Methods and Measurements of Beam Losses in SIS18 relevant for SIS100

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Joint Helmholtz-Rosatom School at FAIR

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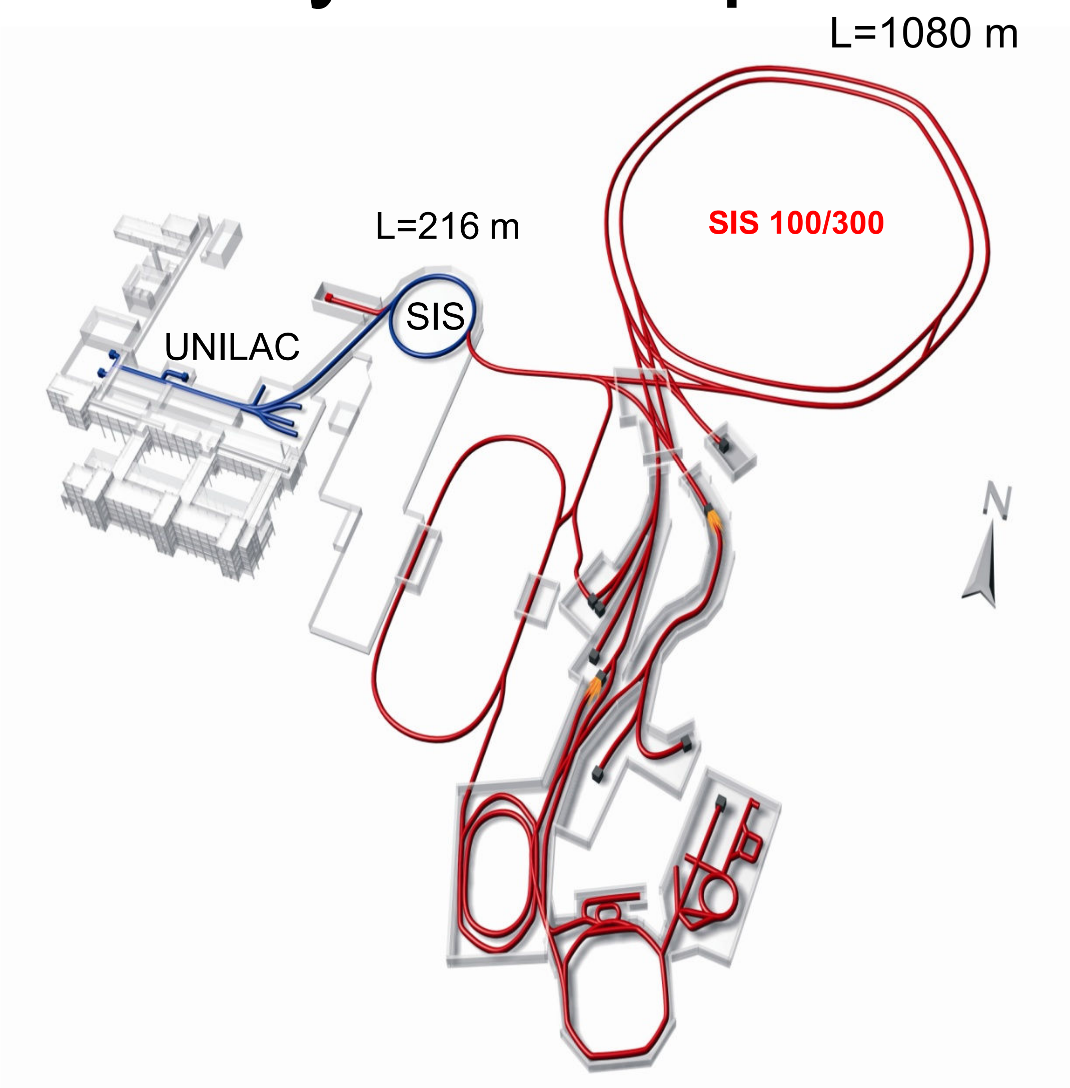
Motivation

and

Overview

FAIR –
Facility for Antiproton and Ion Research



Gain Factors

- Beam intensity:
  factor **100 – 1000**
- Beam energy: factor **15**
- New research topics and opportunities

Existing SIS18 as injector for FAIR:

high beam energies;
high beam intensities;
high beam quality

‘Beam loss budget’

Beam loss induced effects in the vacuum chamber or surrounding accelerator components:

activation: loss of ‘hands-on-maintenance’ (~ 5%)

Ref. **I. Strasik et al., PRSTAB 13, 071004 (2010)**

damage: persistent change of material properties

quenching: sudden loss of superconductivity

desorption: increase of the vacuum pressure

Ref. **P. Spiller**

Transversal

beam dynamics

3D Particle Coordinates

Beam Particle coordinates

(longitudinal)

$$z = s - s_0$$

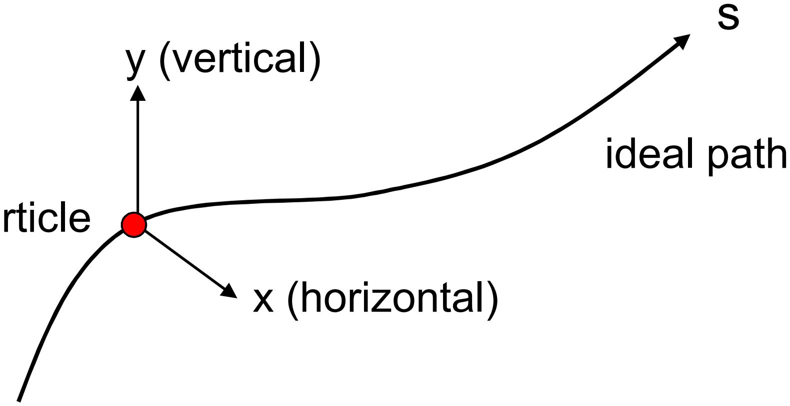
$$\frac{\Delta p}{p_0} = \frac{\Delta W}{\beta_0^2 W_0}$$

(transverse: horizontal)

$$x, x' = \frac{dx}{ds}$$

(transverse: vertical)

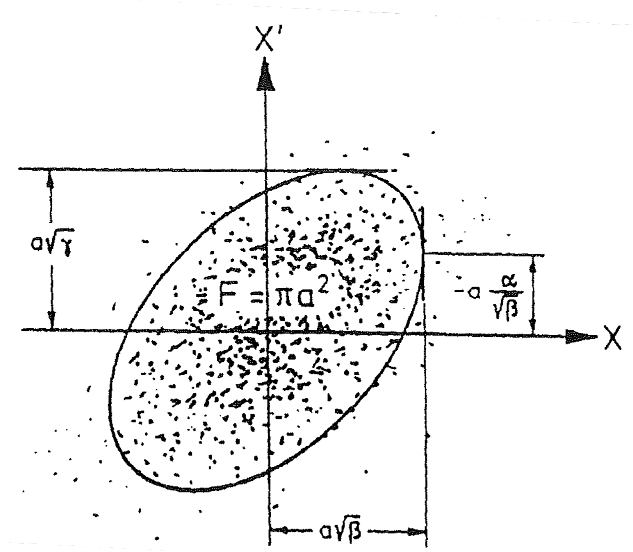
$$y, y' = \frac{dy}{ds}$$



$$\vec{r} = \left(z, \frac{\Delta p}{p}, x, x', y, y' \right)$$

Important Definitions

Beam emittance ε is the phase space area occupied by the beam and defined by the largest ellipse. **UNITS** ε **[mm mrad] !**



