Optimal Transverse Bunch Feedback to Minimize Emittance Growth

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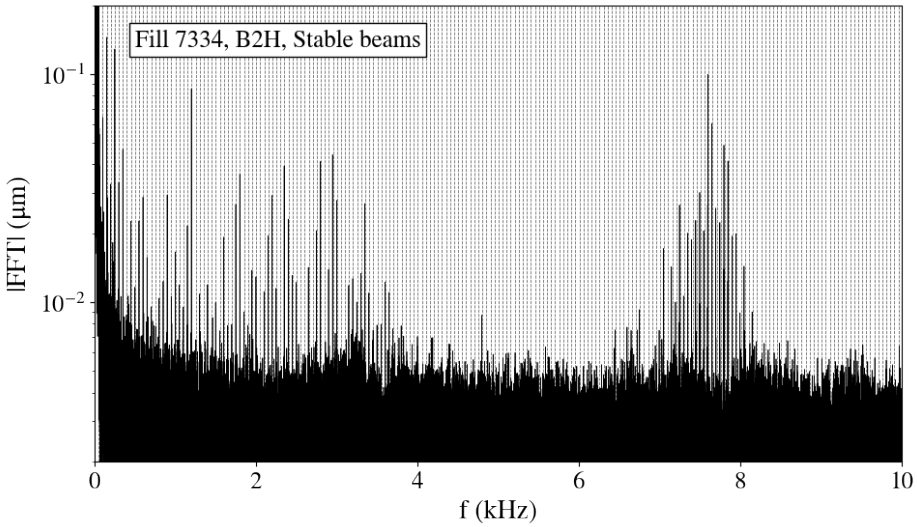
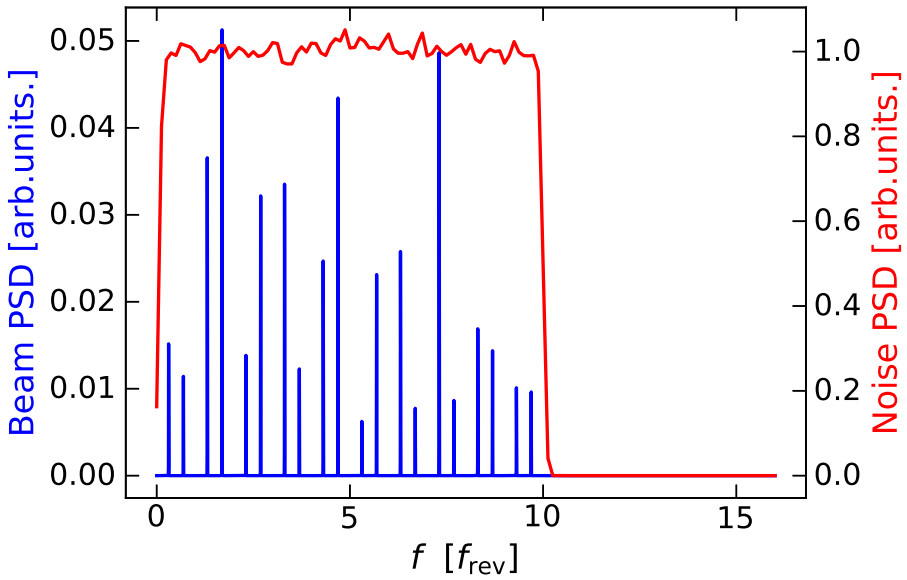
Noise

- Theory predicts that the LHC beam screen filters noise beyond $f_{\mathrm{cutoff}} < 150\,\mathrm{Hz}$.
  [M. Morrone *et al.*]
- Measurements show 50 Hz lines up to $f_{\mathrm{max}} \sim 10\,\mathrm{kHz}$.
  [S. Kostoglou *et al.*]
- The noise will only excite multi-bunch modes of frequency $f_{\mathrm{c}} < f_{\mathrm{max}}$.
- **Idea**: Investigate how different feedback filters damp the coherent multi-bunch motion.





