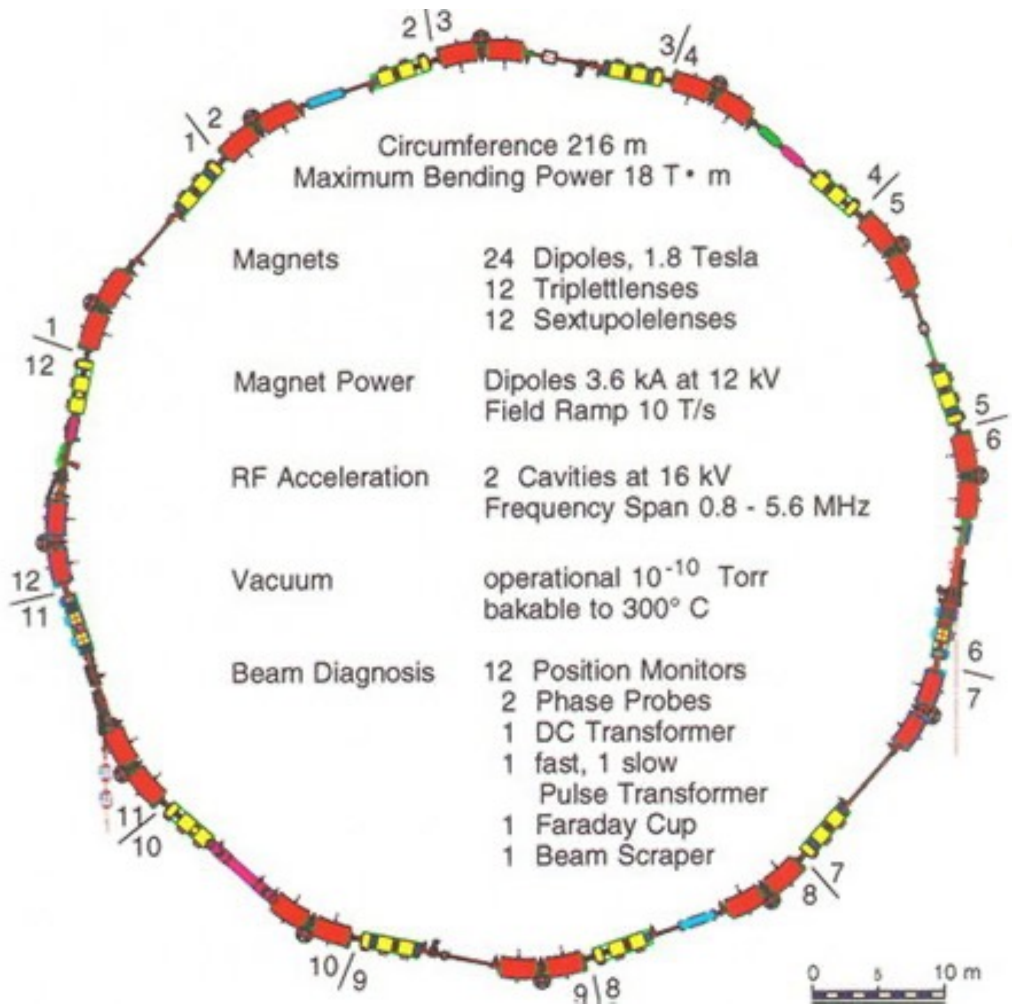
High Intensity Effects in a Circular Accelerators

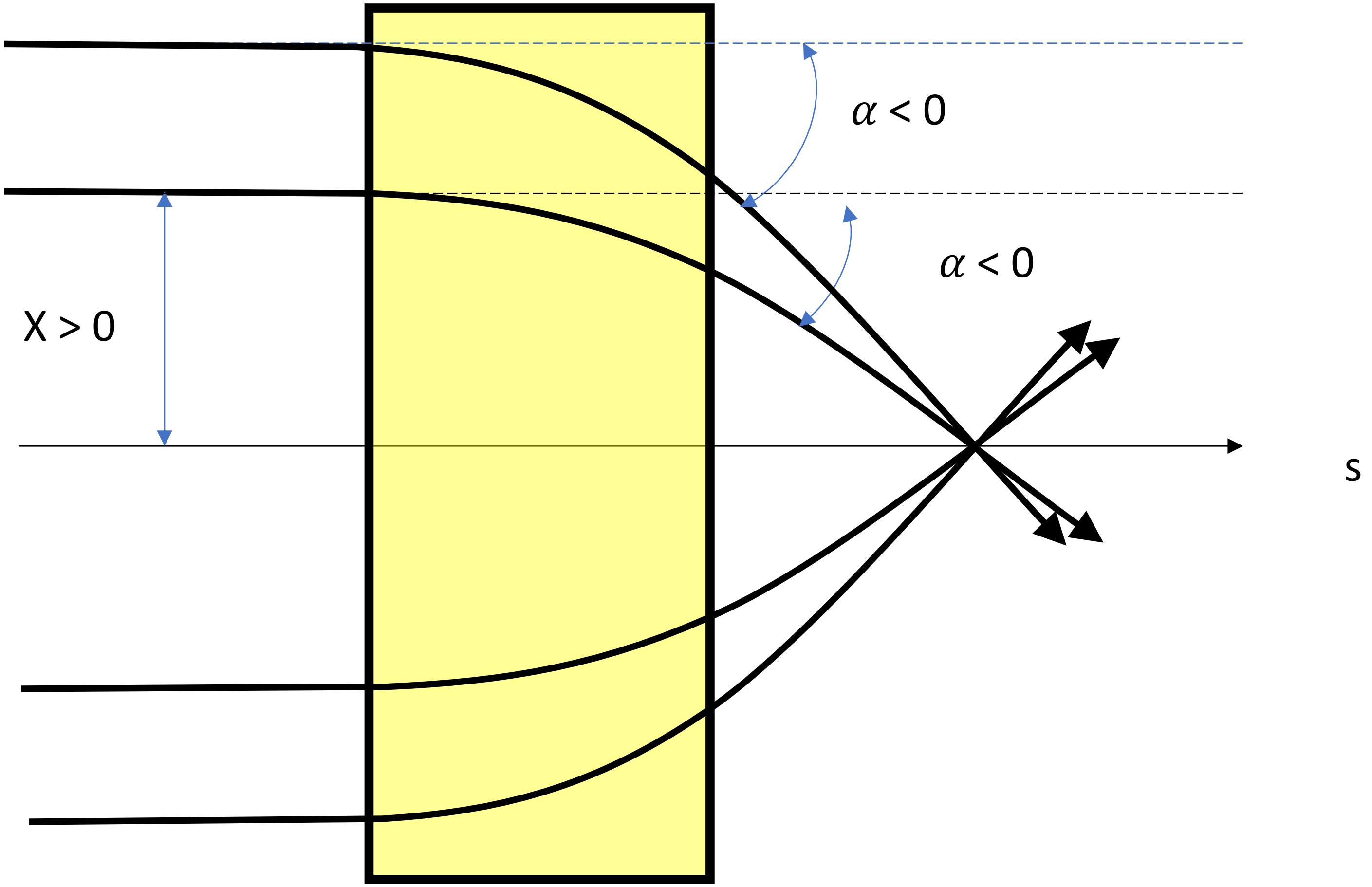
OP School, 9 November 2021

G. Franchetti, GSI

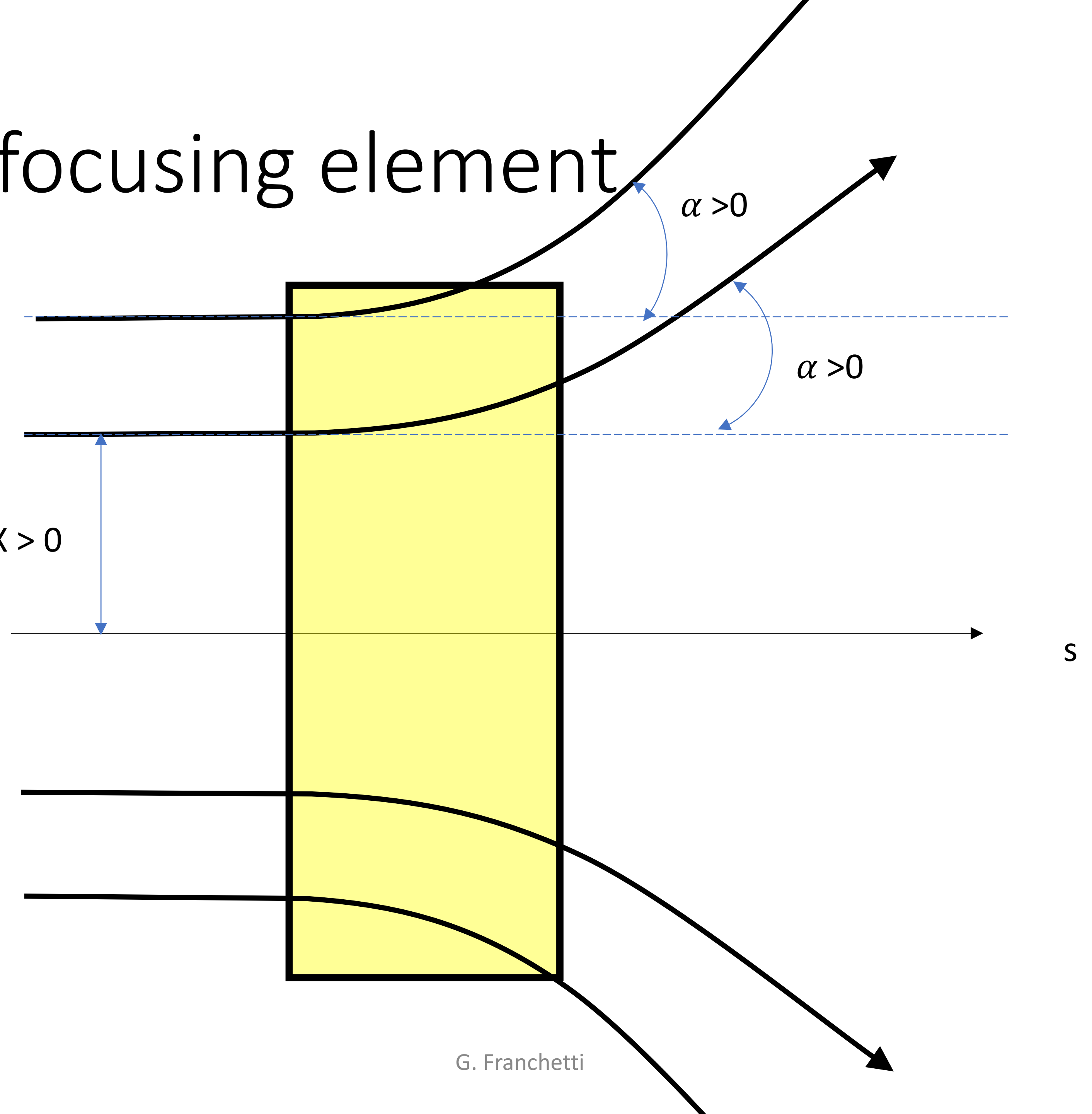


2\3
3/4
1\2
4/5
Circumference 216 m
Maximum Bending Power 18 T • m
Magnets
24 Dipoles, 1.8 Tesla
12 Triplettlenses
12 Sextupolelenses
1/12
Magnet Power
Dipoles 3.6 kA at 12 kV
Field Ramp 10 T/s
5/6
RF Acceleration
2 Cavities at 16 kV
Frequency Span 0.8 - 5.6 MHz
12/11
Vacuum
operational 10^{-10} Torr
bakable to 300° C
6/7
Beam Diagnosis
12 Position Monitors
2 Phase Probes
1 DC Transformer
1 fast, 1 slow
Pulse Transformer
1 Faraday Cup
1 Beam Scraper
11/10
8\7
10/9
9\8
0 5 10 m

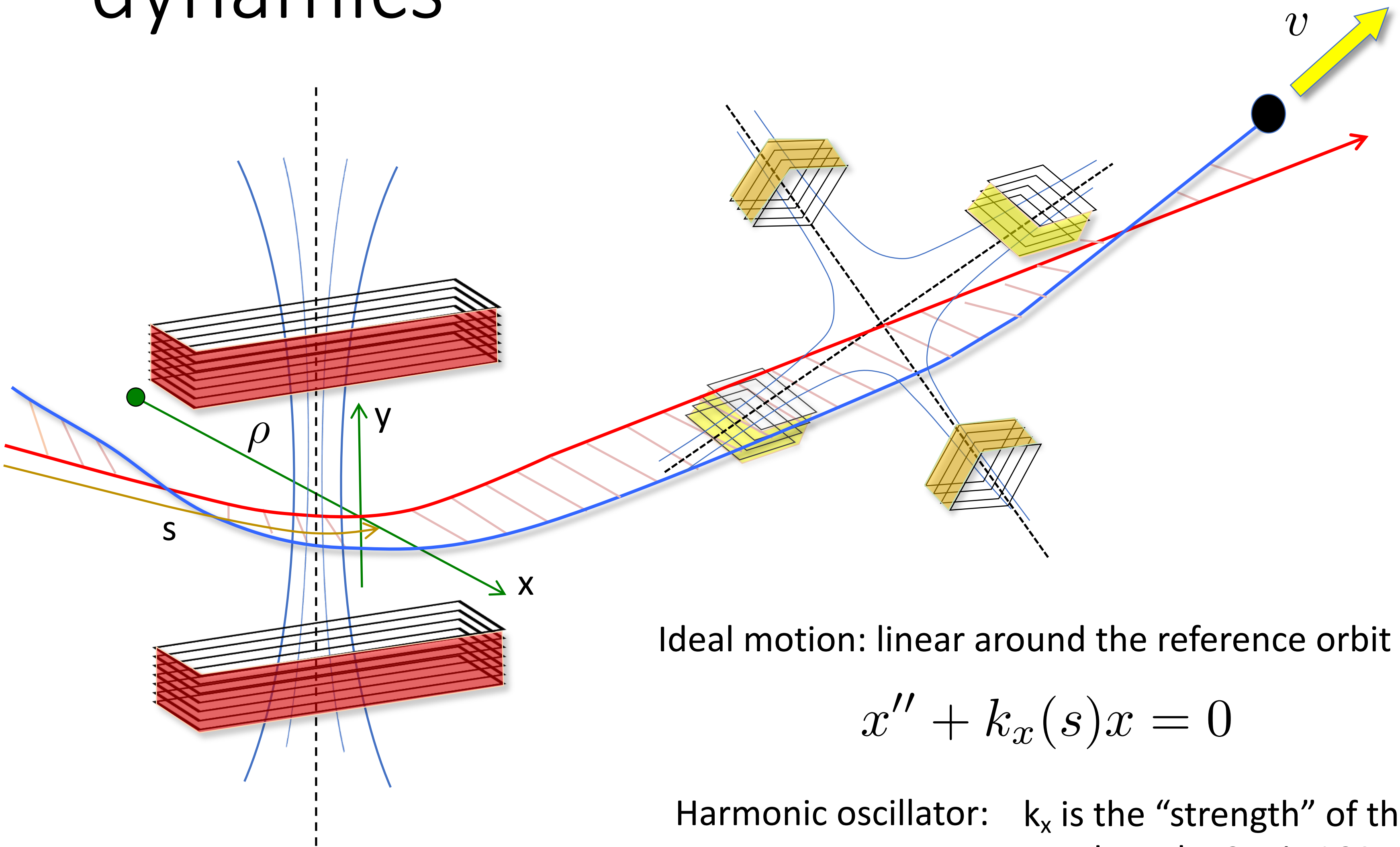
Focusing element



Defocusing element



Reference frame of beam dynamics



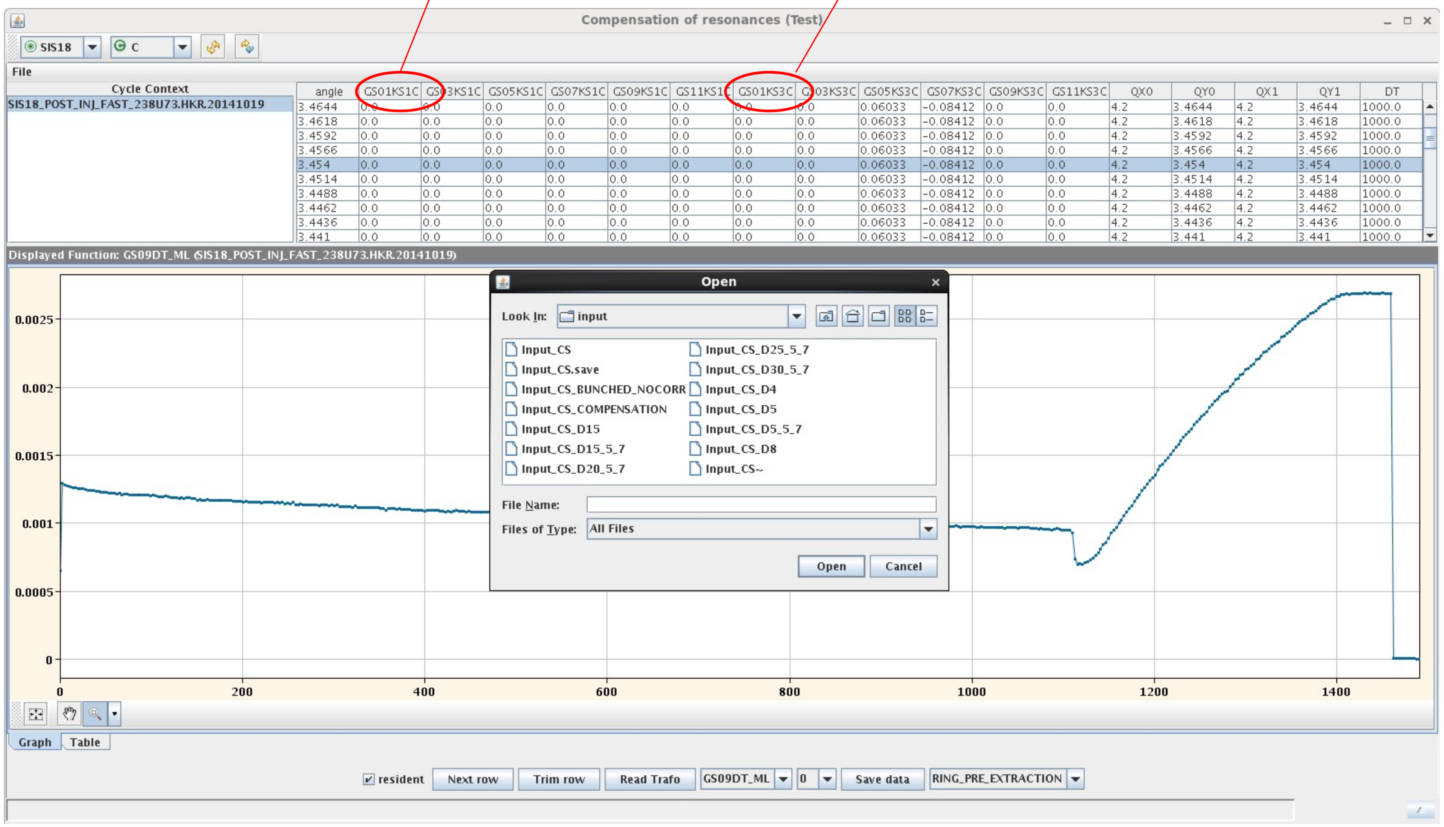
Ideal motion: linear around the reference orbit

