# Impedance, its Allies, and the Beam Guards

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# Instability Gang

Impedance:
SB, CB

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SB, CB

Space
Charge

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Impedance:
SB, CB

Space Charge

Space Charge

# Instability Gang

Impedance:
SB, CB

Space
Charge

E-Cloud

# Instability Gang

Impedance:
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E-Cloud

Beam-Beam

## Instability Gang

## Beam Guards

Impedance:
SB, CB

Landau Damping:
T-T, L-T

Space
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Landau Damping:
T-T, L-T

Feedback

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# Beam Guards

# Content

- Single bunch, no frequency spread
- Coupled bunch contribution
- Why damper is useless for many machines
- Transverse frequency spread: broken Landau damping
- Longitudinal-to-transverse Landau damping
- How to fix Landau damping
- E-cloud remarks.

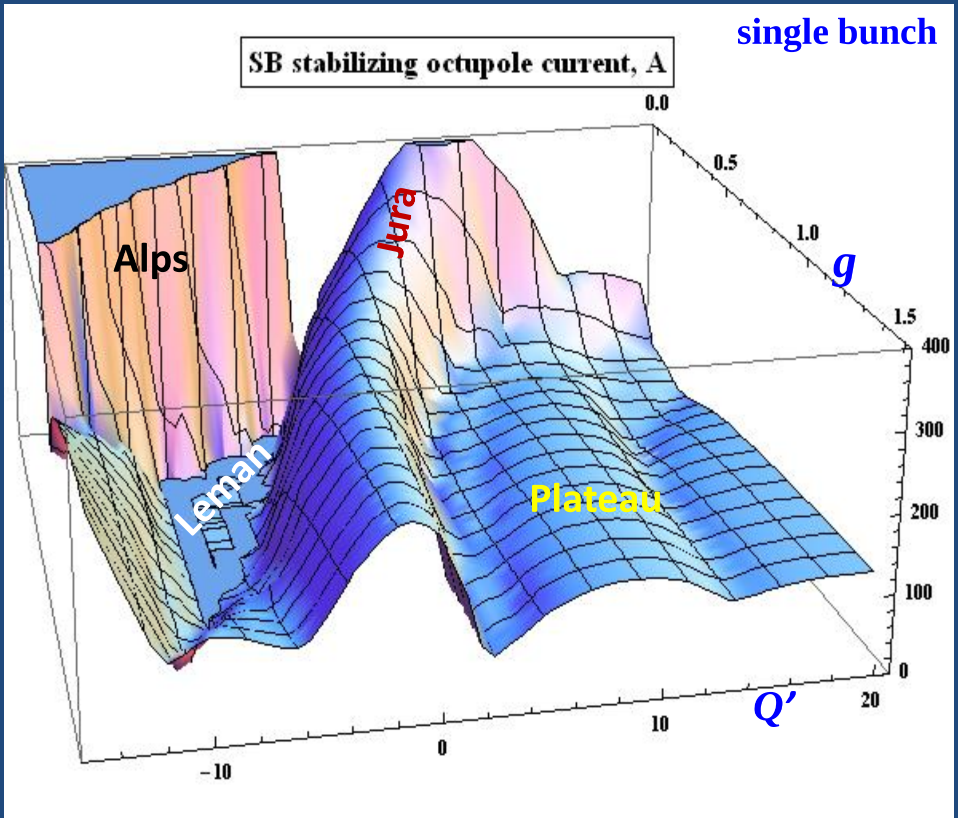
# Coupled-Bunch (CB) Wake and Damper

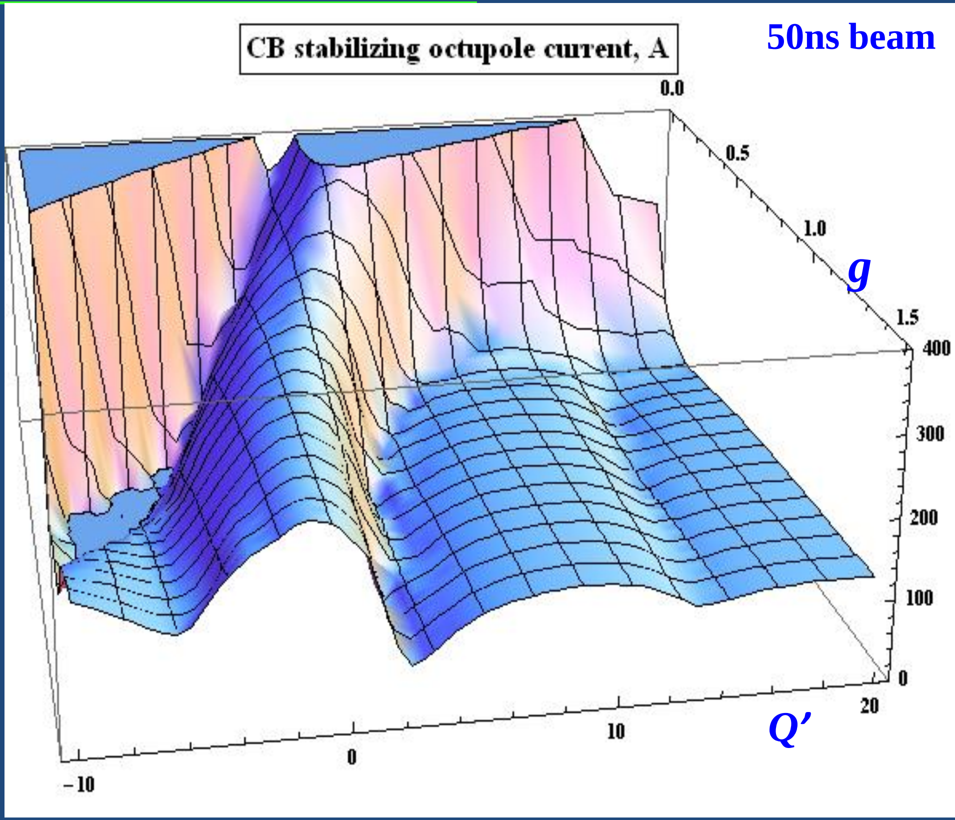
- Typically, geometrical and HOM wakes decay fast and so can be neglected for CB modes.
- Thus, CB interaction is dominated by resistive wall wake.
- Since the bunch length is normally small compared with the bunch separation, CB interaction is predominantly a cross-talk of bunch centroids.
- Bunch-by-bunch (BBB) damper blocks bunch centroids; thus, they cannot cross-talk.
- Therefore, CB wakes do not matter for sufficiently high damper gain:

$$g \gg |\Delta\Omega_{\mathrm{CB}}|$$

A. Burov, “Transverse modes for flat inter-bunch wakes”, FERMILAB-PUB-13-009-AD

# Coupled-Bunch Factor for LHC



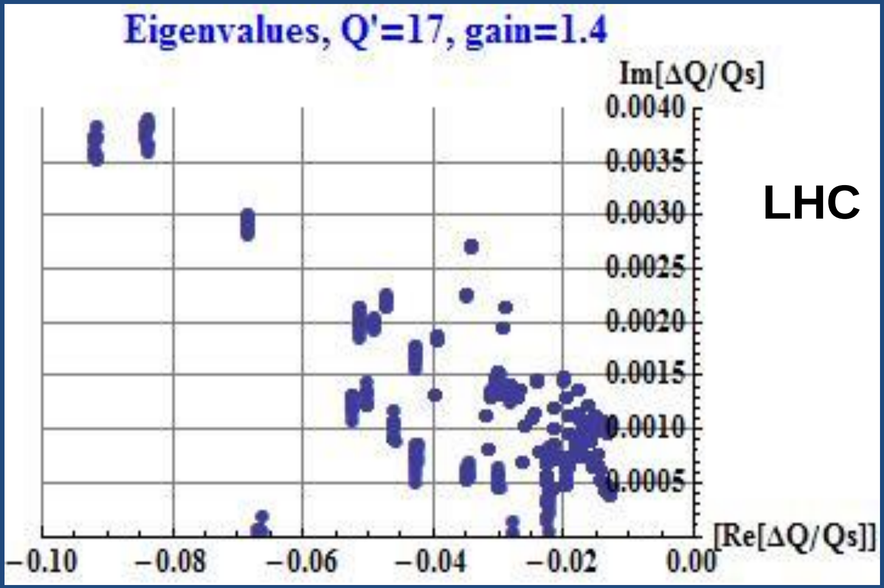



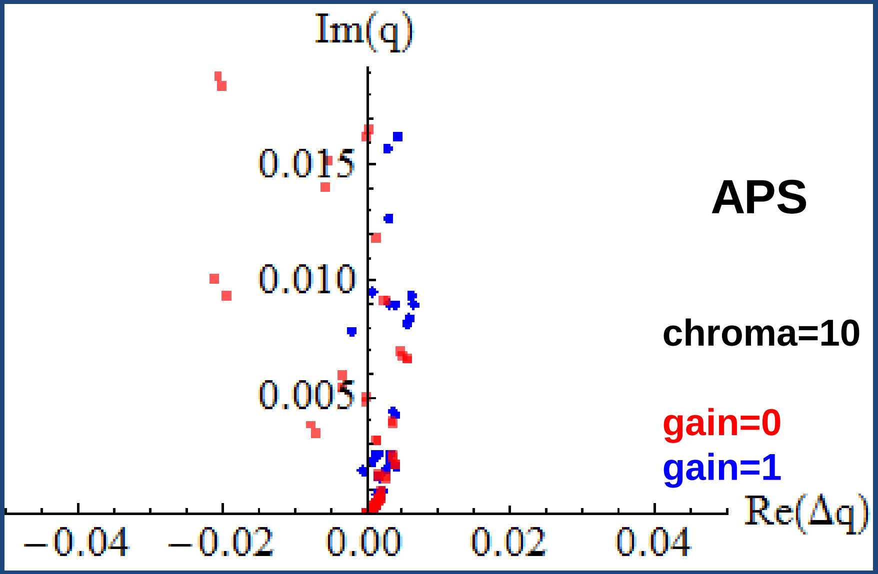

For high enough gain, there is no SB vs CB difference of the stabilizing octupole currents. For the same reason, strong-strong beam-beam effects are suppressed by the damper.

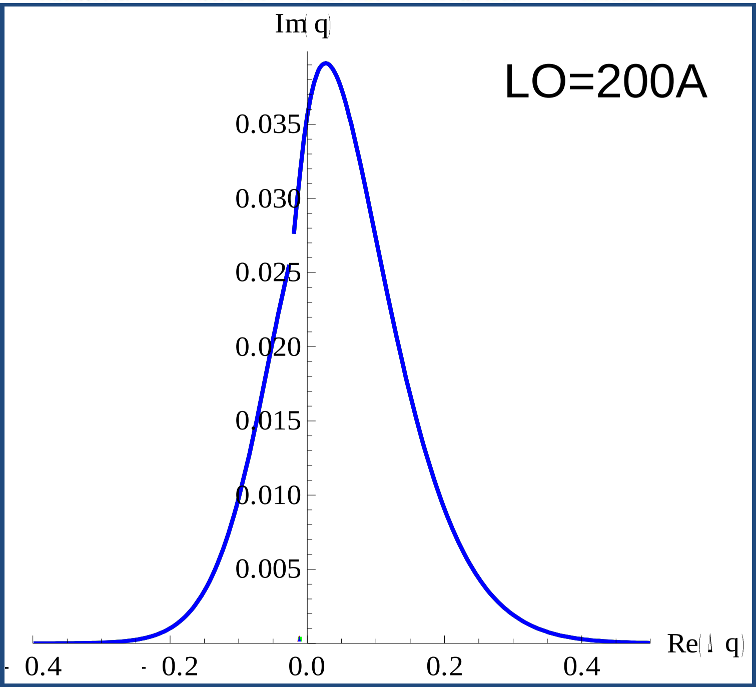
At high chromaticity the damper is not so effective (depends on the impedance though).

