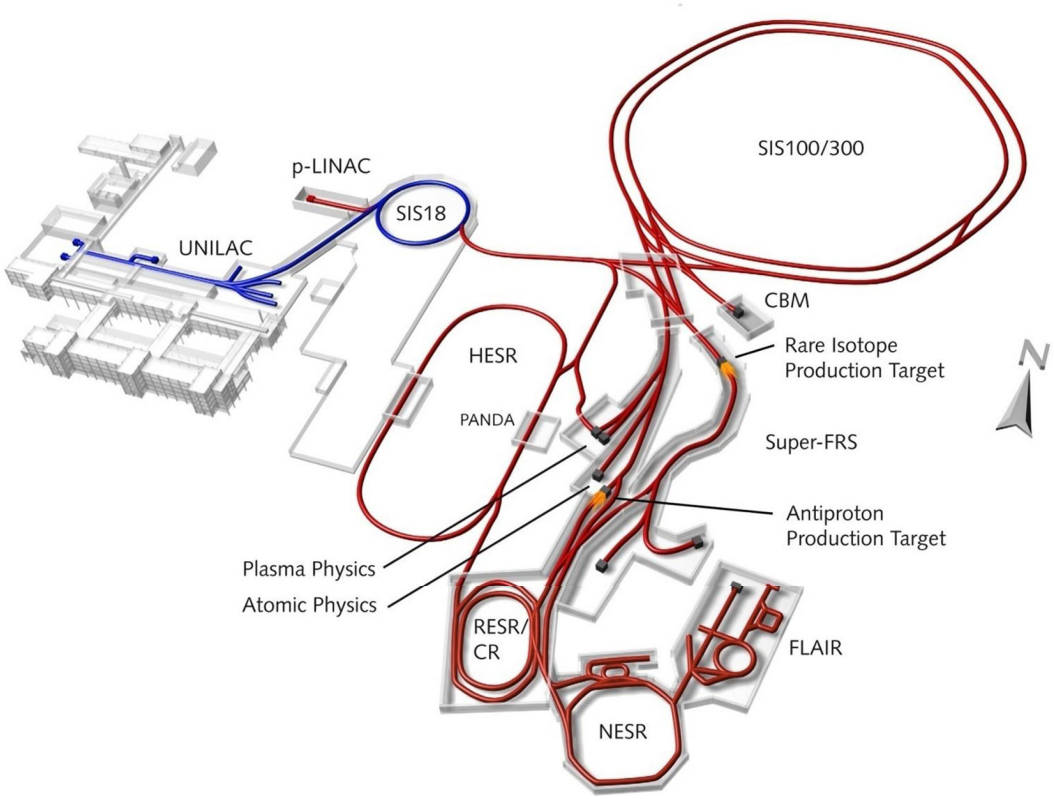
The quest for understanding the incoherent effects of space charge

G. Franchetti, GSI

@ Fermilab, April 12th 2016

Motivation

FAIR



Primary Beams

- 5×10^{11}/s; 1.5-2 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 over present in intensity
- 2×10^{13}/s 30 GeV protons
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u (up to 90 GeV protons)

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 - 30 GeV

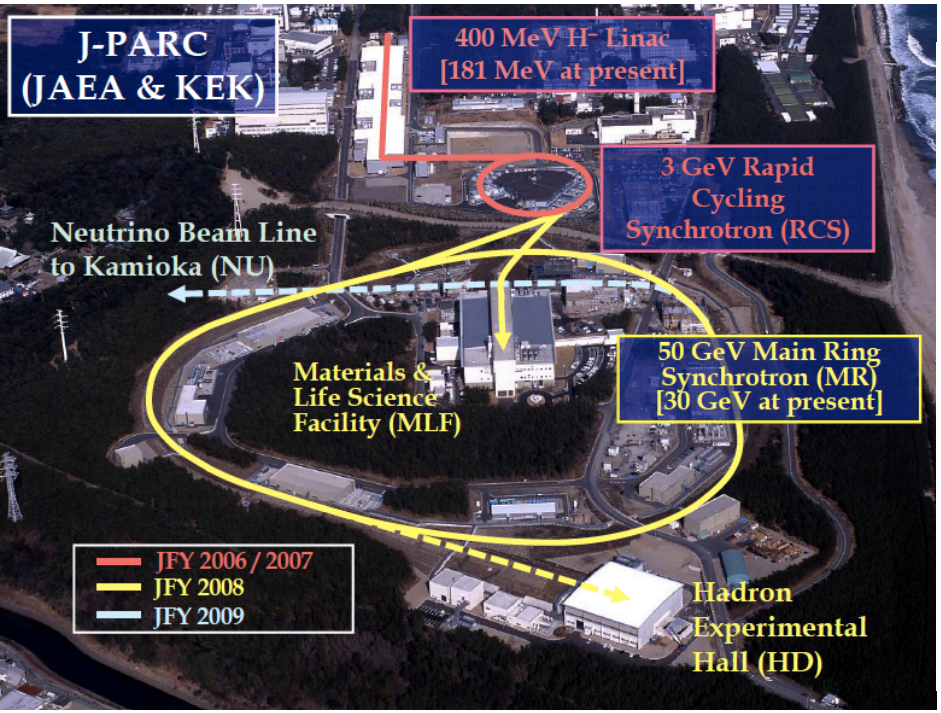
Storage and Cooler Rings

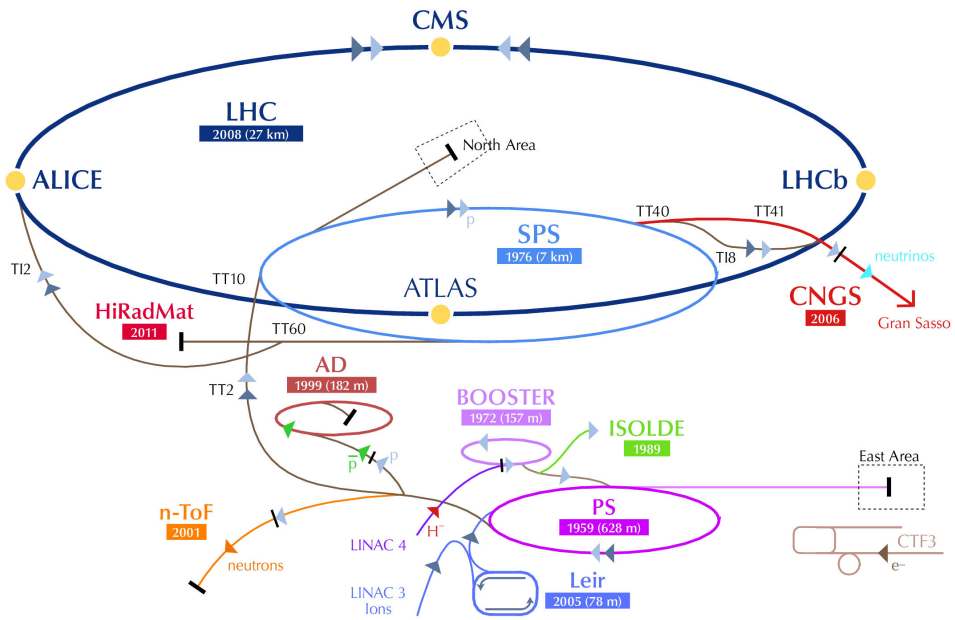
- Radioactive beams
- e – A collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons

Key Technical Features

- Cooled beams
- Rapidly cycling superconducting magnets

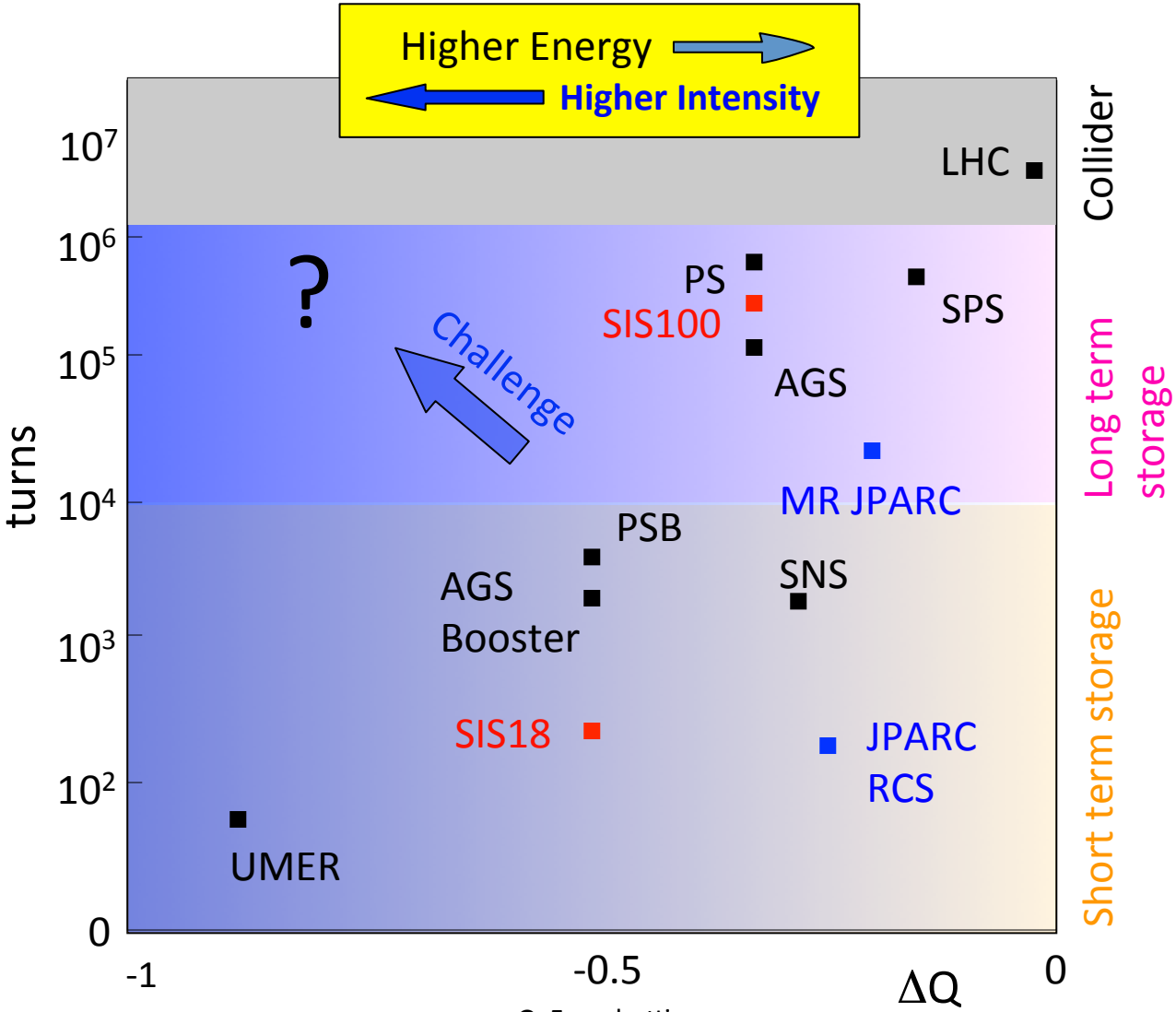
J-PARC & LIU





Param. @ LHC collision	Nominal[1] 25 ns	Today * 50 ns	HL-LHC[1] 25 ns	HL-LHC[1] 50 ns
Int/bunch	1.15E11	~1.6E11	2.2E11	3.5E11
Bunches	2808	1374	2808	1404
Beam current [A]	0.58		1.12	0.89
ε_n[μm]	3.75	~ 2.4	2.5	3.0
β*[m]	0.55	0.6	0.15	0.15
Peak Lumi [cm^{-2} s^{-1}]	1 10^{34}	7.74 10^{33}	9 10^{34}	9 10^{34}

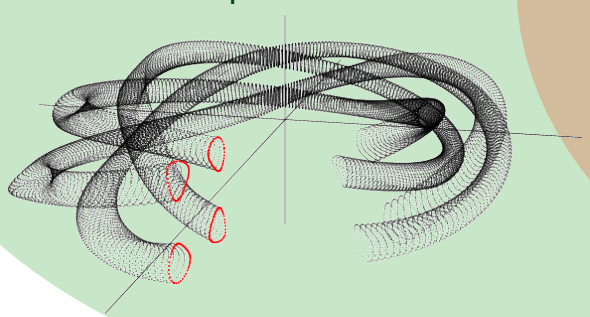
Trends


Higher Energy
Higher Intensity
Collider
Long term storage
Short term storage
LHC
PS
SIS100
SPS
AGS
MR JPARC
PSB
AGS Booster
SNS
SIS18
JPARC RCS
UMER
?
Challenge
turns
10^7
10^6
10^5
10^4
10^3
10^2
0
-1
-0.5
0
ΔQ

Two different accelerator areas overlaps

Nonlinear Resonances

- single particle motion (incoherent)
- orbit deformations
- long term effects: resonances and dynamic aperture



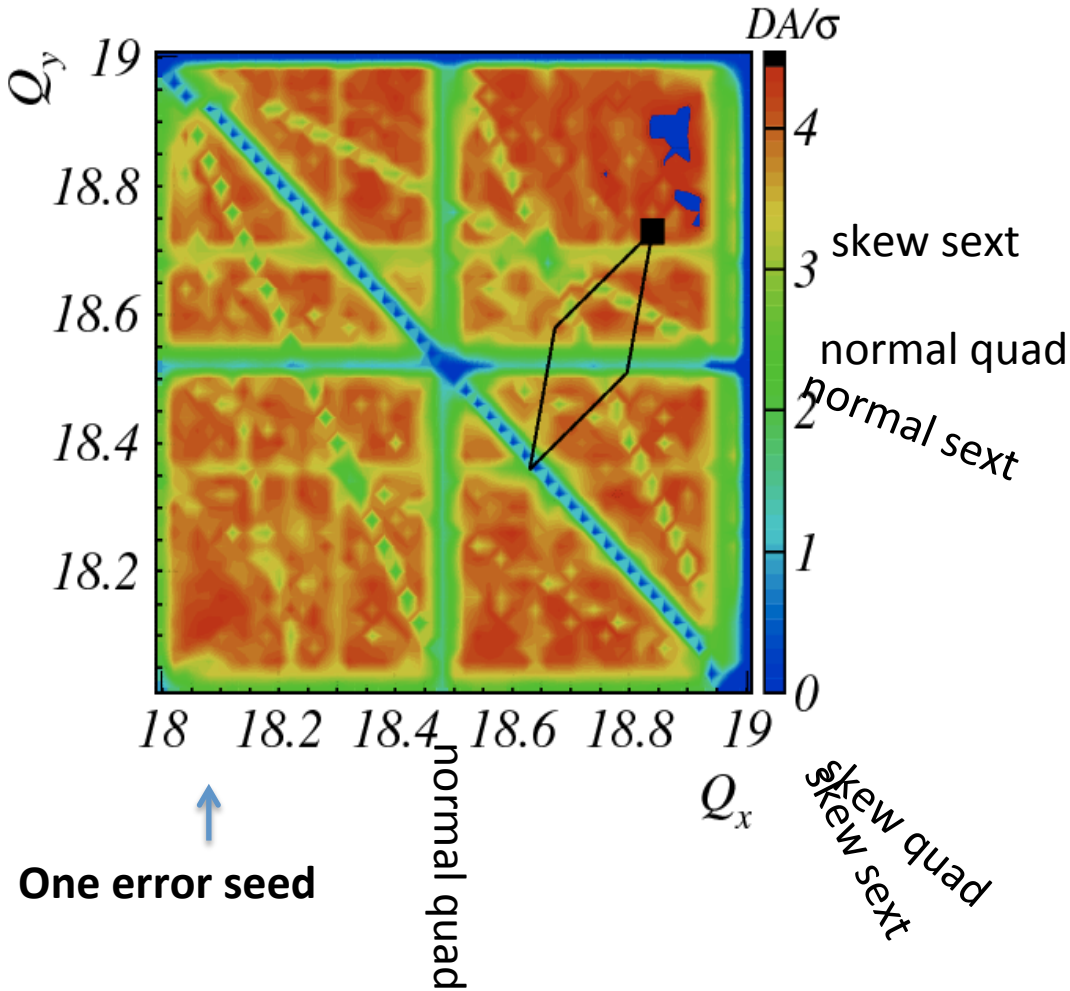
High intensity
Nonlinear errors
Long storage

High Intensity effects

- many particle force (coherent)
- short term effects
- coherent beam motion
- strong in linac

Incoherent effects of space charge

Relevance



Overlapping of space charge tune-spread with lattice resonances

Issues of beam halo prediction and of resonance compensation

The beginning

20th ICFA Advanced Beam Dynamic Workshop on High Intensity
and
High Brightness Hadron Beams,
8-12 April 2002, Fermilab, Chicago, USA.

The quest of the incoherent effects of space charge

2002	2007	2012	2014	2015
1 week	12 days (as users)	1 week	~2 days	4 days
study of the space charge on **1D** 4th order resonance	study of the space charge on **1D** 3th order resonance: proof of principle	study of the space charge on **2D** 3th order resonance	resonance compensation with space charge	Experimental discovery of the fixed-lines
PS	**SIS18**	**PS**	**SIS18**	**SPS**

SIS18, SIS100

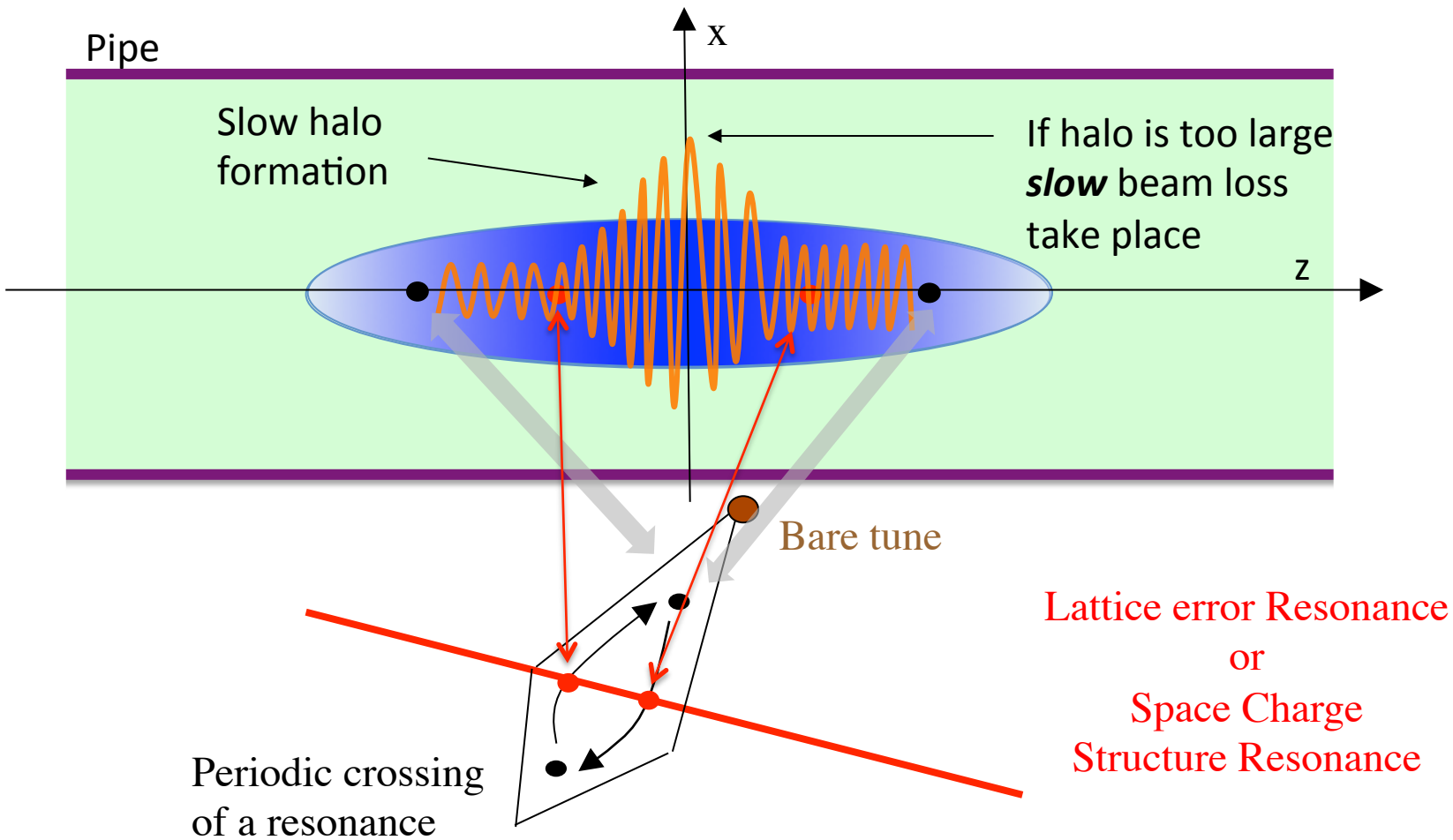
PS, SPS, ..

IOTA

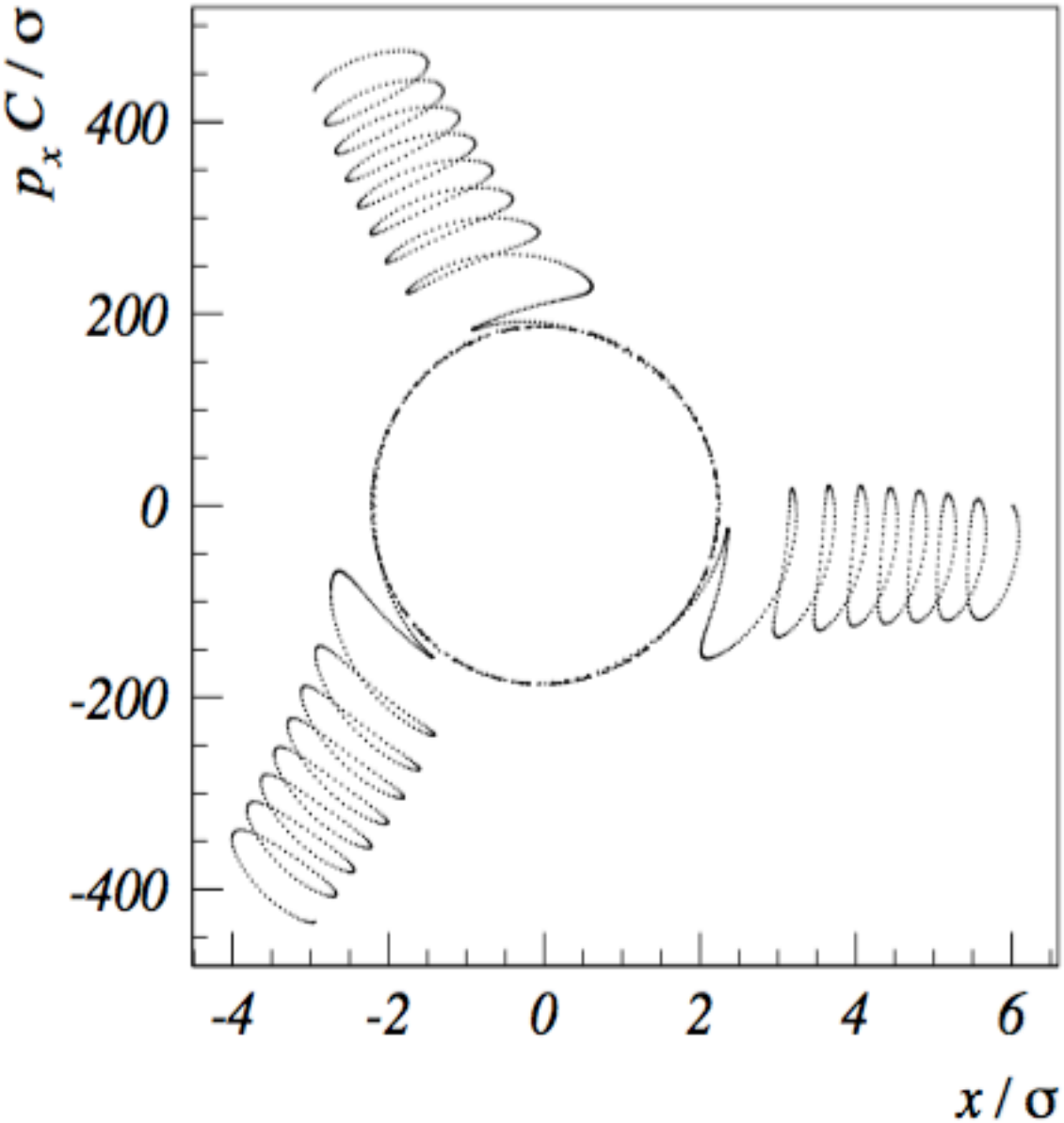
The PS experiment of 2002

"The dawn of the long term effects of space charge"

