Low Level RF

Part 2: Cavity Controller, Problems and Cures

3. What will go wrong?
4. Power amplifier limits
5. Beam Loading
6. Longitudinal instabilities in Synchrotrons
7. LLRF Cures

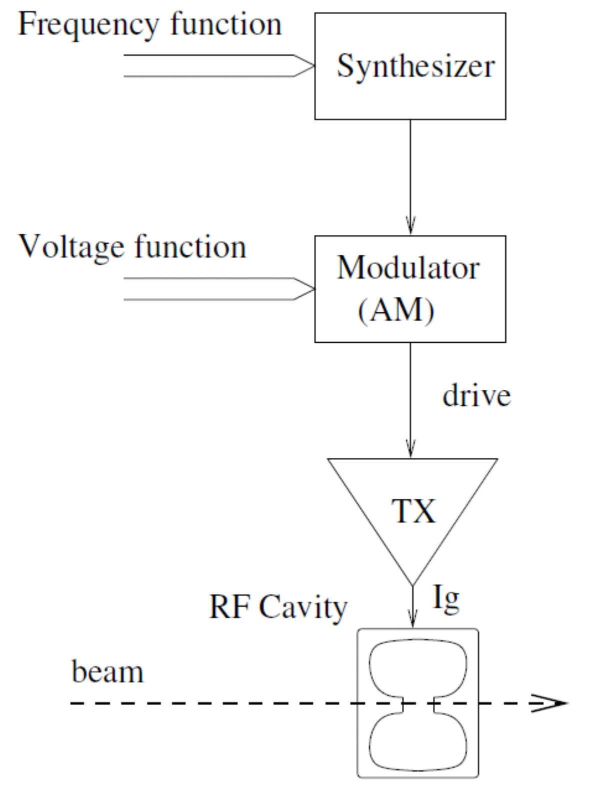
CAS RF

P. Baudrenghien CERN-BE-RF

3. What will go wrong?

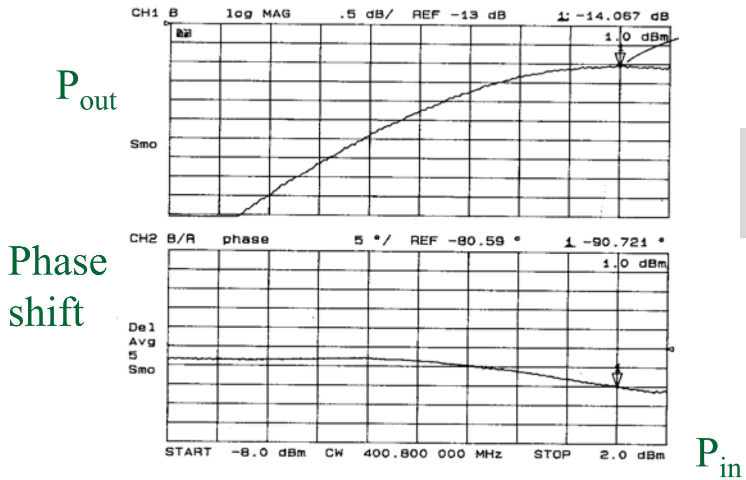
A simplistic RF system (Synchrotron or Linac)

- Simplest system: A cavity driven by a power amplifier whose drive is amplitude modulated and whose frequency comes from a synthesizer (fixed for Linacs, ramped for Synchrotron)
- What will go wrong:
  - The TX will inject amplitude and phase noise that will blow-up the emittance
  - The TX gain and phase shift will drift resulting in poor control of the cavity field
  - The cavity tune will drift resulting in field amplitude and phase change
  - Same effect when the cavity will vibrate with water cooling (Cu) or He pressure (SC)
  - The beam current will modify the cavity field
  - The beam can become unstable above some current threshold



4. Power amplifier limits

Tetrode, klystrons and IOTs are usually operated close to saturation for good efficiency. This makes them very non-linear. Their parameters are also very sensitive to fluctuations in the HV. In addition they are noisy.



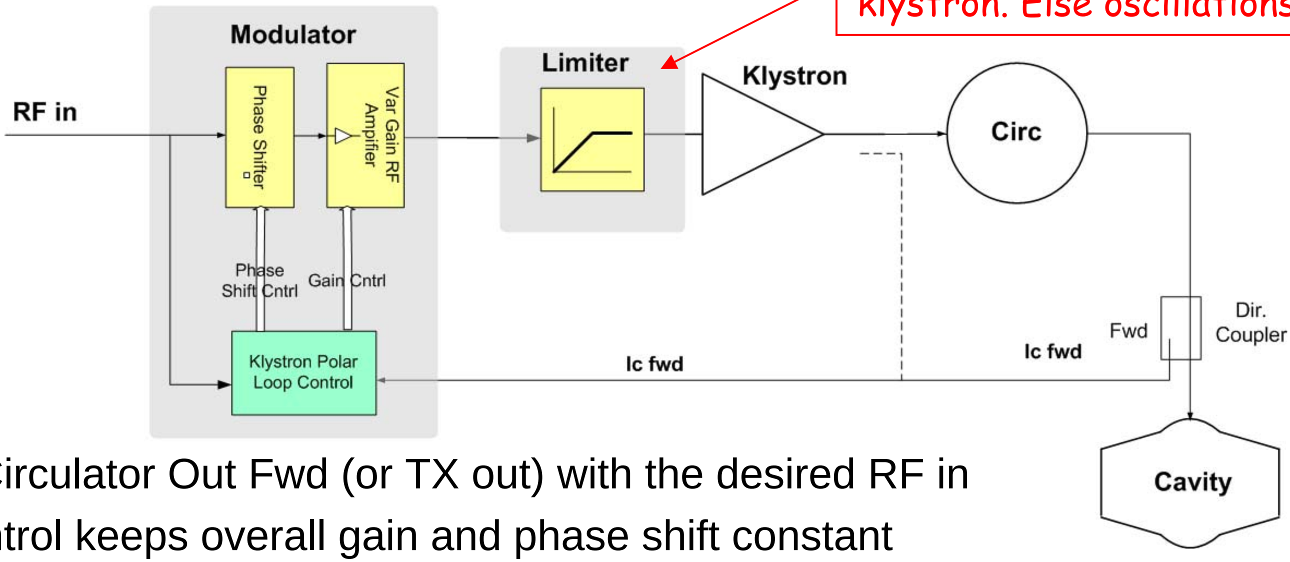
Klystron Power Sweep

- When the TX saturates we observe
  - AM-AM distortion: gain drops with drive level
  - AM-PM distortion: the delay (negative phase shift) increases with drive level
  - If overdriven a klystron will have a negative differential gain
- A tetrode will also be non-linear at very low drive
- Large sensitivity to HV. For the LHC klystrons we have 8.4 degree @ 400.8 MHz per percent HV drift @ 50 kV.
  - In pulsed Linacs the HV will droop during the pulse
  - In both CW and pulsed, the HV will have ripples from rectifiers or switching

LHC 330 kW klystron. Group delay 130 ns @ 400.8 MHz. ~50 kV, 10A DC

Cure: The TX Polar Loop

Prevents overdriving the klystron. Else oscillations!



- We compare the Circulator Out Fwd (or TX out) with the desired RF in
- The modulator control keeps overall gain and phase shift constant
- Correction BW depends on the overall loop delay. That includes waveguides/cables (layout) and TX/circulator group delays (BW)
- The TX Polar Loop will be an inner loop inside the RF feedback (see later). Time constants must be optimized.
- Intended at PEPII but not implemented (P. Corredoura). This Klystron Polar Loop is operational on the LHC CW klystrons (the loop controller is a simple integrator). It will be implemented on the Linac4 pulsed klystrons as well
- Note that the HV ripples create multiplicative noise. This changes the klystron beam β and thereby acts on RF phase shift (and gain). A polar loop is therefore more appropriate a regulation than an additive feedback loop

Performances in static conditions (LHC)

Pout vs DC parameters (HV and Icath)

HV or Icath	Pg Loop Open	Pg Loop Closed
Icath = 6.4 A		
HV=51.5 kV	123 kW	109 kW
HV=46.4 kV	117 kW	109 kW
HV=41.3 kV	102 kW	109 kW
HV=50 kV		
Icath=4.4 A	44 kW	109 kW
Icath=5.1 A	67 kW	109 kW
Icath=5.8 A	94 kW	109 kW
Icath=6.3 A	126 kW	109 kW

Pout vs DC parameter (HV)

HV	Phase Shift @ 400.8 MHz	Phase Shift @ 400.8 MHz
Icath = 6.4 A	Loop Open	Loop Closed
HV=52.9 kV	34 degrees	-0.2 degrees
HV=51.9 kV	17.4 degrees	0.0 degrees
HV=50.9 kV	0 degrees	0.0 degrees
HV=47.8 kV	-74.4 degrees	0.0 degrees

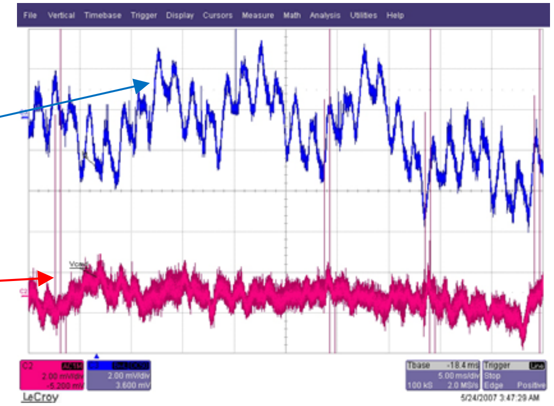
Left: Keep modulator input constant, observe klystron output power @ 400 MHz when varying HV or Cathode current
Right: Keep modulator input constant, measure klystron phase shift @ 400 MHz when varying HV

Compensation for HV ripples (phase)

LHC CW klystrons

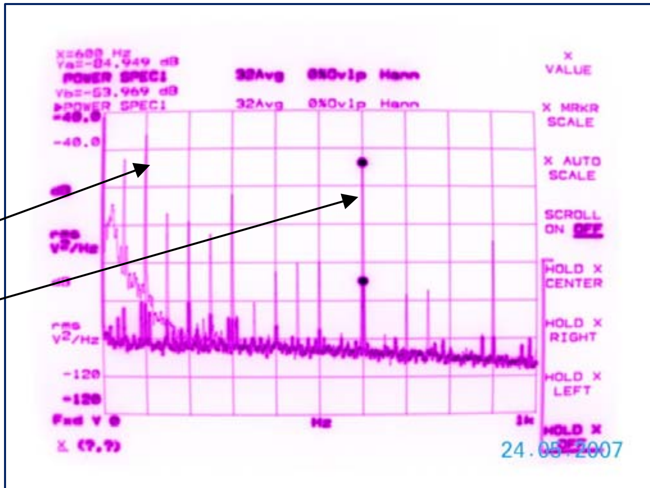
Phase compensation

Phase Noise



Left: **Loop open**. Phase noise Ig-Ref: Mainly 100 Hz and 600 Hz due to HV ripples. Calib 10 mV/dg @ 400 MHz. ~3.5 dg pkpk (10 mV/div, 5 ms /div)
Rigth: **Loop closed**. Red trace = phase noise Ig-Ref. Calib 10 mV/dg @ 400 MHz. ~0.2 dg pkpk (2 mV/div, 5 ms /div). Blue trace = phase compensation.

