Instability latency in the HL-LHC – a first look at crab cavities

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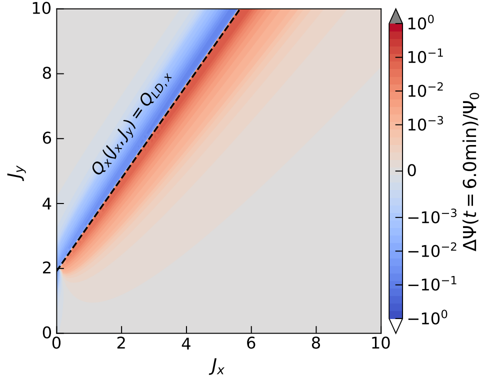
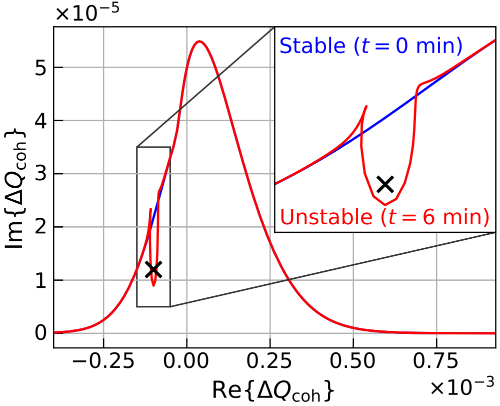
CERN BE-ABP-HSC Section meeting, July 2020

Loss of Landau damping by diffusion [WP2 2019-11-26].

A diffusion is centred at the mode tune, $Q_x(J_x, J_y) = Q_{\mathrm{LD}m,x}$.
Example with head-tail mode and rigid-bunch noise.





Noise Excited Wakefields [LMC 2019-12-04].

Wakefields drive coherent modes $\exp[-i\omega_{\text{rev}} Q_{\text{coh}m} t]$ → Landau damping stabilizes the modes $\Delta Q_{\text{coh}m} \rightarrow \Delta Q_{\text{LD}m}$ → External noise $\xi(t)$ excites the modes to finite amplitudes → Diffusion of particles that are resonant with the modes

Diffusion coefficient

$$D \propto \frac{\sigma_{\xi i}^2(Q)\eta_{mi}^2 |\Delta Q_{\text{coh}m}|^2}{\text{Im}\{Q_{\text{LD}m}\}^2} B(Q)$$

[ABP Forum 2019-11-07].

- $\sigma_{\xi i}^2(Q) \quad \left[\frac{\varepsilon_g}{\beta_{\text{eff}}}\right]$: PSD of noise type at tune Q,
  – Noise types: dipolar, headtail ...
- η_{mi}: Efficiency of the noise type i on head-tail mode m.
- $\Delta Q_{\text{coh}m}$: Impedance-driven tune shift.
- $\text{Im}\{Q_{\text{LD}m}\}$: Growth rate of damped mode. Impedance + Landau damping.

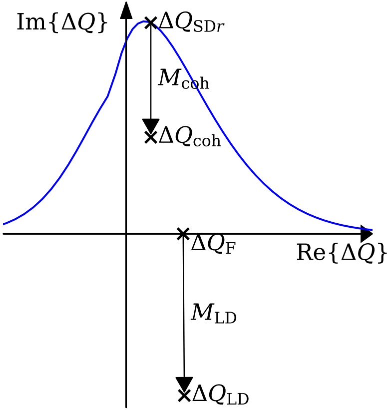
Analytical Latency Estimate

- In the limit $|\mathrm{Im}\{\Delta\omega_m\}/\,\mathrm{Re}\{\Delta\omega_m\}| \ll 1$:

$$\frac{L}{\tau_\mathrm{rev}} = \frac{(\mathrm{Im}\{\Delta Q_{\mathrm{SD}r0} - \Delta Q_\mathrm{coh}\})^5}{\mathrm{Im}\{\Delta Q_{\mathrm{SD}r0}\} a^2 |\Delta Q_\mathrm{coh}|^2} \frac{\mathrm{Re}\{\alpha_0\}^4}{J_{x,\mathrm{eff}} \sigma_{\xi i}^2 \eta_{mi}^2} \cdot \frac{\tilde{I}}{2.5},$$

$$1 \leq \tilde{I} = \int_0^1 \frac{5x^4 \mathrm{d}x}{1 - \frac{\mathrm{Im}\{\Delta Q_{\mathrm{SD}r0} - \Delta Q_\mathrm{coh}\}}{\mathrm{Im}\{\Delta Q_{\mathrm{SD}r0}\}}(1-x)} \leq 1.25$$