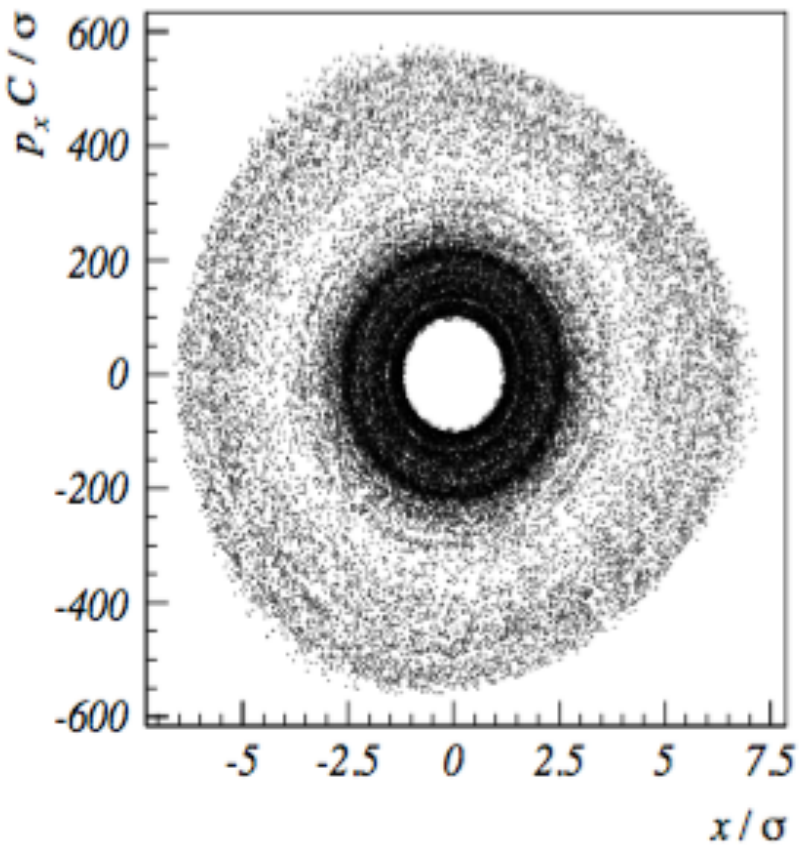
The mechanism

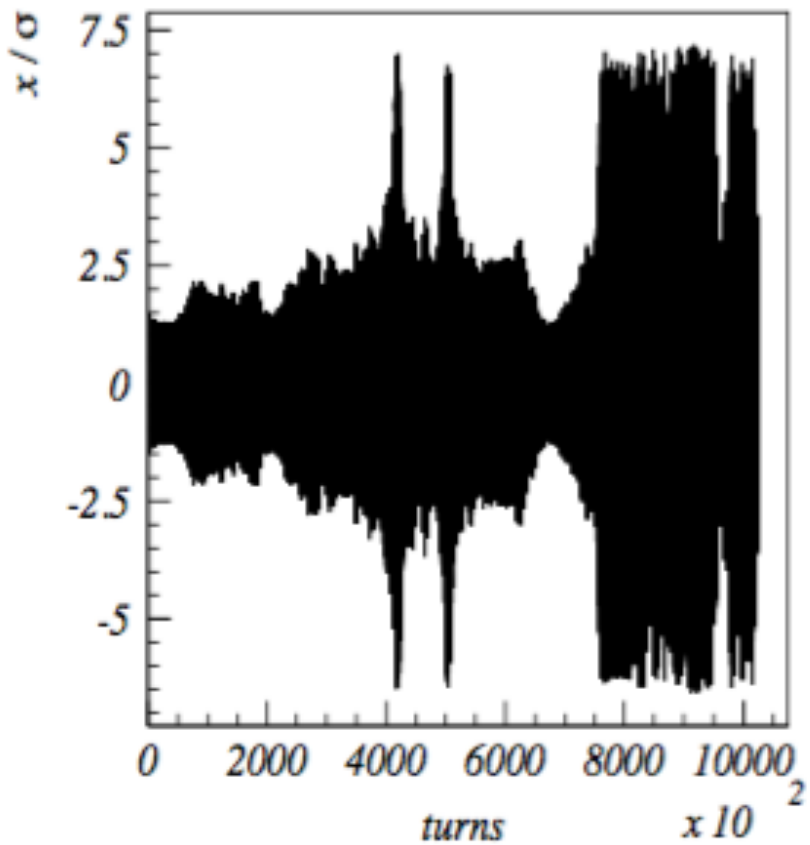


Trapping Fermilab 2002



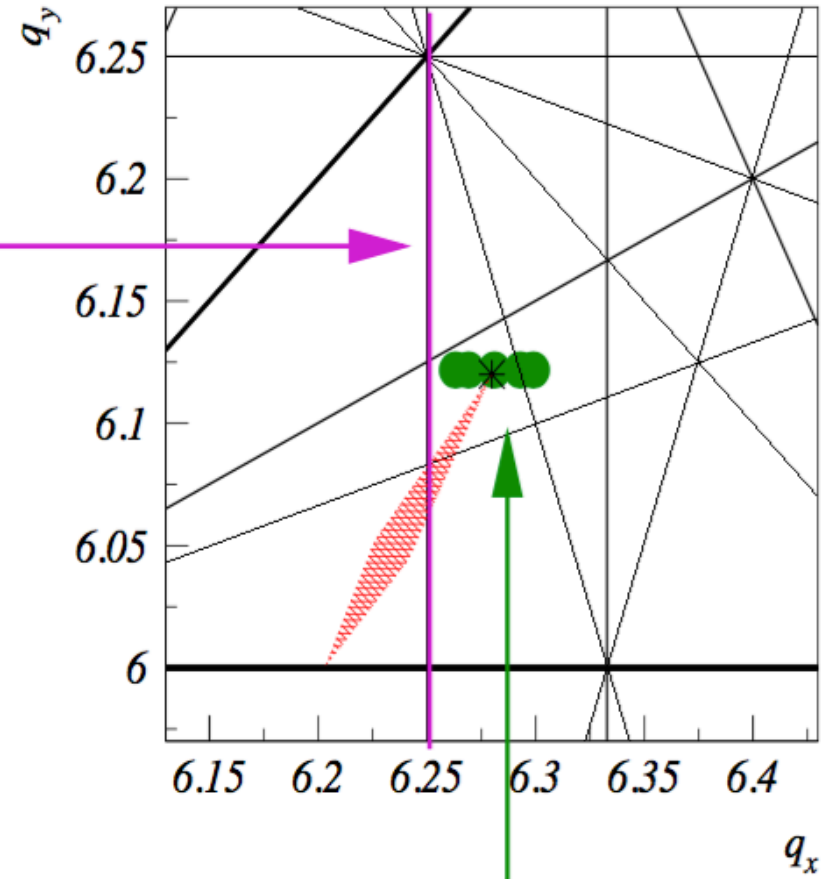
Scattering Fermilab 2002





The PS experiment

excitation of
4th order resonance
by using 1 octupole



scan of qx0
from 6.32 to 6.25
qy0 = 6.12

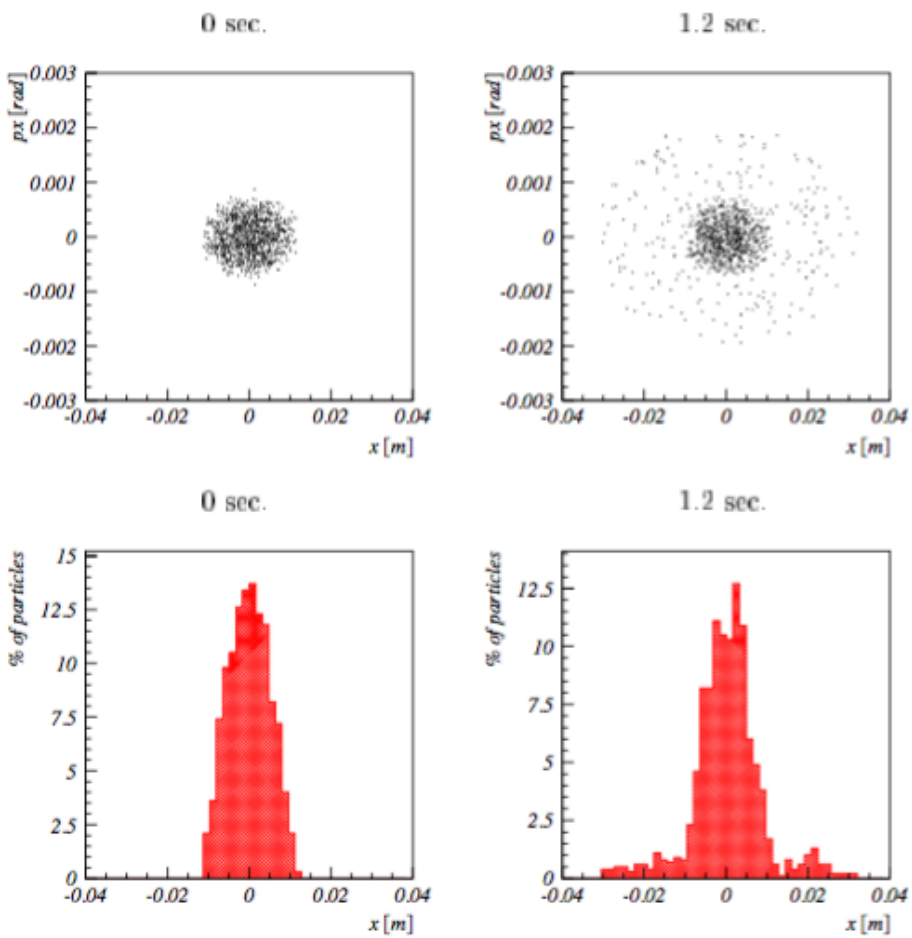


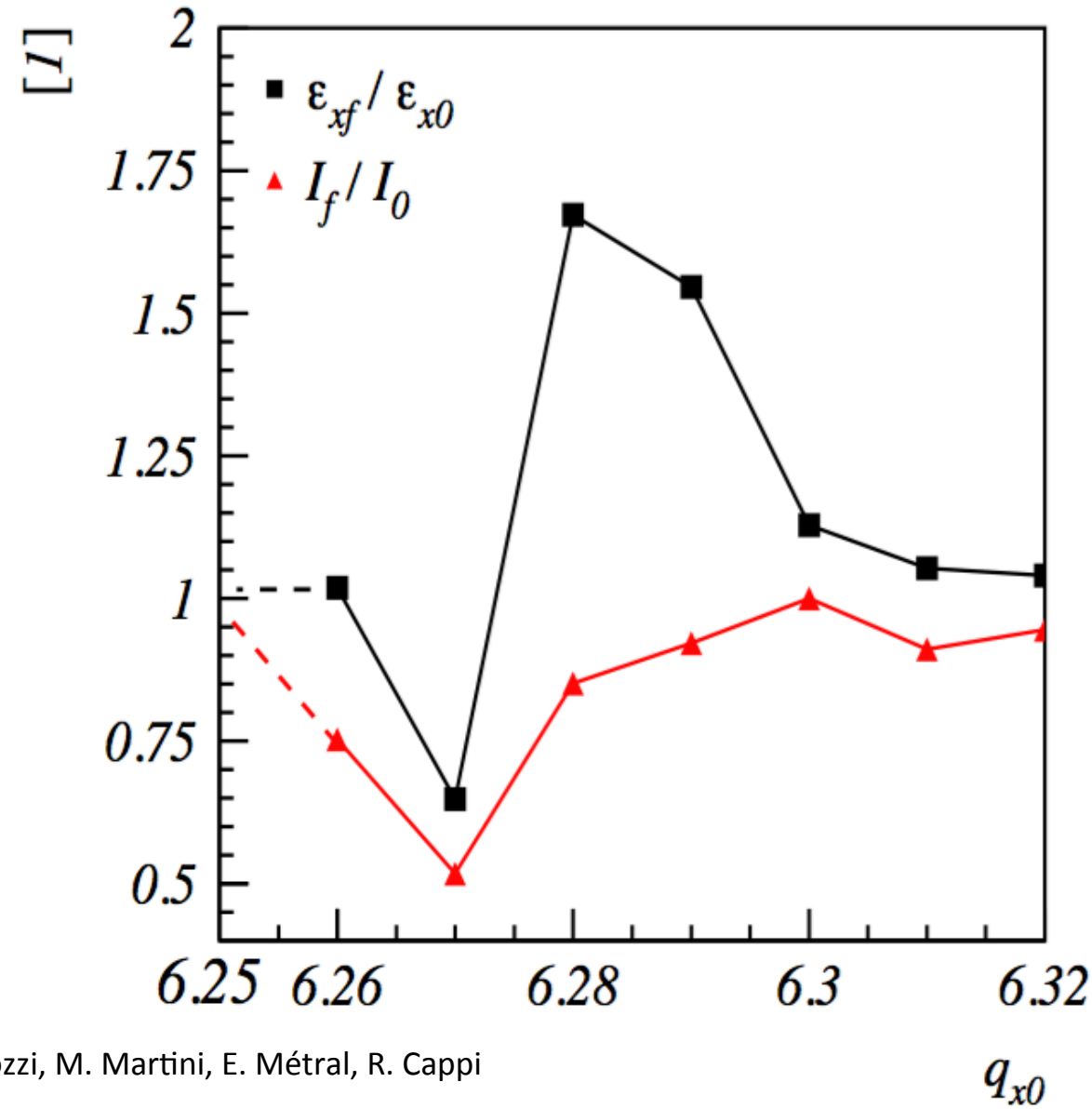
Figure 4: Horizontal particle distribution and phase space at injection and after 500000 turns. The working point is $\nu_x = 6.35, \nu_y = 6.25$.

My expectations in 2002

Great expectations…

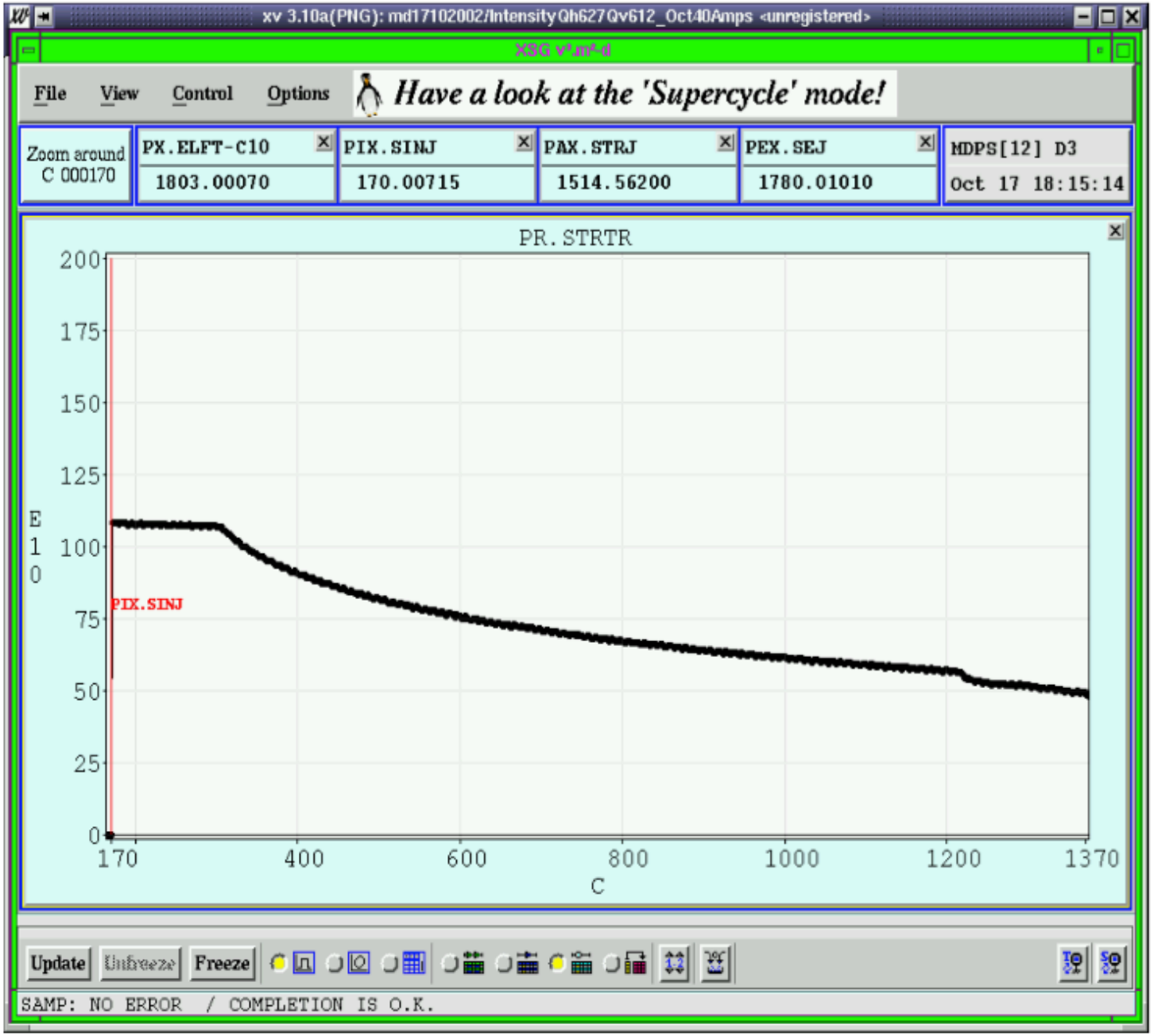
PS experiment on Resonance Crossing: Summary

qy0 = 6.12
K_3 = 49 m^{-3}
Dqx = 0.077
Dqy = 0.12
flat–top 1.2 sec
turns $5*10^5$

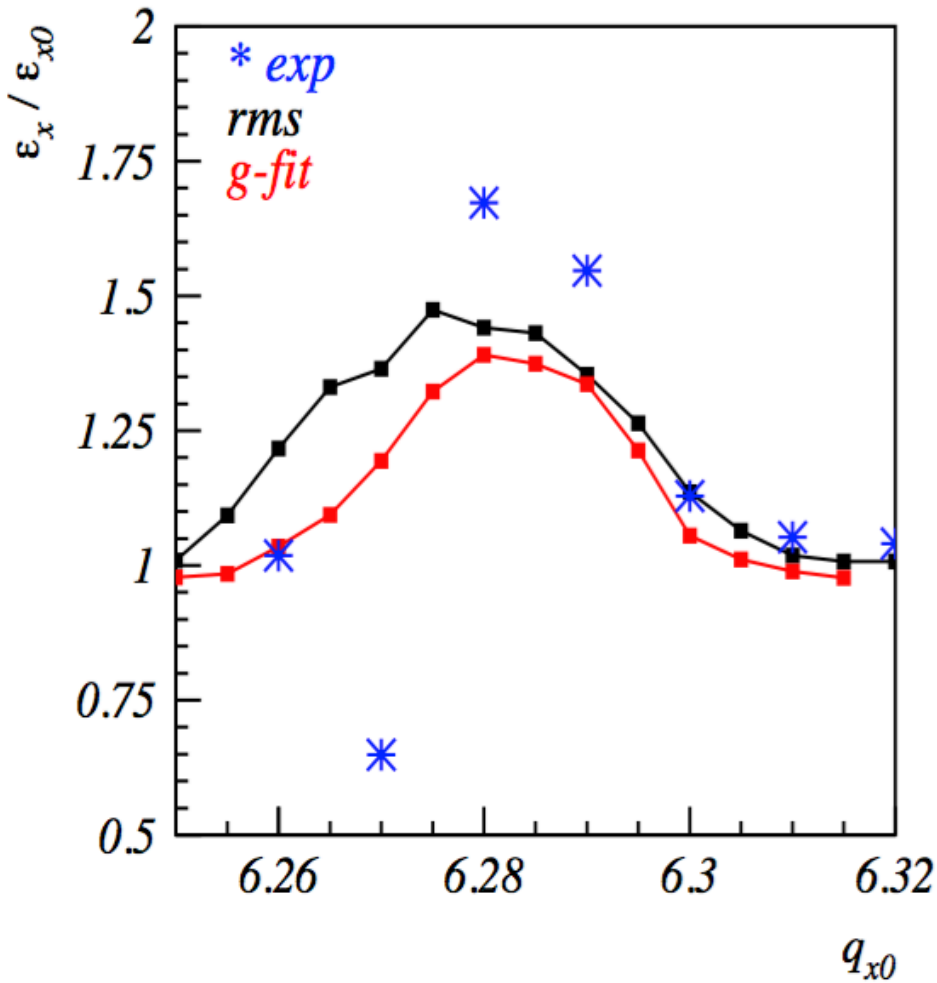


G. Franchetti, I. Hofmann, M. Giovannozzi, M. Martini, E. Métral, R. Cappi

qx0 = 6.27 qy0 = 6.12 I_octupole=40 Amps



Benchmarking: experiment vs simulation



No Halo ☹

Great expectations…

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **6**, 124201 (2003)

Space charge and octupole driven resonance trapping observed at the CERN Proton Synchrotron

not really proved

G. Franchetti and I. Hofmann
GSI, 64291 Darmstadt, Germany

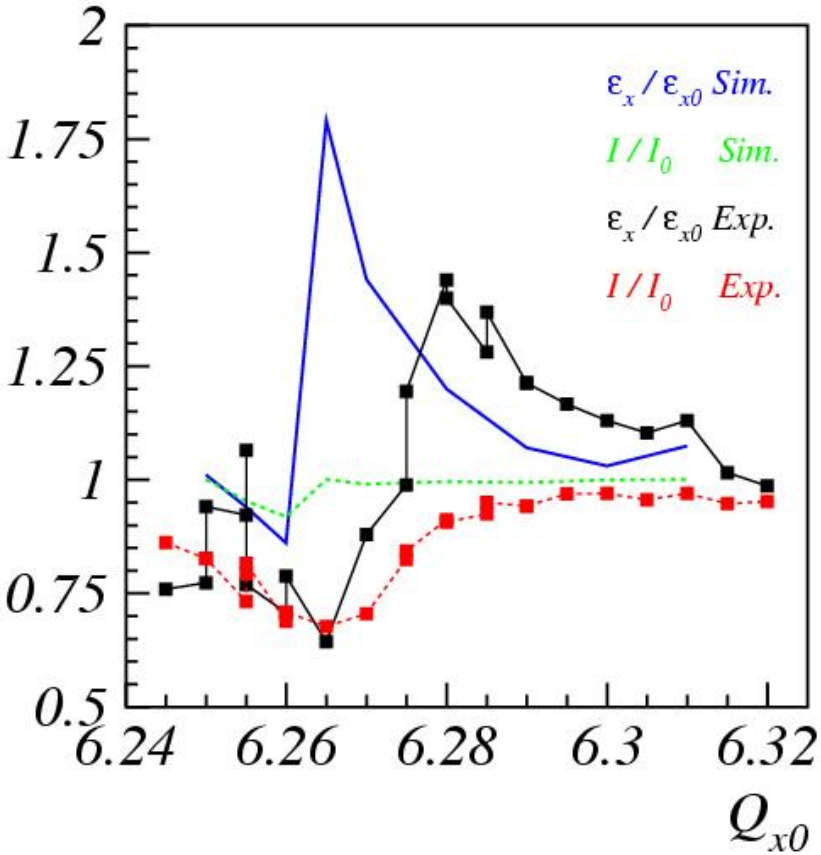
M. Giovannozzi, M. Martini, and E. Metral
CERN, 1211 Geneva, Switzerland

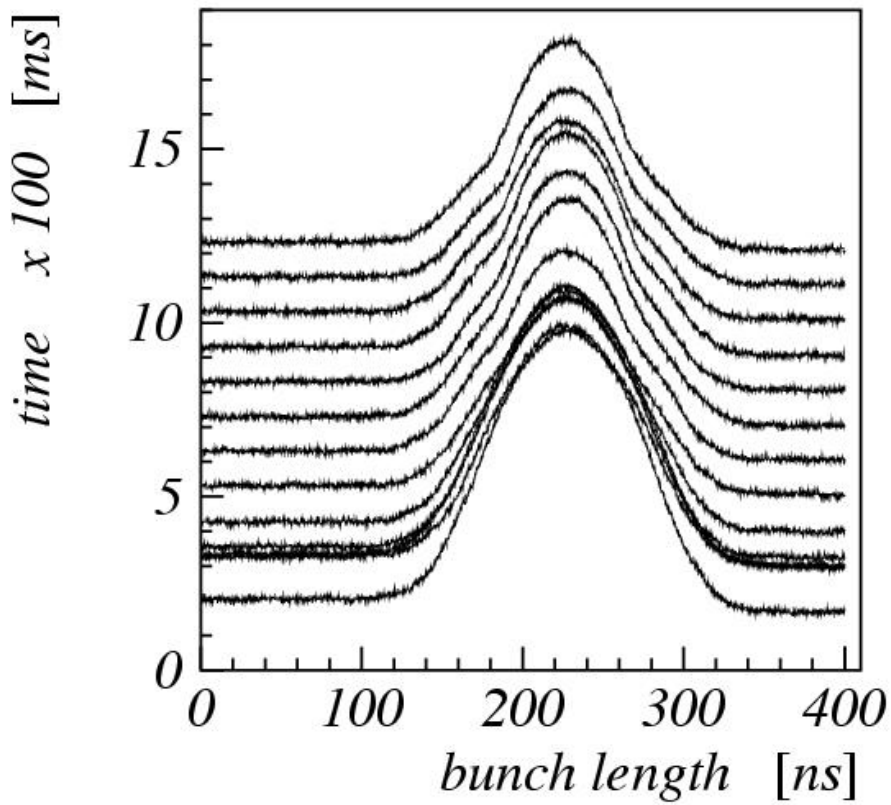
(Received 22 August 2003; published 5 December 2003)

The combined effect of space charge and nonlinear resonance on beam loss and emittance was measured in a benchmarking experiment over a 1.2 s long flat bottom at 1.4 GeV kinetic energy in the presence of a single controllable octupole. By lowering the working point towards the resonance, a gradual transition from a loss-free core emittance blowup to a regime dominated by continuous loss was found. We compare the observation with 3D simulations based on a new analytical space charge model and obtain good agreement in the emittance blowup regime. Our explanation is in terms of the synchrotron oscillation, which causes a periodic tune modulation due to space charge, and leads to

Further analysis of the experiment

R. Cappi, G. Franchetti, M. Giovannozzi, I. Hofmann, E. Metral, M. Martini, R.Steeremberg ICFA2004





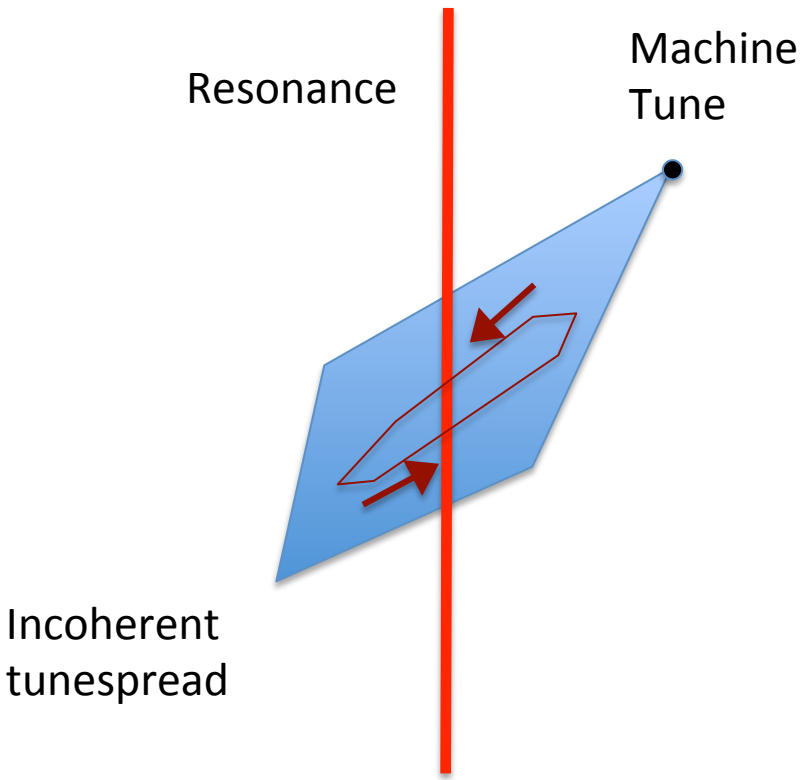
4th-order resonace

The GSI campaign of 2007-2008

"A new hope"

Experiment on space charge driven nonlinear resonance crossing in an ion synchrotron
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).

Schematic of the study



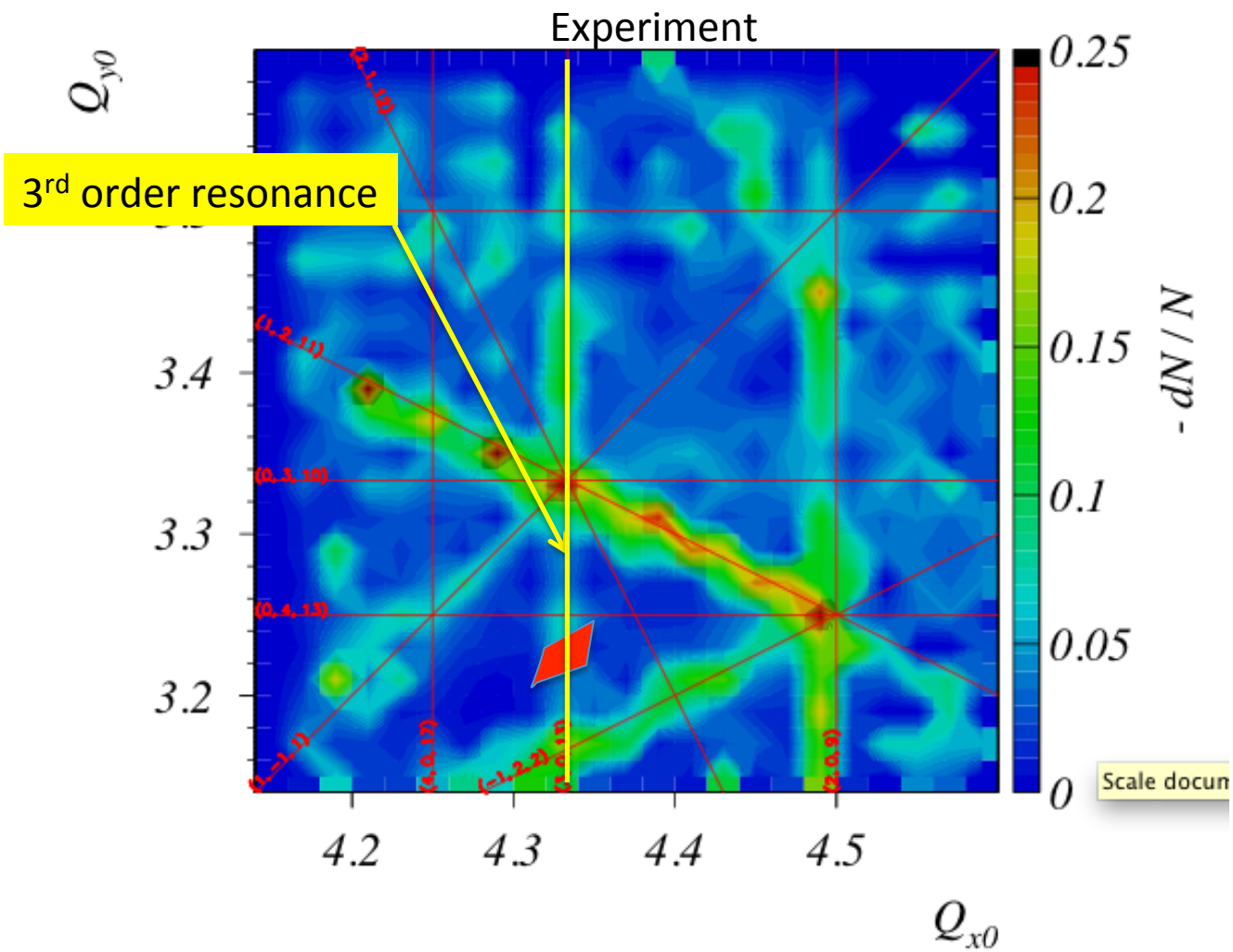
Aim

Study the beam dynamics
of a high intensity bunched beams
stored for several 10^5 turns

Relevant Issue

Can we make a proof of principle ?

