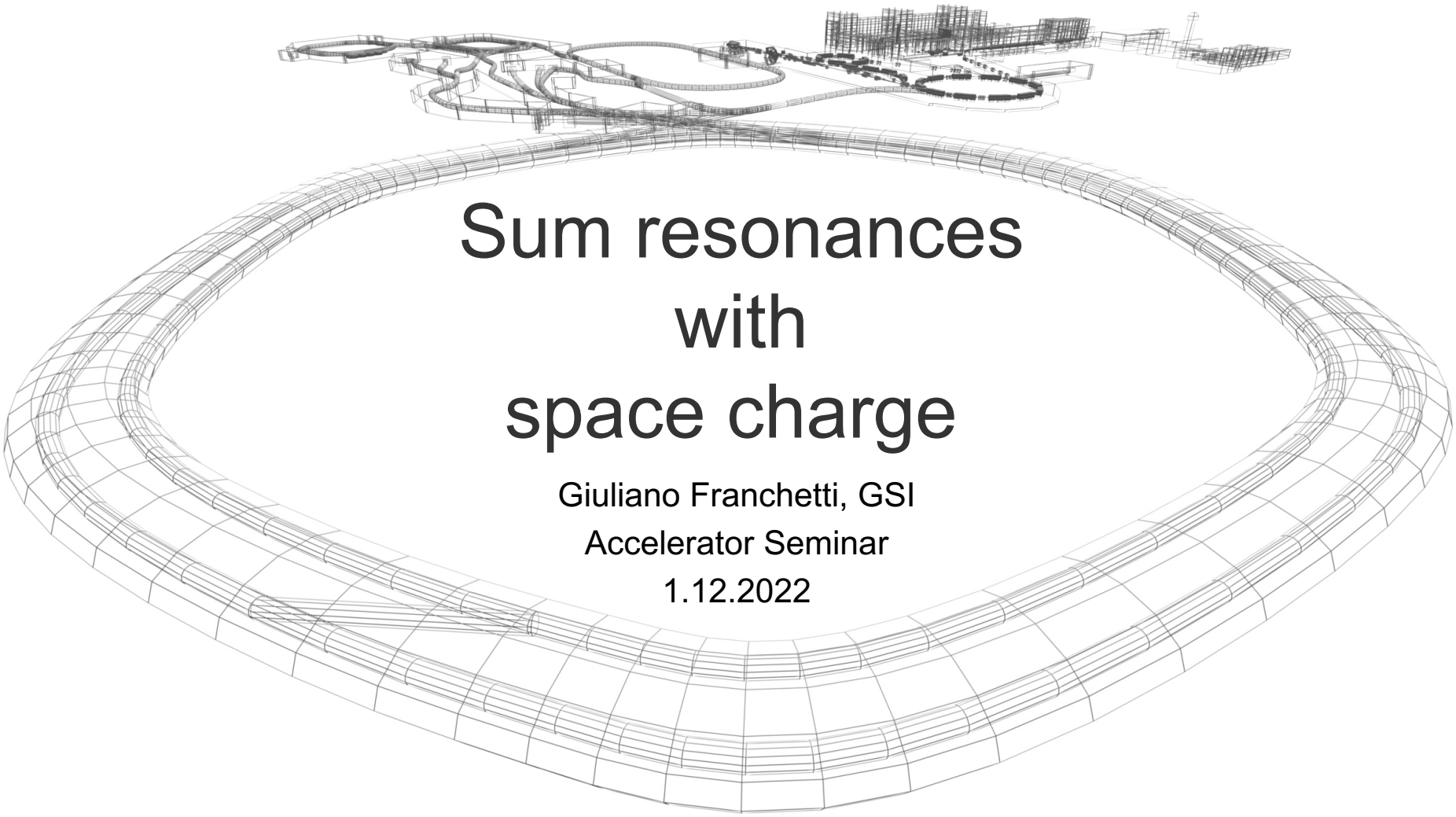
GSI Helmholtzzentrum für Schwerionenforschung GmbH



Sum resonances with space charge

Giuliano Franchetti, GSI

Accelerator Seminar

1.12.2022

Overview

The case for accelerators and projects

Space charge effect in nonlinear rings

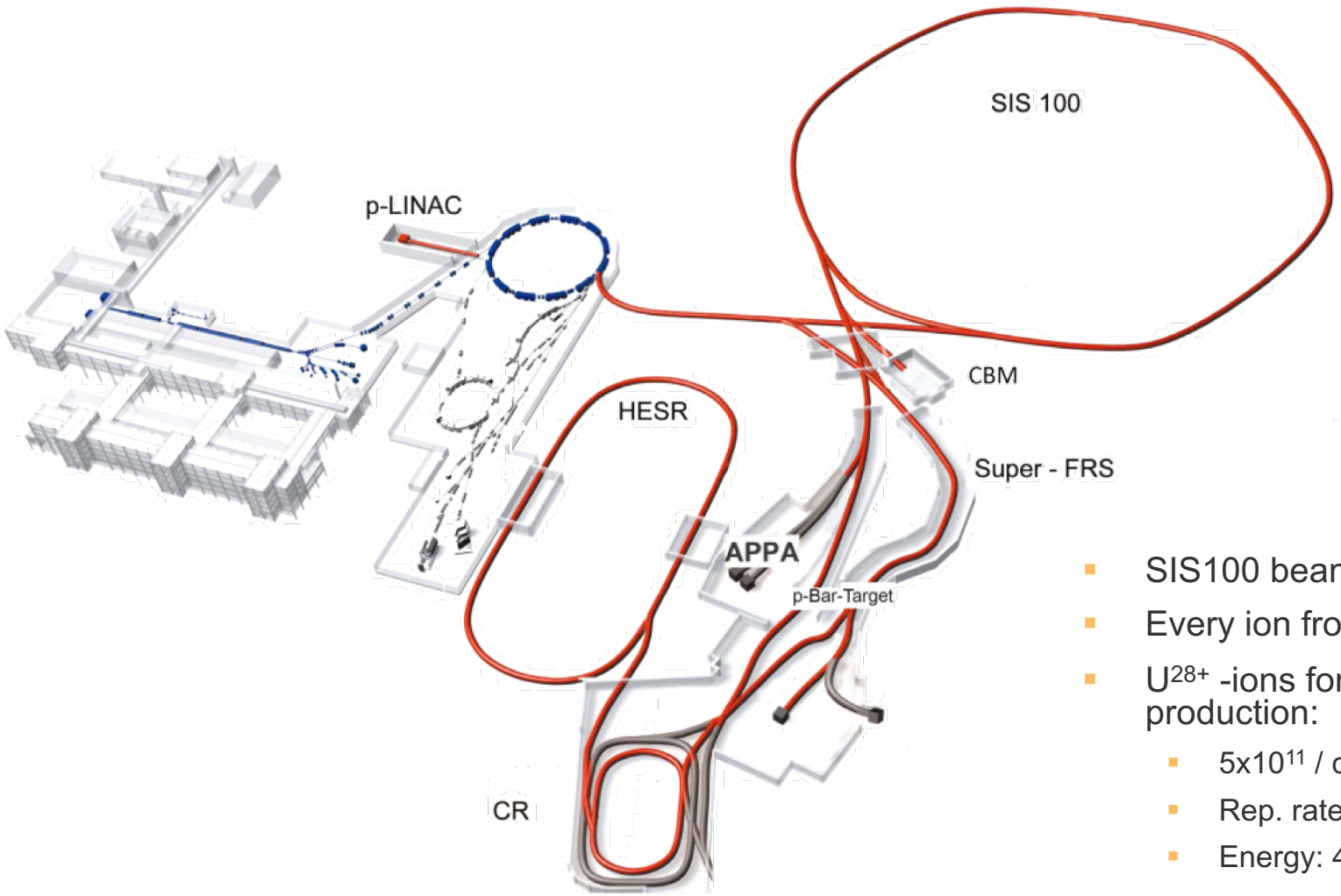
One dimensional resonances

The coupled resonances

Experiment and simulations

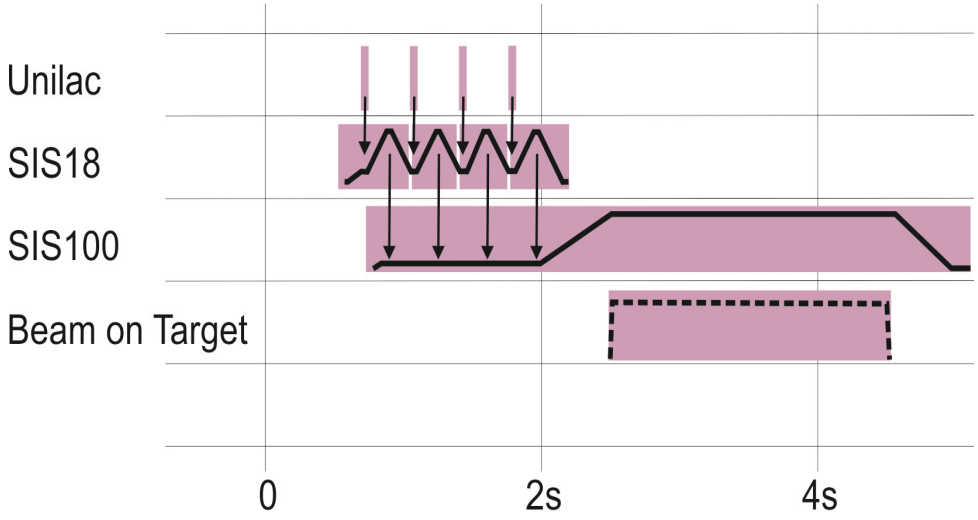
Conclusion / Outlook

Motivation: the FAIR project



- SIS100 beam parameters:
- Every ion from p to U
- U^{28+} -ions for RIB production:
  - $5x10^{11}$ / cycle
  - Rep. rate: 0.5 Hz
  - Energy: 400–2715 MeV/u

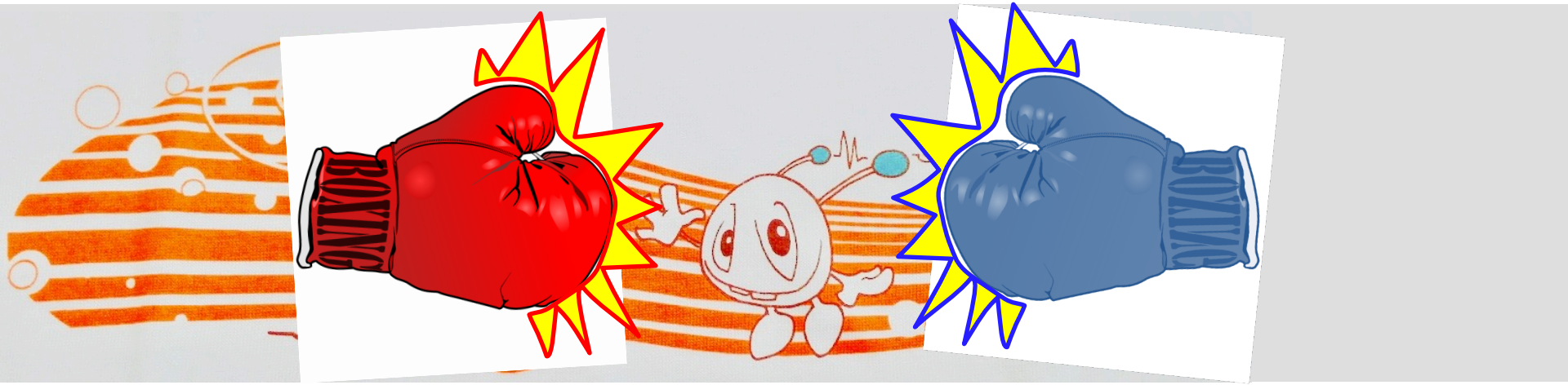
Injectors for FAIR



SIS100:
$5x10^{11}$ U^{28+} ions per cycle
$3x10^{11}$ U^{28+} ions per second

Accelerator case

High intensity bunch stored for many turns



Particles subject to Space charge

Space charge tune-shift
Amplitude dependent detuning

Structure resonances
Collective effects
impedances

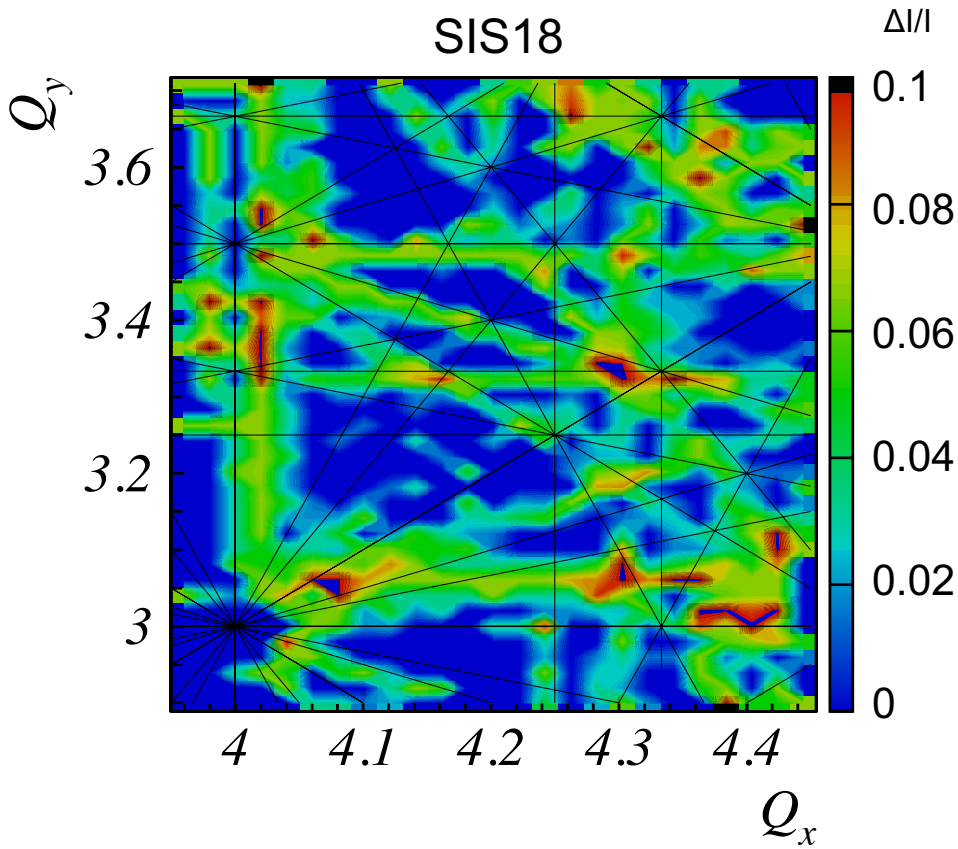
Particles are subject to the nonlinear motion

Error and structure resonances
Dynamic aperture

Chromatic effects

Single particle nonlinear dynamics

Error / Structure Resonances
SIS18

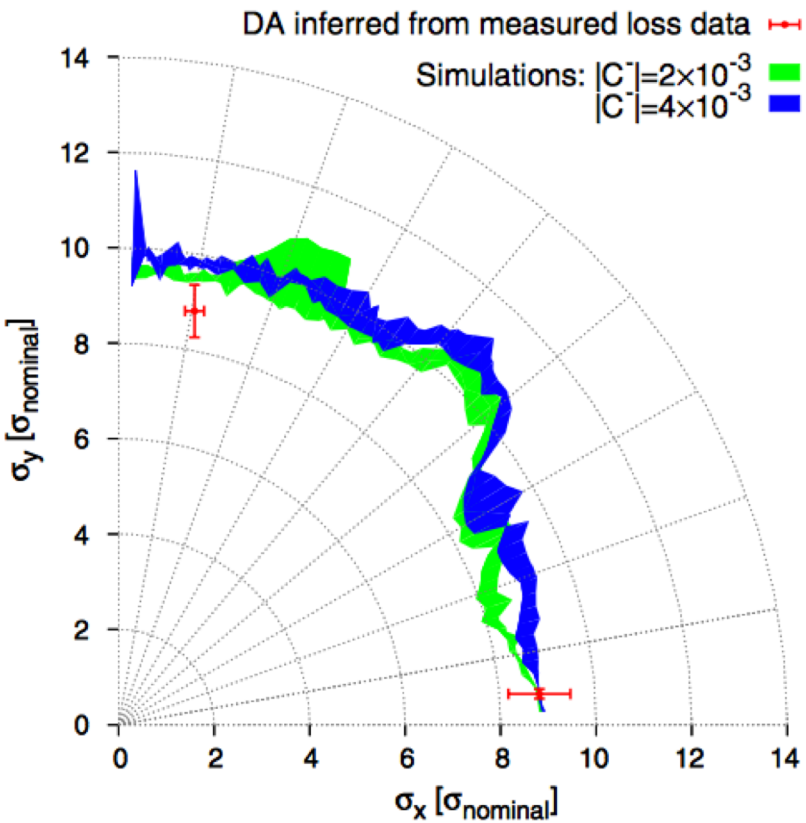


Lattice induced nonlinear resonances

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

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

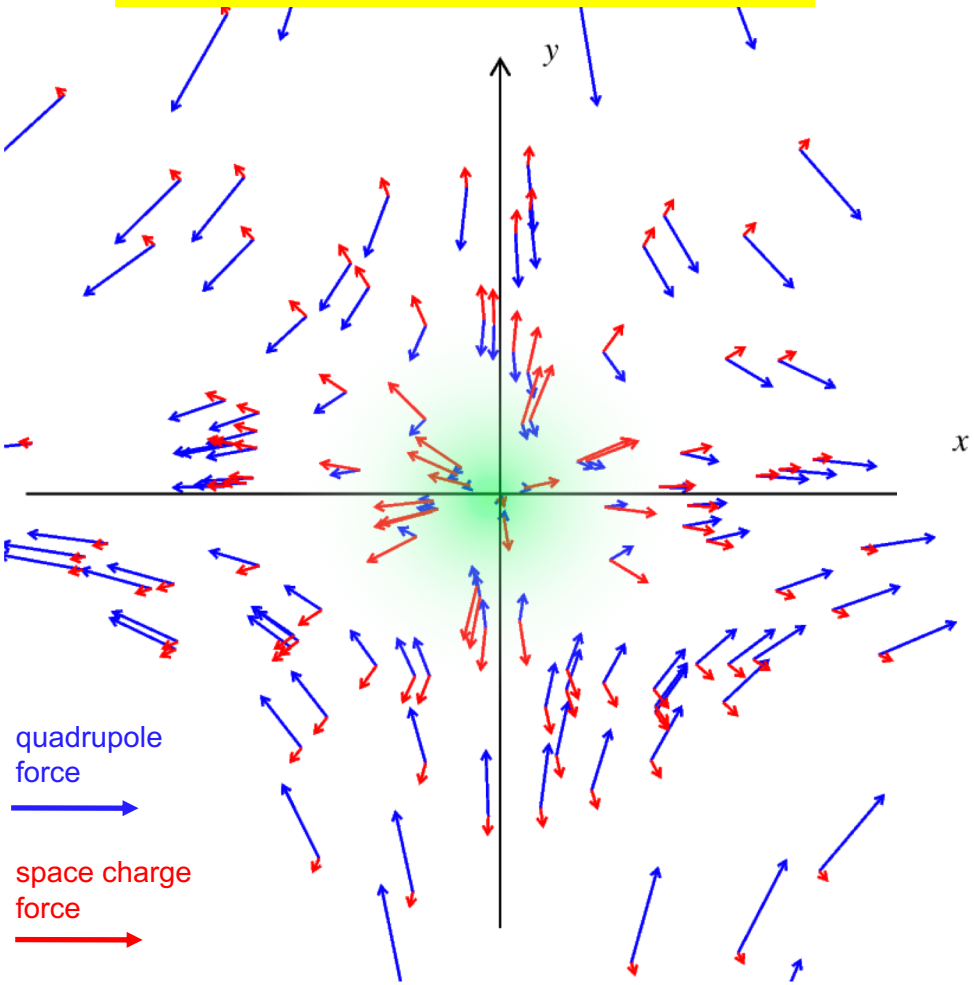
Dynamic Aperture: LHC



E. H. Maclean, R. Tomás, F. Schmidt, and T. H. B. Persson
Phys. Rev. ST Accel. Beams **17**, 081002

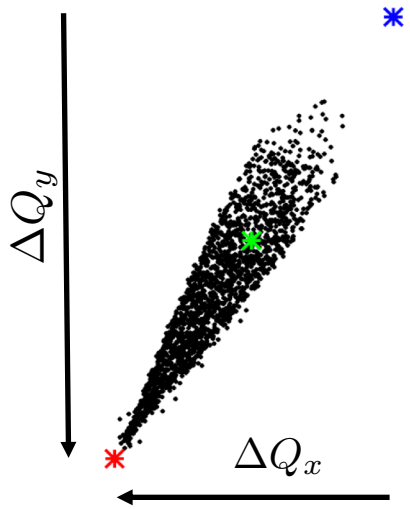
Space charge vs. magnets force

Example in a focusing quadrupole



Space charge tune-spread

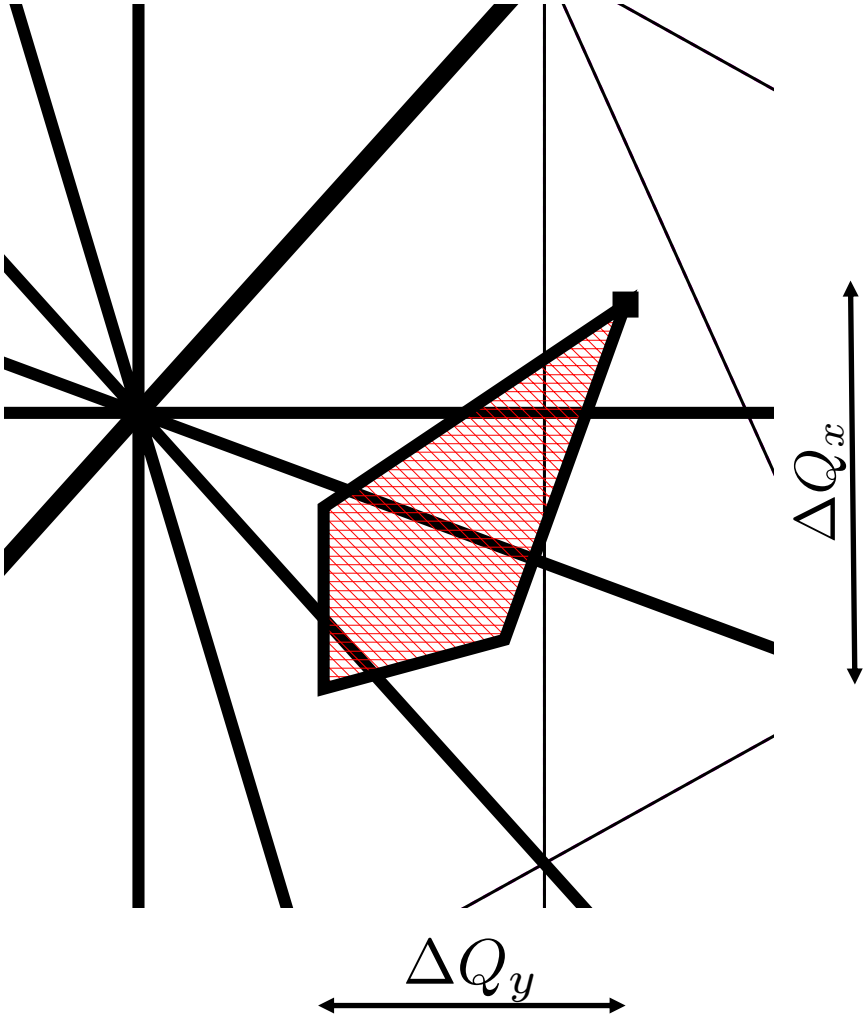
Gaussian distribution



SIS100

$$\Delta Q_x \sim -0.2$$
$$\Delta Q_y \sim -0.3$$

The space charge limit



Tolerable space charge tune-shift in order not to overlap with resonances

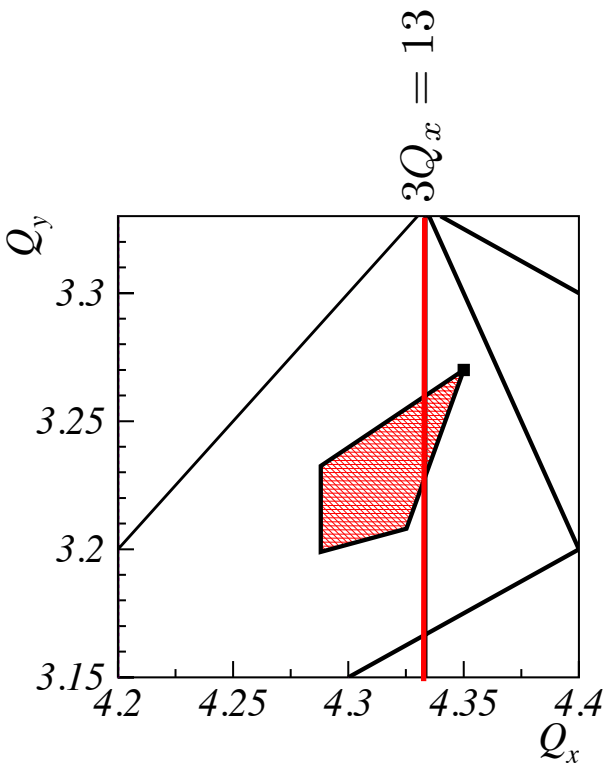
If resonances are too many, or the incoherent tune-shift is too large there is always a resonance overlapping

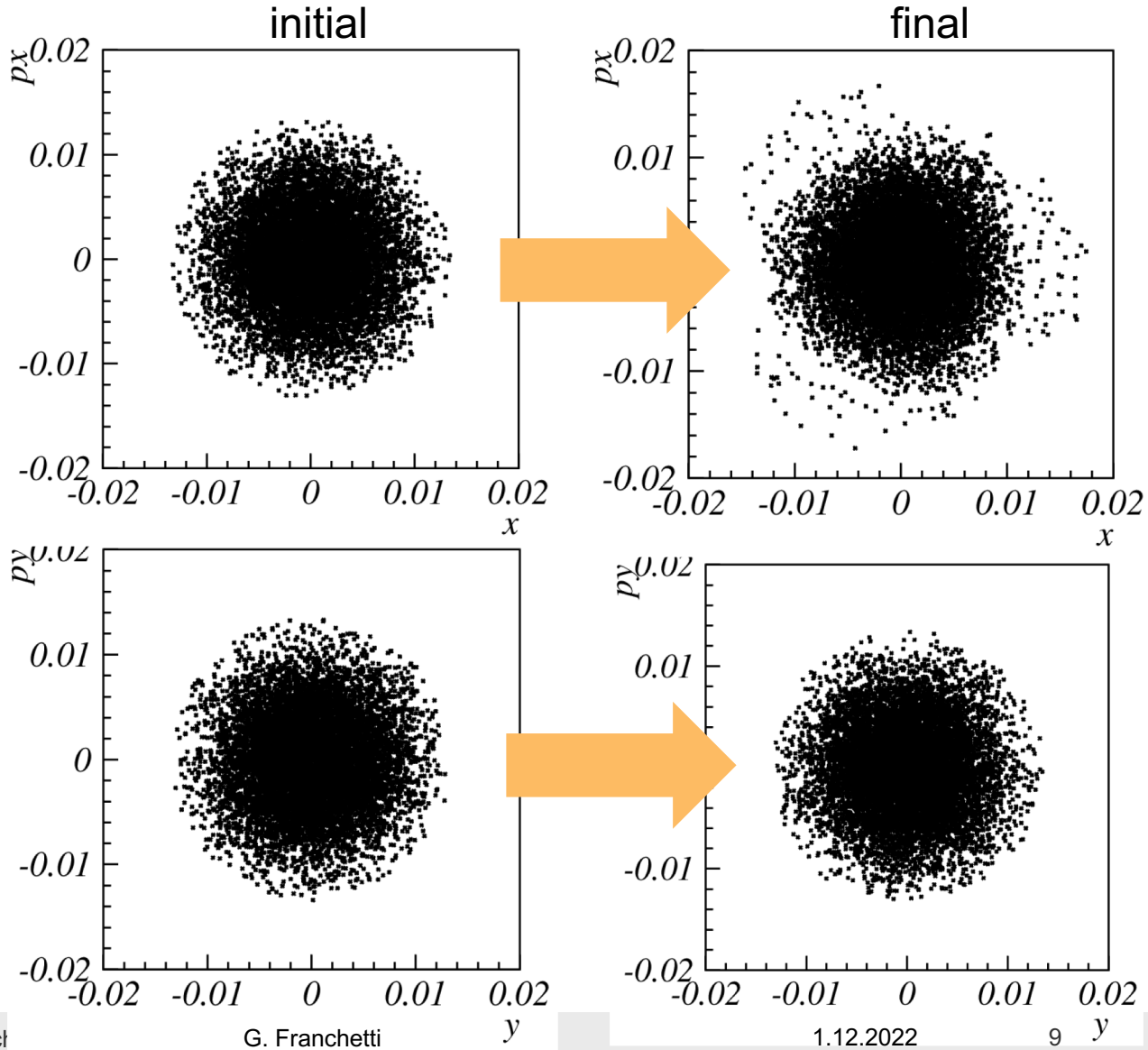
Textbook wisdom: maximum space charge tuneshift is of 0.5

What happens if space charge tune-spread overlaps a resonance?