Theory

Transverse feedback

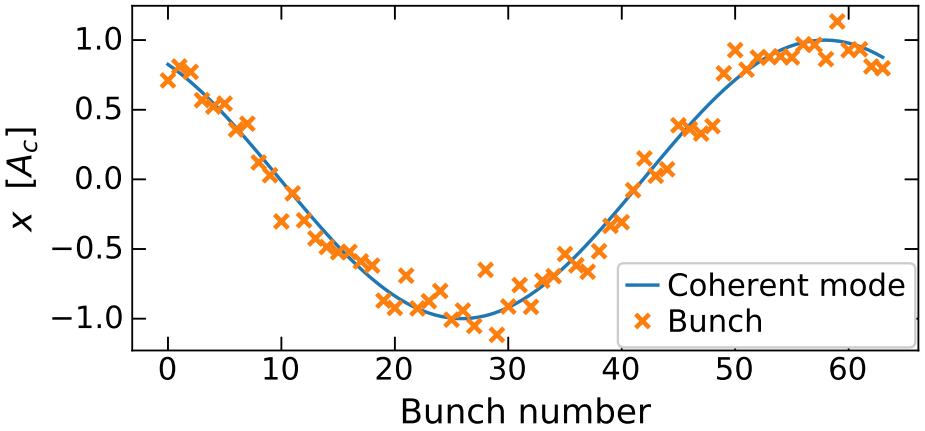
- Feedback limits emittance growth rate and maintains stability.
- **Ideal** feedback acts on bunch position x_b (excl. phase advance)

$$x_b \to x_b - gx_b = \boldsymbol{x_b(1-g)}$$

- **Real** feedback acts on measured position $x_{bm} = x_b - \delta_{bm}$

$$x_b \to x_b - gx_{bm} = \boldsymbol{x_b(1-g) + g\delta_{bm}}$$

- Do not need full bandwidth (FBW) feedback to damp low-frequent beam modes.



- Can reduce the term $\boldsymbol{g\delta_{bm}}$ without reducing feedback efficiency!

Low bandwidth (LBW) feedback

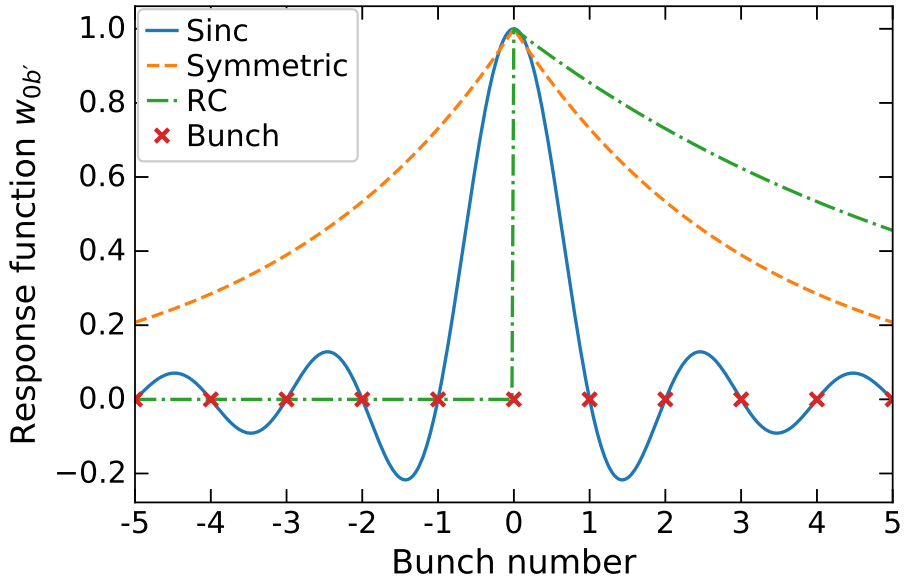
- **Low bandwidth** real feedback depends on neighbors

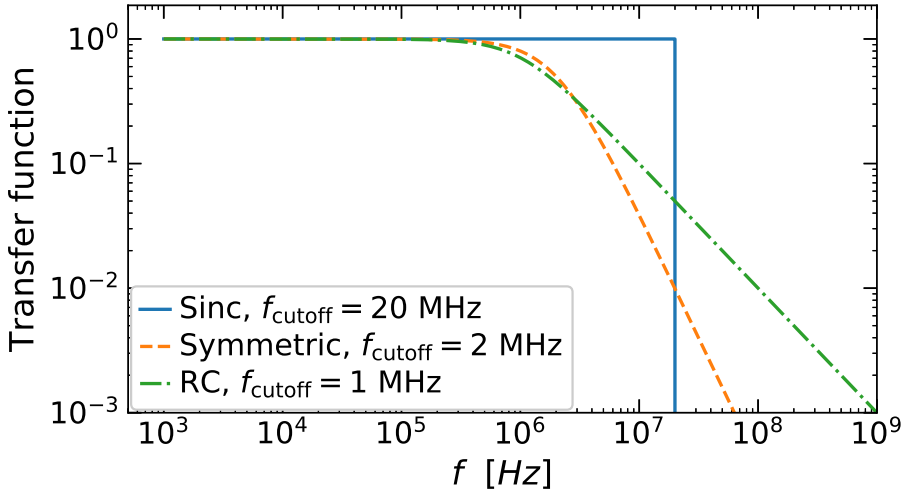
$$x_b \to \boldsymbol{x_b} - \boldsymbol{g} \sum_{\boldsymbol{b'}} \boldsymbol{w_{bb'} x_{b'm}}$$