Choice of the resonance



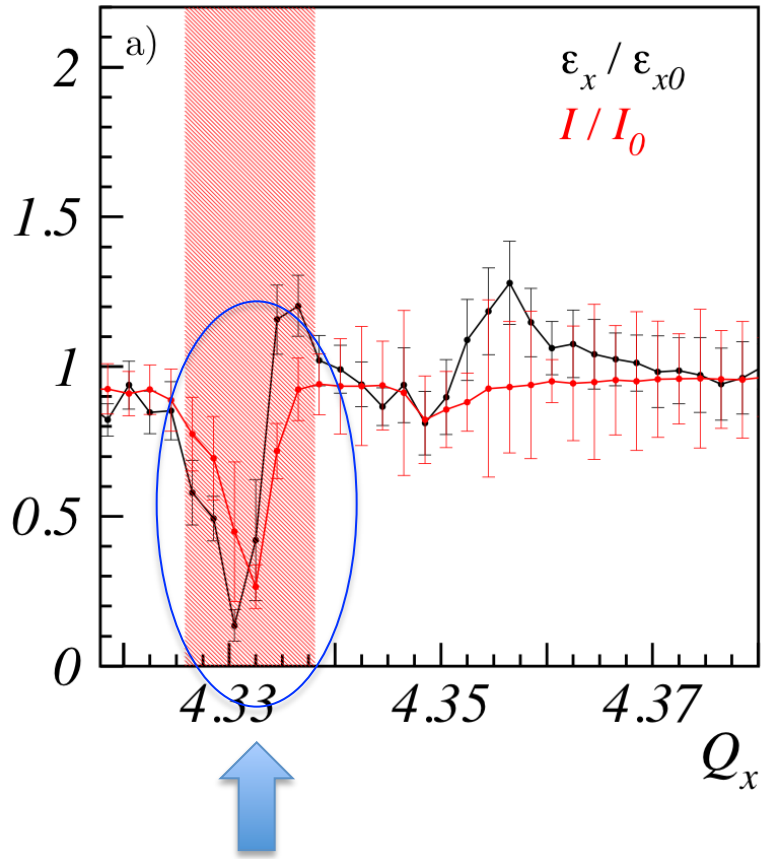
Systematic studies on the effect of the synchrotron motion on the bunched beam dynamics

Systematic in the experiments

	low intensity (**L**)	high intensity (**H**)
Coasting Beam (**CB**)	only single particle nonlinear dynamics: transverse blow-up and beam loss	no resonance periodic crossing: but transverse emittance growth
Bunched Beam (**BB**)	single particle nl dynamics + chromaticity: larger transverse beam blow-up	Space charge trapping/scattering effects: beam loss/ bunch-shortening

Scan at low intensity

Experiment



$\Delta Q_x = -0.008 / -0.011$

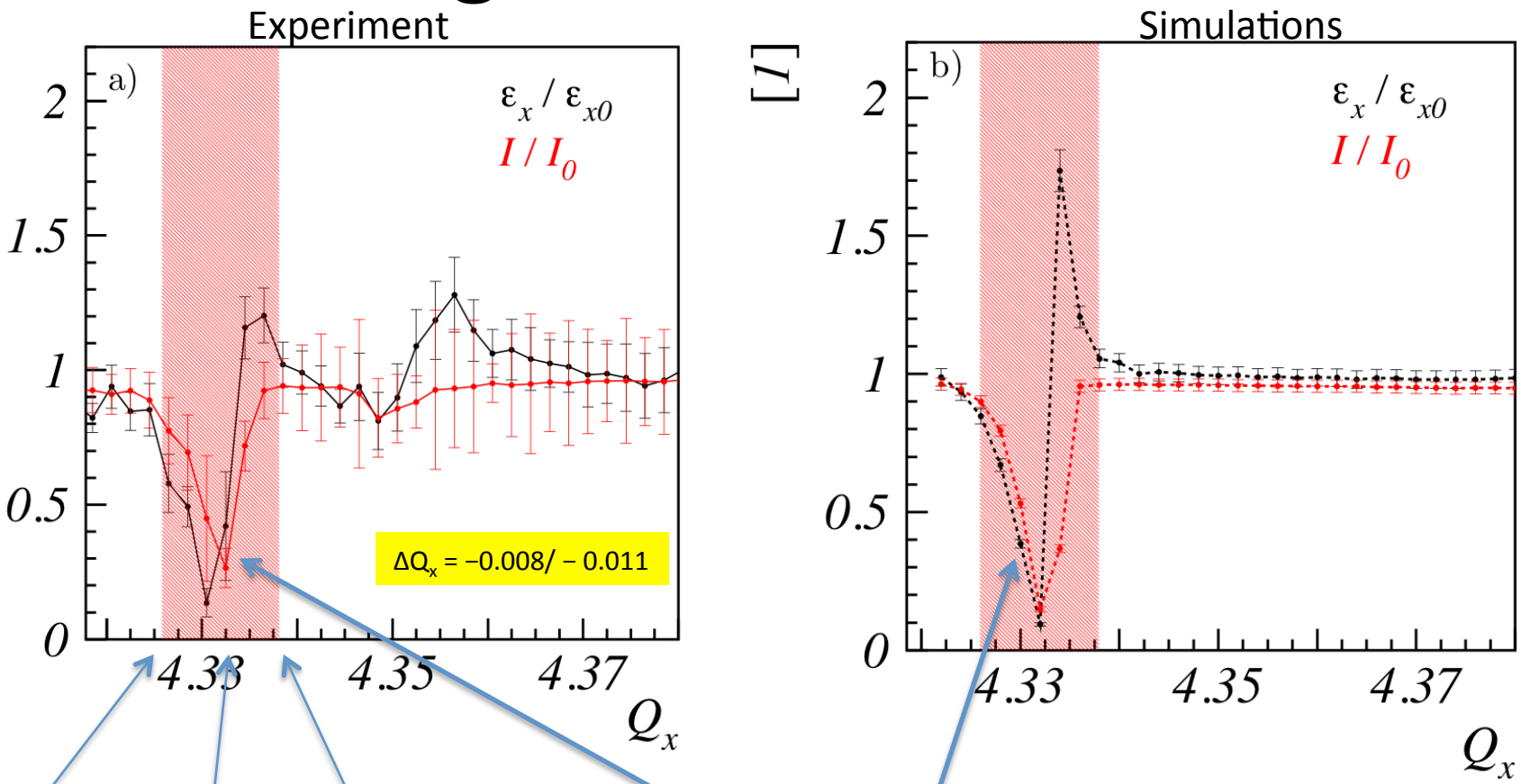
1) Chromatic correction sextupoles
2) Possible 4th order nonlinearities (octupoles)

Model:

1 Sextupole driving the 3rd order resonance
1 Octupole to match the slope in beam loss

Beam loss appears titled → indication of detuning effects

Modeling of the nonlinear SIS18



Below resonance

On the resonance

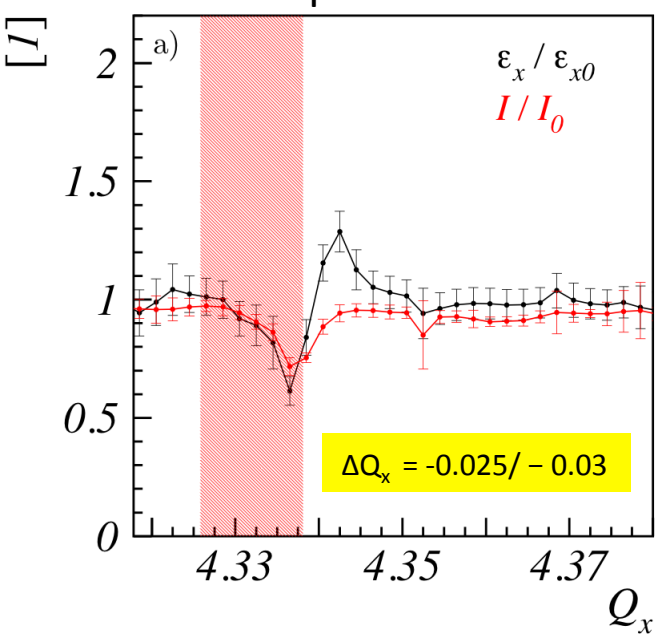
Above the resonance

The pattern of beam loss is "similar"

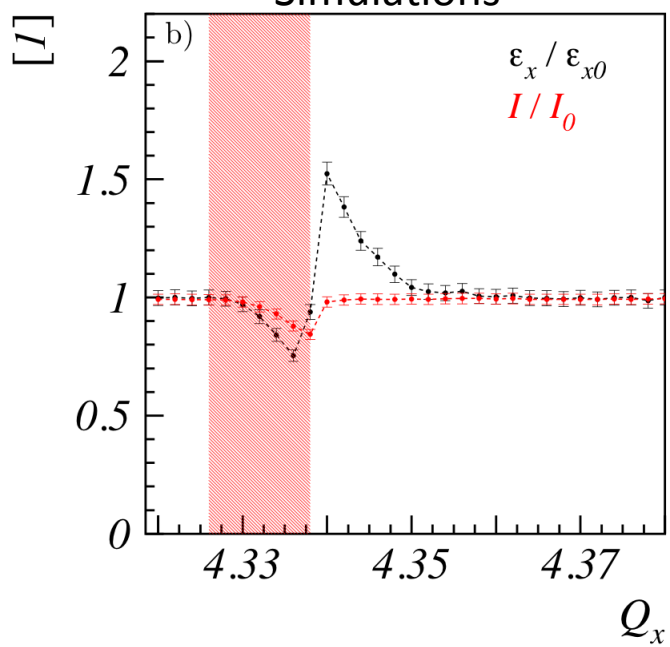
The effect of the space charge

Effect of the space charge on a coasting beam

Experiment



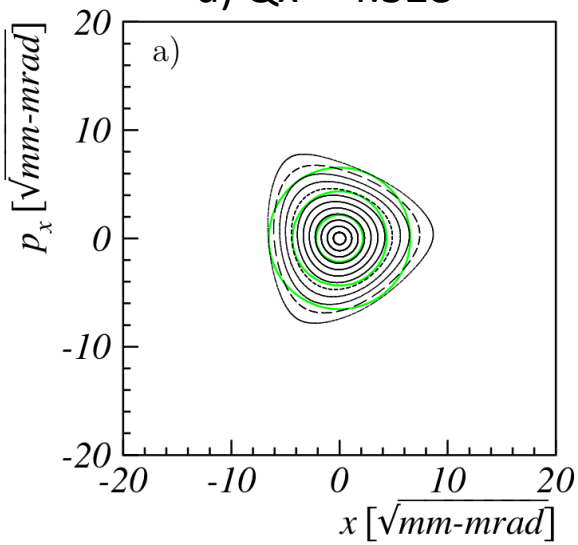
Simulations



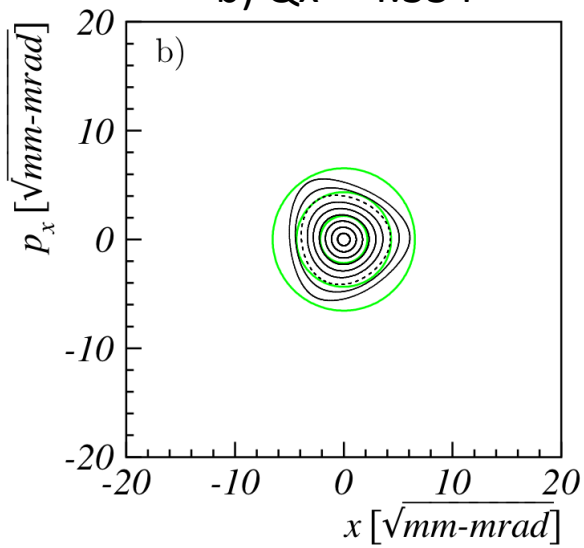
The peak of the emittance shifts on the right because of the space charge detuning

The effect of space charge: a phase space view

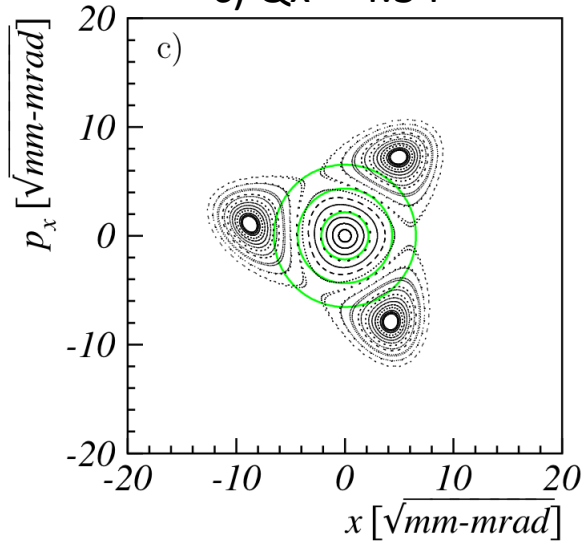
a) Qx = 4.328



b) Qx = 4.334



c) Qx = 4.34

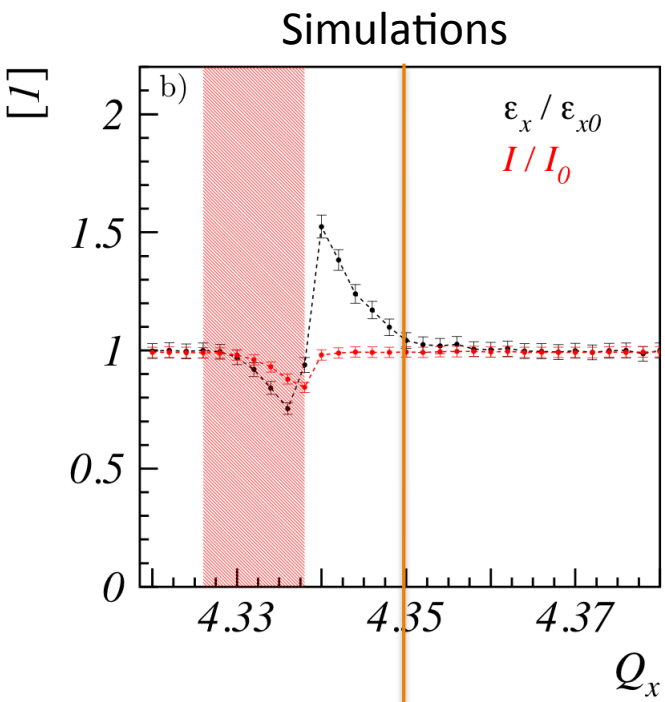


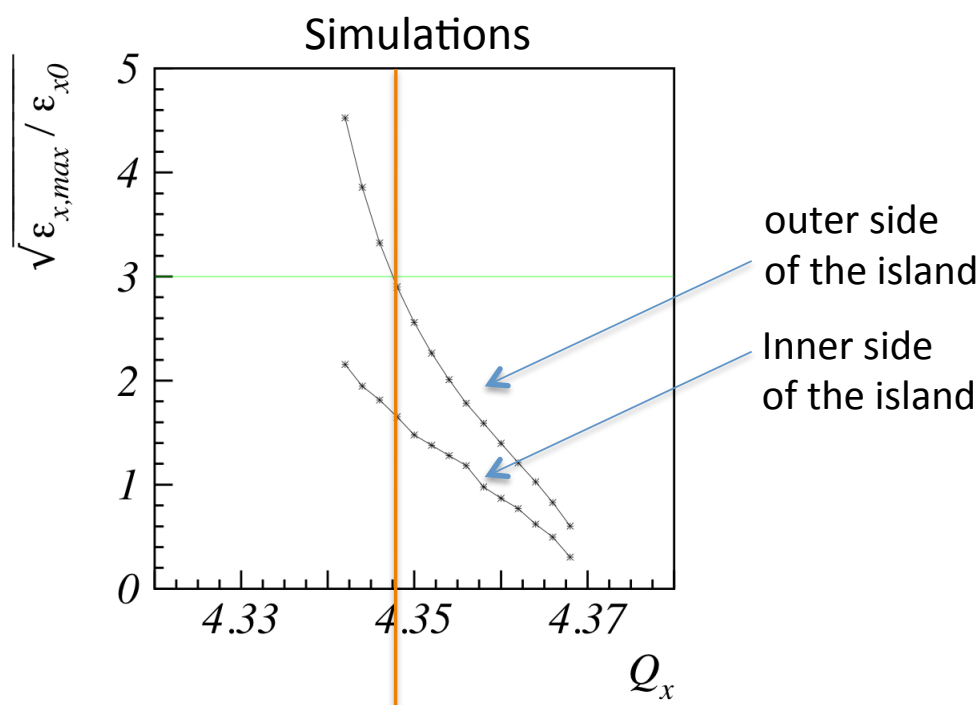
Below the resonance:
space charge stabilizes
a larger phase space area

On the resonance
The detuning of the
space charge
enlarge the separatrix

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

Origin of the emittance growth (incoherent)





Emittance growth region

No Emittance growth region

Here the islands are inside the beam

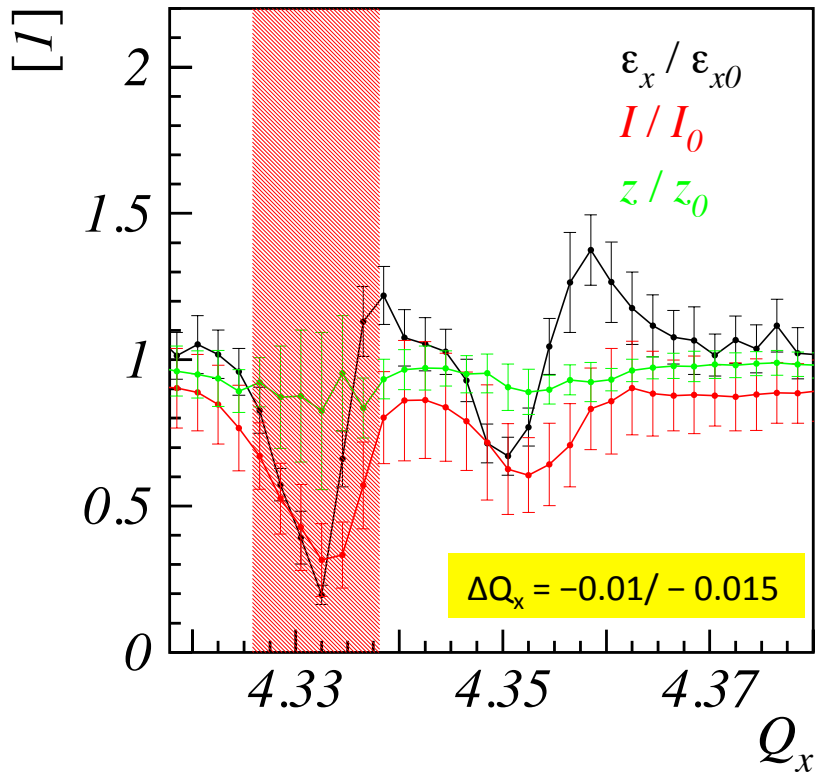
Here the islands are inside the beam

What happen with a Bunched beam ?

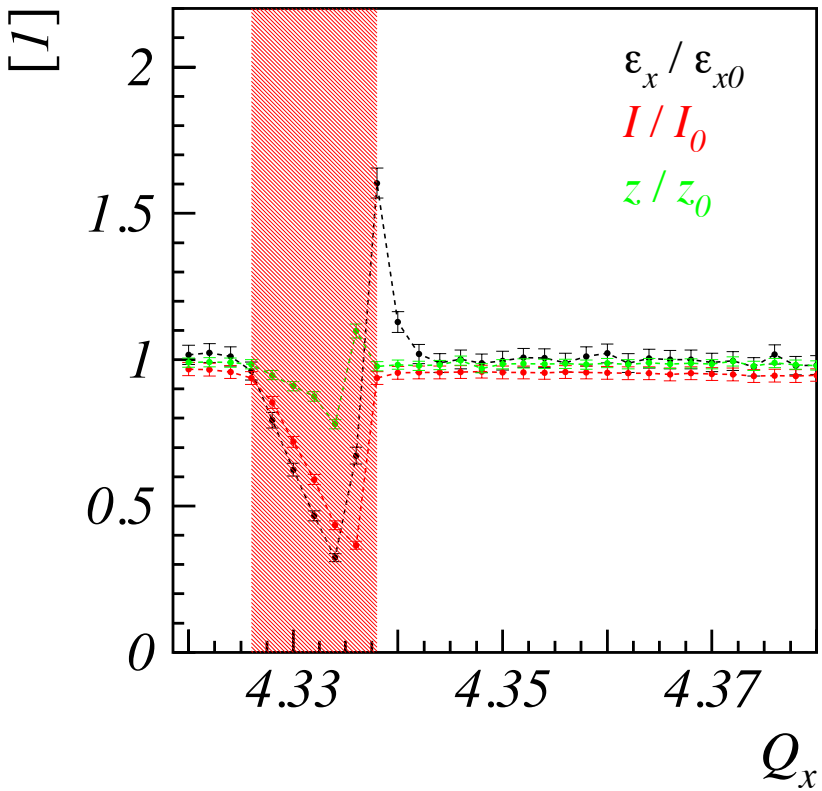
Low intensity

Chromaticity compensated with built-in control setting: not checked after set

Experiment



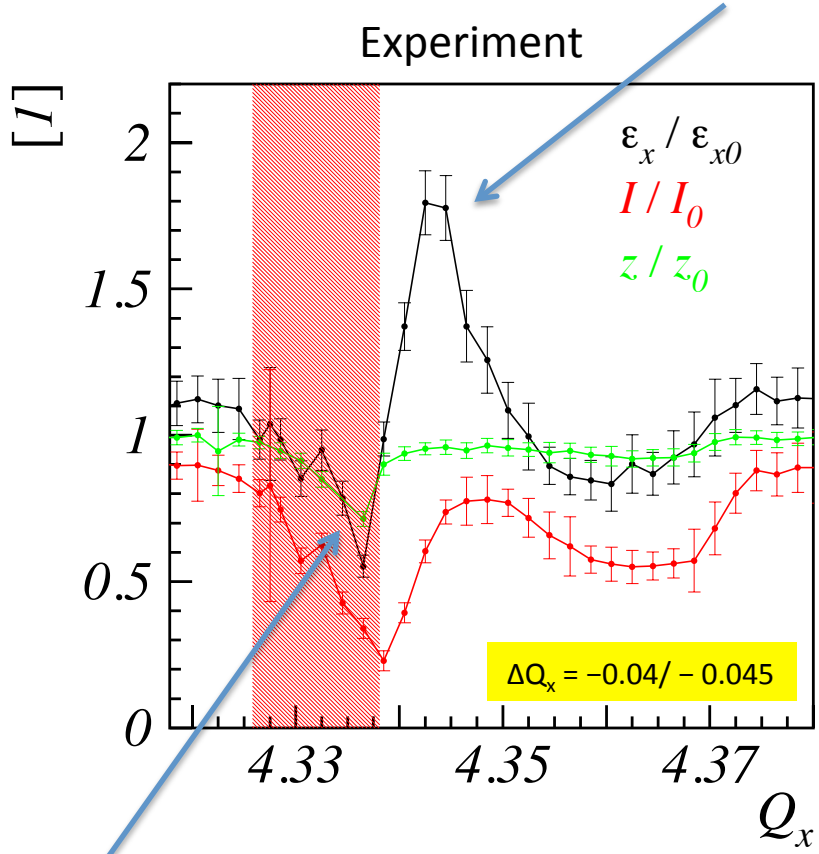
Simulations

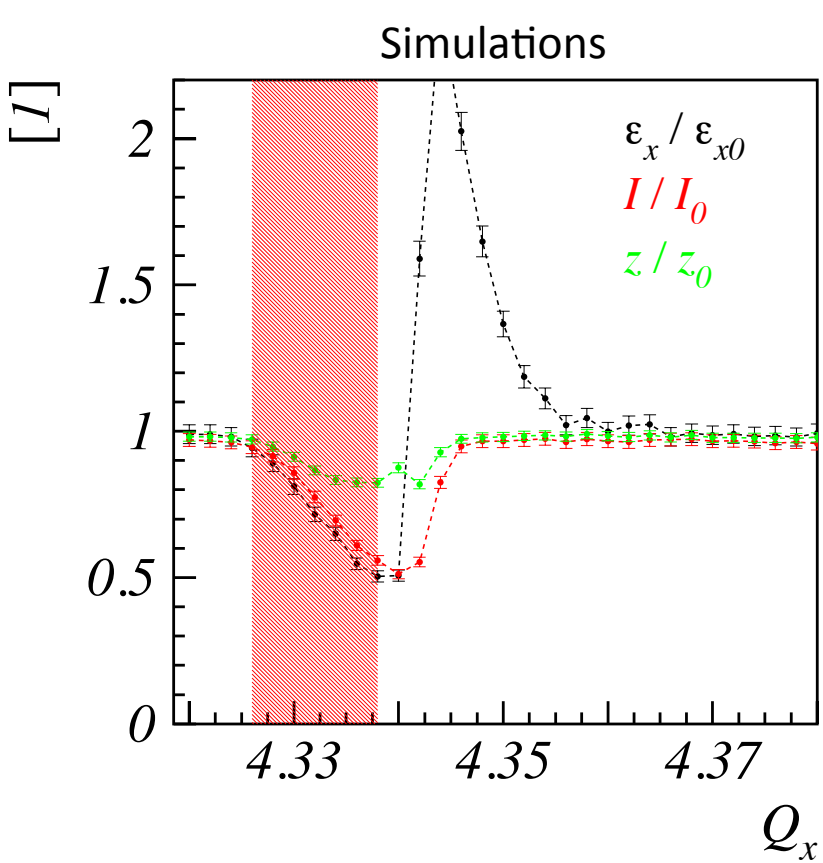


The beam loss stop-band is enlarged

Bunched beam at high intensity

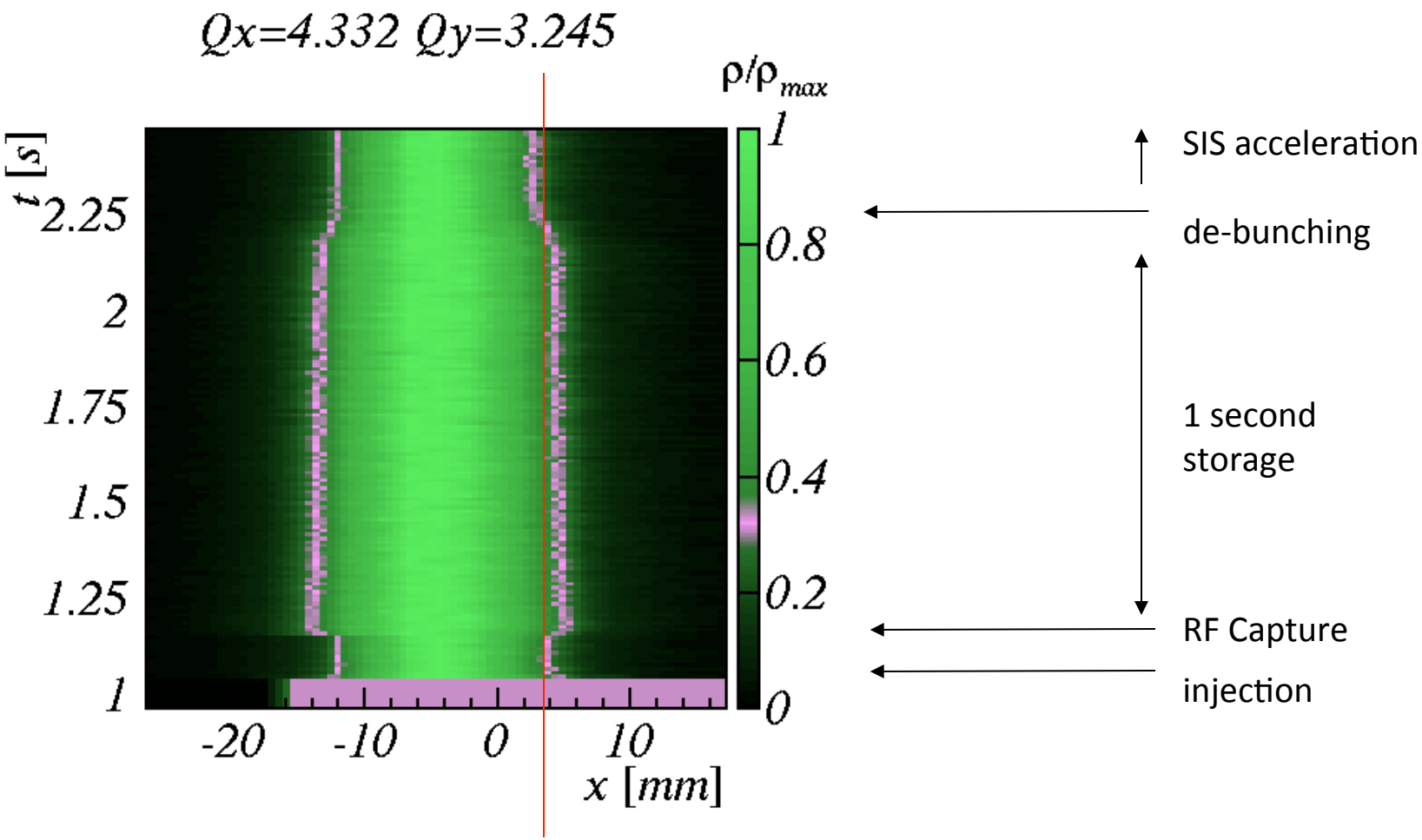
Large emittance growth





The bunch is shorter !

