Tapering options in the future low emittance high energy collider FCC-ee

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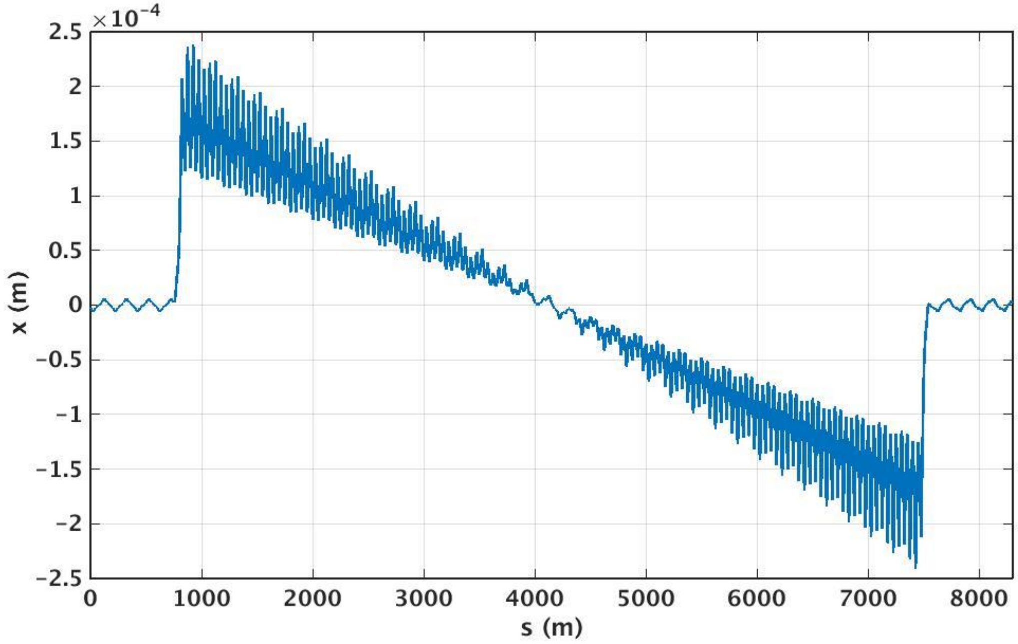
Sawtooth-Effect

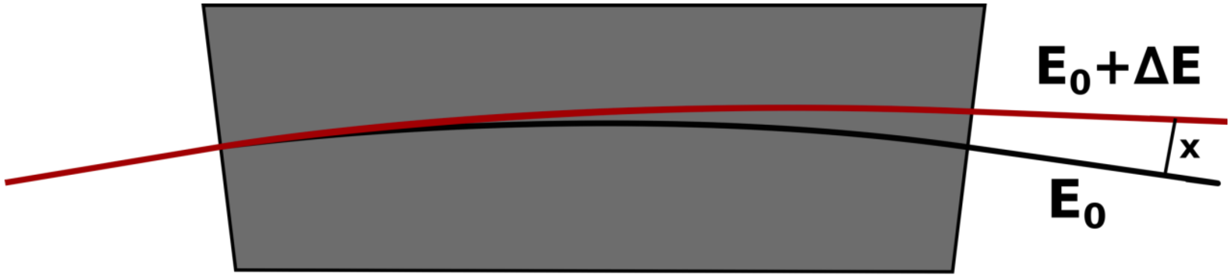
Energy loss through synchrotron radiation and energy gain in RF cavities leads to characteristic “Sawtooth-Effect”



Energy Dependent Bending Angle

$$x_D = D(s)\frac{\Delta E}{E_0}$$

$$\frac{\alpha}{l} = \frac{c}{E}B \qquad \alpha_{Dipole}(\Delta E) = \alpha_0(1 - \frac{\Delta E}{E_0})$$



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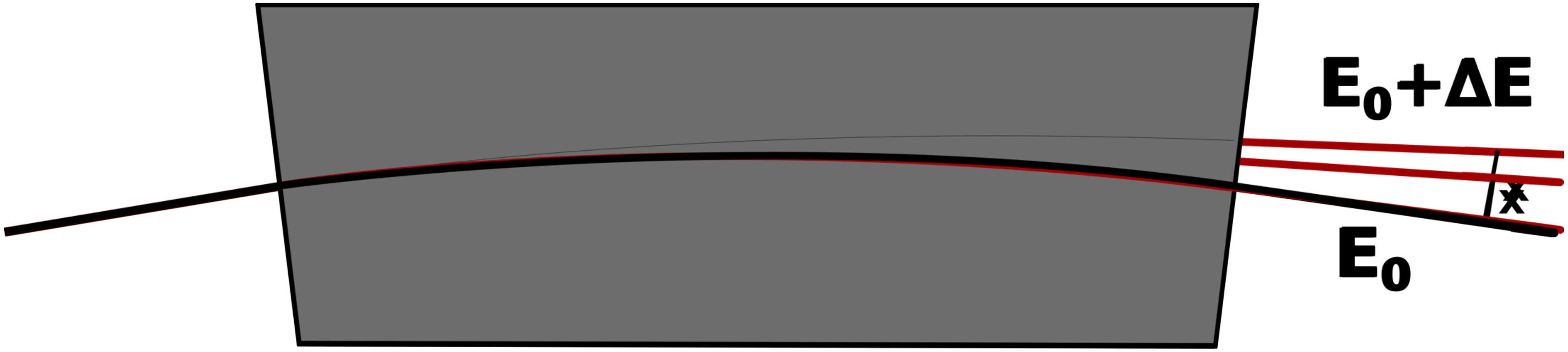
Normally the sawtooth-effect would just be accepted, but in FCC-ee, the sawtooth orbit is in the mm-range ➔ feeddown-effect of sextupoles and quadrupoles creates additional magnetic fields that distort the optics

What is Tapering?

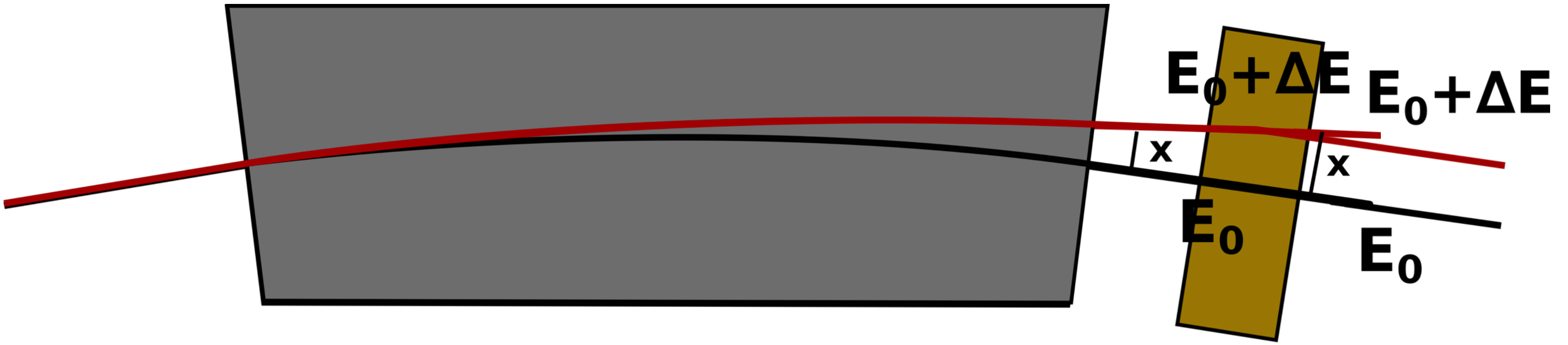
Tapering: Adjusting the strength of each magnet so that the beam with local energy of $E_0+\Delta E$ is on the design orbit

