LATTICES FOR SYNCHROTRONS WITH STRONG DIRECT SPACE CHARGE

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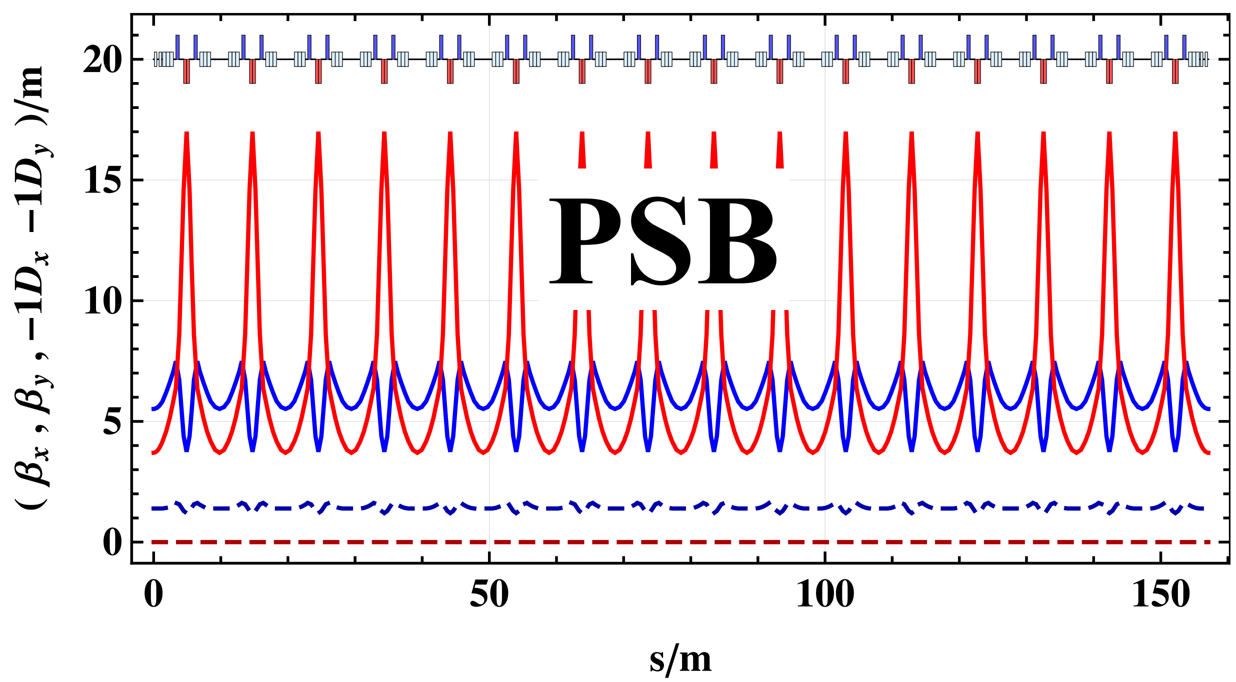
Acknowledgements: AccNet-EuCARD

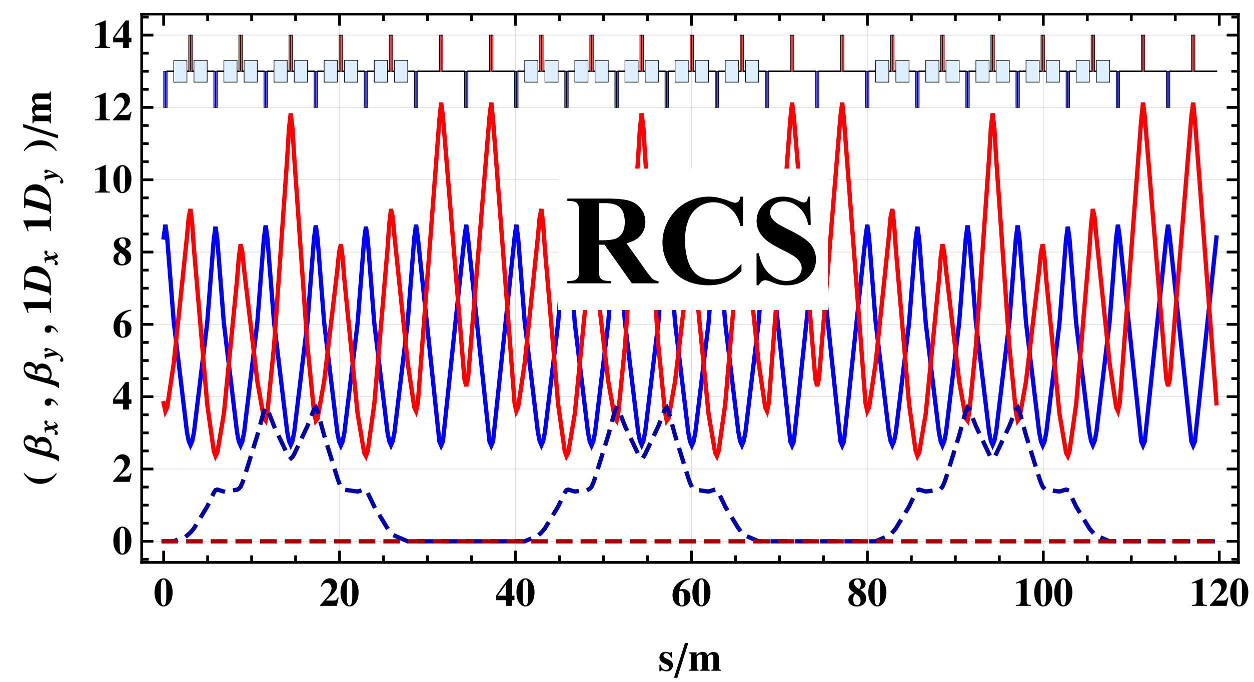
Outline

- Motivation
- Optics studies
- Summary

Motivation

RCS as alternative to the PS-Booster 2 GeV Upgrade (2011)





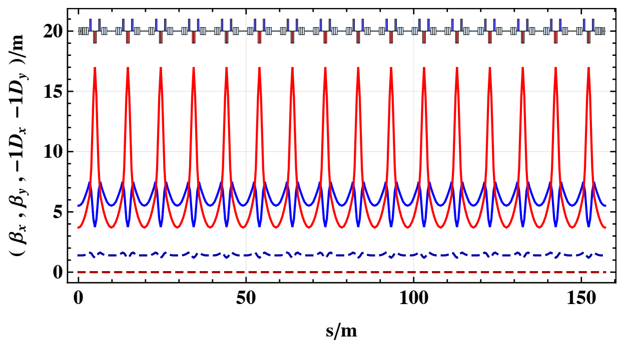
➡ How do the linear optics influence the machine performance under consideration of strong direct space-charge effects?