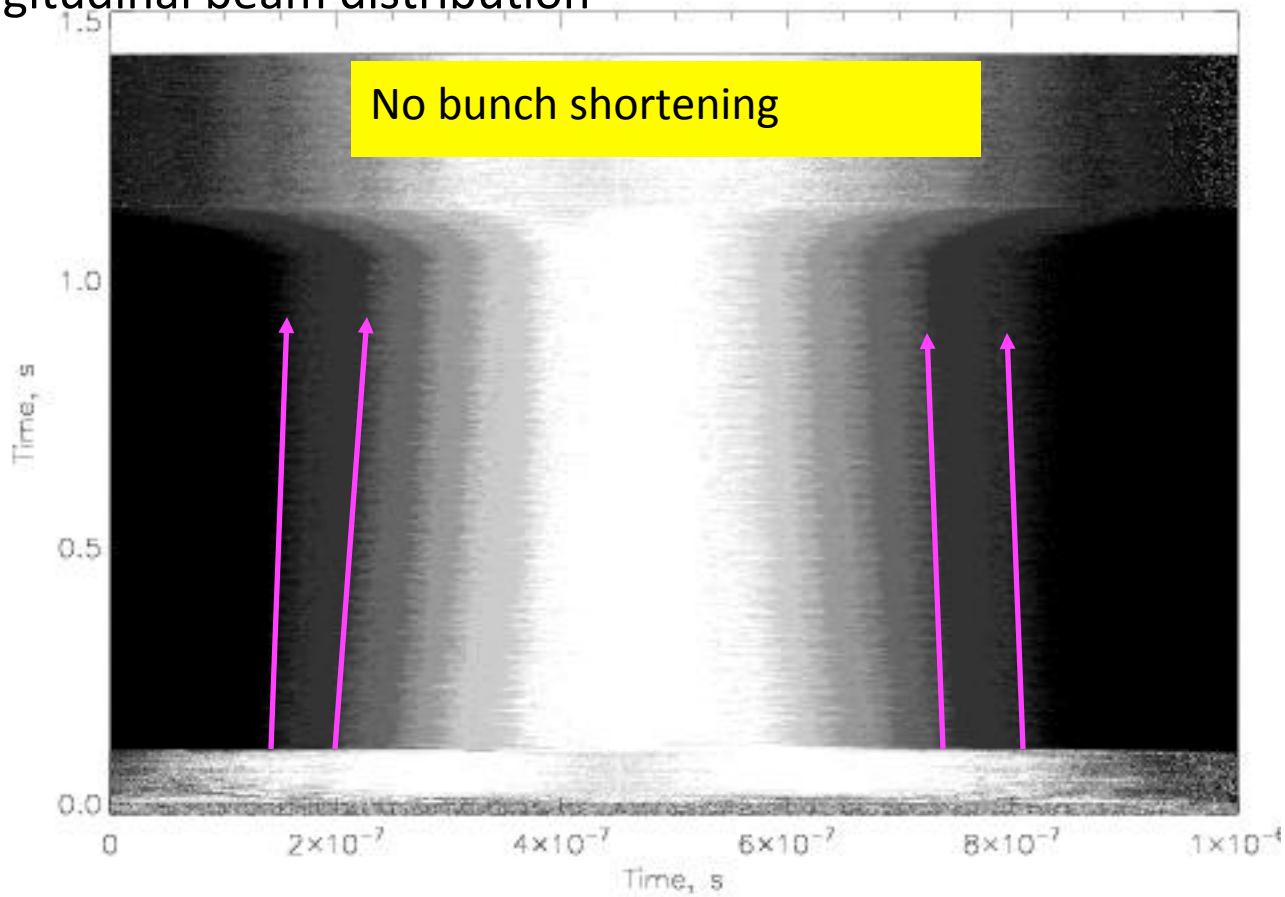
Transverse evolution BBH



BBH: longitudinal evolution

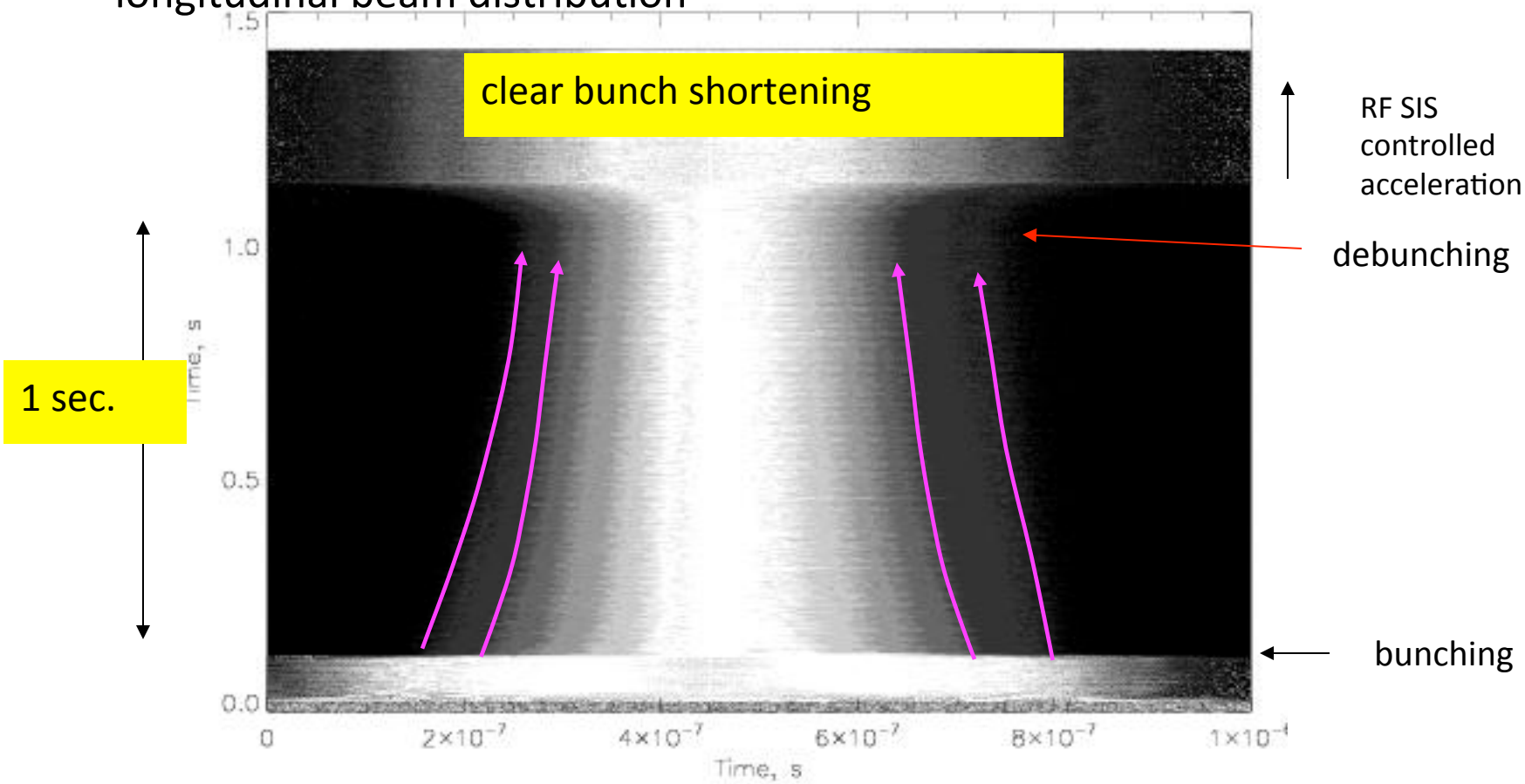
time evolution of the longitudinal beam distribution

at Qx=4.344 (no beam loss)

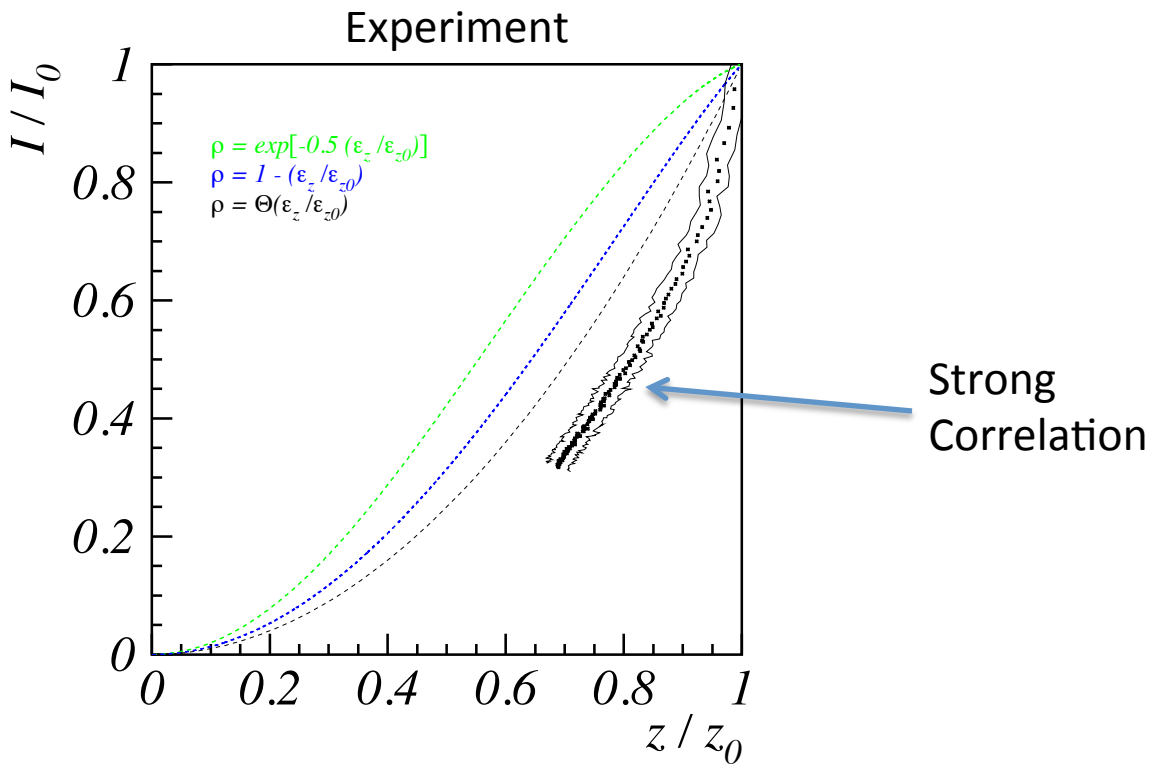


BBH: longitudinal evolution with transverse induced beam loss

time evolution of the longitudinal beam distribution at Qx=4.340 (with beam loss)



Bunch length vs. beam survival



This effect happens only when the resonance takes place

Summary

	Coasting beam	Q_x	Bunched beam	Q_x
Low intensity	$\sim 0.8 \times 10^9$		$\sim 0.4 \times 10^9$	
$(\delta p/p)_{rms}$	4.8×10^{-4}		1.3×10^{-3}	
$\Delta Q_{x,sc/y,sc}$	$-0.008/-0.011$		$-0.01/-0.015$	
$(I_1/I_0)_{min}$	0.26	4.3325	0.31	4.3325
$(\epsilon_1/\epsilon_0)_{max}$	1.20	4.3365	1.21	4.3385
z_1/z_0			0.79	4.3325
High intensity	$\sim 3.0 \times 10^9$		$\sim 1.2 \times 10^9$	
$(\delta p/p)_{rms}$	4.8×10^{-4}		1.3×10^{-3}	
$\Delta Q_{x,sc/y,sc}$	$-0.025/-0.03$		$-0.04/-0.045$	
$(I_1/I_0)_{min}$	0.72	4.3365	0.23	4.3385
$(\epsilon_1/\epsilon_0)_{max}$	1.28	4.3425	1.79	4.3425
z_1/z_0			0.71	4.3365

Tentative proof of principle reached ! (with critics of referees)

Experiment 2007-2008 → publications 2010

2012 → present

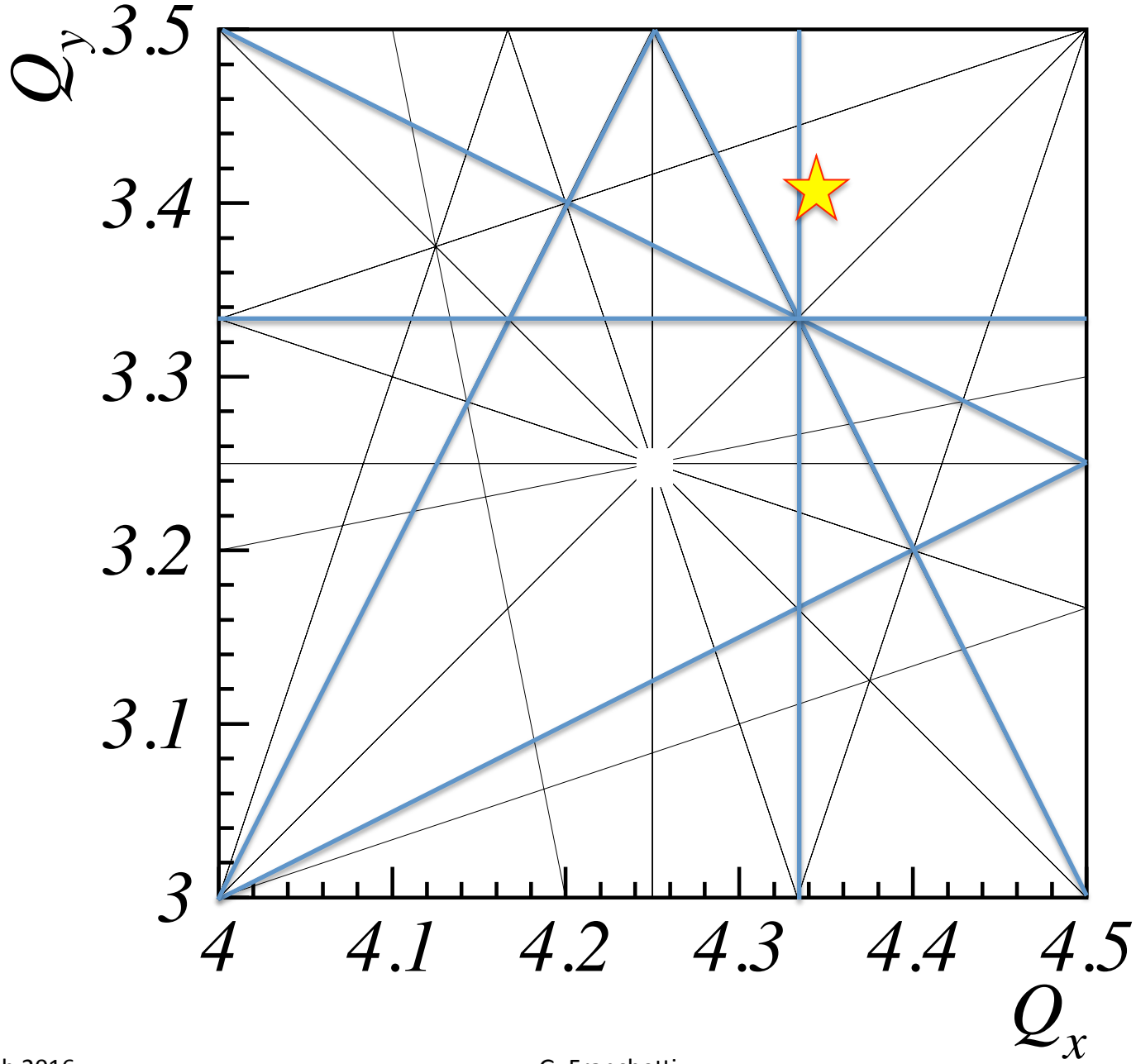
Space charge and coupled resonances

The new development started from the invitation of Frank Schmidt to MD in PS

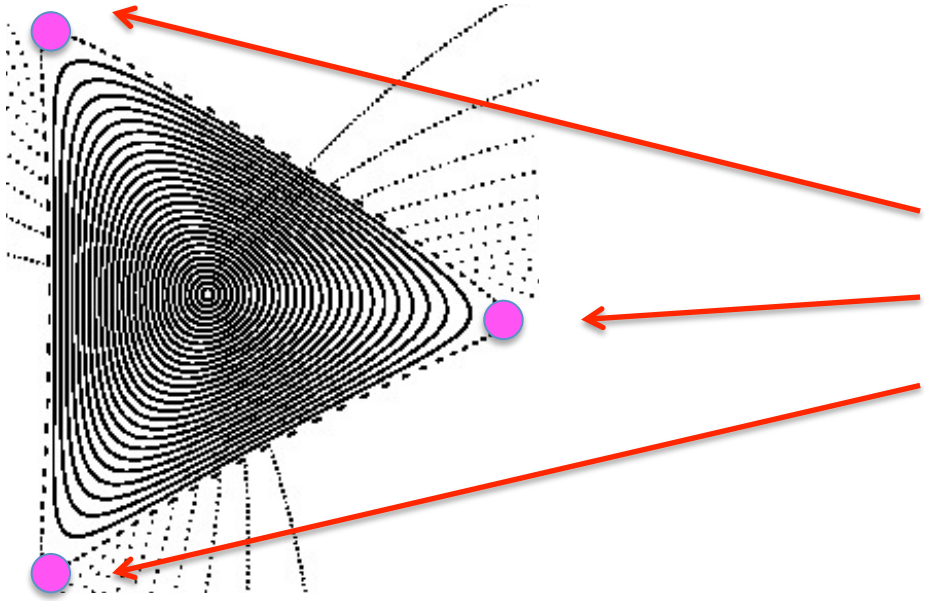
Effect of space charge on 3rd order coupled resonance

Unexplored

Very difficult also without space charge


Q_y
3.5
3.4
3.3
3.2
3.1
3
4
4.1
4.2
4.3
4.4
4.5
Q_x

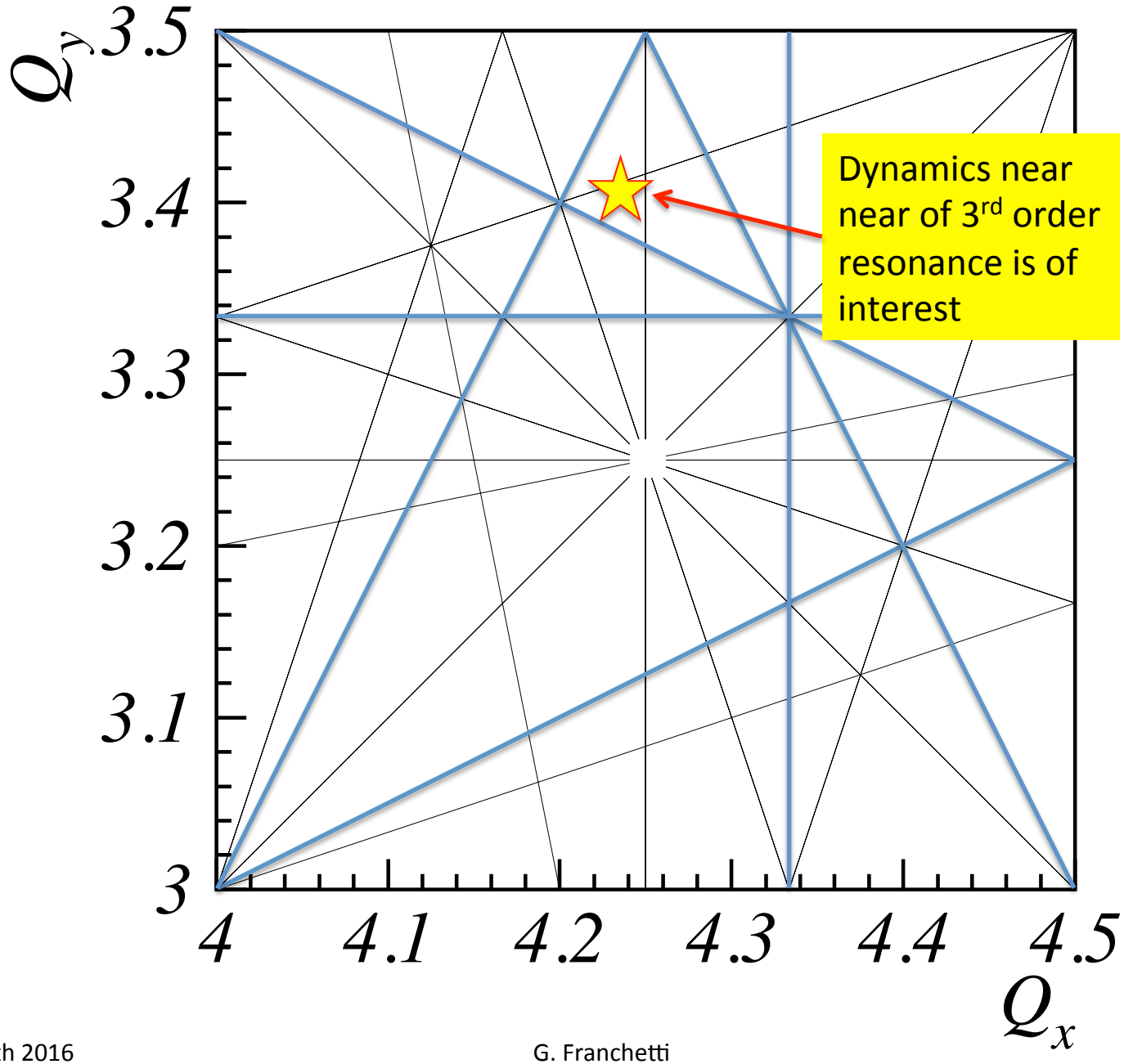
In proximity of $3Q_x = N$



Unstable fix points

stable orbits are "bounded" by the unstable fix points

Close to $Q_x + 2Q_y = N$


Q_y
3.5
3.4
3.3
3.2
3.1
3
4
4.1
4.2
4.3
4.4
4.5
Q_x
Dynamics near near of 3rd order resonance is of interest

Unfortunately coupled resonances require a 4D treatment of the dynamics

$$nQ_x + mQ_y = N$$

structure of resonances is controlled by the equations

$$\frac{d^2x}{ds^2} - k_x x = \quad Re\left[\sum_{n=2}^{M}(k_n(s) + ij_n(s))\frac{(x+iy)^n}{n!}\right]$$

$$\frac{d^2y}{ds^2} - k_y y = -Im\left[\sum_{n=2}^{M}(k_n(s) + ij_n(s))\frac{(x+iy)^n}{n!}\right]$$

Do we find fix points in proximity of

$$2Q_y + Q_x = N \ ?$$

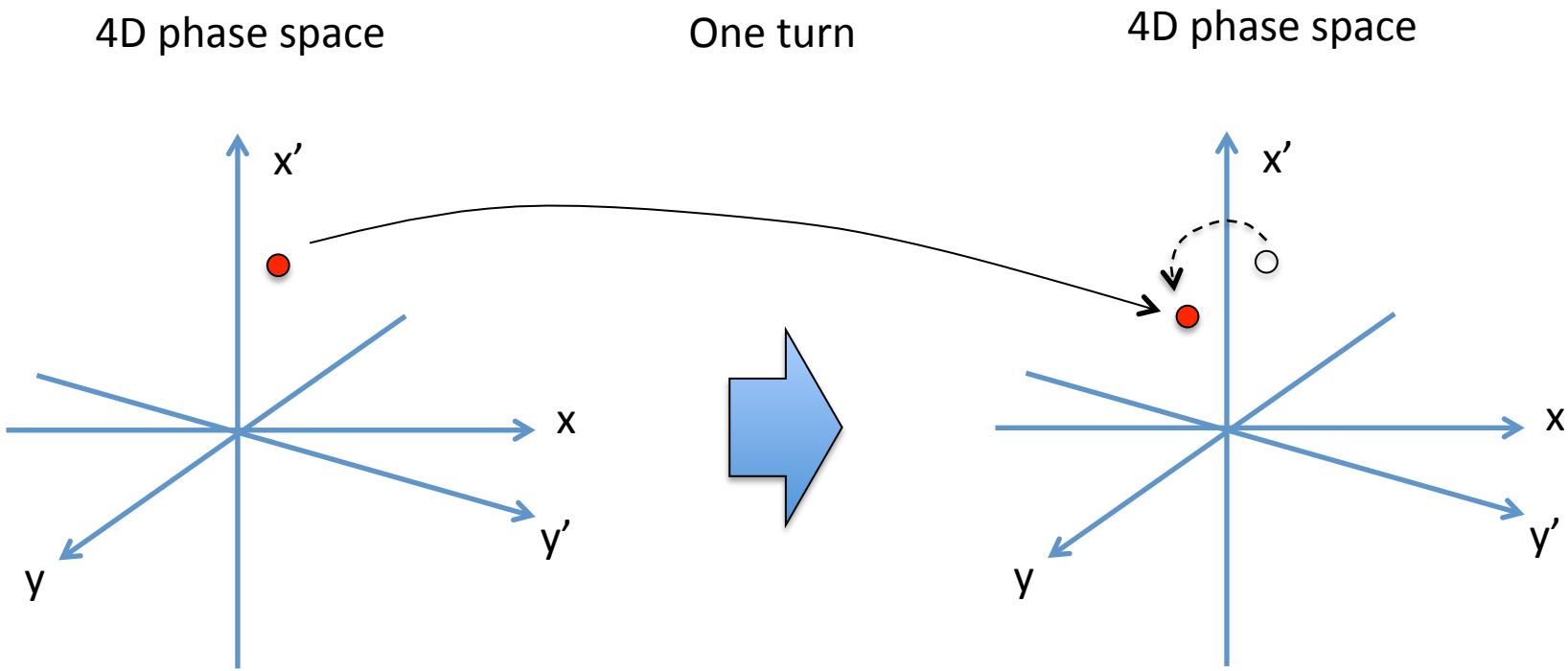
Wrong concept!