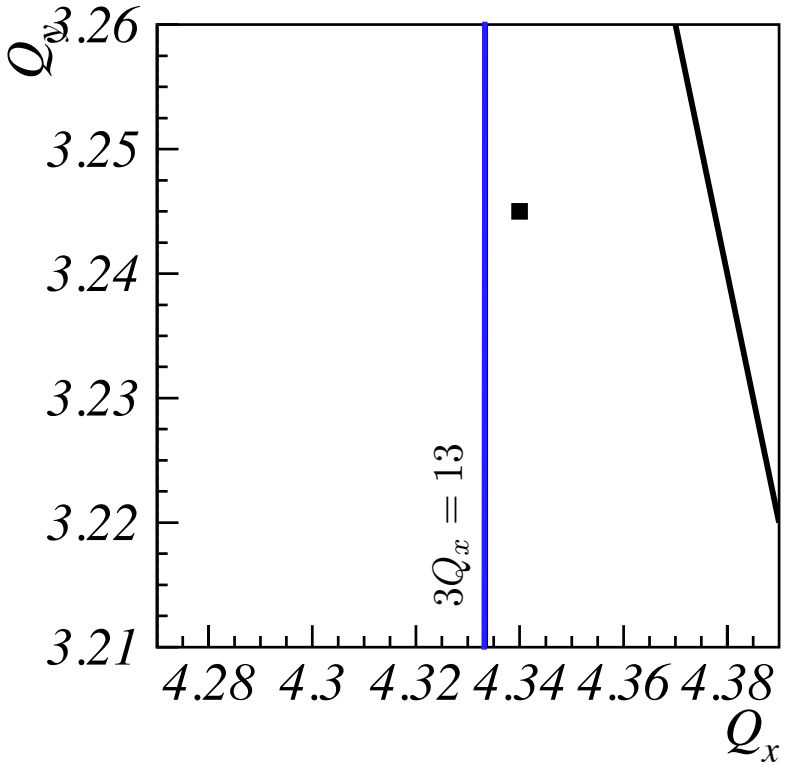
Example: Coasting beam and 1D resonance

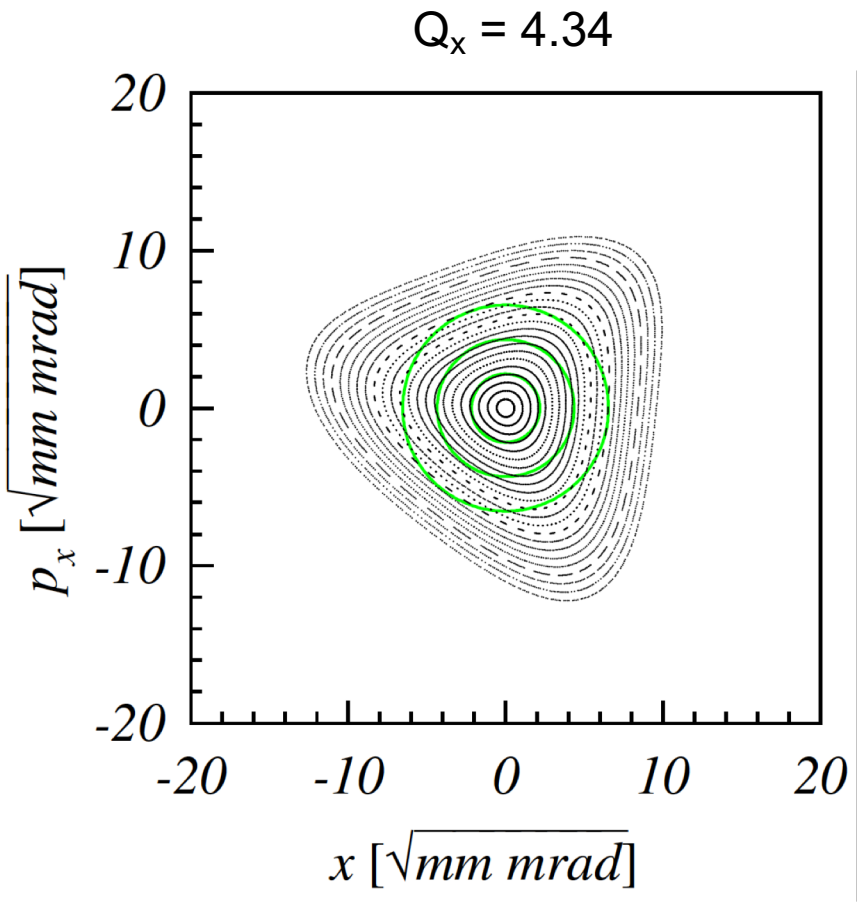
PIC simulation



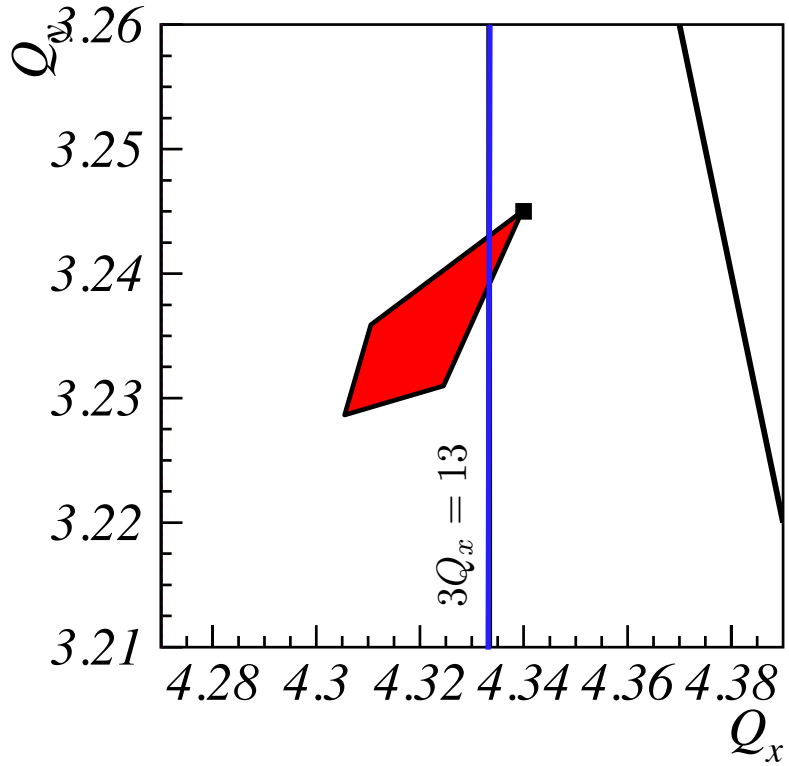


Interpretation

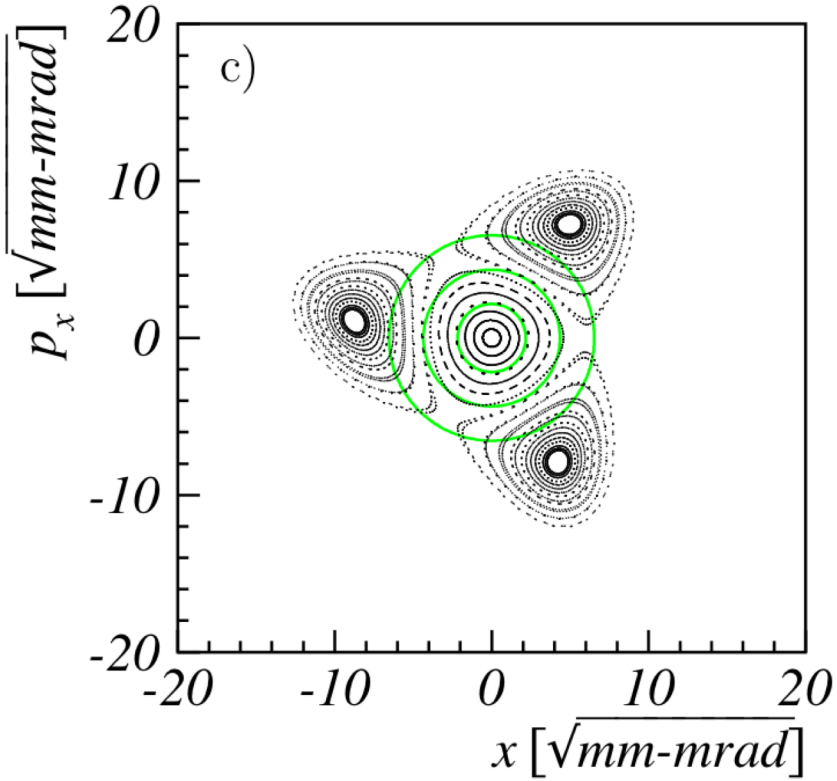




Interpretation

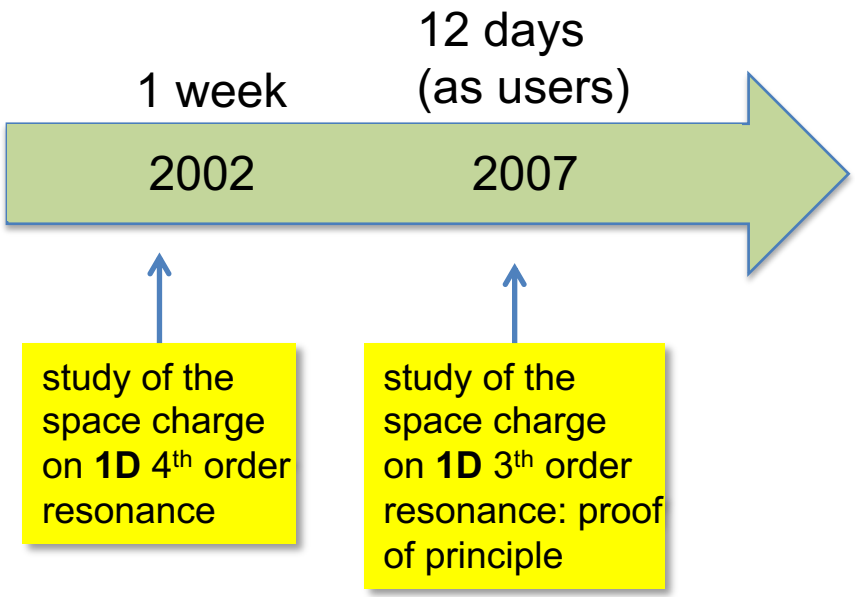


$Q_x = 4.34$



Above the resonance: Large stable 3rd order islands are created

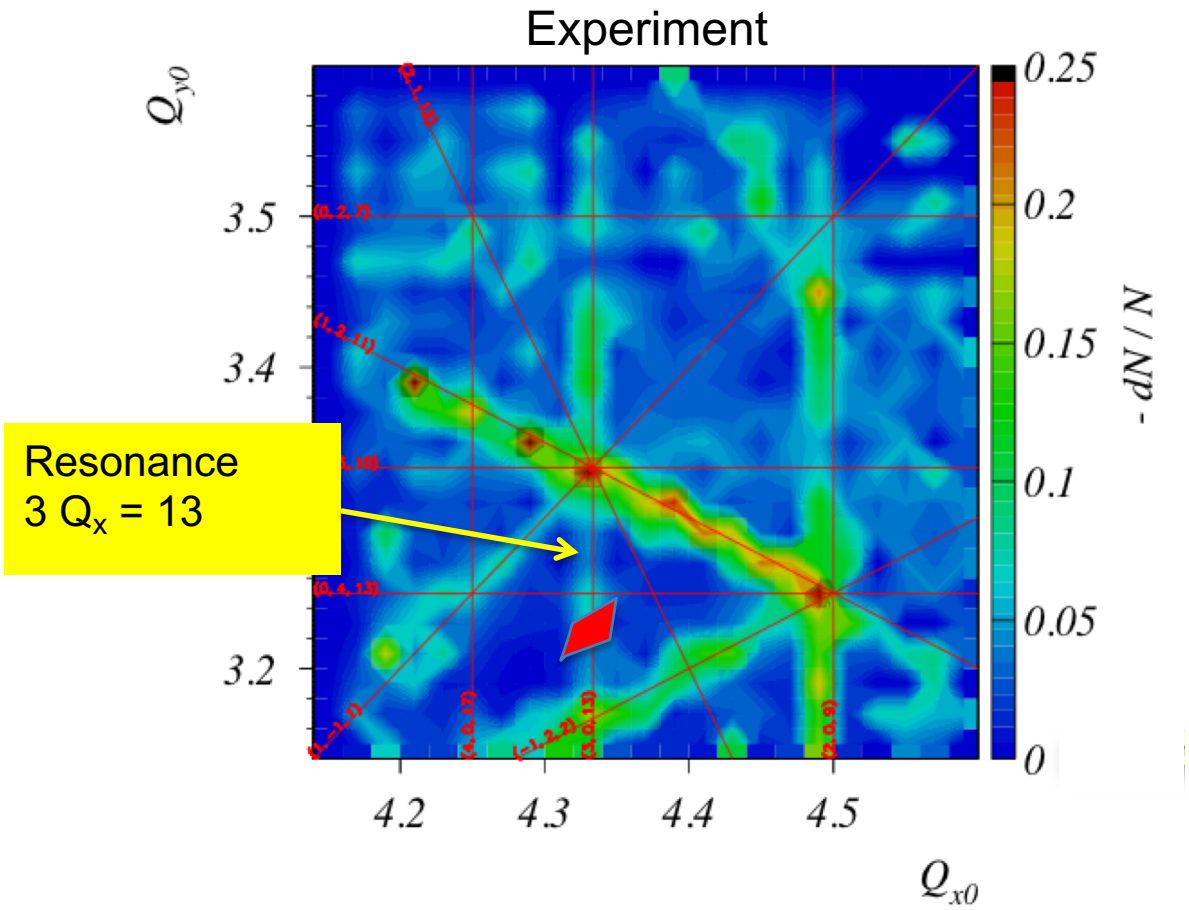
The quest of the incoherent effects of space charge



PS

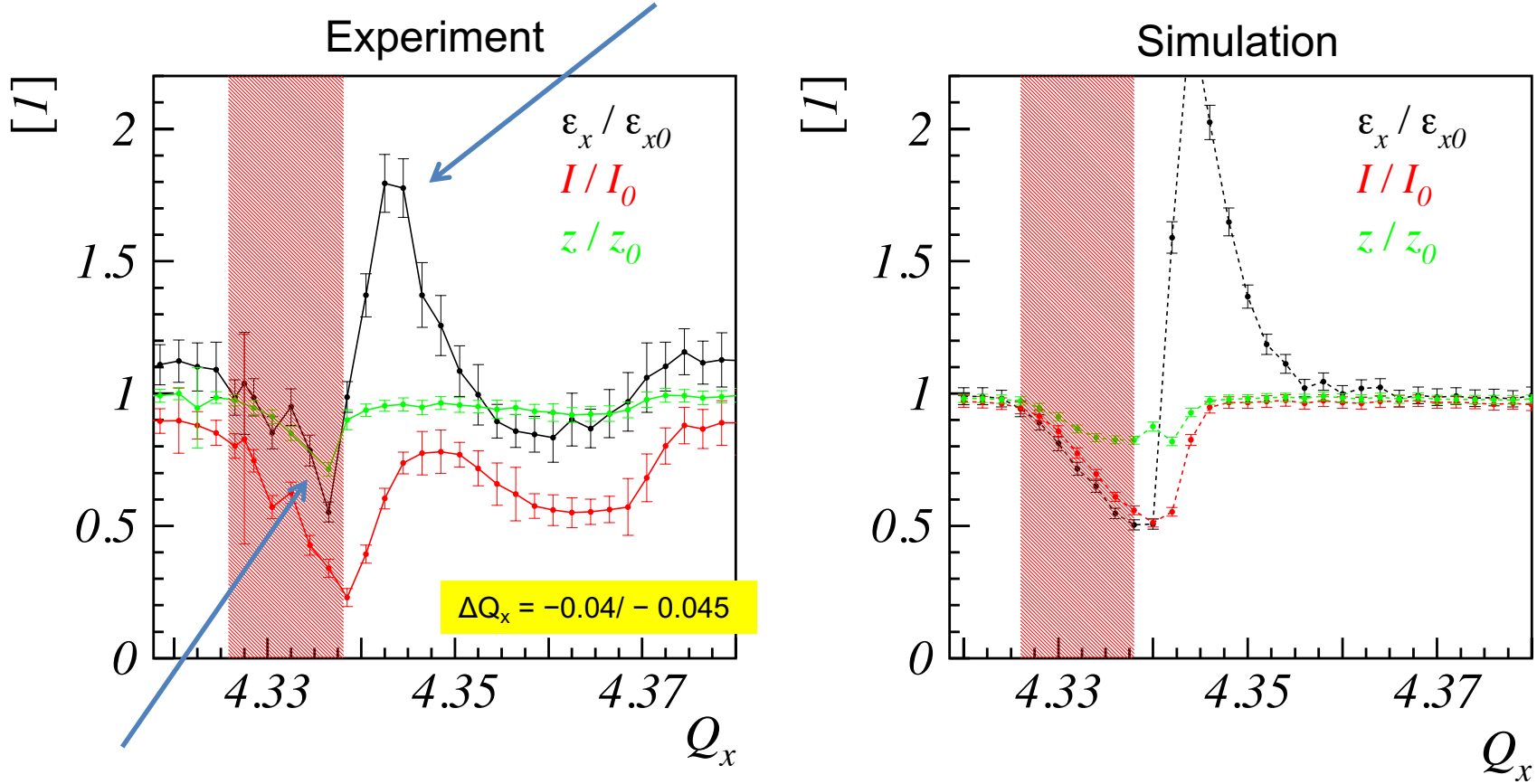
SIS18

1D third order resonance



The GSI Campaign (2007-2010)
Bunched beam at high intensity

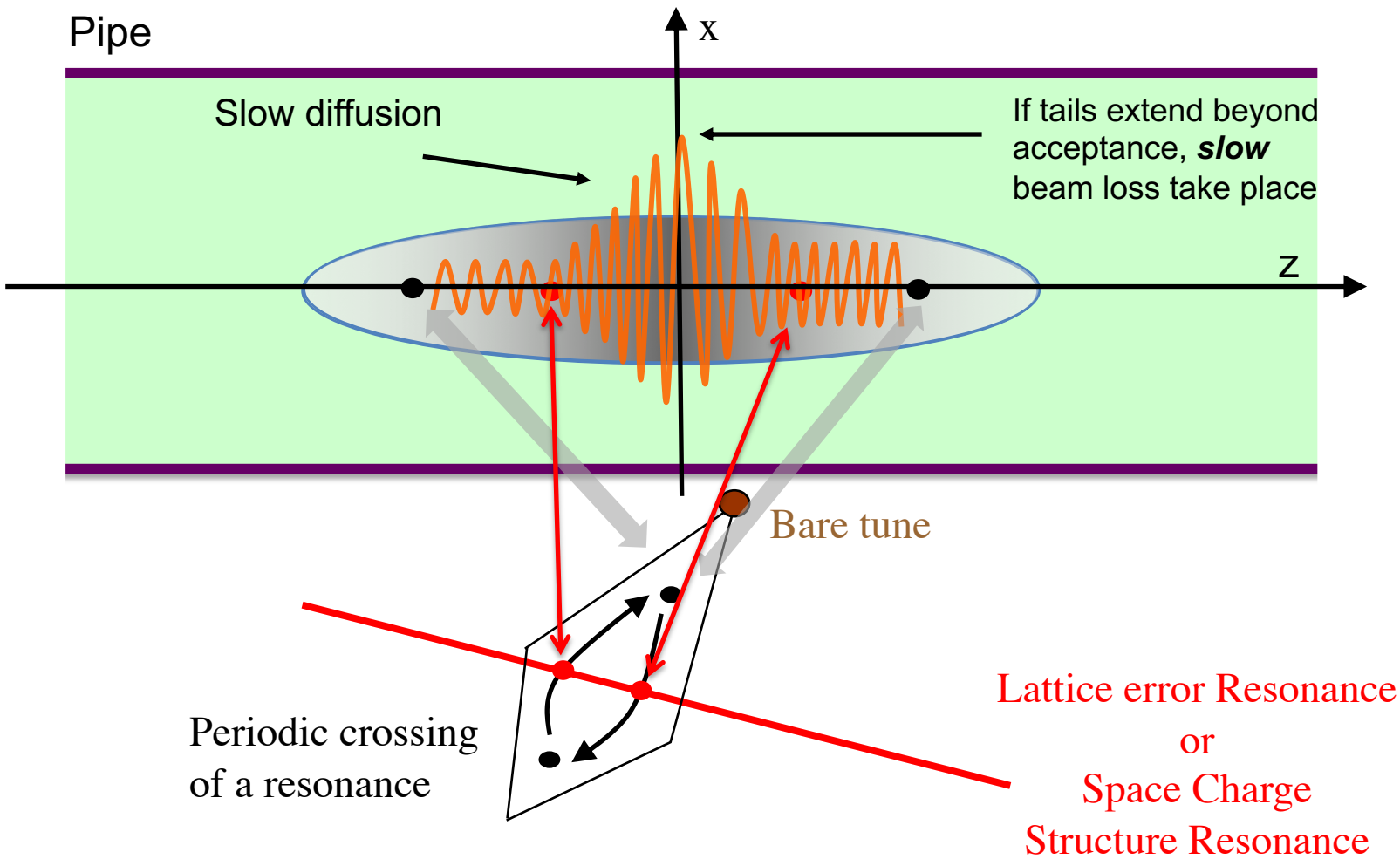
Large emittance growth



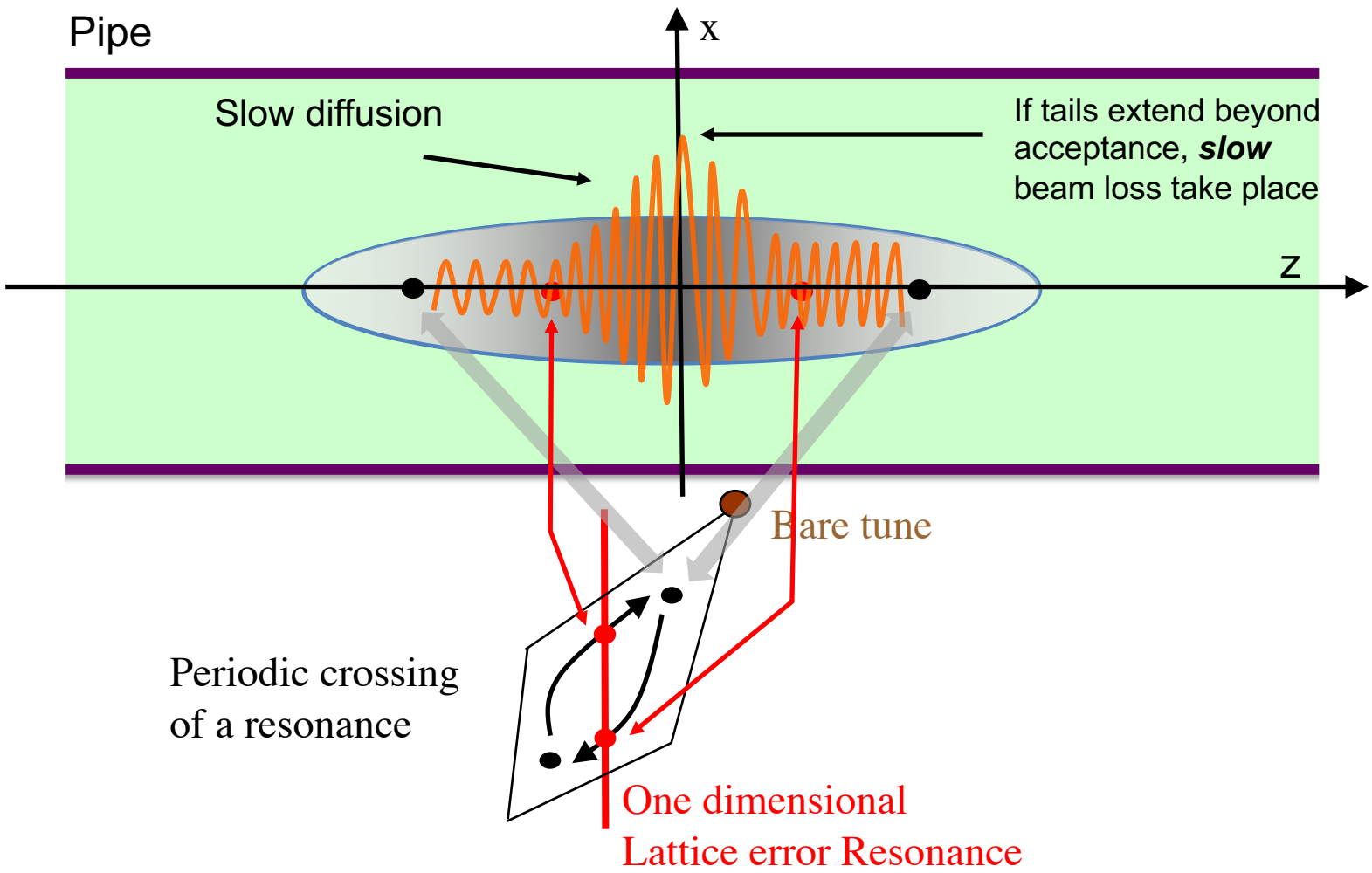
The bunch is shorter !

