Some topics of proton driver complex

Shinji Machida, STFC/Rutherford Appleton Laboratory

WP3 Proton Driver Complex Meeting #12

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UKRI Science and Technology Facilities Council
ISIS Neutron and Muon Source

Outline

- Goal and issues
- Flexible Momentum Compaction (FMC) lattice
- Bunch rotation fundamentals
- Another way of creating a short bunch

Goal and issues

Goal of a proton driver complex

Create a short proton bunch at 5, 10 GeV or energy in between.

- Repetition rate = 5 Hz
- Beam power = 2 MW
    - 5×10^{14} ppp at 5 GeV
    - 2.5×10^{14} ppp at 10 GeV
- Bunch length = 2 ns (rms)

With **accumulator** ring and **compressor** ring after injector linac

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Issues of accumulator

- Injection
  - **Charge exchange injection** by foil or laser
    - Laser stripping should be a baseline.
      - High injection energy (5 or 10 GeV) makes the system easier than J-PARC (0.4 MeV) and SNS (1-1.3 GeV).
- (microwave) **instabilities**
  - Isochronous
    - no spread of the revolution frequency
  - Small momentum spread
    - sextupole does not make much tune spread
  - 2000 turns (only).
    - No issue if the growth time is longer.

Issues of compressor

- Compress bunch
  - **High RF voltage** to rotate a bunch in phase space
  - Synchrotron tune depends on amplitude
    - **Nonlinear RF** waveform
    - **Higher order momentum compaction factor**
- **Space charge effects**
  - Very small bunching factor after phase rotation.
    - Both transverse and longitudinal have space charge effects.

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"Baseline" scheme

CERN scheme
- Accumulator
  - **Small eta** (or zero, i.e. isochronous) ring to keep the bunch structure.
- Compressor
  - **Large eta** ring with the enough RF voltage rotates the long bunch quickly.

Fermilab scheme
- Accumulator
  - **Large eta** ring to suppress microwave instability.
- Compressor
  - **Small eta** ring to reduce requirements of the RF voltage but with longer time.

(half) bucket height $B_h = \sqrt{\frac{2eV}{h\pi\beta^2 E\eta}}$

Synchrotron tune $Q_s = \sqrt{\frac{heV\eta}{2\pi\beta^2 E}}$

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Control of eta (and its higher order) is the key of the PD rings design.

FMC lattice

Flexible Momentum Compaction (FMC) lattice

e.g. J-PARC RCS and MR

3 FODO module

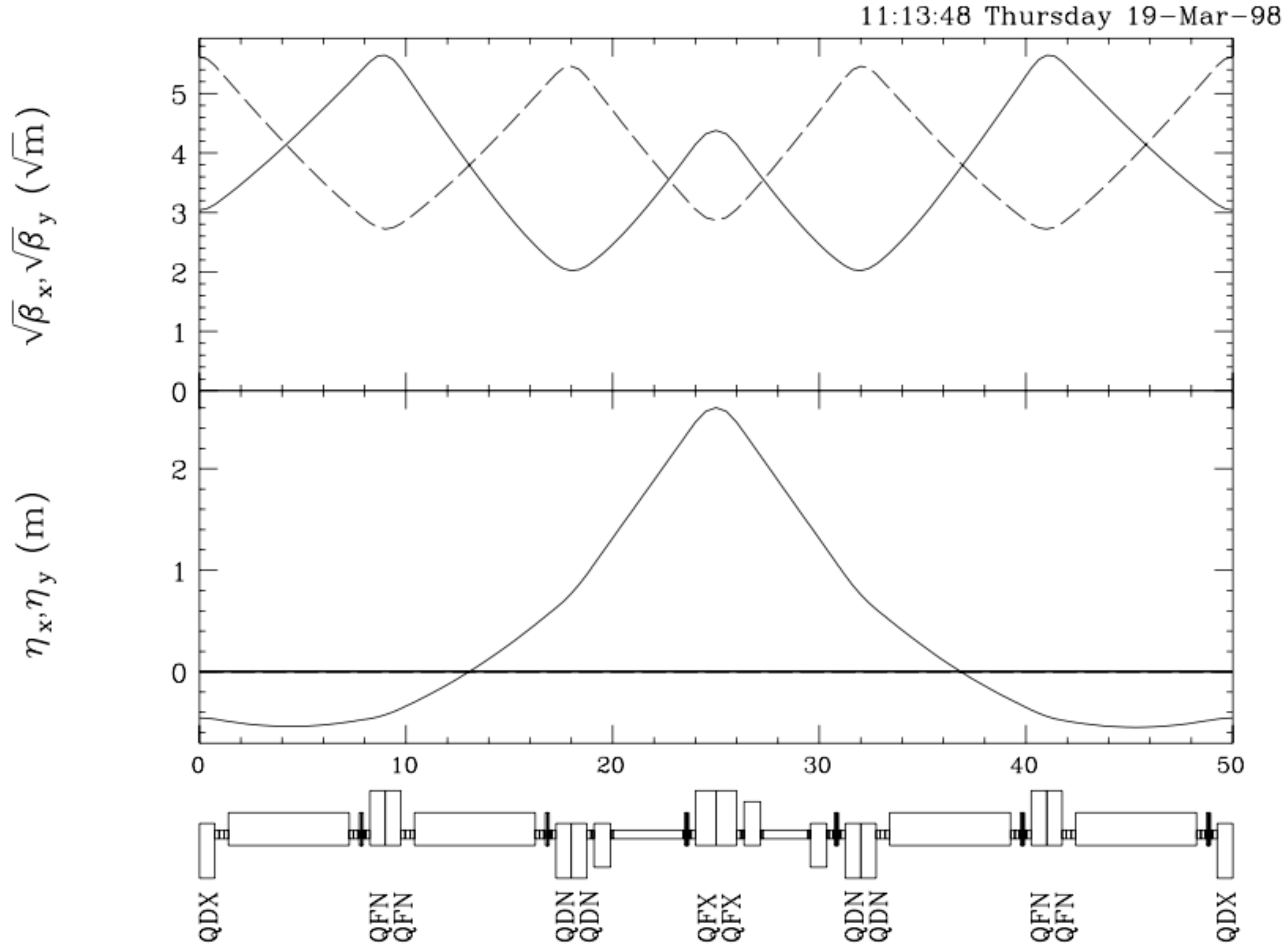


Figure 1: Beam optics functions of the module in arc section of the JHF 50 GeV main ring. $\beta_x^{1/2}$:solid line, $\beta_y^{1/2}$:dashed line.

$$\alpha_1 = \frac{1}{L}\int_0^L \frac{D_x}{\rho} ds = \frac{Q_x}{L}\int_0^{2\pi} \frac{\beta_x D_x}{\rho} d\phi$$

$$D_x(s) = \beta_x^{1/2}(s)\, Q_x^2 \sum_k \frac{a_k e^{jk\phi}}{Q_x^2 - k^2}$$

$$a_k = \frac{1}{2\pi}\int_0^{2\pi} \frac{\beta_x^{3/2}}{\rho} e^{-jk\phi} d\phi$$

$$\alpha_1 = \frac{2\pi Q_x^3}{L}\sum_k \frac{|a_k^2|}{Q_x^2 - k^2} \qquad |a_0^2| = \frac{L}{2\pi Q_x^3}$$

$$\sim \frac{1}{Q_x^2}$$

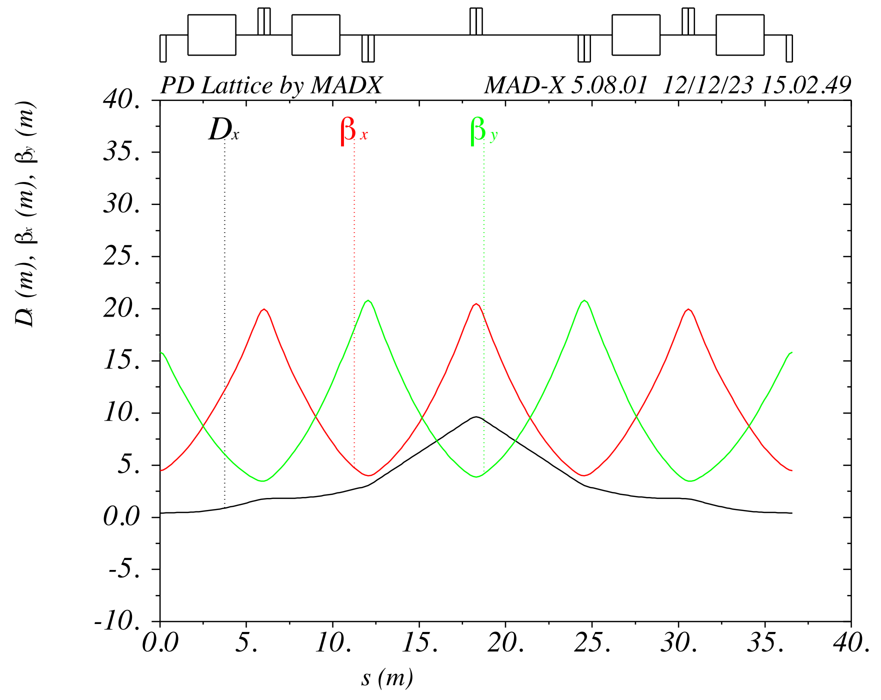
Usually this is true since a_0 (DC component) is dominated.

Other harmonic a_k can be large by particular arrangement of **dipole (rho)** and/or **quadrupole (phi)**.

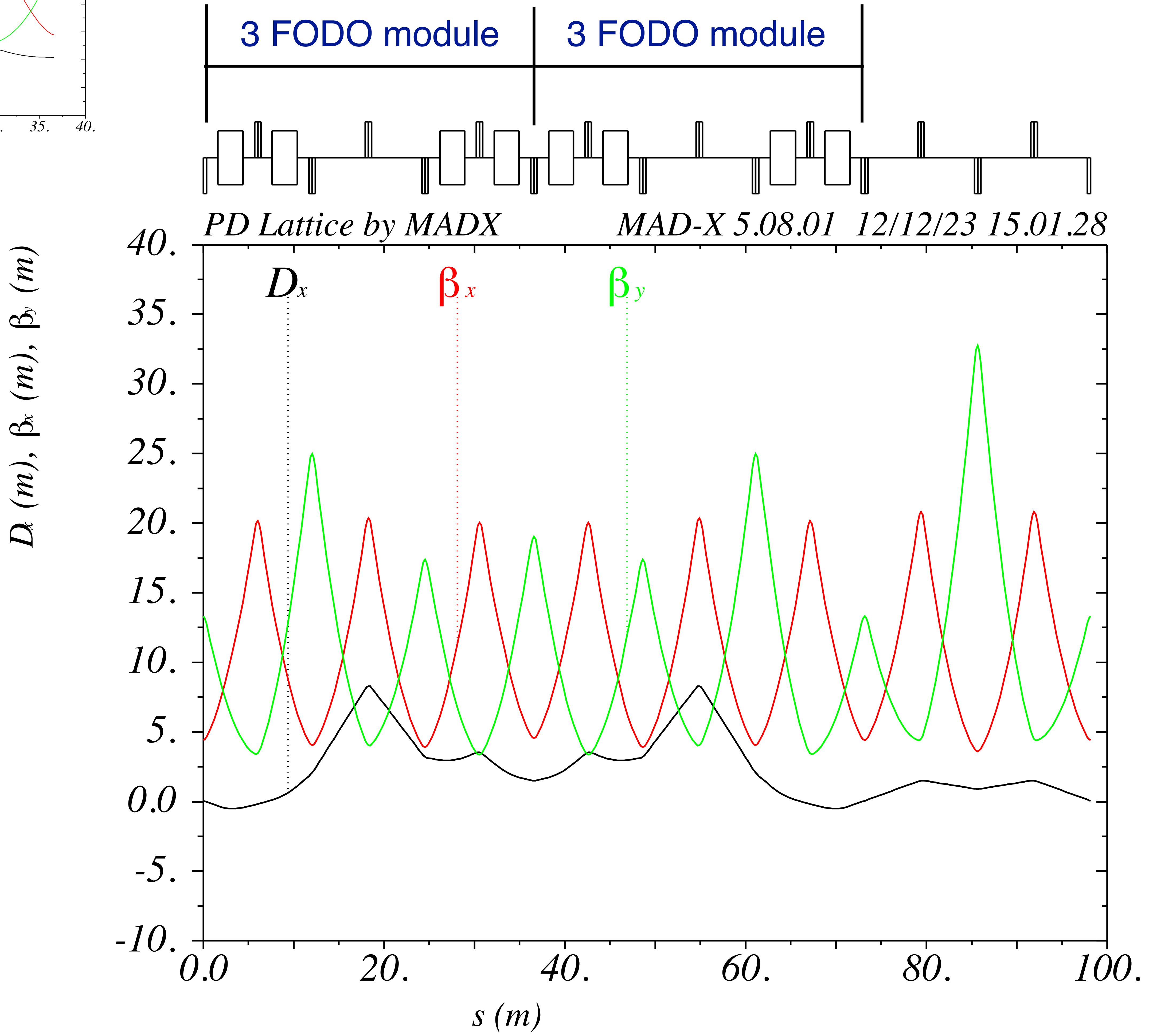
(Looks similar to a Double Bend Achromat lattice.)

J-PARC RCS *like* lattice (3 fold symmetry)

3 FODO module



x 2 + straight section = **100 m** per super period (3 fold sym -> total 300 m.)



- J-PARC RCS is total 348.333 m because straight section is longer by one more FODO cell.
- J-PARC RCS lattice has 7 families of quadrupole to make a proper matching.
- Here I used only QF and QD.

