Recent Developments in Understanding Beam Loss in High-intensity Synchrotrons

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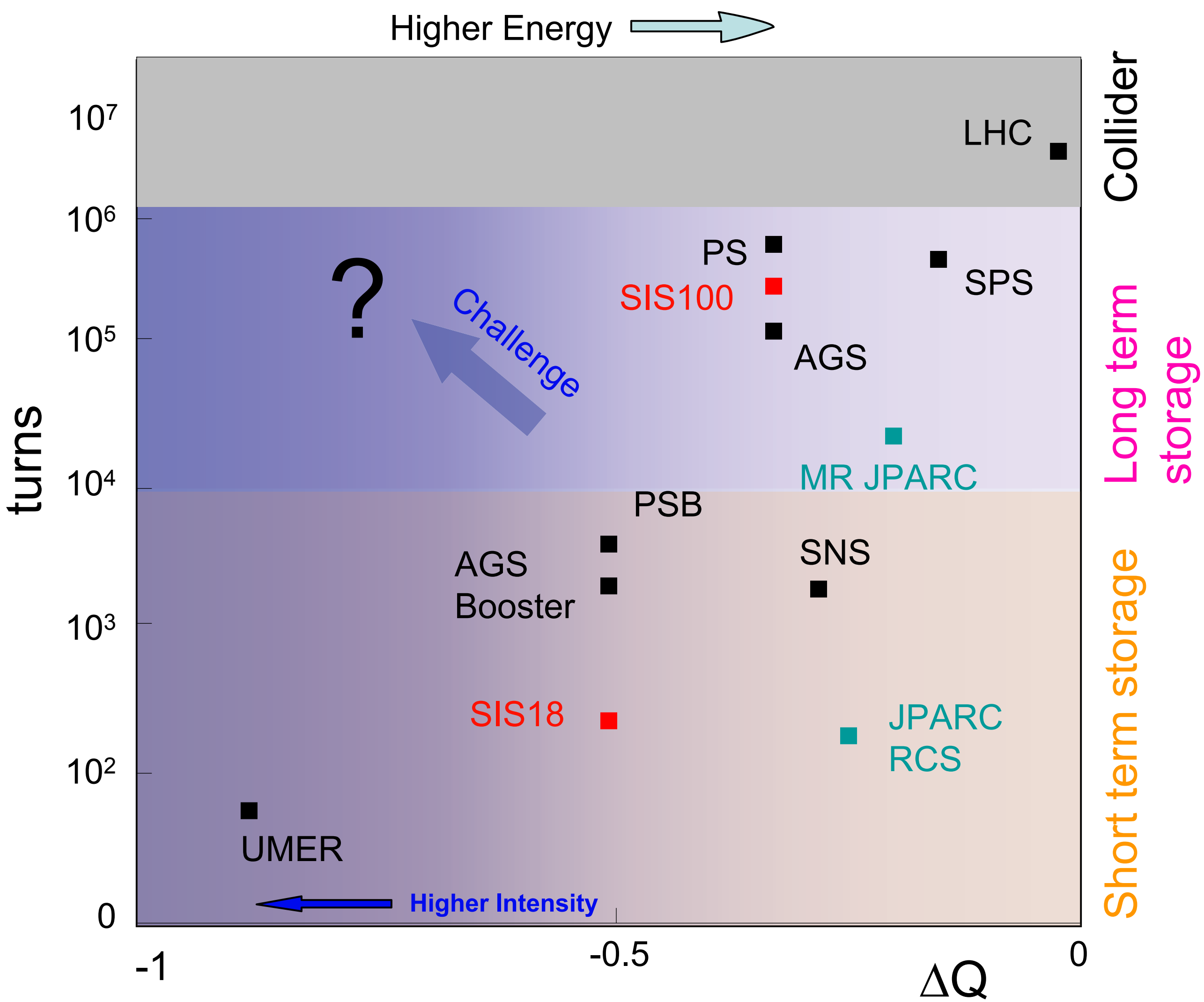
26/6/2007
GSI, Darmstadt

Overview

- High intensity effect for short term storage / long term beam loss mechanisms in absence of space charge
- Role of the transverse detuning in a single passage through a resonance
- Particle trapping
- High intensity bunch dynamics in proximity of a resonance
- Elements of beam loss predictions/ example for SIS100
- Outlook

Accelerators at the high intensity frontier



FAIR @ PAC07

D.Kraemer, THXAB02,talk

G.Moritz, FRYKI01,talk

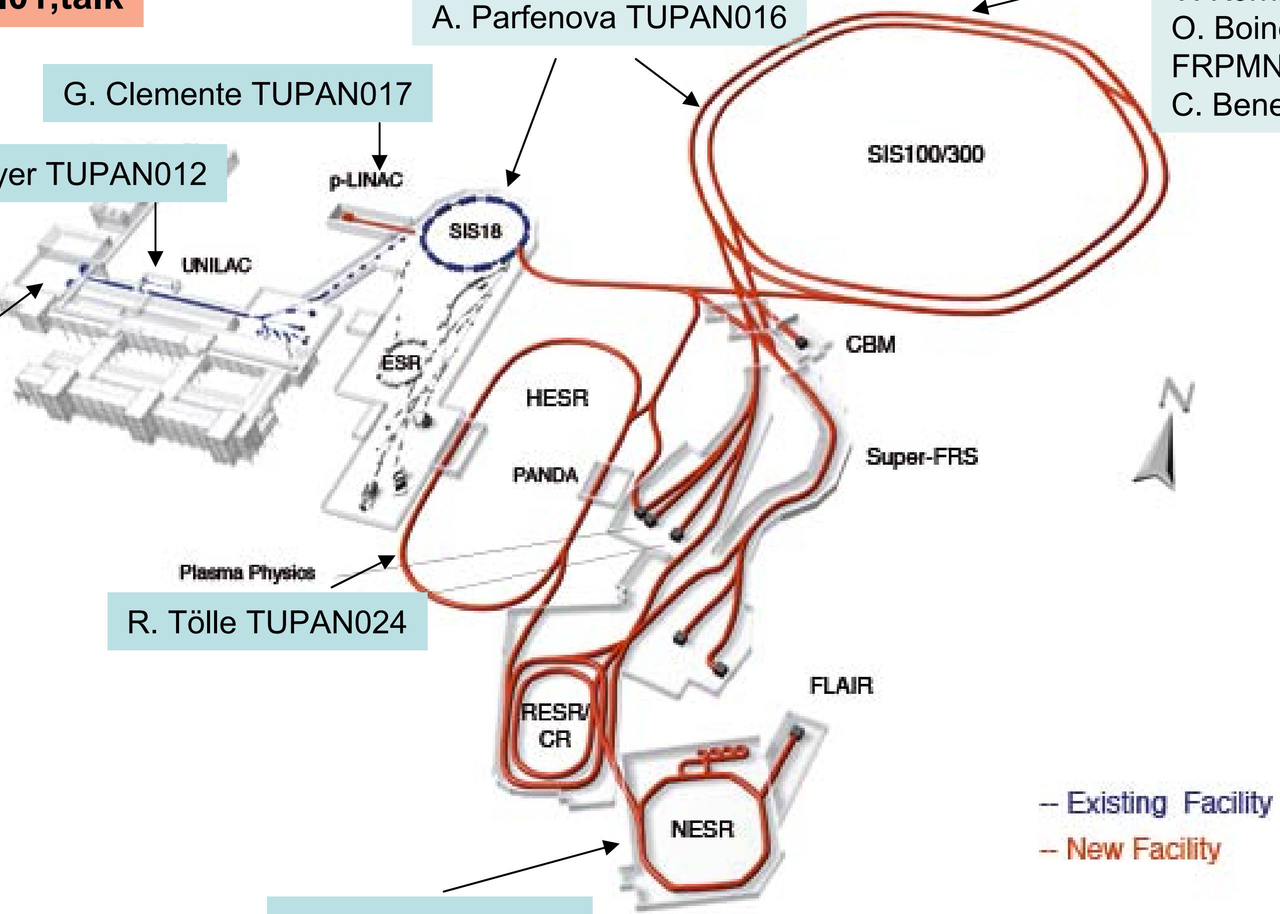
U. Blell MOPAN012
C. Omet TUPAN013
A. Parfenova TUPAN016

P. Spiller TUPAN014
J. Stadlmann TUPAN015
V. Kornilov TUPAN018,
O. Boine-frankhenhem, FRPMN014
C. Benedetti THPAN030

G. Clemente TUPAN017

W. Bayer TUPAN012

J. W. Stetson, talk

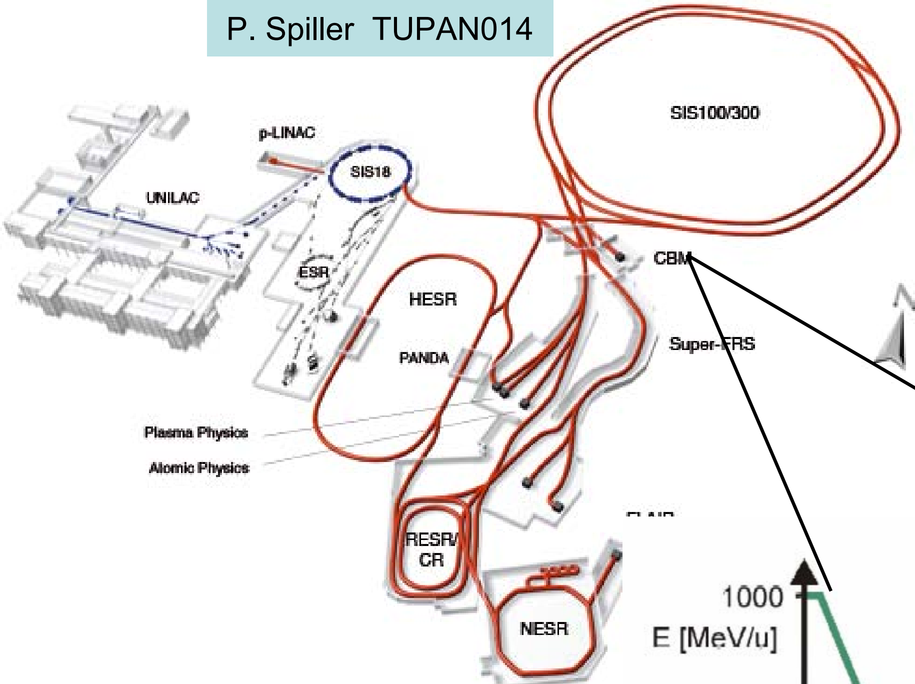


R. Tölle TUPAN024

M.Steck TUPAN016

SIS100 high intensity scenario

P. Spiller TUPAN014



Intensity in SIS18 Booster(after acceleration)