G. Franchetti, O. Chorniy, I. Hofmann, W. Bayer, F. Becker, P. Forck,T. Giacomini, M. Kirk, T. Mohite, C. Omet, A. Parfenova, P. Schuett
Phys. Rev. ST Accel. Beams **13**, 114203 (2010).

Space charge and resonances

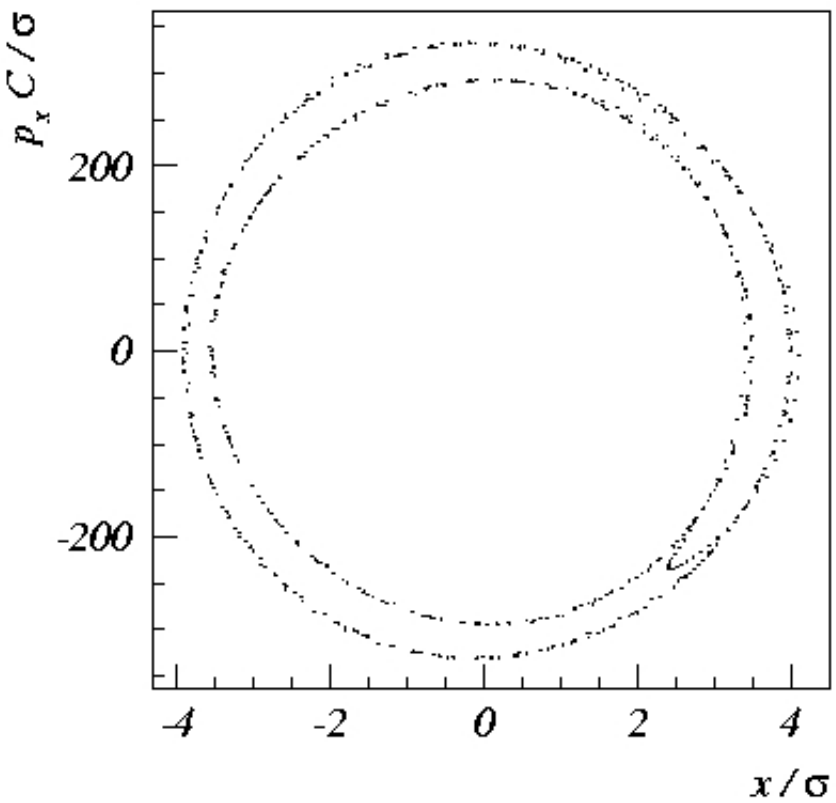


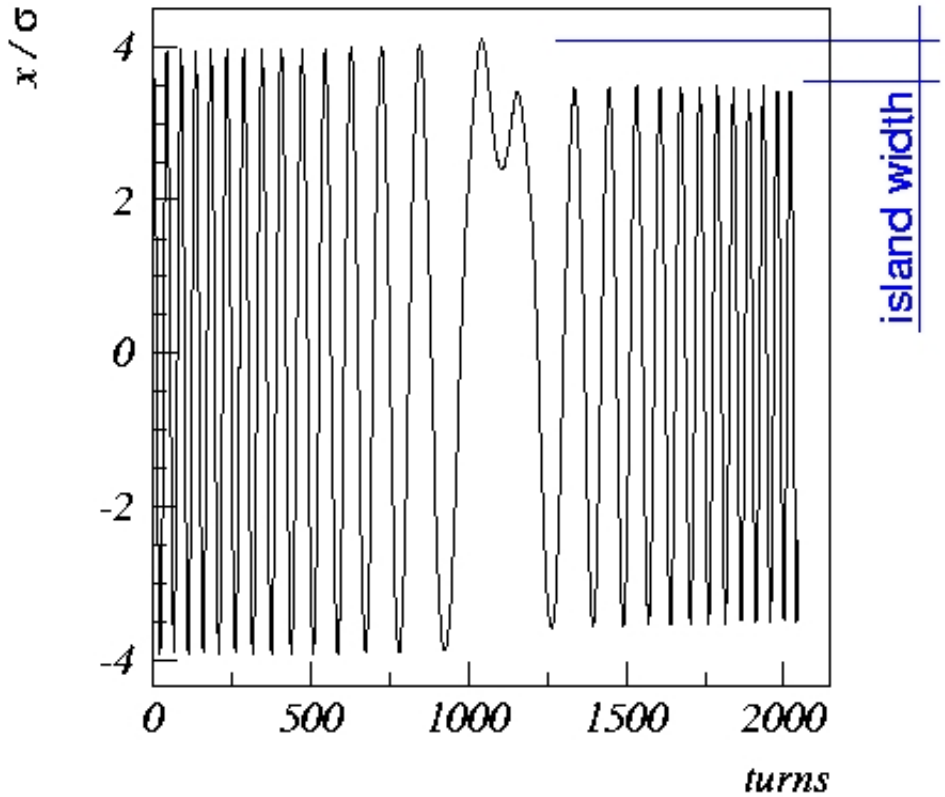
Space charge and resonances



Scattering

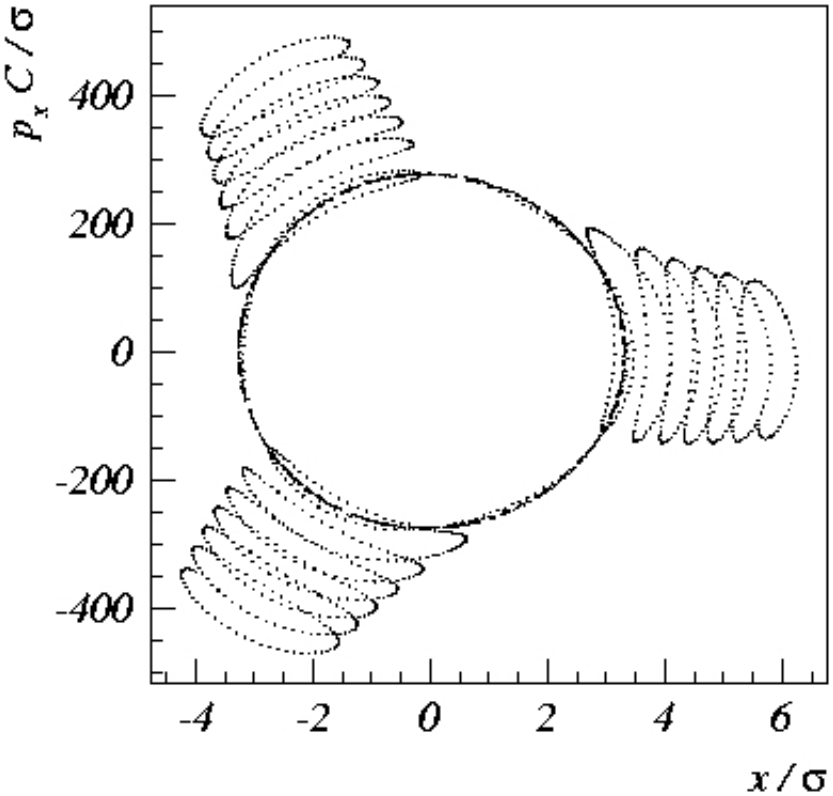
Fast resonance crossing → „scattering“ of the invariant

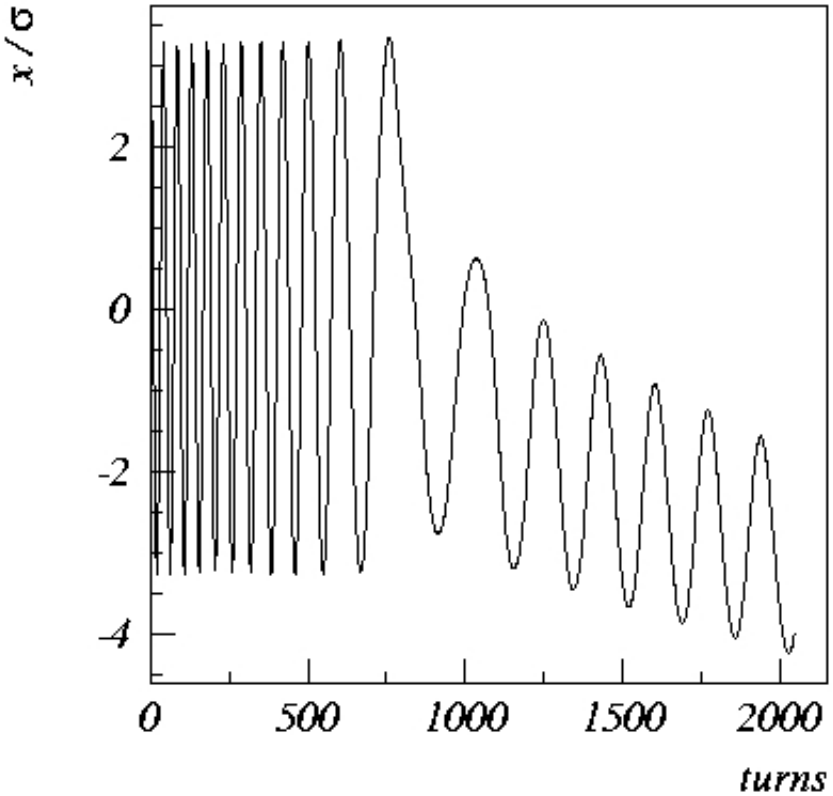




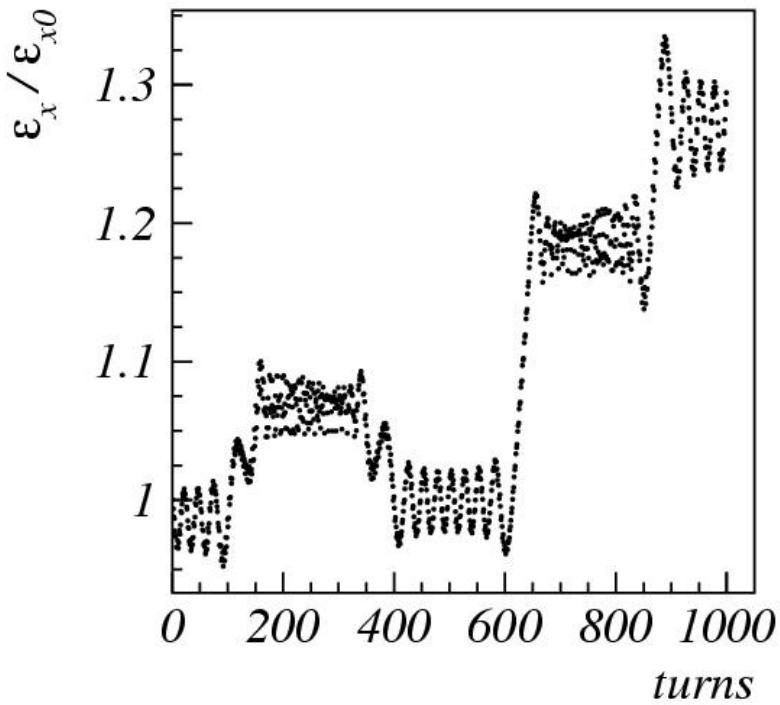
Trapping

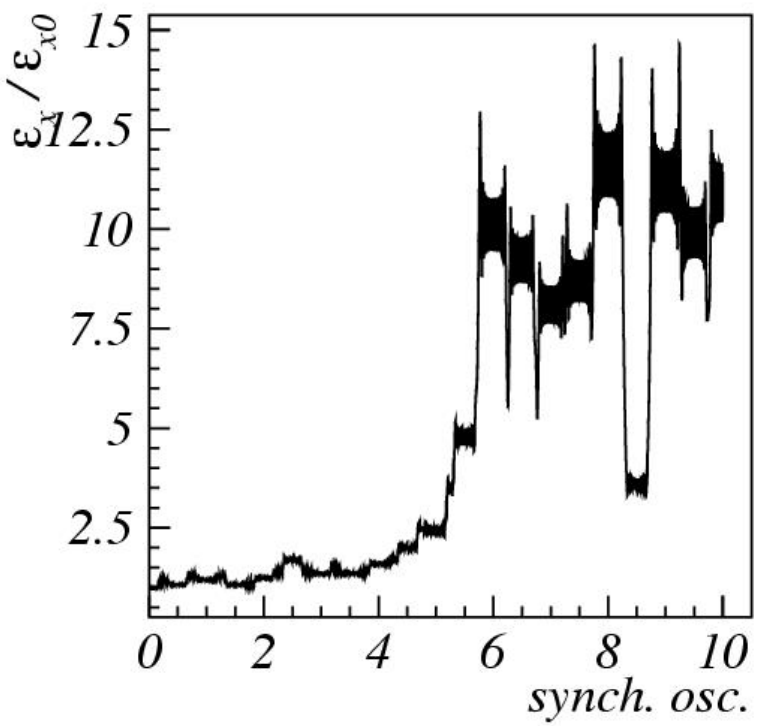
Slow resonance crossing → „Trapping“ in the island



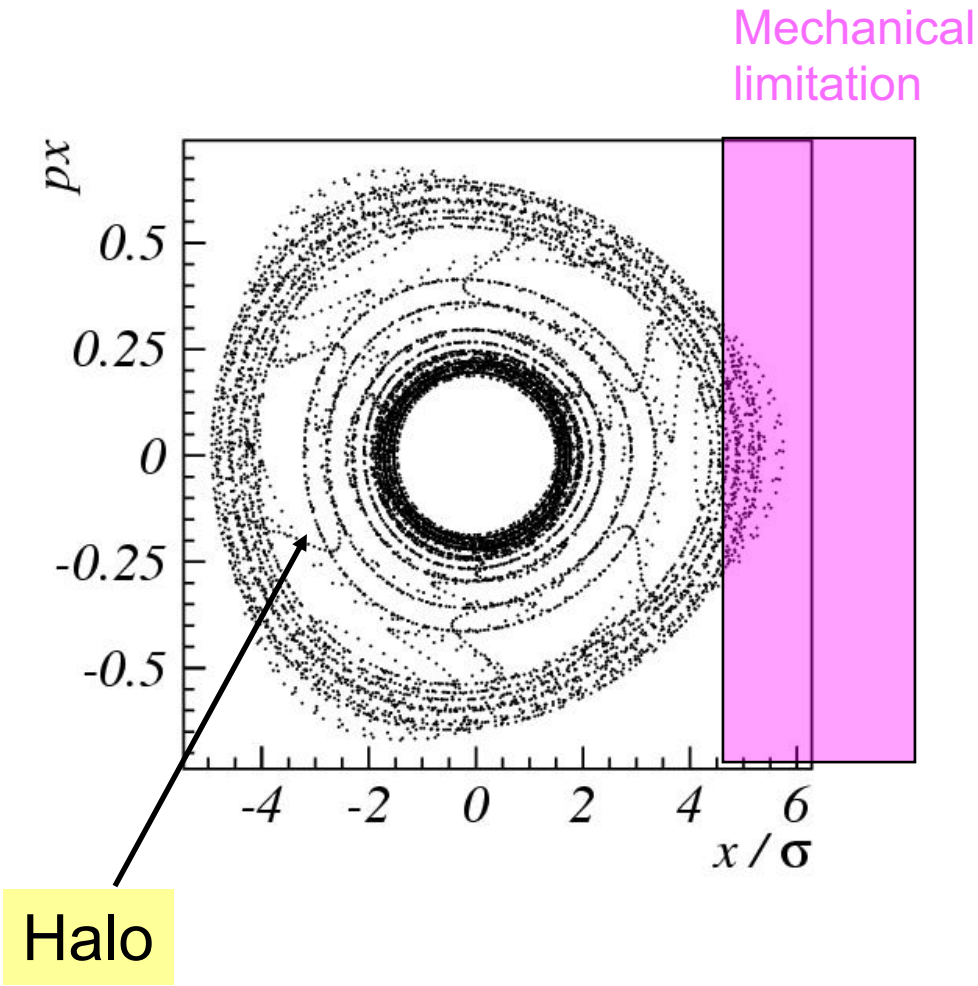


Periodic crossing in a scattering regime

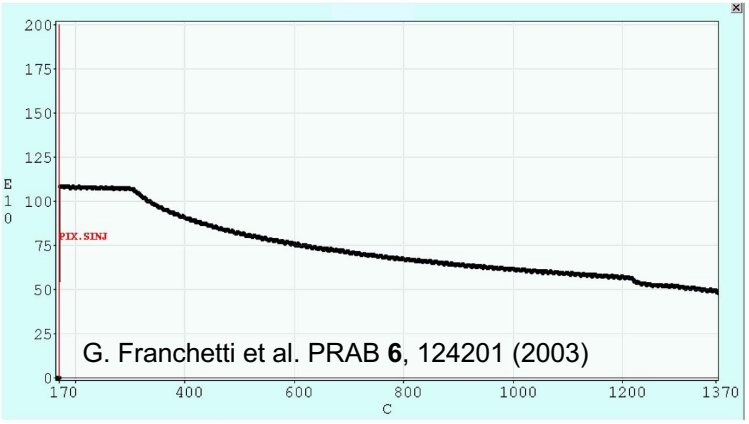




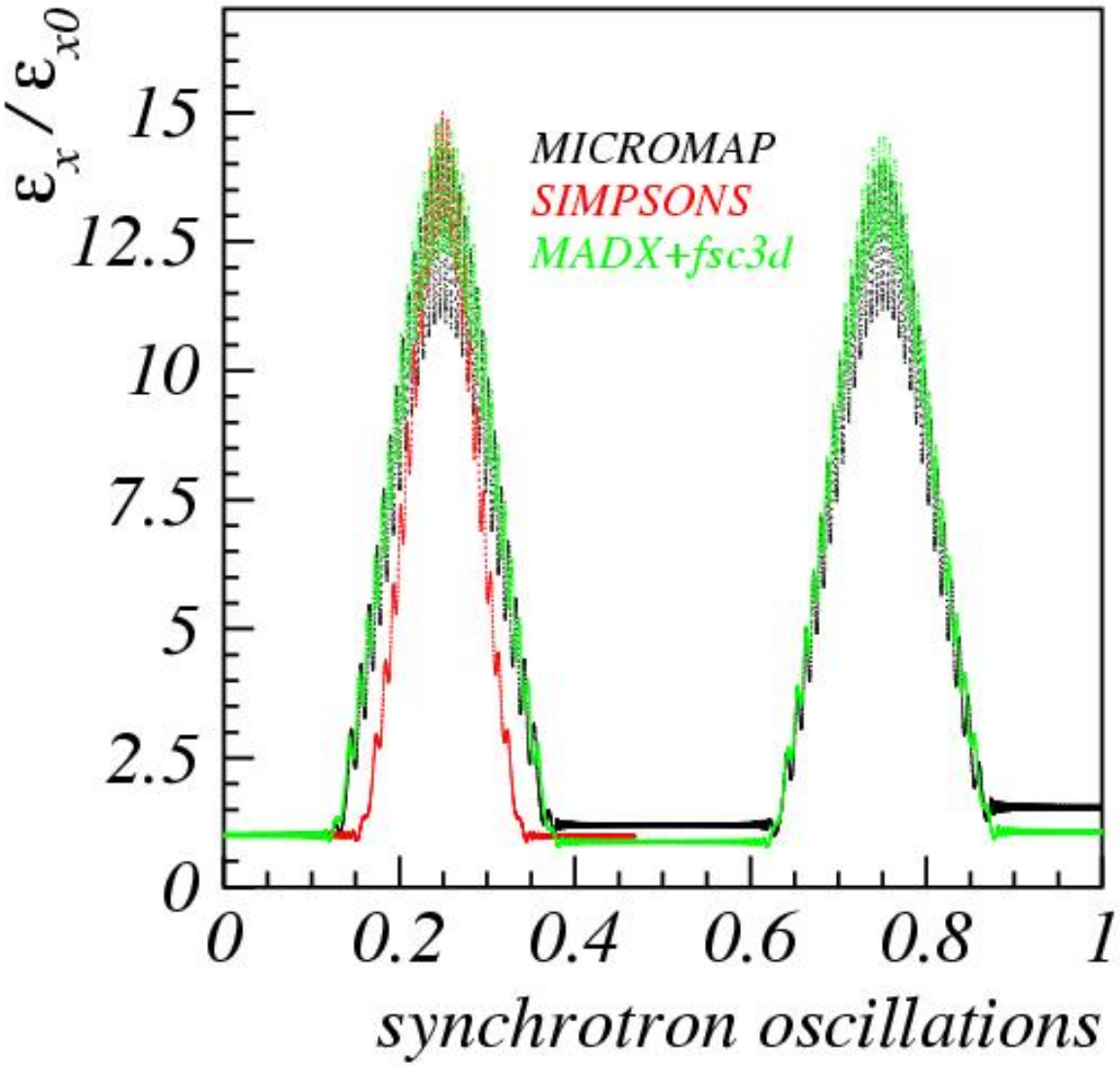
Long term beam loss



The scattering regime creates a nonlinear diffusional regime eventually leading to long term slow beam loss



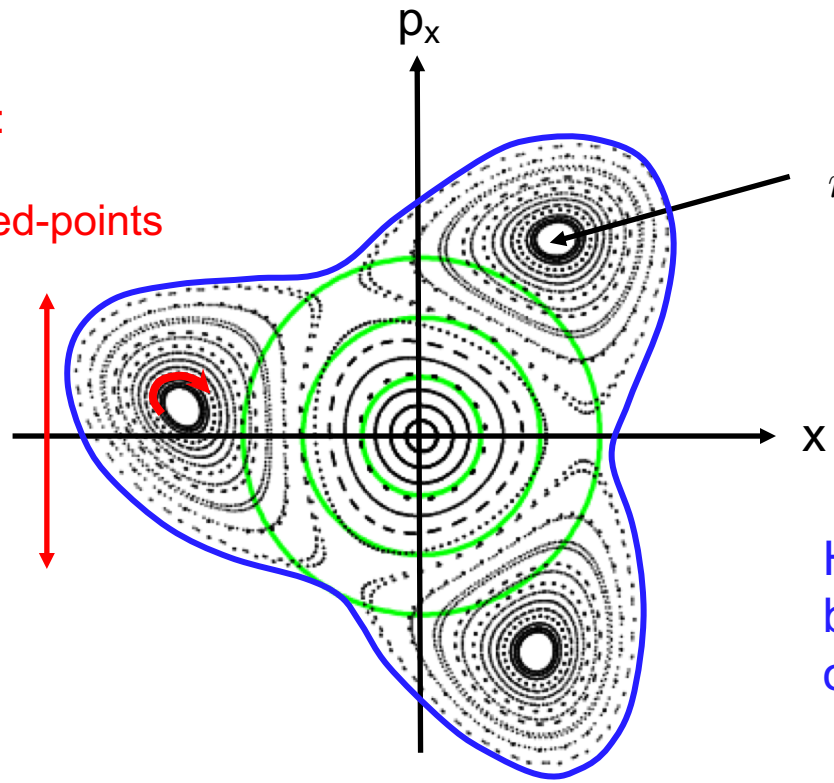
Trapping



If trapping takes place fast beam loss would appear quick and large!