PSD in dBV²/Hz, 10 dB/div, DC to 1 kHz. Phase noise. Compares loop On and loop off.
Measured reduction
- 50 dB @ 50 Hz
- 30 dB @ 600 Hz



5. Beam Loading

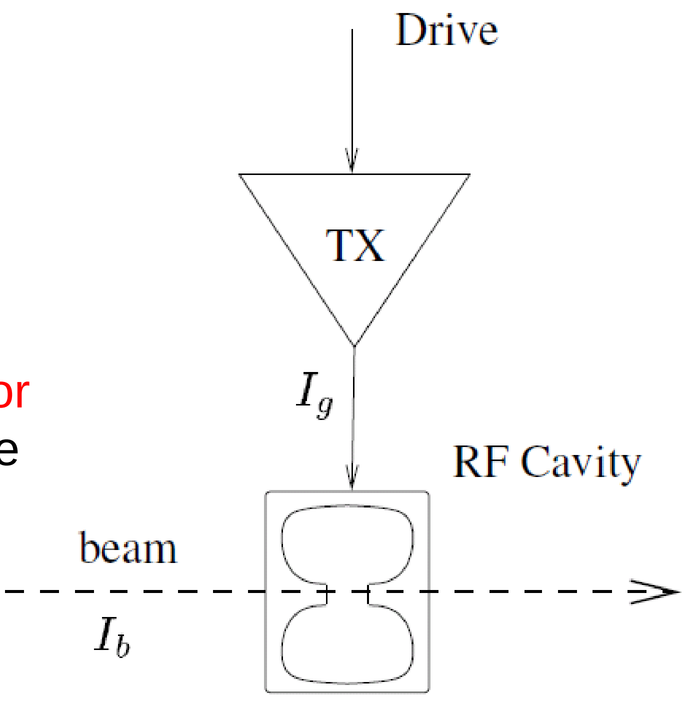
The beam current induces a voltage when crossing the cavity. To keep accelerating voltage constant, that calls for adapting the generator output

Mechanism

- Beam= charged particles in motion = current
- Cavity=resonant impedance
- Beam Crossing the cavity -> Beam induced electro-magnetic wave called wakefield
- The total voltage seen by the beam is the vector sum of the voltage due to the generator and the beam loading

$$\boxed{V_t = V_{RF} + V_b = Z_{RF}\, I_g + Z_b\, I_b}$$

- For high intensity machines the beam loading can be greater than the RF voltage



$$V_t = V_{RF} + V_b = Z_{RF}\, I_g + Z_b\, I_b$$

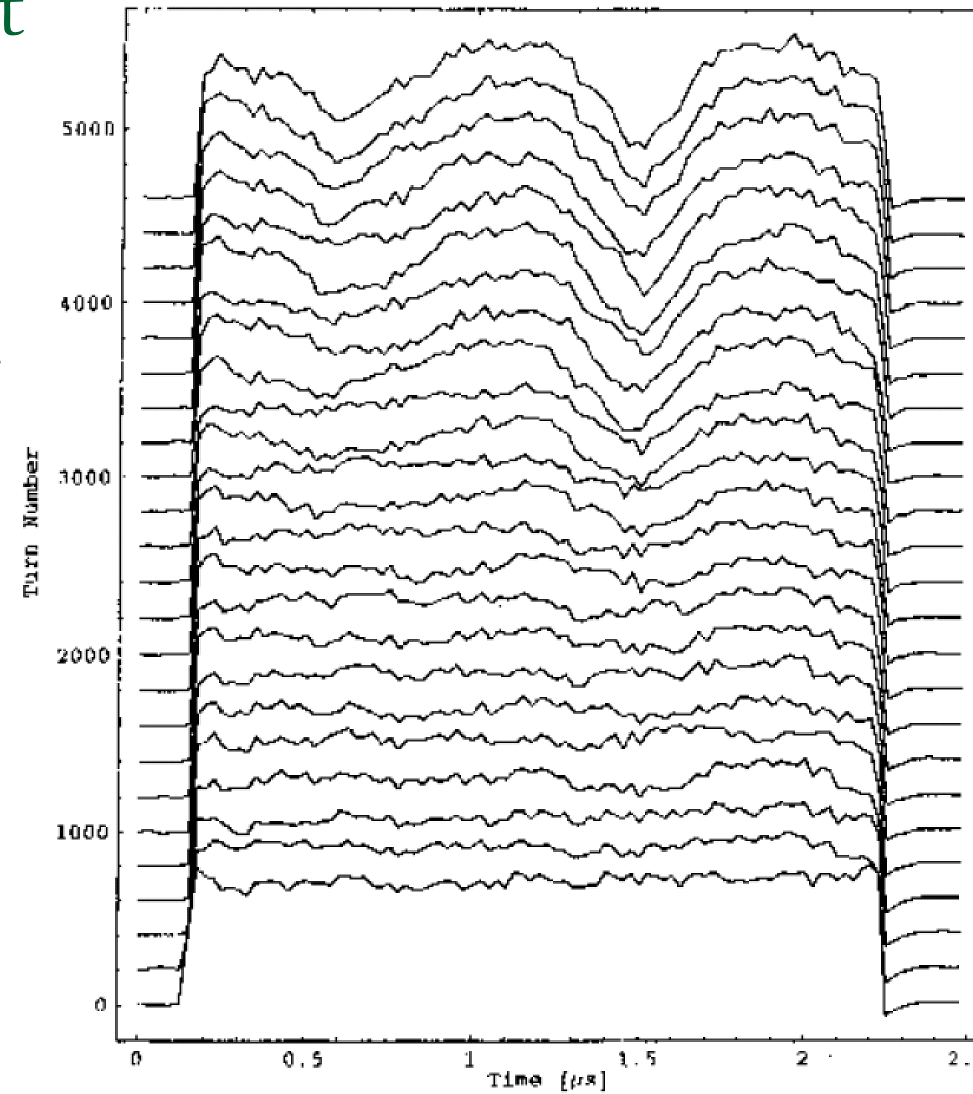
Consequences:

- In stationary conditions, V_{RF} must compensate V_b, to keep V_t at the desired value. This calls for extra RF power
- In transient situations the voltage V_t will vary. Transient Beam Loading:
  - At injection it must settle to the stationary value in a time short compared to the synchrotron period to avoid mismatch, filamentation and emittance blow-up
  - If the beam contains holes (beam dump hole for example), V_t will vary along the batch and the stable phase and bucket area will not be correct for the bunches in the head of the batch
- It may make the LL Loops go unstable.
  - In the 70s the PSB LLRF consisted of the classic combination of cavity amplitude and phase loops plus tuning loop. These early LLRF systems were much inspired by AM and FM demodulation. Perfect at low beam current, as the cavity voltage is then predominantly determined by the generator, the system showed its limits when the beam induced voltage became comparable to the total cavity voltage. In this situation a variation of the amplitude of generator current also modifies the phase of the cavity voltage. The loops become coupled and go unstable. Note that this is not a beam instability but an instability of the LLRF loops. Pedersen gave a full analysis [Pedersen]. The PSB LLRF is still based on amplitude/phase/tuning loops but the impact of Beam Loading has been reduced using RF feedback and 1-T feedback (see below). In modern high current machines I/Q Demodulation is now used instead of amplitude and phase loops.

[Pedersen] F. Pedersen, Beam Loading effects in the CERN PS Booster, IEEE Transaction on Nuclear Sciences, NS22, 1975

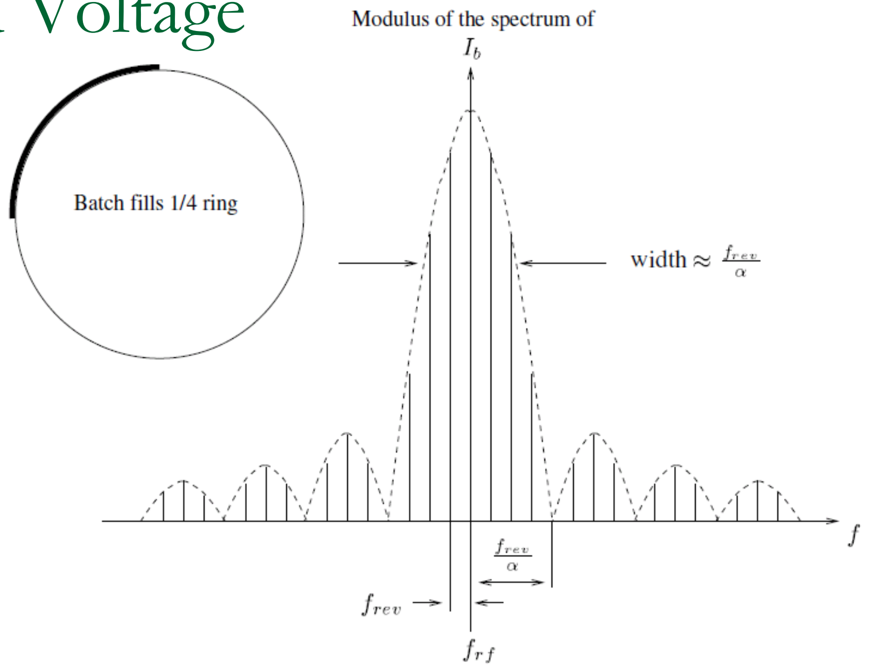
Example: The SPS at injection

Beam loss due to uncompensated transient beam loading in the CERN SPS. The beam consists of one batch of 81 bunches (0.5E11/bunch) filling 2 μs out of the 23μs period. The cavity filling time is 800 ns. Each trace shows the envelope of the bunch intensity along the batch. The bottom trace is the first turn. Traces are separated by 200 turns. The capture voltage is 550 kV, similar to the beam induced voltage. The cavity response to the beam current step distorts the buckets resulting in loss at some locations along the batch



