HEADTAIL simulation studies of Landau damping through octupoles in the LHC.

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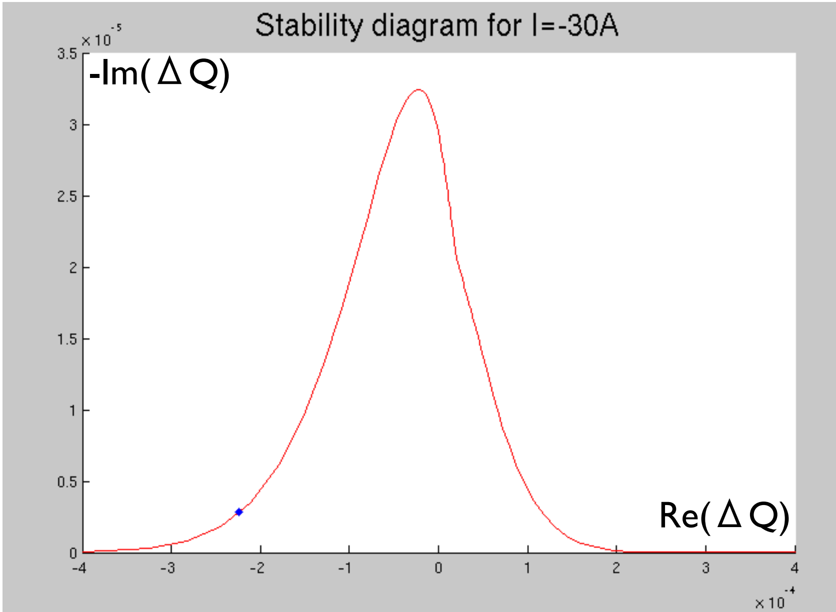
Objective

HEADTAIL

-> average position
  -> tune-shift
    -> stabilizing current

THEORY

-> tune-shift
-> stabilizing current
-> stability diagram



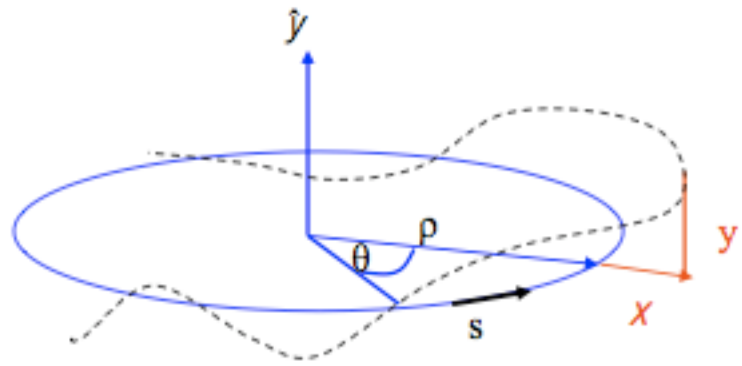
➔ Compare HEADTAIL and Theory and try to plot the stability diagram using HEADTAIL

Contents

Accelerator Physics

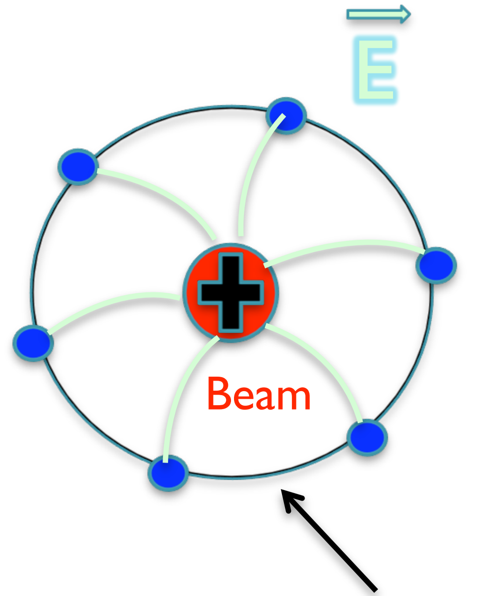
- Betatron and synchrotron oscillations
- Betatron and synchrotron tune
- Chromaticity: $Q' = \frac{\Delta Q}{\Delta p / p}$
- Betatron frequency: $\omega = Q \cdot \Omega_0$
- Emittance: ε $\propto$ area in phase-space (x , $x' = dx/ds$)

  $\propto$ stability zone



Impedance & Wake fields

- Induced current



- If discontinuities or resistivity

  →Wake fields

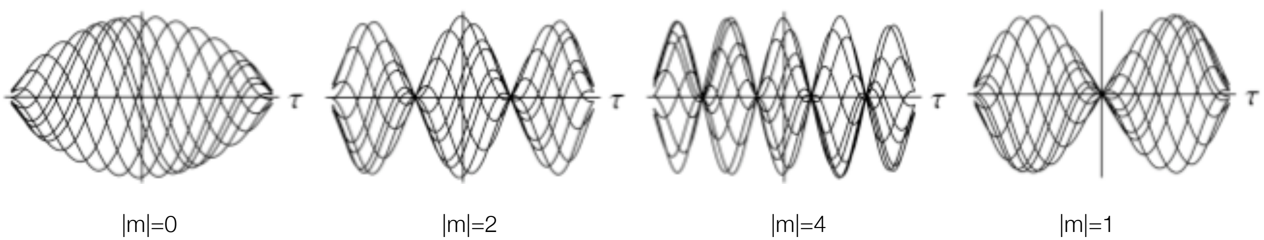
- Impedance=FFT(wake field)
- Motion ∝ $\exp(j\omega t) = \exp(j(\omega r + j\omega i)t)$

  $= \exp(j.\omega r.t) * \exp(t/\tau)$

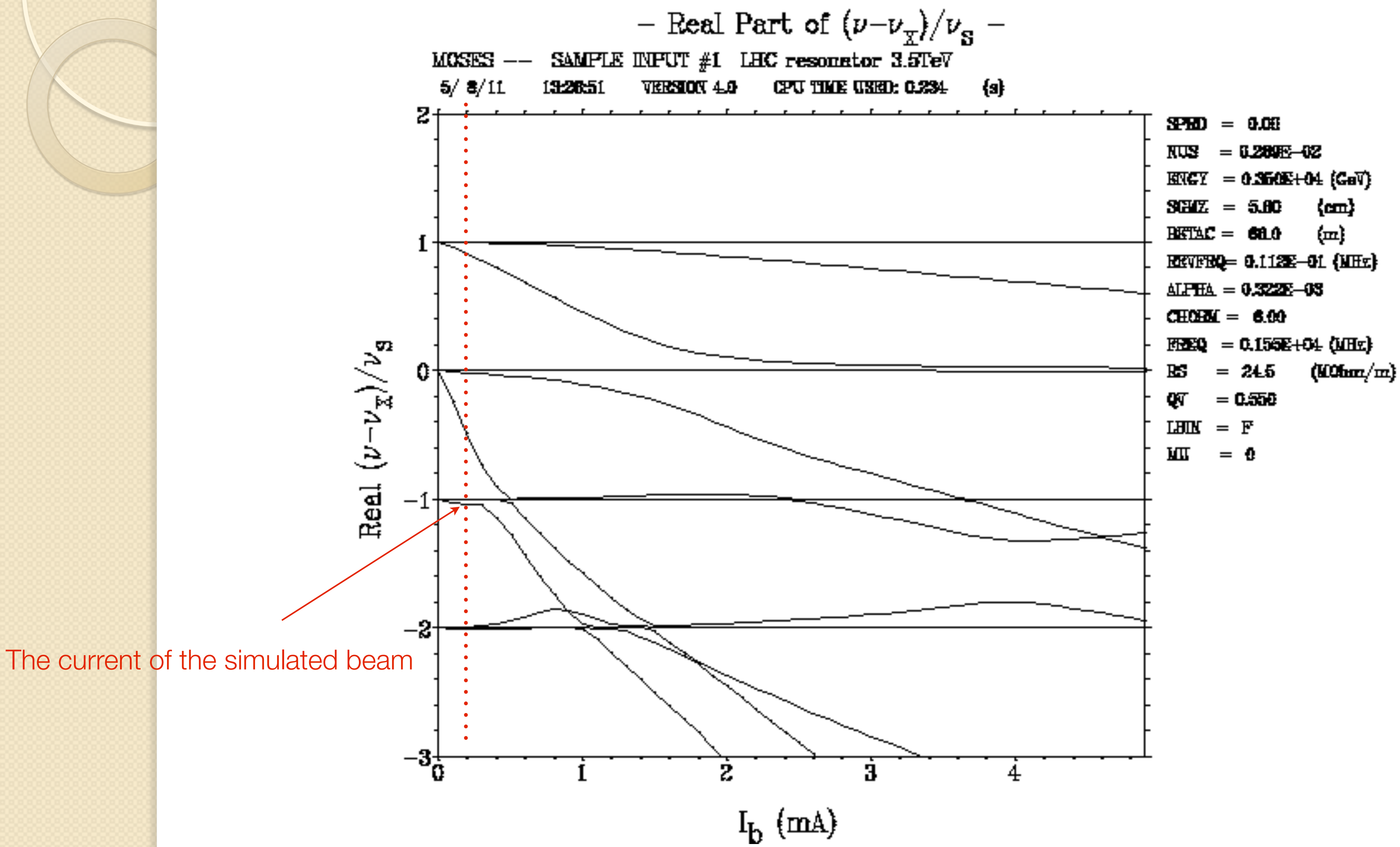
  with $\tau = -1/\omega i$

Instabilities

- Wake fields effects:
  - -Short-range
  - -Long-range
- Head-tail instability vs. TMCI
- Head-tail mode number (m,q): number of nodes in a pick-up signal (Head-tail: q=m)



TMCI threshold



Instabilities

At low intensity, the complex frequency of the most coherent mode is (Sacherer formula) :

$$\Delta\omega^{x}_{c,mm} = \left(\omega_c - \omega_{x0} - m\omega_s\right) = \left(|m|+1\right)^{-1} \frac{j e \beta I_b}{2 m_0 \gamma Q_{x0} \Omega_0 L_b} \frac{\sum_{k=-\infty}^{k=+\infty} Z_x\left(\omega^x_k\right) h_{m,m}\left(\omega^x_k - \omega_{\xi_x}\right)}{\sum_{k=-\infty}^{k=+\infty} h_{m,m}\left(\omega^x_k - \omega_{\xi_x}\right)}$$

with

$$h_{m,m}(\omega) = \frac{\tau_b^2}{2\pi^4}\left(|m|+1\right)^2 \frac{1+(-1)^{|m|}\cos(\omega\tau_b)}{\left[(\omega\tau_b/\pi)^2 - \left(|m|+1\right)^2\right]^2}$$

$$\omega^x_k = \left(k + Q_{x0}\right)\Omega_0 + m\omega_s, \qquad -\infty \le k \le +\infty$$

$$\omega_{\xi x} = Q_{x0}\,\Omega_0 \frac{\xi_x}{\eta}$$

Landau damping

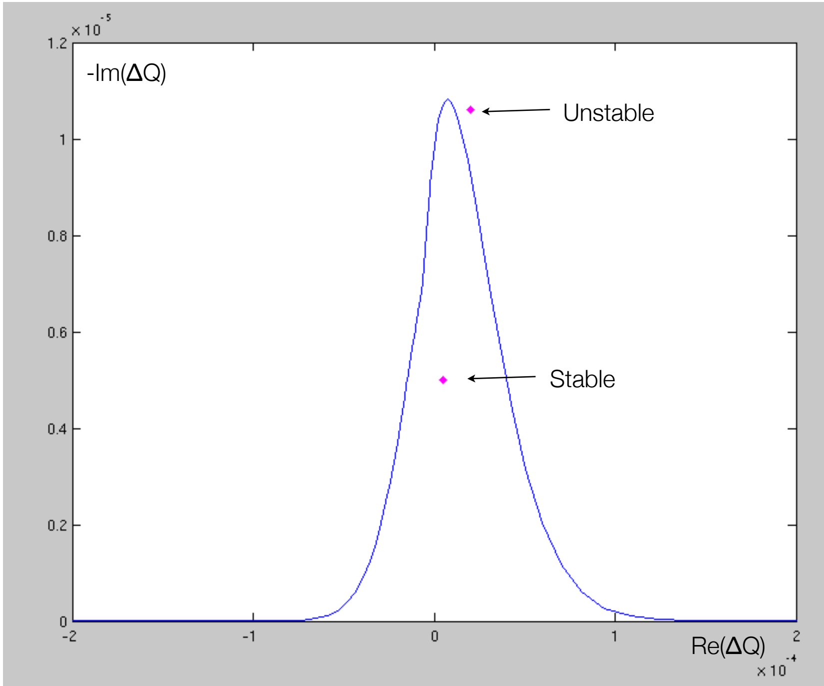
- Landau damping: energy transfer from the coherent mode into incoherent motion
- If coherent mode frequency is not in the coherent spectrum → no landau damping