Of course tapering every magnet in the ring is both expensive and difficult to maintain ➔ just dipole tapering and remachting the optics using dispersion suppressors and matching sections



Analytical Tapering

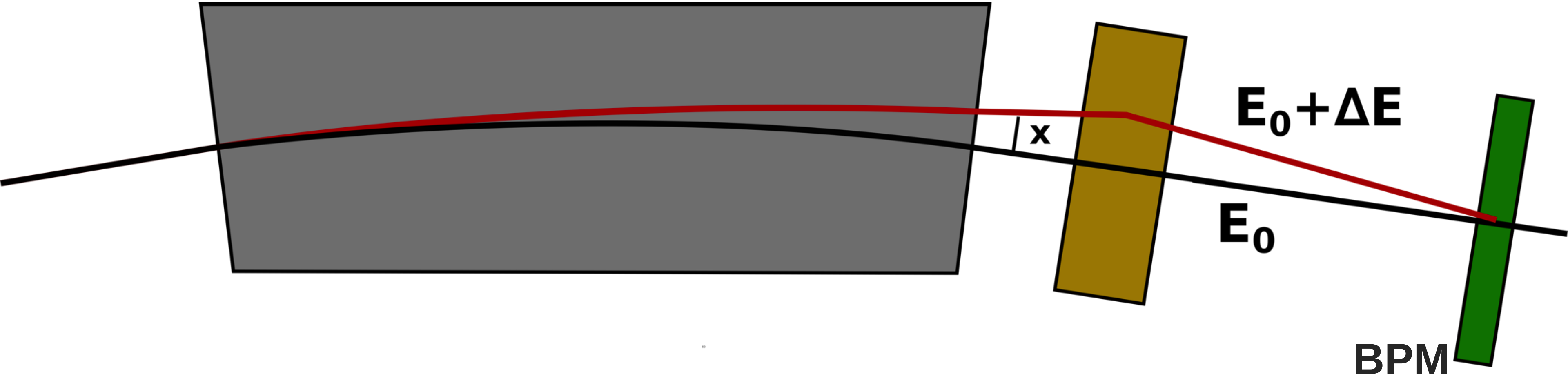
$$\alpha_{Dipole}(\Delta E) = \alpha_0 (1 - \frac{\Delta E}{E_0}) \rightarrow \alpha_{Kicker}(\Delta E) = \alpha_0 \frac{\Delta E}{E_0}$$



Numerical Tapering

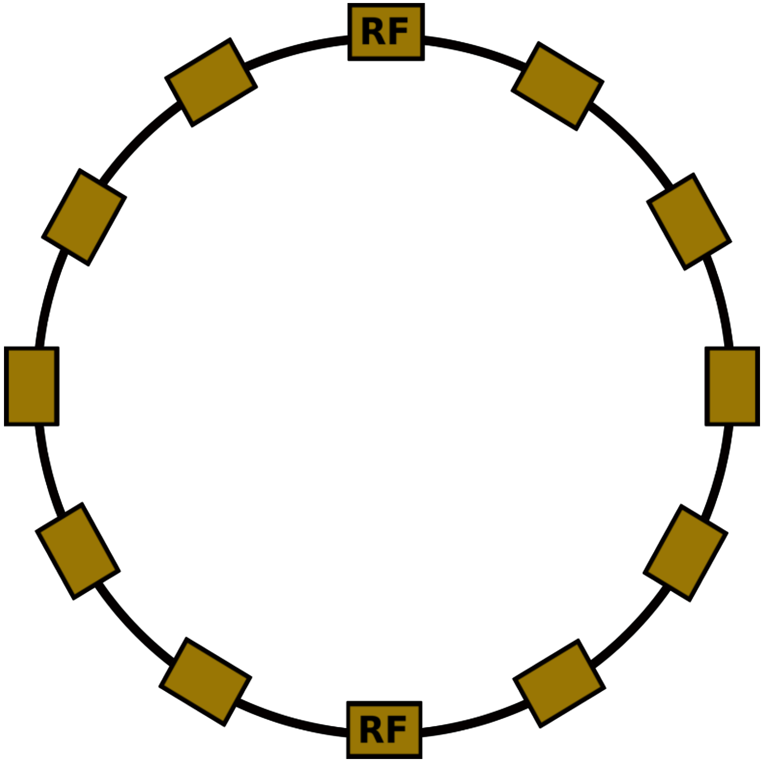
- Kicker don't just compensate the energy dependent dipole bending angles, but the orbit is optimized numerically
- Kicker strength α_{Kicker} calculated using orbit correction in MAD-X

$$\alpha_{Kicker}(\Delta E) = ?$$



The Lattices

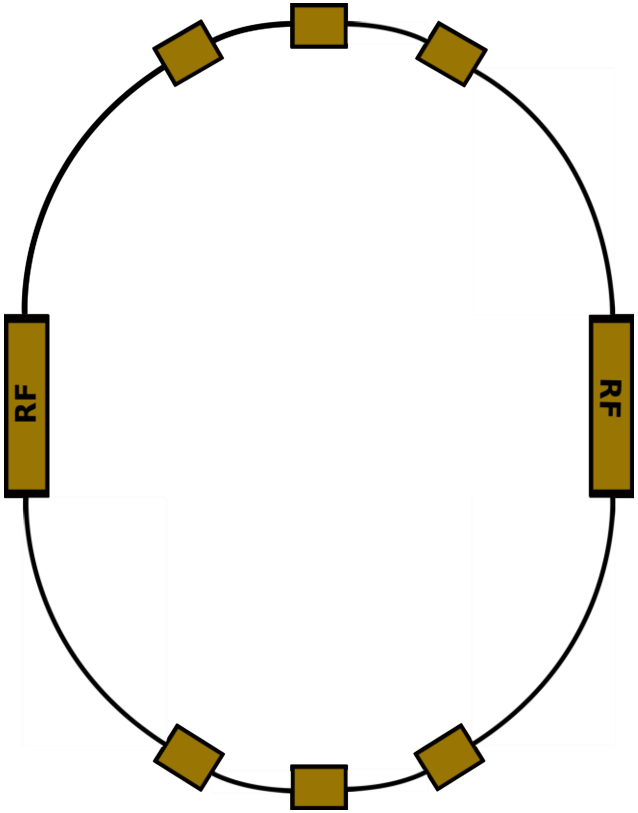
FCC-ee 12-fold



- Circumference: 100 km
- Energy: 175 GeV
- Energy Loss/Turn ≈ 8046 MeV
- 12 RF Sections (L= 1.8 km)
- 12 Arcs (L= 6.8 km)