1.5×10^{11} U^{28+} -ions /cycle

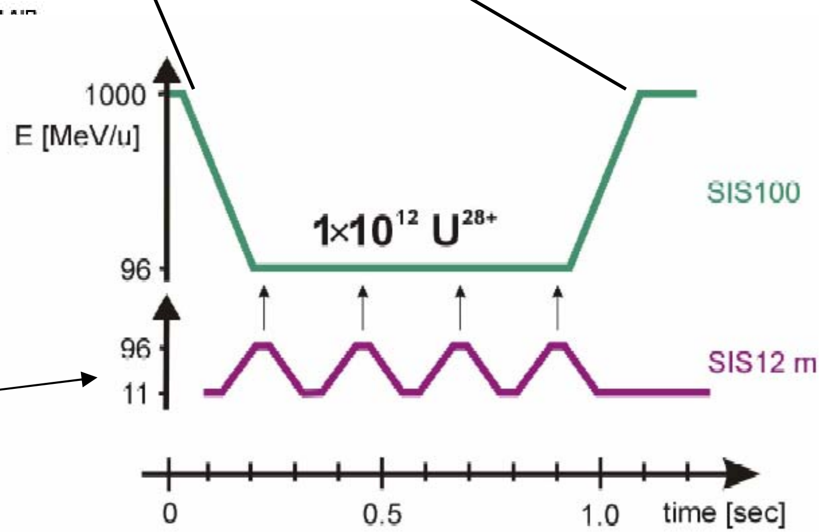
4 matched bunch-to-bucket of 2 SIS18 bunches

Intensity in SIS100

6×10^{11} U^{28+} -ions /cycle

First bunch @ 150 MeV/u

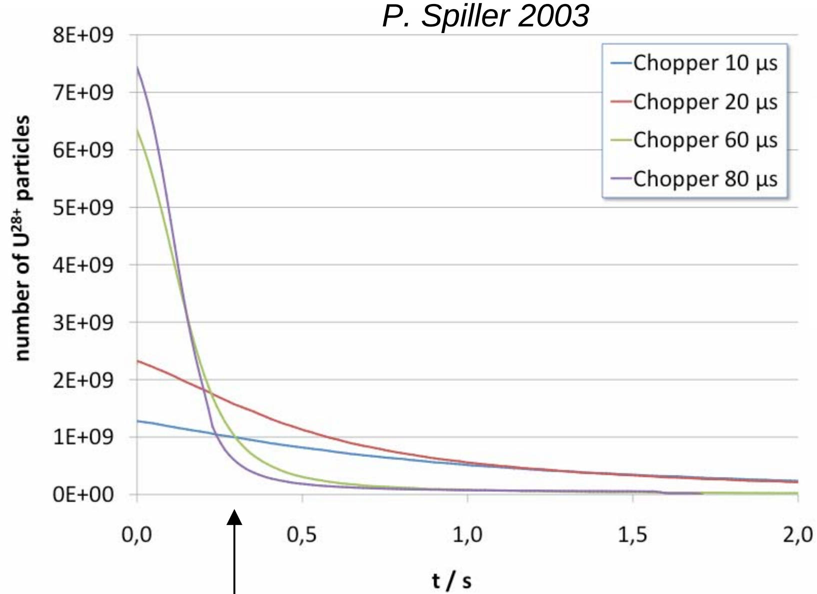
$N_{ions} = 0.75 \times 10^{11}$
$\varepsilon_{x/y} = 35/15$ mm-mrad (2σ)
$\Delta Q_x \sim -0.15$, Gaussian
$\Delta Q_x \sim -0.21$ Gaussian
Turns = 1.5×10^5 (1 sec.)

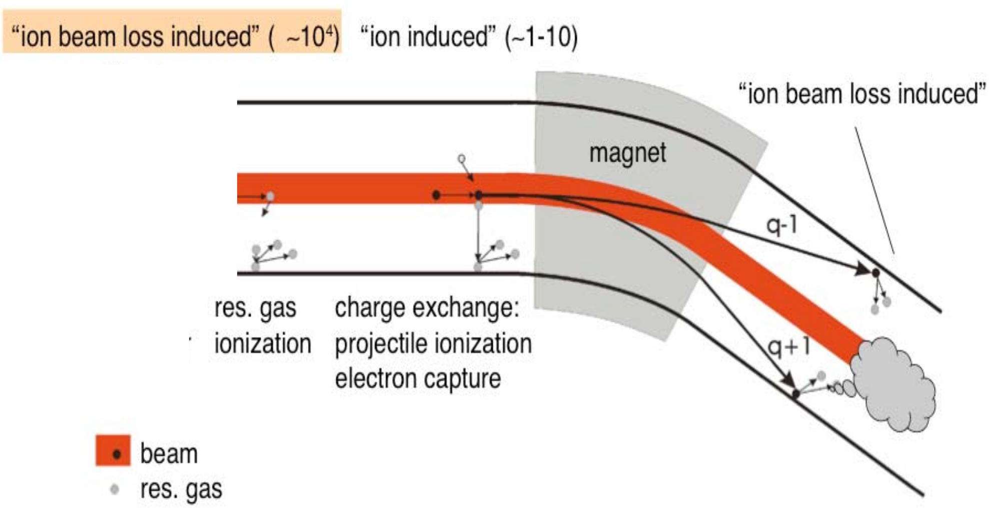


Reasons for beam loss limitations

Experimental findings in SIS18

P. Spiller 2003





Courtesy of H. Kollmus ICFA-HB2004

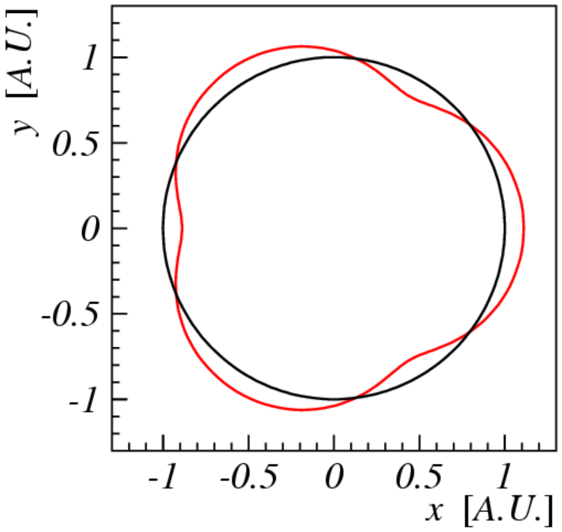
C. Omet TUPAN013

Very poor beam lifetime when the Chopper window is > 60 μs

High intensity effect for short term storage

Coherent resonances for collective beam modes $\omega = n_x Q_{x0} + n_y Q_{y0} + \Delta\omega$

3rd order mode



Unstable when

$$\boxed{\omega = n}$$

I.Hofmann Phys. Rev. E 57, 4713, (1998).

The growth rate of depends on the tune depression

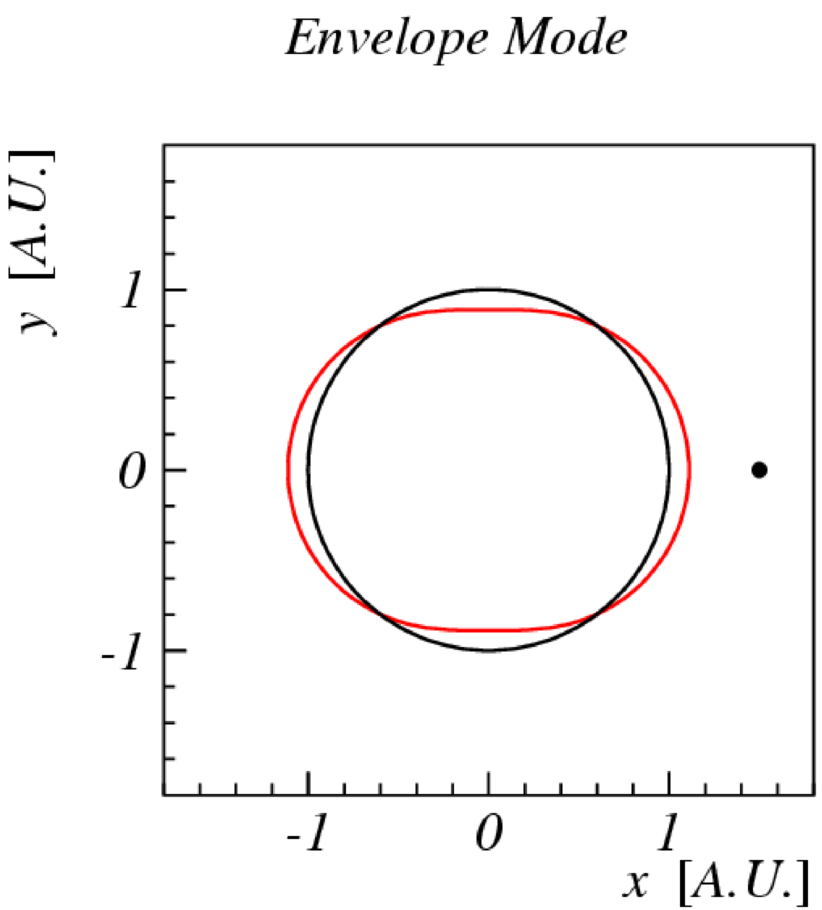
Space charge resonances: driven by the space charge itself (Montague)