Stability diagram

- Dispersion relation:

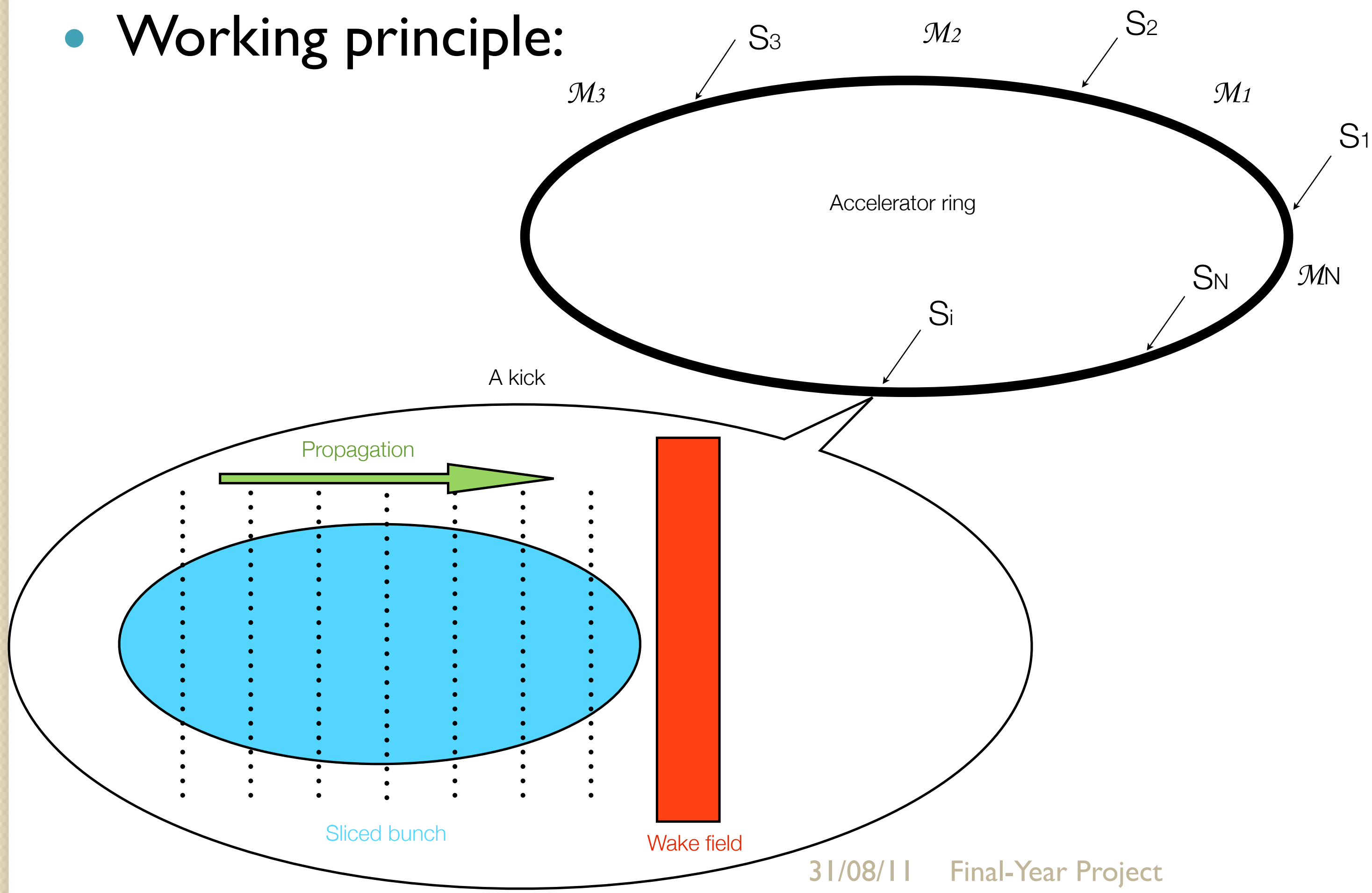
$$1 = -\,\Delta Q^{x}_{coh} \int_{J_x=0}^{+\infty} dJ_x \int_{J_y=0}^{+\infty} dJ_y \, \frac{J_x \dfrac{\partial f(J_x, J_y)}{\partial J_x}}{Q_c - Q_x(J_x, J_y) - m\,Q_s},$$

$$Q_x(J_x, J_y) = Q_0 + a_0 J_x + b_0 J_y$$



HEADTAIL

- Tracking simulation code
- 2 versions: -HEADTAIL_ecloud
  -HEADTAIL_impedance
- Working principle:



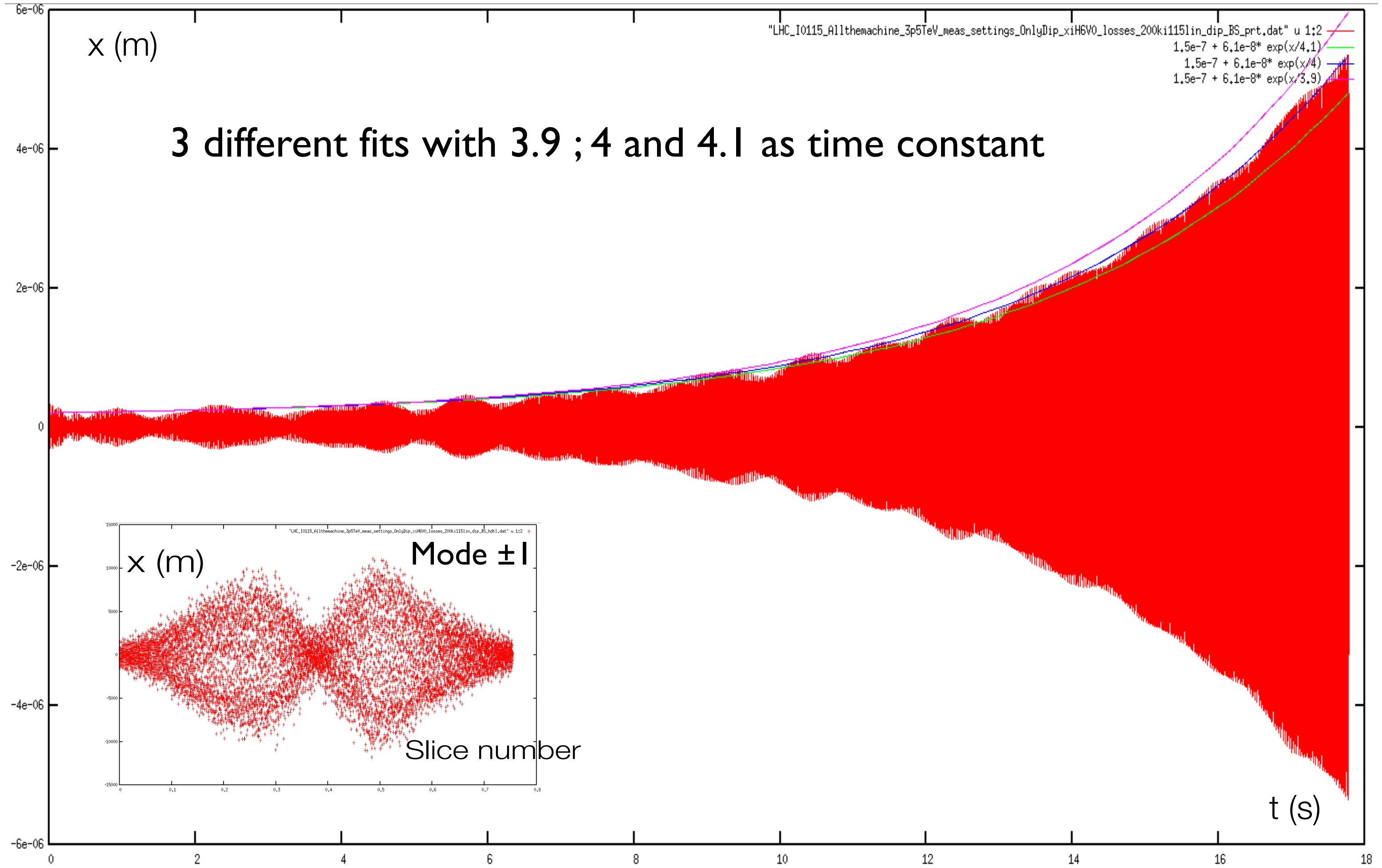
LHC simulations

Main Parameters :

- Single bunch
- Energy: 3.5 TeV
- Collimator settings: MD May 17th 2010
- Impedance: Only dipolar component
- Linear bucket
- Intensity: 1.15e11 p/b
- Horizontal chromaticity: 6
- No space-charge

Sacherer's formula gives: ➔ ΔQ= -1.64 E-4 – i 3.78E-6

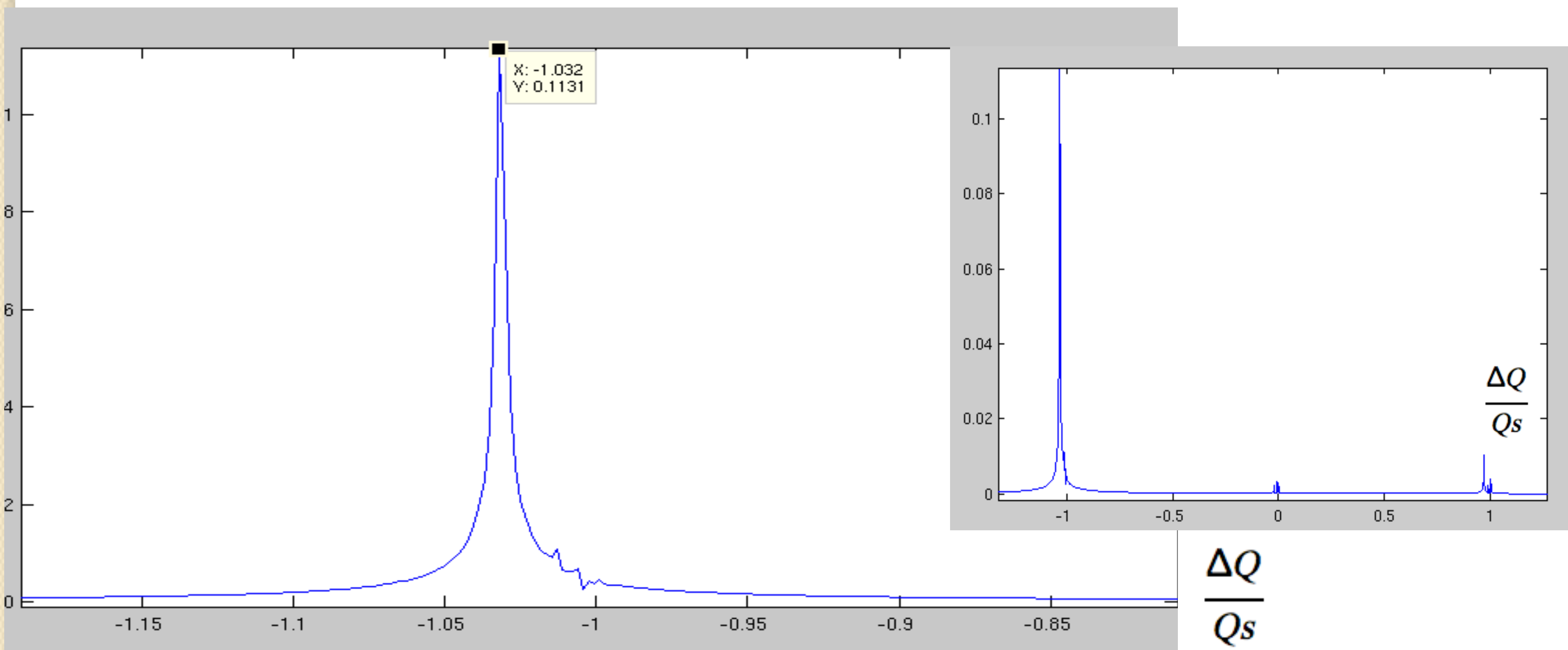
Average horizontal position & Imaginary tune-shift