Optics Studies

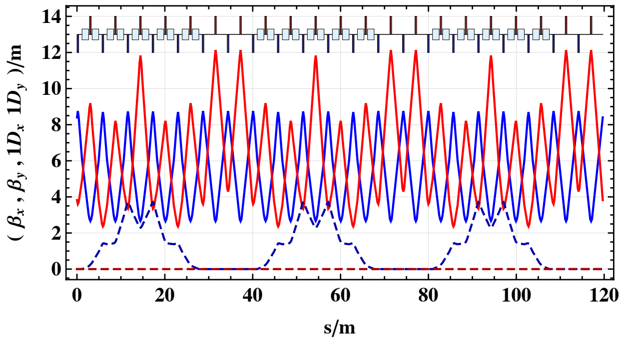
characteristics:

- variation of the beam size
- symmetry
- periodicity (number of lattice cells)
- phase advance per cell
- influence of dispersion (dispersion suppression schemes)

PSB



RCS



Objective of the simulations:

Design lattices/optics which allow to investigate the impact of the different optics characteristics on the emittance evolution under consideration of direct SC effects.

Many optics have been studied and compared (see [1]). In this talk only two studies are presented:

- symmetry and the relevance of systematic resonances
- influence of dispersion and the dispersion suppressor scheme

[1] M. Fitterer, *Design Study of the Large Hadron Electron Collider and a Rapid Cycling Synchrotron as Alternative to the PS Booster Upgrade at CERN,* PhD Thesis, to be published

Optics Studies

Simulation code: PTC-ORBIT
Beam parameters: LHC 25 ns beam

} for further details see backup slides

Simulated effects:

- linear lattice (only dipoles and quadrupoles)
- no fringe fields (dipole fringe fields can not be disabled, but dynamic aperture studies show that the effect of the dipole fringe fields is expected to be small)
- no field or alignment errors

