The Use of a Damping System in a Synchrotron for Short-Time Excitation of Coherent Oscillations of Particles

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XIII International Scientific Workshop in Memory of V. P. Sarantsev

September 3–8 2019, Alushta, Russia

September 5, 2019

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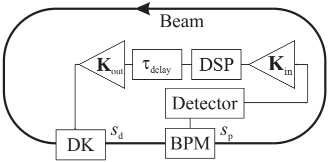
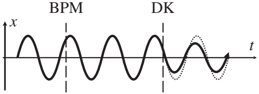
Transverse feedback system at the LHC (CERN)

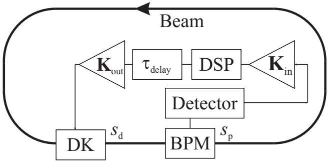


BPM – beam position monitor
DK – damper kicker
$\mathbf{K}_{\rm in}$, $\mathbf{K}_{\rm out}$ – analog amplifiers
DSP – digital sinal processor



$$g = \left| \sqrt{\hat{\beta}_{\rm d}\hat{\beta}_{\rm p}}\, \Delta x'_{\rm d} \,/ x_{\rm p} \right| < 1$$

Transverse feedback system at the LHC (CERN)



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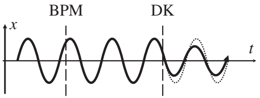
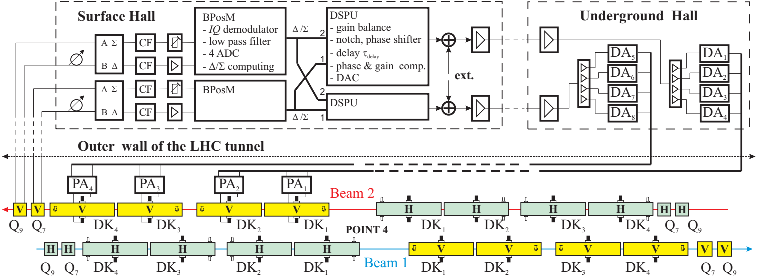
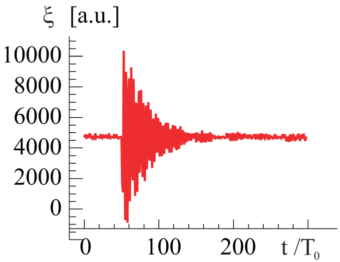


$$g = \left| \sqrt{\hat{\beta}_d \hat{\beta}_p}\, \Delta x'_d / x_p \right| < 1$$

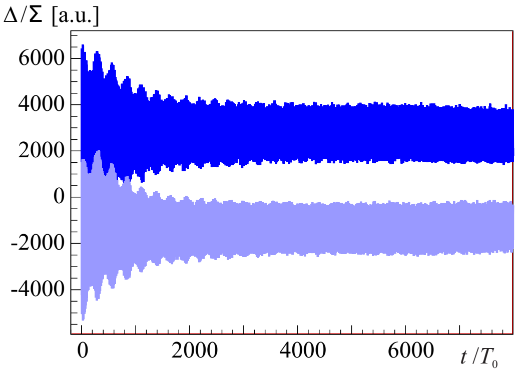
LHC accelerates and collides two counter-rotated beams at 6.5 TeV (beam stored energies $\gtrsim$ 300 MJ)

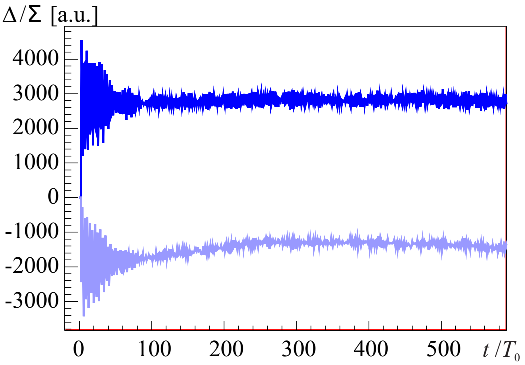


LHC Damper (CERN–JINR digital transverse feedback system)
works reliably since May 2010



