Coherent Effects with Beam-beam and Impedance

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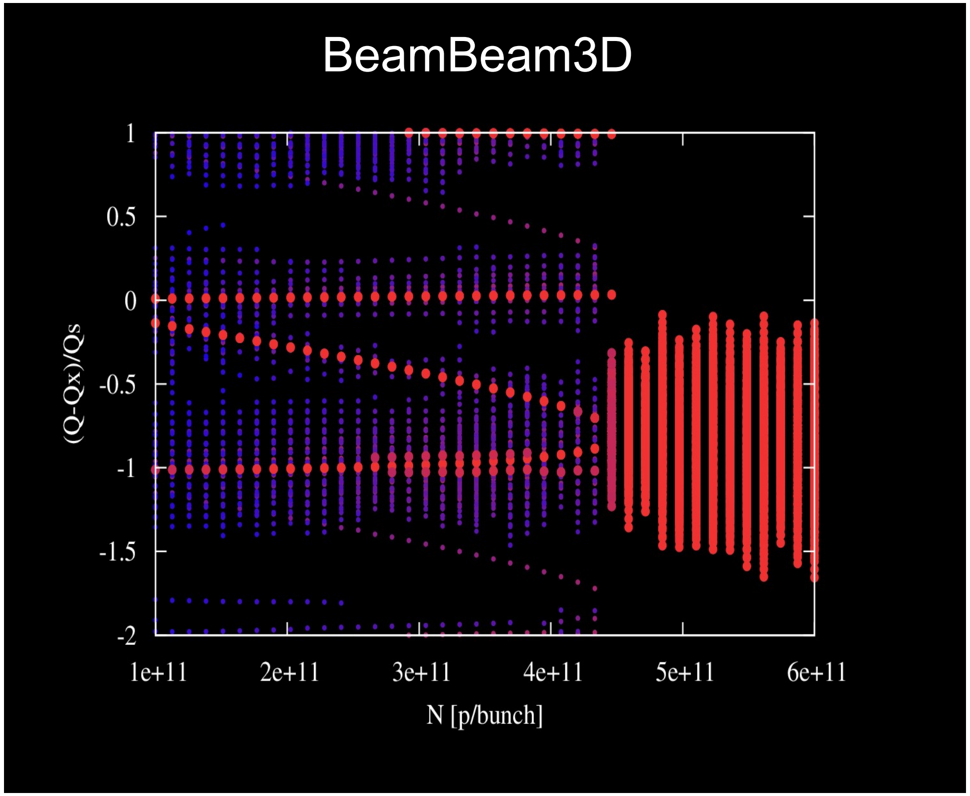
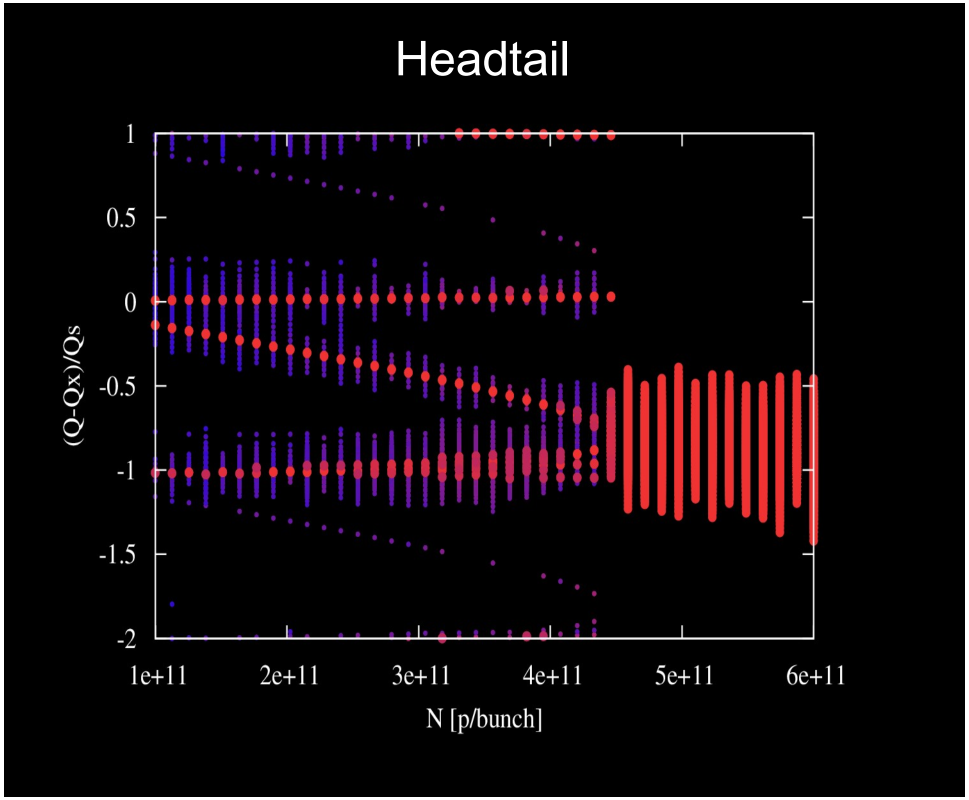
Thanks to X. Buffat, A. Burov, N. Mounet and T. Pieloni

Models

- Two models developed to study the combined effect of BB and impedance:
  - **Hollow beam model:** based on the work by Perevedentsev et al. Allows to see all the modes and study their stability → fast but no Landau damping
  - **Macro-particle model:** based on BeamBeam3D by J. Qiang, added impedance → slow but includes Landau damping
- Complementary tools to study how these effects couple

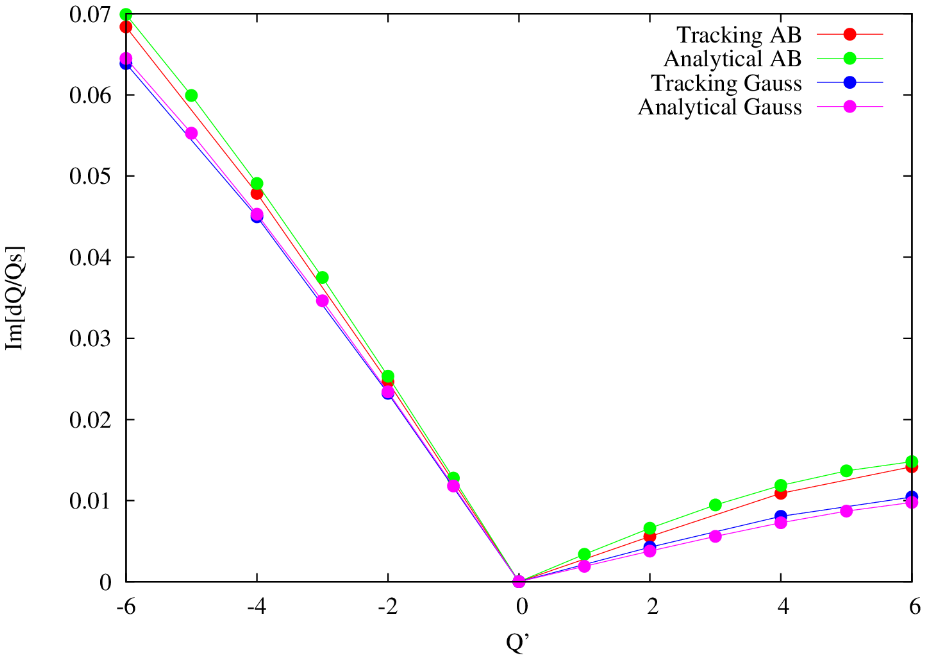
Impedance in BeamBeam3D

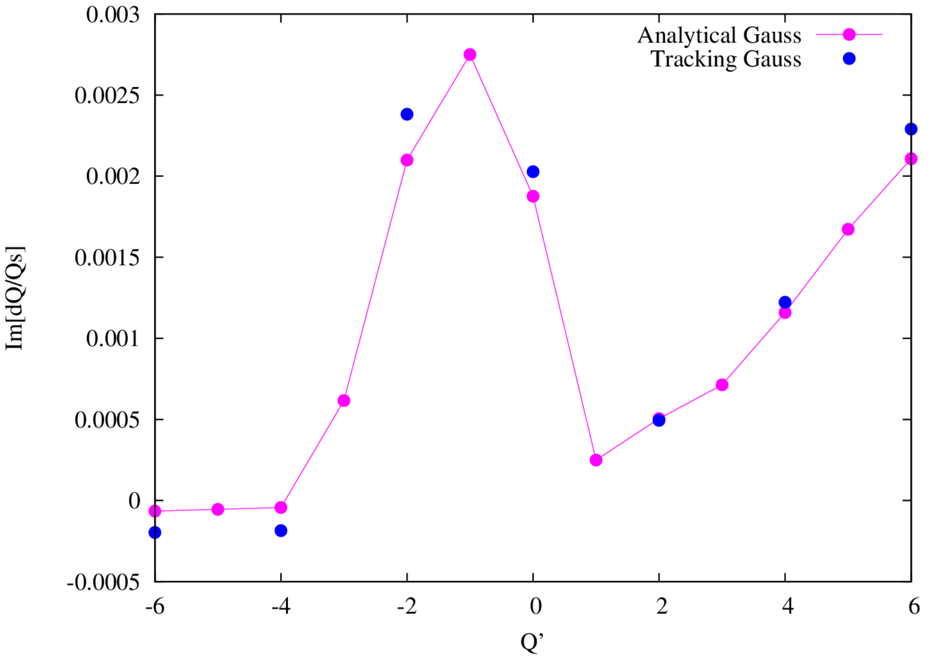




→ Used the impedance model for current LHC collimators settings / optics
→ Good agreement between headtail and BeamBeam3D

Comparison with Theory



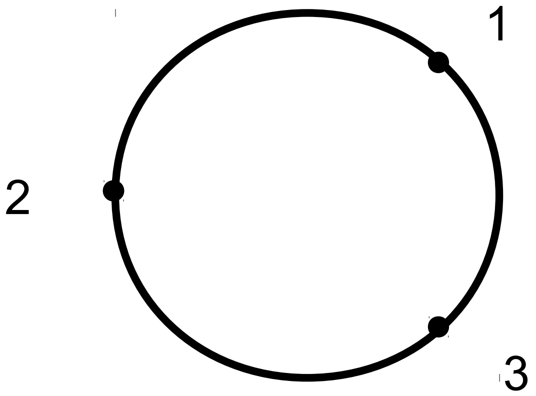


→ Comparison of tracking with Nicolas and Alexey's new theory *(analytical values courtesy of A. Burov)*

→ Without damper excellent agreement

→ With damper maximum error of the order 10% at Q'=-2.0 for Gaussian distribution

Hollow Beam Model



$$M = C \otimes B$$

$$B = \begin{pmatrix} \cos\mu_\beta & \sin\mu_\beta \\ -\sin\mu_\beta & \cos\mu_\beta \end{pmatrix}$$

