TMC Instability in the SPS :

HEADTAIL simulations and MOSES calculations

E. Métral, G. Rumolo, B. Salvant, R. Tomás

Agenda

- Context
- Methods
  - HEADTAIL Simulations
  - Sussix algorithm
  - MOSES calculations
- Results

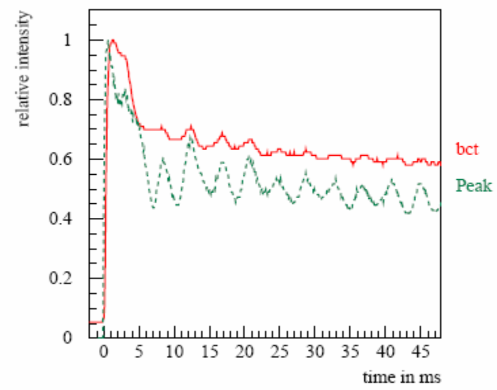
  Real Tune shift and Imaginary tune shift (instability rise time) for
  - Chromaticity = 0 and no coupling
  - Chromaticity ≠ 0 and no coupling

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

  } Flat beam pipe
- Outlook and Perspectives

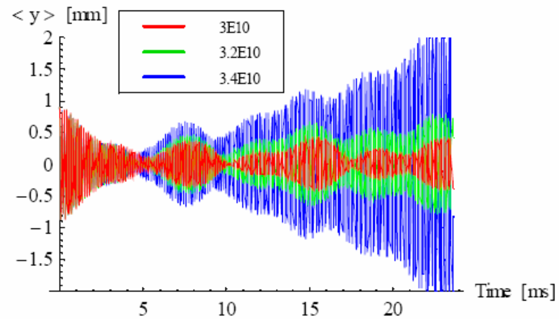
Context

- Measurements in the SPS (2003)
  - LHC type Single bunch - intensity=1.15 p/b – low longitudinal Emittance.
    → very fast transverse instability
    → Travelling-wave pattern
    → depends on ξ_y
    => is this measured instability a TMCI?



H. Burkhardt et al, proc EPAC 2004

- HEADTAIL Simulations
  - Using a broadband impedance model, simulation yield
    → a fast ξ_y dependant instability with a travelling wave pattern.
    => is this simulated instability a TMCI ?



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

- Theory
  - Intensity threshold due to coupling by a broadband impedance can be calculated with Sacherer's model
  - MOSES calculates real and imaginary tune shifts in the mode-coupling formalism

Therefore : - how do MOSES calculations compare with HEADTAIL simulations?
- Can we find reasons to believe that we observe TMCI in HEADTAIL?

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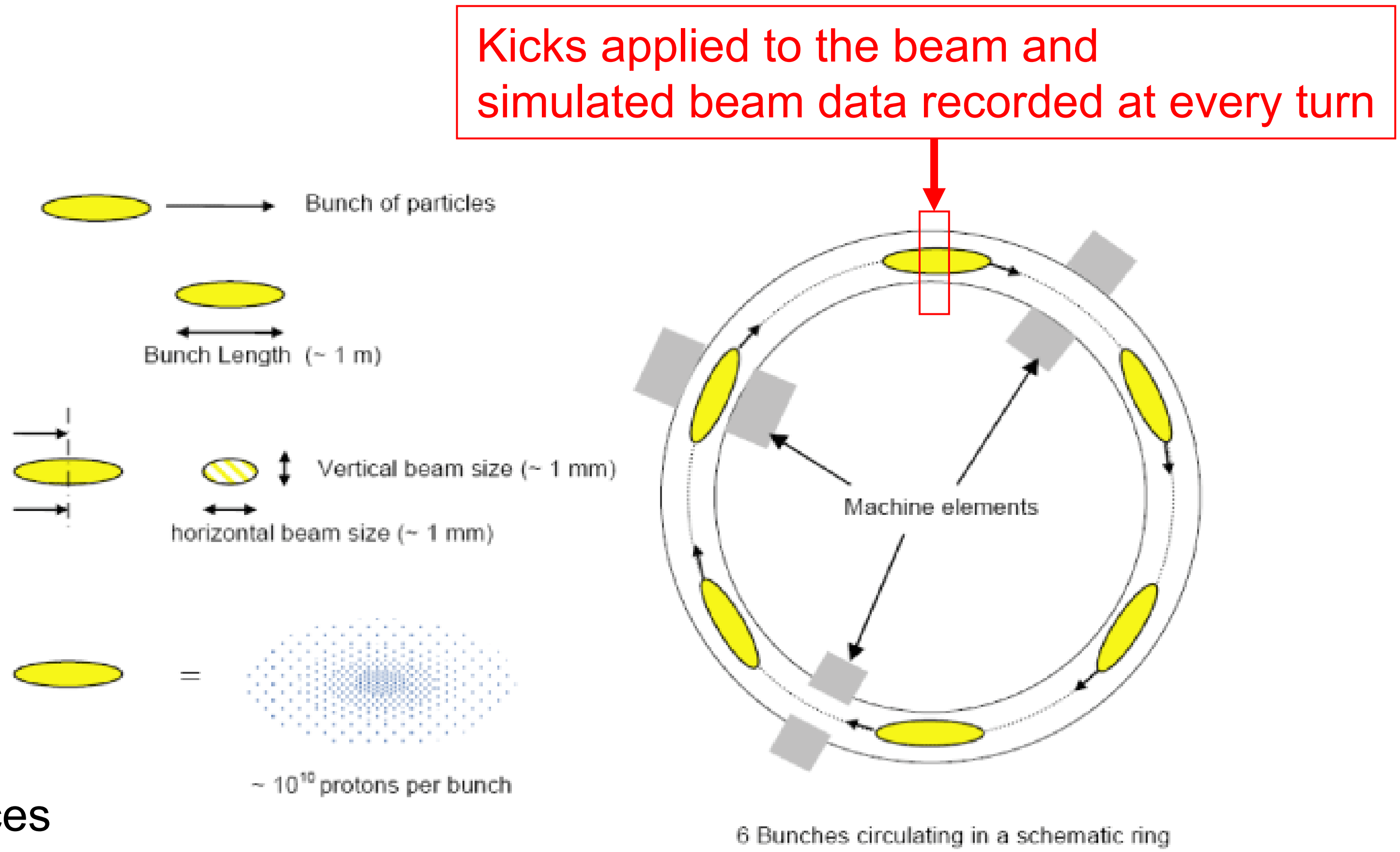
HEADTAIL Simulations (*)



- 500 slices
- 10^6 macroparticles
- Frozen Wake field (i.e. the wake field is not recalculated at every turn)
  → only to be applied if the bunch is matched in the bucket
- Simulations over 10,000 turns (~ 0.23 sec)
- Linear Bucket

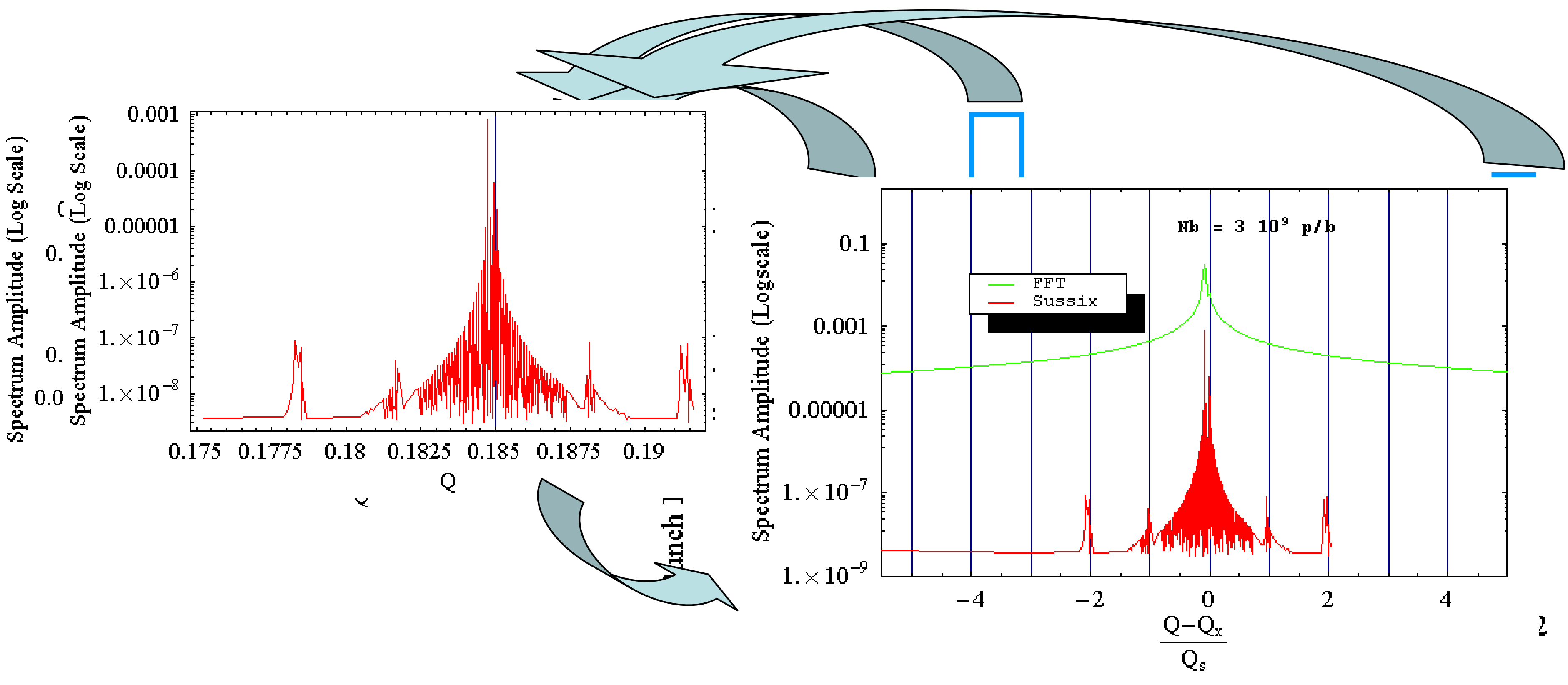
(*) G. Rumolo, F. Zimmermann, SL-Note 2002-036-AP

Headtail Simulated beam parameters

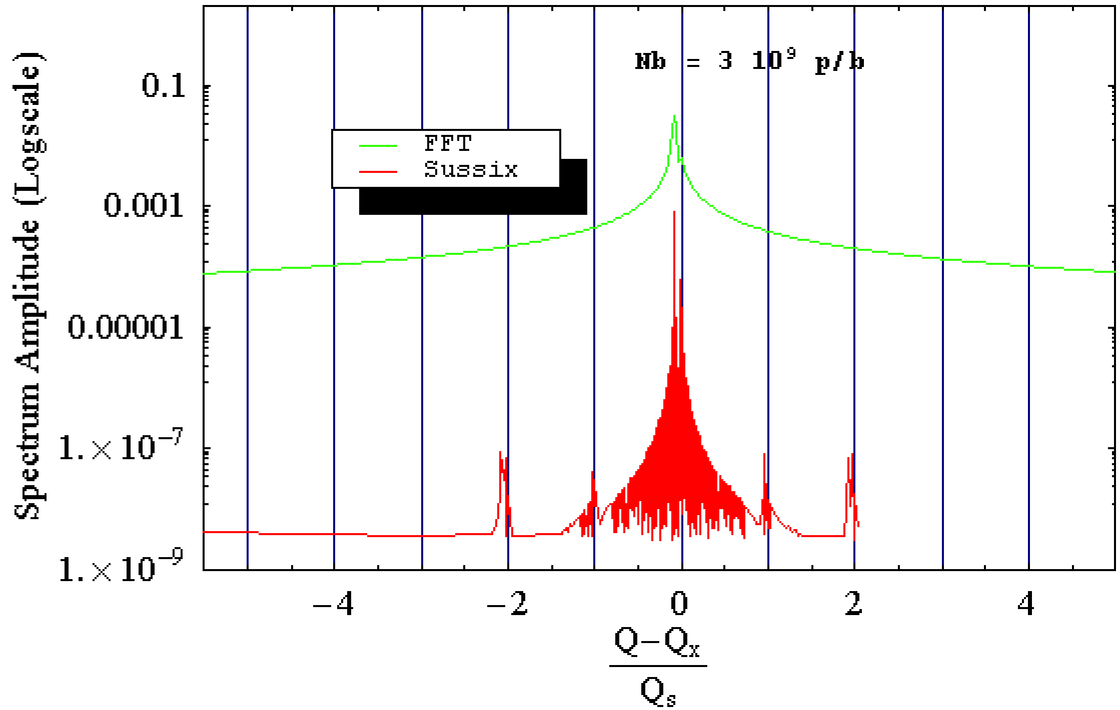
Parameter	Symbol	Value	Unit
Circumference		6911	m
Number of bunches		1	
Relativistic Gamma		27.7286	
Rms beam sizes	σ_x, σ_y	1.8	mm
Horizontal Tune	Q_x	26.185	
Vertical Tune	Q_y	26.13	
chromaticities	$\xi_{x,y}$	0 / 0	
Bunch length		0.21	
Longitudinal Momentum spread	$\Delta p/p_0$	$9.3\ 10^{-4}$	
Synchrotron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

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 $Q_x=0$



Comparison of FFT and SUSSIX



- 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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  - Chromaticity ≠ 0 and no coupling

  } Round beam pipe

  - Chromaticity = 0 and no coupling
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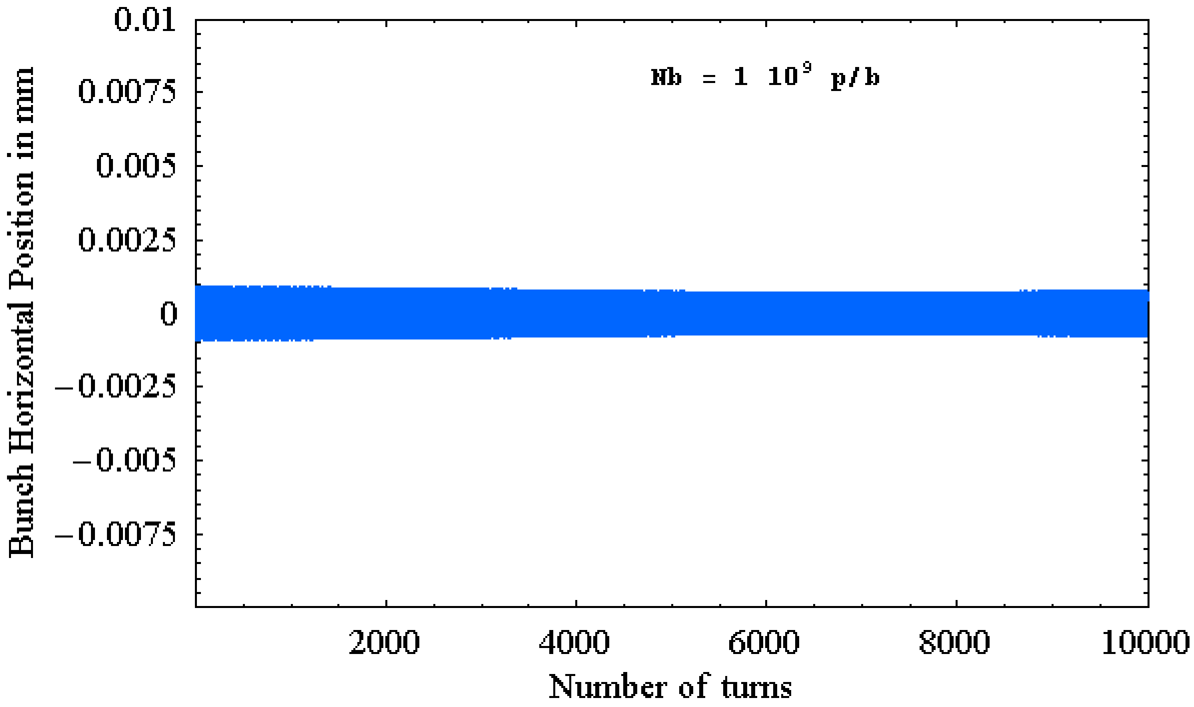
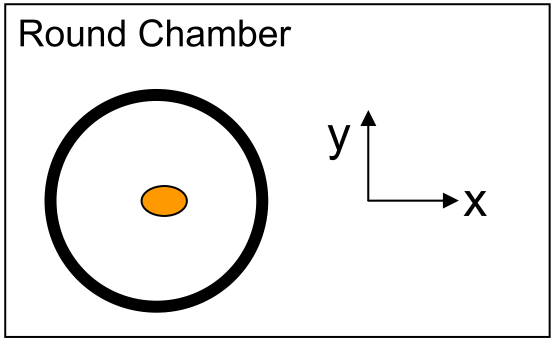
  } Flat beam pipe