Metral et al. EPAC 2004, WEPLT029; I.Hofmann et al. PAC 2005, MOPC003

2:1 resonance

Intrinsic incoherent resonances
individual particles inside the beam can get ▪ ▪ into resonance with an oscillating beam mode.
Example: 2:1 resonance in Linac
-> halo formation, parametric resonance

Space charge force resonant with particle frequency



Mismatch conversion into tails
I.Hofmann et al. EPAC 2002, WEYGB001

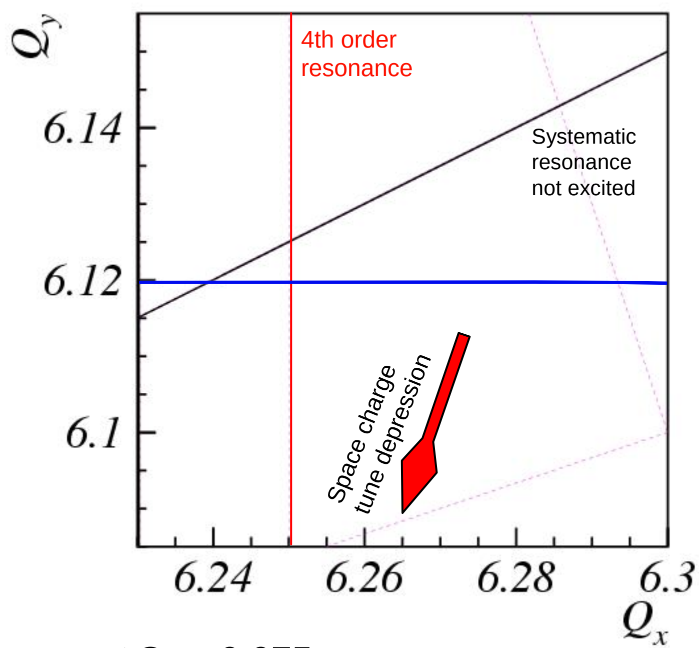
Estimates of this effect in SIS100

C. Benedetti THPAN030

Self consistent coasting beam response to machine resonance

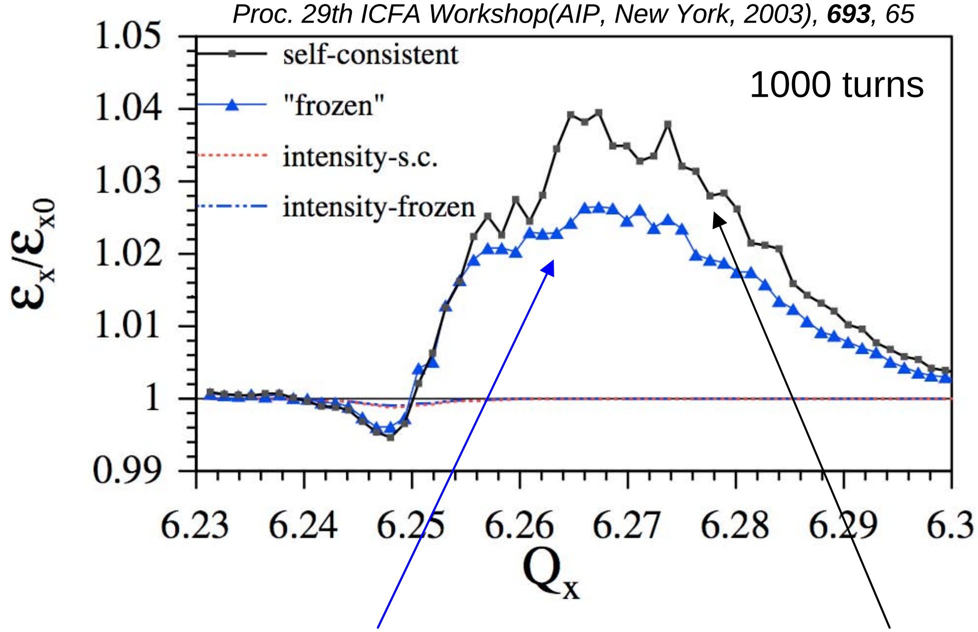
Driven inchoerent resonances: the beam modes are resonantly driven by the machine resonances: **collective beam response**

Sextupole strength used in the CERN-PS experiment



$\Delta Q_x = 0.075$

I. Hofmann, G. Franchetti, J. Qiang, R. Ryne
*Proc. 29th ICFA Workshop(AIP, New York, 2003), **693**, 65*



No appreciable collective beam response

Envelope errors excite space charge induced resonances *S. Machida NIM A 384 (1997) 316*

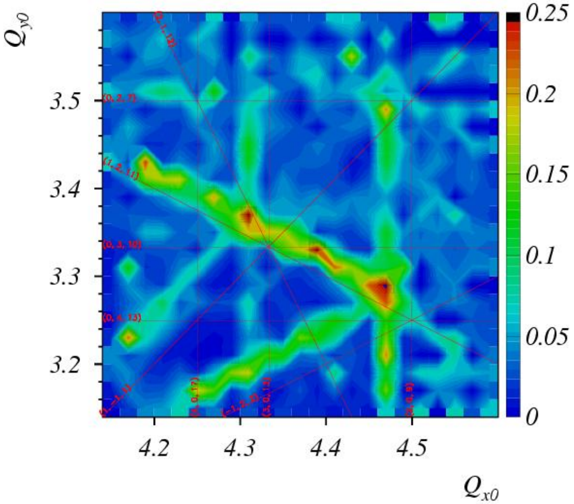
Long term beam loss in absence of space charge

Lattice induced nonlinear resonances

$$n_x Q_{x0} + n_y Q_{y0} = m$$

G. Guignard, CERN 78-11, (1978);
A. Bazzani et al., CERN94-02 (1994).

SIS18 resonances



Transverse-longitudinal coupling induces synchro-betatron resonances

$$Q_{x,y} = n \pm m Q_z$$

A. Piwinski and A. Wrulich, DESY 76/07 (1976).

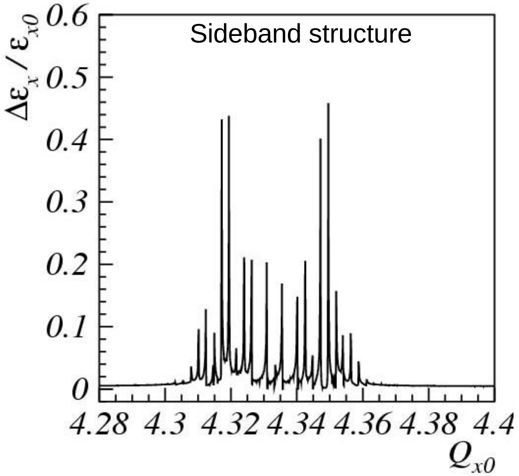
Example with SIS18

Chromaticity only

$\Delta p/p = 4.5 \times 10^{-3}$

$Q_{z0} = 1/144$

10 synch. Osc.



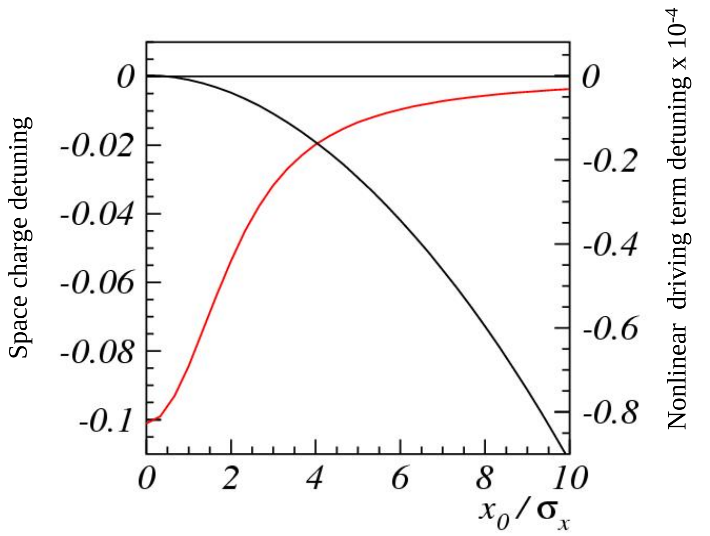
Role of the space charge detuning

Standard nonlinear components $\Delta Q_a(\epsilon_x) = a_1\epsilon_x + a_2\epsilon_x^2 + O(\epsilon_x^3)$

The space charge $\Delta Q_x \propto \dfrac{1}{1+[x_m/(2\sigma_x)]^2}$

The space charge detuning has a different nature from the lattice nonlinear errors induced detuning

	small amplitudes	large amplitudes
Lattice nonlinear error	zero	Large
Space charge	Maximum	zero