Close $2Q_y + Q_x = N$ there are **fix-lines**

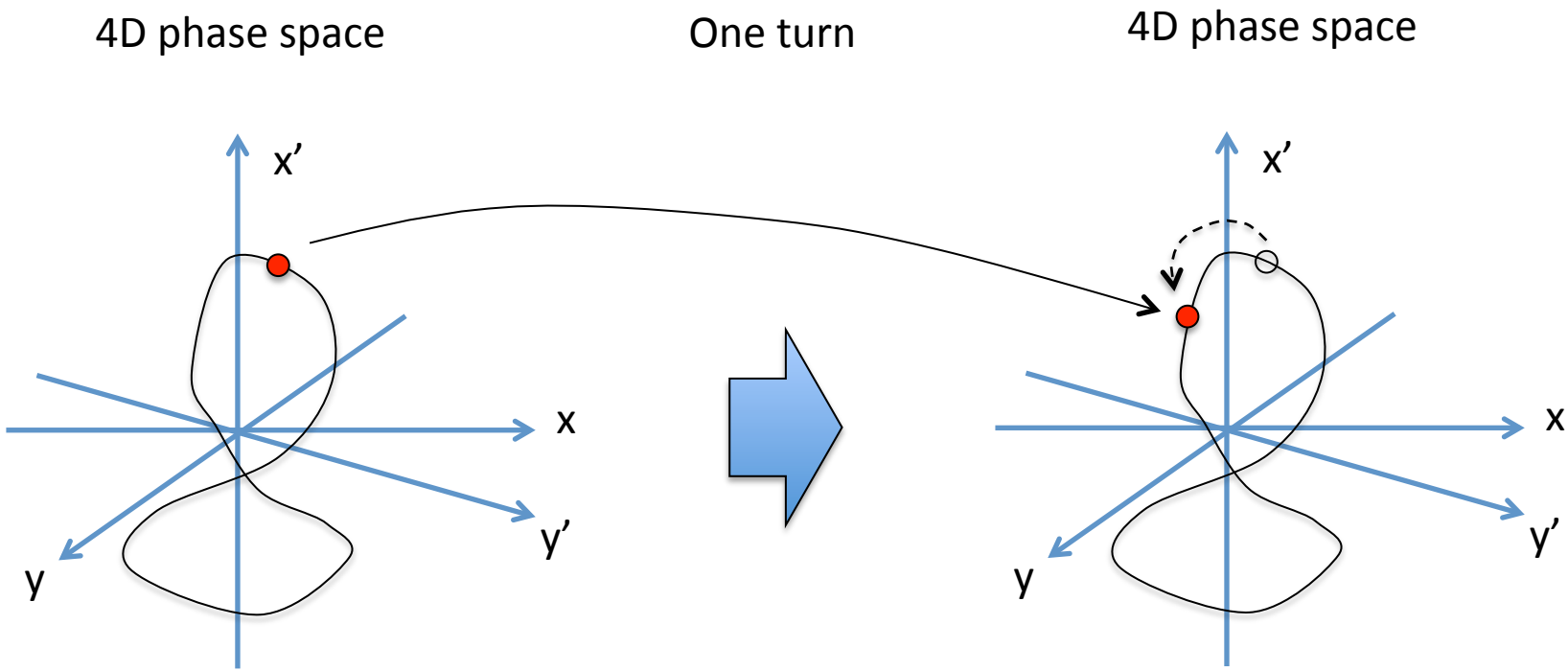
F. Schmidt
PhD

These are closed lines in the 4D phase space
of which we can only see the projections

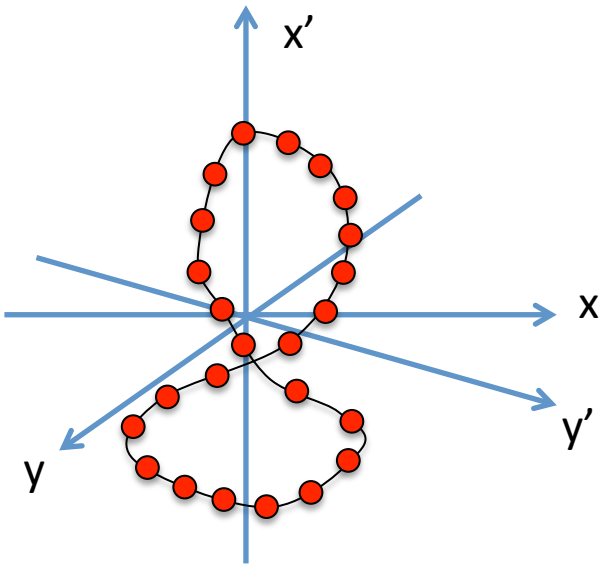
Close to the resonance



Close to the resonance

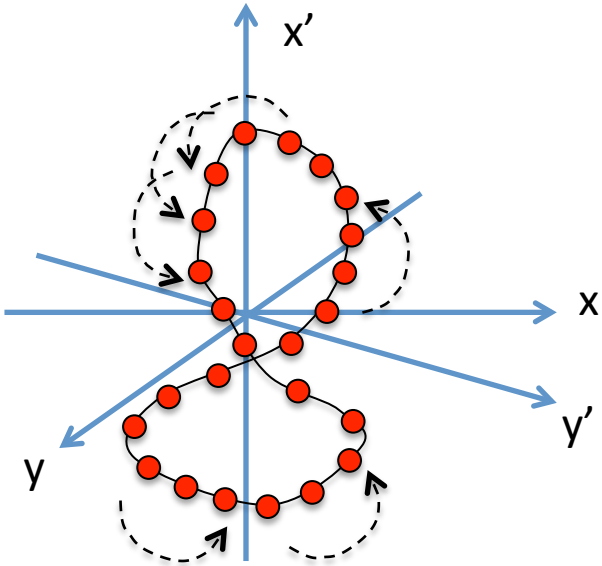


4D phase space



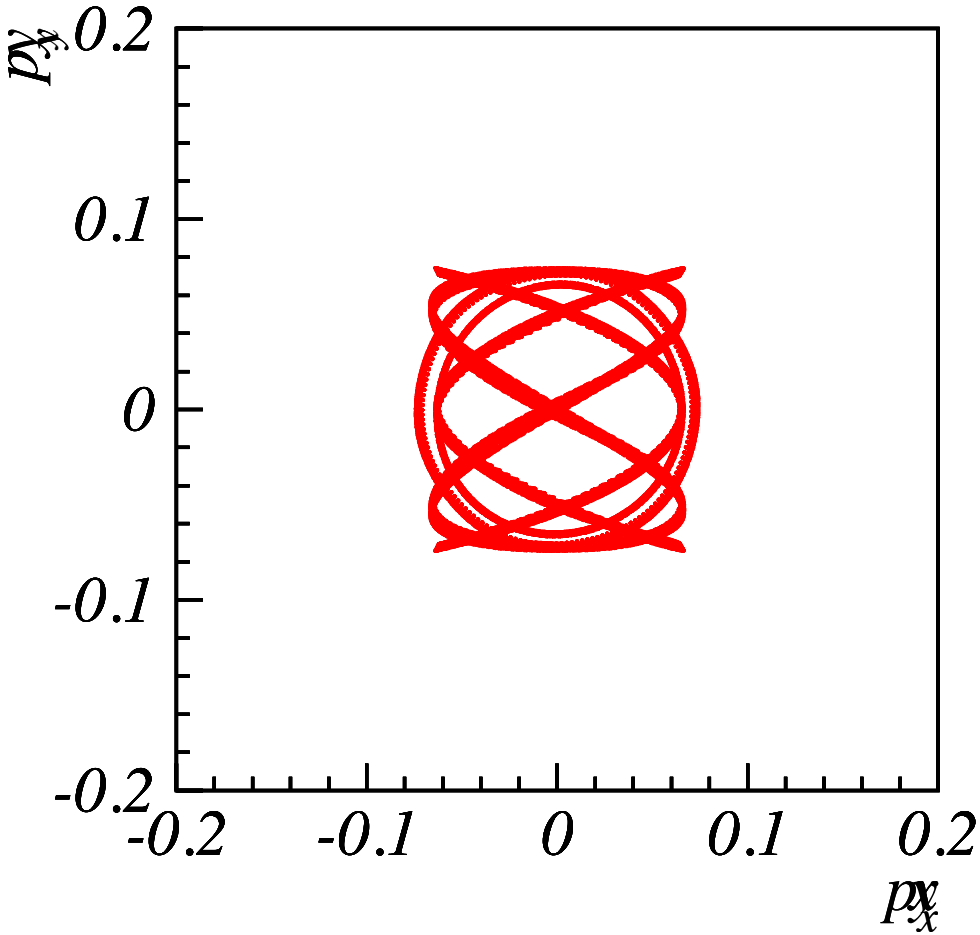
One turn

4D phase space



After one turn each point on the fix-line is mapped into the fix-line

Fix-line projections



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Extended treatment in
http://arxiv.org/abs/1504.04389

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Analytic form

projection of a fix-line close to the 3rd order coupled resonance

$$x_t = \sqrt{\beta_x a_x}\cos[-2(Q_y - t_y)t + \pi M]$$
$$y_t = \sqrt{\beta_y a_y}\cos[(Q_y - t_y)t]$$

a_x, a_y are the invariant of the fix line, they depends on the "distance" from the resonance, and they are **CONSTANT**

M is an integer that depends on the sign of $\Delta_r = -N + Q_x + 2Q_y$, the "distance" of the resonance

t_y parameter that specify the canonical transformation in which makes a_x, a_y time independent.

t parameter which parameterize the fix-line

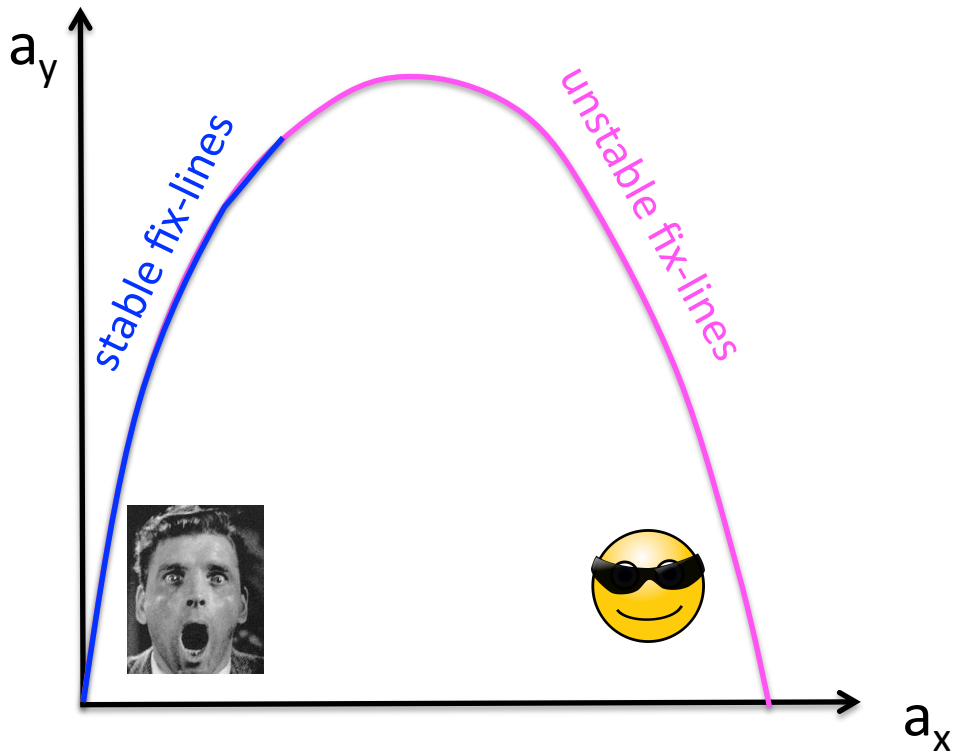
How many fix-lines ?

Near $3Q_x = N$ there are 3 unstable fix points

Near $2Q_y + Q_x = N$ there are **infinite** fix-lines !!

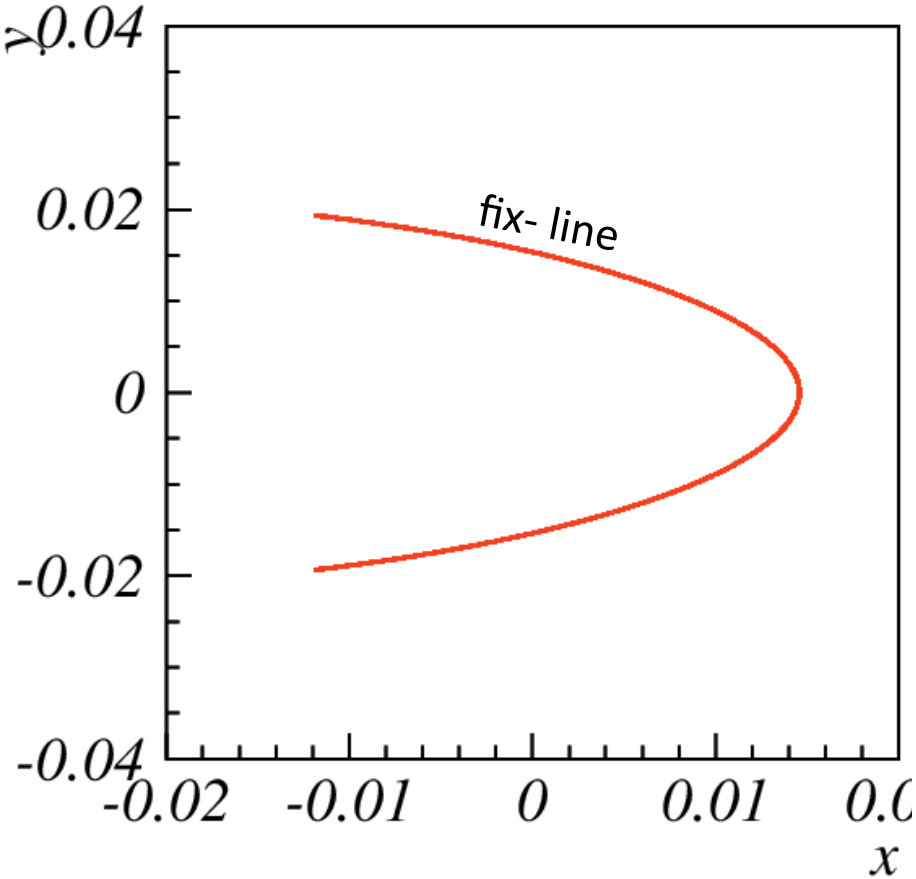
What is the meaning of this ?

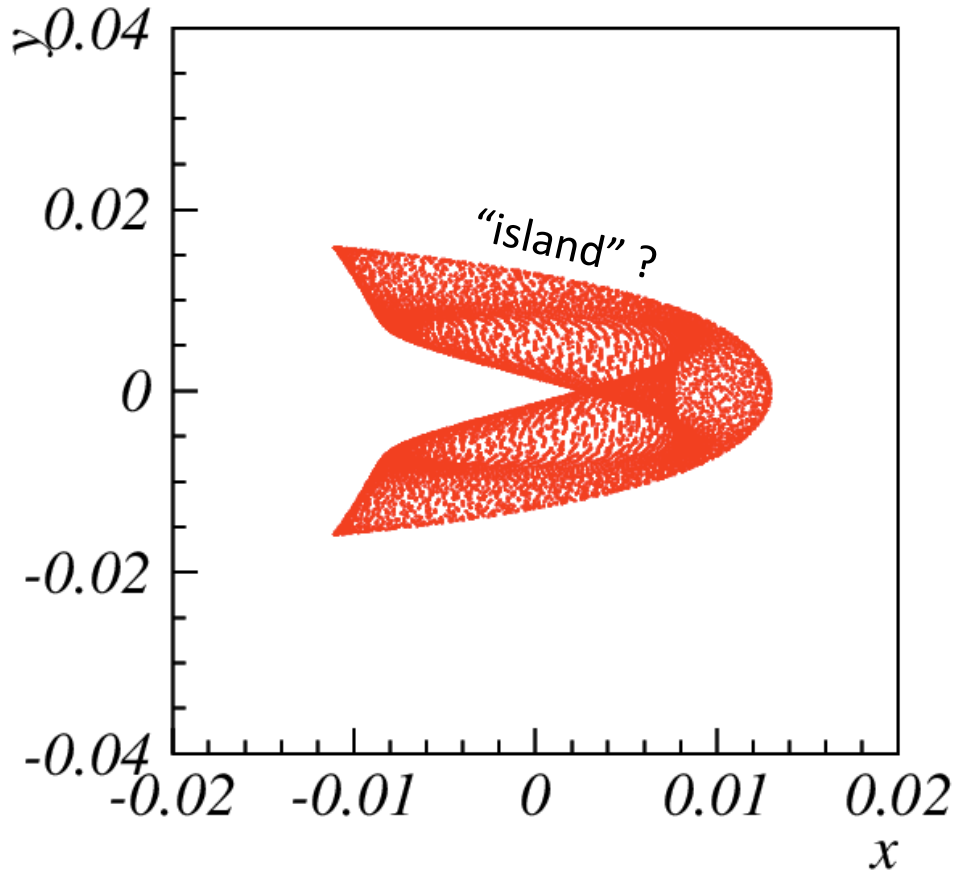
All fix-lines



$$0 = \Delta_r \Lambda (-1)^M \left[\frac{1}{2\sqrt{\tilde{a}_x}} \tilde{a}_y + 2\sqrt{\tilde{a}_x} \right] + \frac{\Delta_r^2}{2}$$

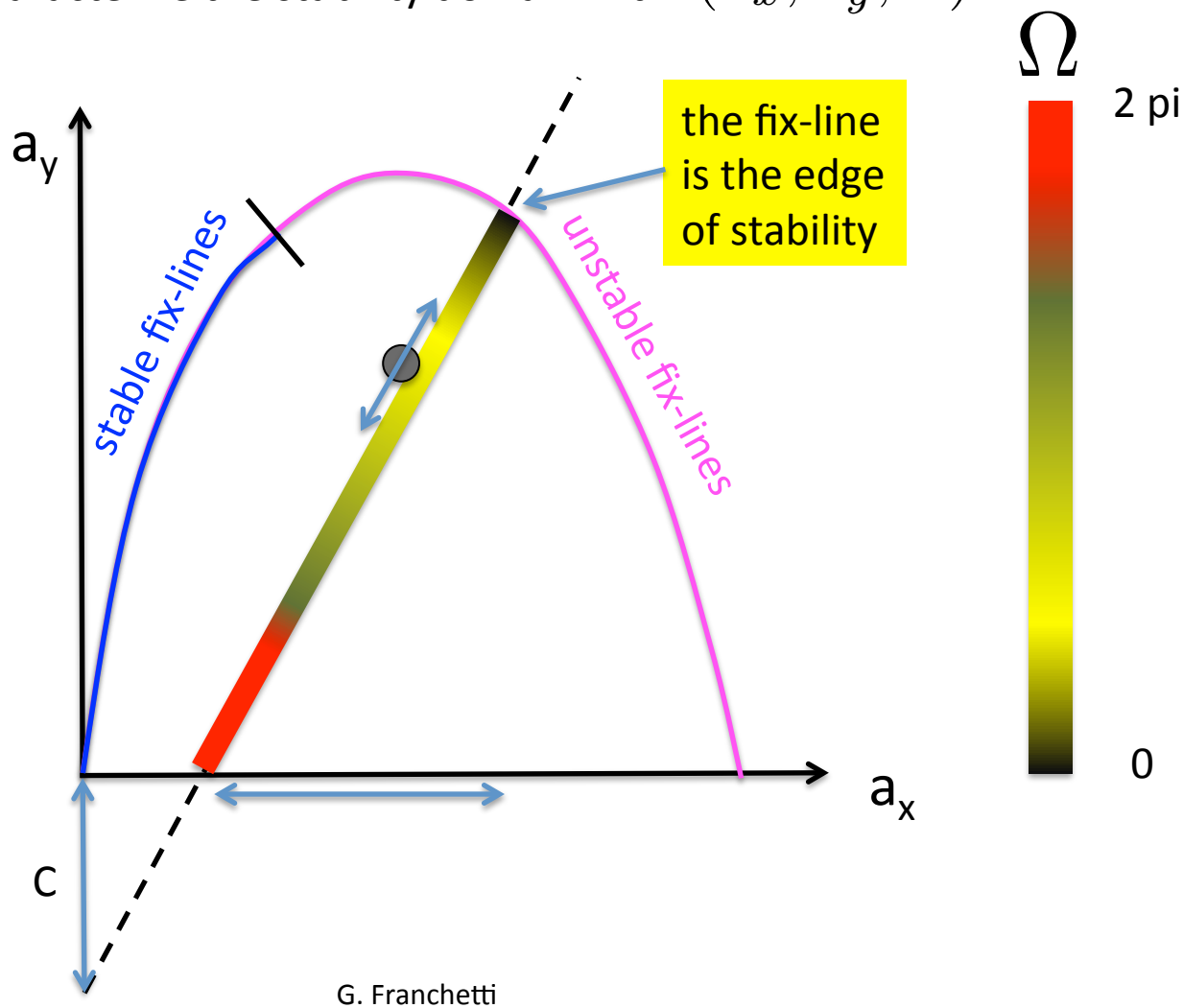
Islands (Tori)



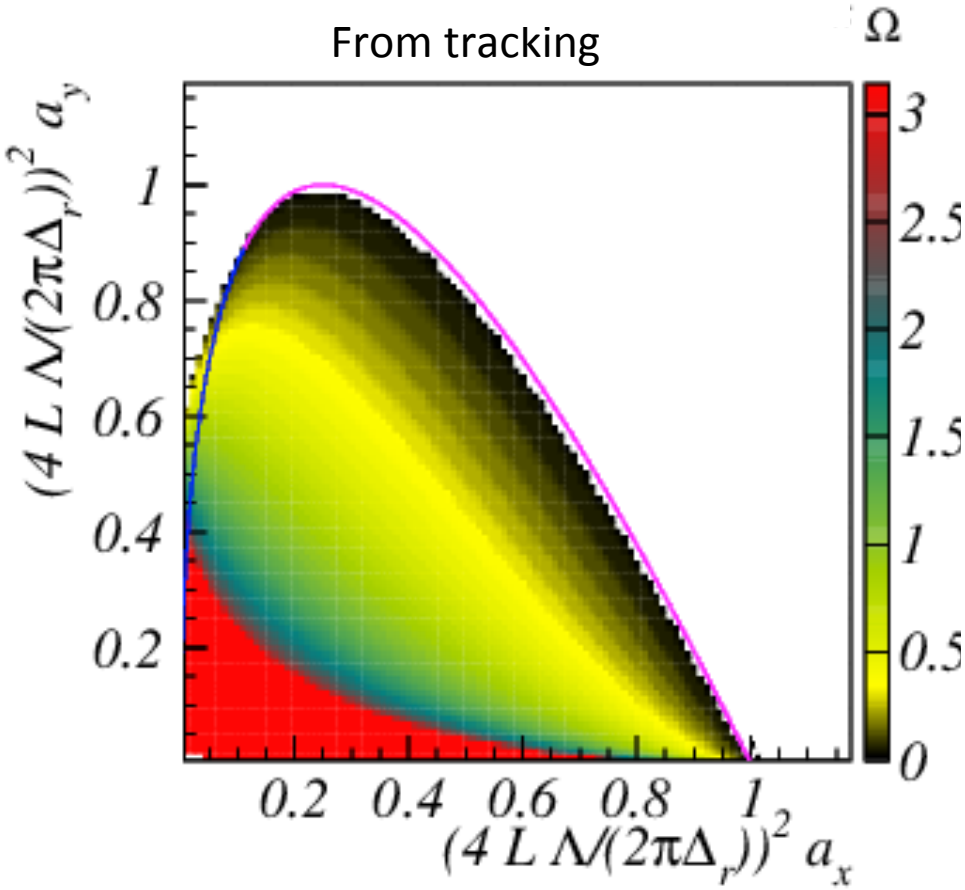


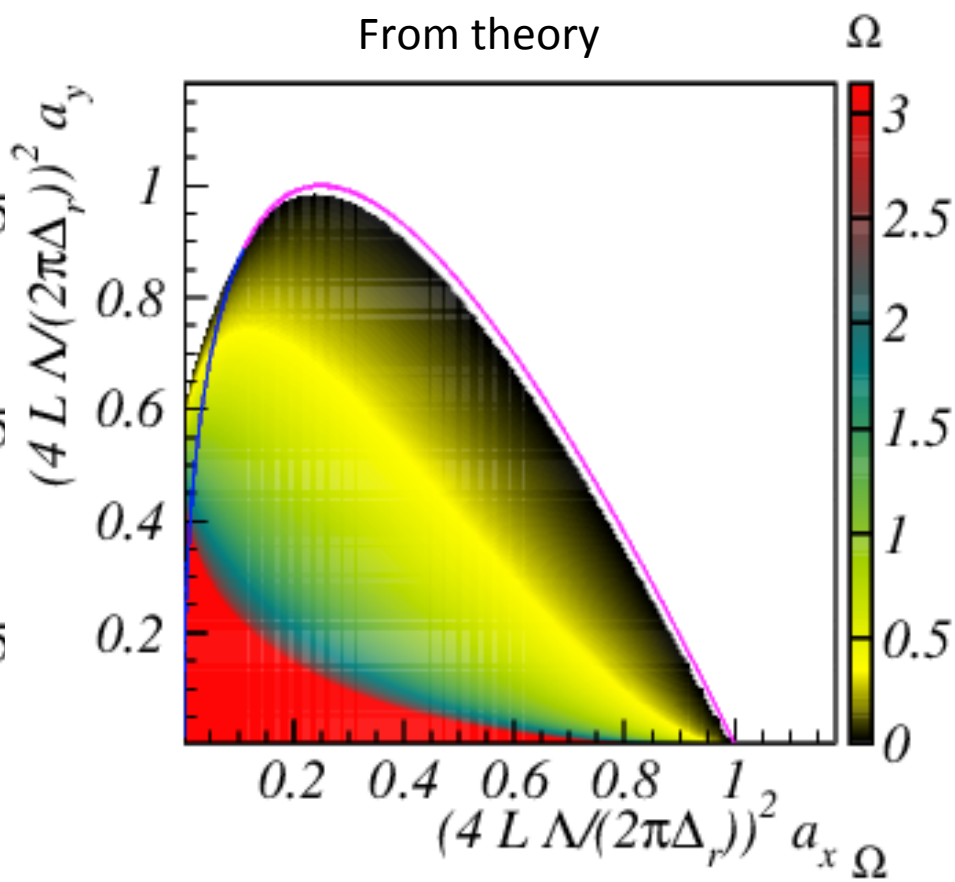
Stability domain

We can characterize the stability domain with (a_x, a_y, Ω)



Stability domain

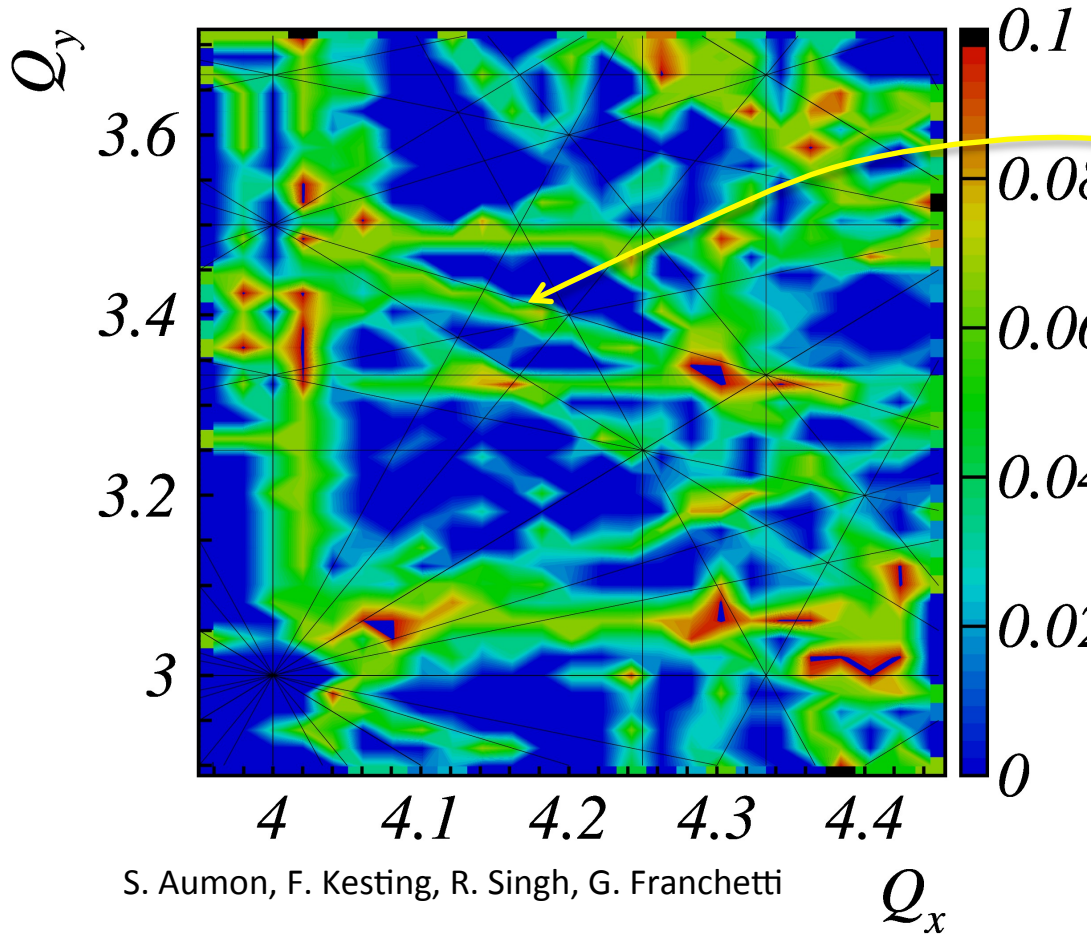




Really good! also in situation off of the “single harmonics limit”

We are ready to go !

