Transverse Mode Coupling Instability in the SPS :

HEADTAIL simulations and MOSES calculations

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CERN / GSI Meeting on Collective Effects in ***CARE-HHH APD BEAM'07***

Oct. 3 2007

Agenda

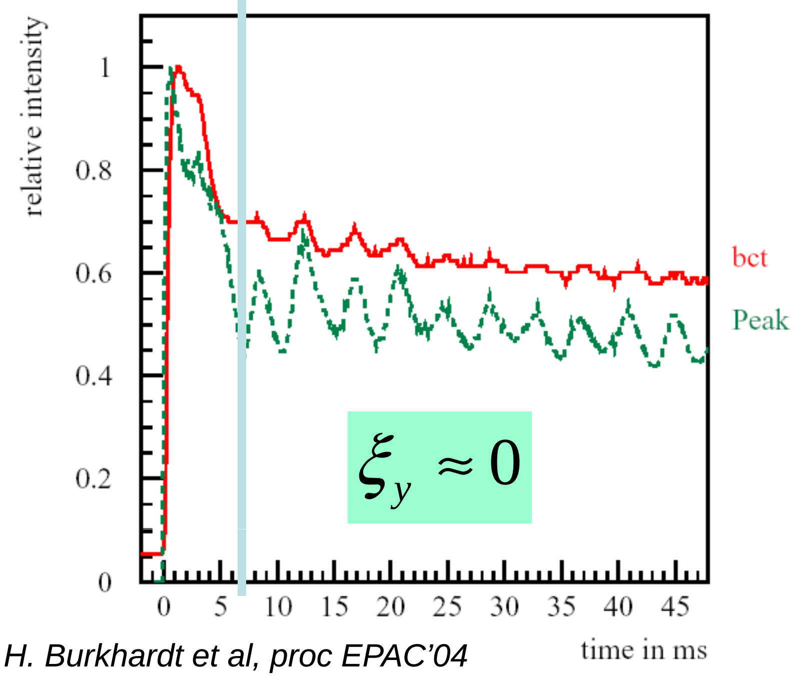
- Context
- Methods
- Simulation results
- Outlook and Perspectives

Context

$$N_b \approx 1.2\,10^{11}\ \text{p/b} \qquad p = 26\ \text{GeV/c} \qquad \varepsilon_l \approx 0.2\ \text{eVs} < \varepsilon_l^{\text{LHC}} = 0.35\ \text{eVs}$$

Measurements in the SPS (2003)

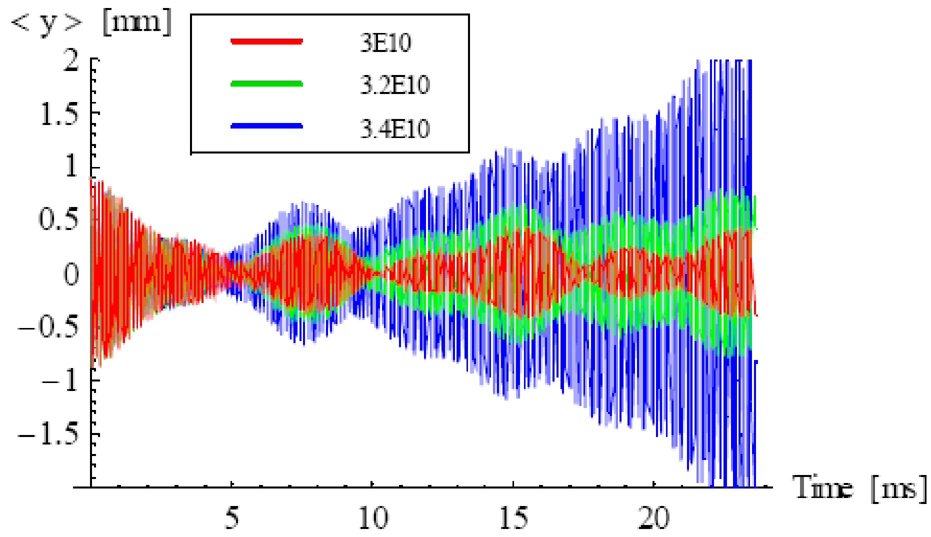
$\text{Synchrotron period} \approx 7\ \text{ms}$



H. Burkhardt et al, proc EPAC'04

=> Typical signature of a TMCI

HEADTAIL Simulations



E.Metral and G. Rumolo, proc EPAC'06

=> Typical signature of a TMCI

Is it indeed a TMCI ? → need to observe modes shifting and coupling

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    - MOSES calculations
    - HEADTAIL simulations
    - Sussix algorithm
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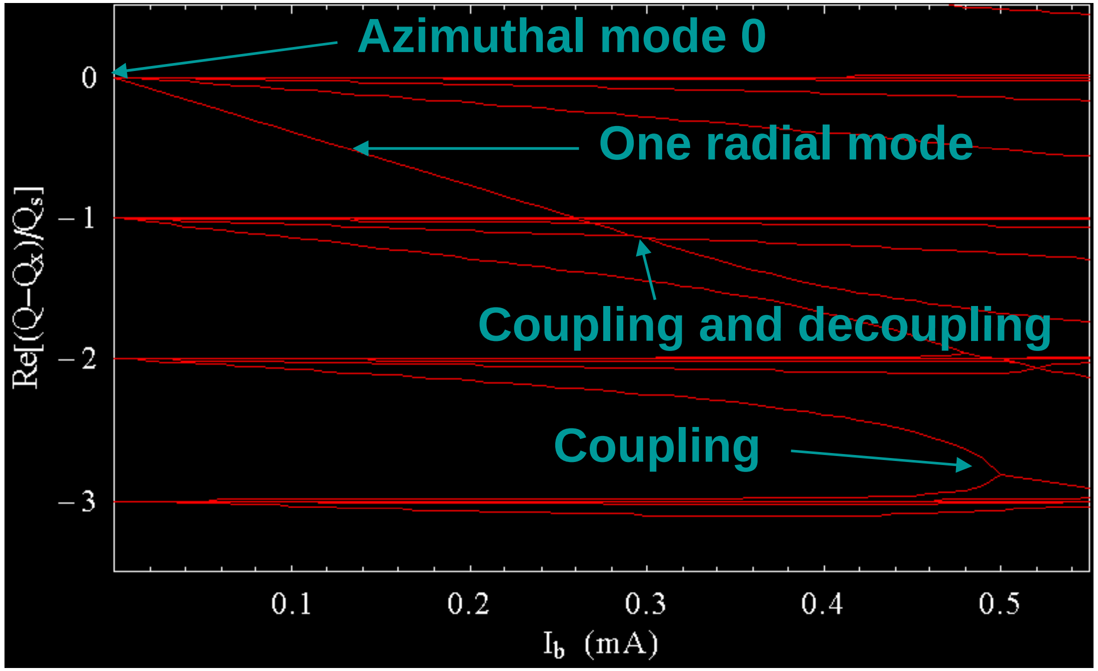
Methods : *MOSES calculations*

- MOSES (Y.H. Chin, CERN-LEP-Div-Rep-88-005-TH) :
  - computes coherent tune shifts as a function of beam current ΔQ (I_{beam}) for a gaussian beam interacting with a resonator impedance.

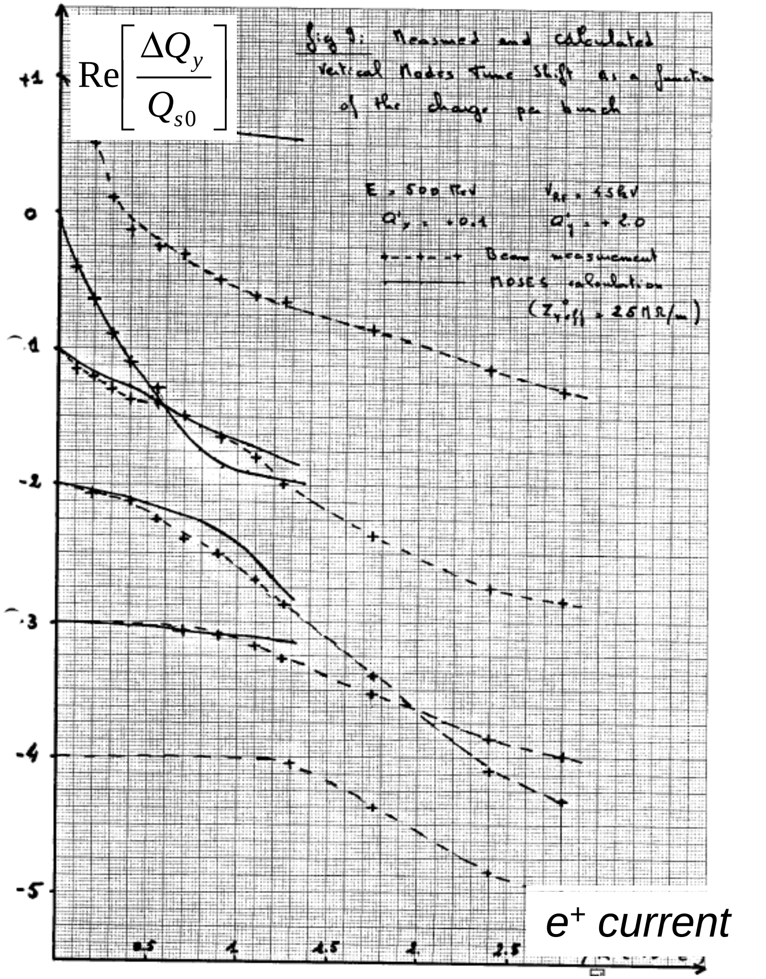
Benchmark of MOSES with Measurements at EPA

Example of MOSES output

Example for a SPS beam with low longitudinal emittance interacting with a broadband impedance (see parameters p. 7)



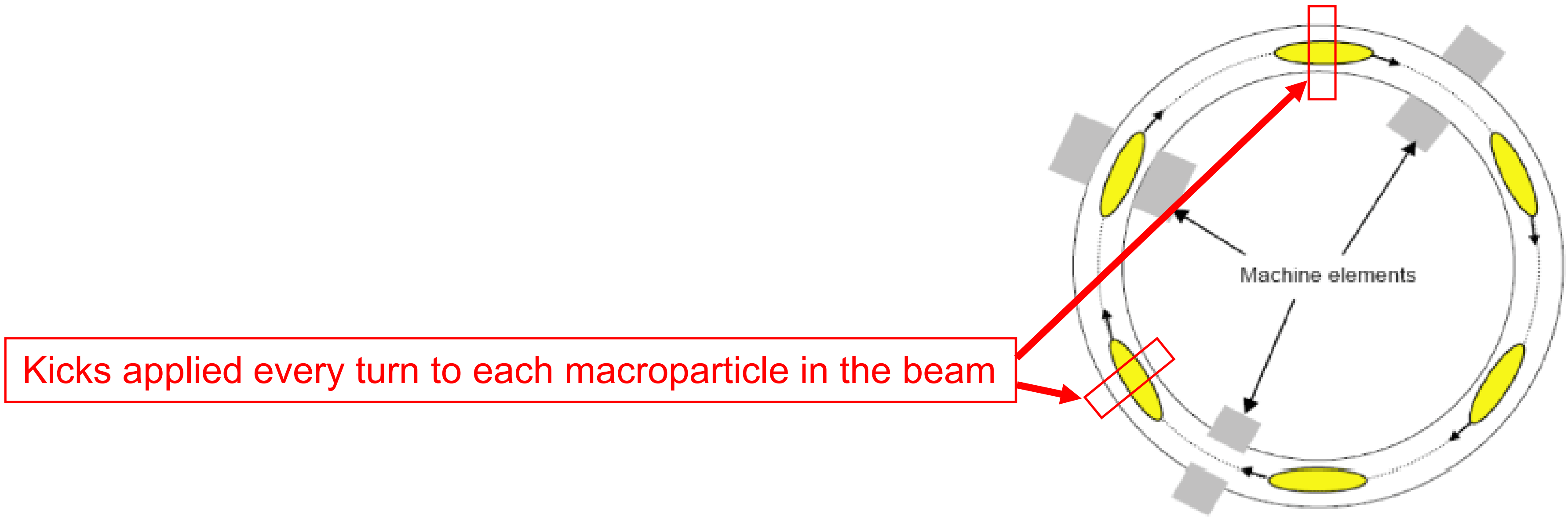
Courtesy E. Metral



In « Transverse Mode Measurements with positrons in EPA »
D Brandt, JP Delahaye, A Hofman, LEP Note 595 (1987)

Methods : *HEADTAIL Simulations*

- HEADTAIL (G. Rumolo, F. Zimmermann, SL-Note 2002-036-AP, CERN 2002) :
  - Code that simulates the interaction of a single bunch of macroparticles with disturbance phenomena (e.g. electron cloud, impedance, space-charge).
  - Interactions are modelled by one or more kicks given at each turn.



6 Bunches circulating in a schematic ring

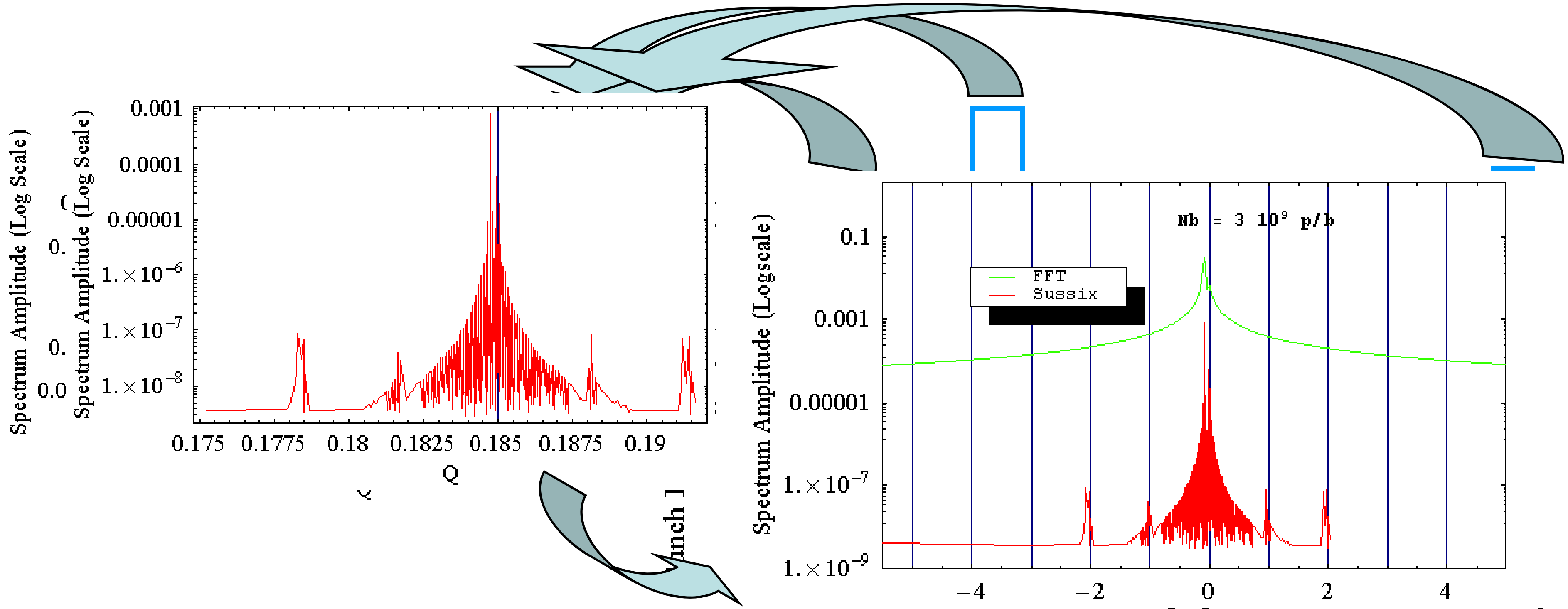
- In this specific case,
  - No space charge, no amplitude detuning
  - Impedance of the whole machine is modelled by a broadband impedance
  - Bunch (10^6 macroparticles) is divided into 500 longitudinal slices
  - Frozen Wake field (i.e. the wake field is not recalculated at every turn)
    - → only to be applied if the longitudinal bunch shape does not change significantly over the simulation time (i.e. no longitudinal impedance, bunch matched to the bucket)
  - Simulations over 10,000 turns (~ 0.23 sec)
  - Linearized Bucket

Headtail Simulated beam parameters

Parameter	Symbol	Value	Unit
Circumference		6911	m
Number of bunches		1	
Relativistic Gamma		27.7286	
Initial Rms beam sizes	σ_x, σ_y	1.8	mm
Horizontal Tune	Q_x	26.185	
Vertical Tune	Q_y	26.13	
Chromaticities	$\xi_{x,y}$	0 / 0	
Initial Bunch length		0.21	
Initial Longitudinal Momentum spread	$\Delta p/p_0$	$9.3\ 10^{-4}$	
Synchrotron Tune	Q_s	$3.24\ 10^{-3}$	
Cavity Harmonic Number		4620	
Momentum Compaction Factor		$1.92\ 10^{-2}$	
Transverse BroadBand shunt impedance		10	MΩ/m
Transverse BroadBand resonant frequency		1	GHz
Transverse BroadBand quality factor		1	
Kick amplitude (both x and y)		0.9	mm
Average Beta function over the ring	β_x, β_y	40	m
Type of geometry		Round or flat	