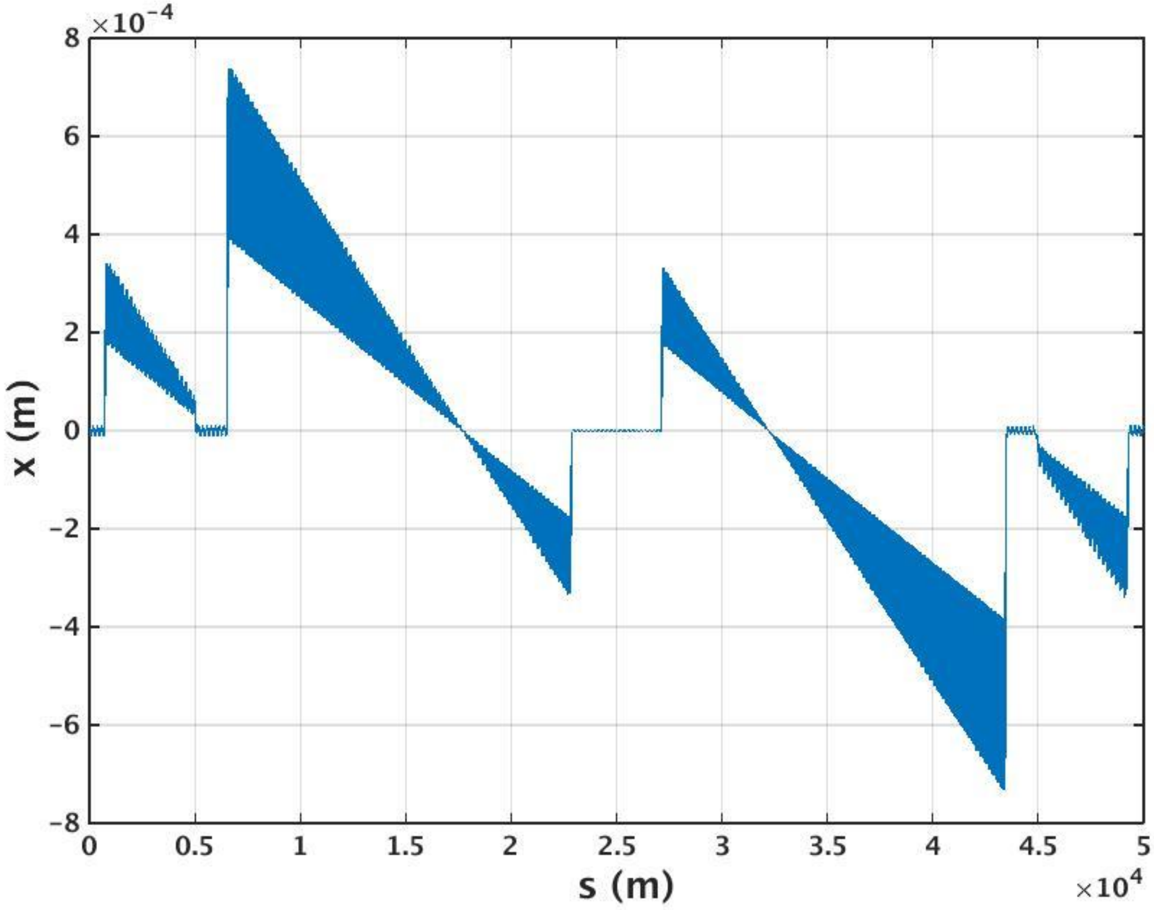
The Lattices

FCC-ee Racetrack

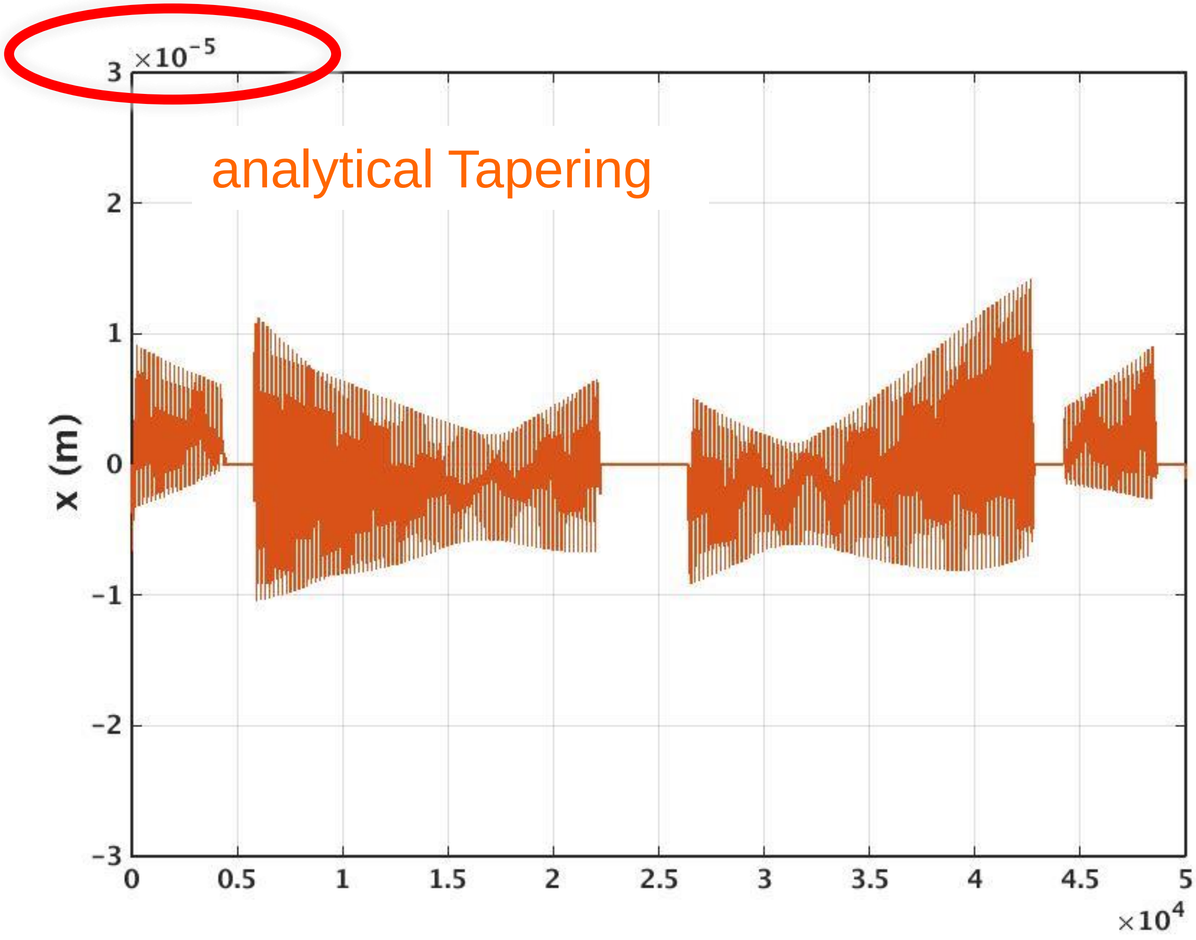


- Circumference: 100 km
- Energy: 175 GeV
- Energy Loss/Turn ≈ 7870 MeV
- 4 Short Arcs (L= 4,4 km)
- 4 Long Arcs (L= 16,4 km)
- 6 Short RF Sections (L= 1,4 km)
- 2 RF Section (L= 4,2 km)