$$x'' + k_x(s)x = 0$$

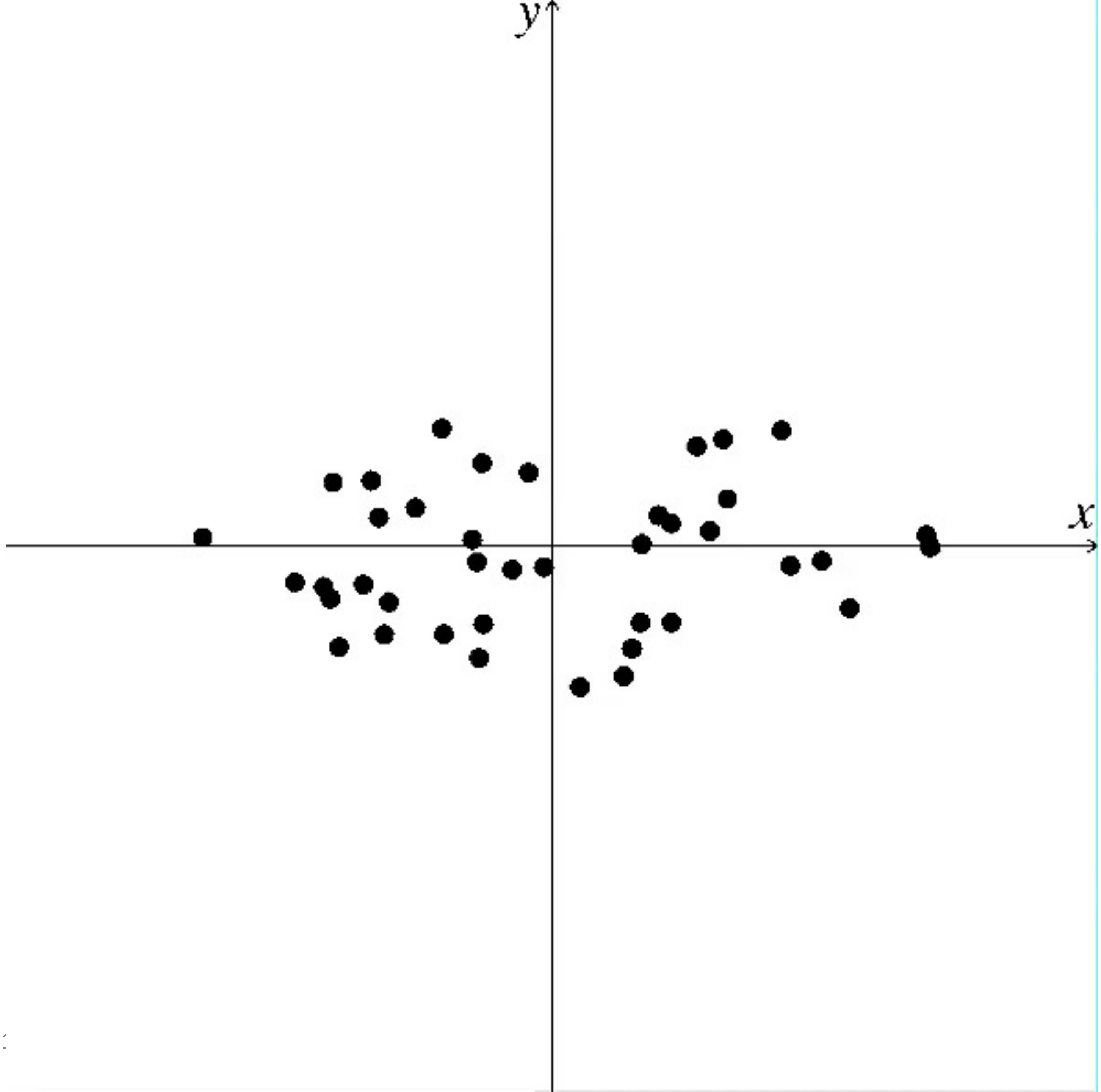
Harmonic oscillator: k_x is the “strength” of the quadrupole. Set in LSA

LSA allows the settings of the elements strength: example

Quadrupole correctors   Sextupole correctors

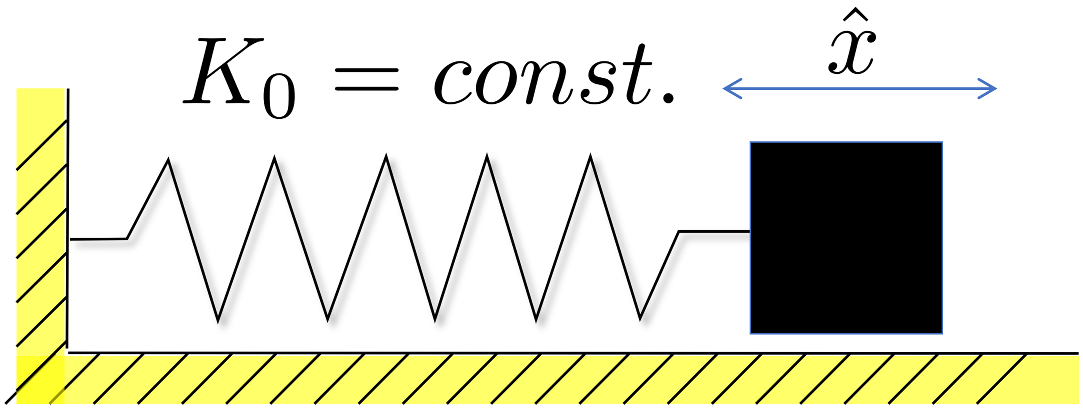


Example from H. Liebermann


y
x

$$x'' + k_x(s)x = 0$$

$$K_0 = const.$$



$K_0 > 0$ Stable motion

$K_0 < 0$ Unstable motion

$$\hat{x} = \sqrt{\beta_x \epsilon_x} \sin(\omega s + \psi_0)$$

amplitude

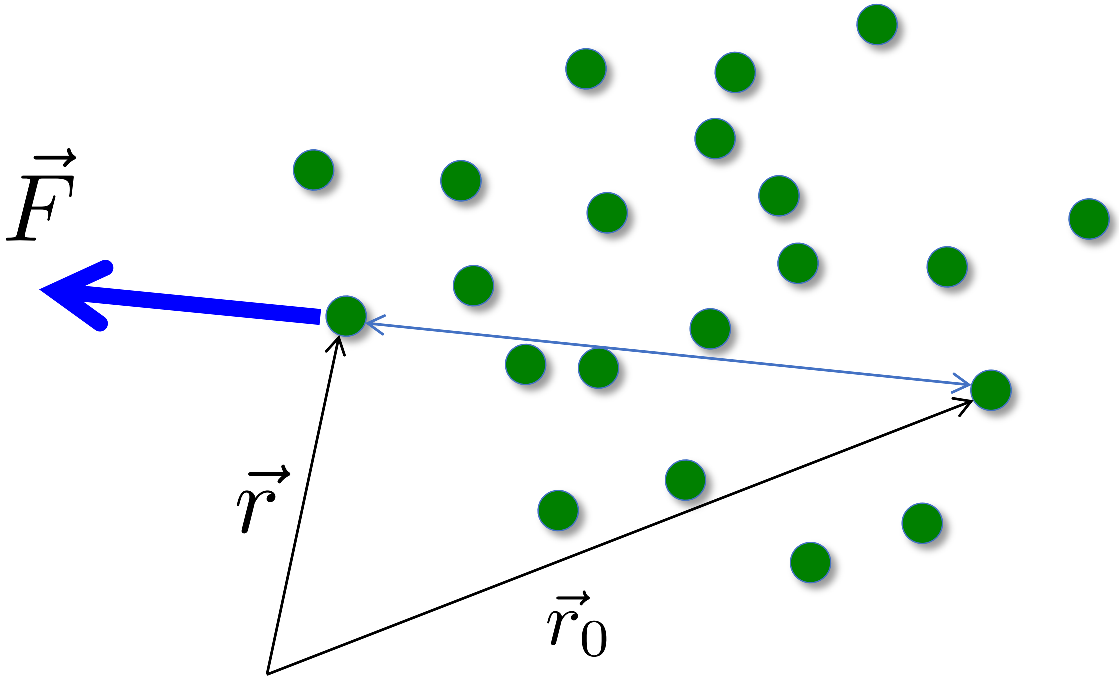
Phase advance $\omega = \sqrt{K_0}$

initial phase

$$\beta_x = 1/\sqrt{K_0}$$

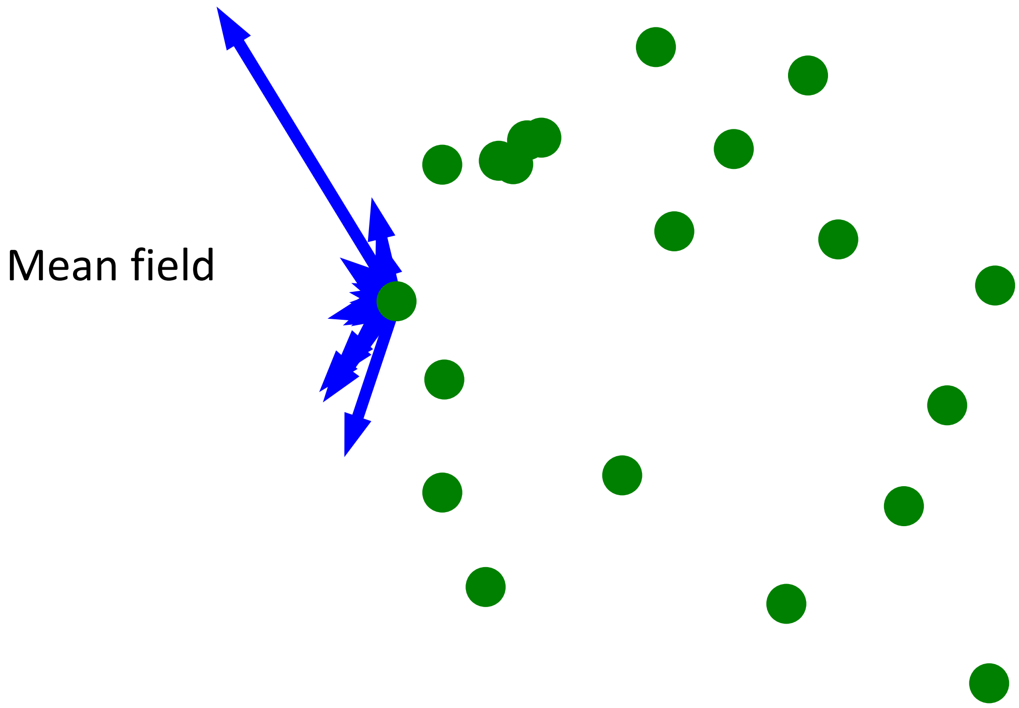
Coulomb Forces

$$\vec{F} = \frac{1}{4\pi\epsilon_0}\frac{q^2}{|\vec{r}-\vec{r}_0|^3}(\vec{r}-\vec{r}_0)$$