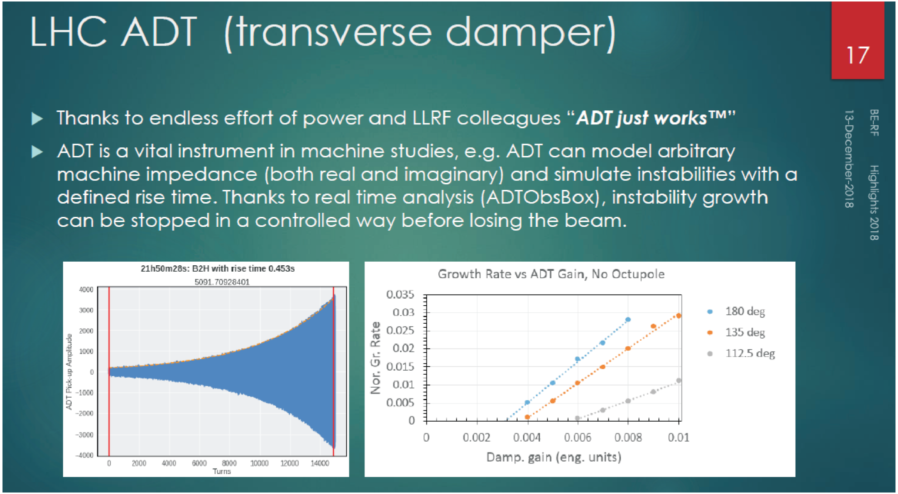
Damping of transverse oscillations after injection: $\tau_d / T_0 = 40$





Damping of horisontal injection errors (beam 1): Damper OFF (left) and Damper ON (right); signals from $Q7$ (top) and $Q9$ (bottom).

Zhabitsky V.M. et al. Beam Tests of the LHC Transverse Feedback System. RuPAC-2010. Pp. 275-279.



Highlights 2018. BE-RF Annual Meeting. CERN, 17.12.2018

short time excitation of transverse oscillations;

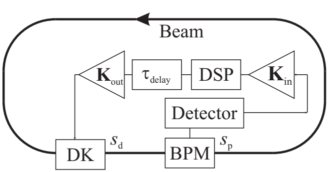
low intensity bunch;

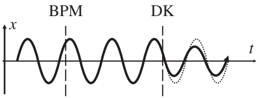
small gain g;

$Q_0 = \text{const}$;

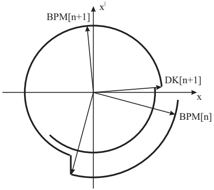
variation of a feedback chain parameter.

Transverse feedback system





$$g = \left| \sqrt{\hat\beta_d \hat\beta_p}\, \Delta x'_d / x_p \right| < 1$$



$$\widehat{X}_i(n,s_2) = \widehat{M}(s_2|s_1)\widehat{X}_i(n,s_1)$$

$$\widehat{X}_i(n,s) = \begin{pmatrix} x_i(n,s) \\ x'_i(n,s) \end{pmatrix}$$

$$s_p \leqslant s < s_d: \quad \widehat{X}_i(n+1,s) \equiv \widehat{X}_i(n,s+C_0) = \widehat{M}(s+C_0|s)\widehat{X}_i(n,s) + \widehat{M}(s+C_0|s_d)\begin{pmatrix} 0 \\ \Delta x'_d \end{pmatrix}$$

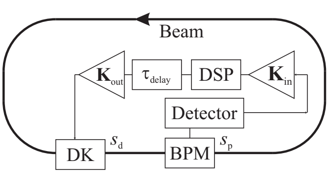
For feedback: $\Delta x'_d = g\varkappa\, F_d\big(x_i(n,s_p)\big)/\sqrt{\hat\beta_d \hat\beta_p}$

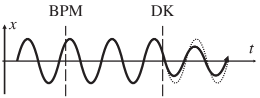
$\xi_n = x_i(n,s_p) \quad \Rightarrow \quad \xi_{n+2} - 2\,\xi_{n+1}\cos\mu + \xi_n = g\varkappa\cdot\big(F_d(\xi_n)\sin\eta + F_d(\xi_{n+1})\sin(\mu-\eta)\big)$

where: $\mu = 2\pi Q_0 = \Omega T_0\,, \quad \Omega = \omega_0 Q_0\,, \omega_0 = 2\pi/T_0\,, \quad \eta = \psi(s_d|s_p) = \psi(t_d|t_d-\tau)$

Digital feedback chain with FIR-filter: $F_d(\xi_n) = \frac{1}{H_0}\sum_{m=0}^{N_f}\big(\xi_{n-(m+\hat q)} + \delta\xi_p\big)\, b_m\,;$