- Efficient gain damping a mode of frequency $f_\mathrm{c} = \omega_\mathrm{c}/2\pi$

$$g_\mathrm{c} = g \sum_{b'} w_{bb'} \cos[\omega_\mathrm{c}(t_{b'} - t_b)]$$

- Effect depends on the coherent mode frequency relative to the filter's cutoff frequency
  - $f_\mathrm{c} \ll f_\mathrm{cutoff} \to g_\mathrm{c} > g$
  - $f_\mathrm{c} \gg f_\mathrm{cutoff} \to g_\mathrm{c} \ll g$





Emittance growth rate

- The emittance growth rate without feedback is equal to

$$\frac{\dot{\epsilon}_{\mathrm{tot}}}{\epsilon_0} = \frac{\sigma^2_{\mathrm{Noise}}}{2}$$

- The feedback reduces the growth rate for FBW feedback [V. Lebedev]

$$\frac{\dot{\epsilon}_{\mathrm{tot}}}{\epsilon_0} = \frac{\sigma^2_{\mathrm{Noise}} + g^2\sigma^2_{\mathrm{BPM}}}{2} \cdot \left\langle \frac{\left(1-\frac{g}{2}\right)^2 4\pi^2\Delta Q^2}{\left(\frac{g}{2}\right)^2 + \left(1-\frac{g}{2}\right) 4\pi^2\Delta Q^2} \right\rangle$$

- The LBW feedback can further reduce the growth rate caused by the machine noise if $g_{\mathrm{c}} > g$

$$\frac{\dot{\epsilon}_{\mathrm{Noise}}}{\epsilon_0} = \frac{\sigma^2_{\mathrm{Noise}}}{2} \cdot \left\langle \frac{\left(1-\frac{g_{\mathrm{c}}}{2}\right)^2 4\pi^2\Delta Q^2}{\left(\frac{g_{\mathrm{c}}}{2}\right)^2 + \left(1-\frac{g_{\mathrm{c}}}{2}\right) 4\pi^2\Delta Q^2} \right\rangle$$

- The BPM noise induced growth rate is challenging to tackle analytically. Wait for the numerical results!