SIS18@2014

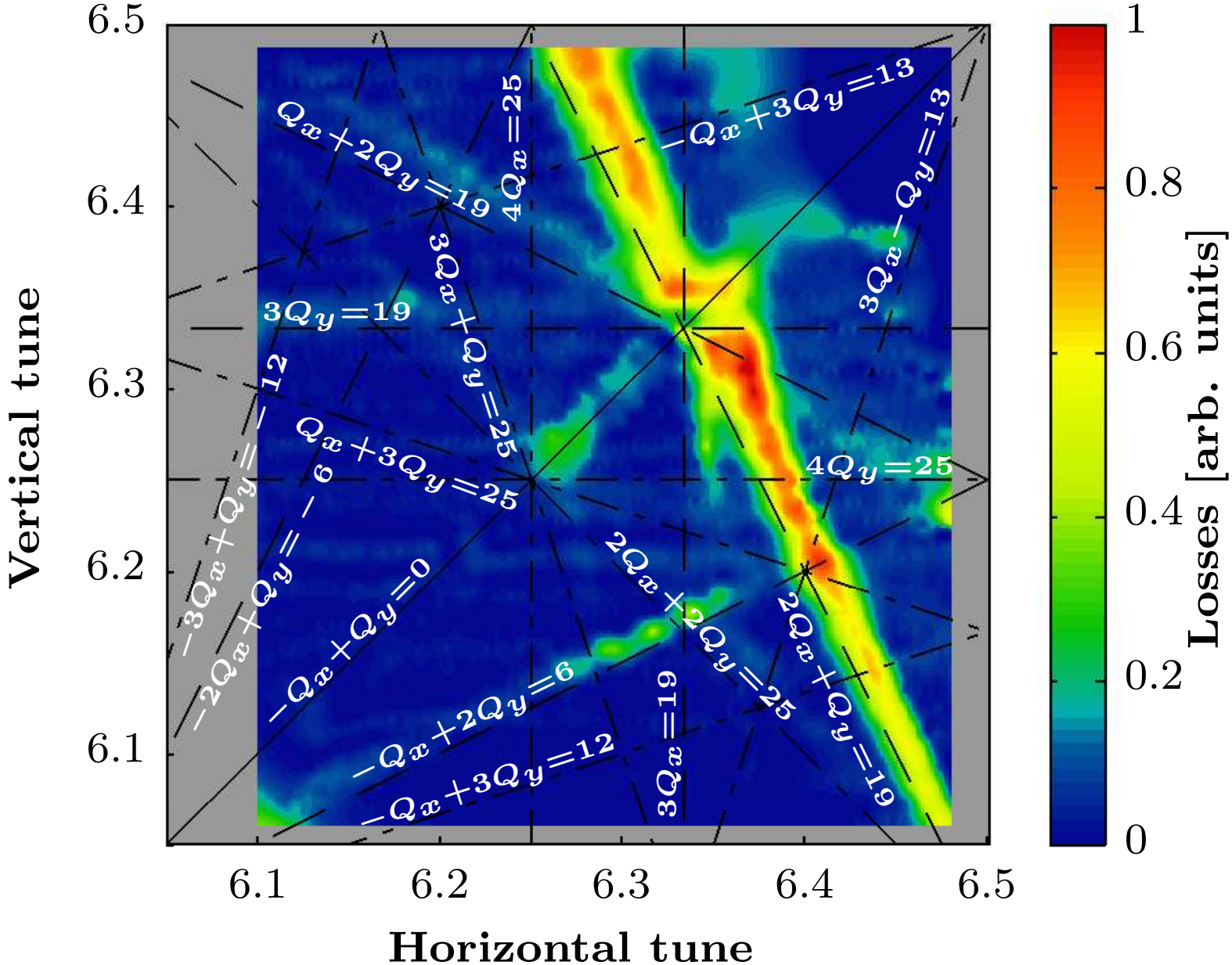


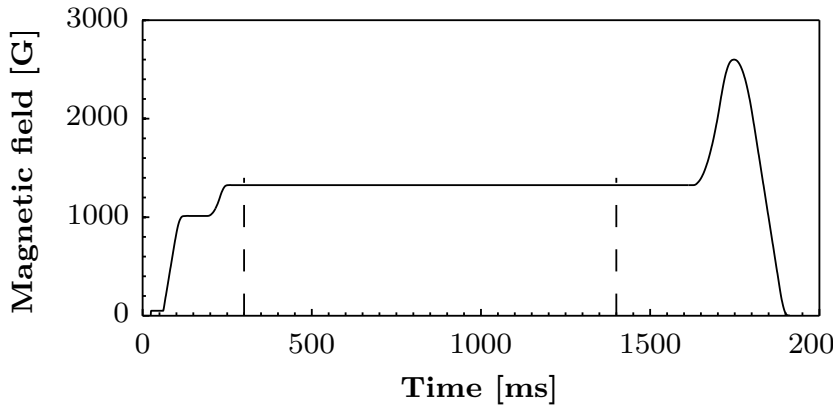
Now we understand better what is the dynamics here

Fundamental ingredient to create complex halo (hence to predict halo extension and maybe density), for high intensity bunched beams

The PS experiment of 2012 “towards the unknown”

G. Franchetti, S. Gilardoni, A. Huschauer, F. Schmidt, R. Wasef


Vertical tune
Horizontal tune
Losses [arb. units]
6.1
6.2
6.3
6.4
6.5
0
0.2
0.4
0.6
0.8
1
$Q_x+2Q_y=19$
$4Q_x=25$
$-Q_x+3Q_y=13$
$3Q_x-Q_y=13$
$3Q_y=19$
$3Q_x+Q_y=25$
$-3Q_x+Q_y=-12$
$Q_x+3Q_y=25$
$4Q_y=25$
$-2Q_x+Q_y=-6$
$-Q_x+Q_y=0$
$2Q_x+2Q_y=25$
$2Q_x+Q_y=19$
$-Q_x+2Q_y=6$
$-Q_x+3Q_y=12$
$3Q_x=19$



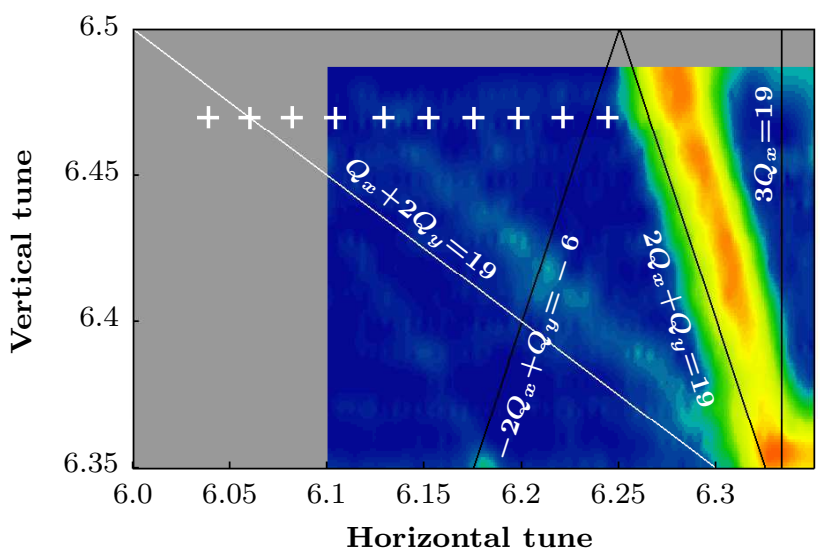


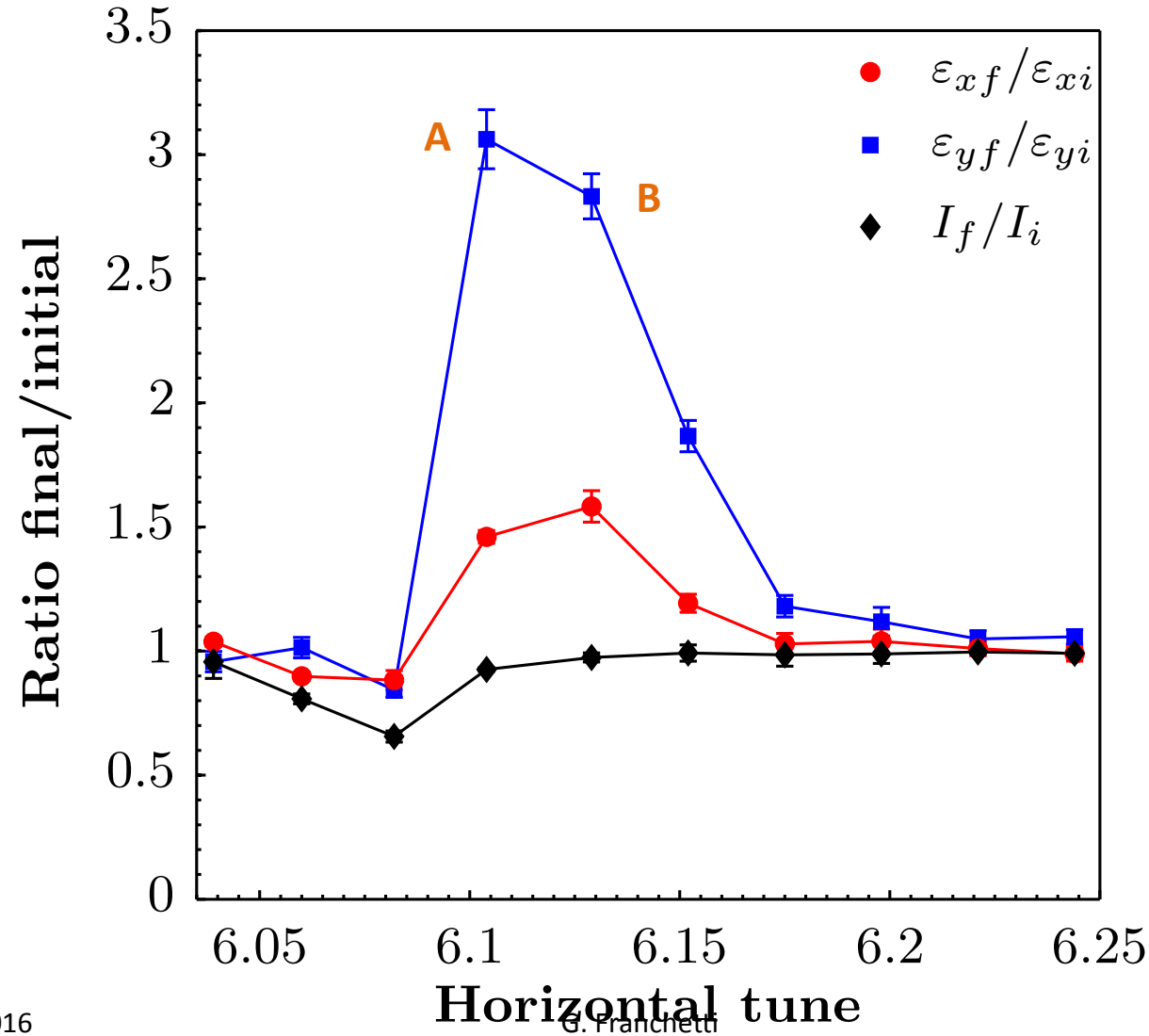
TABLE I. Beam and machine parameters.

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

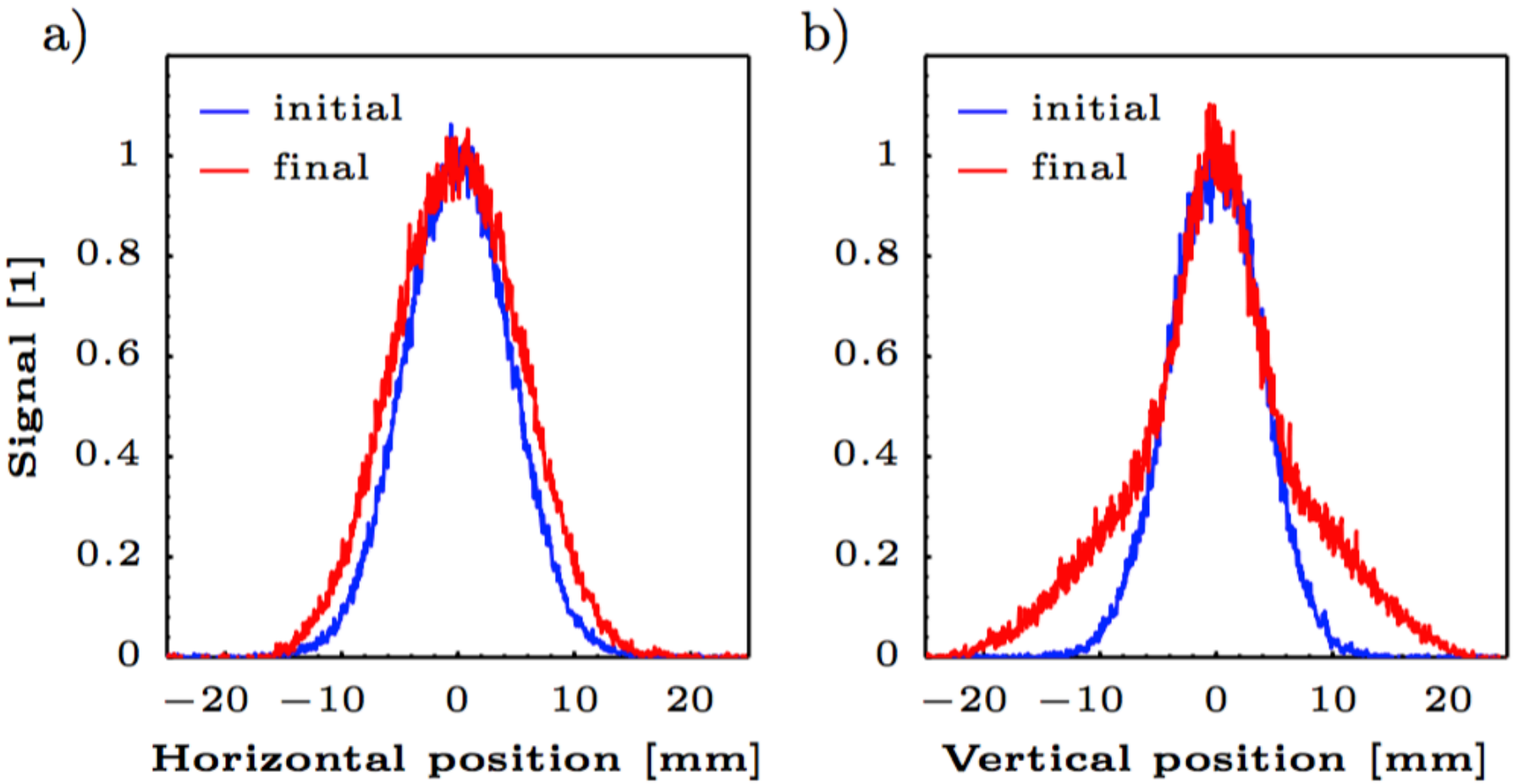
[a] The tune spread is calculated according to Ref. [18].

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

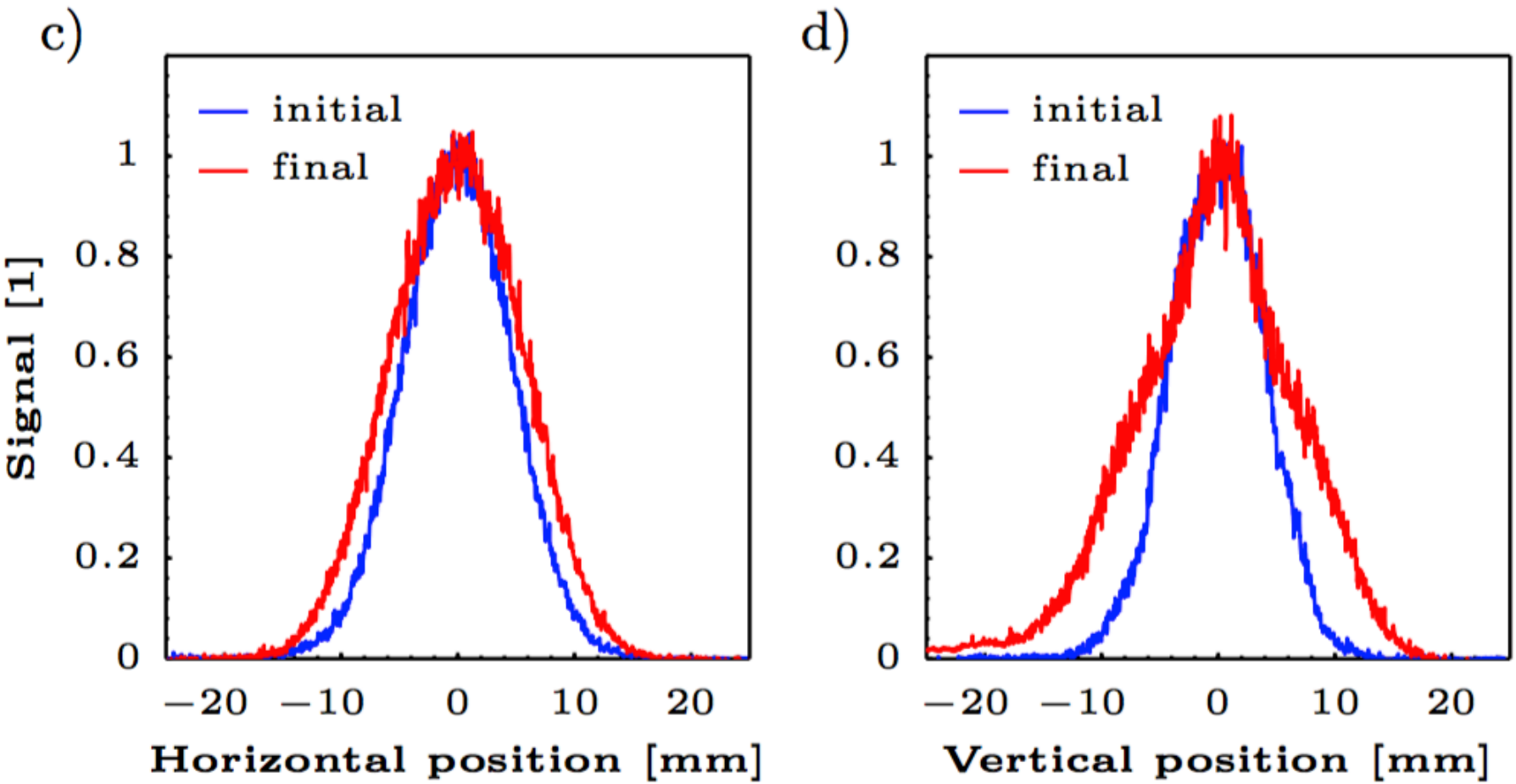
PS campaign results

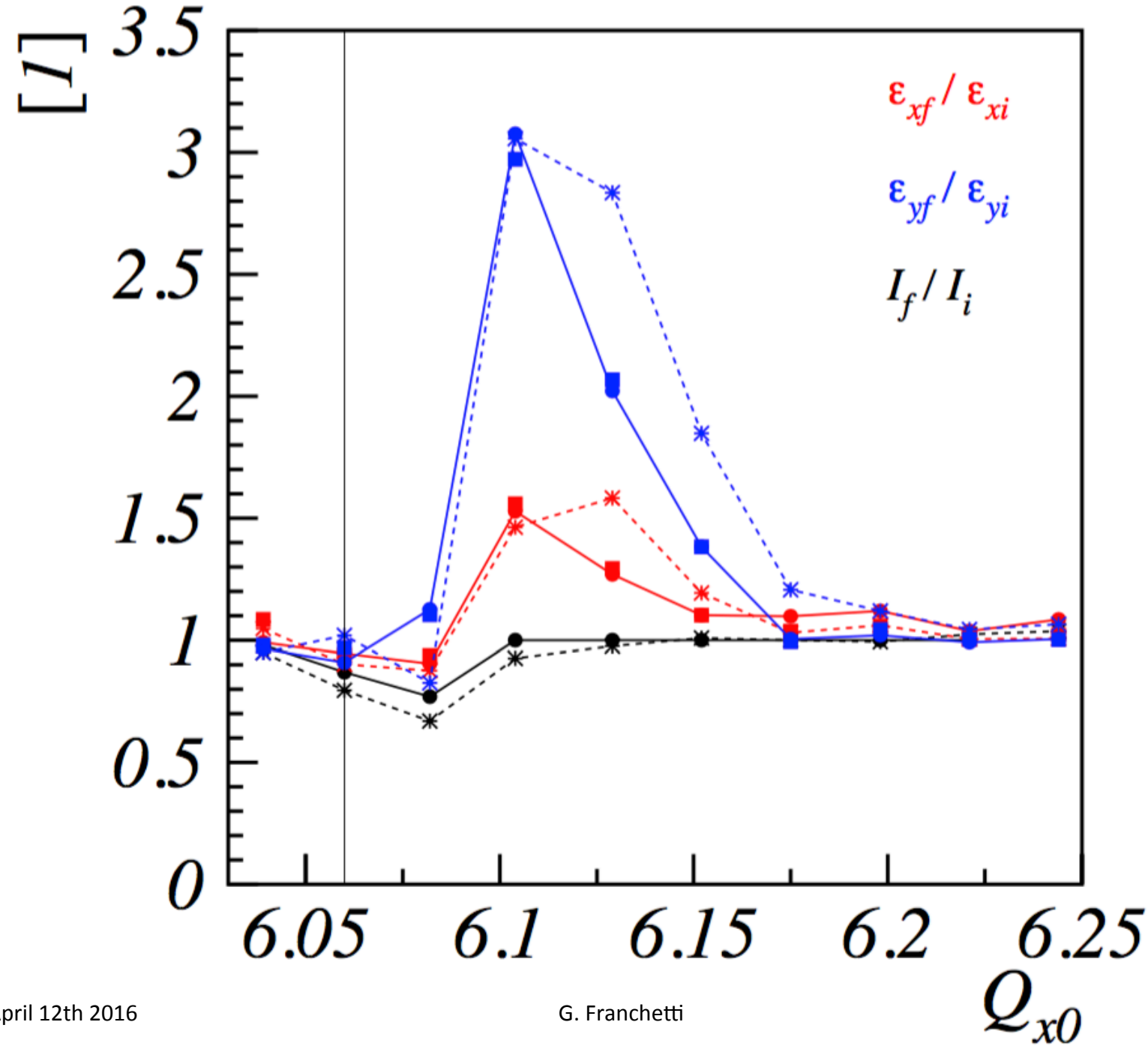


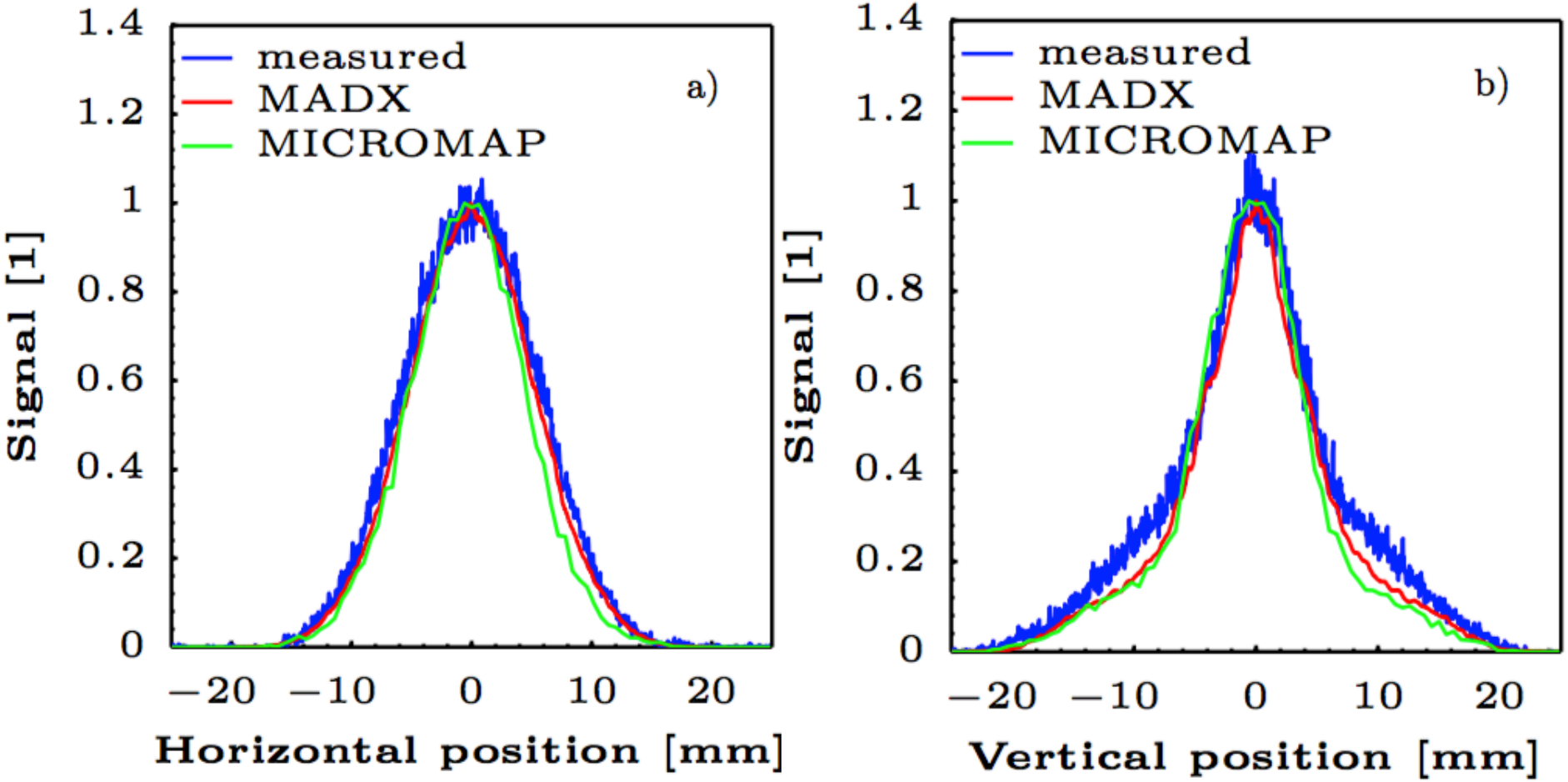
Beam Profiles (A)



Beam Profiles (B)

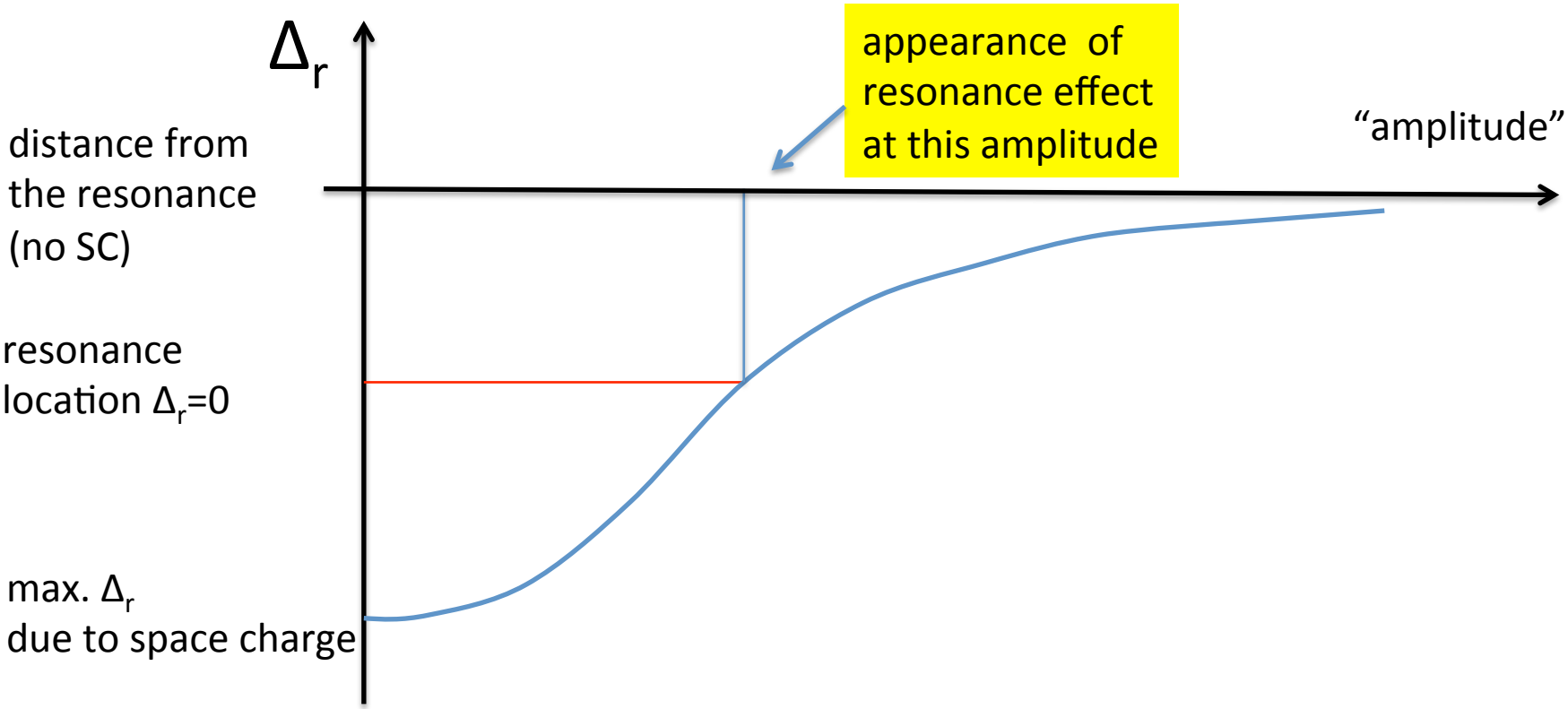



[1]
3.5
3
2.5
2
1.5
1
0.5
0
6.05
6.1
6.15
6.2
6.25
Q_{x0}
$\varepsilon_{xf} / \varepsilon_{xi}$
$\varepsilon_{yf} / \varepsilon_{yi}$
I_f / I_i