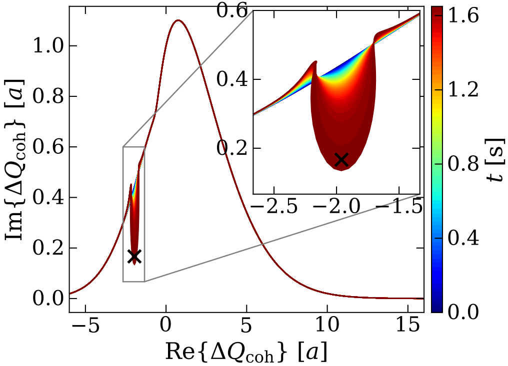
- Assumed nonphysically that $\alpha = \mathrm{d}M_\mathrm{LD}/\mathrm{d}M_\mathrm{coh}$ was a constant $\alpha(t=0) = \alpha_0$ (≈ 1).
- What mostly matters in the end is:
  - $L \propto (\mathrm{Im}\{\Delta Q_{\mathrm{SD}r0} - \Delta Q_\mathrm{coh}\})^5$ – Octupole margin.
  - $L \propto 1/\sigma_{\xi i}^2 \eta_{mi}^2$ – Strength of noise on mode m.
    - (Summation over i implied)



Numerical and Experimental Verification

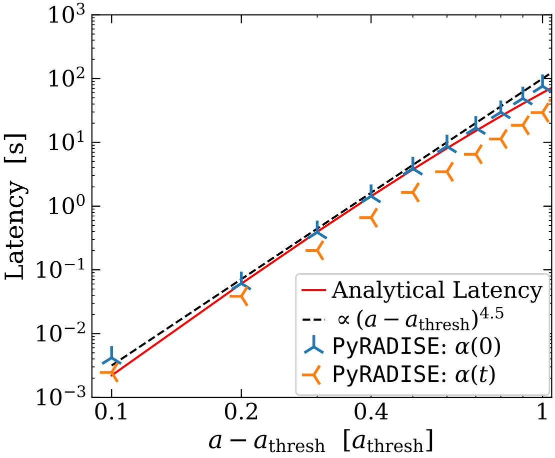
Test case – Drilling

- Example case:
  - $\Delta Q_{\text{coh}} = (-147 + 12.5\text{i}) \times 10^{-6}$
  - $a_x = 7.5 \times 10^{-5} = 1.5 a_{\text{thresh}}$
  - $b_x = -0.7 a_x$
  - $\eta_{mi}\sigma_{\xi i} = 1 \times 10^{-4}\ \sigma_{x'}$
    (Scale by $L \propto 1/(\eta_{mi}\sigma_{\xi i})^2$)
- Numerical latency is 1.65 s.
- Analytical latency is 3.84 s.
- When enforced constant α:
  Numerical latency is 3.88 s.
  - Derivation is accurate, with one too strong, but necessary, assumption.



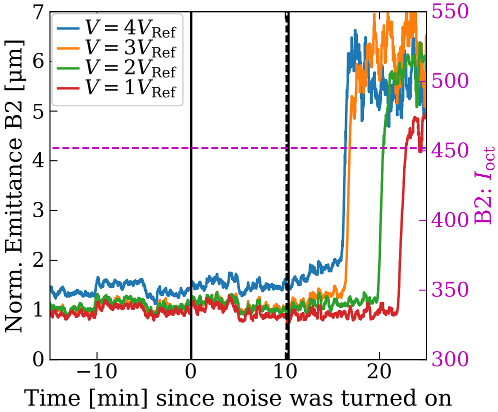
Test case – Dependence on Octupole margin