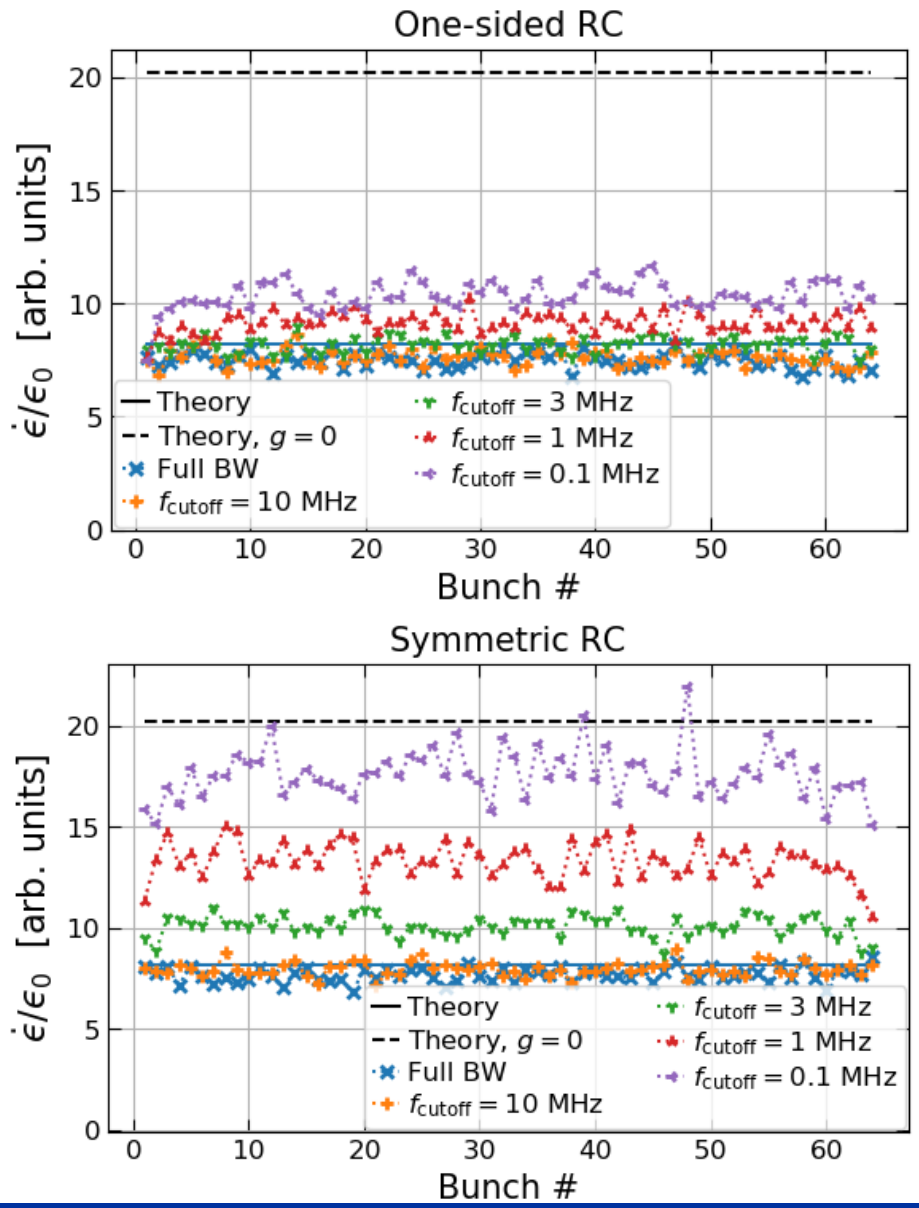
Numerical Results

Numerical setup

- 64 bunches.
- 10^6 particles per bunch.
- 10^5 turns.
- Bunch separation $\Delta t = 25\,\mathrm{ns}$.
- Single bunch feedback gain $g = 0.01 = 2/\tau$, unless stated otherwise.
- Linear detuning $Q_x = Q_{x0} + 10^{-3} J_x - 7 \times 10^{-4} J_y$ (normalized actions).
- Different noise sources of rms amplitude $\sigma_{\mathrm{HF,LF,BPM}}$:
  - High frequent noise, uncorrelated between bunches.
  - Low frequent flat noise spectrum up to $f_{\mathrm{max}} = f_{\mathrm{rev}} = 11.245\,\mathrm{kHz}$.
  - Uncorrelated pickup noise $\rightarrow$ LBW feedback correlates the kicks.