- Outlook and Perspectives

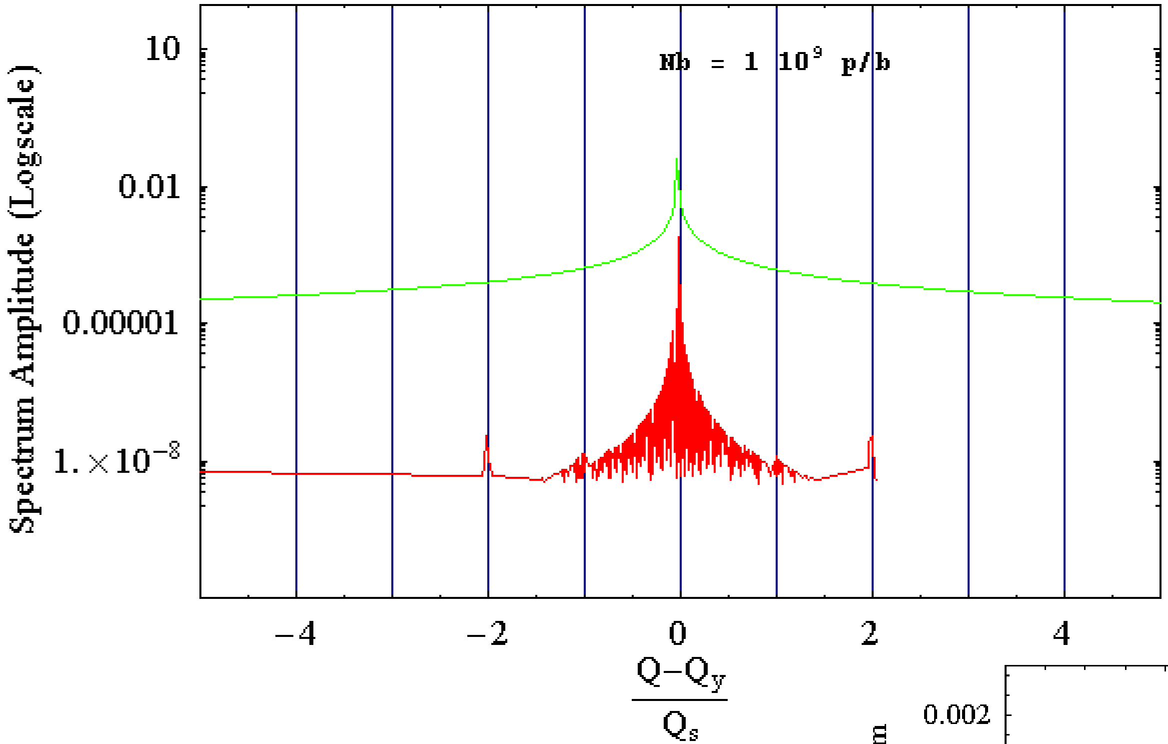
Round beam pipe / no chromaticity / no coupling
simulated BPM signal

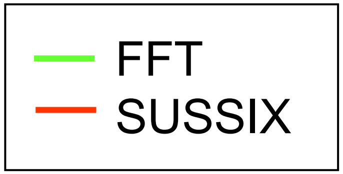
- Motion of the centroid of the bunch

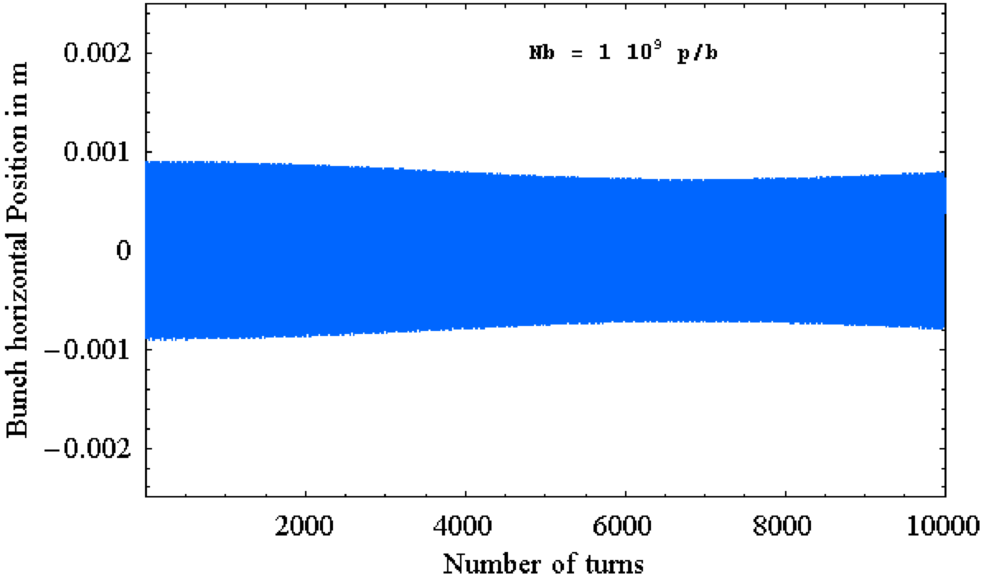




Round beam pipe / no chromaticity / no coupling
Frequency Analysis



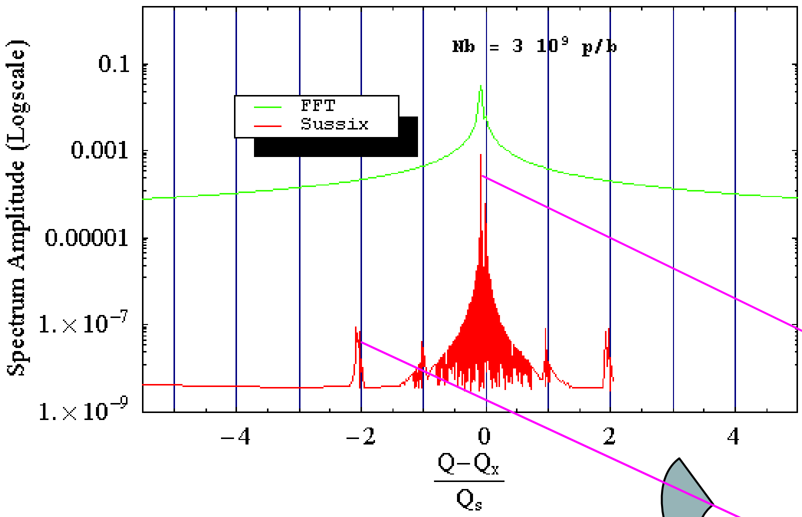




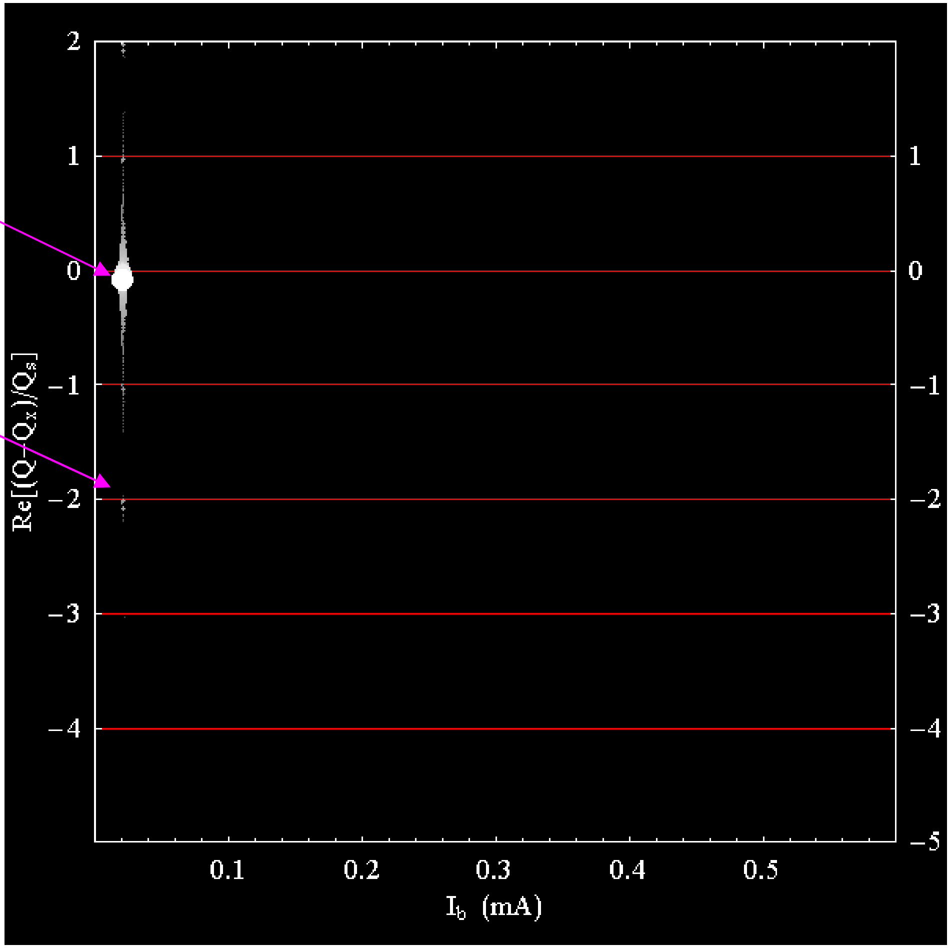
Round beam pipe / no chromaticity / no coupling

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

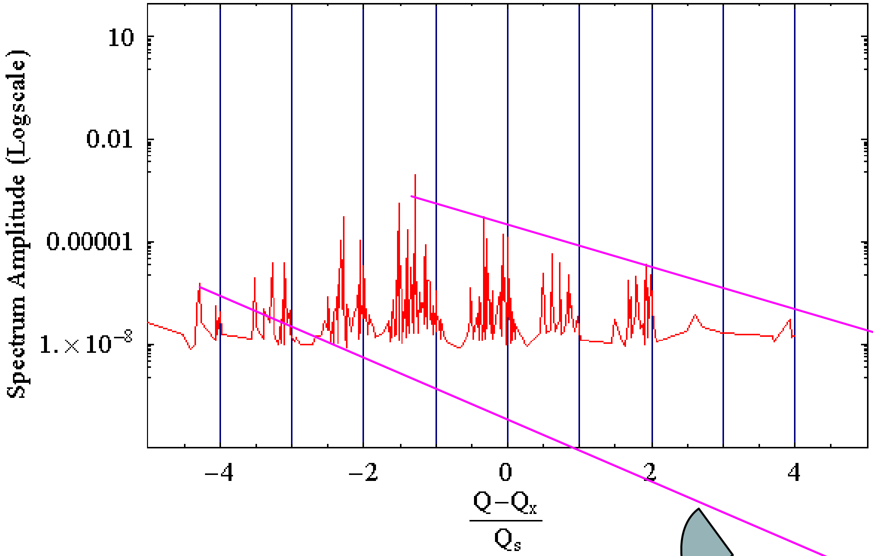


Round beam pipe / no chromaticity / no coupling

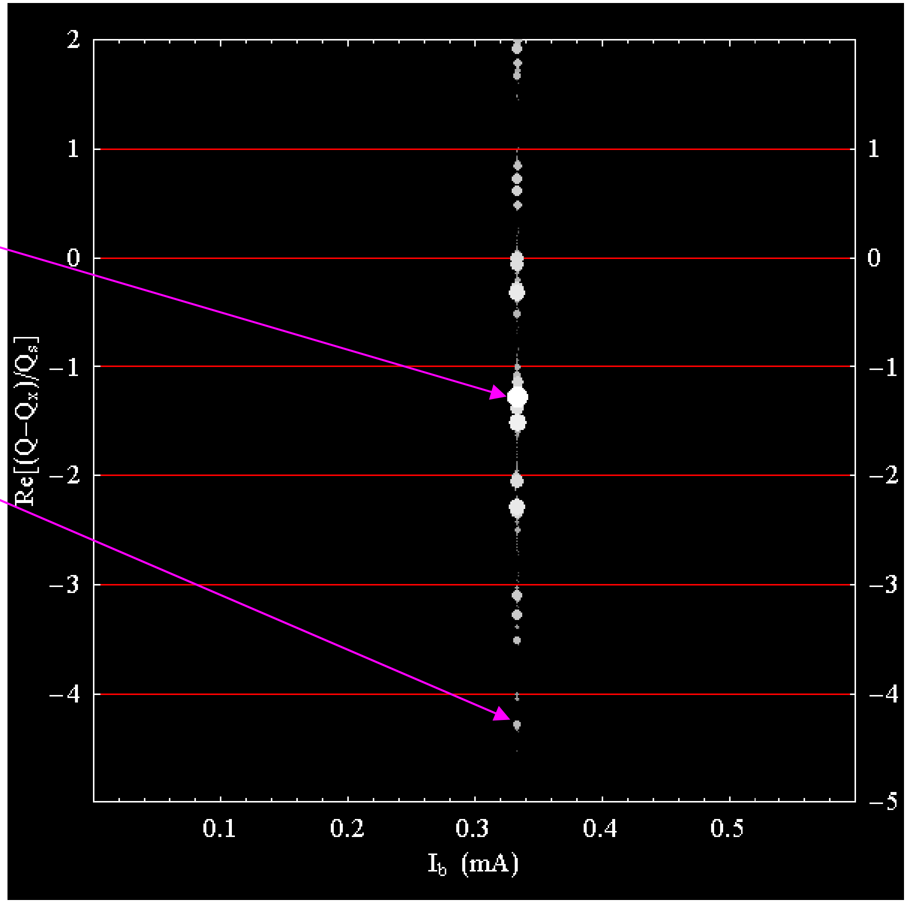
Displaying the real part of the tune shift Re[ΔQ] as a function of current

(Another example)

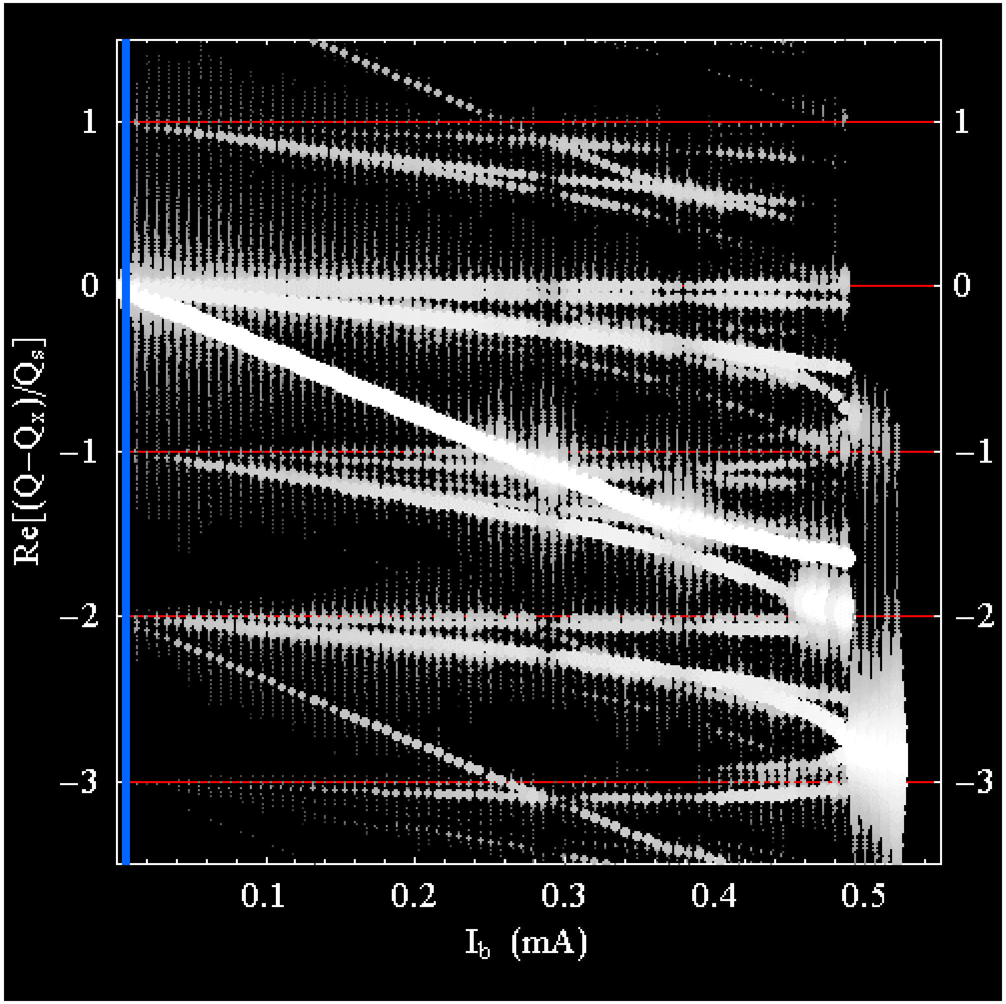
for Nb = 48 10^9 p/b (I_b = 0.33 mA)

