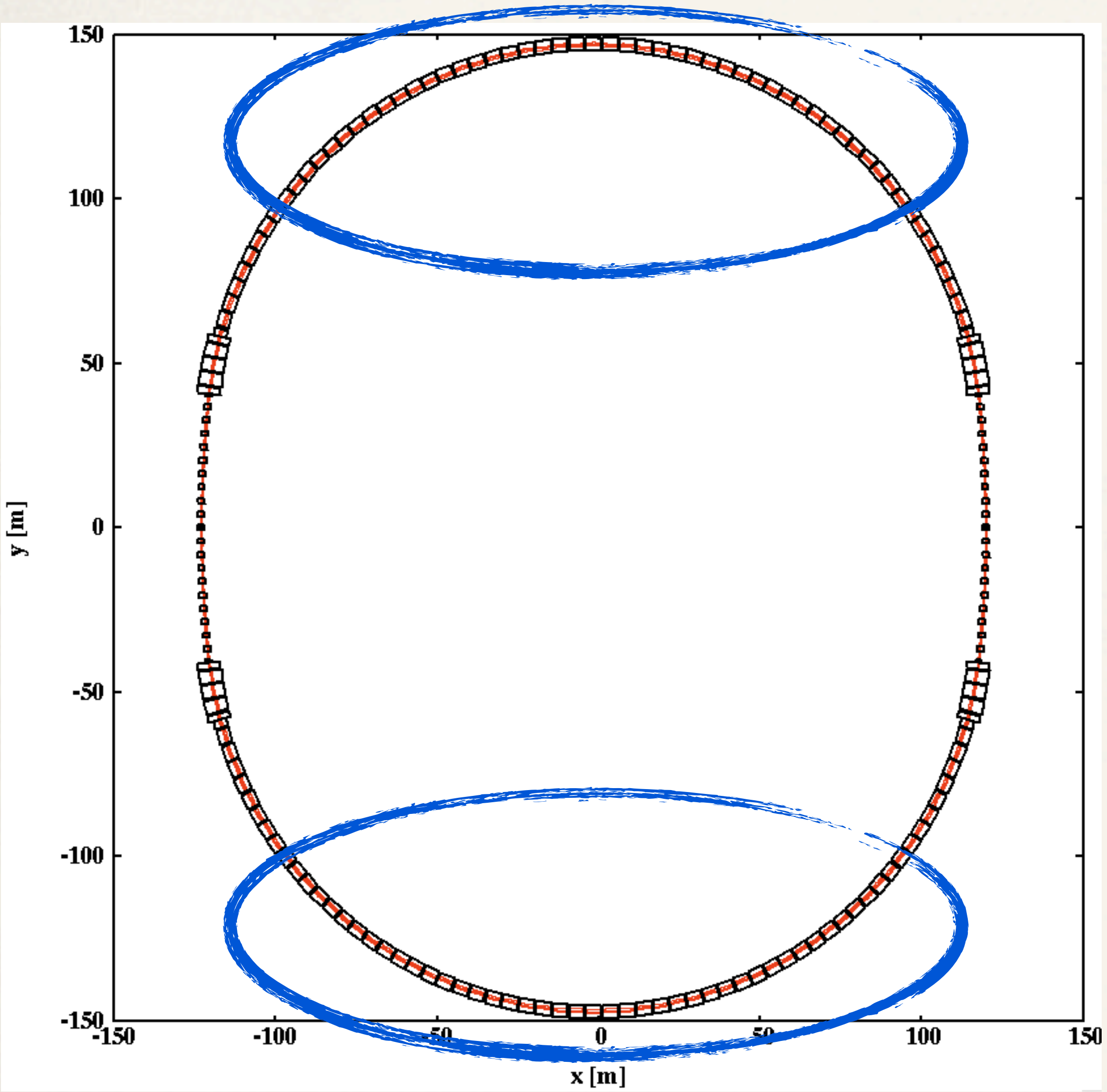


Figure 8 - Schematic view of a 3 to 10 GeV double beam muon FFAG ring with 2 excursion reduced insertions.

Table 2 - Ring main cells parameters

Mean radius	120 m
Number of cells	2×30
cell opening angle	5 deg.
Field index k	145
Packing factor	0.9
B_{max}	2.3 T
Horiz. phase adv. per cell	92.9 deg.
Verti. phase adv. per cell	31.1 deg.