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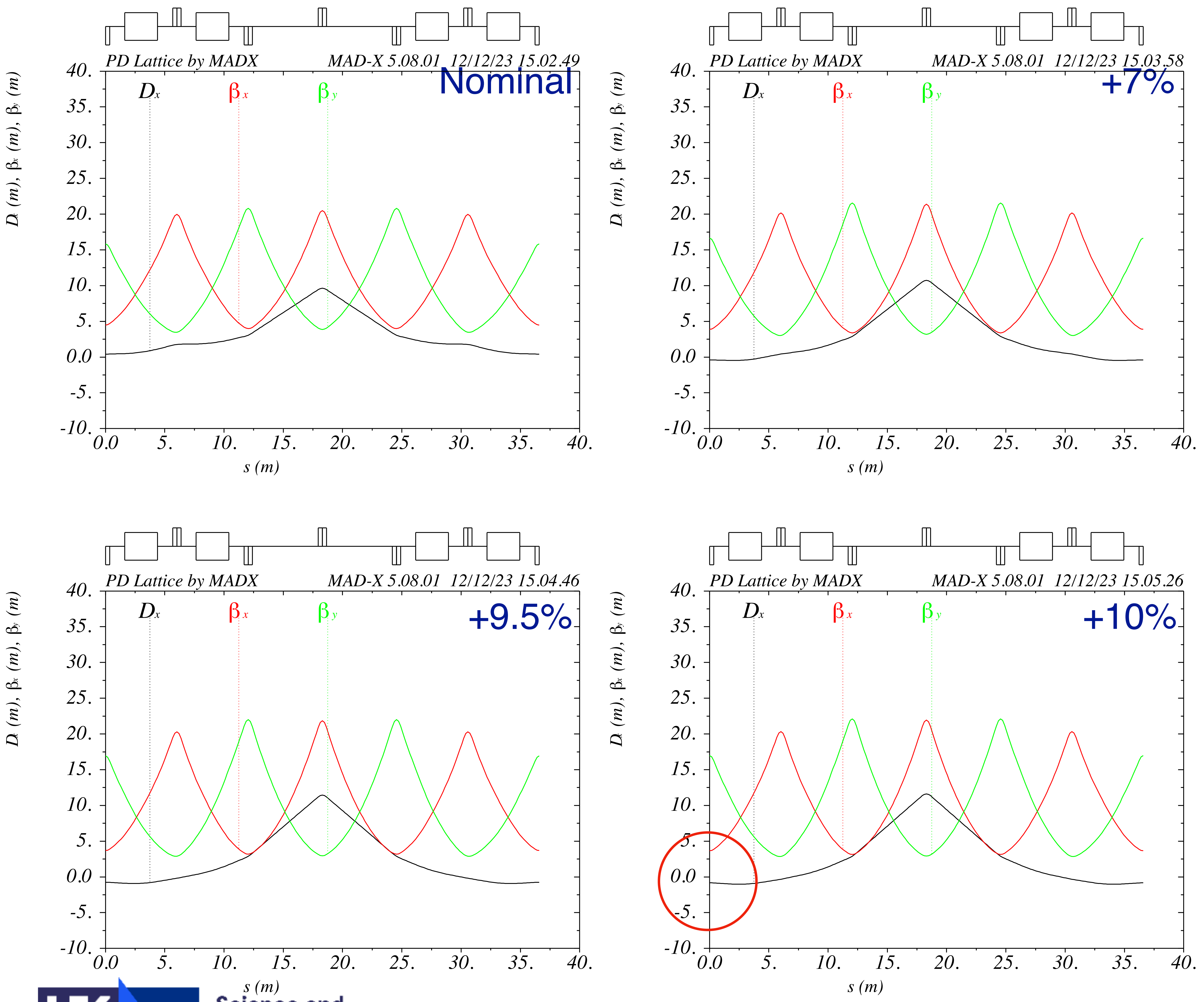
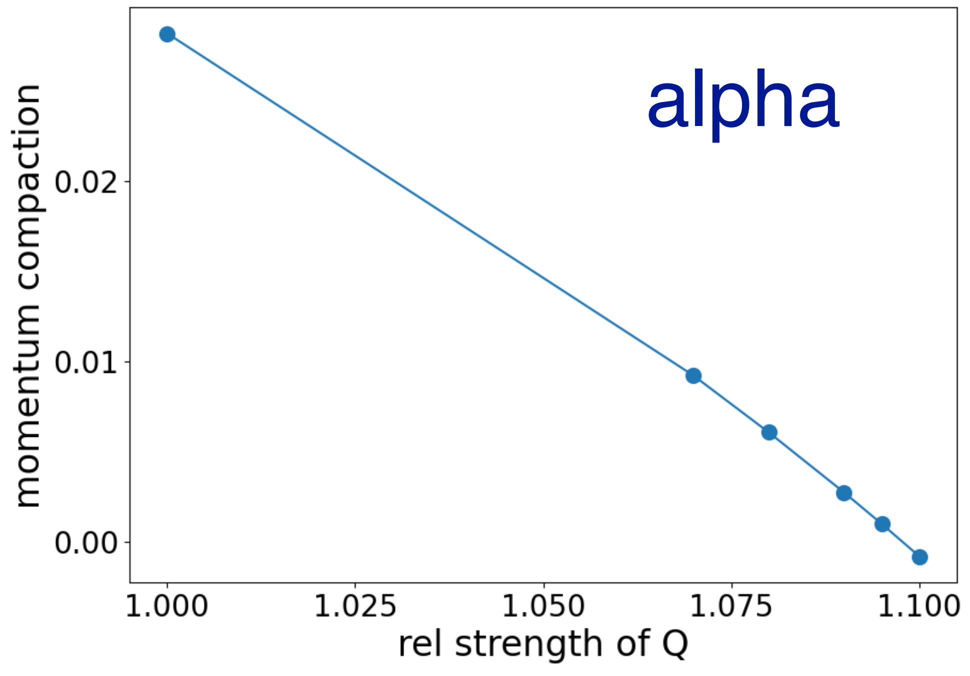
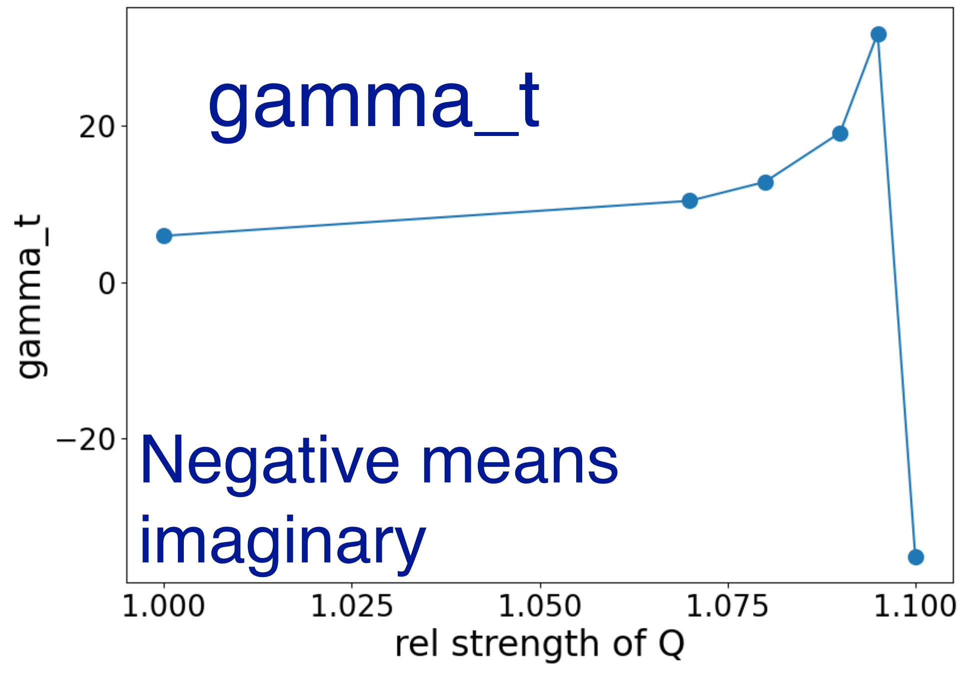
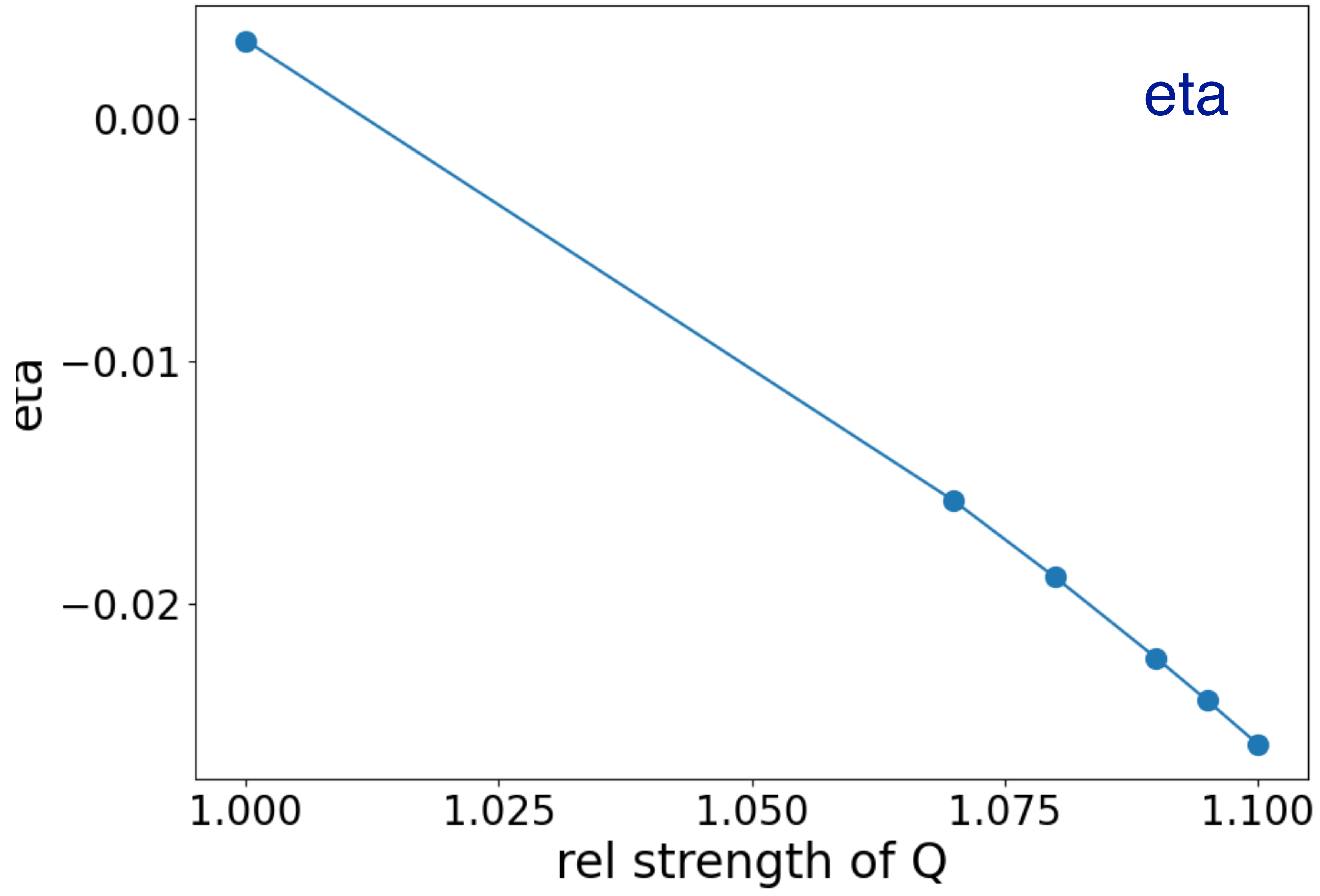
J-PARC RCS *like* lattice (3 fold symmetry)

change quadrupole strength



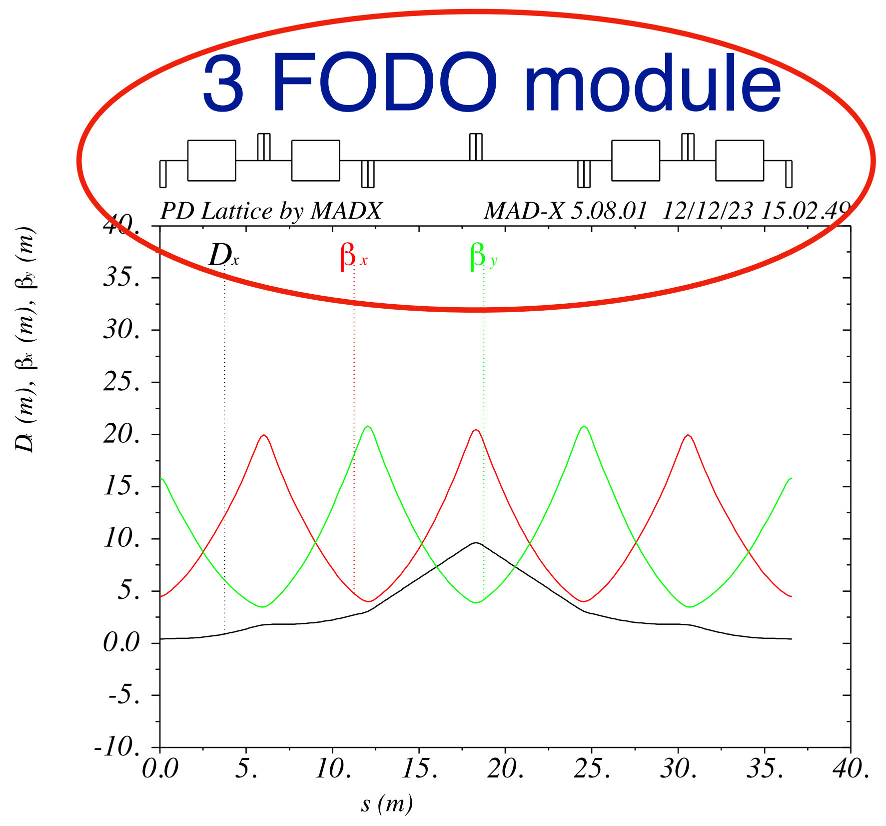




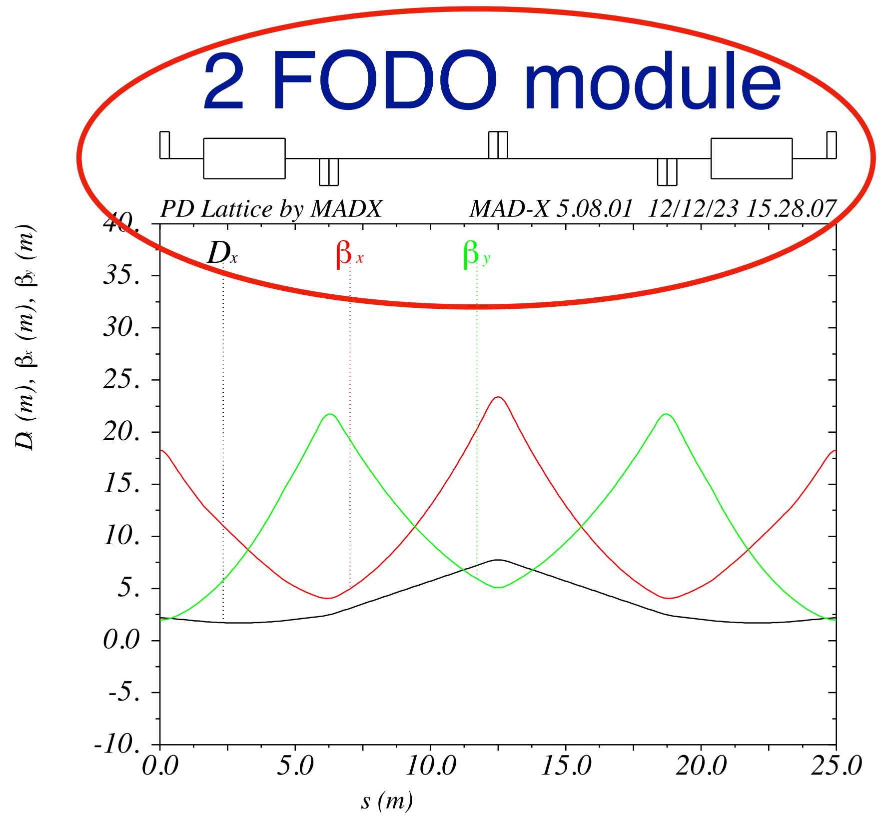


By changing the quadrupole strength 10%, transition gamma change from gt~"Qx" to imaginary (eta from 0 to 0.025).