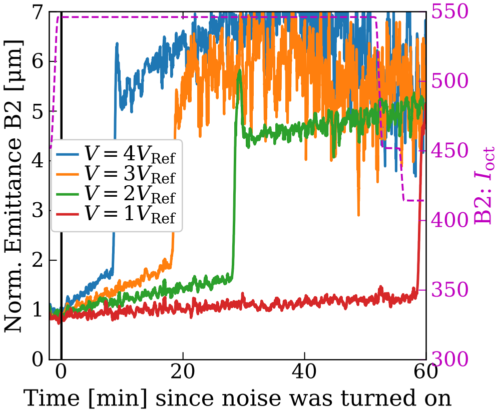
- Example case with various a_x:
  - $\Delta Q_{\mathrm{coh}} = (-147 + 12.5\mathrm{i}) \times 10^{-6}$
  - $b_x = -0.7a_x$
  - $\eta_{mi}\sigma_{\xi i} = 1 \times 10^{-4}\ \sigma_{x'}$ (Scale by $L \propto 1/(\eta_{mi}\sigma_{\xi i})^2$)
- Analytical latency $\sim$ numerical$\times 2$.
- Latency scales approximately as $(I_{\mathrm{oct}} - I_{\mathrm{oct,thr}})^{4.5} \propto (a - a_{\mathrm{thresh}})^{4.5}$
  - Faster at small margins



Latency Experiment (MD3288)

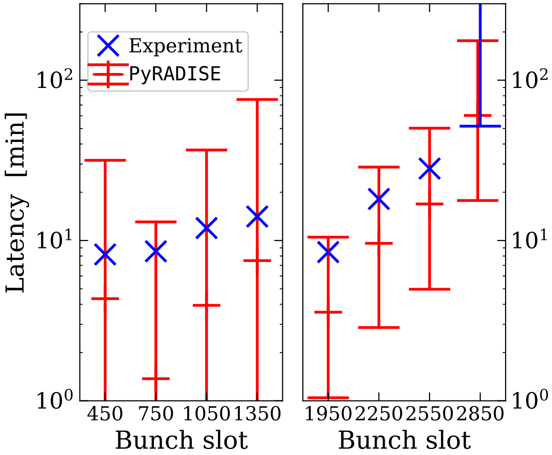
- Latencies measured in the LHC, with BSRT drifts.





Latency Experiment (MD3288) vs. PyRADISE

- Calculated latency with PyRADISE for these bunches with individual:
  - Emittance
  - Bunch length
  - Intensity
  - Noise amplitude
- Large error bars due to small uncertainty in emittance (10% $\rightarrow$ factor $\sim$2).
- Good agreement, considering that the latency scales over multiple orders of magnitude.



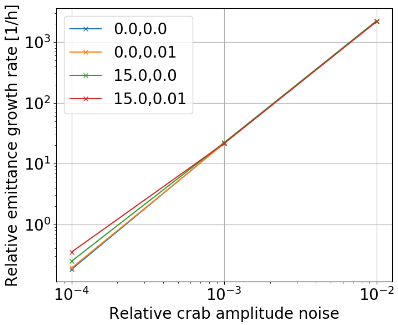
Crab Cavities

Crab Cavities (CC)

The CCs can affect the latency in three ways:

1. CC impedance modifies the coherent single-bunch tune shift ΔQ_{coh}.
   - Small impact on the resulting latency.
   - The latency in the LHC will be compared to the HL-LHC including this impedance.
2. CC impedance introduces high-frequency multi-bunch modes with $\mathrm{Im}\{\Delta Q_{\mathrm{coh}m}\}$ larger than normal. The octupole threshold $I_{\mathrm{oct,thr}}$ grew $\sim 5\%$.
   [227th HSC meeting 2020-06-15].
   - Initial checks show a small reduction of the latency.
   - The same latency achieved by also increasing I_{oct} by $\sim 5\%$ (backup)
3. CC amplitude noise can drive head-tail modes with large $(\eta_{m1}\sigma_{\xi 1})^2$ (implemented in `COMBI`, ongoing work in `PyRADISE/BimBim`).