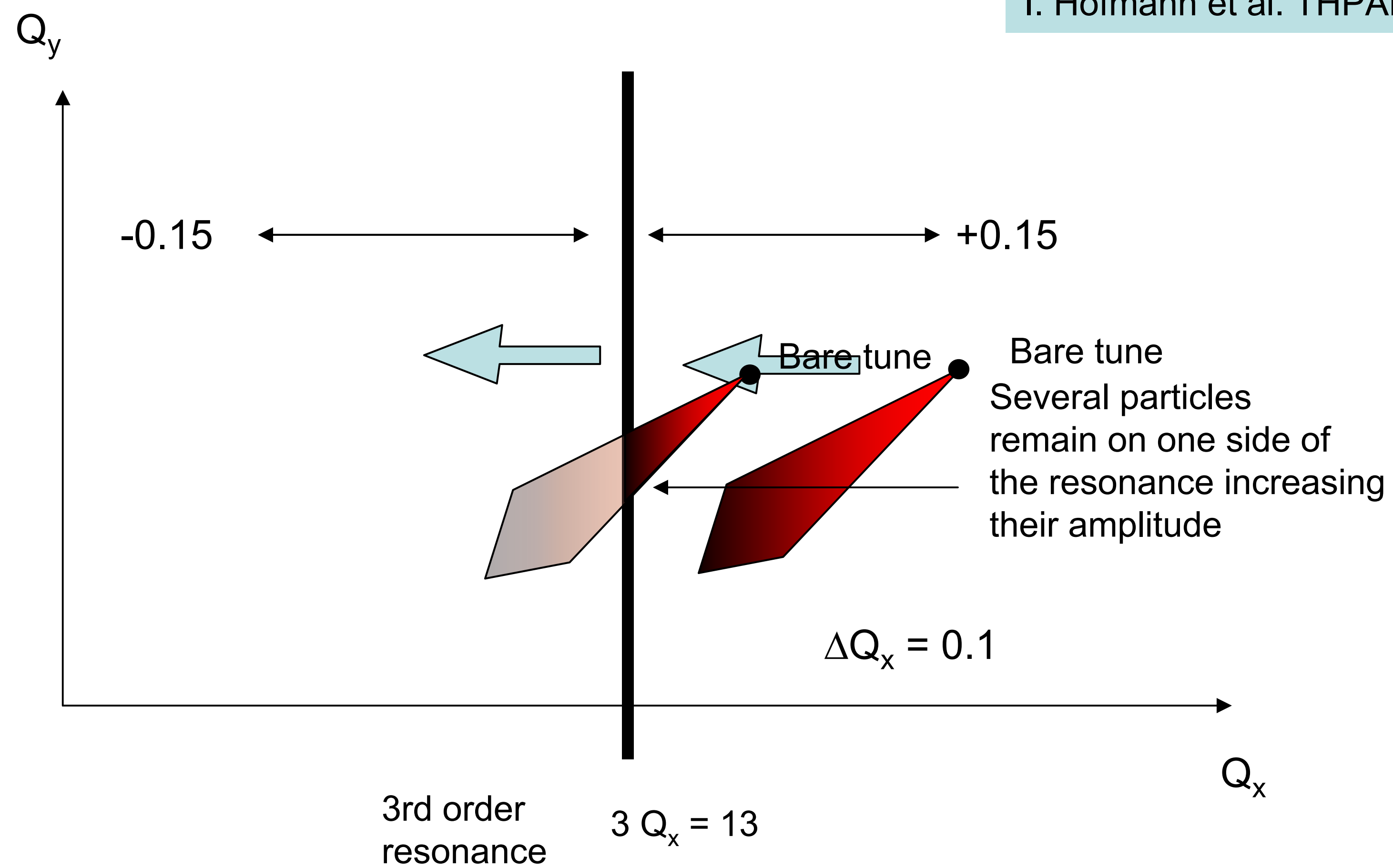
Consequence: when the bare tune is set near a resonance, the particle amplitude evolves as

Amplitude growth → detuning → Exit from the resonance → Amplitude Stops growing

Single passage through a resonance

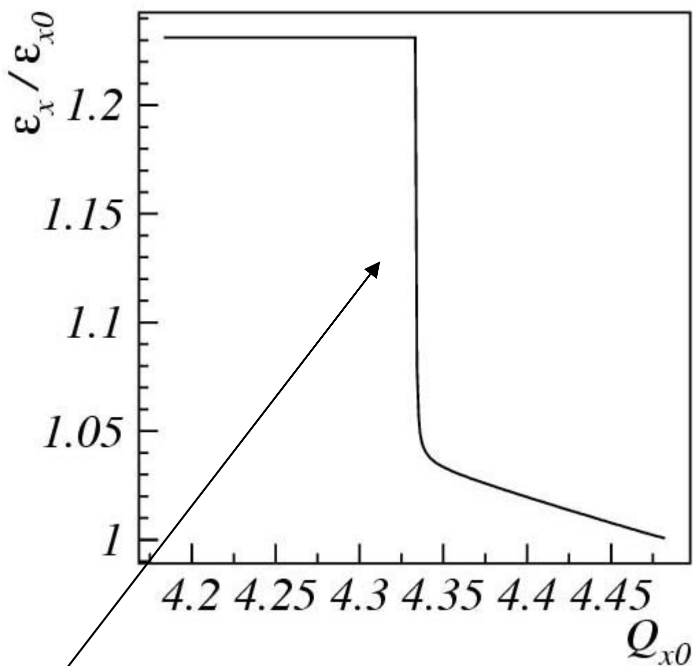
The role of transverse detuning is **different** when the stop-band is dynamically crossed

I. Hofmann et al. THPAN017

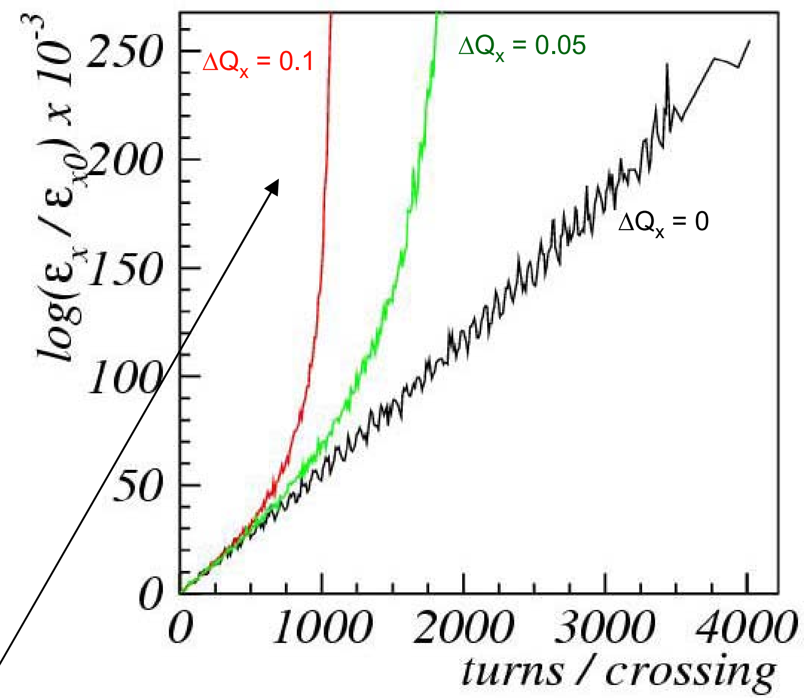


Effect of space charge for a single passage through a resonance

Example of resonance crossing in 1.4 x 10^6 turns of a beam with low space charge



Rms emittance growth for different Speeds of resonance crossing



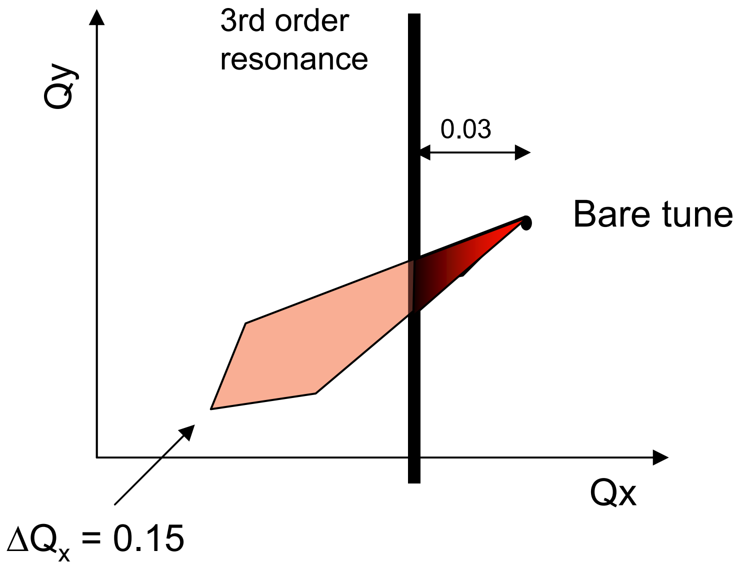
This jump depends on how long the particle remains inside the stop-band

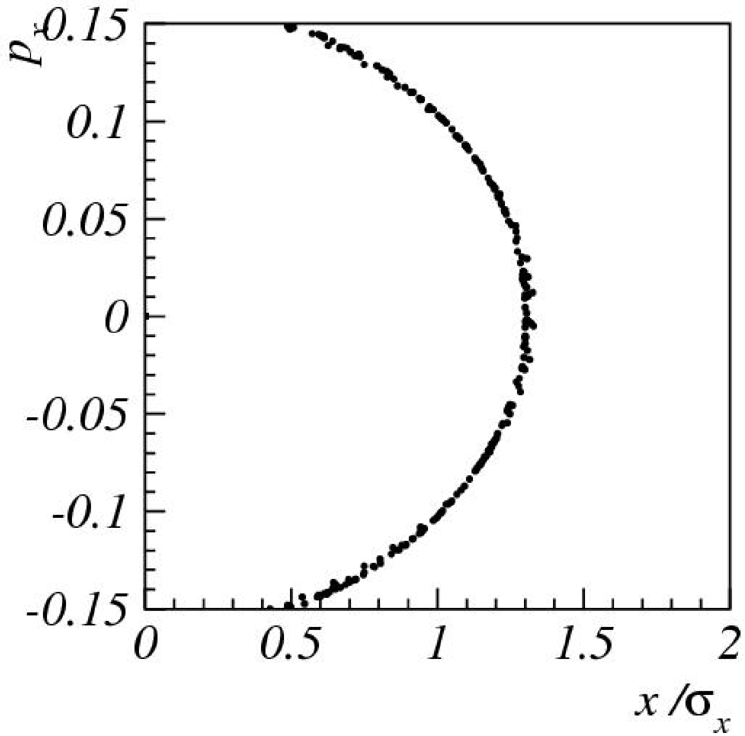
In presence of space charge the beam is more sensitive to the 3rd order stop-band