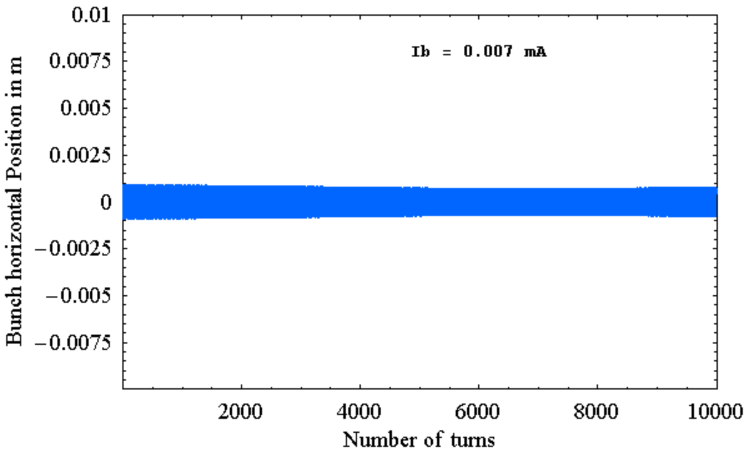


Displaying the Sussix spectrum on one line



Round beam pipe / no chromaticity / no coupling
➔ displaying *Re[ΔQ]=f(I_b)*

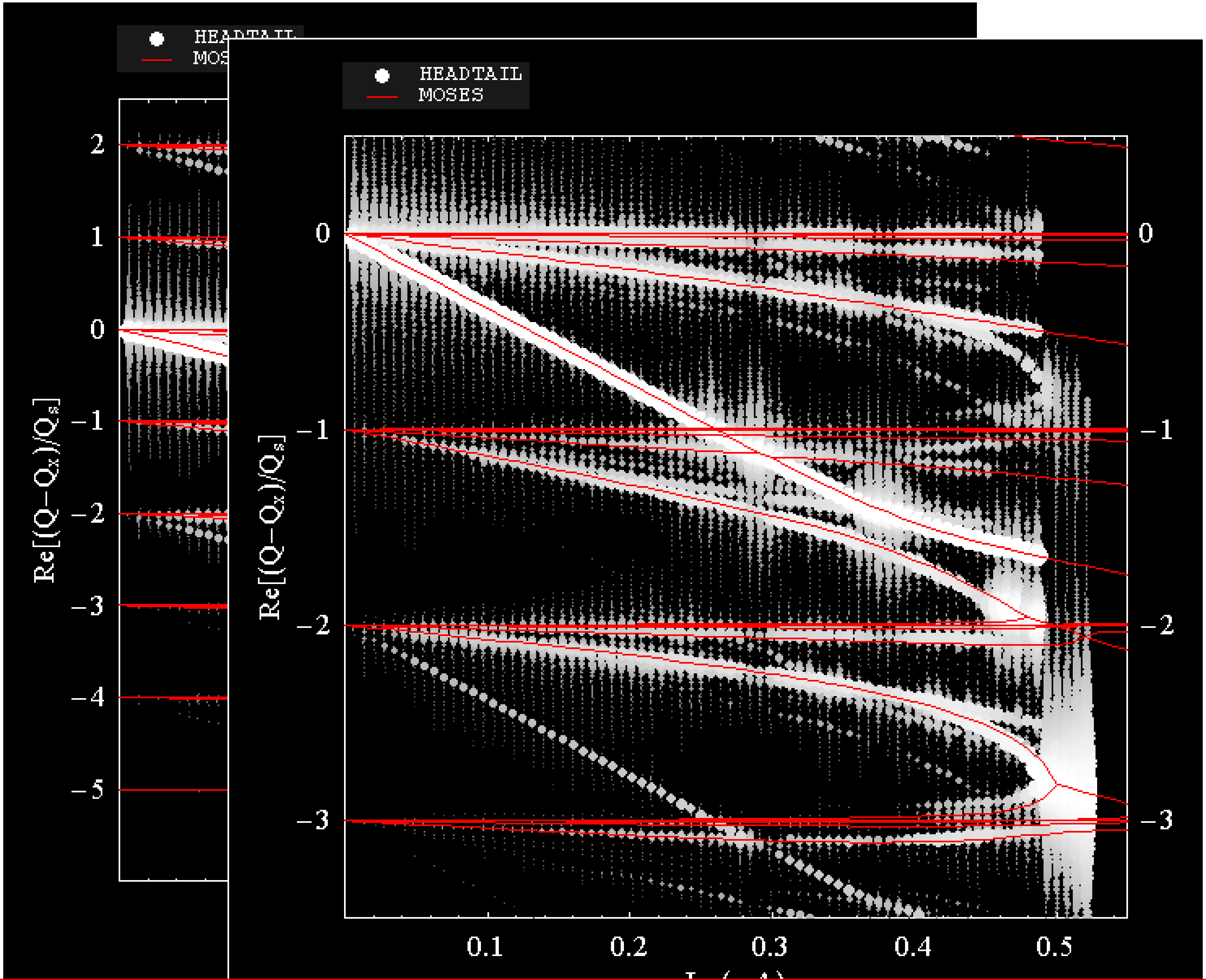




→ Transverse modes are observed to shift, couple and decouple with current

Round beam pipe / no chromaticity / no coupling

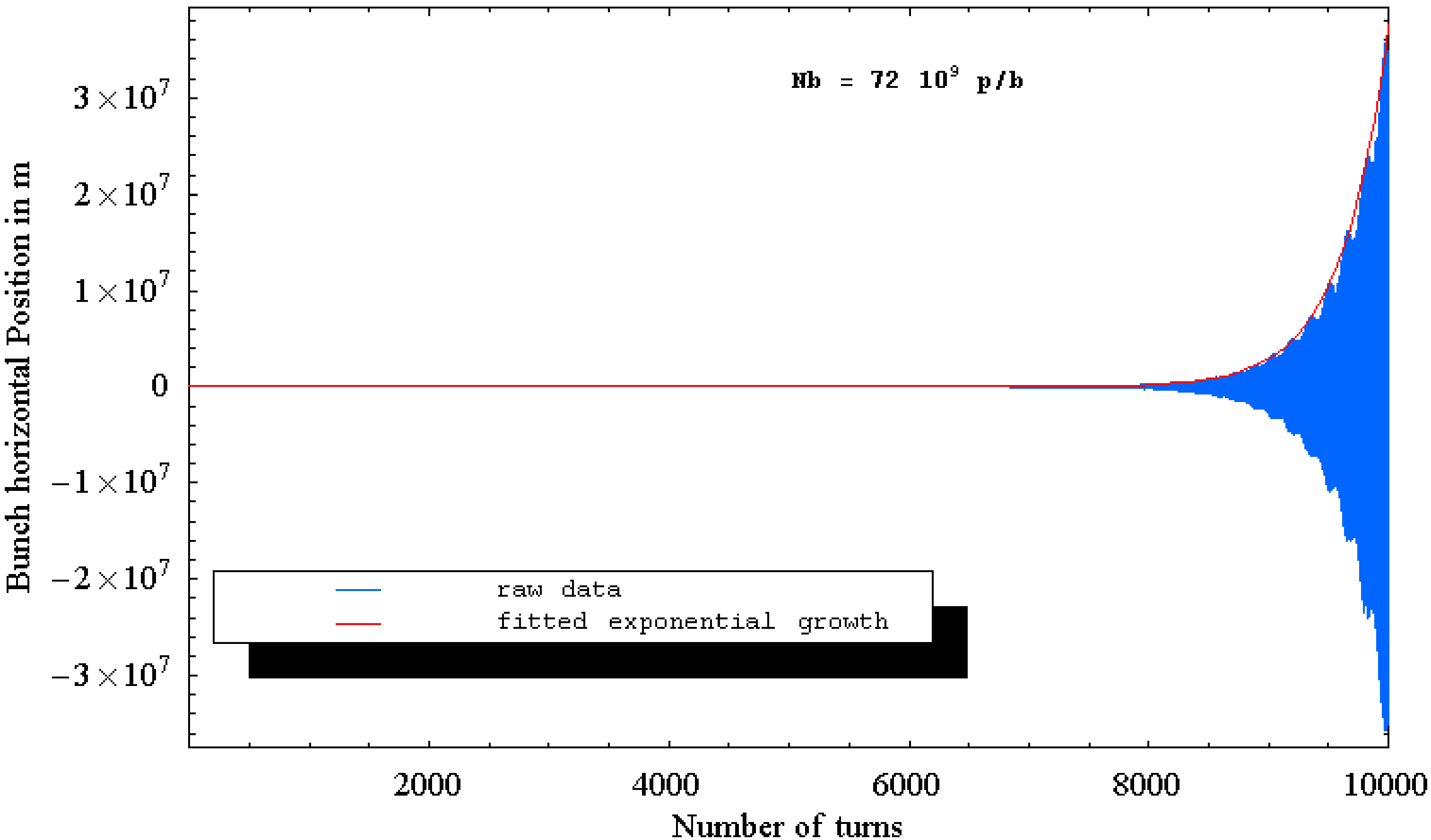
Re[ΔQ]=f(I_b) and comparison with MOSES



- MOSES and HEADTAIL agree for the mode shifting and coupling

Round beam pipe / no chromaticity / no coupling

Extracting the imaginery part of the tune shift Im[ΔQ]

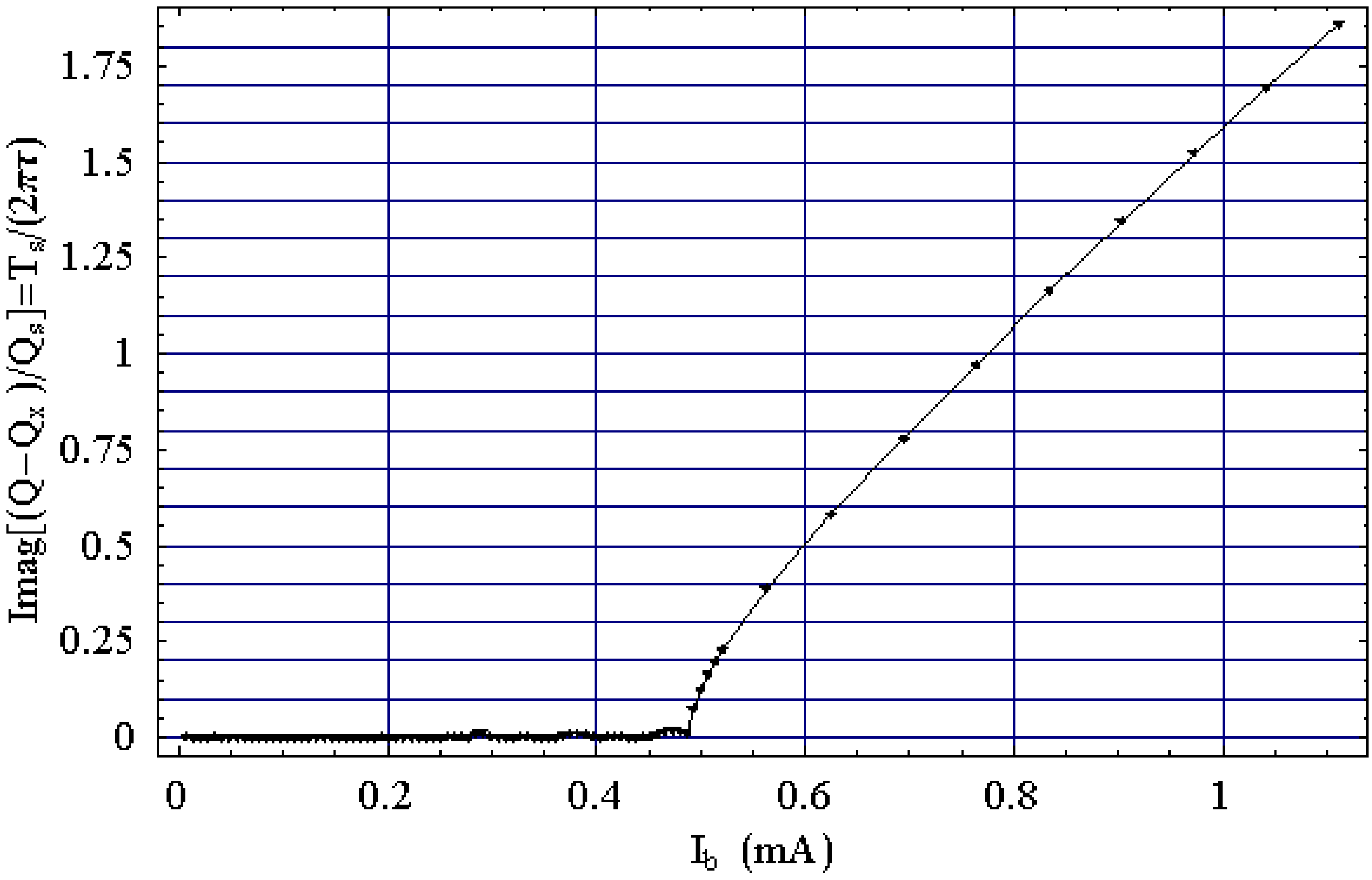


- Exponential fit of the growth of the instability : *f(x)=A exp(B.t)*

Growth rate

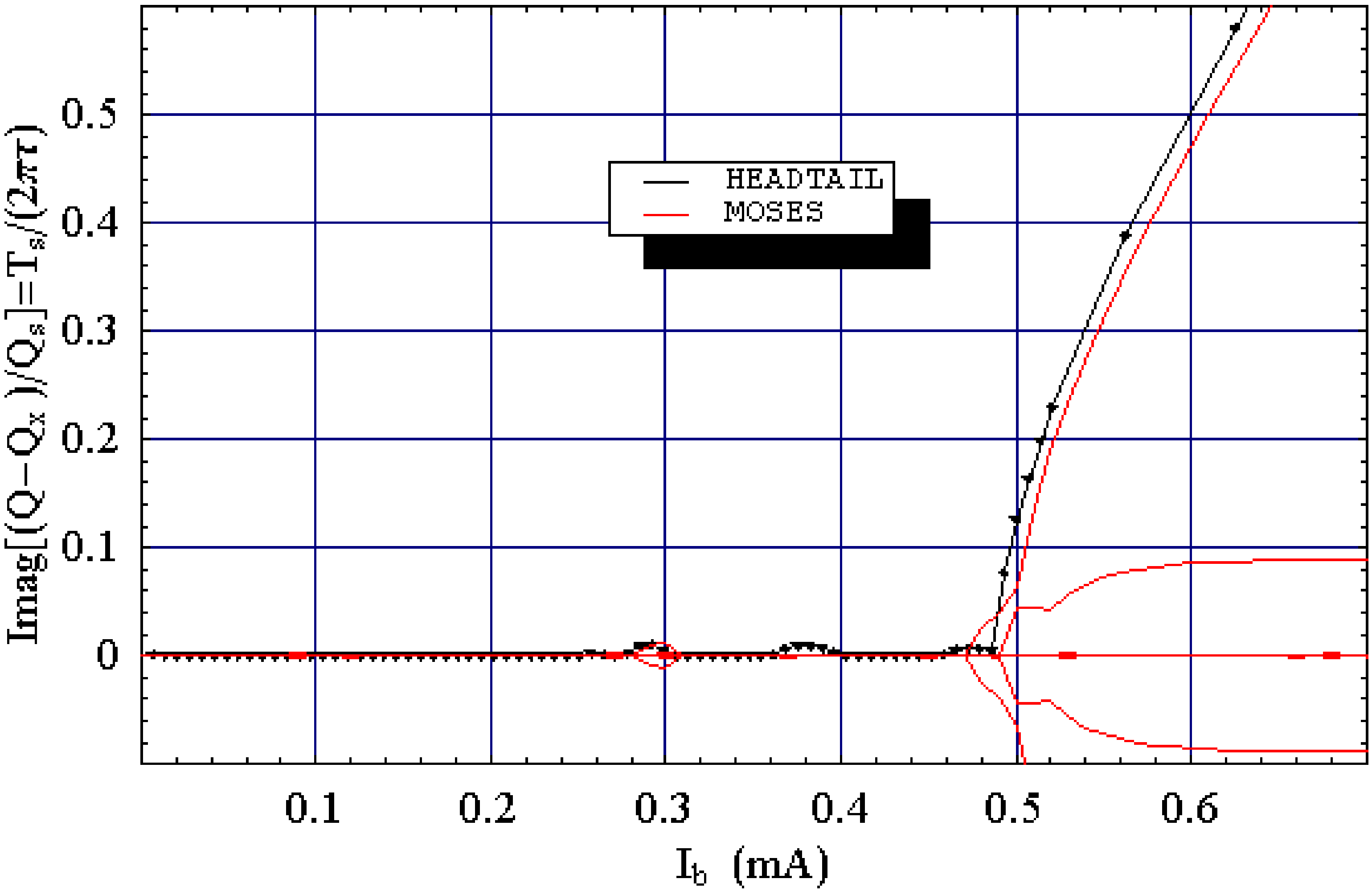
Round beam pipe / no chromaticity / no coupling