Racetrack Lattice, 8 RF Sections



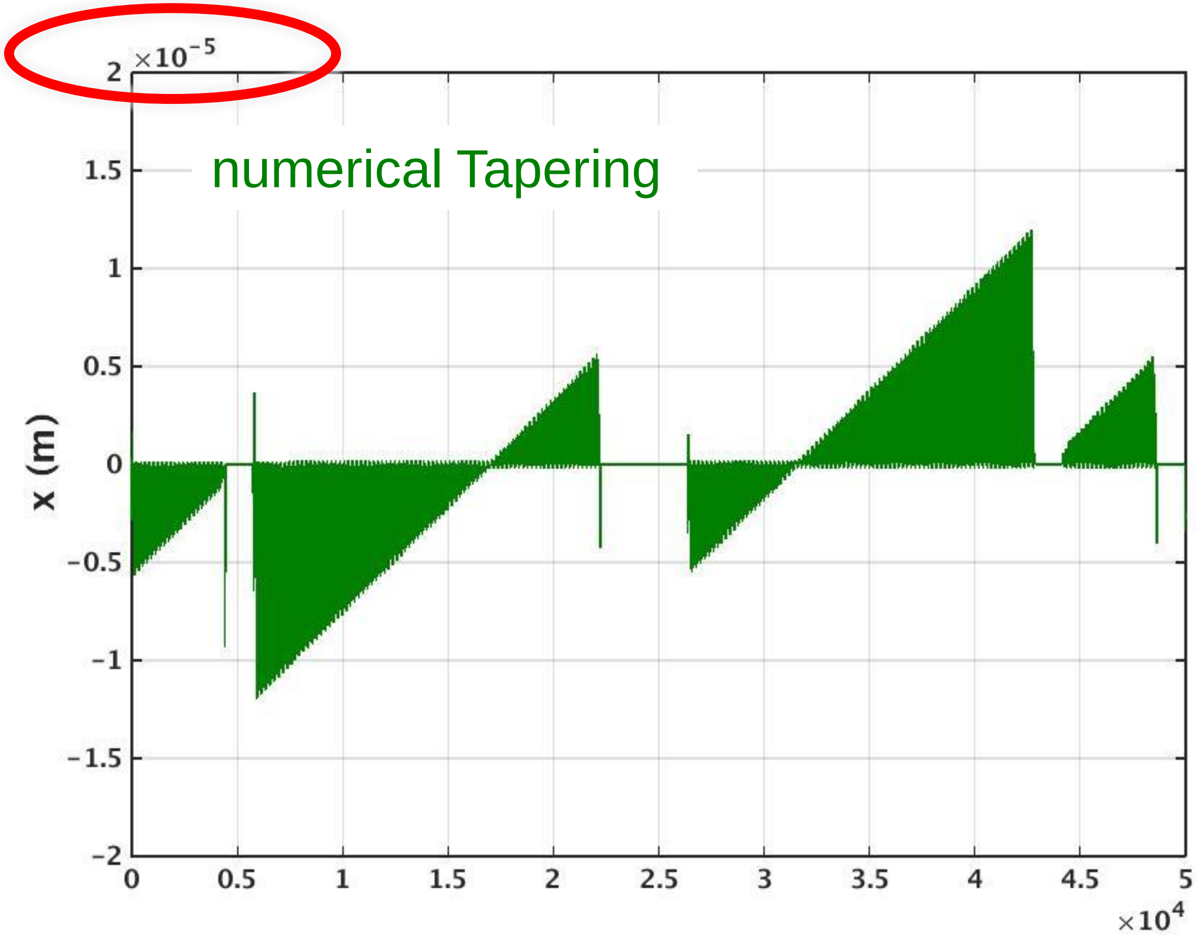
Racetrack Lattice, 8 RF Sections



- sextupoles off
- no IPs
- kicker length: 0.0 m

- β_x-Beat: 1%
- β_y-Beat: 1,5%
- D_x-Beat: 4%

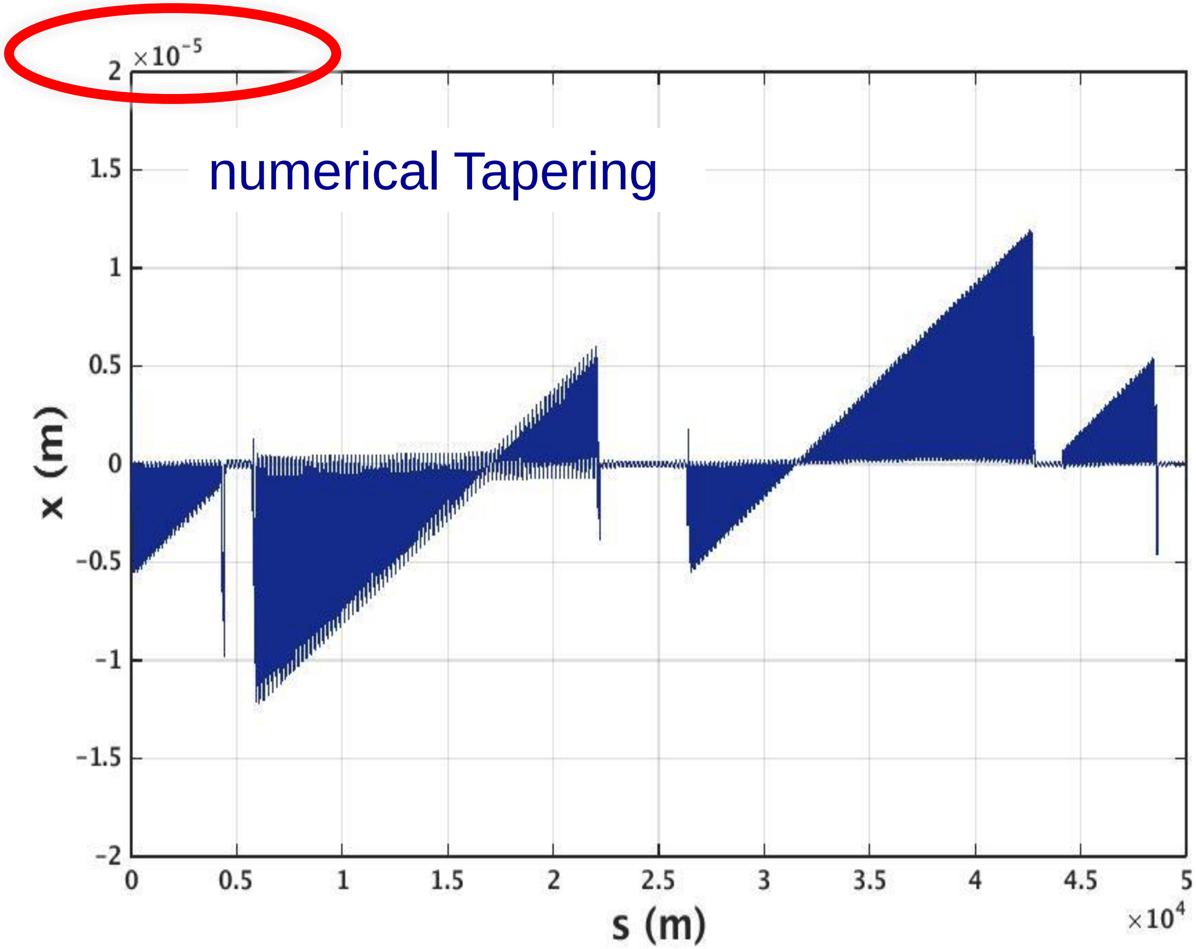
Racetrack Lattice, 8 RF Sections



- sextupoles off