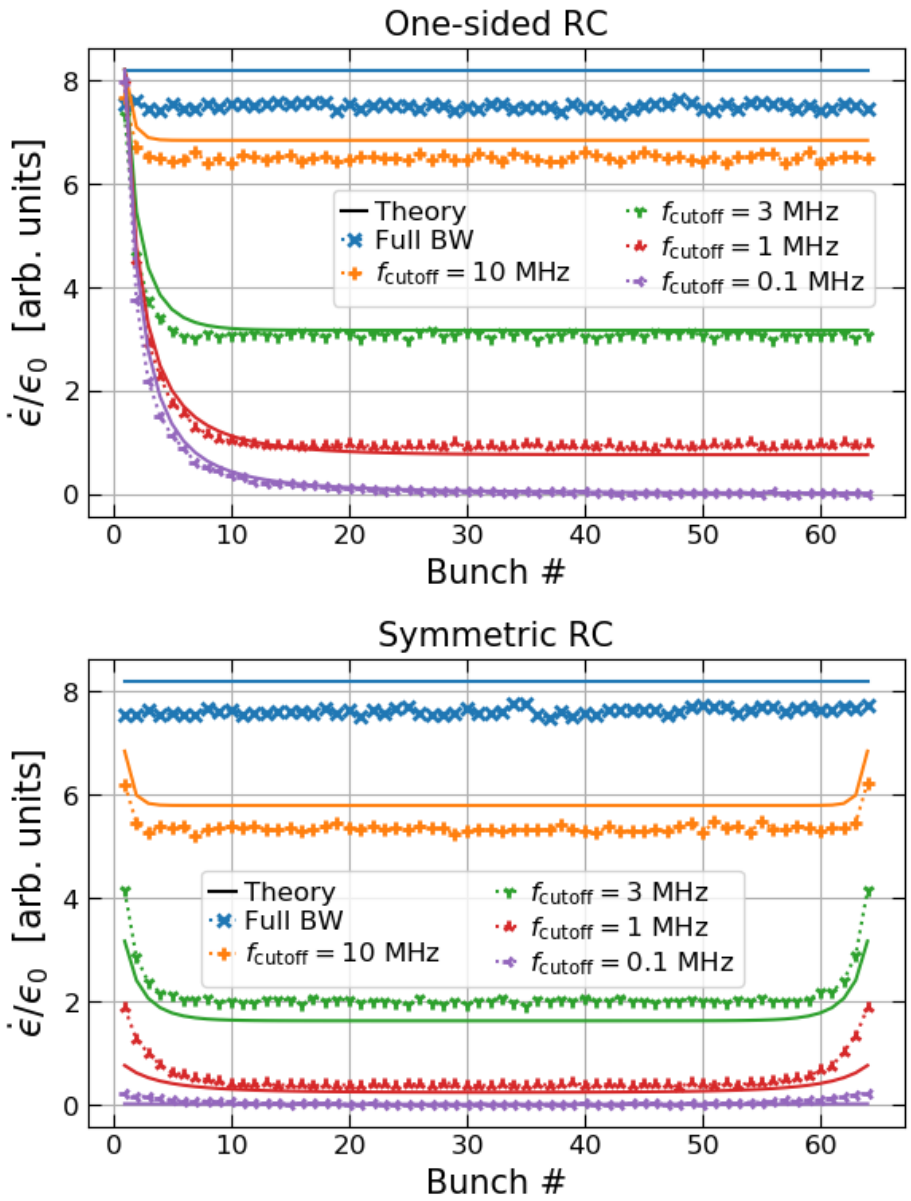
High-frequency (HF) machine noise

- No correlation between the kicks on neighboring bunches.
- Lead to uncorrelated multi-bunch motion.
- LBW feedback will not help, $g_c < g$.
- **HF noise is qualitatively different from the LHC noise.**



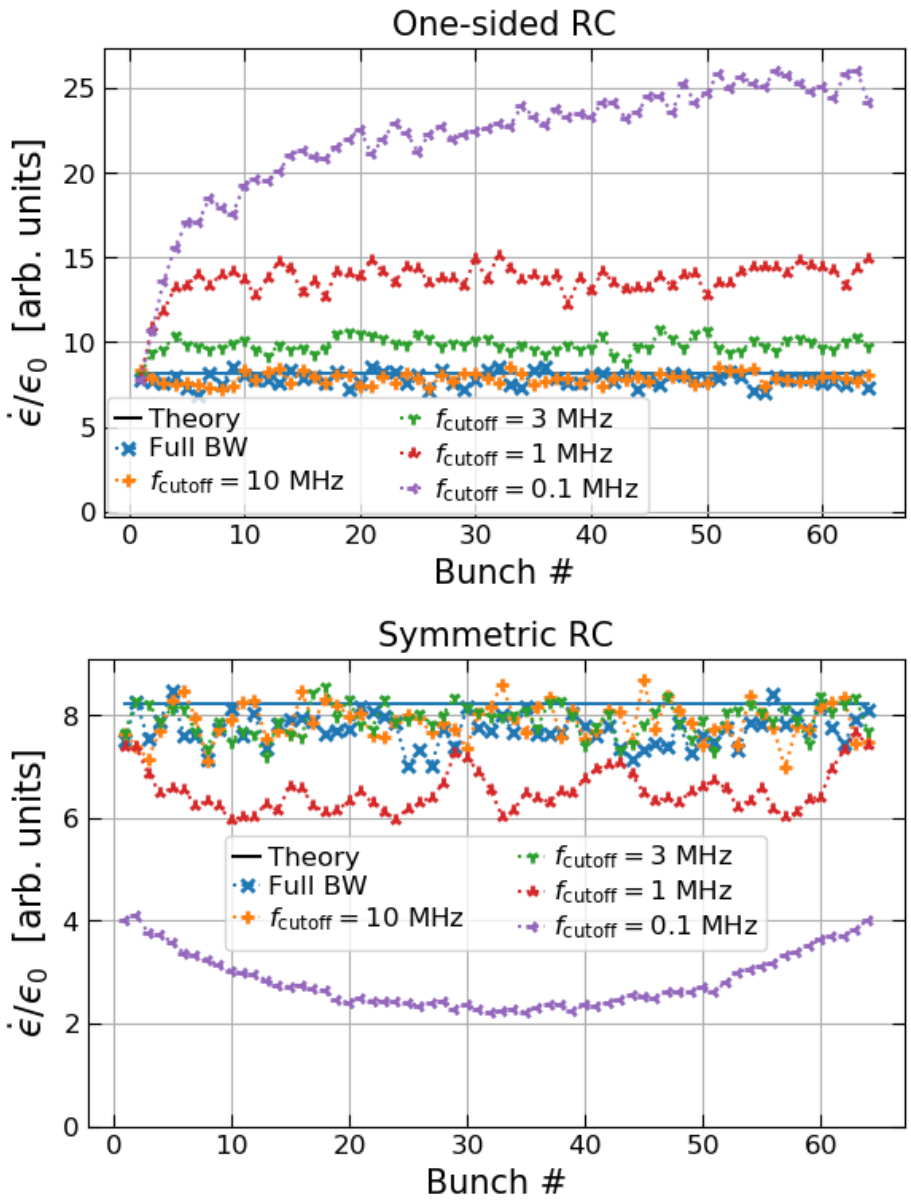
Low-frequency (LF) machine noise

- Correlation between the kicks on neighboring bunches.
- Lead to correlated multi-bunch motion of $f_c \leq f_{\max}$.
- LBW feedback will help if $f_{\max} = f_{\text{rev}} \ll f_{\text{cutoff}}$.
- **This noise is qualitatively similar to the LHC noise.**