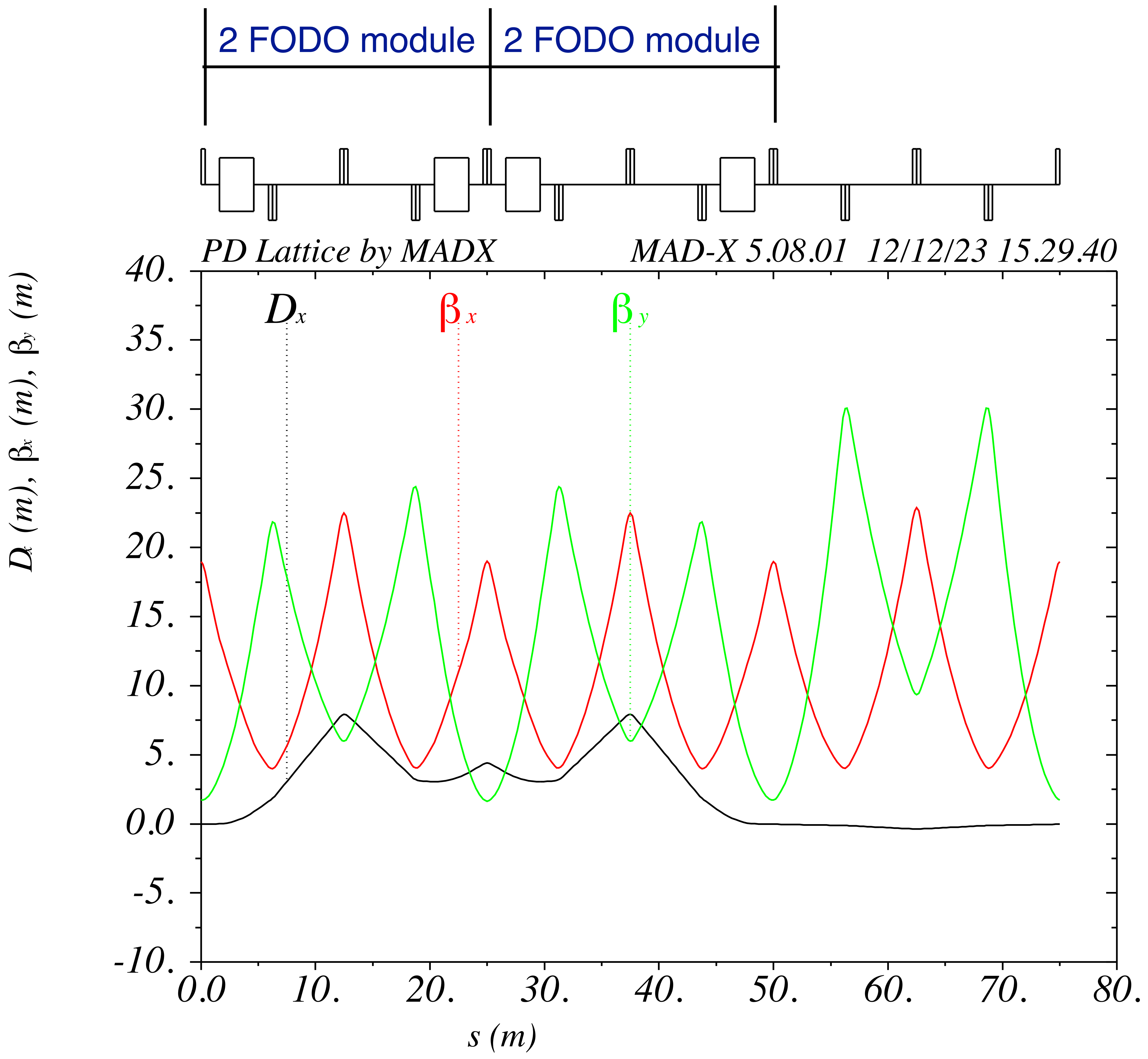
4 fold symmetry



x 2 + straight section = **100 m**
per super period
(3 fold sym -> total 300 m.)



x 2 + straight section = **75 m**
per super period
(4 fold sym -> total 300 m.)



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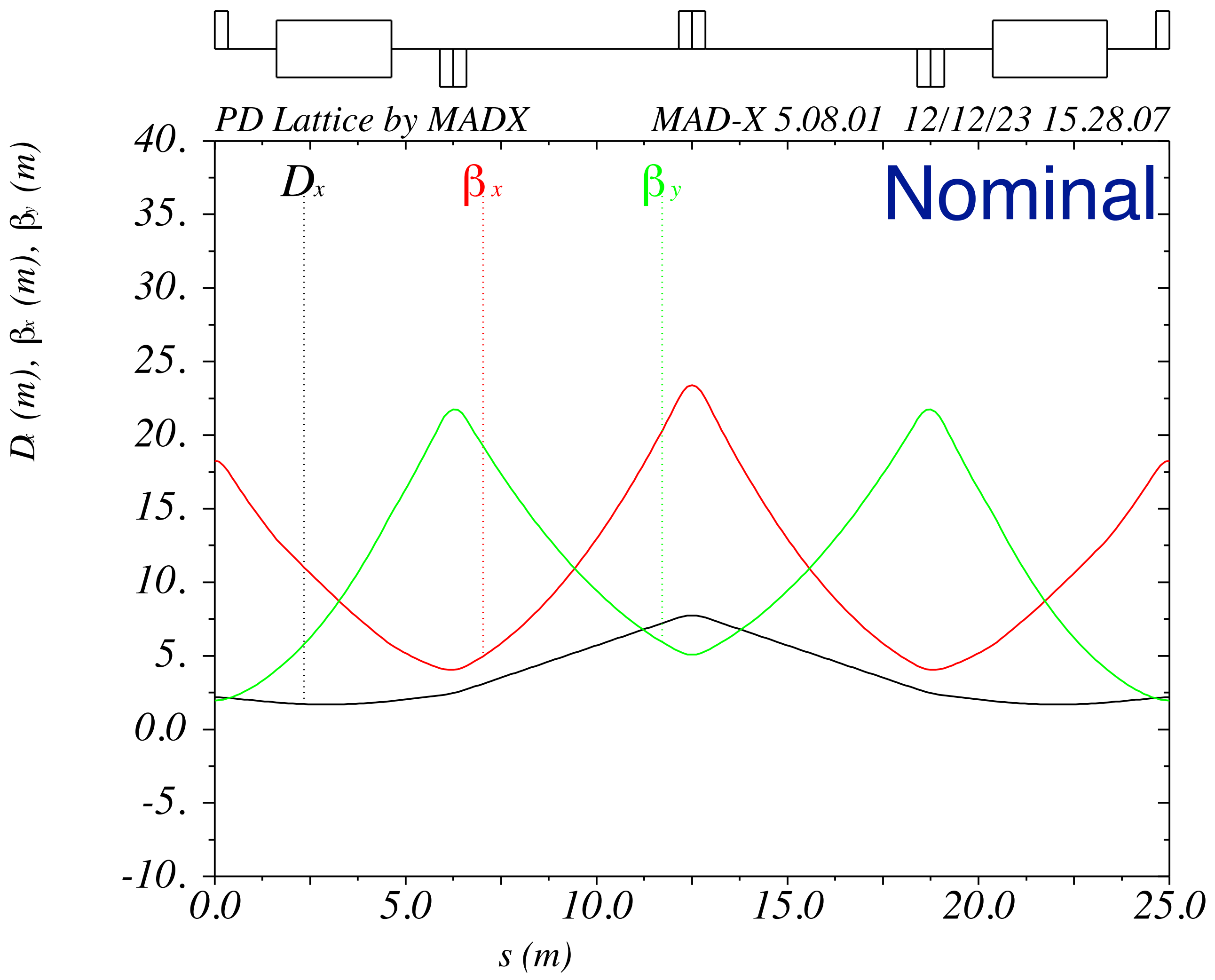
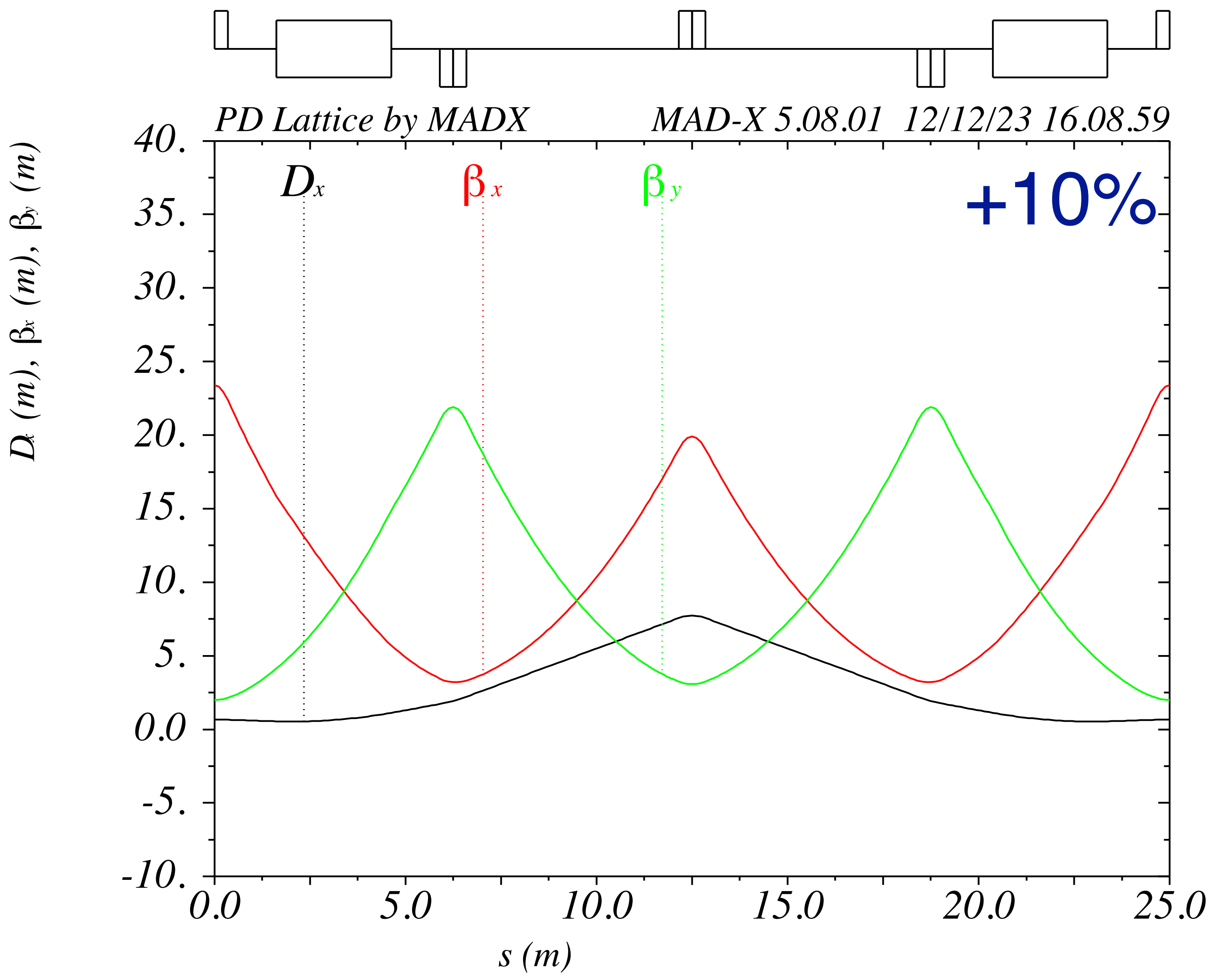
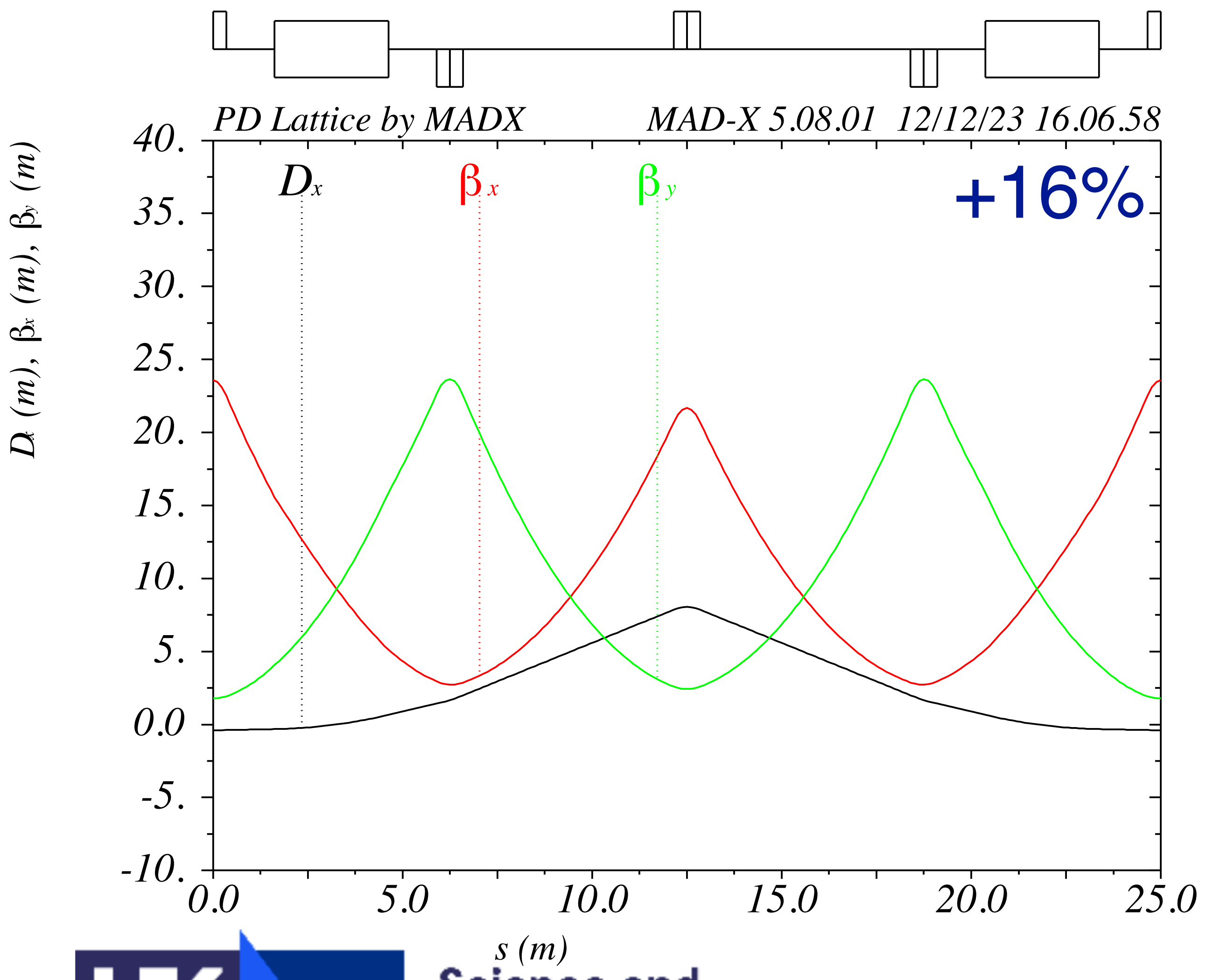
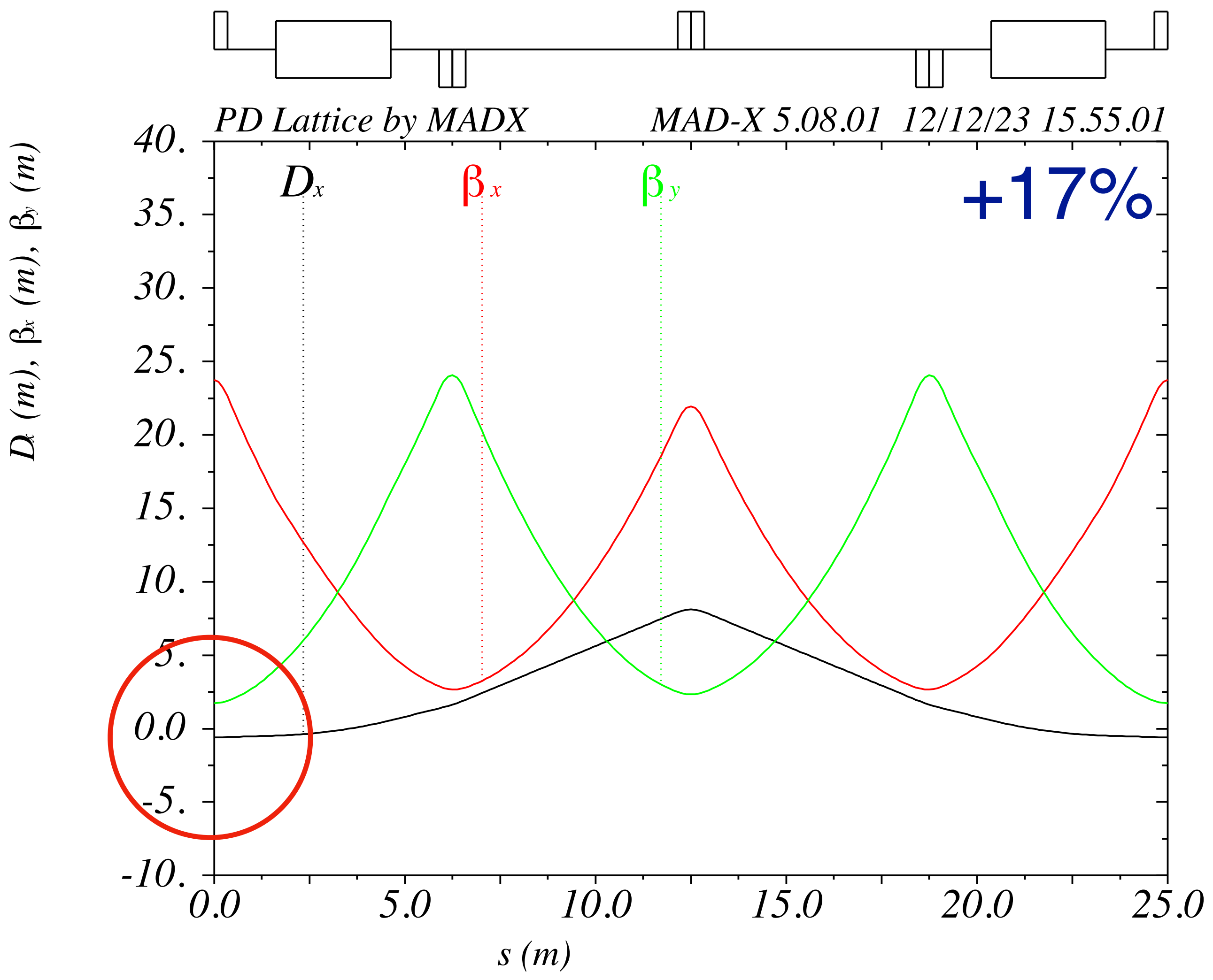
4 fold symmetry