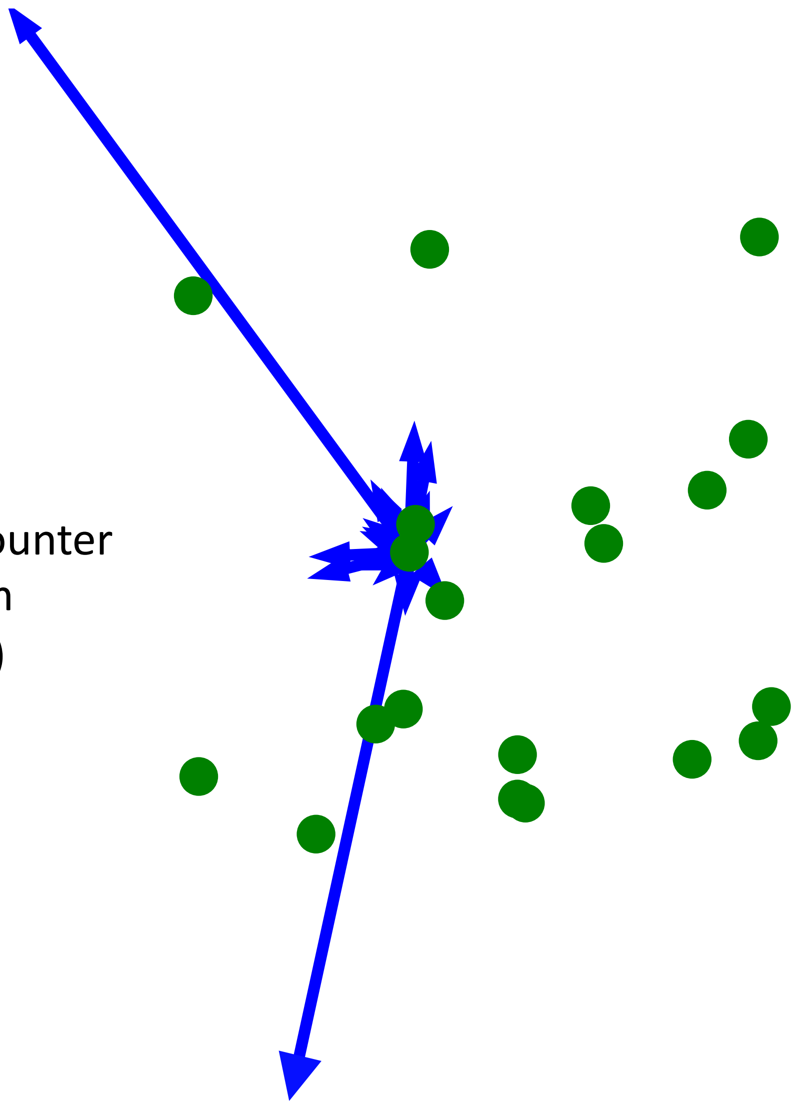


C. Coulomb

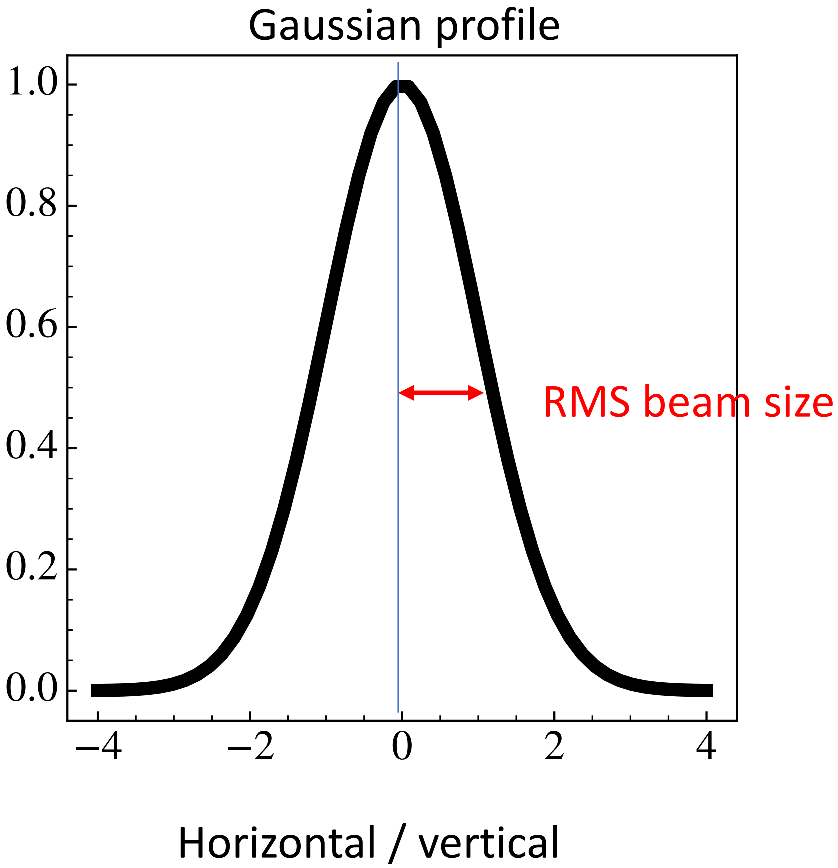
Total Coulomb Forces on one particle

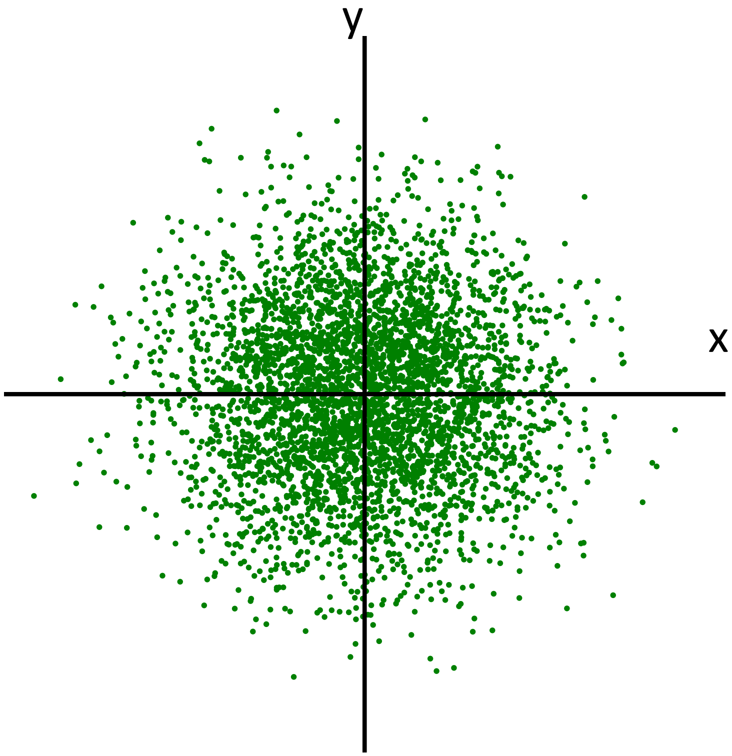


Close encounter
(IntraBeam
Scattering)