Reference ➔ displaying $Im[\Delta Q]=f(I_b)$



Round beam pipe / no chromaticity / no coupling

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



- MOSES and HEADTAIL also agree for the rise times

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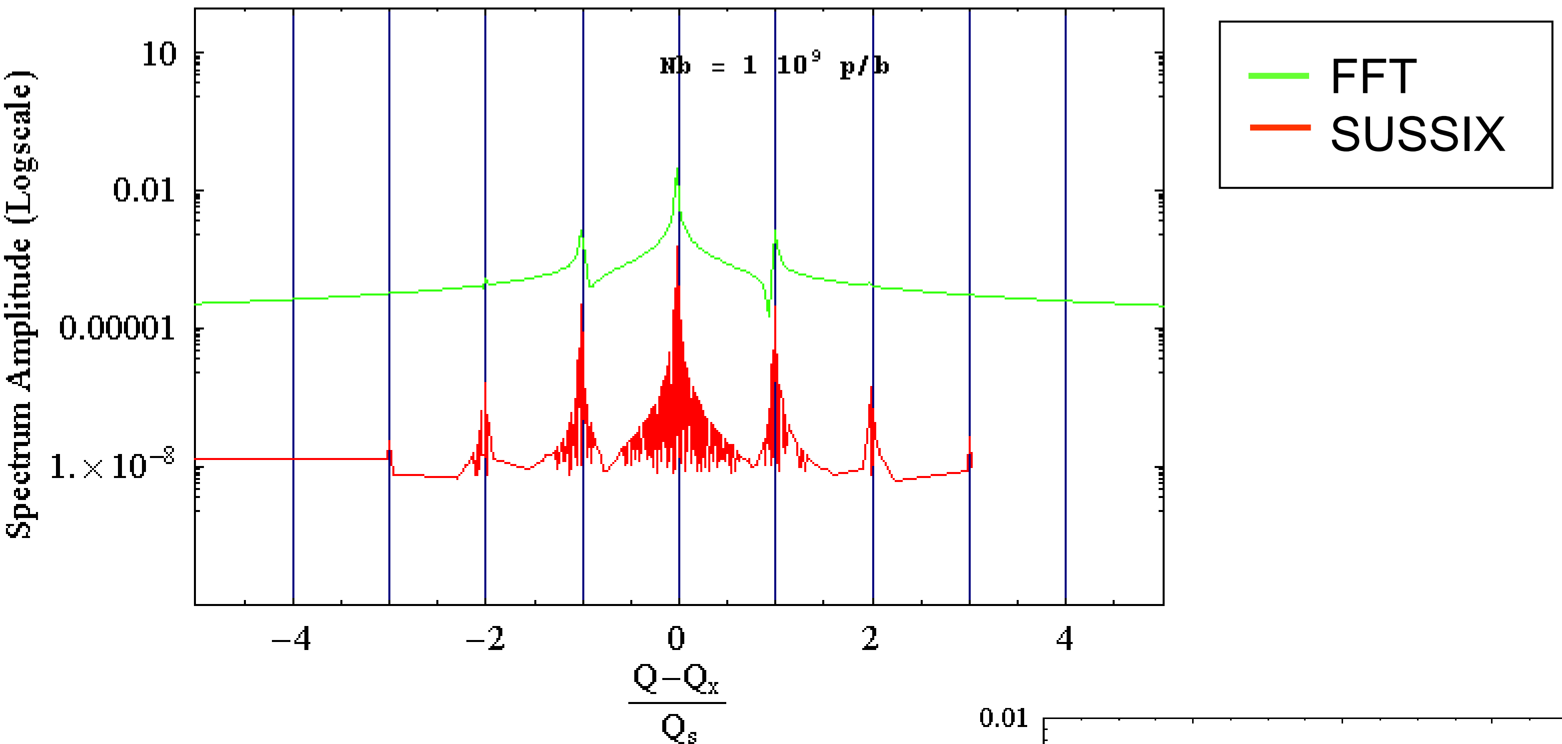
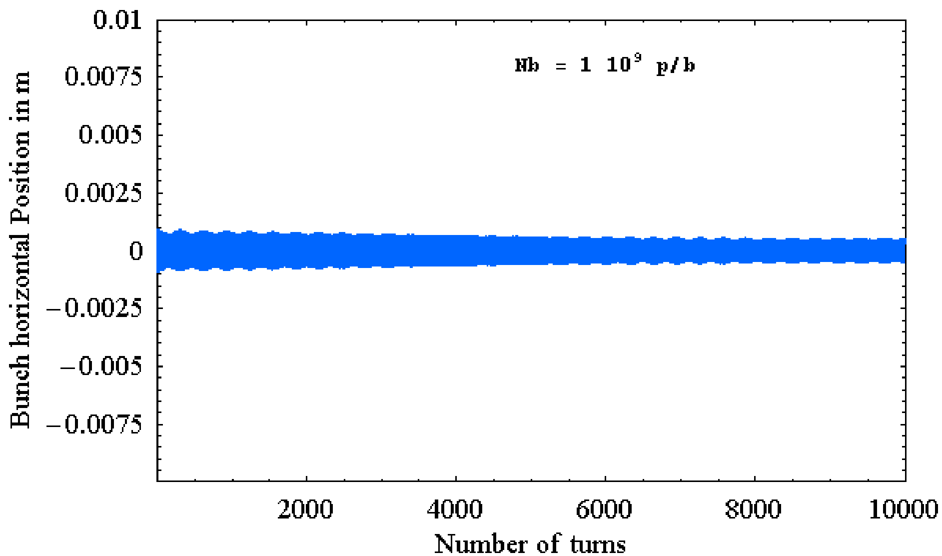
  - Chromaticity = 0 and Linear Coupling

  } Flat beam pipe

- Outlook and Perspectives

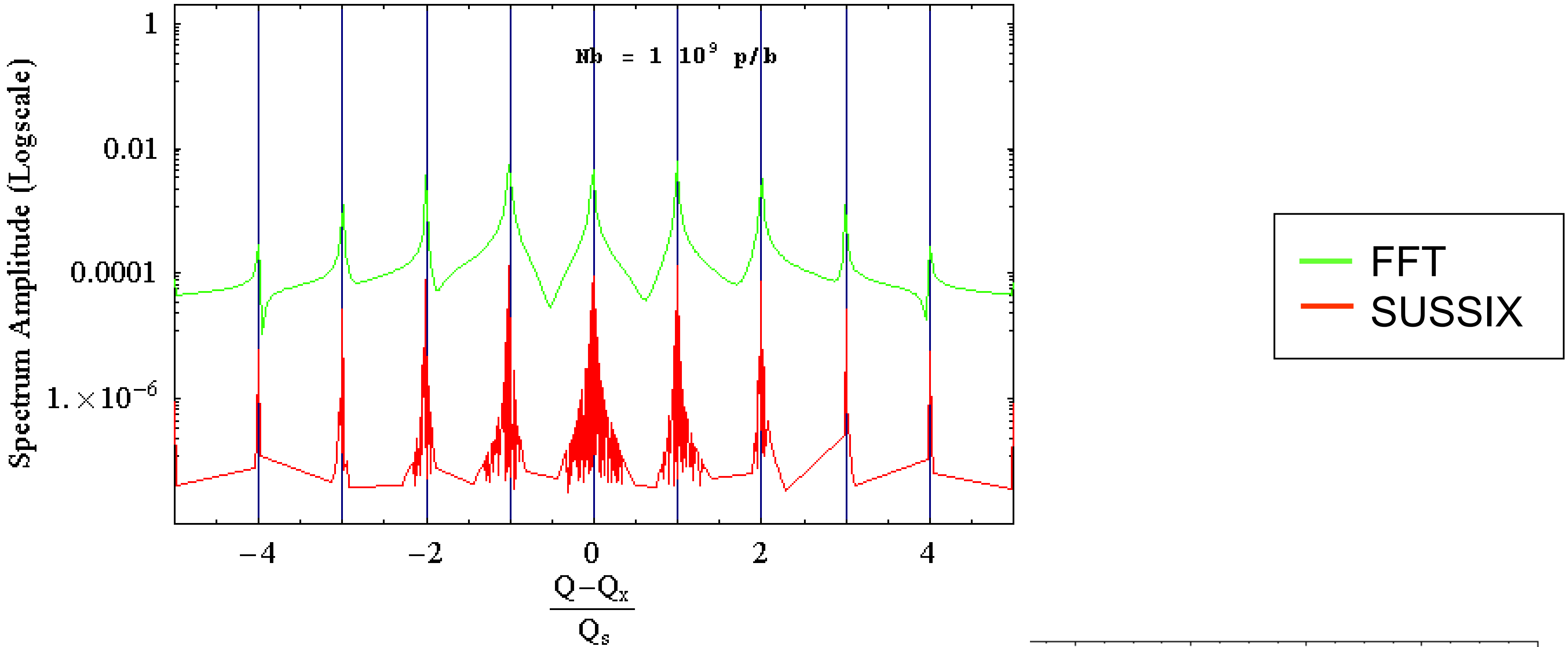
Round beam pipe / chromaticity = 1/Q / no coupling
Frequency Analysis (horizontal plane)

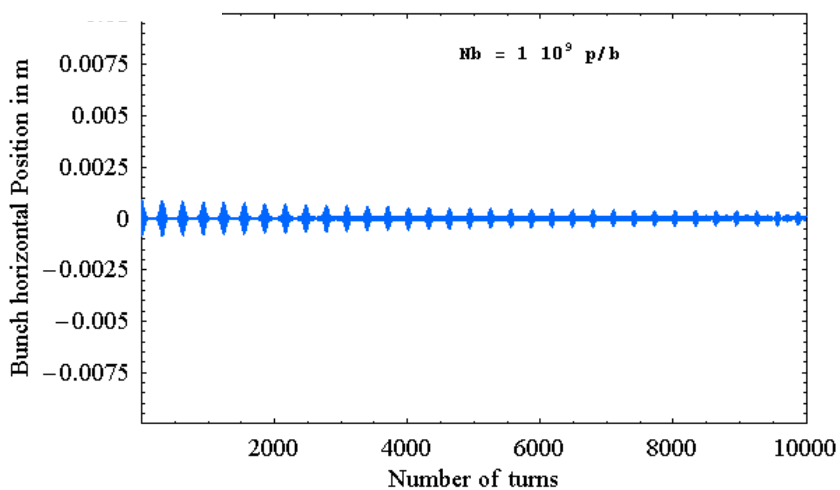




- $\xi \neq 0$ => oscillations decohere but do not recohere after T_s.
- ξ couples Q_s with $Q_{x,y}$ => modes are stronger but they still clearly shift and couple

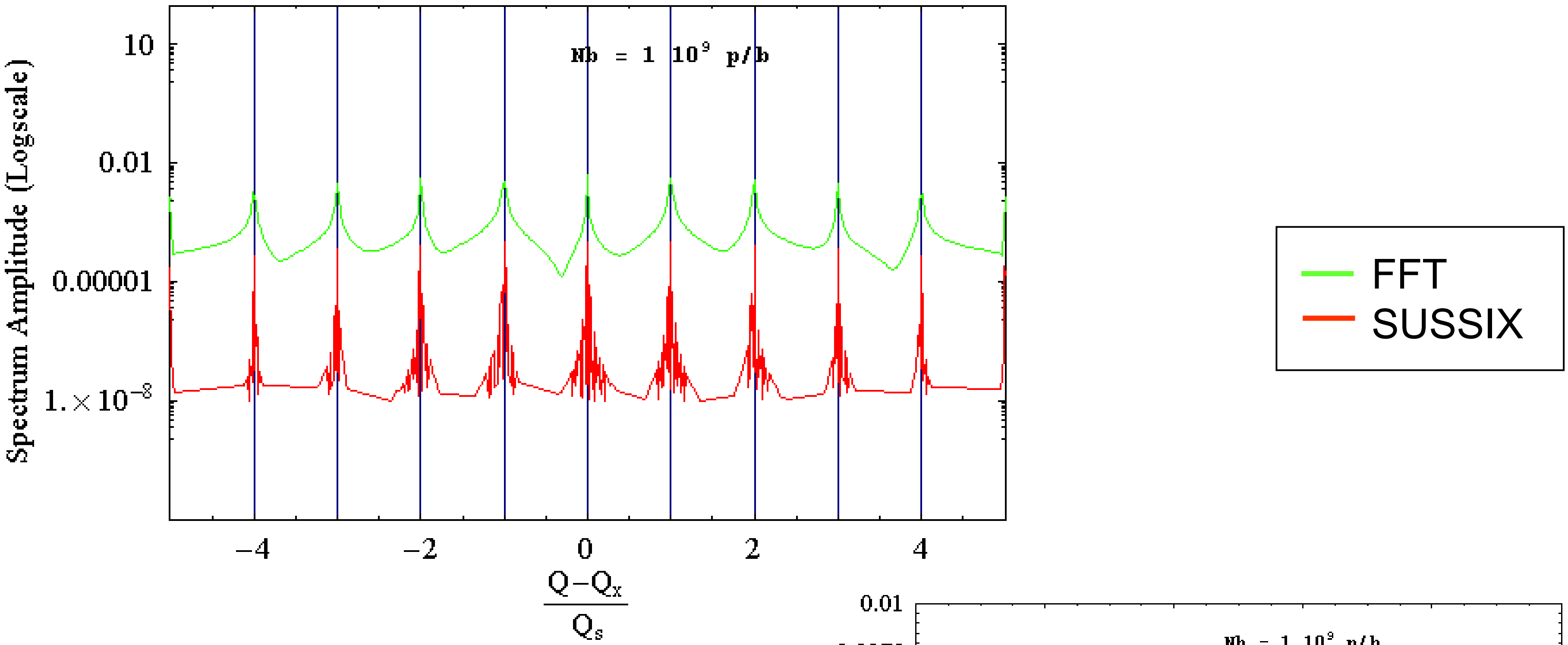
Round beam pipe / chromaticity = 5/Q / no coupling
Frequency Analysis (horizontal plane)



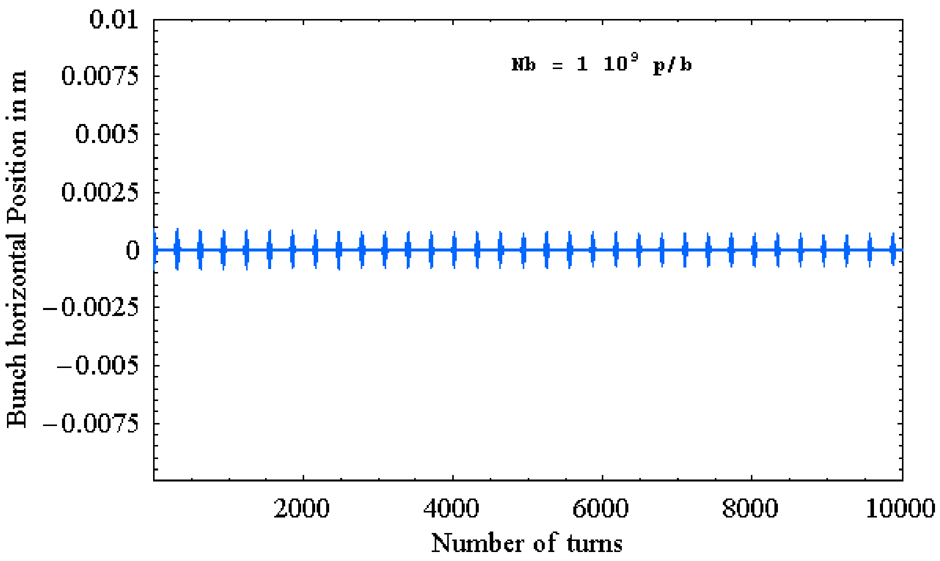


- ξ≠0 => oscillations decohere and recohere after T_s.
- ξ couples Qs with Qx,y
  => modes still clearly shift, but it is not clear whether the instability is due to coupling.