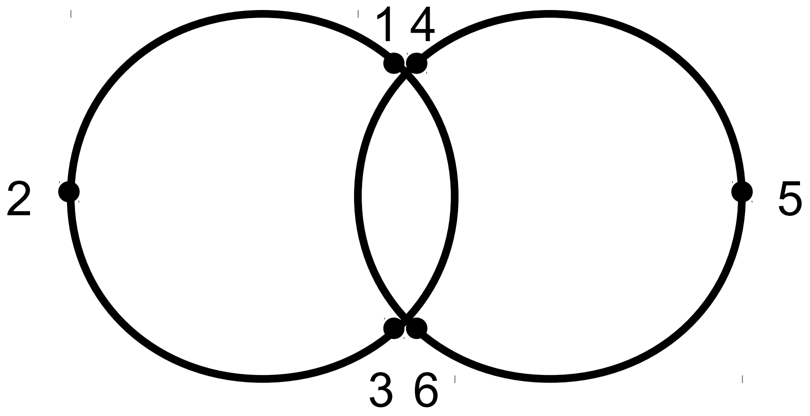
$$C_{ij} = \frac{\sin N\varphi_{ij}}{N \sin\varphi_{ij}}$$

$$\varphi_{ij} = \frac{1}{2}\left(\mu_s - (N - i + j)\frac{2\pi}{N}\right)$$

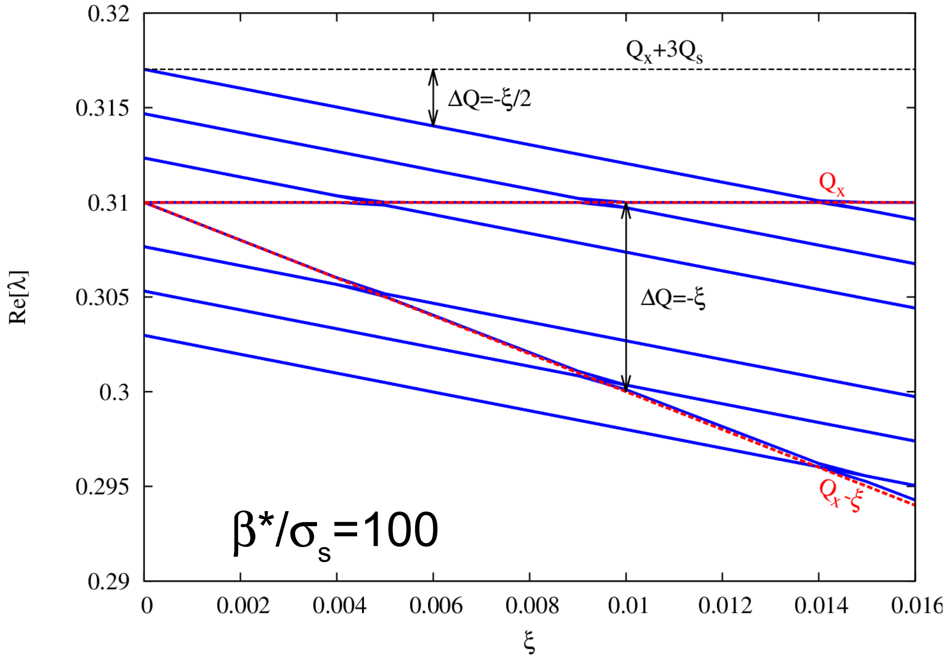
$$M_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \otimes M$$

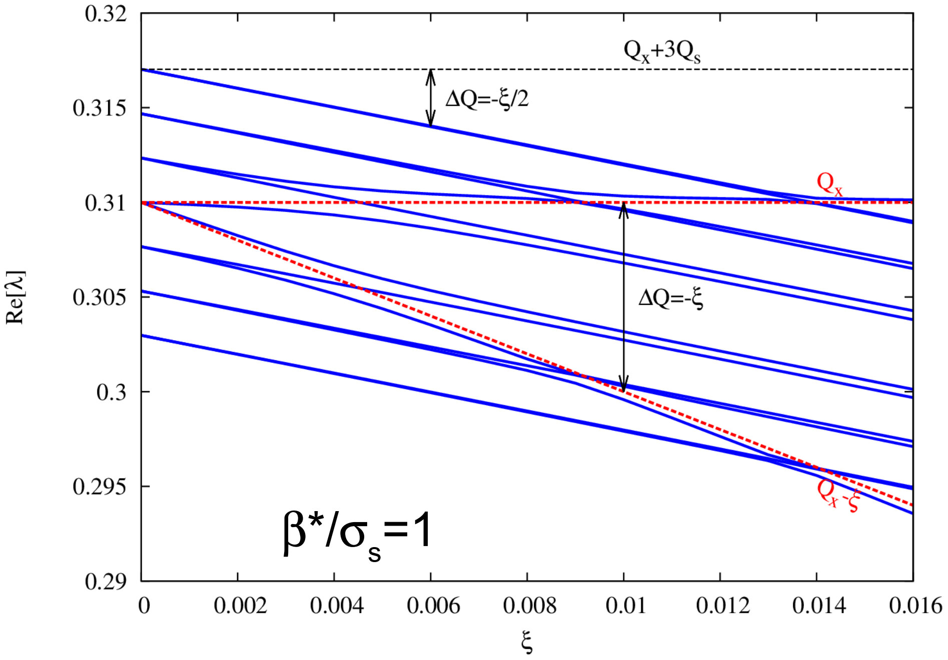
$$\Delta p_1 = -\frac{2\pi\xi}{3}\left[(x_1 - x_6) + (x_1 - x_4)\right]$$

$$\Delta p_i = \sum_{j=1}^{i-1} Q x_j$$



Synchro-Betatron Modes





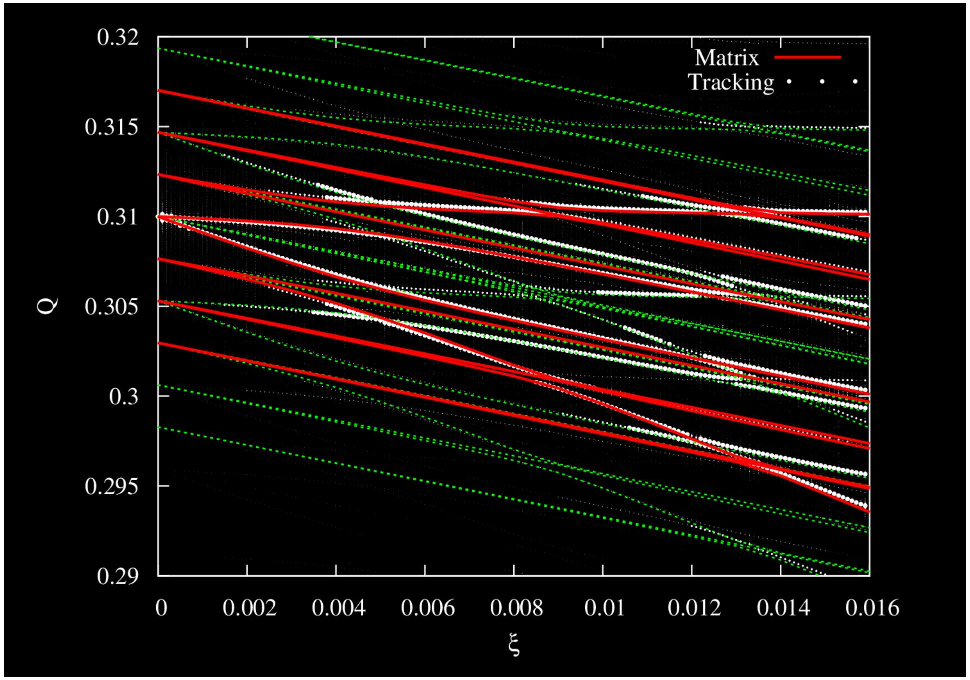
→ In these plots beam-beam only

→ For large ratio β^*/σ_s – non synchro-betatron coupling introduced by BB: side-bands deflected by the coherent tune shift + coherent modes at Q and Q-ξ (linear BB kick)

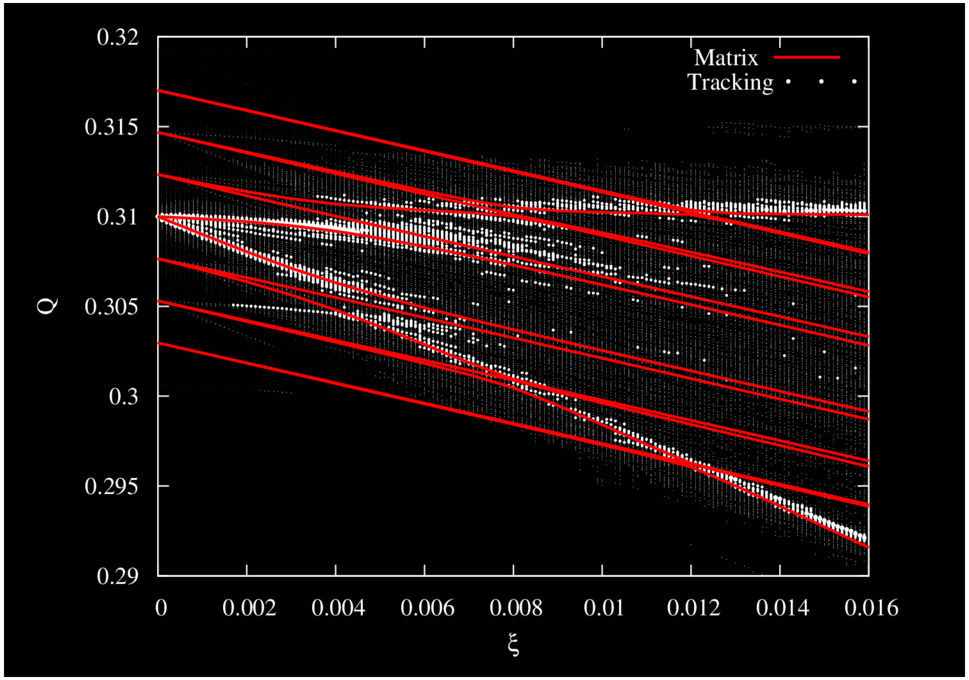
→ Small ratio β^*/σ_s – the beam-beam can deflect the side bands – more complex picture

Comparison with Tracking

Linear Kick + Hollow beam

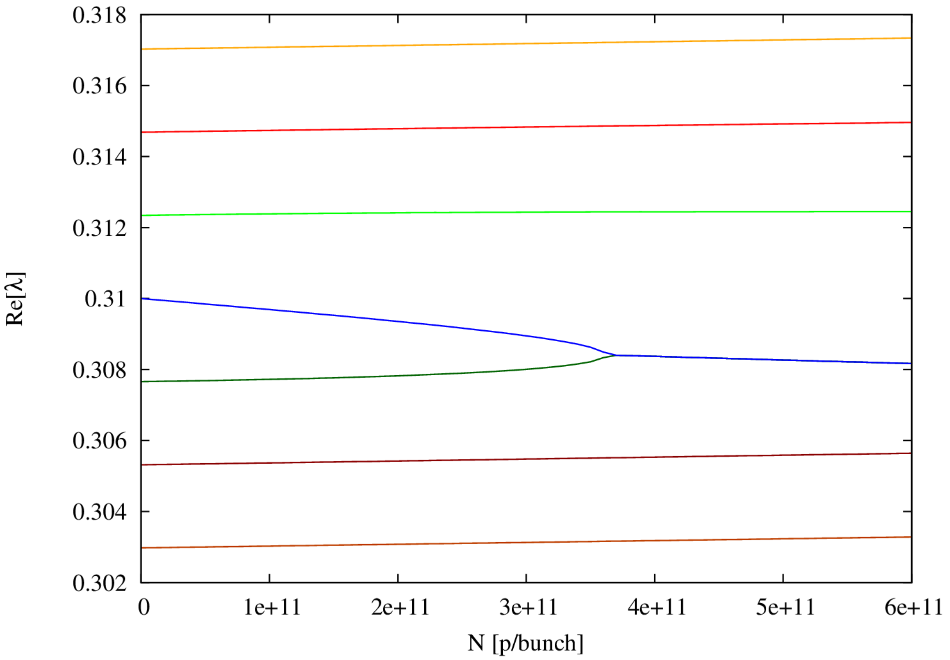


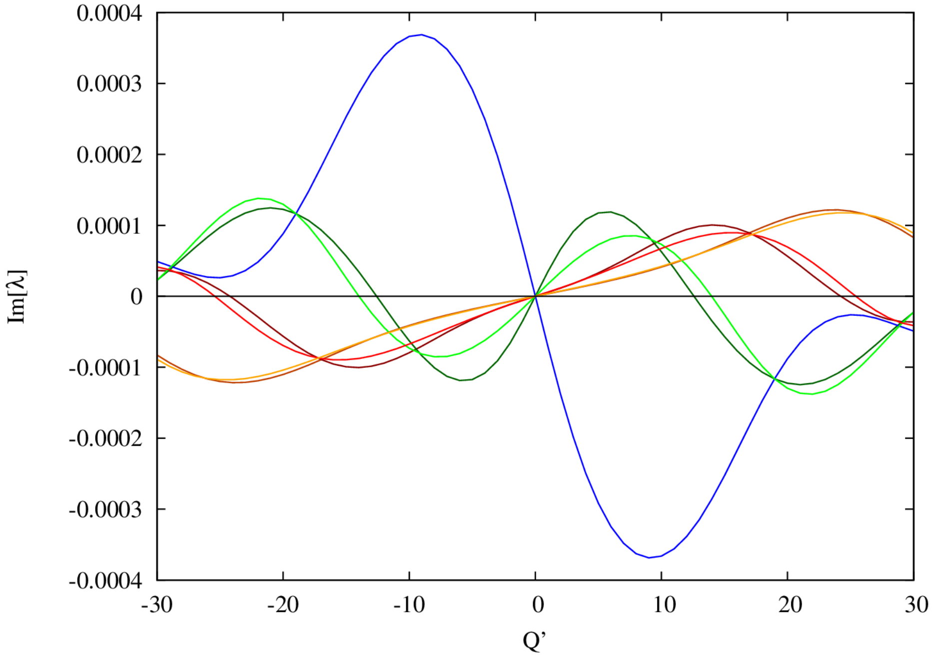
6D Gaussian Kick



→ Three models for the beam-beam kick possible: linear, Gaussian, Poisson solver
→ Hollow beam + linear kick direct comparison
→ Used a ratio of β^*/σ_s of 1 to enhance the coupling
→ Results qualitatively the same – reflection at +/-2Q_s (in green) seen in the tracking
→ 6D Gaussian case rescale by Yokoya factor (wrong!) / most of the modes damped
→ With beam-beam only : system always stable