- no IPs
- kicker length: 0.0 m

- β_x-Beat: 2%
- β_y-Beat: 2%
- D_x-Beat: 5%

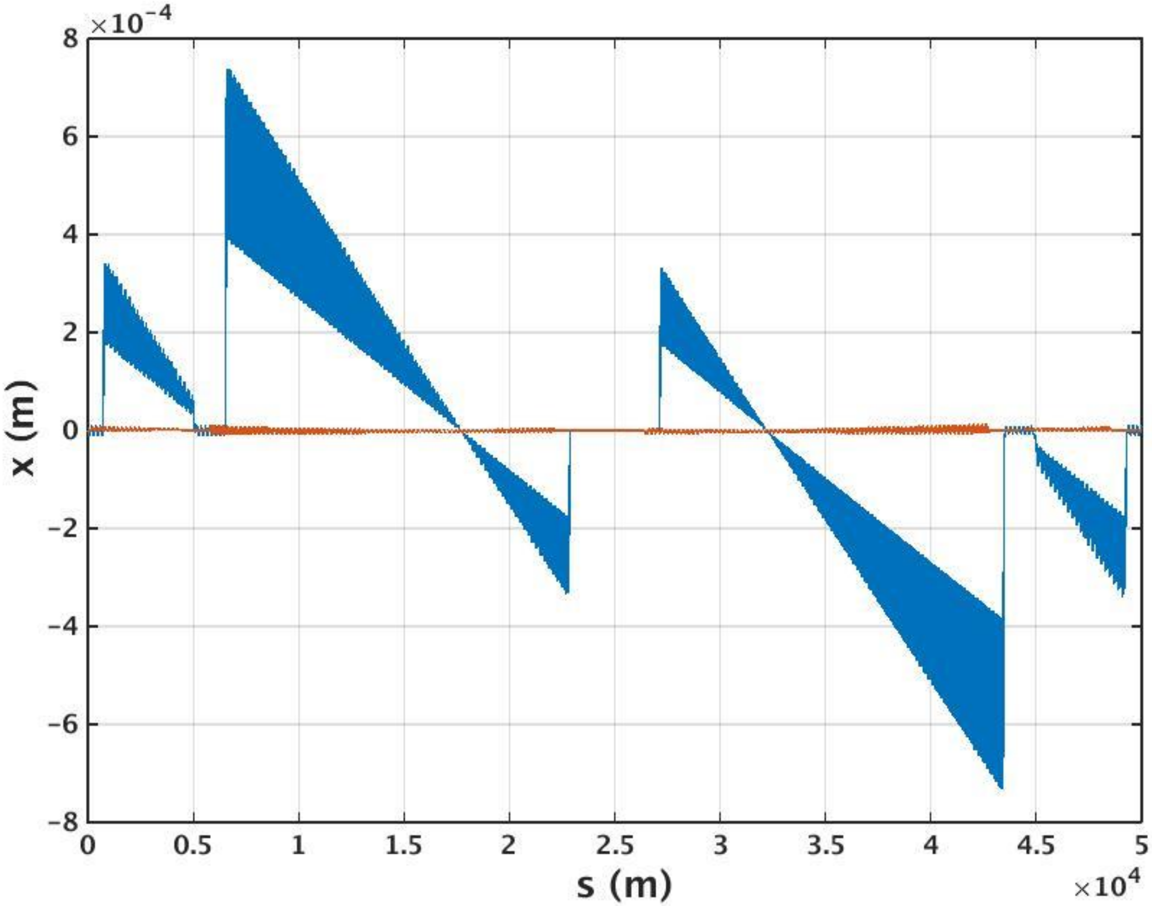
Racetrack Lattice, 8 RF Sections



- sextupoles on
- 2 IPs
- kicker length: 0.2 m

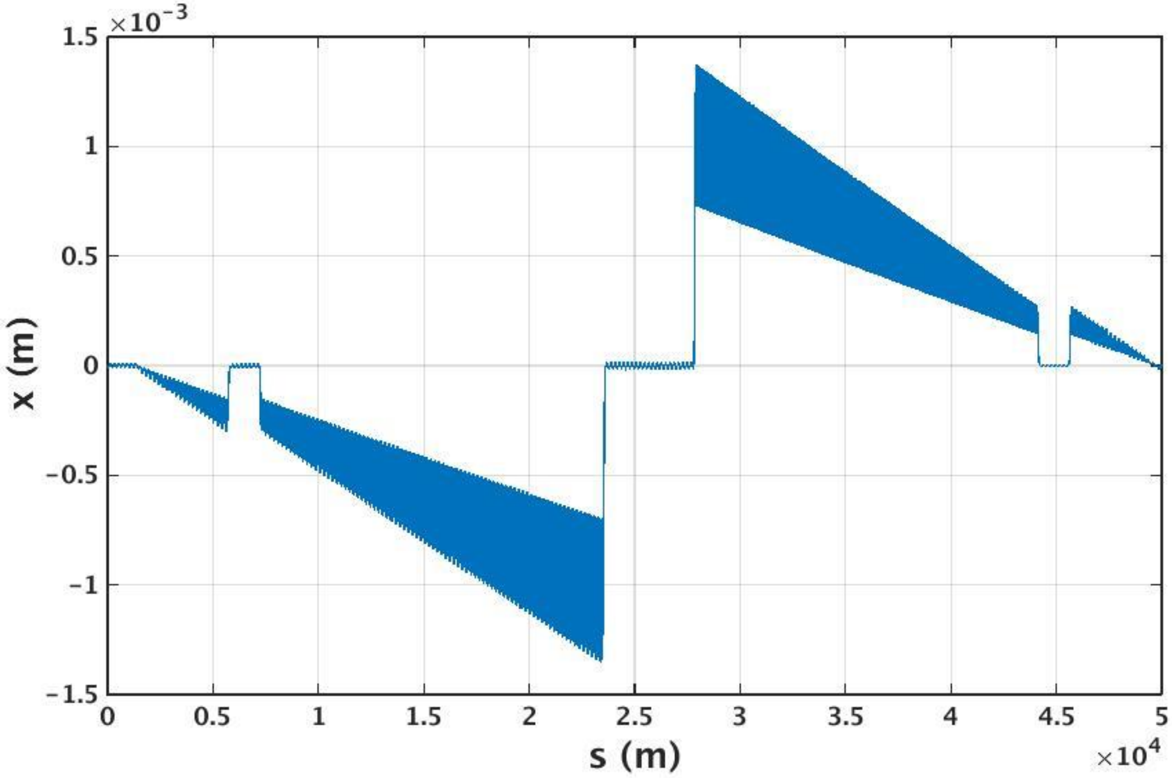
- β_x-Beat: 6%
- β_y-Beat: 12%
- D_x-Beat: 5%