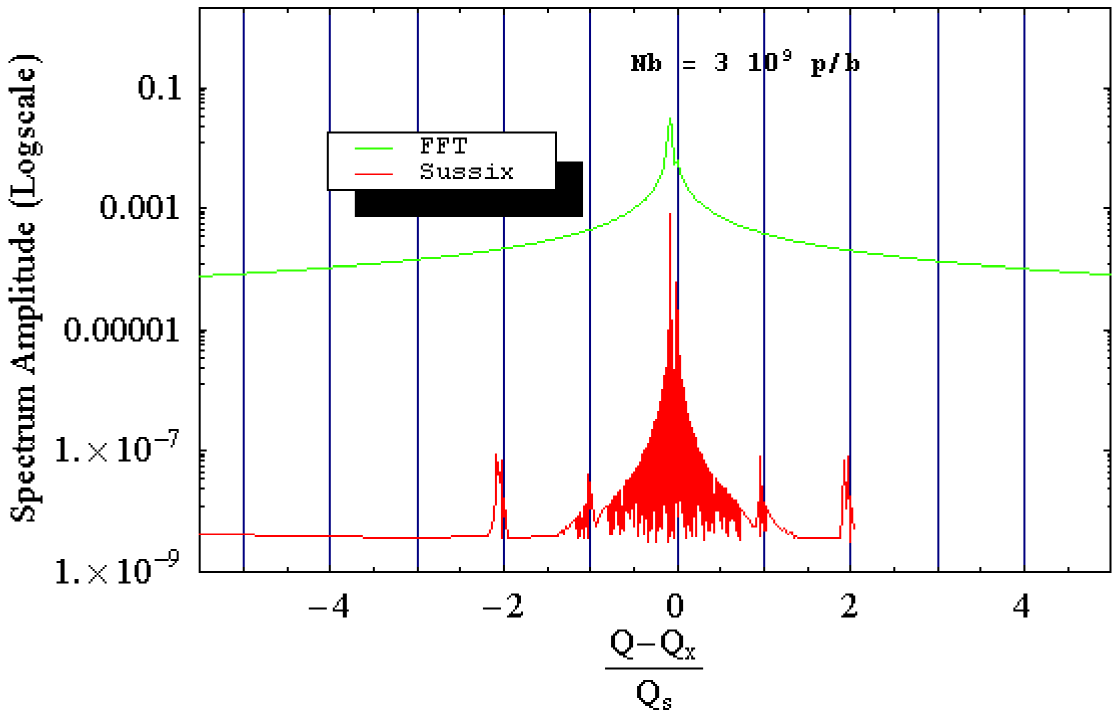
Methods : *What to do with HEADTAIL outputs ?*

1. Extract the position of the centroid of the bunch (vertical or horizontal) turn after turn → simulated BPM signal
2. Apply a classical FFT to this simulated BPM signal (*x*)
3. Apply SUSSIX* to this same simulated BPM signal (actually $x - j\,\beta_x x'$)
4. Normalize the tune spectrum Q to Q_s, and translate it so that Q_x=0



(*) *Sussix code* : R. Bartolini, F. Schmidt, *SL Note 98-017AP, CERN 1998*
Theory behind Sussix : R. Bartolini, F. Schmidt, *LHC Project Report 132, CERN 1997*
J. Laskar et al., *Physica D 56, pp. 253-269 (1992)*

Methods → *Comparison of FFT and SUSSIX analysis*



- FFT frequency points are fixed and equally spaced (by 1/Npoints)
- Sussix frequency points are not predefined
- Sussix features:
  - Input = complex signal ($x - j\,\beta_x x'$)
  - Iterative method to find the main peaks in the region of interest
  - Hanning filter to reduce noise due to windowing in the time domain
  - Fourier analysis, not FFT

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- Simulation results

    Real Tune shift and Imaginary tune shift (instability rise time) for

    - Chromaticity = 0 and no coupling
    - Chromaticity ≠ 0 and no coupling

    } Round beam pipe

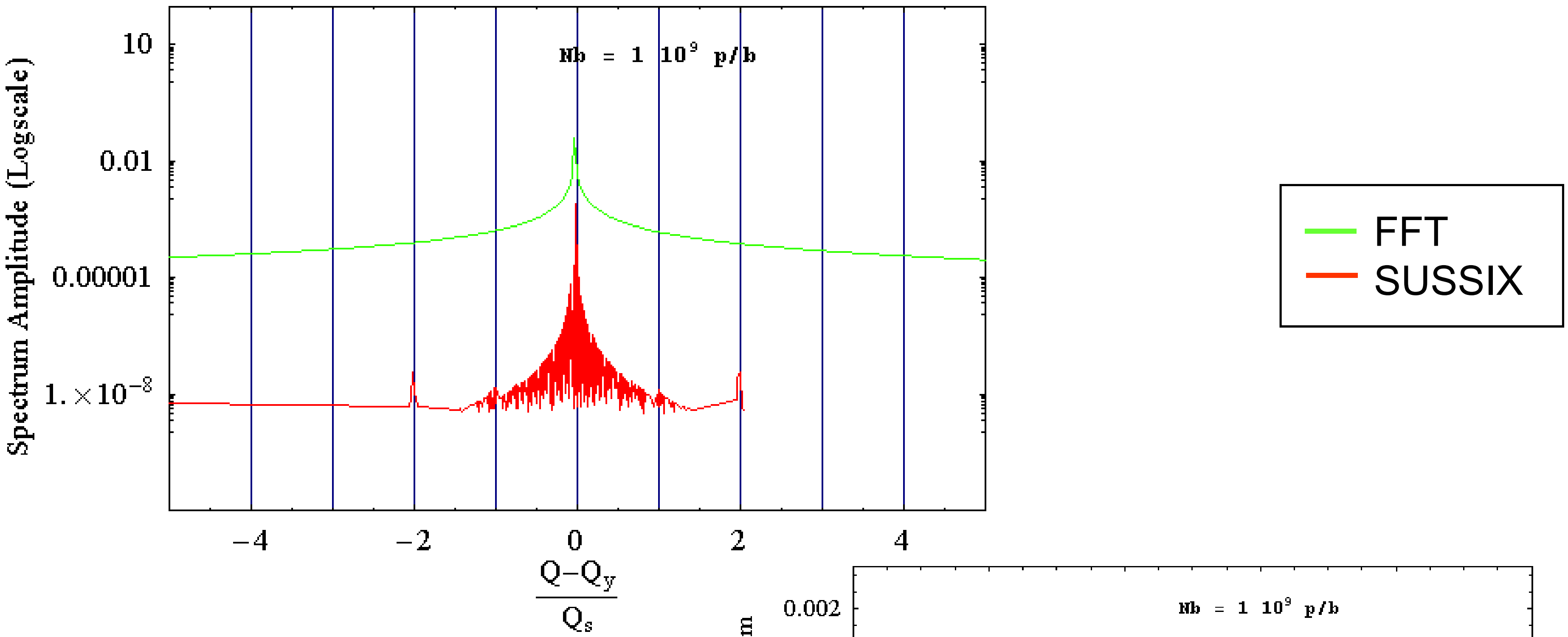
    - Chromaticity = 0 and no coupling
    - Chromaticity = 0 and Linear Coupling

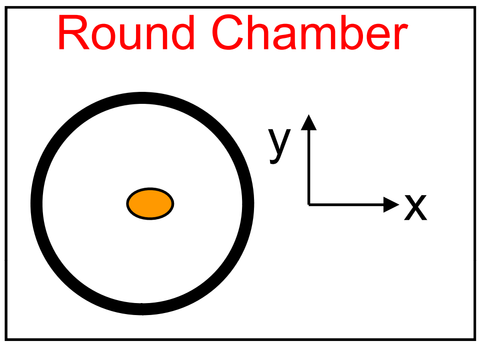
    } Flat beam pipe

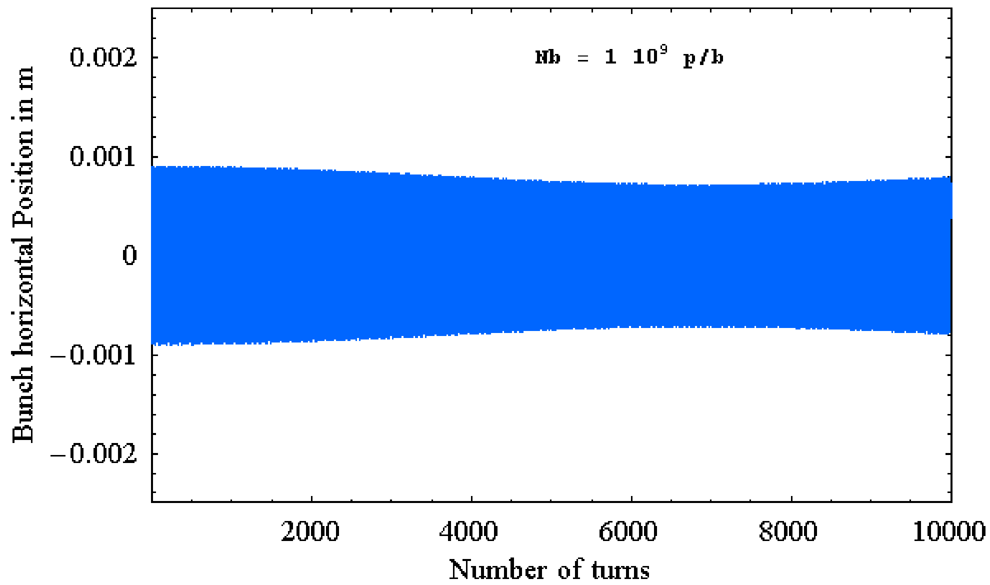
- Outlook and Perspectives
    - Longitudinal Mode Coupling
    - First Measurements in the SPS

Simulation Results : Round beam pipe / no chromaticity / no coupling

Frequency Analysis



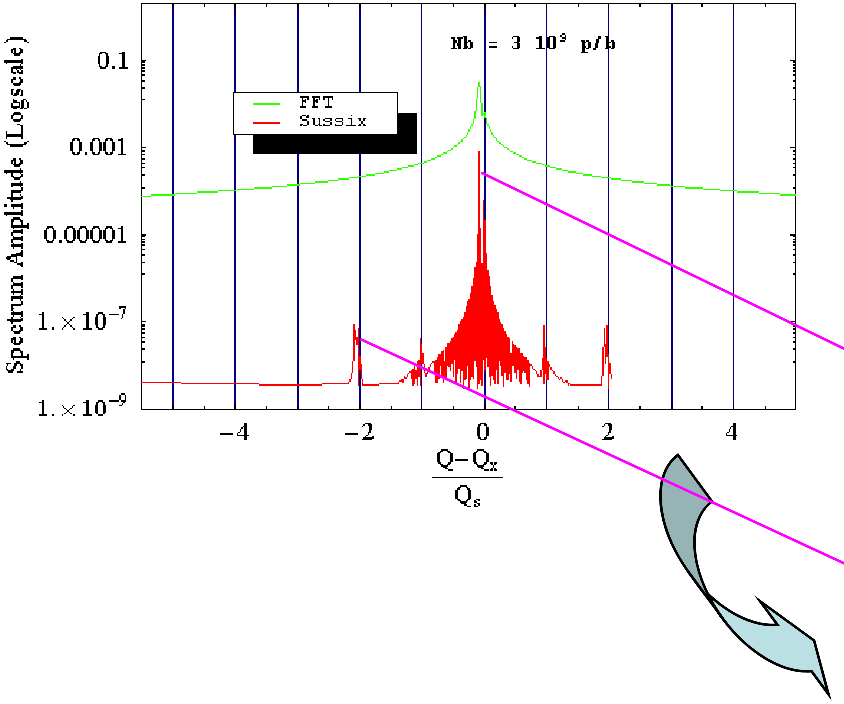




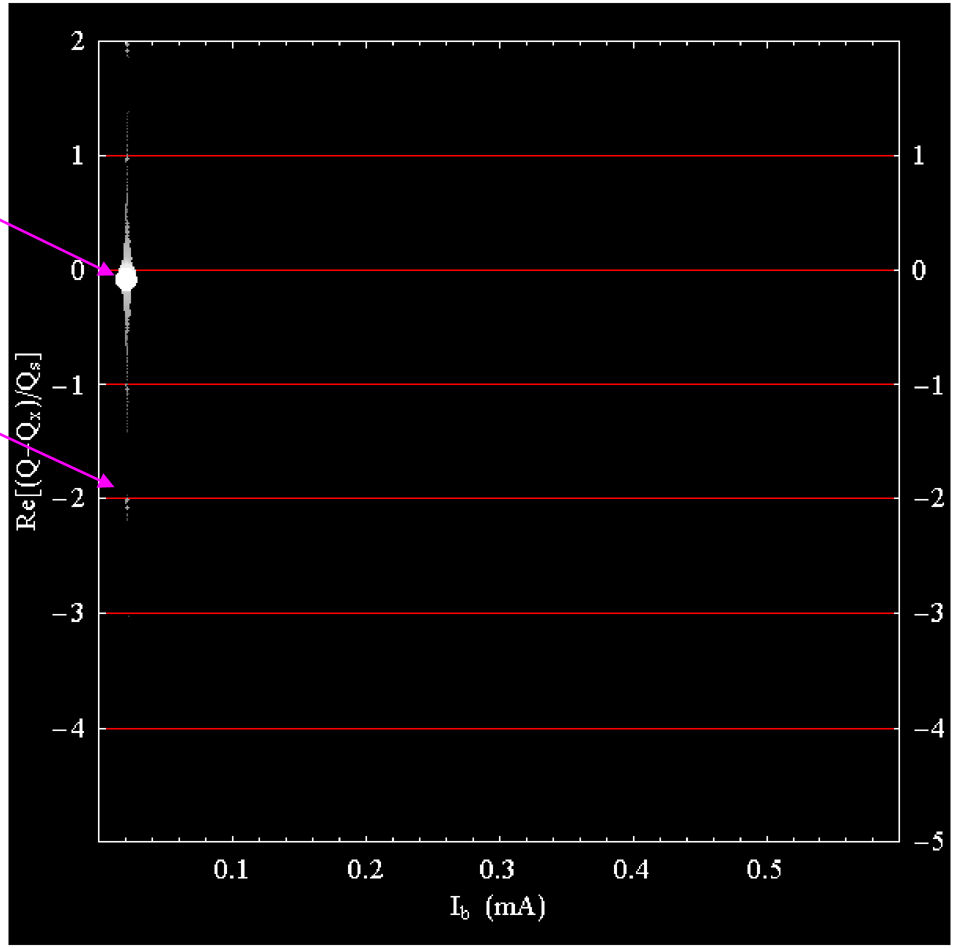
Simulation Results : Round beam pipe / no chromaticity / no coupling

Displaying the real part of the tune shift Re[ΔQ] as a function of current

for Nb = 3 10^9 p/b (I_b = 0.02 mA)



Displaying the Sussix spectrum on one line

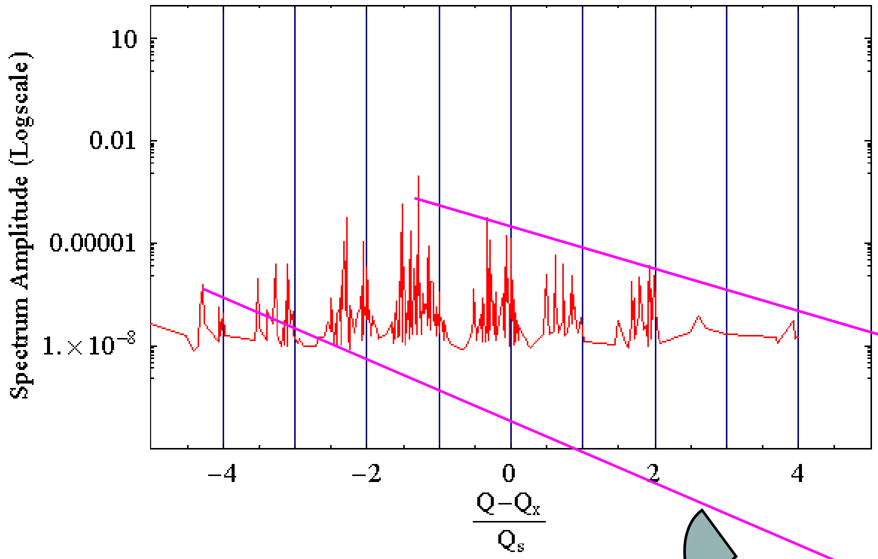


Simulation Results : Round beam pipe / no chromaticity / no coupling

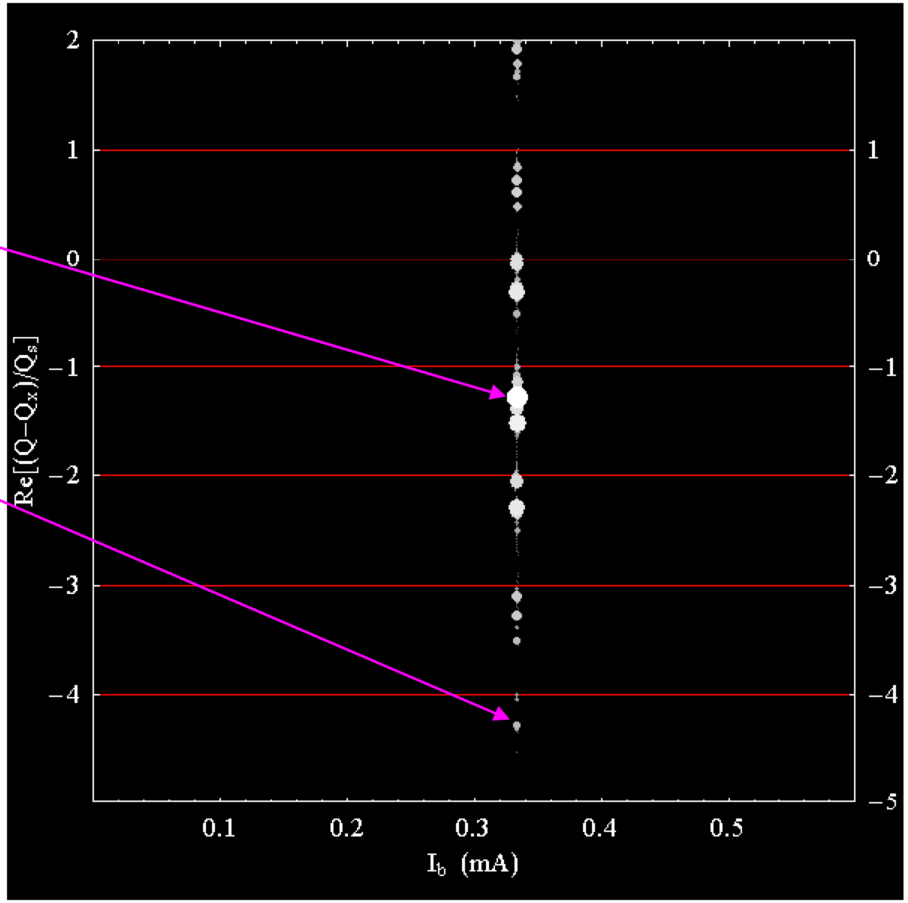
Displaying the real part of the tune shift Re[Δ**Q**] as a function of current