Late 90s: *SPS as LHC injector* upgrade

Spectrum of the Beam Induced Voltage in a Synchrotron



Spectrum of the beam current with a batch that covers only $\frac{1}{4}$ of the ring. The rectangular envelope has a sinx/x spectrum that is sampled by the Frev lines

- In a circular machine, stable, uniformly filled, the spectrum of the beam current would be a series of lines at multiples of the RF frequency. Only the fundamental at the RF frequency couples to the cavity → a single line at f_{RF}

$$i_b(t) = I_0 \cos(2\pi\, f_{RF}\, t)$$

- Most machines are not uniformly filled. The beam current spectrum will be the spectrum of the beam envelope, sampled at the revolution frequency and its harmonic, and shifted at f_{RF}

$$i_b(t) = I_0 \cos(2\pi\, f_{RF}\, t)[a_0 + a_1 \cos(2\pi\, f_{rev}\, t) + a_2 \cos(4\pi\, f_{rev}\, t) + \ldots]$$

- Compensation of beam loading is therefore only needed around the frequencies

$$\boxed{f = f_{RF} \pm n\, f_{rev}}$$

Revolution frequency line index

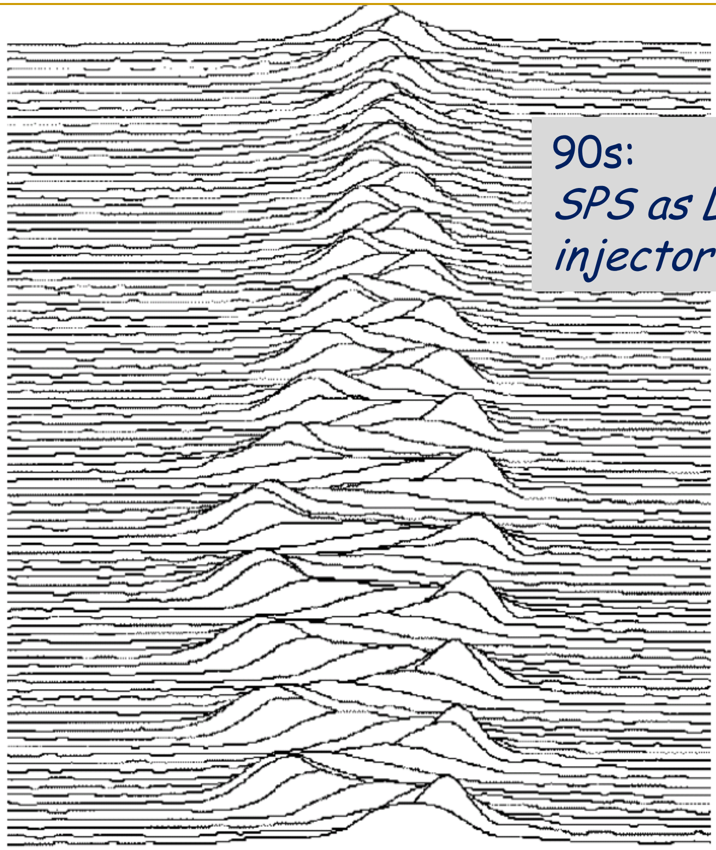
6. Longitudinal Instabilities in Synchrotron

Above a certain current threshold, the bunch(es) start developing oscillations in the bucket(s). These can be rigid oscillations (dipole mode), or shape oscillations (quadrupole mode and higher). If not damped these oscillations cause emittance blow-up through filamentation and finally loss when the bucket is full

6.1 Mechanism

$\boxed{I_b \text{ -> } V_b \text{ -> } I_b \text{ loop}}$

- If the wakefield created by the passage of the bunch in the cavity has not decayed to zero by the next passage, it will act back on the bunch
- If the gain/phase shift of this natural beam/cavity feedback is unfavorable, instability will arise: The bunch starts a oscillating in the bucket
- The situation gets worse if we have many bunches in the machine. The wakefield created by one bunch will act on the following one when it crosses the cavity, thereby creating coupling between the synchrotron oscillations of the individual bunches
- This effect, very important in high intensity synchrotrons, can lead to coupled-bunch longitudinal instability



90s:
SPS as LEP injector

Dipole mode. MR of the e+ bunch in the SPS. Horiz 10 ns. 10 turns between traces. Instability grows to 3 ns max, then is damped by radiation damping as energy increases.

The beam current is the sum of the motion of all particles present in the accelerator. The coupled-bunch instability is a Collective effects: All particles in a bunch start oscillating coherently or even successive bunches start oscillating with a fixed pattern. It will be enhanced if all particles have the exact same synchrotron frequency. Inversely, making the various oscillators a bit different using tune or energy spread will be stabilizing. This is called Landau damping and is very important for hadron machines

Spectrum of Oscillating Beam

- In the previous section we have derived, the beam current for a stable non-uniformly filled machine

$$i_b(t) = I_0 \cos(2\pi f_{RF} t)[a_0 + a_1 \cos(2\pi f_{rev} t) + a_2 \cos(4\pi f_{rev} t) + \ldots]$$

- When the bunches start oscillating in dipole mode at f_s, their time of passage in the cavity is modulated at that frequency: phase modulation. The current becomes

$$i_b(t) = I_0 \cos(2\pi f_{RF} t)[a_0 + a_1 \cos(2\pi f_{rev} t + \varepsilon \sin(2\pi f_s t)) + a_2 \cos(4\pi f_{rev} t + \varepsilon \sin(2\pi f_s t)) + \ldots]$$

- In the frequency domain the phase modulation will appear as +- f_s side-bands around each revolution frequency line
- Finally, considering also higher modes of oscillation: quadrupole at twice the synchrotron frequency, sextupole…each revolution frequency harmonic is surrounded by a series of synchrotron sidebands. The spectrum contains lines at

$$\boxed{f = f_{RF} \pm n f_{rev} \pm m f_s}$$

Revolution frequency line index

Mode index: m=1 is dipole, m=2 is quadrupole

Conclusion: To prevent coupled-bunch instability the cavity impedance must be reduced on the synchrotron side-bands of the revolution frequency lines

Modes and growth rates

- We will consider a machine with *M* uniformly spaced bunches, undergoing a small oscillation in dipole mode only (*m*=1)
- Let us take a picture of the bunches at instant *t*, and observe the phase error $\phi_k(t)$ of bunch *k*
- If all bunches oscillate in phase, we get

  $$\phi_k^{(0)}(t) = \sin\left(2\pi\ f_s\, t\right)$$

  and the beam induced voltage shows f_s sidebands around f_{RF}. This is the (only) mode that the Phase Loop (lecture 1) damps
- For a phase advance of $2\pi/M$ between successive bunches, we get

  $$\phi_k^{(1)}(t) = \sin\left(2\pi\ f_s\, t + 2\pi\, k\, \frac{1}{M}\right)$$

  and the beam induced voltage shows f_s sidebands around f_{RF}+- f_{rev}
- Generalizing, for a phase advance of $2\pi p/M$ between successive bunches, we get

  $$\phi_k^{(p)}(t) = \sin\left(2\pi\ f_s\, t + 2\pi\, k\, \frac{p}{M}\right)$$

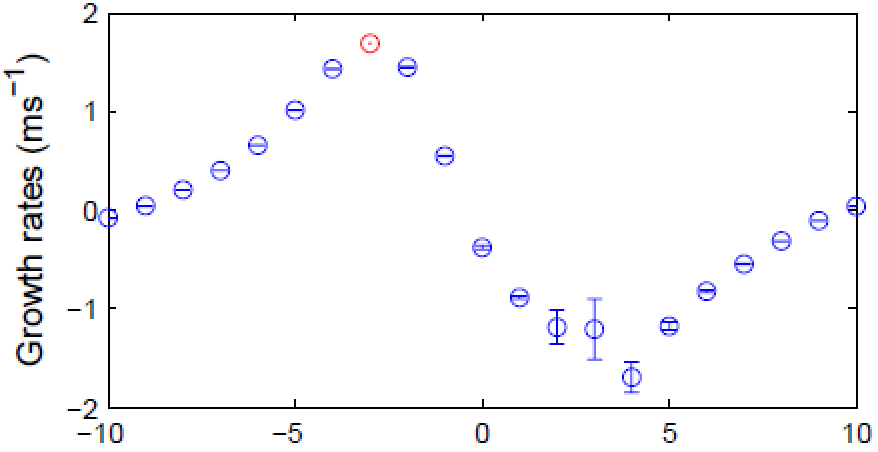
  corresponding to the f_s sidebands around f_{RF}+- $p.f_{rev}$
- With *M* uniformly spaced bunches, we have M eigenmodes of dipole oscillation. Any pattern can be reproduced as a linear combination of these eigenmodes. The advantage of this decomposition is that it is easy to compute a growth rate for each eigenmode