Racetrack Lattice, 8 RF Sections

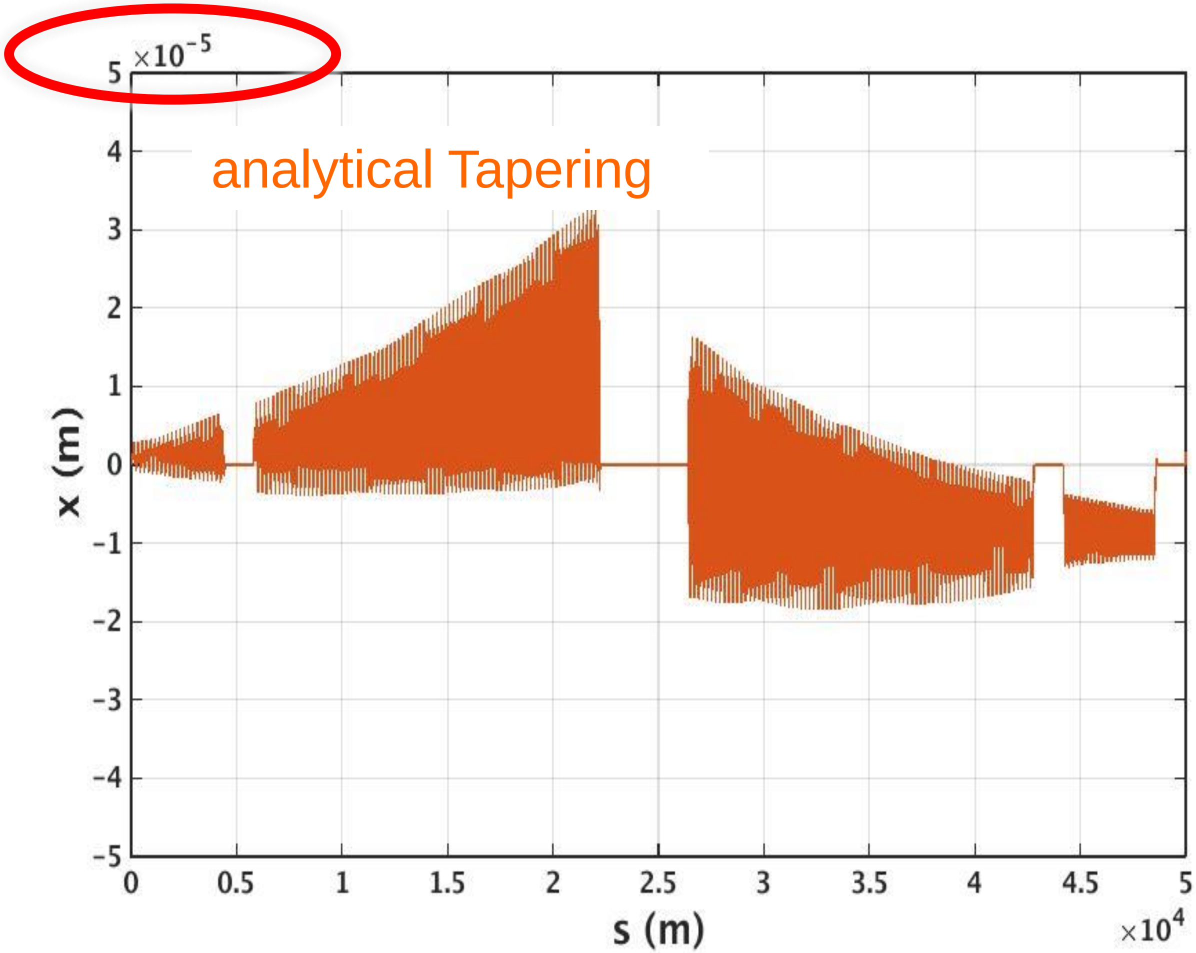


➔ tapered orbit
≈ factor 70 smaller

Racetrack Lattice, 2 RF Sections



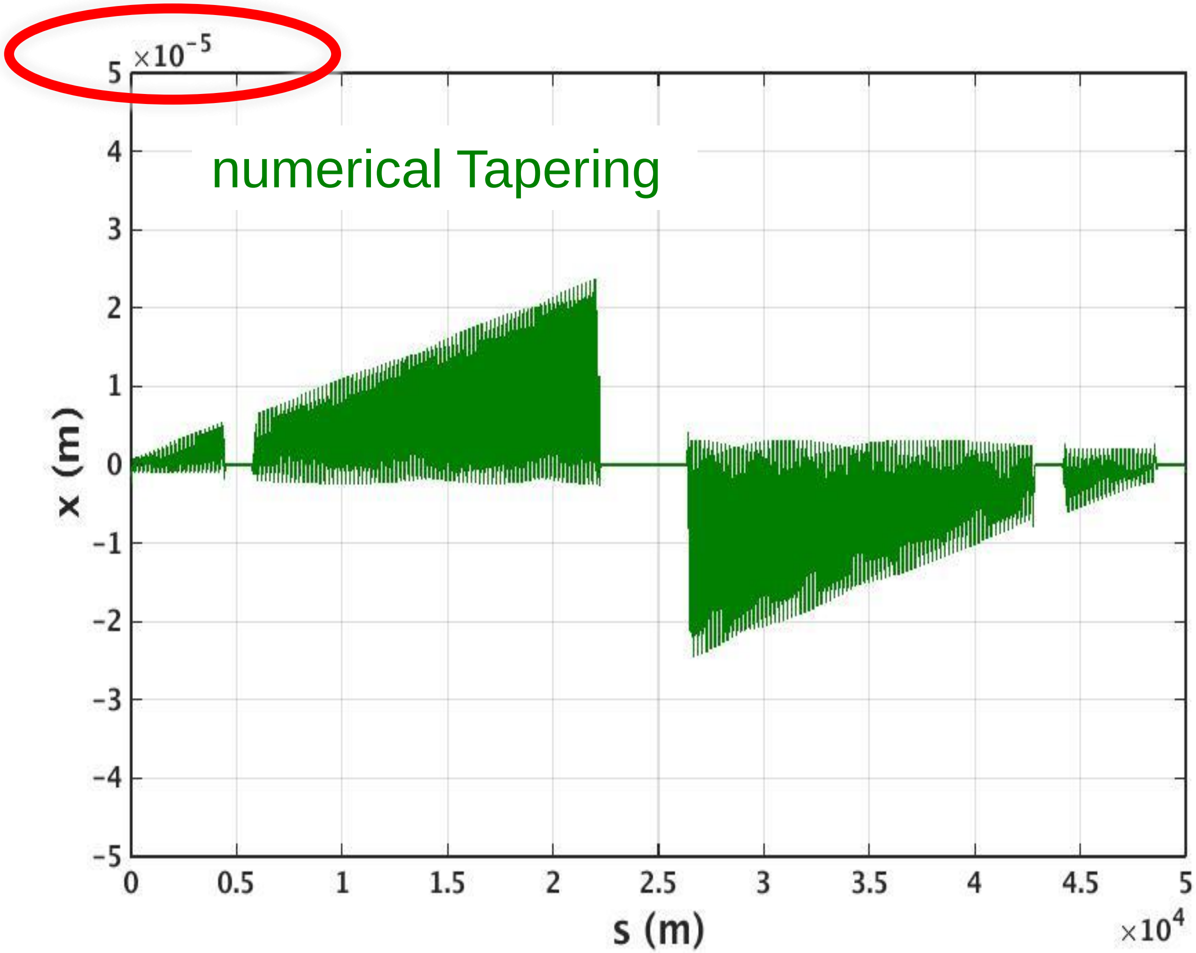
Racetrack Lattice, 2 RF Sections



- sextupoles off
- no IPs
- kicker length: 0.0 m

- β_x-Beat: 3%
- β_y-Beat: 5%
- D_x-Beat: 5%

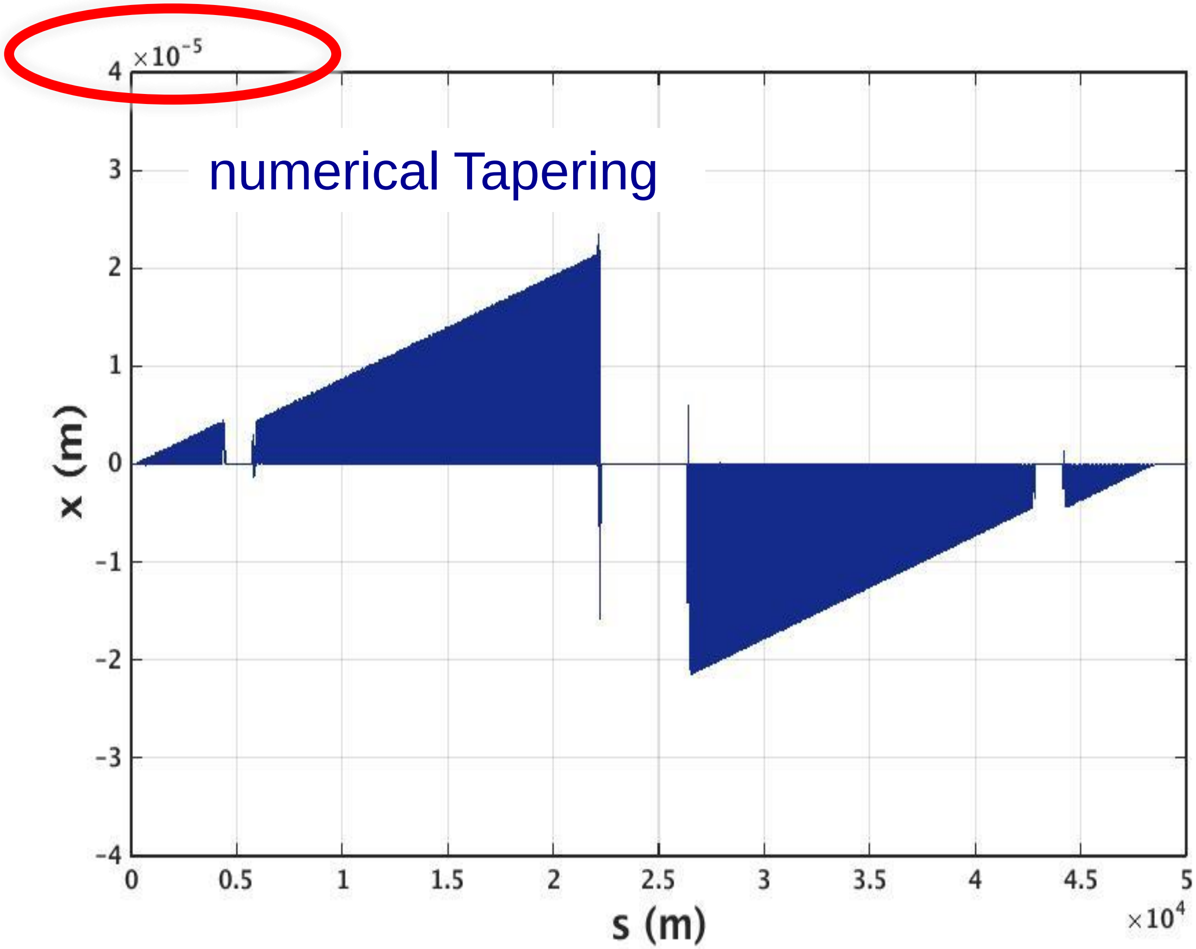
Racetrack Lattice, 2 RF Sections



- sextupoles off
- no IPs
- kicker length: 0.0 m

- β_x-Beat: 5%
