Transverse Stability and Instability Factors in Hadron Colliders

Alexey Burov

Fermilab

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Wakes / Impedances

Linear response on beam perturbations is described by means of wakes (time domain) and impedances (frequency domain)

It is important to distinguish intra-bunch, or single-bunch (SB) and inter-bunch, or coupled–bunch (CB), wakes.

CB wakes: flat (low frequency) or head-tail (high frequency)

Sources of wakes:

- resistive wall, dielectric walls
- longitudinal inhomogeneity
- HOMs
- beam-beam
- e-cloud, ions (for pbar beams)
- e-lens
- feedbacks

Dampers (Feedbacks)

The most important parameter is the bandwidth.

Dampers can be categorized into 3 groups:

low-frequency,

bunch-by-bunch (BBB)

head-tail, or broad-band.

Landau damping (LD)

LD is the beam immune system against the instability:

A transfer of the collective energy into incoherent one.

This requires resonant particles, i.e. the coherent frequencies to be located inside the incoherent band. Sufficient non-linearity is necessary.

Landau elements:

- external multipoles,
- beam–beam,
- potential well, Q''
- RFQ,
- e-cloud,
- e-lens

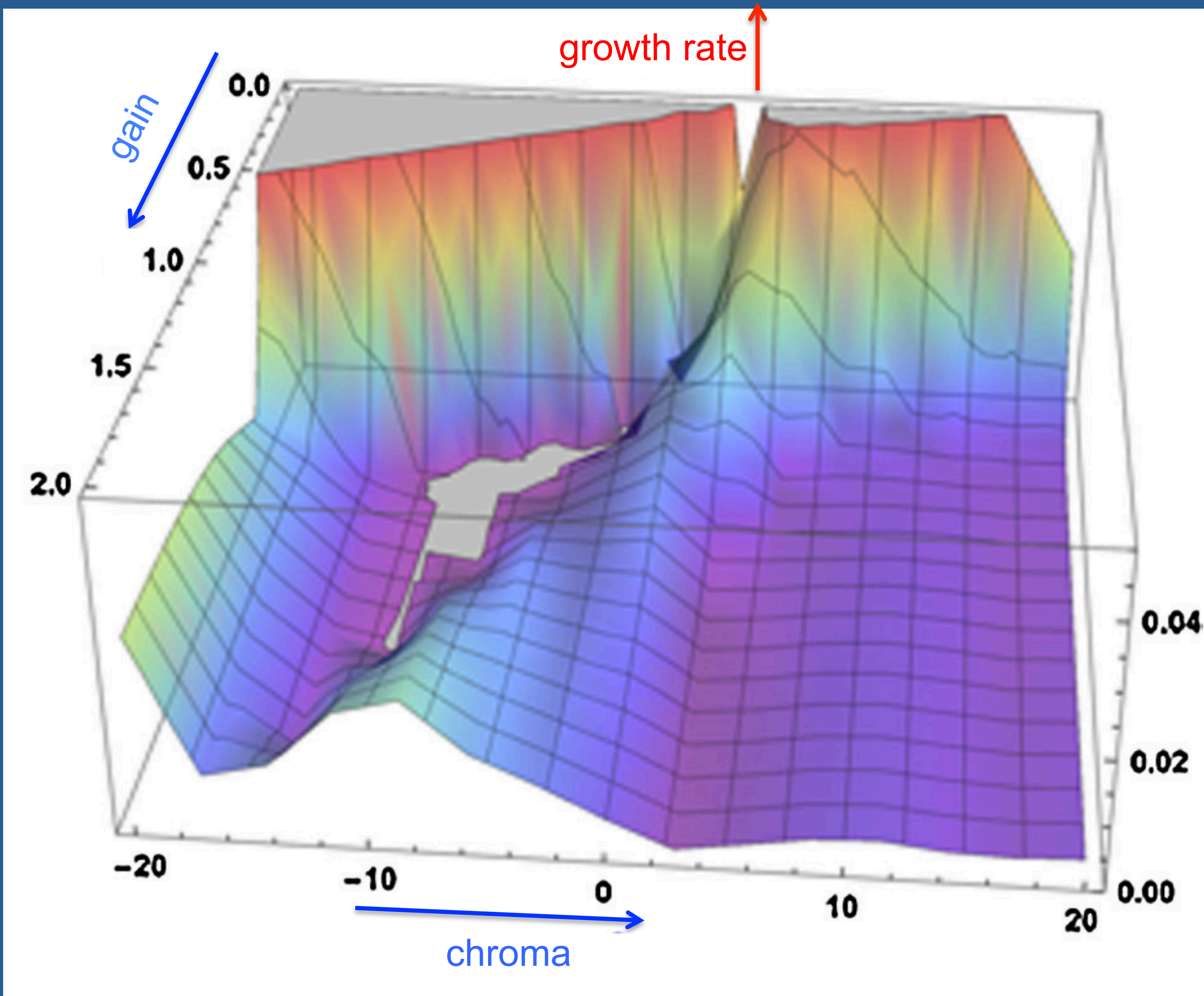
When the analysis fails

To make the beam stable, the stability factors have to win.

To understand the game, the players must be seen together, in their interaction and complementarity.

A move of the player cannot be understood on a basis of analytical one-by-one approach.