- SC model: 2 1/2 D with adjusted grid

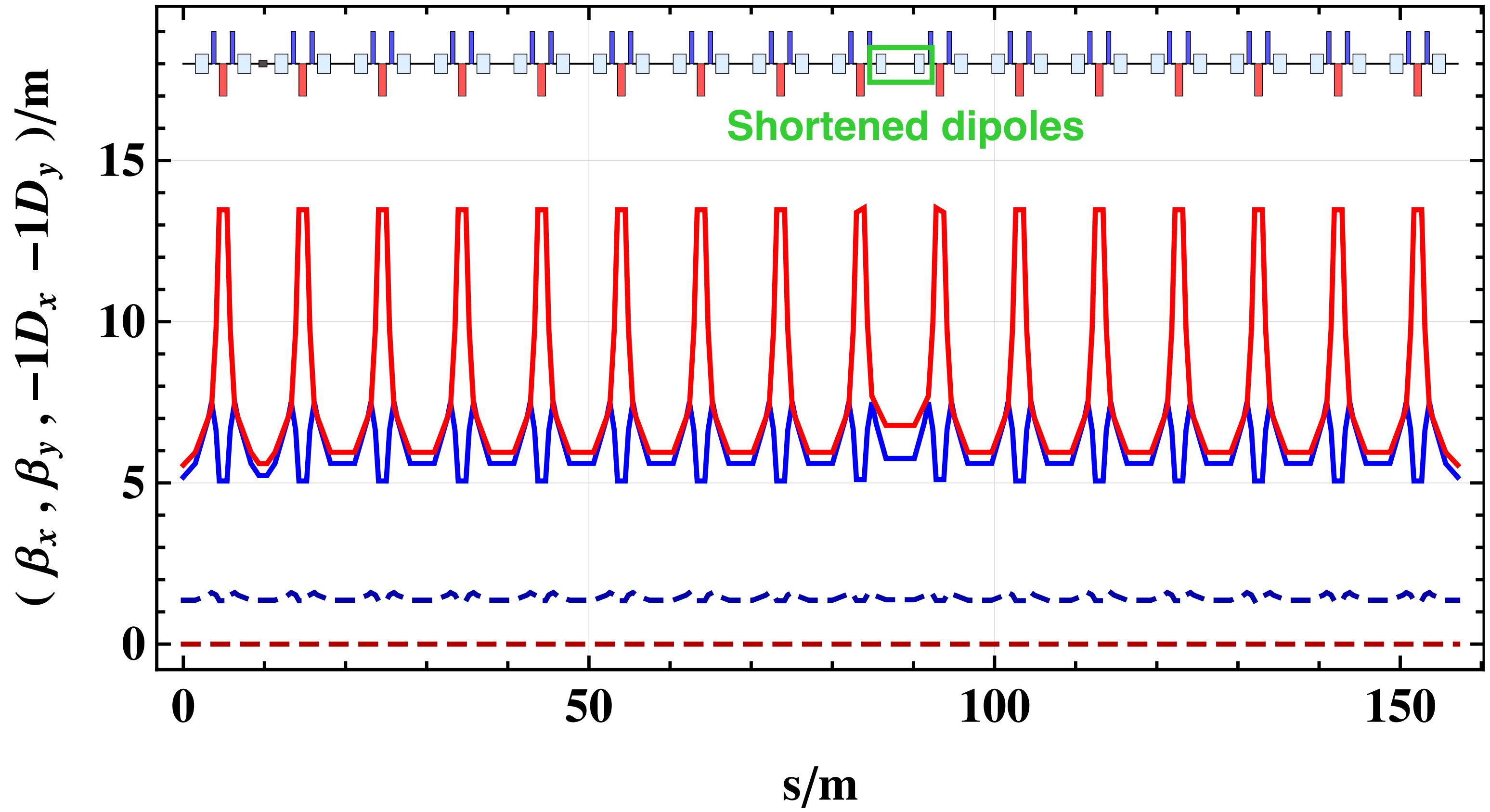
➡ no lattice non-linearities

➡ non-linear effects only due to SC

Optics Studies - Symmetry

1. Influence of "weak" symmetry breaking

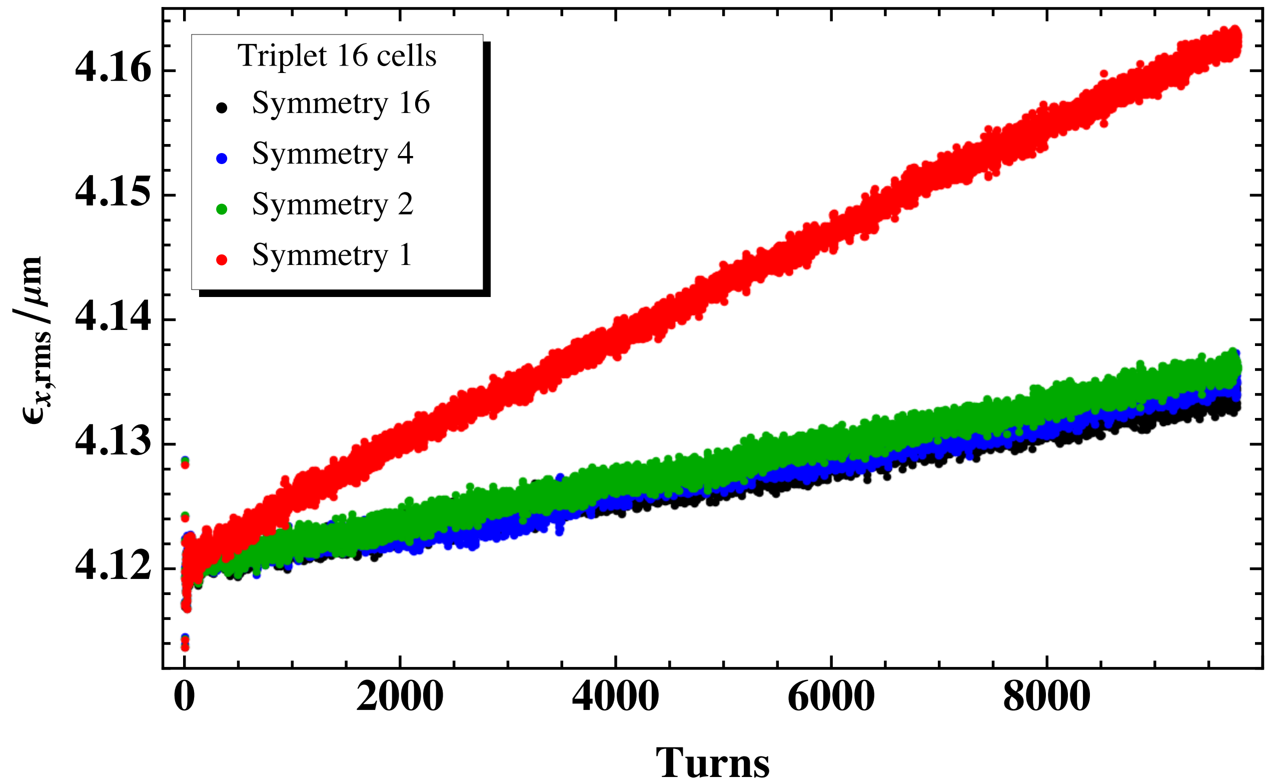
Lattice: PS Booster lattice (16 cell triplet lattice), $Q_{x/y}$=4.28/3.55
Symmetry: 16, 4, 2 and 1, symmetry is broken by shortening the bends in 4, 2 and 1 triplet cell(s), beta-beating correction with triplet adjacent to shortened bends