- β_y-Beat: 6%
- D_x-Beat: 6%

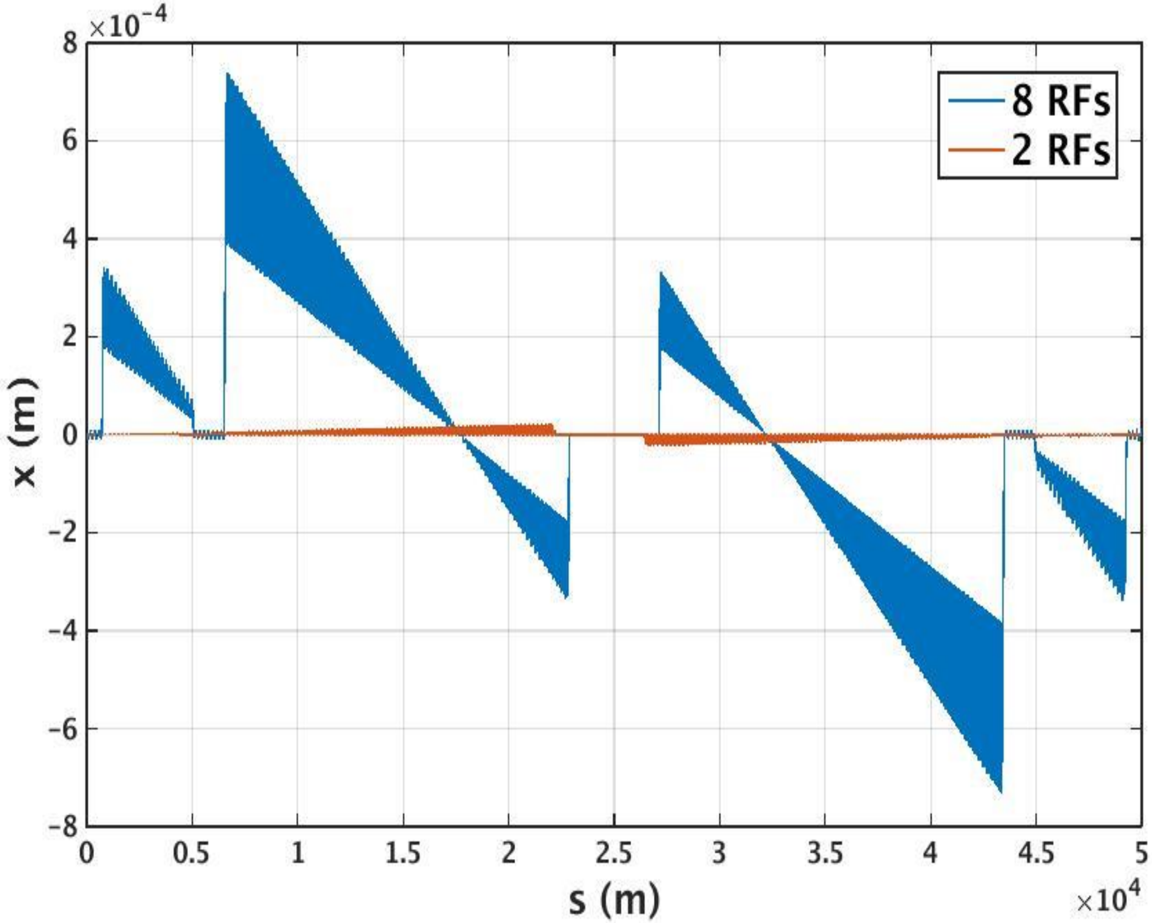
Racetrack Lattice, 2 RF Sections



- sextupoles on
- 2 IPs
- kicker length: 0.2 m

- β_x-Beat: 9%
- β_y-Beat: 14%
- D_x-Beat: 2%

8 vs. 2 RF sections



➔ tapered orbit with 2 RF sections still ≈ factor 40 smaller than untapered orbit with 8 RF sections

Kicker Strengths & Emittances

Magnet:	B*l (Tm):
Arc Dipole	$5.56*10^{-1}$
Kicker (175 GeV, 8RFs)	$7.82*10^{-4}$
Kicker (175 GeV, 2RFs)	$6.42*10^{-3}$