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

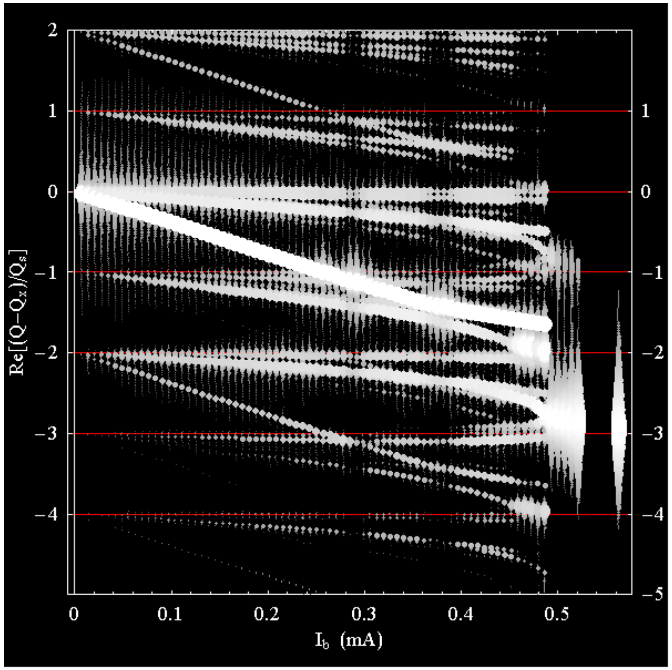


- ξ couples Qs with Qx,y
=> modes are not observed to shift anymore
=> Headtail instability?



Round beam pipe / various chromaticities / no coupling
Frequency Analysis (horizontal plane)

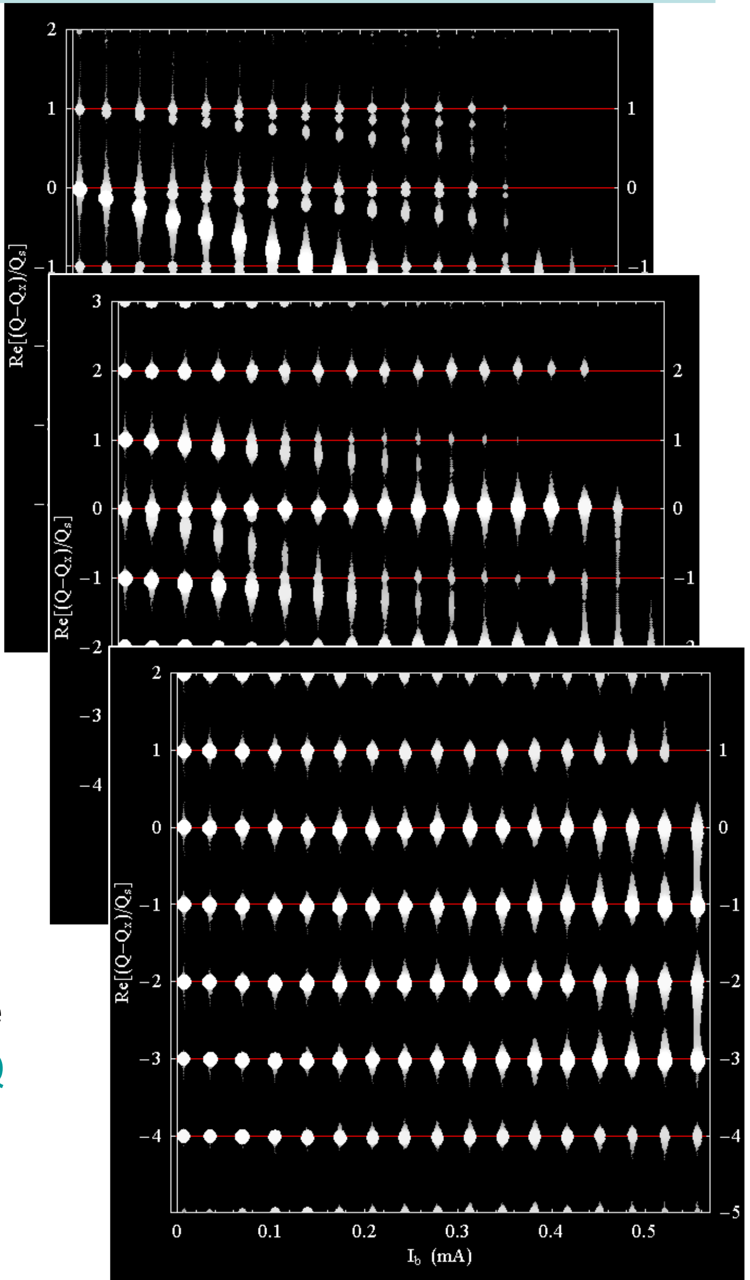
Reference (Round Chamber)



Reference
+ ξ = 1/Q

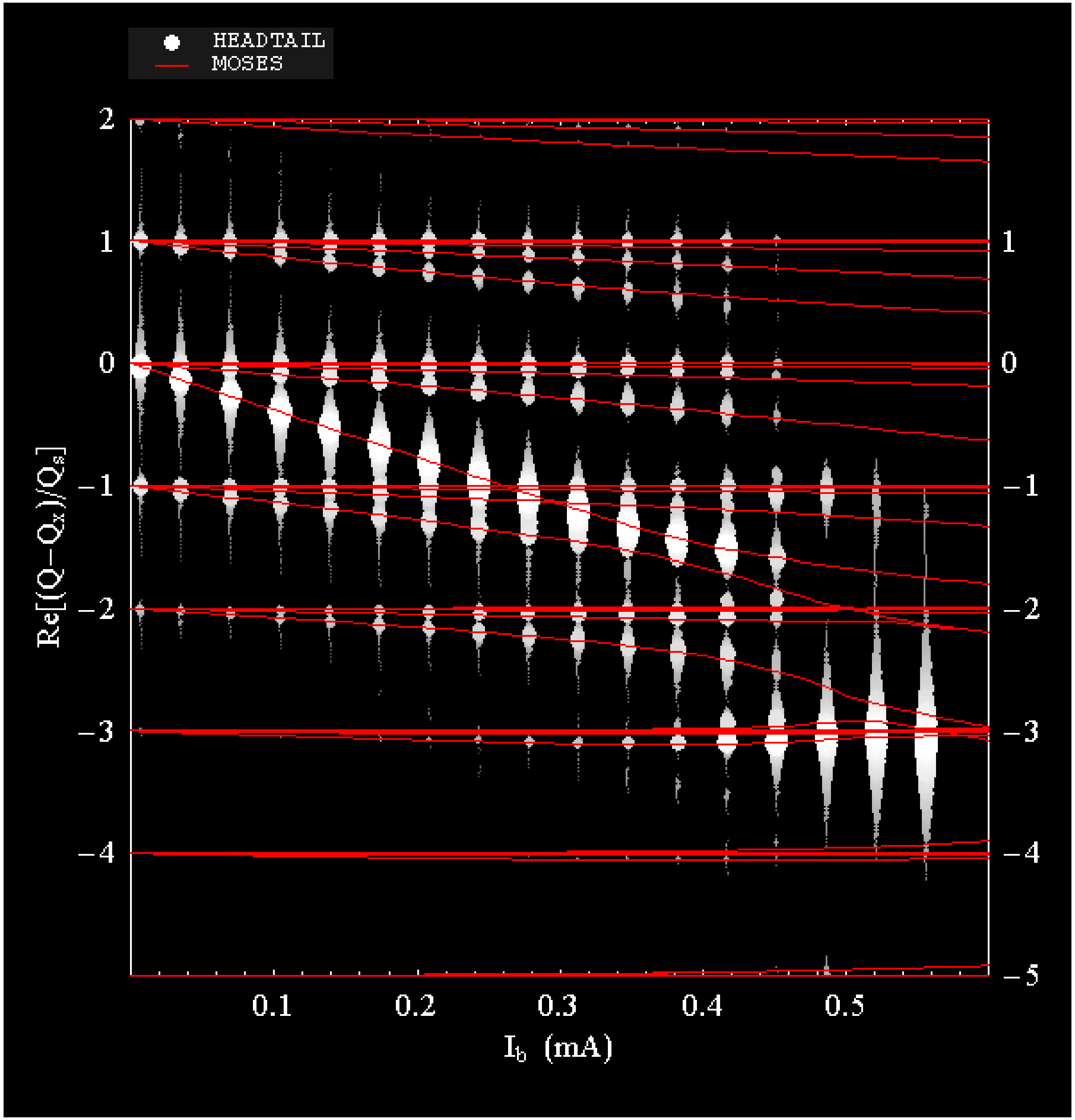
Reference
+ ξ = 5/Q

Reference
+ ξ = 10/Q



Round beam pipe / chromaticity = 1/Q / no coupling

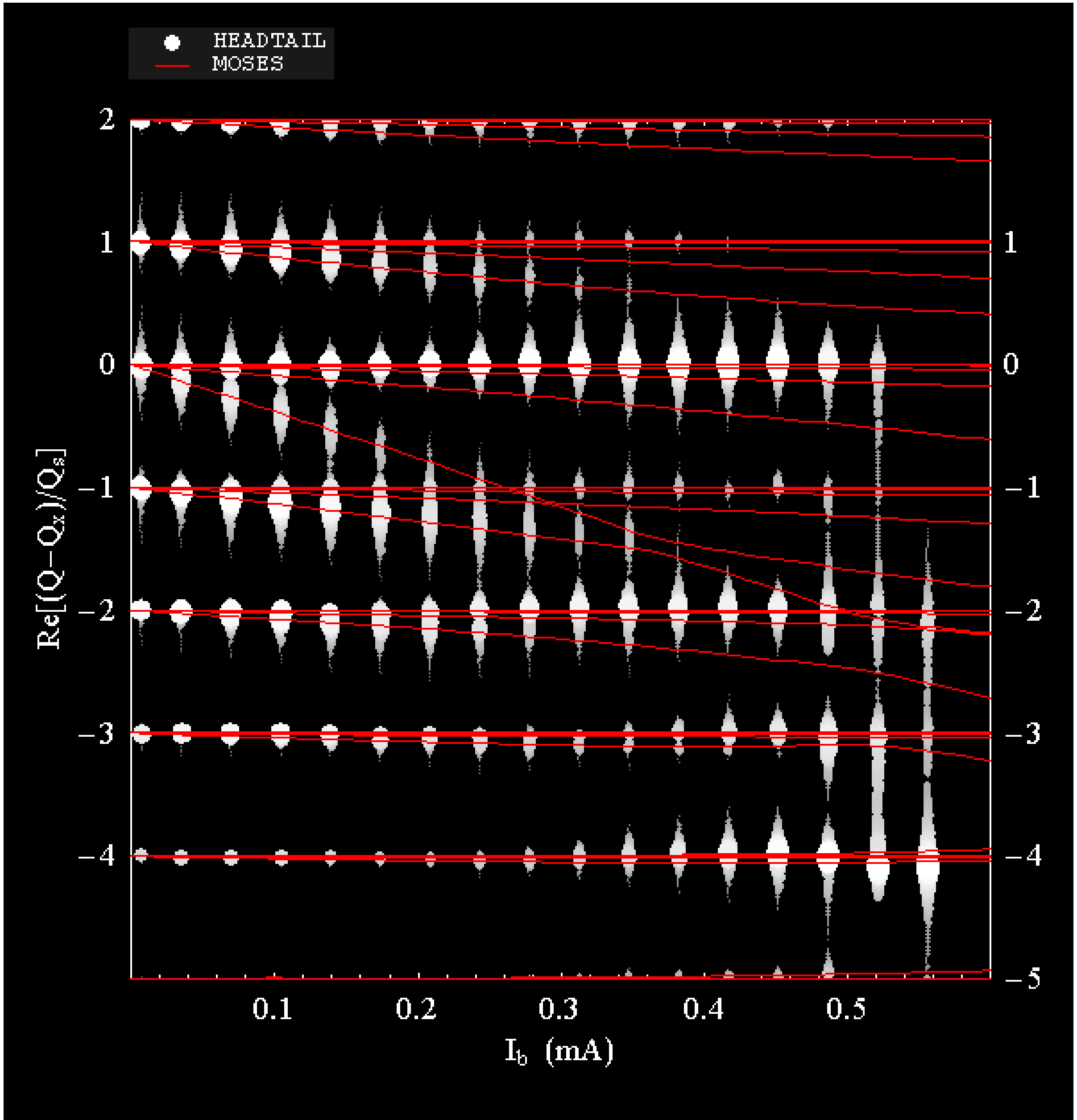
Frequency Analysis (horizontal plane)



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

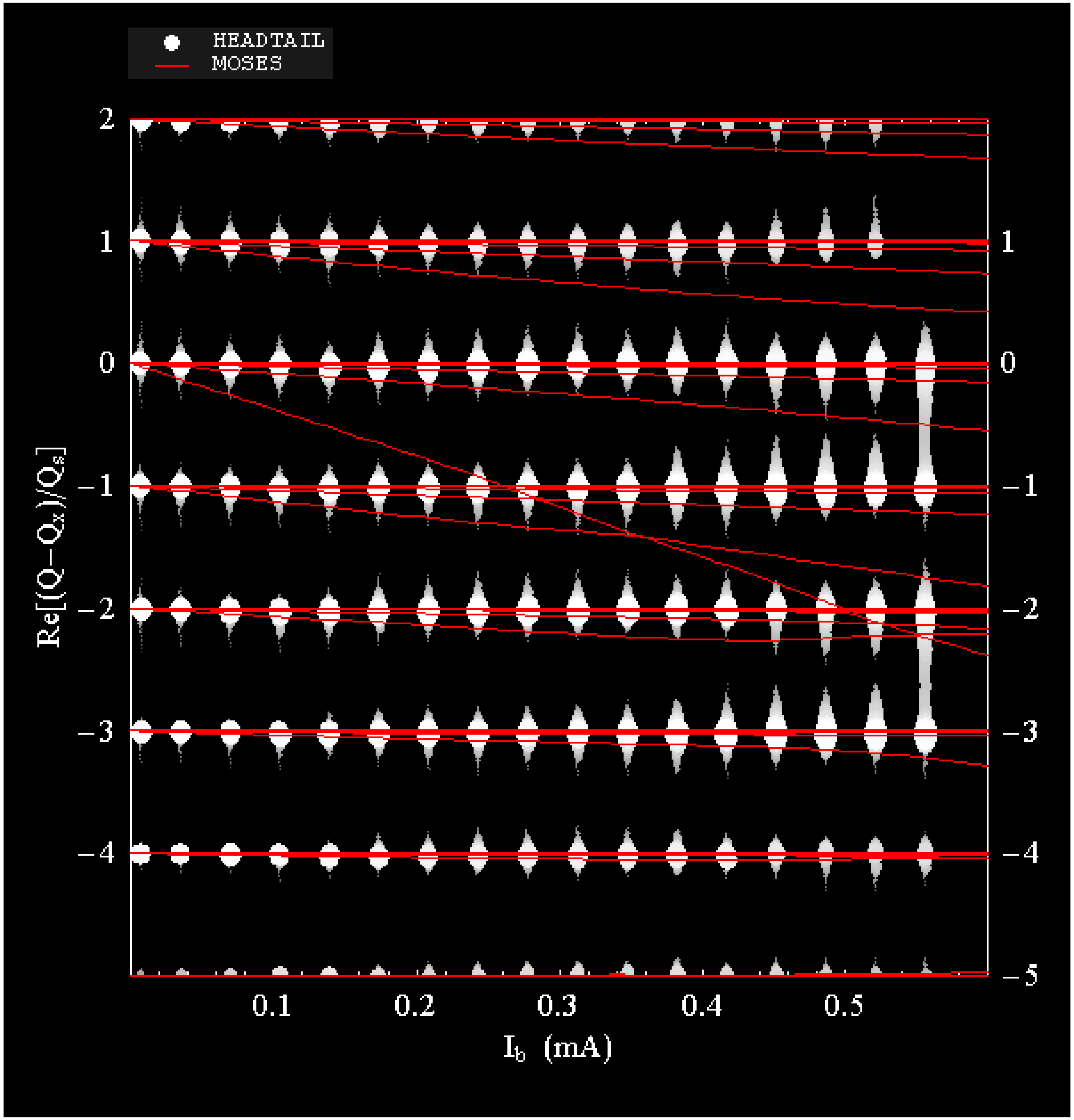
Round beam pipe / chromaticity = 5/Q / no coupling