Impedance



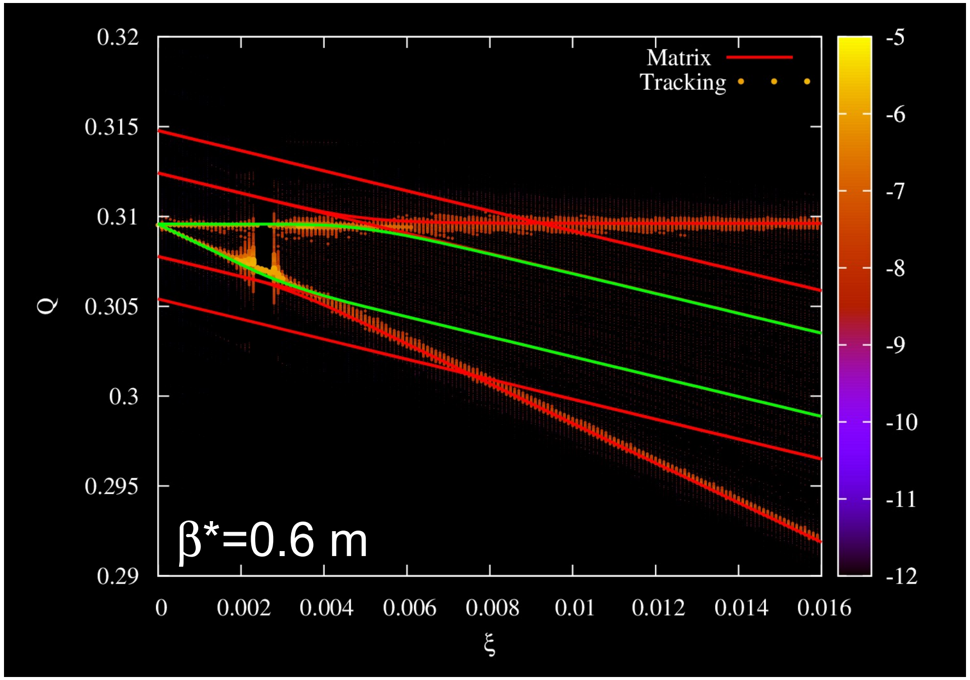


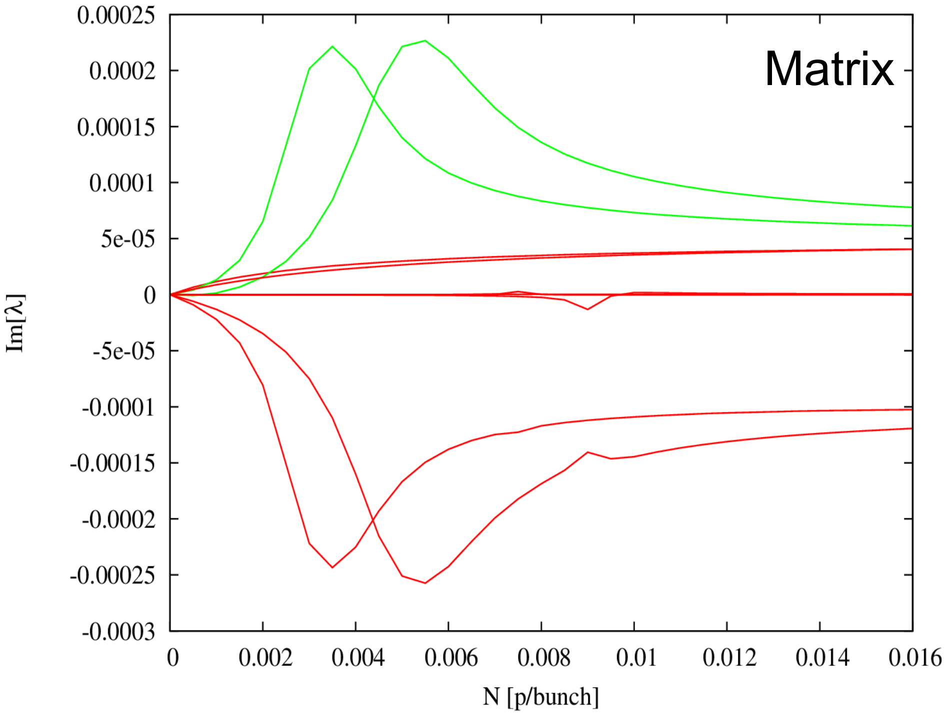
→ The wake used in the matrix model is constant (more complicated functions available but convergence is slower)

→ Tune the value of this constant to obtain about the same TMCI threshold

→ Modes stability as a function of Q' consistent with previous studies

BB + Impedance





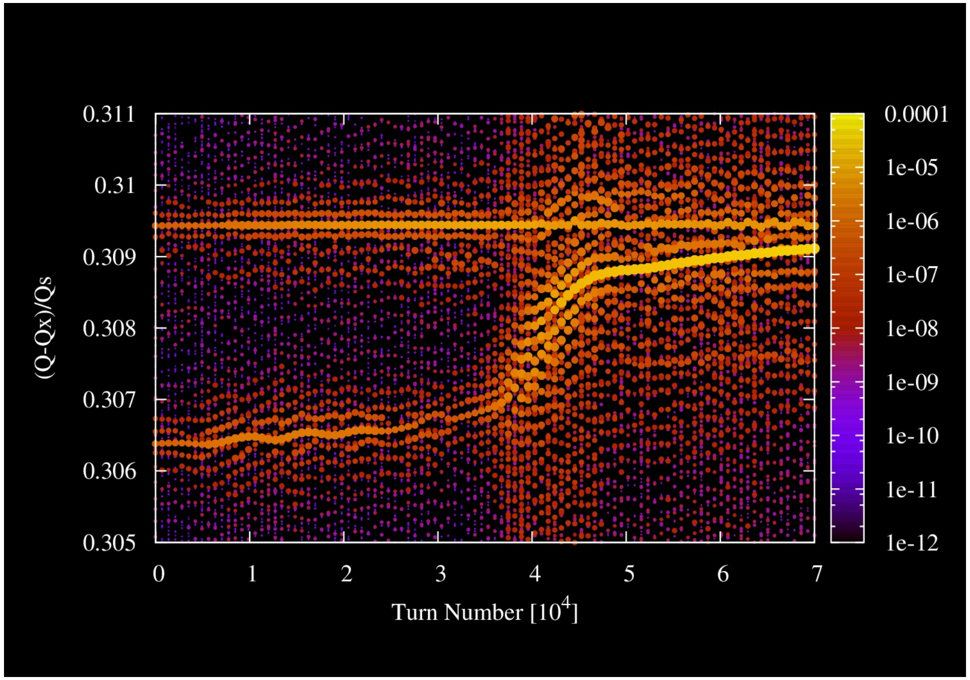
→ Matrix model: never stable – most unstable mode 0 shown in green

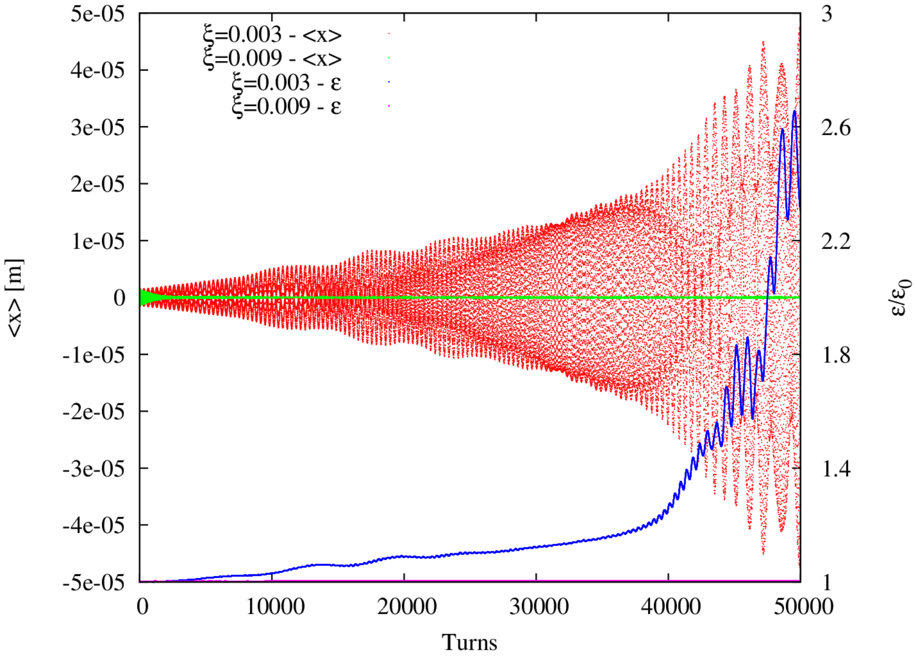
→ Multi-particle – mode 0 unstable up to a certain beam-beam parameter

→ Modes don't overlap for these parameters but instability becomes stronger as mode 0 approaches mode -1 – mode coupling?