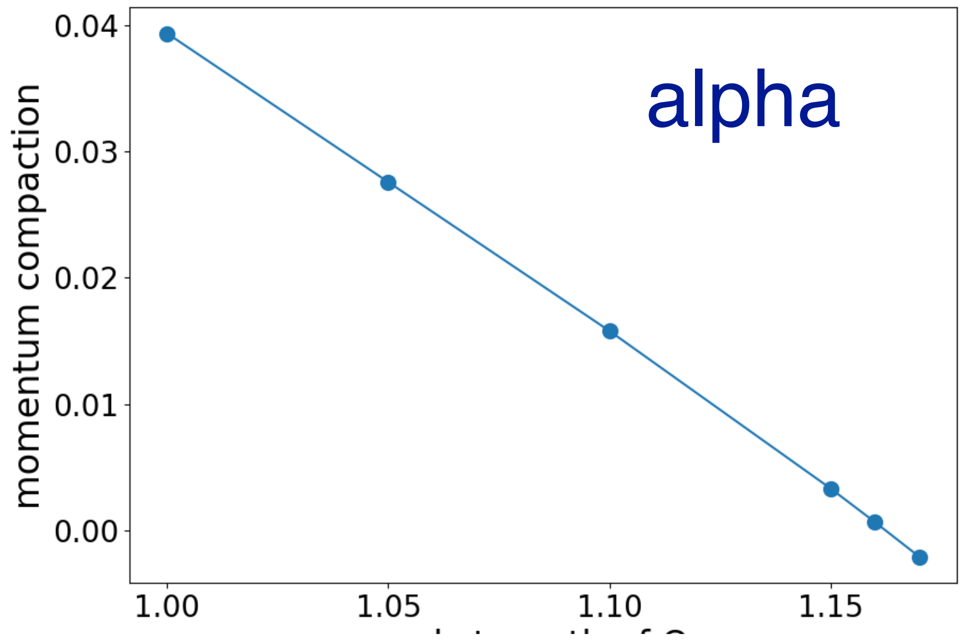
change quadrupole strength

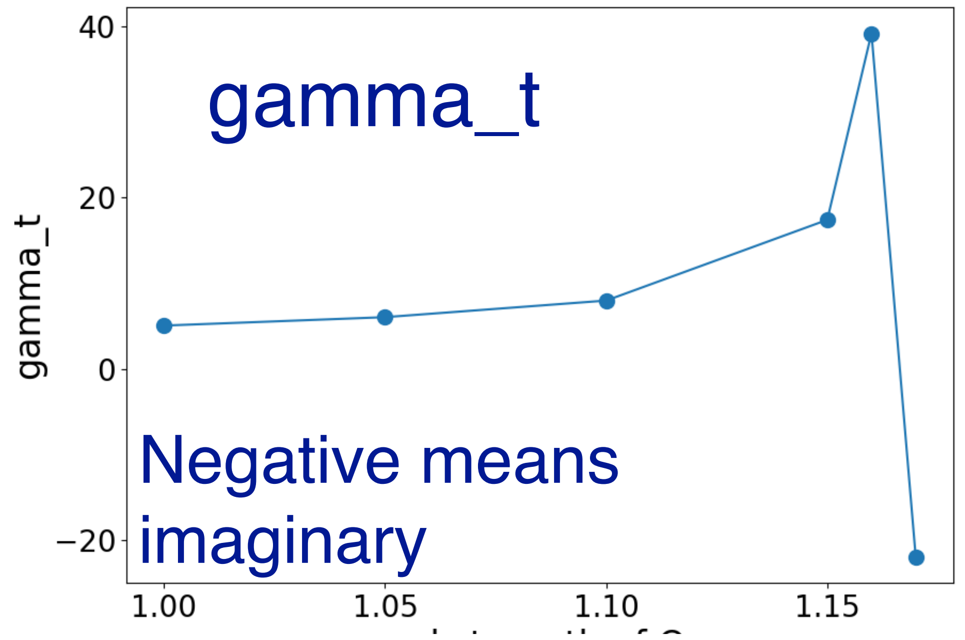


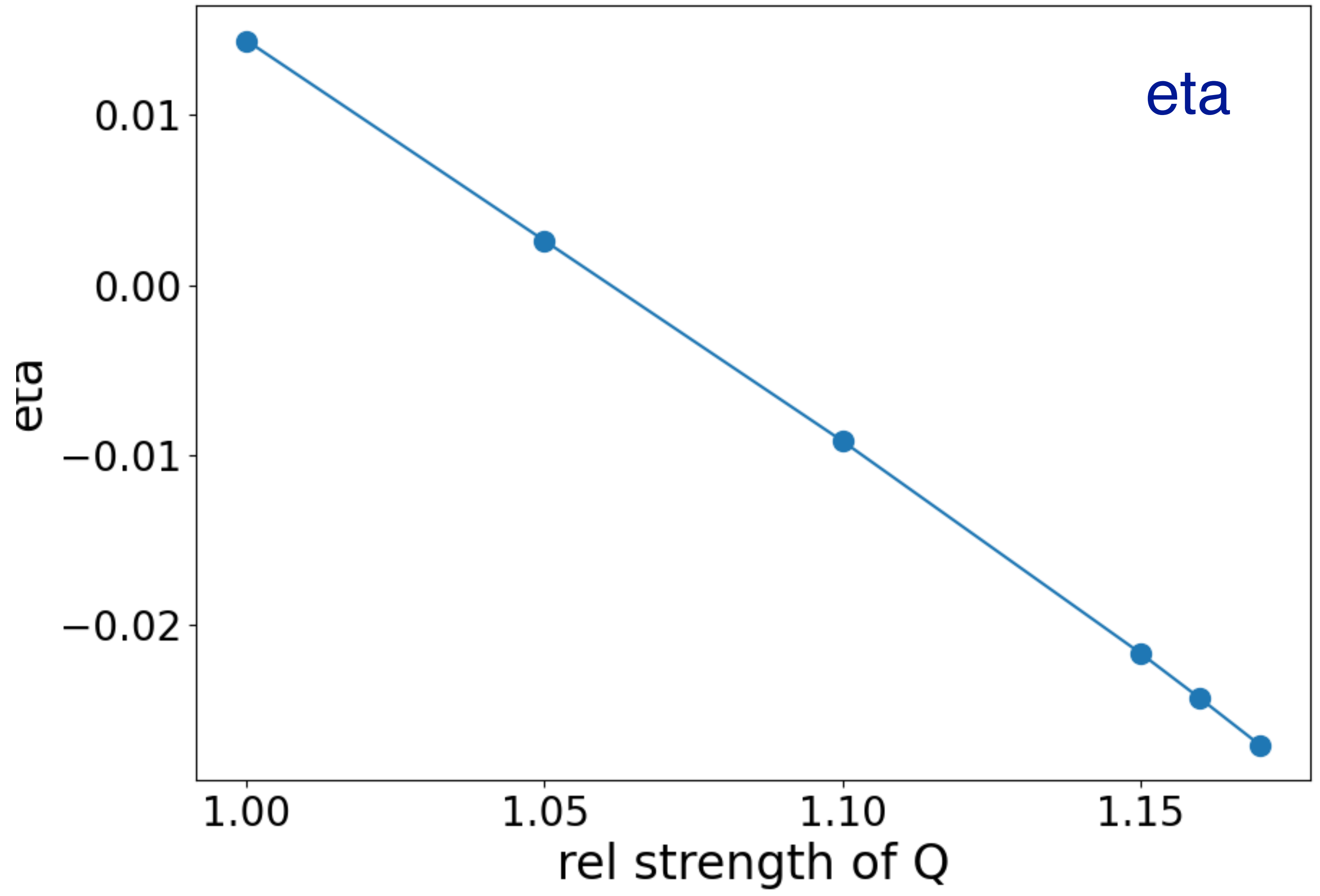












By changing the quadrupole strength 17%, transition gamma change from gt~“Qx” to imaginary (eta from 0 to 0.025).

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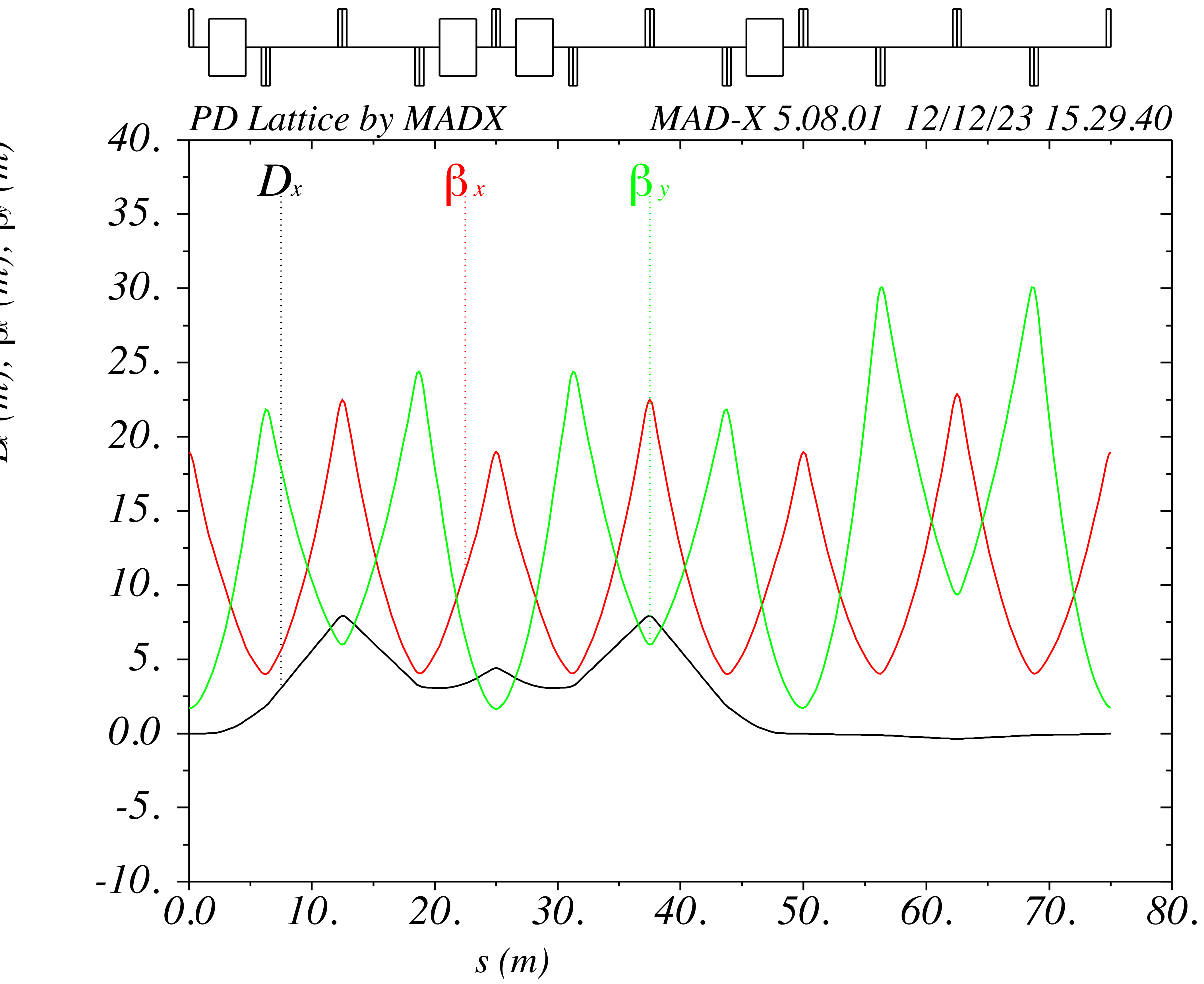
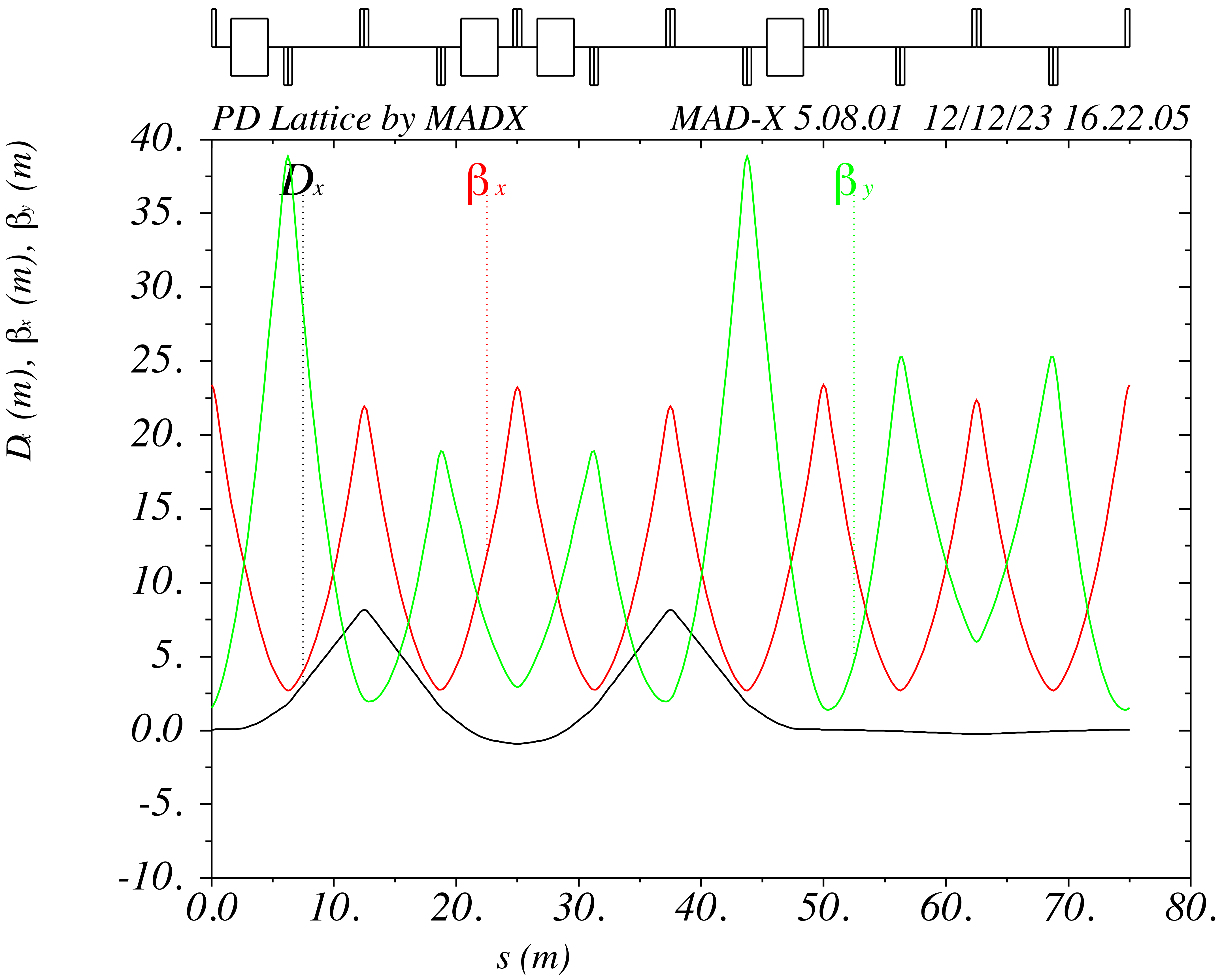
My proposal is 4 fold symmetry lattice for AR and CR (300 m)