(Another example)

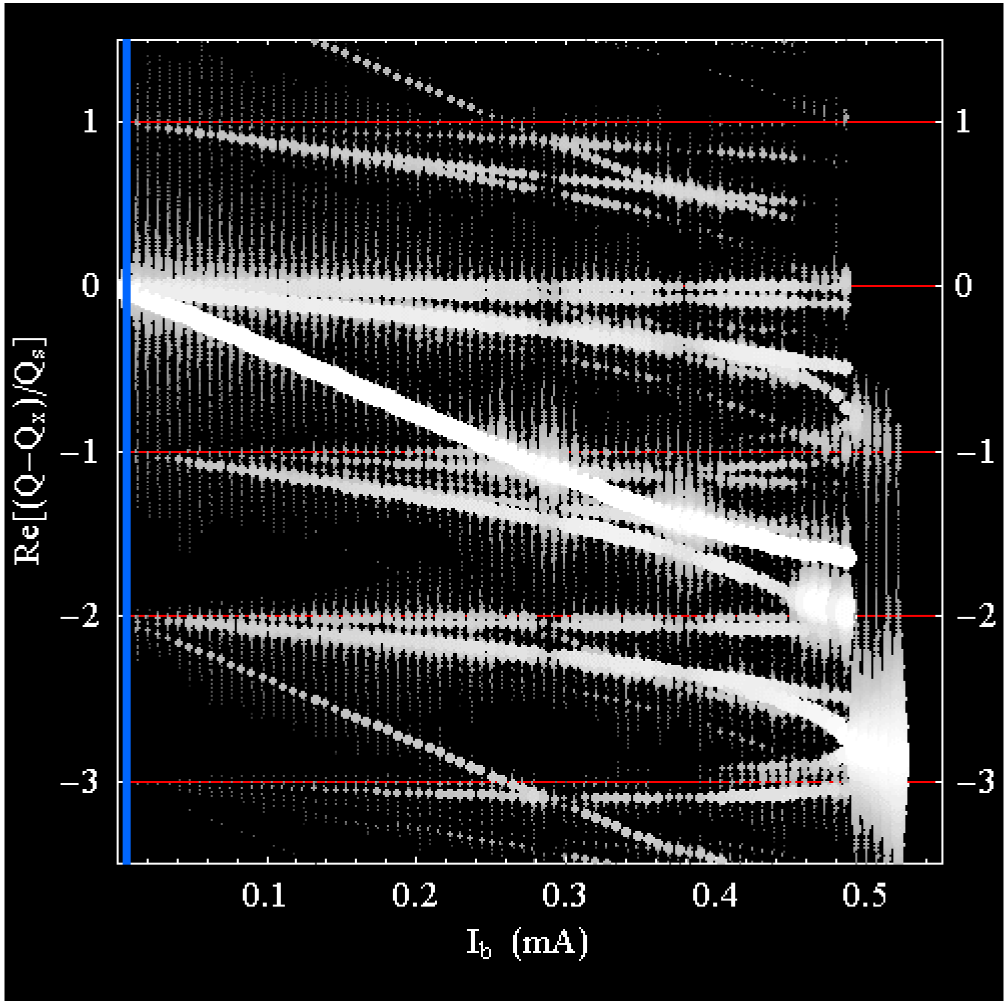
for Nb = 48 10^9 p/b (I_b = 0.33 mA)

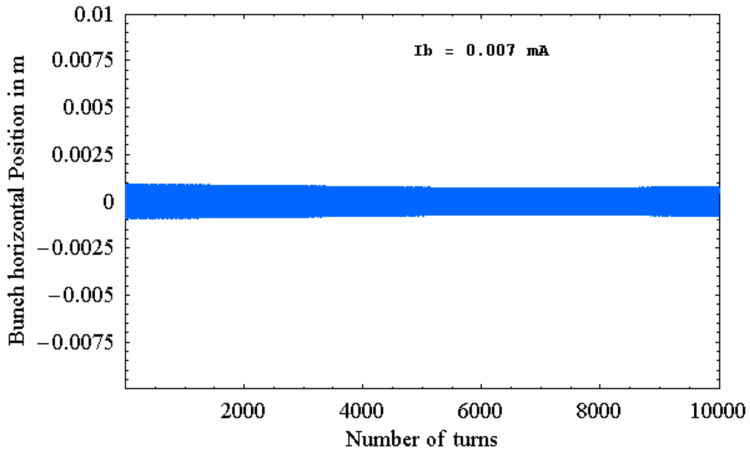


Displaying the Sussix spectrum on one line



Simulation Results : Round beam pipe / no chromaticity / no coupling displaying ***Re[ΔQ]=f(I$_b$)***

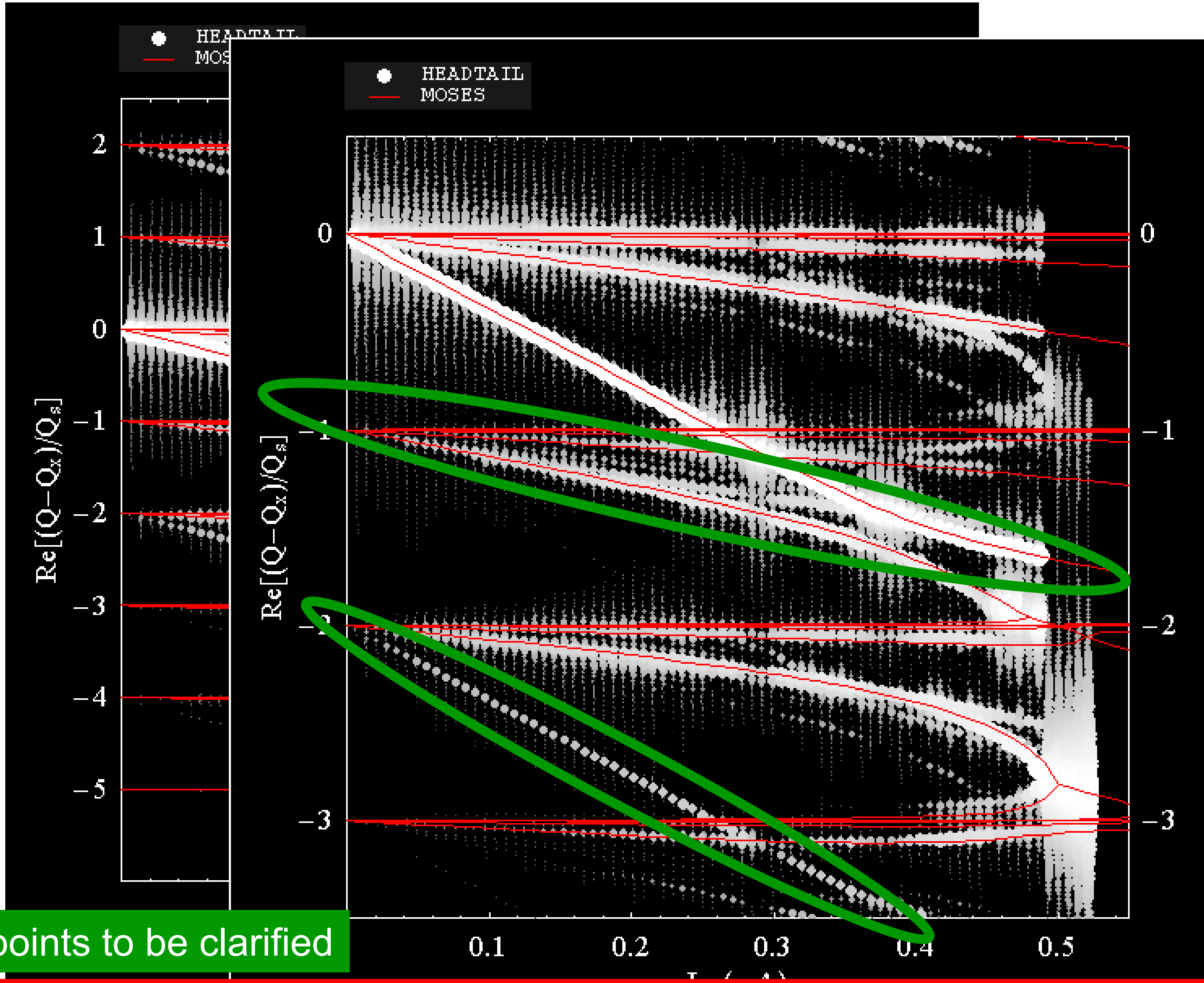




→ Transverse modes are observed to shift, couple and decouple with current

Simulation Results : Round beam pipe / no chromaticity / no coupling

Re[ΔQ]=f(I_b) and comparison with MOSES

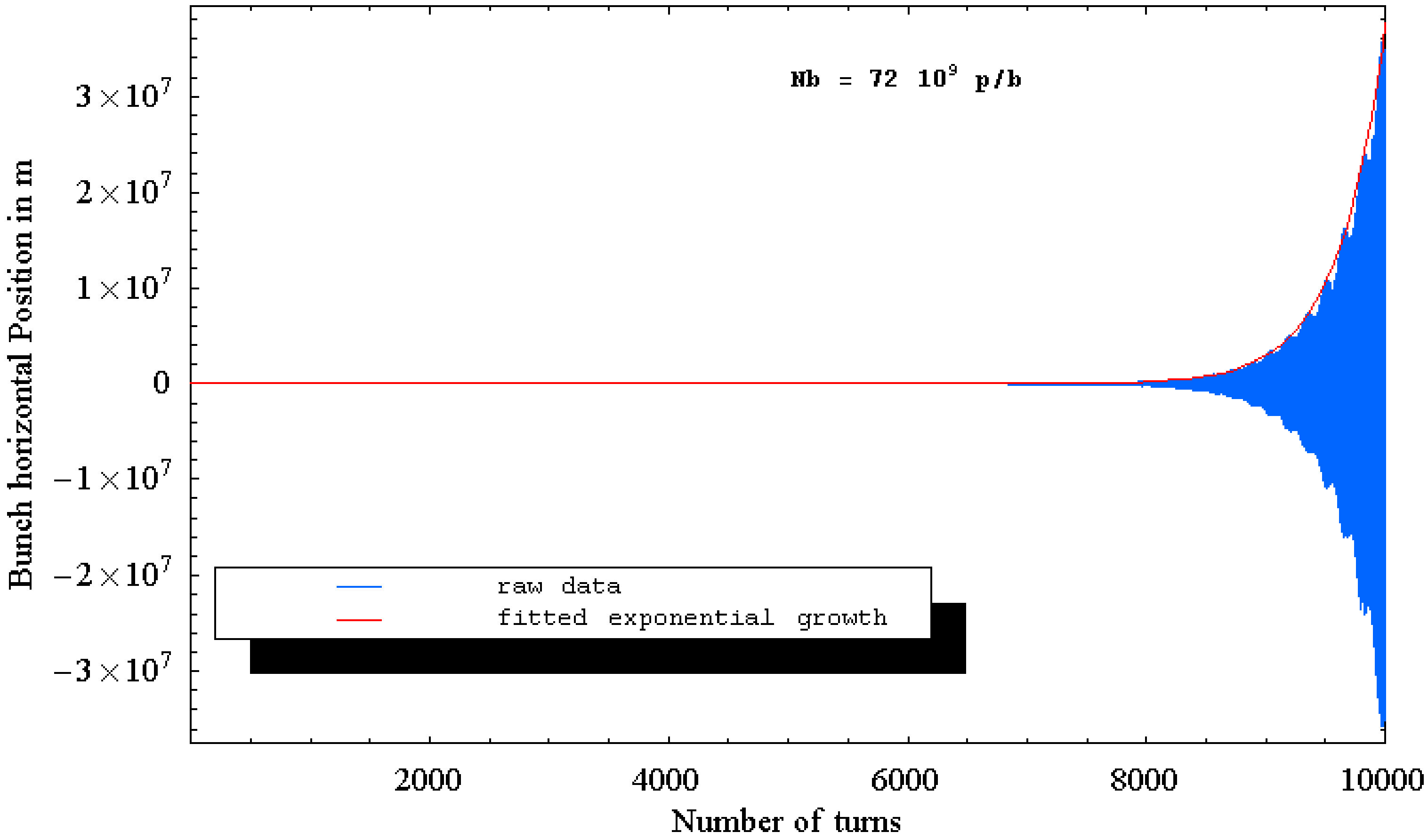


However points to be clarified

- MOSES and HEADTAIL agree for the mode shifting and coupling

Simulation Results : Round beam pipe / no chromaticity / no coupling

Extracting the imaginery part of the tune shift Im[ΔQ] → ***instability growth rates***

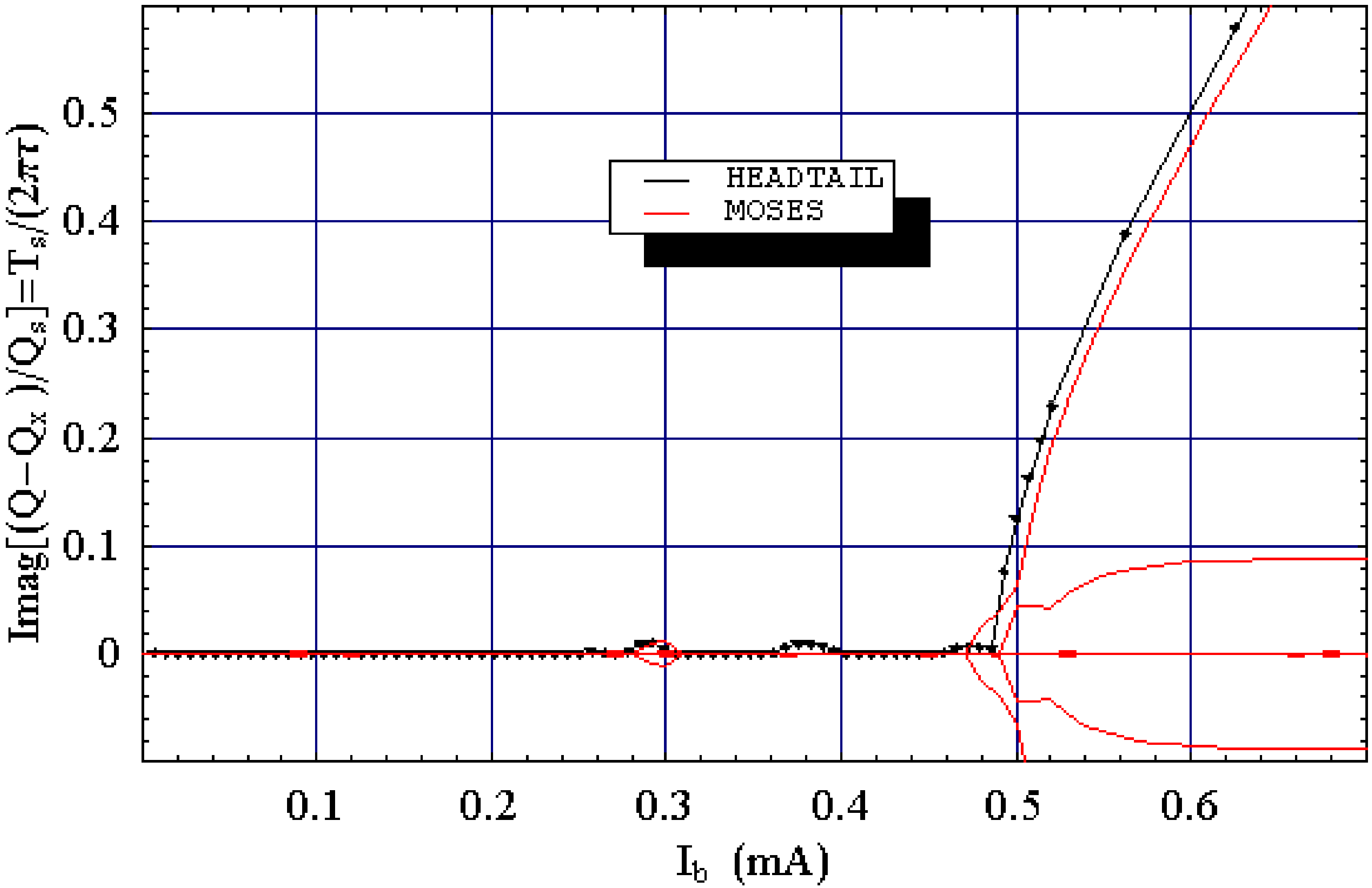


- Exponential fit of the growth of the instability : *f(x)=A exp(B.t)*

↑ Growth rate

Simulation Results : Round beam pipe / no chromaticity / no coupling

$Im[\Delta Q]=f(I_b)$ and comparison with MOSES



rise times from MOSES and HEADTAIL are following the same pattern

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  - Chromaticity ≠ 0 and no coupling