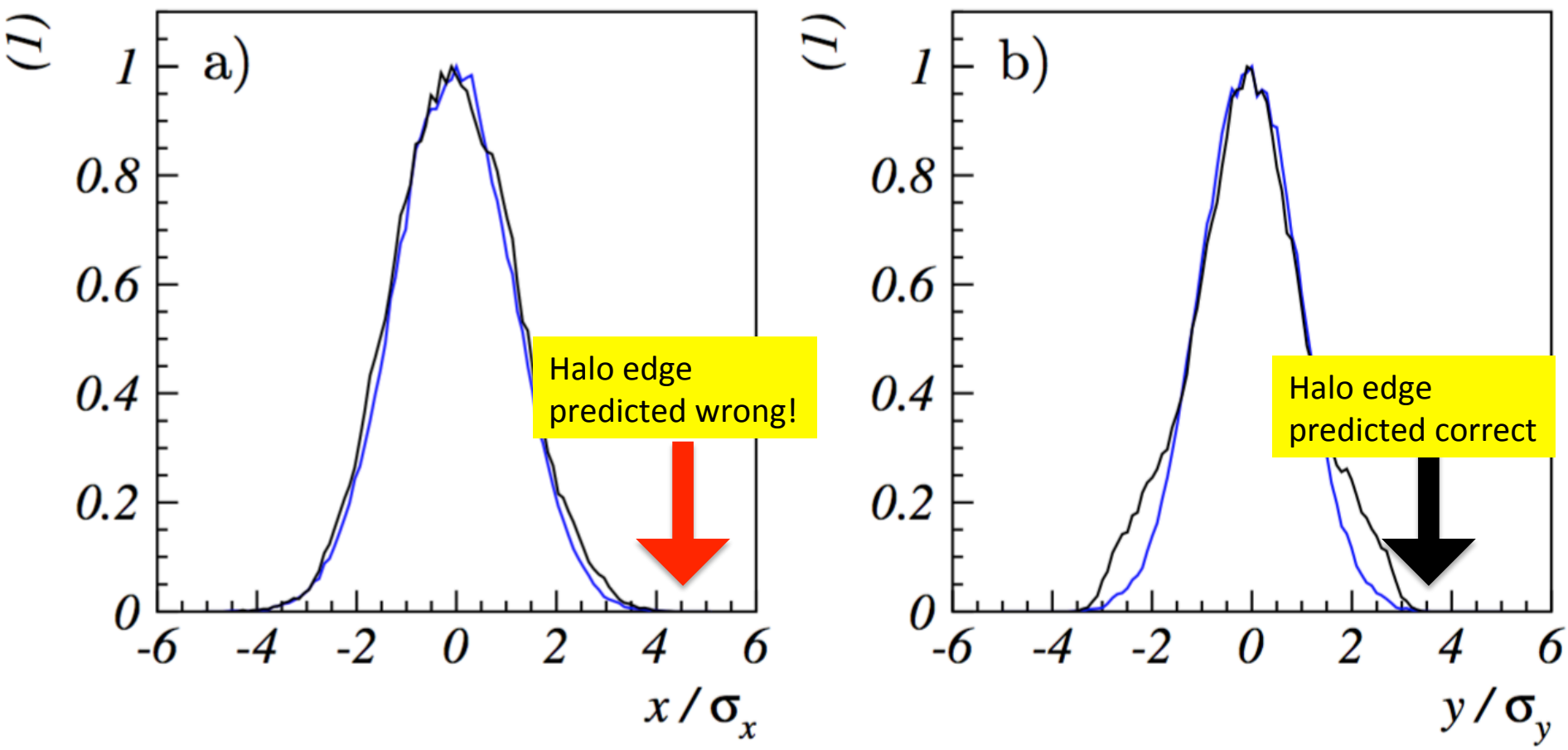

measured
MADX
MICROMAP
a)
Signal [1]
Horizontal position [mm]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−20
−10
0
10
20
measured
MADX
MICROMAP
b)
Signal [1]
Vertical position [mm]

Amplitude detuning

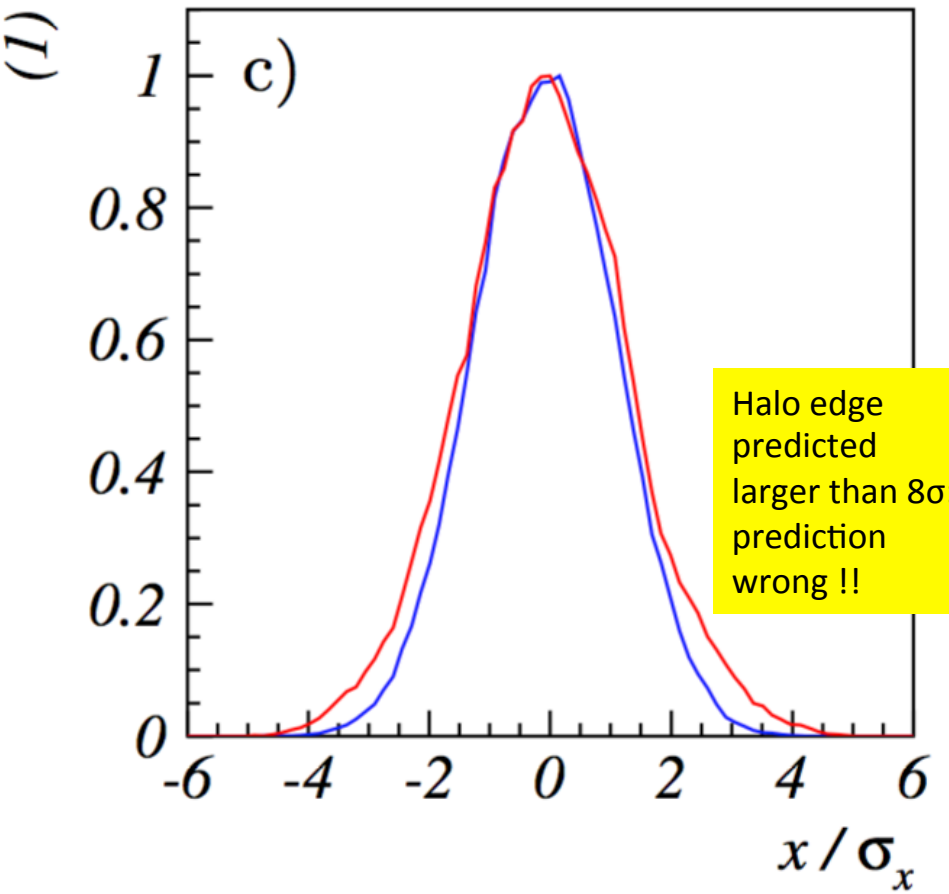
Distance from the resonance $\Delta_r = Q_x + 2Q_y - N$



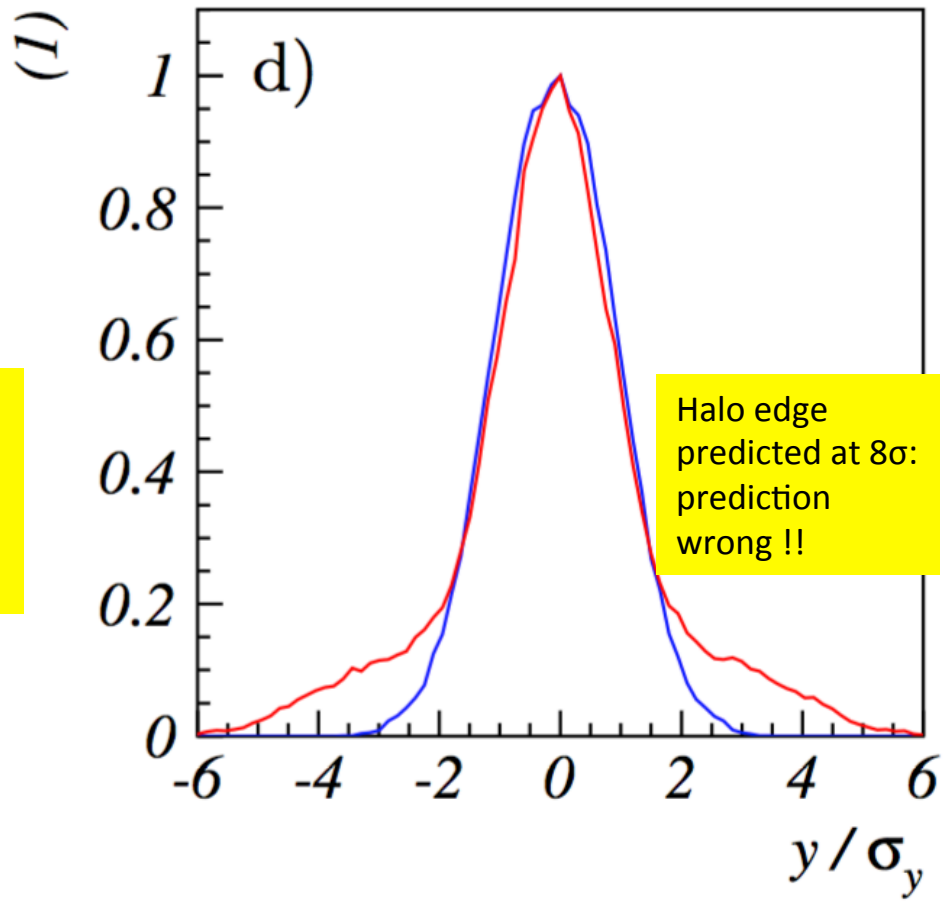
Without chromaticity



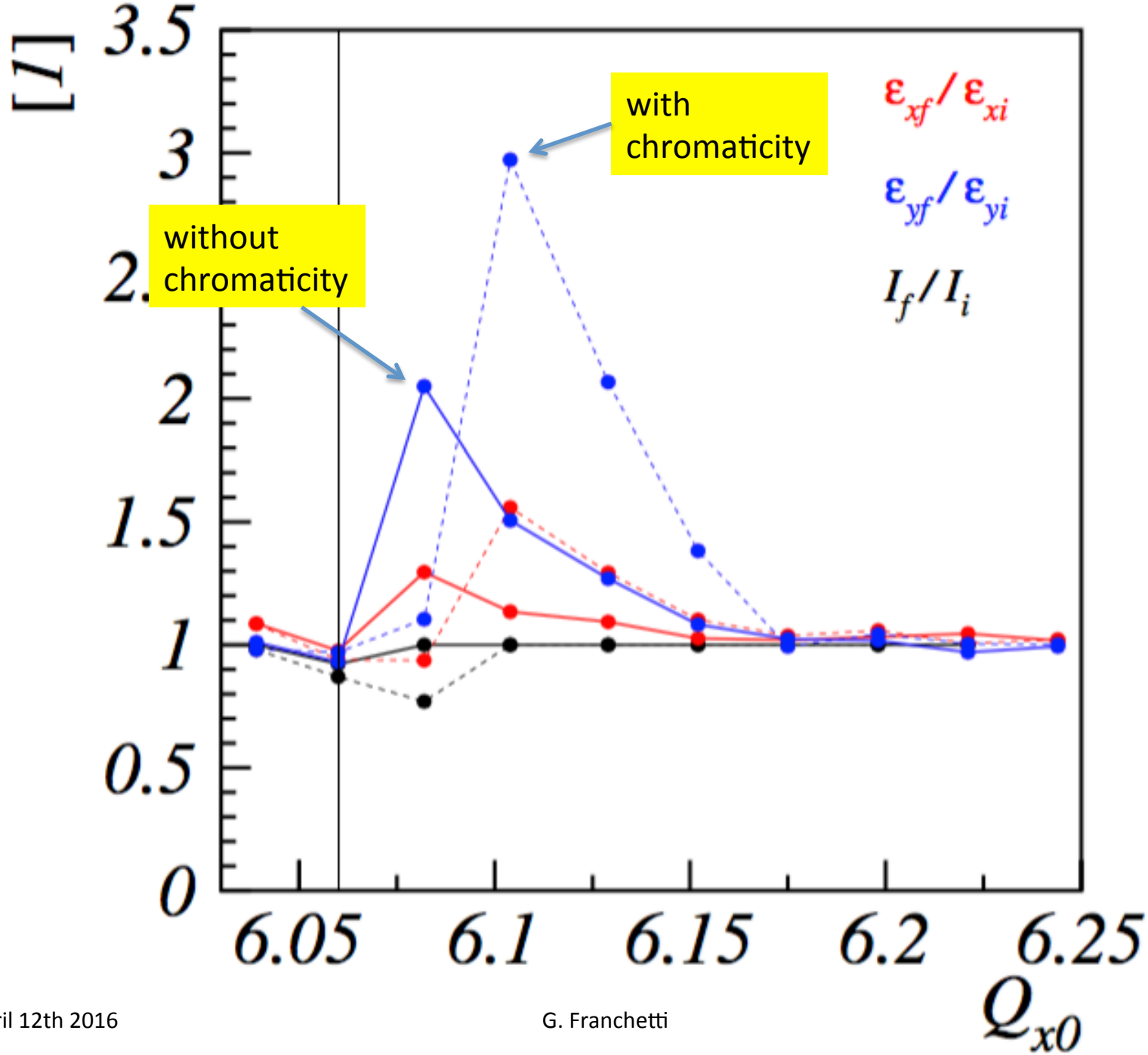
Including chromaticity



Halo edge predicted larger than 8σ: prediction wrong !!



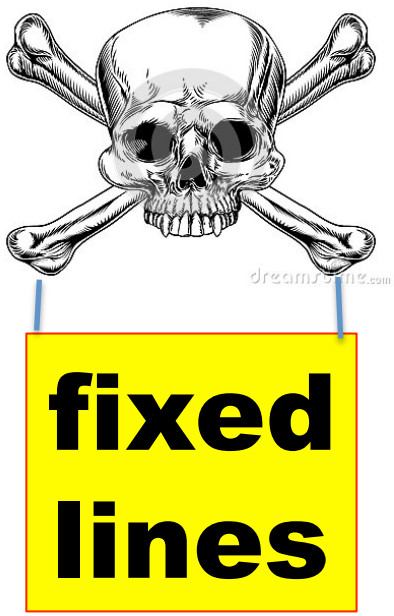
Halo edge predicted at 8σ: prediction wrong !!

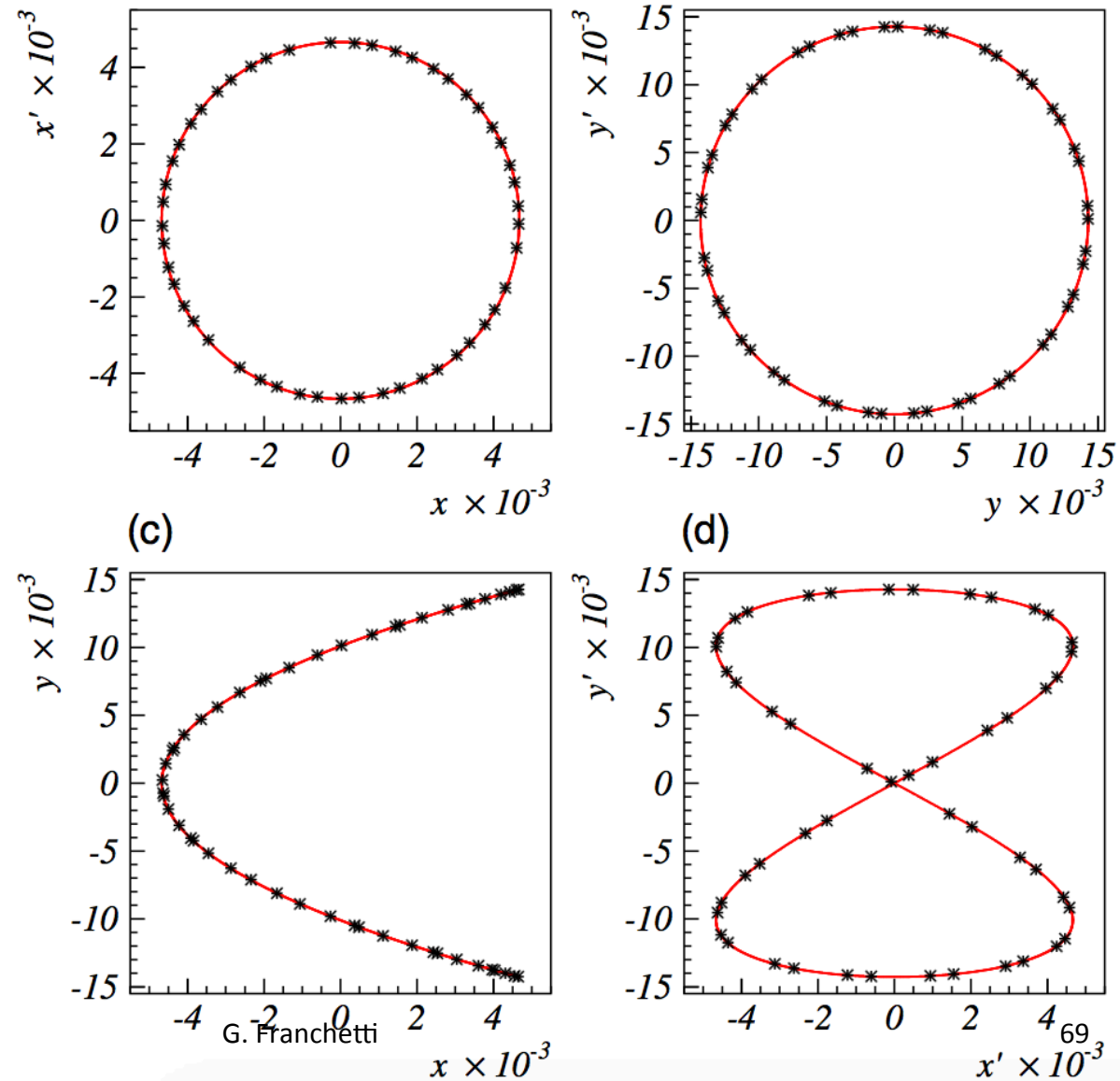

[1]
3.5
3
2.
2
1.5
1
0.5
0
6.05
6.1
6.15
6.2
6.25
Q_{x0}
with chromaticity
without chromaticity
$\varepsilon_{xf}/\varepsilon_{xi}$
$\varepsilon_{yf}/\varepsilon_{yi}$
I_f/I_i

Something seems very wrong!

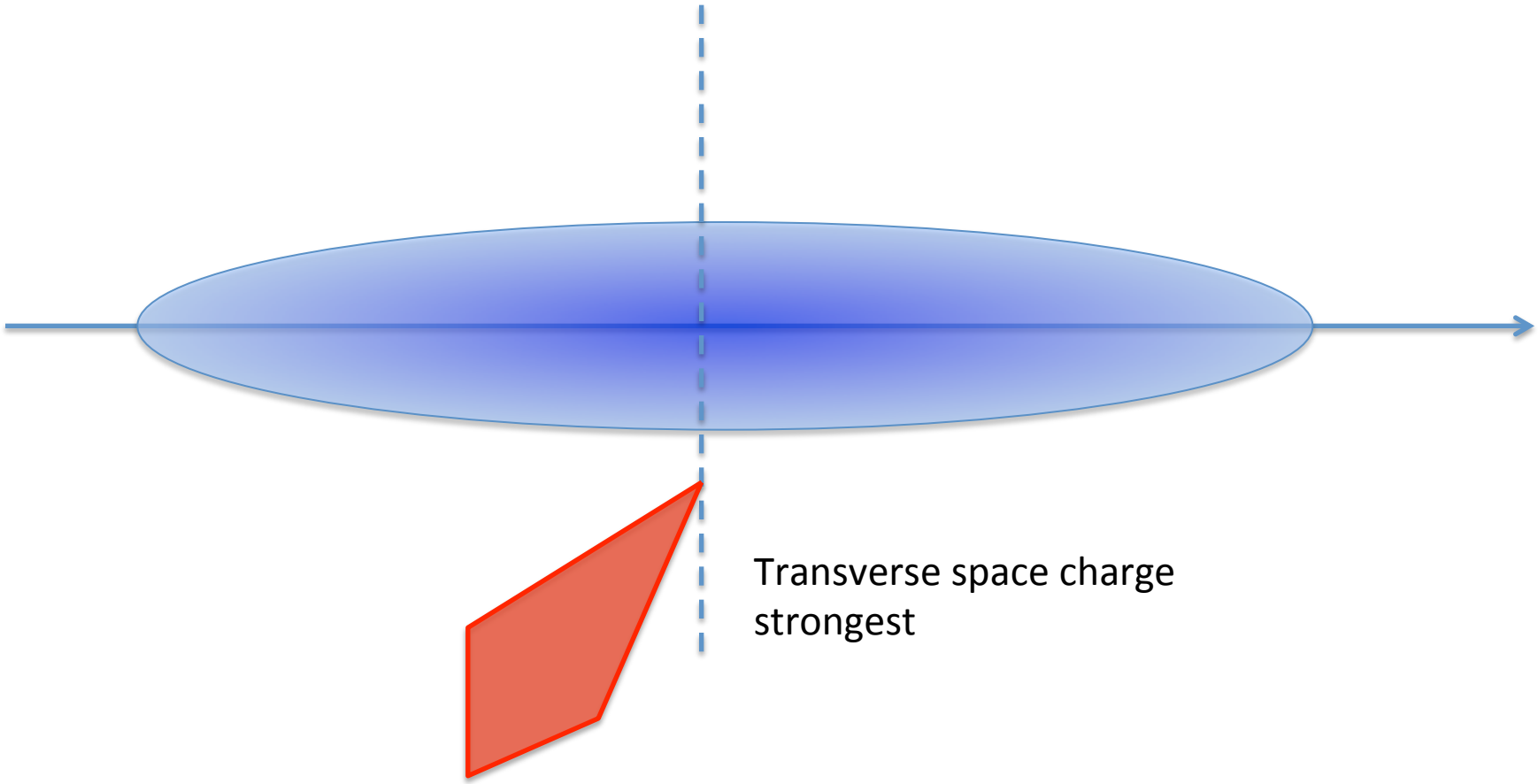
The -x- profile does not exhibit an halo, and the -y- profile have a smaller halo than expected

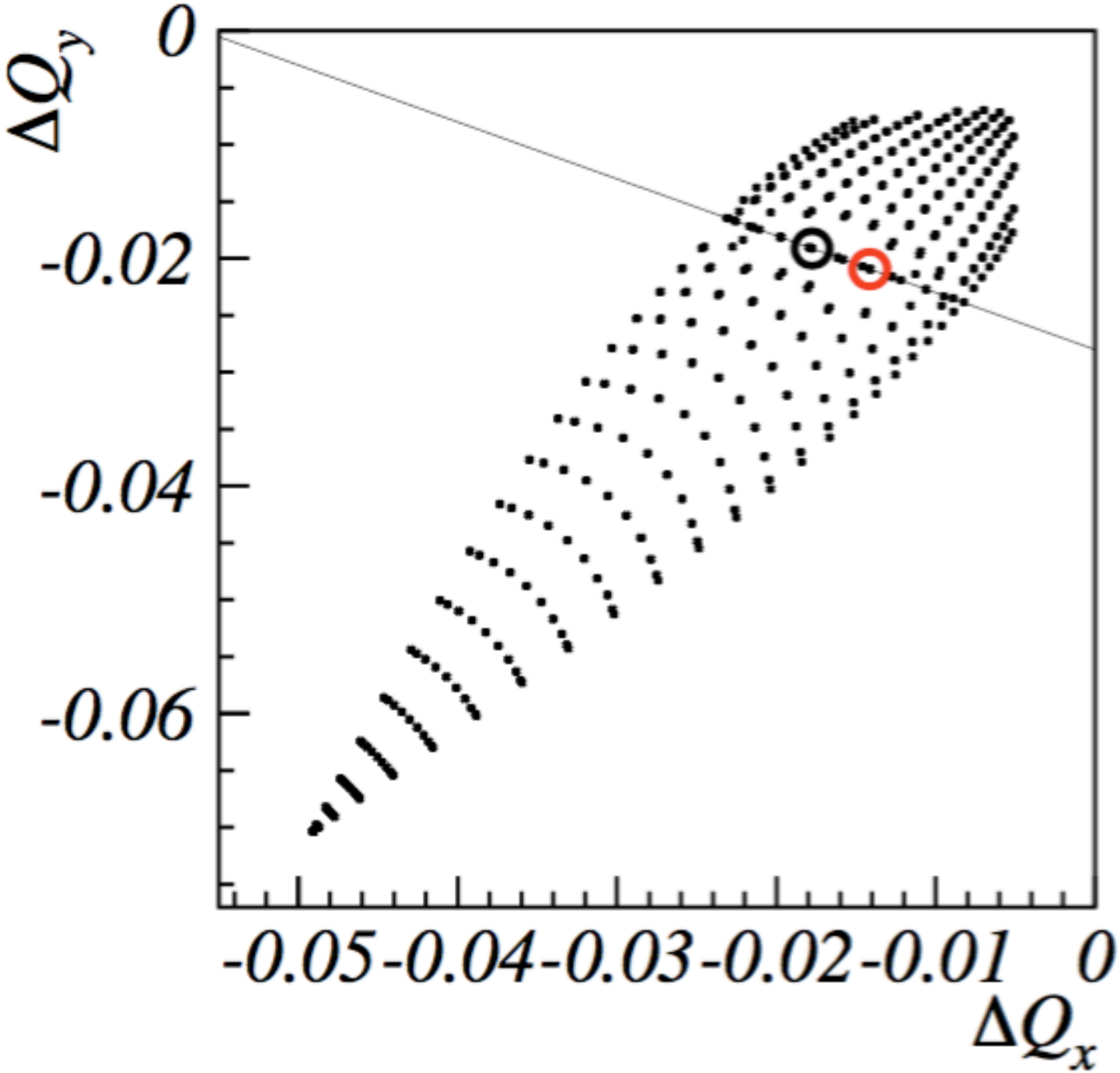
Coupled dynamics on the resonance

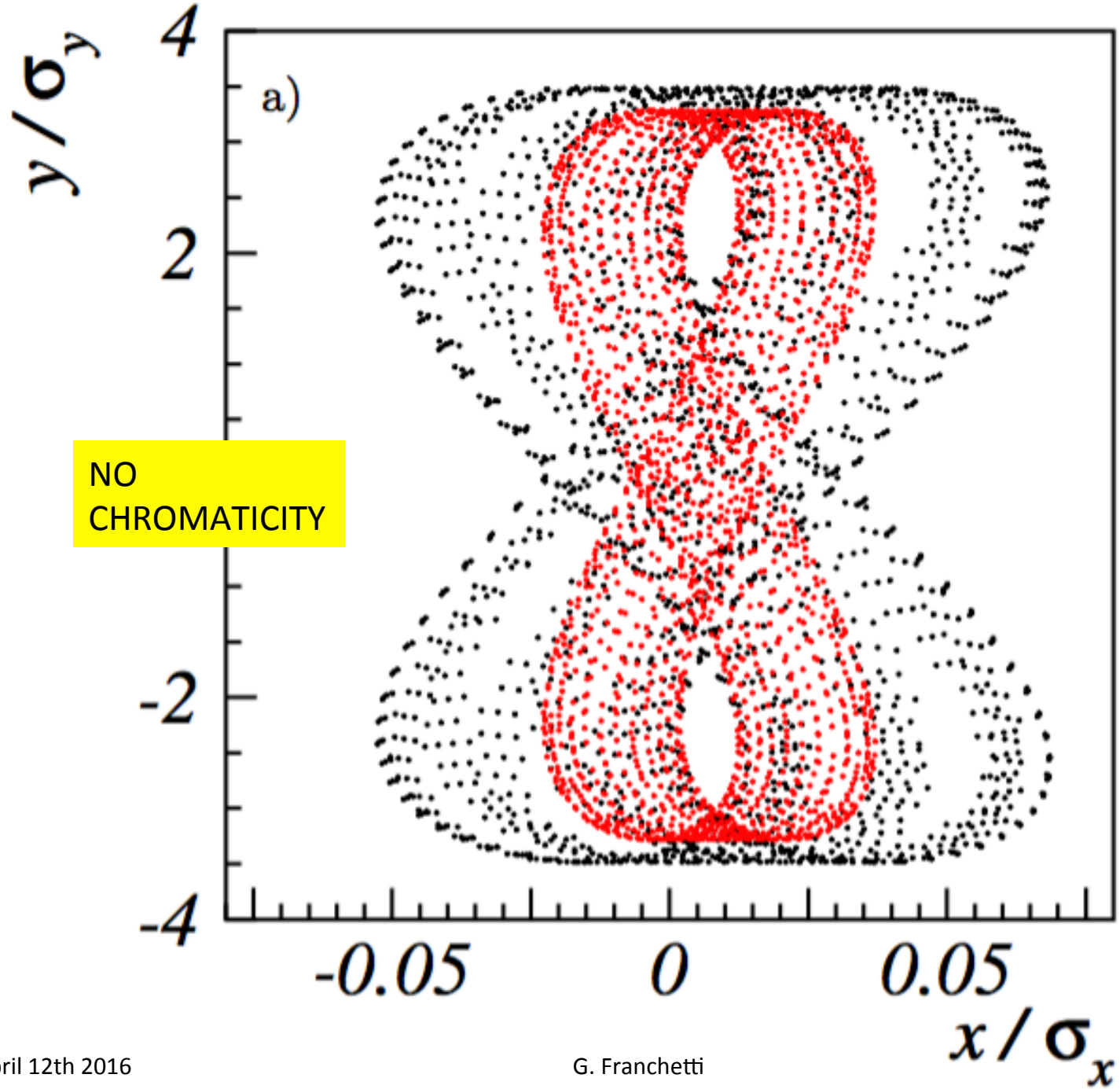




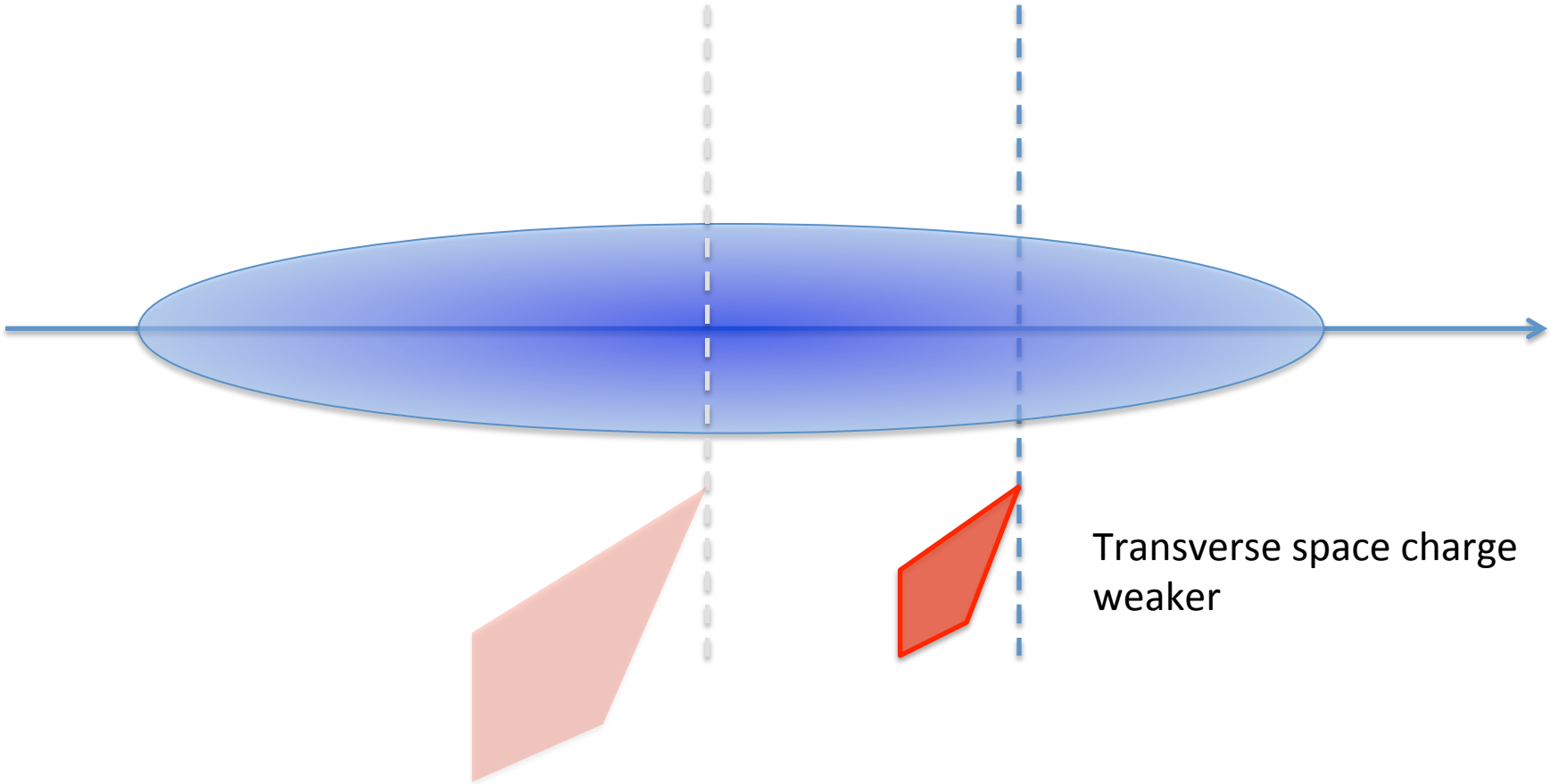
SPS campaign on May 2015: “The Dream of Glory”