This result stems from the strong detuning - amplitude dependence

Particle trapping in phase space

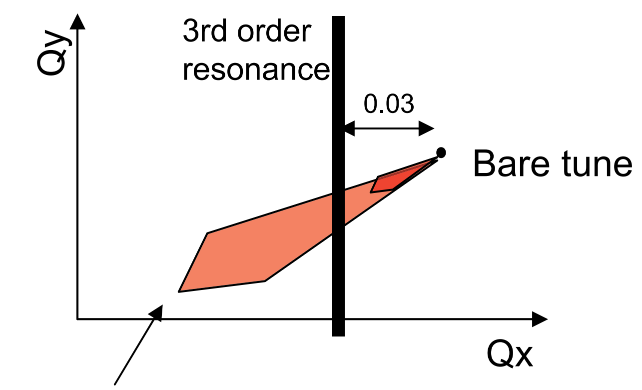
Increasing steadily the space charge





Particle trapping into a resonance

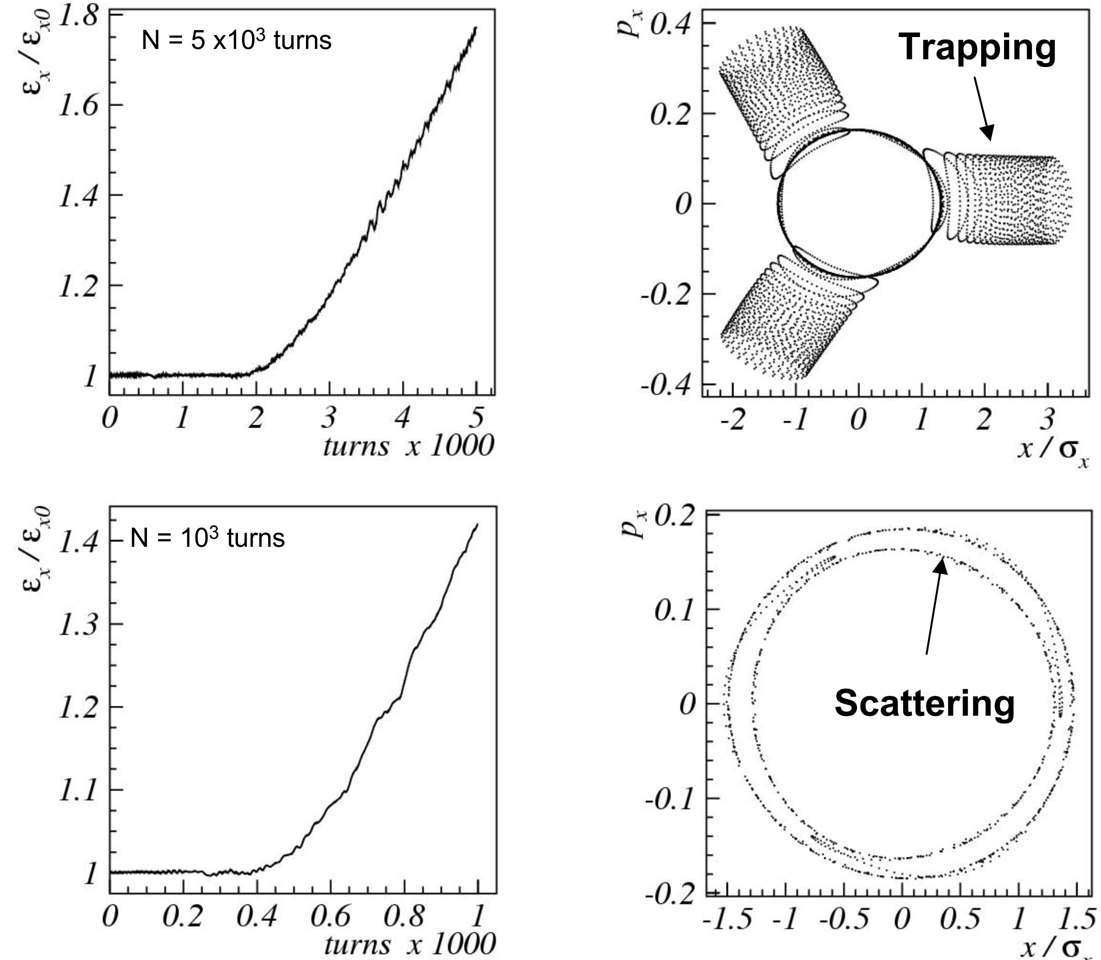
Space charge increased in N turns



$\Delta Q_x = 0.15$

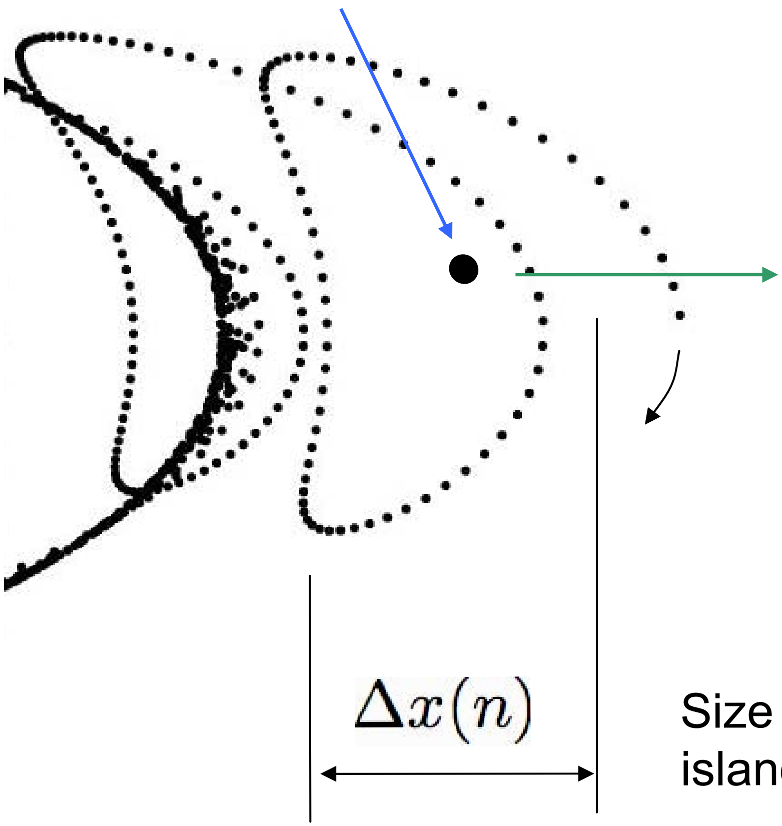
Full beam emittance

Test particle



Adiabatic / Non adiabatic Regimes

Condition for a particle to remain trapped



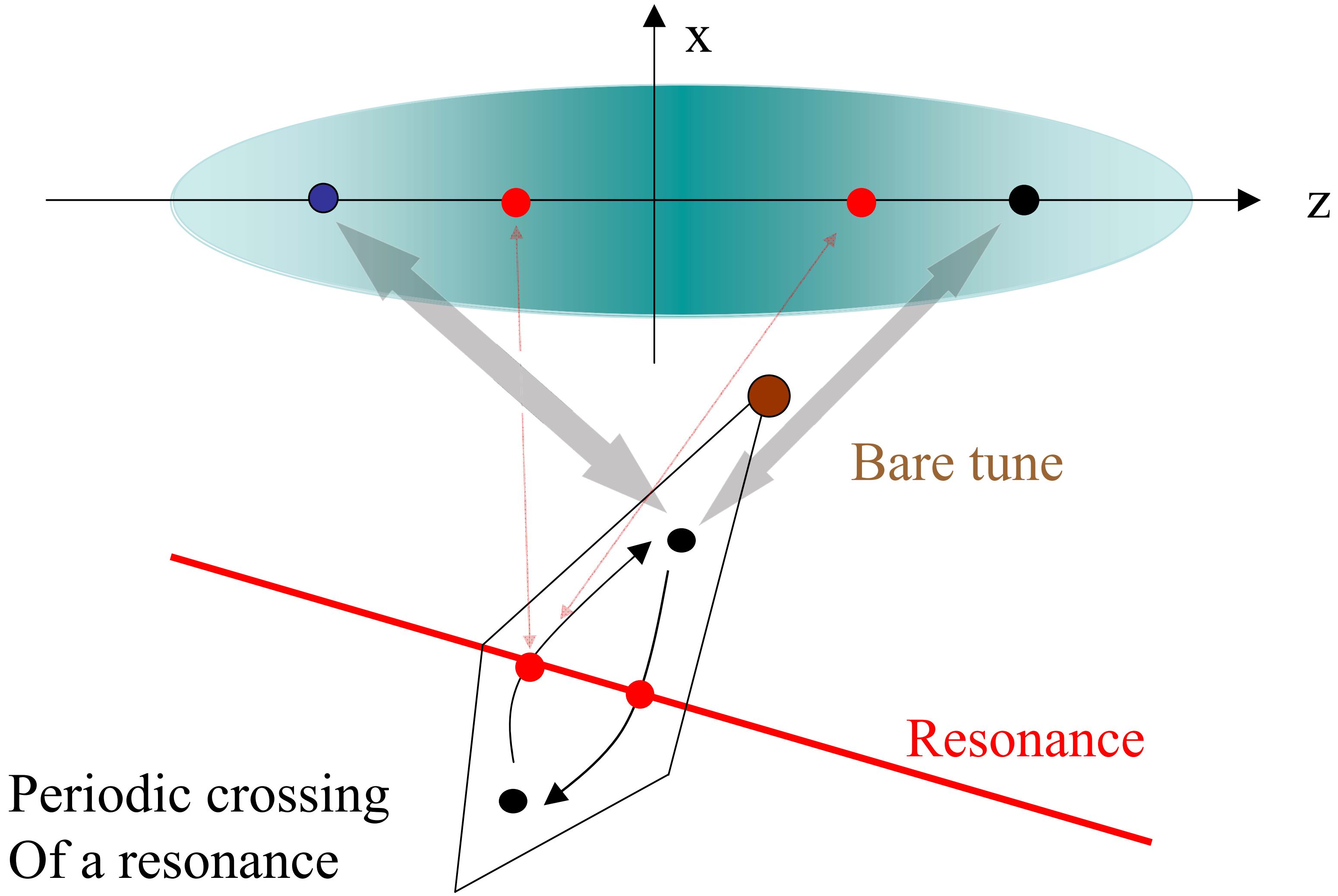
If during 1 revolution around the fixed point the island moves less than its size than the particle can remain trapped

$$T \equiv \frac{\partial x_f(n)}{\partial n} \frac{1}{Q_{xf}(n)\Delta x(n)}$$

T << 1 characterize the adiabatic regime

A.W. Chao and Month NIM 121, 129 (1974).
A. Schoch, CERN Report, CERN 57-23, (1958)
A.I. Neishtadt, Sov. J. Plasma Phys. 12, 568 (1986)

What happens when the space charge tune spread crosses a resonance ?