1D resonance and space charge
Summary

Resonance strength:
- Island size
- Tunes around fixed-points



Determined by

$$n[q_{x0} + \Delta Q_x(X)] = N$$

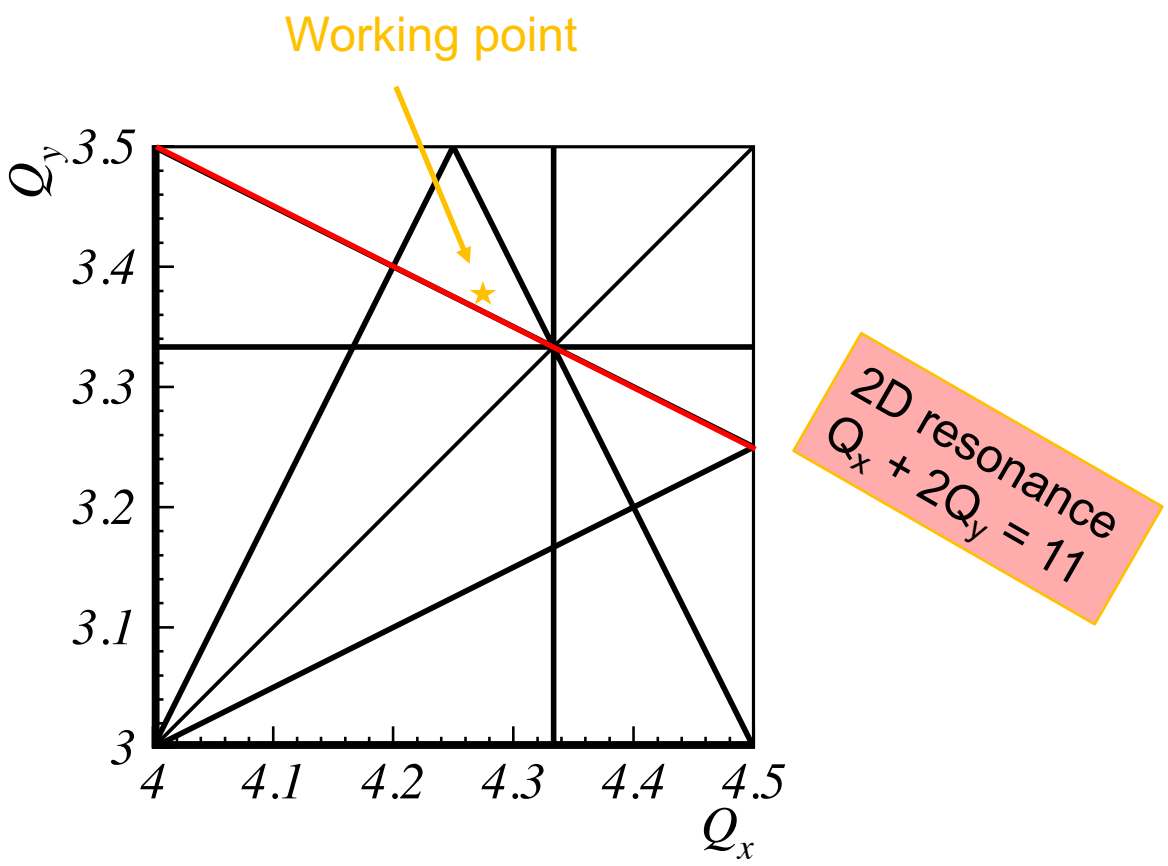
Halo size is determined by the outer position of islands

Longitudinal motion and space charge drives islands away too fast

"scattering regime"

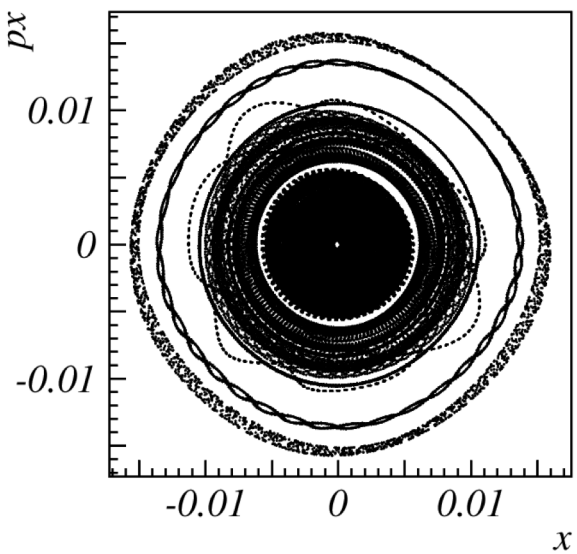
(Role of chromaticity, left out in this talk)

The difficulty of the coupled dynamics

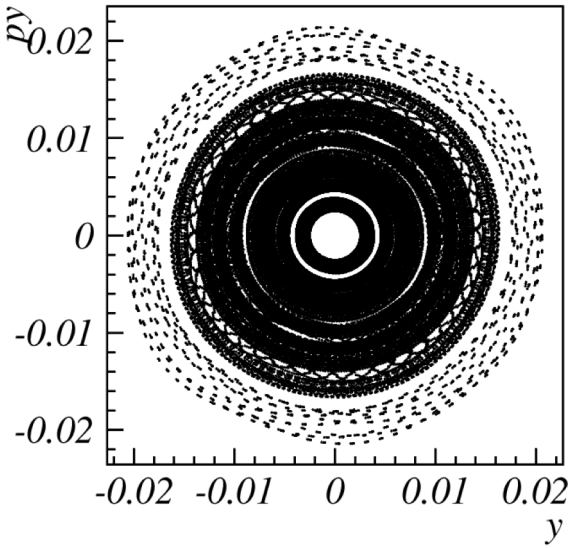


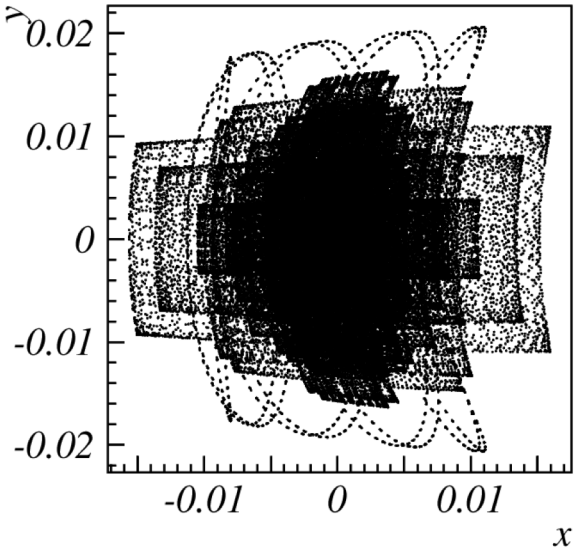
The difficulty of the coupled dynamics

Near the resonance $Q_x + 2\,Q_y = 11$ $Q_x = 4.27$, $Q_y = 3.3575$



Orbits become fuzzy

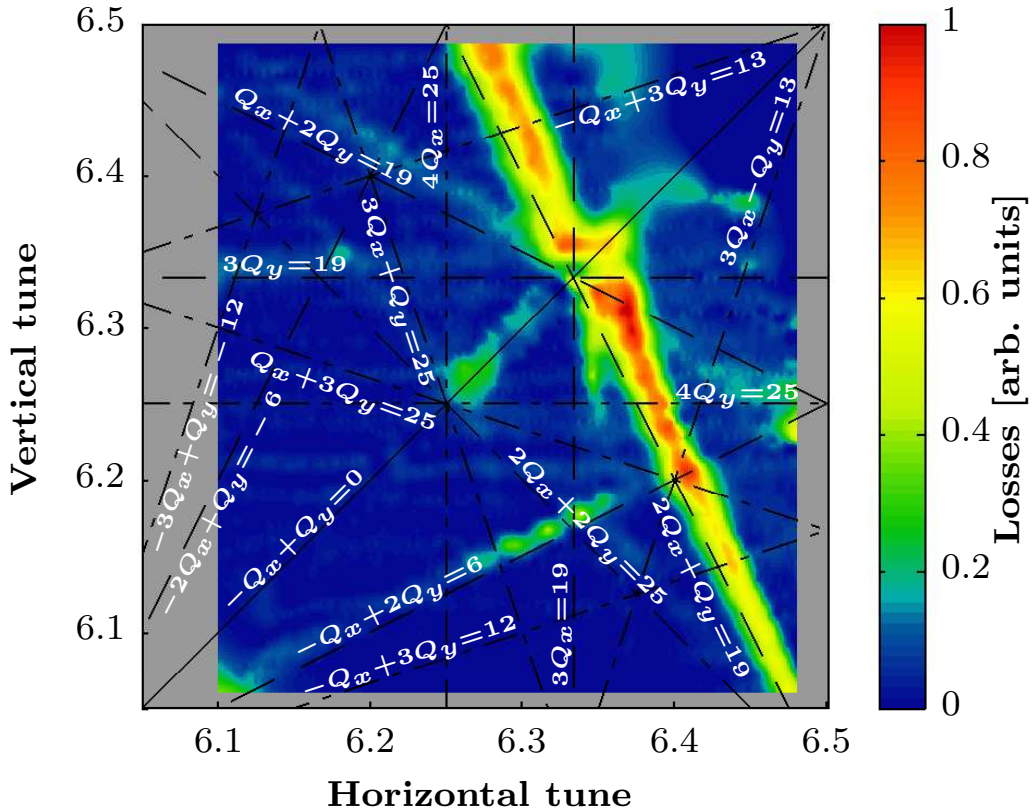


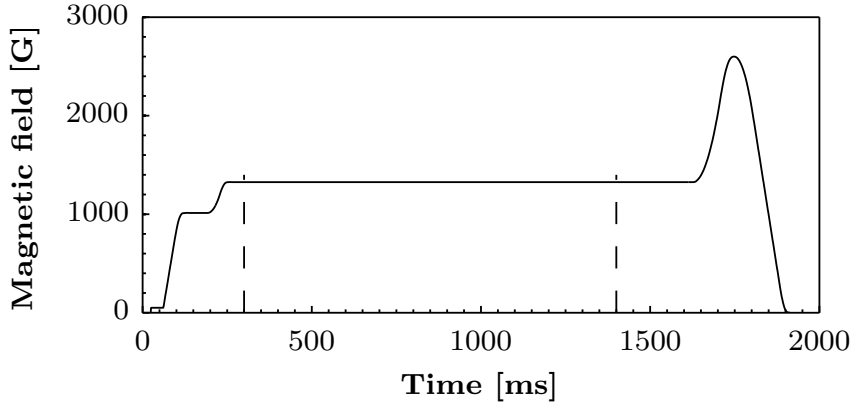


Very difficult to understand what is going on.

The 2012 CERN-PS measurement campaign

Machine experiment campaign to investigate coupled nonlinear resonances
and space charge





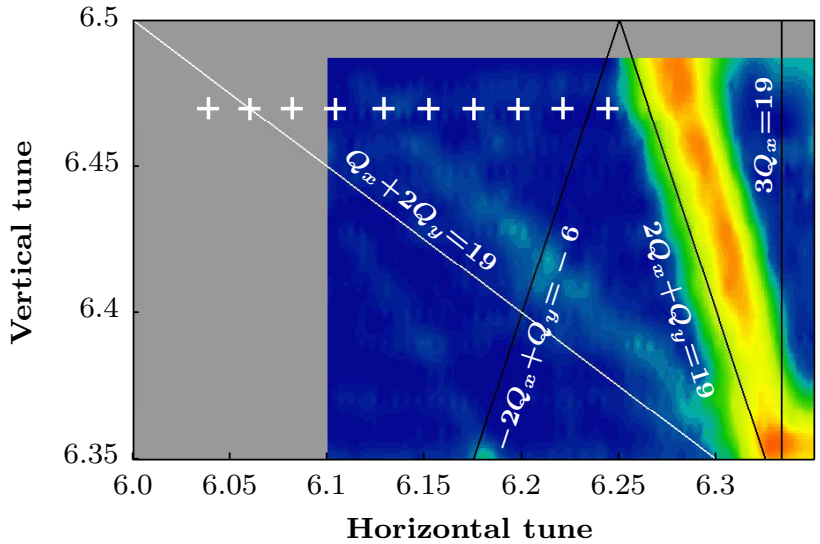


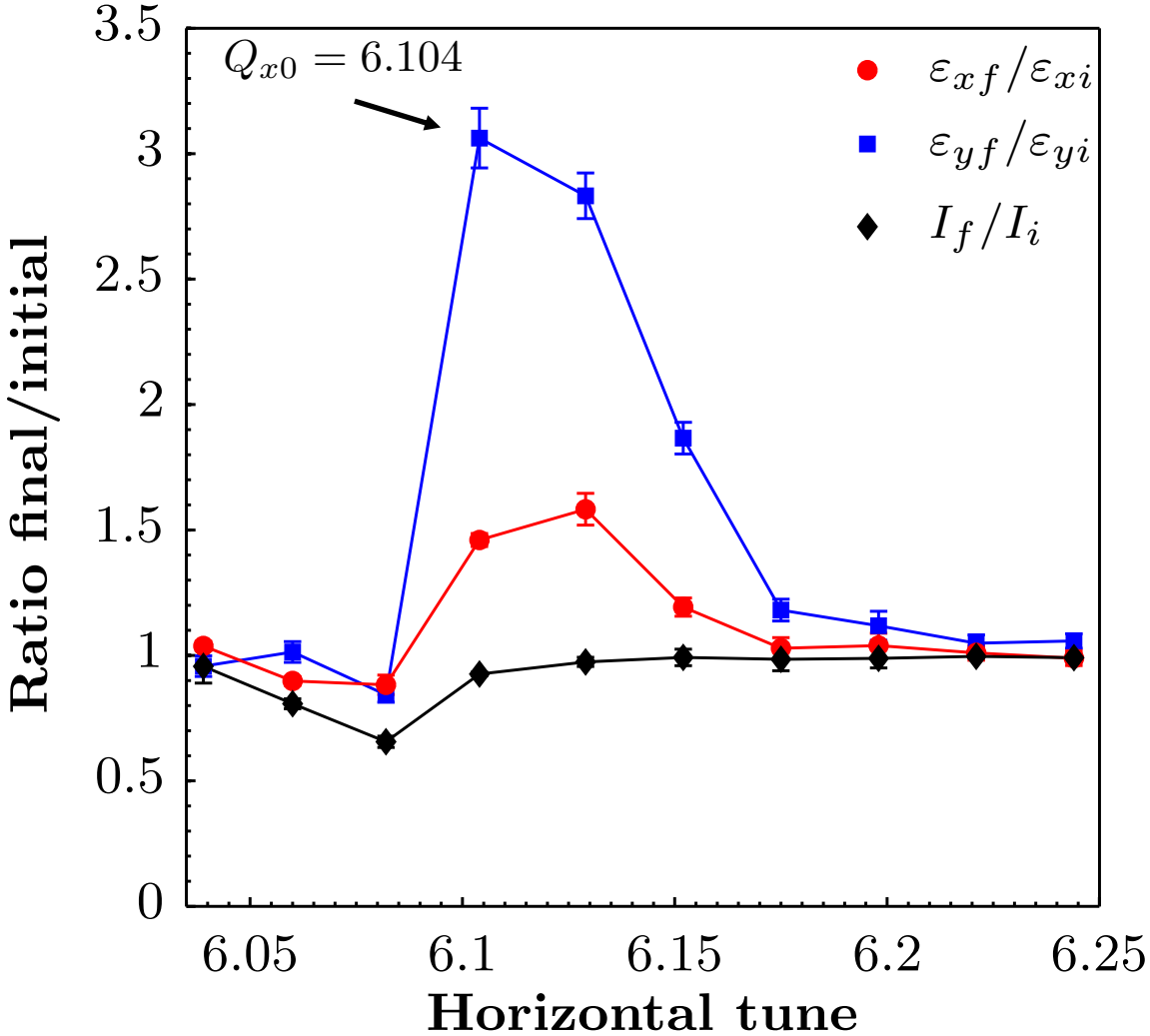
TABLE I. Beam and machine parameters.

Parameter	Value
Intensity N_p [10^{10} p]	55
Normalized horizontal rms emittance ε_x^n [mm mrad]	3.6
Normalized vertical rms emittance ε_y^n [mm mrad]	2.2
Rms bunch length σ_t [ns]	33
Rms momentum spread $\frac{\Delta p}{p}$ [10^{-3}]	0.95
Horizontal maximum tune spread $\Delta Q_{x,\max}$ [a]	-0.05
Vertical maximum tune spread $\Delta Q_{y,\max}$ [a]	-0.071
Sextupole current I_{SX} [A]	2
Harmonic number h	8
RF voltage V_{RF} [kV]	20.5
Horizontal linear chromaticity ξ_x [b]	-0.83
Vertical linear chromaticity ξ_y [b]	-1.12
Energy of stored beam [GeV]	2
Turns stored	497646
Storage time [s]	1.1
Relativistic β	0.948
Relativistic γ	3.14
Synchrotron tune	1163^{-1}
Horizontal flying w. (SS68 at 422.8 m) β_x [m]	12.40
Vertical flying w. (SS64 at 397.7 m) β_y [m]	21.75

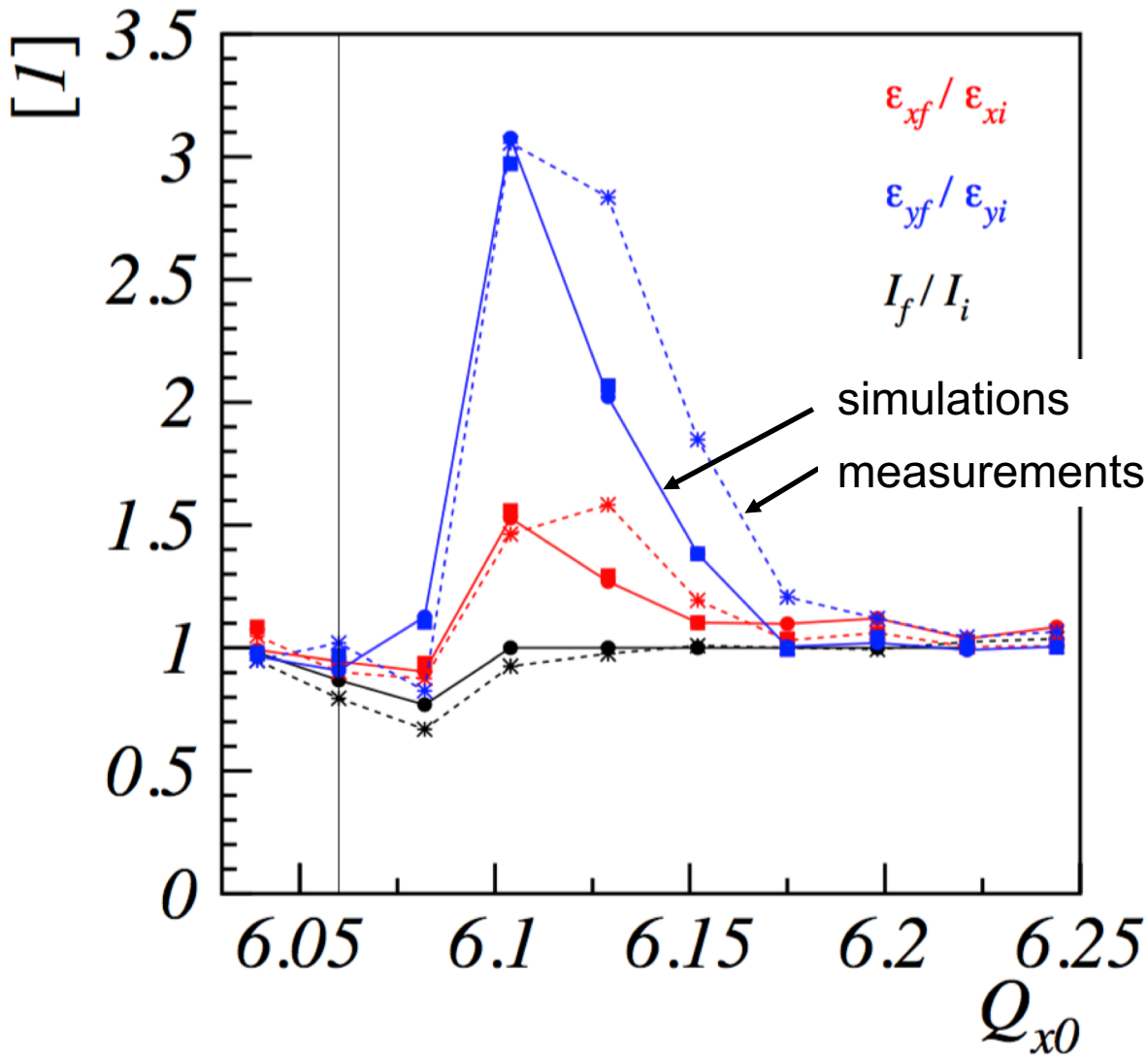
[a] The tune spread is calculated according to Ref. [18].

[b] $\xi_{x,y} = \frac{Q'_{x,y}}{Q_{x,y}} = \frac{\Delta Q_{x,y}/Q_{x,y}}{\Delta p/p}$