LHC, 25ns, ImpF=1.5. Lake evaporates at ImpF=1.7



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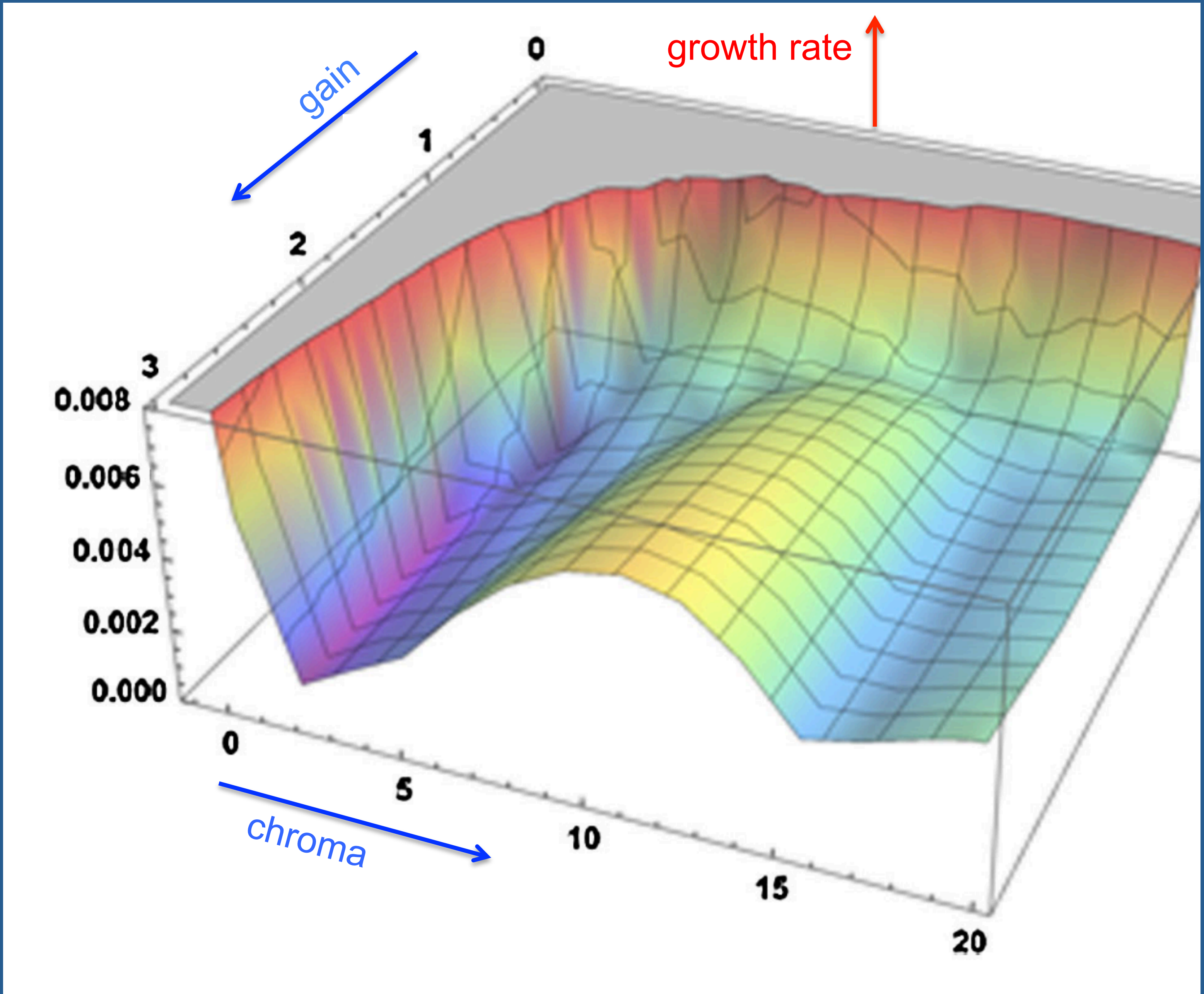
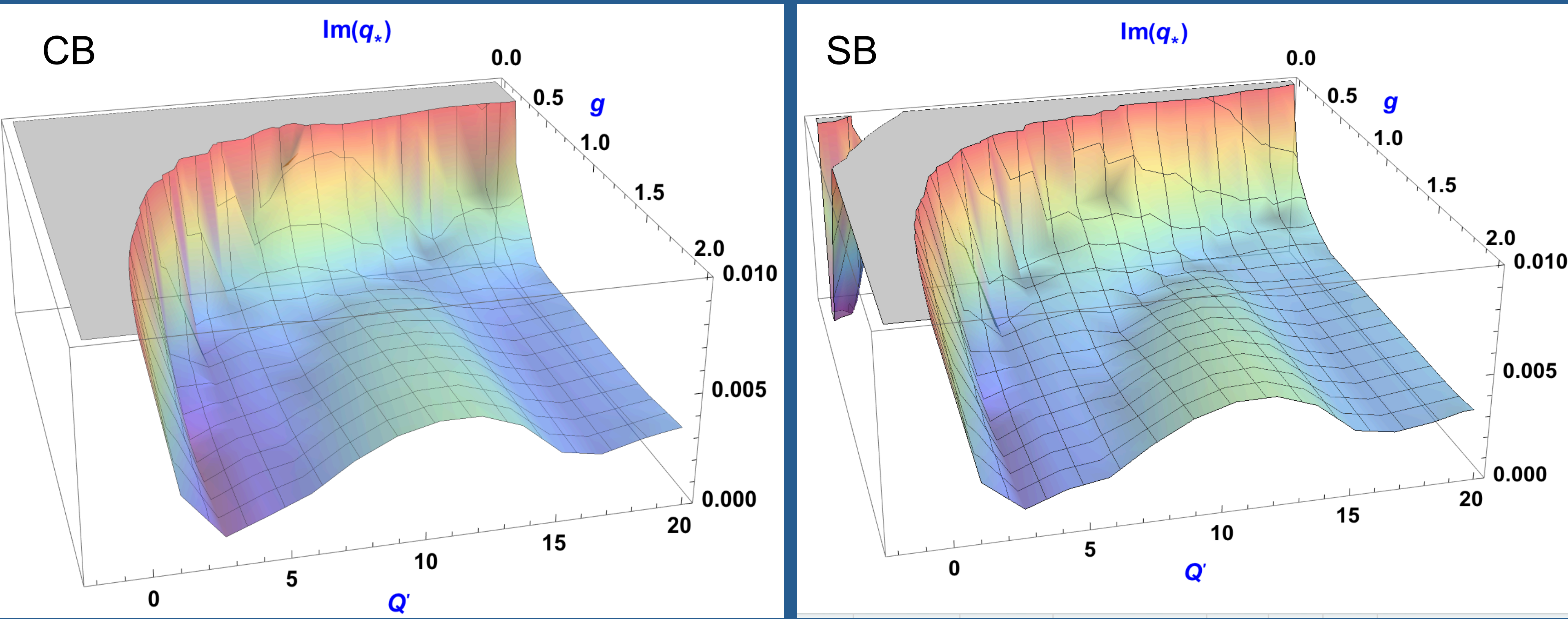
LHC, 25ns, ImpF=2.4. No lakes.