eta ~ 0

(5.738, 6.358)

eta ~ -0.025

(6.977, 7.727)

Transverse tune and beta beating can be optimised by introducing more families of quadrupole (J-PARC RCS has 7 families).

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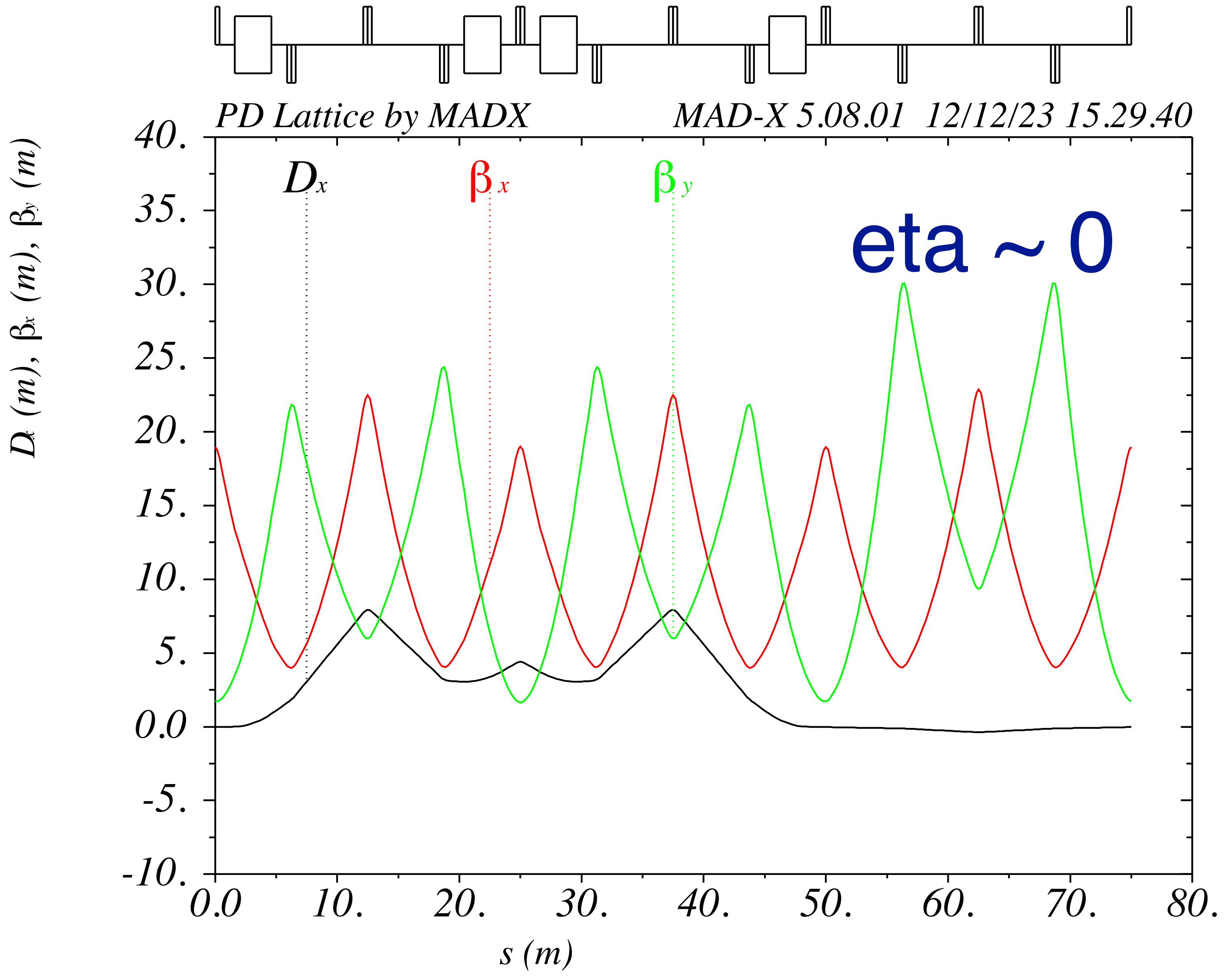
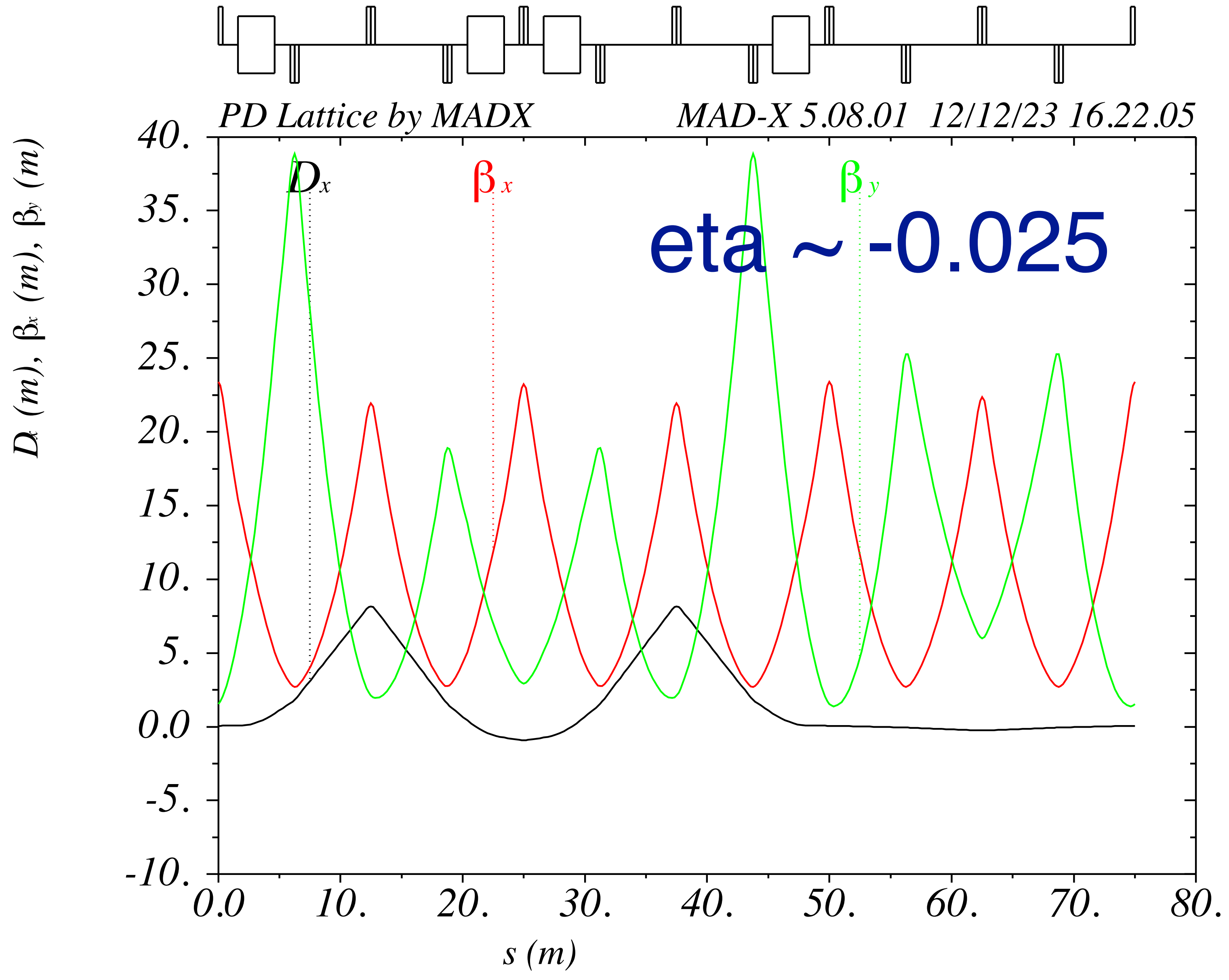
Further investigation

- If the lattice of AR and CR is identical only with different momentum compaction factor,
  - Can we change the optics from AR to CR by pulse quadrupoles while the beam is circulating?
  - The same technique of the transition jump scheme should work
    - but some issues, e.g. matching.
- If the pulse magnets idea do not work,
  - Is it a good idea to make two identical lattice for AR and CR, but operate differently?





AR	CERN scheme	CR
CR	Fermilab scheme	AR

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Higher order of eta

Phase rotation will inevitably increase momentum spread.

- Chromaticity correction
- Higher order momentum compaction factors

$$\frac{\Delta\omega}{\omega_0} = -\left(\eta_0 + \eta_1\delta + \eta_2\delta^2 + ...\right)$$

$$\eta_0 = \left(\alpha_0 - \frac{1}{\gamma_0^2}\right) \qquad \eta_1 = \frac{3\beta_0^2}{2\gamma_0^2} + \alpha_1 - \alpha_0\eta_0$$

$$\eta_2 = -\frac{\beta_0^2\left(5\beta_0^2 - 1\right)}{2\gamma_0^2} + \alpha_2 - 2\alpha_0\alpha_1 + \frac{\alpha_1}{\gamma_0^2} + \alpha_0^2\eta_0 - \frac{3\beta_0^2\alpha_0}{2\gamma_0^2}$$

$$R = R_0\left(1 + \alpha_0\delta + \alpha_1\delta^2 + ...\right)$$

All order of the moment compaction factor is zero in vFFA.

- Sextuple, octupole, … can correct it to some extent in any lattice.

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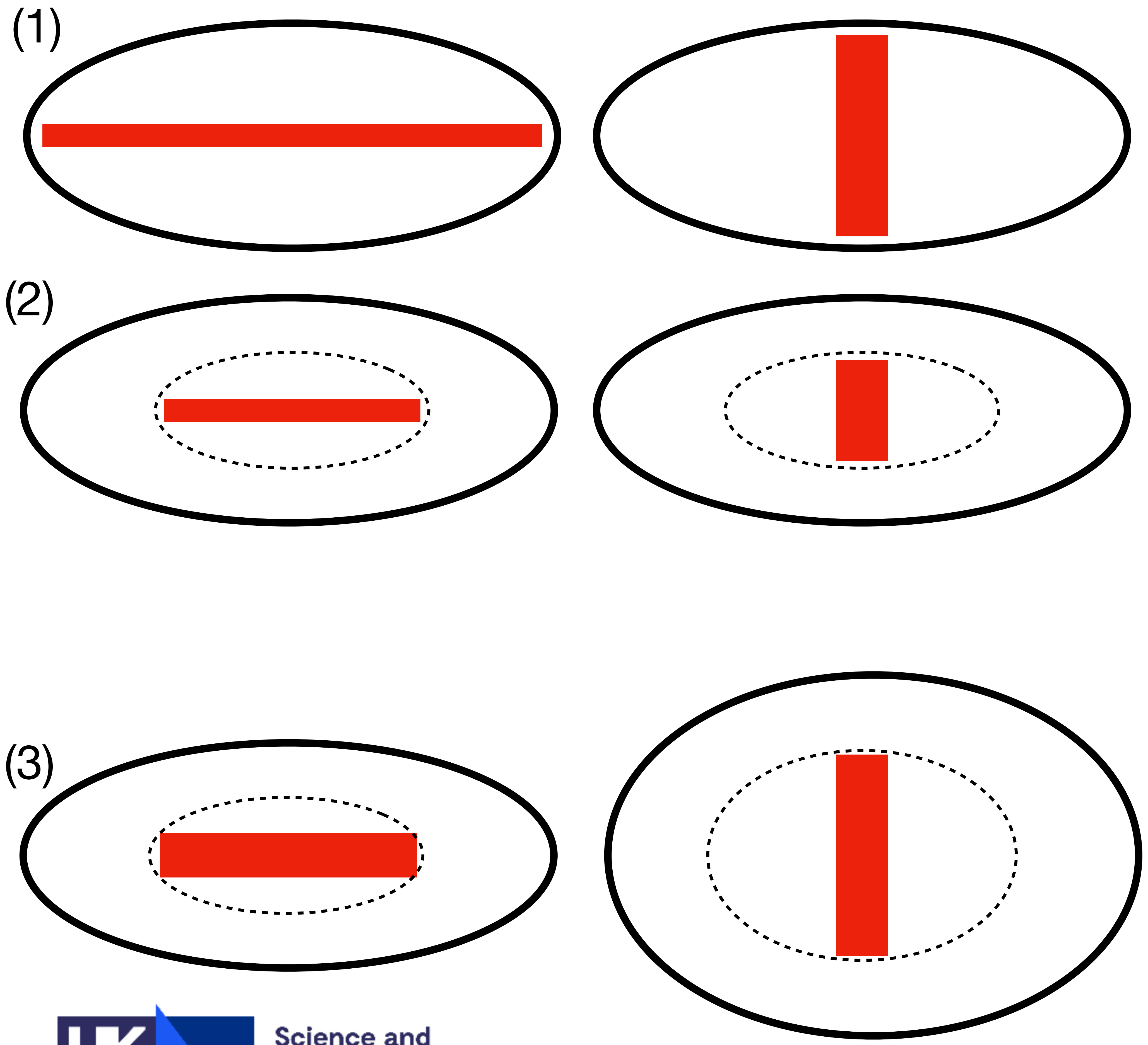
Bunch rotation fundamentals

Conservation of longitudinal emittance

$$\varepsilon_L = \Delta t \Delta E \propto \Delta t \left(\Delta p / p \right)$$



c.f. Revolution time of a 300 m ring is ~1000 ns.