CC Amplitude Noise in COMBI



- Relative noise amplitude definition

$$\delta_z = \frac{\delta x'(z)}{\sigma'} = \delta_0 + z\delta_1$$

where δ_0 is the rel. rigid bunch kick, and δ_1 is the rel. crab amplitude noise

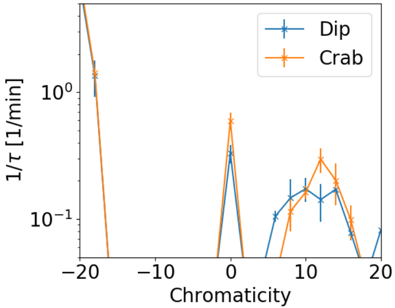
$$\delta_1 = \frac{1}{z}\frac{\Delta x'_{CC}}{\sigma'_{CC}} = \frac{\Delta\phi_{CC}}{\sigma_{\text{IP}}} = \frac{\Delta V_{CC}}{V_{CC}}\frac{\Delta\phi_{CC}}{\sigma_{\text{IP}}}$$

- The targeted maximum emittance growth driven by CC noise is 1.6 %/h [CERN-ACC-NOTE-2018-0002] – The transverse feedback is ineffective in reducing it. The corresponding maximum amplitude noise (without phase noise) is

$$\sqrt{\langle\delta_1^2\rangle} = 2.6 \times 10^{-5}$$

First CC Latency simulations with COMBI

- LHC 2018 flat top
  (Q' =15, 100 turns ADT time)
  - Dip. noise $\sigma_{\xi 0} = \sqrt{\langle \delta_0^2 \rangle} = 1 \times 10^{-3}$
    ($\sim$10 times measured LHC noise floor including the ADT)
  - Crab amp. noise $\sigma_{\xi 1}/\sigma_z = \sqrt{\langle \delta_1^2 \rangle} = 5 \times 10^{-5}$
    ($\sim$2 times the specification)

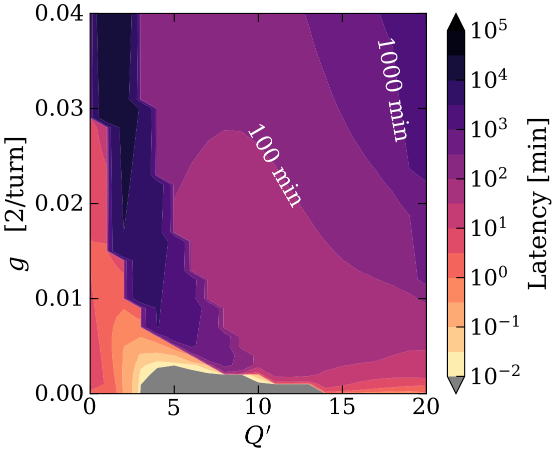


- The latencies are comparable, although the kicks from crab amplitude noise are much lower than the ones from the dipole noise ($\sigma_{\xi 1} = 4 \times 10^{-6} \ll 1 \times 10^{-3}$).
- Difference likely caused by the ADT, which improves the stability of modes with large η_{m0} but not those with large η_{m1}, thus increasing the latency with dipolar noise.
- Next step: confirm hypothesis by implementing and calculating η_{m1} in `BimBim`.

LHC vs HL-LHC (dipolar noise only)

LHC – Latency of the worst mode

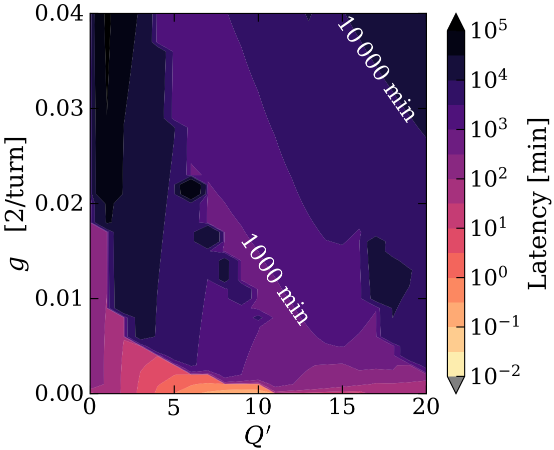
- Scan of ∼2018 LHC.
  - $\varepsilon_n = 2\,\mu\text{m}$
  - $I_{\text{oct}} = 280\,\text{A}$
  - $N = 1.1 \times 10^{11}$ ppb
  - $4\sigma_s = 1.1\,\text{ns}$
  - $E = 6.5\,\text{TeV}$
  - $\sigma_\xi = 1 \times 10^{-4}\sigma_{x',2\,\mu\text{m}}$
- Local optimum found, as in MD3288, for $Q' \approx 5$ and $g = 0.01$, compared to the more normal $Q' \approx 15$.