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

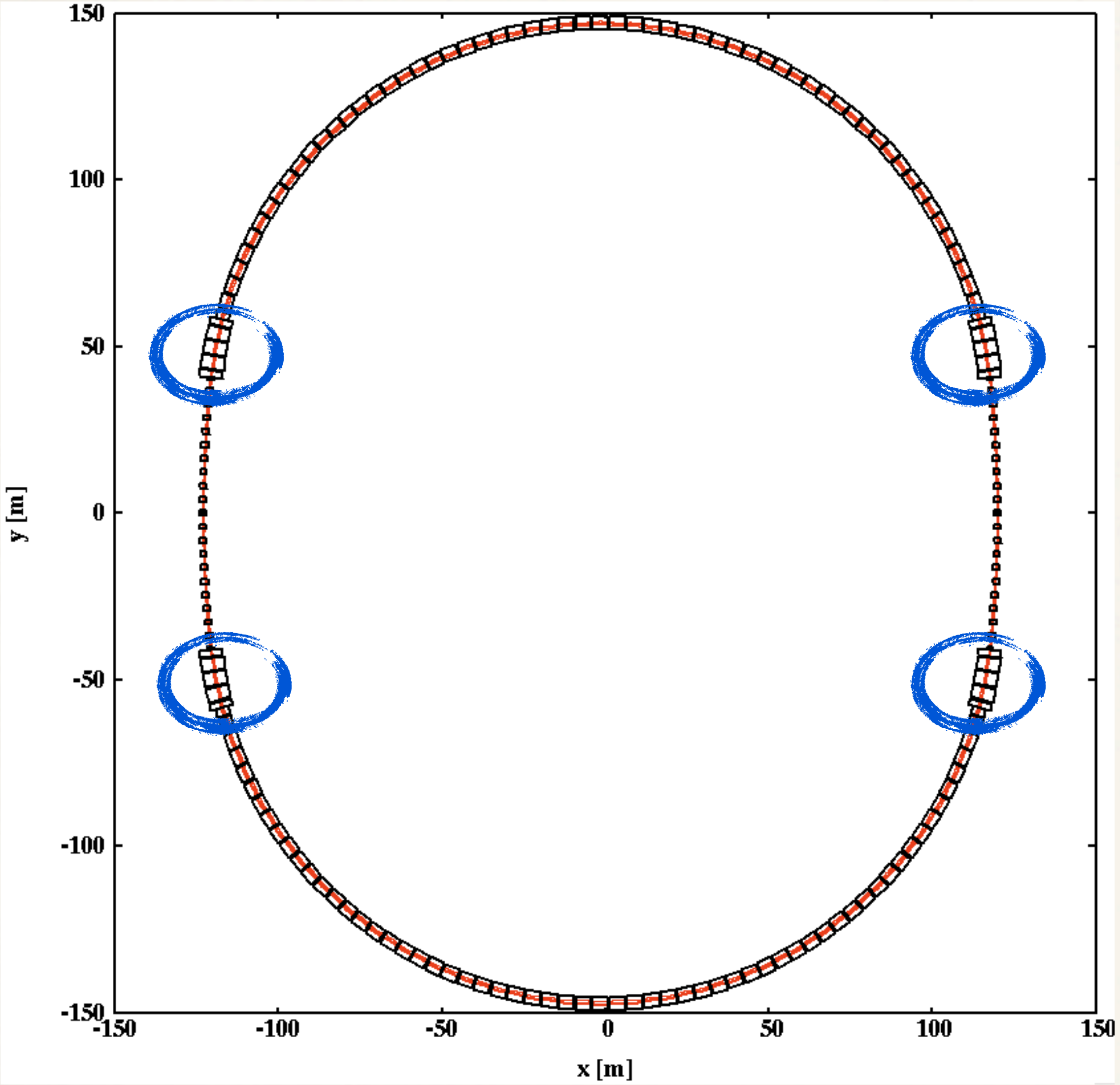


Figure 8 - Schematic view of a 3 to 10 GeV double beam muon FFAG ring with 2 excursion reduced insertions.

Table 3 - Dispersion suppressor cells parameters

Mean radius	120 m
Number of cells	4×2
cell opening angle	4.24 deg.
Field index k	192.4
Packing factor	0.9
B_{max}	2.7 T
Horiz. phase adv. per cell	90.0 deg.
Verti. phase adv. per cell	26.6 deg.

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

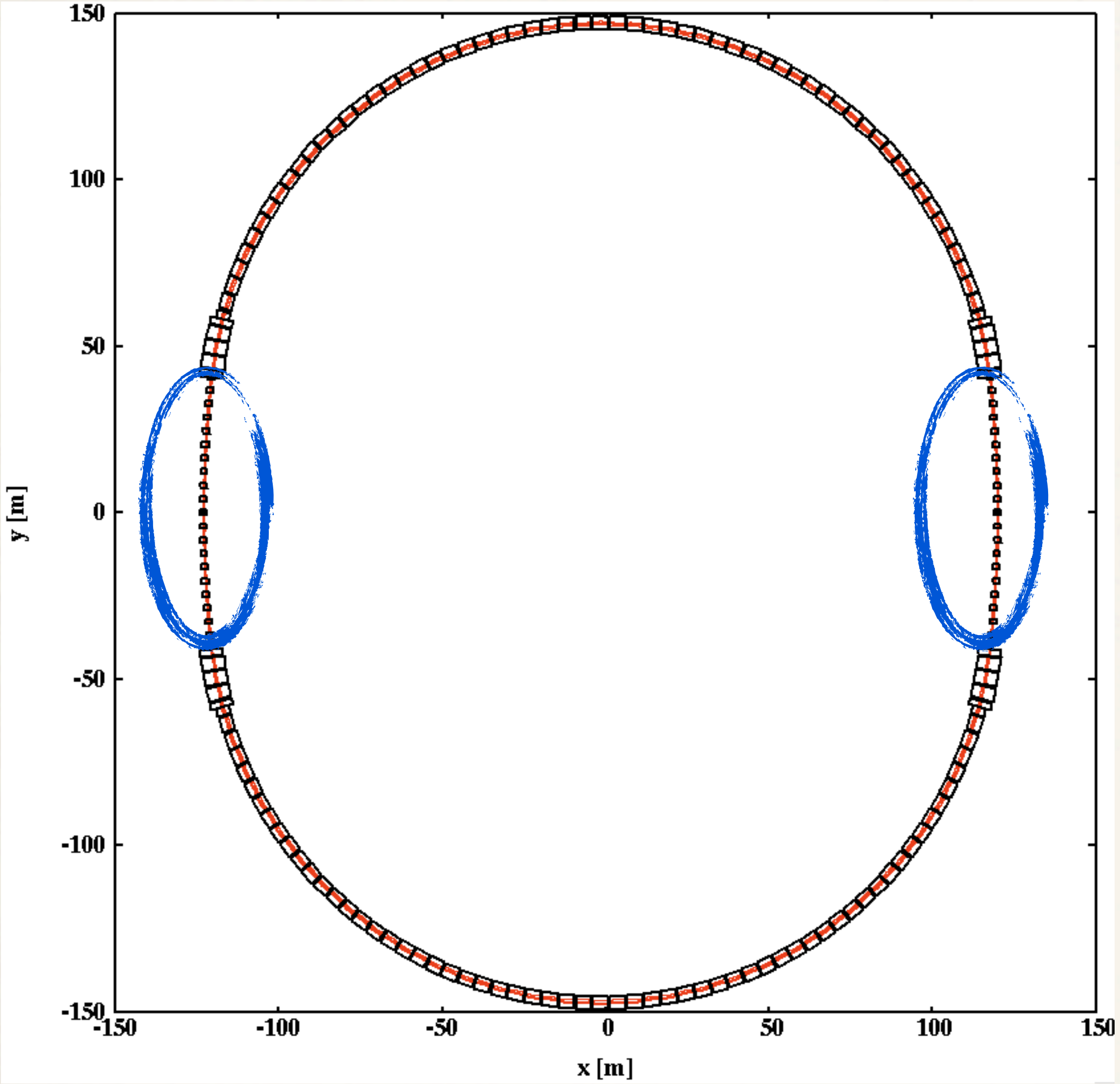


Figure 8 - Schematic view of a 3 to 10 GeV double beam muon FFAG ring with 2 excursion reduced insertions.

Table 4 - excursion reduced areas cells parameters

Mean radius	360 m
Number of cells	2×10
cell opening angle	1.304 deg.
Field index k	858.1
Packing factor	0.3
B_{max}	2.4 T
Horiz. phase adv. per cell	55.9 deg.
Verti. phase adv. per cell	14.8 deg.

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

Study of linear parameters using Runge-Kutta stepwise tracking in soft edge field model:

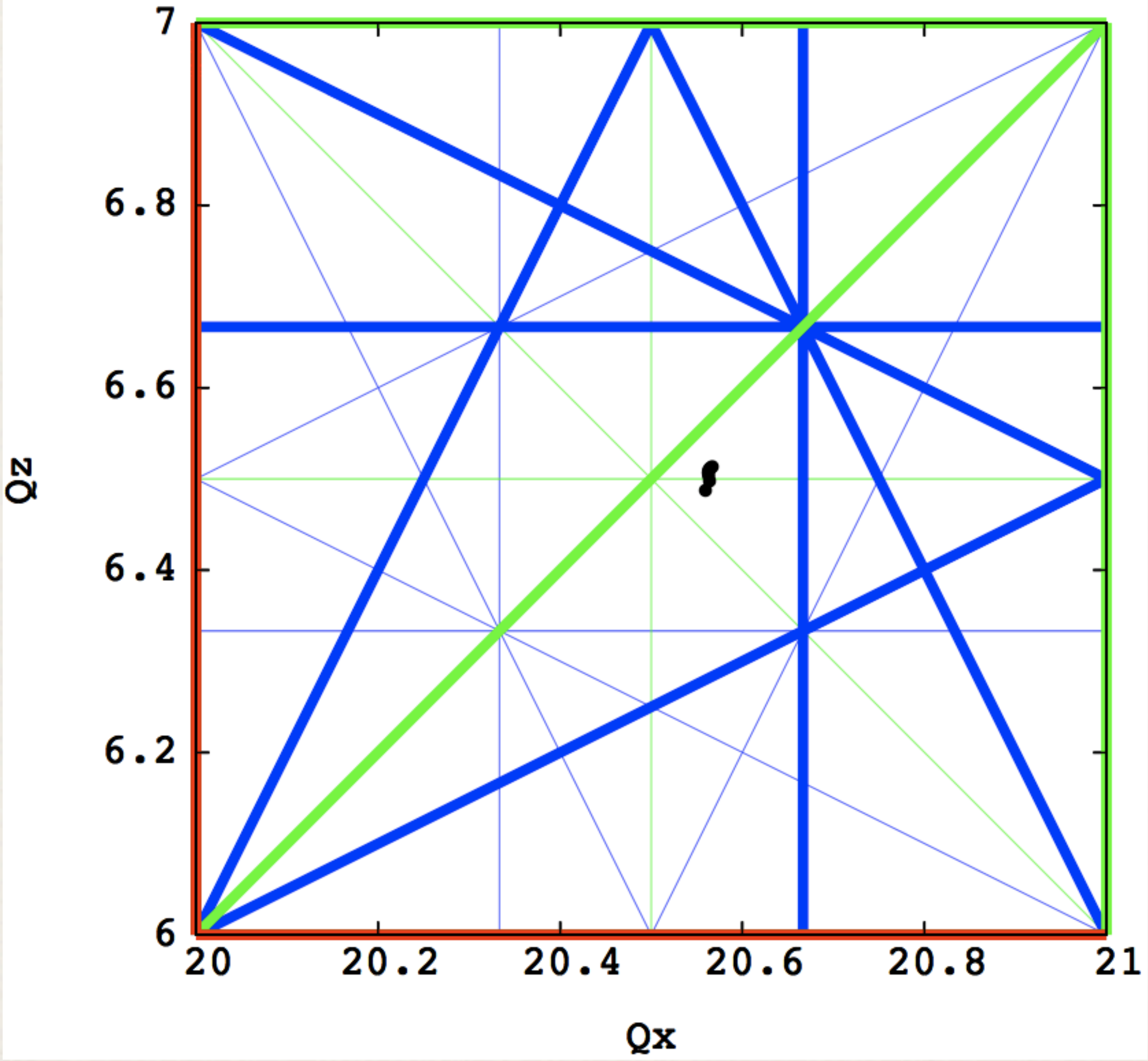


Figure 9 - Tune variation between 3 and 10 GeV in the lattice with insertions (from stepwise tracking in a soft edge field model).

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

Study of linear parameters using Runge-Kutta stepwise tracking in soft edge field model:

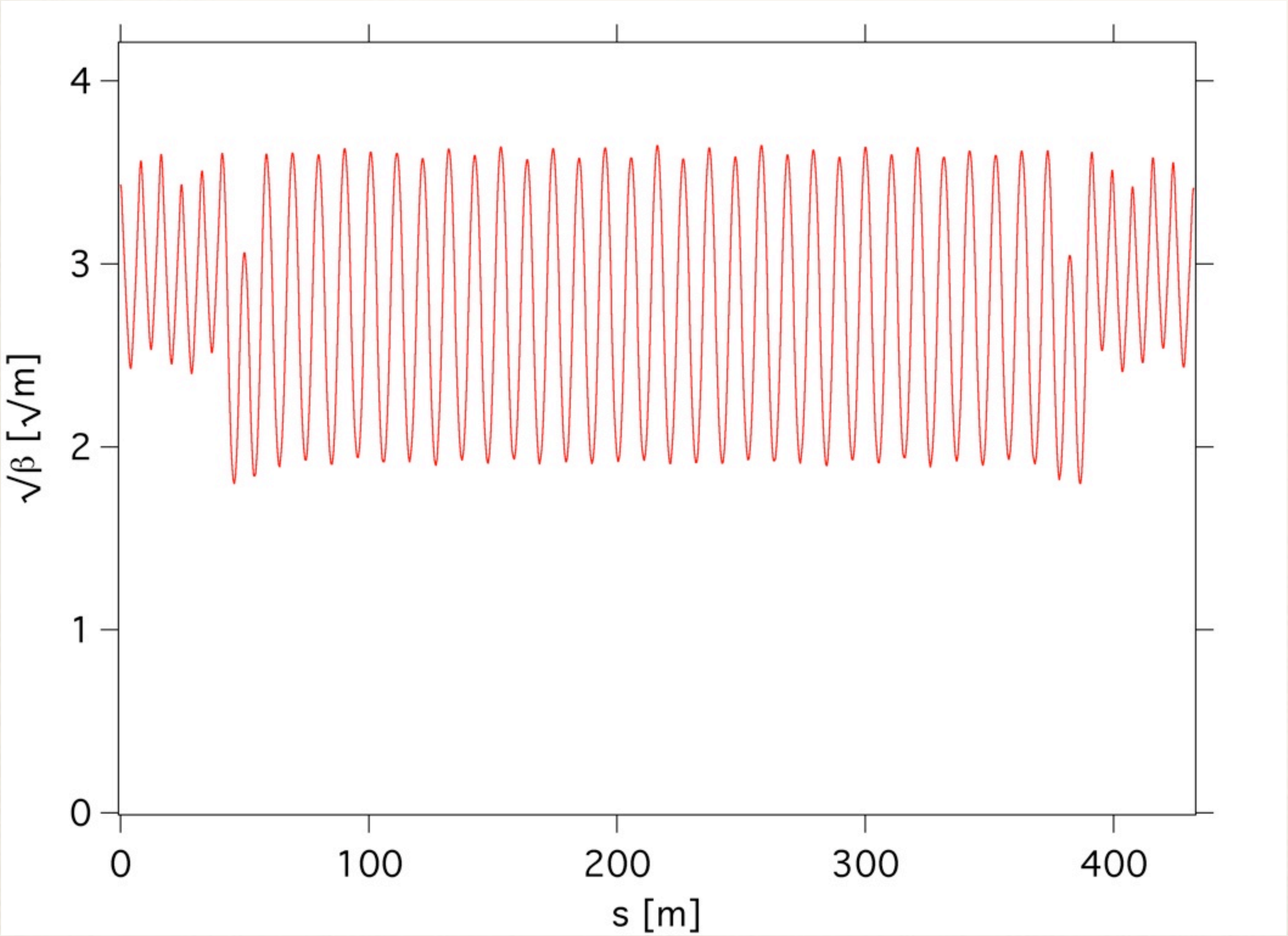


Figure 10 - **Horizontal** beta function at 6 GeV (half a turn is presented).