	Initial width	Initial dp/p	Final width	Fial dp/p	Bucket height
	+/- 500 ns	+/- 0.01%	+/- 5 ns	+/- 1%	+/- 1%
(1)	+/- 500 ns	+/- 0.1%	+/- 5 ns	+/- 10%	+/- 10%
(2)	+/- 250 ns	+/- 0.1%	+/- 5 ns	+/- 10%	+/- 10%
(3)	+/- 250 ns	+/- 0.2%	+/- 5 ns	+/- 10%	+/- 20%

$$\Delta p_f \propto \frac{\varepsilon_L}{\Delta t_f} = \frac{r \Delta t_i^2}{\Delta t_f} \quad \text{where} \quad r = \frac{\Delta p_i}{\Delta t_i}$$

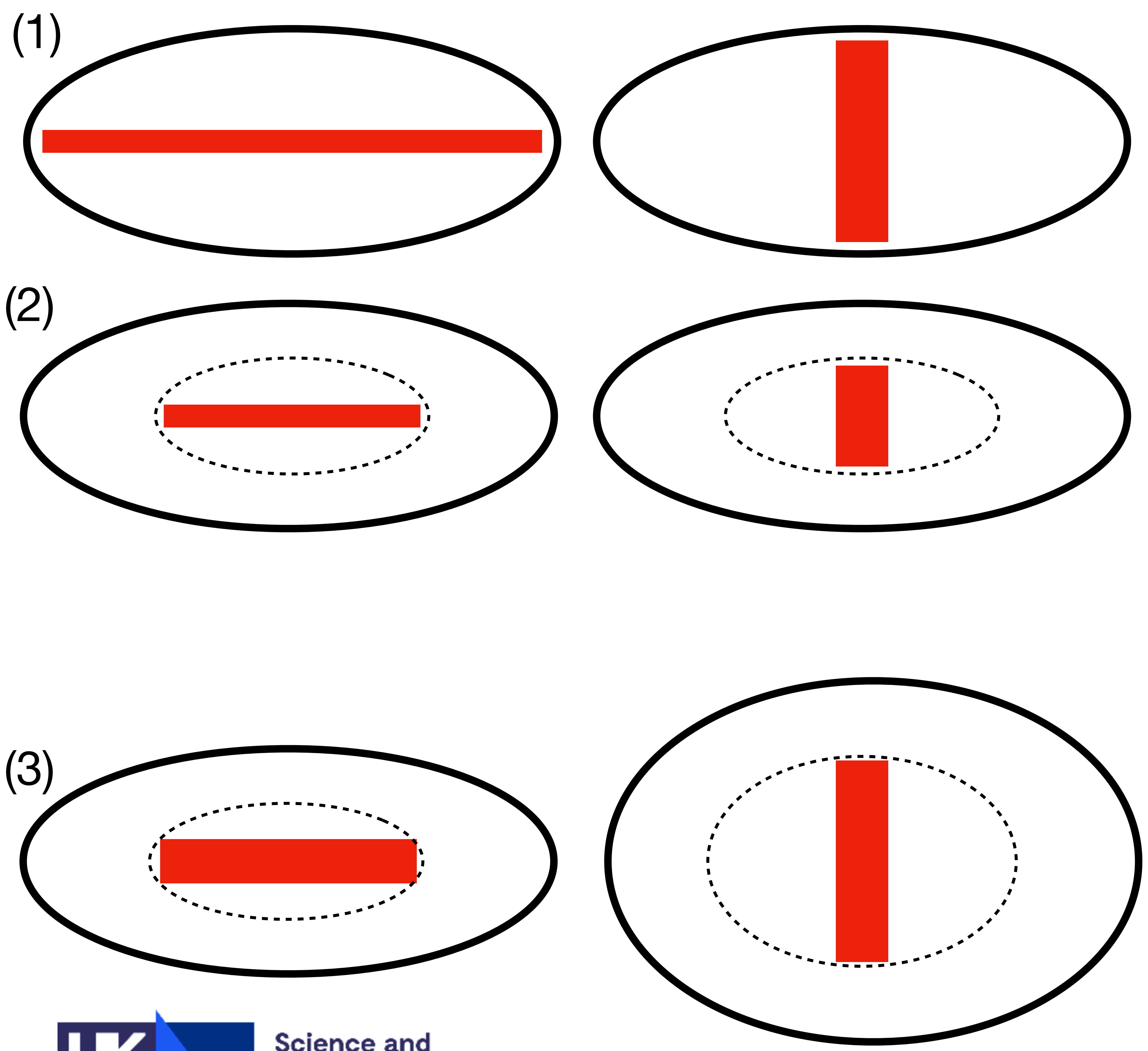
$$B_h \propto \Delta p_f \frac{T_{rev}/2}{\Delta t_i}$$

$$B_h \propto \frac{T_{rev}/2}{\Delta t_f} r \Delta t_i \left(= \frac{T_{rev}/2}{\Delta t_f} \Delta p_i \right)$$

Required RF bucket height

$$\varepsilon_L = \Delta t \Delta E \propto \Delta t \left(\Delta p / p\right)$$

$$B_h \propto \frac{T_{rev}/2}{\Delta t_f} r \Delta t_i \left(= \frac{T_{rev}/2}{\Delta t_f} \Delta p_i \right) \quad \text{where} \quad r = \frac{\Delta p_i}{\Delta t_i}$$



- Small initial momentum spread reduces the required RF bucket height.
    - **Pre-bunching** (reduce dt_i and increase r) should be avoided
    - **Capture in the RF bucket (and acceleration)** should be avoided
    - **Beam stacking** should be avoided

because all increase the required RF bucket height.

- If we want to accelerate the beam in AR, "phase displacement" acceleration may be the only option?
    - How long does it take?
    - Effects of scattering?

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“Phase displacement”

$$2\pi\delta u = \text{bucket area}$$

Theory of cyclic accelerators
A.A. Kolomensky and A. N. Lebedev

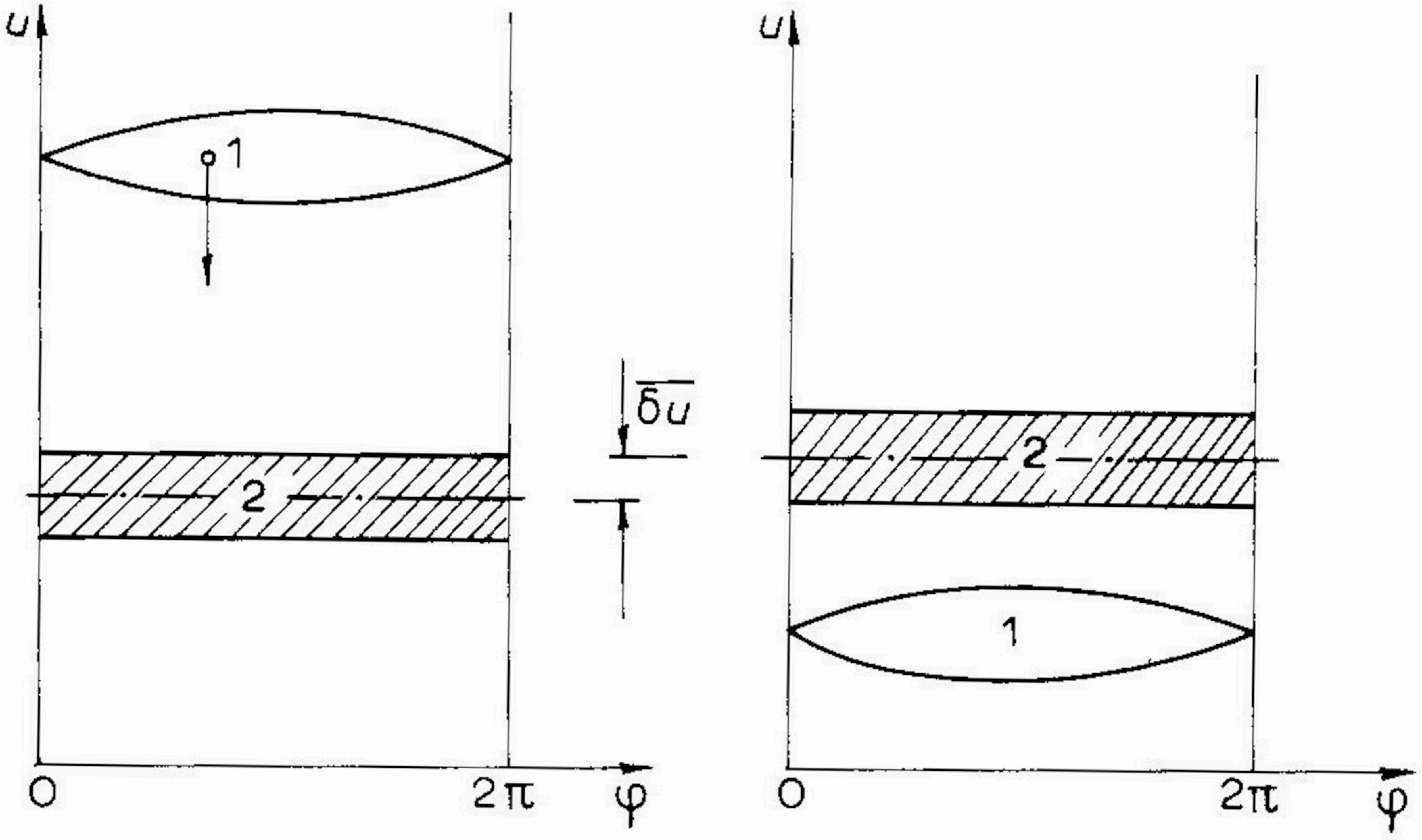

Fig. 81. Illustration of the phase displacement mechanism. 1, region occupied by the bucket; 2, region occupied by the beam; δu, mean displacement along co-ordinate u caused by the motion of the bucket.

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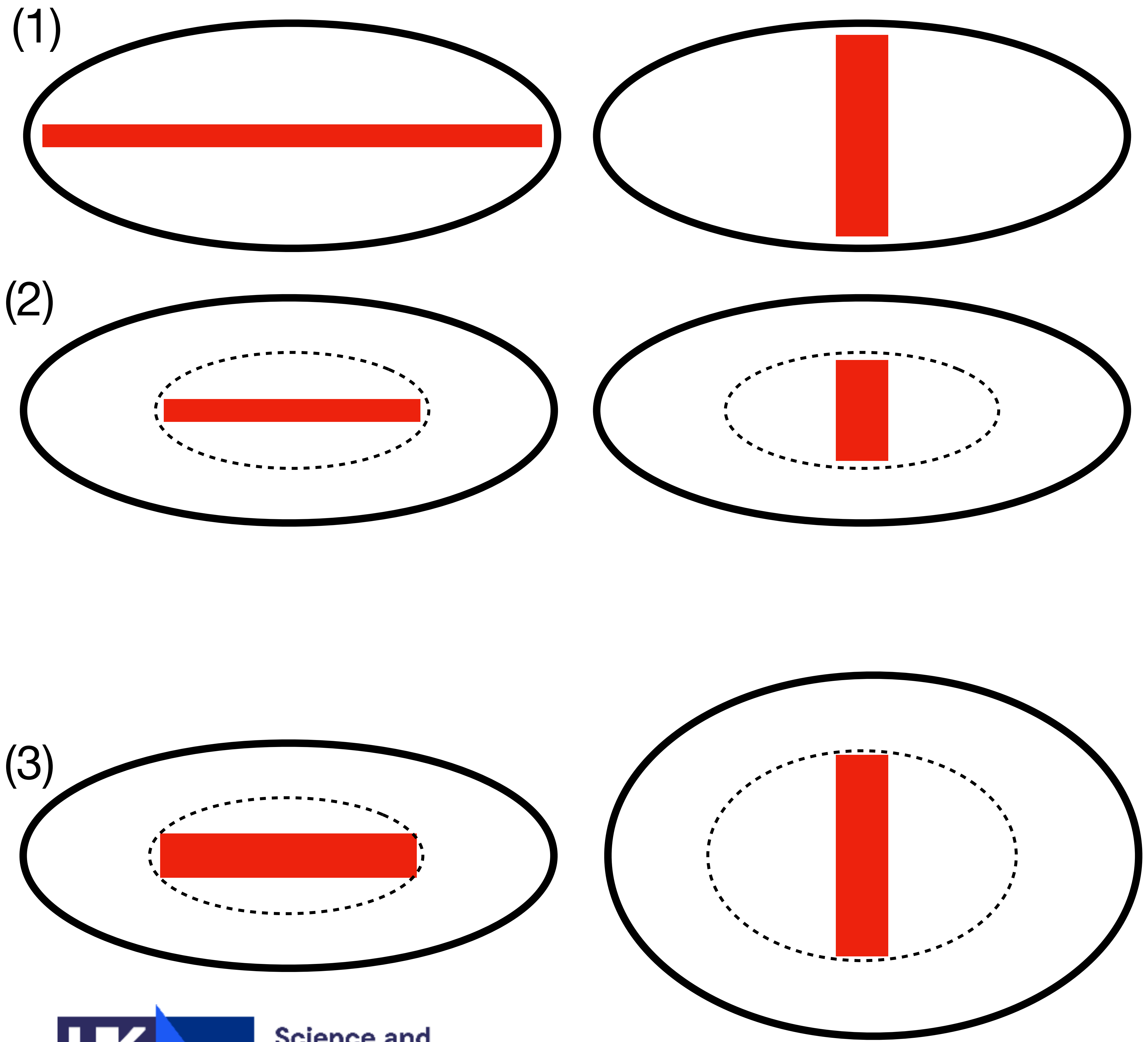
Required RF voltage

$$\varepsilon_L = \Delta t \Delta E \propto \Delta t \left(\Delta p / p\right)$$

$$B_h \propto \frac{T_{rev}/2}{\Delta t_f} r \Delta t_i \left(= \frac{T_{rev}/2}{\Delta t_f} \Delta p_i \right) \quad \text{where} \quad r = \frac{\Delta p_i}{\Delta t_i}$$



- Shorter bucket reduces the required RF bucket height proportional.
- In terms of harmonic number h,

$$B_h \propto \frac{\Delta p_i}{h \Delta t_f}$$

- RF bucket height is proportional to *V* and *h*

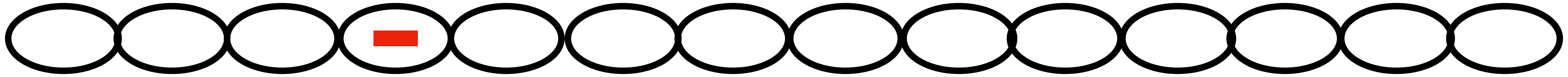
$$B_h \propto \sqrt{\frac{V}{h}} \quad \text{therefore} \quad V \propto \frac{1}{h}$$

is necessary for different *h*.