→ ξ~0.003 seems to be the most critical → focus on this point for now

Instability





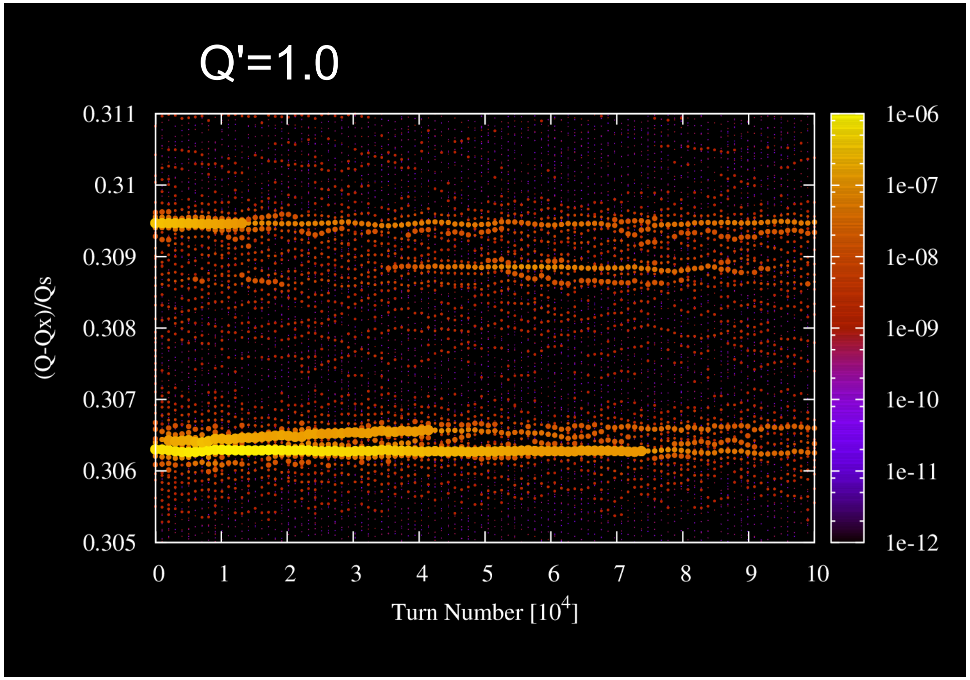
→ Look at two cases ξ=0.003 and ξ=0.009

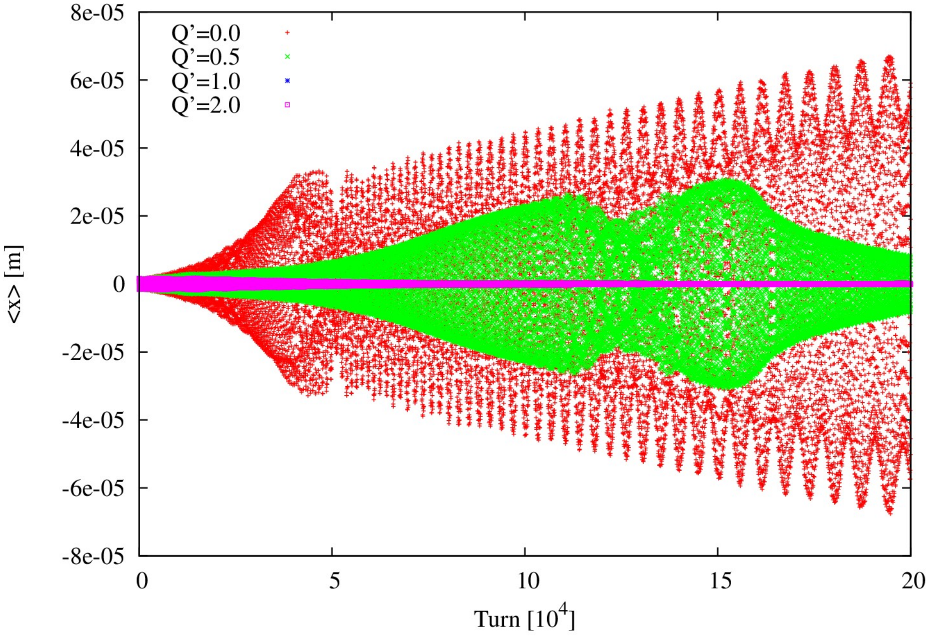
→ ξ=0.009 stable – no emittance blow up observed

→ ξ=0.003 unstable – strong emittance blow up leading to reduction of beam-beam parameter

→ Instability seen on both beams – both σ and π modes rising

Chromaticity



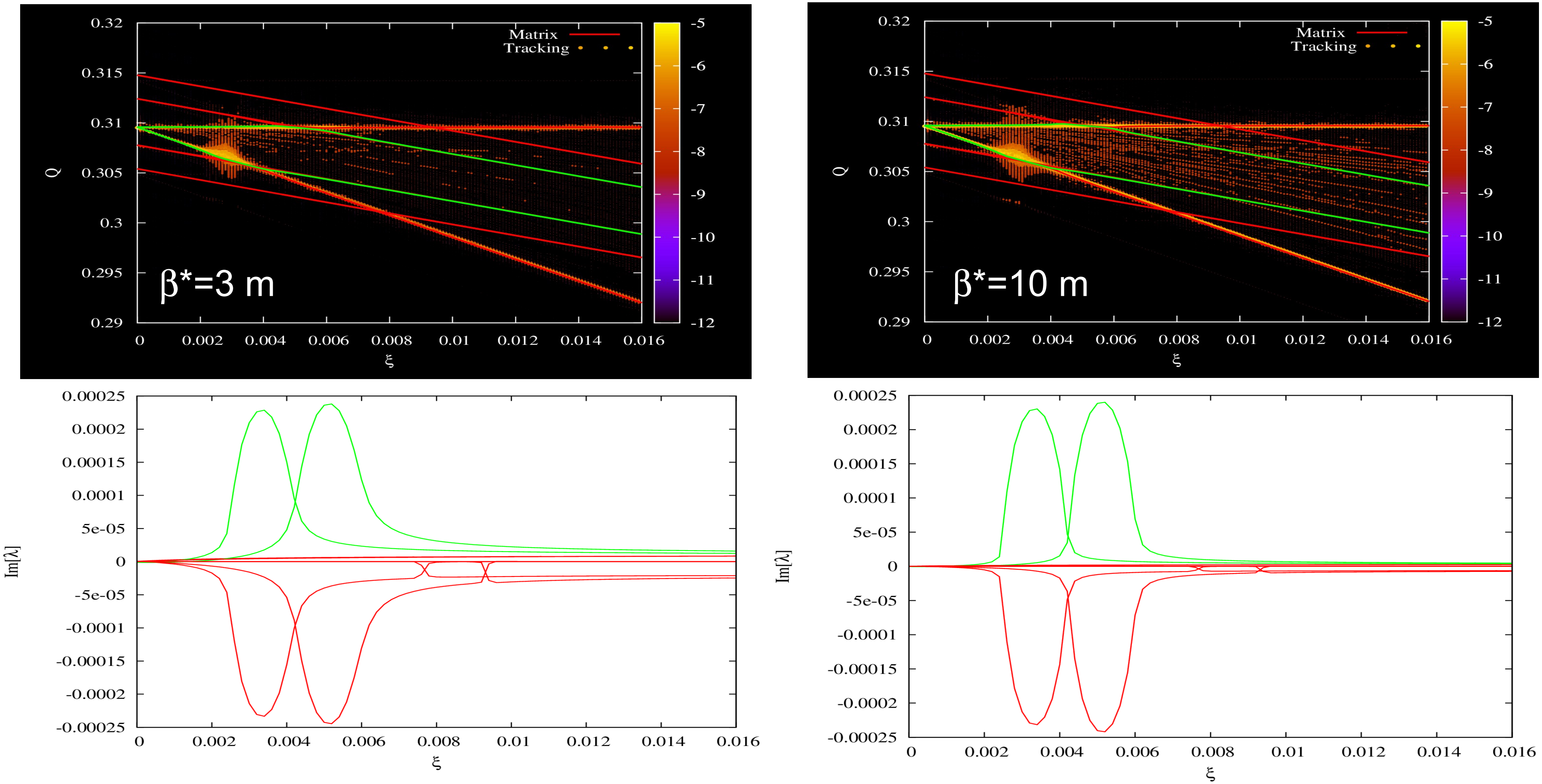


→ A small positive chromaticity stabilizes the mode 0, mode -1 becomes the most unstable (from impedance theory)

→ Landau damping provided by the beam-beam tune spread stabilizes mode -1

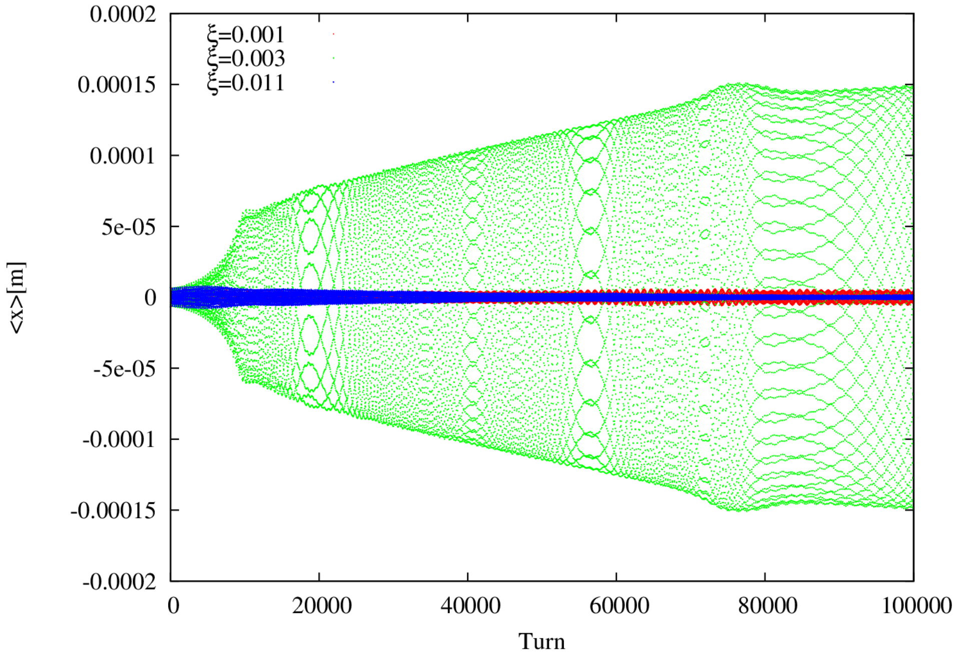
→ True for β*=0.6 m where modes 0 and -1 couple only weakly (both can be observed on the FFT spectrum for Q'=1.0)