Area (emittance) is conserved moving through the channel

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon$$

The **beam envelope** x_m is characterized by the maximum value of **x** at a given position **s**

$$x_m = \sqrt{\beta\varepsilon}$$

Acceptance (admittance) ***a*** is the maximum emittance that a beam transport system is able to transmit

Twiss parameters

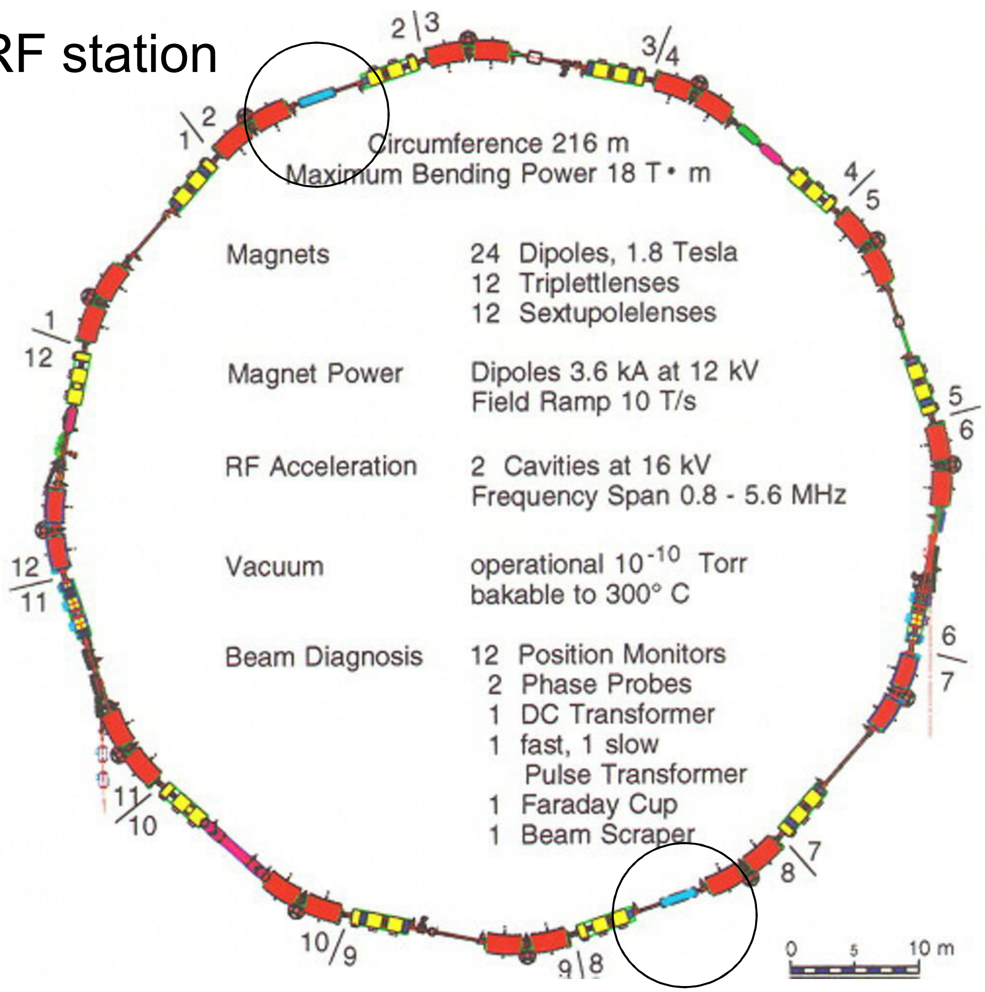
$$\beta = w^2(s) \qquad \alpha = -\frac{1}{2}\beta' \qquad \gamma = \frac{1+\alpha^2}{\beta}$$

beta- **alfa-** **gamma-** functions

Ref. **E.Courant, H. Snyder , Theory of the synchrotrons**

Heavy Ion Synchrotron SIS18

RF station



SIS18: C=216 m

RF station ω_{RF}

- Constant orbit radius
- Variable magnetic fields
- ‚Synchronous‘: $h\omega_0 = \omega_{RF}$

Revolution frequency:

$$\omega_0 = \dot{\theta} = \frac{qB_y}{\gamma m} = \frac{v_s}{R}$$

CLOSED ORBIT

Magnetic Rigidity:

$$B_y R = \frac{p_s}{q}$$ = 18 Tm (SIS18)

Circular accelerators

Hill's Equation
$$\begin{cases} Z''(s) + K(s)Z = 0 \\ K(s) = K(s+L) \end{cases}$$

$Z = (x/y)$ Transversal coordinate: x or y

General solutions for constant focusing K > 0

$$Z(s) = w(s)\sqrt{\varepsilon}\cos(\psi(s)+\psi_0)$$

amplitude function

ψ_0, ε are determined by the initial conditions

Phase advance $\sigma = \psi(s) - \psi(s+L)$

Betatron frequency/ or
Tune/ or
Working point (Q_x,Q_y)

is a number of betatron oscillations per revolution

Betatron tune $Q = \dfrac{N\sigma}{2\pi}$

N is number of periods

C=NL is circumference of the accelerator

Ref. SY Lee, Accelerator Physics, 2004

Linear imperfections and All That

In presence of field errors (and high order terms), the basic equations become

$$x''(s) + K(s)x = \frac{\Delta B_y}{B\rho}$$

$$y''(s) + K(s)y = -\frac{\Delta B_x}{B\rho}$$

where expansion of the magnetic field is

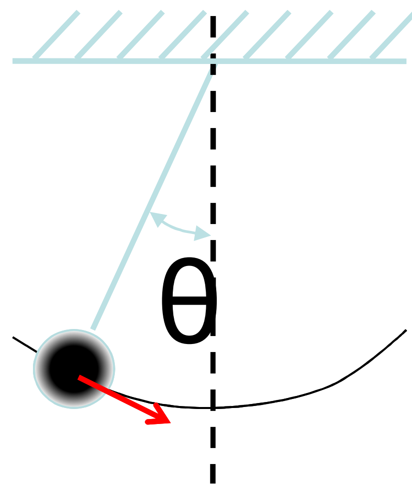
$$\Delta B_y + \Delta B_x i = B\rho \sum_{n=0}^{\infty} (k_n + j_n i) \frac{(x+iy)^n}{n!}$$

k_n, j_n normal and skew multipole coefficients

Resonances

The periodicity in circular accelerator may enhance small perturbative effects otherwise negligible

Example:



small oscillations

Give a hammer little kick at the maximum amplitude of the pendulum and the amplitude will increase

period of kick $T_k = T_o$

No matter how small is the hammer kick:
after each oscillation the amplitude of the oscillation will increase