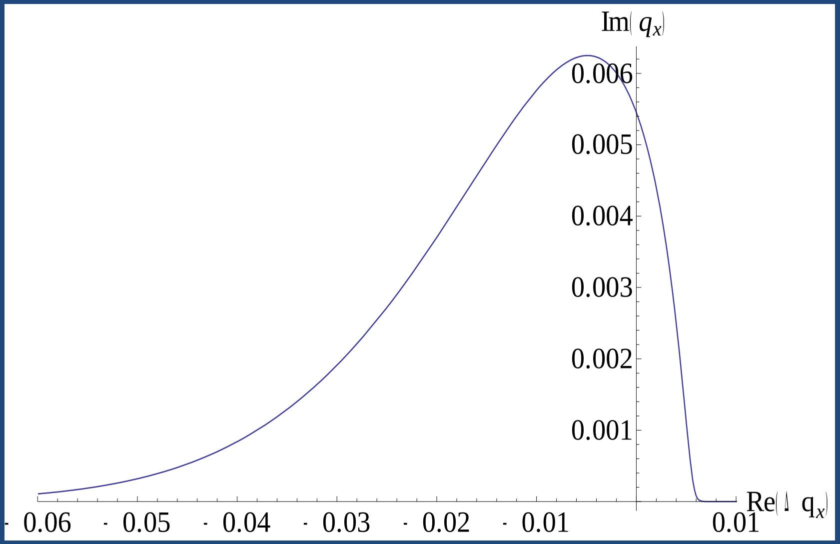
A. Burov, "Nested Head-Tail Vlasov Solver, Phys. Rev. ST Accel. Beams **17**, 021007 (2014)