➔Rise-time = 4.02s which leads to Im(Δ Q)= -3.5 E-6

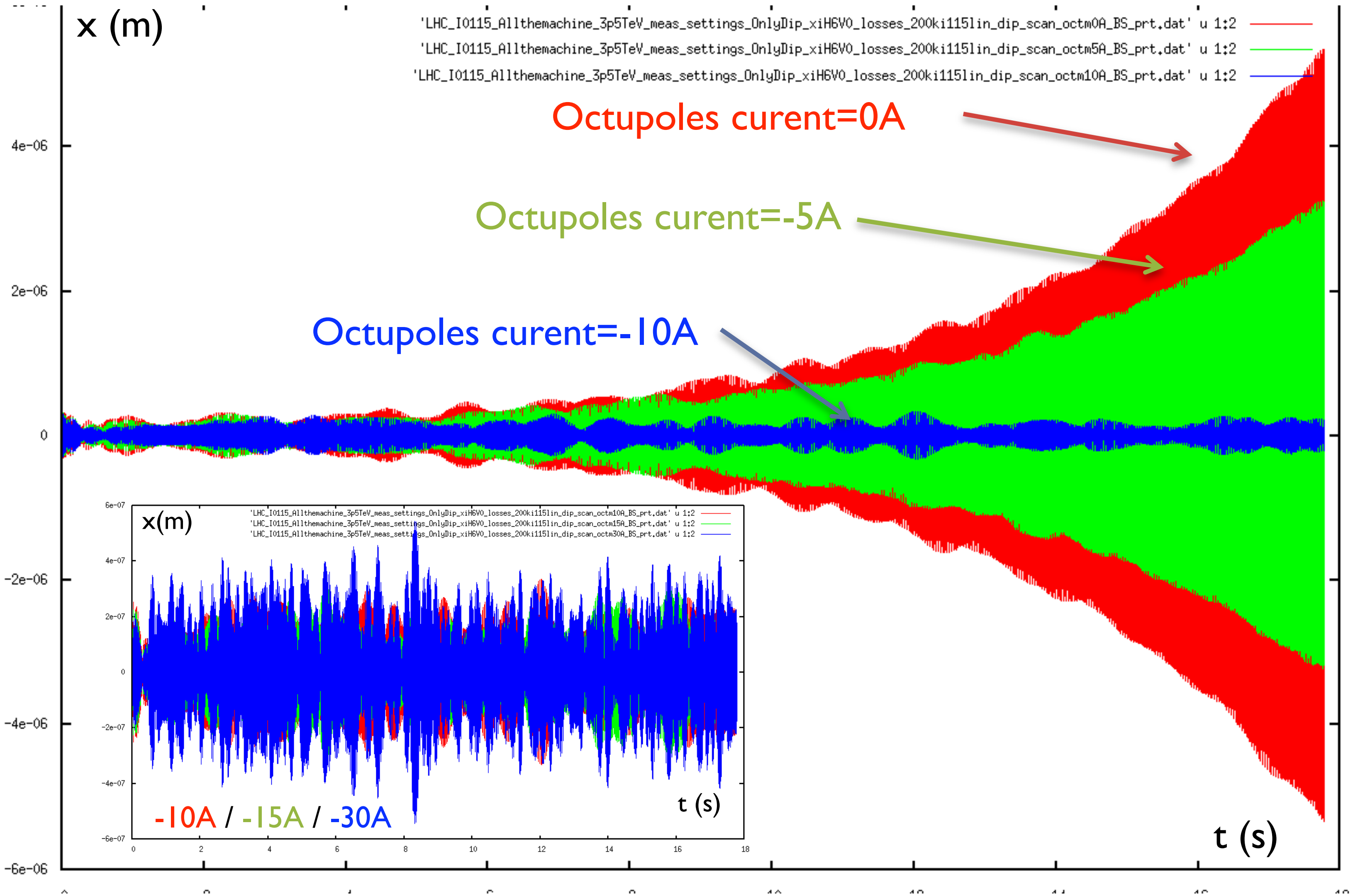
Real tune-shift

Obtained with an FFT of the average horizontal position

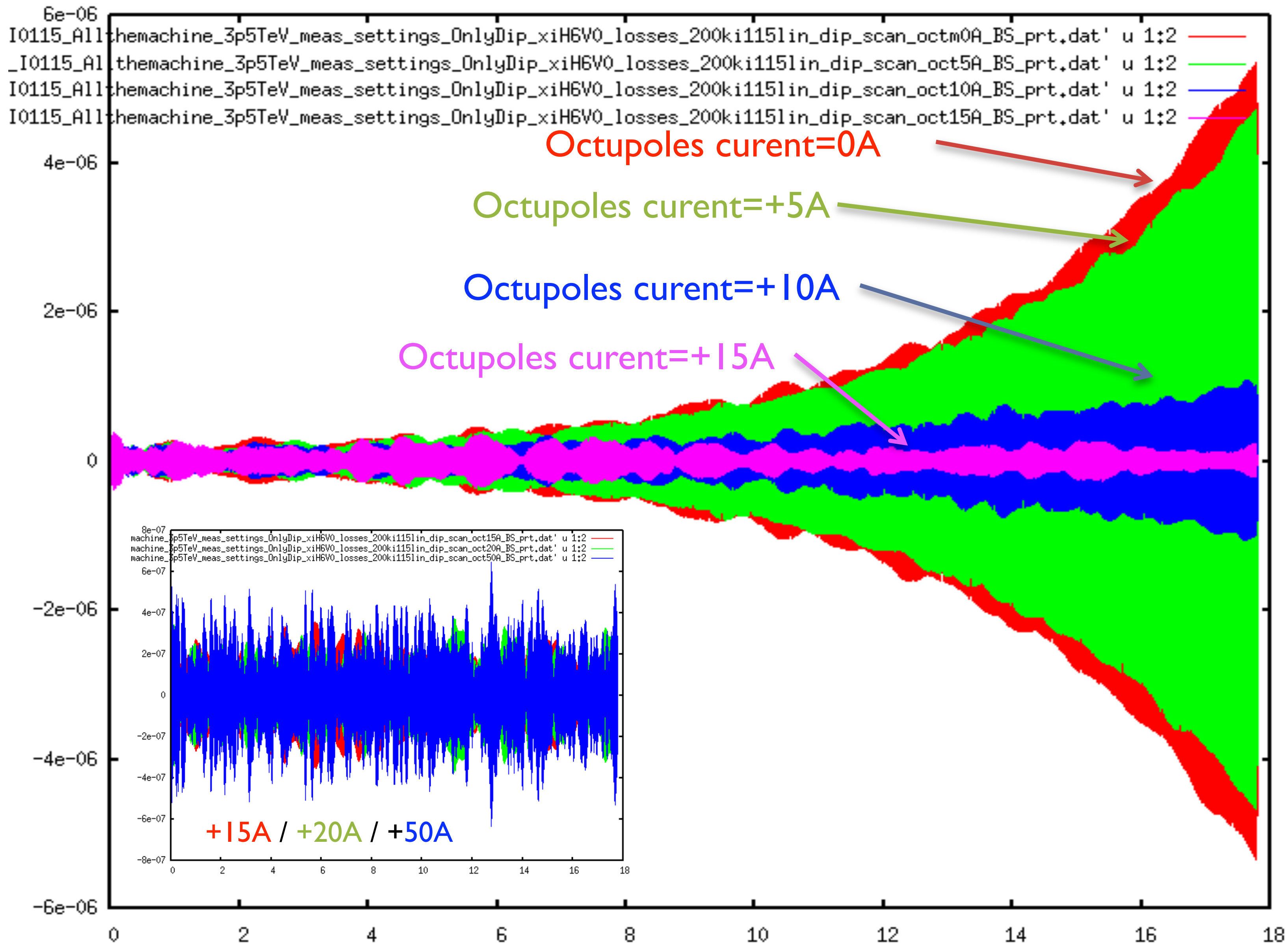


➔Re(Δ Q)= -9.28 E-5

HEADTAIL Simulations

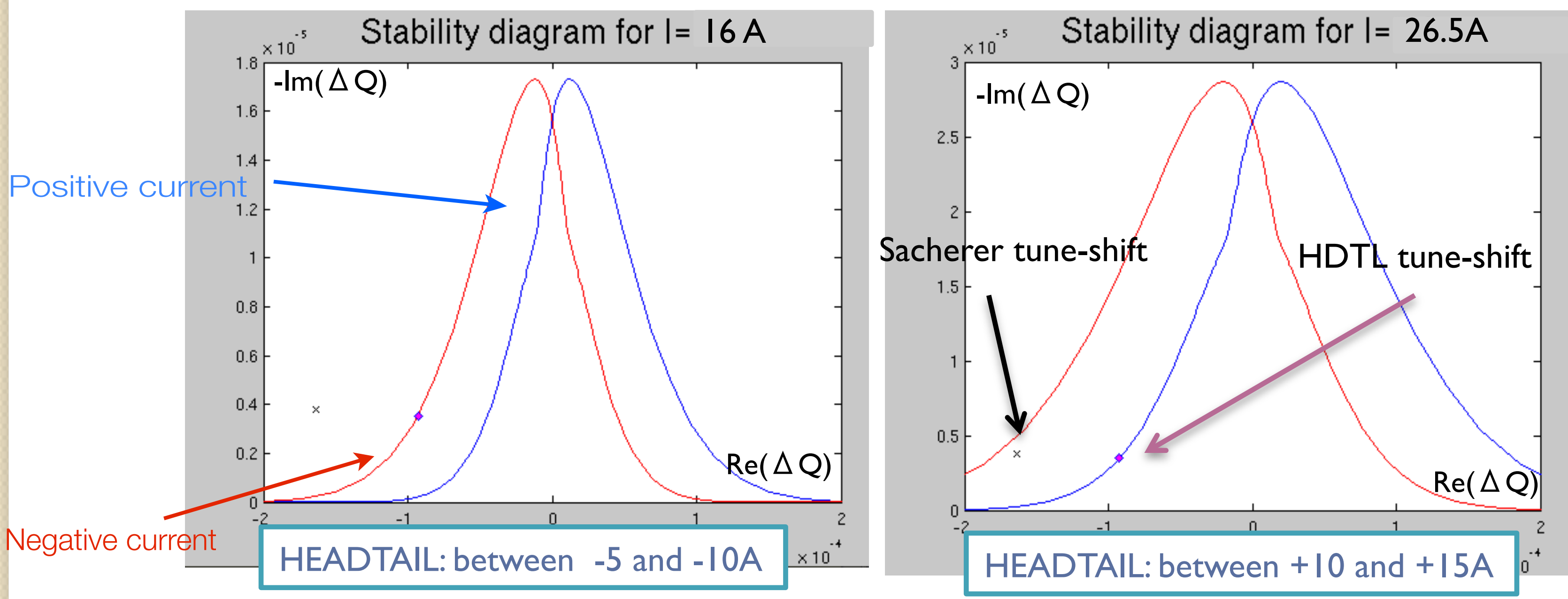


HEADTAIL Simulations



Stability diagrams

For a Gaussian transverse distribution I obtain:



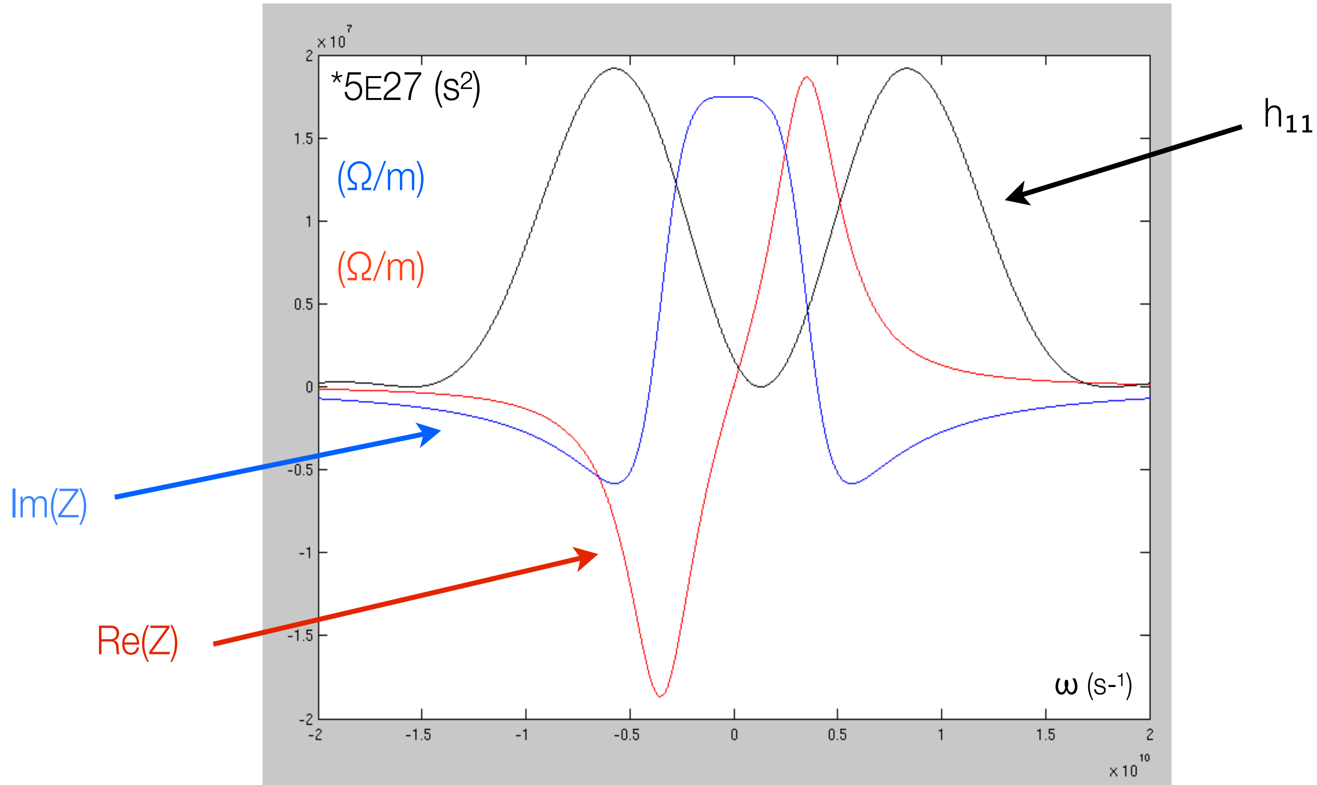
→ There is a factor 2 between the HEADTAIL current and the stability diagram

Scan of the stability diagram

Resonator impedance :

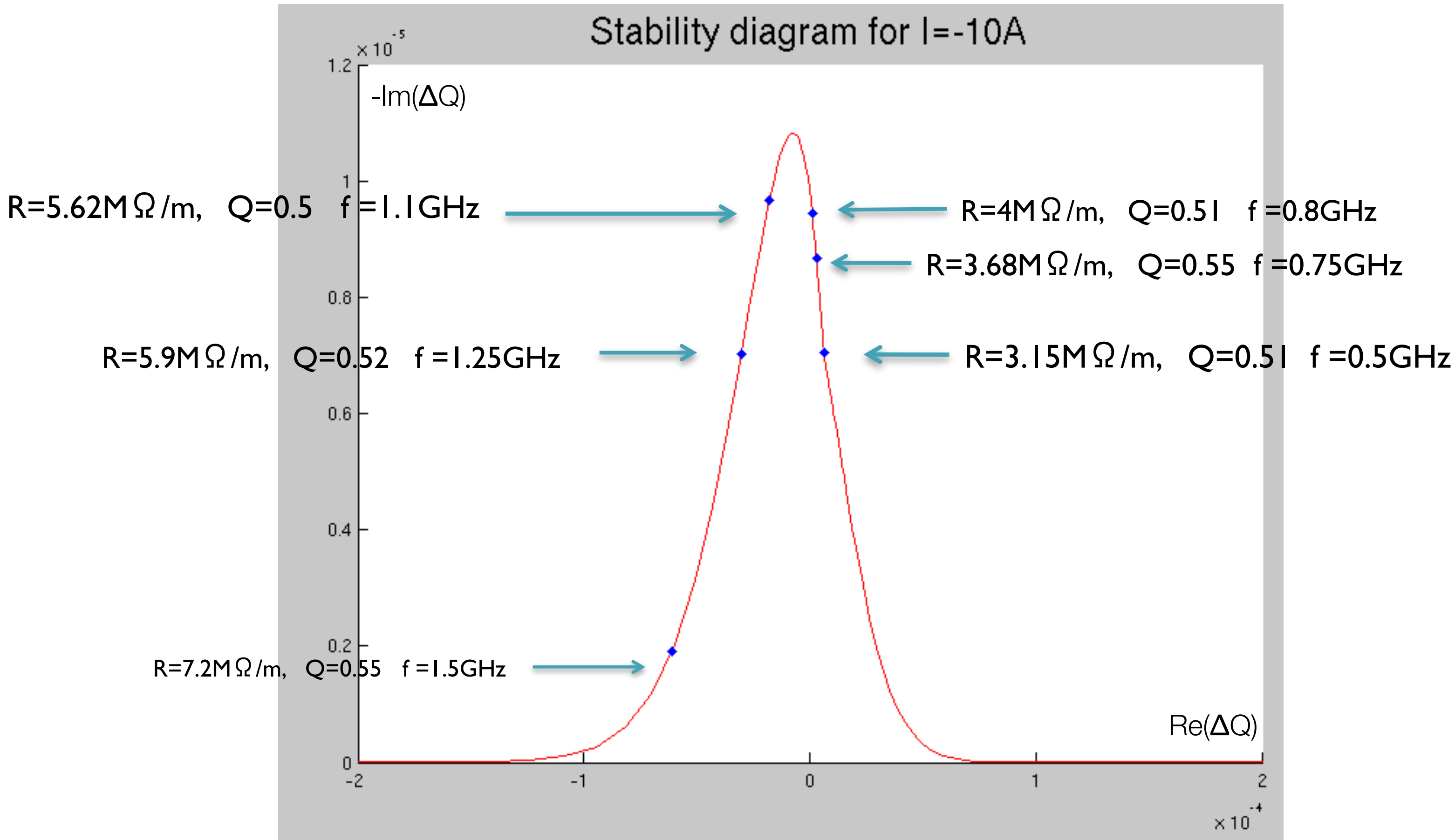
$$Z^{\perp}(\omega) = \frac{\omega_r}{\omega} \frac{R_{\perp}}{1 + jQ\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)}$$

with $R_{\perp}$ the shunt impedance, ω_r the resonance frequency and Q the quality factor

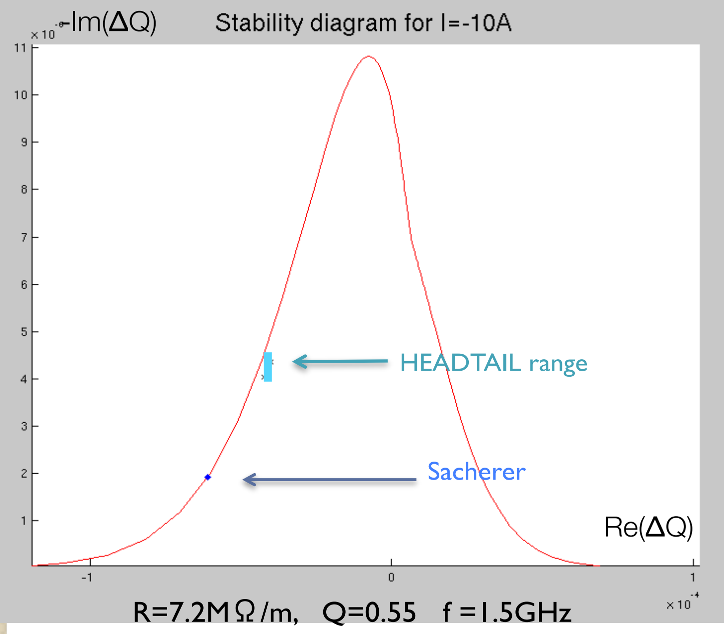


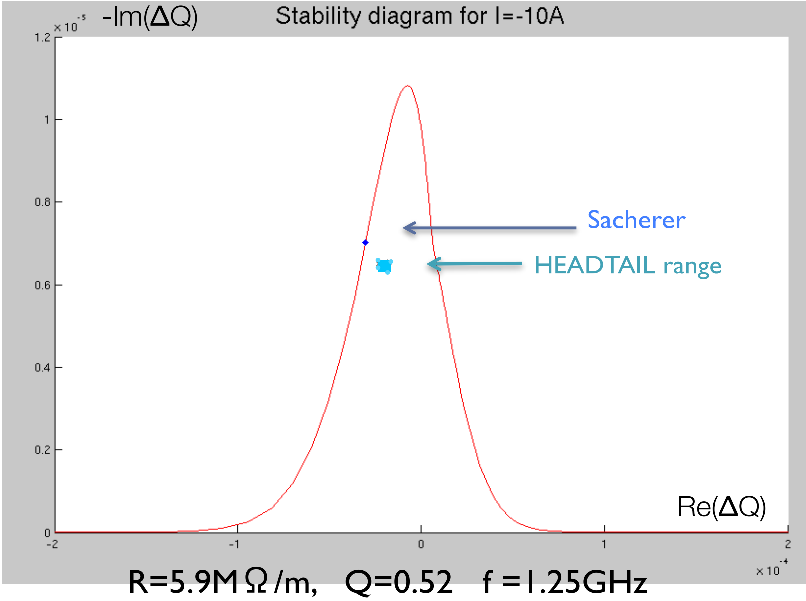
Scan at -10 A

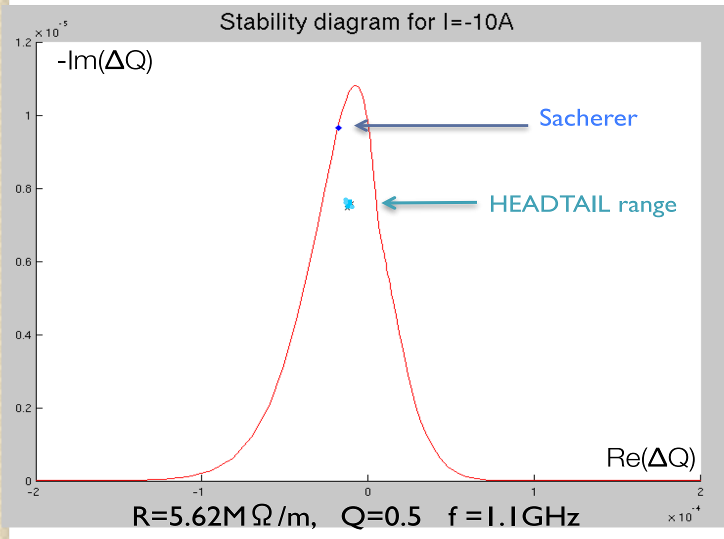
- As a trade-off between the mode coupling threshold and the instability rise time, I chose a current of -10A.