Transverse feedback system





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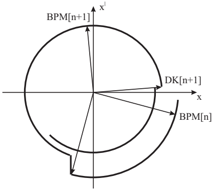

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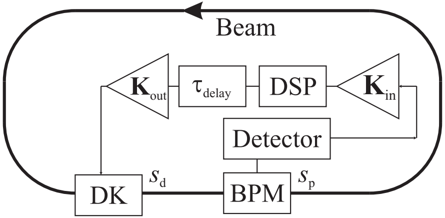
where: $\mu = 2\pi Q_0 = \Omega T_0\,, \quad \Omega = \omega_0 Q_0\,, \omega_0 = 2\pi / T_0\,, \quad \eta = \psi(s_{\rm d}|s_{\rm p}) = \psi(t_{\rm d}|t_{\rm d} - \tau)$

Digital feedback chain with FIR-filter: $F_{\rm d}(\xi_n) = \frac{1}{H_0} \sum_{m=0}^{N_{\rm f}} \big(\xi_{n-(m+\hat{q})} + \delta\xi_{\rm p}\big)\, b_m\,; \quad \sum_{m=0}^{N_{\rm f}} b_m = 0$

Characteristic equation for $\xi_n = {\rm const} \cdot z_r^n$

$$z_r^2 - 2\,z_r\cos\mu + 1 = g\varkappa\, z_r^{-\hat{q}}\big(\sin\eta + z_r\sin(\mu - \eta)\big) H(z_r)/H_0 \quad \Rightarrow \text{ if } g = 0 \text{ then } z_r = {\rm e}^{\pm {\rm j}\mu}$$

$$H(z_r) = \sum_{m=0}^{N_{\rm f}} b_m\, z_r^{-m} \quad \Rightarrow \text{for } z_r^{(0)} = {\rm e}^{{\rm j}\mu} = {\rm e}^{{\rm j}2\pi Q_0} = {\rm e}^{{\rm j}\Omega T_0} \quad \Rightarrow \quad H(\Omega) = \sum_{m=0}^{N_{\rm f}} b_m\, {\rm e}^{-{\rm j}m\Omega T_0}$$



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Characteristic equation for feedback with FIR-filter $H(z)$:

$$z_r^2 - 2\,z_r\cos\mu + 1 = g\varkappa\, z_r^{-\hat q}\big(\sin\eta + z_r\sin(\mu-\eta)\big)H(z_r)/H_0$$

If $z_r = \exp\big(\alpha_{\rm d} + {\rm j}\,2\pi(Q_0 + \Delta Q_{\rm d})\big)$ then for $g \ll 1$:

$$\alpha_{\rm d} = -\frac{g}{2}\,\frac{|H(\Omega)|}{H_0}\,\varkappa\sin\Psi\,, \quad \Delta Q_{\rm d} = -\frac{g}{4\pi}\,\frac{|H(\Omega)|}{H_0}\,\varkappa\cos\Psi, \quad \Psi = \eta + 2\pi\hat q\,Q_0 - \arg H(\Omega)$$

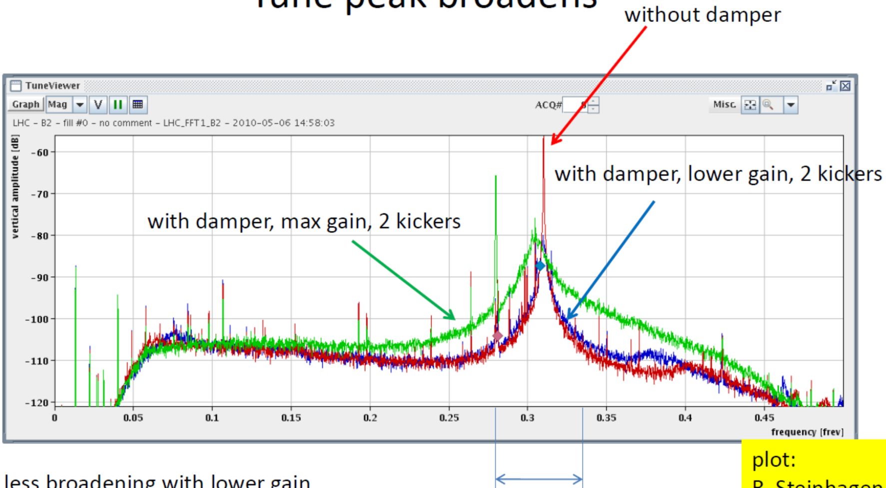
Damping mode: $\varkappa\sin\Psi > 0$

Optimal damping: $\varkappa\sin\Psi = 1 \quad \Rightarrow \cos\Psi = 0 \quad \Rightarrow \Delta Q_{\rm d} = 0$