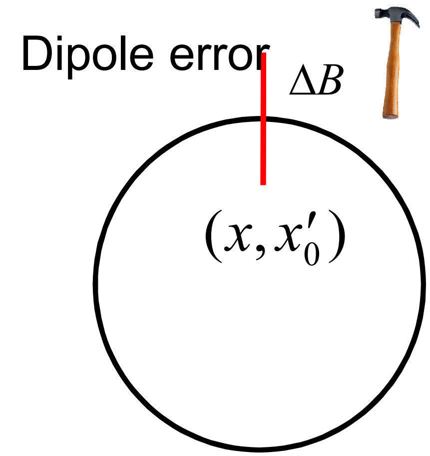
Dipole and Quadrupole field errors

DIPOLE (STEERING) ERROR

Transverse kick by the error dipole field ΔB:

$$\Delta x' = \theta \qquad \theta = \frac{\Delta B}{B}\frac{l}{R}$$

Closed orbit: $$x(s) = \theta \frac{\sqrt{\beta_0}\sqrt{\beta_s}}{2\sin \pi Q}\cos(\psi(s) - \pi Q)$$



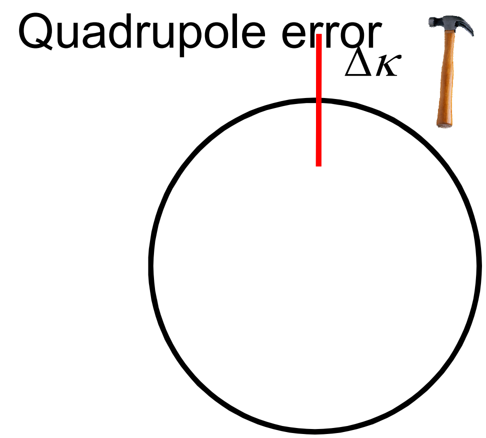
Stop band is the range of tune values for which the motion is unstable

Stop band: $Q \neq n$

QUADRUPOLE (GRADIENT) ERROR

$$\Delta Q = \frac{\beta_0}{4\pi}\Delta k ds$$

Stop band: $Q \neq \frac{n}{2}$



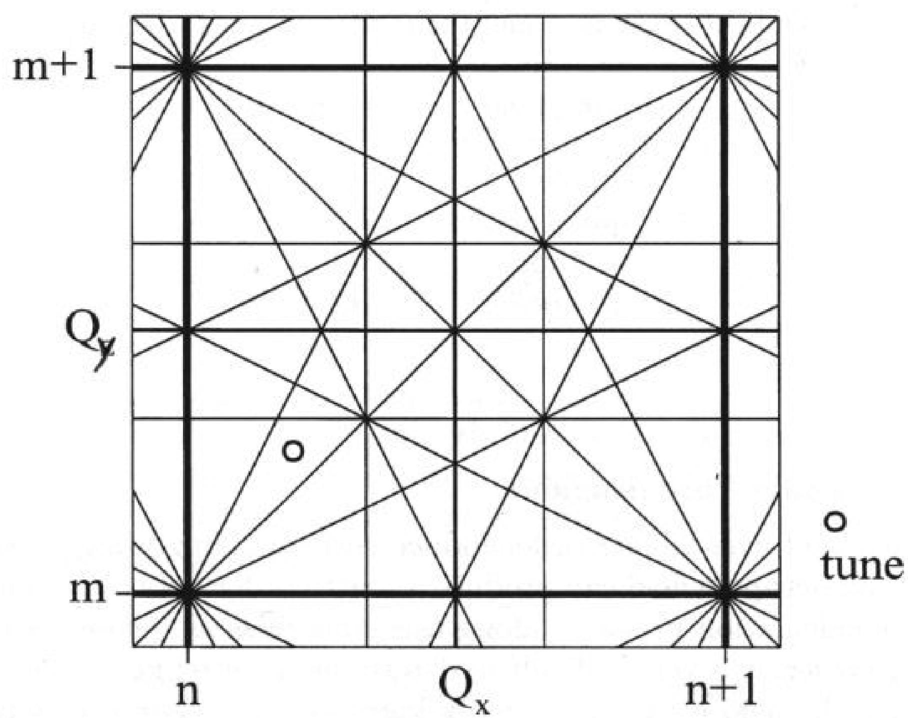
Ref. **SY Lee, Accelerator Physics, 2004**

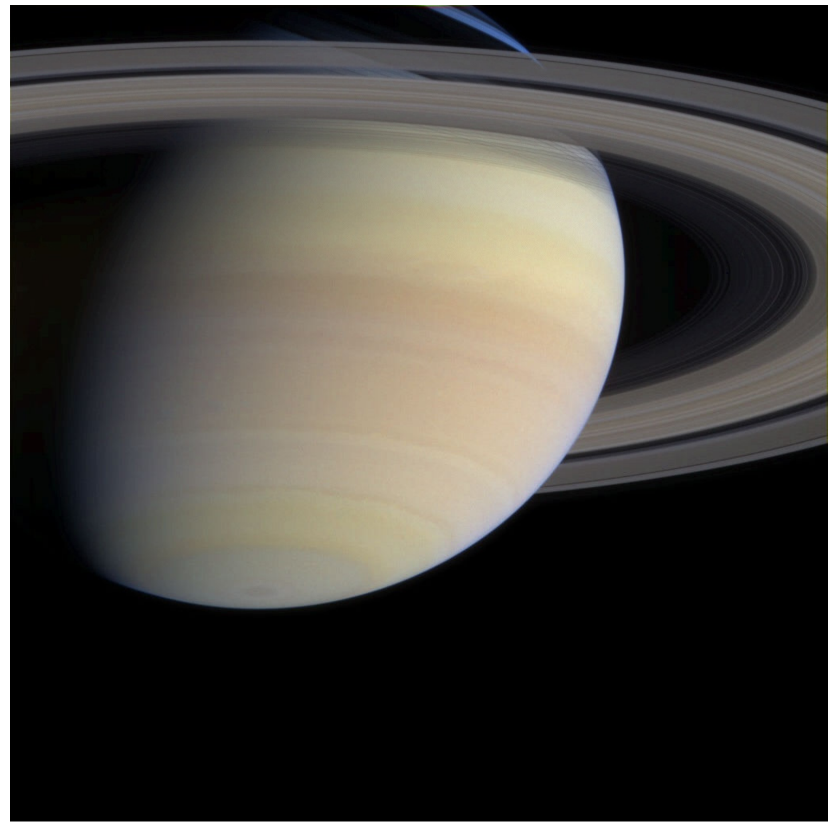
Tune and betatron resonances

Order of resonance:
|n+m|

m, n, p are integer

$$nQ_x + mQ_y = p$$





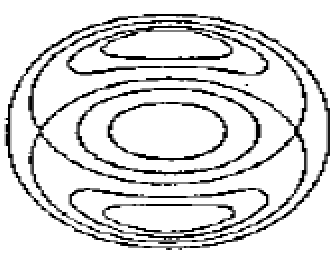
Dynamic Aperture

Dynamic aperture

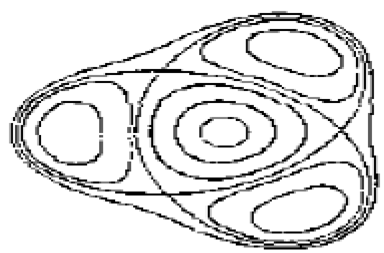
is a stability region in phase space, where particles have stable motion, will be stored indefinitely