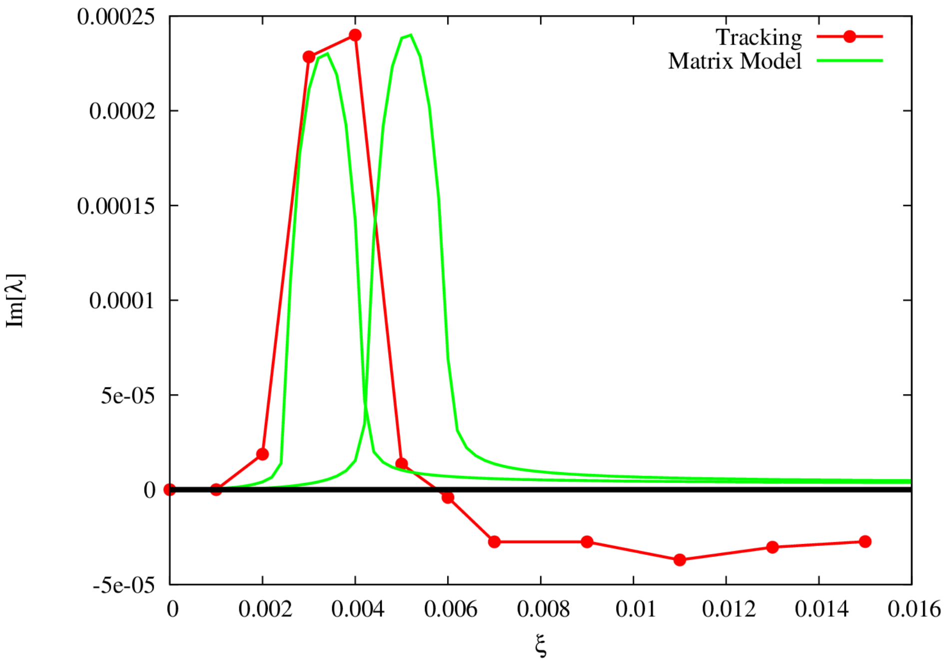
Effect of β*



→ For higher β* modes 0 and 1 overlap: probably results in stronger coupling

Intensity Scan



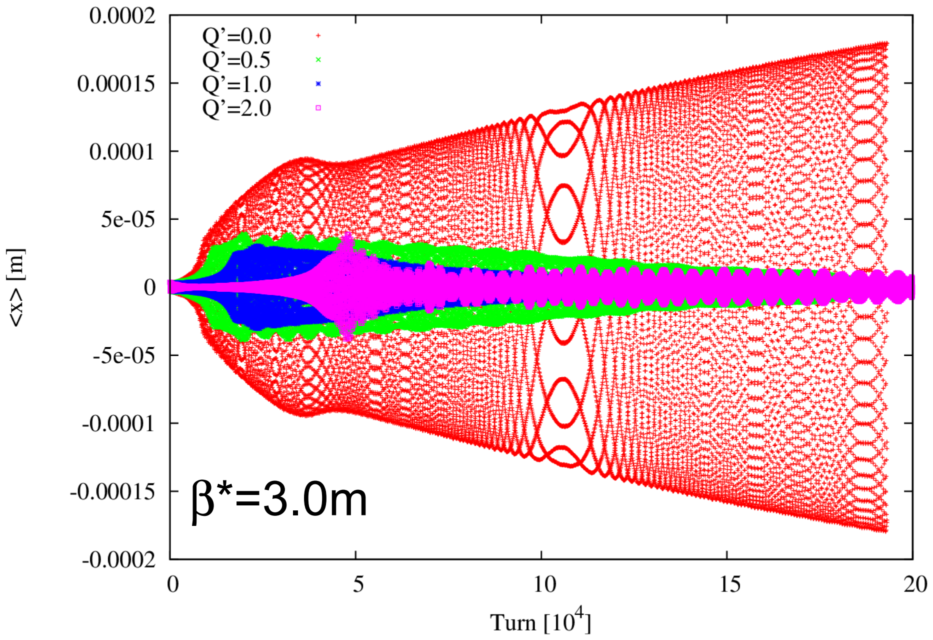


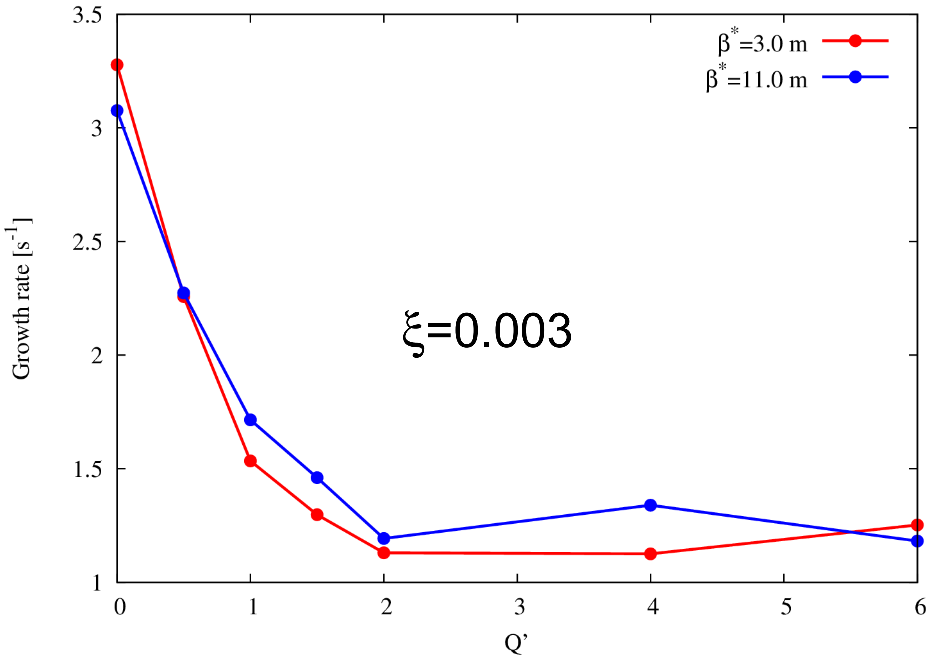
→ Intensity scan for β*=10m with Q'=0

→ Comparable growth rate as for matrix model – maximum is ~ 0.4s

→ Only the coupling with mode -1 is observed – related to TMCI?

Chromaticity



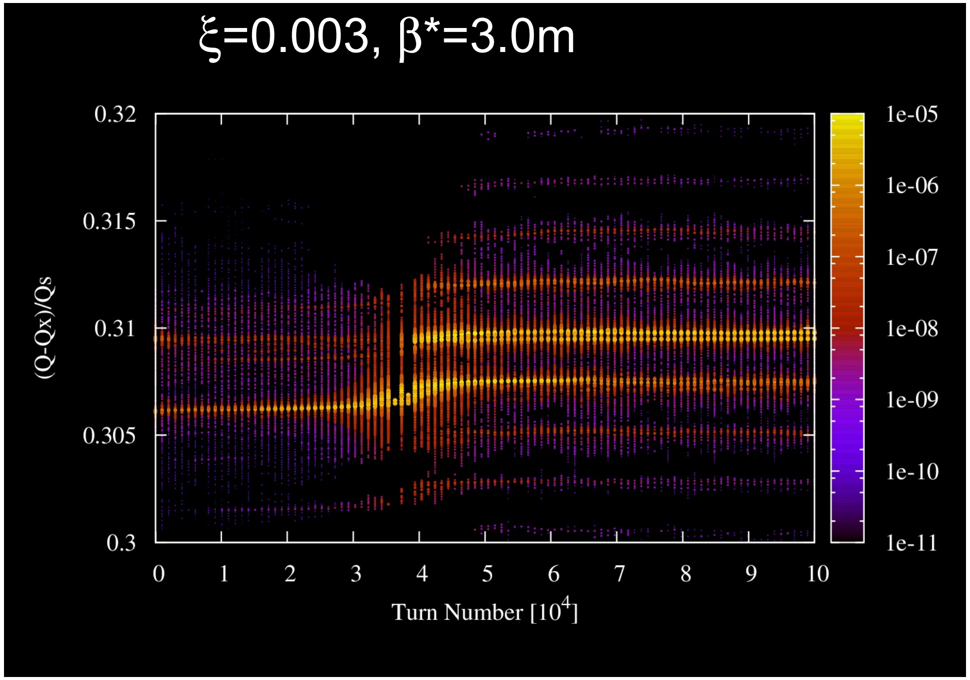


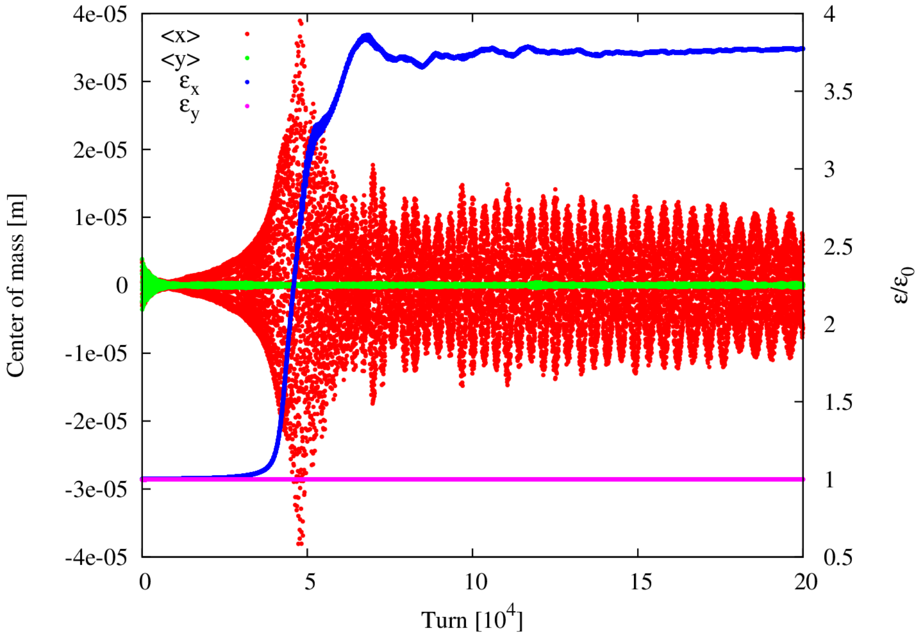
→ For large β* even at large chromaticity the beam is not stabilized

→ Even though is doesn't stabilize the beam large chromaticity helps

→ Need to probe Q'>6 – beam could eventually become stable

Q'=2.0



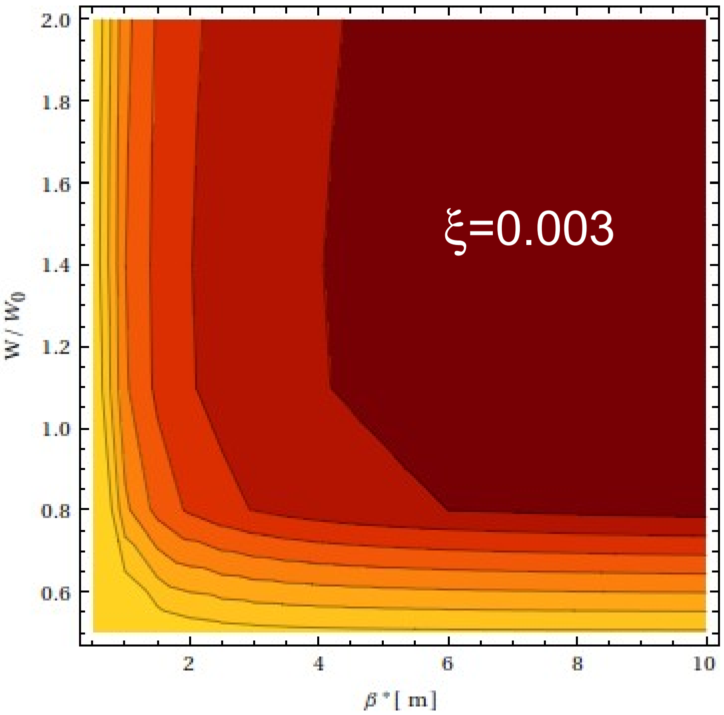


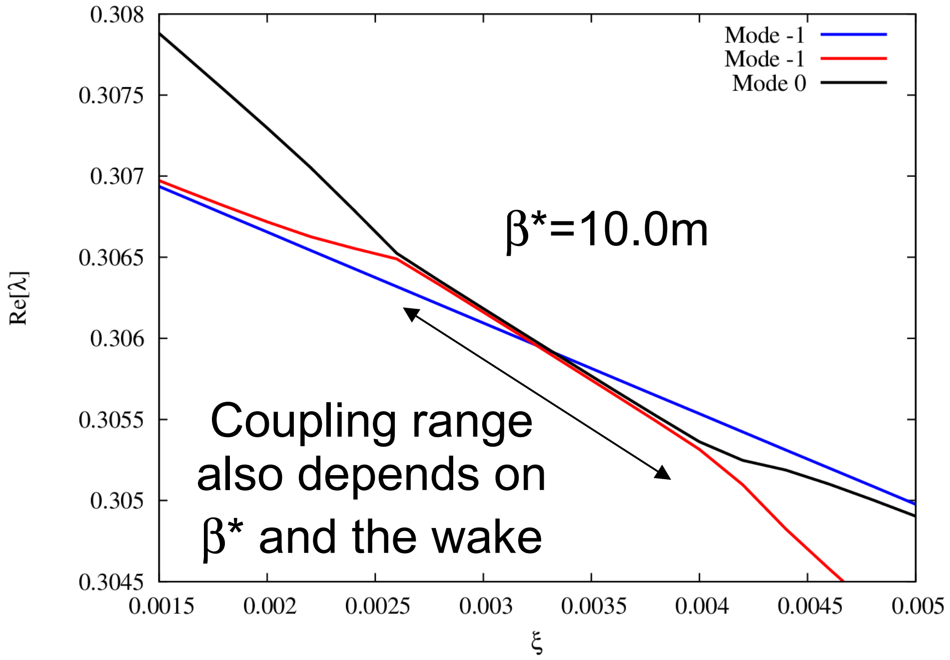
→ Instability rises only in the horizontal plane

→ Emittance blows up and instability rises until ξ becomes small enough to decouple the modes 0 and 1

→ Once the modes are decoupled we are back to a situation similar to the case of β*=0.6 m with positive chromaticity and beams are stable