Asymptotic behaviour:

$$\lim_{n\to\infty}\widehat{X}[n,s] = \lim_{z\to 1}(z-1)\,\widehat{\mathbf{X}}(z,s) = 0 \quad \Rightarrow H(\Omega=0) = \sum_{m=0}^{N_{\rm f}} b_m = 0$$

Tune peak broadens



plot:
R. Steinhagen

less broadening with lower gain
reduction of tune peak, i.e.
residual oscillations by more than 20 dB

range were FB works well
(limits 45 degrees phase error)

Höfle W. Transverse damper operation (presentation). Evian 2010. CERN–ATS–2011–017.

Phase balance tuning

LHC Damper feedback chain with notch and Hilbert filters:

$$H(z=e^{\mathrm{j}\,\Omega T_0}) = (1-z^{-1})\left(z^{-3}\cos\varphi + z^{-2}(1-z^{-2})\,\frac{2\sin\varphi}{\pi} + (1-z^{-6})\,\frac{2\sin\varphi}{3\pi}\right)$$

Phase balance ($g \ll 1$): $\Psi = \eta + 2\pi\hat{q}\,Q_0 + \Omega\tau_\phi$, where $\tau_\phi = -\Omega^{-1}\arg H(\Omega,\varphi)$ is the phase delay depending on parameter φ at the constant angular frequency $\Omega = \Omega_\beta = \{Q_0\}\,\omega_0 = \{Q_0\}\,\frac{2\pi}{T_0}$.

If $\varkappa\sin\Psi(Q_0,\varphi_0) = 1$ then $\{Q\} = \{Q_0\} + \frac{g}{4\pi}\sin(\Omega\,\delta\tau_\phi)$, $\frac{T_0}{\tau_\mathrm{d}} = \frac{g}{2}\cos(\Omega\,\delta\tau_\phi)$, $\delta\tau_\phi = \tau_\phi(\varphi) - \tau_\phi(\varphi_0)$

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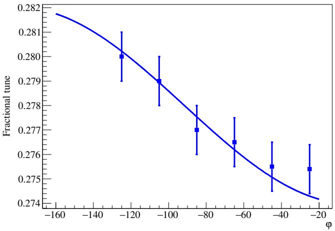

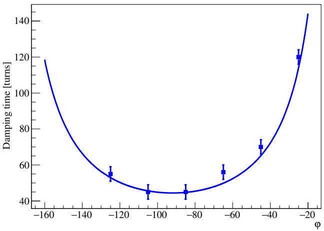

Fractional tunes $\{Q\}$ (left) and damping times τ_d/T_0 (right) in dependence on the Hilbert filter parameter φ at $Q_0 = 64.278$ and $\hat{q} = 2$ (Experimental data from: Höfle W. et al. LHC Transverse Damper Observations versus Expectations. CERN–ATS–2011–017. Pp. 107–114.)

Damping parameters in dependence on tune deviations

Phase balance: $\Psi = 2\pi Q \cdot \big(\nu/Q + \hat{q}\big) - \arg H(\Omega, \varphi)\,, \;\; \Omega = Q\,\omega_0\,,\; \nu = \eta/2\pi\,,\; Q = Q_0 + \Delta Q_0$.
If $\varkappa \sin\Psi(Q_0, \varphi_0) = 1$ and $\varphi = \varphi_0 =$ const, then $\Psi = \Psi(Q_0, \varphi_0) + \Delta\Psi$ and for $|\Delta\Psi| \ll 1$:
$\Delta\Psi \approx \big(\nu(Q_0)/Q_0 + \hat{q}\big)\Delta Q_0 + \tau_g \omega_0 \Delta Q_0\,,$ where $\tau_g = -\dfrac{\partial \arg H(\Omega)}{\partial\Omega} > 0$ is the group delay.

$$\Delta Q_{\mathrm{d}} = \frac{g}{4\pi}\,\frac{|H(\Omega)|}{H_0}\sin\Delta\Psi\,, \qquad \frac{T_0}{\tau_{\mathrm{d}}} = \frac{g}{2}\,\frac{|H(\Omega)|}{H_0}\cos\Delta\Psi$$