Phase space paths in the vicinity of resonances of order:

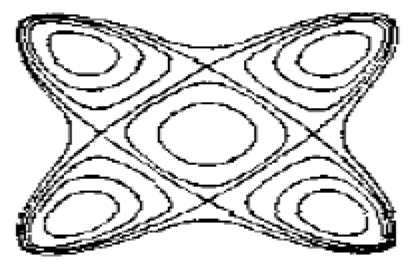
n=2



n=3



n=4



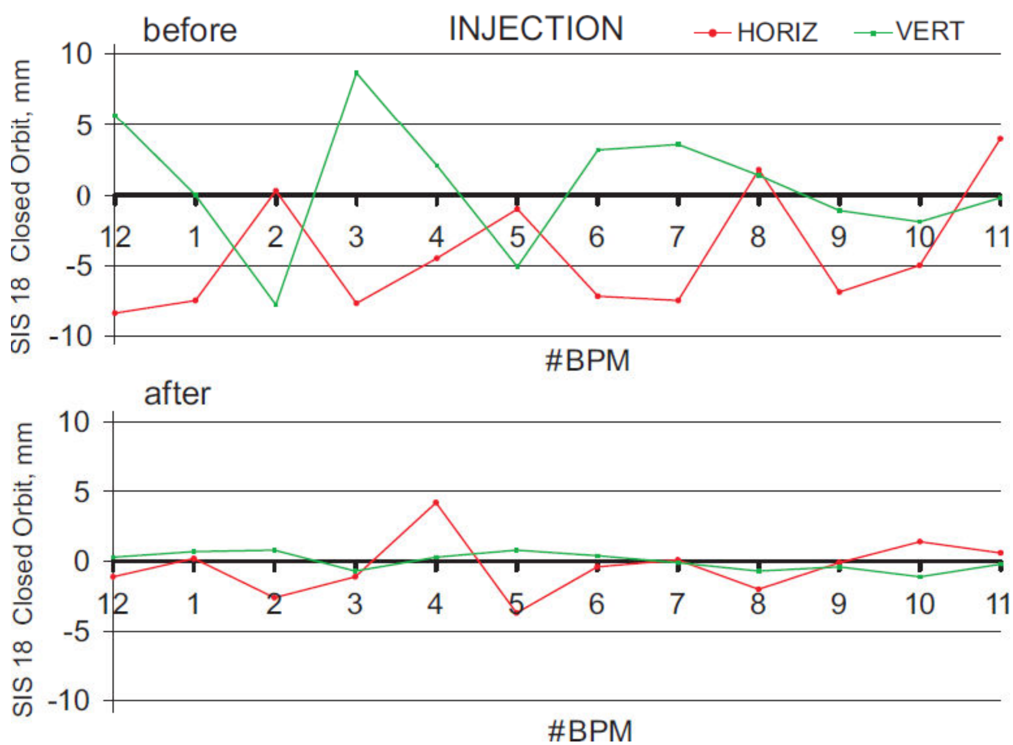
Ref. A. Schoch, Theory of linear and nonlinear perturbations of betatron motion in alternating gradient synchrotrons, CERN 1958

Beam loss dynamics measurements in the SIS18

Closed orbit distortion in the SIS18

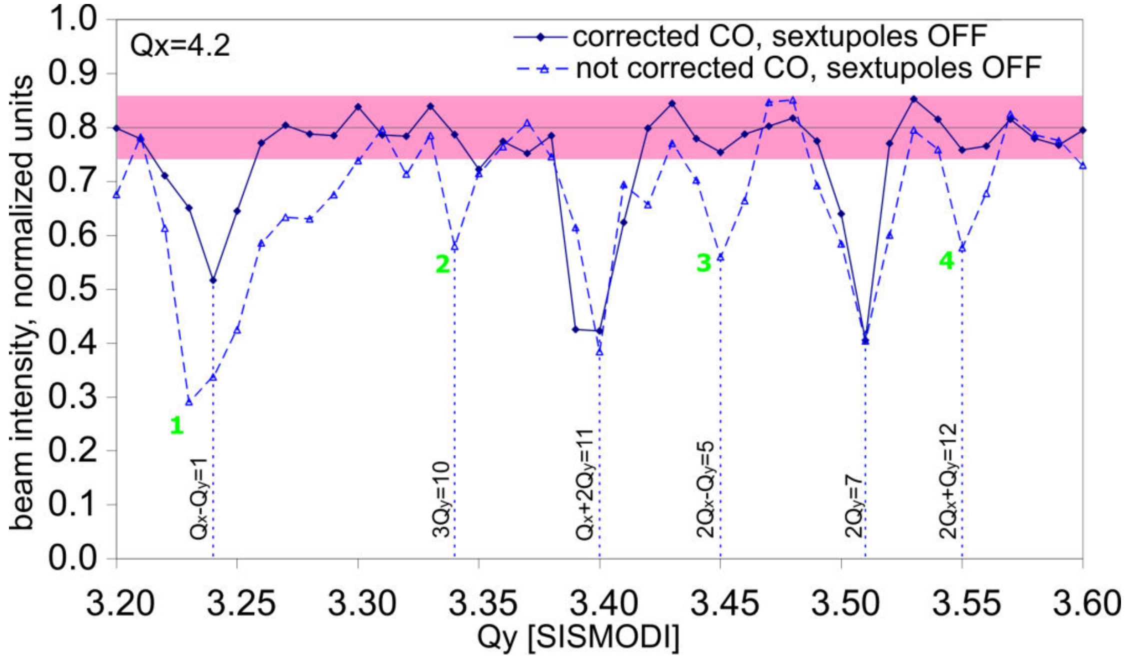
Superposition of dipole errors: $$\theta = \sum_j \theta_j = \sum_j \frac{l_j}{R}\frac{\Delta B_j}{B} \approx \frac{\Delta B}{B} \approx 10^{-4}\ \mathrm{rad}$$

Estimated amplitude for SIS18: $$|\hat{x}| \approx \frac{(10^{-4}\ \mathrm{rad})(30\ \mathrm{m})}{2\sin\pi 4.2} \approx 1\ \mathrm{cm}$$



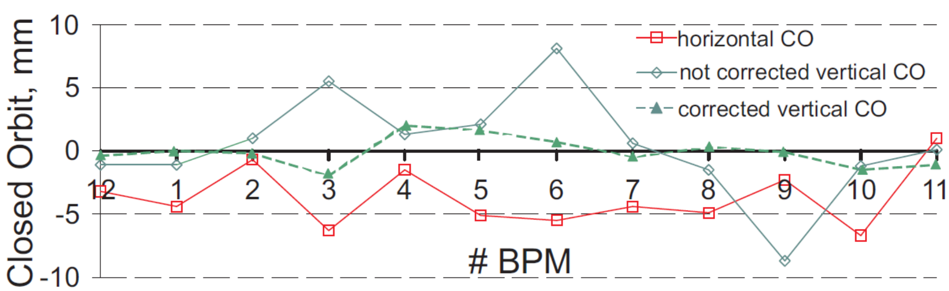
Ref. **A. Parfenova et al., SIS18 Closed Orbit Correction, GSI internal report, 2006**