CB Flat wake and BBB damper

Flat CB wake, as well as LR beam-beam impedance, is fully removed from the scene by BBB dampers:



LHC growth rates vs gain and chroma for 25ns beam, 7TeV, Nb=2.2E11, Qs=0.002, omega_s=140 s^{-1}; ImpFact=2

BBB dampers only partly help with SB wakes

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CB HT Wake

$$\Omega^{(l)} - \omega_\beta - l\omega_s = -i\frac{Nr_0 c}{2\gamma T_0^2\omega_\beta}\sum_{p=-\infty}^{\infty} Z_1^\perp(\omega')J_l^2\left(\frac{\omega'\hat{z}}{c} - \chi\right). \quad (6.188)$$

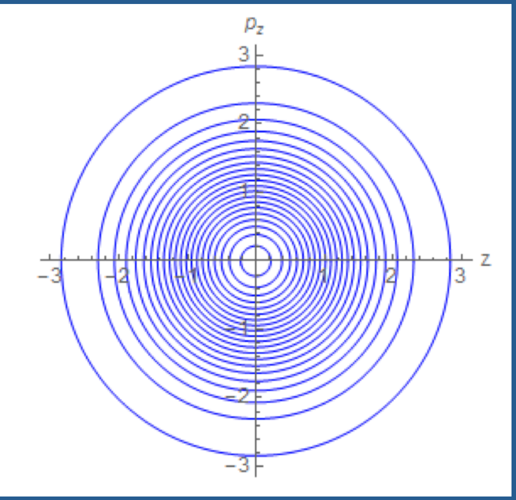
$$Z_m^\perp = \frac{c}{\omega}\frac{R_S}{1 + iQ\left(\frac{\omega_R}{\omega} - \frac{\omega}{\omega_R}\right)}$$

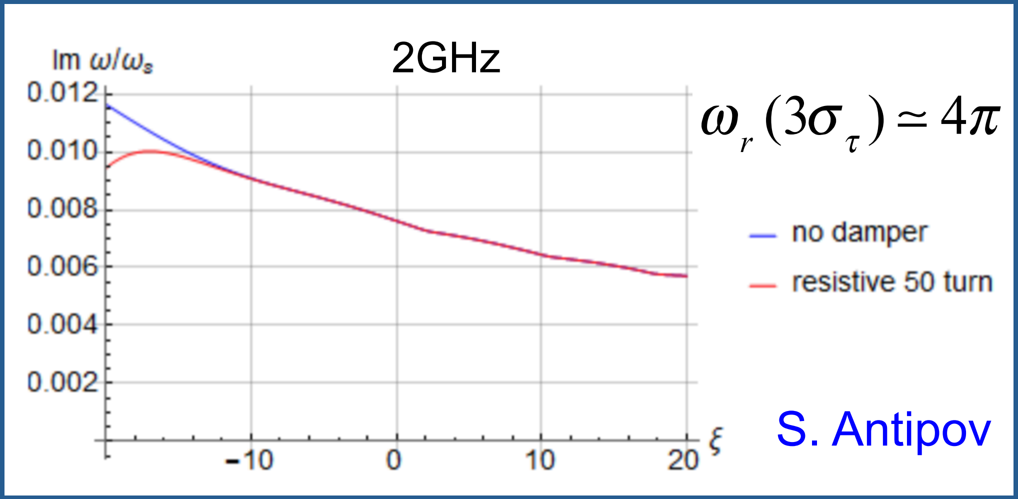
From A. Chao

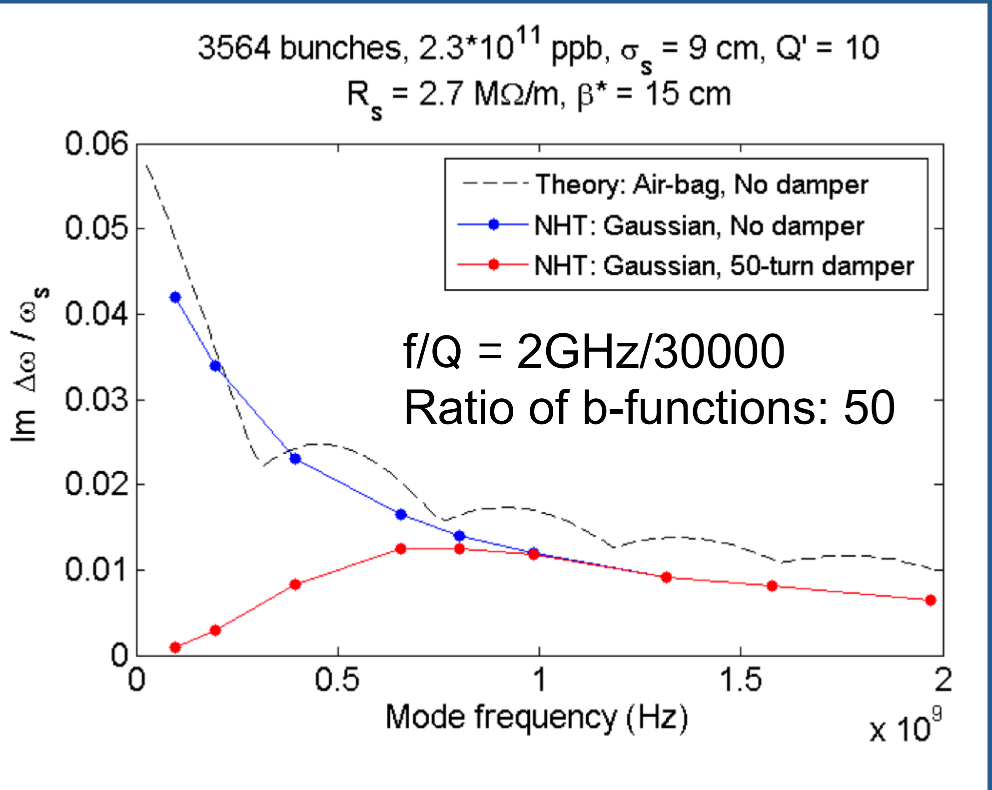
$$\operatorname{Im}\Omega^{(l)} = \frac{N_{tot} r_p c R_s}{T_0 \gamma Q_x \omega_r Z_0} J_l^2(\omega_r \hat{\tau} + \chi)$$

For high-frequency modes, the air-bag approximation is not sufficient.

