Status of studies of: The impact of noise on beam stability

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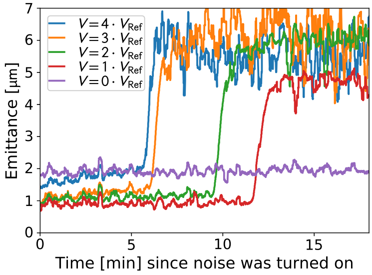
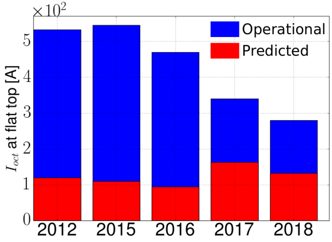
Latent Instability due to Noise

- Instabilities of high latencies have been observed in LHC before collision.
- Reproduced in dedicated experiments. [S.V. Furuseth *et al.*, WEPTS044, IPAC 2019.]
- The instabilities are driven by noise, not caused by machine variations.
- This mechanism is linked to the discrepancy between the predicted and required octupole current in the LHC. [X. Buffat *et al.*, Evian Workshop 2019].





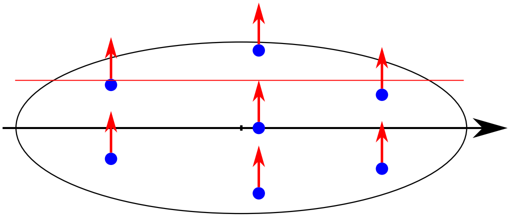
Noise definitions

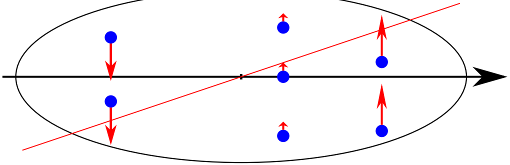
Rigid-bunch/dipolar noise: Equal stochastic kicks to all particles in a bunch, as the low-frequent noise in the LHC.

Crab amplitude noise: Kick dependent on longitudinal phase

$$\Delta p \propto \sin(\phi_s)\Delta V.$$

[Crab Noise, P. Baudrenghien, 2015]

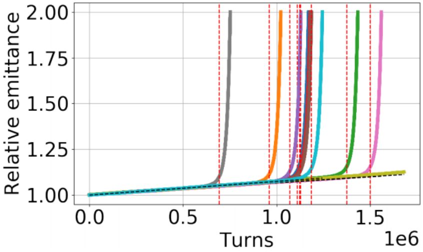




L2D2 –
Loss of Landau damping Driven by Diffusion

Noise Excited Wakefields – Numerical Model

- Simulations with ideal damper (G), linear detuning (I_{oct}), chromaticity, white noise (σ_ξ) and wakefields.
  - No lattice non-linearities.
- Challenging and time consuming to get results.
  - 10 simulations with different seeds return a large spread.
- Beyond a numerical threshold, the latency (τ) for one case scales as



$$\tau \propto \frac{I_{\text{oct}}^3 G}{\sigma_\xi}$$

Noise Excited Wakefields – Analytical Model

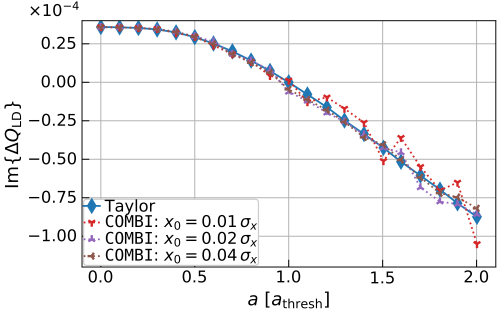
1. **Transverse wakefields drive eigenmodes $|m\rangle$ of complex eigenfrequencies ω_m. Modes evolve like $\exp[-\mathrm{i}\omega_m t]$.**
2. **Landau damping changes the eigenfrequencies to Ω_m.**
3. **Noise, $\xi(t)$, excites the stable eigenmodes. The impact on mode $|m\rangle$ is proportional to $\eta_m = \langle\xi|m\rangle$.**
4. **Wakefields transfer the mode energy to single particles.**
5. **This mechanism can be modeled as a frequency dependent diffusion, with diffusion coefficient**