Measured resonance beam loss 1.1 s after injection



For the corrected Closed Orbit the resonances 2, 3 and 4 either do not exist or are very weak

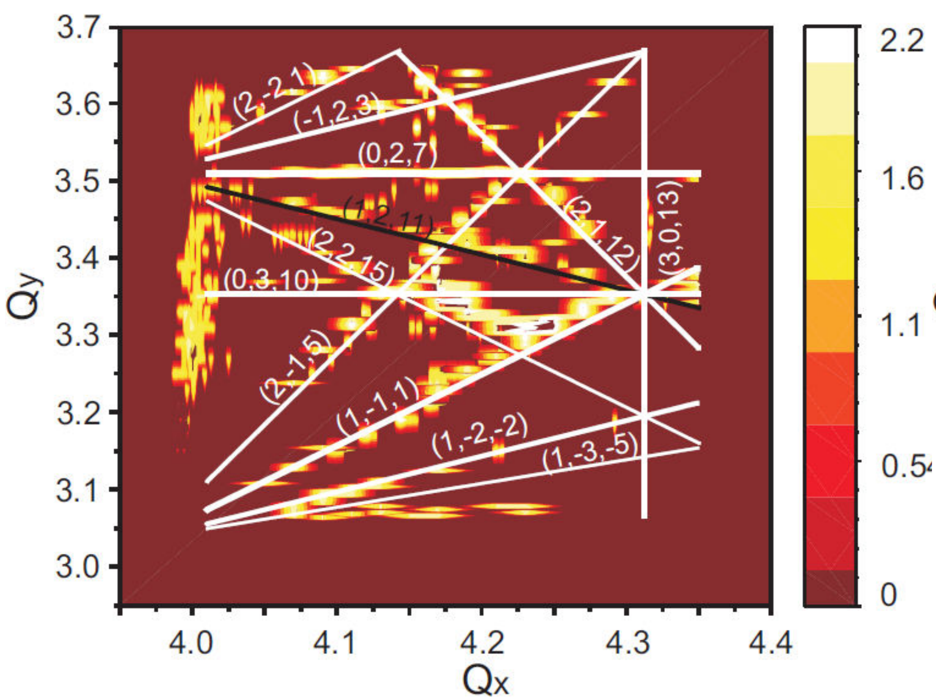
Vertical CO corrected and distorted



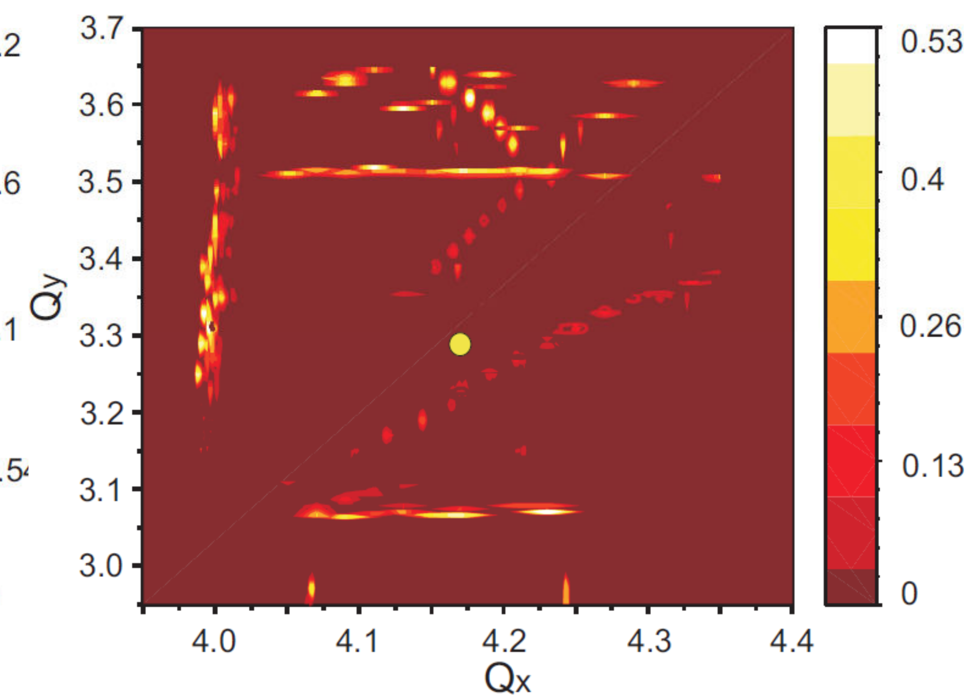
Ref. A. Parfenova et al., Resonance beam loss SIS18, GSI internal report, 2007

SIS18 measured Tune Diagram

Log(ΔI) ⇦ beam loss representation ⇨ ΔI/I



to identify the resonances



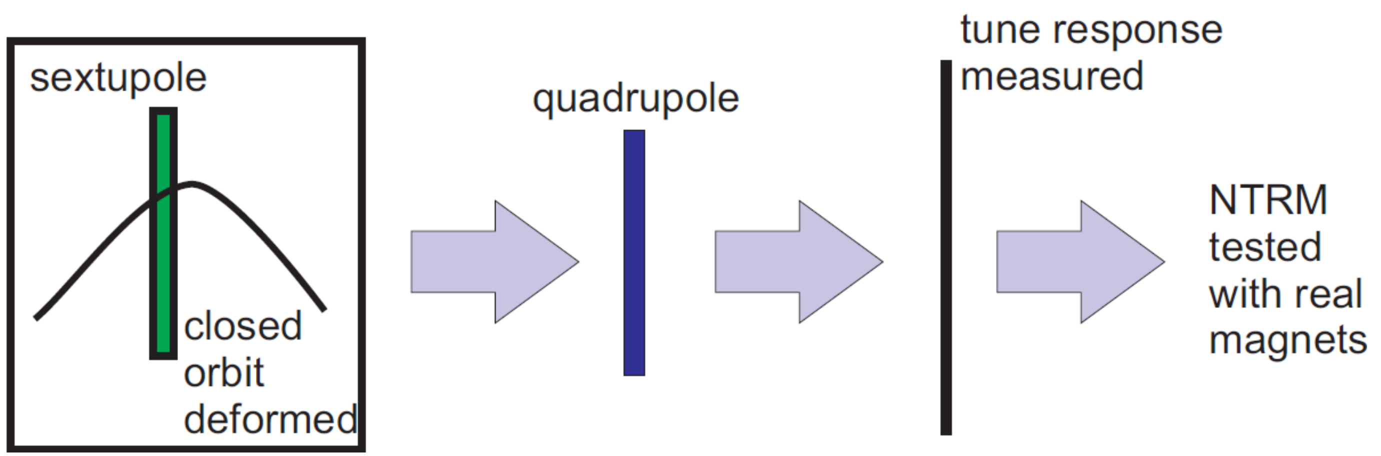
to see their strength

We change the tune and measure the particle current (beam loss)

Ref. A. Parfenova et. al, Measurement of SIS18 resonance tune diagram, 2010

Method to diagnose lattice nonlinearities

Nonlinear Tune Response Matrix (NTRM) method
explores the feed down effect of the nonlinear components at level of linear tune on the closed orbit



benchmarked with sextupoles at the SIS18
first results with octupoles' benchmarking at the CERN SPS