CB HT Wake (CC for Hi Lumi)







BBB dampers are almost useless against CB high-freq wakes.

Chroma also does not help much.

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Landau elements (LE): octupoles, RFQs, Q”

Octupoles as LE are ineffective and unreliable:

their nonlinearity is small where it is needed and large where it is not.

their effect is unreliable, since it depends on the far tails of the beam.

Q” requires (too?) serious optical modifications,

RFQ promises a better solution,

But maybe the best one is e-lens.

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Stability Diagram, weak head-tail, No SC

Stability diagram (SD) is defined as a map of real axes ν on the complex plane Δq :

$$\Delta q = \left(-\int \frac{J_x \partial F / \partial J_x}{\nu - \delta\nu_x + io} d\Gamma \right)^{-1}$$

$$d\Gamma = dJ_x dJ_y$$

$$\delta\nu_x(\kappa_x, \kappa_y) = 2\delta\nu_{\max} \int_0^{1/2} \frac{I_0(\kappa_x u) - I_1(\kappa_x u)}{\exp(\kappa_x u + \kappa_y u)} I_0(\kappa_y u)\, du;$$

$$\kappa_{x,y} = \frac{a_{x,y}^2}{2\sigma_e^2}; \quad \delta\nu_{\max} = \frac{I_e}{I_A} \frac{m_e}{m_p} \frac{\sigma_x^2}{\sigma_e^2} \frac{L_e}{4\pi\varepsilon_n} \frac{1+\beta_e}{\beta_e},$$

To be stable, the coherent tune shift has to be below the SD.

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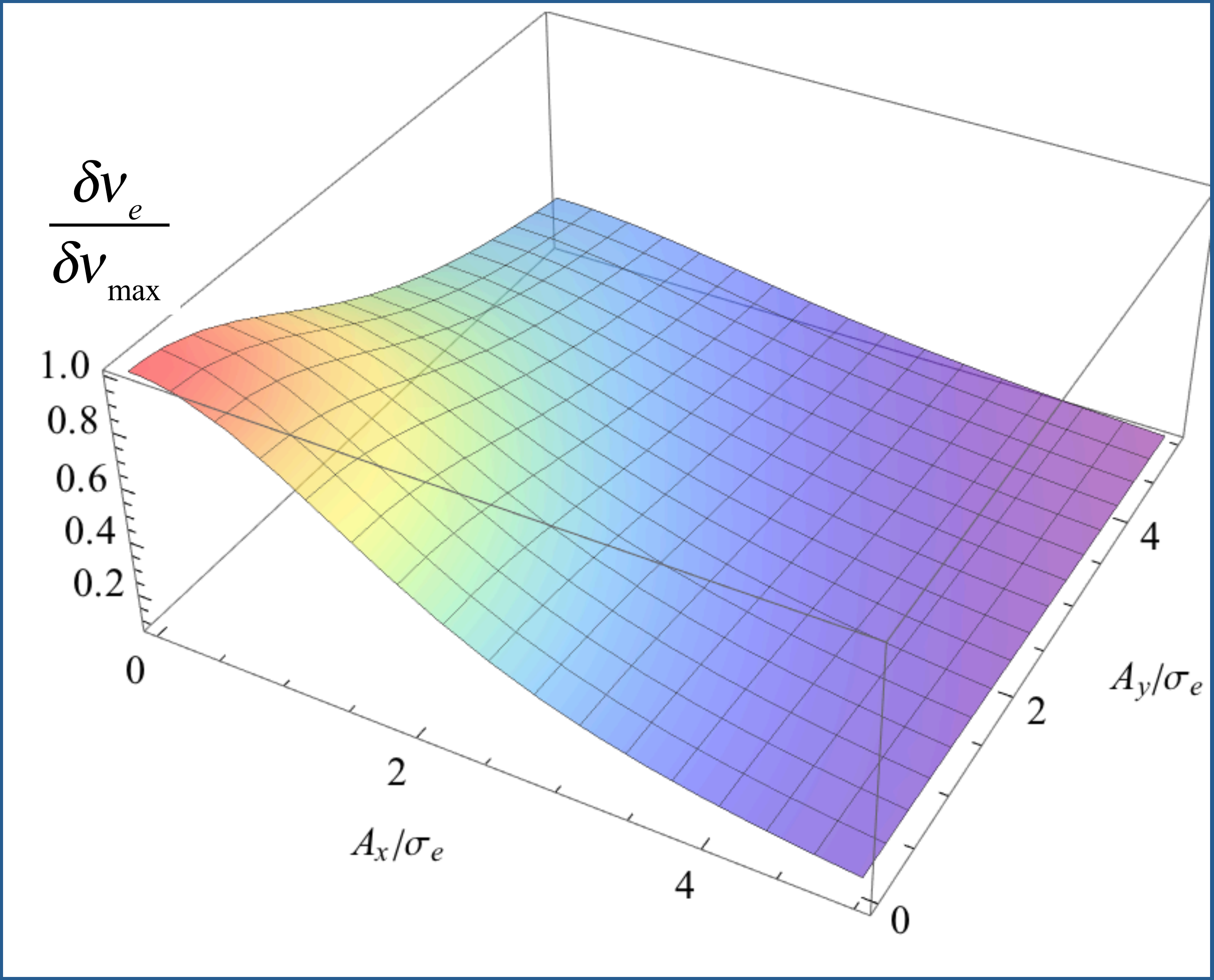
E-Lens Tune Shift