In backup, comparison to octupole margin.

HL-LHC – Latency of the worst mode (with CC)

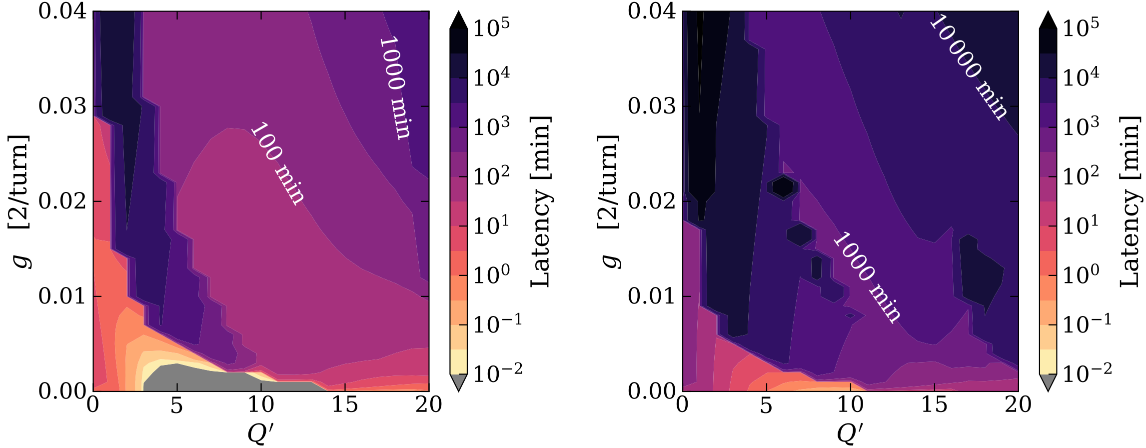
- Scan at end of ramp in design HL-LHC, including CC impedance.
  - $\varepsilon_n = 1.7\,\mu\text{m}$ (tails cut at 3σ)
  - $I_{\text{oct}} = 550\,\text{A}$
  - $N = 2.3 \times 10^{11}$ ppb
  - $4\sigma_s = 1.2\,\text{ns}$
  - $E = 7\,\text{TeV}$
  - $\sigma_\xi = 1 \times 10^{-4}\sigma_{x',2\,\mu\text{m}}$
- Much longer latencies than in 2018 LHC.
- Slightly shorter latencies than without the CC impedance.



In backup, comparison to octupole margin.

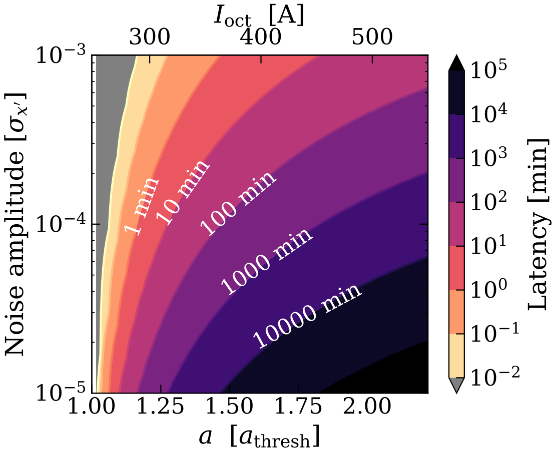
LHC vs HL-LHC

Latency (only dipolar noise) is predicted to be longer in the HL-LHC (right) than in LHC 2018.