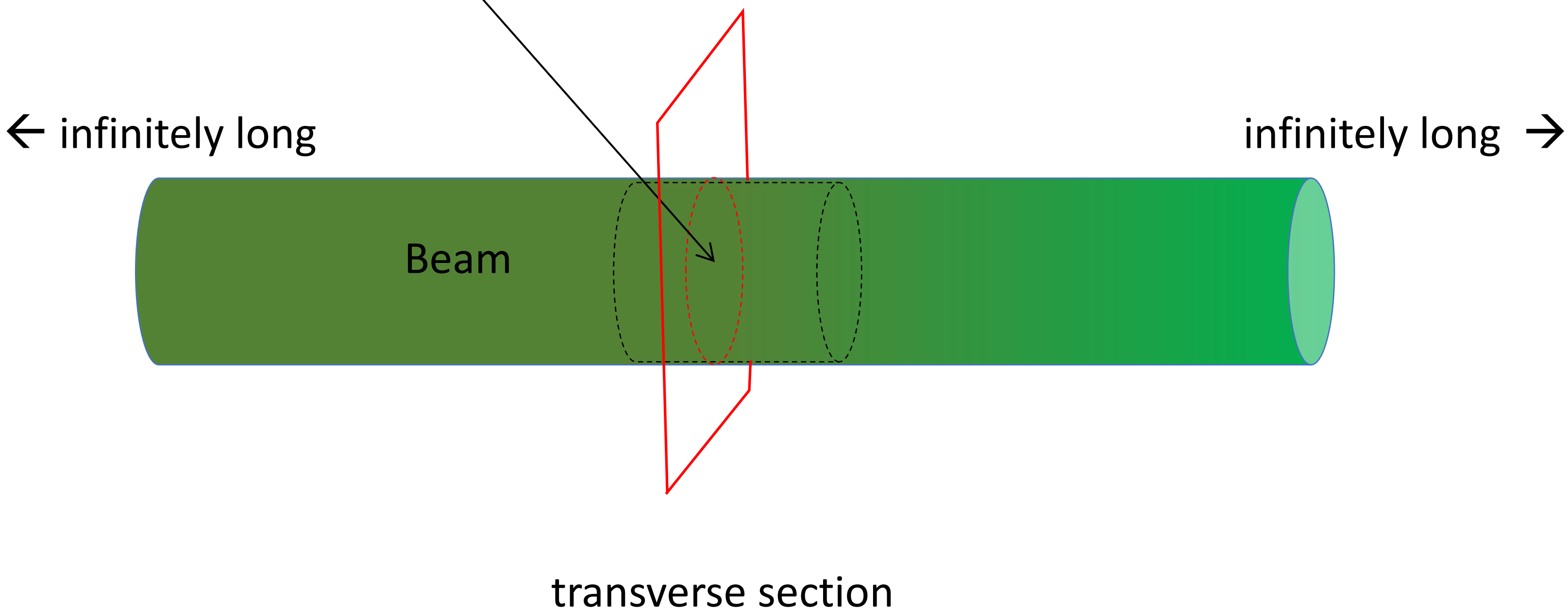
Regular Beam → transverse profile



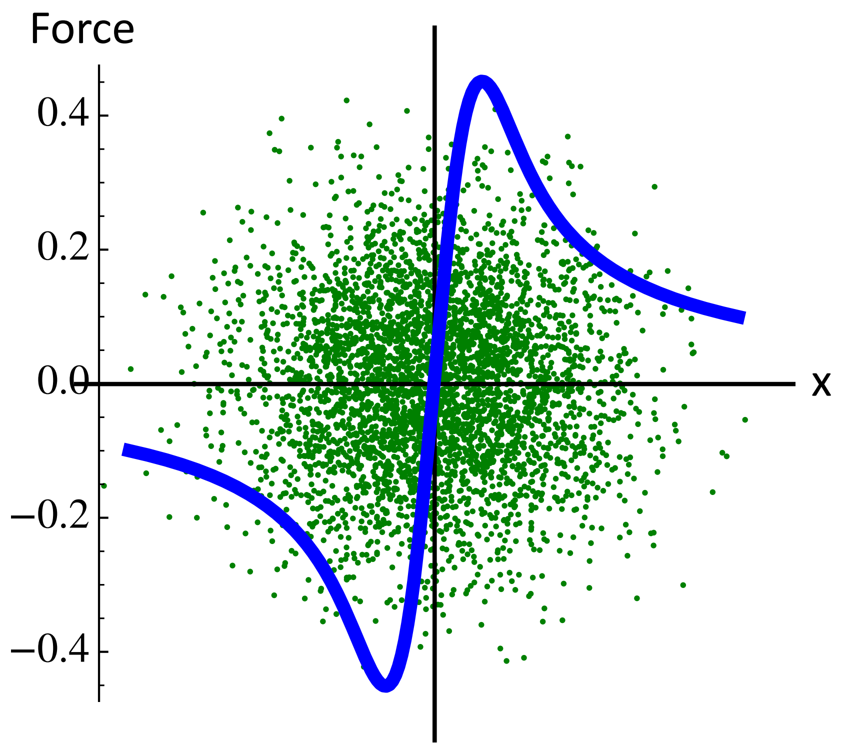


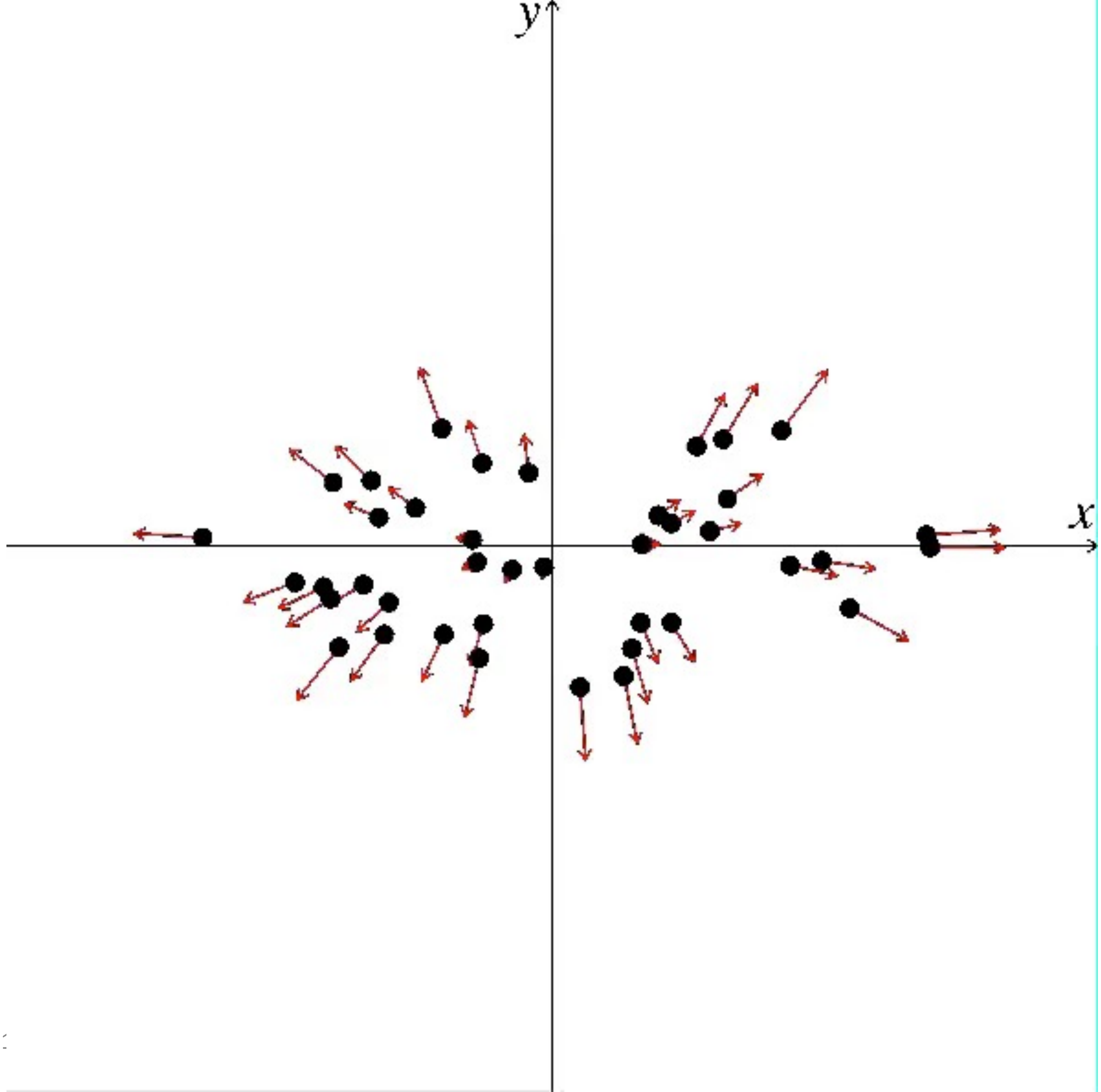
Transverse space charge forces

Space charge forces here are similar to those created by an ideal coasting beam

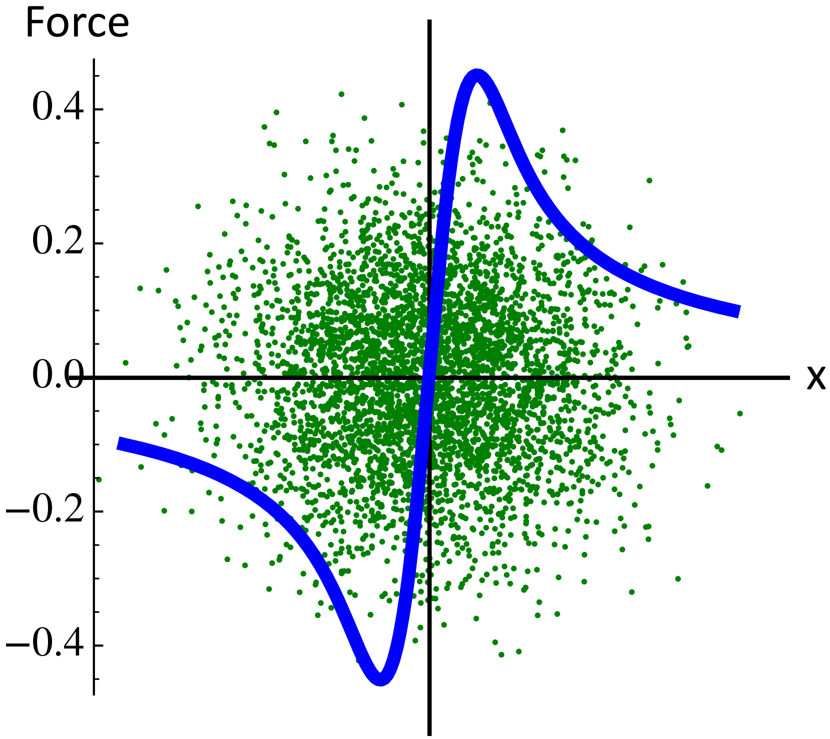


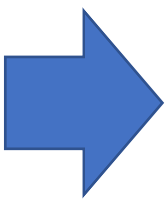
Space charge forces



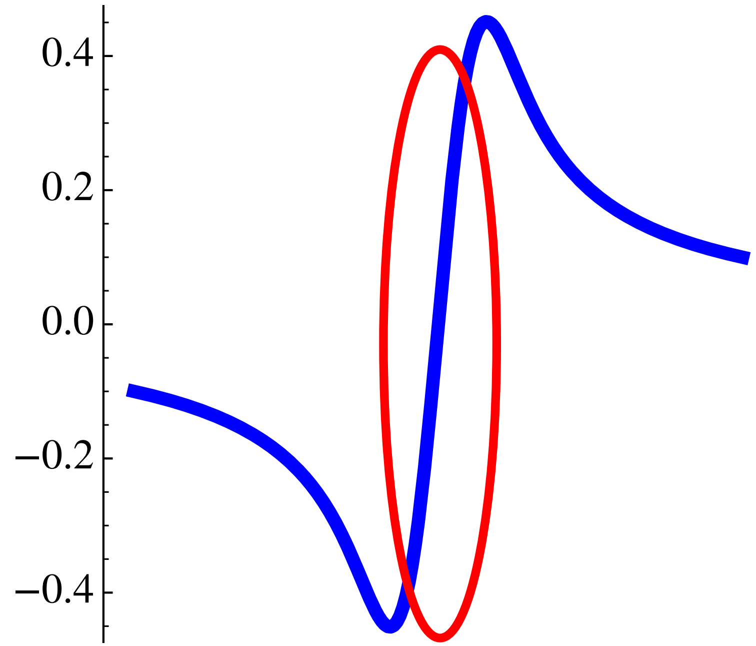

y
x

Effect of high intensity on optics



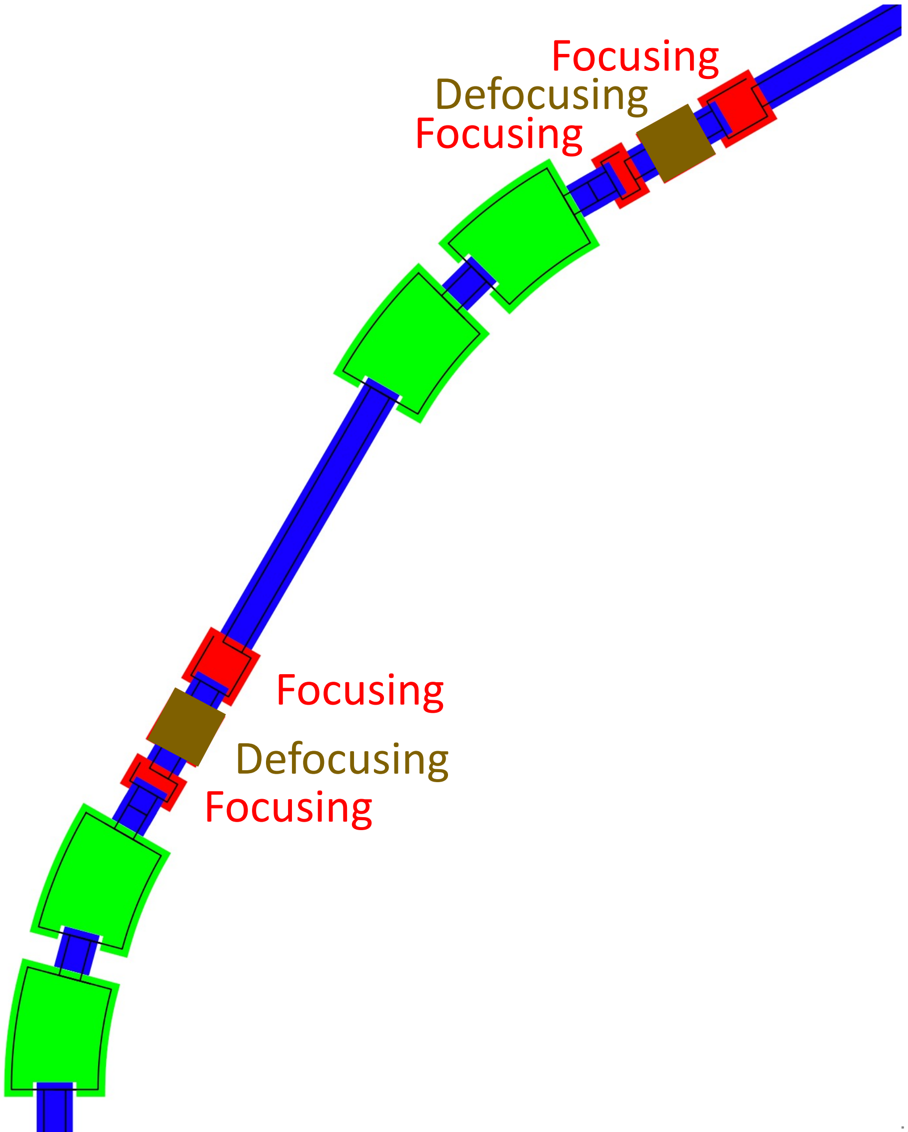


Look only at particles in the beam core

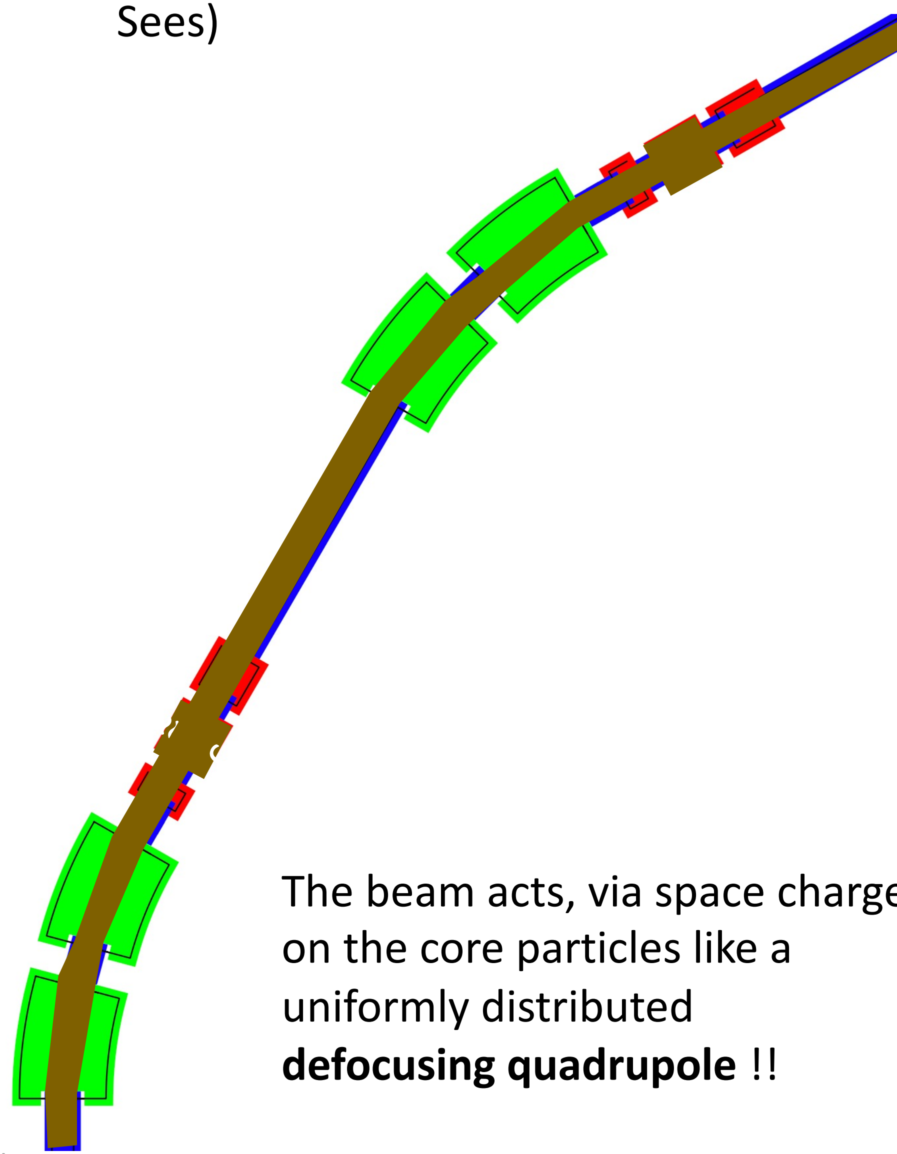


LINEAR DE-FOCUSING FORCE

Naked lattice
(what one ion alone sees)



Lattice with a High intensity beam
(what one particle in the bea center
Sees)



The beam acts, via space charge, on the core particles like a uniformly distributed **defocusing quadrupole** !!

Effect of high intensity on optics

Naked lattice

$$x'' + k_x(s)x = 0$$

quadrupoles

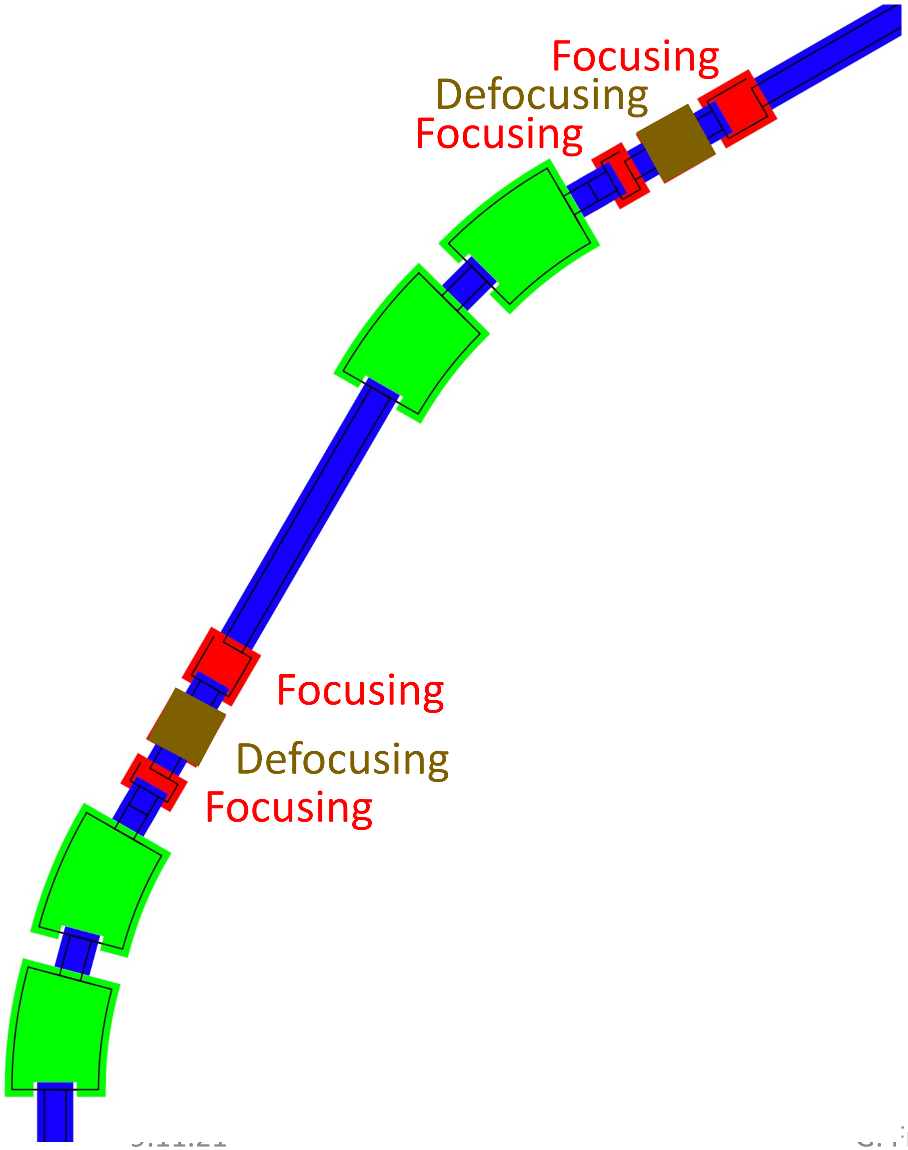
High intensity beam:
core particles

$$x'' + k_x(s)x - \boxed{k_{SC,x}(s)x} = 0$$

quadrupoles

Defocusing effect of
Space charge

Naked lattice



Optical functions

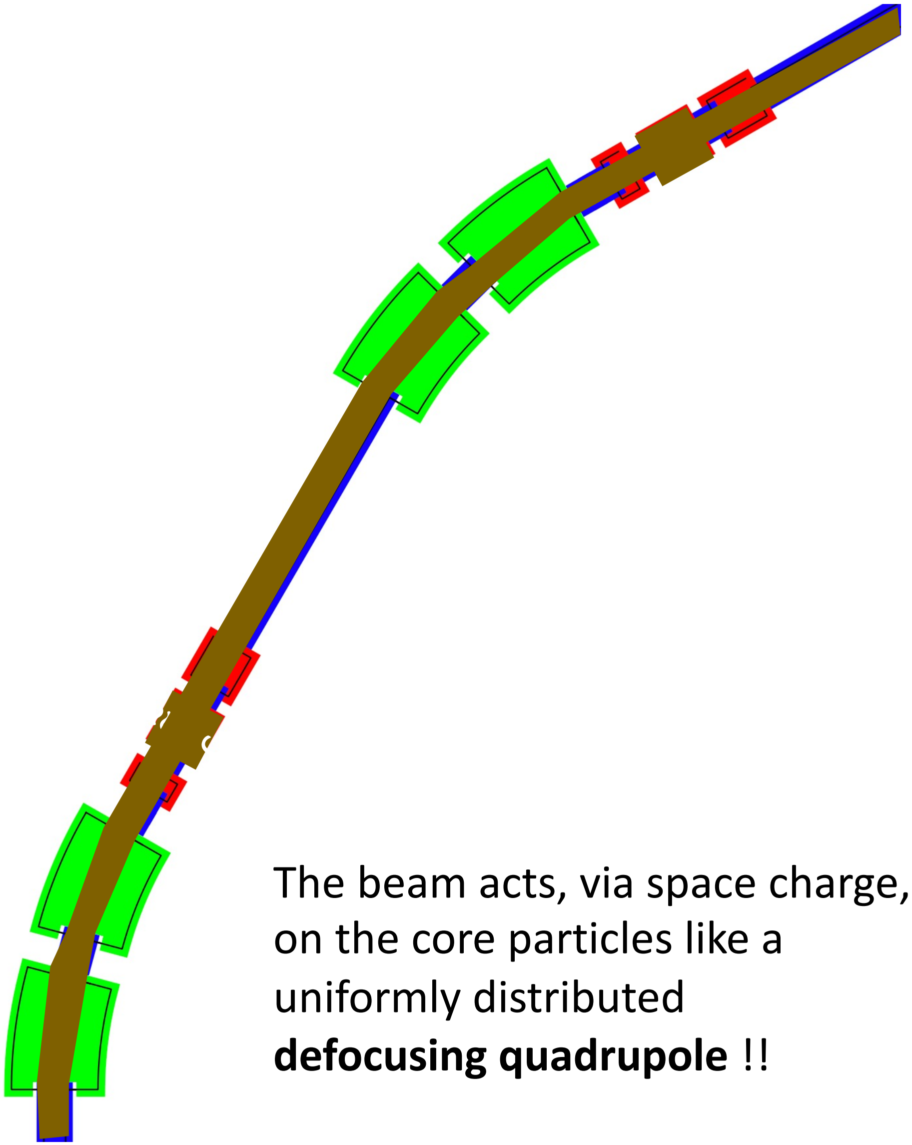
β_x, α_x, D_x, D'_x — depends on local position "s"

Q_x ← tune

β_y, α_y — depends on local position "s"

Q_y ← tune

Lattice with a High intensity beam



The beam acts, via space charge, on the core particles like a uniformly distributed **defocusing quadrupole** !!

Modified Optical functions

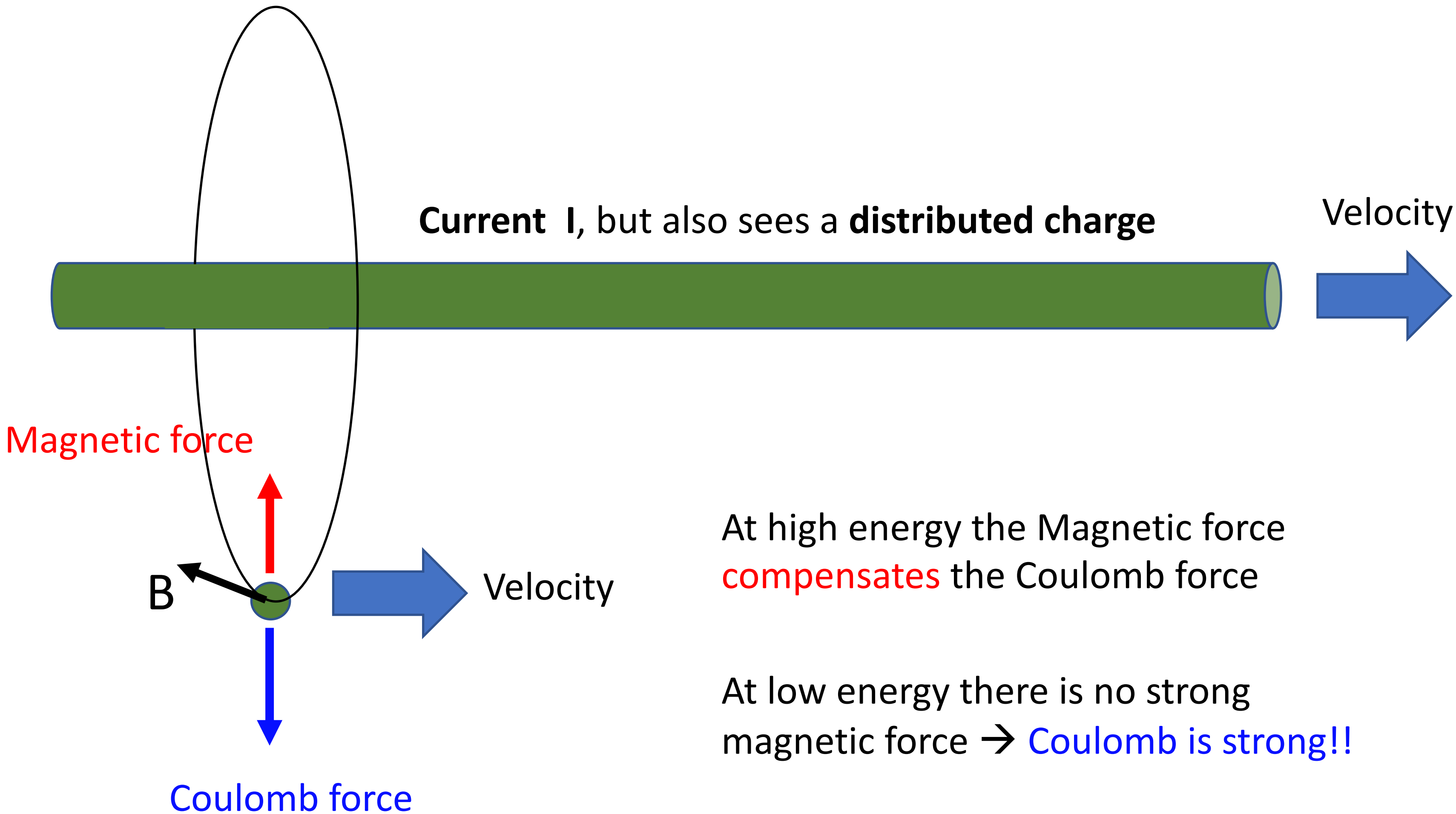
β_x, α_x, D_x, D'_x — depends on local position "s"

Q_x ← "depressed" tune

β_y, α_y — depends on local position "s"

Q_y ← "depressed" tune

The effect of the beam energy



At high energy the Magnetic force compensates the Coulomb force

At low energy there is no strong magnetic force → Coulomb is strong!!