  } Round beam pipe

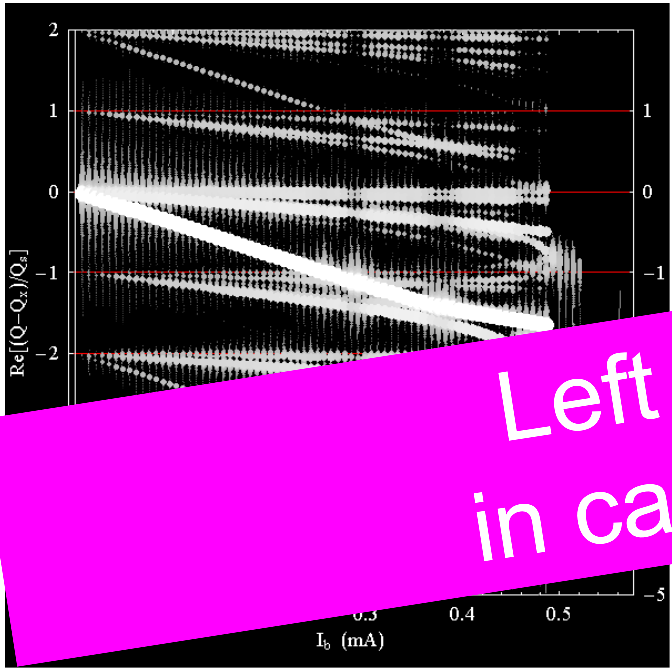
  - Chromaticity = 0 and no coupling
  - Chromaticity = 0 and Linear Coupling

  } Flat beam pipe

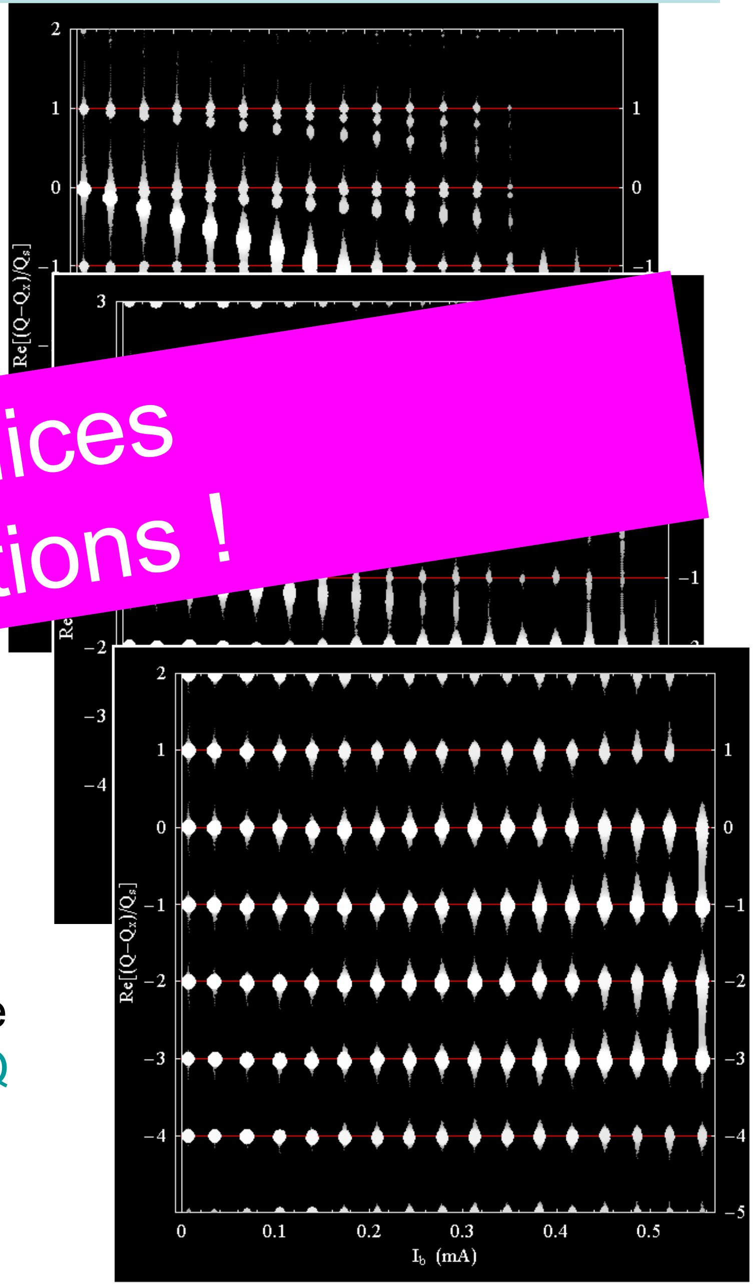
- Outlook and Perspectives
  - Longitudinal Mode Coupling
  - First Measurements in the SPS

Simulation Results : Round beam pipe / **various chromaticities** / no coupling
Frequency Analysis

Reference (Round Chamber)



Reference
+ ξ = 1/Q



Reference
+ ξ = 10/Q

Left for appendices
in case of questions !

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  - Chromaticity = 0 and no coupling } Round beam pipe
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  - Chromaticity = 0 and no coupling } Flat beam pipe
  - Chromaticity = 0 and Linear Coupling } Flat beam pipe

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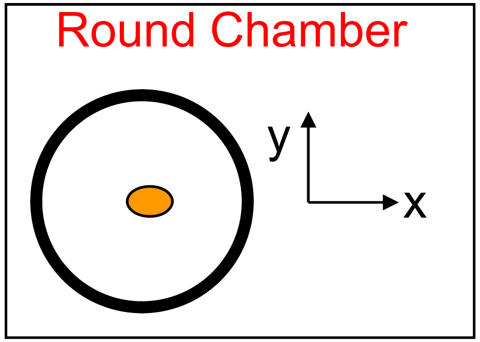
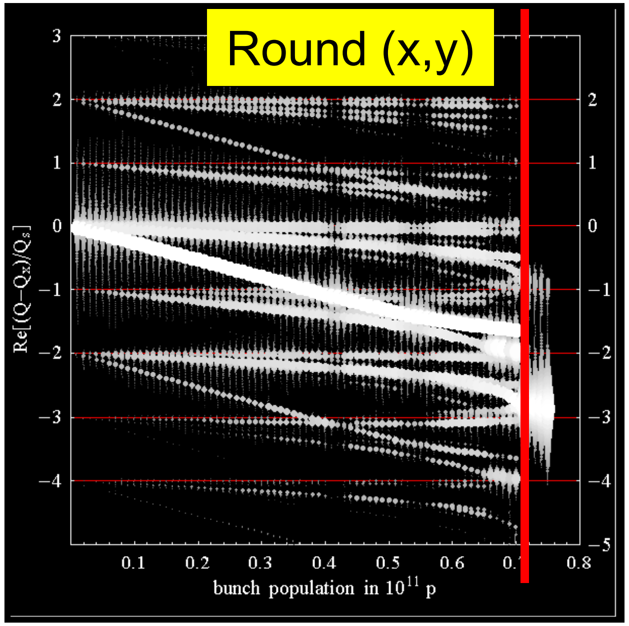
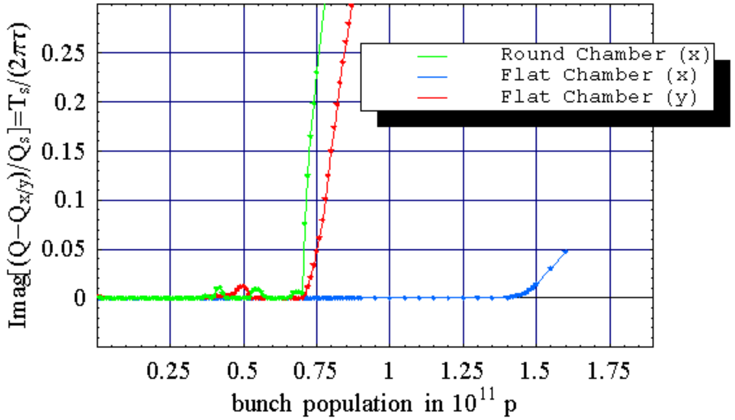
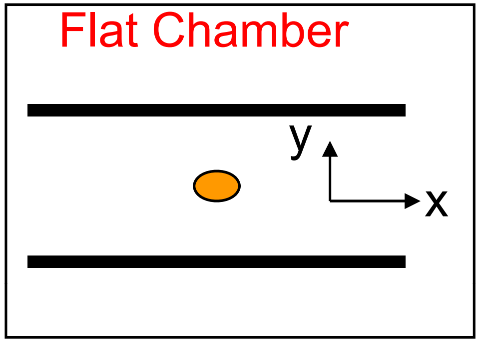
Simulation Results : **Flat beam pipe** / no chromaticity / no coupling

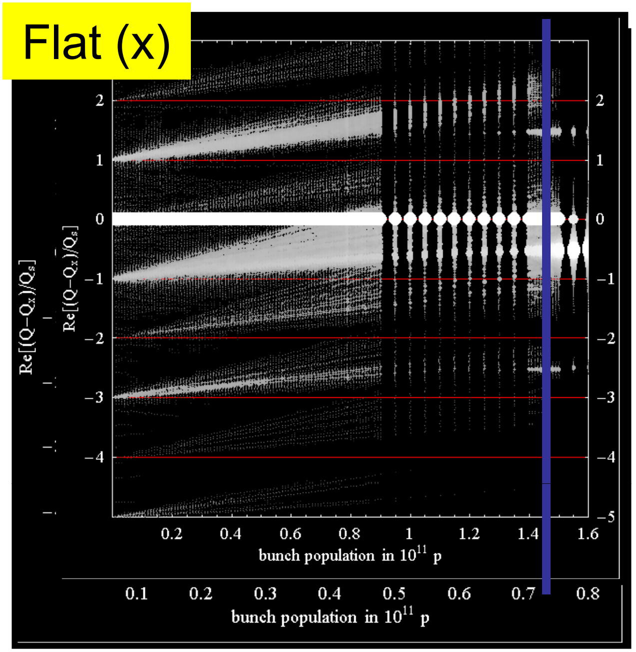
$\Delta Q_{x,y} = f(I_b)$

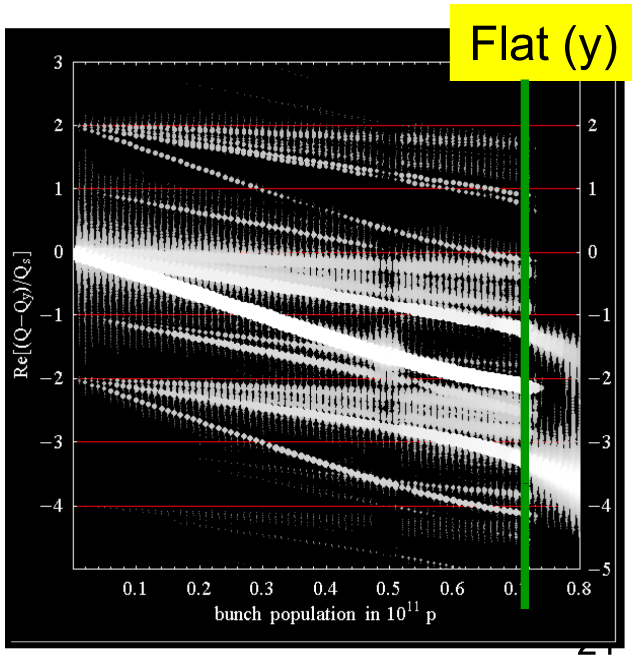












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    - Chromaticity = 0 and no coupling
    - Chromaticity = 0 and Linear Coupling

    } Flat beam pipe
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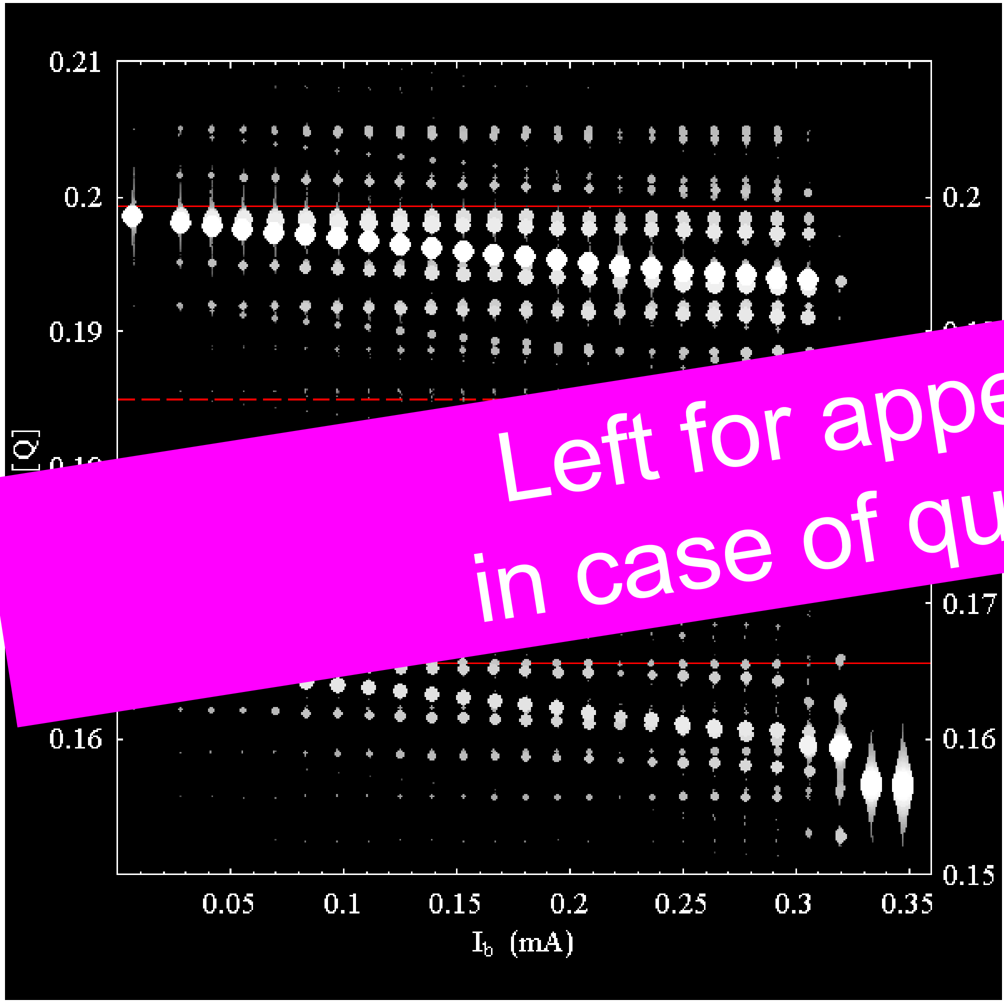
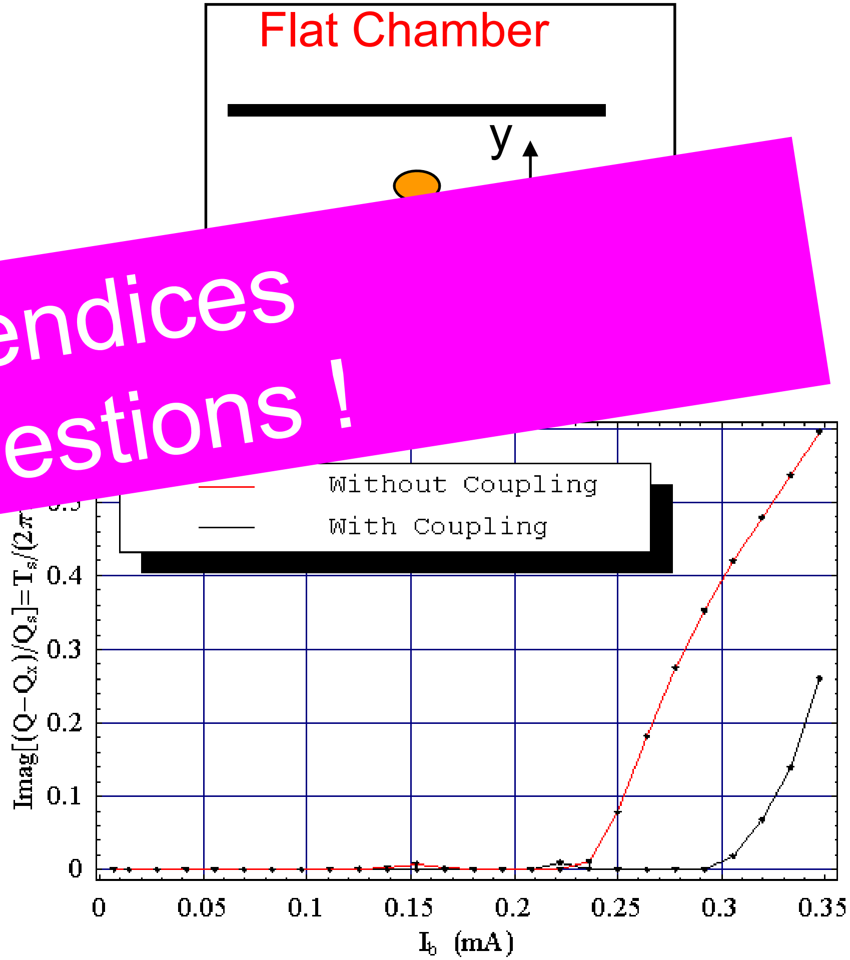
Simulation Results : **Flat beam pipe** / no chromaticity **/** **Linear coupling**
➔ ***Frequency Analysis***