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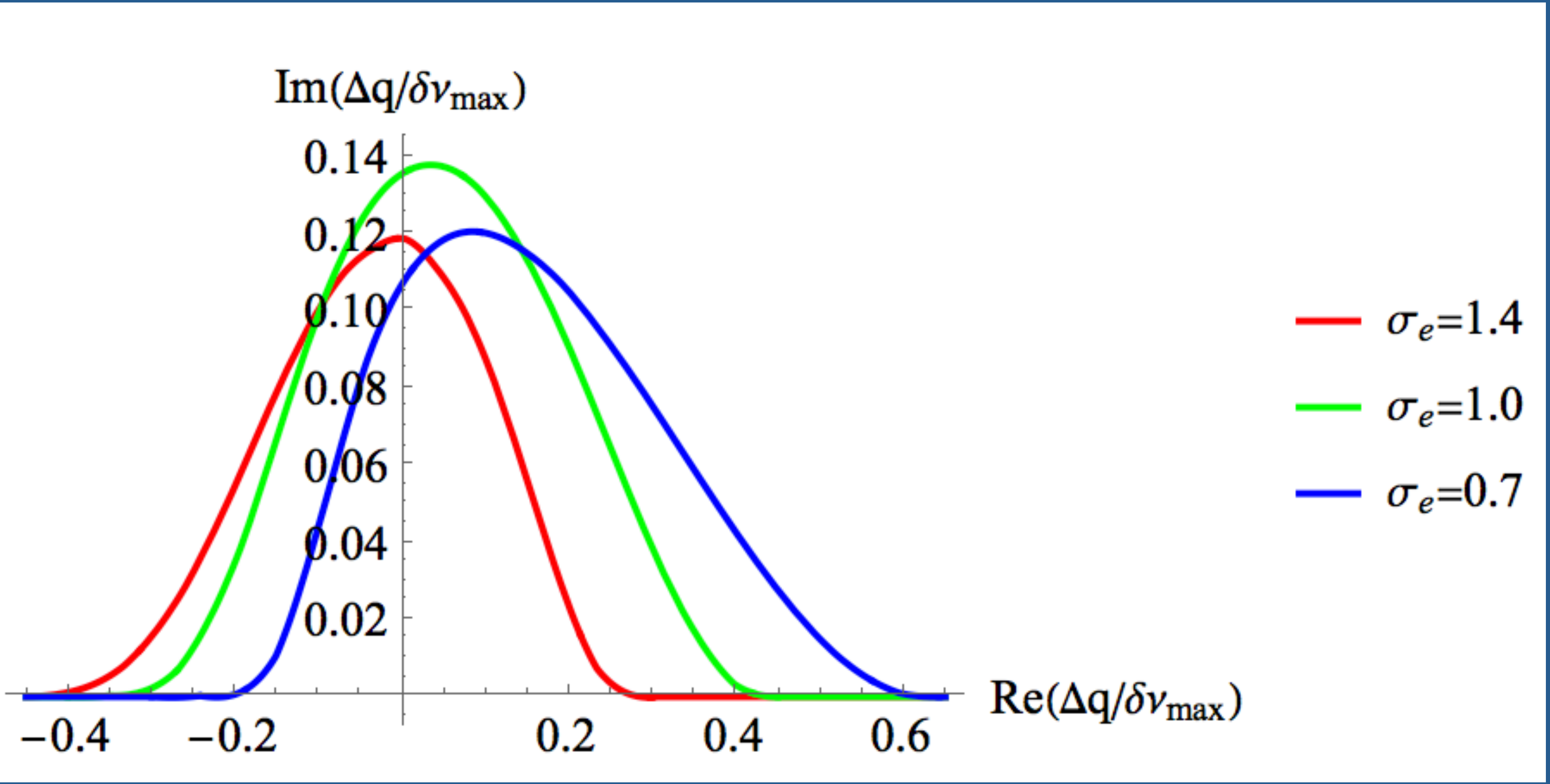
E-Lens Stability Diagrams



SDs for various lens sizes with the same max current density

TABLE I: Electron beam requirements to generate the tune shift $\delta\nu_{max}$ =0.01 in the 7 TeV LHC proton beams with $\varepsilon_n = 2.5\mu$m

Parameter	Symbol	Value	Unit
Length	L_e	2.0	m
Beta-functions at the e-lens	$\beta_{x,y}$	240	m
Electron current	I_e	0.8	A
Electron energy	U_e	10	kV
e-beam radius in main solenoid	σ_e	0.28	mm
Fields in main/gun solenoids	B_m / B_g	6.5/0.2	T
Max. tune spread by e-lens	$\delta\nu_{\max}$	0.01	

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E-Lens Summary

A standard, few meters long e-lens would do the job of 20 000 LHC-type octupoles for the LHC or FCC.

E-lens SD is core-based, so it is robust

E-Lens can be bunch-dependent

A problem of SD collapse can be fully excluded.