Space charge tuneshift

Modified Optical functions

β_x, α_x, D_x, D'_x — depends on local position "s"

Q_x ← "depressed" tune

β_y, α_y — depends on local position "s"

Q_y ← "depressed" tune

Optical functions

β_x, α_x, D_x, D'_x — depends on local position "s"

Q_x ← tune

β_y, α_y — depends on local position "s"

Q_y ← tune

Space charge tuneshift

$$\Delta Q_x = Q_x - Q_x$$

$$\Delta Q_y = Q_y - Q_y$$

Space Charge tuneshift

$$\Delta Q_{x,\mathrm{sc}} = \frac{\bar{\beta}_x}{2} R_{\mathrm{acc}} \frac{K}{\sqrt{\bar{\beta}_x \epsilon_x}(\sqrt{\bar{\beta}_x \epsilon_x} + \sqrt{\bar{\beta}_y \epsilon_y})}$$

$$\Delta Q_{y,\mathrm{sc}} = \frac{\bar{\beta}_y}{2} R_{\mathrm{acc}} \frac{K}{\sqrt{\bar{\beta}_y \epsilon_y}(\sqrt{\bar{\beta}_x \epsilon_x} + \sqrt{\bar{\beta}_y \epsilon_y})}$$

Average rms horizontal beam size

Average rms vertical beam size

$$K = \frac{qI}{2\pi\epsilon_0 m c^3 \beta^3 \gamma^3}$$

K = perveance

ε_x , ε_y = rms emittance

Space Charge tuneshift

$$K = \frac{qI}{2\pi\epsilon_0 m c^3 \beta^3 \gamma^3}$$

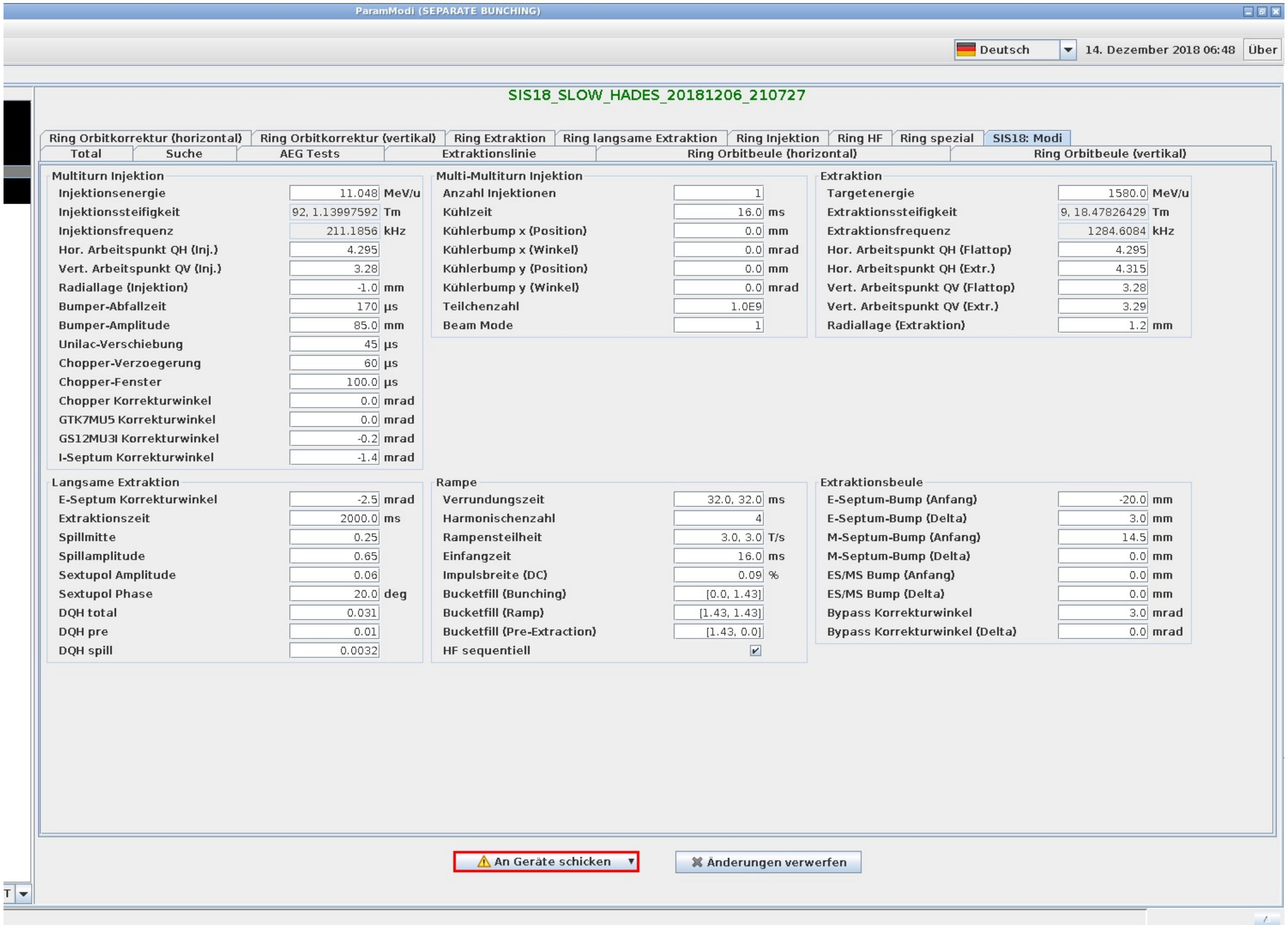
Relativistic gamma:
with high energy is large

The perveance is a combination of

q = charge state
M = ion mass
γ, β <=> the beam energy
I = beam current

Different beams can have the same Perveance !!!

Example


ParamModi (SEPARATE BUNCHING)
Deutsch
14. Dezember 2018 06:48
Über
SIS18_SLOW_HADES_20181206_210727
Ring Orbitkorrektur (horizontal)
Ring Orbitkorrektur (vertikal)
Ring Extraktion
Ring langsame Extraktion
Ring Injektion
Ring HF
Ring spezial
SIS18: Modi
Total
Suche
AEG Tests
Extraktionslinie
Ring Orbitbeule (horizontal)
Ring Orbitbeule (vertikal)
Multiturn Injektion
Injektionsenergie 11.048 MeV/u
Injektionssteifigkeit 92, 1.13997592 Tm
Injektionsfrequenz 211.1856 kHz
Hor. Arbeitspunkt QH (Inj.) 4.295
Vert. Arbeitspunkt QV (Inj.) 3.28
Radiallage (Injektion) -1.0 mm
Bumper-Abfallzeit 170 µs
Bumper-Amplitude 85.0 mm
Unilac-Verschiebung 45 µs
Chopper-Verzoegerung 60 µs
Chopper-Fenster 100.0 µs
Chopper Korrekturwinkel 0.0 mrad
GTK7MU5 Korrekturwinkel 0.0 mrad
GS12MU3I Korrekturwinkel -0.2 mrad
I-Septum Korrekturwinkel -1.4 mrad
Multi-Multiturn Injektion
Anzahl Injektionen 1
Kühlzeit 16.0 ms
Kühlerbump x (Position) 0.0 mm
Kühlerbump x (Winkel) 0.0 mrad
Kühlerbump y (Position) 0.0 mm
Kühlerbump y (Winkel) 0.0 mrad
Teilchenzahl 1.0E9
Beam Mode 1
Extraktion
Targetenergie 1580.0 MeV/u
Extraktionssteifigkeit 9, 18.47826429 Tm
Extraktionsfrequenz 1284.6084 kHz
Hor. Arbeitspunkt QH (Flattop) 4.295
Hor. Arbeitspunkt QH (Extr.) 4.315
Vert. Arbeitspunkt QV (Flattop) 3.28
Vert. Arbeitspunkt QV (Extr.) 3.29
Radiallage (Extraktion) 1.2 mm
Langsame Extraktion
E-Septum Korrekturwinkel -2.5 mrad
Extraktionszeit 2000.0 ms
Spillmitte 0.25
Spillamplitude 0.65
Sextupol Amplitude 0.06
Sextupol Phase 20.0 deg
DQH total 0.031
DQH pre 0.01
DQH spill 0.0032
Rampe
Verrundungszeit 32.0, 32.0 ms
Harmonischenzahl 4
Rampensteilheit 3.0, 3.0 T/s
Einfangzeit 16.0 ms
Impulsbreite (DC) 0.09 %
Bucketfill (Bunching) [0.0, 1.43]
Bucketfill (Ramp) [1.43, 1.43]
Bucketfill (Pre-Extraction) [1.43, 0.0]
HF sequentiell
Extraktionsbeule
E-Septum-Bump (Anfang) -20.0 mm
E-Septum-Bump (Delta) 3.0 mm
M-Septum-Bump (Anfang) 14.5 mm
M-Septum-Bump (Delta) 0.0 mm
ES/MS Bump (Anfang) 0.0 mm
ES/MS Bump (Delta) 0.0 mm
Bypass Korrekturwinkel 3.0 mrad
Bypass Korrekturwinkel (Delta) 0.0 mrad
An Geräte schicken
Änderungen verwerfen

$$R_{acc} = 34m$$

Energy = 11.048 MeV/u ➡ $\gamma = 1.01177, \quad \beta = 0.15$

Silver: Mass 107, Charge +45

Number of particles = 10^9 → I = 1.5 mA

Perveance:

$$K = 1.12 \times 10^{-8}$$ (no units, it is a pure number)

Average beta functions

$$\overline{\beta}_x = \frac{R_{acc}}{Q_x} \quad \rightarrow 8 \text{ m}$$

$$\overline{\beta}_y = \frac{R_{acc}}{Q_y} \quad \rightarrow 10.4 \text{ m}$$

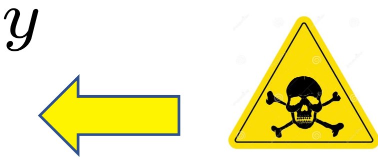
Example

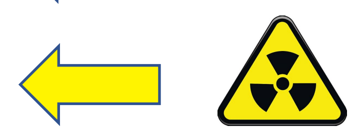
N particles = 10^9

ϵ_x	ϵ_y	$\Delta Q_{sc,x}$	$\Delta Q_{sc,y}$
5	5	-0.017	-0.02
30	15	-0.0035	-0.0057

N particles = 10^{11}

ϵ_x	ϵ_y	$\Delta Q_{sc,x}$	$\Delta Q_{sc,y}$
5	5	-1.7	-2
30	15	-0.35	-0.57





Discussion

Effective tunes of particle in the beam core

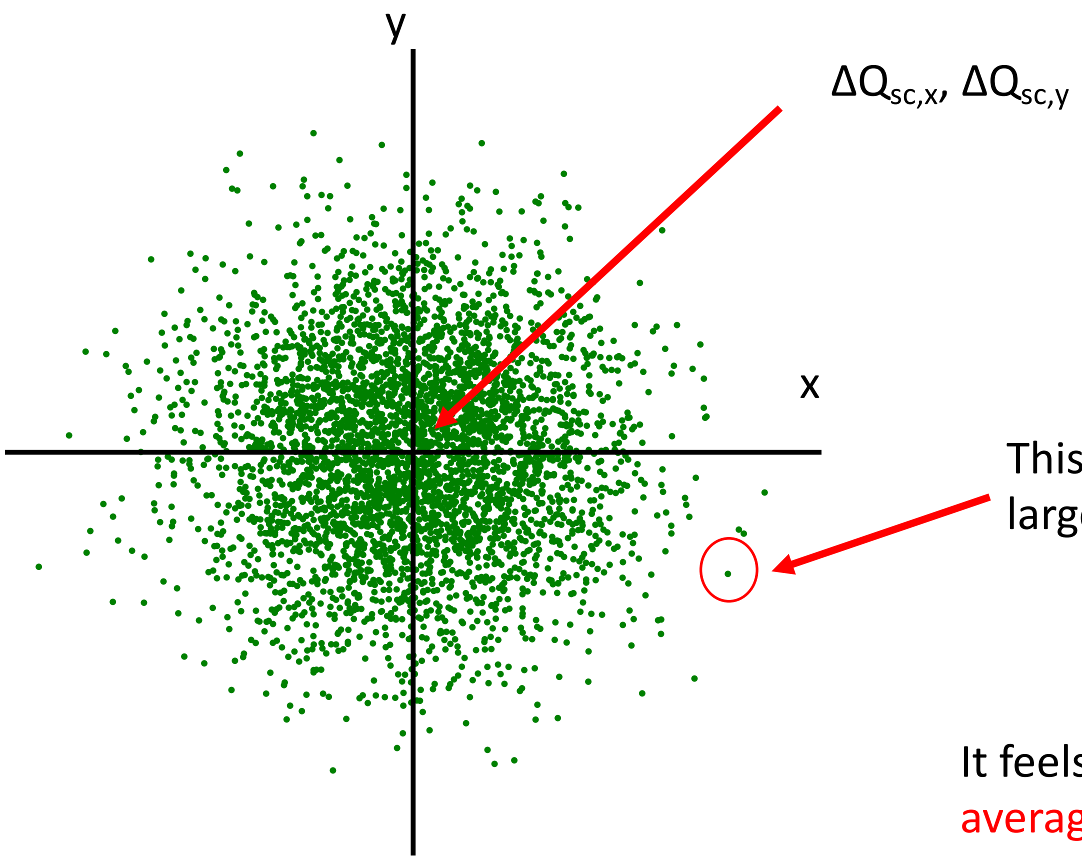
$$Q_x = Q_{x0} + \Delta Q_{sc,x}$$

Depressed Tune | Machine Tune | Space charge tuneshift

If $$Q_{x0} = 4.295$$

but $$\Delta Q_{sc,x} = -0.295$$

Effective tune in the center of beam → $Q_x = 4$!!!!