Ref. **G. Franchetti, A. Parfenova, I. Hofmann, PRSTAB 11, 094001 (2008)**
Ref. **A. Parfenova, G. Franchetti, submitted to NIM (2010)**
Ref. **A. Parfenova et al., Contributed Invited IPAC Kyoto (2010)**

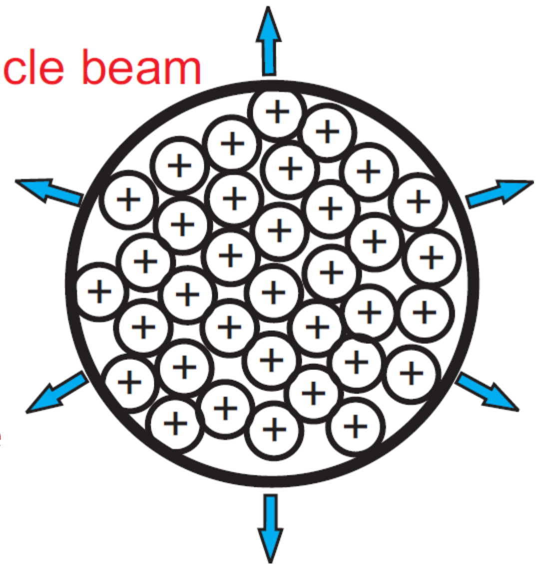
Beam dynamics
in the presence
of space charge

Transverse space charge force:

Defocusing Lorentz force on a particle **inside the beam**:

$$F_r = q(E_r - v_0 B_\theta) = \frac{qE_r}{\gamma^2} = \frac{qI}{2\pi\varepsilon_0\beta_0 c\gamma_0^2}\frac{r}{a^2}$$

particle beam



Equation of motion with space charge force

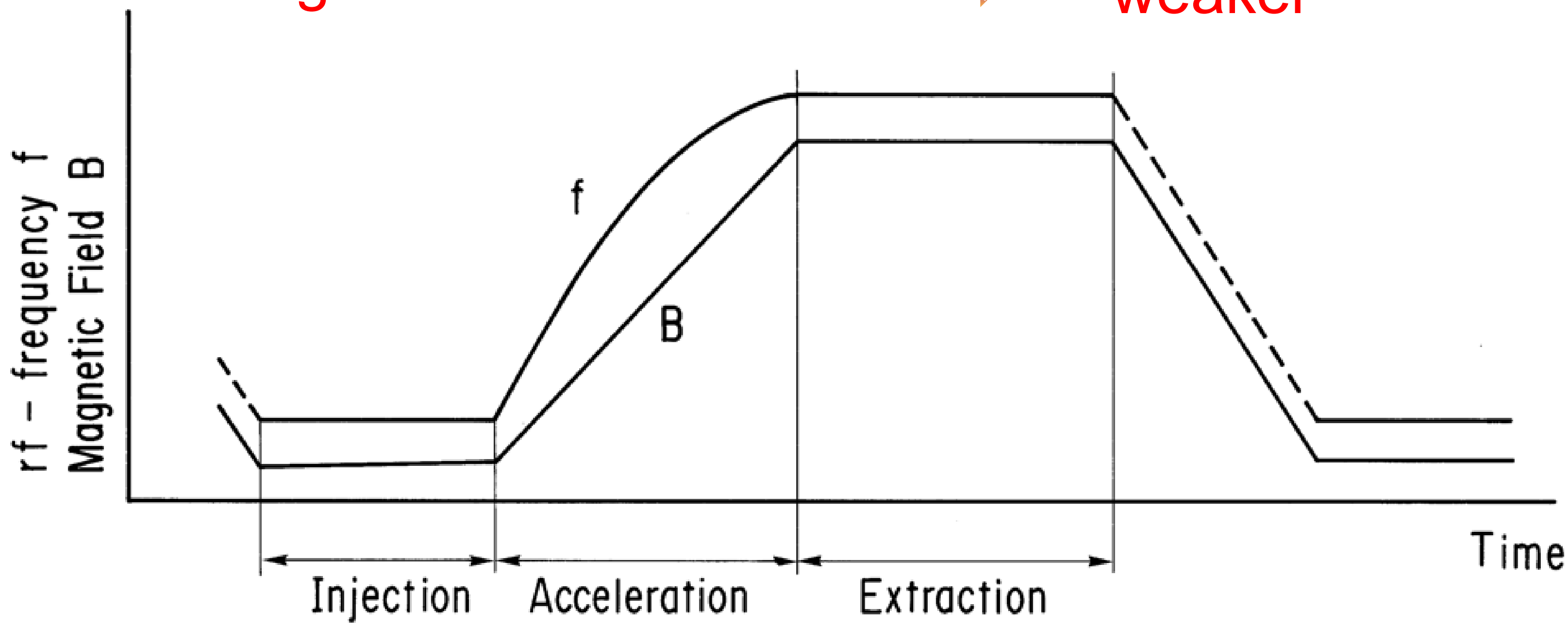
$$x'' + \kappa_x(s)x = \frac{1}{\gamma m v_0^2} \times (\text{space charge force})$$

$$x'' + \left(\kappa_x(s) - \frac{K}{x_m^2(s)}\right)x = 0$$

Perveance: $K = \frac{qI}{2\pi_0\varepsilon_0 mc^3\beta^3\gamma^3}$

A Synchrotron Cycle

Space charge stronger → Space charge weaker



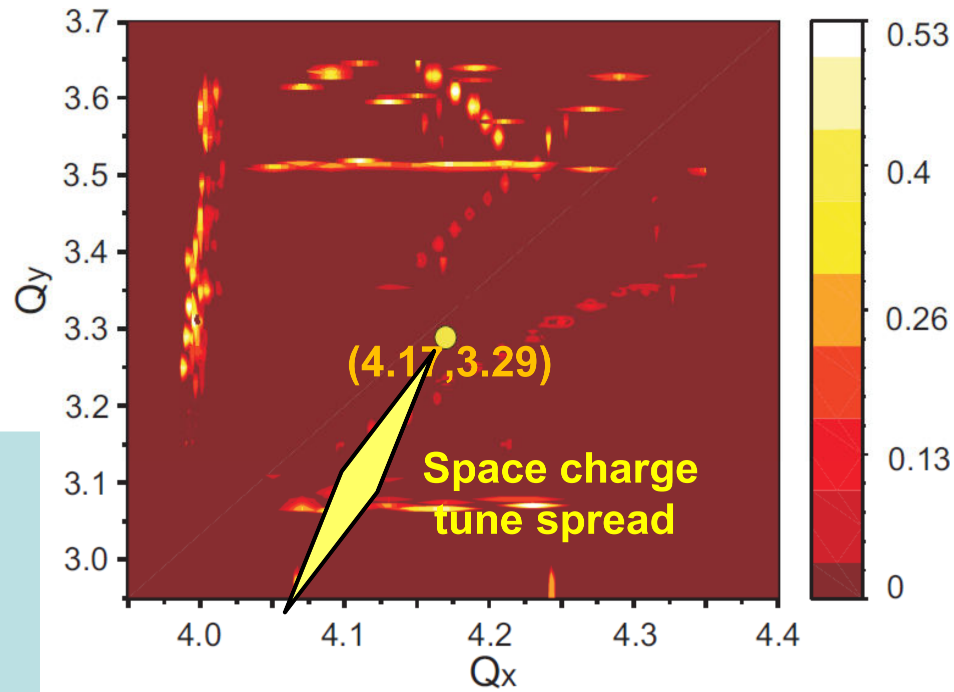
SPACE CHARGE TUNE SPREAD

space charge tune shift

$$\Delta Q_v = N \frac{q^2}{A} \frac{1}{\beta^2 \gamma^3} \frac{g}{B_f} \frac{R_{accelerator}}{\varepsilon_v + \sqrt{\varepsilon_h \varepsilon_v}}$$