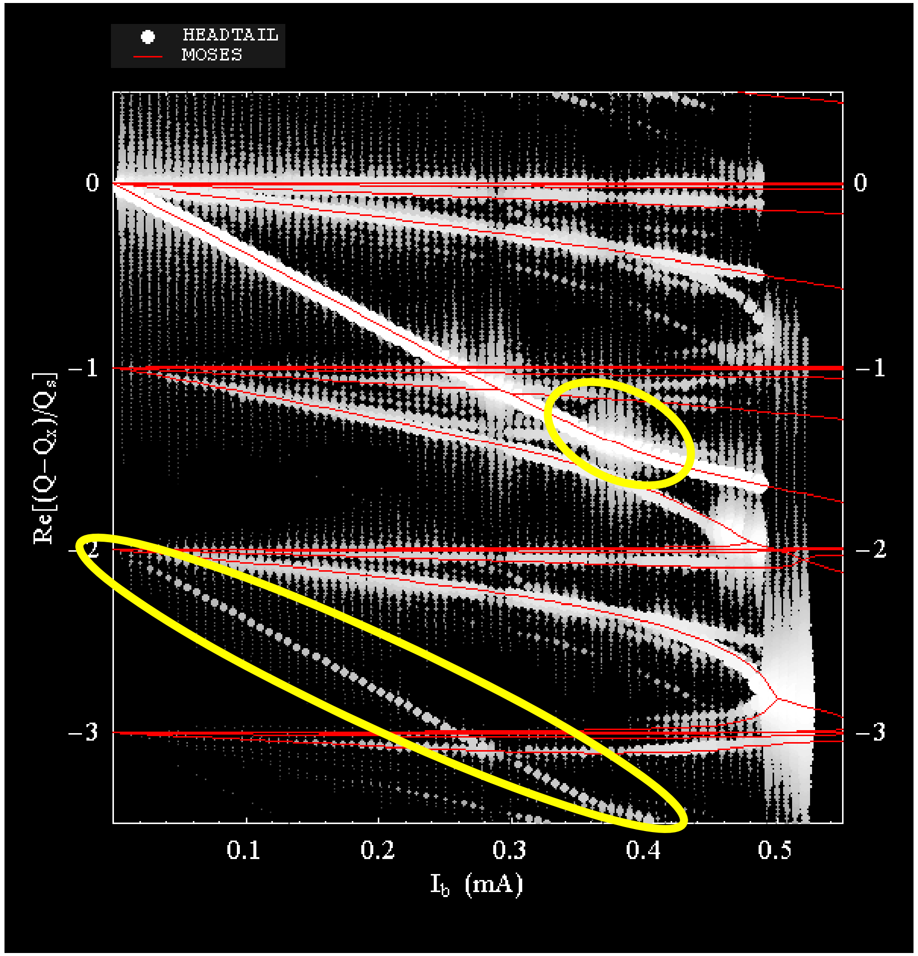


Left for appendices in case of questions !

With Linear Coupling, Instability Threshold is raised by 31% ± 6%

Outlook

- Agreement of MOSES and HEADTAIL for most modes shifting and coupling with current.
- We can now apply HEADTAIL to more realistic impedances. Indeed, MOSES calculations only hold for gaussian bunches interacting with resonator impedances.
- Some points remain to be clarified:
  - Several radial modes are observed in HEADTAIL, which are not predicted by MOSES (ex: -2)
  - Parallel behaviour of this mode -2 with mode 0 is suspect.
  - One of these radial modes (-1) couples with the main tune in HEADTAIL, leading to a weak instability.



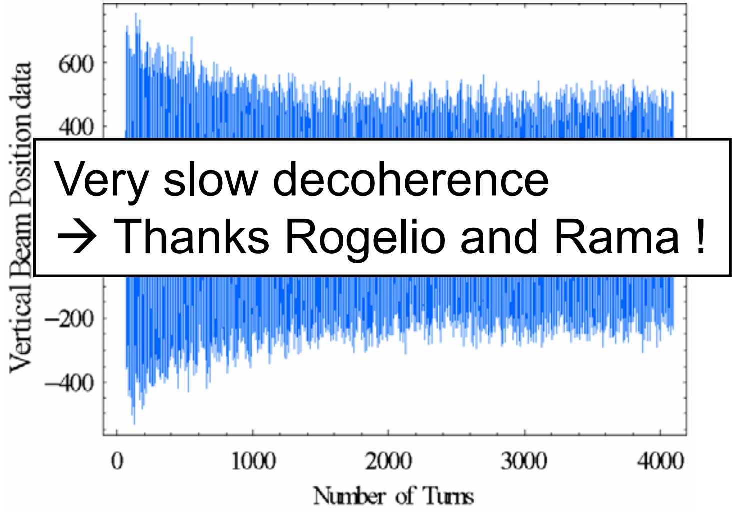
Perspectives (1)

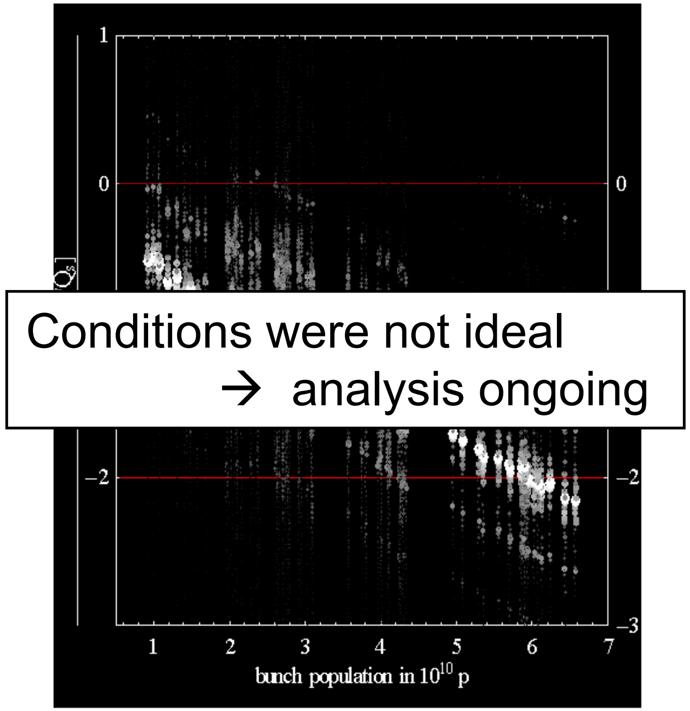
- It is now clear that the HEADTAIL simulated instability is a TMCI

- What about the real instability in the machine ???

  → MD proposed in 2007 to see whether we can get more information on the modes shifting and coupling.

  → first results:

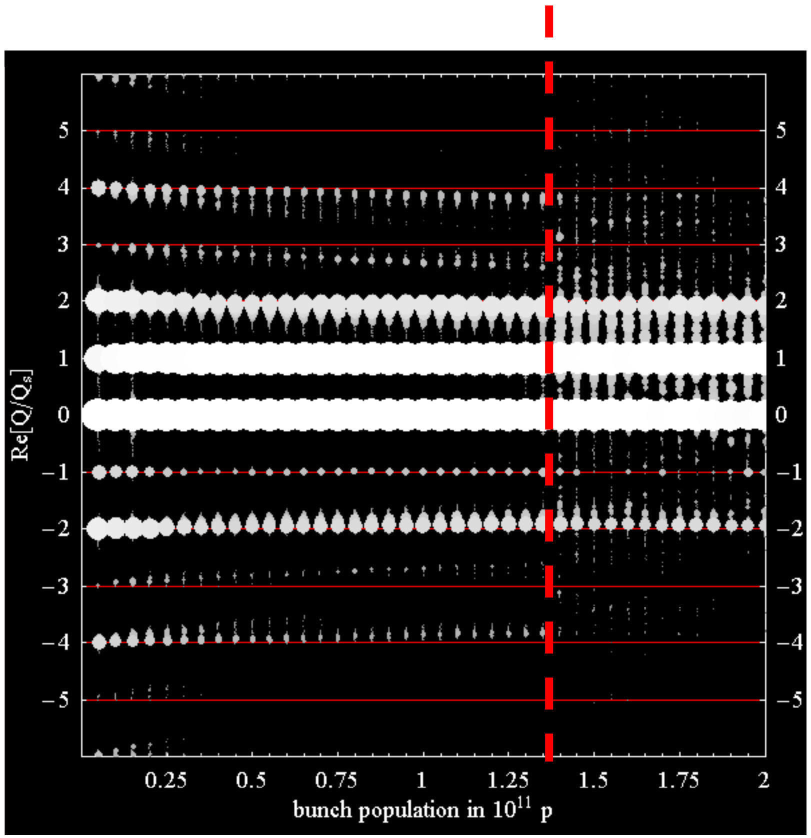


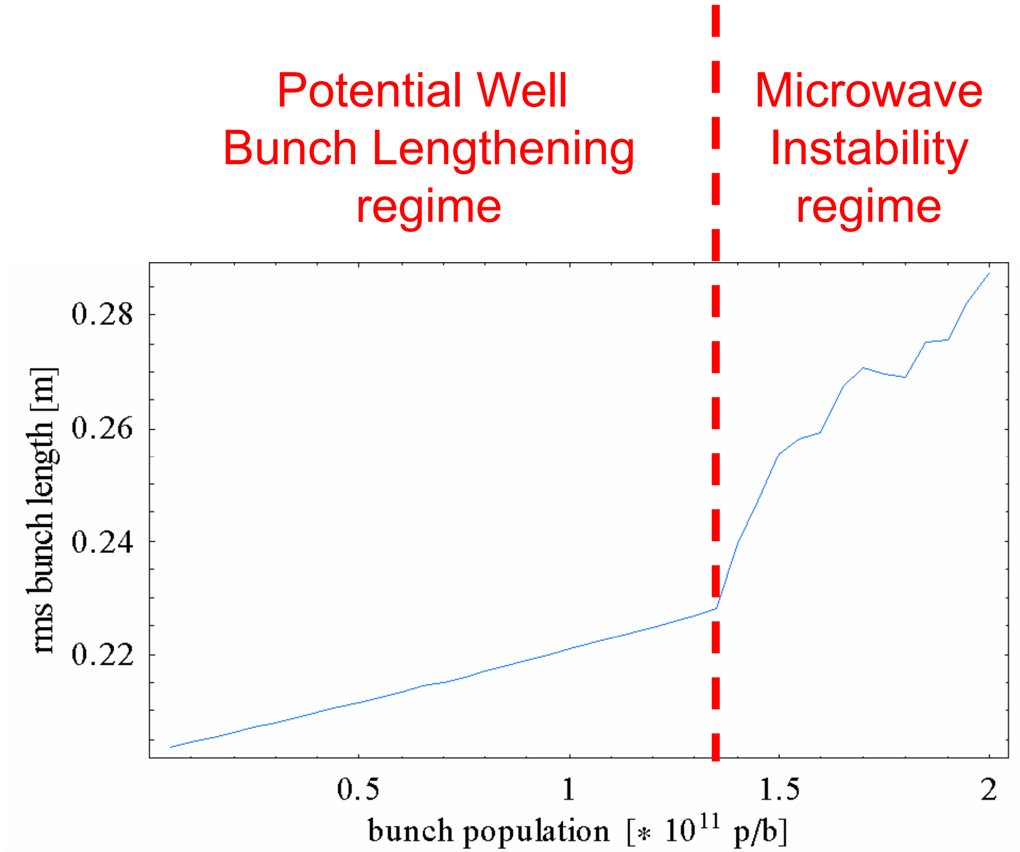


Perspectives (2)

- Following L. Rivkin's idea, a similar study could be performed for the longitudinal mode coupling.

First simulation results with a longitudinal broadband impedance ($Z/n=10\ \Omega$ / f_r=1GHz / Q=1)





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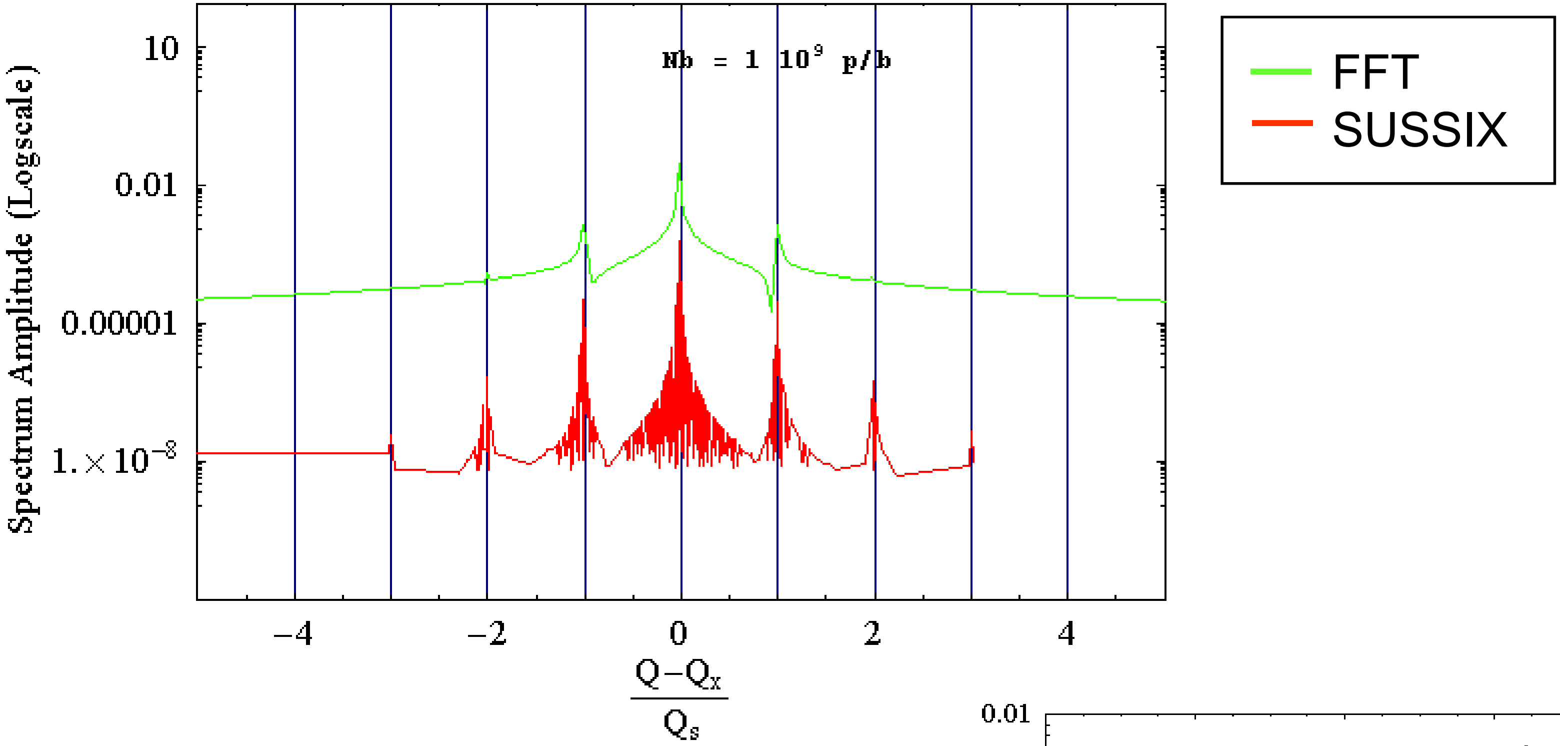
Bruno Zotter