Differences with synchro-betatron resonances

Chromaticity induced tune modulation by linear synchrotron oscillation

$$Q_x = Q_{x0} + \xi \frac{\Delta p}{p_0} \cos(\frac{Q_{z0}}{R} s)$$

The transverse amplitude - tune dependence is unaffected by the tune modulation

Space charge induced transverse detuning amplitude

$$\Delta Q_x = \Delta Q_{x0} e^{-z^2/(2\sigma_z^2)} \frac{1}{1 + (\epsilon_{xs}/\epsilon_{x0})\lambda}$$

The transverse amplitude - tune dependence is also **z - dependent** via synchrotron oscillations

This is the main difference with respect to all ripple/chromaticity induced tune modulations ⇒ No space charge Induced sidebands

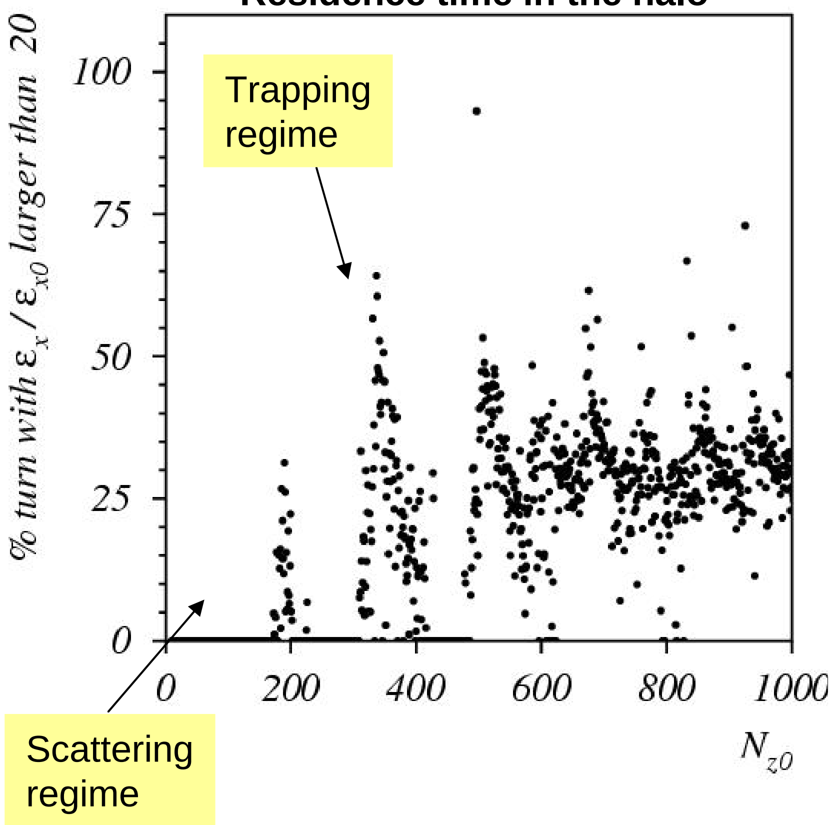
Trapping and scattering regime vs. synch. tune

$x = 1.5\,\sigma_x$
$y = y' = p_z = 0$
$z = 3\sigma_z$

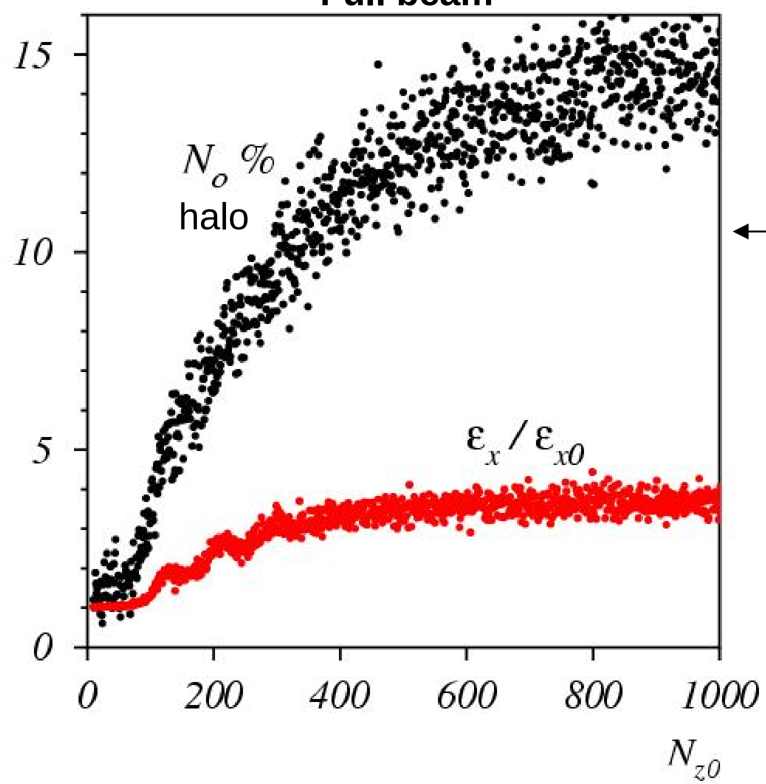
$\Delta Q_x = -0.1$ $\quad Q_{x0} = 4.34333$, $Q_{y0} = 3.29$

$$\frac{\Delta N}{N} = \alpha \frac{Q_{x0} - Q_{x,res}}{|\Delta Q_x|}$$

Residence time in the halo

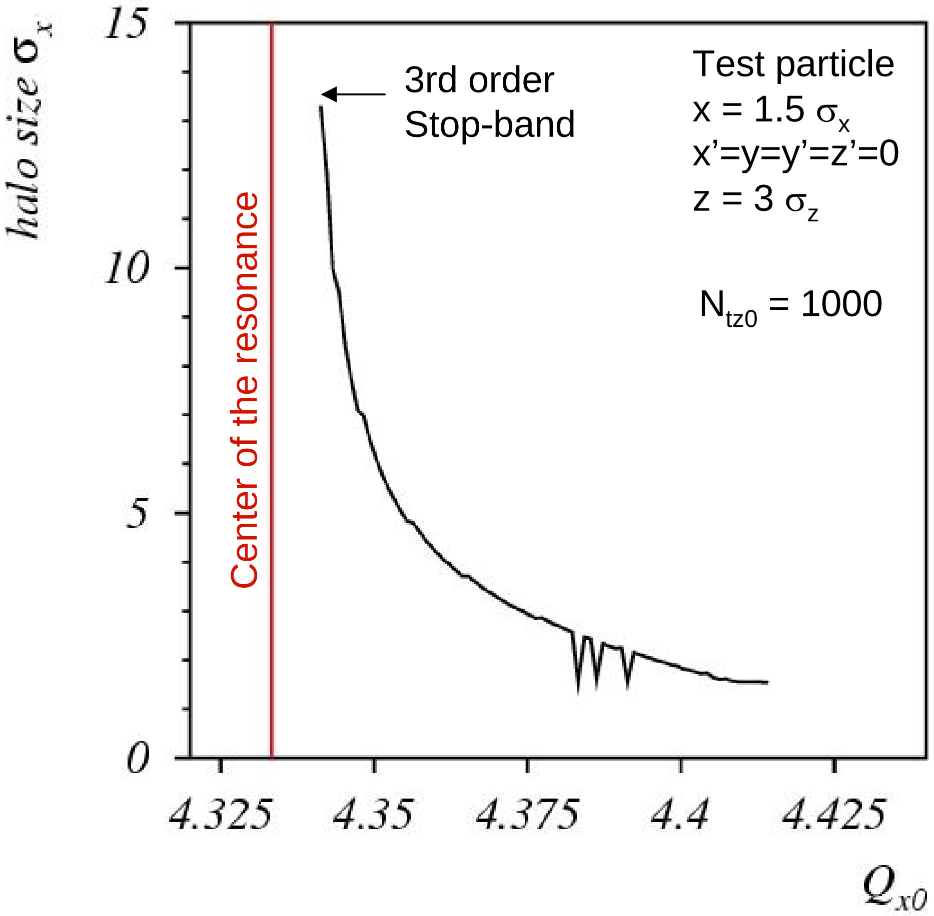


Full beam



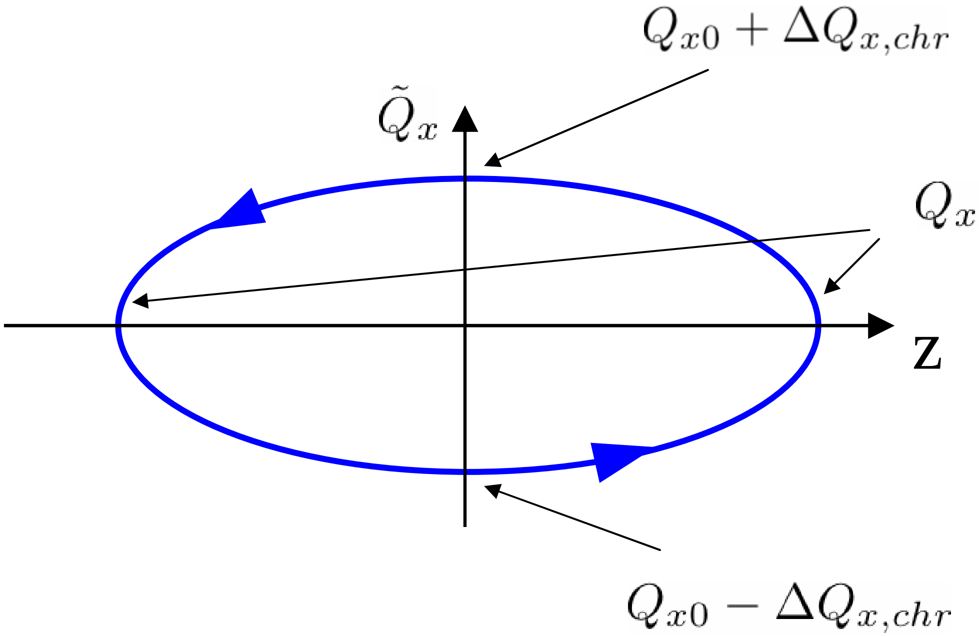
Halo size

Particles by trapping or scattering diffuses out and form an halo.
The outer position of the halo is function of the distance from the resonance