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

Study of linear parameters using Runge-Kutta stepwise tracking in soft edge field model:

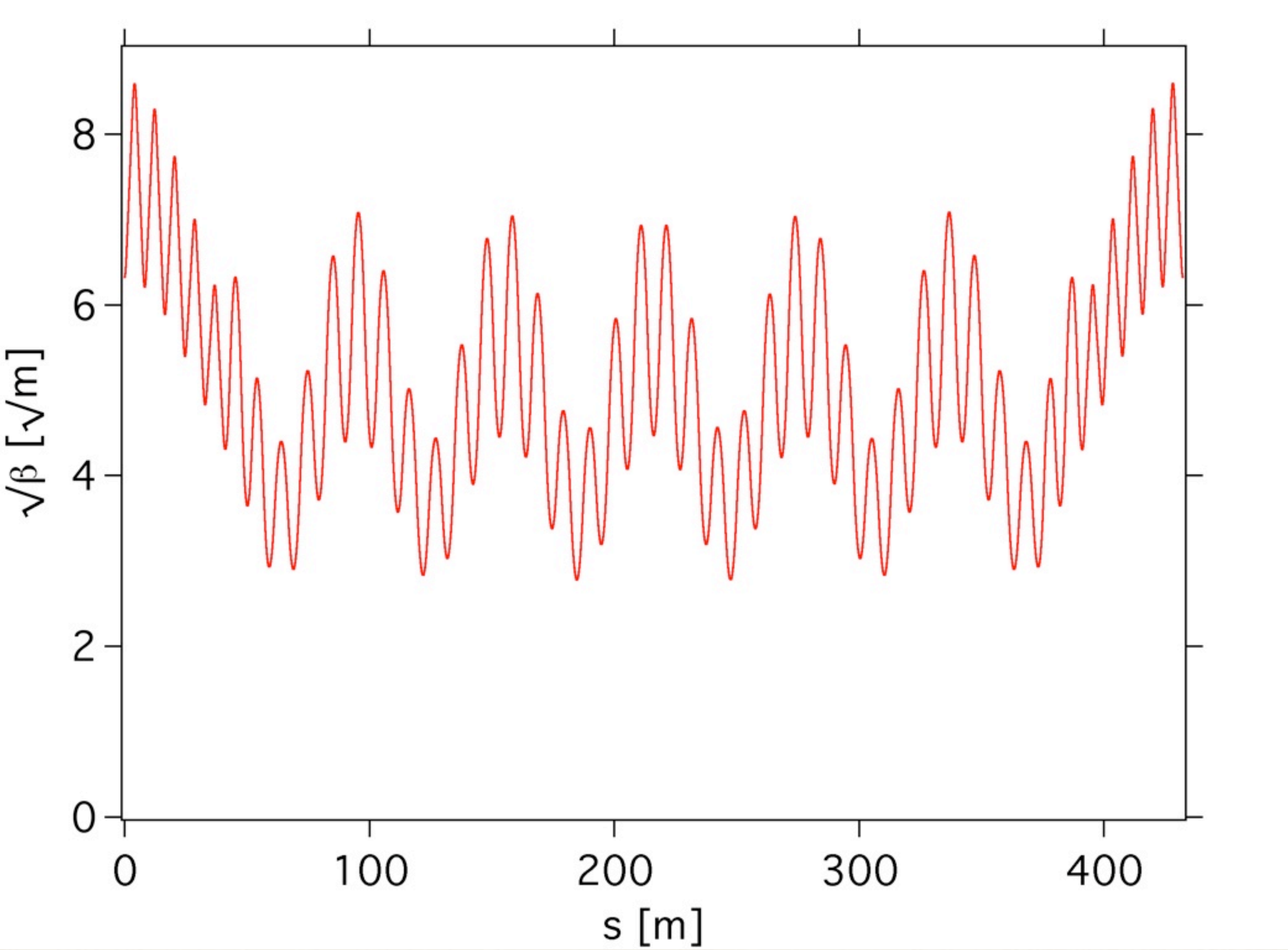


Figure 11 - **Vertical** beta function at 6 GeV (half a turn is presented).

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

Beta function variation with energy:

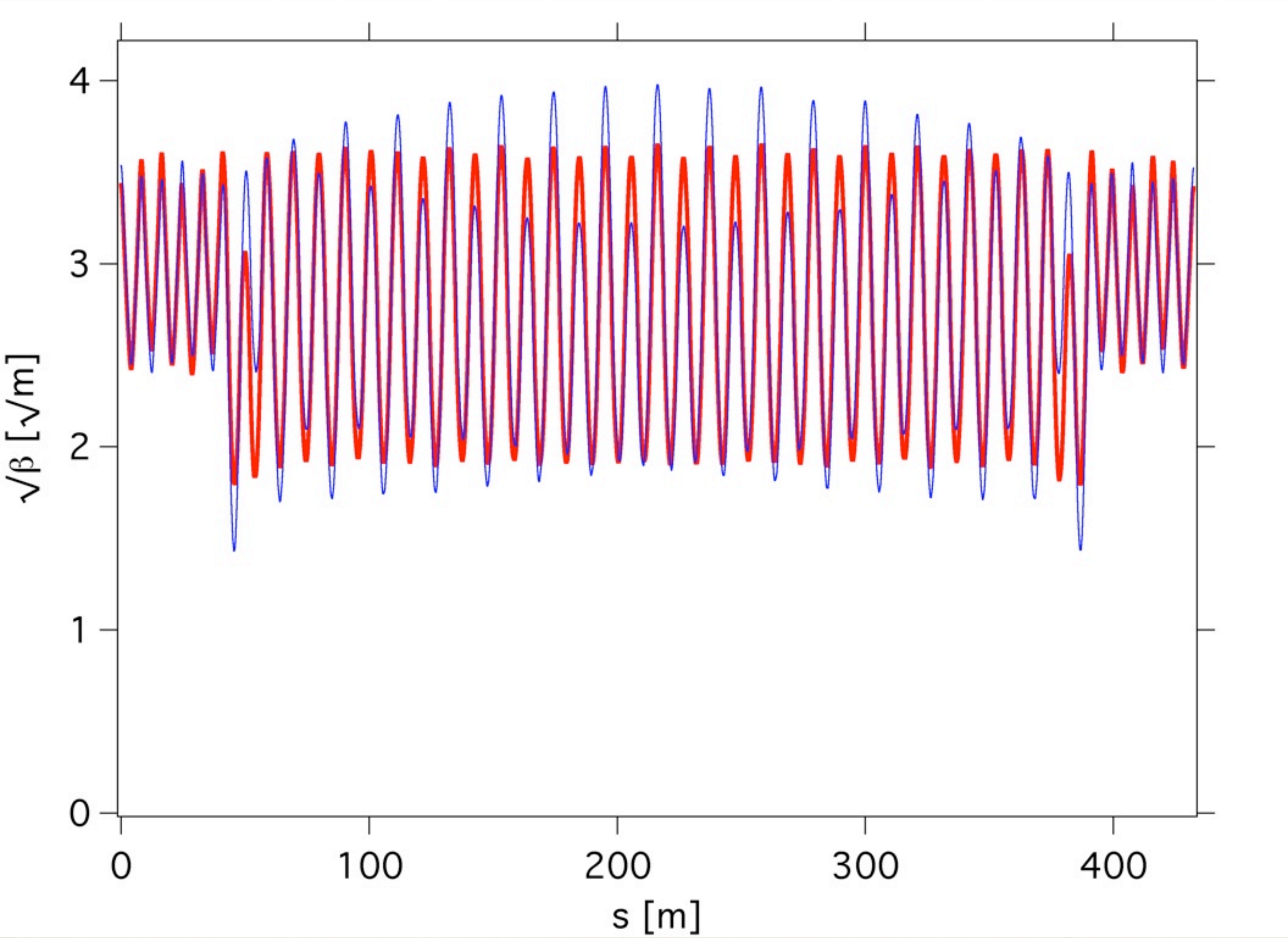


Figure 12 - **Horizontal** beta function at 3 GeV (blue) and 6 GeV (red).