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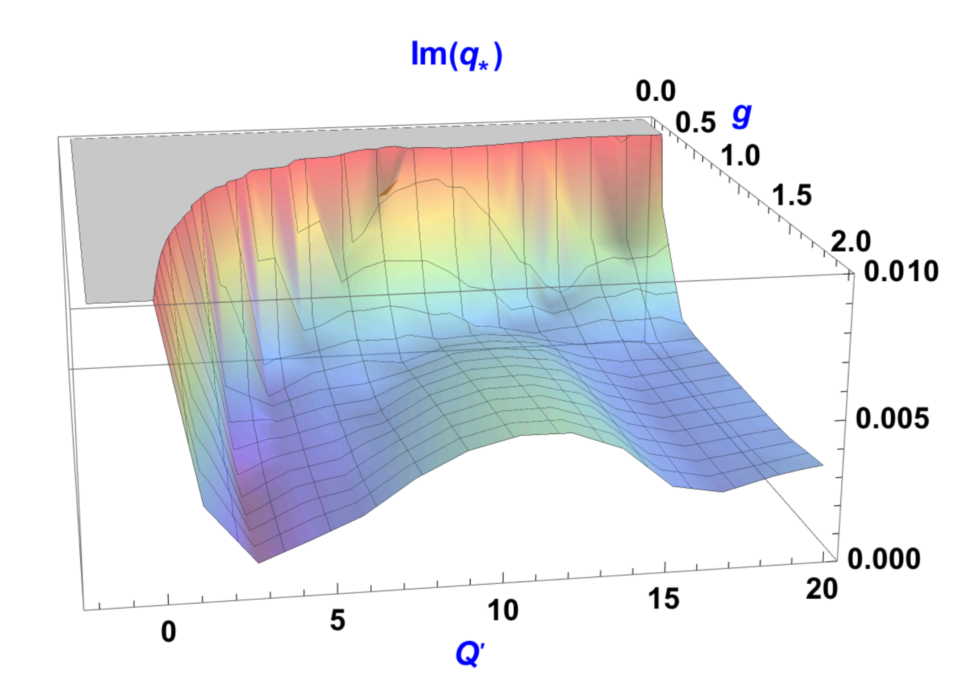
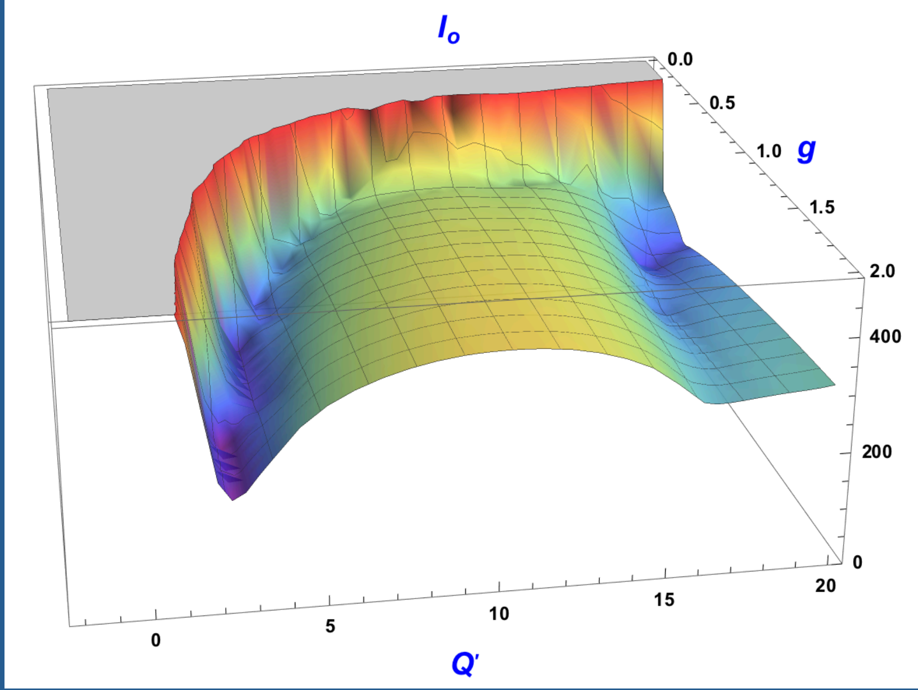
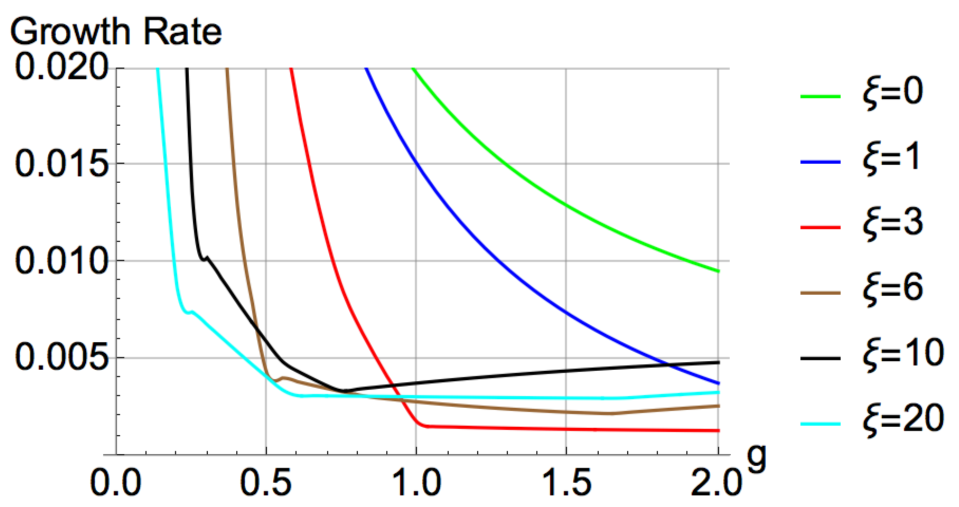
Many thanks for your attention!

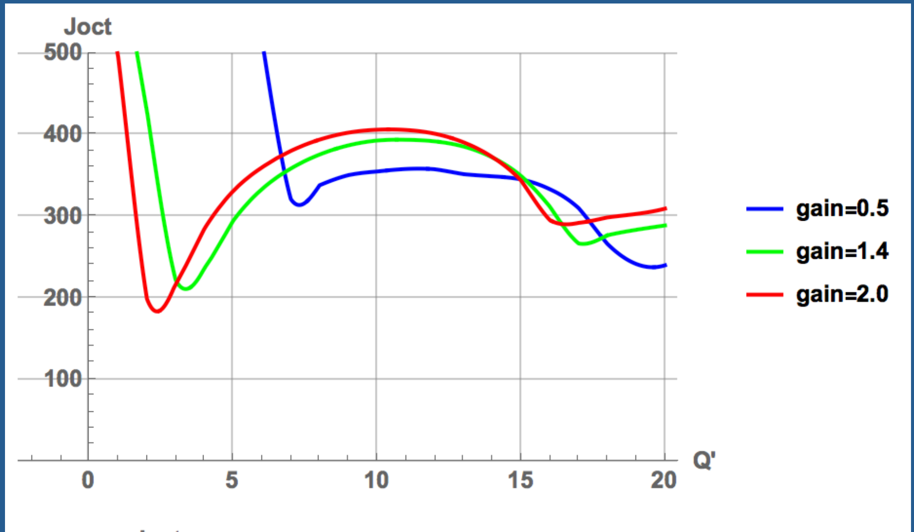
My very special gratitude for the organizers
of this impressive workshop
in the charming ancient city of Benevento.