Frequency Analysis (horizontal plane)



- No obvious mode coupling here

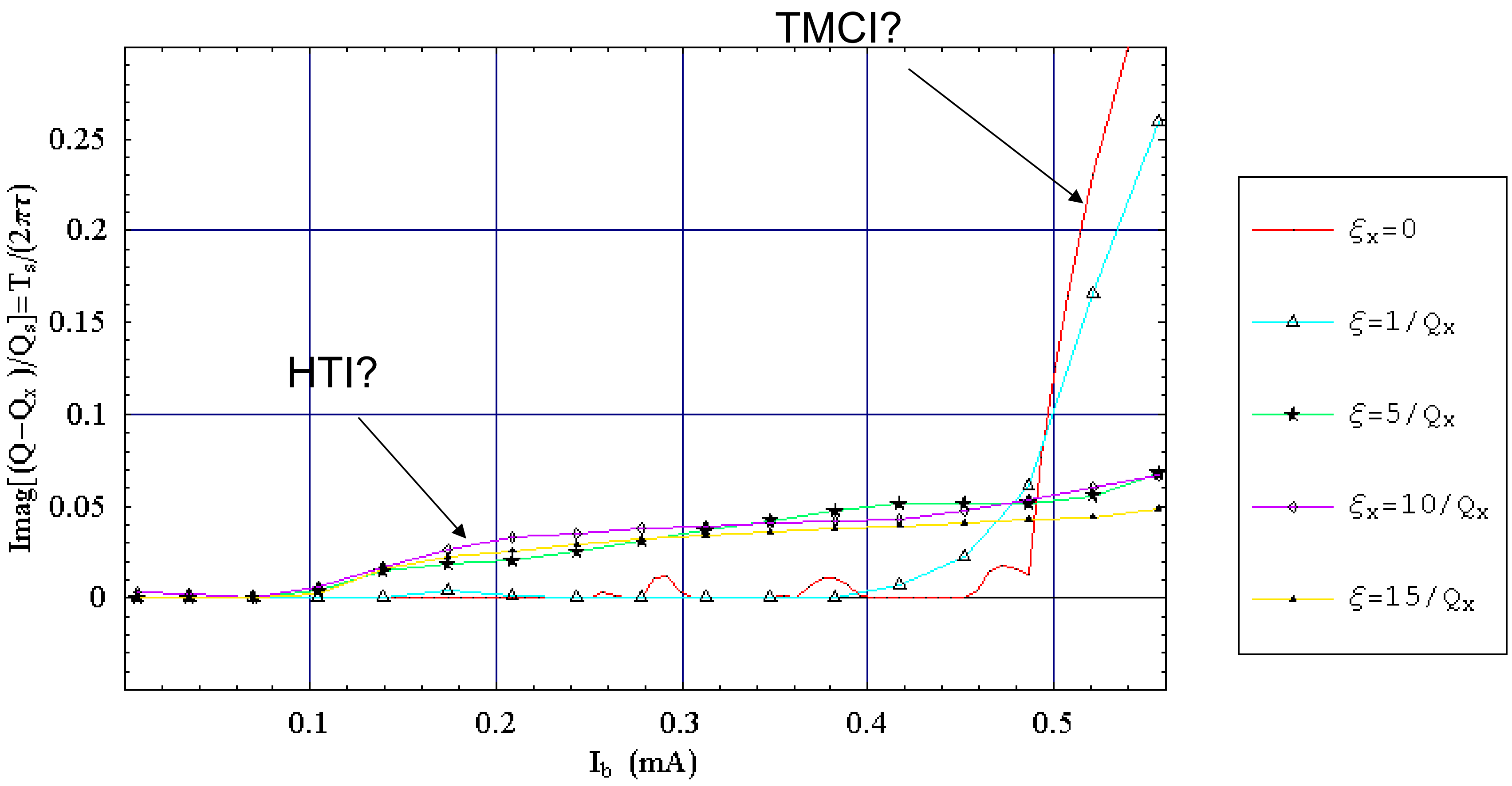
Round beam pipe / chromaticity = 10/Q / no coupling
Frequency Analysis (horizontal plane)



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

Round beam pipe / various chromaticities / no coupling

Rise times (horizontal plane)



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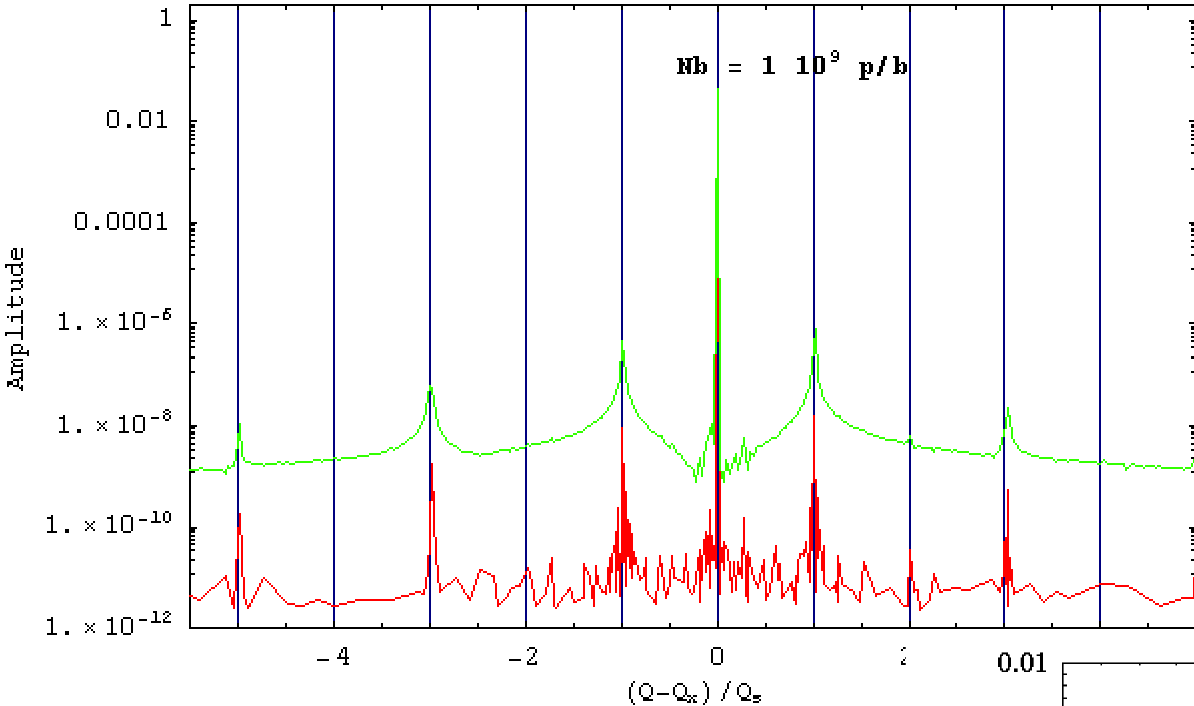
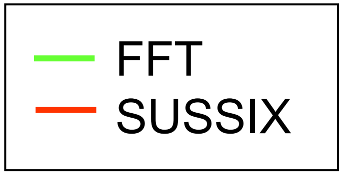
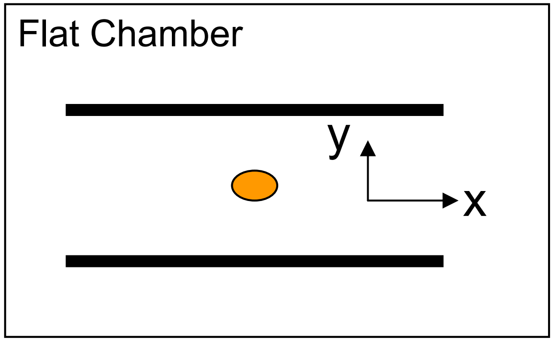
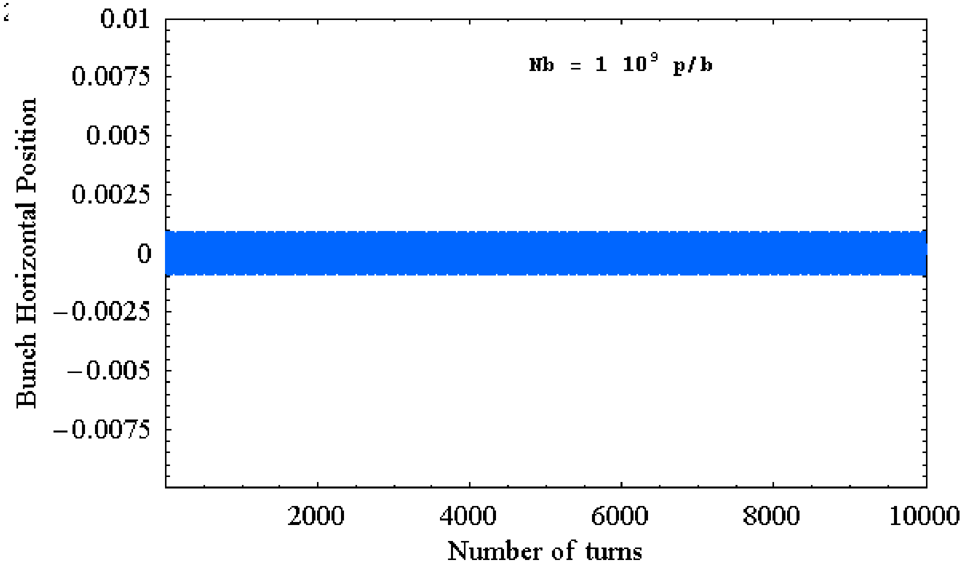
Flat beam pipe / no chromaticity / no coupling
➔ *Frequency Analysis (horizontal plane)*



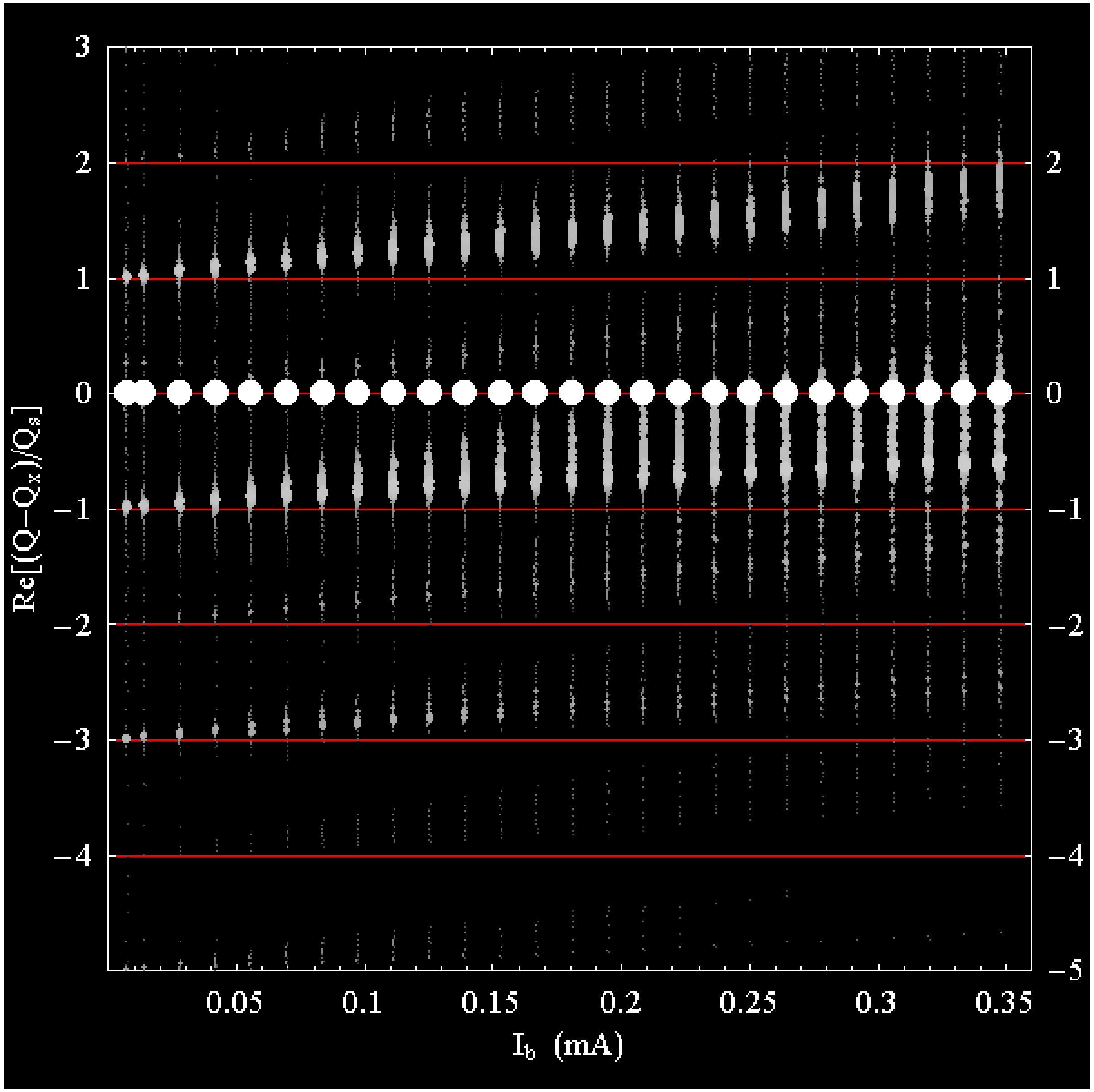






Flat beam pipe / no chromaticity / no coupling

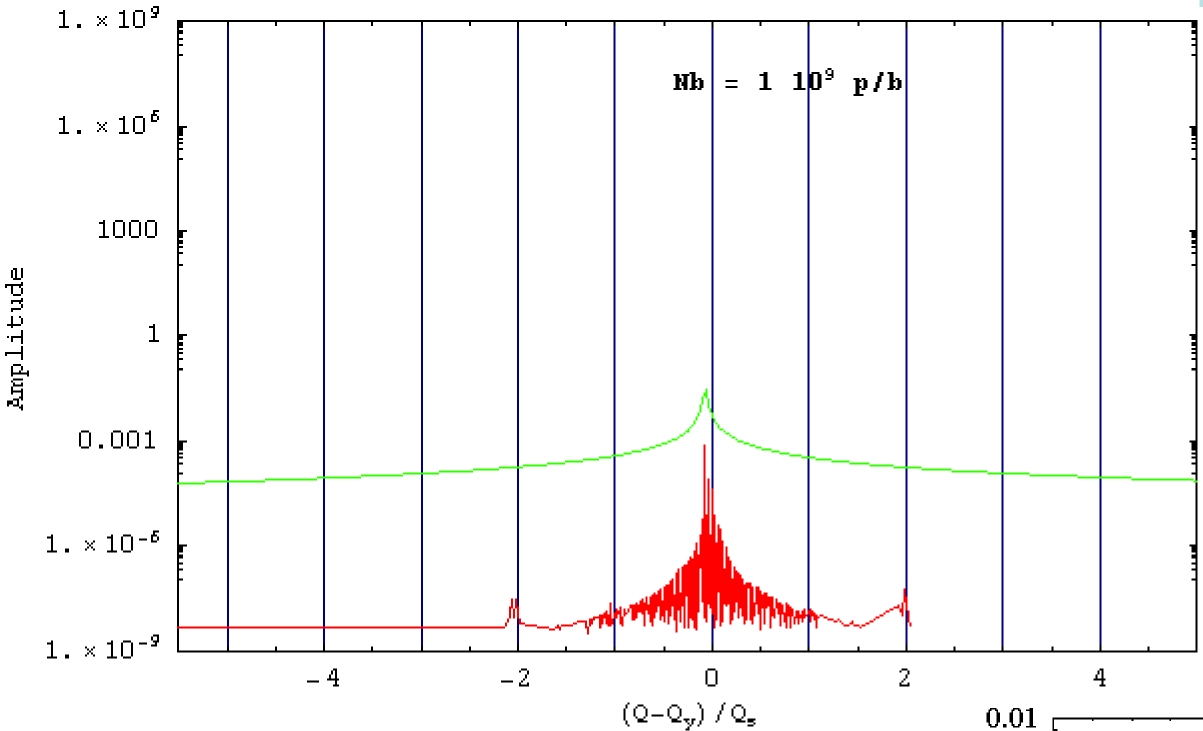
➔ *Re[ΔQ$_x$]=f(I$_b$)*

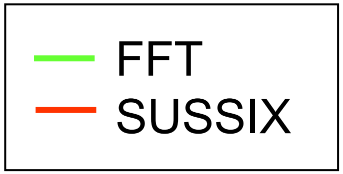


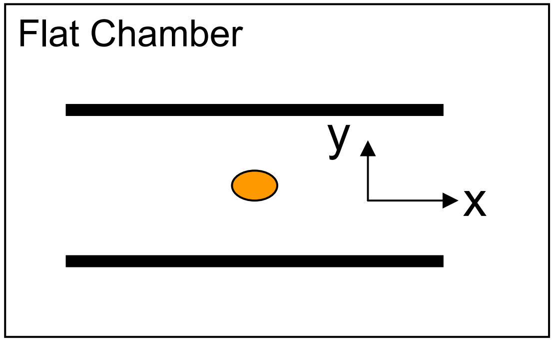
Flat beam pipe / no chromaticity / no coupling
➔ $Im[\Delta Q_x] = f(I_b)$