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

Very large transverse acceptance: here ~ 50 000 π.mm.mrad (normalized) at 6 GeV.

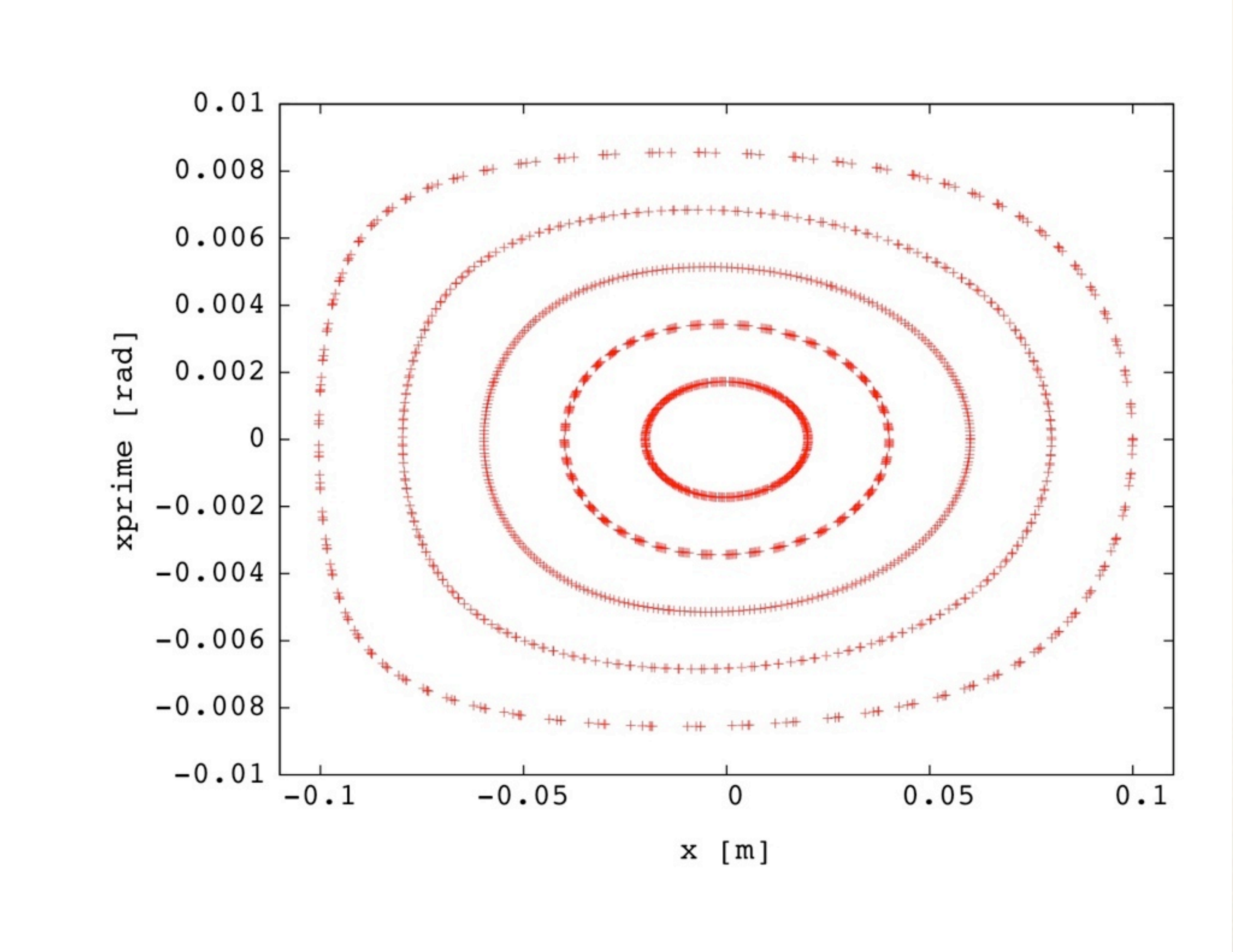


Figure 13 - **Horizontal** phase space plot of 5 particles (E_{kin} = 6 GeV)with different initial amplitudes (over 300 turns).

Conclusion

Advantages of this scheme:

* Large transverse acceptance.
* Large longitudinal acceptance, and no emittance degradation during acceleration.
* Possible with RF frequency in the 200 MHz to 400 MHz range.
* Can accelerate μ+ and μ− simultaneously.

To be improved:

* Assuming super-ferric type of magnets (Bmax ~ 2.5T) ring size is still large (about 850 m circumference).
* Excursion in the reduced excursion area is still about 0.5 m-, needs to be further reduced.

Thank you!

Additional material...

1st example: 3 to 10 GeV muon double beam FFAG

4D tracking - 8 turns acceleration cycle with a constant RF peak voltage = 1.6 GV/turn:

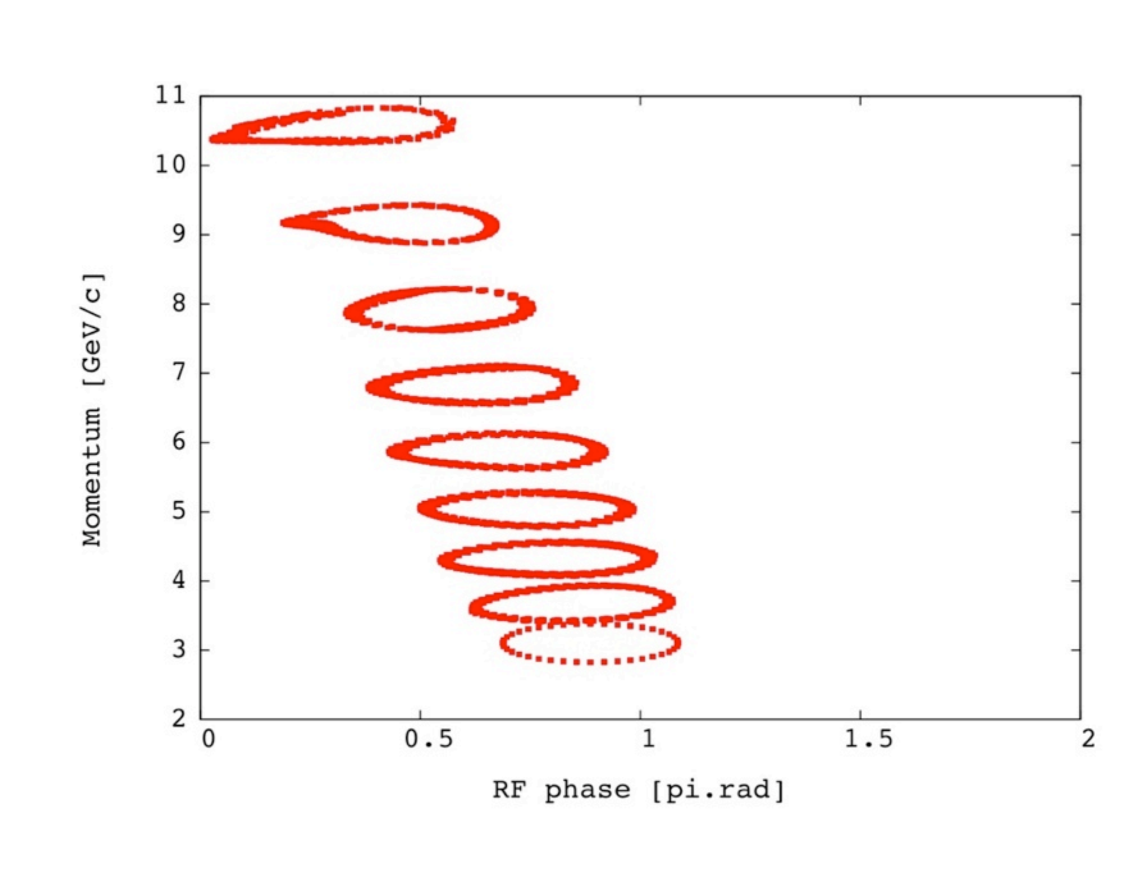


Figure 5 - 8 turns acceleration cycle plotted in the **longitudinal phase space**, at the location of the first cavity. Initial beam emittance is **0.21 eV.s x 10 000 π mm.mrad (normalized)**.

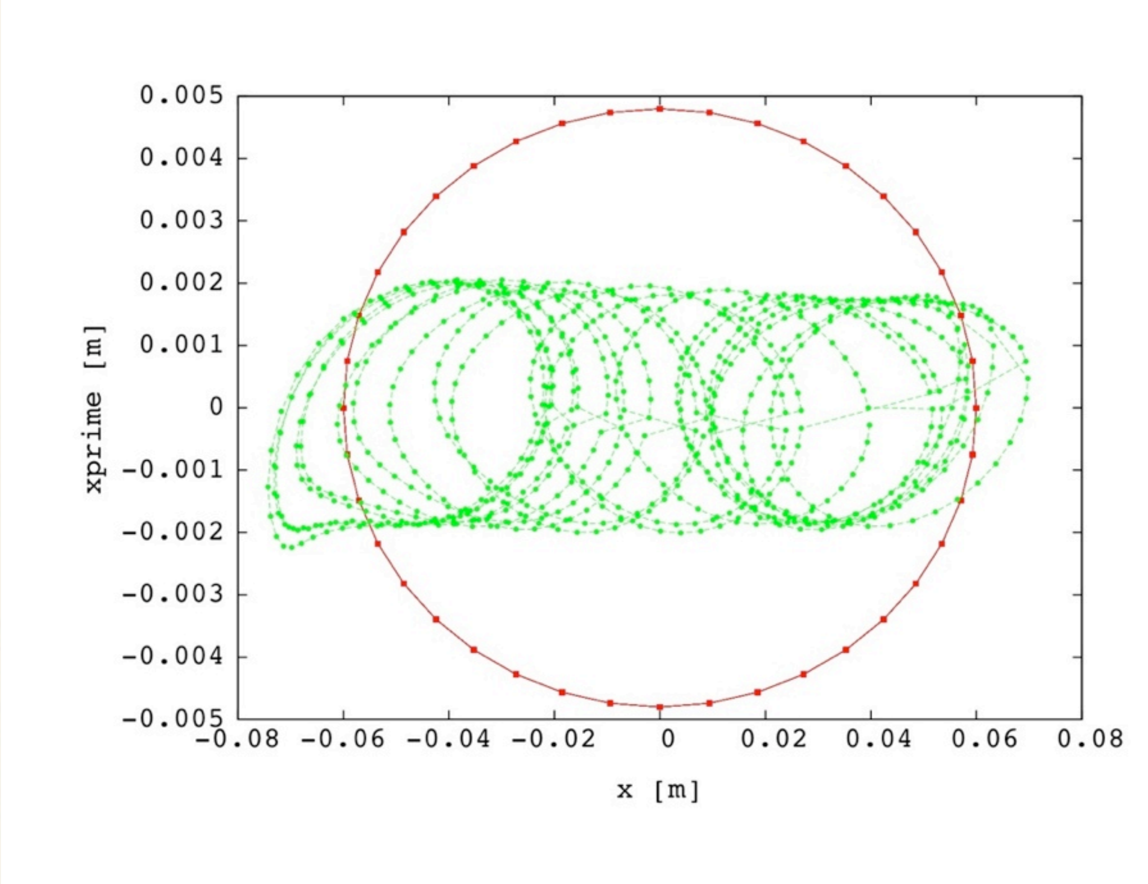
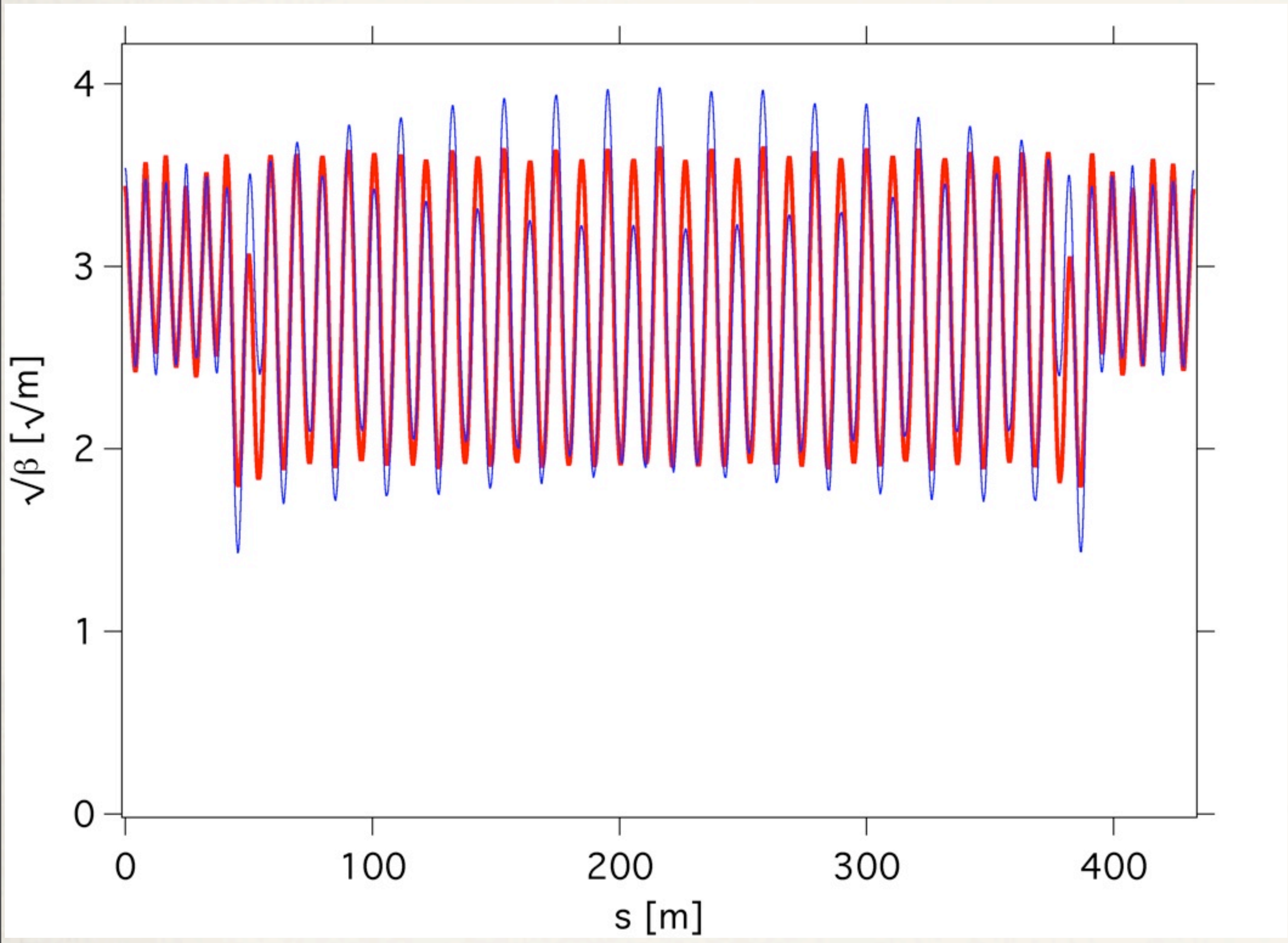