Mode Coupling





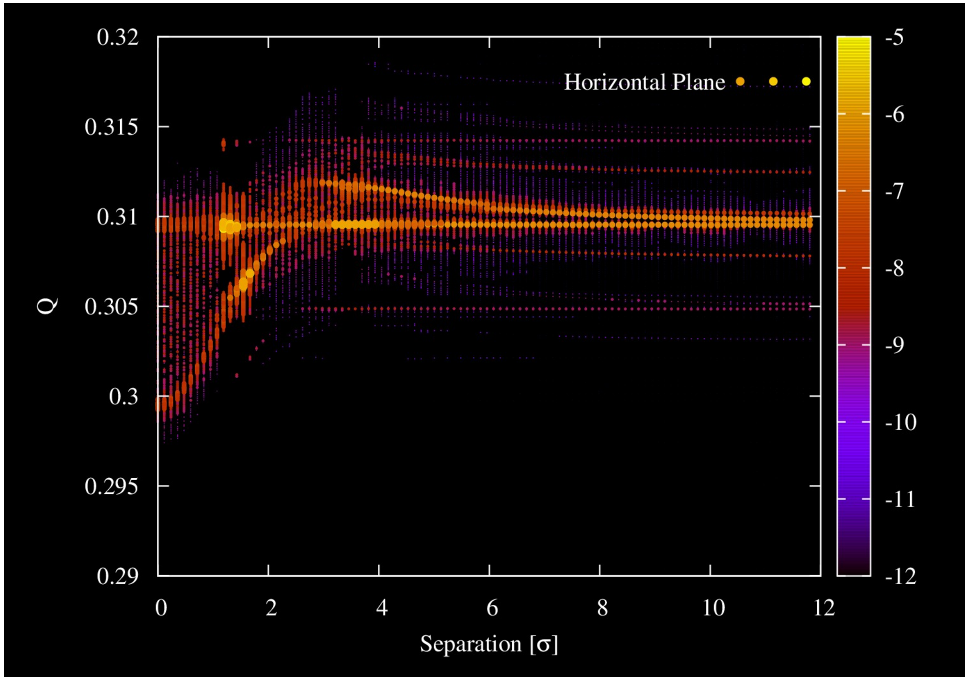
Coupling range also depends on β* and the wake

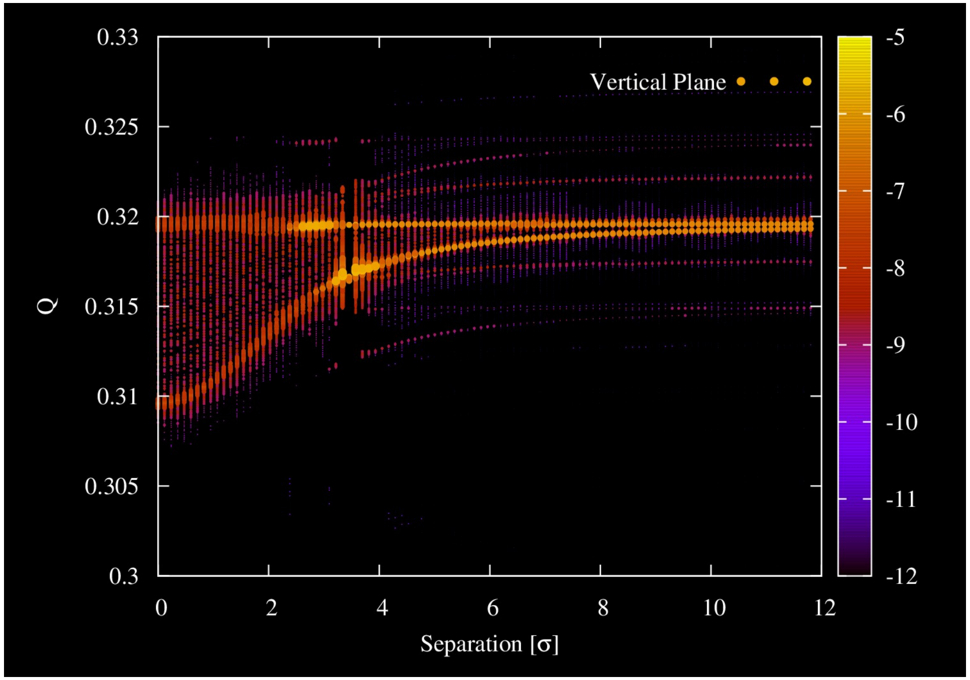
→ Look at the distance between modes 0 and -1

→ Depends both on the value of β* and the wake

→ When ξ is reduced or increased the modes can decouple as seen in simulations

Separated Beams



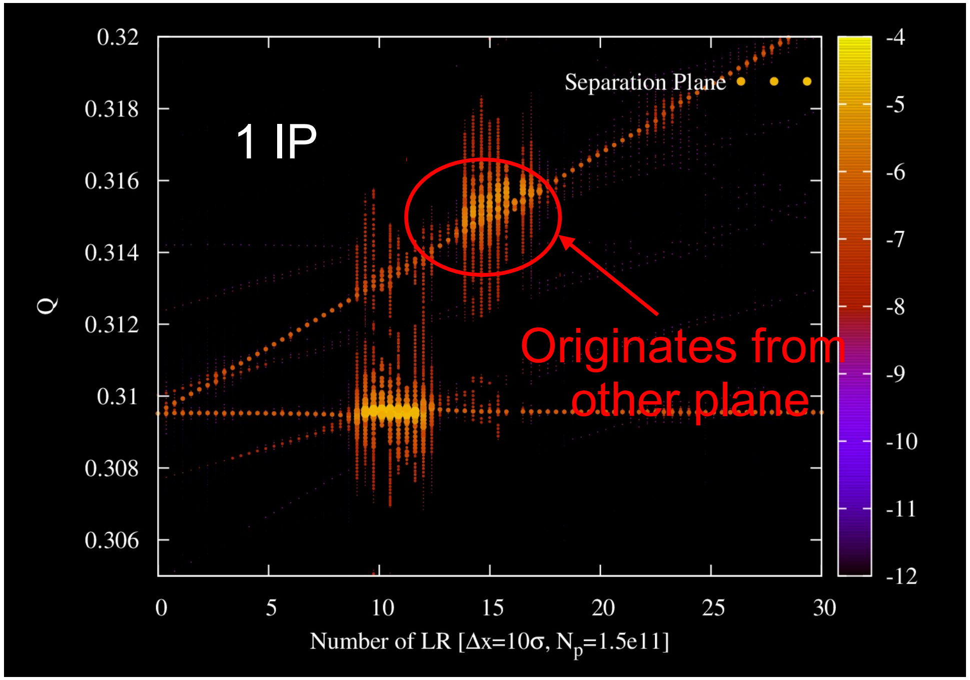


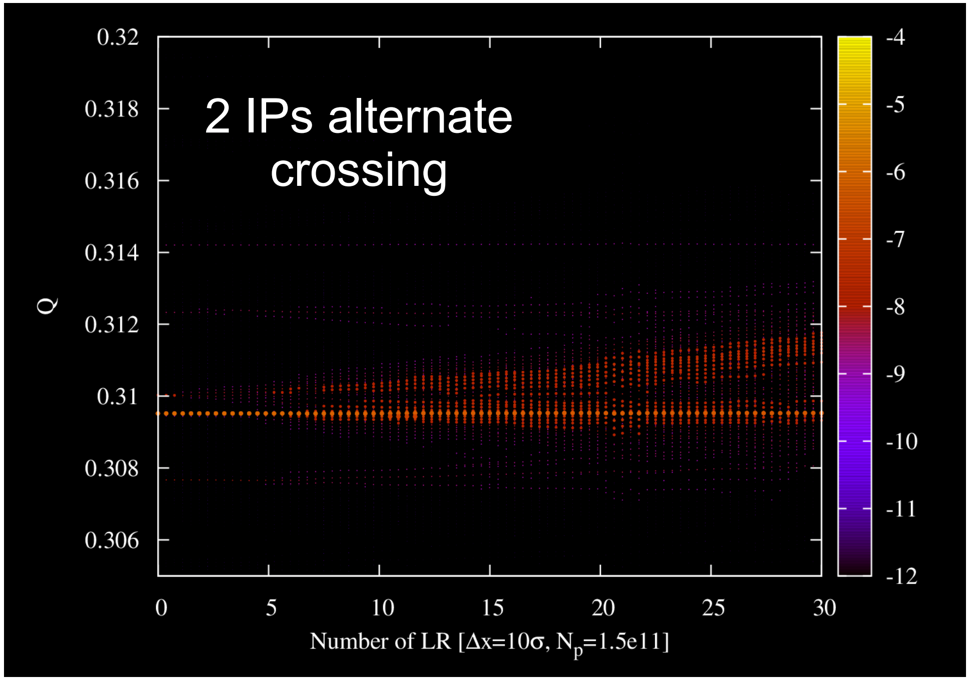
→ Single head-on interaction – apply separation in the horizontal plane

→ Same behavior is observed when the π or σ modes cross the +/-1 modes

→ To be noted that now the instability appears in different places depending on the plane

Long-range Interactions



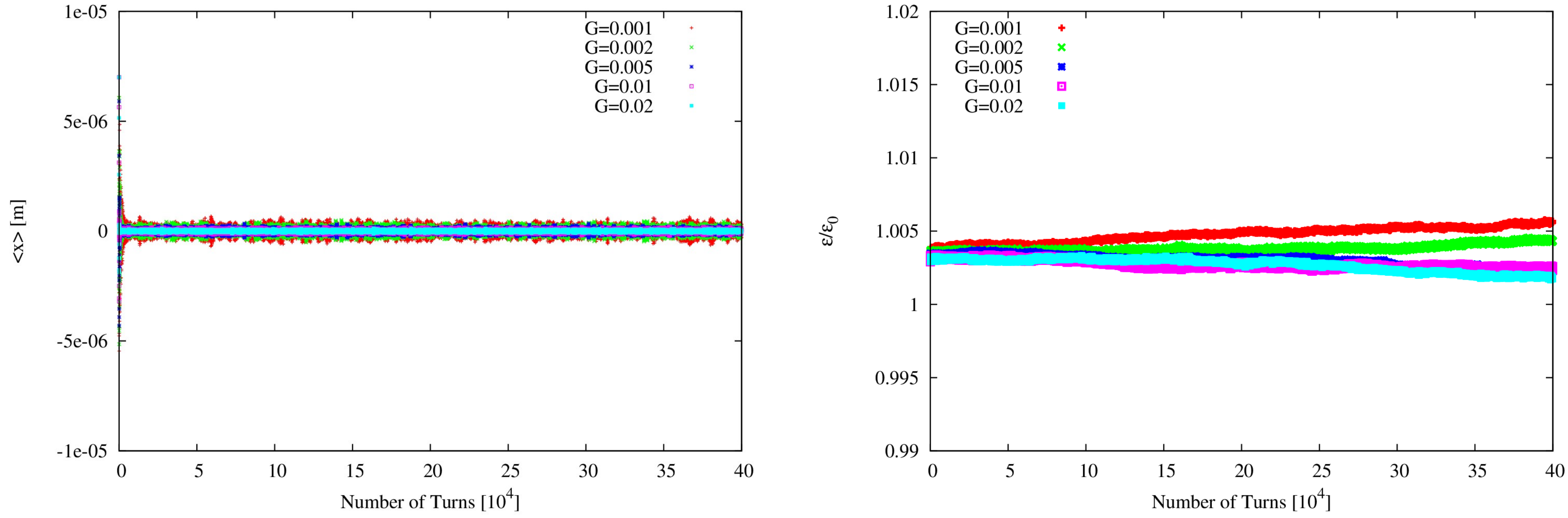


→ Very simplistic model: all LR are lumped in one interaction separated by 10σ. The BB kick is computed in 4D (round beams). The number of long-range is increased by scaling the intensity

→ Not representative of what is in the actual machine

→ However, LR modes can also couple +/1 headtail modes. The alternate crossing cancels the tune shifts of the two planes: always stable even for high number of LR