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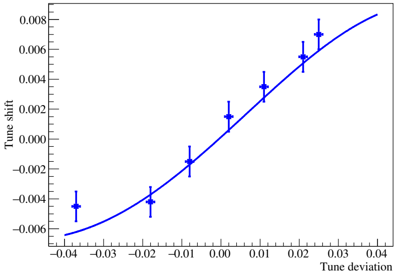
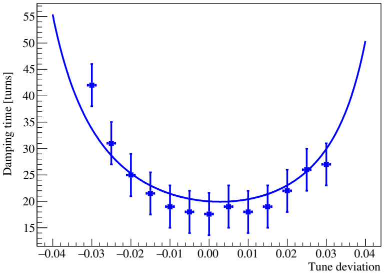
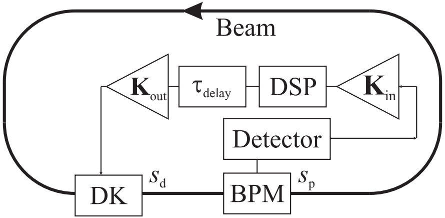




Tune shifts $\Delta Q_{\rm d}$ (left) and damping times $\tau_{\rm d}/T_0$ (right) in dependence of the tune deviations ΔQ_0 from $Q_0 = 59.295$ at $\hat{q} = 0$ (Experimental data from: Komppula J. et al. MD4036: New ADT signal processing for large tune acceptance. CERN–ATS–NOTE–2019–0008).

"Smooth approximation"



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"Smooth approximation":

$$\ddot{\xi}(t) + \Omega^2\xi(t) = \frac{g\varkappa\Omega}{T_0}\,F_{\rm d}\big(\xi(t-\tau)\big), \quad \Omega = 2\pi Q_0/T_0$$

$\Rightarrow$ differential equation with delayed argument.

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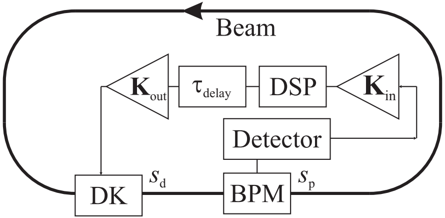

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Digital feedback chain with FIR-filter: $F_\mathrm{d}\big(\xi(t-\tau)\big) = \frac{1}{H_0}\sum\limits_{m=0}^{N_\mathrm{f}}\big(\xi(t-\tau_m)+\delta\xi_\mathrm{p}\big)b_m;\ \tau_m = \tau-(m+\hat q)T_0$

Krylov–Bogoliubov averaging method ($g \ll 1$): $\quad \xi = a\sin\phi + g\varkappa\,\delta\xi_{10} + \ldots;\quad \phi = \Omega t + \ldots$

$$\dot a = \frac{1}{2\pi\Omega}\int_0^{2\pi}\frac{1}{H_0}\sum_{m=0}^{N_\mathrm{f}}\big(a\sin(\phi-\Omega\tau_m)+\delta\xi_\mathrm{p}\big)b_m\cos\phi\,d\phi = \alpha_\mathrm{d}\,\frac{a}{T_0}$$

$$\dot\phi = \Omega - \frac{1}{2\pi a\Omega}\int_0^{2\pi}\frac{1}{H_0}\sum_{m=0}^{N_\mathrm{f}}\big(a\sin(\phi-\Omega\tau_m)+\delta\xi_\mathrm{p}\big)b_m\sin\phi\,d\phi = (Q_0+\Delta Q_\mathrm{d})\,\frac{2\pi}{T_0}$$

$$\alpha_\mathrm{d} = -\frac{g}{2}\,\frac{|H(\Omega)|}{H_0}\,\varkappa\sin\Psi\,,\quad \Delta Q_\mathrm{d} = -\frac{g}{4\pi}\,\frac{|H(\Omega)|}{H_0}\,\varkappa\cos\Psi\,,\quad \Psi = \eta + 2\pi\hat q\,Q_0 - \arg H(\Omega),\quad \eta = \Omega\tau$$

$$H(\Omega) = \sum_{m=0}^{N_\mathrm{f}} b_m\,\mathrm{e}^{-\mathrm{j}m\Omega T_0};\ H_0 = |H(\Omega_\beta)|;\ \Omega_\beta = \{Q_0\}\,\frac{2\pi}{T_0};\quad \delta\xi_{10} = \frac{\delta\xi_\mathrm{p}}{2\pi Q_0 H_0}\sum_{m=0}^{N_\mathrm{f}} b_m \Rightarrow \sum_{m=0}^{N_\mathrm{f}} b_m = 0$$