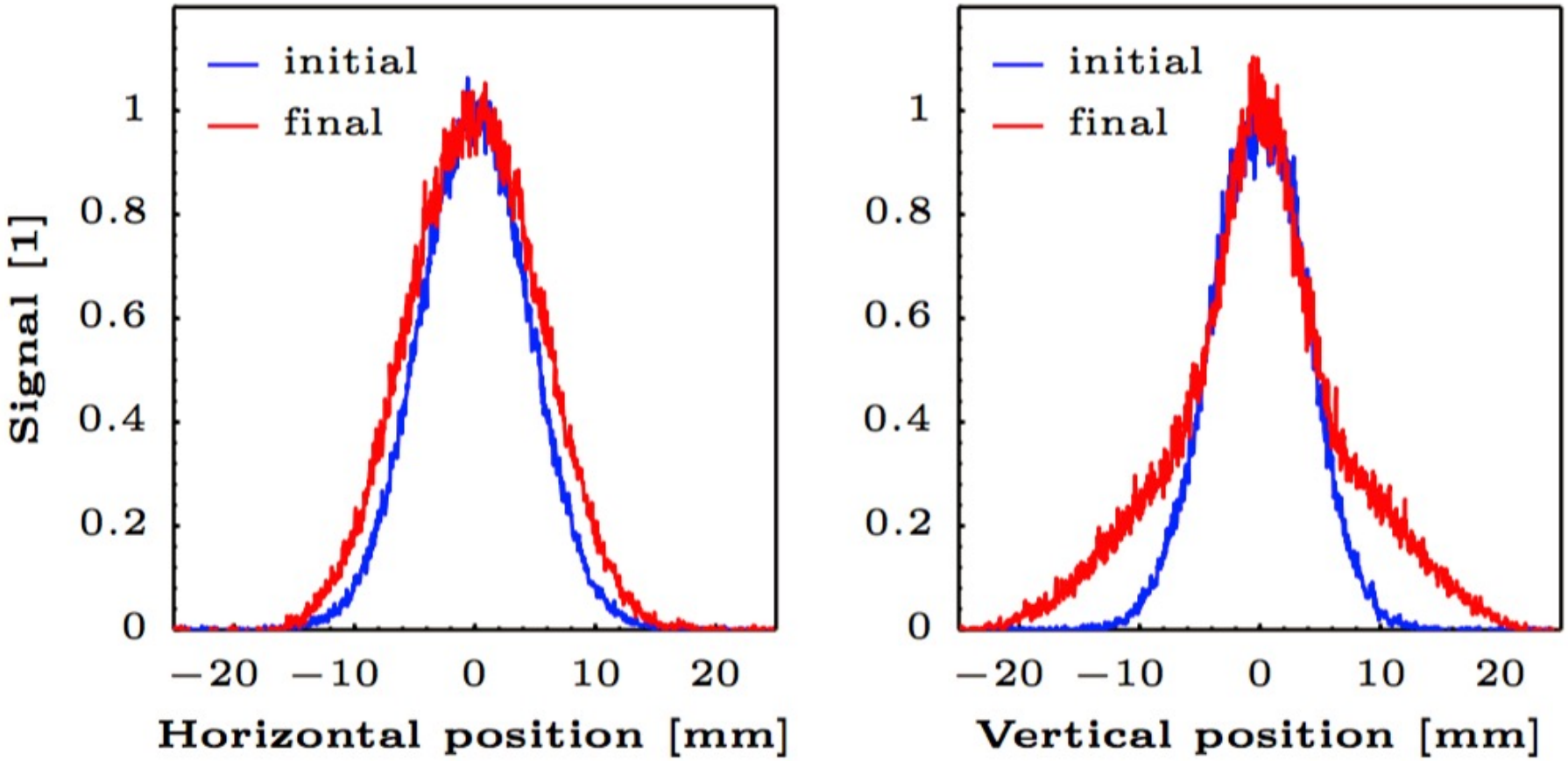
PS campaign results



Comparison with simulations

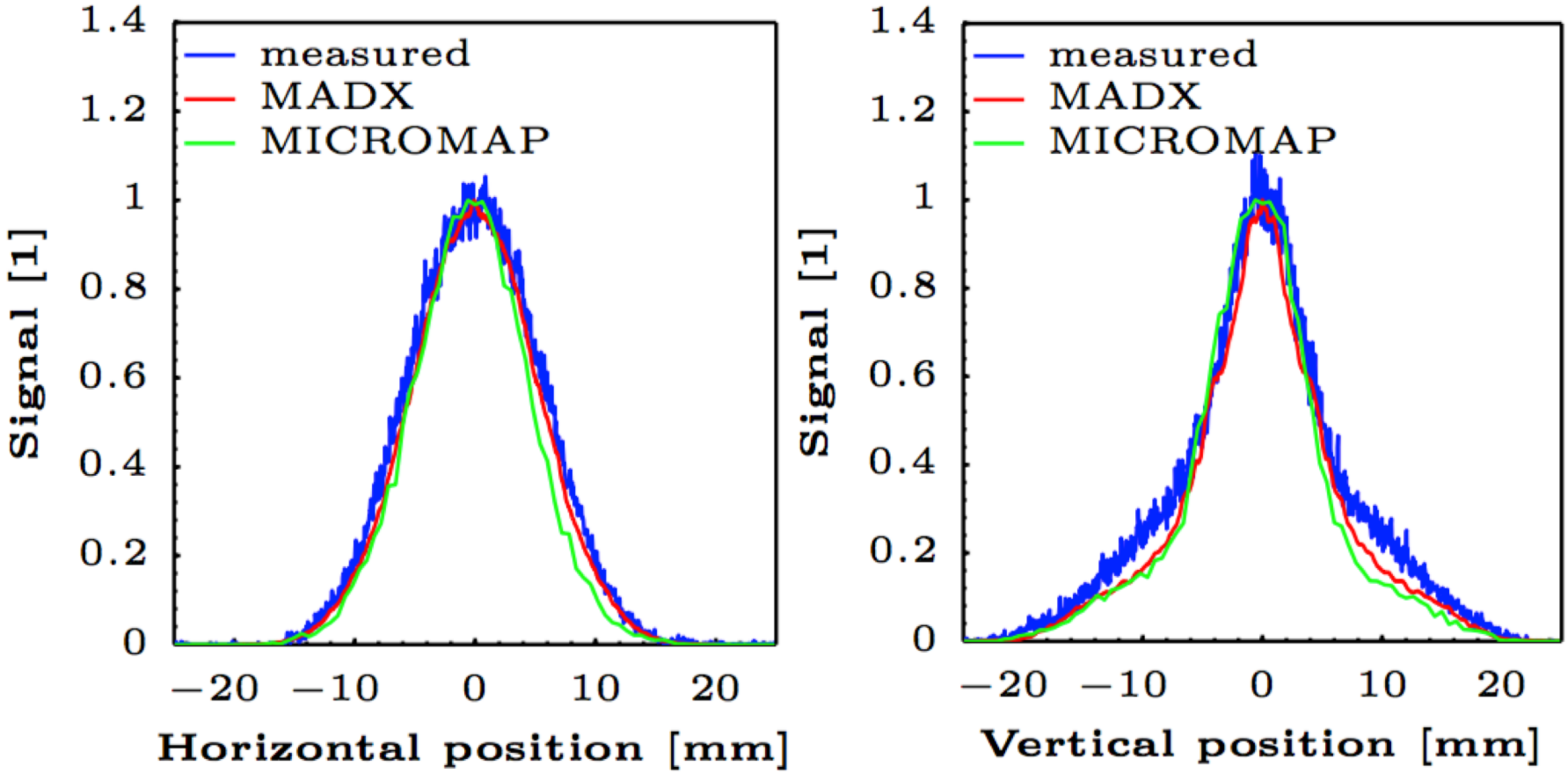


Beam Profiles for $Q_{x0} = 6.104$



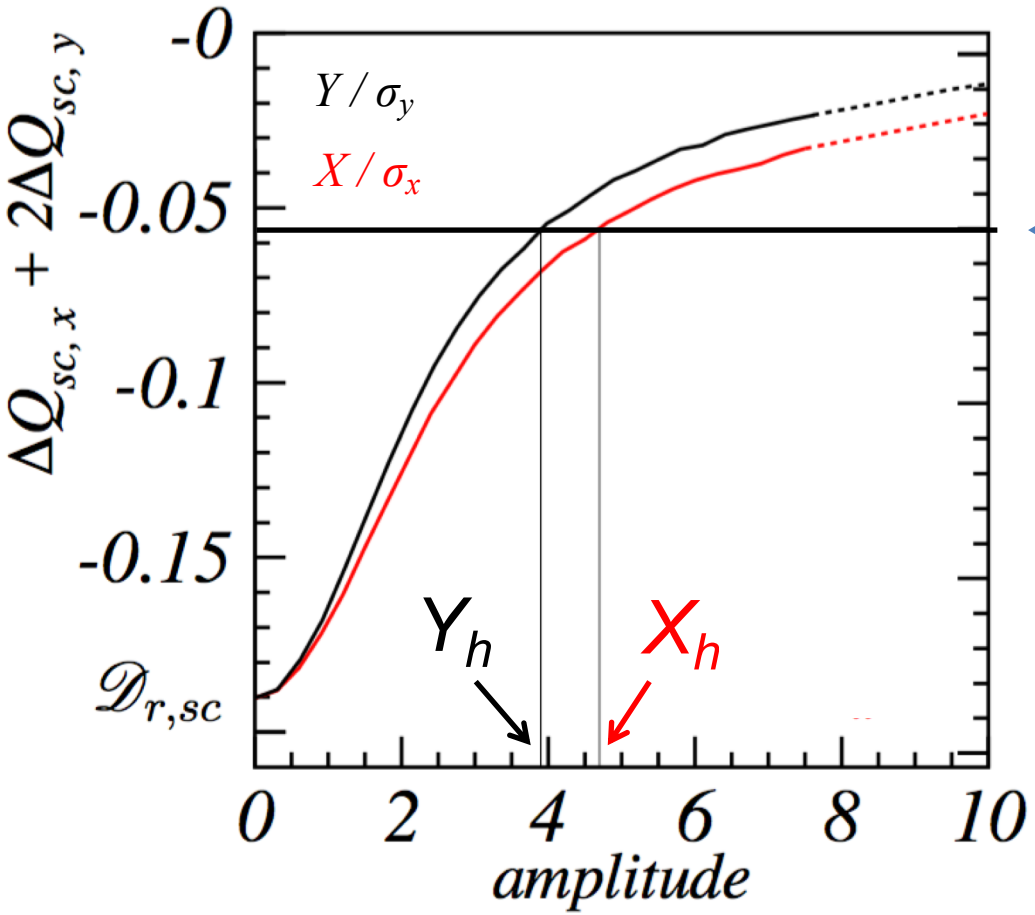
Experiment-Code
Beam Profile benchmarking

$$Q_{x0} = 6.104$$



Resonant particles: usual approach does not explain findings

$$\Delta_{r0} = Q_{x0} + 2Q_{y0} - 19 \quad \Rightarrow \quad \Delta_{r0} = 0.056$$



$$\Delta_{r0} = 0.056$$

"resonant detuning cancel Δ_{r0} and makes particle resonant"

The coupled dynamics on the resonance

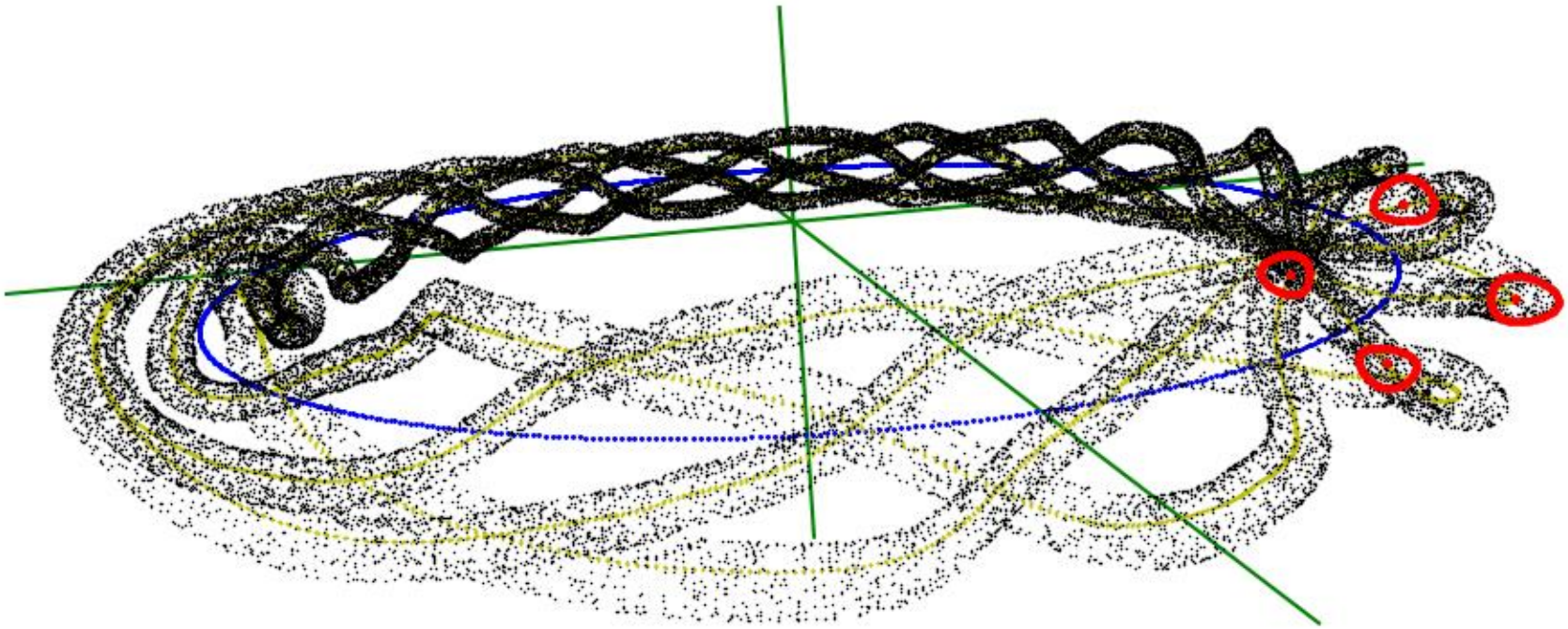
F. Schmidt PhD thesis, *and others*

G. Franchetti and F. Schmidt
Phys. Rev. Lett. **114**, 234801 (2015).

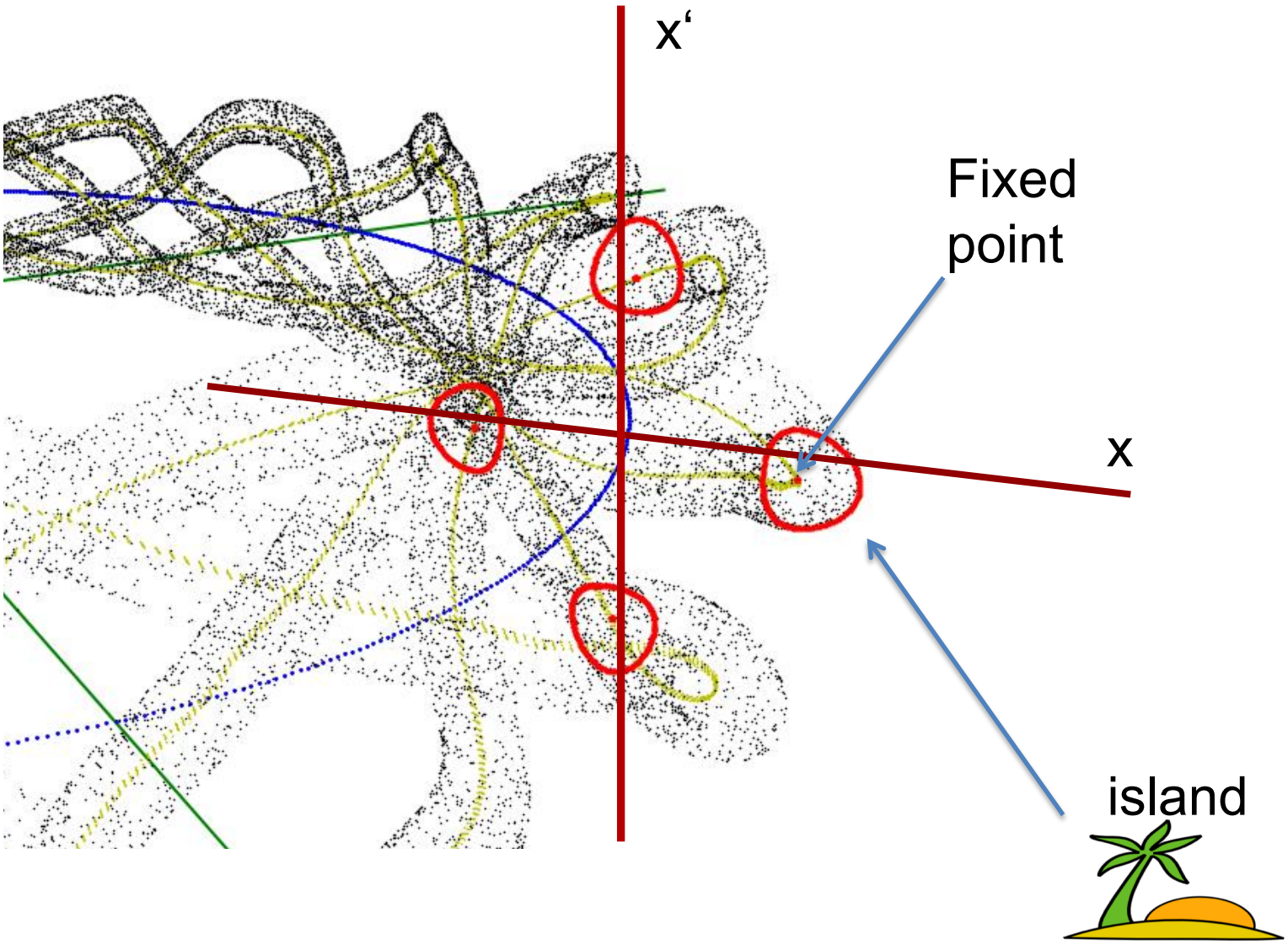
G. Franchetti and F. Schmidt
http://arxiv.org/abs/1504.04389

Fully coupled 4D dynamics

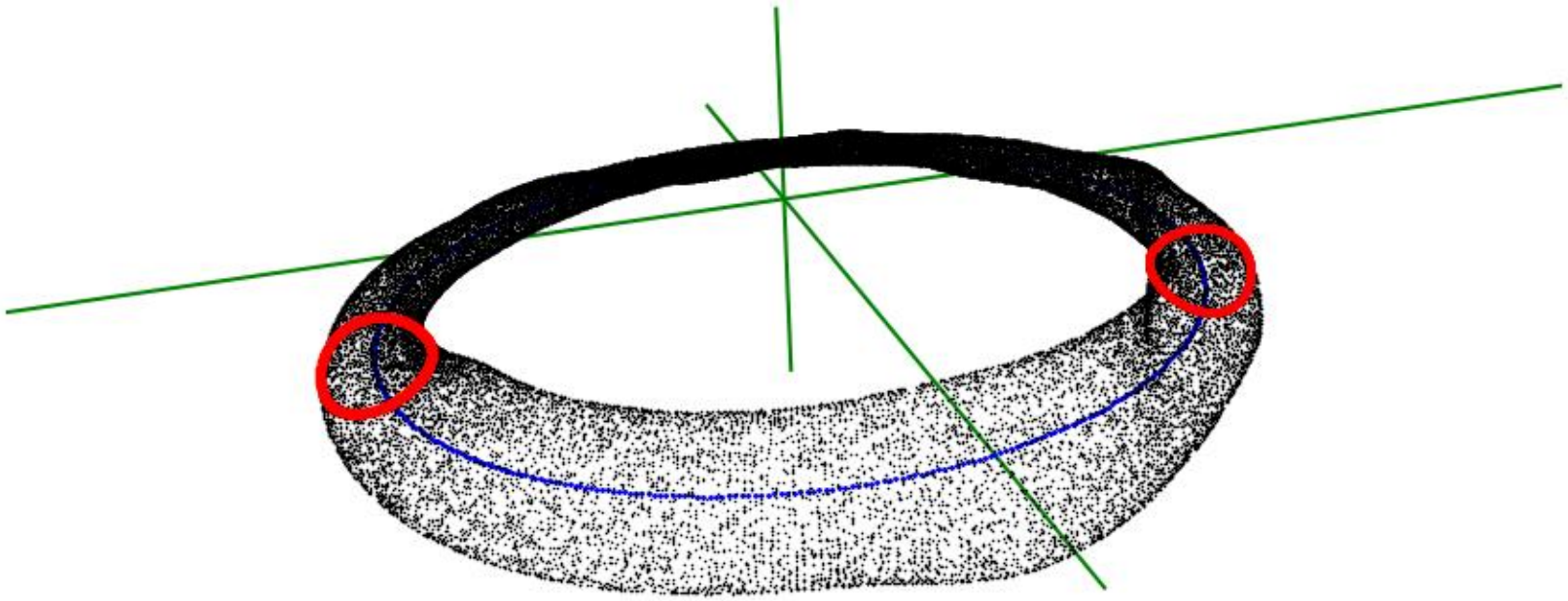
Fixed point: 1D resonance (x-px)



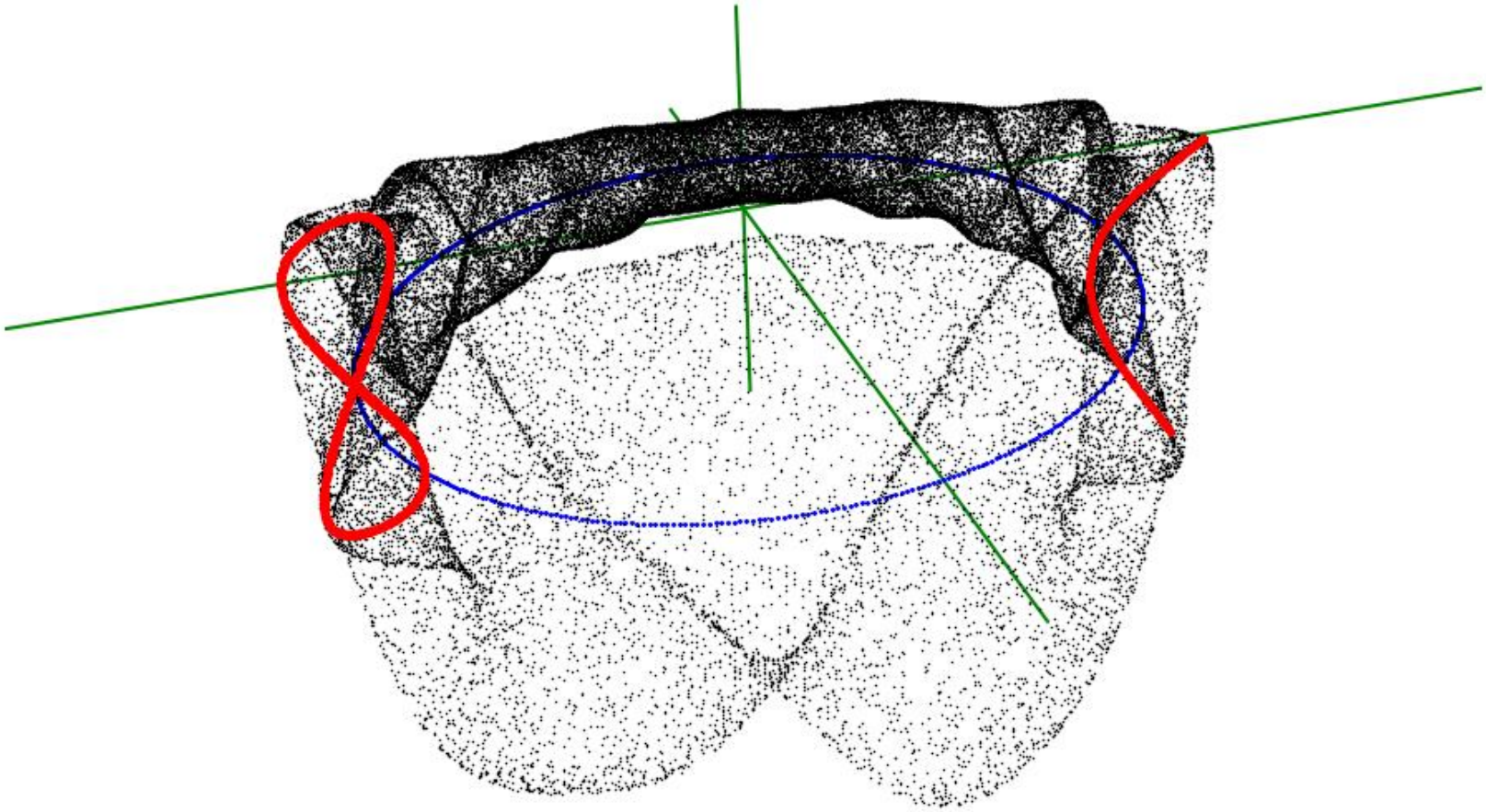
Poincare‘ section of the 1D resonance (stable)



Fixed line x-px

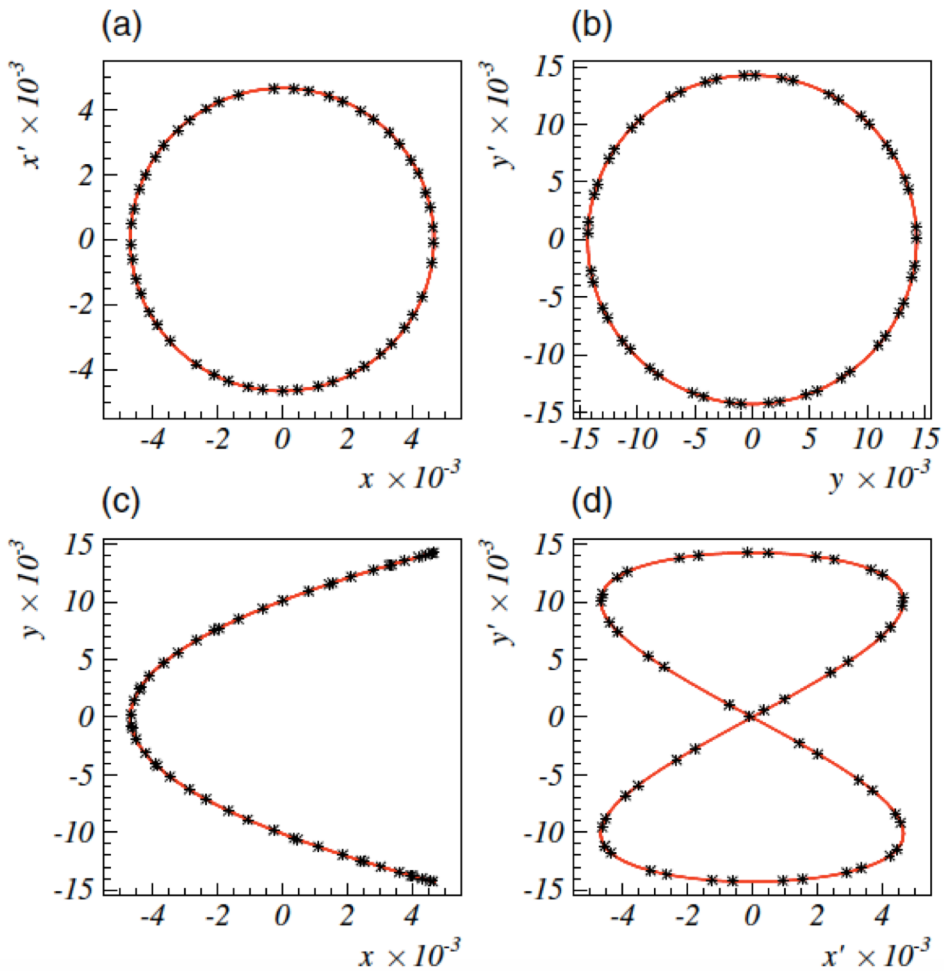


Fixed line x-y



Fixed lines in the physical space

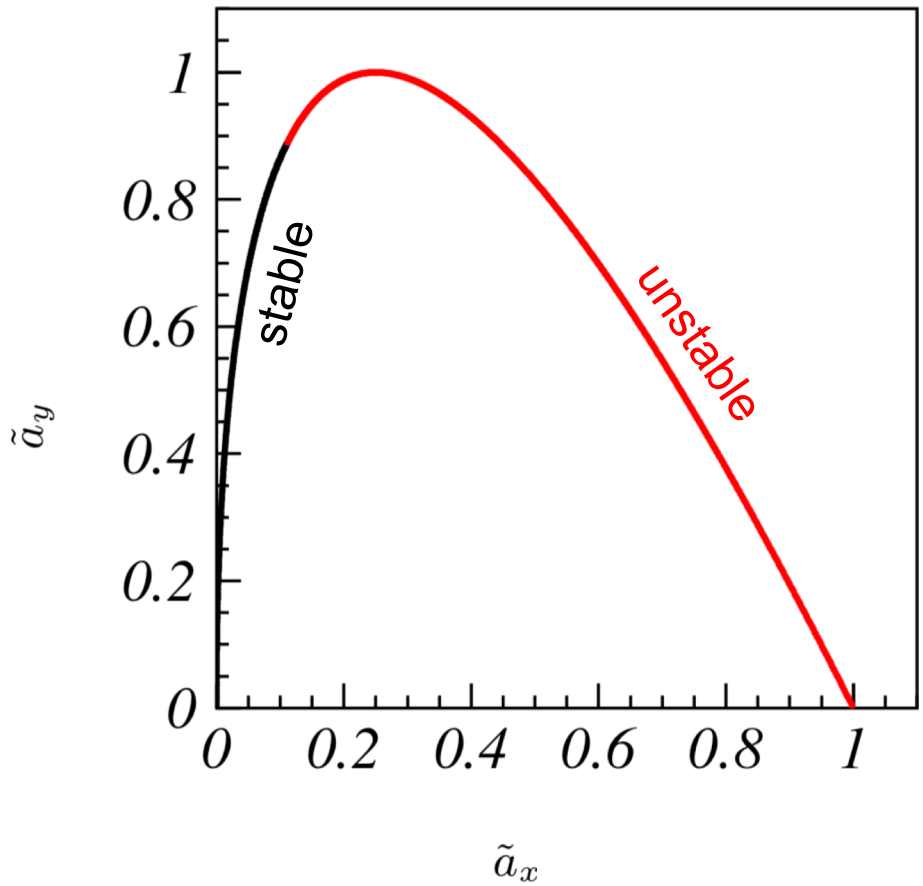
$$x(t) = \sqrt{\beta_x a_x}\cos(-2t + \pi M),$$
$$y(t) = \sqrt{\beta_y a_y}\cos(t),$$