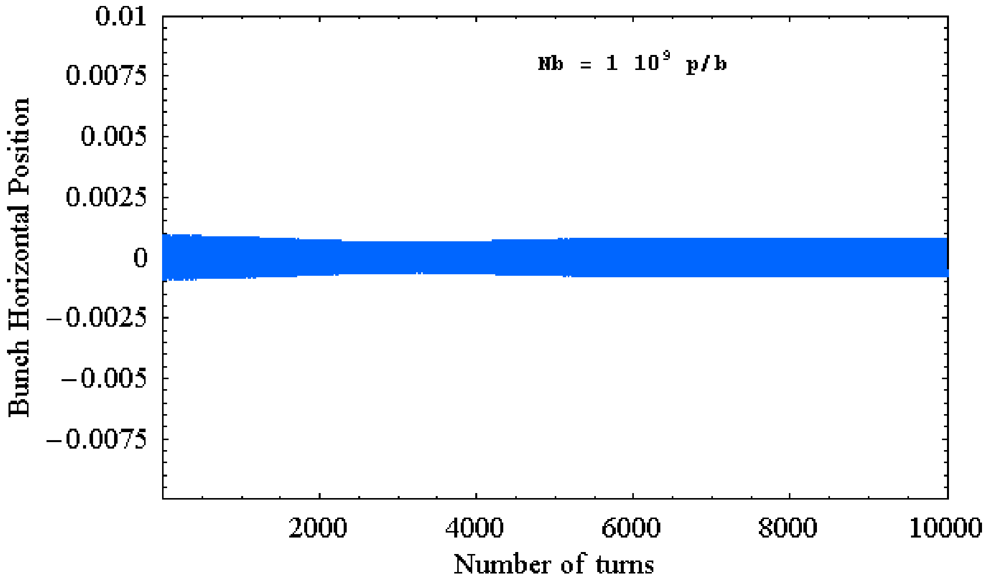
Instability threshold not met -> $Im[\Delta Q_x] = 0$

Flat beam pipe / no chromaticity / no coupling
➔ *Frequency Analysis (vertical plane)*



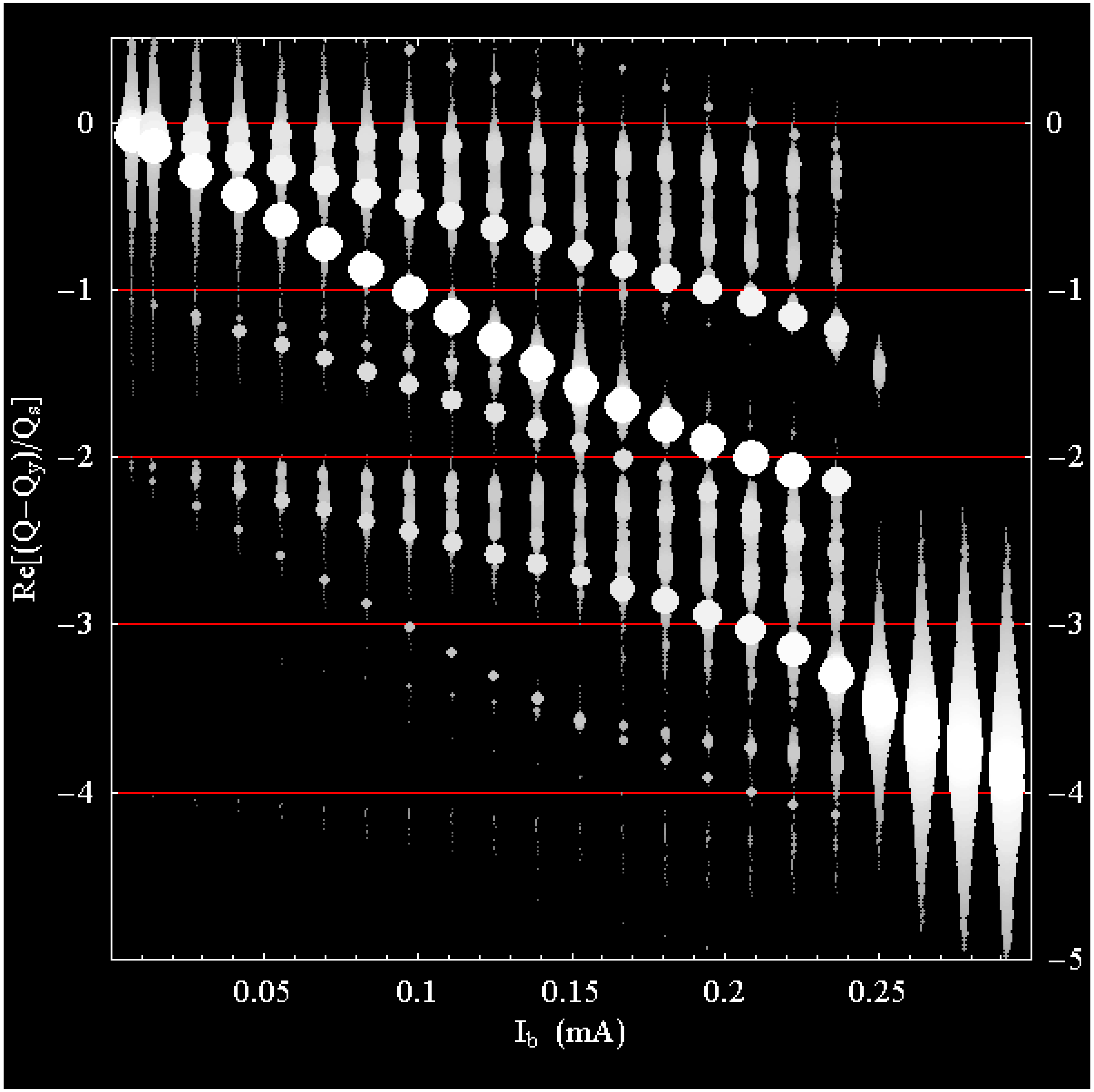






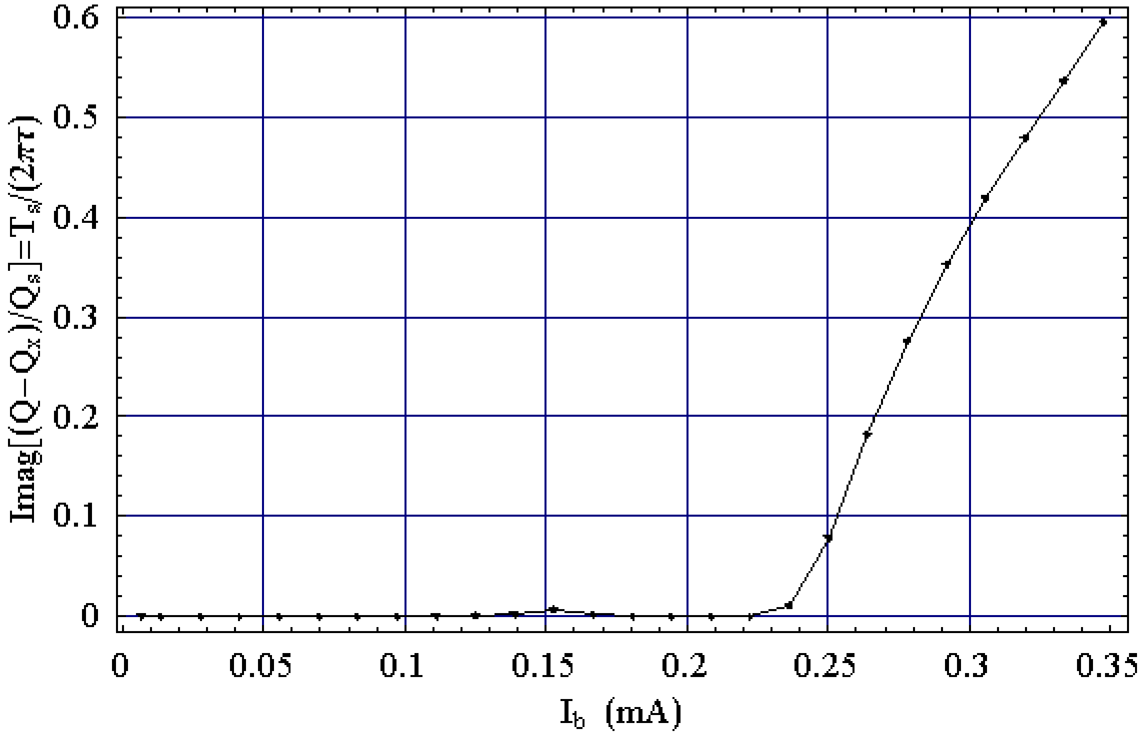
Flat beam pipe / no chromaticity / no coupling

➔ $Re[\Delta Q_y]=f(I_b)$



Flat beam pipe / no chromaticity / no coupling

➔ $Im[\Delta Q_y] = f(I_b)$



Instability Threshold = 0.24 mA

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  } Flat beam pipe

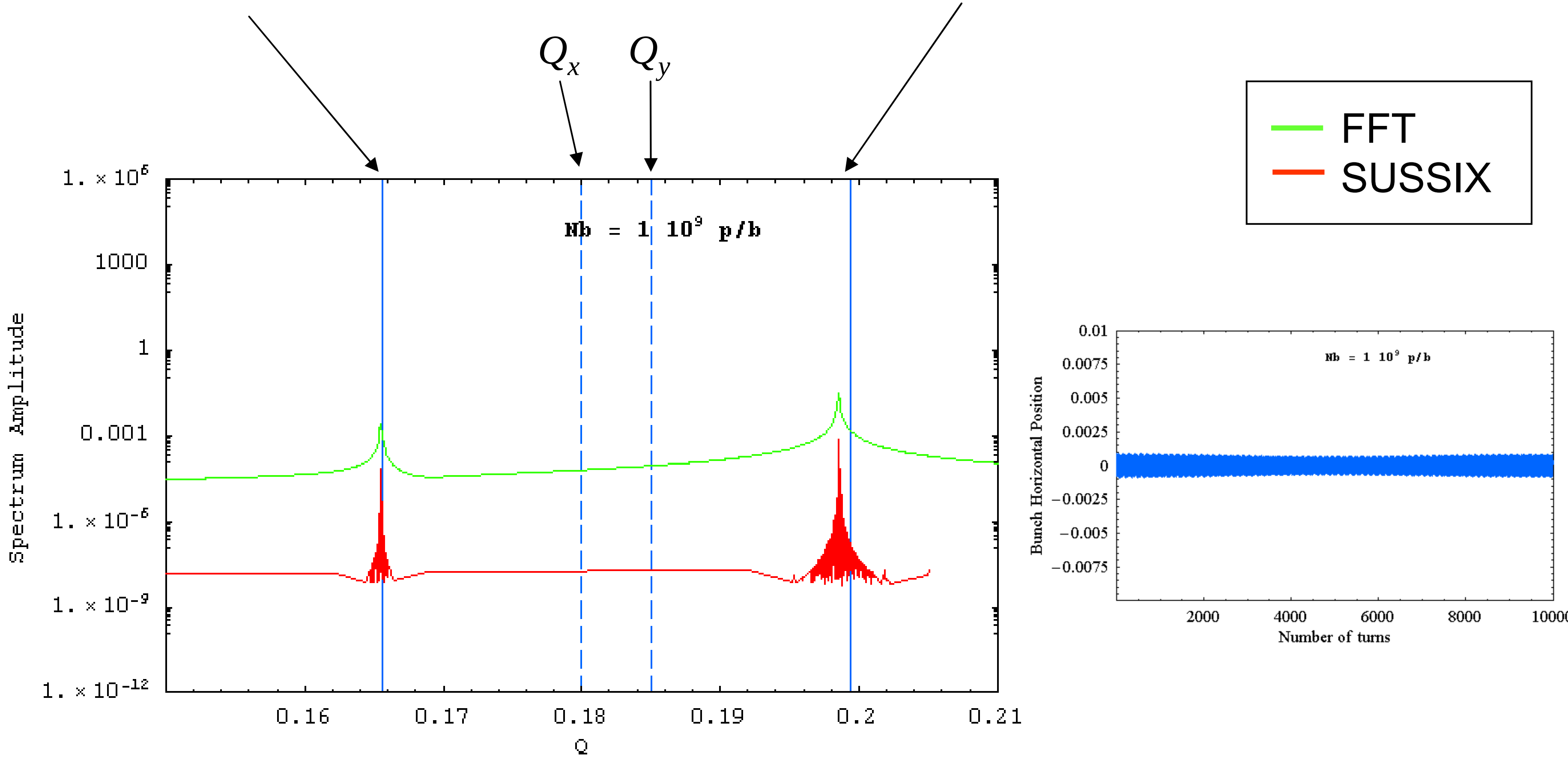
- Outlook and Perspectives

Flat beam pipe / no chromaticity / Linear coupling

➔ ***Frequency Analysis (horizontal plane)***

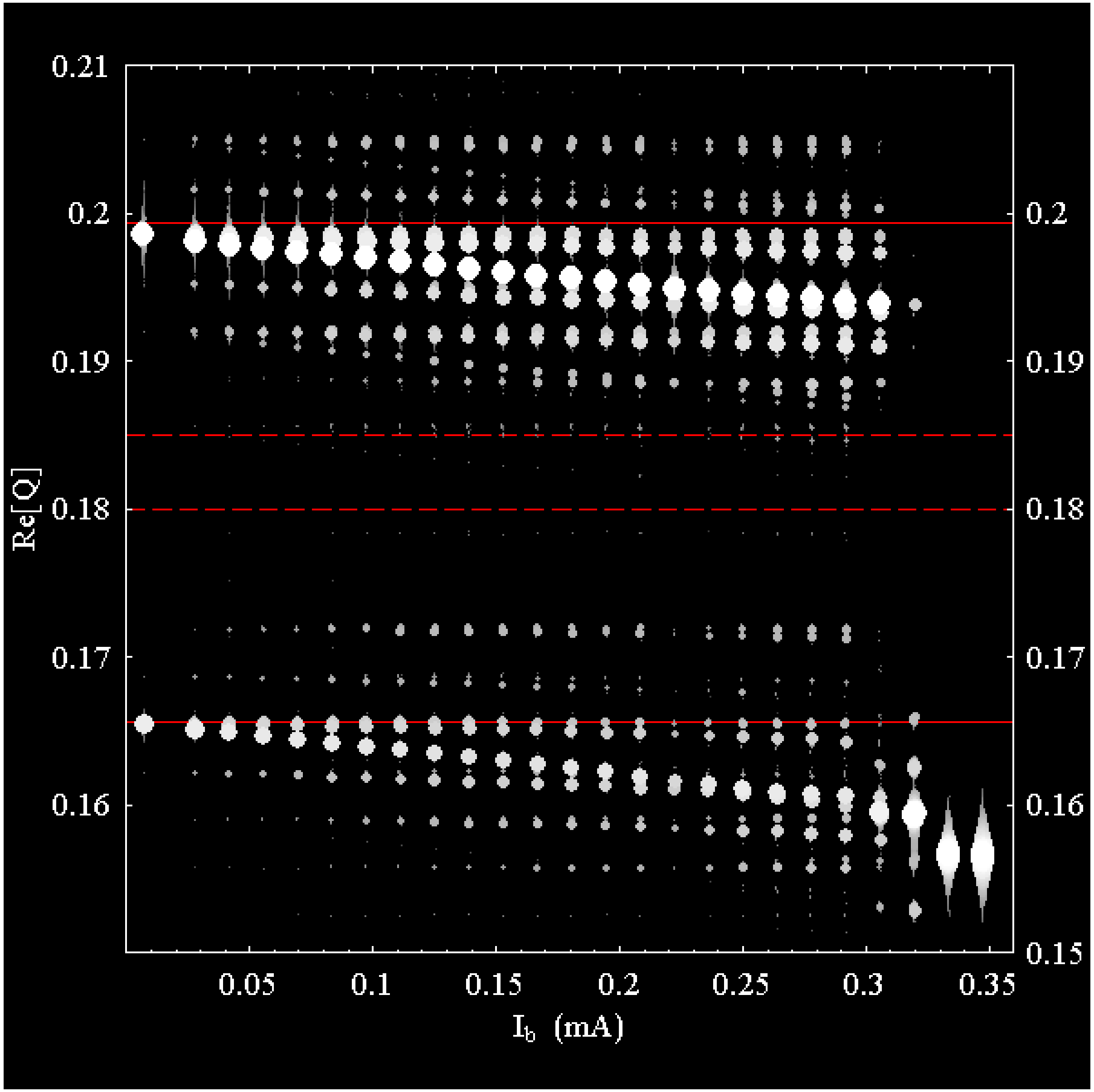
$$Q_u = \frac{Q_x + Q_y}{2} - \frac{1}{2}\sqrt{\left(Q_x - Q_y\right)^2 + \left|C\right|^2}$$