Short-time positive feedback mode: Basic model

- Differential equation for transverse oscillations with external force for feedback ("smoth approximation"):
$$\ddot{\xi}(t) + \Omega^2 \xi(t) = \frac{g \varkappa \Omega}{T_0} F_{\rm d}(\xi(t-\tau)).$$

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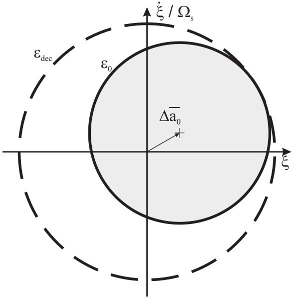
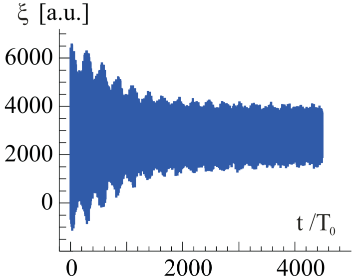
- Phase mixing:





$$\ddot{\xi}(t) + \Omega^2 \xi(t) = -\frac{2}{\tau_{\mathrm{dec}}} \dot{\xi}(t).$$

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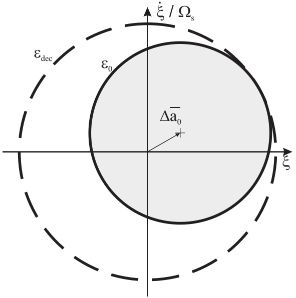
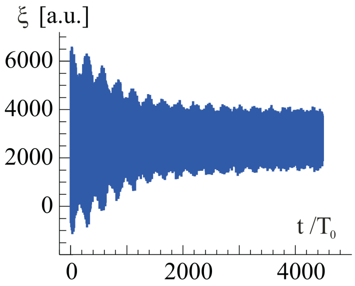




$$\ddot{\xi}(t) + \Omega^2 \xi(t) = -\frac{2}{\tau_{\rm dec}}\, \dot{\xi}(t).$$

- Basic equation for short-time positive feedback mode:

$$\ddot{\xi}(t) + \Omega^2 \xi(t) = \frac{g\varkappa\Omega}{T_0} F_{\rm d}(\xi(t-\tau)) - \frac{2}{\tau_{\rm dec}}\, \dot{\xi}(t).$$

Ideal feedback chain: increments and tune shifts

- Ideal feedback chain:

$$F_{\mathrm{d}}(\xi(t-\tau)) = \xi(t-\tau).$$

- Krylov–Bogoliubov averaging method ($g \ll 1$):

$$\dot{a} = (\alpha_{\mathrm{d}} - \alpha_{\mathrm{dec}})\,\frac{a}{T_0}\,, \qquad \alpha_{\mathrm{d}} = -\frac{g}{2}\,\varkappa\sin(\Omega\tau)\,, \quad \alpha_{\mathrm{dec}} = \frac{T_0}{\tau_{\mathrm{dec}}}\,,$$

$$\dot{\phi} = (Q_0 + \Delta Q_{\mathrm{d}})\,\frac{2\pi}{T_0}\,, \quad \Delta Q_{\mathrm{d}} = -\frac{g}{4\pi}\,\varkappa\cos(\Omega\tau)\,, \qquad \eta = \Omega\tau.$$

- Positive feedback mode:

$$\varkappa\sin(\Omega\tau) < 0, \qquad |\alpha_{\mathrm{d}}| = \frac{g}{2}|\sin(\Omega\tau)| > \alpha_{\mathrm{dec}} = \frac{T_0}{\tau_{\mathrm{dec}}}\,.$$

- Optimal regime:

$$\varkappa\sin(\Omega\tau) = -1$$

$\Rightarrow$ betatron phase advance between detector BPM and damper kicker DK equals an odd number of $\pi/2$ radians

$$\Rightarrow \quad \Delta Q_{\mathrm{d}} = 0$$

Feedback chain with FIR-filter: increments and tune shifts

- Feedback chain with digital FIR filter:

$$F_{\mathrm{d}}\big(\xi(t-\tau)\big) = \frac{1}{H_0}\sum_{m=0}^{N_{\mathrm{f}}}\big(\xi(t-\tau_m)+\delta\xi_{\mathrm{p}}\big)b_m; \qquad \tau_m = \tau-(m+\hat{q})T_0\,.$$