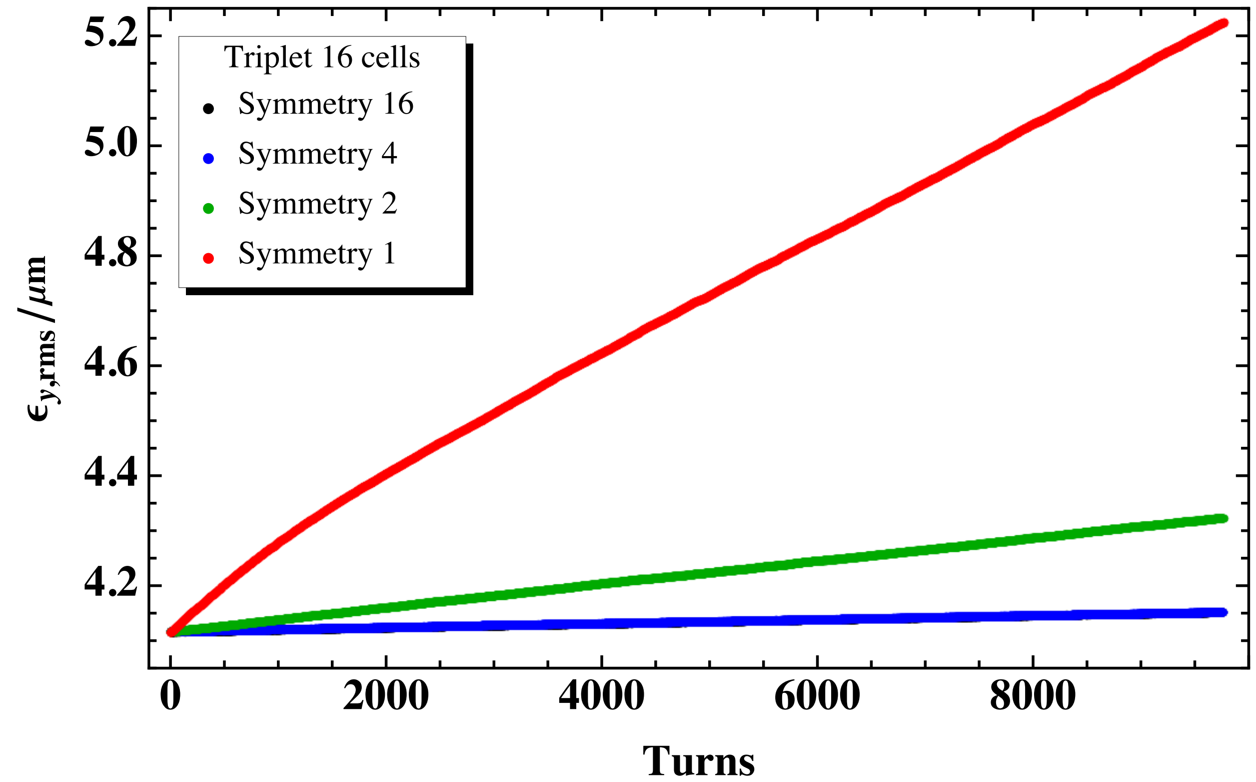


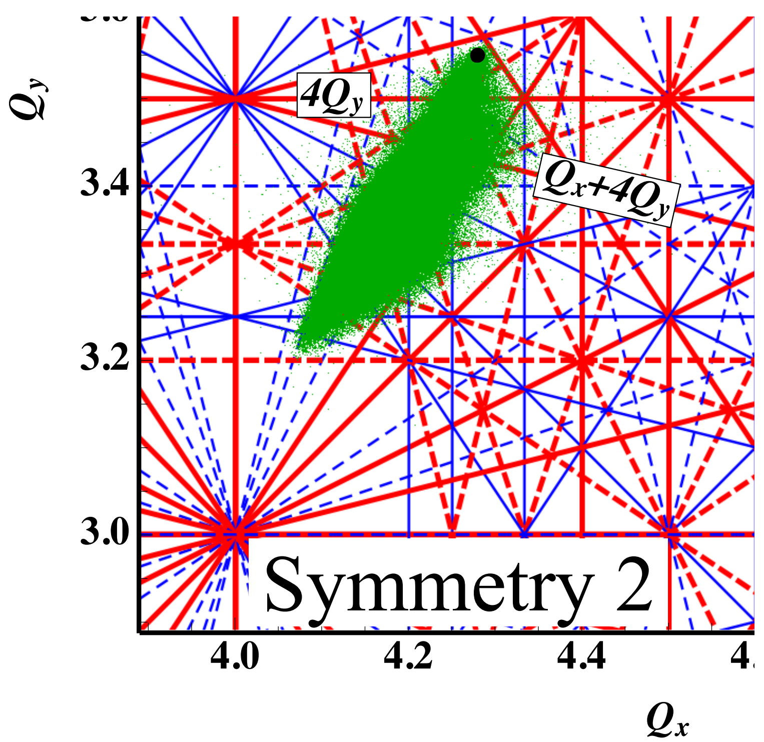
PS Booster Upgrade:

It was proposed to shorten the bends in the injection region due to space reasons
⇒ Reduction from symmetry 16 to symmetry 1!

Optics Studies - Symmetry







Fourier analysis of the beam moments after 1024 turns

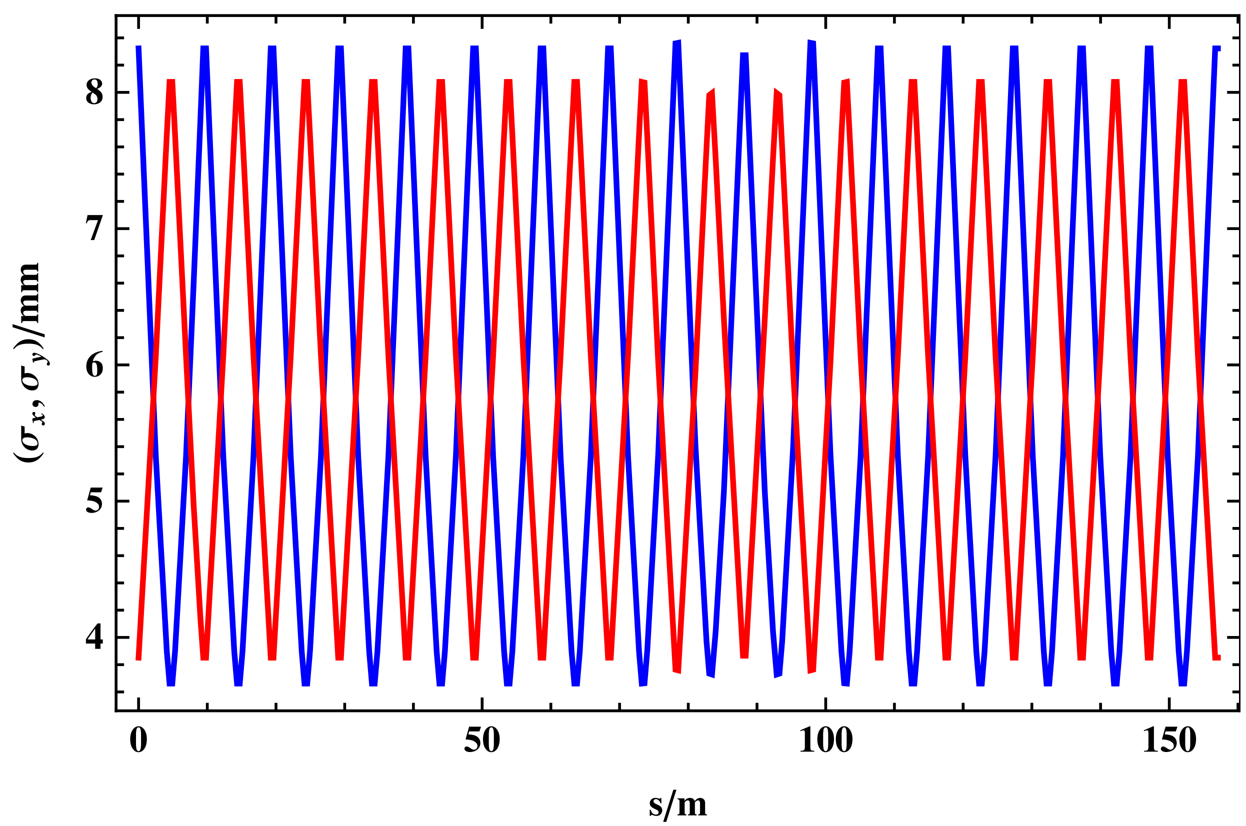
⇒ Excitation of the $4Q_y$ and Q_x+4Q_y resonance in the case of symmetry 2 and 1

- Emittance growth due to excitation of systematic resonances
- High symmetry of the machine is important!