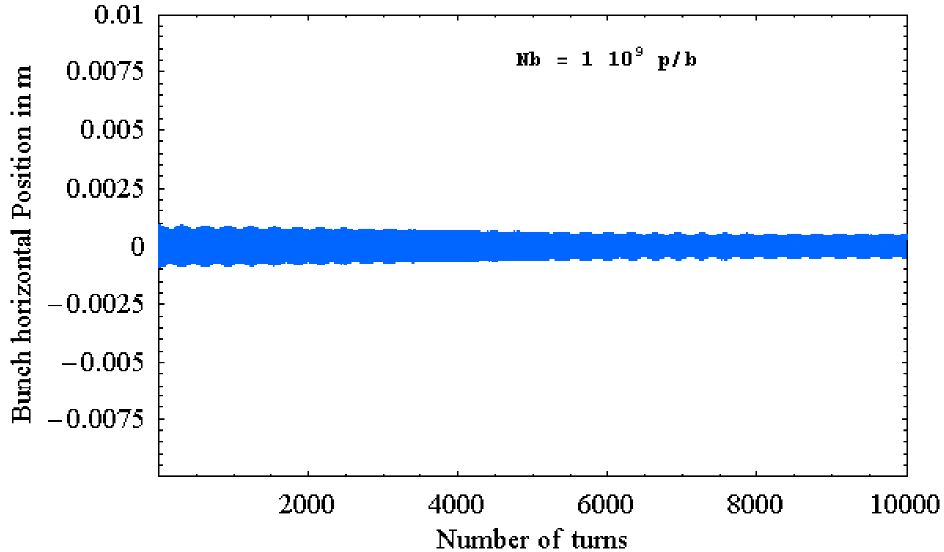
… and of course …

Elias, Giovanni and Rogelio for the great teamwork

Round pipe with Chromaticity

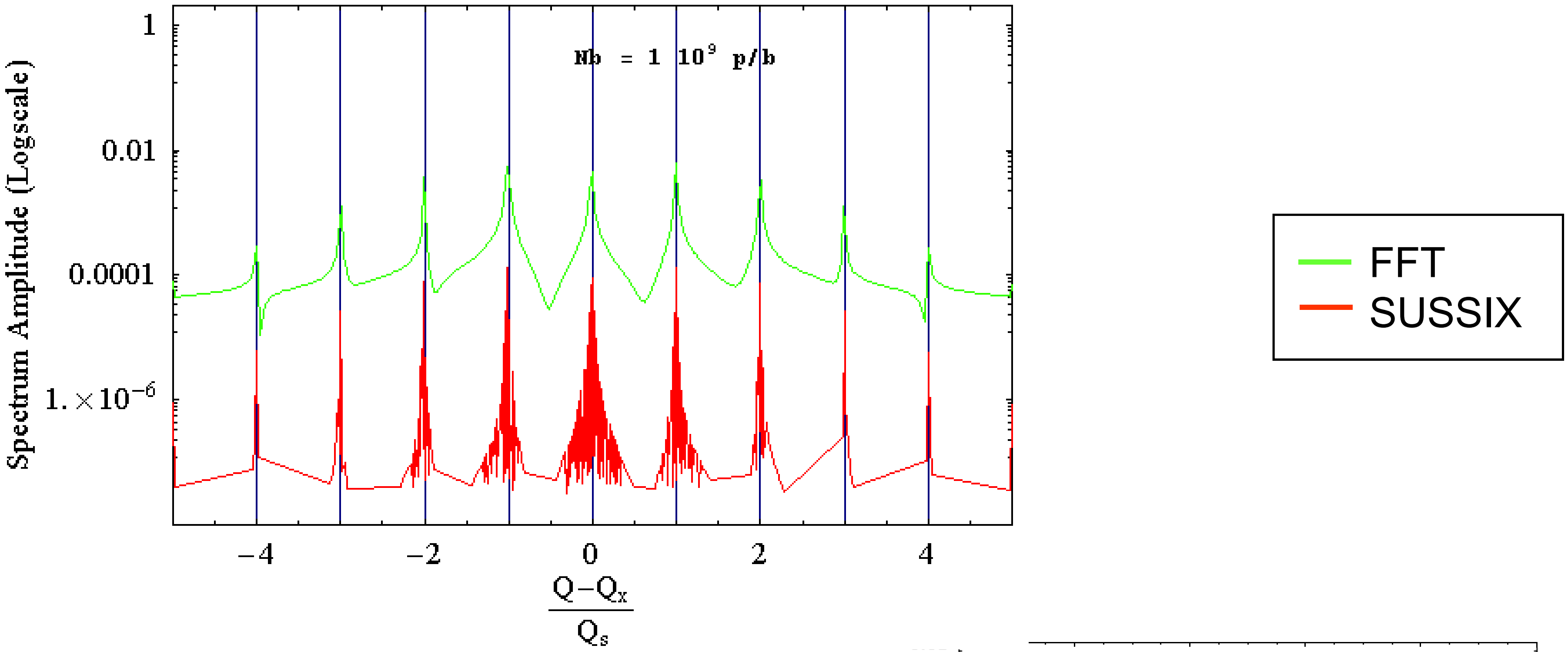
Round beam pipe / chromaticity = 1/Q / no coupling
Frequency Analysis (horizontal plane)





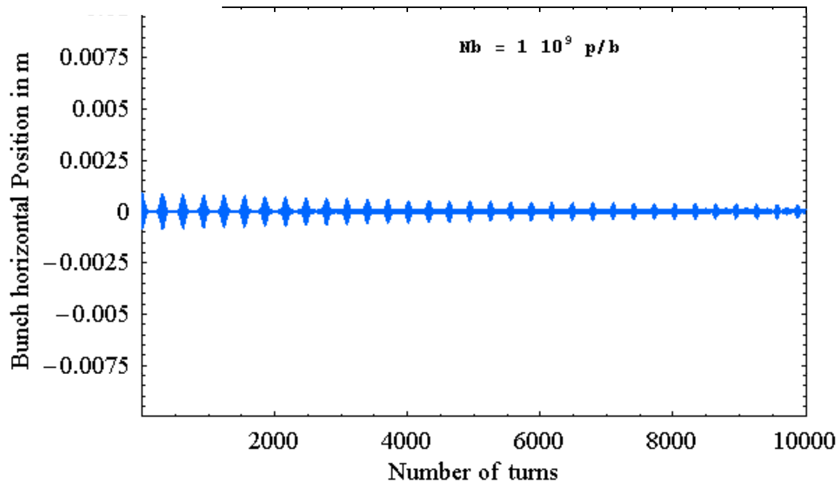
- $\xi \neq 0$ => oscillations decohere but do not recohere after T_s.
- ξ couples Q_s with $Q_{x,y}$ => modes are stronger but they still clearly shift and couple

Round beam pipe / chromaticity = 5/Q / no coupling
Frequency Analysis (horizontal plane)

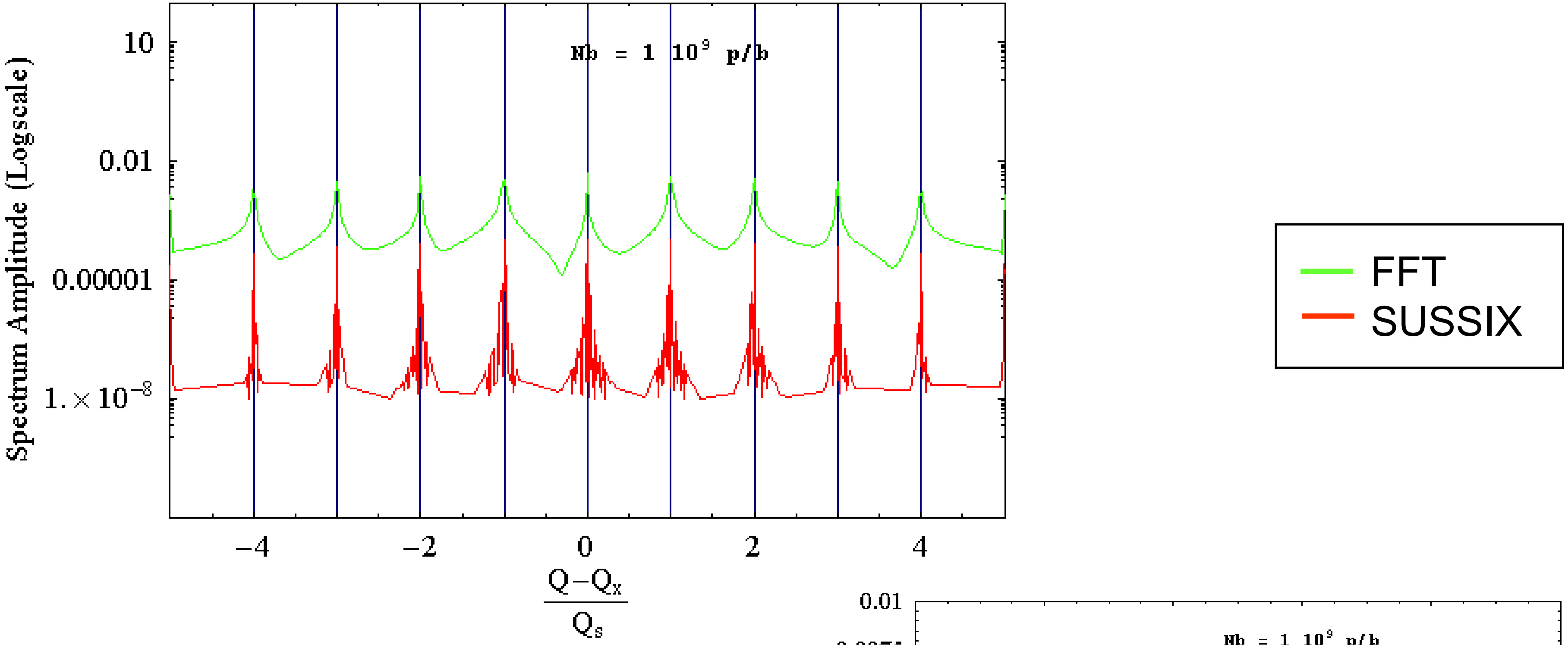


- ξ≠0 => oscillations decohere and recohere after T_s.

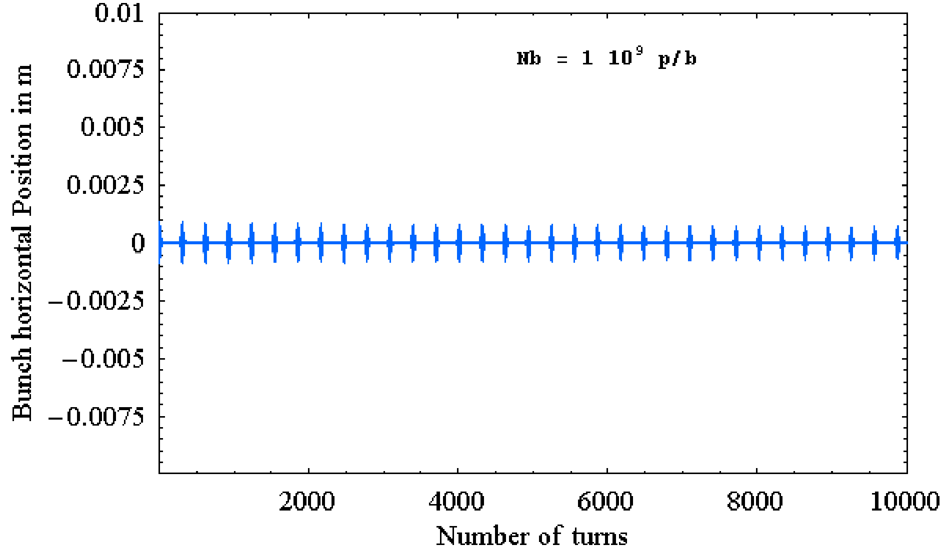
- ξ couples Qs with Qx,y
=> modes still clearly shift, but it is not clear whether the instability is due to coupling.



Round beam pipe / chromaticity = 10/Q / no coupling
Frequency Analysis (horizontal plane)



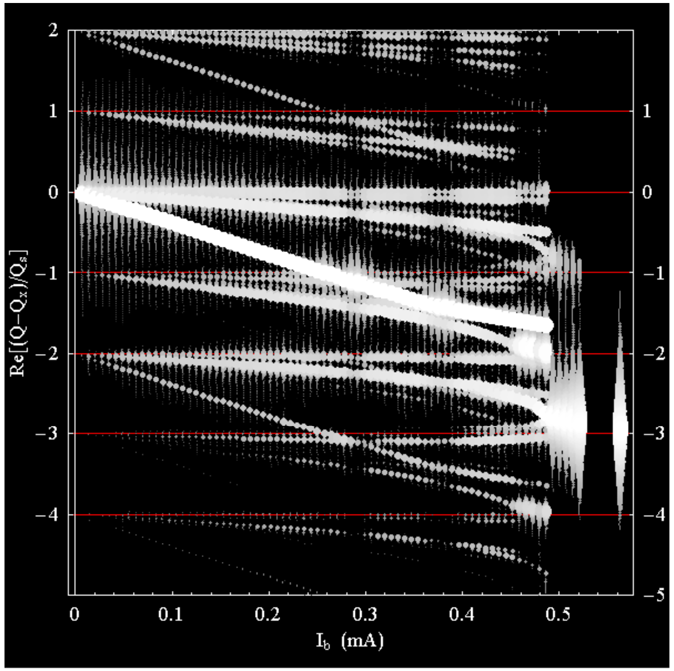
- ξ couples Qs with Qx,y
  => modes are not observed to shift anymore
  => Headtail instability?



Simulation Results : Round beam pipe / **various chromaticities** / no coupling

Frequency Analysis

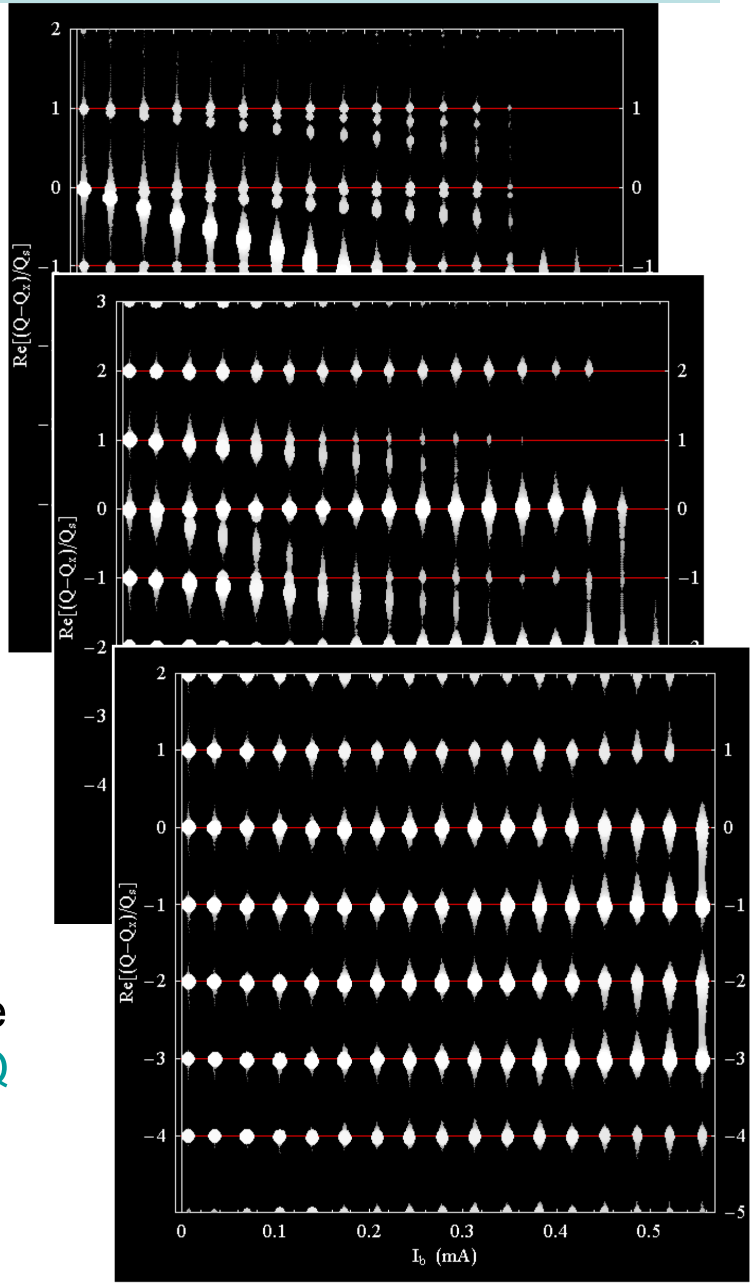
Reference (Round Chamber)



