One-turn delay filters in LLRF feedback controllers of circular accelerators

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One-Turn Delay Filters in Feedback Controllers

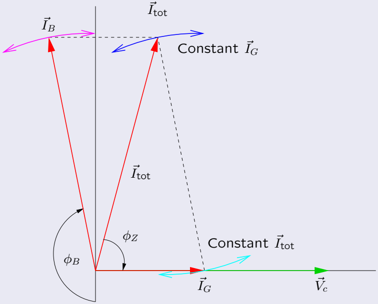
- Strong RF feedback is used in high current circular accelerators to reduce the transient beam loading and the effective cavity fundamental impedance
- The gain of these systems is limited by the total group delay (fundamental loop stability limit)
- The SPS at CERN has transmitters on the surface. When the intensity was increased in the early 1980s, there was a need for impedance reduction, but the 3 μs loop delay would significantly reduce the maximum gain
  - Insufficient effective impedance reduction
- D. Boussard came up with One-turn delay feedback technique
- Since then, it has been used in many machines (PS, PEP-II, LHC among others)

One-Turn Delay Filters in Feedback Controllers

- **Trade bandwidth for gain**
- The principle is to provide gain only around the revolution harmonics and add extra delay to make the system delay equal to one turn, so that the added open loop phase is a multiple of 360° on the revolution harmonics
- Two goals:
  - For transient beam loading compensation what matters is the gain at $n \cdot f_{rev}$ (expect for injection transients) – LHC
  - The reduction of longitudinal coupled-bunch instabilities is defined by the effective impedance at the synchrotron sidebands of the revolution harmonics – PEP-II

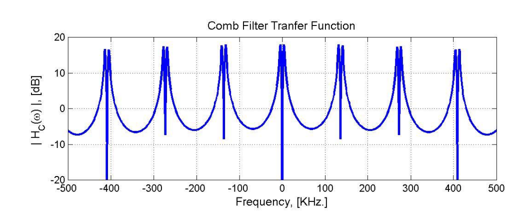
PEP-II Low/High Energy Rings (LER/HER)

- At PEP-II transient beam loading compensation is impractical (need twice the power)
- One-turn delay feedback was only used for effective impedance reduction
  - The current at PEP-II rings was pushed to 2 times the design value
  - As a result longitudinal coupled-bunch instabilities (5X the design estimates) were really limiting the machine performance and reliability



- Stability at PEP-II was achieved by a piecemeal approach (multiple RF FB loops for impedance reduction, longitudinal dampers for the rest)
- LLRF set for optimal impedance reduction. The magnitude of the dominant growth rate was used as a metric to set the LLRF parameters

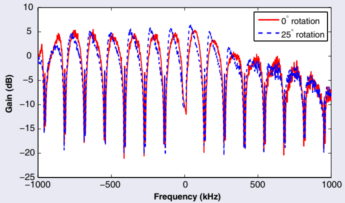
PEP-II Implementation



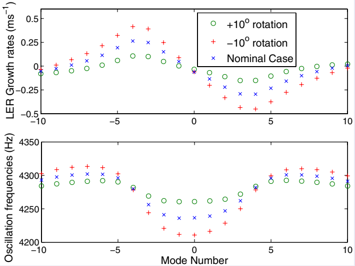
- Transfer function notched at the revolution harmonics with symmetric peaks at the synchrotron sidebands (3 to 7 kHz range)
- The growth rate for the k^{th} mode:

$$GR_k \propto Z^{||}(f_{RF} + kf_{rev} + f_s) - Z^{||}(f_{RF} - kf_{rev} - f_s)$$

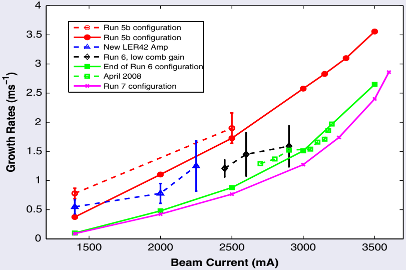
- Detuning more than 180 kHz $\longrightarrow$ "Comb Rotation" - "Asymmetric Comb Filters" to minimize the GR of unstable modes.
- Stability margin for RF loops $\longleftrightarrow$ Instability growth rates



Closed loop transfer function of LER RF station. $\phi_c = 0^o, \phi_c = 25^o$



Growth rates for LER $I_b = 1.4A$ - $\phi_c = -10^o, 0^o, -10^o$



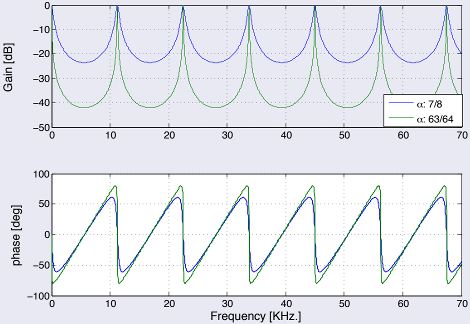
Growth rates for the LER. Summary of last runs including improvements in the LLRF and new criteria to set the One-turn delay feedback parameters ('Comb rotation')

LHC Implementation

- More concerned with transient beam loading than impedance reduction (at least for nominal design beam currents of 0.55 A DC)
  - The One-turn delay feedback provides additional gain at rev harmonics, even outside the band of the RF FB (phase equalization)
  - Also, very low synchrotron frequencies -> hard to implement "two-peak" filter
  - As a result, gain at the revolution harmonic with sufficient bandwidth to cover the first synchrotron sidebands (smaller reduction for quadrupole motion)
- The impedance presented by the RF station to the beam is reduced by both the direct feedback loop and the One-turn delay feedback

LHC implementation

- The One-turn delay feedback is included in the direct path of LLRF and has a transfer function in base-band given by $H_{OTDF}(s) = G_c e^{-j\Phi_c} H_{LP}(s) e^{-sT_d} \frac{1-\alpha}{1-\alpha e^{-sT_{rev}}}$
- The factor α selects the bandwidth of each notch filter around the revolution harmonics and can be selected in the range $7/8, 15/16, ..., 63/64$.



- Frequency response of the filter $\frac{1-\alpha}{1-\alpha e^{-sT_{rev}}}$ for $\alpha = 7/8, 63/64$

Comparison between the PEP-II and LHC designs

- For the PEP-II RF stations the One-turn delay feedback was designed and configured to minimize the interaction between the beam dynamics and the RF station impedance.
  - Biasing loop response away from optimal phase margin setting provided asymmetric response beneficial to growth rate reduction
  - The One-turn delay feedback provides additional impedance reduction of the RF station around the synchrotron band frequencies. No gain around the revolution harmonic frequencies
- For the LHC RF stations the One-turn delay feedback provides gain at the revolution harmonics to reject transient beam loading
  - The stability margins for the longitudinal beam dynamics are presently not so critical as the PEP-II case. The One-turn delay feedback parameters are optimized to achieve maximum stability margins in the RF station

Conclusions

- One idea, many applications
- Counteract the limitation due to the loop delay
- But multiple benefits: reduced transient beam loading (better control of V_{cav} extending to higher BW), improved beam stability (coupled-bunch instabilities), even reduced phase noise

Thank you for your attention