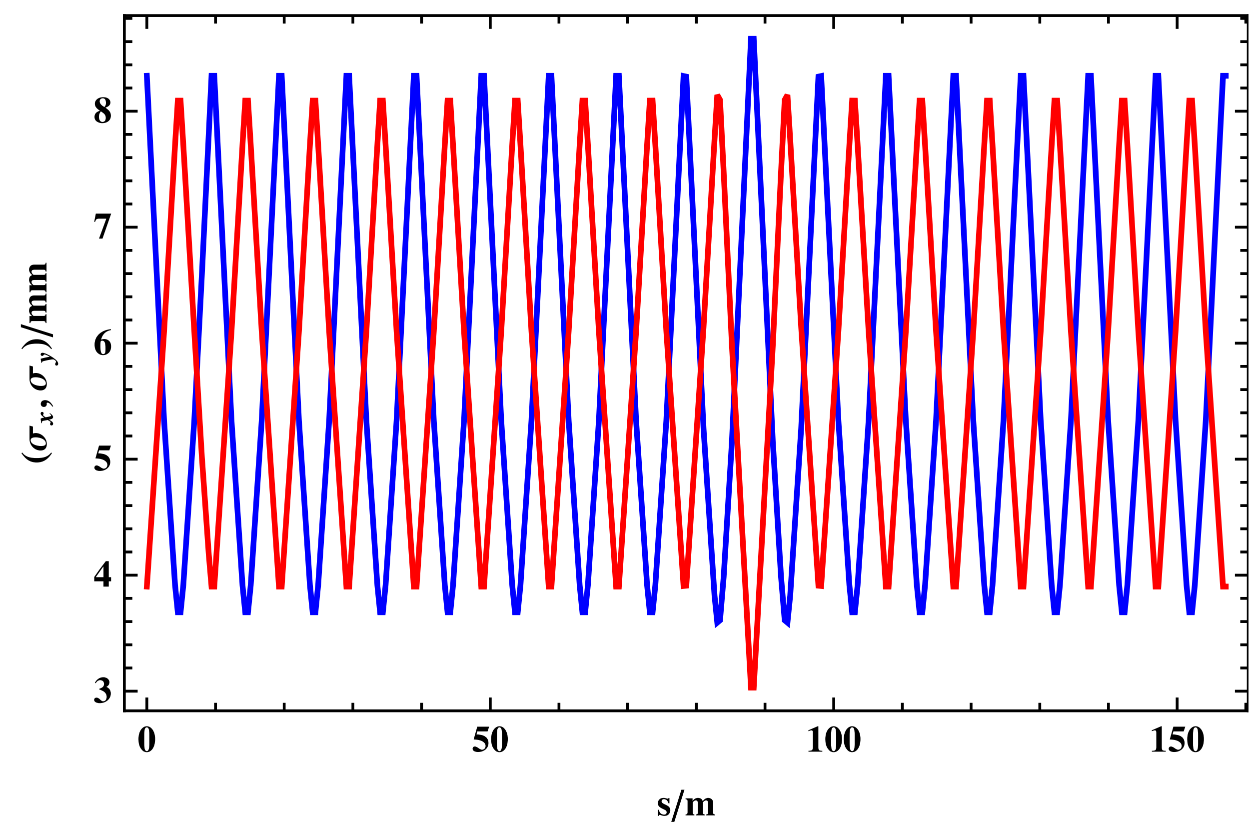
Optics Studies - Symmetry

2. "Weak" and "strong" symmetry breaking

Lattice: 16 cell FODO lattice, symmetry 1, $Q_{x/y}$=4.28/3.55, symmetry breaking by shortening the bends in 1 cell, beta-beating correction by matching the β-function to the arc with individual quadrupoles