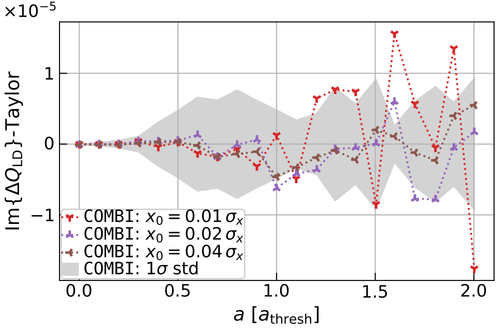
$$D(\omega) = J \cdot \frac{\omega_{\mathrm{rev}}}{2} \cdot \frac{\eta_m^2 \sigma_\xi^2 |\Delta\omega_m|^2}{\mathrm{Im}\{\Omega_m\}^2} \cdot B(\omega; \Omega_m) \cdot C(\omega_m, \Omega_m).$$

- See more details of the derivation in [ABP Forum 2019-11-07].

Step 2: Landau Damped Modes

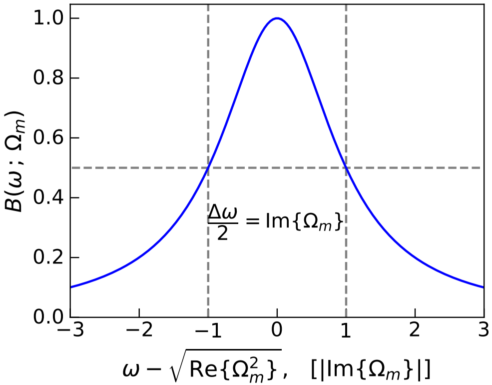
- Find Ω_m inside the stability diagram with a linear extrapolation.
- Simulations with COMBI ($Q' < 0$) support the linear extrapolation outside the stability diagram as expected, but also inside.

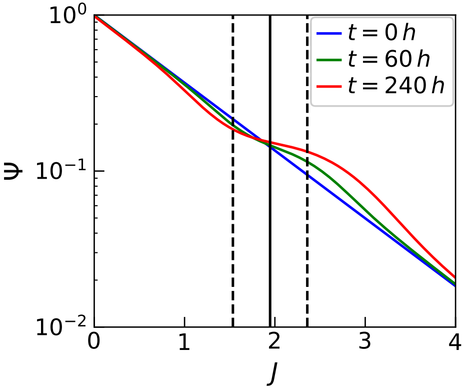




Wakefield driven Diffusion in 1D

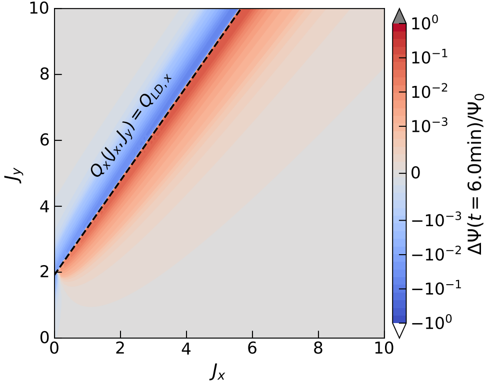
The diffusion is centred at the mode frequency, $\omega(J) = \Omega_m$.

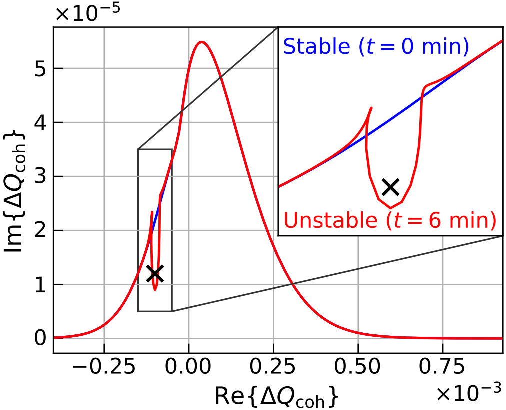




Wakefield driven Diffusion in 2D, $\eta_m = 0.01$

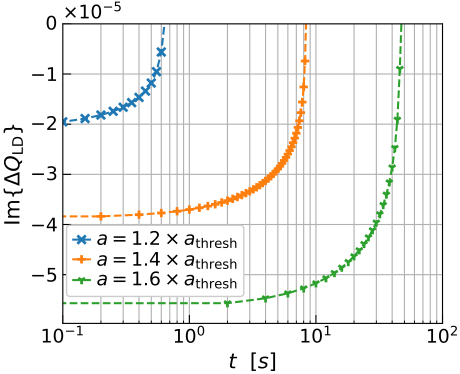
The diffusion is centred at the mode frequency, $\omega(J_x, J_y) = \Omega_{m,x}$.
Mode 1 and rigid-bunch noise.