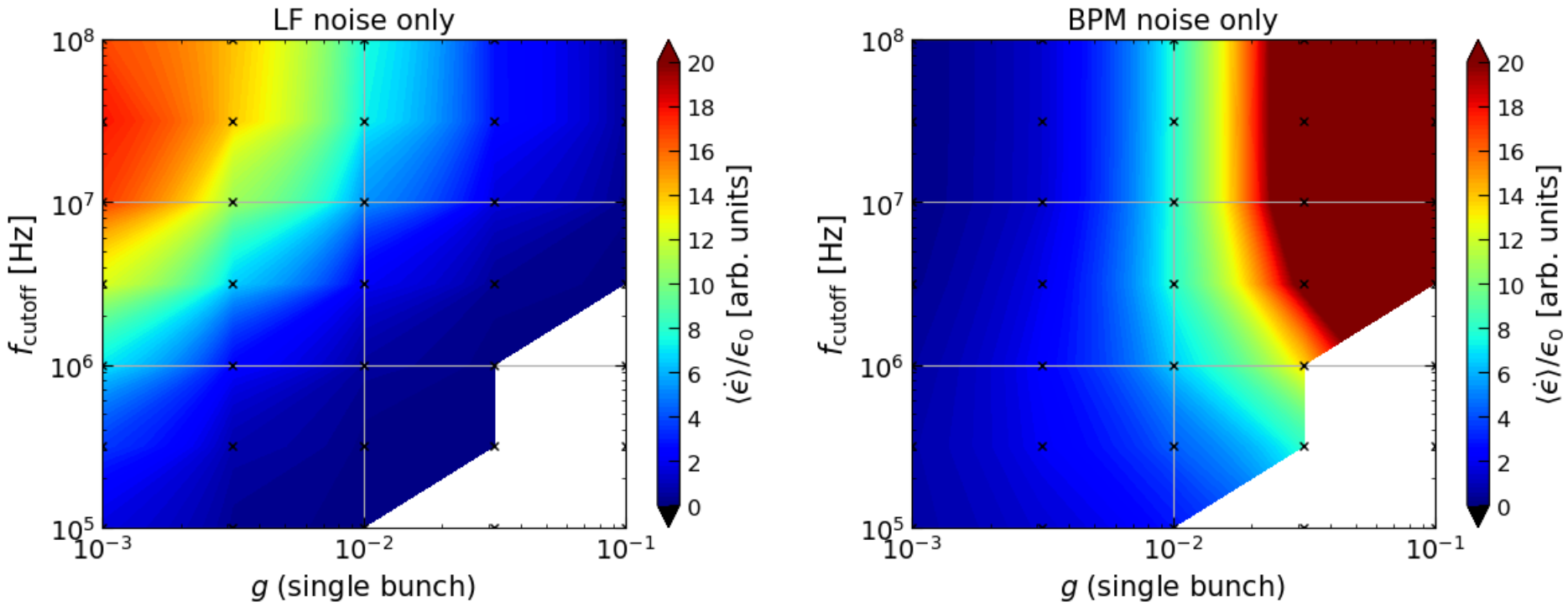
Beam position monitor (BPM) noise

- Position measurement error is assumed uncorrelated.
- BPM noise is inflicted on the beam by the feedback. $\rightarrow$ BPM noise has the same spectrum as the feedback.
- **LBW feedback helps marginally for symmetric feedback only.**



Gain and bandwidth scan

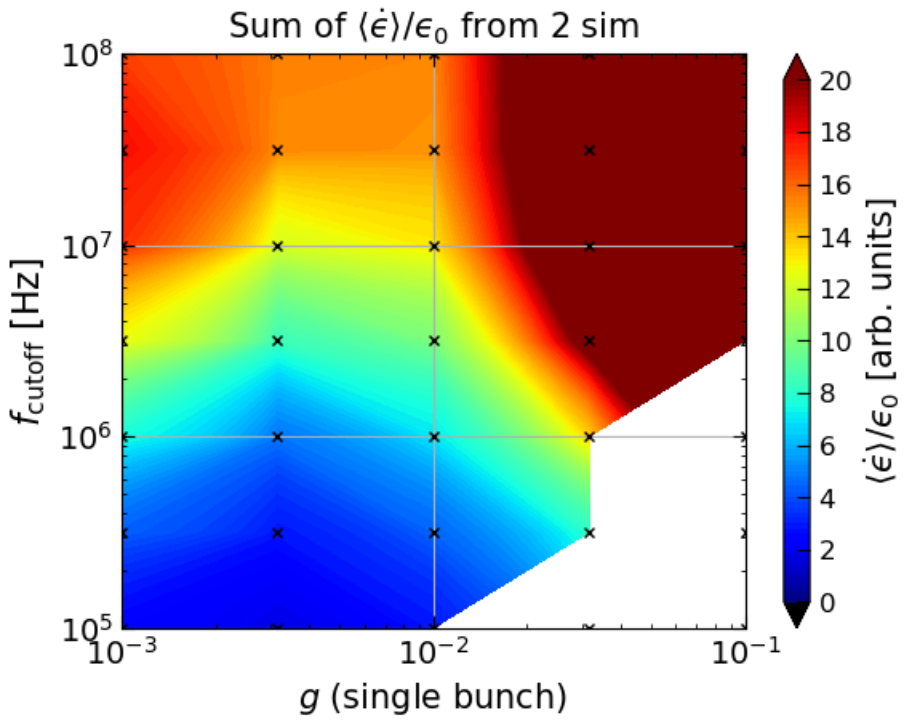
- For each g, f_{cutoff}, present average growth rate over 64 bunches, using a symmetric LBW feedback.