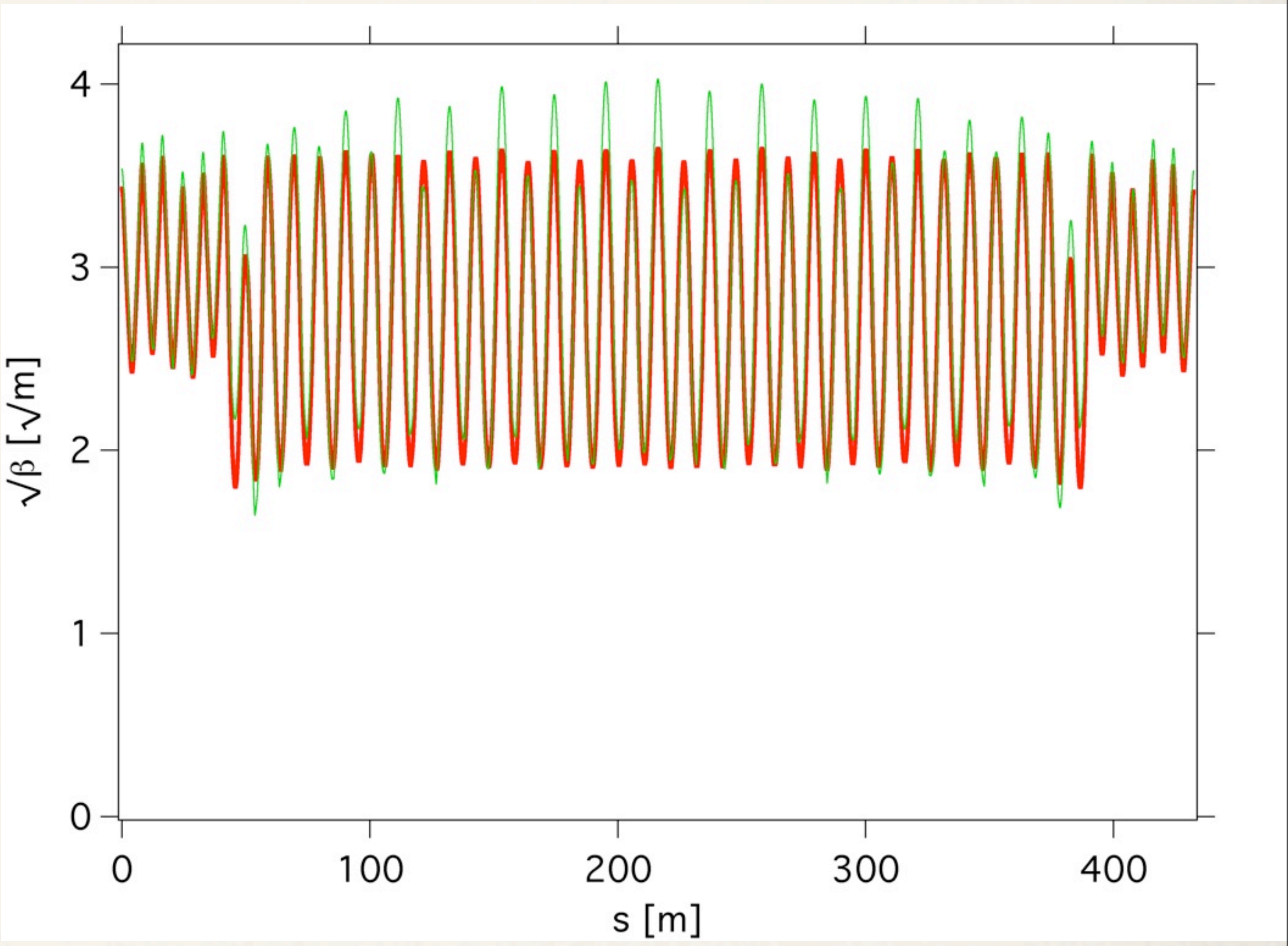
Figure 6 - First turn (red squares) and last turn (green dots) of the 8 turns acceleration cycle plotted in **transverse phase space**. Initial beam emittance is **0.21 eV.s x 10 000 π mm.mrad (normalized)**.