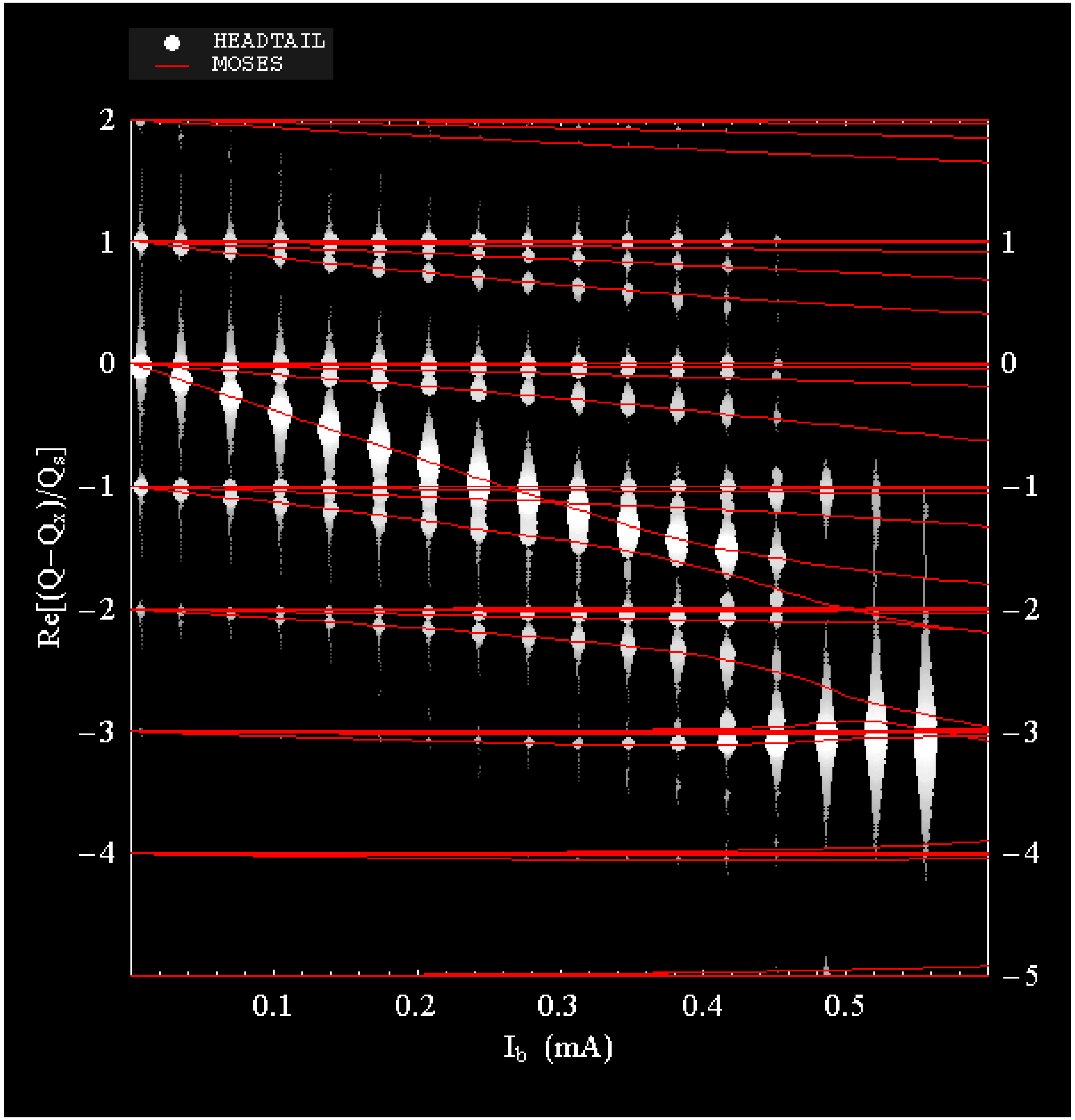
Reference + ξ = 1/Q

Reference + ξ = 5/Q

Reference + ξ = 10/Q

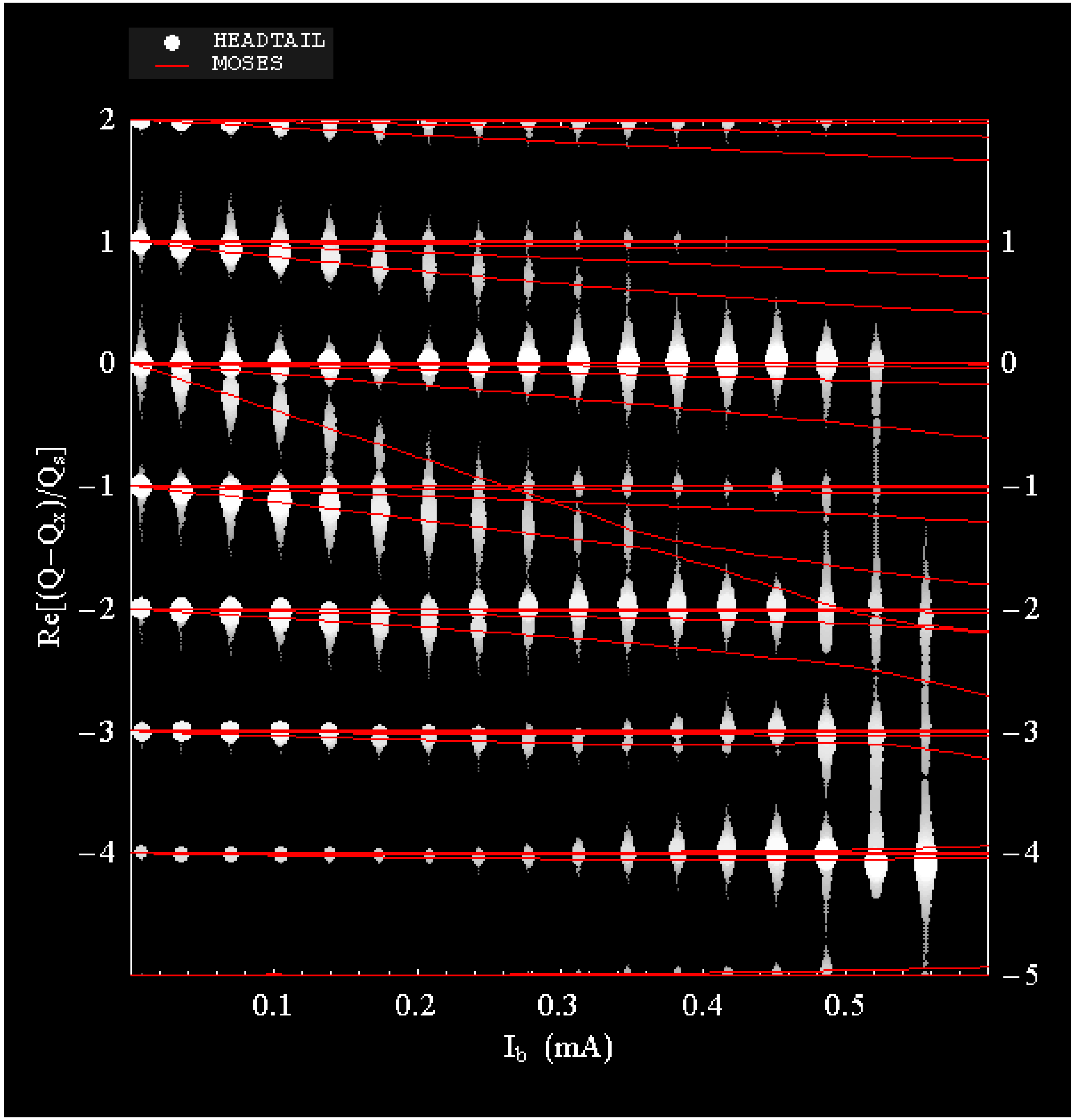


Simulation Results : Round beam pipe / **chromaticity = 1/Q** / no coupling
Frequency Analysis



- It looks like mode -2 and -3 do not couple anymore, even though ξ is small.
- Mode -3 couples with itself????

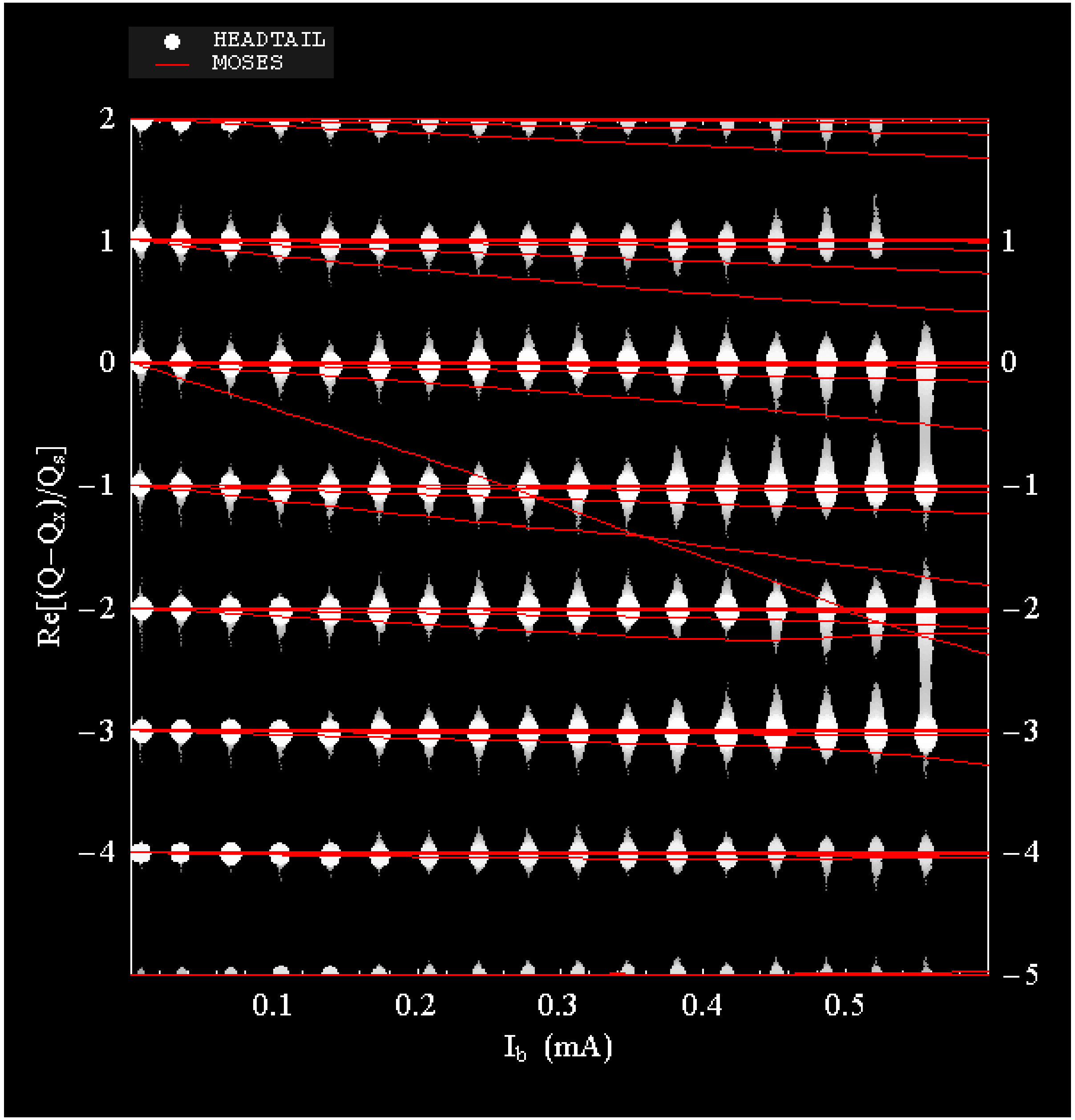
Simulation Results : Round beam pipe / **chromaticity = 5/Q** / no coupling
Frequency Analysis



- No obvious mode coupling here

Simulation Results : Round beam pipe / **chromaticity = 10/Q** / no coupling

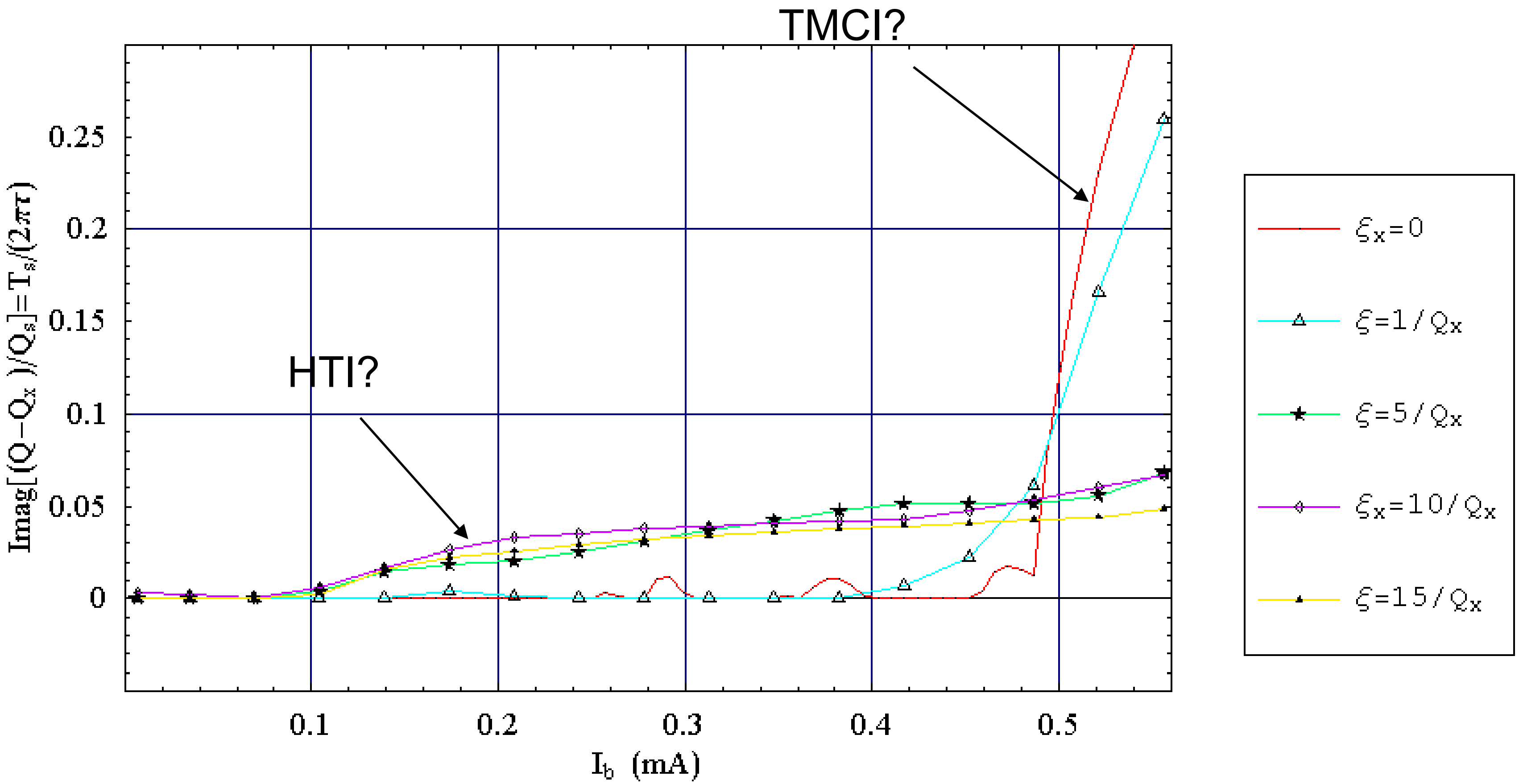
Frequency Analysis



- Mode shifting can not be seen anymore
- No obvious mode coupling here

Simulation Results : Round beam pipe / **chromaticity = 1/Q** / no coupling

Instability rise-times

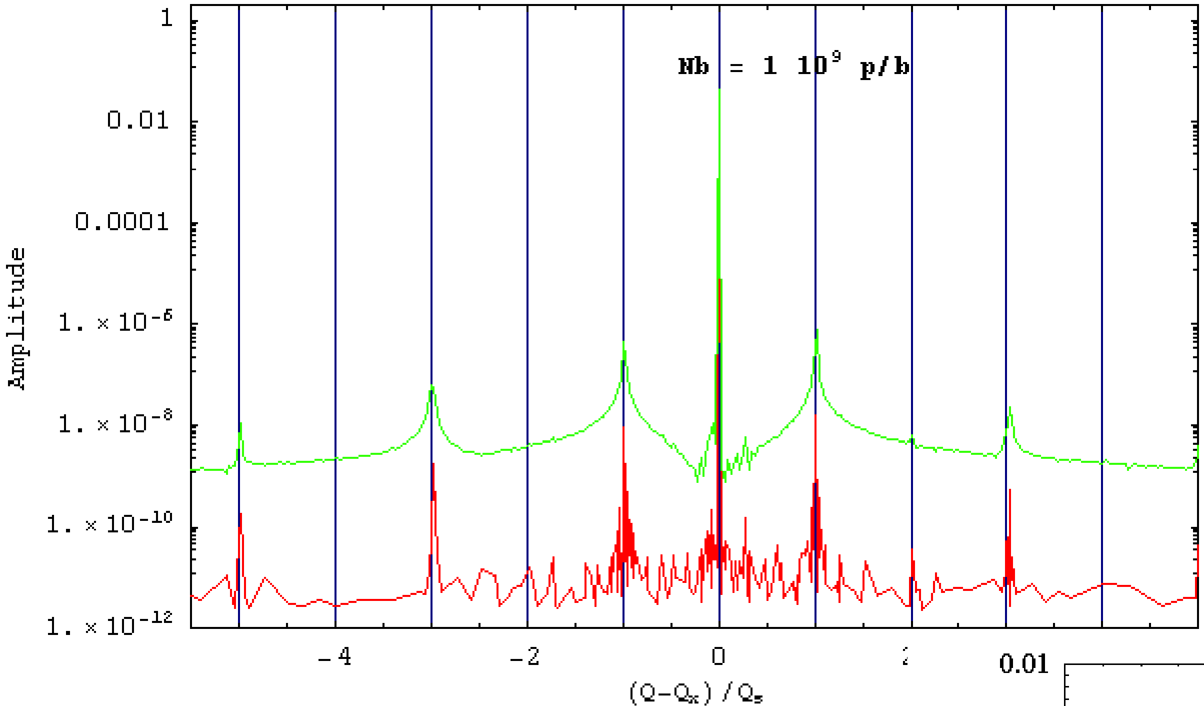


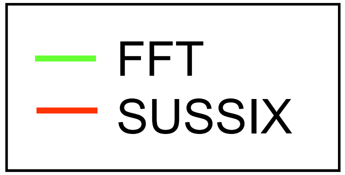
Increasing the chromaticity leads to an increase of the instability threshold, if low instability growth rates are slower than damping rates.