- Krylov–Bogoliubov averaging method ($g \ll 1$):

$$\dot{a} = (\alpha_{\mathrm{d}}-\alpha_{\mathrm{dec}})\,\frac{a}{T_0}\,, \qquad \dot{\phi} = (Q_0+\Delta Q_{\mathrm{d}})\,\frac{2\pi}{T_0}\,,$$

$$\alpha_{\mathrm{d}} = -\frac{g}{2}\,\frac{|H(\Omega)|}{H_0}\,\varkappa\sin\Psi\,, \qquad \Delta Q_{\mathrm{d}} = -\,\frac{g}{4\pi}\,\frac{|H(\Omega)|}{H_0}\,\varkappa\cos\Psi\,,$$

where phase balance:

$$\Psi(\Omega) = \eta+2\pi\hat{q}\,Q_0-\arg H(\Omega), \qquad \eta \equiv \Omega\tau = 2\pi Q_0\,\tau/T_0\,.$$

and transfer function of feedback chain:

$$H(\Omega) = \sum_{m=0}^{N_{\mathrm{f}}} b_m\,\mathrm{e}^{-\mathrm{j}\,m\Omega T_0}\,; \quad H_0 = |H(\Omega_\beta)|; \quad \Omega_\beta = |\{Q_0\}|\,\frac{2\pi}{T_0}\,.$$

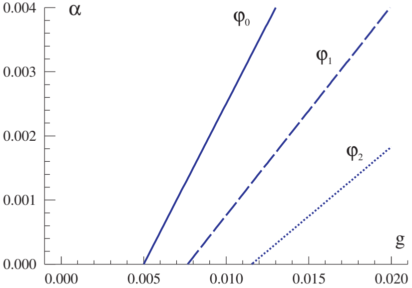
- Positive feedback mode:

$$\varkappa\sin\Psi < 0, \qquad \alpha_{\mathrm{d}} = -\frac{g}{2}\,\frac{|H(\Omega)|}{H_0}\,\varkappa\sin\Psi > \alpha_{\mathrm{dec}}\,, \qquad \sum_{m=0}^{N_{\mathrm{f}}} b_m = 0.$$

- Optimal regime: $\varkappa\sin\Psi = -1 \quad \Rightarrow \quad \Delta Q_{\mathrm{d}} = 0.$

LHC Damper with short-time positive feedback mode

- horizontal oscillations of Beam 2 at injection: $Q_0 = 64.28, \quad \hat{q} = 1$
- feedback chain ($\eta = 0.183 \cdot 2\pi$, $\hat{q} = 1$) with notch and Hilbert filters:
  $$H(z) = (1 - z^{-1}) \left(z^{-3} \cos\varphi + z^{-2}(1 - z^{-2}) \frac{2\sin\varphi}{\pi} + (1 - z^{-6}) \frac{2\sin\varphi}{3\pi} \right)$$
- decrement of natural damping of coherent transverse oscillations due to phase mixing of particles: $\alpha_{\text{dec}} = 0.0025$



Dependence of increment α on gain g: $\varphi_0 = \varphi_{\text{opt}}$ (solid), $\varphi_1 = \varphi_0 - 45°$ (dashed), $\varphi_2 = \varphi_0 - 60°$ (dotted)

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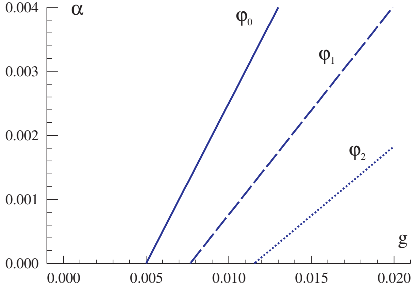