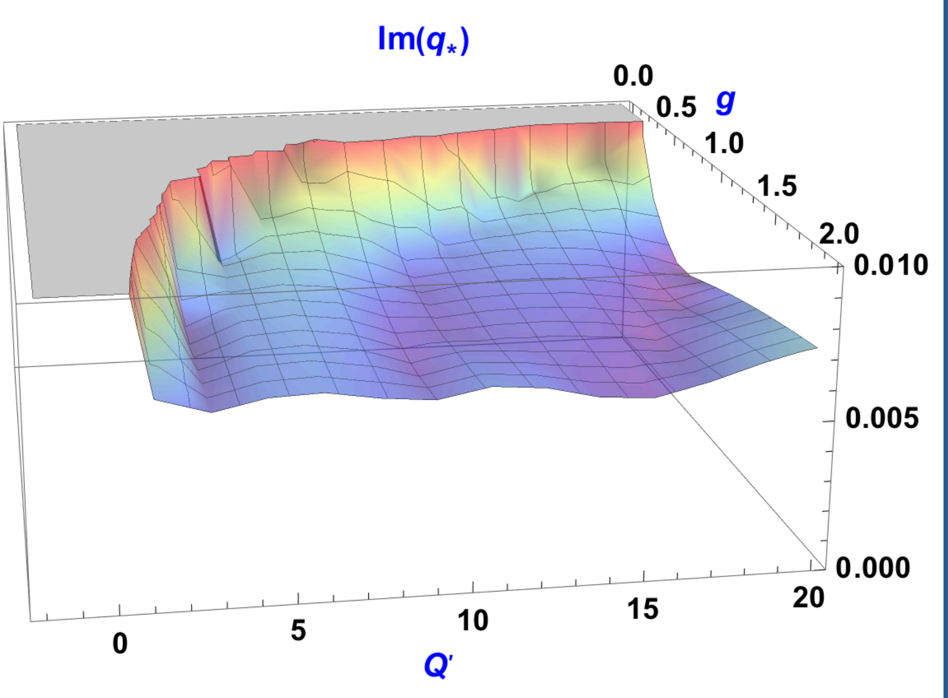




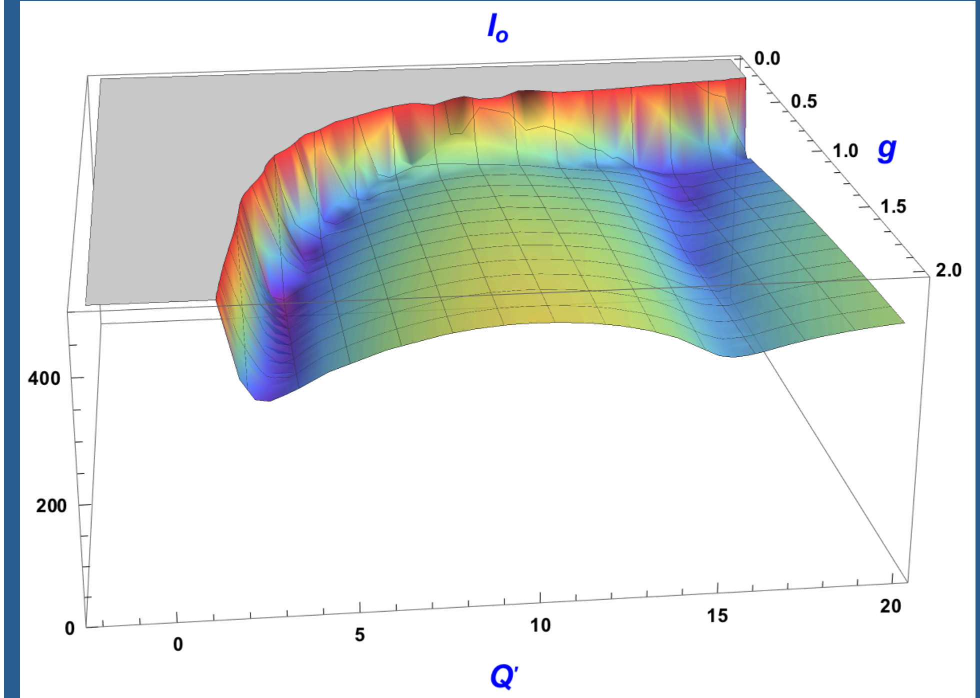
KHOM=0, Nb=2.2E11, 25ns beam, ImpF=2





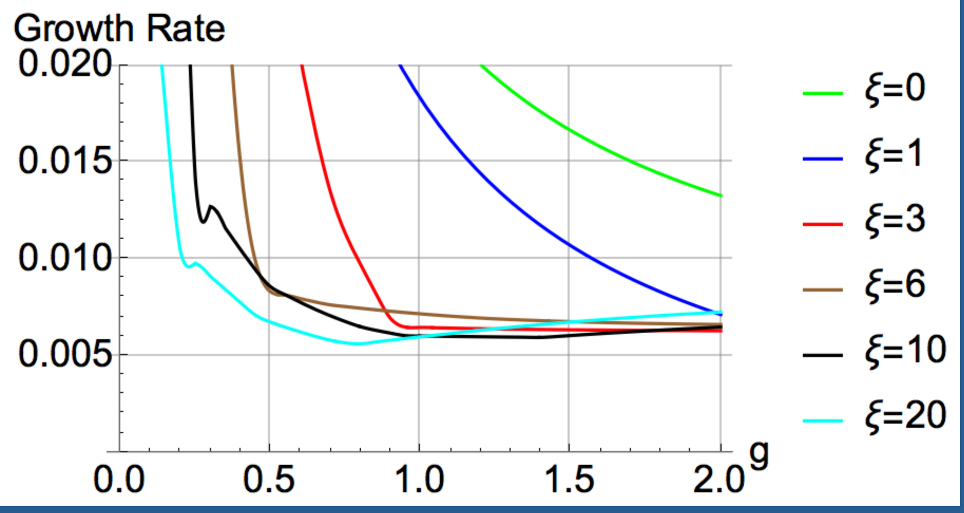


Im(q_*)
g
0.0
0.5
1.0
1.5
2.0
0.010
0.005
0.000
0
5
10
15
20
Q′

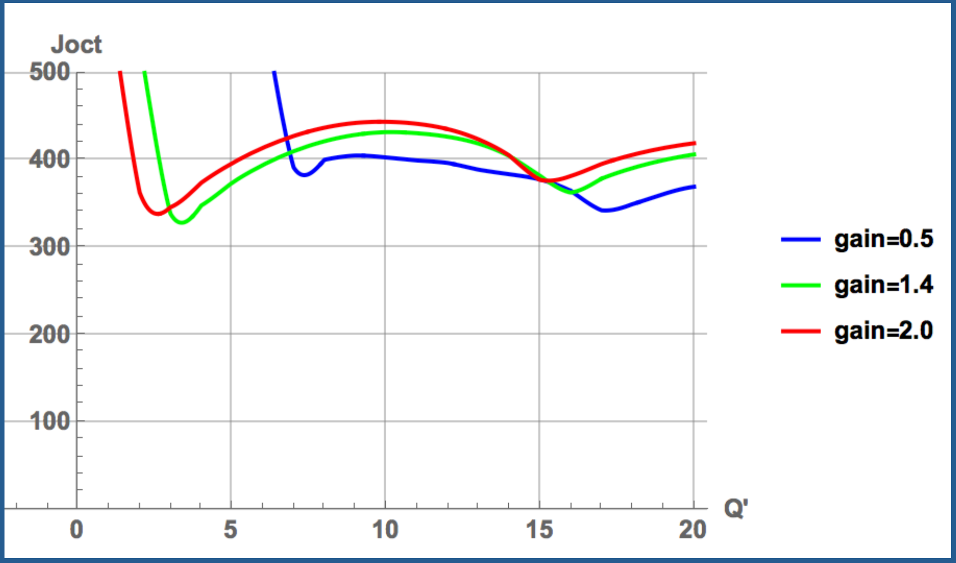


I_o
g
0.0
0.5
1.0
1.5
2.0
400
200
0
0
5
10
15
20
Q′

KHOM=0.07



Growth Rate
0.020
0.015
0.010
0.005
0.0
0.5
1.0
1.5
2.0
g
ξ=0
ξ=1
ξ=3
ξ=6
ξ=10
ξ=20



Joct
500
400
300
200
100
0
5
10
15
20
Q'
gain=0.5
gain=1.4
gain=2.0