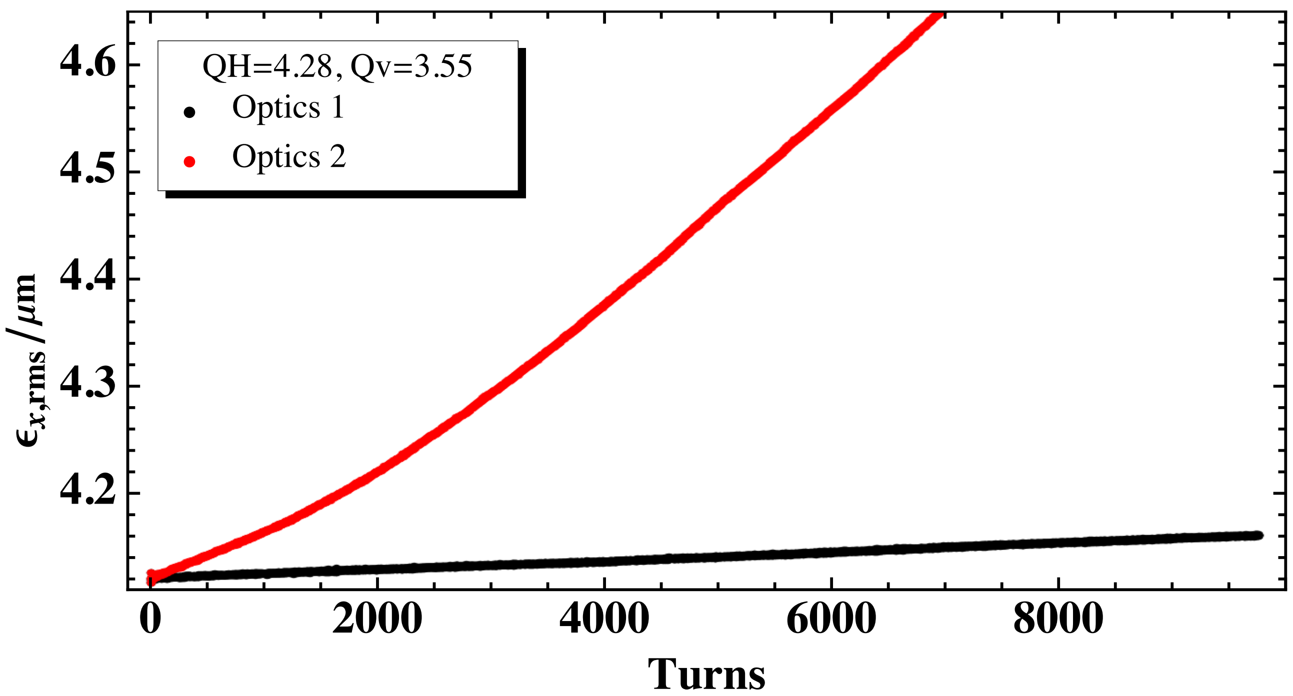


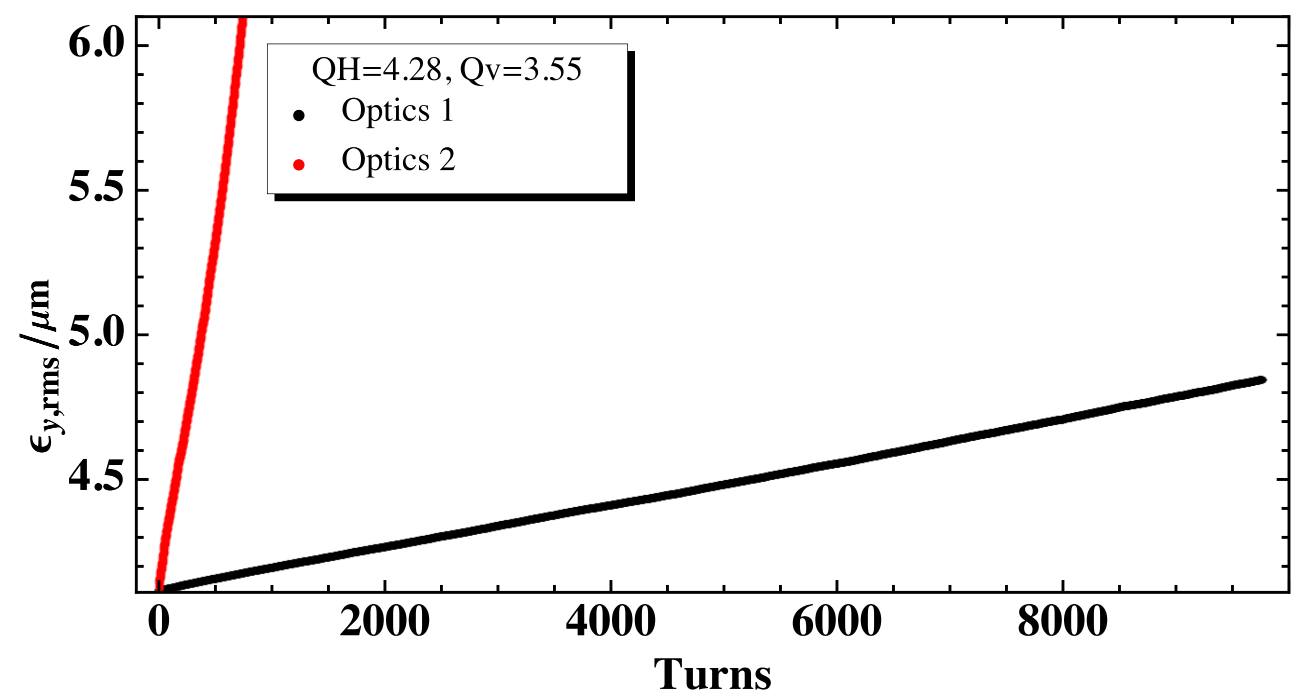
"small" variation (Optics 1)



"large" variation (Optics 2)

Optics Studies - Symmetry





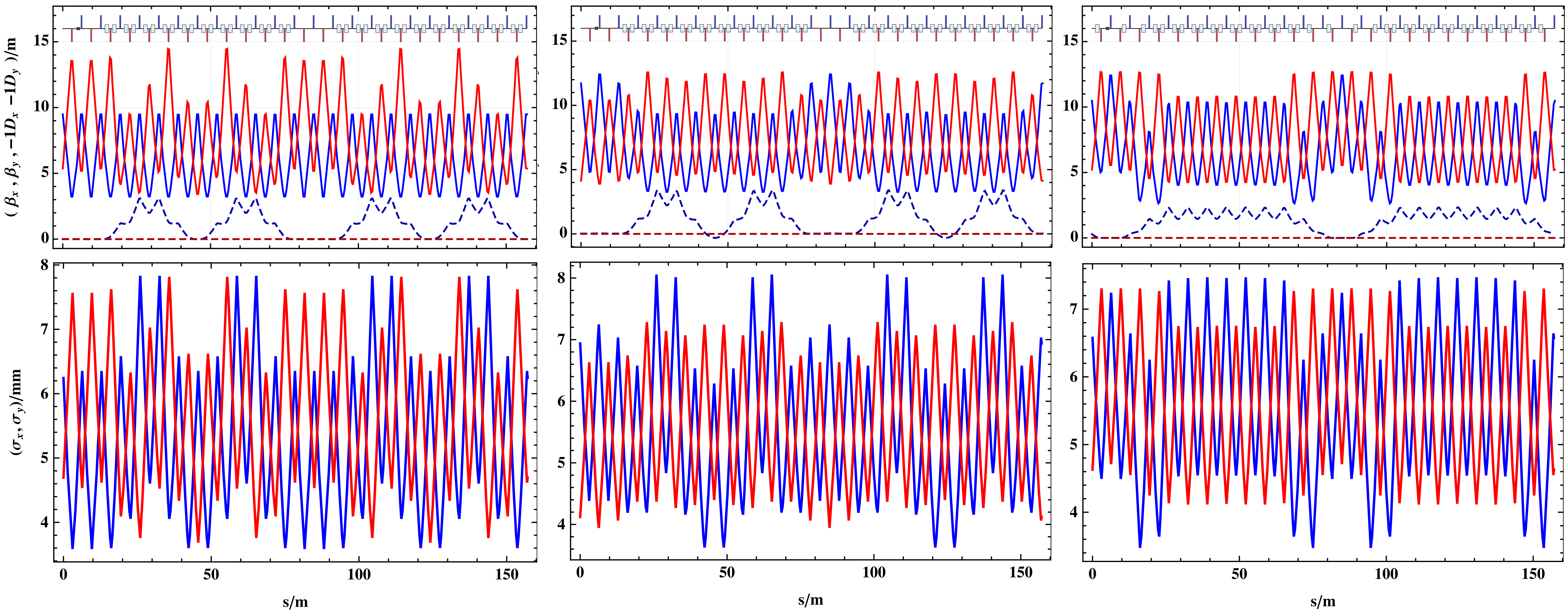
- in the case of only a small distortion of the β-function/dispersion the symmetry is only weakly broken
  - ⇒ remaining effect of systematic and non-systematic resonances of original (!higher!) symmetry
  - ⇒ smaller emittance blow-up
- already a slightly larger distortion leads to a “stronger” breaking of the symmetry