6.2 Threshold. Electron machines

- Electron synchrotron are very relativistic. Due to radiation damping the bunches are very short and the dominant bunch mode is dipole (*m*=0)
- If the impedance of the machine elements is known, (and that is normally the case for the resonant structures - RF cavities, kickers - and the vacuum chamber), one can compute the growth rates for all M dipole modes
- For example if the dominant impedance is the cavity impedance around the fundamental, the growth rate of p^{th} mode is approximated

$$\frac{1}{\tau^{(p)}} \approx -\frac{\Omega_s I}{2V\cos\phi_s}\left\{\begin{array}{l}\mathrm{Re}\left[Z_{eff}\left(2\pi\, f_{RF}+2\pi\, p\, f_{rev}+\Omega_s\right)\right] \\ -\mathrm{Re}\left[Z_{eff}\left(2\pi\, f_{RF}-2\pi\, p\, f_{rev}-\Omega_s\right)\right]\end{array}\right\}$$

- The beam will be stable if there is no growth rate faster than the radiation damping time (below 5 ms in LEP at 104.5 GeV/beam)



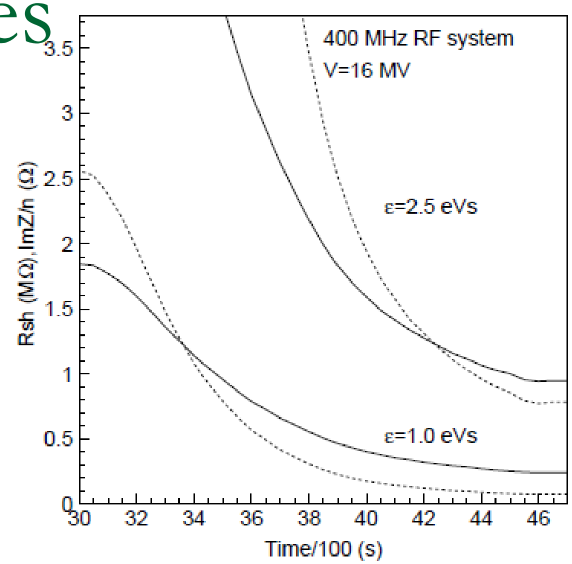
PEP II, SLAC. Shown are growth rates for various dipole modes of the PEPII e+e- collider. The -3 mode has growth time ~600 μs. The PEPII radiation damping time is 19 ms (HER) and 30 ms (LER). The Longitudinal Damper provided the needed extra damping (~150 μs time). Courtesy of T. Mastorides.

6.3 Threshold. Proton machines

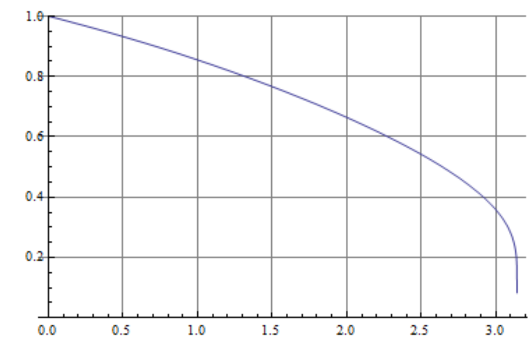
- There is virtually no radiation damping (24 hours damping time in the LHC at 7 TeV) because g is too low
- Bunches are long and we can observe high order bunch modes (quadrupole, sextupole,…)
- The only natural damping is the Landau damping due to the energy and synchrotron frequency spread: The particles in the bunches do not all oscillate coherently, thereby reducing the collective effect
- For a given beam current, one can compute a threshold on the maximum cavity impedance , valid on all f_{rev} side-bands [Shaposhnikova]

$$\boxed{R_{\max} \propto |\eta| \frac{E}{I_b} \left(\frac{\Delta E}{E}\right)^2 \frac{\Delta\Omega_s}{\Omega_s}}$$

- Observations:
  - R_{max} decreases with energy. In an acceleration cycle, instabilities are first appearing at top energy
  - R_{max} increases with the relative synchrotron tune spread $\Delta\Omega_s/\Omega_s$. The relative Energy spread is also stabilizing. Large and almost full buckets are more stable. But caution with loss…



Narrow-band impedance threshold Rsh (solid line) during the LHC acceleration ramp Reproduced from [Shaposhnikova]



Synchrotron Tune vs. pk deviation (Lecture 1)

[Shaposhnikova] E. Shaposhnikova, Longitudinal beam parameters during acceleration in the LHC, LHC project Note 242, Dec 8, 2000

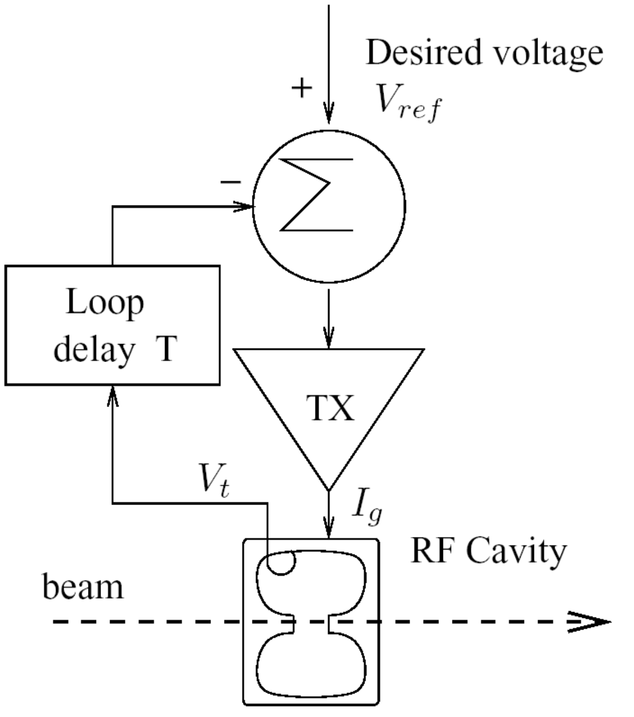
7. LLRF Cures

7.1 RF feedback (or Direct Feedback)

- *"… with feedback it is possible to reduce the distortion generated by the amplifier, to make the amplification substantially independent of the electrode voltage and tube constants, and to reduce greatly the phase and frequency distortion"* F. Terman.
- Feedback reduces the effects of beam loading by reducing the effective cavity impedance. It reduces the effect of other noise sources as well (TX ripples, tune variations, microphonics) and it improves precision by making the RF voltage independent of amplifiers non-linearity, gain and phase drifts
- It is the preferred method wherever feasible

Works on all sources of perturbations
Works for Synchrotrons and Linacs

- Principle: Measure the accelerating voltage in the cavity, compare it to the desired voltage and use the error to regulate the drive of the power amplifier
- It is a real RF feedback, not an amplitude and phase loop
- but it can be implemented using I/Q Demodulators



RF or Direct Feedback

Analysis

- A SWC near resonance can be represented as an RLC circuit

$$Z(\omega) = \frac{R}{1 + j\,2Q\dfrac{\Delta\omega}{\omega_0}}$$

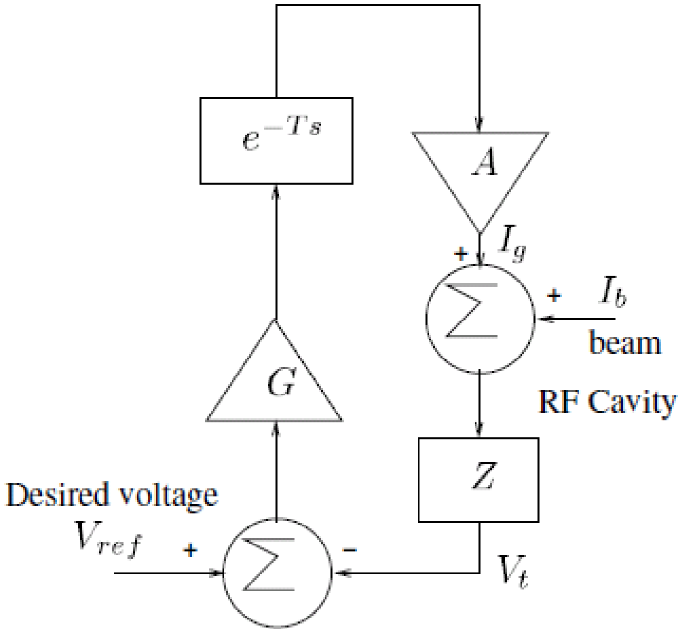
$$\Delta\omega = \omega - \omega_0$$

- With the feedback loop, the beam loading voltage is

$$V_t(\omega) = \frac{Z(\omega)}{1 + G\,A e^{-iT\Delta\omega}\,Z(\omega)}\,I_b(\omega)$$

- A large gain G.A means good impedance reduction. Stability in presence of the delay T will put a limit. Outside its bandwidth the cavity is purely reactive and its impedance can be approximated

$$Z(\omega) \approx \frac{R}{j\,2Q\dfrac{\Delta\omega}{\omega_0}}$$

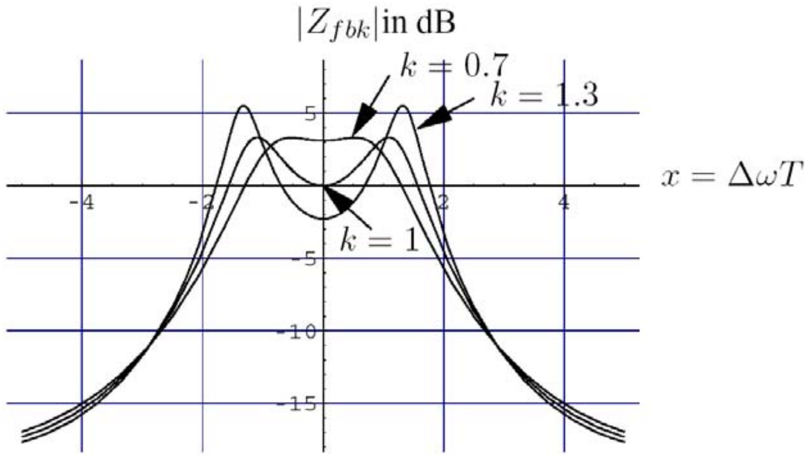


RF or Direct Feedback

- To keep a 45 degrees phase margin the open-loop gain must have decreased to 1 when the delay has added an extra -45 degrees phase shift, that is at $\Delta\omega=\pi/(4T)$

$$G\,A\left|Z\left(\frac{\pi}{4T}\right)\right|\leq 1$$

$$G\,A\leq\frac{\pi}{2}\frac{Q}{R\,\omega_0}\frac{1}{T}$$



Closed Loop response for varying gains. K=1 corresponds to the maximal gain. The optimally flat is obtained for k=0.7