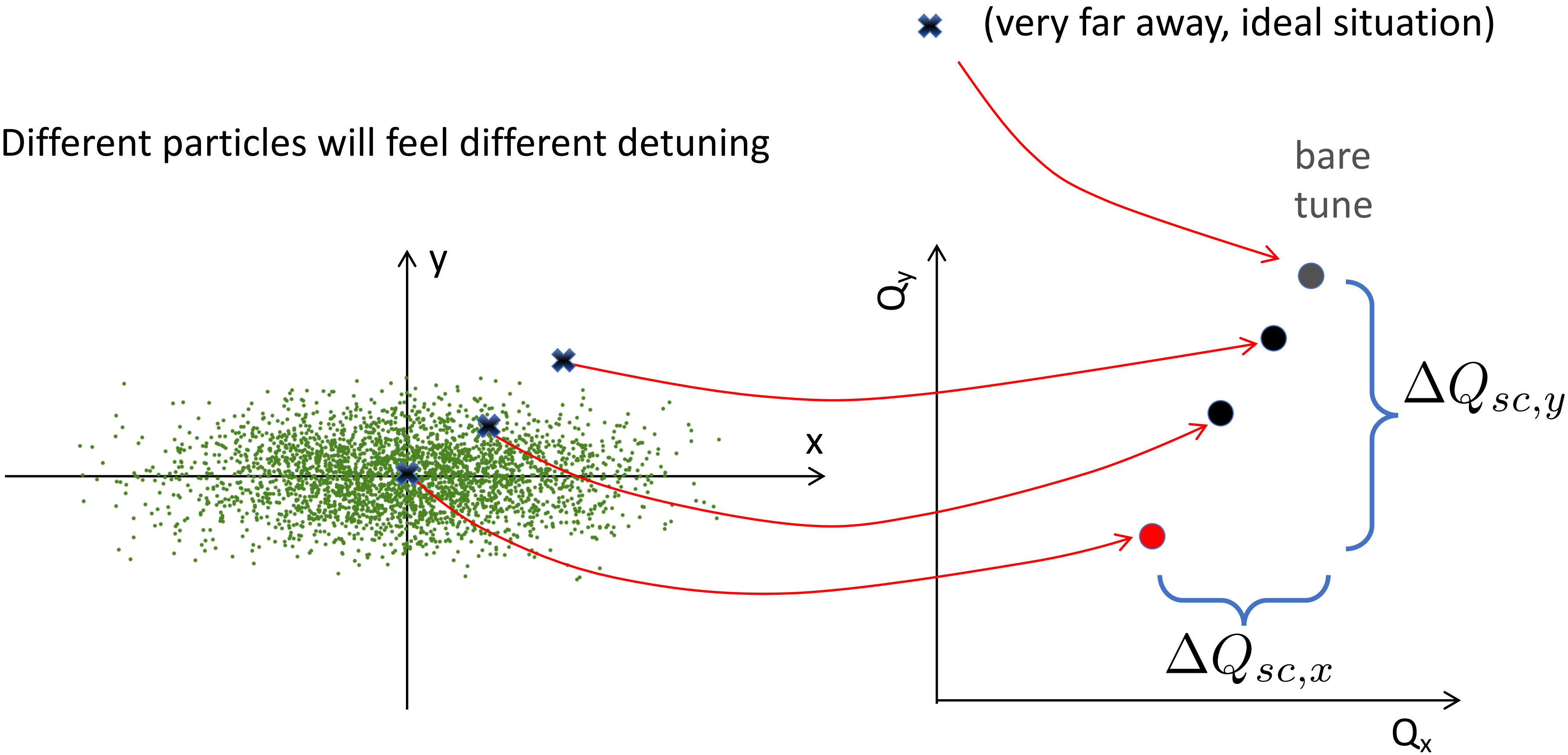


This particle makes large oscillations

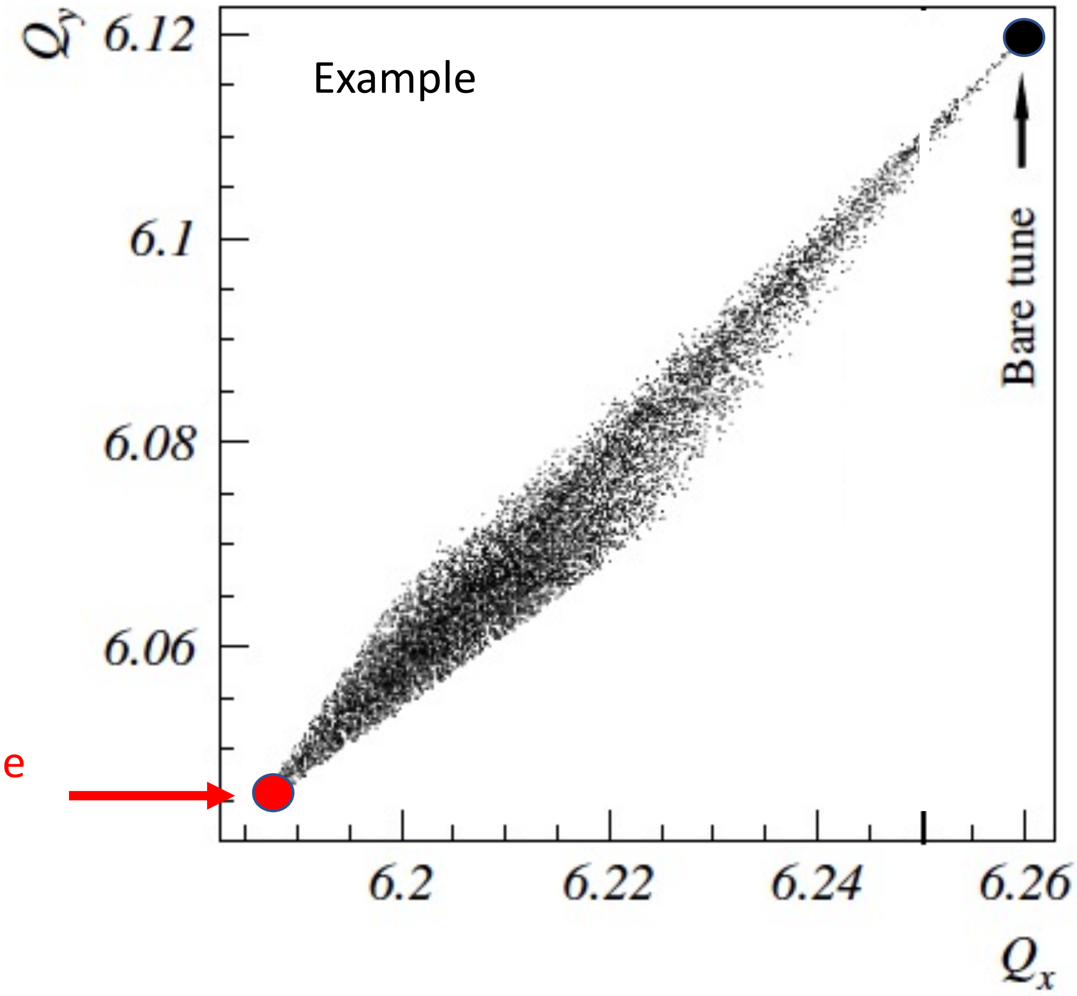
It feels a smaller average particle density

The space charge tuneshift is weaker

Different particles will feel different detuning



The space charge tune-spread



Particle in the beam core

Space charge tunespread is a measure of the high intensity

Rings $\Delta Q_{sc,x} = -0.5$ ⇒ $$\frac{Q_x}{Q_{x0}} = 0.9 \div 0.95$$

Linacs ⇒ $$\frac{\psi_x}{\psi_{x0}} \sim 0.6 \div 0.7$$

↑ Phase advances rather than tunes

Mismatching issues

Modified Optical functions

Suppose a beam with

ε_x, ε_y

is matched for the **naked** optics

$$\beta_x \quad \alpha_x \quad D_x \quad D'_x$$

depends on local position "s"

$$Q_x$$

← "depressed" tune

$$\beta_y \quad \alpha_y$$

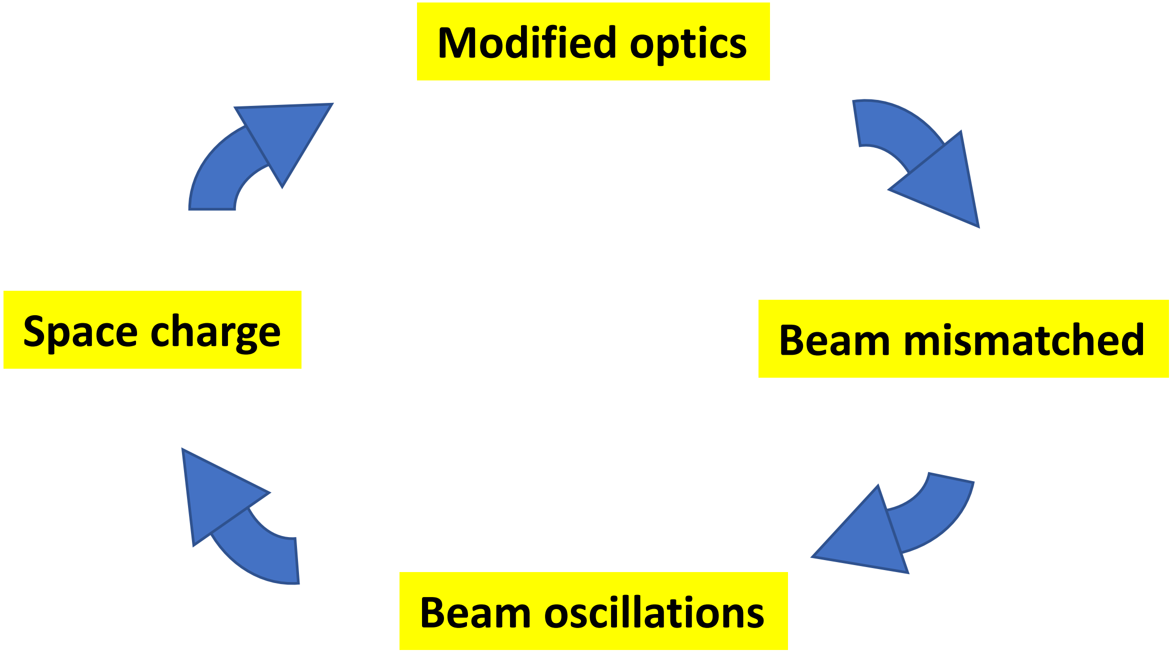
depends on local position "s"

$$Q_y$$

← "depressed" tune

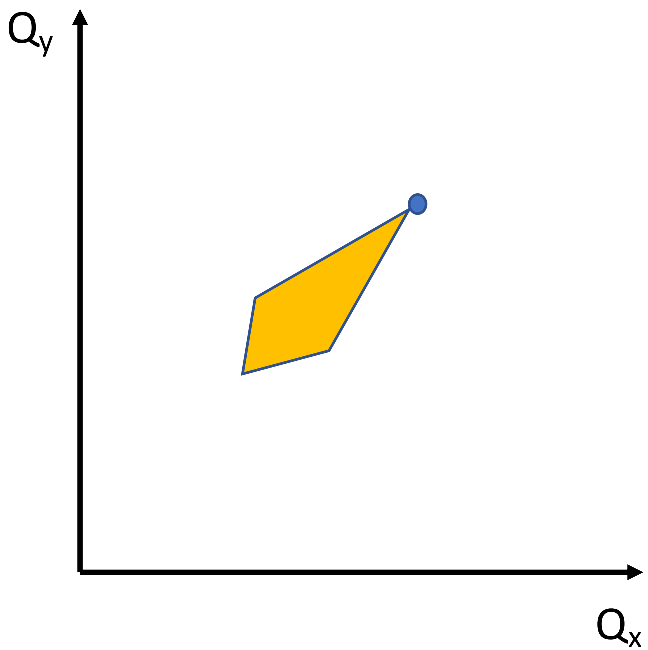
⇒ The beam is **mismatched** with respect to the modified optics !!!!

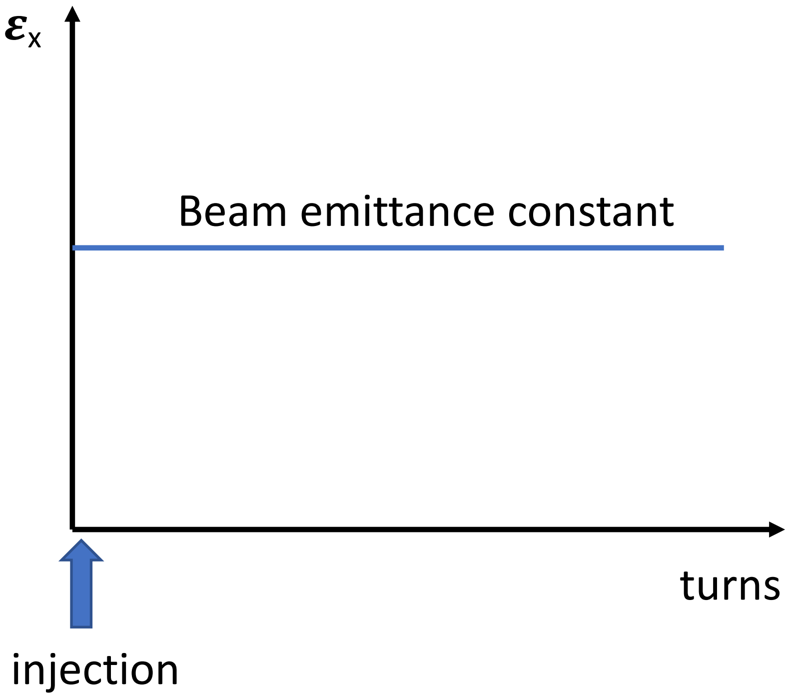
The matching issue



Matched beam and high intensity

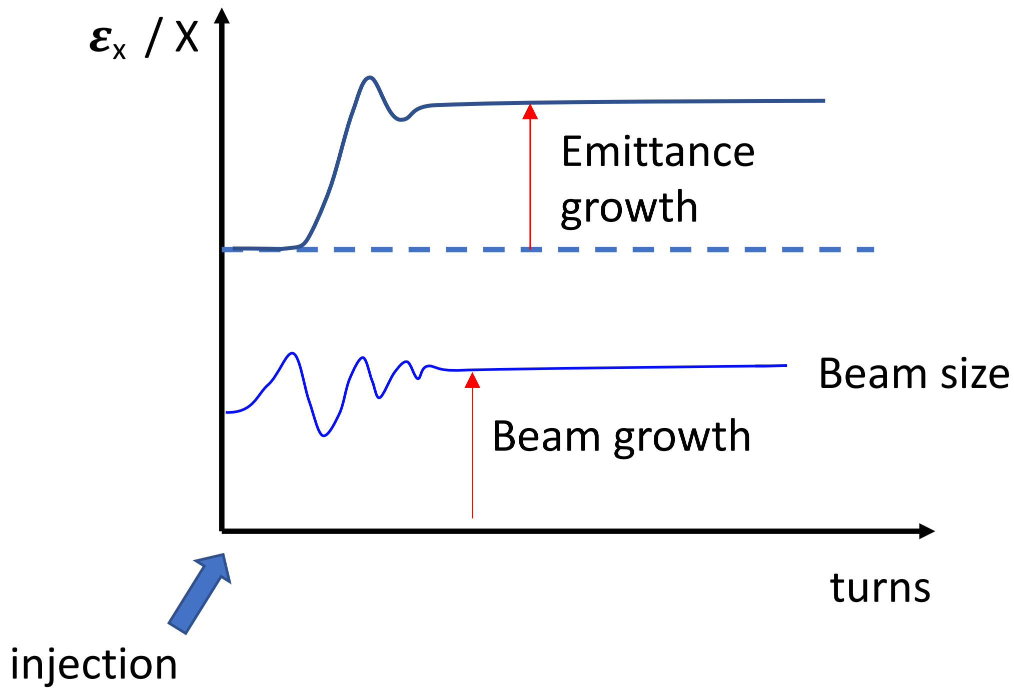
Coasting beam



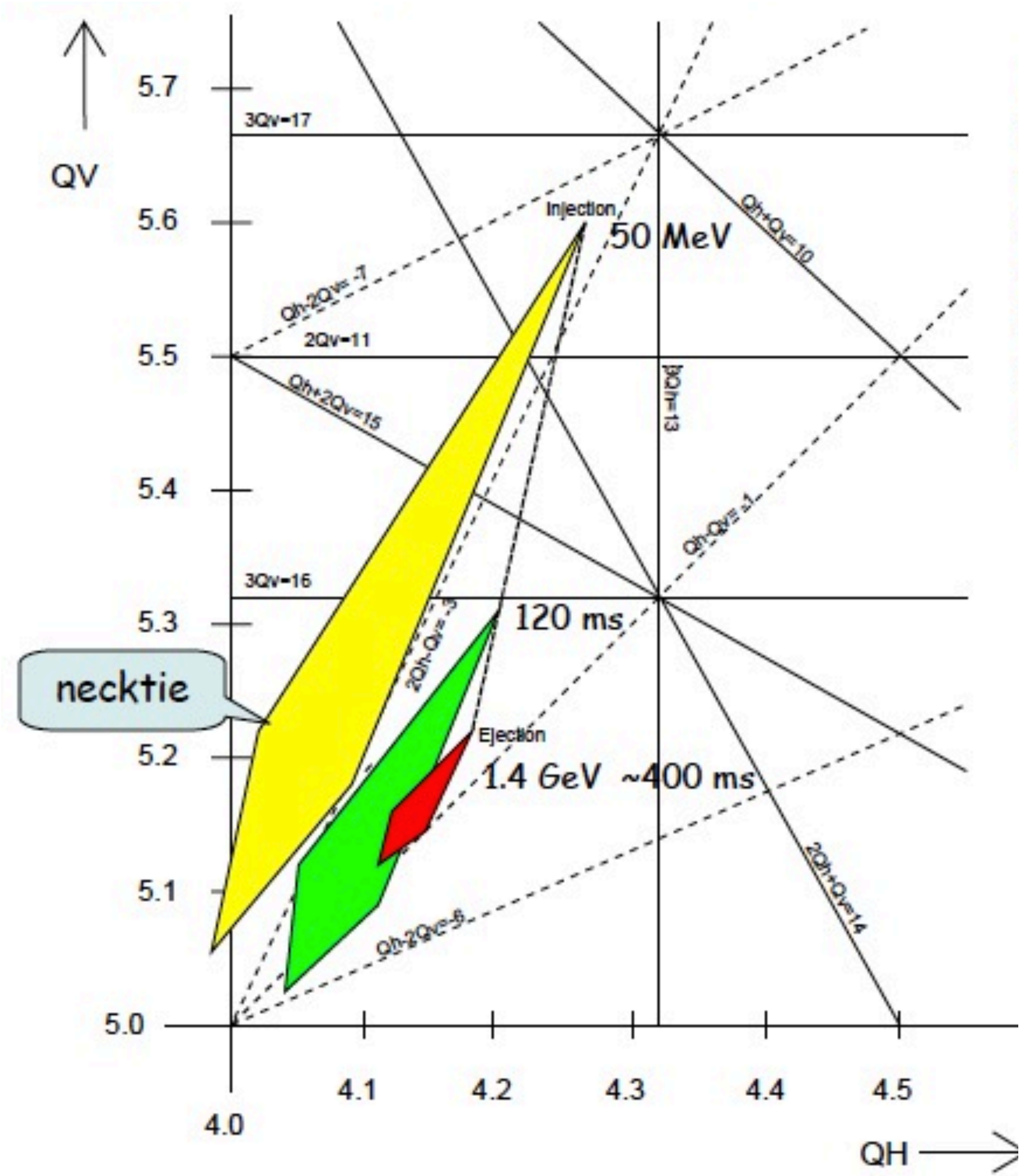


Mismatched beam and high intensity

Coasting beam



Effect is fast and depends on ΔQ_{sc} and the “naked optics”



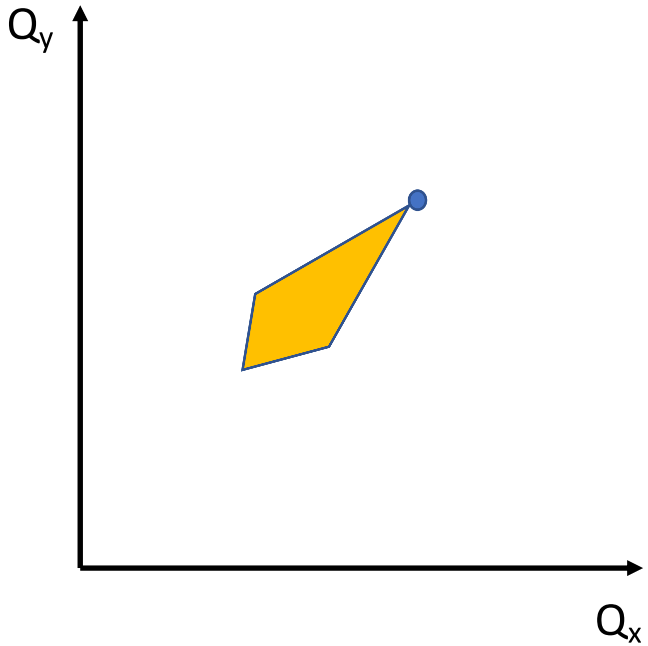
Resonances

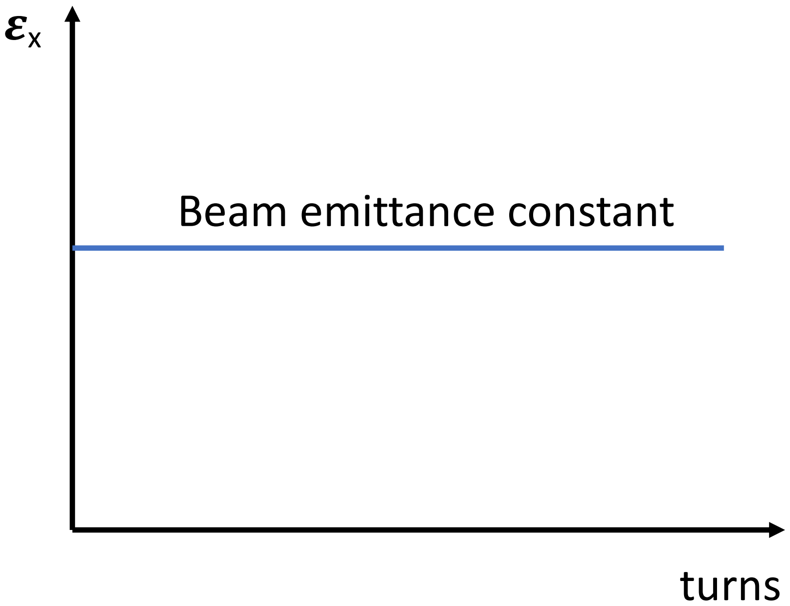
Issues

1) Space charge + resonances in coasting beams
2) Space charge + resonances in bunched beams
3) Collective beam response to direct space charge forces ?