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

Beta function variation with energy:



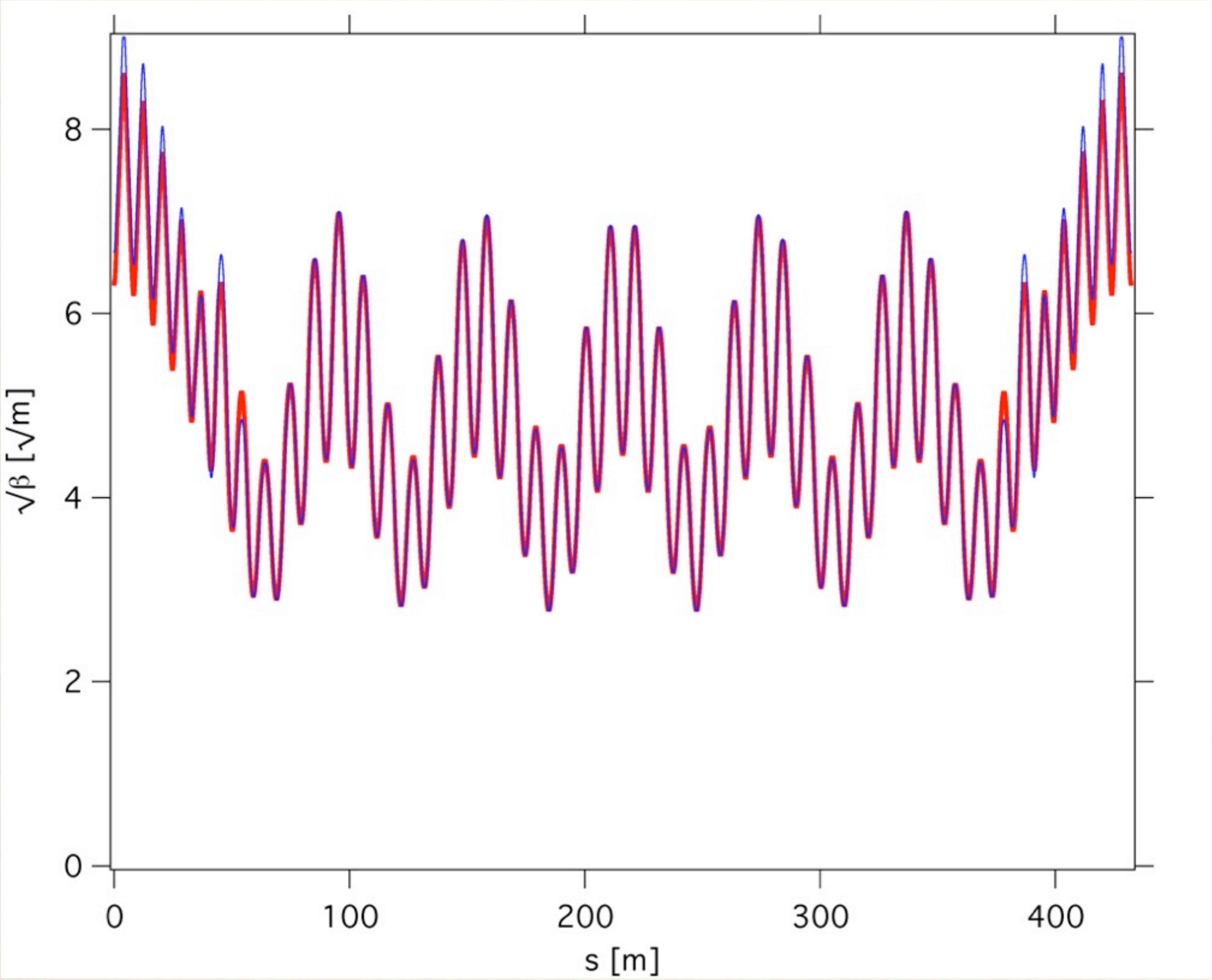
Horizontal beta function at 6 GeV (red) and 3 GeV (blue).



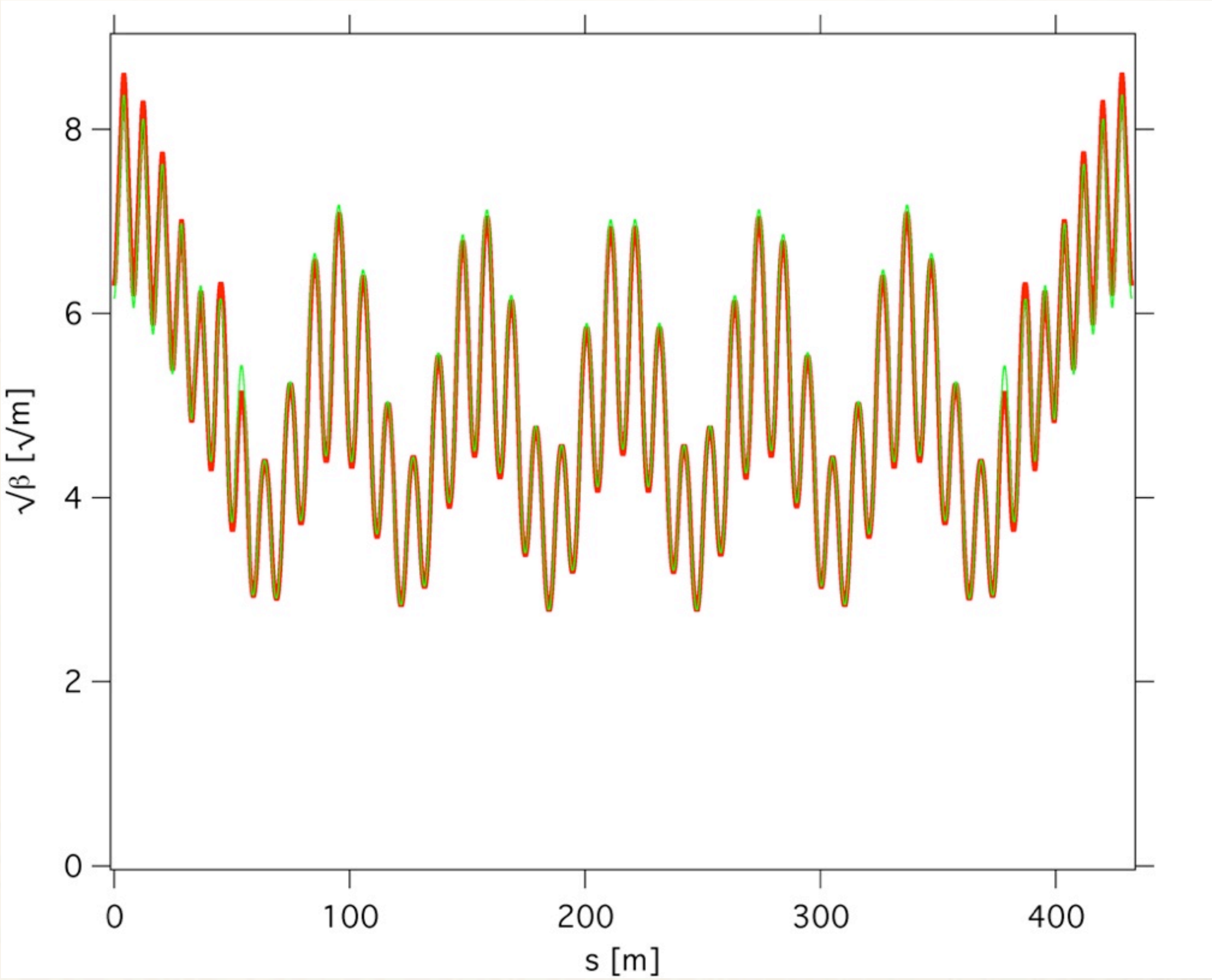
Horizontal beta function at 6 GeV (red) and 10 GeV (Green).

3 to 10 GeV muon double beam FFAG + **excursion reduced areas**

Vertical beta function variation with energy:



Vertical beta function at 6 GeV (red) and 3 GeV (blue).



Vertical beta function at 6 GeV (red) and 10 GeV (Green).