G.Franchetti & F. Schmidt
Phys. Rev. Lett. **114**, 234801 (2015)

Infinite fixed lines

$Q_x + 2Q_y = m$



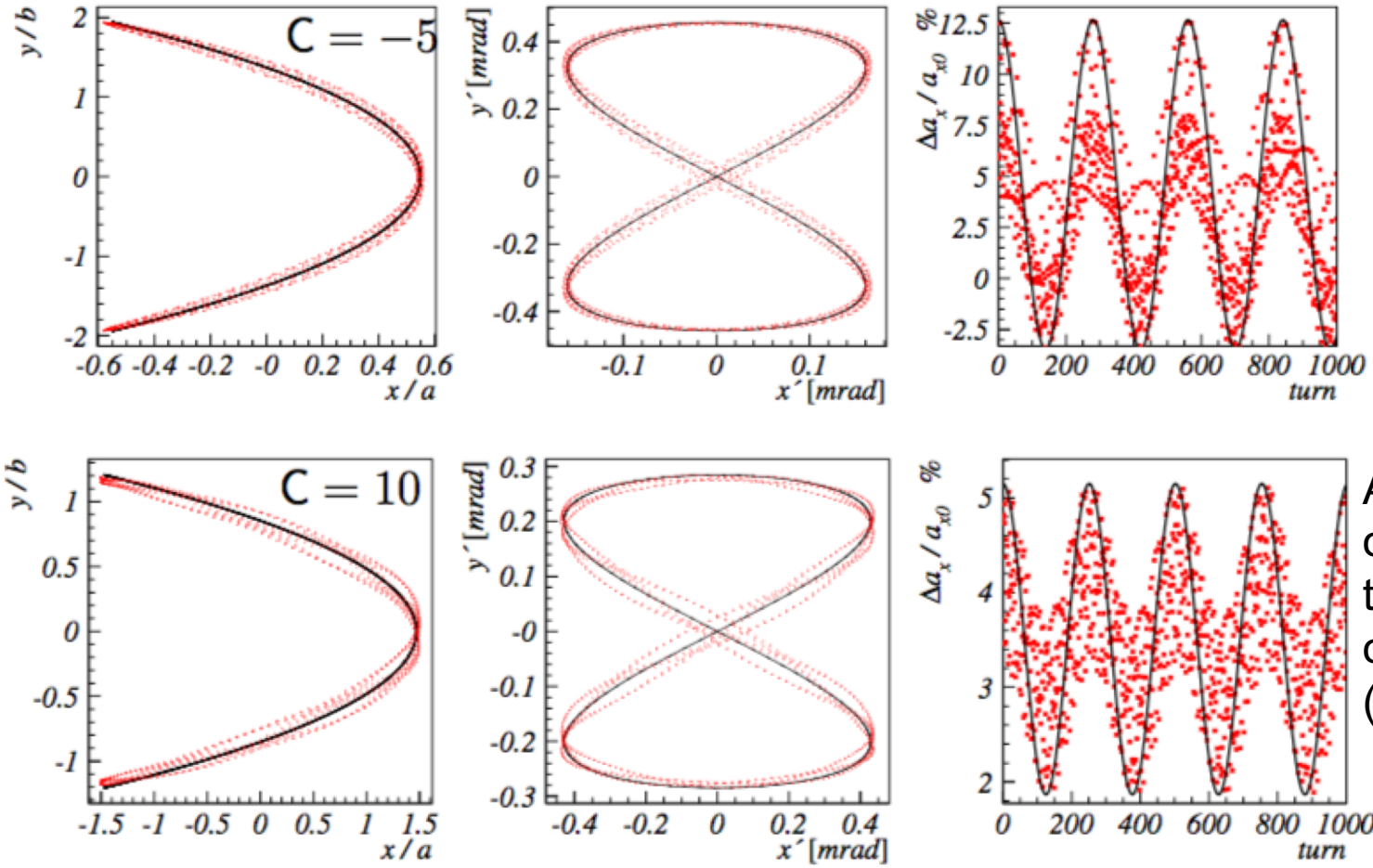
G. Franchetti and F. Schmidt
Phys. Rev. Lett. **114**, 234801 (2015).

$$\tilde{a}_y = \frac{(2\pi\Delta_r)^2}{4\Lambda^2 L^2}\tau(1-\tau)$$

$$\tilde{a}_x = \frac{(2\pi\Delta_r)^2}{16\Lambda^2 L^2}(1-\tau)^2$$

$$0 \leq \tau \leq 1$$

Fixed lines with space charge



PS-Exp. parameters

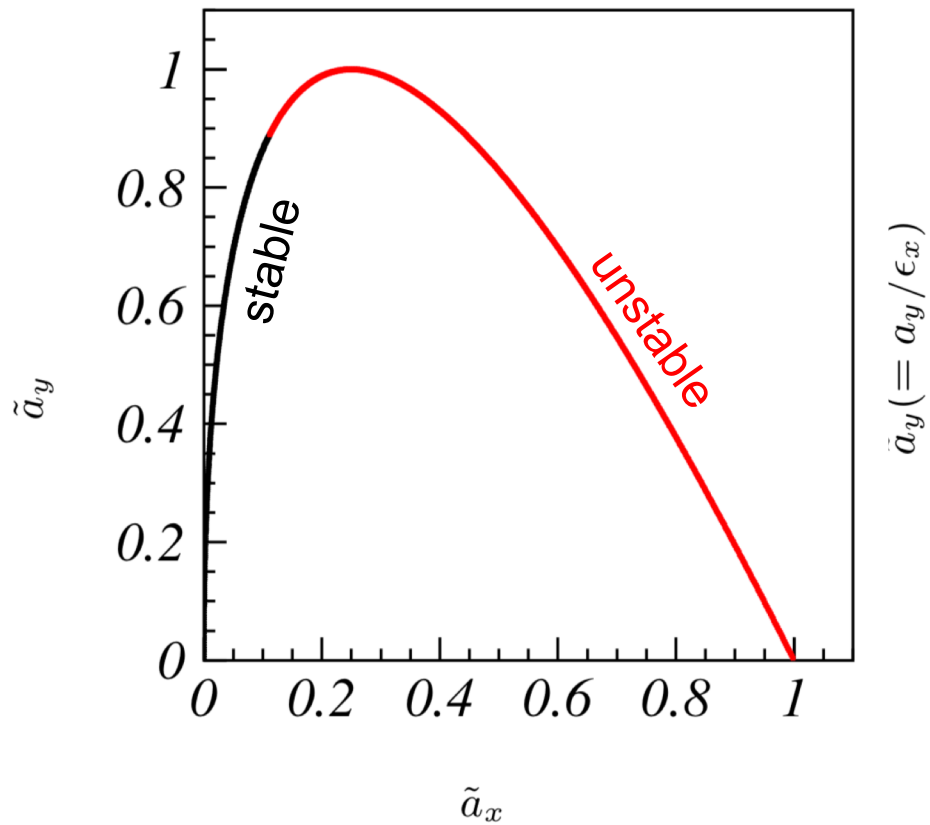
Qx + 2Qy = 19

DQx = -0.05

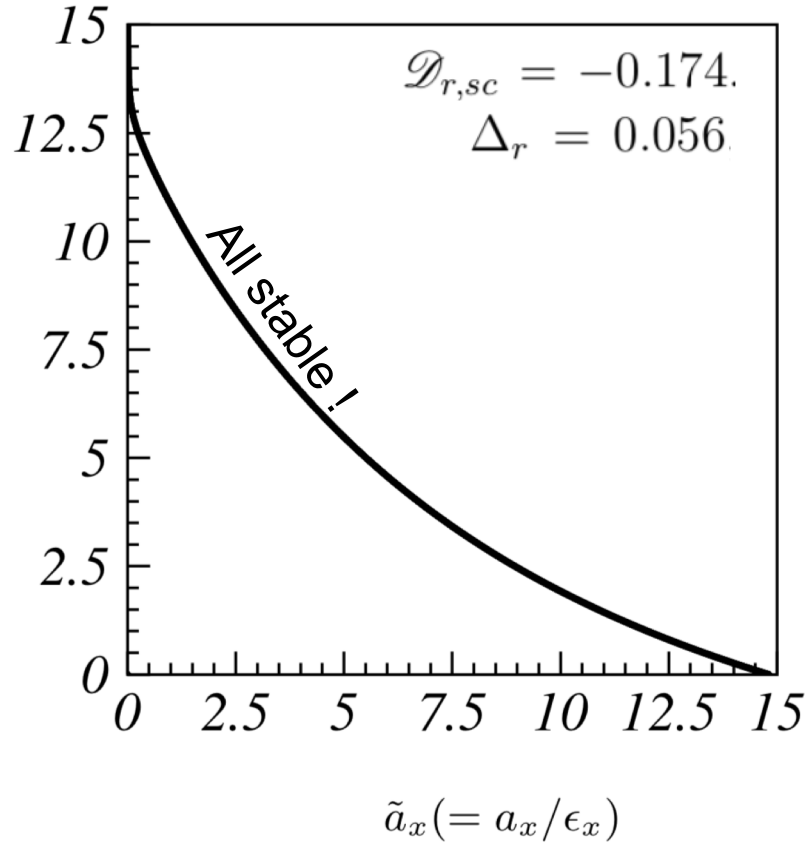
Analytic prediction of the secondary tunes for resonances of any orders … (hence the stability)

Effect of space charge on the "infinite" fixed lines: third order resonance

Pure $Q_x+2Q_y=19$. No space charge, no additional detuning

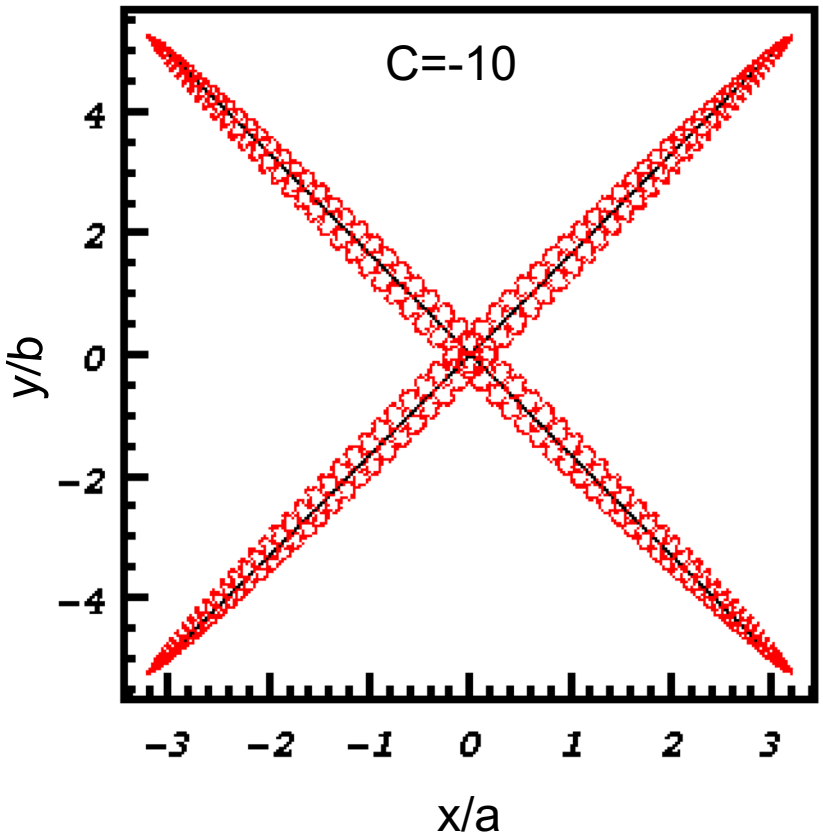


Collection of fixed-lines $Q_x+2Q_y=19$ in presence of space charge

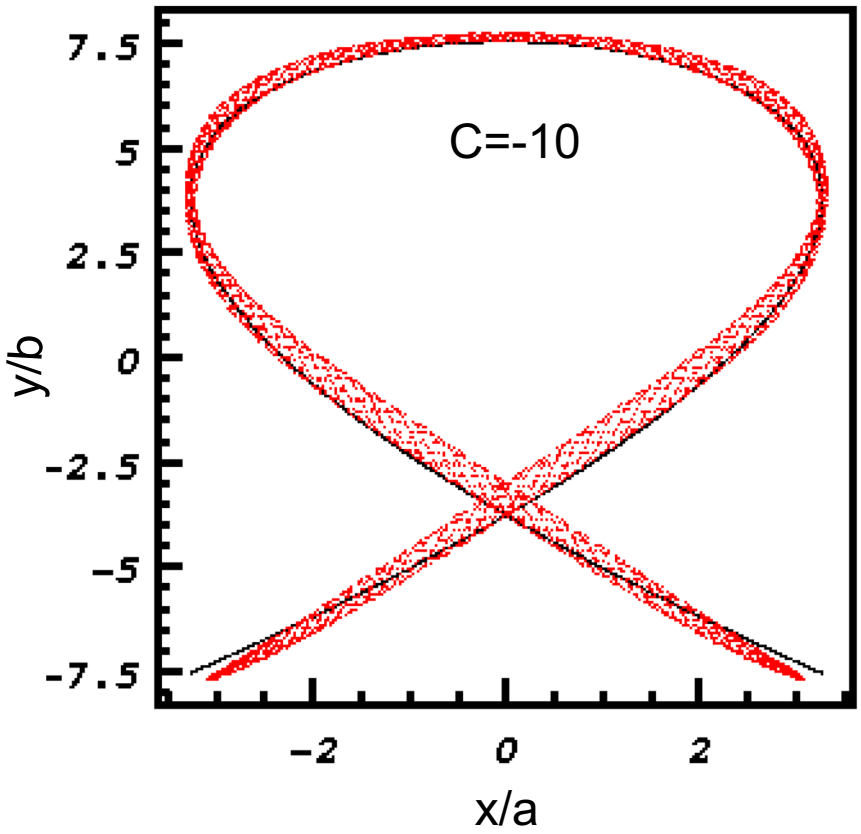


With higher order resonances, fixed lines and space charge

2 Qx + 2 Qy = 19 (normal)

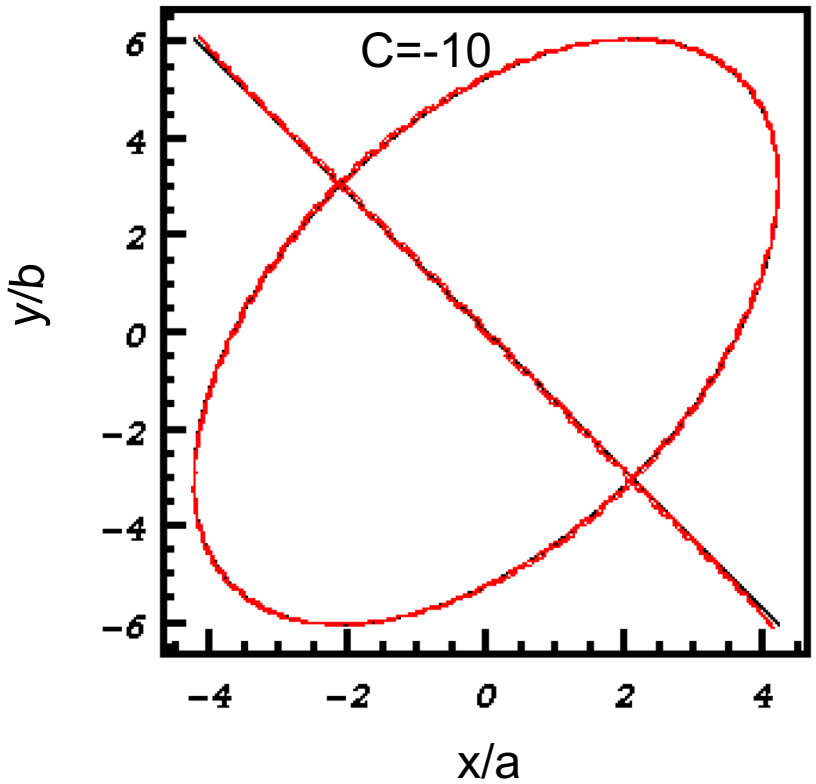


3 Qx + 2 Qy = 19 (skew)

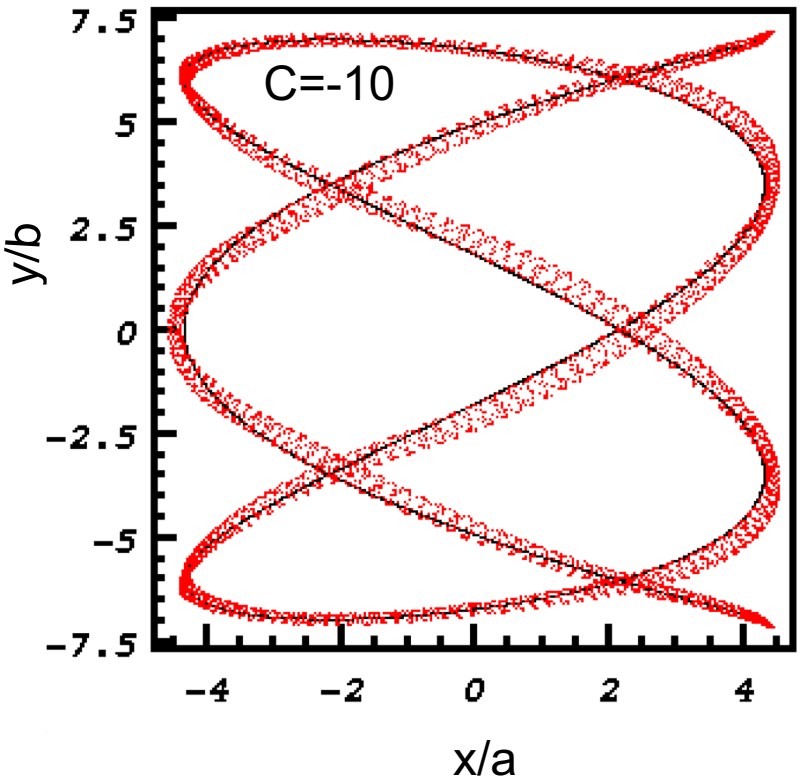


With higher order resonances, fixed lines and space charge

3 Qx + 3 Qy = 29 (skew)



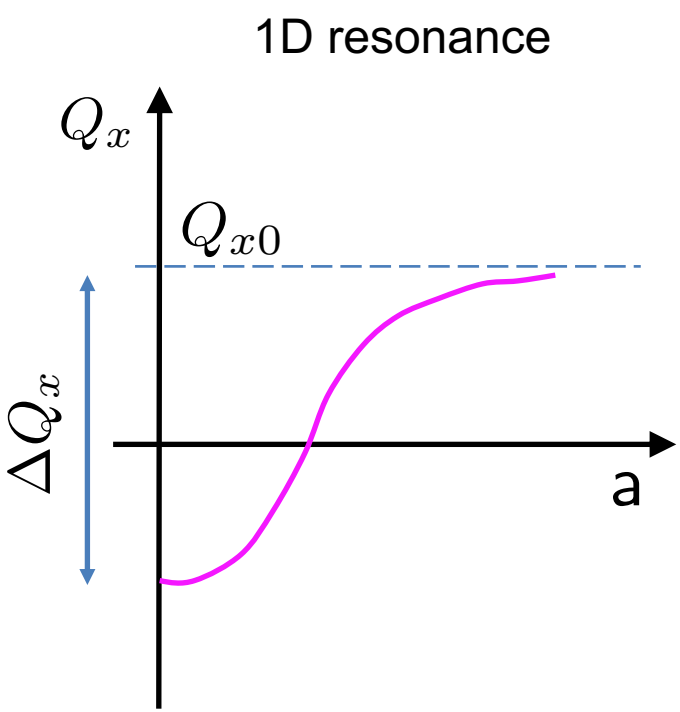
3 Qx + 6 Qy = 49 (normal)

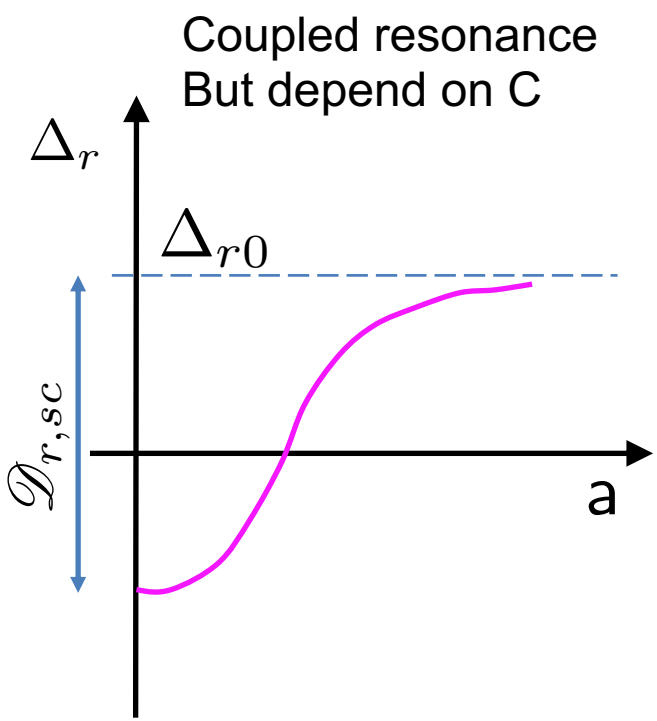


Similarity with 1D resonances

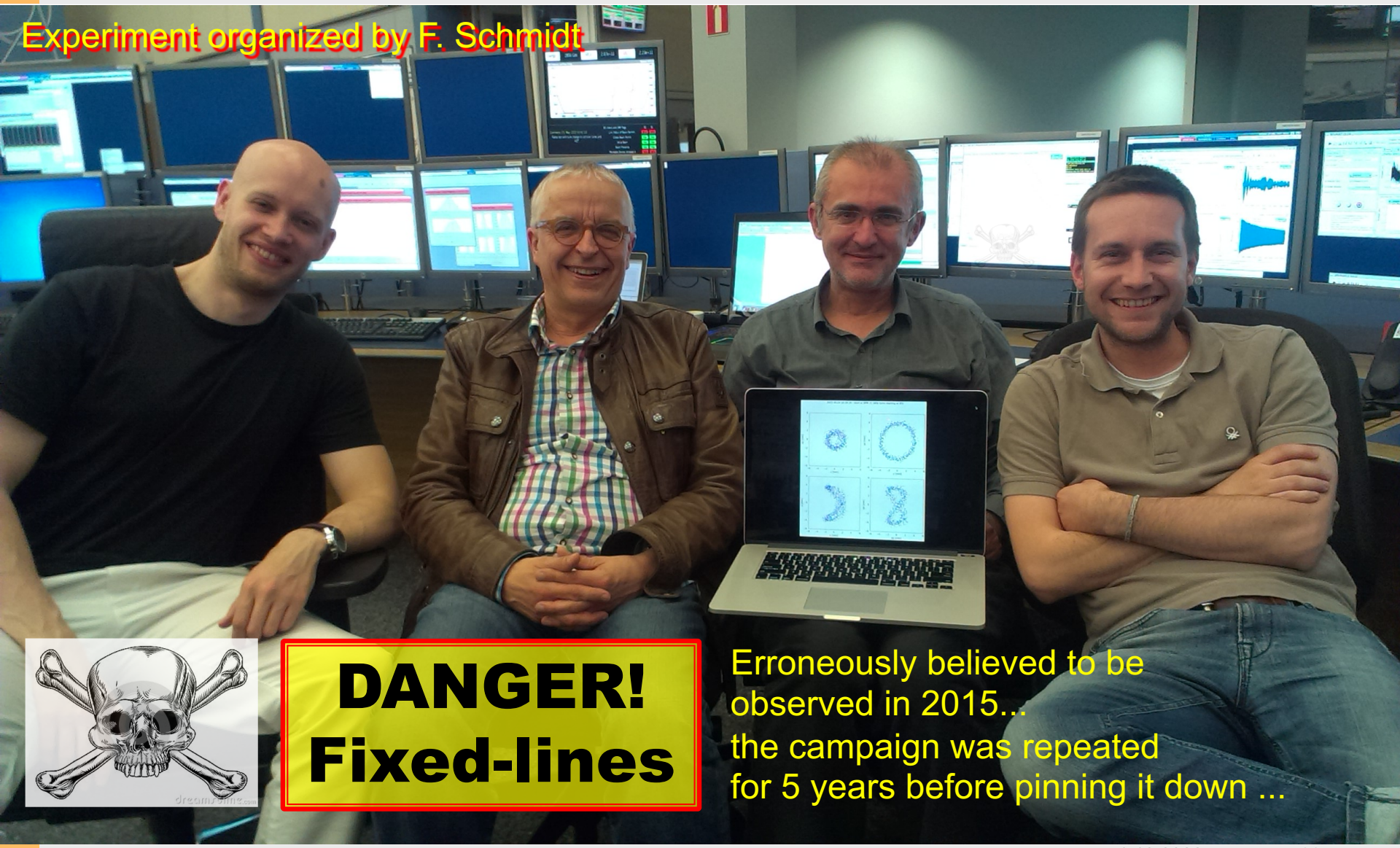
This term is an “amplitude dependent *resonance detuning*”

$$\Delta_r = \Delta_{r0} + \mathscr{D}_{r,sc} N_x \frac{d\mathcal{V}_{sc}}{d\mathsf{a}}$$