➡ a larger variation of the beam envelope can lead to a “stronger” breaking of the symmetry in turn leading to a larger emittance blow-up

Optics Studies - Dispersion

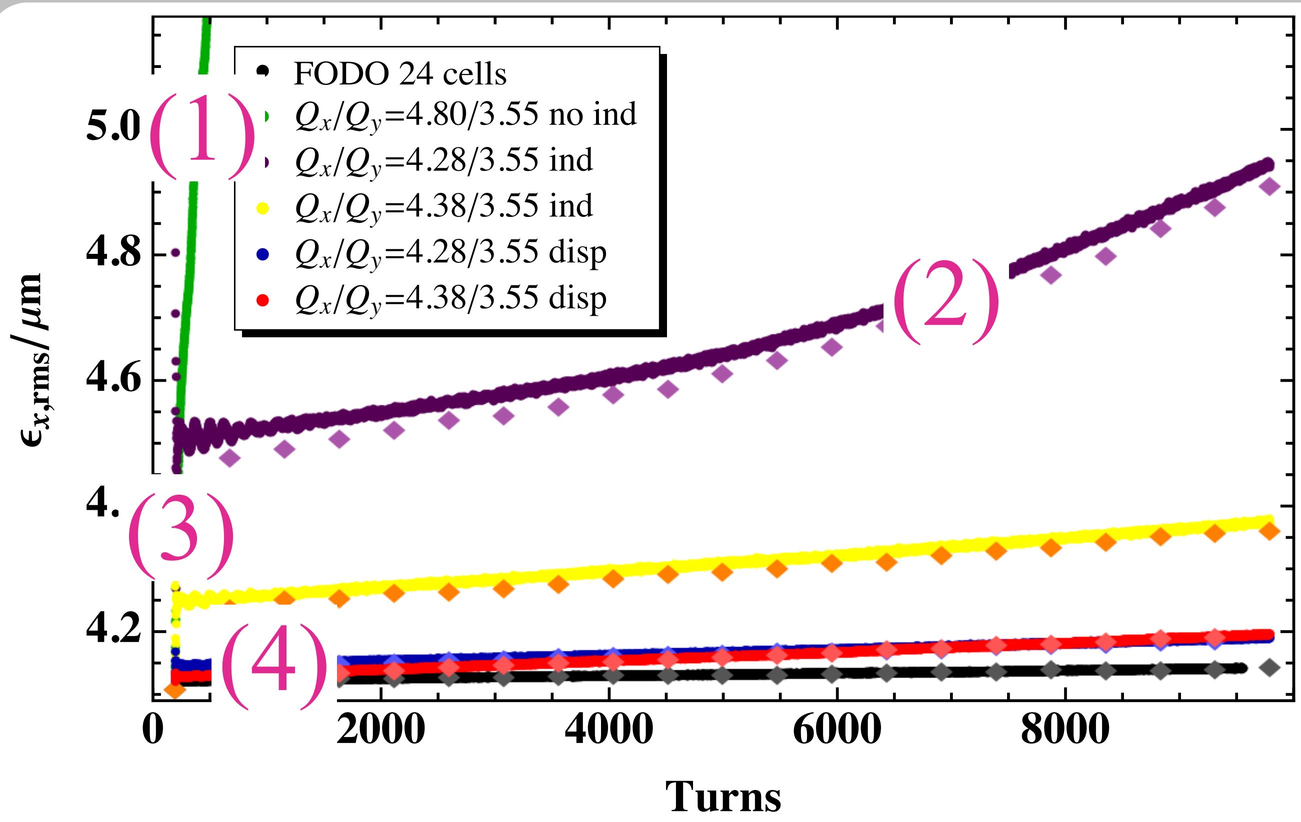
Comparison of a dispersion suppression by adjusting the phase advance per arc to n·2π with a half missing bend scheme

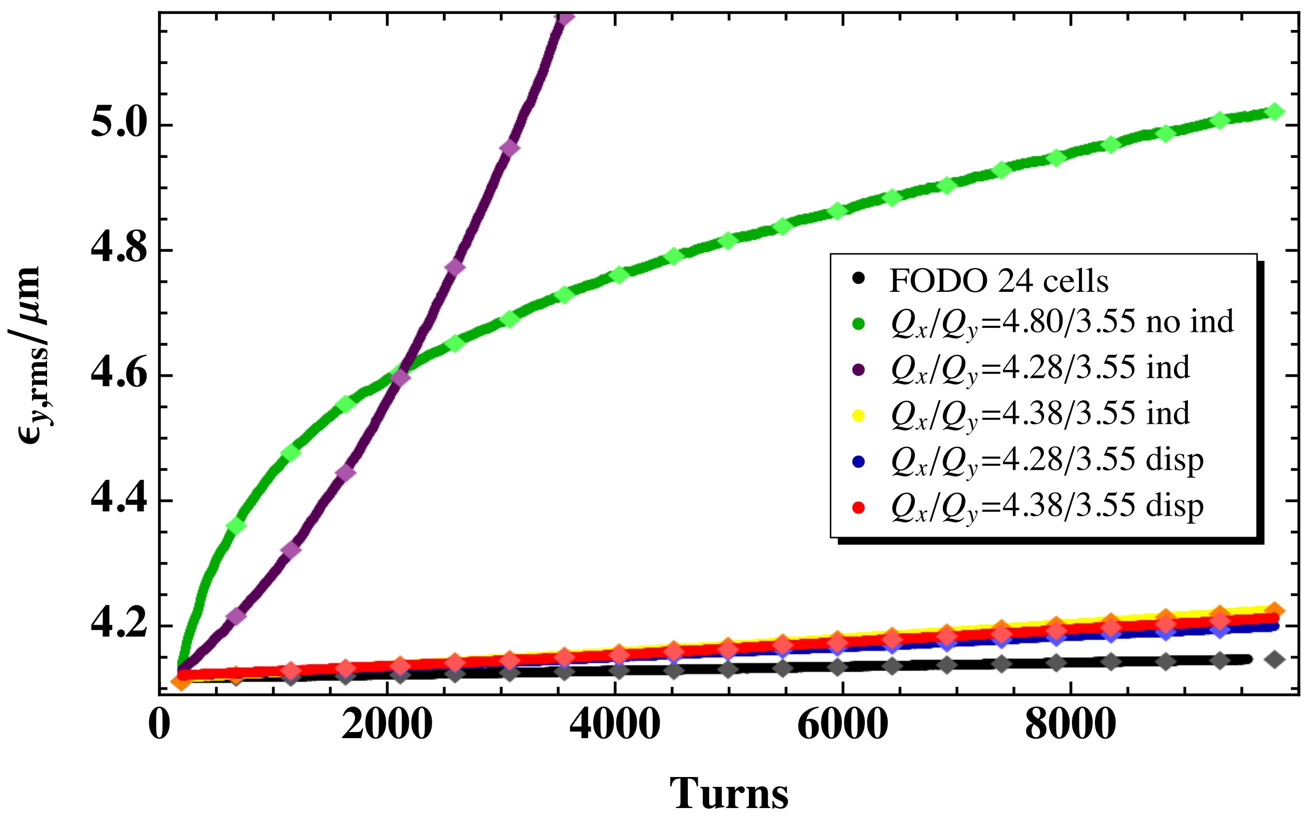
Lattice: 24 cell FODO lattice with 2x2 cells per straight sections (⇒ symmetry 2)