- The best way is to increase *h* as large as possible if we can keep the initial momentum spread the same.

Option 1: Use high harmonic number with shortly chopped linac pulse

- We know a small bunching factor will be suffered from transverse space charge effects.
- However, the bunching factor is still larger than that right after the phase rotation.



- When V ~ 1/h, synchrotron tune is constant. No gain (or lost) of the rotation speed.

New requirements to the injector linac

- Chopper is different from the original design. Large chopping factor.
- “fast-slow” chopper developed at RAL should extract small fraction without partial chopping.
- Pulse length should be longer unless the peak current can be higher.

- The extreme scheme is to inject only one linac bunch of “325 or 350 MHz” per turn. It is short, ~ 1ns and no phase rotation is necessary.

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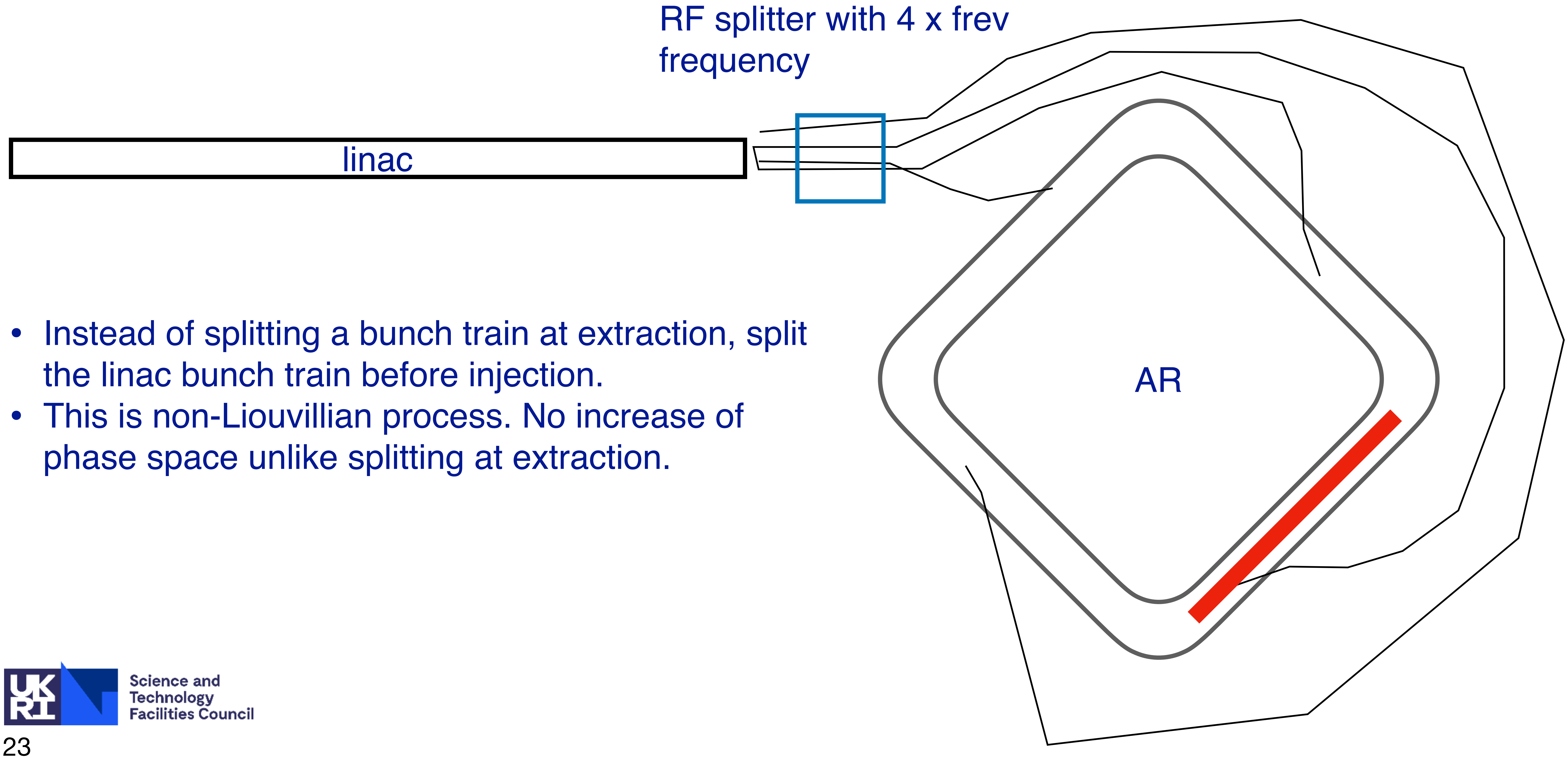
Option 2: Injection only 1/4 of the ring by splitting the injection line



- Instead of splitting a bunch train at extraction, split the linac bunch train before injection.
- This is non-Liouvillian process. No increase of phase space unlike splitting at extraction.

Transverse space charge effects

Extreme case, namely all the protons form one short bunch of 2 ns.

$$\sigma_t = 2 \text{ ns} \qquad T_{rev} = 1 \ \mu\text{s}$$

Space charge tune shift of Gaussian beam profile.

$$\epsilon = \frac{r_p n_t}{4\pi \Delta Q \beta^2 \gamma^3 B_f}$$

Bunching factor when longitudinal shape is Gaussian.

$$B_f = \frac{\sqrt{2\pi}\sigma_t}{T_{rev}}$$

Table shows when we assume $\Delta Q = 1$

	5 GeV	10 GeV
beta	0.9874	0.9963
gamma	6.3289	11.6579
beta^2 gamma^3	247.18	1572.72
geo rms emittance	49.228 pi mm mrad	3.8724 pi mm mrad
nor rms emittance	307.94 pi mm mrad	40.977 pi mm mrad

c.f. $\beta = 25 \text{ m}$

$$\sqrt{\beta \varepsilon_{rms}} = 35 \text{ mm}$$

Coherent limit (because of high energy)?

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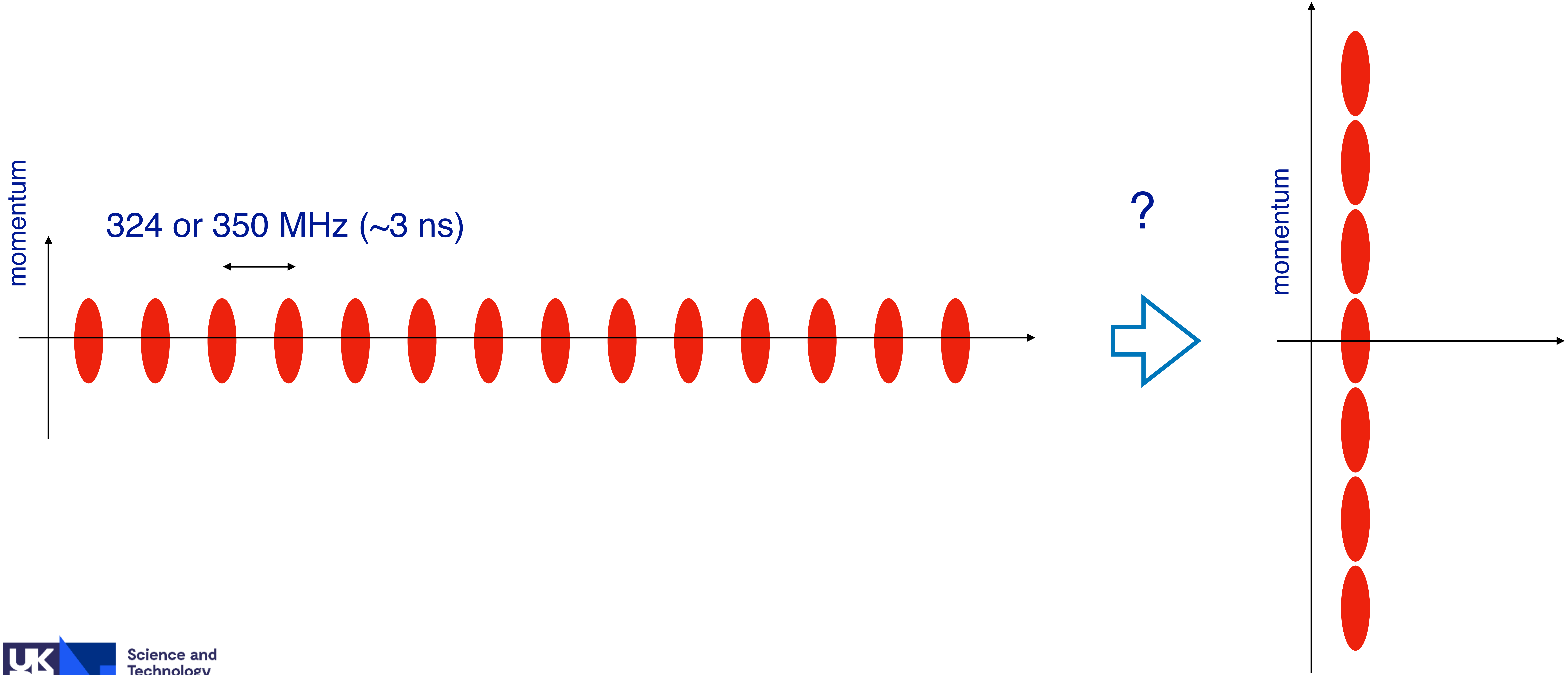
Another way of creating a short bunch

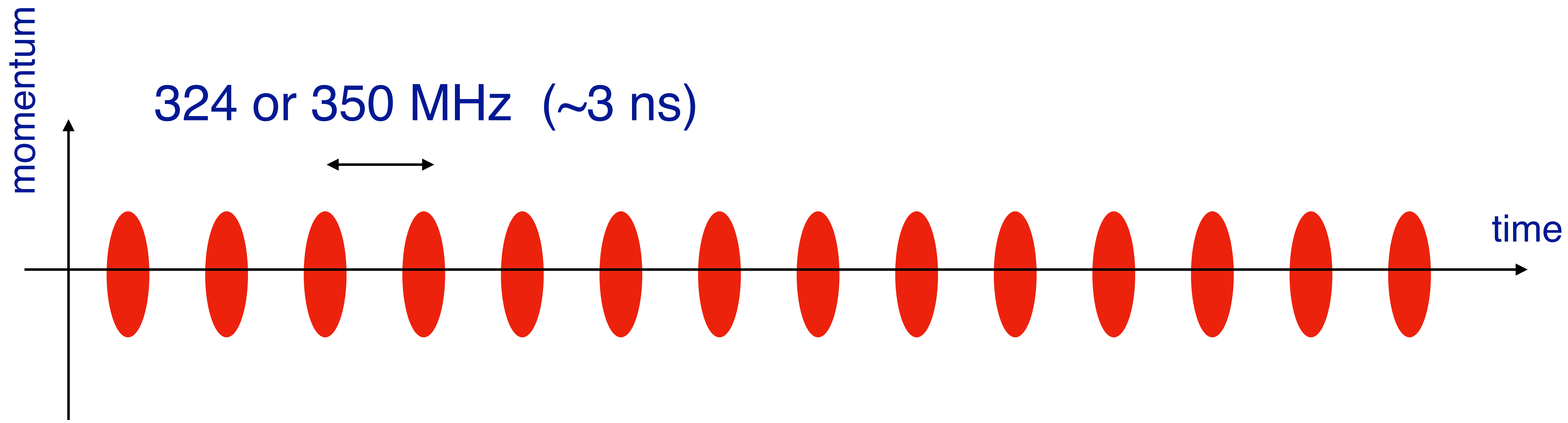
Can we use linac micro bunches directly?

- 324 or 350 MHz linac frequency means bunch width is < 1 ns.



Multiturn injection into AR

- Make eta=0 (isochronous) at AR.
- Inject linac bunches on top of the previously injected bunches to keep the linac RF structure.
- Paint phase space transversely.



Assume that each linac micro bunch as **100%** size of dt = +/-0.5 ns and dp/p = +/-0.001

Total longitudinal emittance is

$$eL = N * dt * (dp/p) = \sim 300 * 0.5 \text{ ns} * 0.001 = 0.15 \text{ ns}$$

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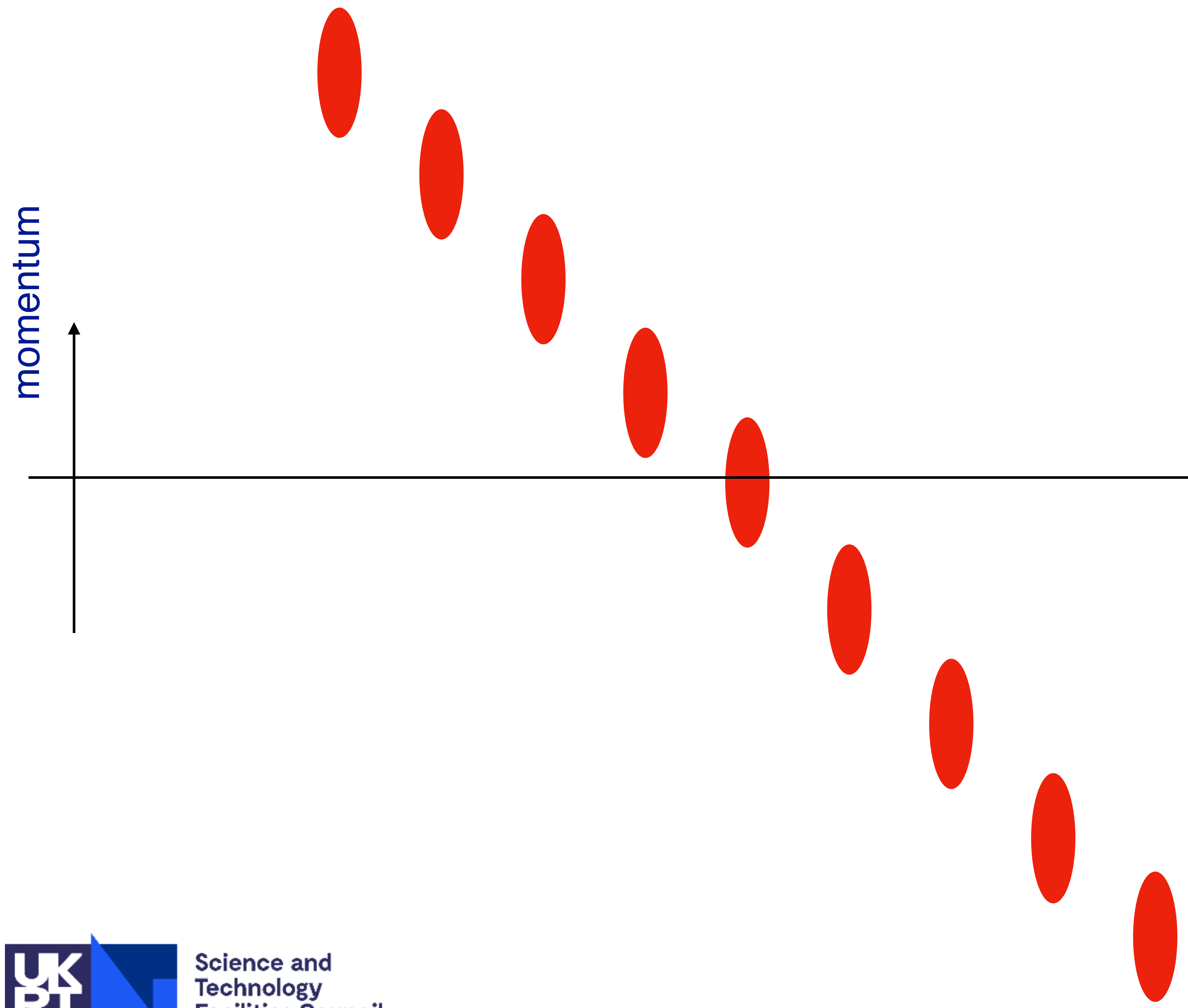
Apply saw tooth RF in AR

- Introduce energy difference depending on the longitudinal position in the ring.
- Bunch should not move in phase because eta=0.