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



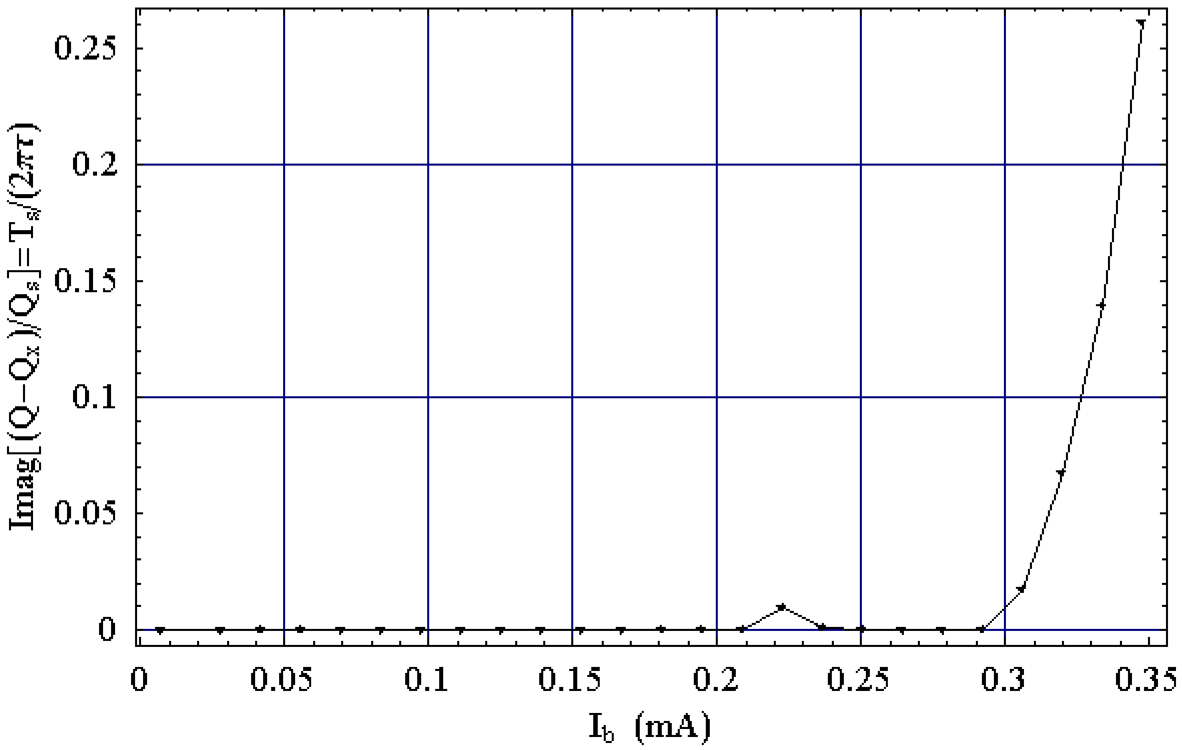
Headtail and the theory lead to the same coupled tunes

Flat beam pipe / no chromaticity / **Linear coupling**
→ $Re[\Delta Q_y]=f(I_b)$

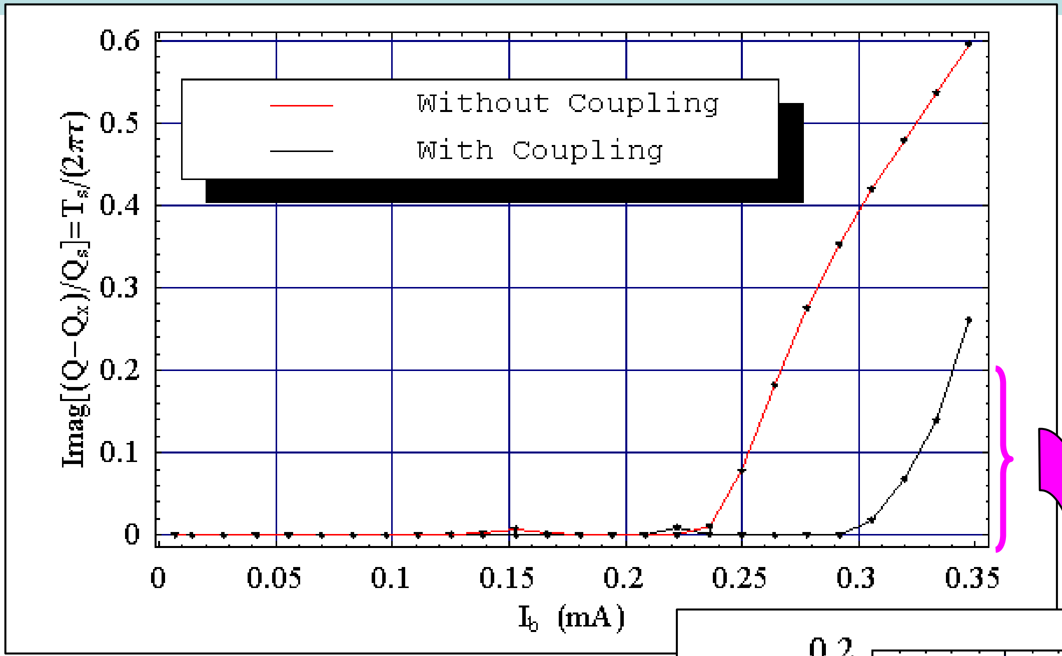


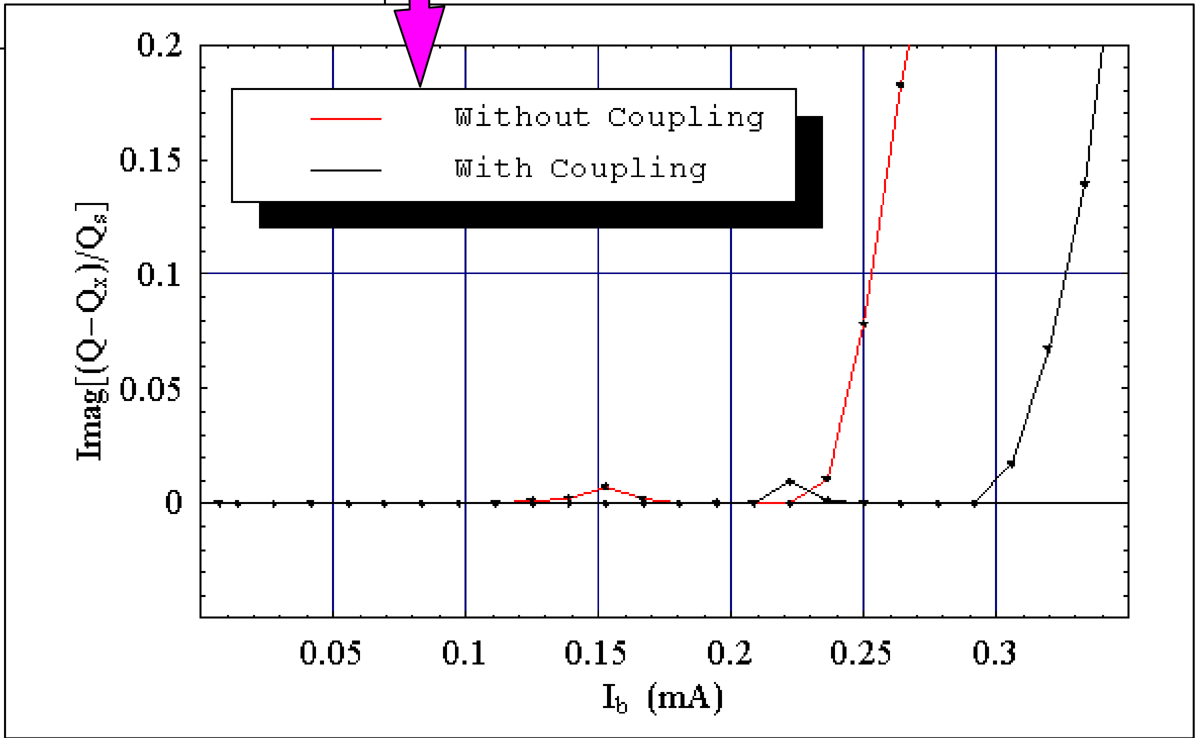
Flat beam pipe / no chromaticity / Linear coupling

➔ $Im[\Delta Q_x]=f(I_b)$



Effect of adding Linear Coupling → $Im[\Delta Q_x]=f(I_b)$

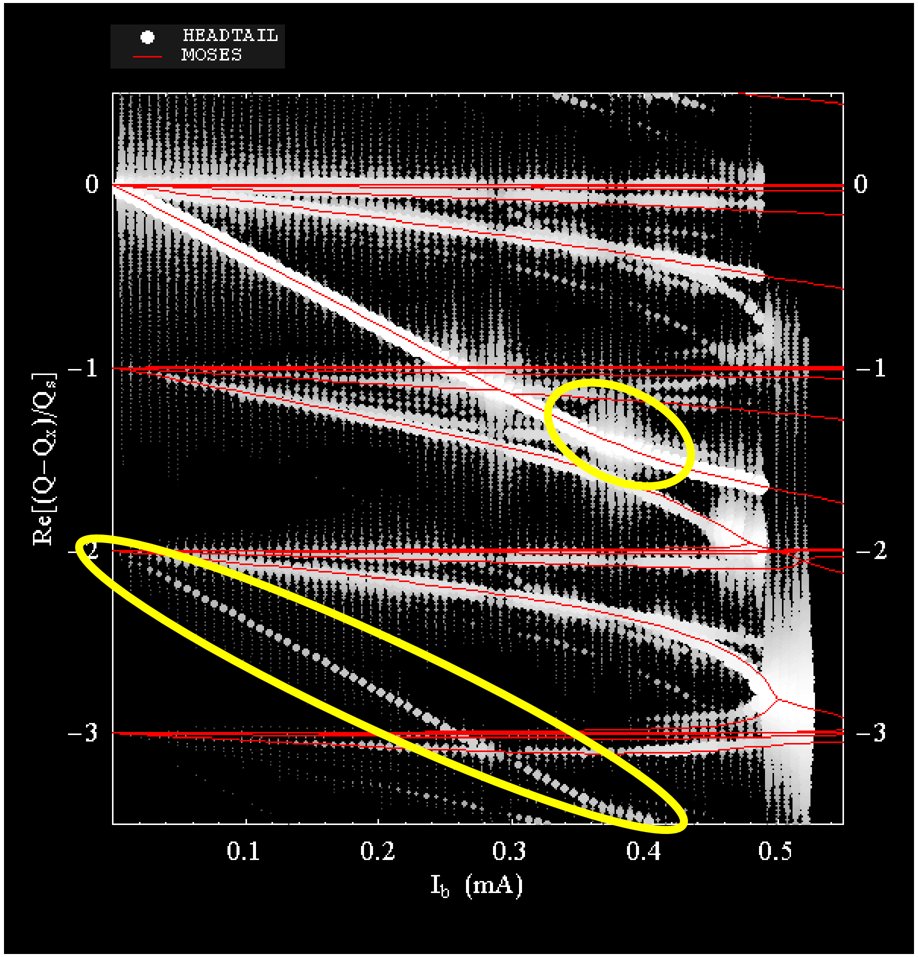




With Linear Coupling, Instability Threshold is raised by
(42-32)/32 = **31% ± 6%**

Outlook

- Agreement of MOSES and HEADTAIL for most modes shifting and coupling with current.
- HEADTAIL is therefore a very interesting tool to understand the reasons behind such fast instabilities. It could then be used to raise limiting current thresholds in the machine.
- Some questions remain:
  - Several radial modes are observed in HEADTAIL, which are not predicted by MOSES (ex: -2)
  - In particular, one of these radial modes (-1) couples with the main tune in HEADTAIL, leading to a weak instability.

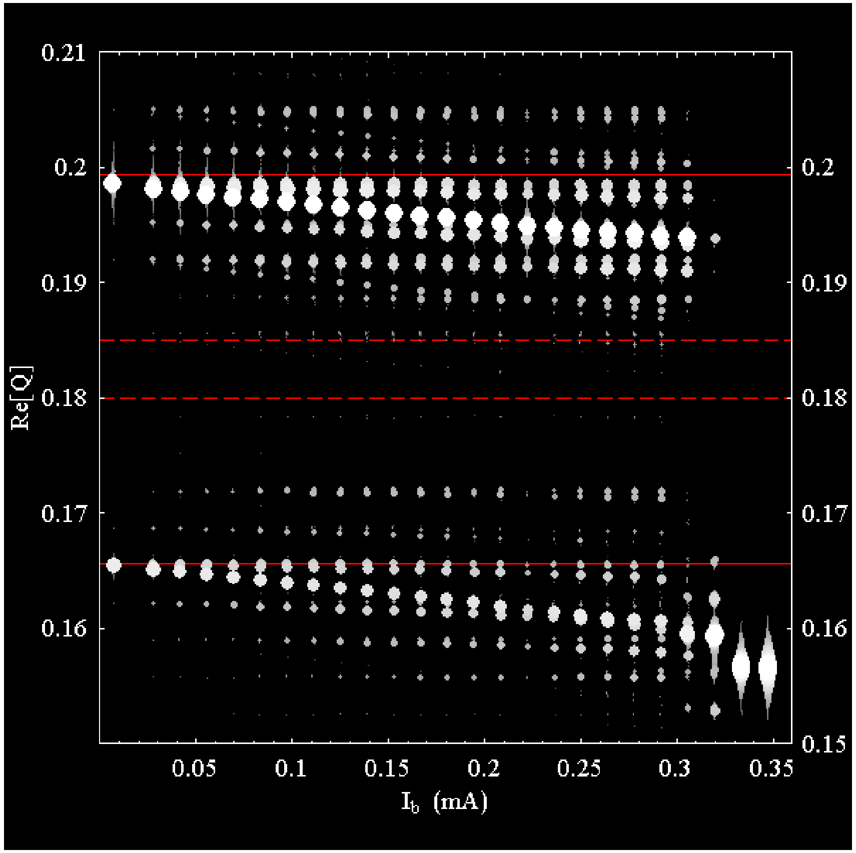


Perspectives

- These studies were performed with a broadband resonator. More realistic Resistive Wall models of impedance are under implementation, and could soon be inputs of Headtail.
- The space charge model needs to be implemented and checked.
- A similar study could be performed for the longitudinal mode coupling. (L. Rivkin)
- 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.



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