HO with Damper

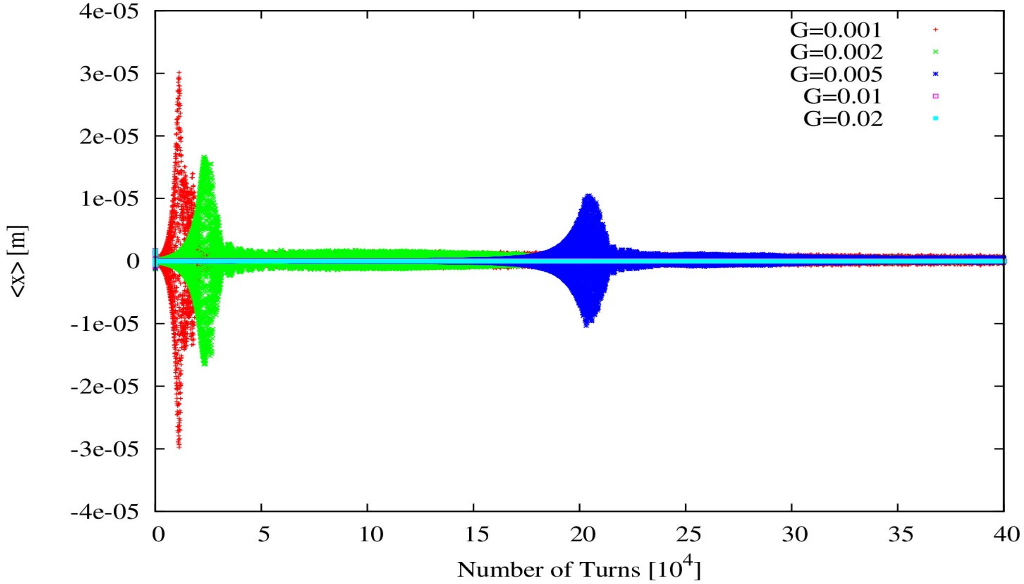


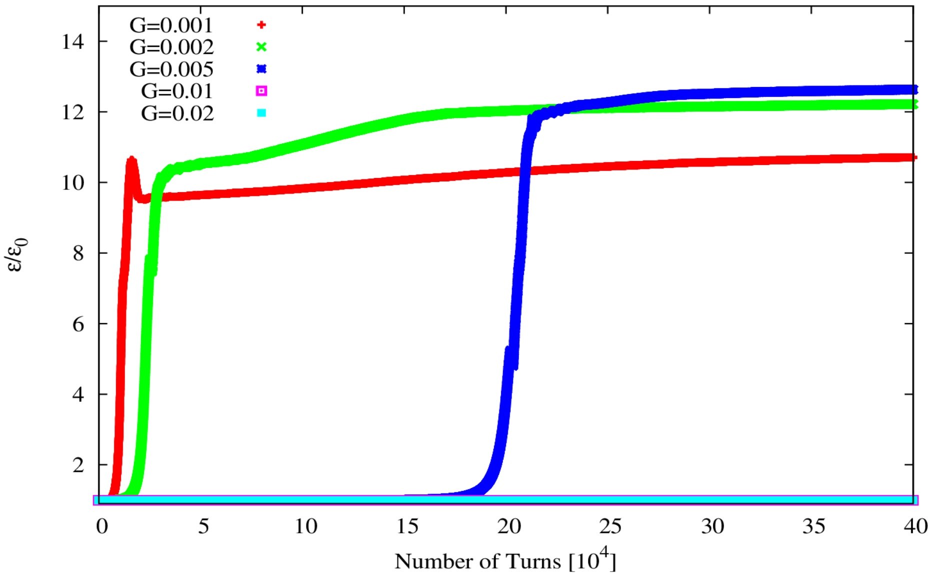
→ Look at instability around ξ~0.003 for worst case scenario of β^*=10m

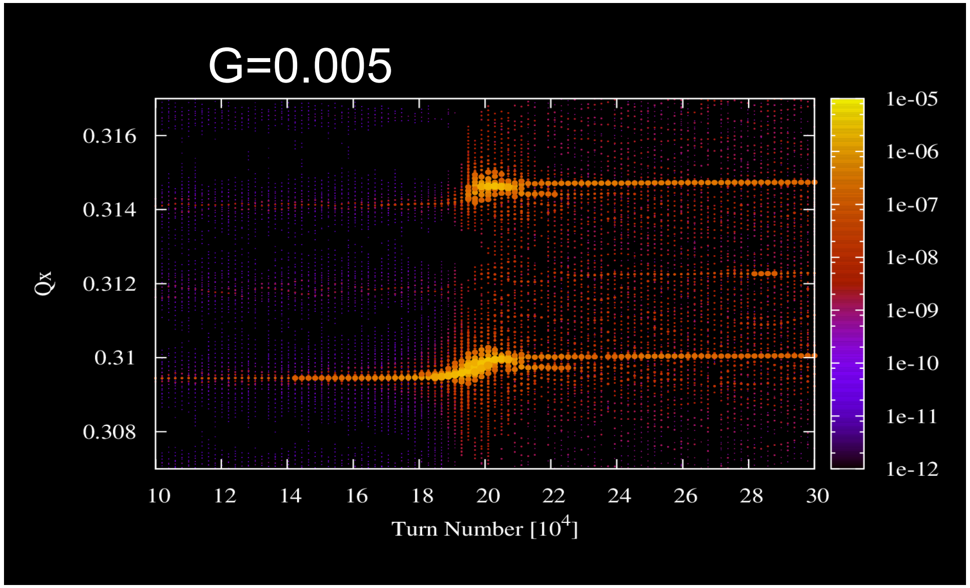
→ Even at very small gain (20 times less than nominal) the instability is damped

→ No significant emittance blow-up observed – a positive chromaticity of 2.0 did not affect the results

LR with Damper







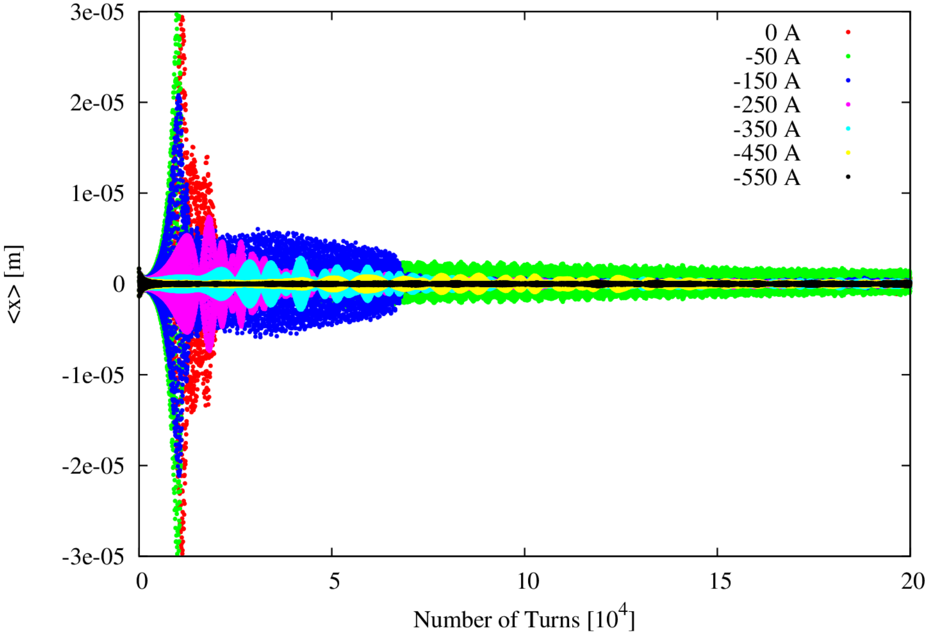
→ Look at the instability around 10 LR – coupling between modes σ and -1

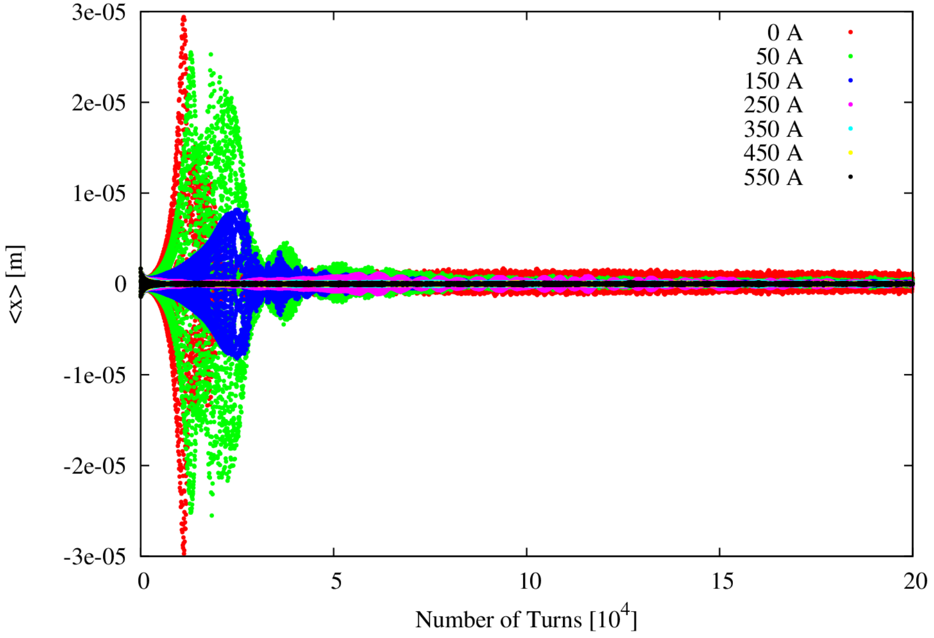
→ Instabilities observed up to G=0.005 (physics settings 50 turns = 1/G)

→ Rises time of the instability gets slower as the gain is increased

→ Strong emittance blow-up observed (no losses in the code) – seem to converge to about the same value for all gain settings.

Dependency on Octupoles Current





→ Octupoles can cure long-range instabilities (here 10LR – coupling between σ and -1)

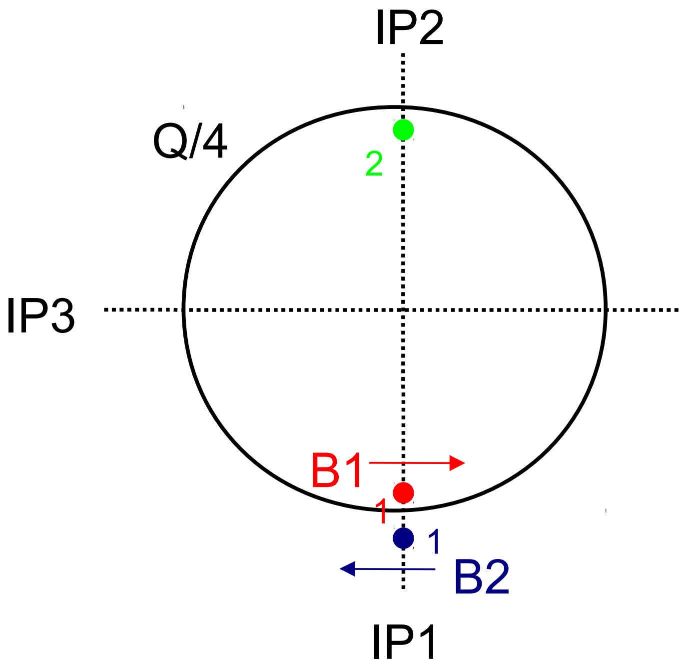
→ Negative polarity (old one): stable between 350 and 450 A

→ Positive polarity (new one): stable between 250 and 350 A

→ Heard recently that impedance could be underestimated by a factor 2 → threshold should be revised

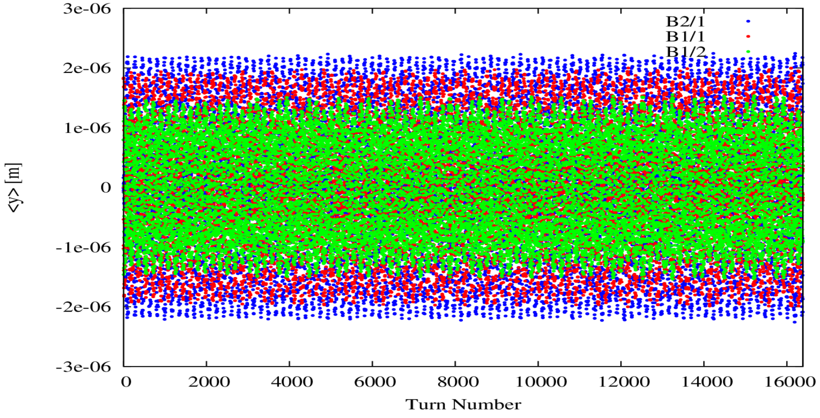
→ For HO case octupoles have no impact on stability