- Flat response will be achieved with

$$G\,A\approx\frac{Q}{R\,\omega_0}\frac{1}{T}$$

leading to the effective cavity impedance at resonance

$$\boxed{R_{\min}=\frac{R}{1+G\,A\,R}\approx\frac{R}{Q}\omega_0\,T}$$

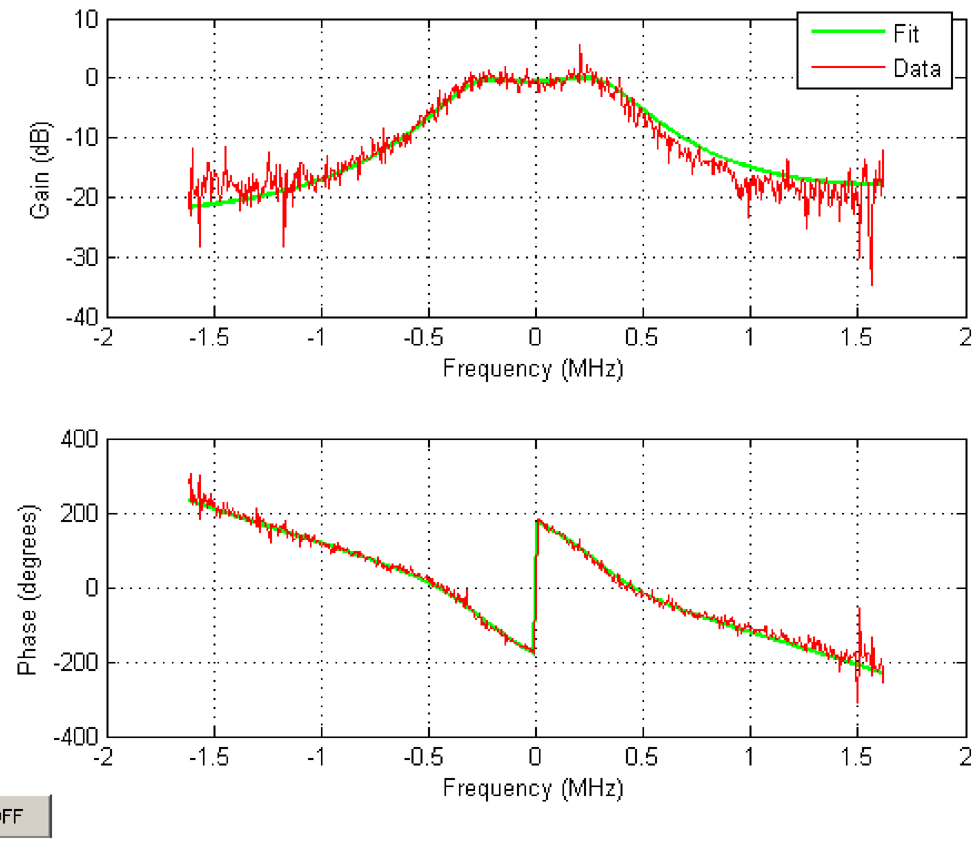
and the 2-sided closed loop BW with feedback

$$\boxed{\Delta\omega_{-3}\approx\frac{2.6}{T}}$$

- The final performances depend on Loop delay T and cavity geometry R/Q. It does not depend on the actual Q
- Lesson: Keep delay short and TX broadband to avoid group delay

- Advantages:
  - Relatively insensitive to small drifts in amplifier gain and phase
  - Broadband impedance reduction achievable if the total loop delay T is small -> Place the amplifier next to the cavity
  - Easy for a single-cell cavity
- Limitations:
  - Can be complex for multicell cavities. Cluster of resonances with different phase shifts
  - Gain limited by the loop delay T
- Caution:
  - We have considered the TX response as a linear gain G. Not very realistic…
  - TX non-linearity will degrade the performances of the feedback. Best is to simulate using a TX model including saturation
  - For regulation we need extra TX power. Rule of thumb: TX must not be operated above ~70% power saturation level (SNS 76%, JPARC 66%, Linac4 76%)
- One TX feeding several independent cavities:
  - The RF feedback can only regulate the voltage sum. We loose much freedom
  - Power to individual cavities can be adjusted with Power I/Q Modulator, but we now have regulation at the MW level, instead of mW…Reduced regulation BW
  - The decision of splitting klystron power must consider field stabilization issues. Simulations needed

Example: The LHC



Measured Closed Loop response with the RF feedback. Q_L=60000 without feedback (~7 kHz 2-sided BW). With feedback we get 700 kHz BW. The effective impedance is reduced by ~ 100 resulting in a Q_{eff}~600.
Loop delay 650 ns, R/Q=45 ohm.
The LHC cavities are equipped with movable couplers and Q_L can be varied from 10000 to 100000. But, with feedback, Q_{eff} ~600 in all positions.

7.2 The 1-Turn Feedback

or Long-Delay feedback or Comb-Feedback

- To reduce the effective cavity impedance, the RF feedback is the best solution. But it is not applicable if the loop delay is long
- The SPS was designed in the 70's as a 300 GeV proton accelerator. When increasing beam current in the early 80's, the impedance of the cavities at the fundamental appeared as a limit. Their amplifiers were located on the surface, far away from the tunnel. With this 2.6 μs loop delay, the RF feedback would only cover the first two revolution sidebands (f_{rev}=43 kHz)
- In 1985 D. Boussard implemented the first 1-Turn Delay Feedback on that machine [Boussard]

SPS Traveling Wave Cavity in the SPS tunnel. Backward Wave Structure, 90 degrees phase advance/cell, 200.22 MHz centre freq

Good for beam loading and instabilities (if cavity impedance at fundamental is the source)
Works for Synchrotrons only

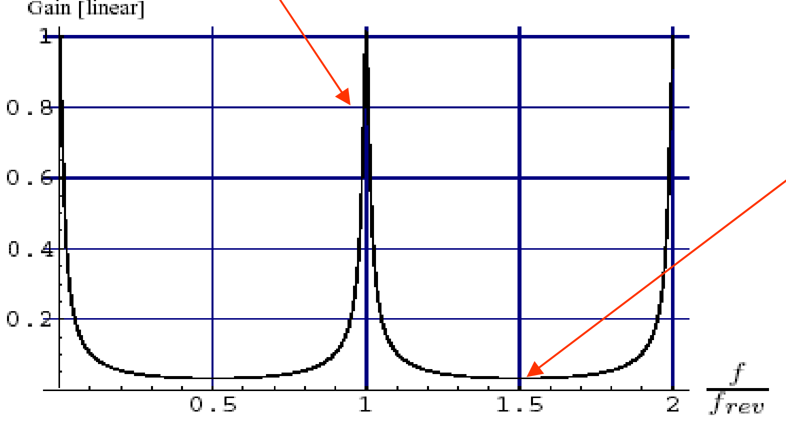
[Boussard] D. Boussard, Control of cavities with high Beam Loading, PAC1985, Vancouver, May 1985

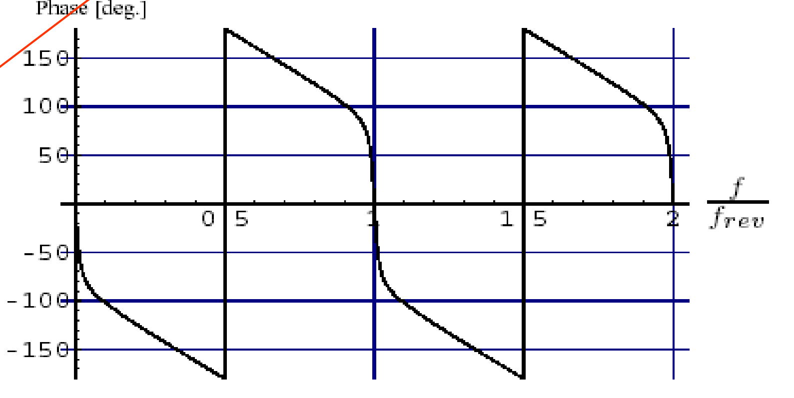
1-T Feedback. Why?

- For transient beam loading compensation and prevention of instabilities we only need to damp the cavity impedance on (transient beam loading) or around (long. Instabilities) the revolution frequency sidebands
- Idea:
  - Provide large open-loop gain and 0 degree phase shift on the revolution frequency sidebands
  - Reduce gain between sidebands so that wrong (180 degree) open-loop phase shift does not lead to loop instability

2-sided -3 dB BW is (1-a)/π

Attenuation between peaks is (1-a)/2





1-T feedback. How?