# One-Sided Tune Shifts and Stability Diagrams



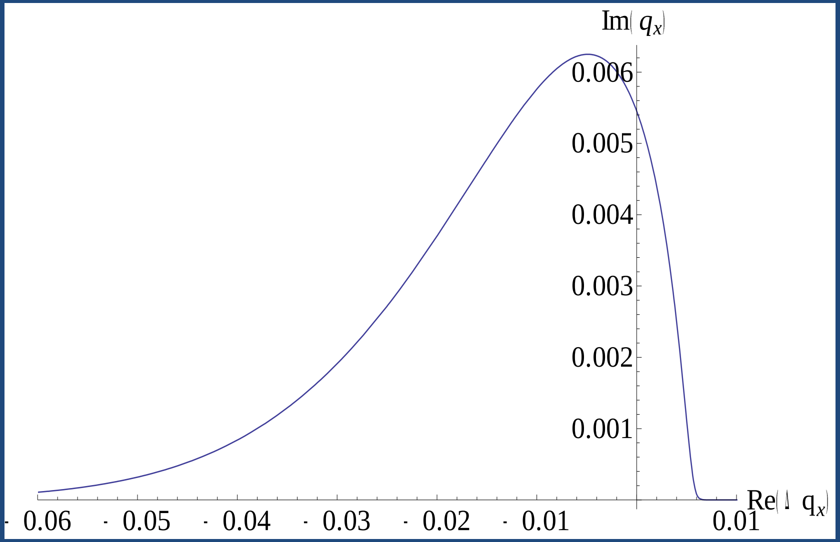



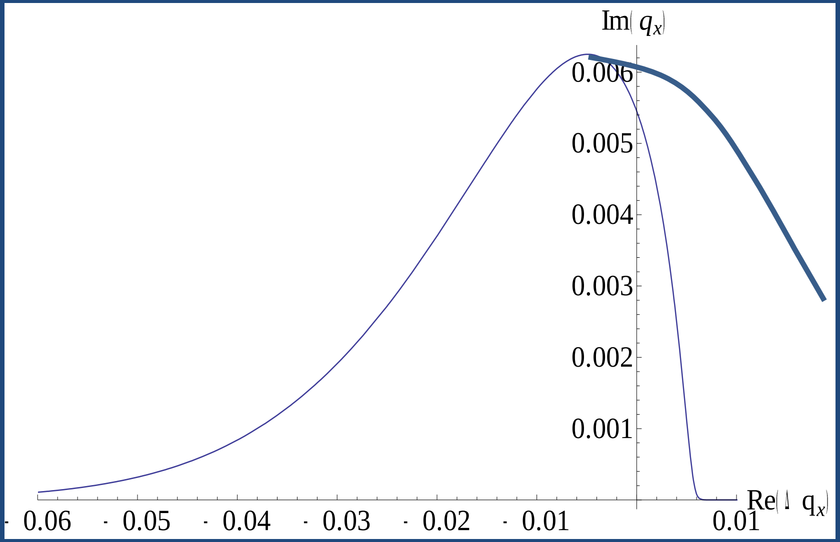



$$\delta q_x = A_{xx} J_x + A_{xy} J_y$$

$$\langle J_i \rangle = \varepsilon_i$$

# L-T Landau Damping: 2nd order chromaticity may help!




$$\delta q_x = A_{xx} J_x + A_{xy} J_y$$
$$\langle J_i \rangle = \varepsilon_i$$

$$\delta q_x = A_{xx} J_x + A_{xy} J_y + q_x'' J_z / (4\beta_z)$$