Resonances and high intensity

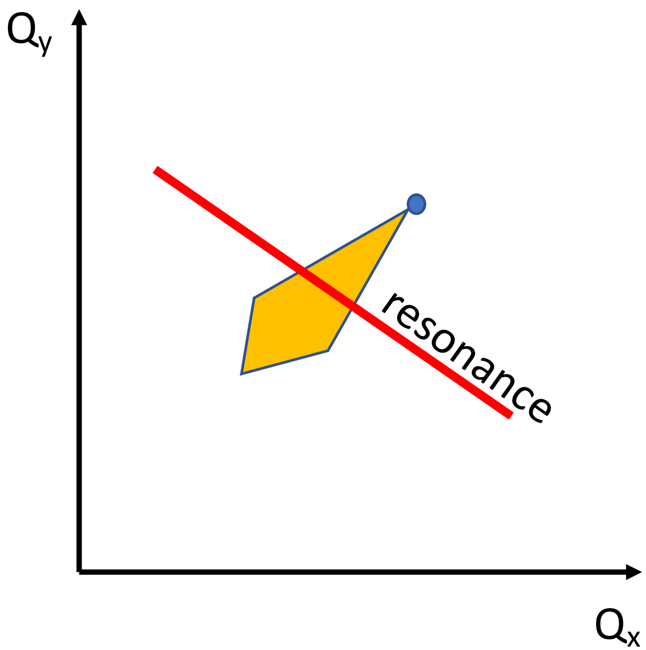
Coasting beam

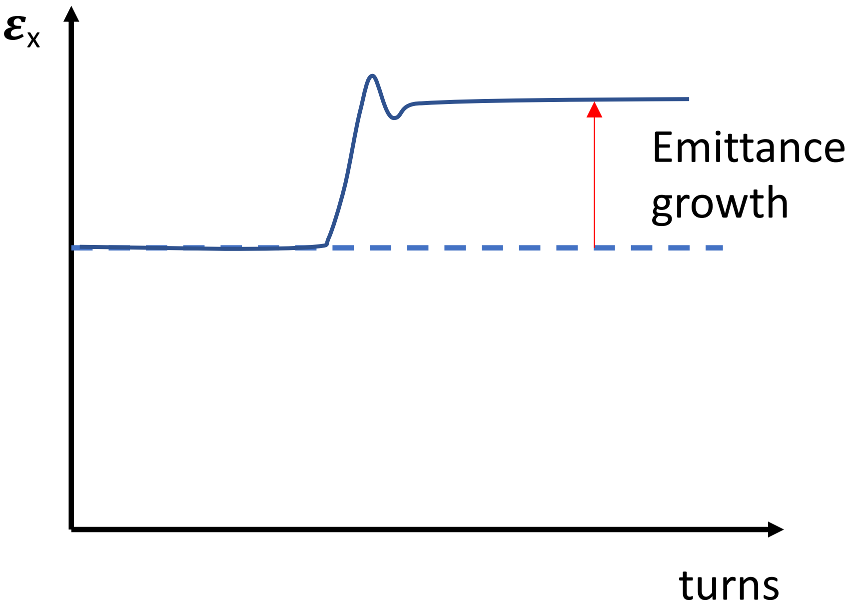




Resonances and high intensity

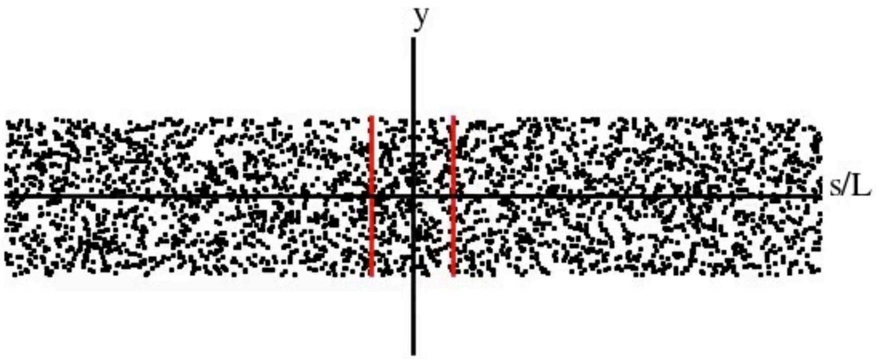
Coasting beam

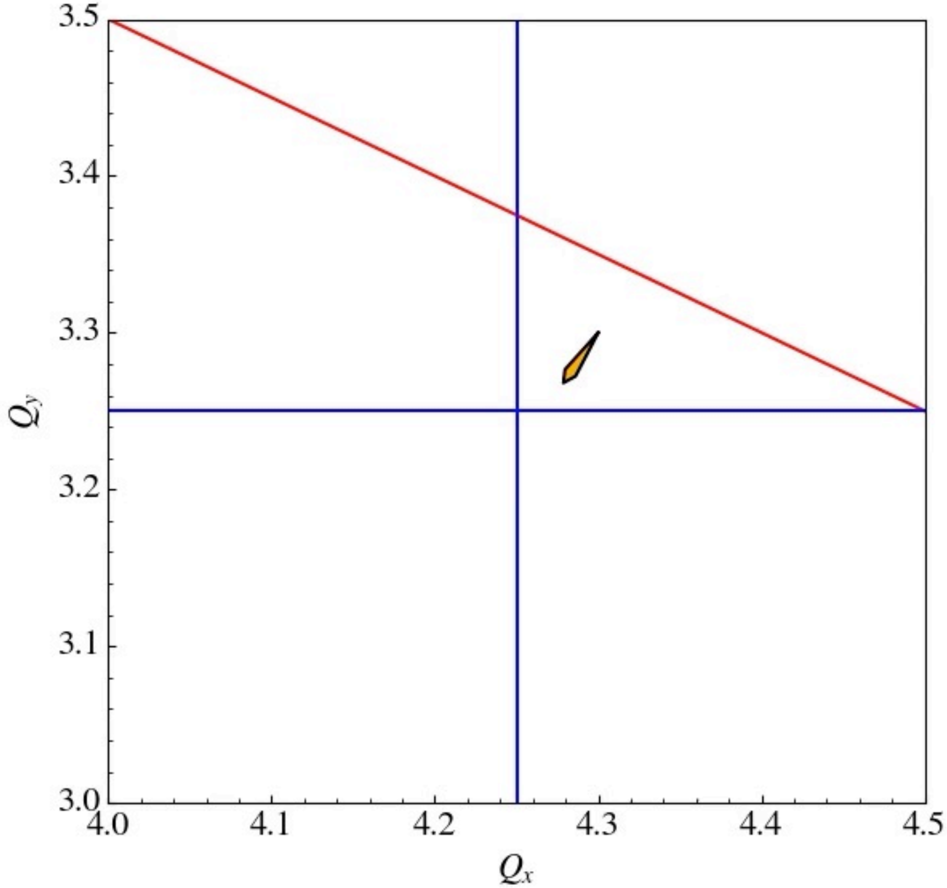




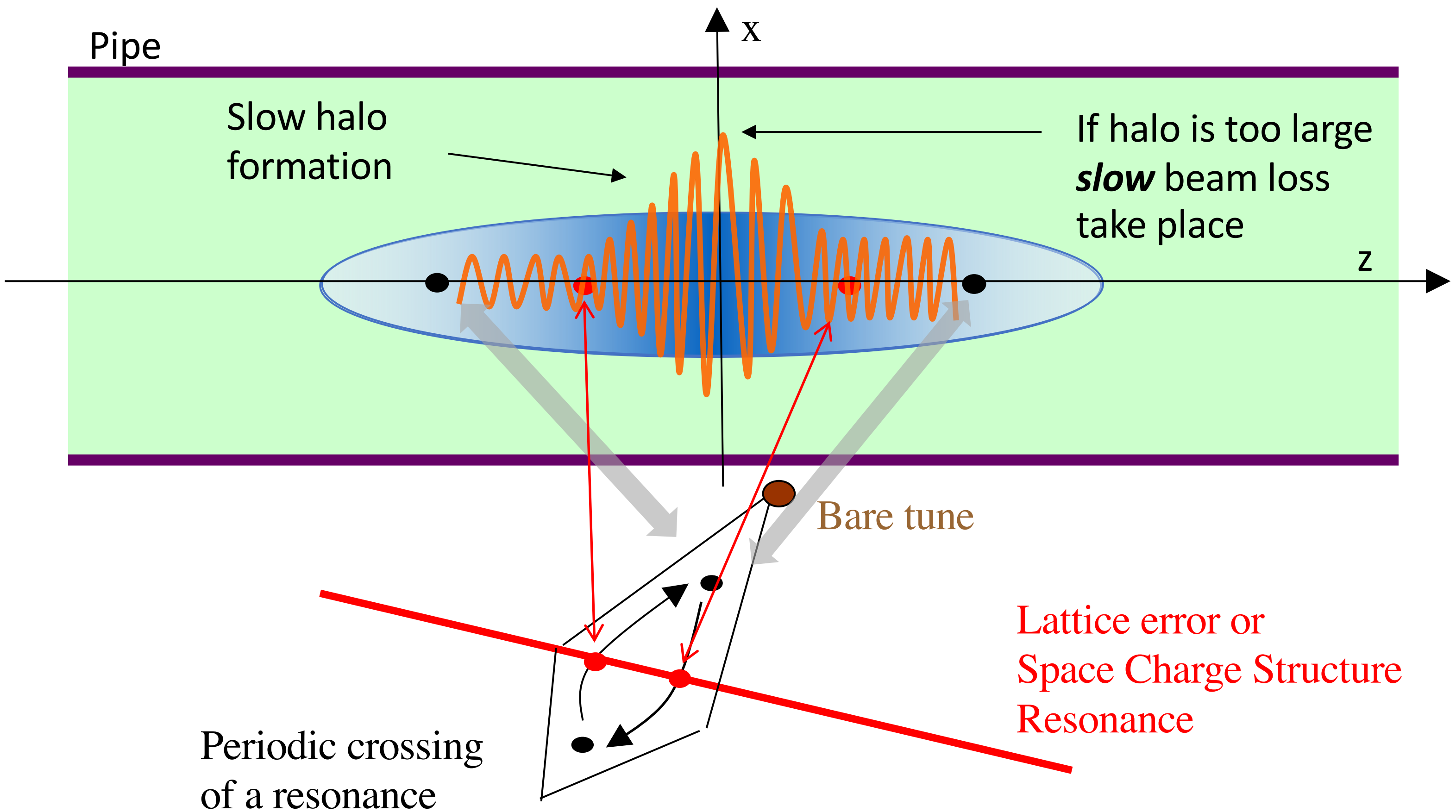
Effect is fast and depends on DQ_{sc} and the “strength” of the resonance