- Trivial: simple IIR filter plus 1-T delay

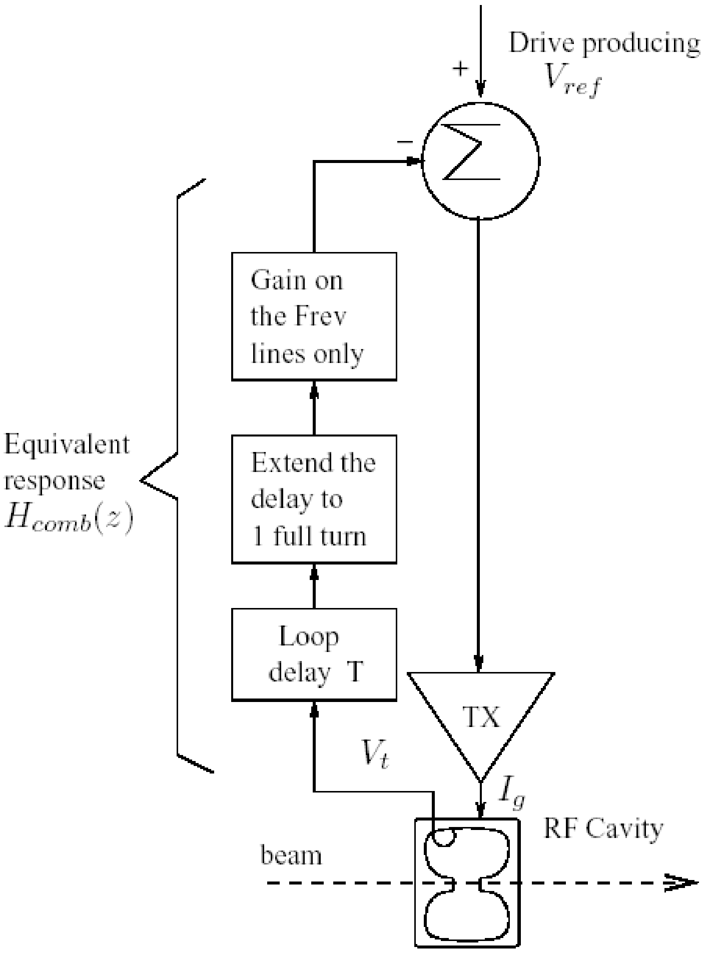
$$H_{comb}(z) = G\frac{1-a}{1-az^{-M}}z^{-M}$$

$$with\ f_{ck} = M \cdot f_{rev}$$

- Two parameters to be chosen: open-loop gain G and geometric ratio a
- a fixes the bandwidth -> related to the synchrotron frequency (dipole) or its harmonics

$$\Delta f_{-3dB} = \frac{1}{2\pi}(1-a)f_{rev} > f_s$$

- a governs the decay of the transient at injection



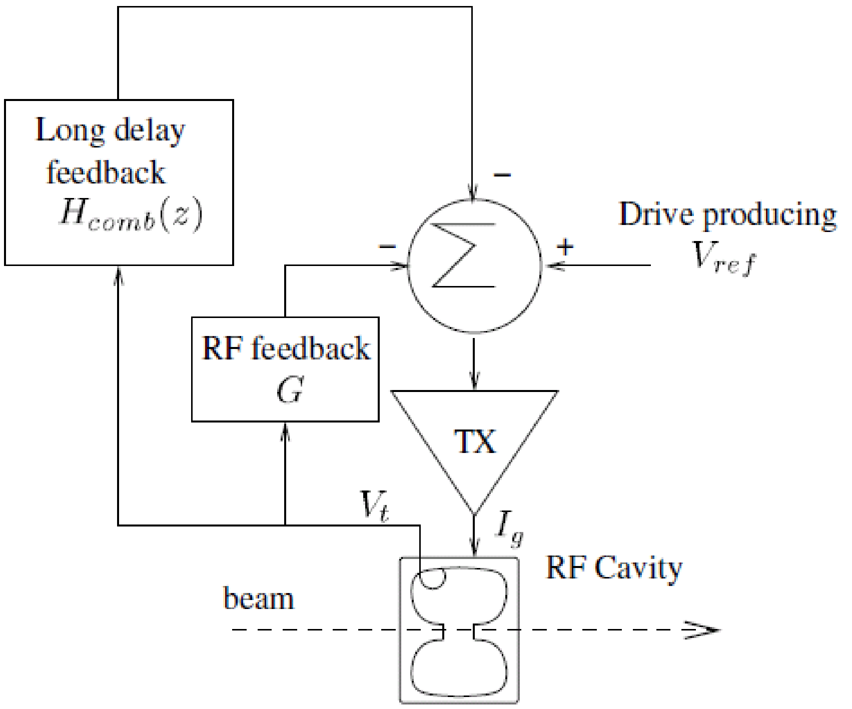
1-T feedback. How (cont'd)

- G is limited by stability considerations:
  - Halfway between peaks the phase shift is 180 degrees
  - And the gain must be below 1/3 to respect the canonical 10 dB gain margin
  - Thus:

$$G\frac{(1-a)}{2}<\frac{1}{3}$$

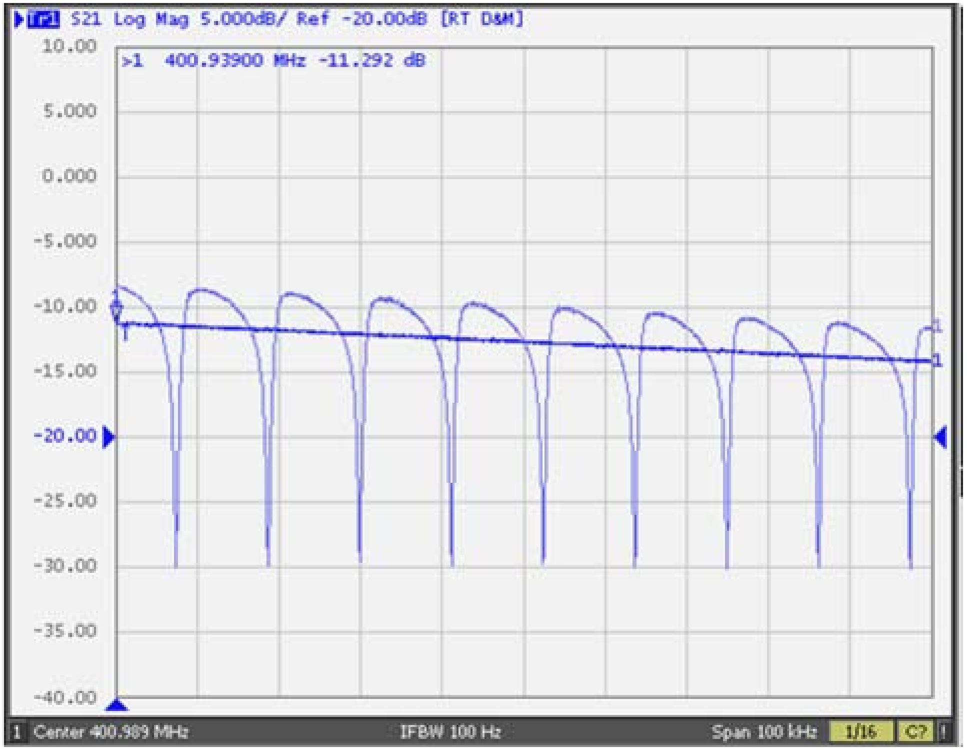
- In the SPS:
  - G= 10, a = 15/16 thus G(1-a)/2 = 10/32 < 1/3
  - -3 dB BW = 428 Hz (single-sided)
  - Synchrotron frequency between 100 Hz and 400 Hz for LHC beam (but as high as 1 kHz for FT)
- In the LHC:
  - $f_s/f_{rev} < 5\ 10^{-3}$ and we use a= 15/16 and G=10

- We have not considered the cavity response in the derivation. If narrow-band it will modify the open-loop response (+- 90 degrees phase shift) and the 1-T fdbk cannot extend much beyond the cavity BW
- Solution: Flatten the cavity response with an RF feedback, then increase the gain on the revolution frequency lines with the 1-T feedback
- Caution: TX linearity will limit the performances. In PEPII cavity impedance reduction was actually limited by the TX driver non-linearity. Measure, model and simulate…



Combined RF feedback and 1-T feedback

Example: The LHC



Effective Cavity Impedance with RF feedback alone (smooth trace) and with the addition of the 1-T feedback (comb). The cavity centre frequency is 400.789 MHz. We look at a band offset by +200 kHz to +300 kHz. Frev= 11 KHz. The 1-T feedback provides ~ 20 dB additional impedance reduction on the Frev lines.

7.3 1-T Feedforward

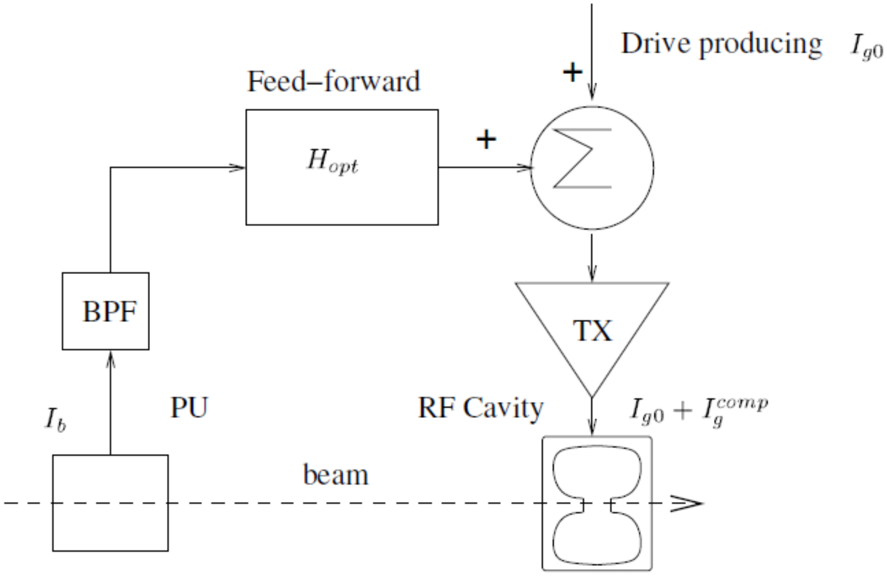
- Idea: Measure the beam current I_b with a pick-up and feed it back via the generator to compensate for the beam loading
- Recall that

$$V_t = V_{RF} + V_b = Z_{RF}\, I_g + Z_b\, I_b$$

so we want the generator to produce a current $I_{g,comp}$ such that

$$Z_{RF}\, I_{g,comp} = -Z_b\, I_b$$

- For a SWC, Z_{RF} and Z_b are proportional. It is thus very easy to implement
- A 1-T delay must be inserted in the feed-forward path. As the synchrotron frequency is much smaller than the revolution frequency, the PU signal does not change significantly between successive turns