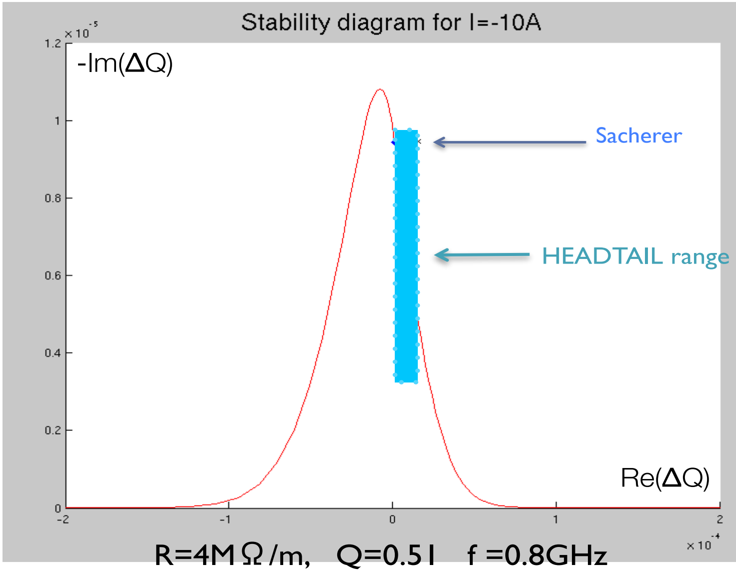


Results at -10 A

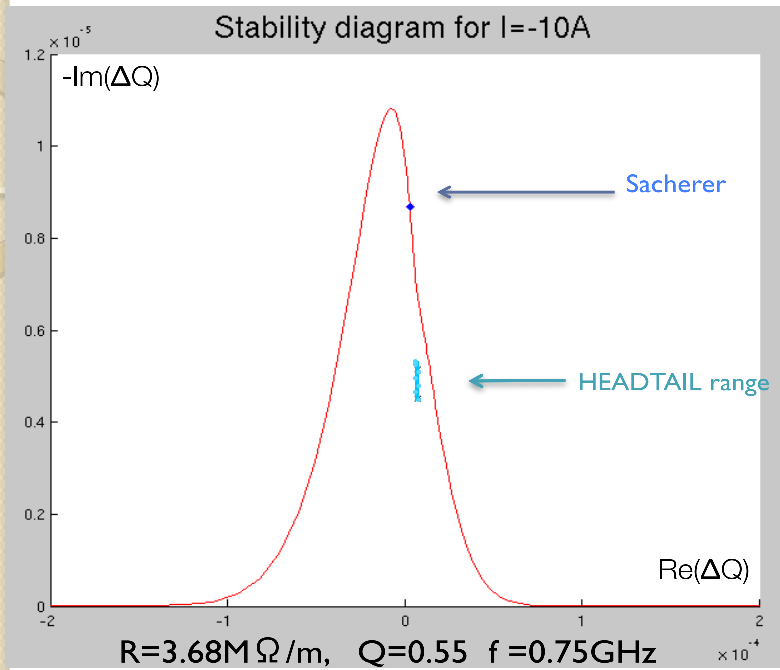




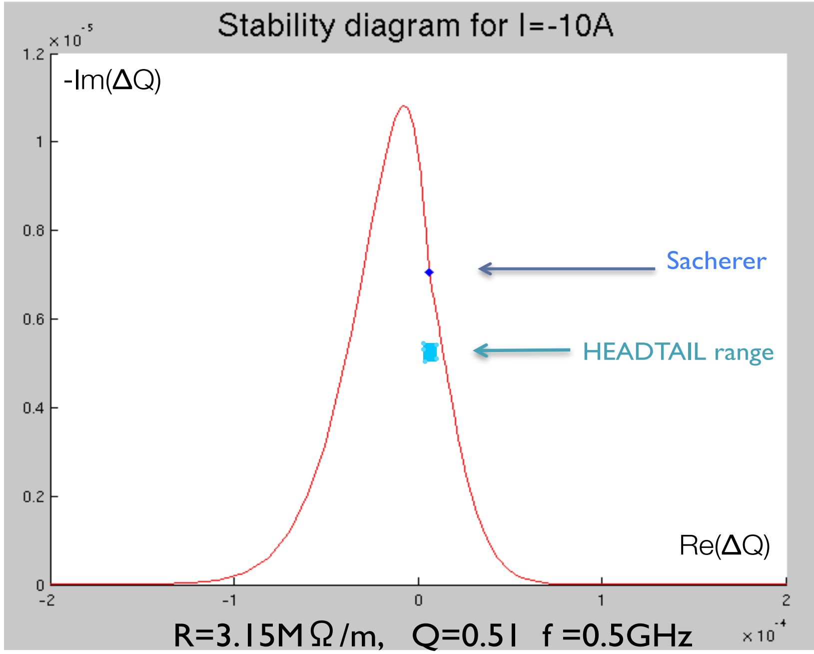




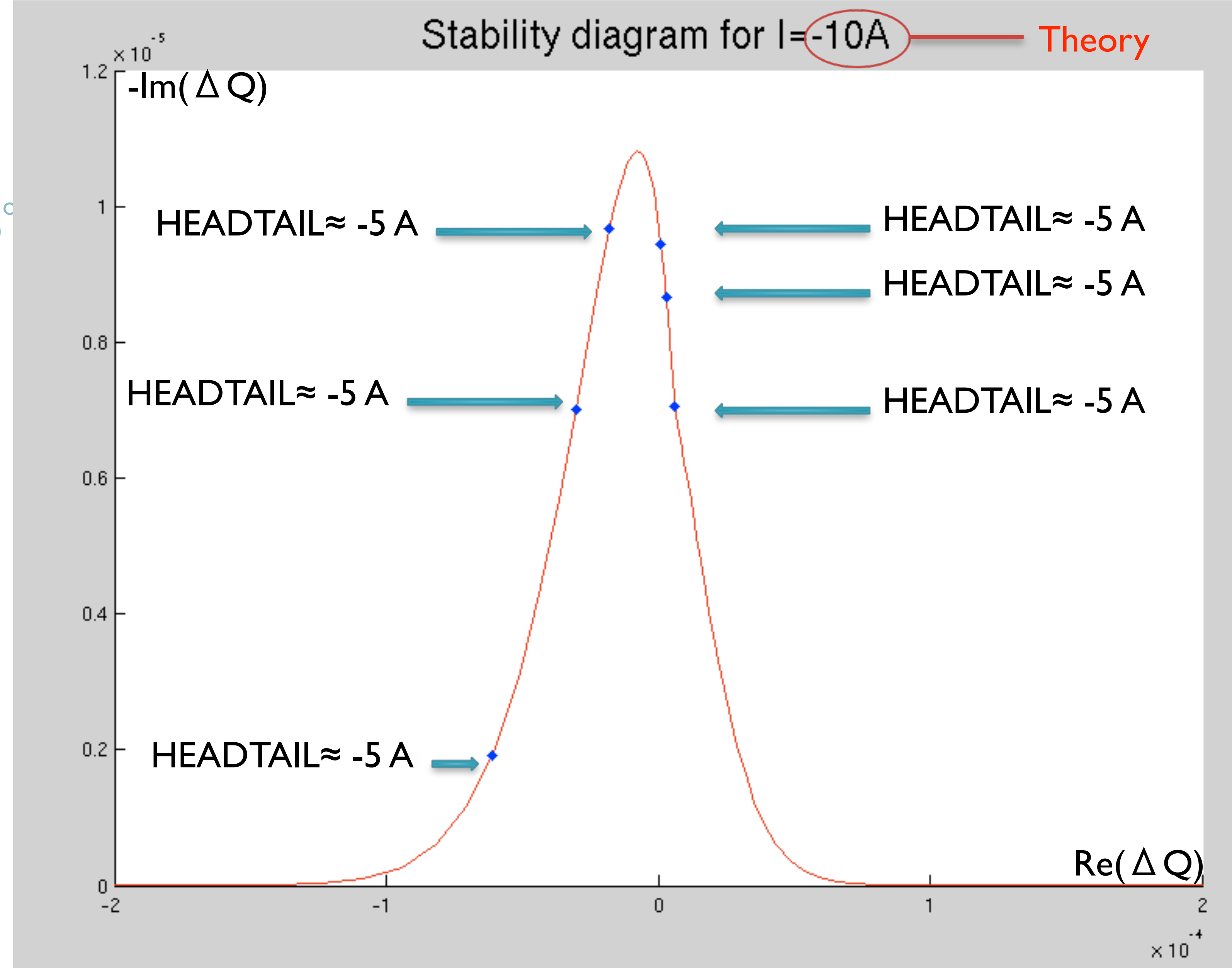
Results at -10 A



R=3.68MΩ/m, Q=0.55 f =0.75GHz



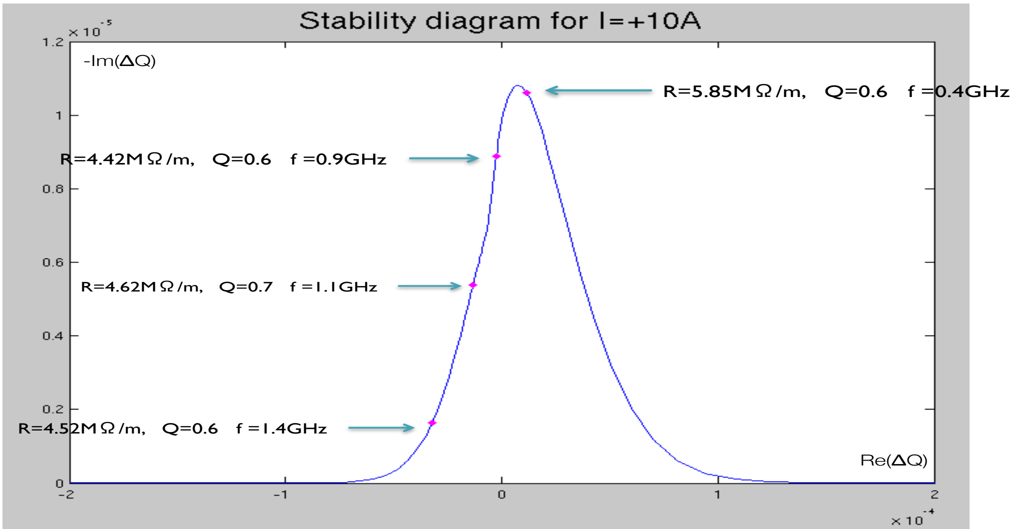
R=3.15MΩ/m, Q=0.51 f =0.5GHz



All points are stabilizing between -4A and -6A

Conclusion and Future work

- Successful check of the stability diagram and its shape
- Check the reason why there is a factor 2 between HEADTAIL and the theory : - error in stability diagram implementation
  - error in the HEADTAIL conversion of the octupole current
  - There is a difference between theory and simulation
- Finalize the work with the +10A curve that I already scanned and launched its simulations
- Study several transverse distribution and see their effect