$$\langle J_i \rangle = \varepsilon_i$$



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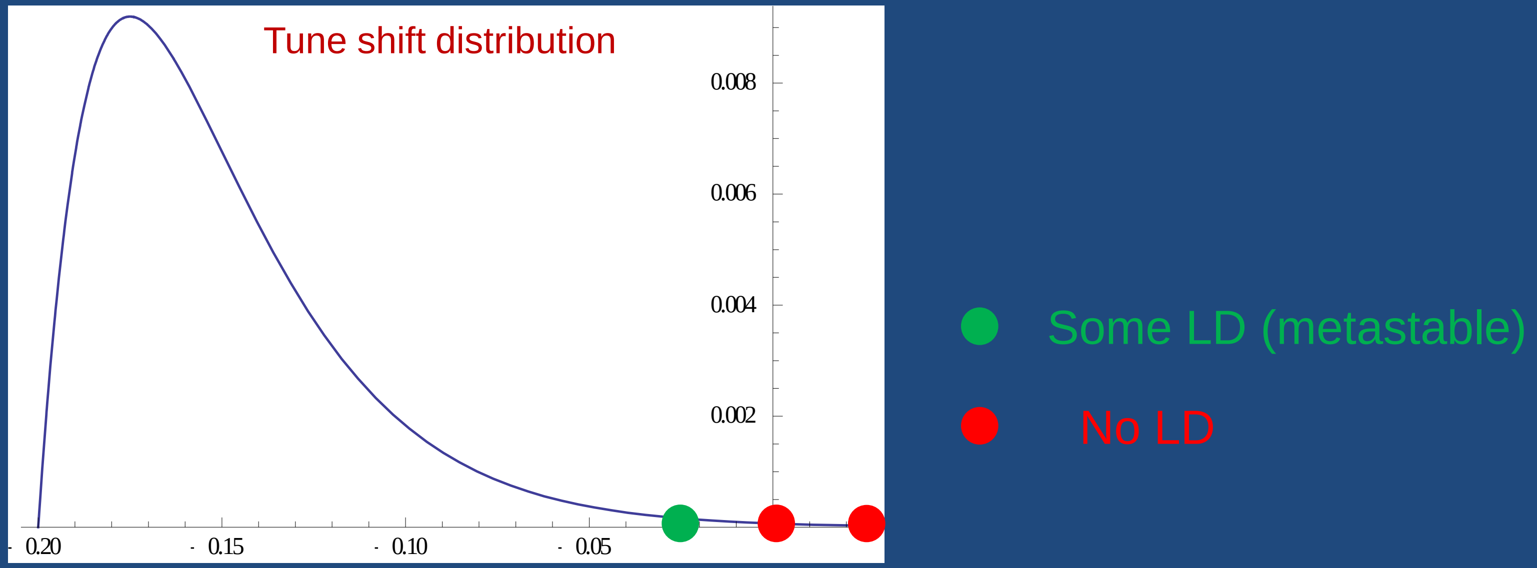
# Space Charge, Impedance and Octupoles

- Space charge (SC) moves incoherent tunes down, while its influence on the coherent ones is normally smaller.

- Thus, Landau damping is normally suppressed by the SC.




- Landau octupoles must provide positive tune shifts.