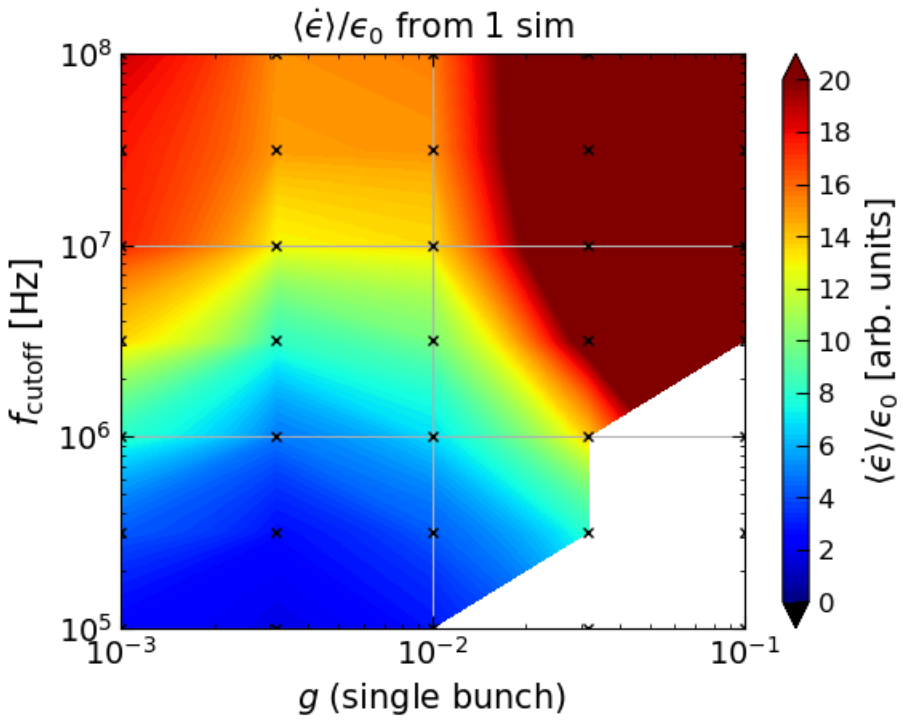


- White area signifies that the beam went unstable due to $g_{\mathrm{c}} > 1.02$.

LF noise and BPM noise

- Different noise sources are uncorrelated → Assume that the emittance growth rate is the sum of the individual growth rates.