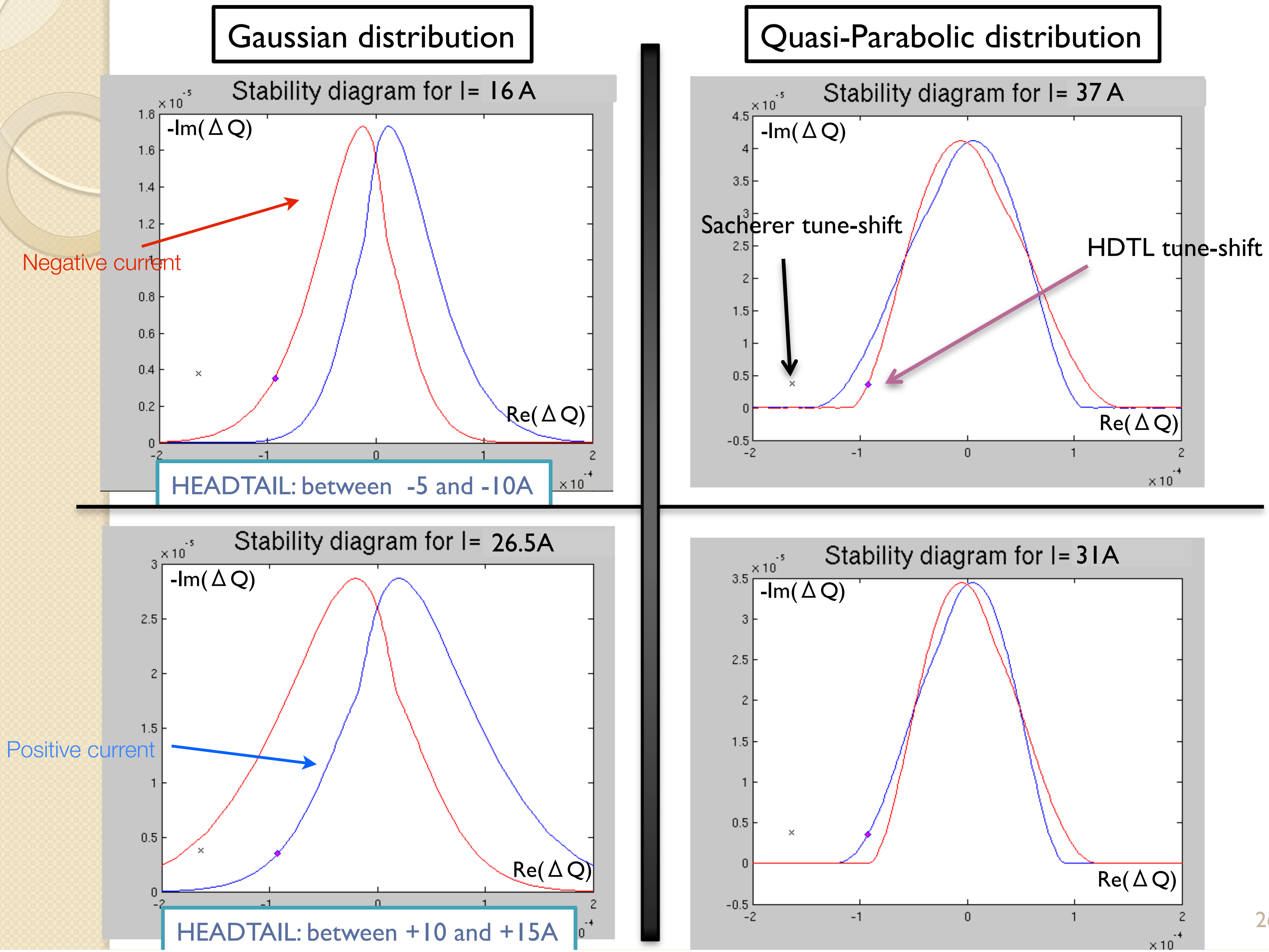


Acknowledgements

I acknowledge all the ICE section for their warm welcome and help; and especially my supervisor and the head of the section *Elias Métral*. As well as *Benoit Salvant* and *Nicolas Mounet* for the huge help and support. I also would like to than *Giovanni Rumolo, Kevin Shing Bruce Li, Hugo Alistair Day and Alexey Burov* for their help and support.

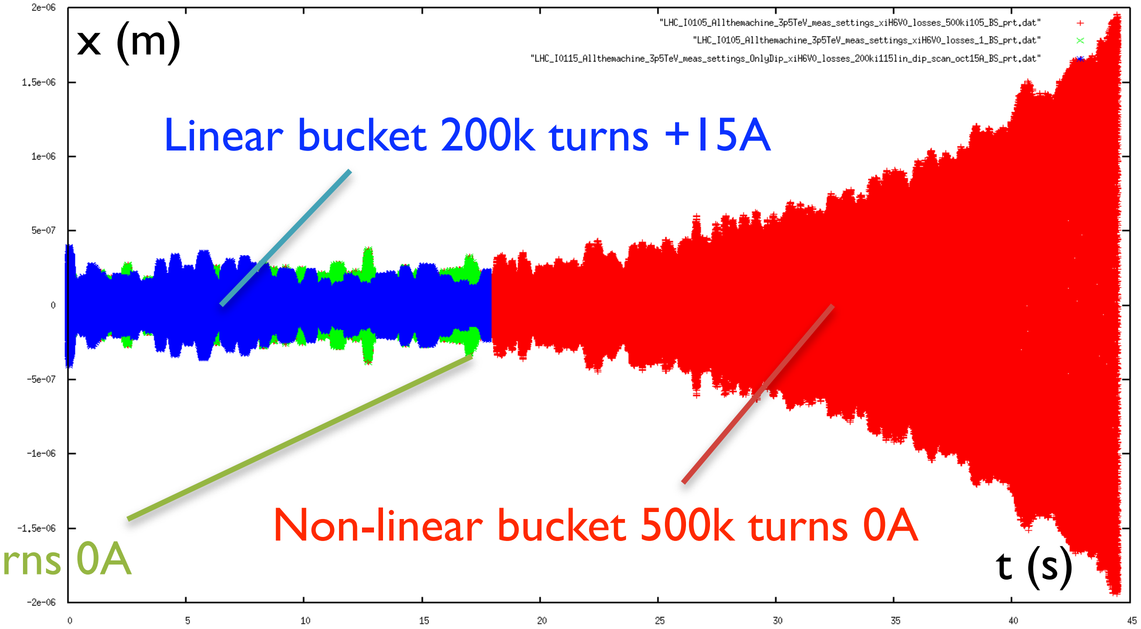
APPENDIX

Stability diagrams

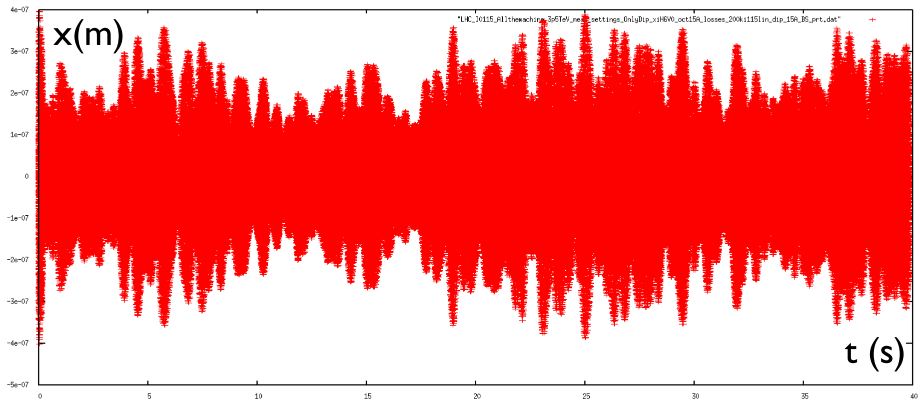


LHC simulations

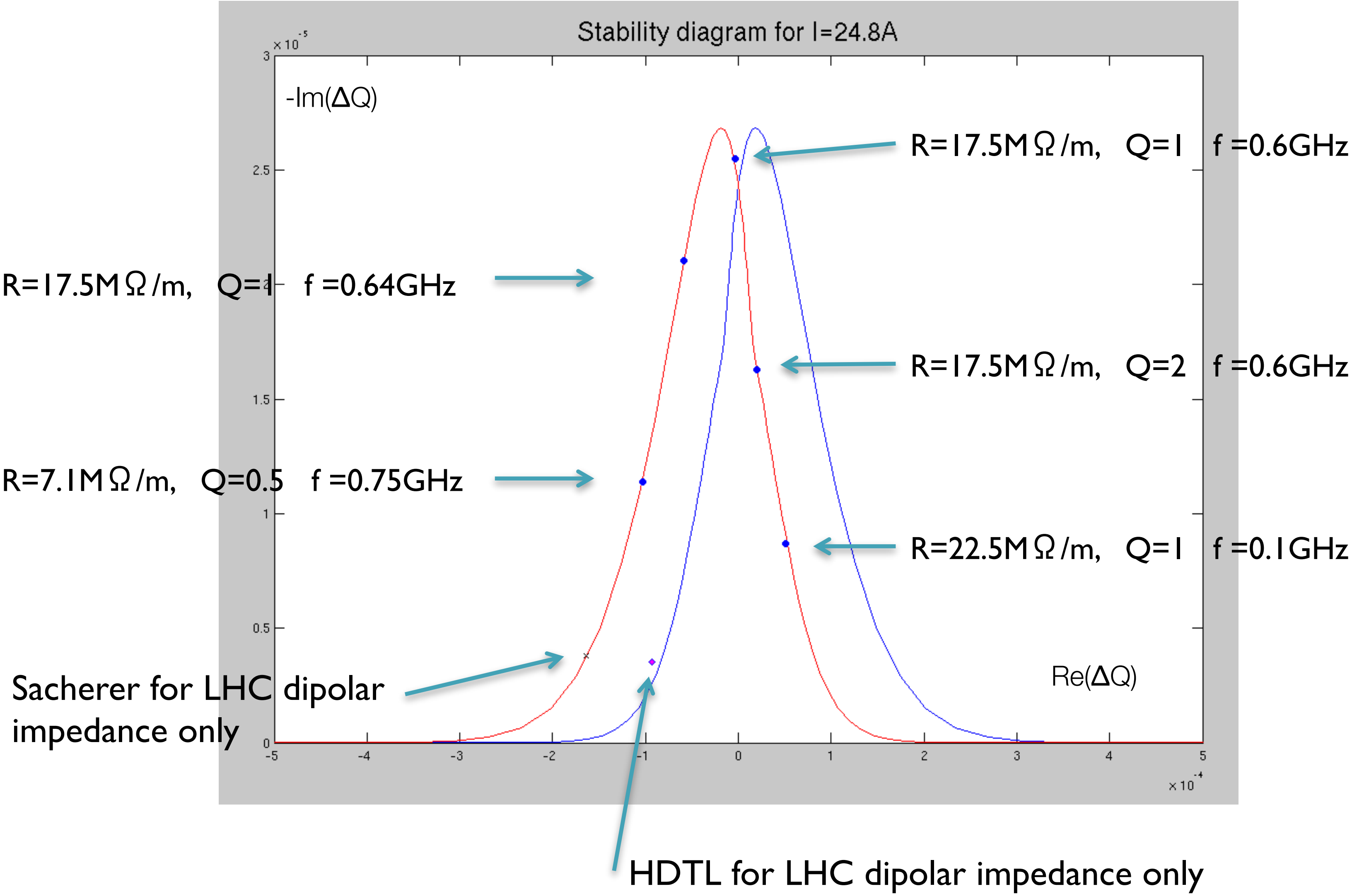
First hypothesis: That the instability will appear later, like the case of non-linear bucket.



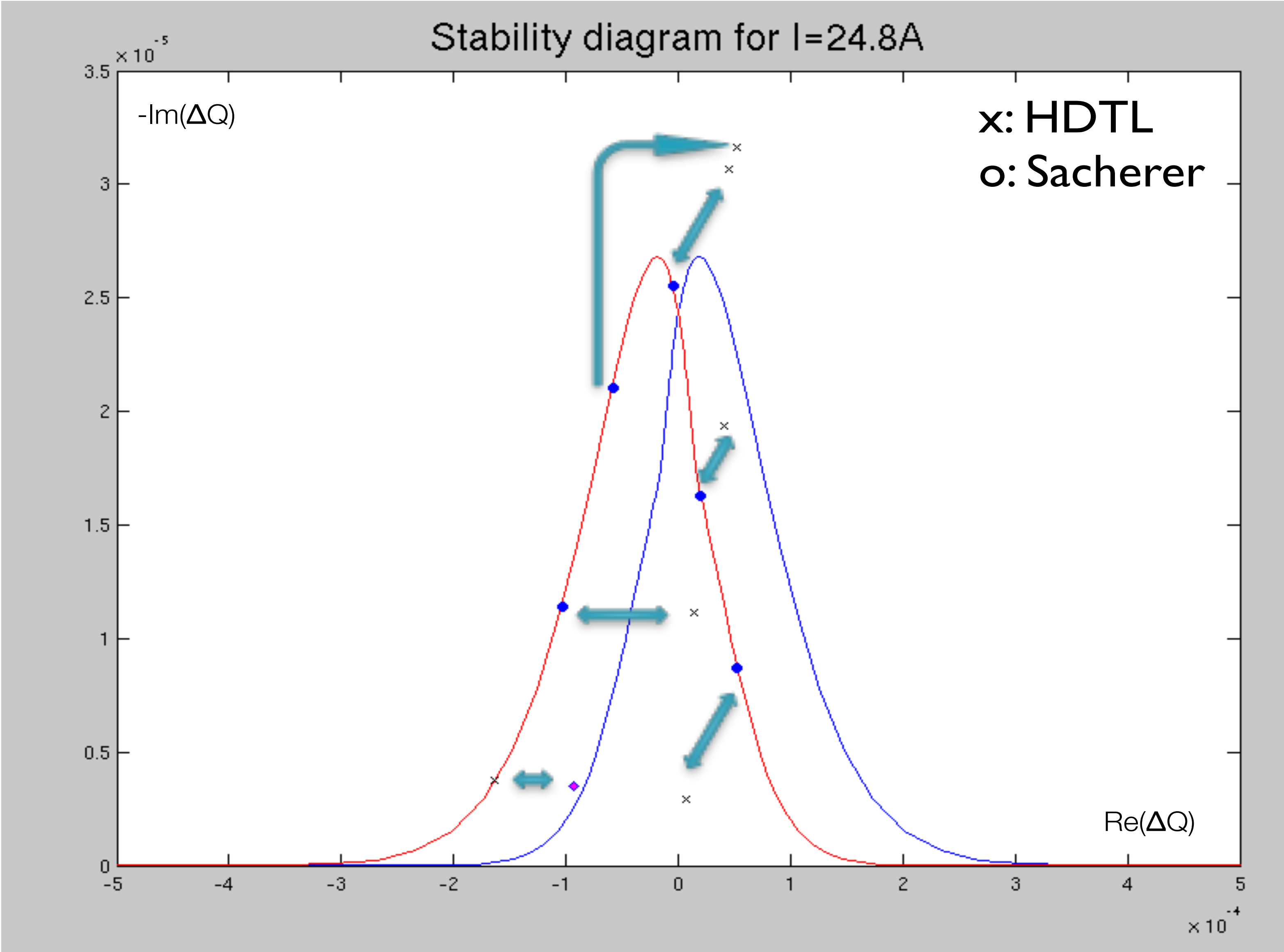
After verification with a 500k turns simulation and +15A, it is still stable. As well as -10A