A. Burov, Head-tail modes for strong space charge, Phys. Rev. ST Accel. Beams **12** (2009)

# Space Charge helps with TMCI



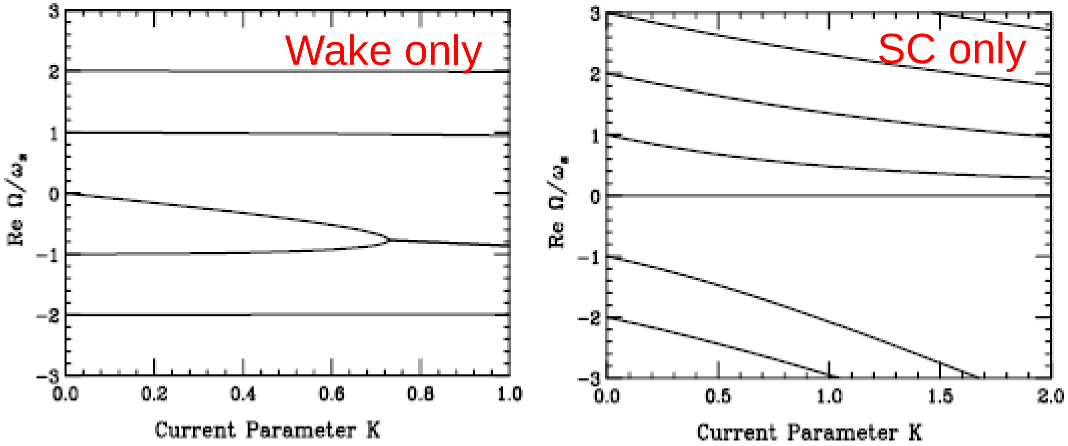



**FIGURE 8.** Left: The transverse wake force shifts mostly the azimuthal 0 mode downward but not the other modes. Instability occurs when the 0 and −1 modes meet with each other. Right: The space-charge force in the absence of the wake forces shifts all modes downward with the exception of the 0 mode.

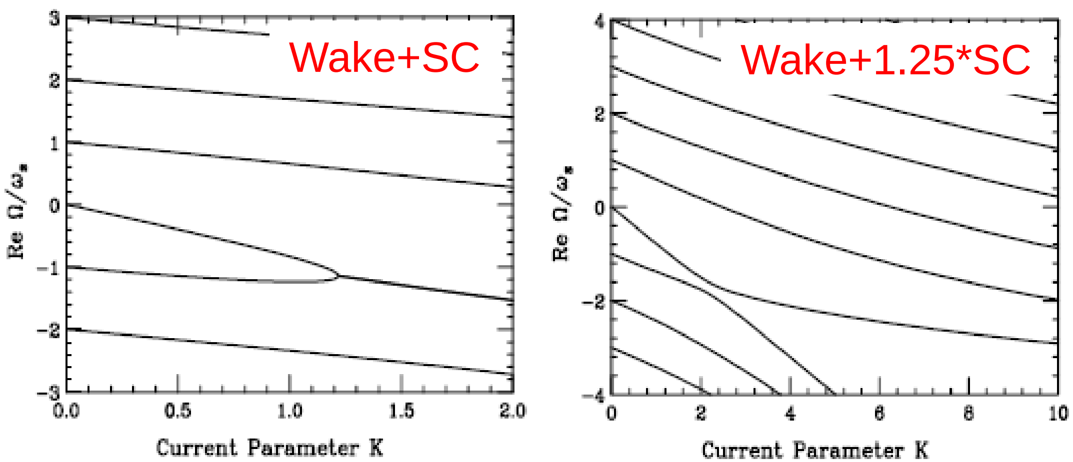



**FIGURE 9.** Left: With the transverse space-charge force added to the wake forces, all modes except the 0 mode are shifted downward, thus requiring the 0 and −1 modes to couple at a much higher current threshold. Right: When space charge reaches the critical value of $\xi = 5$, the −1 mode is shifted away from the 0 mode by so much that they do not couple anymore.

K.Y. Ng, A. Burov,

"**Stability issues of low-energy intense beams**"

AIP Conf. Proc. 496 (1999).

# SC: Intrinsic Landau Damping (LD)

$$\Lambda_L \simeq 0.1\, k^4 \frac{Q_s^4}{\Delta Q_{sc}^3}$$

Mode $\boldsymbol{k}$=**0** is not L-damped in this way (it is normally stable though due to proper sign of the chromaticity).