Space charge tune shift depends on

number of particles
ion spice (charge/mass ratio)
beam size (vert./hor. emittances)
beam energy
beam type (coasting/bunched)
particle distribution (form factor)
accelerator radius



Space charge brings a tune shift with a tune spread

Beam current limits in synchrotrons

Logical space charge limit
for synchrotrons:

$$|\Delta Q|^{max} \leq 0.25$$

Examples CERN PSB/PS/SPS:
$|\Delta Q|_{max} \approx 0.4 / 0.3 / 0.1$

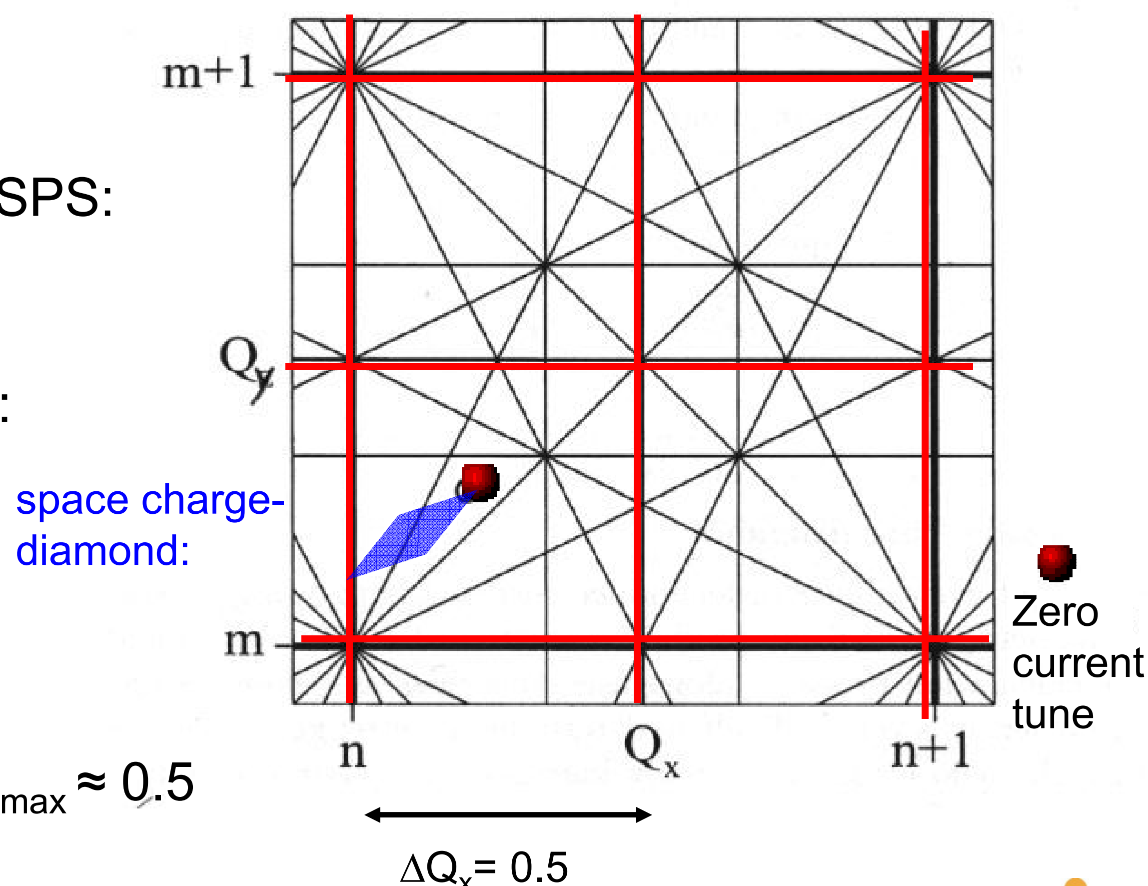
for SIS18 injection energy:
11.4 MeV/u

and particle number:
$\approx 2x10^{11}$ U^{28+}

estimated for SIS 18: $|\Delta Q|_{max} \approx 0.5$

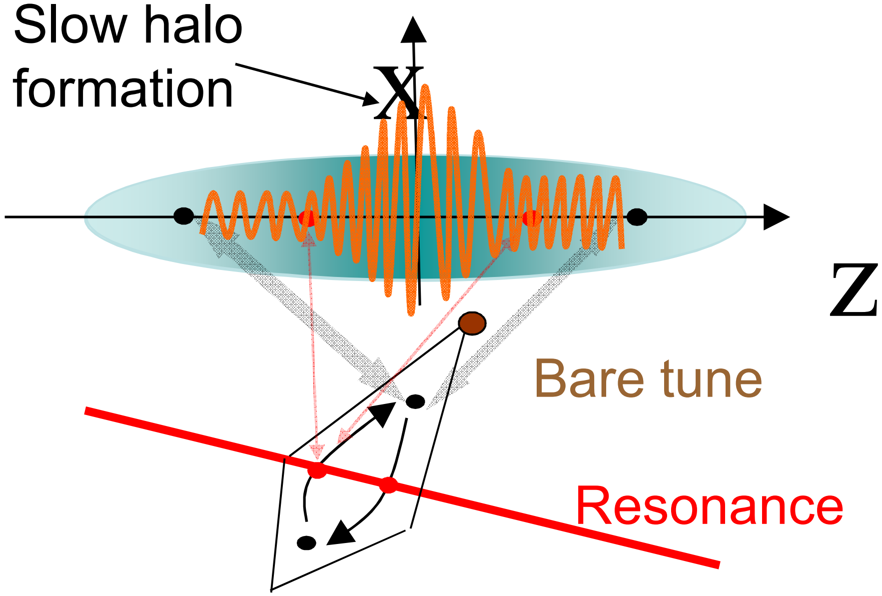
Dipole- and quadrupole error resonances

$nQ_x = p, \quad nQ_y = p$ |n| : 1,2



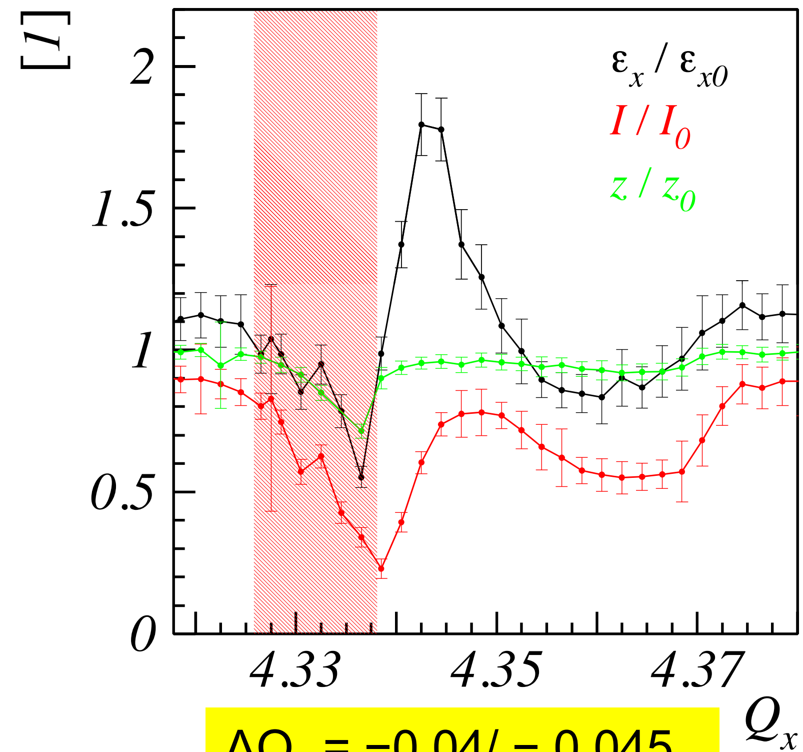
Bunched beam at high intensity

Bunched beams at high intensity stored for a second enhances the transverse-longitudinal coupling