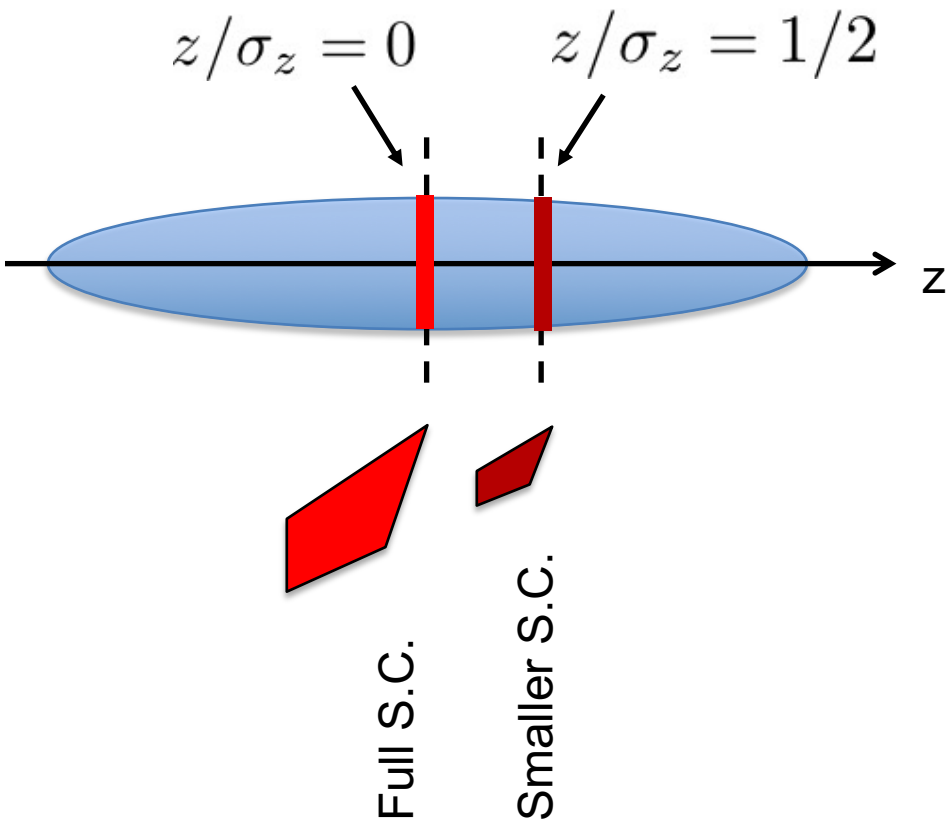


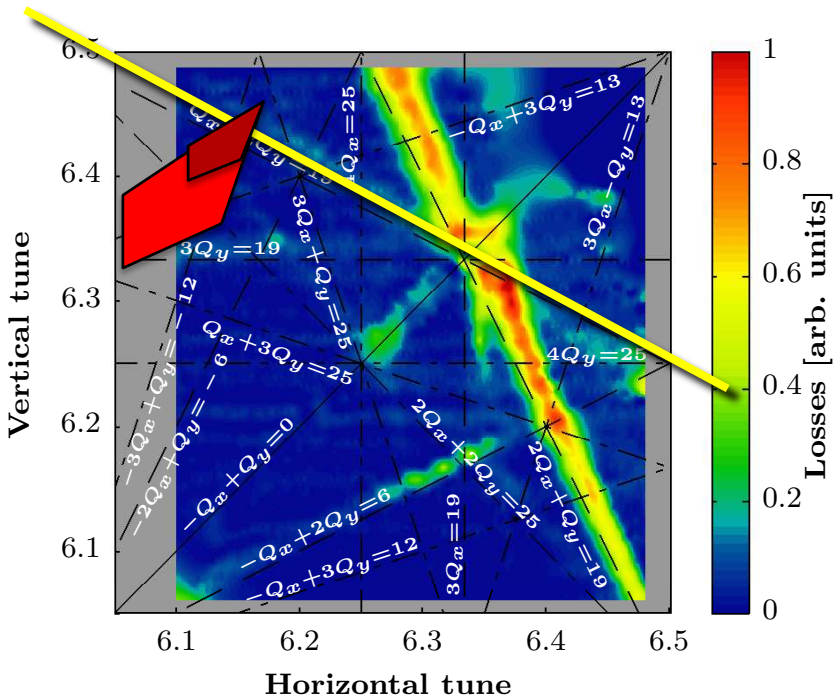
SPS campaign on May 2015



Does fixed-lines play a role with space charge?

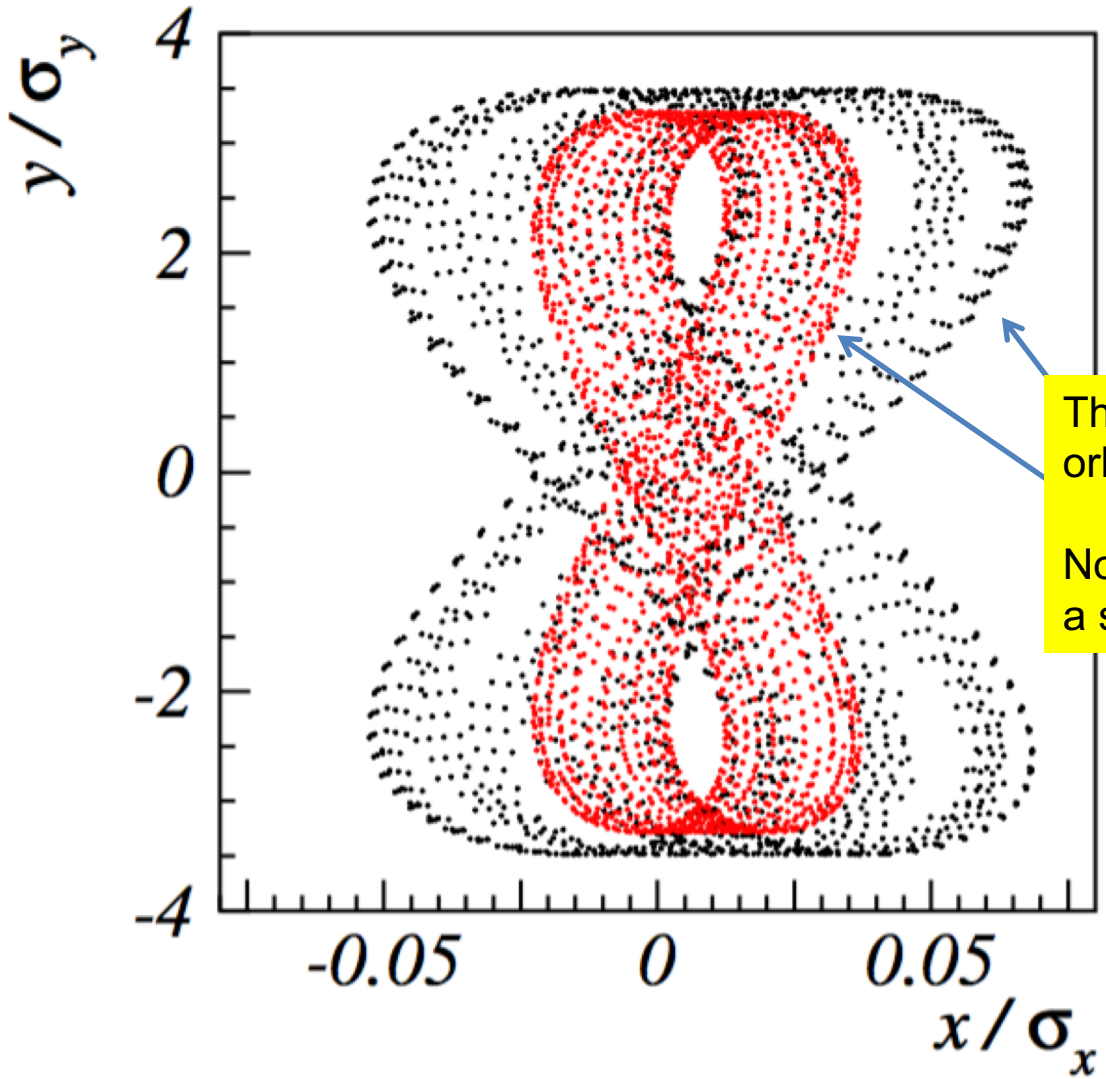
longitudinal motion is kept frozen, so to retrieve Poincare' section orbits





Largest resonant orbits at $z/\sigma_z = 0$

No chromaticity

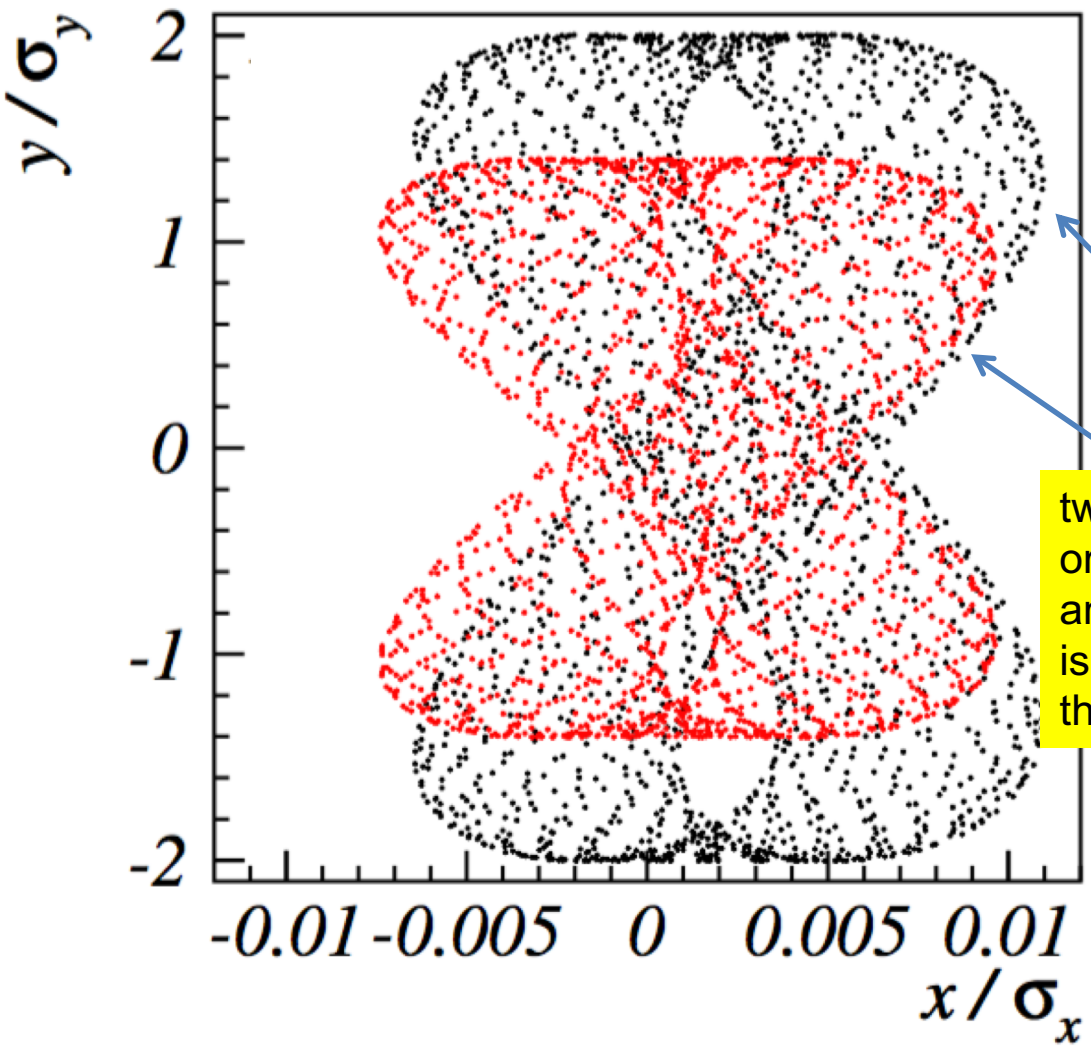


The two larger resonant orbits…

No doubt they have a structure of fixed-lines

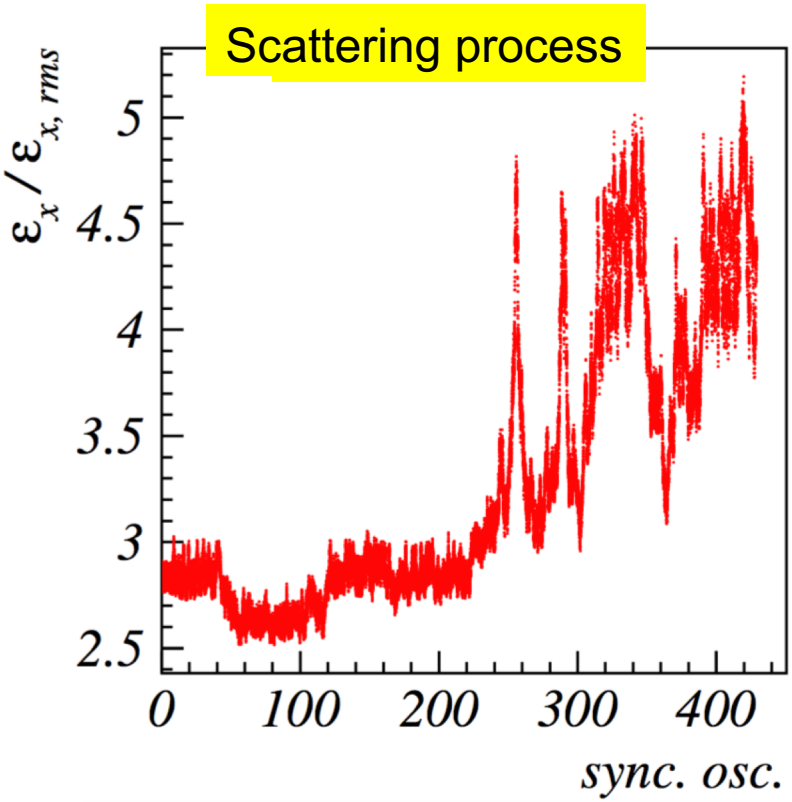
Largest resonant orbits at $z/\sigma_z = 1/2$

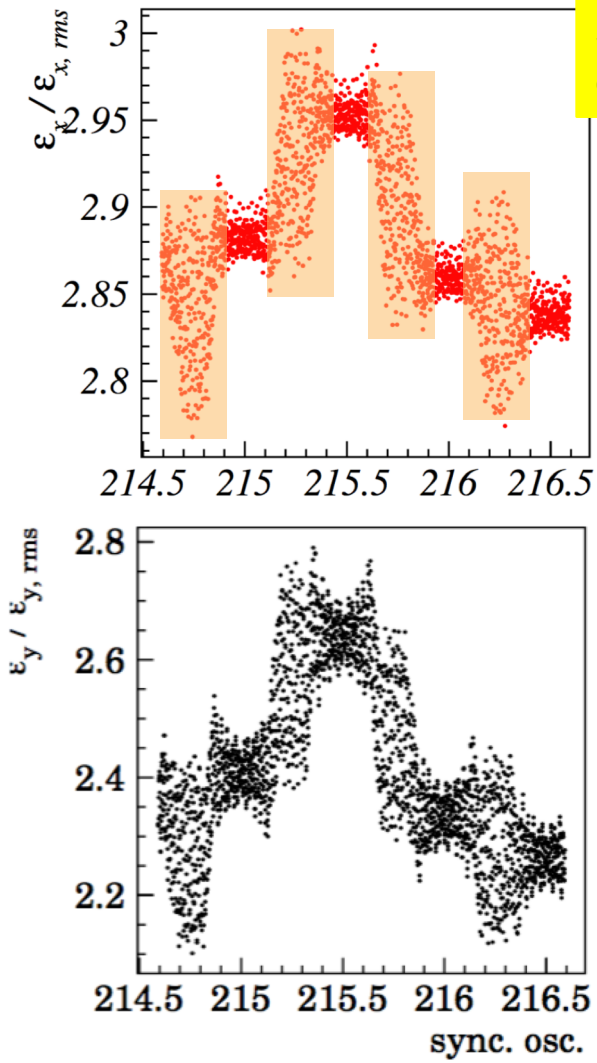
No chromaticity



two larger resonant orbits: now the amplitude of the orbits is smaller, but still have the structure of fixed-lines

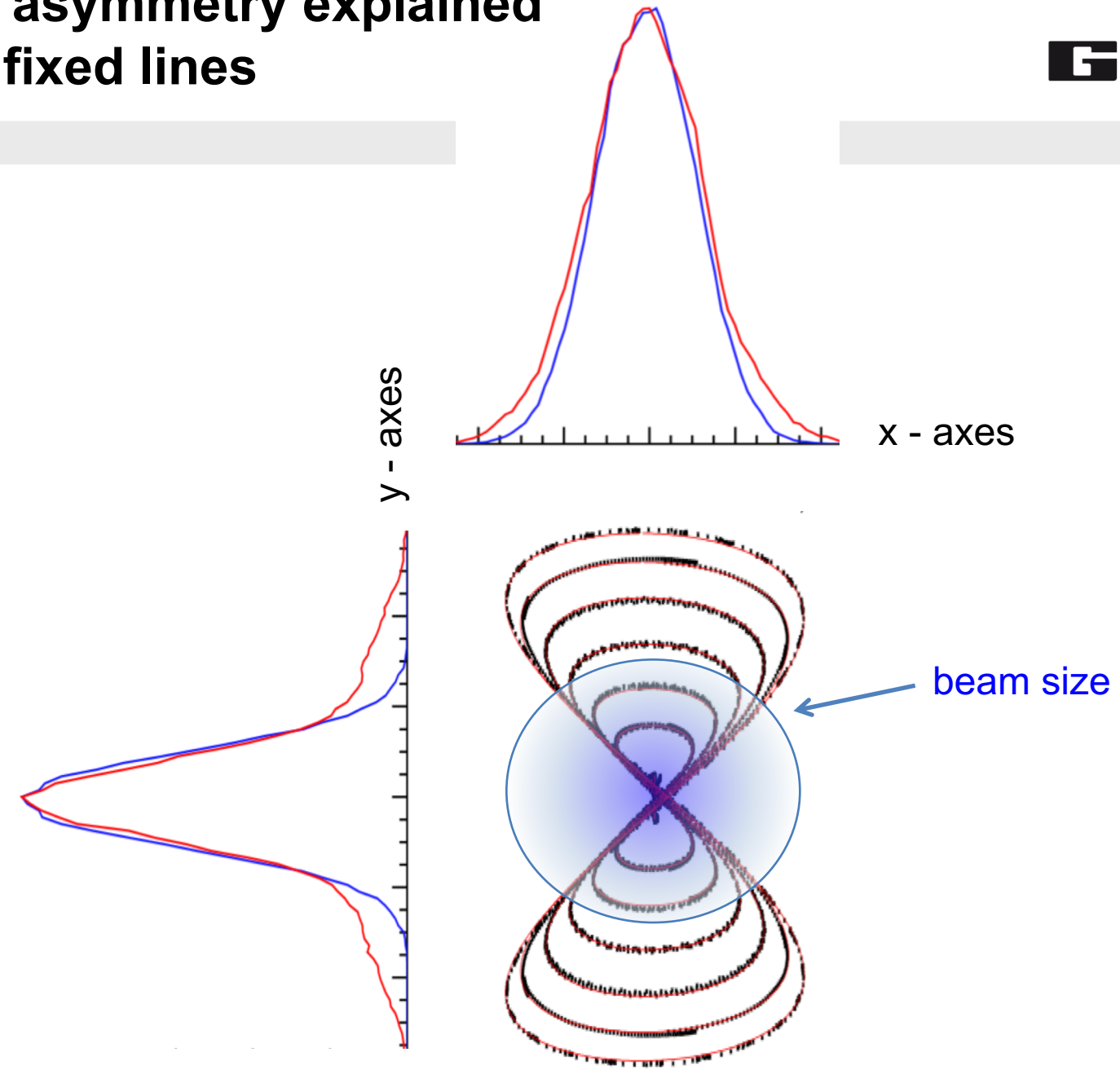
Periodic crossing of fixed-lines





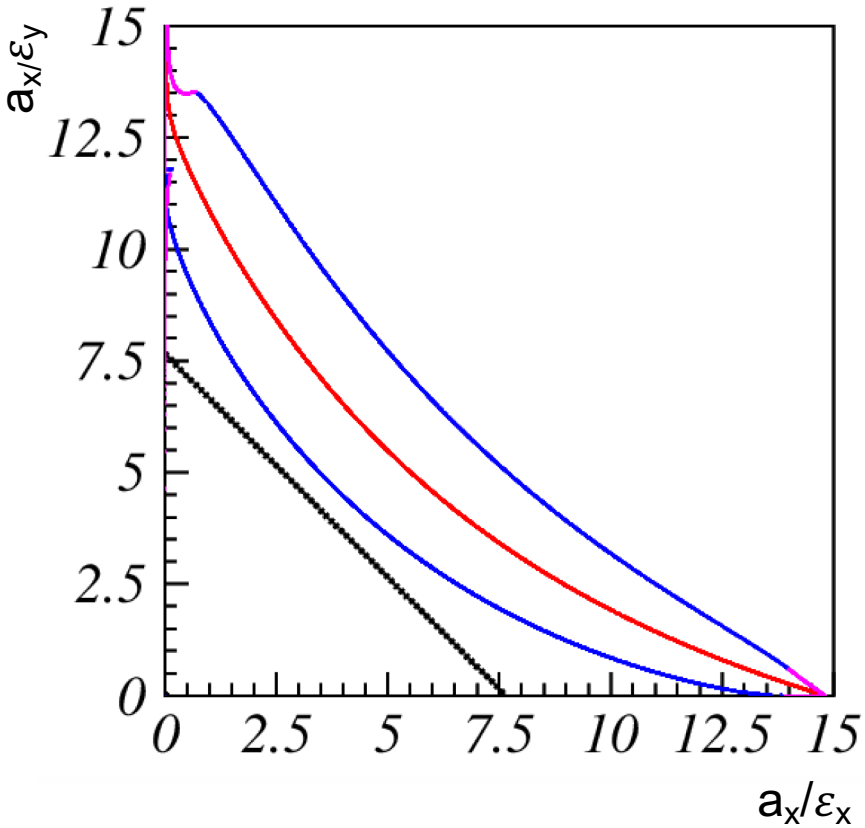
Giuliano Franchetti, Simone Gilardoni, Alexander Huschauer, Frank Schmidt, Raymond Wasef Phys. Rev. Accel. Beams **20**, 081006 (2017).