LD is a steep function of the mode number $\boldsymbol{k}$.

Moderate SC, $\Delta Q_{sc} \simeq Q_s$, may help to stabilize the beam, both due to LD and extension of the TMCI threshold.



AB

# E-Cloud, Space Charge and Octupoles

- E-Cloud introduces both a collective response (wake) and nonlinearity (Landau Damping), so it may be stable if the latter is stronger than the former (proper chromaticity is important).

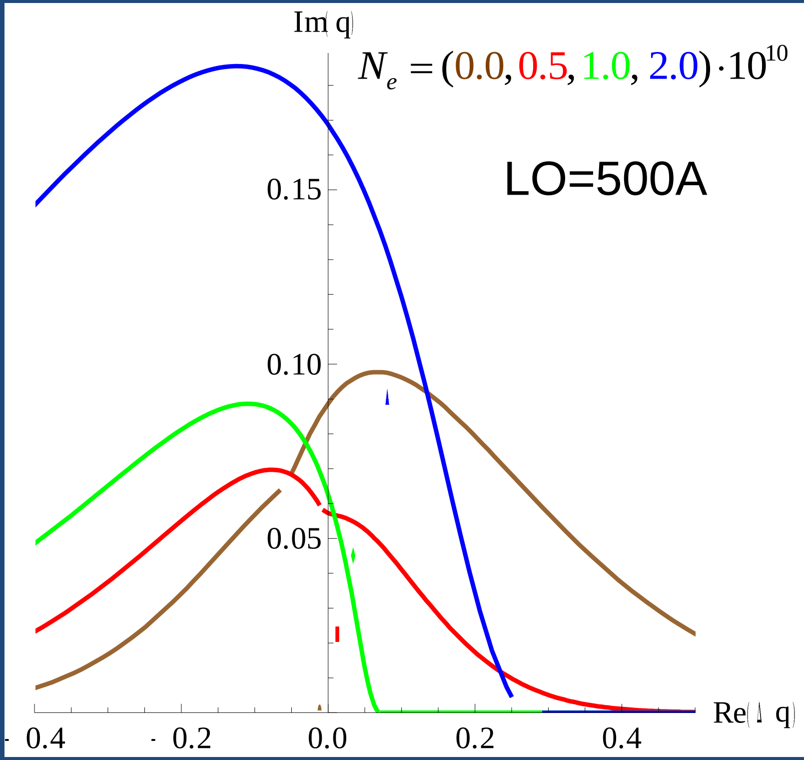
- If SC tune shift exceeds e-cloud one, the LD is suppressed and e-cloud can drive an instability. More e-cloud then stabilizes the beam!

- Positive octupole nonlinearity may be canceled by negative nonlinearity of e-cloud, so the SD will be left-sided and modes with positive tune shifts become unstable. With little e-cloud beam is stable, as well as with big enough.
- For sufficiently intense e-cloud, beam break-up instability develops anyway.

- Damper is not effective, if the e-phase advance >1.

A. Burov, **Three-Beam Instability in the LHC**, FERMILAB-PUB-13-005-AD , 2013

# E-cloud and Octupoles (LHC, EoS, 1 beam)




***Markers – most unstable modes, colors correspond***

Electron wake:

$$W(\tau) \simeq W_0 \sin(\omega_e \tau) \exp\left(\omega_e \tau / 2Q\right);$$

$$W_0 = \frac{N_e r_e c}{4\sigma_\perp^4 \omega_e}, \quad Q \sim 3-5, \ \tau < 0$$

$$\psi_e \equiv \omega_e \sigma_z / c = \begin{cases} 6.5 \text{ rad} & \text{for } \beta\text{=300m} \\ 1.4 \text{ rad} & \text{for } \beta\text{=4km} \end{cases}$$

Instability is driven by e-cloud accumulated in the high-beta area of IR1&5.

It happens due to a right-collapse of the SD + low-frequency e-wake with positive coherent tune shifts.

Impedance-related negative tune shifts are helpful!