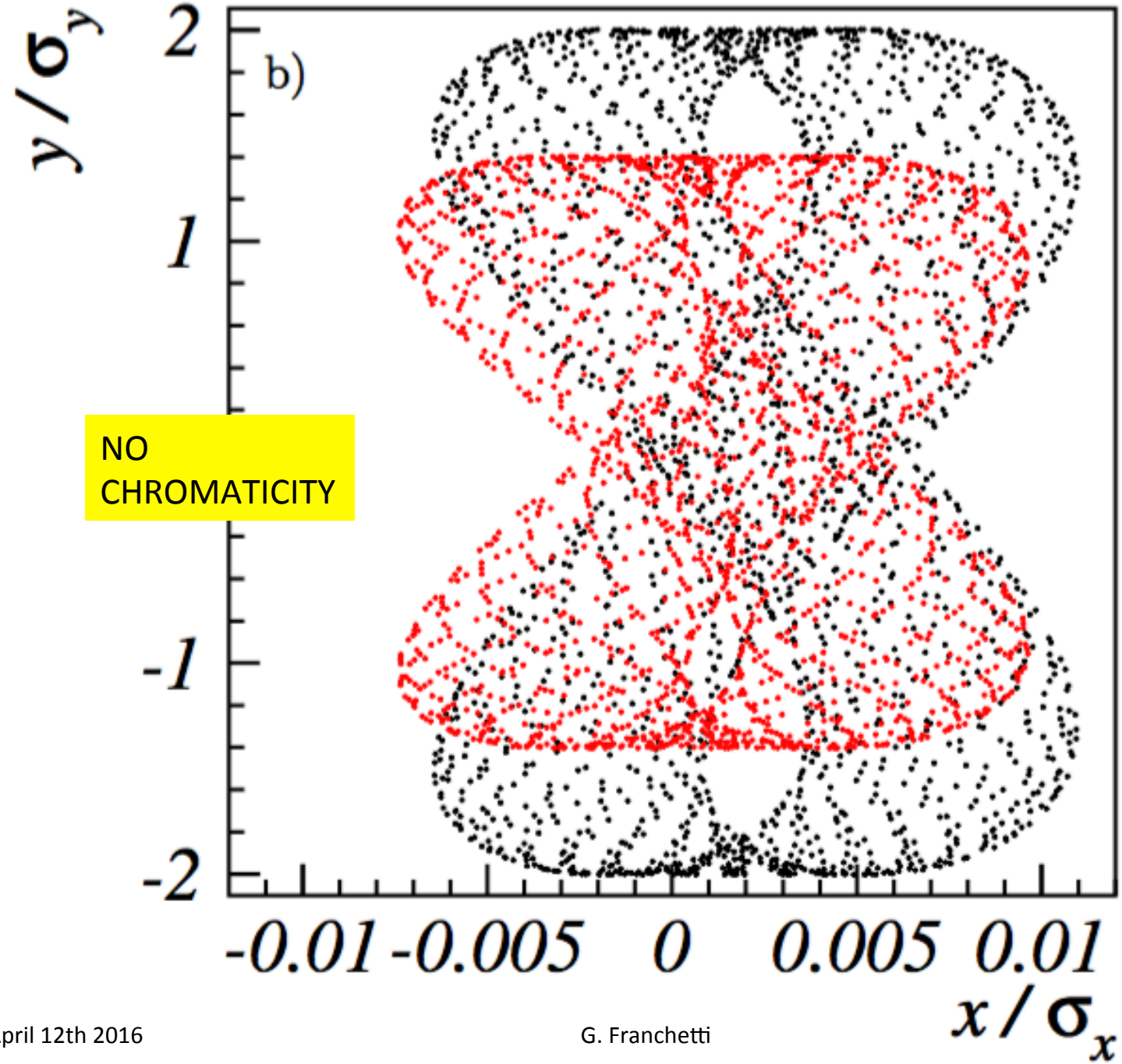

Transverse space charge
strongest


ΔQ_y
0
-0.02
-0.04
-0.06
-0.05
-0.04
-0.03
-0.02
-0.01
0
ΔQ_x



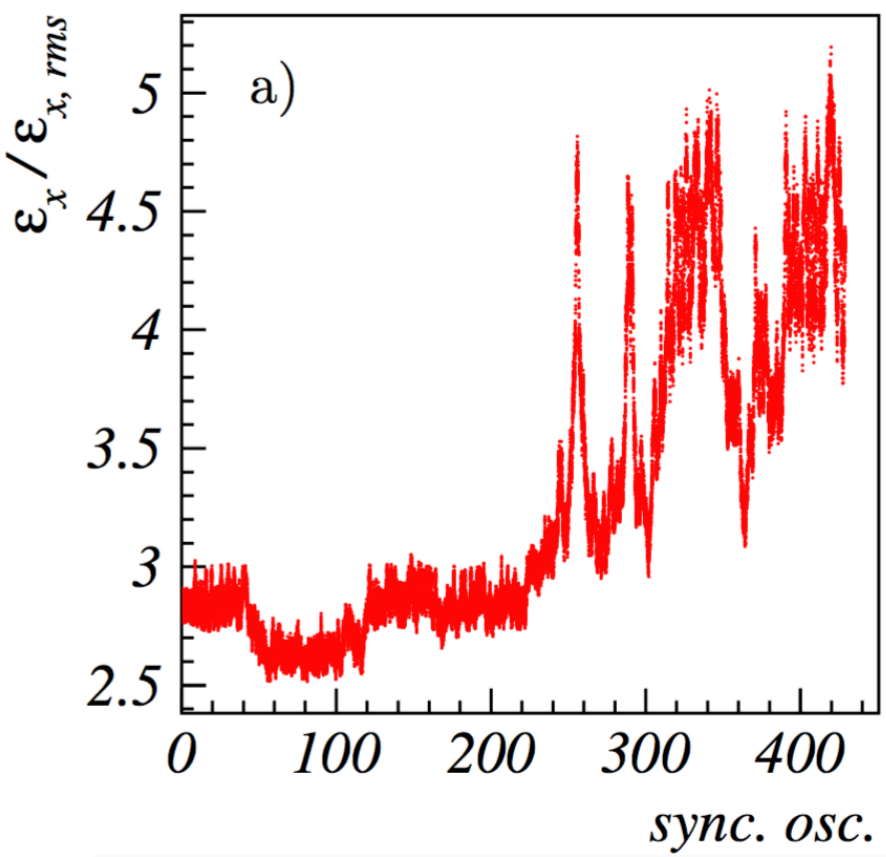
NO CHROMATICITY

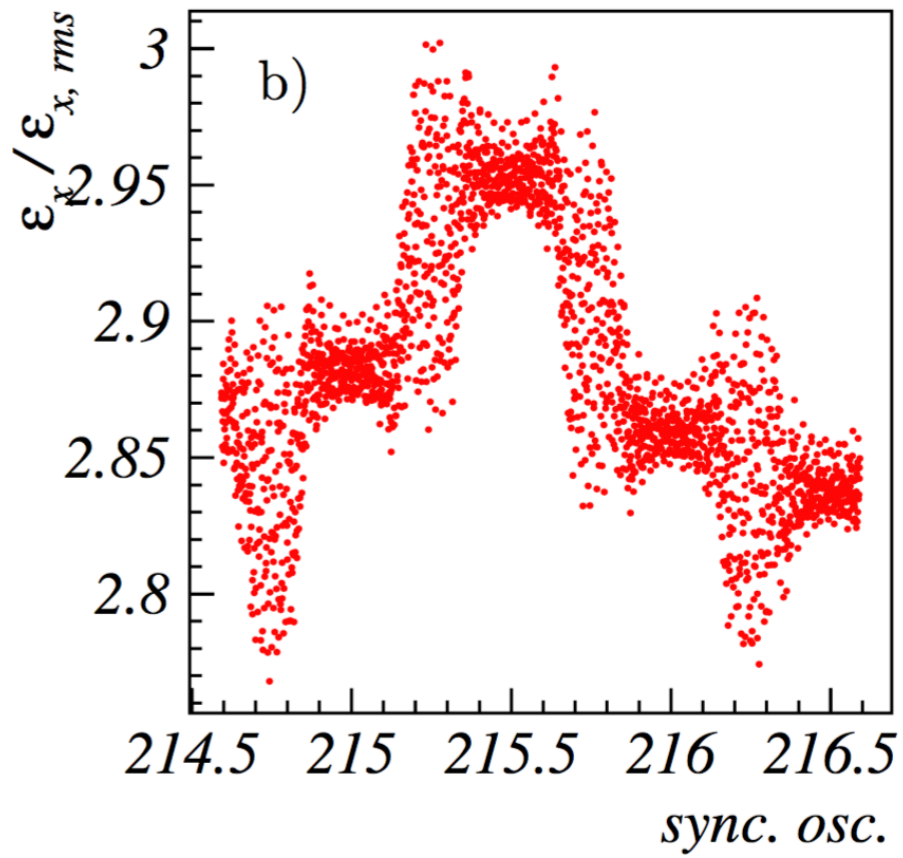

Transverse space charge
weaker


b)
NO
CHROMATICITY
2
1
-1
-2
-0.01
-0.005
0
0.005
0.01
y/σ_y
x/σ_x

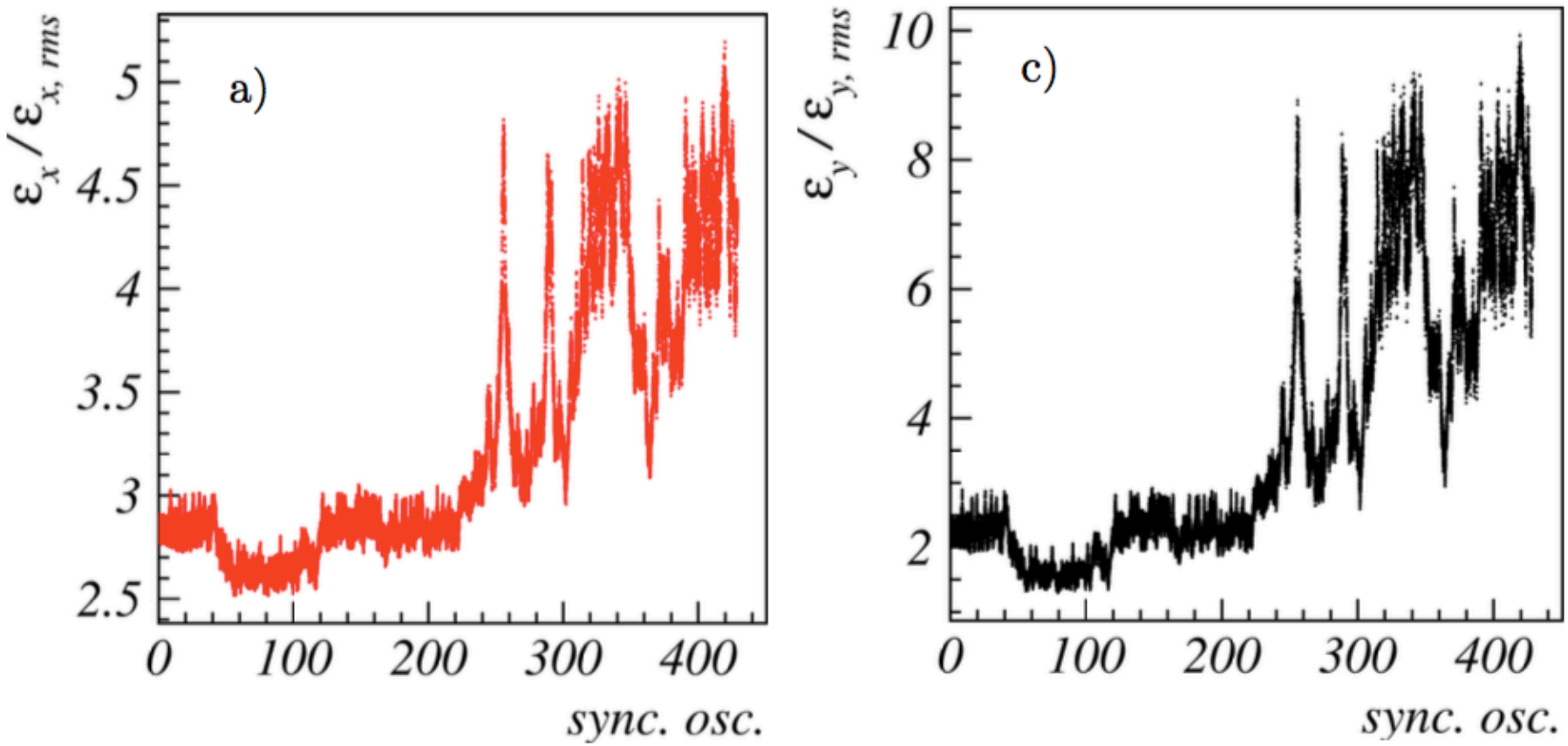
Periodic crossing of fixed lines induced by space charge and synchrotron motion

Scattering (of the invariant)

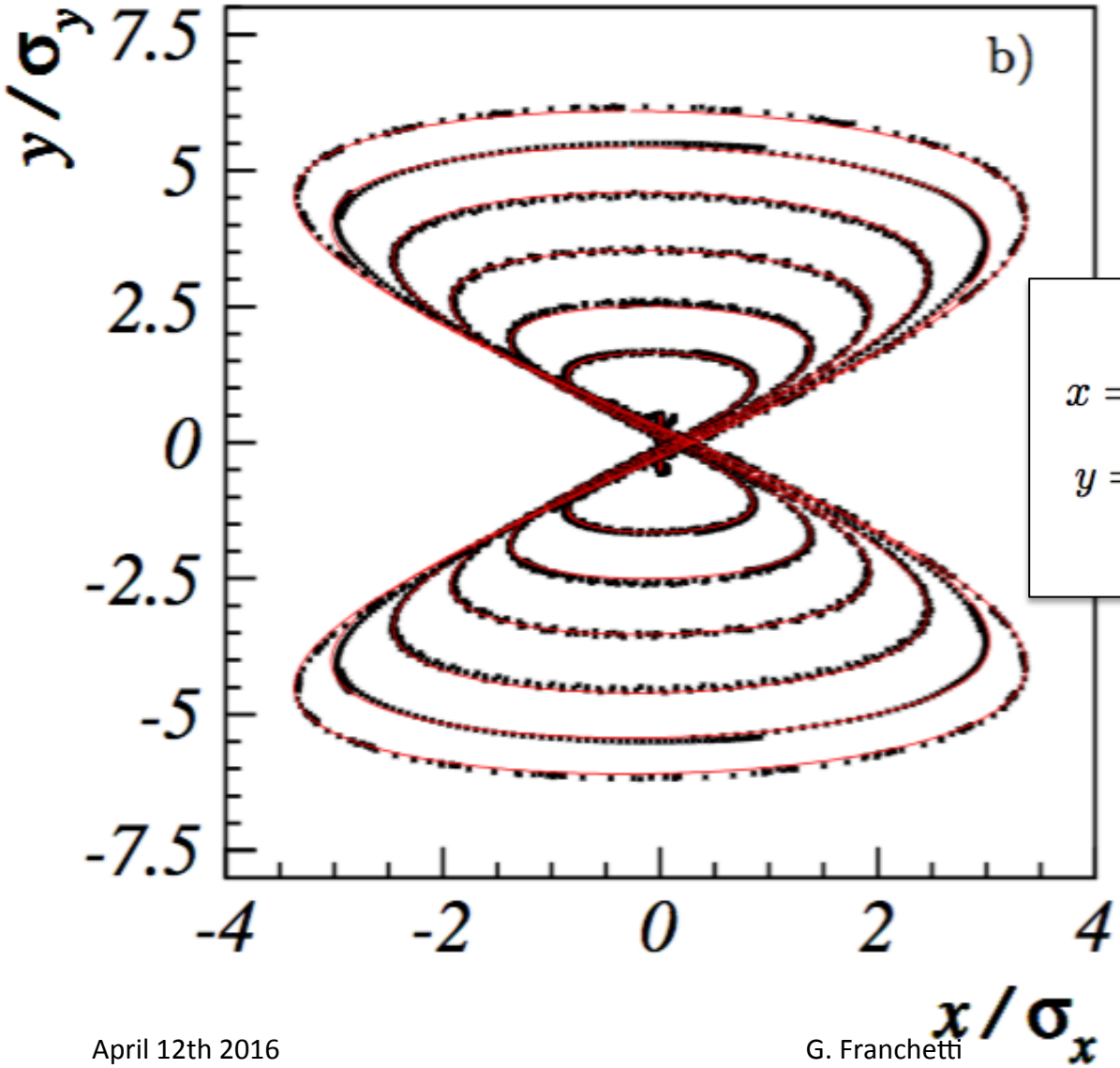




Scattering seems coupled !!



Geometry of the instantaneous fixed-lines is consistent with the halo asymmetry



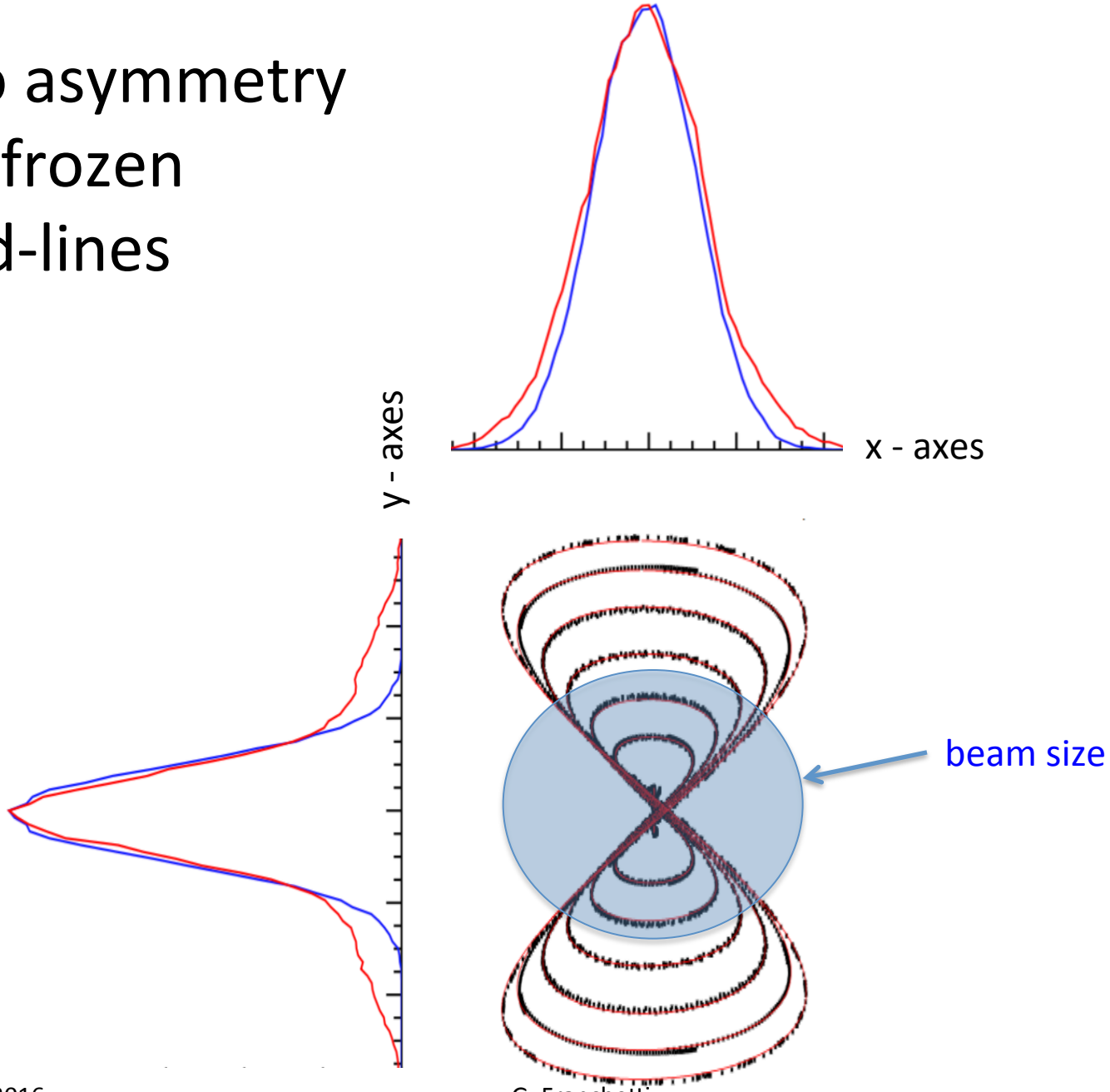
$$x = \sqrt{\beta_x a_x}\cos(-2t - \alpha + \pi M)$$
$$y = \sqrt{\beta_y a_y}\cos(t)$$

To be submitted soon

G. Franchetti, S. Gilardoni,
A. Huschauer, F. Schmidt, R. Wasef

measurement → 2012
completion of study → 2016

Halo asymmetry and frozen fixed-lines



Conclusion / Outlook

- A benchmarking on the 3rd order coupled resonance is achieved for the full PS structure.
- Outstanding asymmetric halo are formed and well retrieved by the simulations
- The fixed-lines are the new objects that explain the dynamics of the resonance
- **Fixed lines are measured in the SPS**
- Simulations shows that the periodic crossing of the fixed-lines causes the asymmetric halo as result of fixed lines geometry.
- Although there are infinite fixed lines, they seem to converge to an adiabatic limit
- **The door are open for massive studies of all coupled resonances**

Status of the quest

In 2002 experimental campaigns started from discussions at HB in Fermilab

The first decade of the millennium was dedicated to studies of interplay of space charge on 1D resonances (laboratories have supported it: GSI, and CERN)

The second decade of the millennium sees an exploration of the unknown territory of 2D resonances and space charge (GSI, and CERN). Nonlinear dynamics studies have revived (forgotten) fundamental topics useful in these new studies

Many open questions remain to be addressed, and a jungle of effects is to be studied

Interesting, Challenging, of Impact
(I want to know the Pythagorean truth!)

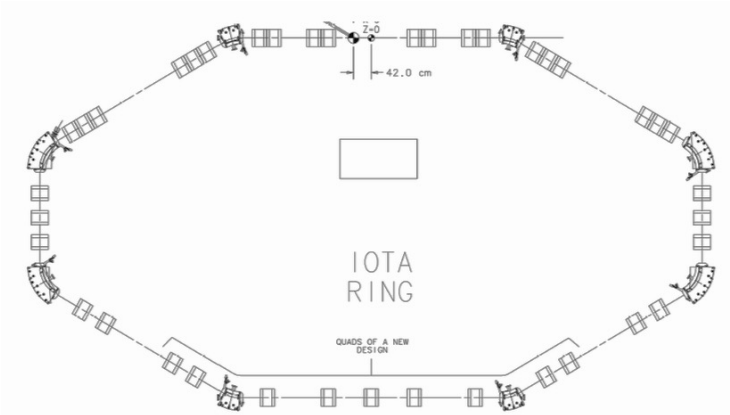
Final Considerations

Experiment of beam physics are absolutely necessary to progress the field. Theory, and simulations are not enough.

Beam physics experiments trigger unpredicted development, which always exceeded my expectation. One experiment open new doors to go through…

In the past 15 years CERN and GSI have contributed greatly allowing beam time for dedicated experimental campaigns

Who are the future players ?

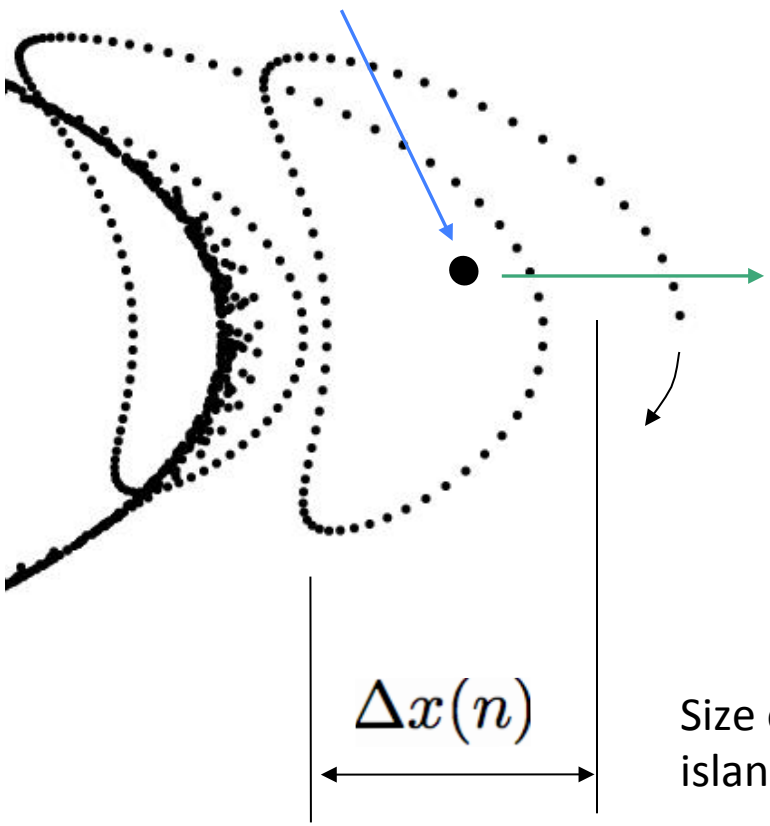


I am looking forward to make experiments with IOTA !

Thank for the attention

Adiabatic / Non adiabatic

Tune on the Fixed point $Q_{xf}(n)$



Speed of the fixed point

$$\frac{\partial x_f(n)}{\partial n}$$

Size of the island

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

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Particle trapping by nonlinear resonances and space charge
G. Franchetti, I. Hofmann
Nucl. Instr. and Meth. A 561, (2006), 195-202