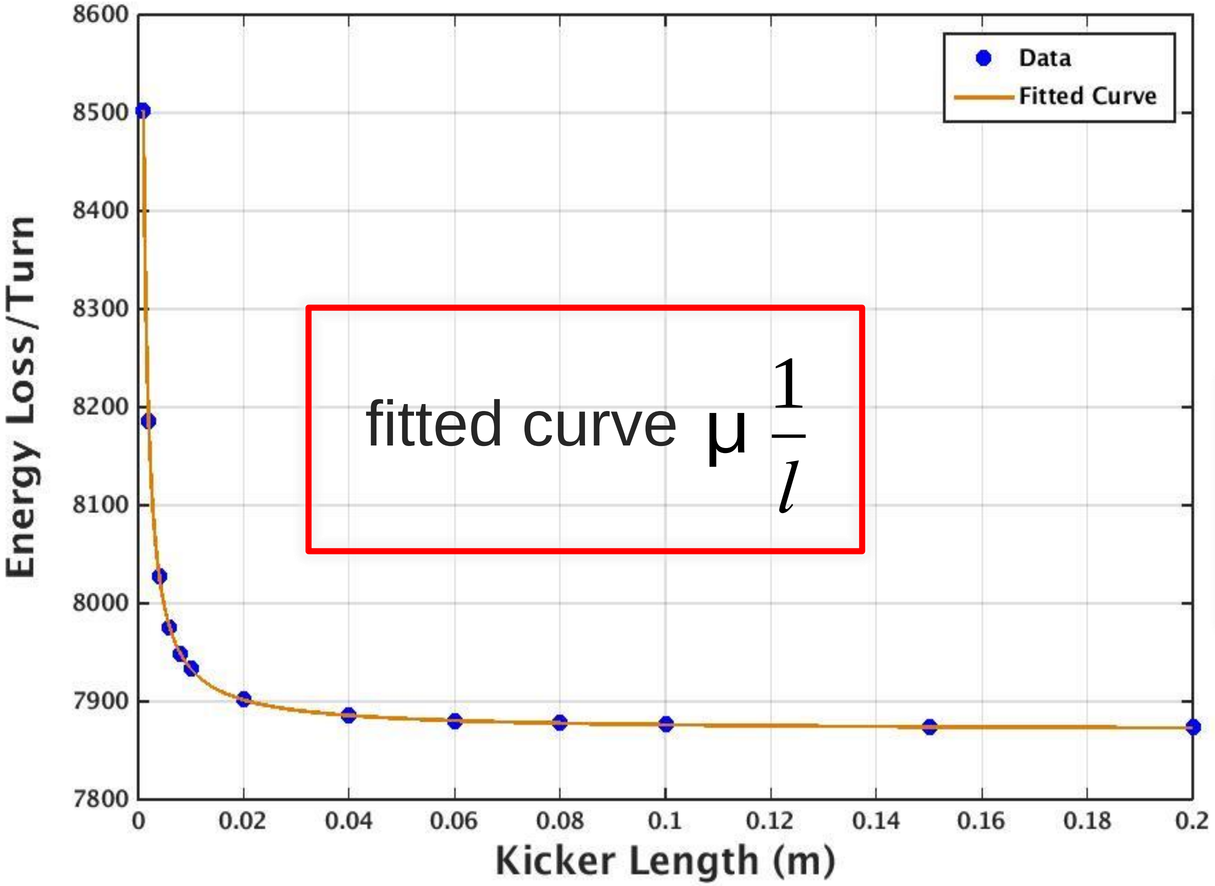
e.g.: for a kicker length of 0.2m, $B_{kick} \approx 0.07*B_{dipole}$ for 8 RFs → $U_{0,\ Kick} \approx$ 400 keV

$B_{kick} \approx 0.57*B_{dipole}$ for 2 RFs → $U_{0,\ Kick} \approx$ 26 MeV

Lattice:	ε_x before tapering (nm*rad):	ε_x after tapering (nm*rad):
8 RFs	0.9263	0.9512
2 RFs	0.9269	0.9728

Correction Kickers in MAD-X

Are correction kickers suited for tapering studies in MAD-X?



in agreement with calculations:

$$U_0 \propto I_2 \propto \frac{\alpha^2}{l}$$

Correction Kickers in MAD-X

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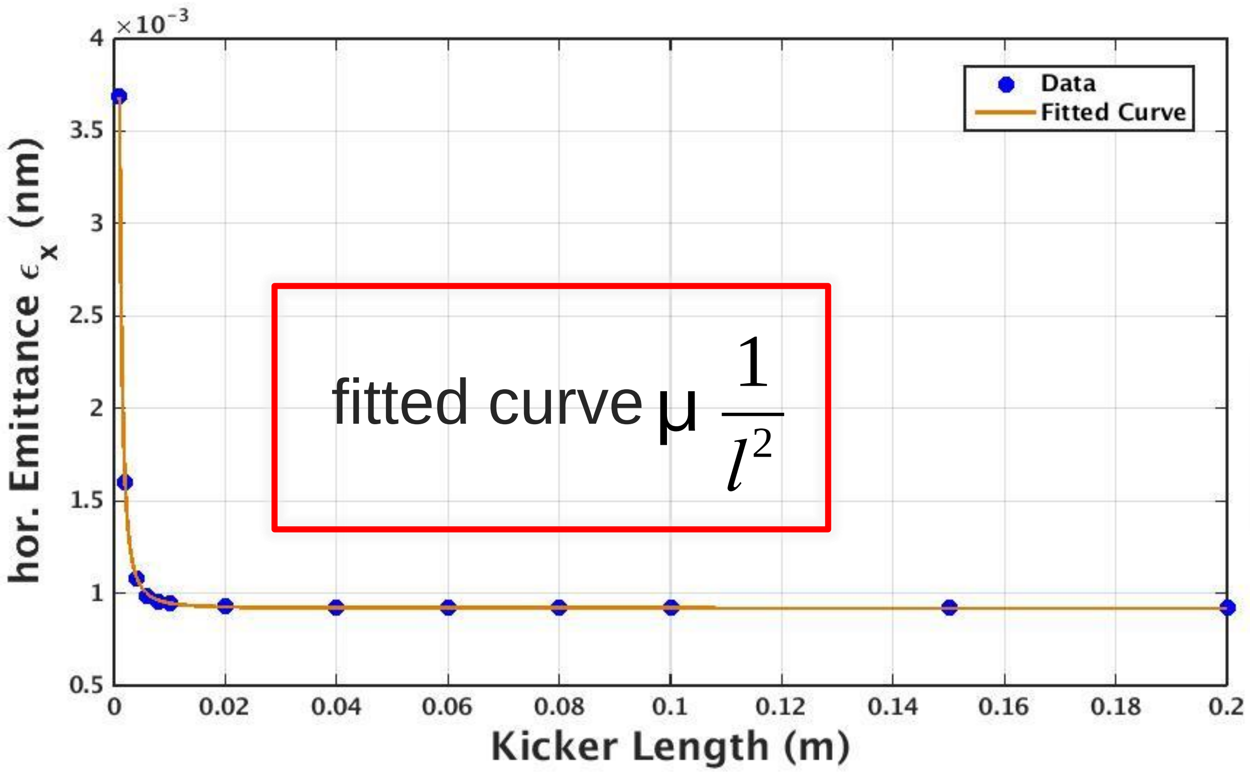

$$\epsilon_x \propto \frac{I5}{I2} \propto \frac{\alpha < \mathcal{H} >}{l}$$

?

Summary & Conclusions

- Several Tapering Methods possible
- Orbit improvement through dipole tapering with kickers: ≈ Factor 50-80 (depending on method, lattice, number of RFs,...)
- Integrated strengths of the tapering kickers are ≤ 1% of the integrated strengths of the arc dipoles
- Emittances are nearly unaffected by the tapering process

- Next Steps: Checking the effects of the kicker magnets on orbit tolerances, using orbit correction kickers (already in the ring) for tapering