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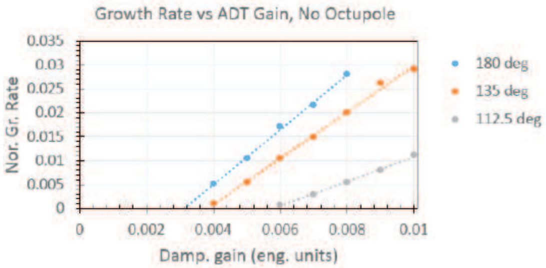
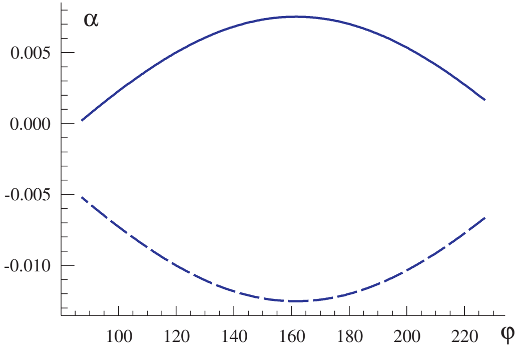
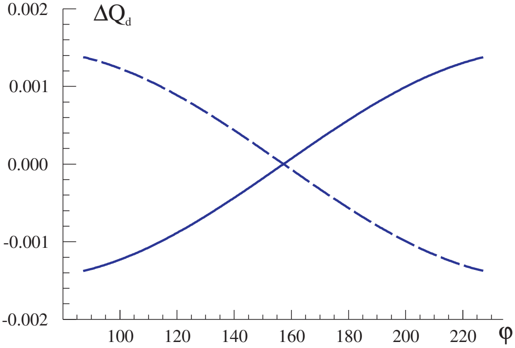


Highlights 2018. BE-RF Annual Meeting. CERN, 17.12.2018

Damper with negative and short-time positive feedback modes



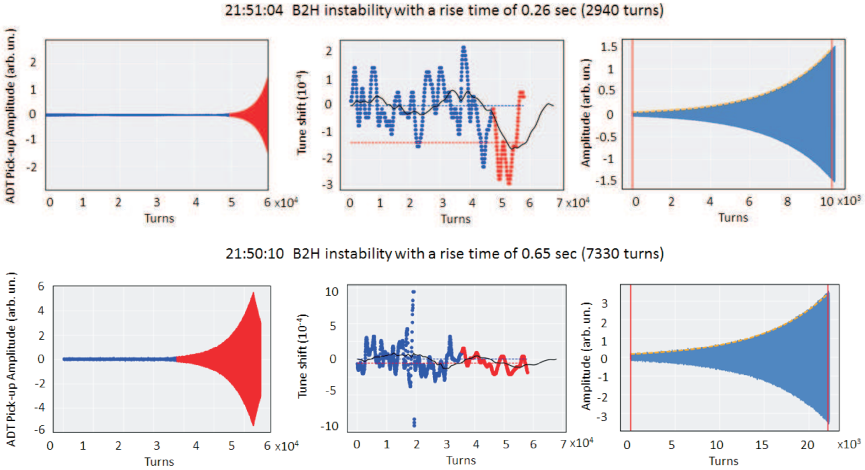
Dependences of increment (solid line) and decrement (dashed line) on Hilbert filter parameter φ at fixed gain $g = 0.02$



Dependences of ΔQ_d on φ with negative (dashed line) and short-time positive (solid line) feedback modes

- resonance condition ($\Delta Q_\mathrm{d} = 0$) for damping or growth of coherent transverse oscillations at $\varphi = \varphi_\mathrm{opt} = 157.1°$
- if short-time positive feedback mode is returned to negative feedback mode at fixed φ then tune Q is jumped when $|\Delta Q_\mathrm{d}| \neq 0$

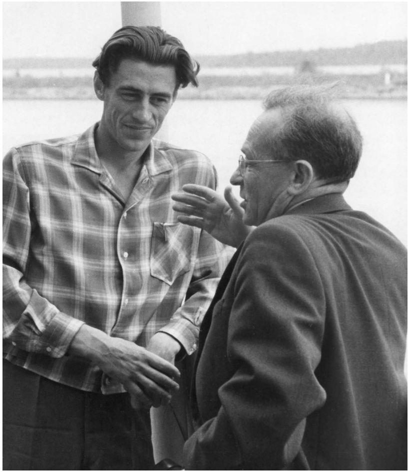
LHC Damper with short-time positive feedback mode



The active feedback system can be used as a source of controlled an arbitrary complex tune shift. Antipov S. et al. Study of Landau damping with Antidamper. CERN–ATS–NOTE–2019–0034.

Conclusion

- Some features of short-time excitation of coherent transverse oscillations of a bunch in a synchrotron using a damping system in the positive feedback mode are revealed.
- The increment of oscillations, depending on the feedback gain, should exceed the decrement of the phase mixing of the particles in the bunch.
- The maximum rate of increment is obtained at zero shift of the coherent frequency relative to the natural frequency of the particles in the bunch.



Thank you for your attention!