HOMs: Comparison of results

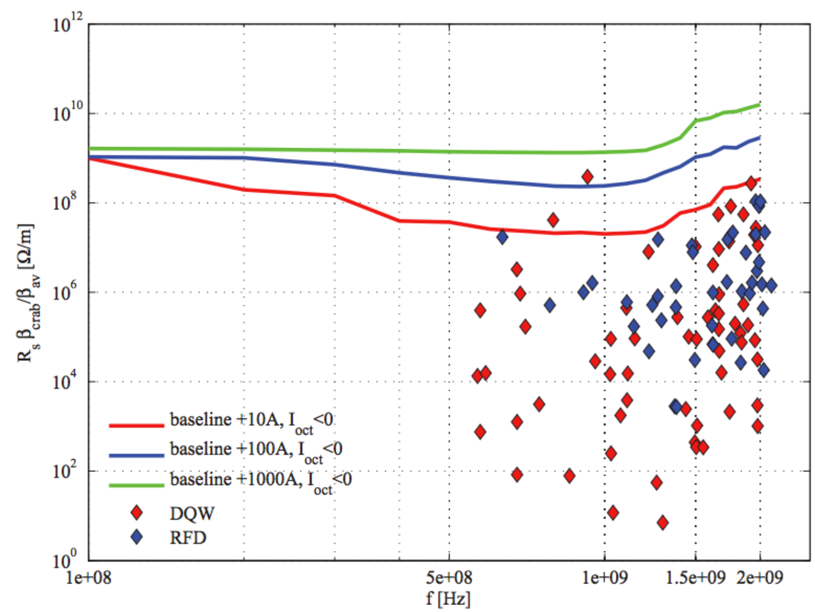
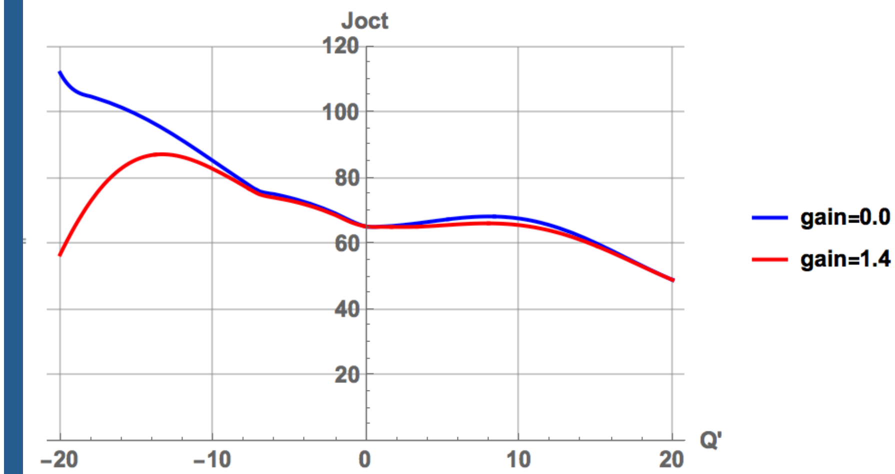


Figure 5: HOM of the DQW and RFD crab cavities and corresponding coupled bunch thresholds for the increase of octupole current over the machine baseline.



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THE HL-LHC IMPEDANCE MODEL AND ASPECTS OF BEAM STABILITY

N. Biancacci, B. Salvant, E. Métral, K. Li, CERN, Geneva, Switzerland

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