If we want to make the final dt_f = +/-5 ns

dp/p = eL/df_f = 0.15/5 = +/-0.03 (3%)

dE/E = beta^2 dp/p

dE ~ dp/p E = +/-0.03 5938 MeV = +/-178 MeV

It takes 178 turns to make the energy difference with 1 MV RF cavity (could be faster by more Volts).

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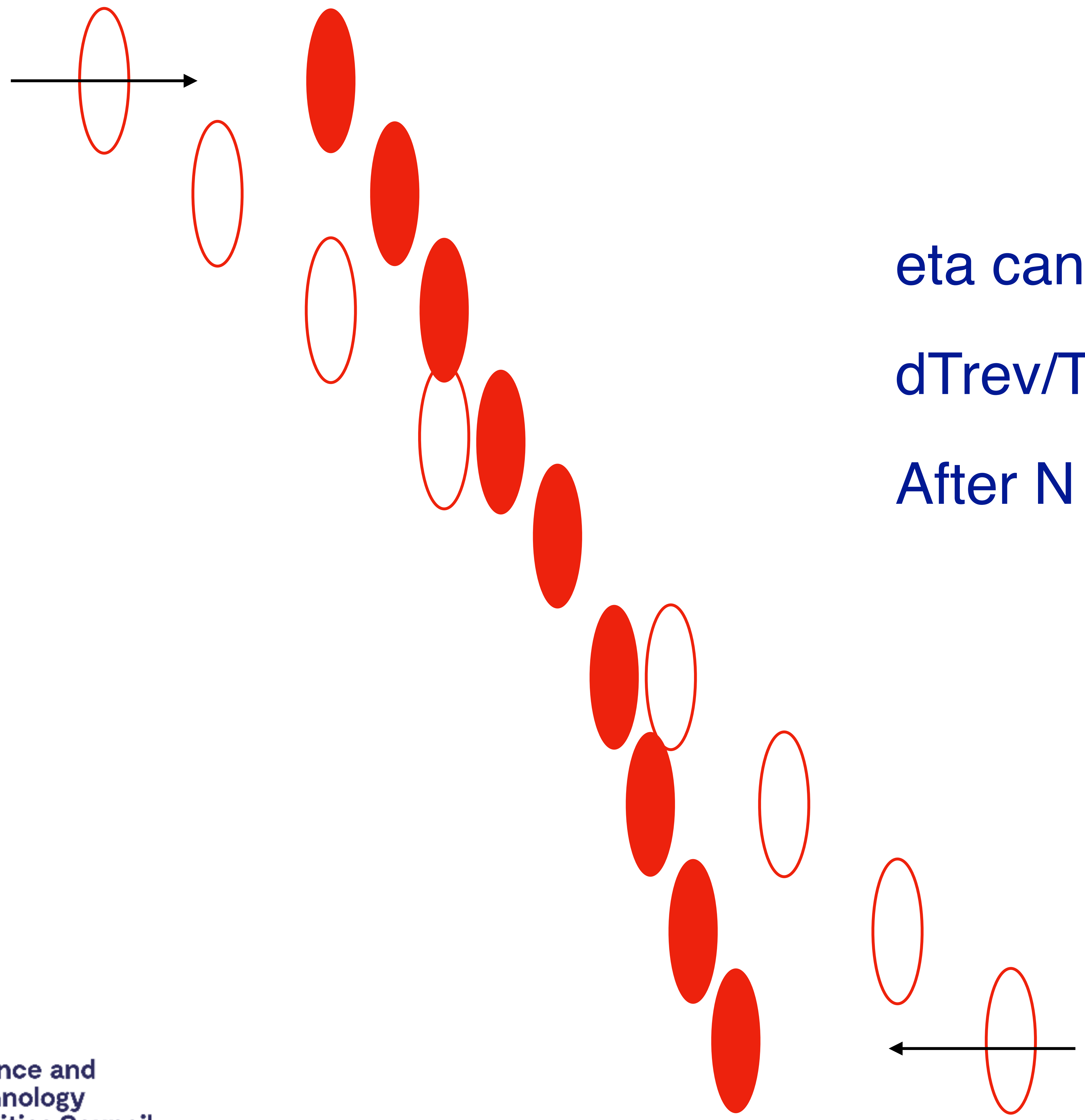
Either change eta in AR or extract all bunch to CR with eta!=0

- Let bunches start moving depends on the momentum. **No RF.**



eta can be 0.025 from the lattice design.

dTrev/Trev = eta dp/p

After N terns, N (dTrev/Trev) = N eta dp/p

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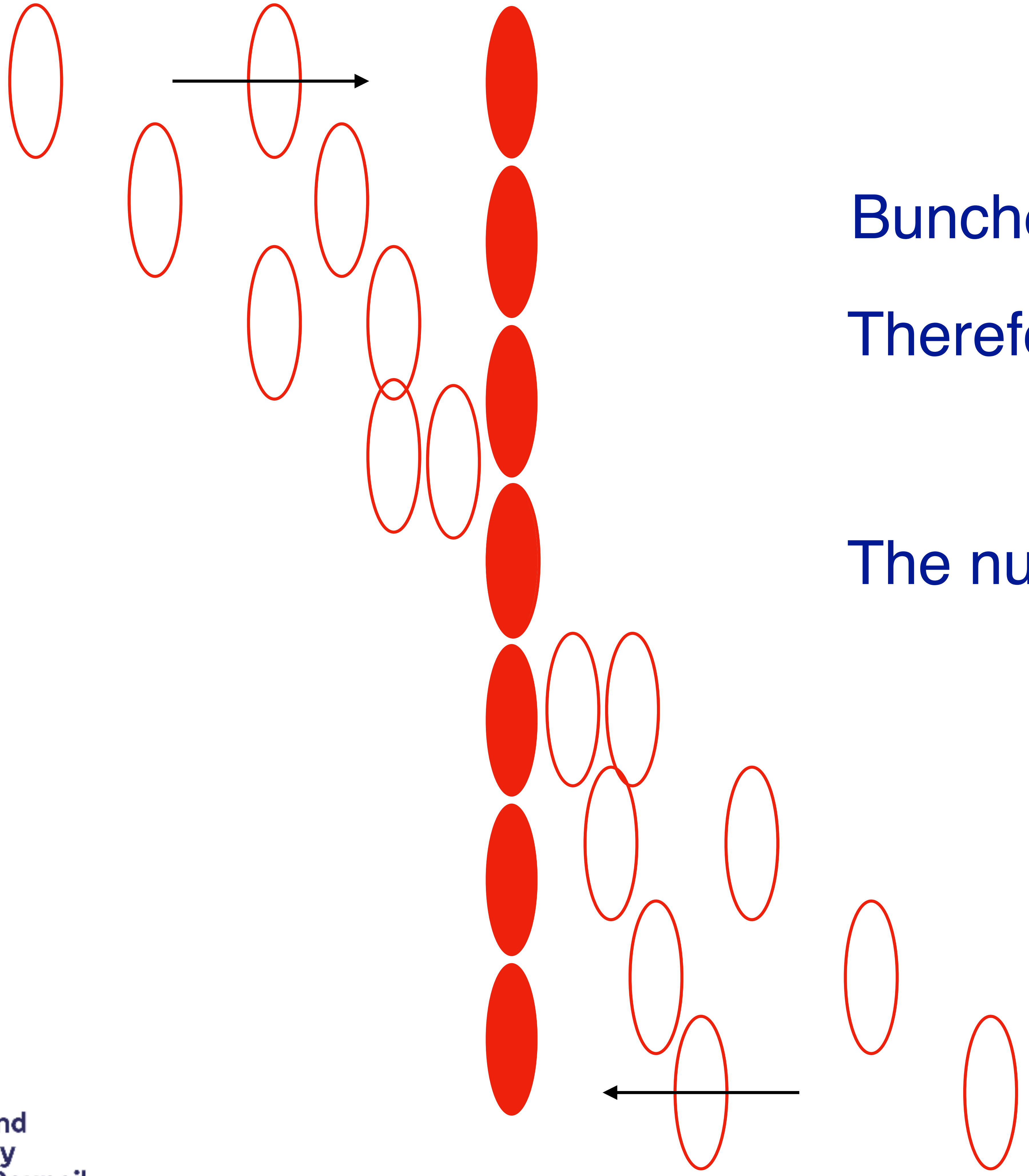
Wait until the bunches line up

- The final width depends on the momentum spread which the saw tooth RF created initially.



Bunches is aligned at straight line when N dTrev = Trev/2

Therefore, N = (1/2) / (eta dp/p) = (1/2) / (0.025 0.03)

= 667 turns

The number can be optimised by different parameters.

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Summary

- Designed a FMC lattice
    - eta can be flexible between 0 ~ 0.025.
    - AR and CR can be the physically identical lattice, but different quadrupole setting.
    - Can be a single ring with pulsed quadrupole?

- Phase rotation fundamentals
    - Longitudinal emittance is preserved.
    - Keep small initial longitudinal emittance is essential.

- Another way to creating a short bunch
    - Can the linac micro bunch structure be preserved?
    - Maybe!

Thank you for your attention.

Longitudinal space charge effects

- Only depends on the local gradient.

$$\Delta U = e\beta c R \frac{\partial \lambda}{\partial s} \frac{g_0 Z_0}{2\beta\gamma^2}$$

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Compressor Tentative Parameters

Table 11.2: Tentative Parameters Compressor.

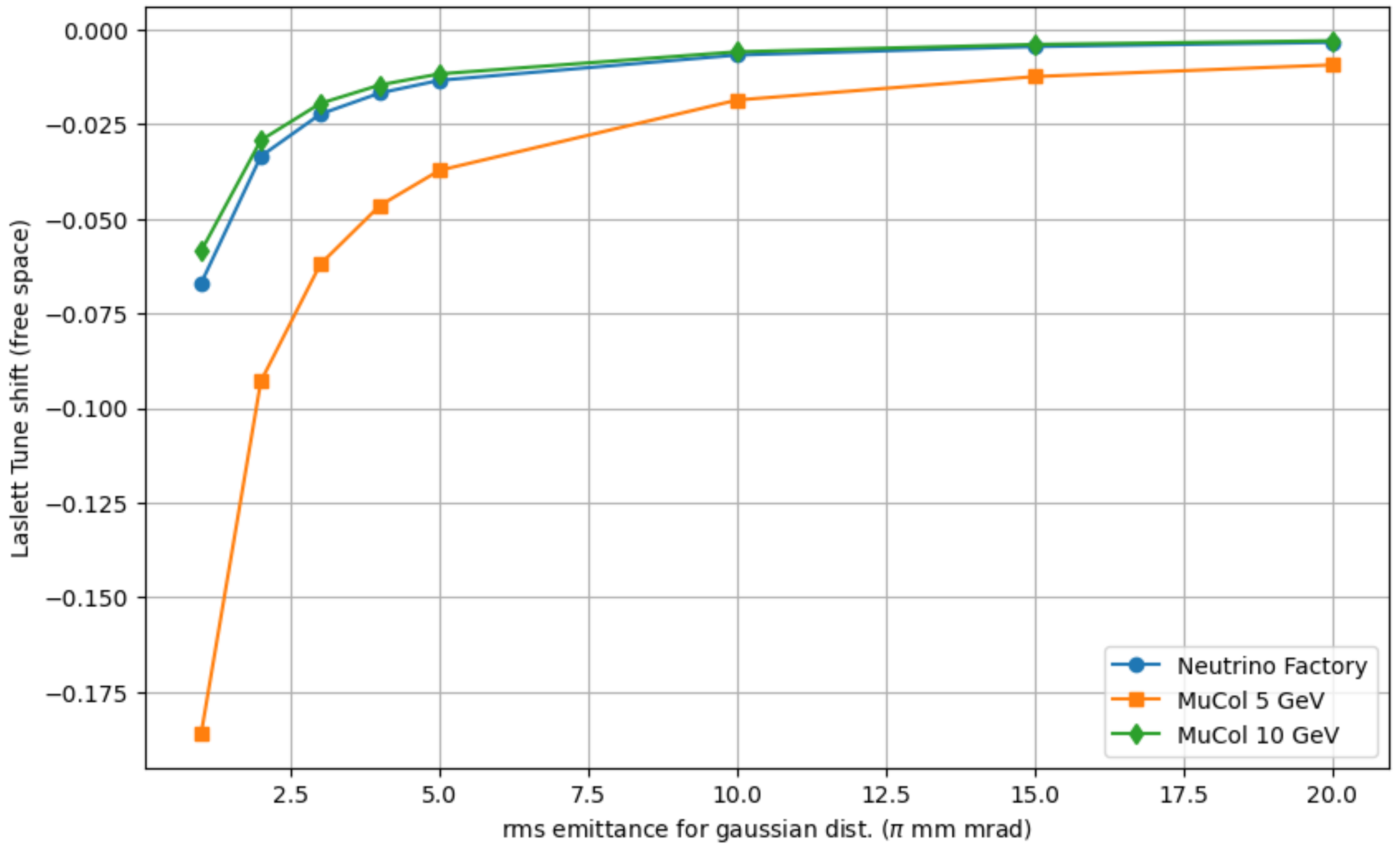
Parameters	Symbol	Unit	Option 1	Option 2
Energy	E_R	GeV	5	10
Circumference	C	m	between 300 to 900	
Protons on target	n_p	-	5×10^{14}	2.5×10^{14}
Final rms bunch length	σ_z	ns	2	
Geo. rms. emittance	$\varepsilon_{x,y}$	π mm mrad	>5	
Max. turn for full rotation	N_{rot}	-	50	

Lower energy : Target and existing design
Higher energy: MAPS study

Green field solution, i.e. we will
Not try to fit the ring in any available tunnel

Laslett tune shift (free space)

$$\Delta\nu = -\frac{n_b r_p}{4\pi\varepsilon\beta^2\gamma^3}$$



The max number of turns before extraction (turn to rotate the bunch) will drive:

1. Ring optics (phase slip factor)
2. RF Amplitude and phase (for rotation)
3. Ring dispersion control (because of the increasing energy spread of the bunch)
4. Amount of tune spread that can be handled

$$\eta = \frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2} \quad ,$$

$$\frac{1}{\gamma_{tr}^2} = \alpha_p = \frac{1}{C}\int_0^C \frac{D(s)}{\rho(s)} ds$$