*Many thanks!*

# Backup slides

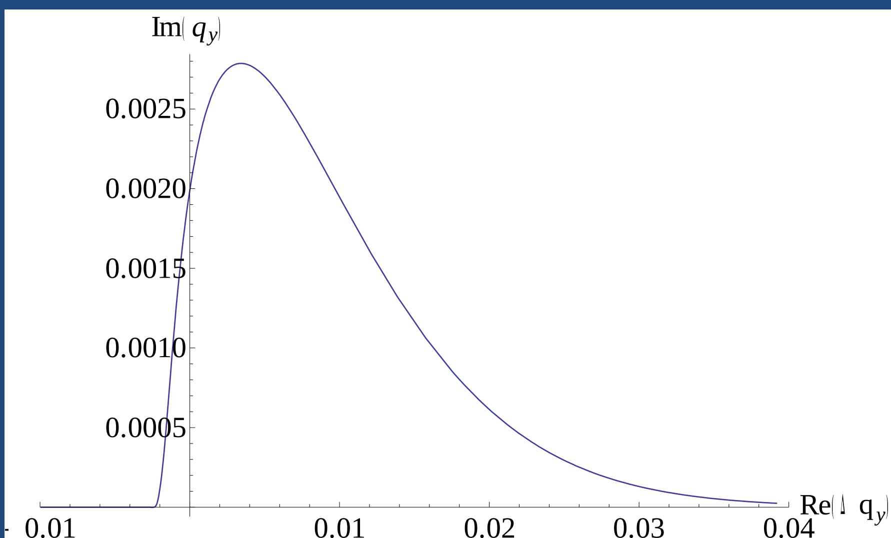
# Transverse-to-Transverse (TT) Stability Diagrams

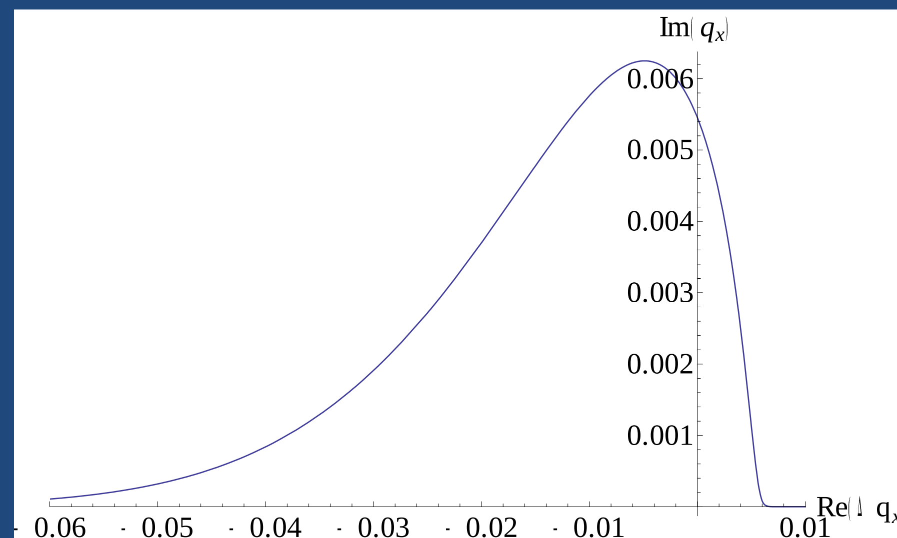
Stability diagram (SD) is defined as a map of real axes $\nu$ on the complex plane:

$$D_l(\nu) = \left( -\int \frac{J_x \partial F / \partial J_x}{\nu - l - \delta q_x + io} d\Gamma \right)^{-1}; \quad \delta q_x = \frac{\delta \omega_x}{\omega_s}; \quad \int F d\Gamma = 1; \quad d\Gamma = dJ_x \cdot dJ_y \cdot dJ_z$$

$$\delta q_x = A_{xx} J_x / \varepsilon_x + A_{xy} J_y / \varepsilon_y$$
$$\langle J_i \rangle = \varepsilon_i$$

To be stable, all the coherent tune shifts $q$ have to be below the SD.




Since normally $\varepsilon_x \gg \varepsilon_y$ , then $|A_{iy}| \ll |A_{ix}|$, so the TT diagrams are very asymmetric.

Matrix $A_{ik}$ was provided to me by *Vadim Sajaev*.