2 π no ind. quad.	2 π ind. quad.	half missing bend
$Q_{x/y}$=4.80/3.55	$Q_{x/y}$=4.38/3.55	$Q_{x/y}$=4.38/3.55

Optics Studies - Dispersion





(1) large (hor.) emittance blow-up in the case of 2π dispersion suppression, no ind. quad. and $Q_{x/y}$=4.80/3.55 due to the excitation of several systematic resonances and the large variation of the beam envelope

(2) reduction of the (hor.) emittance blow-up in the case of 2π dispersion suppression, additional ind. quad.

(3) but strong oscillation of the (hor.) emittance during the first 20 turns, which decreases for hor. WP further away from the integer resonance

(4) half missing bend schemes shows a comparable small emittance blow-up

Optics Studies - Dispersion

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Interpretation of (2) and (3):

- The dispersion and second order dispersion both satisfy differential equations similar to the one of a closed-orbit distortion and are thus most sensitive to tunes close to the integer.
- Due to the SC detuning the single particle tunes differ

➔ Initial oscillation of the hor. emittance is caused by a dispersion and smaller betatron mismatch, which increases for particles with a single particle tune approaching the integer resonance

➔ dispersion seen by the beam particles (including SC!) becomes non-linear

➔ The 2π disp. sup. scheme is very sensitive to the choice of the WP (betatron/disp. mismatch, non-negligible non-linearity of the disp. for hor. WP close to the integer) and shows a larger emittance blow-up than the half missing bend scheme which avoids most problems of the 2π disp. sup. scheme as the dispersion is matched to the arc.

Summary

PTC-ORBIT simulations show that already the linear optics can considerably influence the machine performance (here emittance blow-up)

“Rules of thumb” for a good lattice design:

- high symmetry + careful choice of working point (avoid systematic resonances)
- dispersion should be matched to the arc (dispersion beating can lead to a non-negligible non-linear dispersion due to SC)
- (small variation of the beam size)

Note: For the presented studies a very simplified model is used, thus the picture can change for more realistic machine models.

THANK YOU!

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Motivation

Comparison of optics characteristic of the PS Booster and the RCS

	PS Booster 2 GeV	**RCS**
cell type	triplet	FODO
hor./vert. working point	4.28/4.55	4.20/3.57
number of cells	16	21
hor./vert. phase advance per cell	$96.3^\circ/102.4^\circ$	$72.0^\circ/61.2^\circ$
symmetry	16	3
dispersion free straight sections	-	3
dispersion suppressor scheme	-	$2\ \pi$ over the arc
variation of the beam size	small	large

Machine Parameters

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[2] K. Hanke et al., *PS Booster Energy Upgrade, Feasibility Study, First Report*, tech. rep., CERN, 2010, https://edms.cern.ch/document/1082646/3

[3] K. Hanke et al., *Feasibility Study of a Rapid Cycling Synchrotron to replace the PS Booster*, tech. rep., CERN, 2011, https://edms.cern.ch/document/1154705/1.0.

	PS Booster 2 GeV [2]	**RCS** [3]
inj./extr. energy	0.16/2 GeV	
circumference	1/4 $C_{PS} \approx 157.1$ m	4/21 $C_{PS} \approx 119.7$ m
repetition rate	0.8 Hz	10 Hz
RF voltage	8 kV (h=1), 6 kV (h=2)	60 kV (h=1 to h=4)
injection	H^- charge exchange injection	

simplification/generalization in order to compare the impact of the optics on direct SC effect

Simulation Parameters

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generalized machine parameters

inj./extr. energy	0.16/2 GeV
circumference	1/4 $C_{PS} \approx$ 157.1 m
repetition rate	10 Hz
RF voltage	50 kV* (h=1)
injection	H^- charge exchange injection

➔ **simplified PS Booster lattice as baseline lattice (single harmonic RF with voltage adjusted to 10 Hz cycle, no injection bump, no resonance compensation, rounded magnet lengths)**

➔ **RCS optics or optics to be studied is scaled up to PS Booster circumference**

* RF voltage is adjusted to obtain a longitudinal emittance of 2.8 eVs assuming a parabolic squared distribution in all planes (equivalent to 2 eVs longitudinal emittance for a parabolic distribution)

Simulation Parameters

beam parameters (LHC 25 ns beams)

number of particles per bunch	2.4×10^{12}
norm. hor./vert. emittance	2.5/2.5 µm
long. emittance	2.8 eVs

simulation code: PTC-Orbit (SC routine: 2 1/2 D model with adjusted grid)

check of lattice description in PTC + convergence study

↓

code settings

number of turns	10000
number of macroparticles	5×10^{5}
number of bins	128
distance between SC nodes	1 m