Wakefield driven Diffusion in 2D, $\eta_m = 1$

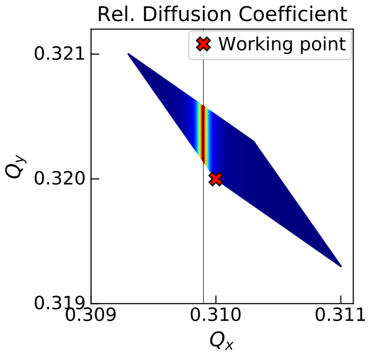
- Latency $\tau \propto 1/D \propto 1/\eta_m^2 = 1$.
- Mode 0 and rigid-bunch noise.
- **Mode 1 and crab amplitude noise.**



Initial results of simplified model.

L2D2 – Loss of Landau Damping due to Diffusion

- To drill a hole in the stability diagram, the diffusion:
  - in the horizontal plane must not depend on the vertical tune.
  - must not be uniform.
  - must be fast comparable to other uniform diffusions (IBS).
- To cause an instability, the hole must be at the tune of an unstable mode!



$$a_{xx}J_x, a_{yy}J_y \in \{0, 10^{-3}\}$$

Impact of L2D2 on HL-LHC

Mitigation of Noise Excited Wakefields

- Reduce the drilling rate, $D \propto \eta_m^2 \sigma_\xi^2 |\Delta\omega_m|^2 / \operatorname{Im}\{\Omega_m\}^2$.
  - Reduce the noise amplitude (σ_ξ).
  - Avoid unstable modes with large η_m, as mode 0 in the LHC.
  - Reduce the impedance ($\Delta\omega_m$).
    - η_m and $\operatorname{Im}\{\Delta\omega_m\}$ depend on Q' and G (see backup).
  - Increase the margin to the stability threshold ($\operatorname{Im}\{\Omega_m\}$).
    - E-lens, enhanced octupole detuning using the telescopic index, etc.
- Reduce the waiting time.
  - Collide as early as possible, to get detuning help from beam-beam interactions.
  - Wait until the beams are colliding to turn on the crab cavities.
- Change the detuning qualitatively.
  - Avoid detuning dependence on d.o.f. in the same plane (RFQ, Q'', $a=0$). TBI.

Experimental Verification

Direct Measurement

- White noise $\rightarrow$ BTF.
  [C. Tambasco *et al.*, MD3291]
- Unstable in 2018.
  Can be surpassed by:
  - Increase I_{oct} before BTF.
  - Retract the collimators before BTF.
  - Use the anti-damper in place of wake or BTF? TBI.

Indirect Measurement (Latency)

- White noise $\rightarrow$ Wait.
  [S.V. Furuseth *et al.*, MD3288]
- Vary parameters to compare to theory (Q', G, I_{oct}, N).
- Difficult to get many data points in the LHC.
  - Can we test in SPS or IOTA (V. Lebedev)? TBI.

Summary

- Noise can cause a **loss of Landau damping** driven by diffusion.
- Instabilities of **high latencies** can develop in high-energy hadron machines with noise and impedance, by changing the distribution.
  - There are wake-independent mechanisms that could cause a similar diffusion, but less consistently (see backup).
- One recommended **mitigation technique** is to reduce the drilling rate, by considering $D \propto \eta_m^2 \sigma_\xi^2 |\Delta\omega_m|^2 \,/\, \mathrm{Im}\{\Omega_m\}^2$.
- **Rigid-bunch noise** is severely detrimental if mode 0 is unstable.
- **Crab amplitude noise may be as problematic** for mode 1!