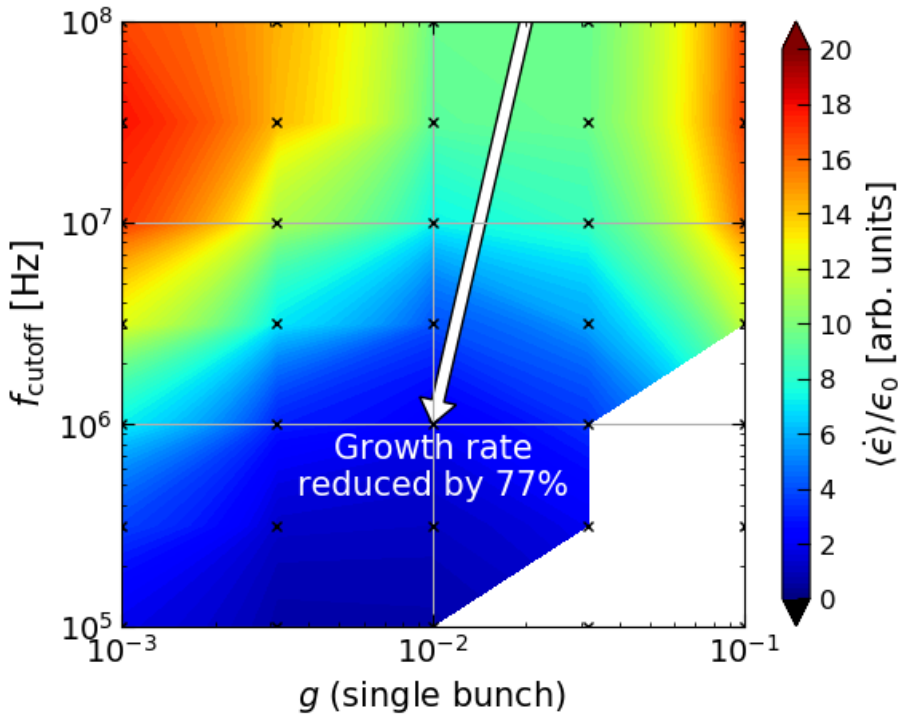


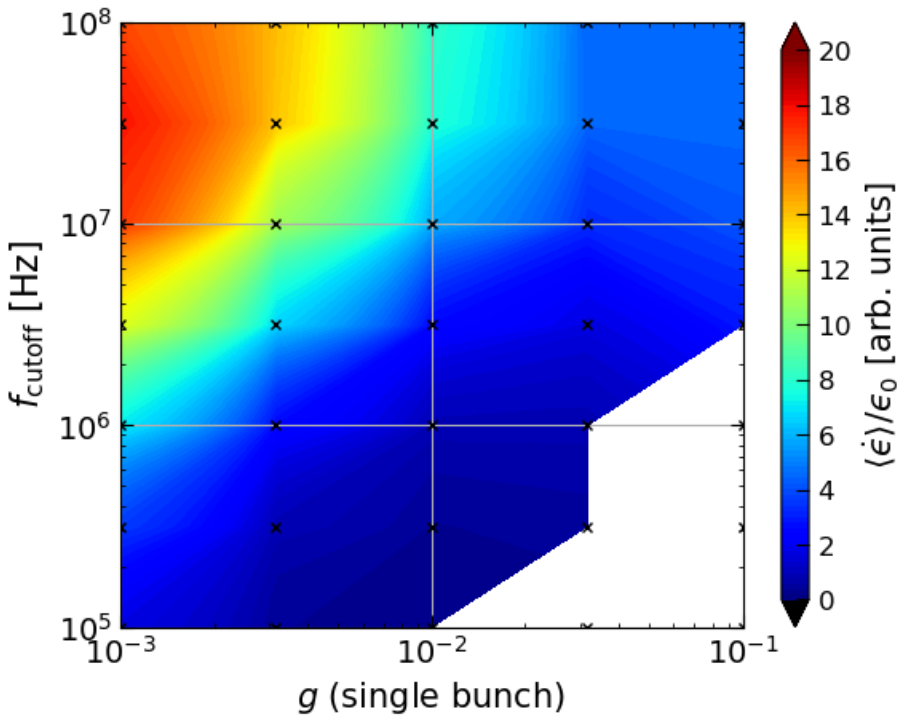


- Relative difference has standard deviation of 3.2%.
- Expect a nonzero difference between equal simulations due to noise.

Optimal transverse feedback

- $\sigma_{\mathrm{BPM}} = 50\sigma_{\mathrm{LF}}$, similar to LHC. [X. Buffat *et al.*]
- $\sigma_{\mathrm{BPM}} = 25\sigma_{\mathrm{LF}}$, if one could half the pickup error.





- BPM noise moves the optimum towards smaller f_{cutoff} and g.
- Reducing the pickup error is important if full bandwidth is needed.

Summary & Outlook

- Using a **LBW feedback can reduce the emittance growth**
  - caused by LF machine noise, as in the LHC, and
  - caused by BPM noise IFF the feedback is symmetric.
- The emittance growth rate from different noise sources can to first order be summed, even if the feedback couples the noise.
- **Reducing the pickup error** will reduce the emittance growth rate, and **allows more optimal scenarios with full bandwidth**.

- **Outlook**:
  - Implement the response function of the ADT in the LHC.
  - Test more LHC relevant beam constellations (8b4e etc.).
  - Include beam-beam and wakefields to see if the LBW feedback still manages to stabilize multi-bunch instabilities.
  - Test the model's prediction in MDs and, if successful, implement an optimal setup for physics in run 3.

Thank you for your attention!

Backup: LF noise and BPM noise

- Include both LF and BPM noise with $f_{\mathrm{cutoff}} = 1\,\mathrm{MHz}$.
  - Max amplitude of either noise type is equal to those studied on previous slides.
- Different noise sources are uncorrelated $\rightarrow$ Emittance growth rate is the sum of the individual growth rates.