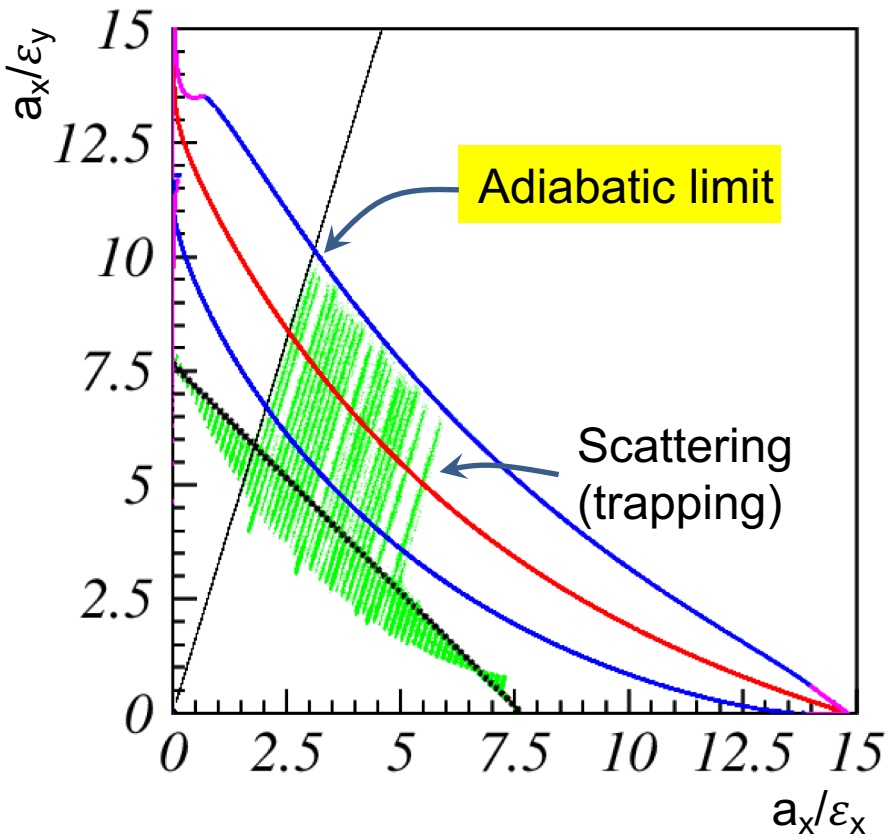
Halo asymmetry explained with fixed lines



Periodic “fixed lines” crossing, alias periodic resonance crossing

$Q_x + 2Q_y = 19$ $\quad Q_x = 6.104 \quad \Delta_r = 0.056 \quad \Delta Q_x = -0.05 \quad \mathscr{D}_{r,sc} = -0.174.$

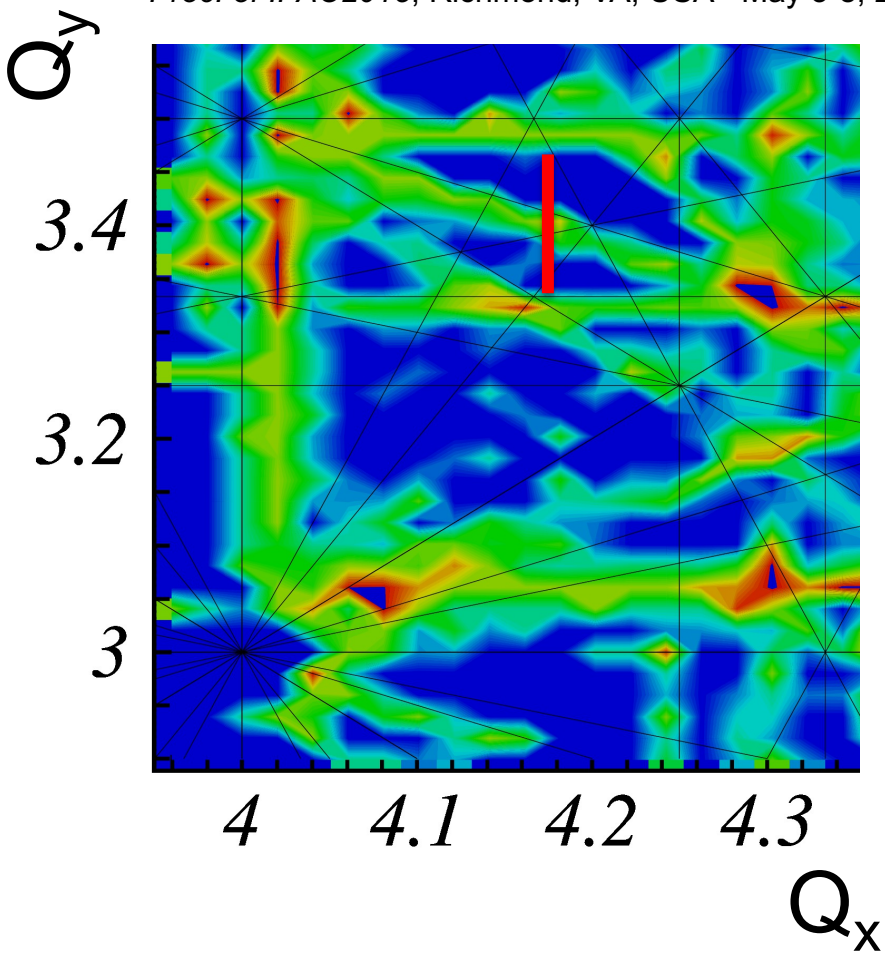


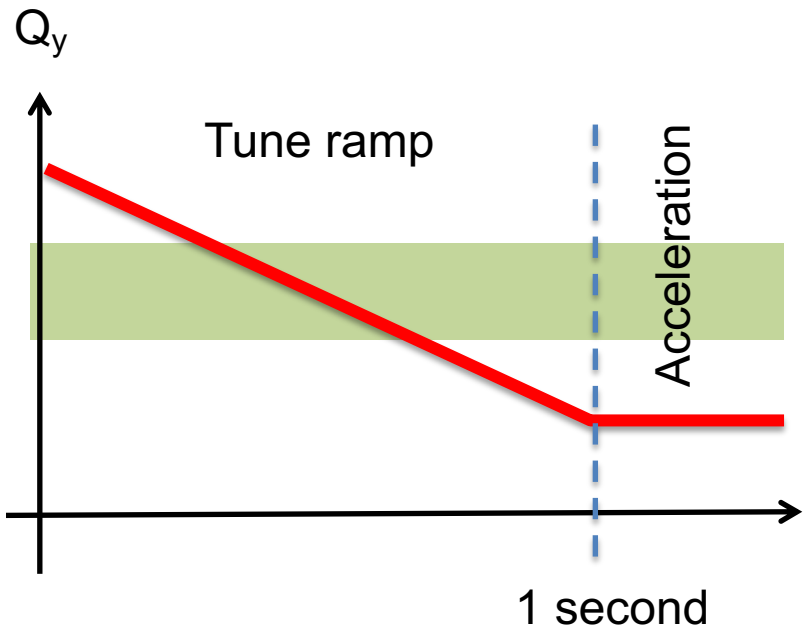


Resonance compensation and SC

G. Franchetti, S. Aumon, F. Kesting, H. Liebermann, C. Omet, D. Ondreka, R. Singh
Proc. of IPAC2015, Richmond, VA, USA - May 3-8, 2015, MOPJE073, MOPWA028, p. 159

2015



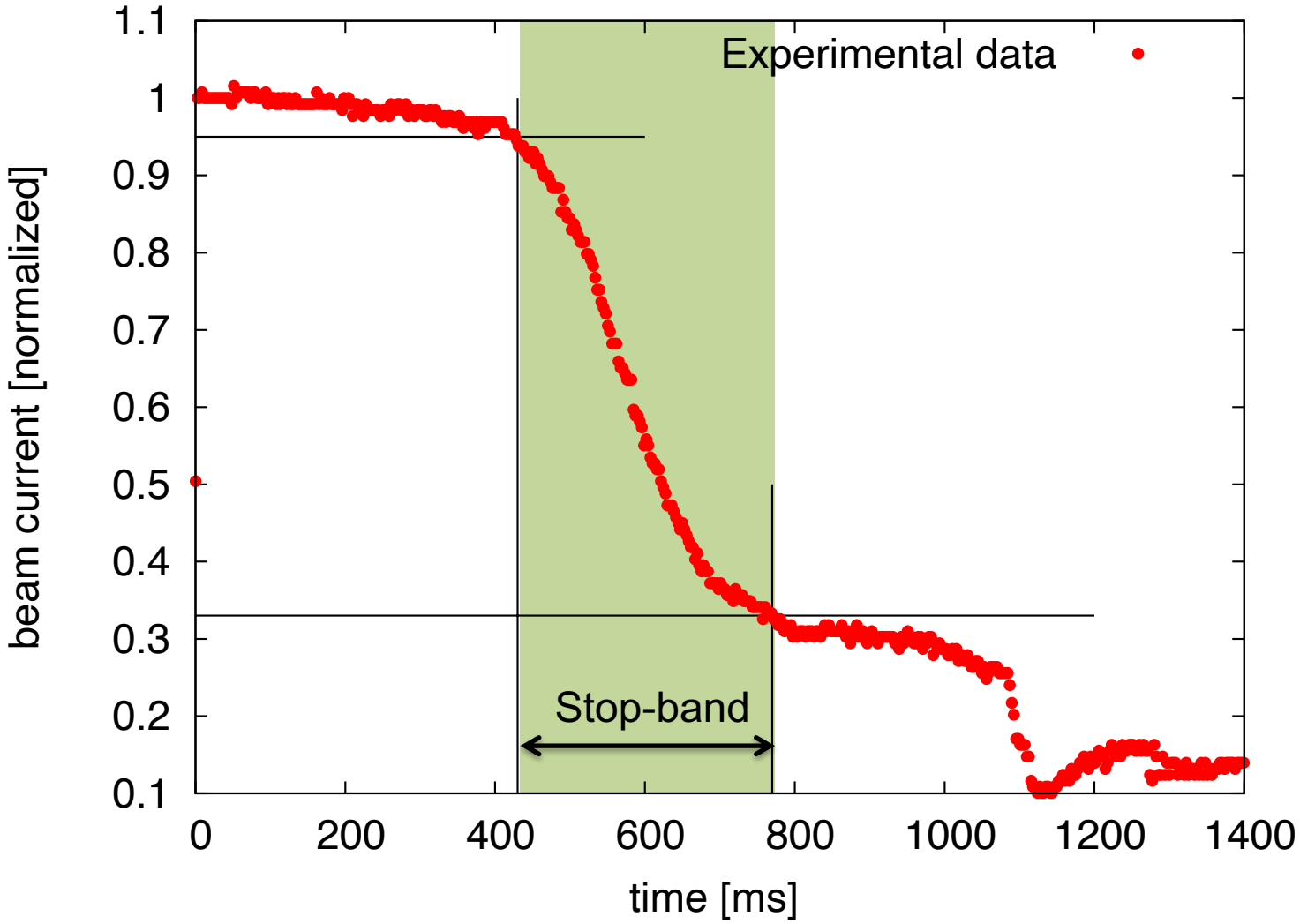


Q_x = 4.2 kept always constant

Beam always coasting

Intensity low

The resonance $Q_x + 2Q_y = 11$



Driving term and beam loss

The pair

$$(\Lambda, \alpha)$$

one pair of sextupoles

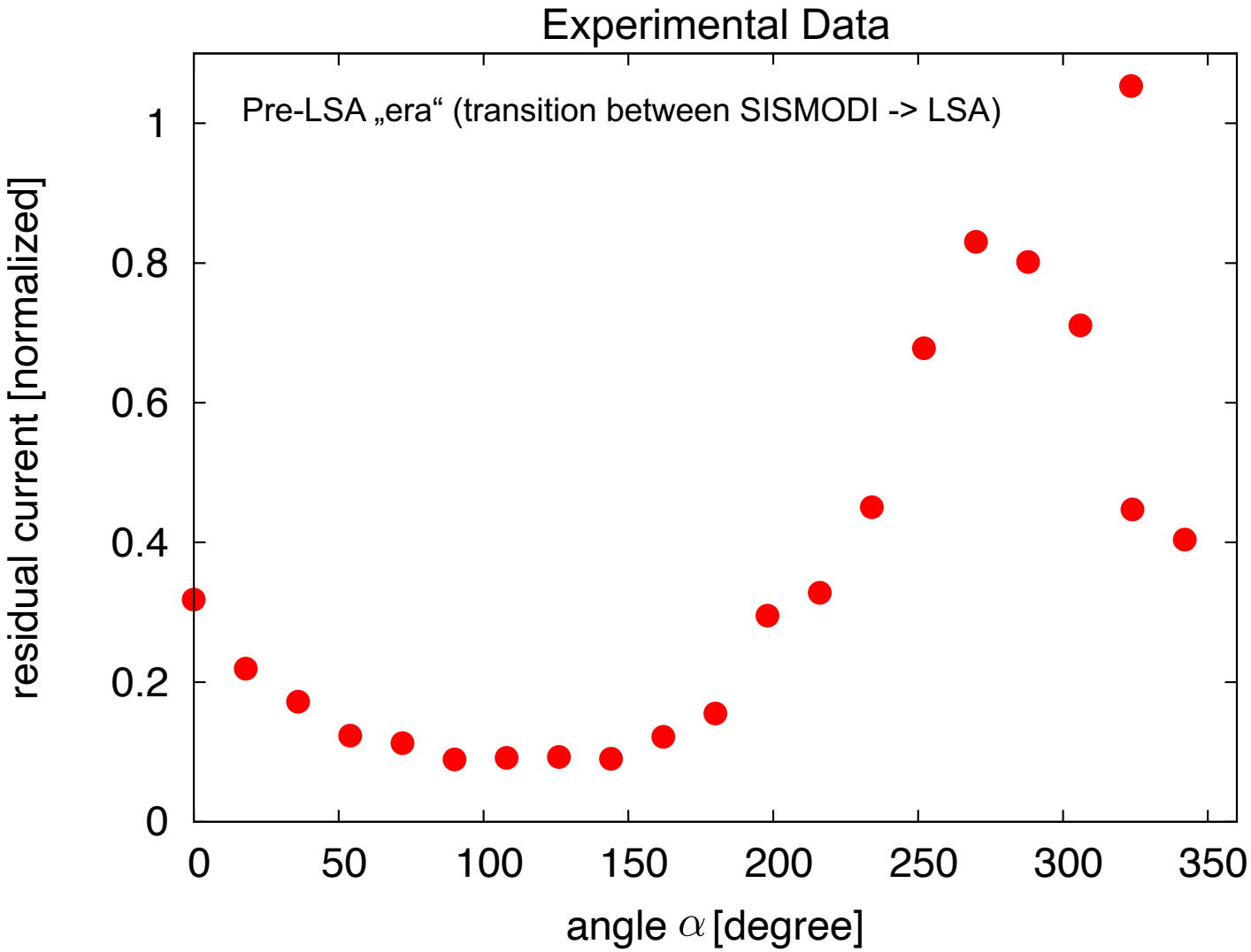
$$(K_{2,1}, K_{2,2})$$

Effective driving term

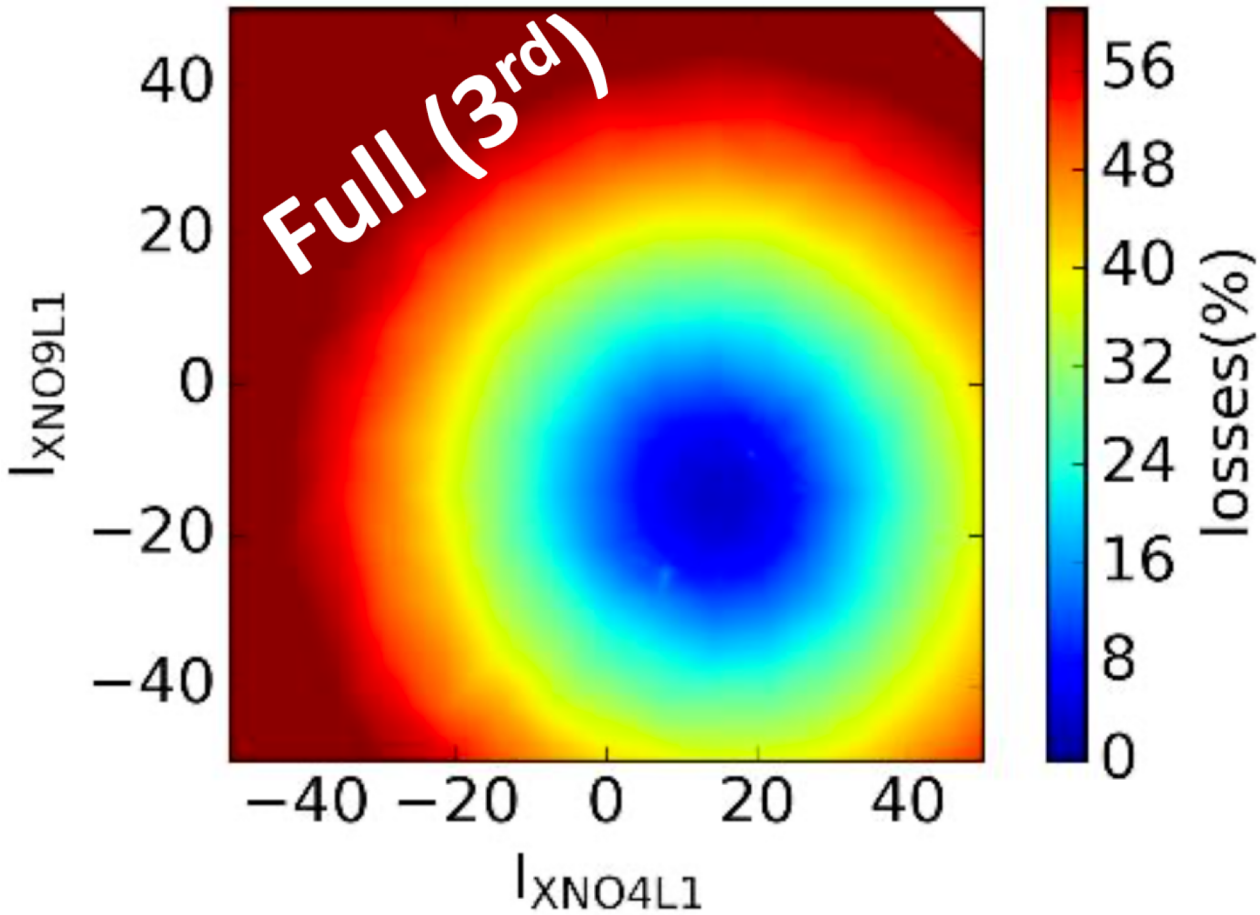
$$\Lambda_{eff}^2 = \Lambda^2 + \Lambda_e^2 - 2\Lambda\Lambda_e \cos(\alpha - \alpha_e)$$

Reduction/cancellation of Λ_{eff} is equivalent reducing beam loss in the resonance crossing process

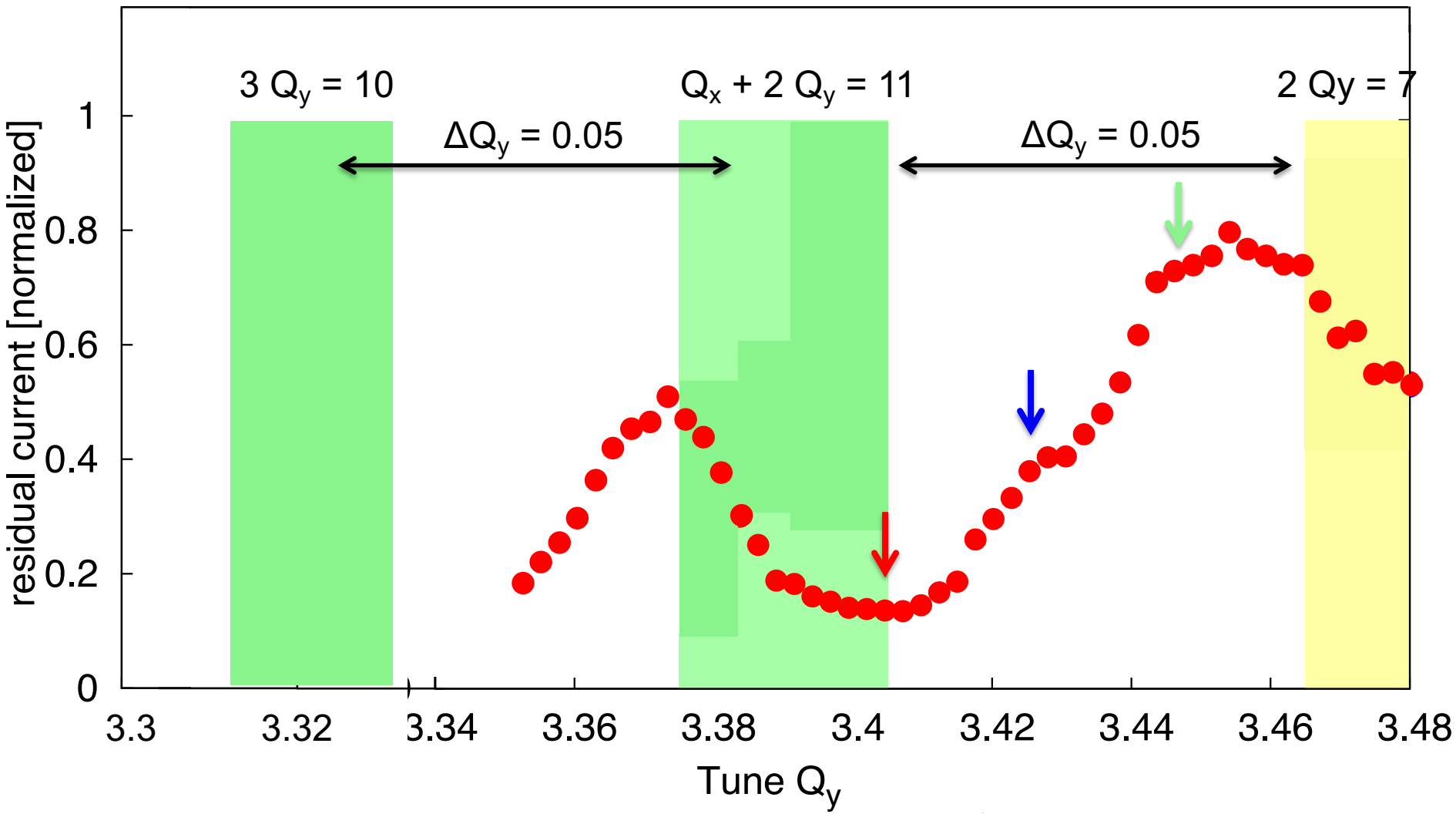
Best correction achieved



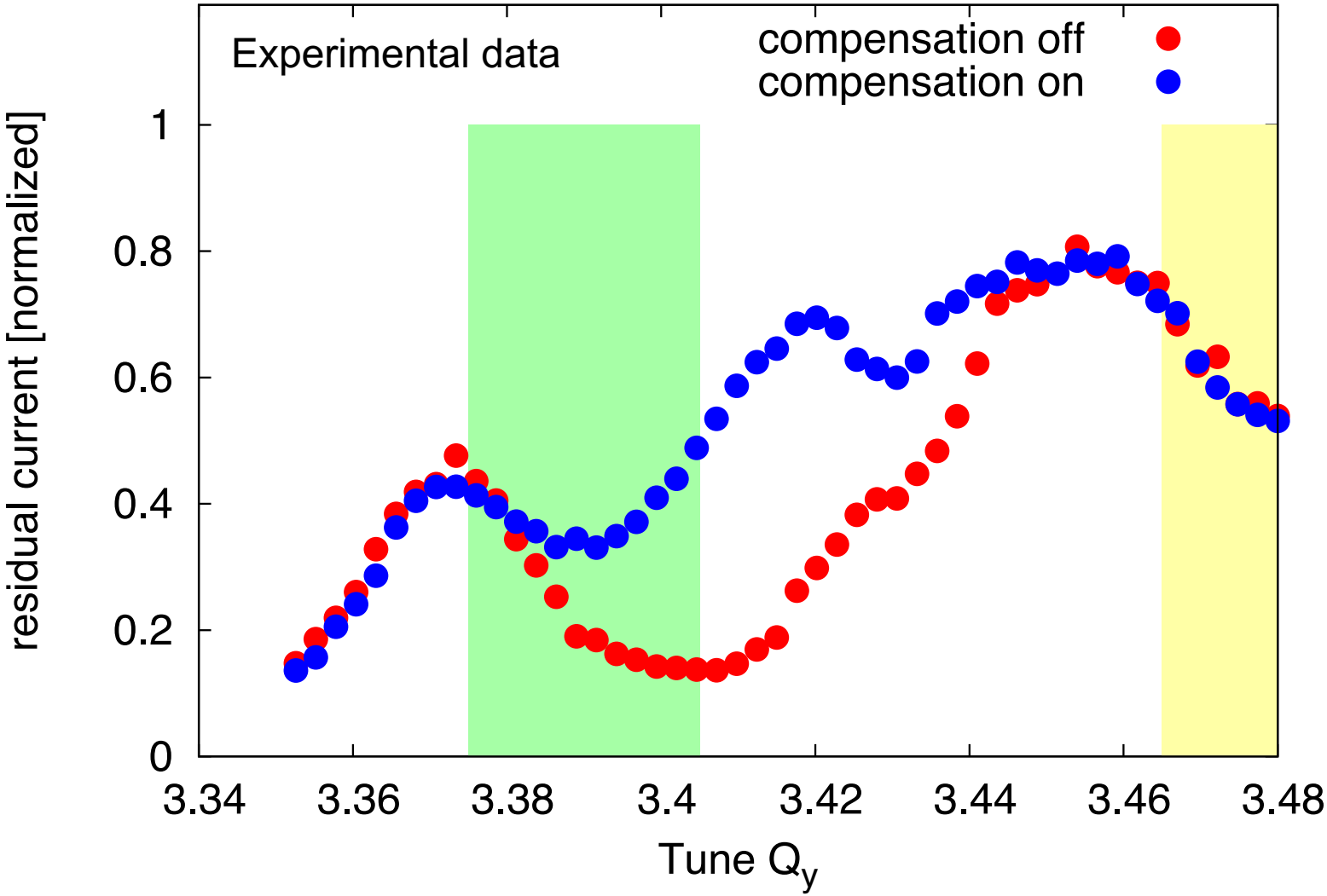
This method is now routine at CERN → F. Asvesta IPAC22



Summary of beam loss after 1 second as function of the machine tune



Effectiveness of the compensation



Conclusion / Outlook

- A successful experiment-code benchmarking of the beam dynamics on the 3rd order coupled resonance is carried out for the full PS structure.
- Outstanding asymmetric halo is formed well retrieved by the simulations
- Thinking in terms of resonance detuning leads paradoxes
- The “fixed-lines” or tori are the new objects that explain the dynamics of diffusion in a high intensity bunch subject to a coupled resonance
- **“Fixed lines” are experimentally measured in the SPS (not shown in this talk)**
- Simulations show that the periodic crossing of the fixed-lines causes the asymmetric halo as result of fixed lines geometry.
- *Particle seems to diffuse to **“one”** fixed-line → adiabatic limit (explained!)*
- **→ Strategies to mitigate particle diffusion: emittance-ratio vs resonance type**

Acknowledgments

GSI	O. Choriny, W. Bayer, O. Boine-Frankenheim, D. Ondreka C. Omet, B. Franczak, P. Forck, T. Giacomini, I. Hofmann, F. Kesting, M. Kirk, H. Kollmus, H. Liebermann, T. Mohite, A. Parfenova, P. Schuett, R. Singh, P. Spiller
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