First scan at -24.8 A



Results at -24.8 A



Verifications of the errors

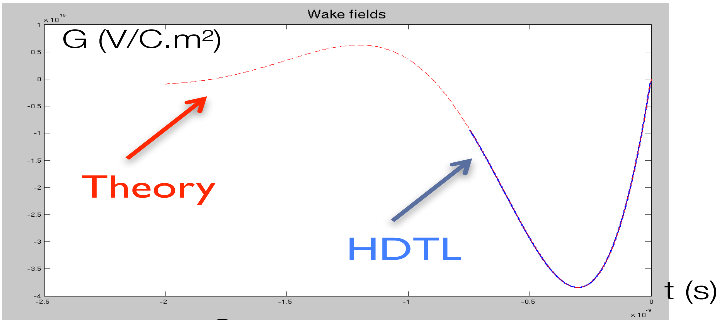
- Comparison of the theoretical wake function and the HEADTAIL one:

$$G_m^{\perp}(t) = \frac{\omega_r^2 R_{\perp}}{Q\,\overline{\omega}_r} e^{-\alpha t} \sin(\overline{\omega}_r\, t)$$

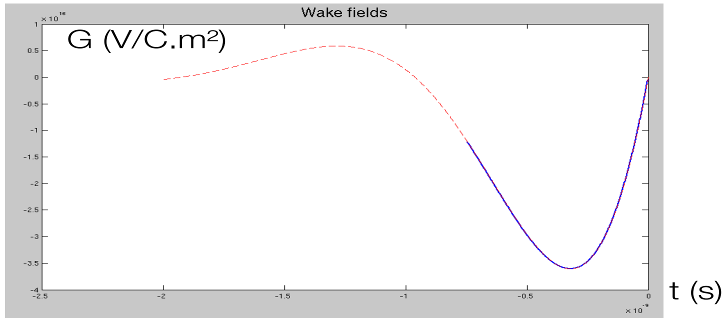
with:

$$\overline{\omega}_r = \omega_r \sqrt{1 - \frac{1}{4Q^2}}$$

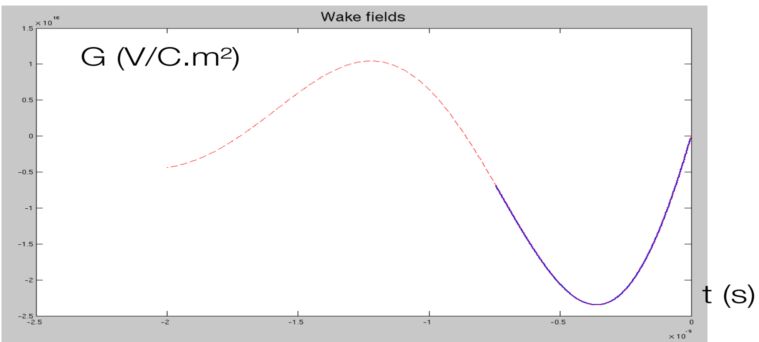
$$\alpha = \frac{\omega_r}{2Q}$$



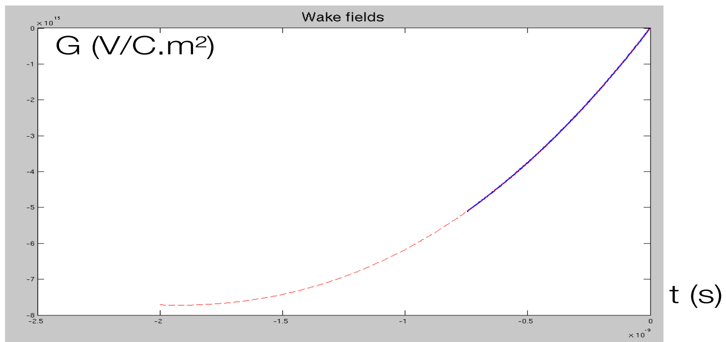
R=17.5MΩ/m, Q=1 f =0.64GHz



R=17.5MΩ/m, Q=1 f =0.6GHz



R=17.5MΩ/m, Q=2 f =0.6GHz



R=22.5MΩ/m, Q=1 f =0.1GHz

Verifications of the errors

- Verification of the HEADTAIL post-processing:

  -Comparison between FFT and SUSSIX

  -Comparison of 2 different methods od fitting

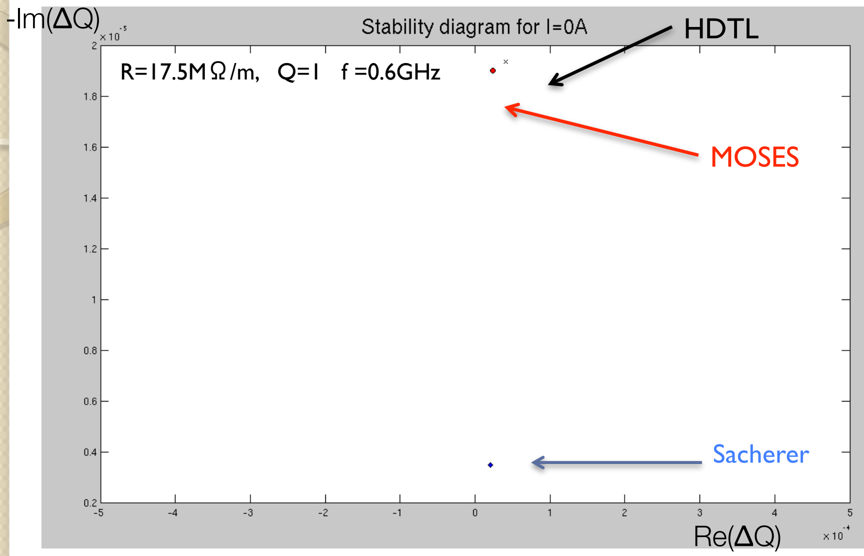
  But in both case there were less than 5% difference.

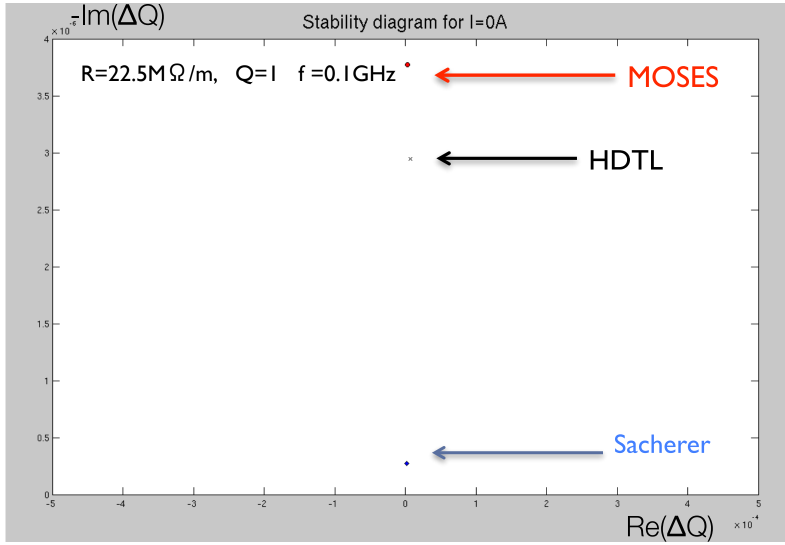
- In Sacherer's implementation, the stop condition was that the ratio of the first neglected term and the sum is less than 10^{-10} but then I put it 10^{-12} and the result was exactly the same.

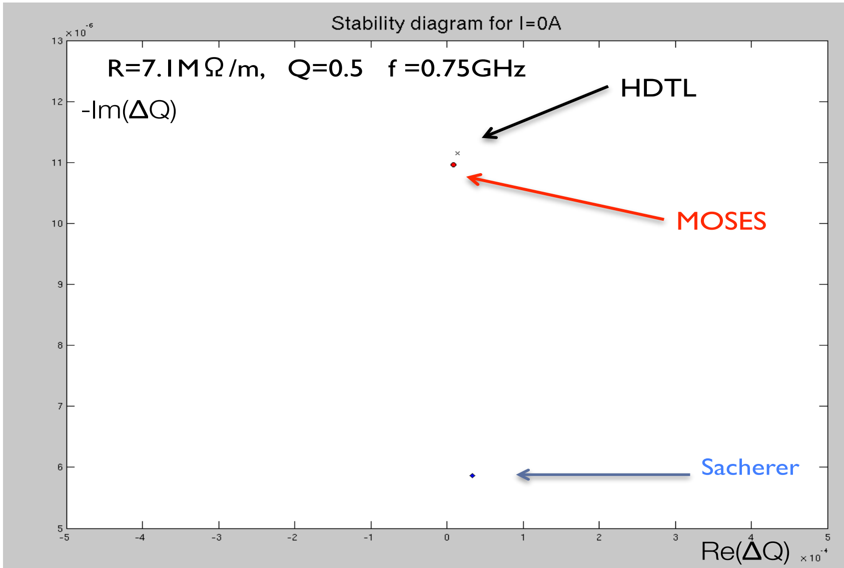
- I found an error in my implementation which corrected the real part to be within a factor 2 error.