The new role of the chromaticity in a high intensity bunch

Effective single particle tune $\tilde{Q}_x$ in presence of the chromaticity



If $Q_{x0} - \Delta Q_{x,chr}$ is below the resonance but Q_{x0} is above the resonance, then during the synchrotron motion there will be z* where δp/p is such that $\tilde{Q}_x$ is **on the resonance**

Chromaticity induced stop-band

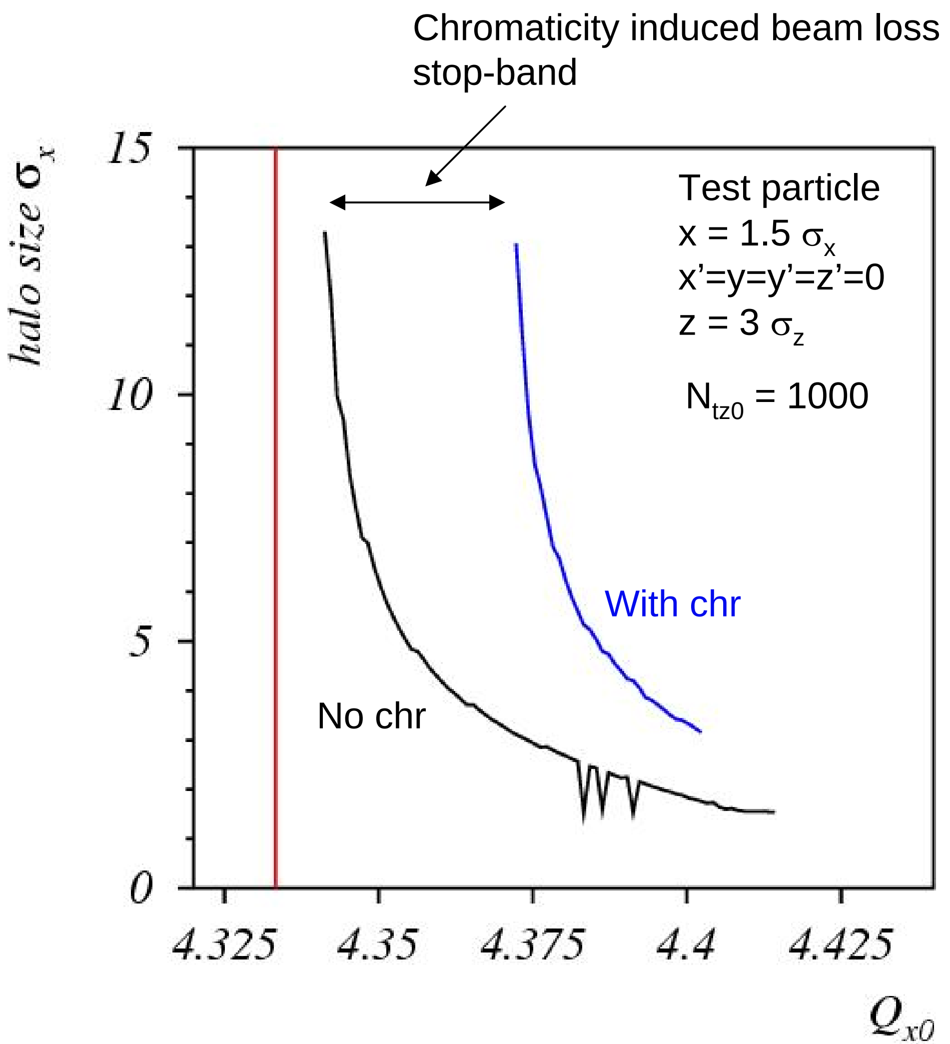
$(\delta p/p)_{max}$ = 7 x 10^{-3}

Natural chromaticity

ξ = -1

The chromaticity induced tune span

$$\Delta Q_{x,chr} = 0.03$$



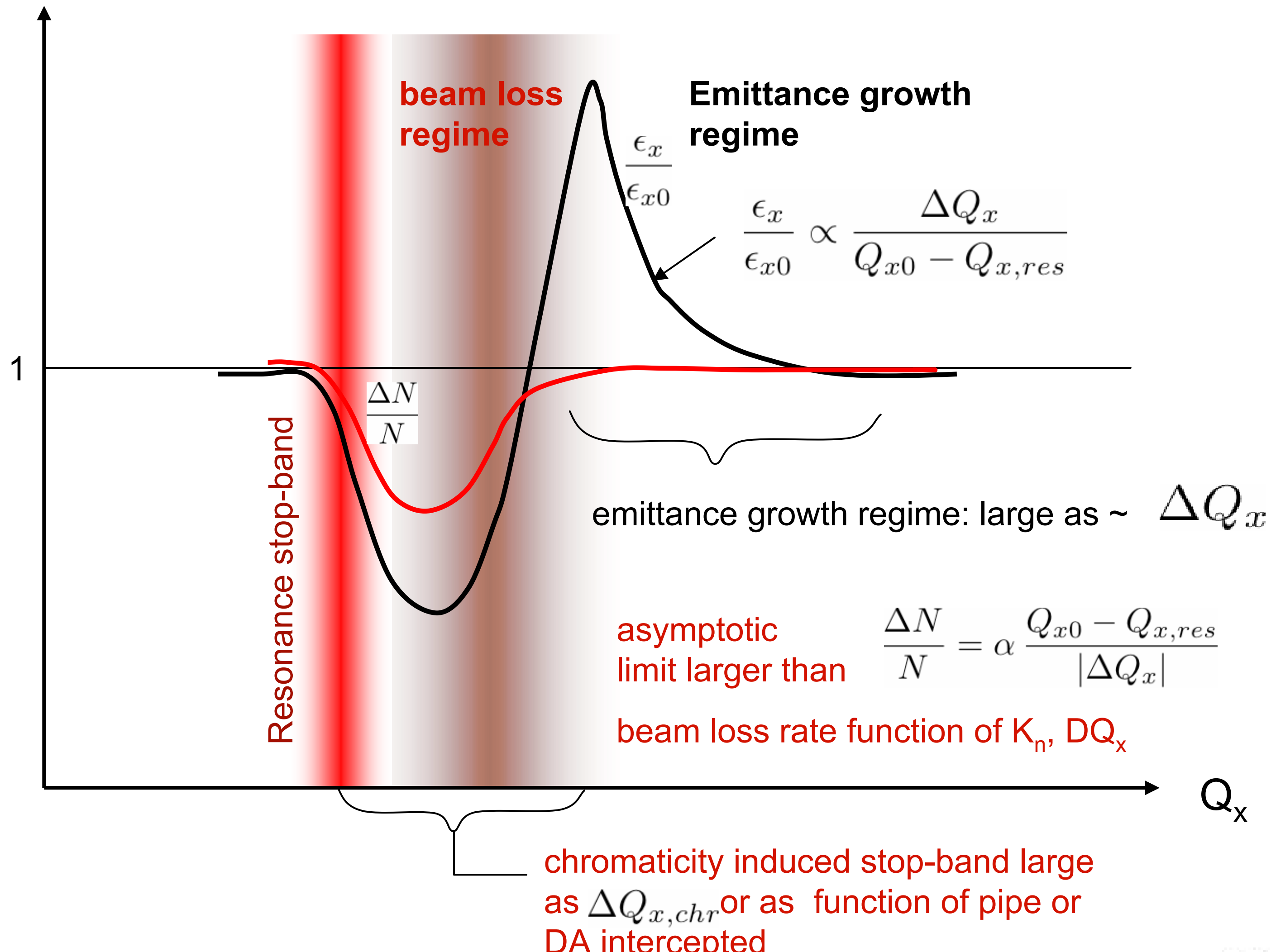
Elements of long term high intensity beam loss prediction