Periodic crossing of a resonance

Experiment

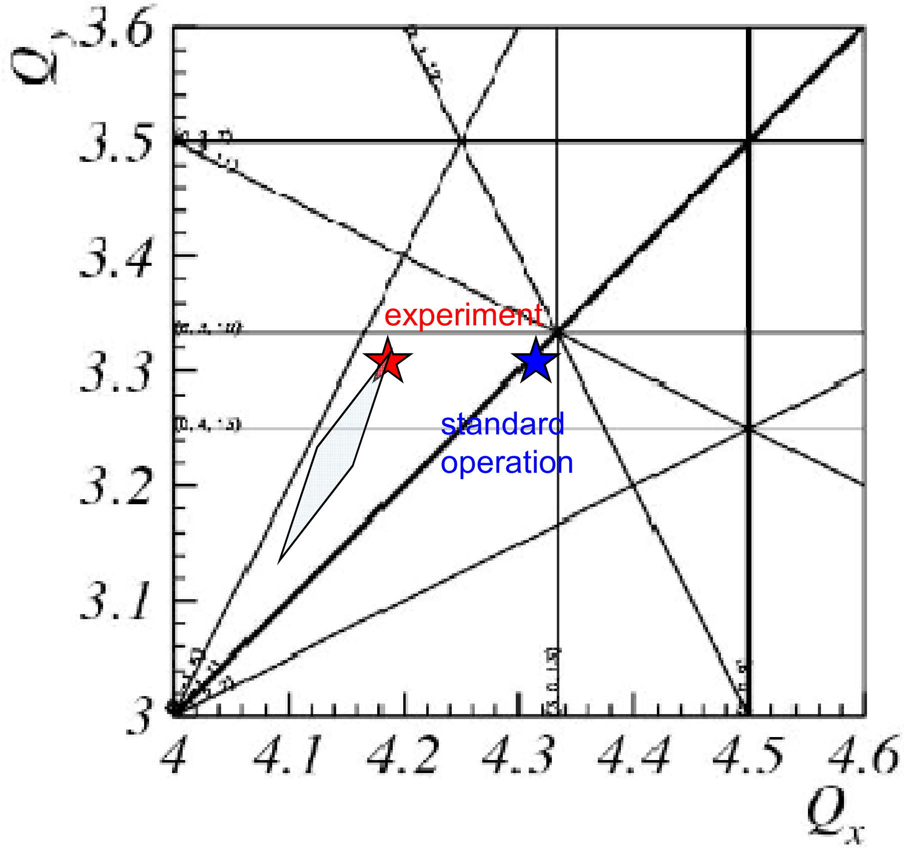


$\Delta Q_x = -0.04 / -0.045$

Courtesy of G. Franchetti

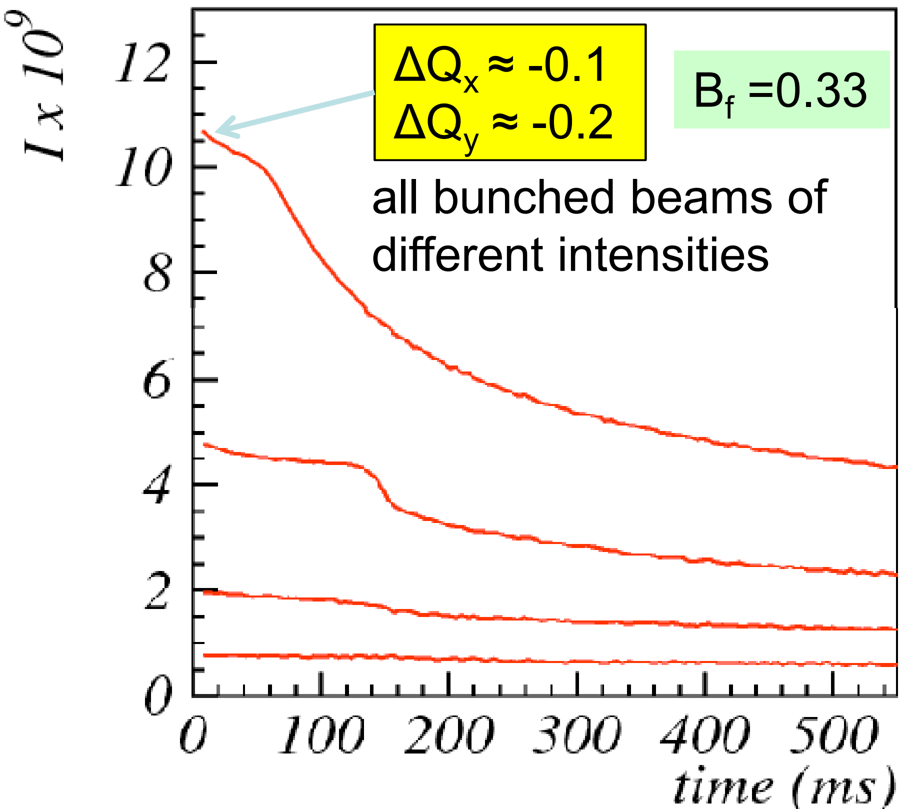
SIS18 experiments

Experiments (08/2008) related to the **space charge limit** for Ar^{+18}



high-intensity working point

$Q_x = 4.17$, $Q_y = 3.24$



Courtesy of G. Franchetti

The gradual beam loss disappears for coasting beams

Conclusion

- The important issue in **high current accelerators** is a control of **the particle beam loss**

- The beam loss depends on many factors

- accelerator optics
- linear/nonlinear magnet errors
- particle distribution
- space charge and etc.

- **The challenge** of the <u>beam loss dynamics simulation study</u> **is to include** all the factors and parameters present in the real machine

Acknowledgment

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