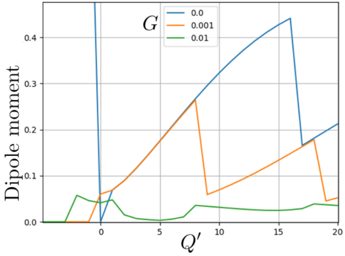
Outlook

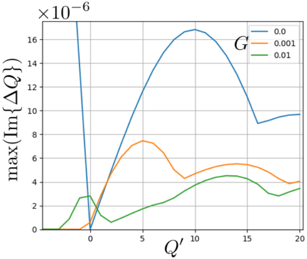
- Further development of the theory (Van Kampen modes, . . .).
- Attempt to estimate the latency without `PyRADISE` (PDE-solver).
- Need a complete understanding of the spectrum of the external noise in the (HL-) LHC (e.g. see next talk).
- Prediction of latency in HL-LHC, with max octupole detuning.
    - With external rigid-bunch noise ($\eta^2 \lesssim 10^{-4}$) – Similar to LHC.
    - With crab amplitude noise ($\eta^2 \sim 1$)– Find a noise acceptance.
- Will the HO beam-beam detuning be sufficient to mitigate L2D2 from crab amplitude noise during STABLE BEAM ($\eta^2 \sim 1$)?

Thank you for your attention!

Backup: Mode description

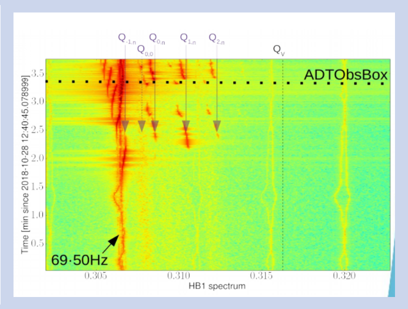
- The chromaticity and gain affects both the moments (η_m) and complex tune shifts ($\Delta\omega_m$) of the modes.
- Figures show the dipole moment and growth rate of the dominant mode.
  - $Q' < 0$: Mode 0 is dominant.
  - $Q' > 0$: Mode 0 is stable. Dipole moment of mode 1,2,... increases.
- To be done: Calculate the dependence of the latency on Q' and G.





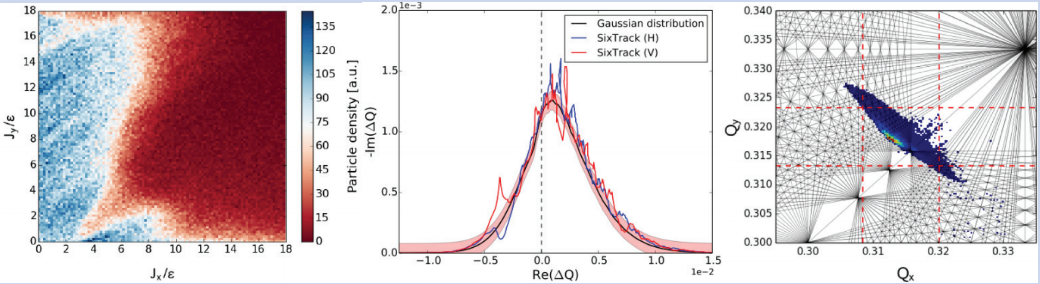
Backup: Diffusion driven by colored noise

- 50 Hz lines may drive a narrow diffusion that cannot be mitigated.
- Non-reproducible instabilities seen in the LHC with $\sim$ 10 times more Landau damping than needed according to the model.
- Not destabilizing unless a 50 Hz line is at the correct frequency.
  - If so, the wakefields will enhance the diffusion.



[X. Buffat, 153rd WP2 Meet.]

Backup: Diffusion driven by non-linearities



[C. Tambasco, PhD Thesis]

- Non-linearities can cause a frequency dependent diffusion.
- Most resonance lines are given by $mQ_x + nQ_y = p$, where $m, n \neq 0$. They do not lead to diffusion for all particles of a specific tune.

Backup: Mitigation Technique

- The diffusion and drilling is narrow in frequency.
- Can try to vary the frequency of the single particles to drill everywhere.
- This might counteract the importance of keeping Ω_j small.
- These calculations were done with constant diffusion coefficient based on the initial distribution.