Towards specification for HL-LHC

- Worst single bunch mode in standard configuration (g =0.02, $Q' \in$[13,17]):
  - $\Delta Q_\mathrm{cohm} = (-99.7+1.947\mathrm{i}) \times 10^{-6}$
  - $\eta_{m0} = 0.0214$
  - $I_\mathrm{oct,thr} \approx 248$ A
  - HL-LHC parameters as on earlier slide
- The noise amplitude is important:
  - $\sigma_{\xi 0} \approx 1 \times 10^{-4} \sigma_{x',2\,\mu\mathrm{m}}$ based on emittance growth rate (assuming wide spectrum).
  - 50 Hz lines found up to $\sigma_{\xi 0} \sim 1 \times 10^{-3} \sigma_{x',2\,\mu\mathrm{m}}$ [S. Kostoglou, 8th HL-LHC collab. meeting 2018-11-16].



Summary

- The diffusion model has been extended, giving an **analytical latency**, which is typically $\sim 2\times$ **numerical latency** found with `PyRADISE`.
- The diffusion model agrees with the **experimental latency** in MD3288.
- The latency of a given mode is found to mainly depend on the **octupole margin** and the **noise amplitude**. Understanding the noise is key to predicting the latency.
- The **latencies in the HL-LHC** has been investigated.
  Without crab cavities (CC) turned on, they will be longer than in the LHC.
- The **crab cavities** can affect the situation in several ways
  - CC impedance has minimal impact on the achievable latency.
  - CC **amplitude noise** with large η_{1m} can be a problem.

- Outlook:
  - Estimate the impact if CC have to be turned on before collision in HL-LHC.

Thank you for your attention!

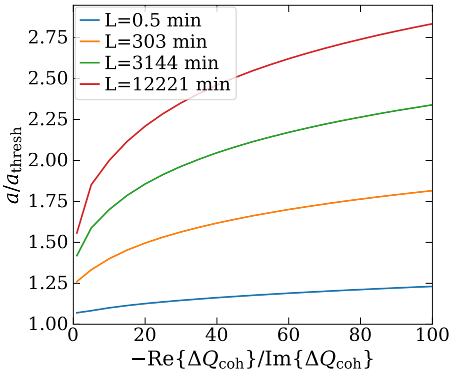
B: Isolatency curves

Q1 If $\mathrm{Im}\{\Delta Q_{\mathrm{coh}}\}$ doubles, what is the latency ?

A1 What matters mostly is the distance to the stability diagram, $(\Delta Q_{\mathrm{SD}r} - \Delta Q_{\mathrm{coh}}) \in \mathbb{I}$. The latency can decrease marginally, or the mode can have become unstable.

Q2 If $\mathrm{Im}\{\Delta Q_{\mathrm{coh}}\}$ doubles, but a_{thresh} only increases by 5%, how much must $a \propto I_{\mathrm{oct}}$ be increased to maintain the same latency.

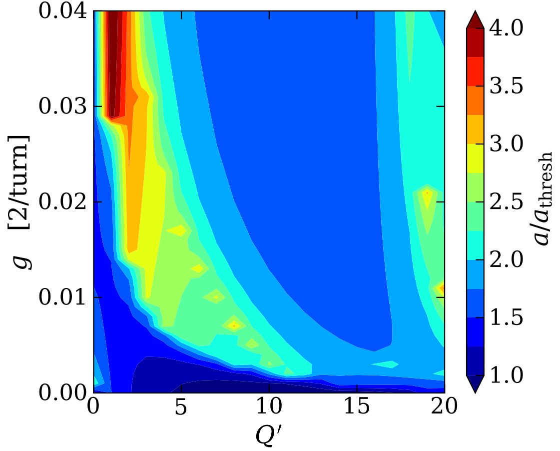
A2 See A1 and isolatency curves for an uncut Gaussian beam on the right. Short answer is to increase a by 5% as well.

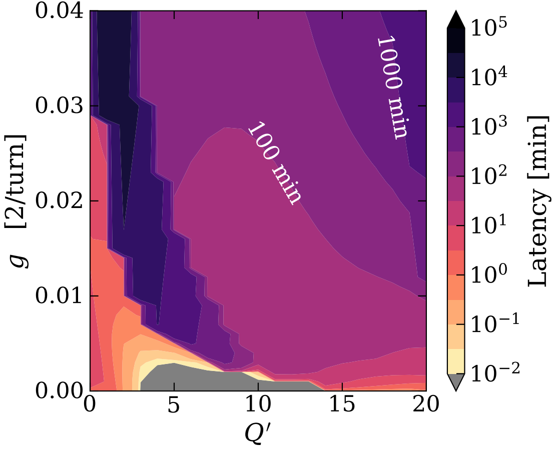


Isolatency curves – How large octupole margin is required to achieve a given latency. Typical worst (HL-) LHC modes have ratios $\in [10, 100]$. The theory assumes large ratios, at small ratio, the latencies are large.