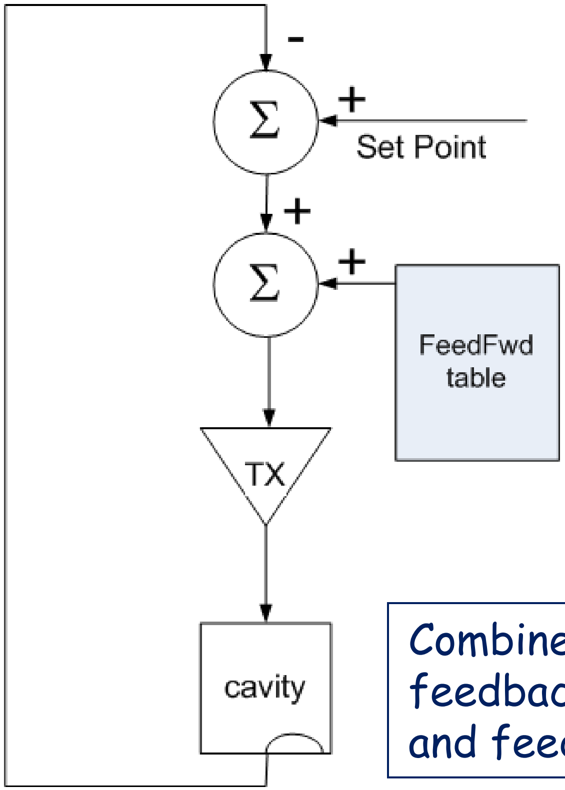


- Limitations:
  - Sensitive to drifts in TX gain and phase
  - Difficult to set-up for a varying RF frequency. The fixed PU to cavity delay must be compensated continuously as the revolution period changes to keep the overall delay equal to exactly one turn

Fair for beam loading and instabilities (if cavity impedance at fundamental is the source)
Works for Synchrotrons only

7.4 Adaptive Feedforward (AFF)

- The RF feedback will take some time to react to a transient, this time being at the minimum the Loop Delay (see above)
- In pulsed Linacs, the beam loading compensation at the head of the batch will not be very good because the first injected bunches will induce a voltage that will be compensated after the Loop Delay only
- As this effect is clearly reproducible from pulse to pulse, a Feed-forward compensation will help
- Other repetitive sources of perturbation can also be corrected with the feed-forward
- These repetitive sources of perturbation will slowly change from pulse to pulse. Adaptive Feedforward (AFF) aims at tracking these changes to best anticipate the correction on the next pulse



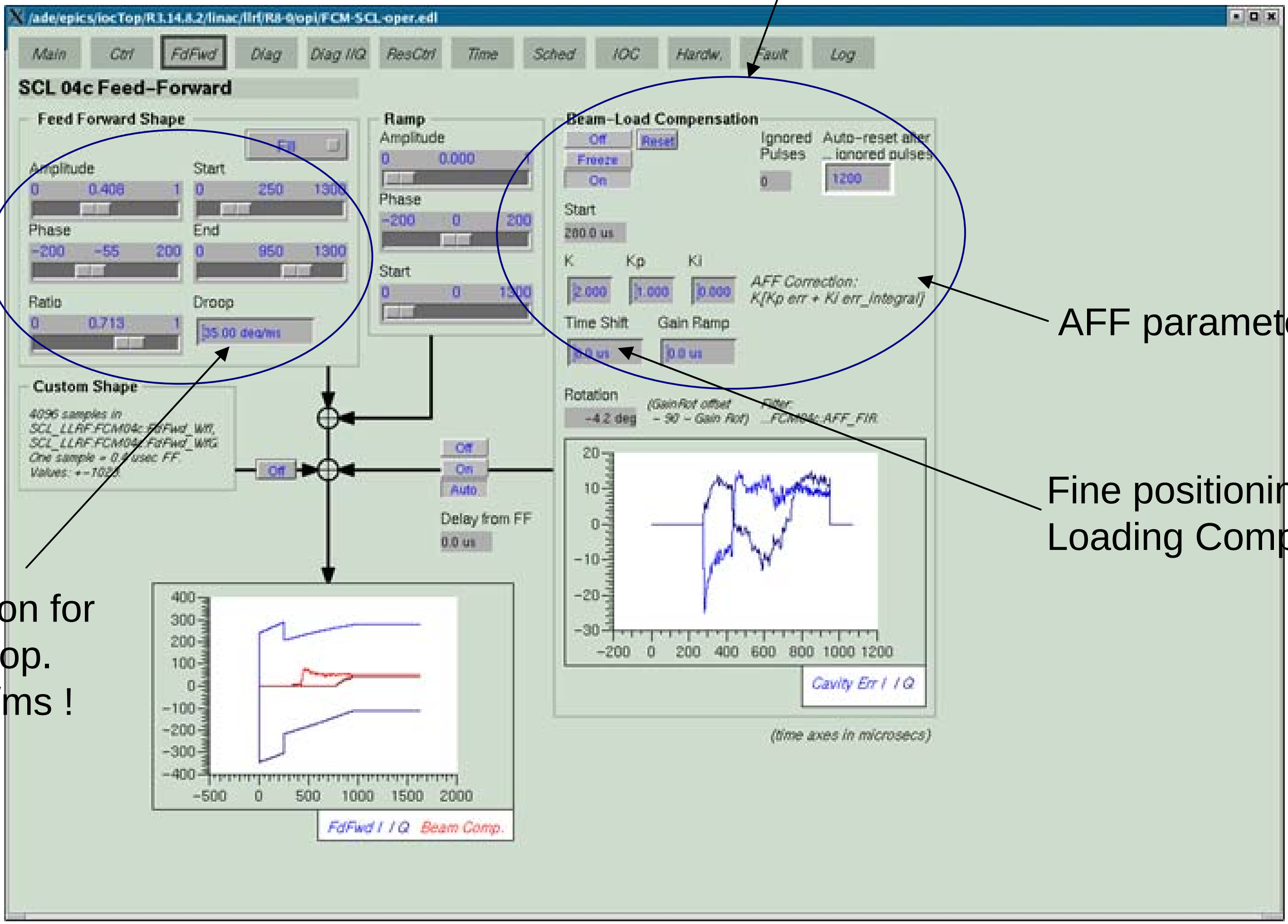
Combined RF feedback and feedfwd

Good for all repetitive disturbances, including beam loading, TX ripples, source current fluctuations, and Lorentz force detuning. Developed and in operation in pulsed Linacs (SNS and FLASH)

SNS Feed-forward compensation

Beam-Loading compensation

Filling settings

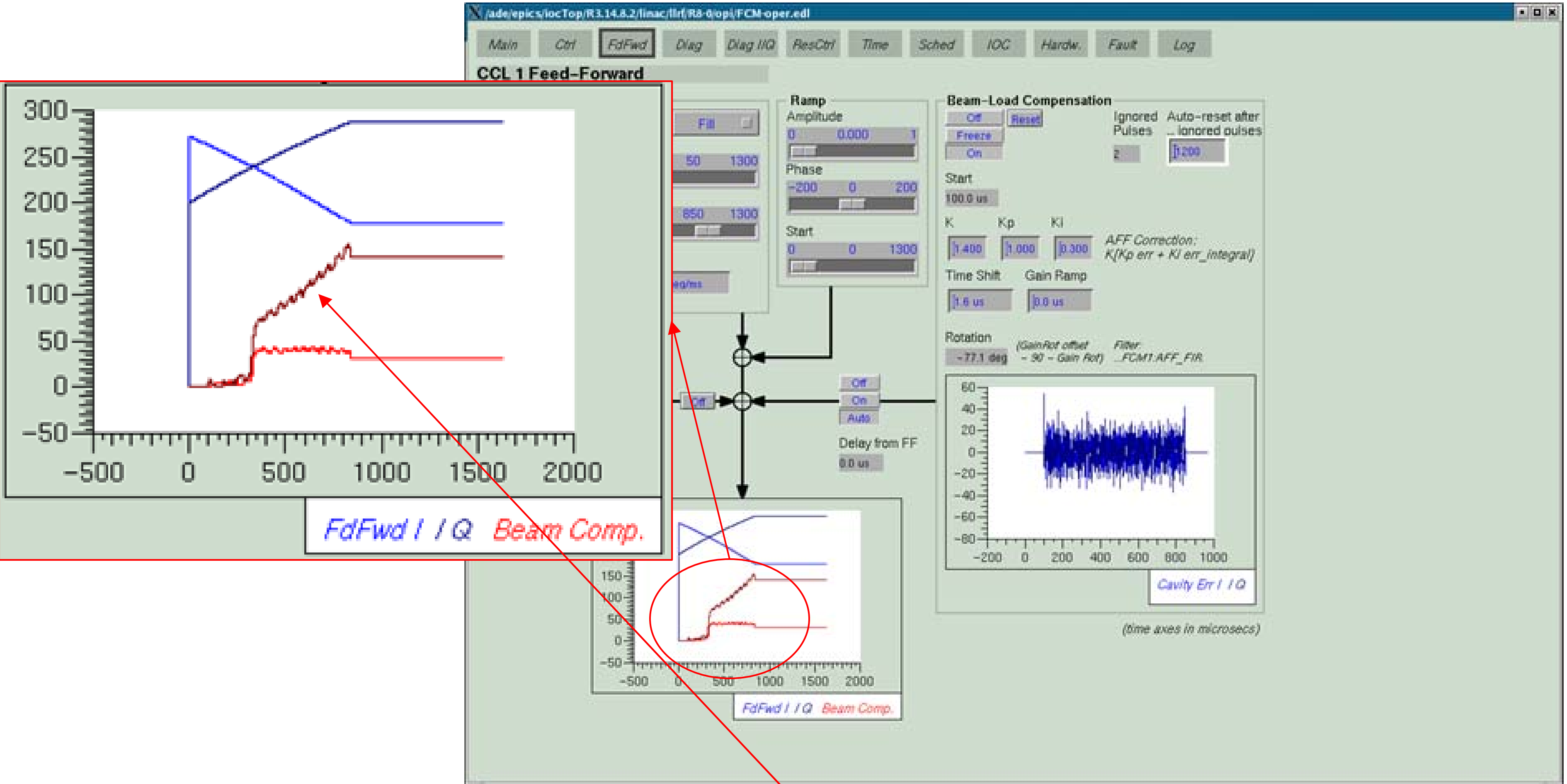


AFF parameters

Fine positioning of Beam Loading Compensation

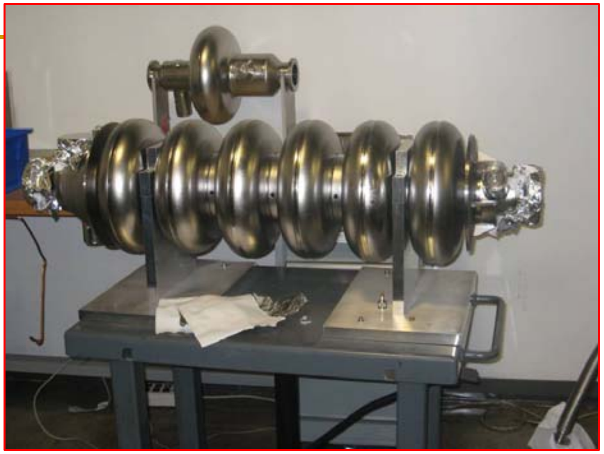
Open-Loop compensation for klystron droop. Here 35 dg/ms !