1) Distance from the resonance $Q_x - Q_{x,res}$

2) Space charge tune-spread ΔQ_x

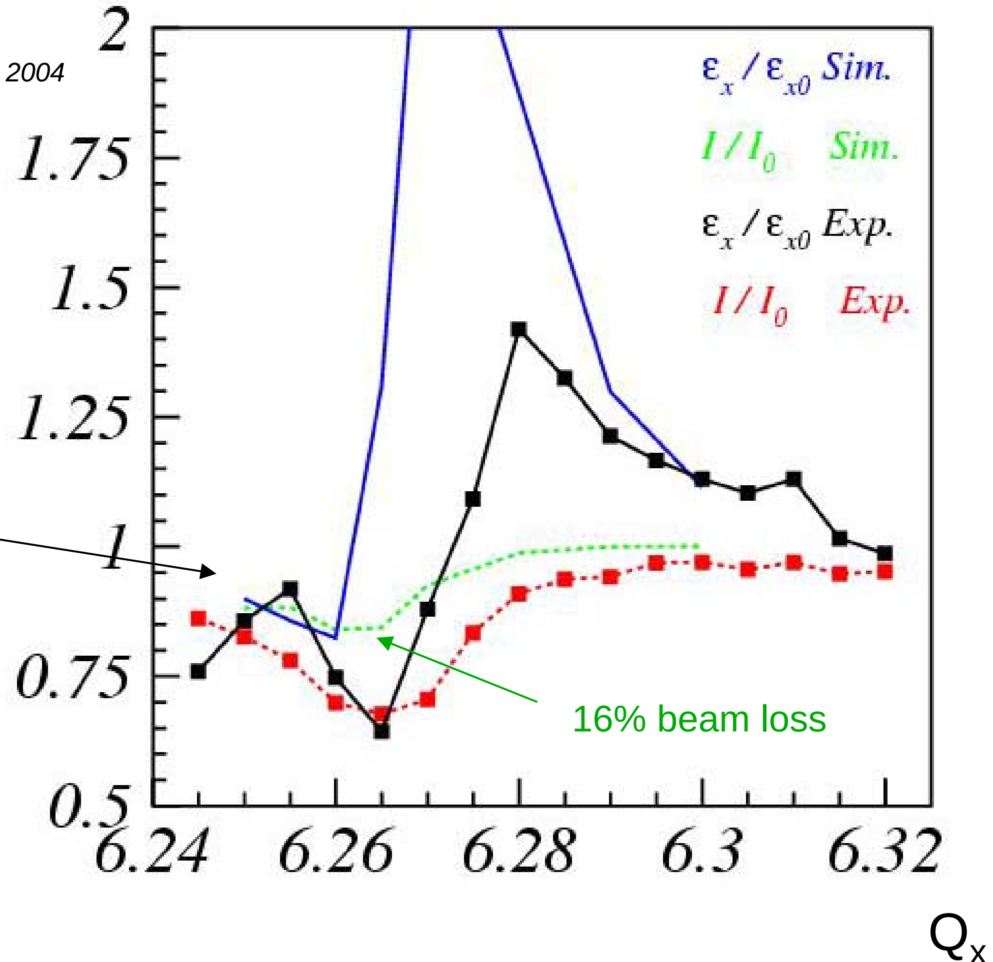
3) Chromaticity tune-spread $\Delta Q_{x,chr}$

4) Resonance strength (driving term) K_n


beam loss
regime
Emittance growth
regime
$\frac{\epsilon_x}{\epsilon_{x0}}$
$\frac{\epsilon_x}{\epsilon_{x0}} \propto \frac{\Delta Q_x}{Q_{x0} - Q_{x,res}}$
1
$\frac{\Delta N}{N}$
Resonance stop-band
emittance growth regime: large as ~ ΔQ_x
asymptotic
limit larger than
$\frac{\Delta N}{N} = \alpha \frac{Q_{x0} - Q_{x,res}}{|\Delta Q_x|}$
beam loss rate function of K_n, DQ_x
Q_x
chromaticity induced stop-band large
as $\Delta Q_{x,chr}$ or as function of pipe or
DA intercepted

Benchmarking with CERN-PS experiment

G.Franchetti, I.Hofmann, M Giovannozzi, E.Metral, M.Martini HHH-CARE Workshop 2004

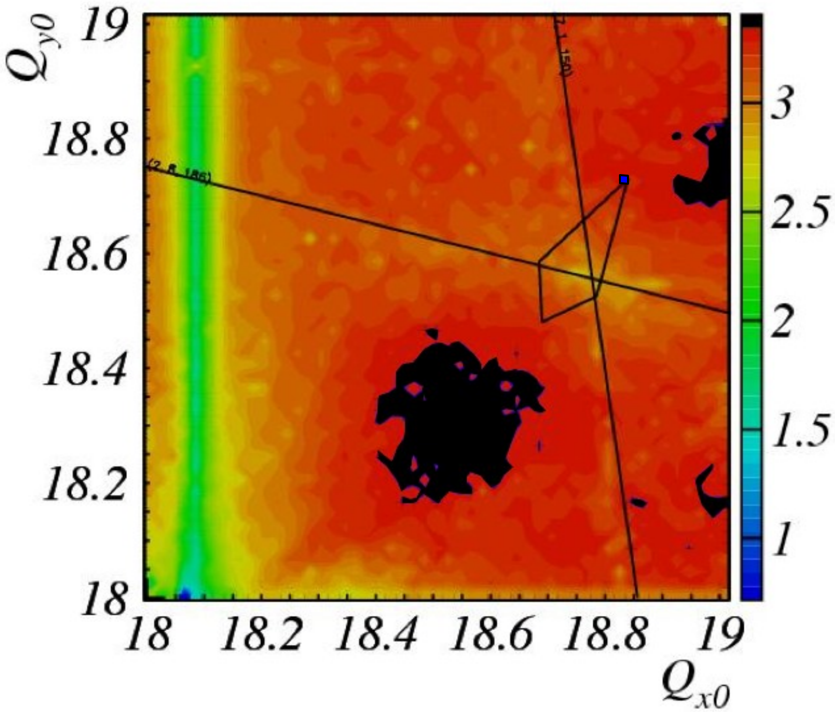


Simulated beam loss predictions have now reached 50% of the measurements

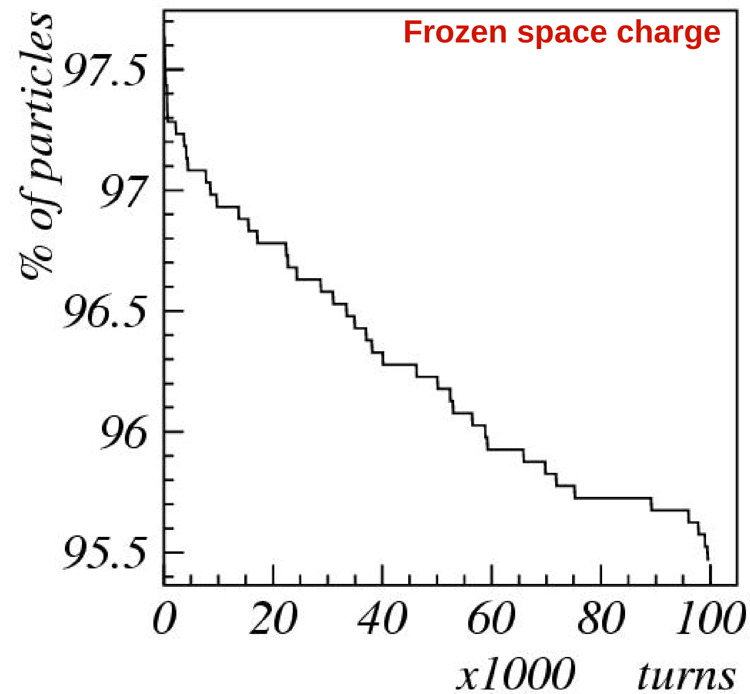
G. Franchetti, I. Hofmann, G. Arduini, E. Benedetto, M. Giovannozzi, T. Linnecar, M. Martini, E. Metral, G. Rumolo, E. Shaposhnikova, F. Zimmermann LHC Lumi 2006, October 16-20 2006, Valencia, Spain

SIS100 high order trapping/scattering induced beam loss

Short term dynamic aperture (10^3 turns) DA/σ



Beam survival vs. storage



Effect of the weak high order resonances

$$2Q_x + 8Q_y = 186$$
$$7Q_x + Q_y = 150$$

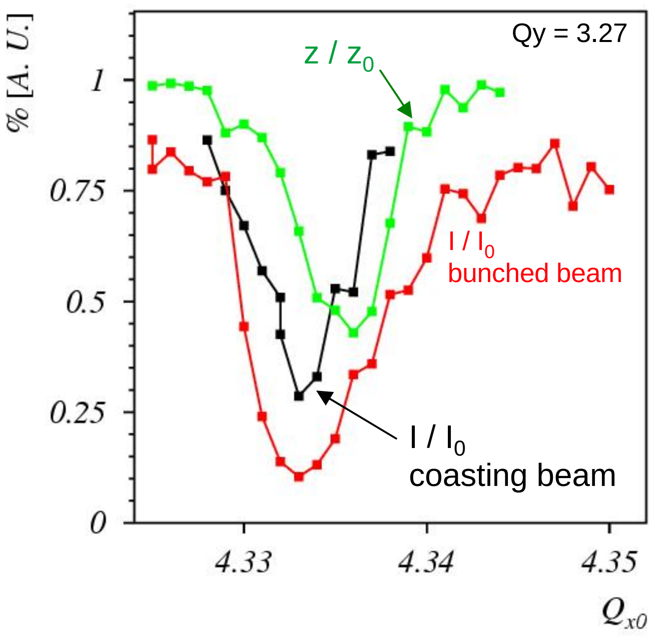
on a Gaussian bunched beam

$\varepsilon_{x/y}$ = 35/15 mm-mrad (2σ)
ΔQ_x ~ -0.15, ΔQ_x ~ -0.21

Ongoing SIS18 experiment to further test our model

S317 Experiment

Experimental studies on trapping effect in high intensity beam are in progress



Bunched beam	Coasting beam
N_{part}= 3.2 x 10^9	N_{part}= 1 x 10^9
ΔQ_x= 0.040	ΔQ_x= 0.005
ΔQ_y= 0.070	ΔQ_y= 0.01
	Bf = 0.45

S317: *O.Choriny, A.Parfenova, C.Omet, M.Kirk, I.Hofmann, G.Franchetti, P.Schuett, P. Spiller, T. Giacomini, P. Forck, T. Mohite, S. Sorge, O. Boine-Frankenheim*

Outlook

Status achieved

We have demonstrated that our theoretical model can predict beam loss over some 10^5 turns within a factor of two of experiment

Prediction for FAIR: SIS100 beam loss

- Effect of the self-consistency on beam loss
- Assessment of the level of resonance compensation for controlling the amount of beam loss on halo collimators
- Evaluation of the impact of the high intensity nonlinear dynamics on the efficiency of the SIS100 halo collimation system

Future application: Incoherent effect in Electron Clouds

The principles of particle trapping driven by high intensity are found in incoherent electron cloud effects.

Thanks to

GSI	O. Choriny, W. Bayer, O. Boine-Frankenheim, C. Omet, B. Franczak, P. Forck, T. Giacomini, I. Hofmann, M. Kirk, H. Kollmus, T. Mohite, A. Parfenova, P. Schuett, P. Spiller
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ITEP	P. Zenkevich, A.Bolshakov, V. Kapin
SRI	A.I. Neishtadt
Univ. Bologna	G. Turchetti, C. Benedetti, A. Bazzani