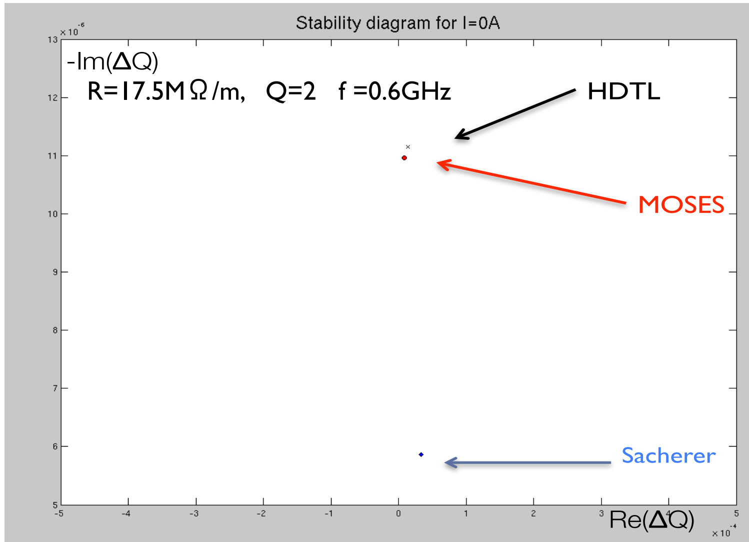
- Then I tried to check with MOSES code (MOde coupling Single bunch instability in an Electron Storage ring)

MOSES vs. HDTL vs. Sacherer

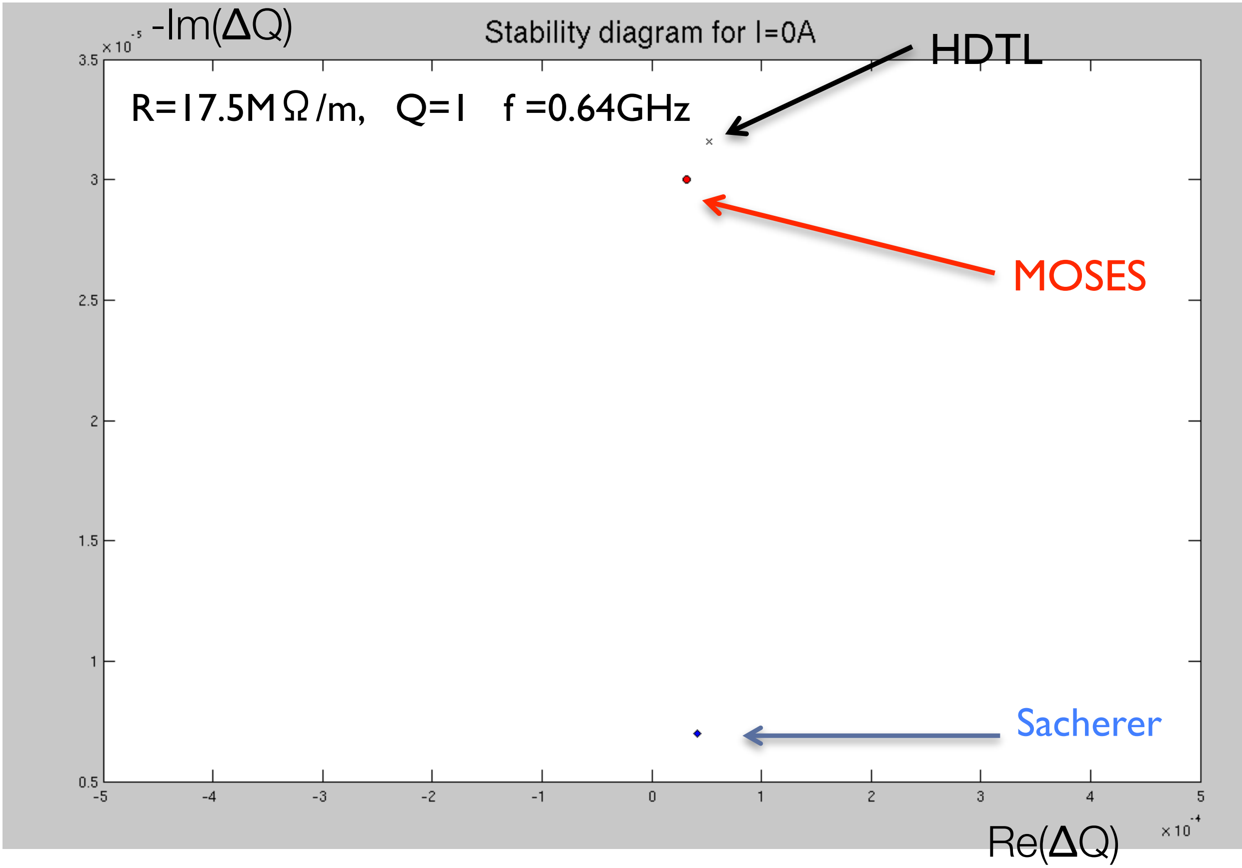








MOSES vs. HDTL vs. Sacherer



HEADTAIL and MOSES are very close. The problem seems to come from Sacherer

MOSES vs. HDTL vs. Sacherer

- There is still a huge difference with the imaginary part.
- Dr. E. Métral tried the cases with his own code and he found a result with a factor 2 on imaginary and real parts.
- I tried then to change the implementation to be an integral instead of a sum.

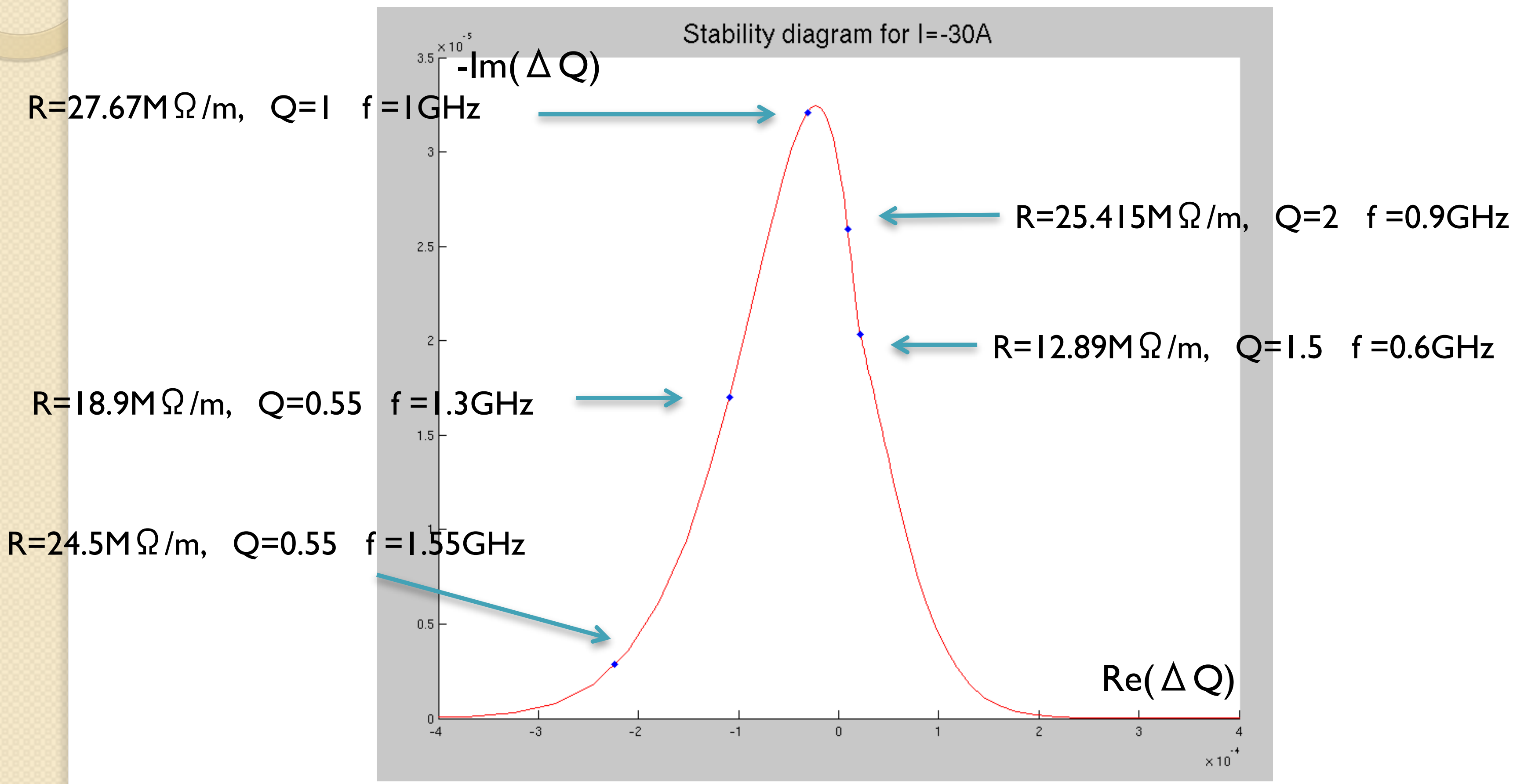
MOSES vs. HDTL vs. Sacherer

	Rs (Mohm/m)	7,1	17,5	17,5	17,5	22,5
	Q	0,5	1	1	2	1
	f(GHz)	0,75	0,64	0,6	0,6	0,1
Headtail	Re(ΔQ)	1,42E-05	5,28E-05	4,49E-05	4,11E-05	7,63E-06
	Im(ΔQ)	-1,12E-05	-3,16E-05	-3,06E-05	-1,93E-05	-2,95E-06
MOSES	Re(ΔQ)	1,05E-05	3,23E-05	3,17E-05	2,25E-05	3,80E-06
	Im(ΔQ)	-1,14E-05	-3,13E-05	-3,10E-05	-1,97E-05	-3,89E-06
	error Re(ΔQ)	26%	39%	29%	45%	50%
	error Im(ΔQ)	2%	1%	1%	2%	32%
Sacherer	Re(ΔQ)	4,85E-06	3,09E-05	3,27E-05	2,57E-05	4,74E-06
	Im(ΔQ)	-1,72E-05	-3,43E-05	-3,39E-05	-2,32E-05	-3,67E-06
	error Re(ΔQ)	66%	41%	27%	38%	38%
	error Im(ΔQ)	55%	8%	11%	20%	24%

Now that the new implementation gives better results, I can scan the curve. But I still have to find the reason why the sum implementation doesn't work.

Scan at -30 A

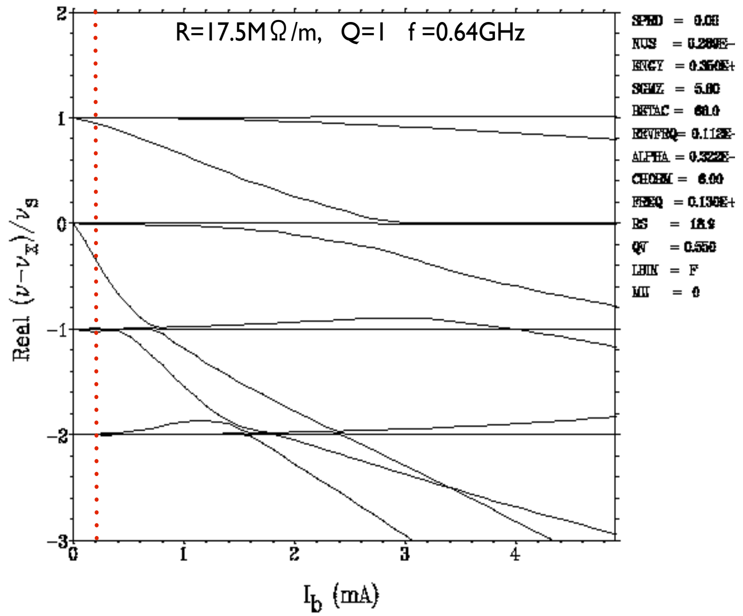
The choice of -30 A was especially to make the scan of the curve easier.

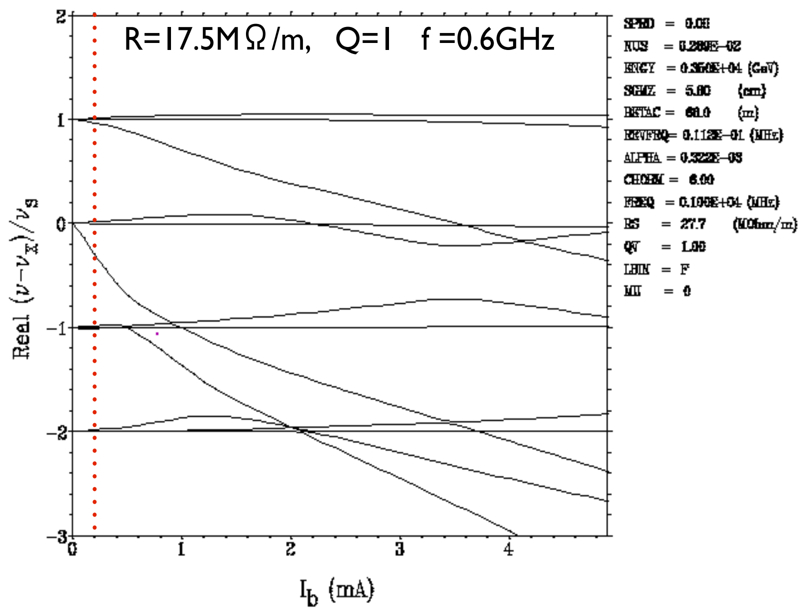


Scan at -30 A

- The results of this scan were also bad. Except for one point.
- After investigation, I noticed that the only point for which the results were close to HEADTAIL was the one with the highest Transverse Mode Coupling threshold.

TMCI threshold





The only case which worked