B: LHC – Latency of the worst mode

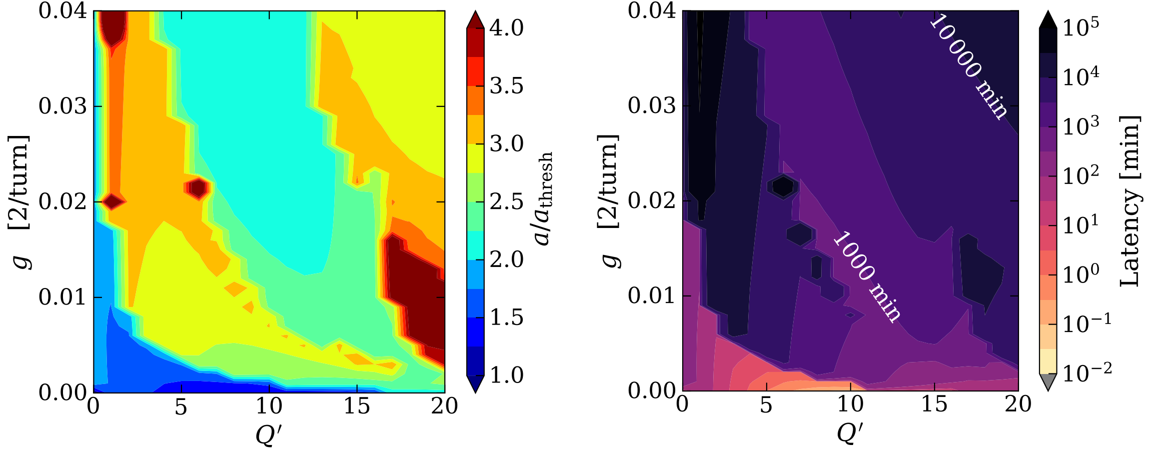
On the left is the octupole margin with $I_{\mathrm{oct}} = 280\,\mathrm{A}$.





B: HL-LHC – Latency of the worst mode (with CC)

On the left is the octupole margin with $I_{\text{oct}} = 550\,\text{A}$.



B: Diffusion dependence on Chromaticity

- The chromaticity modifies the spectrum of single particles

$$\cos[\phi(t)] = \cos\left[\omega_{\mathrm{rev}}\left(Q_0 t + \int_0^t Q'\delta \mathrm{d}t\right)\right]$$
$$= \sum_{n=-\infty}^{\infty} J_{|n|}\left(\frac{Q'\sigma_\delta}{Q_s}\right)\cos[\omega_{\mathrm{rev}}(Q_0 + nQ_s)t],$$

- This is equivalent to the head-tail chromatic phase shift of the mode.
- Hence, the chromaticity does not affect the diffusion directly (but it does indirectly, by modifying ΔQ_{coh} and η).

B: Definitions

- The effective action for a horizontal mode is defined as:

$$J_{x,\text{eff}} = \frac{\int_0^\infty\int_0^\infty \mathrm{d}J^2 J_x^2 \Psi' \delta[J_x - J_{xr}(J_y)]}{\int_0^\infty\int_0^\infty \mathrm{d}J^2 J_x \Psi' \delta[J_x - J_{xr}(J_y)]}$$

- The noise moment of a mode is defined as the normalized inner product between the mode and the noise:

$$\eta_{mi} = \left| \frac{\langle \overline{m_m} \Xi_i \rangle}{\sqrt{\overline{m_m} m_m}\sqrt{\overline{\Xi_i}\Xi_i}} \right|$$

- $\Delta Q_{\text{SD}r}$ is defined as the tune shift of the stability diagram with the same real part as the mode.