Intensity effect during bunching



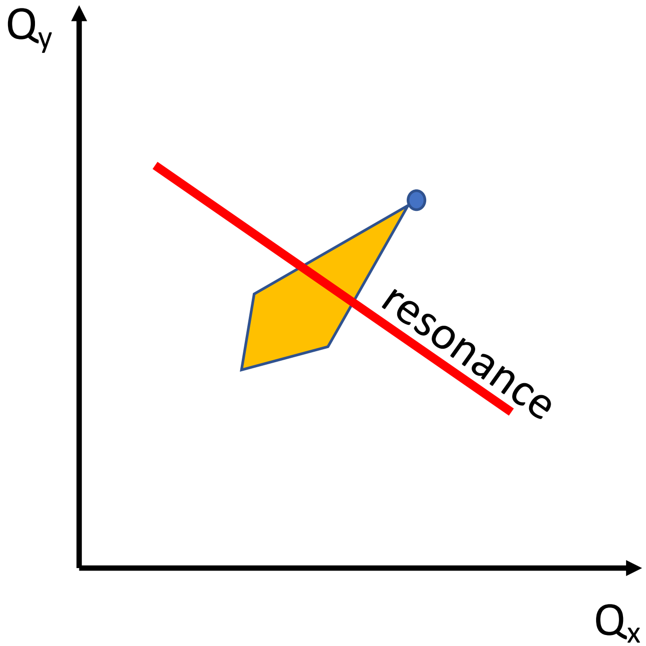


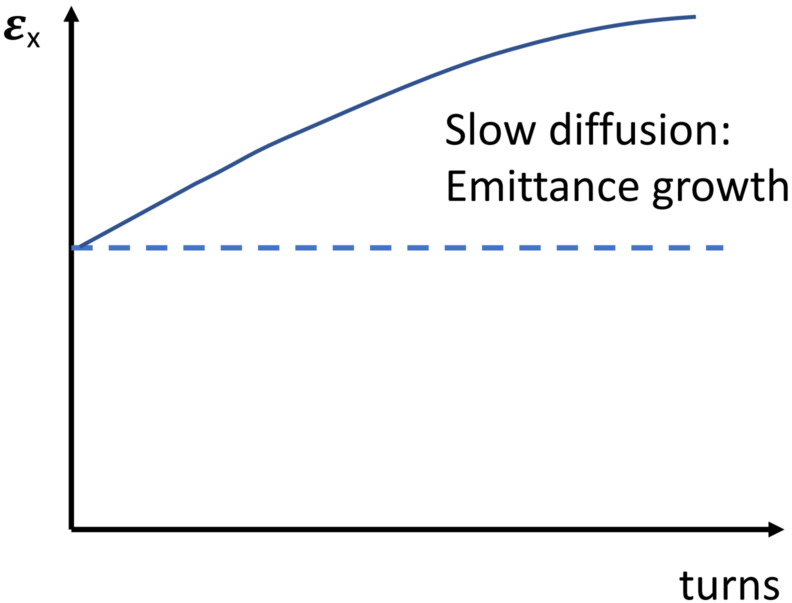
Beam loss mechanism



Resonances and high intensity

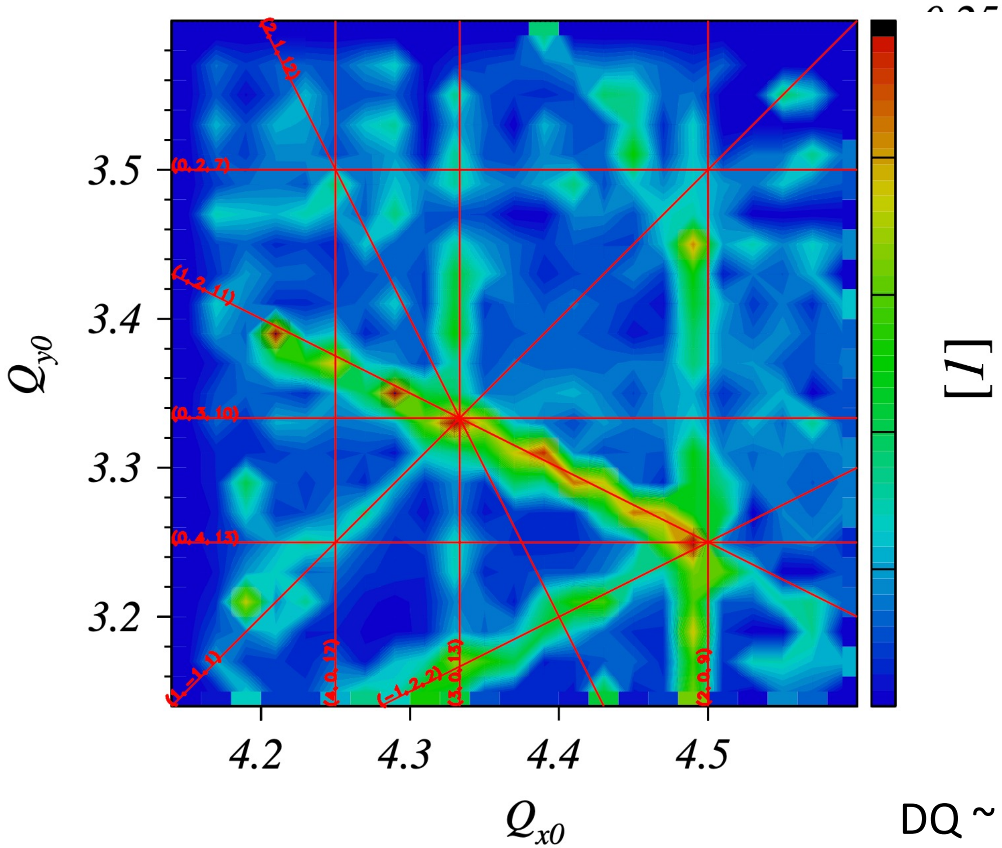
Bunched Beams





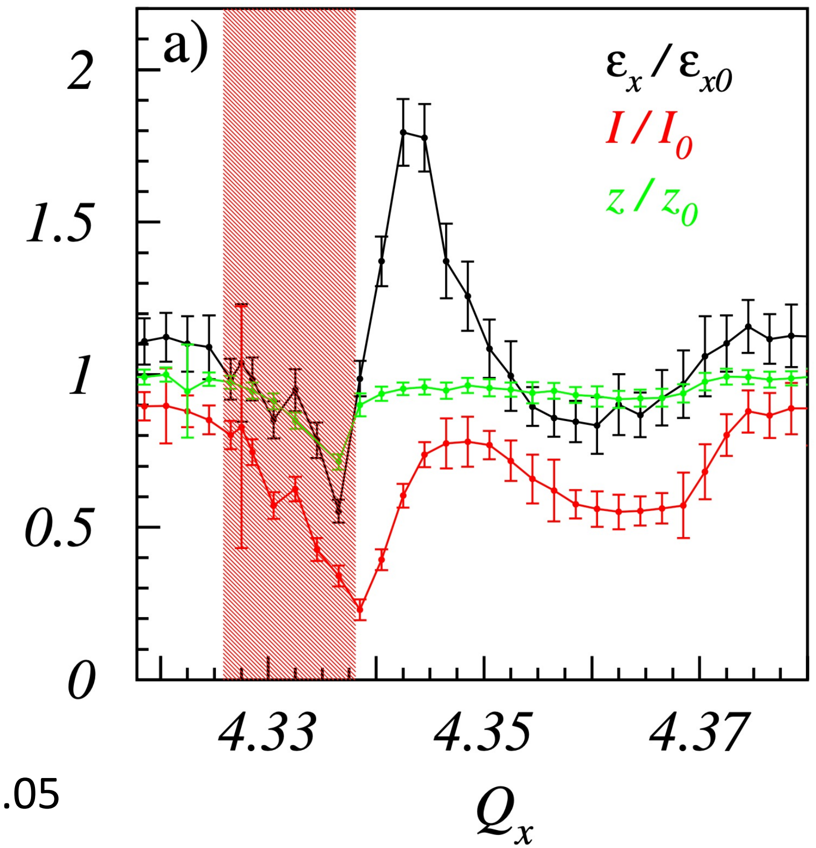
Effect is fast and depends on DQ_{sc}
and the "strength" of the resonance
And the position of the tune with respect to the resonance

High intensity bunched beams and resonances @SIS18

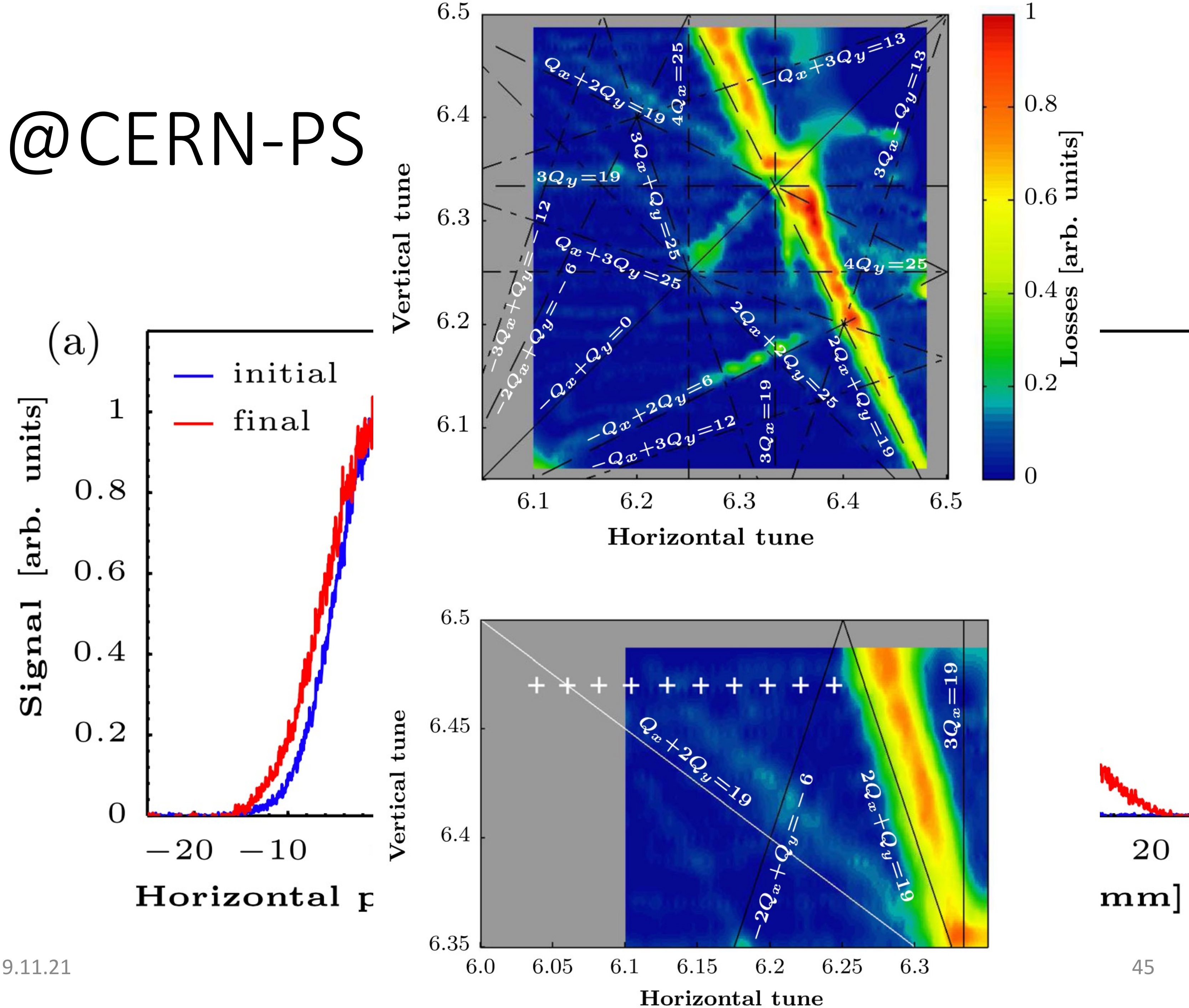


DQ ~ 0.05

Measurements in SIS18

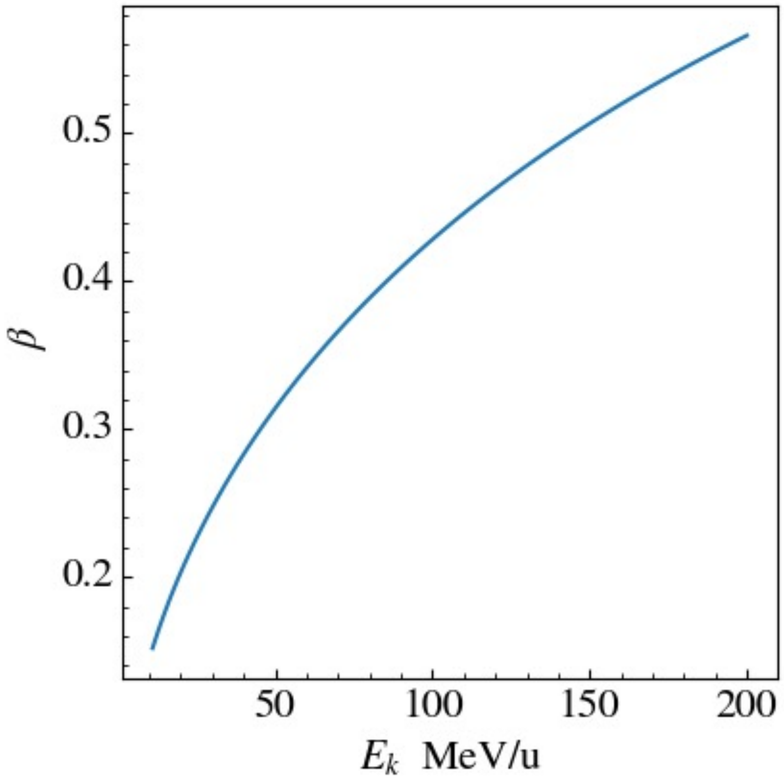


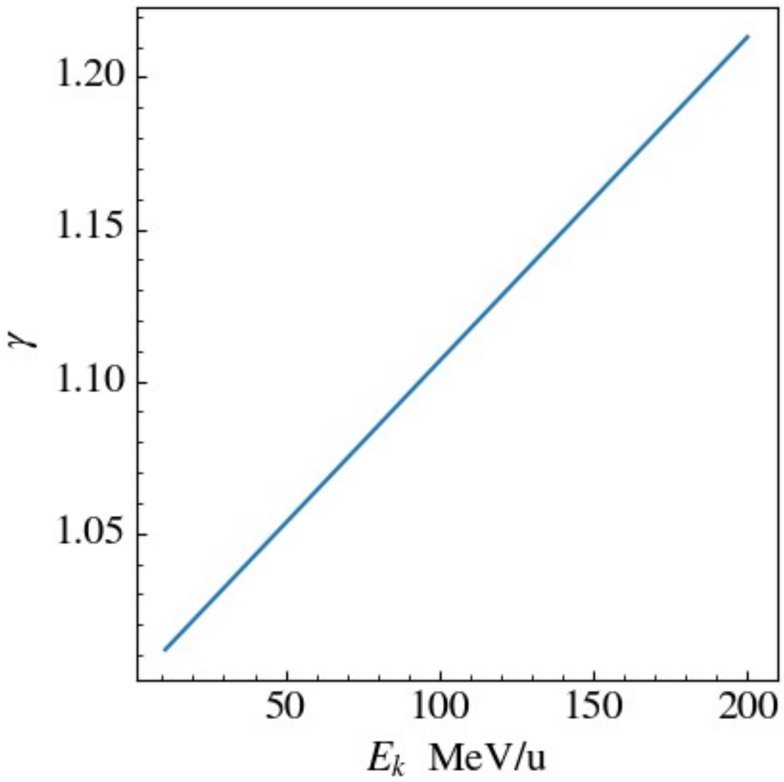
@CERN-PS


(a)
initial
final
Signal [arb. units]
Horizontal p
mm]
Vertical tune
Horizontal tune
Losses [arb. units]
$Q_x+2Q_y=19$
$4Q_x=25$
$-Q_x+3Q_y=13$
$3Q_x-Q_y=13$
$3Q_x+Q_y=25$
$3Q_y=19$
$-3Q_x+Q_y=-12$
$-2Q_x+Q_y=-6$
$Q_x+3Q_y=25$
$4Q_y=25$
$-Q_x+Q_y=0$
$2Q_x+2Q_y=25$
$2Q_x+Q_y=19$
$-Q_x+2Q_y=6$
$-Q_x+3Q_y=12$
$3Q_x=19$

Acceleration

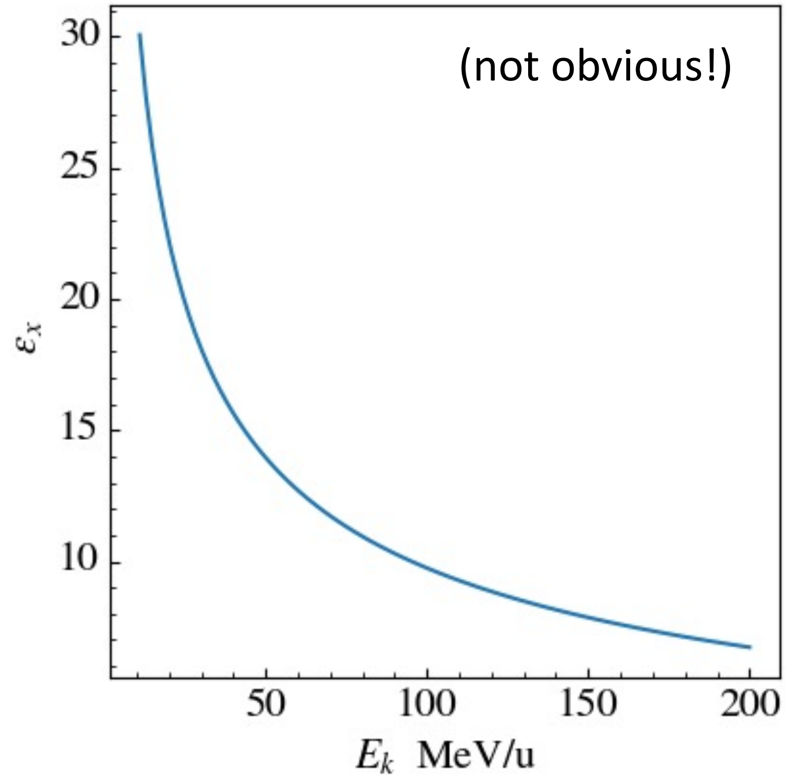
During acceleration



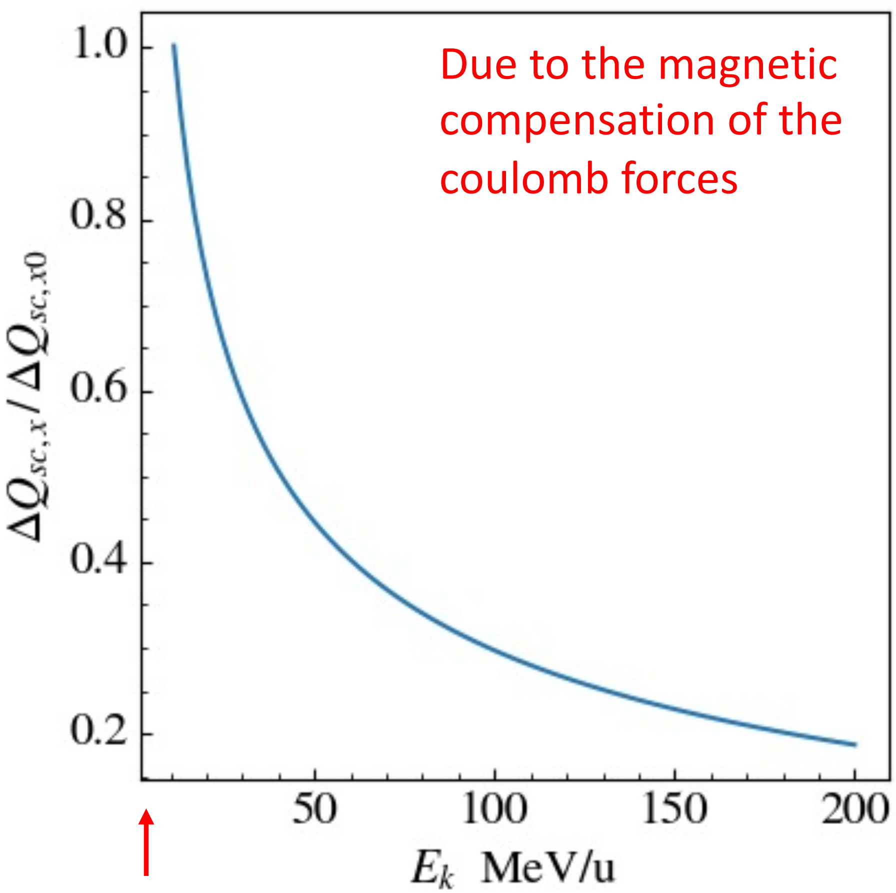


Therefore the current increases

Beam emittance becomes smaller. → the beam beomes smaller



But, the space charge tuneshift become smaller !!



11 MeV/u

Summary

- Space charge tune-shift is the measure of the "high intensity";
- High intensity change machine+beam optics;
- A mismatched beam will create emittance increase;
- Overlapping of space charge tunespread will create emittance increase;
- For a bunched beam the overlapping of tunespread with a resonance; will create a diffusional regime → beam loss;
- In a bunch compression the tunespread increases and may lead to resonance overlapping;
- During acceleration space charge tunespread dumps;

Not addressed:

- High intensity on the longitudinal dynamics;
- High intensity, dp/p and bunch compression;
- Negative mass instability;
- Resistive wall instability;