More Complex Collision Pattern

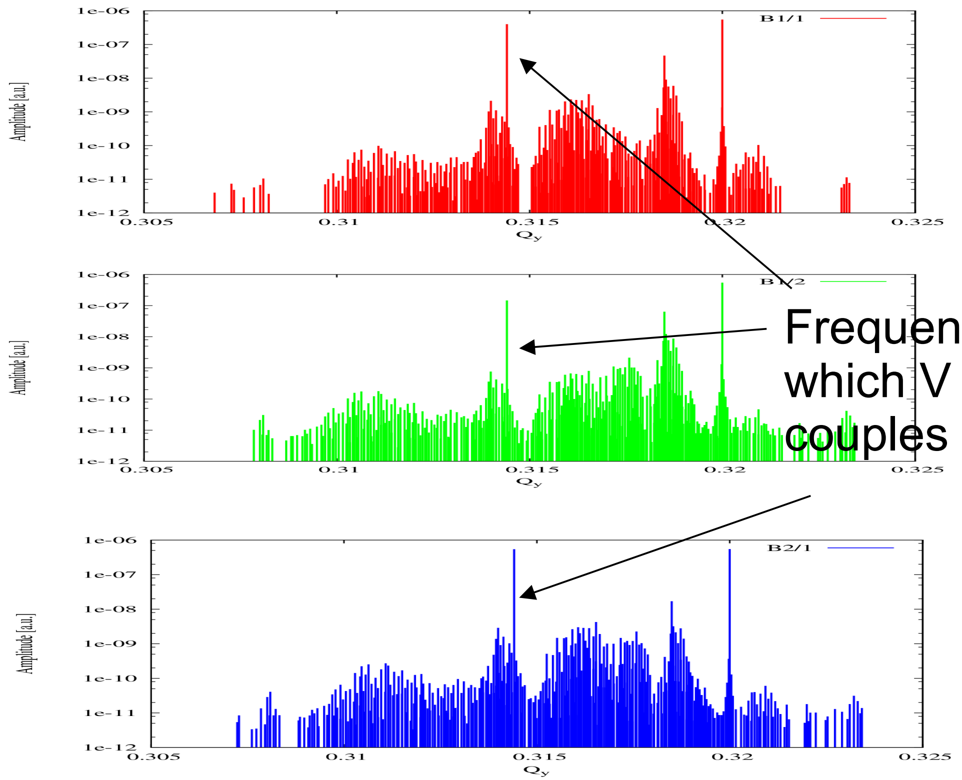


At all IPs equivalent of 7 LR with 10σ separation in H plane

	IP1	IP2	IP3	N_{LR} tot.
B1/1	1	1	0	14
B1/2	0	0	1	7
B1/1	1	1	1	21

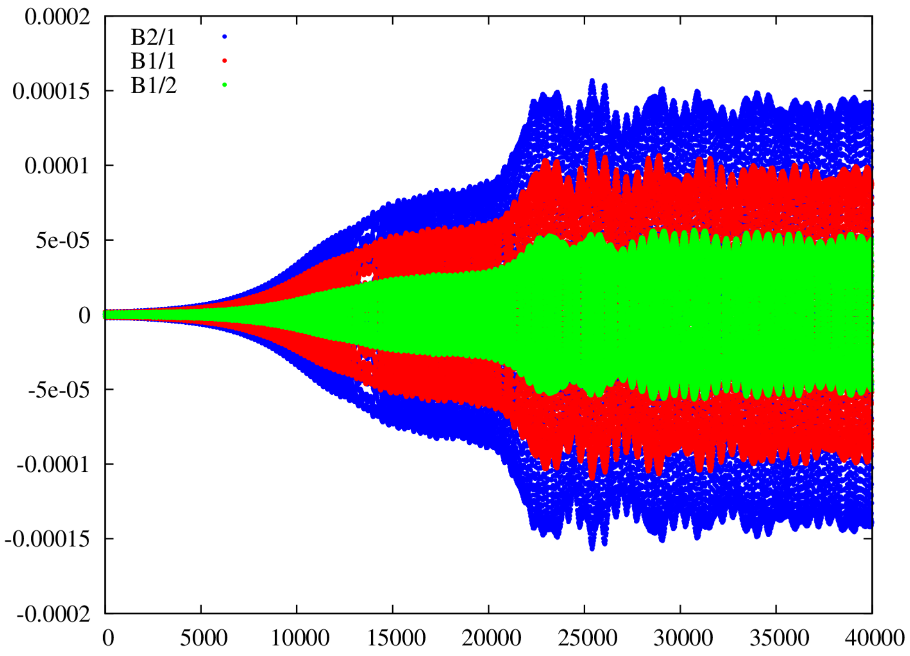


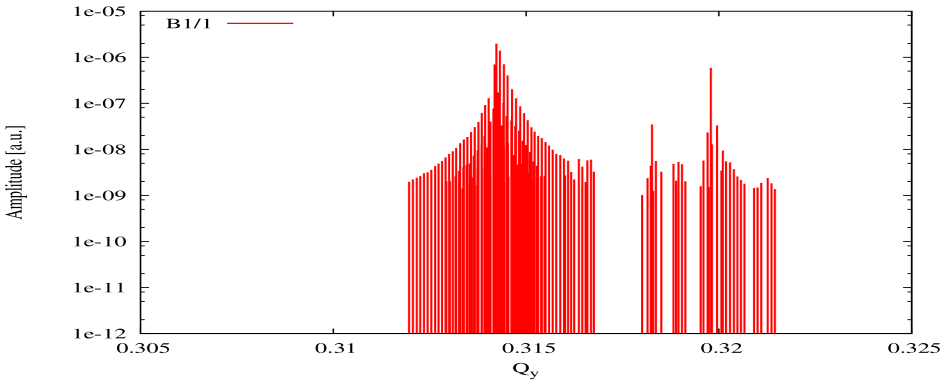
→ BB only all bunches stable

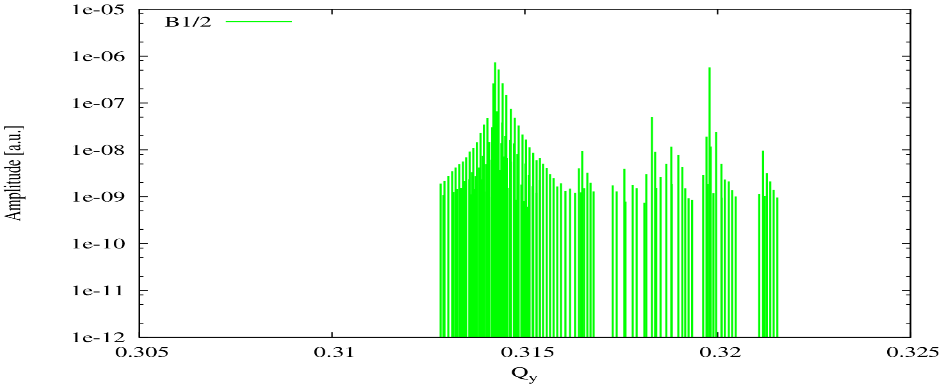


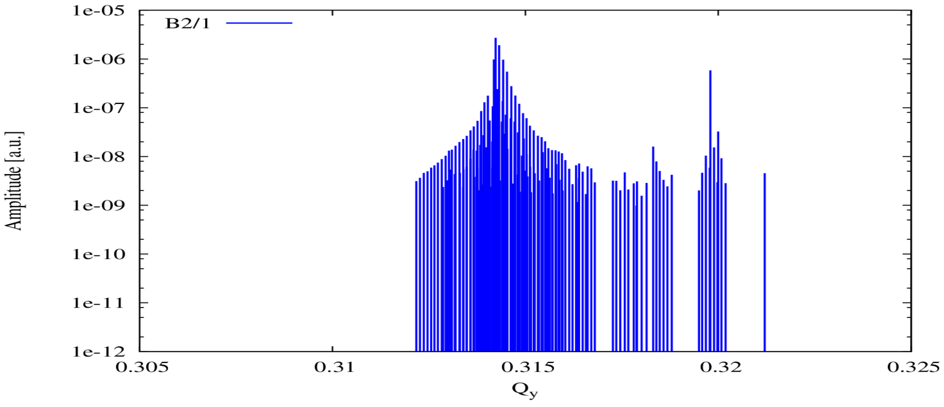
Frequency at which V π-mode couples with -1

Including Impedance







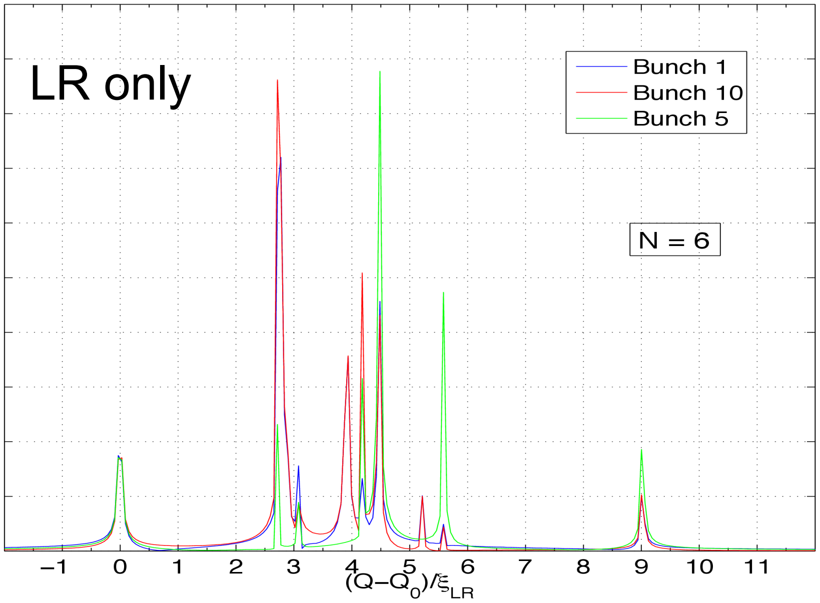


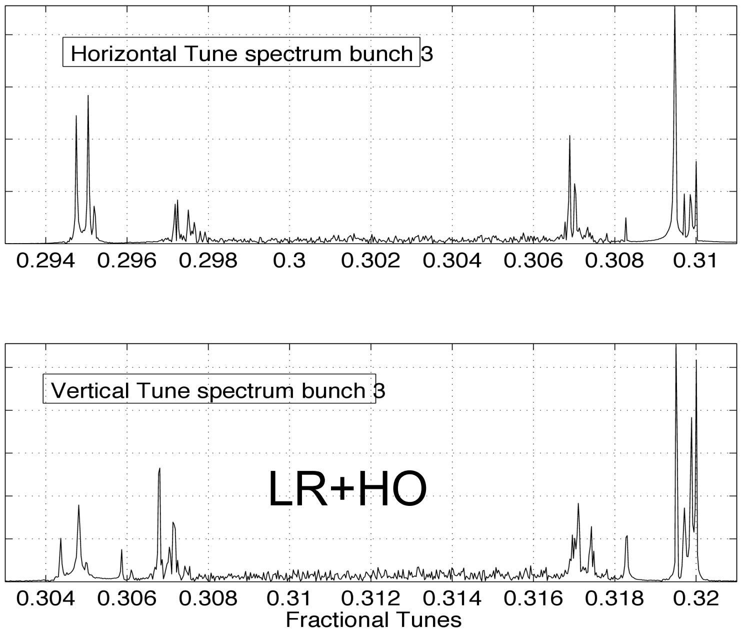
→ Same frequency driving all the bunches unstable

→ Amplitude is different for all bunches but oscillation pattern and rise-times (0.3s) are the same

→ This was only observed for LR – in the case of HO both beams rise with same speed and amplitude

Multiple LR + HO





→ Simulations done with COMBI – BB only (*courtesy of T. Pieloni*)

→ With many bunches multiple peaks appears – increased complexity

→ LR interactions can add up an build large tune shift

→ LR modes always observed even with strong HO

→ Understanding the complete picture may be difficult with single bunch approximation
Impedance in COMBI? Experiment?

Summary

- 2 models developed to study the combined effect of BB and impedance → good agreement
- Coherent modes in the presence of BB and impedance can couple with much lower threshold than TMCI and drive the beams unstable. Appears to be driven by mode -1 in all cases
- **HO (driven by core particles):** high chromaticity helps stabilizing – damper even with small gain can completely cure instability
- **LR (driven by tails particles):** damper much less efficient – still need to investigate chromaticity – octupoles can stabilize the beams (act mainly on the tails)

→ **Future steps:** crossing angle dependency, compare with Alexey's theoretical approach including BB

→ Experimental verification?