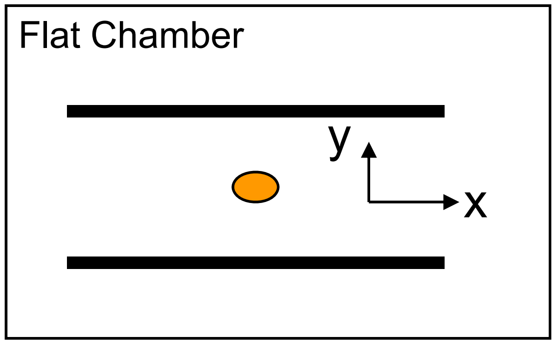
Flat pipe

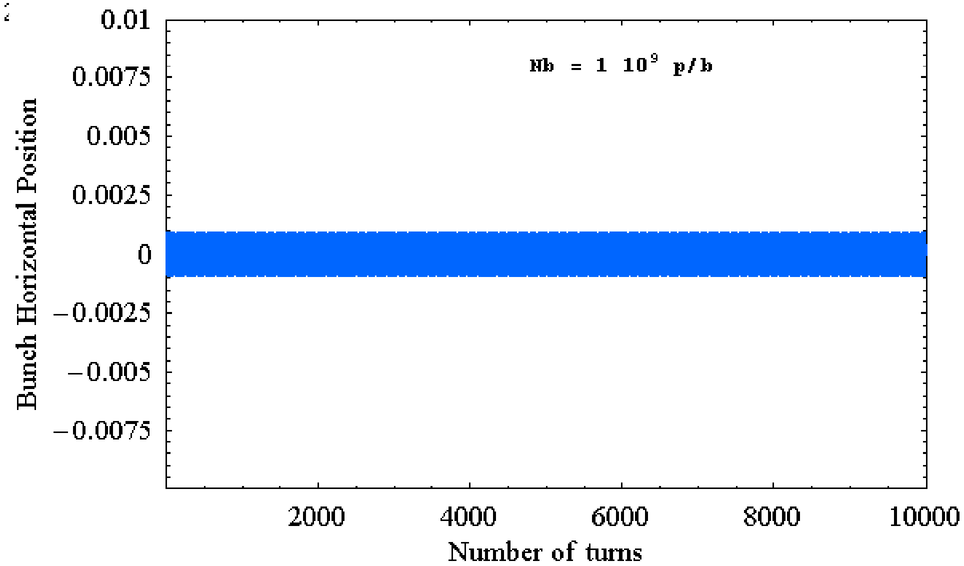
Flat beam pipe / no chromaticity / no coupling

➔ *Frequency Analysis (horizontal plane)*

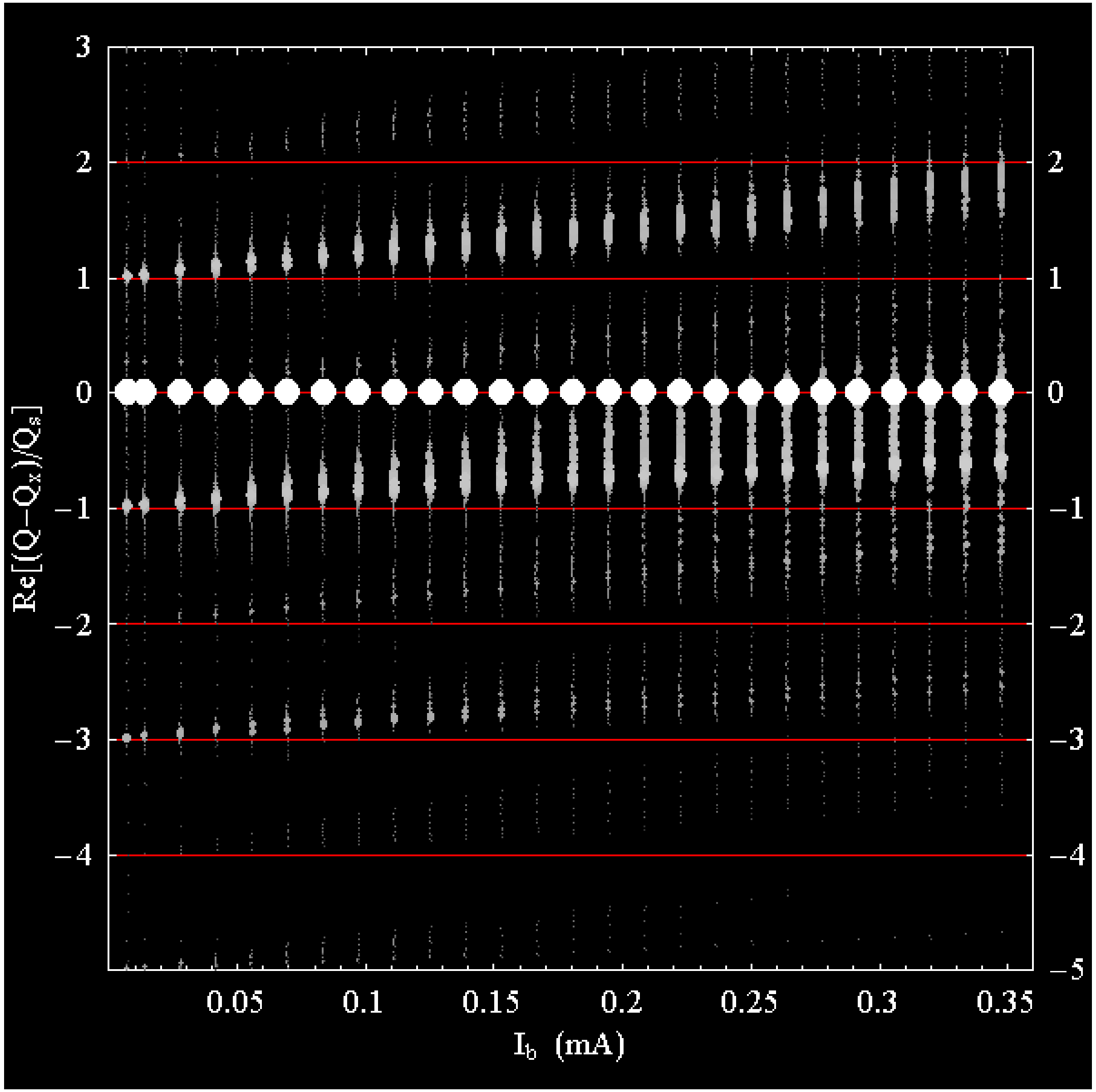








Flat beam pipe / no chromaticity / no coupling
➔ $Re[\Delta Q_x]=f(I_b)$



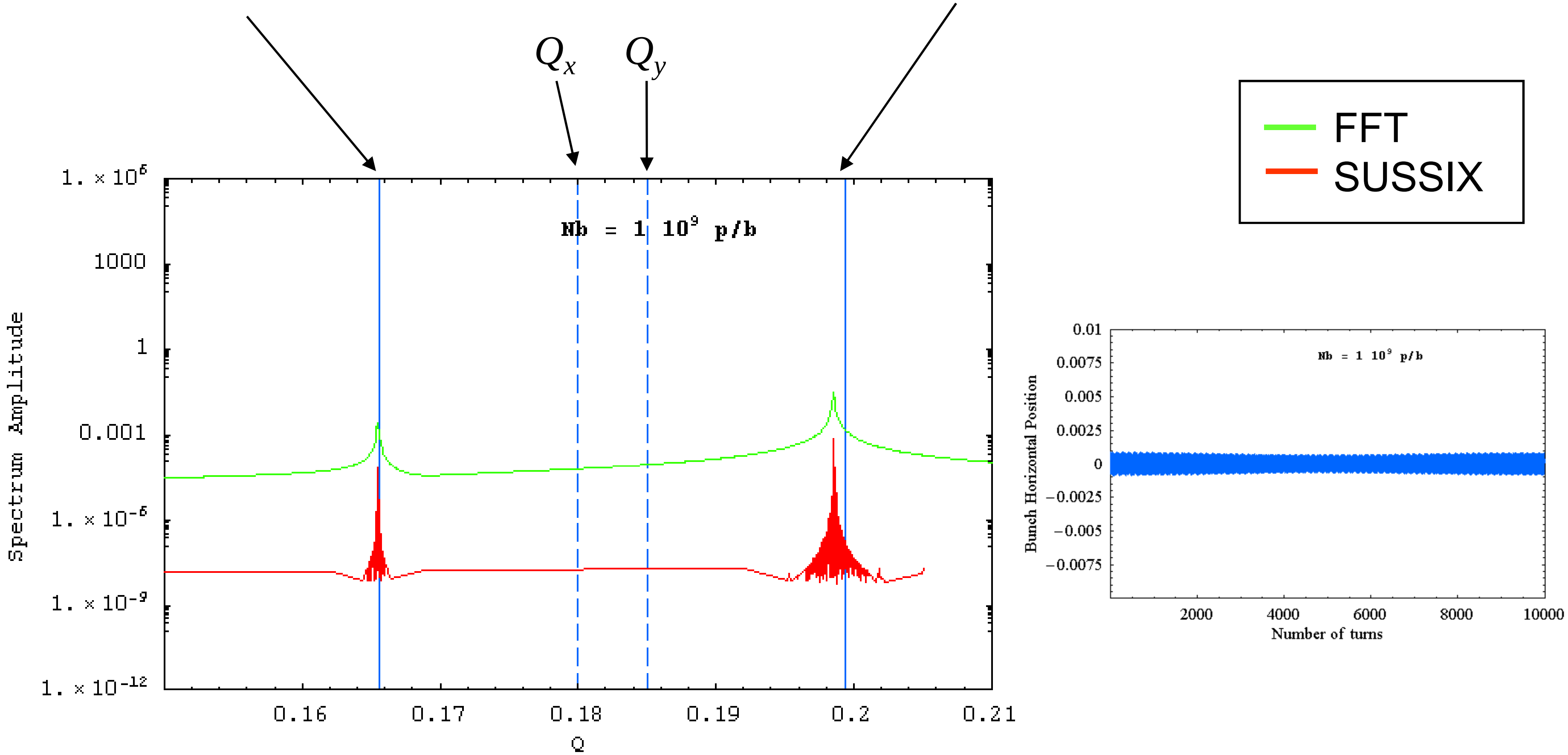
Flat pipe with Linear Coupling

Simulation Results : **Flat beam pipe** / no chromaticity / **Linear coupling**

➔ ***Frequency Analysis***

$$Q_u = \frac{Q_x + Q_y}{2} - \frac{1}{2}\sqrt{\left(Q_x - Q_y\right)^2 + \left|C\right|^2}$$

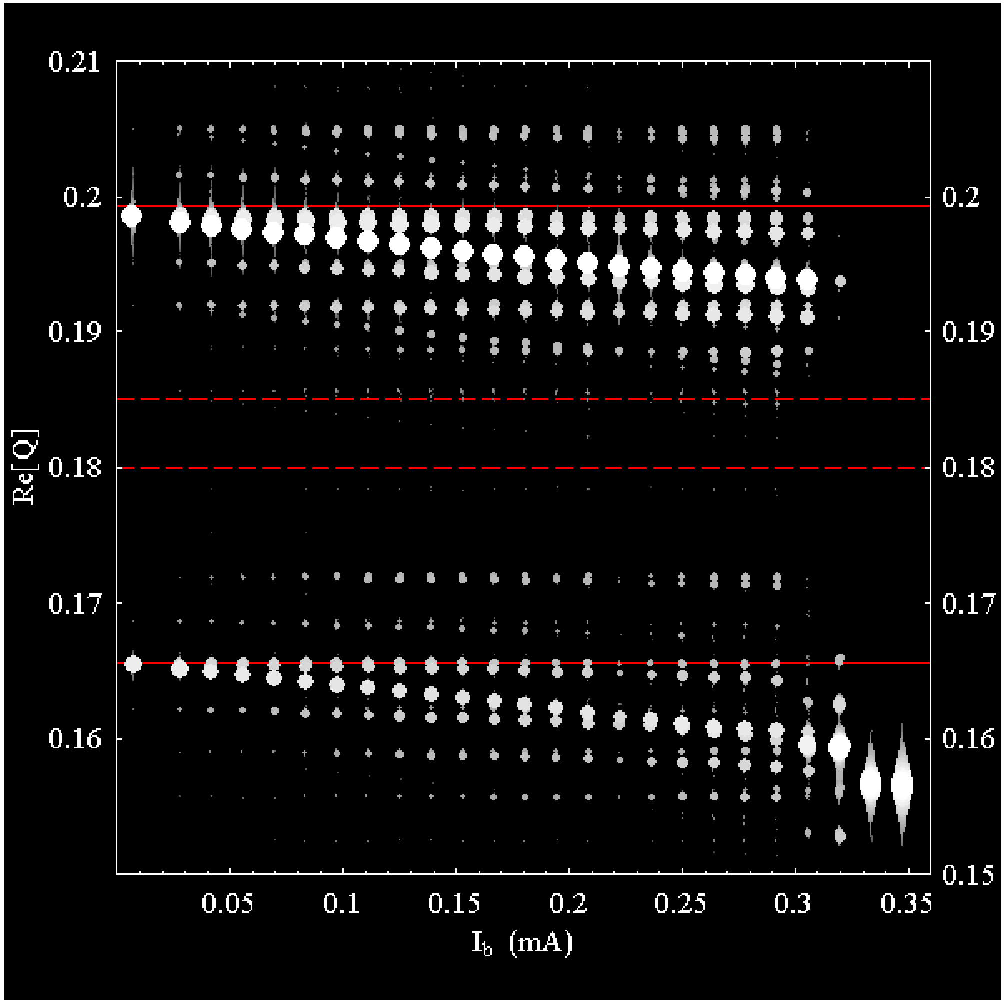
$$Q_v = \frac{Q_x + Q_y}{2} + \frac{1}{2}\sqrt{\left(Q_x - Q_y\right)^2 + \left|C\right|^2}$$

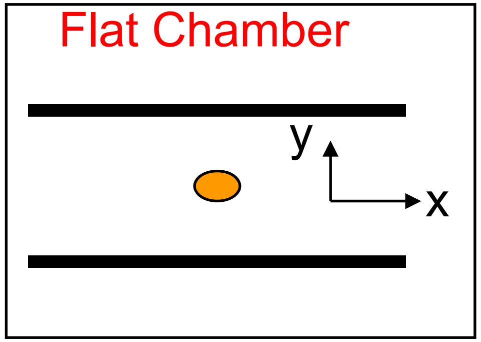


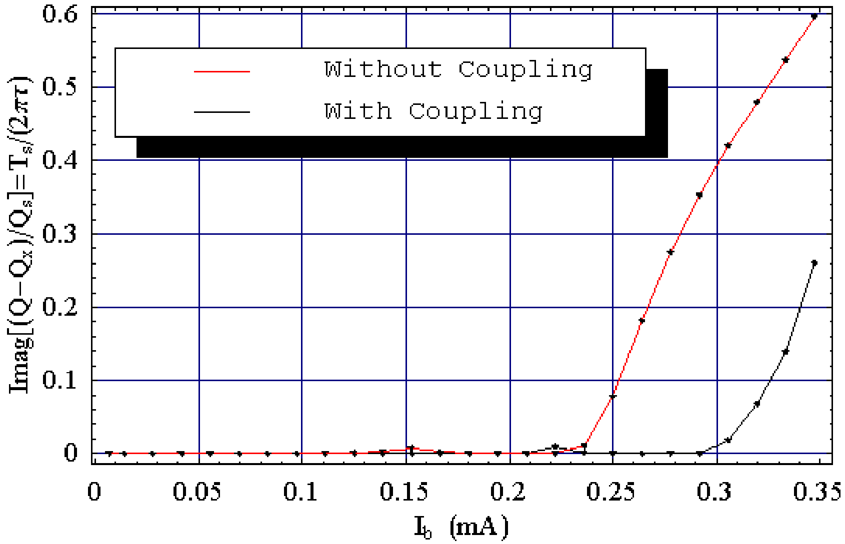
Headtail and the theory lead to the same coupled tunes

Simulation Results : **Flat beam pipe** / no chromaticity **/** **Linear coupling**

➔ ***Frequency Analysis***







With Linear Coupling, Instability Threshold is raised by 31% ± 6%