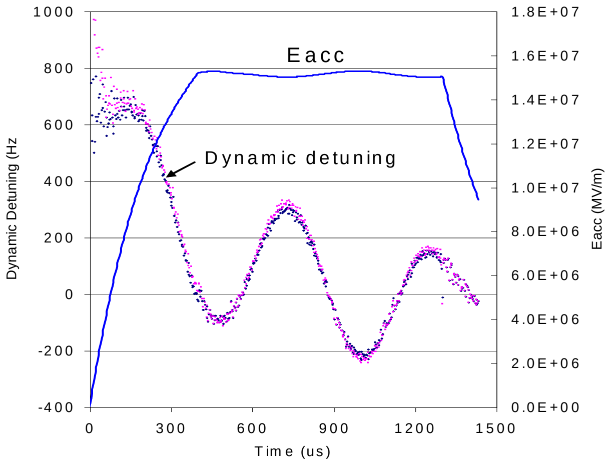
At the SNS, the switching of the HV modulators is synchronized with the rep rate. So the klystron ripples are also repetitive from pulse to pulse and corrected by the Feed-Forward



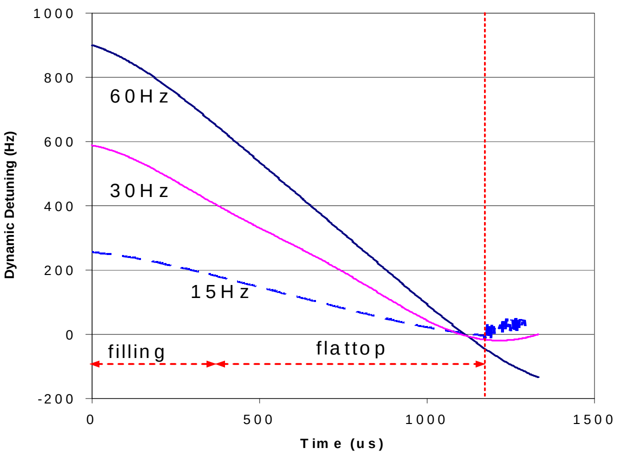
Feed-Forward takes care of the HV ripples at 20 kHz (pulse synchroneous)

The Lorentz force detuning is also synchronous with the rep rate and can be compensated by the AFF
NOTE: Detuning implies more power for a given field. In the SNS the power margin is sufficient to cope with it.





2 kHz resonance in medium beta cavities



High beta cavity at 12.7 MV/m for various rep rates

- Fast piezzo tuners were installed at the SNS start-up but are NOT used anymore. The ~1 kHz detuning can be dealt with by the RF feedback and AFF and… the klystron power margin…

Above plots and info from Sang-Ho Kim, SNS, ORNL

To my knowledge, AFF is presently operational at Flash (Free Electron Laser), Desy and at SNS, with the help of Desy
For scientific publications on the subject query on keywords: “Stephan Simrock” and “Adaptive Feed-Forward”

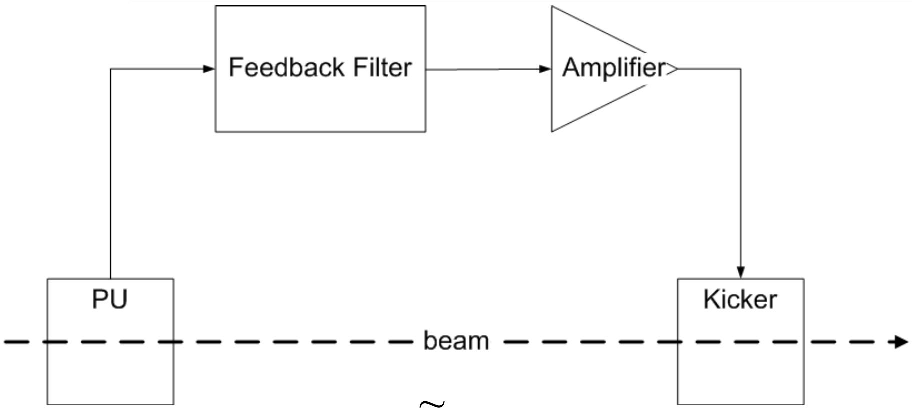
7.5 Longitudinal damper (dipole mode)

- For each bunch, we measure its phase with respect to the RF, and generate a momentum kick at the correct time (act on the same bunch), that is 90 degrees phase shifted with respect to the phase measurement to produce damping
- Let $\phi_k(t)$ be the phase of the RF when the k^{th} bunch crosses the cavity. We have $$\tilde{\phi}_k(t)=\phi_k(t)-\phi_s$$
- We rewrite the synchrotron oscillation with the momentum kick $\Delta p_k(t)$ as driving term

$$\frac{d^2\tilde{\phi}_k}{dt^2}+\Omega_s^2\,\tilde{\phi}_k=-2\pi\frac{\eta h f_{rev}^{\;2}}{p_s}\Delta p_k$$

- To get damping we now make the momentum kick proportional to the derivative of the phase error

Idea: mimic e-machines radiation damping but…only bunch per bunch



$$\Delta p_k=a\frac{d\tilde{\phi}_k}{dt}$$

- And the equation becomes

$$\boxed{\frac{d^2\tilde{\phi}_k}{dt^2}+2\alpha_l\frac{d\tilde{\phi}_k}{dt}+\Omega_s^2\,\tilde{\phi}_k=0}$$

- The damping time constant is

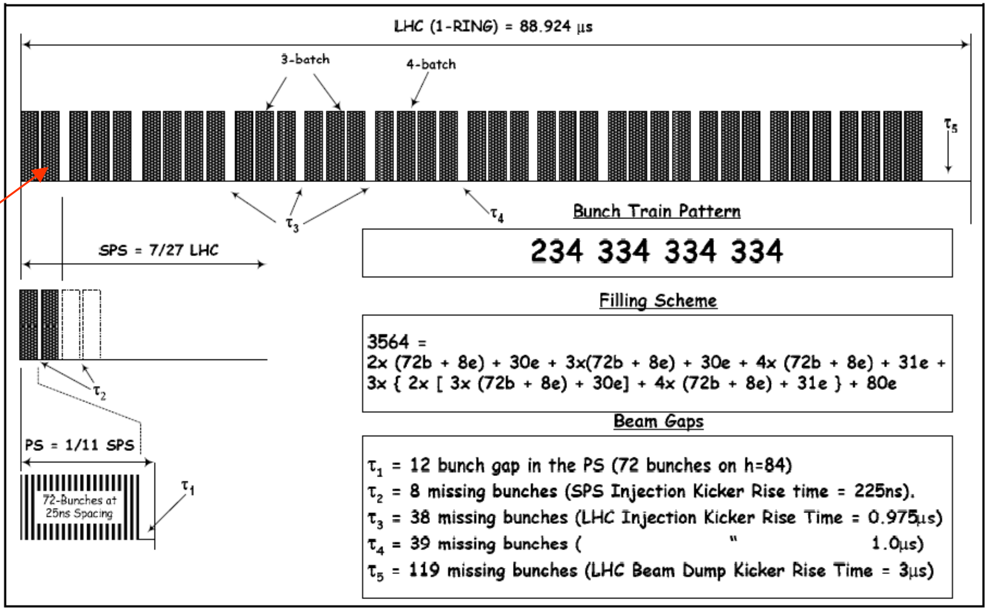
$$\boxed{\tau_l=\frac{1}{\alpha_l}}$$

- The Feedback filter
  - We first derive the filter $H(z)$ with sampling clock F_{rev}
  - It must provide ~90 degrees phase shift at the synchrotron frequency for damping
  - It must have gain around the synchrotron frequency (BPF characteristic)
  - It must have zero gain at DC so that the damper does not attempt to reduce the static bunch phase
  - Designs from J. Fox (SLAC) for PEPII, DaΦne, ALS were implemented using a bank of DSPs, each processing a few bunches.
- Nowadays, series processing in an FPGA is preferred
  - For M bunches, we sample at $F_{ck}=M\,F_{rev}$
  - And we process the data stream with filter $H(z^M)$
  - Then we must add a de*lay* z^{-P} so that measurement and kick correspond to the same bunch
- Remark
  - Large BW required for the acquisition and the power amplifier. The phase of each bunch is sampled independently
  - The synchrotron frequency is much smaller than the revolution frequency (respectively 60Hz and 11 kHz in the LHC at injection). For a given bunch the momentum kick need not be re-computed at each turn. Decimation/interpolation possible

Good for injection transients and dipole instabilities no matter what the source… Works for Synchrotrons only
Widely used in synchrotron light sources. Query John Fox / SLAC

- Variant. Poor man's damper (LHC, PEPII woofer)
  - In the absence of a broadband kicker we can act via the RF cavities
  - Δp is generated by adding to the cavity voltage, a small correction in quadrature with the accelerating voltage (phase modulation)
  - The BW is limited to the Cavity Field control BW
  - Used in the LHC for damping injection phase/energy error in multi-batch injection mode. Not needed for stability (Landau damping sufficient)
  - Needed in PEPII for stability

It takes 12 SPS cycles to fill one LHC ring



LHC filling: It takes 12 injections from the SPS. The transients will be damped