LLRF Lessons Learned
LHC and PEP-II
Relevance to FCC hh/ee

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1. RF NOISE

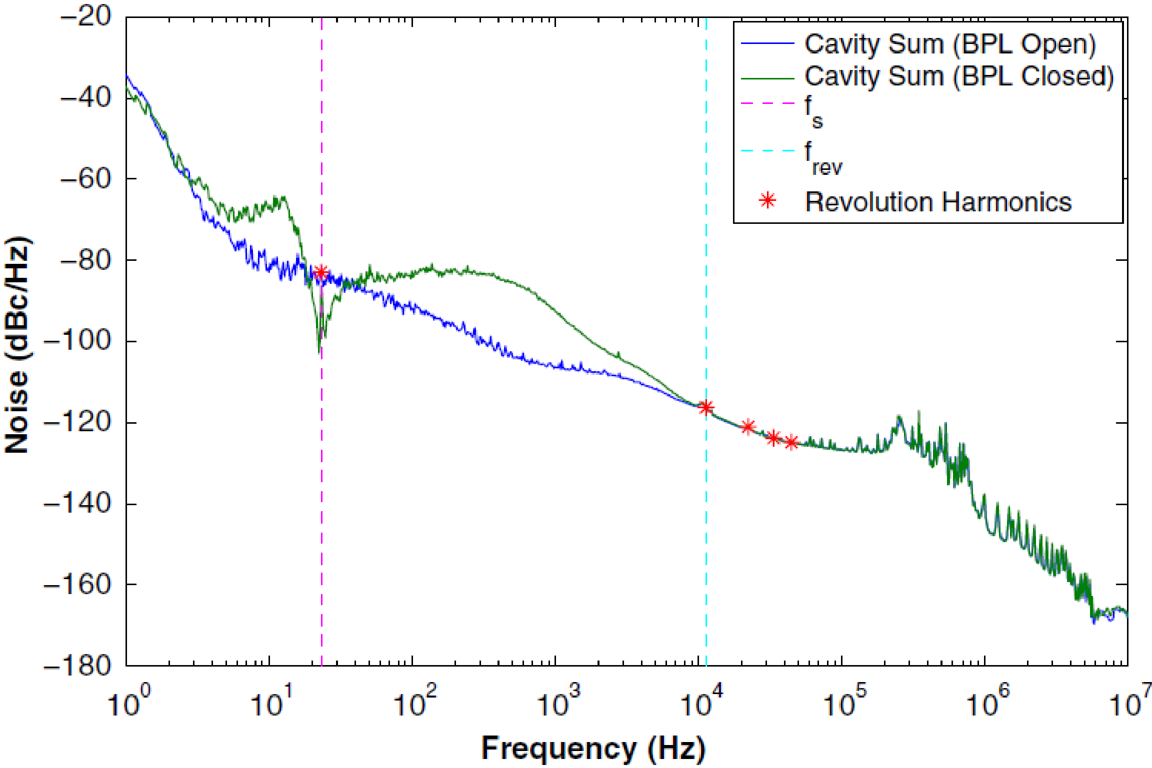
Relevant to hadron colliders only. A major concern for the LHC design, much discussed during external reviews

RF noise (FCC-hh)

- Concerns for LHC
  - Use of klystrons
  - Crossing of f_s=50 Hz during the acceleration ramp [1]
- Experience from SPS p-pbar operation
  - Strong beam phase loop is very efficient with low bucket filling factor-> strong “coherent” response from bunch core
  - In p-pbar, one loop per bunch possible because only 6 bunches and cavity filling time (800 ns) < bunch distance (7 μs)
- In the LHC, one loop per beam
  - Reduces the effect at f_s only (not on the revolution frequency side-bands)
  - But the noise PSD is much stronger close to the carrier when using a VCXO

RF noise (2/3)

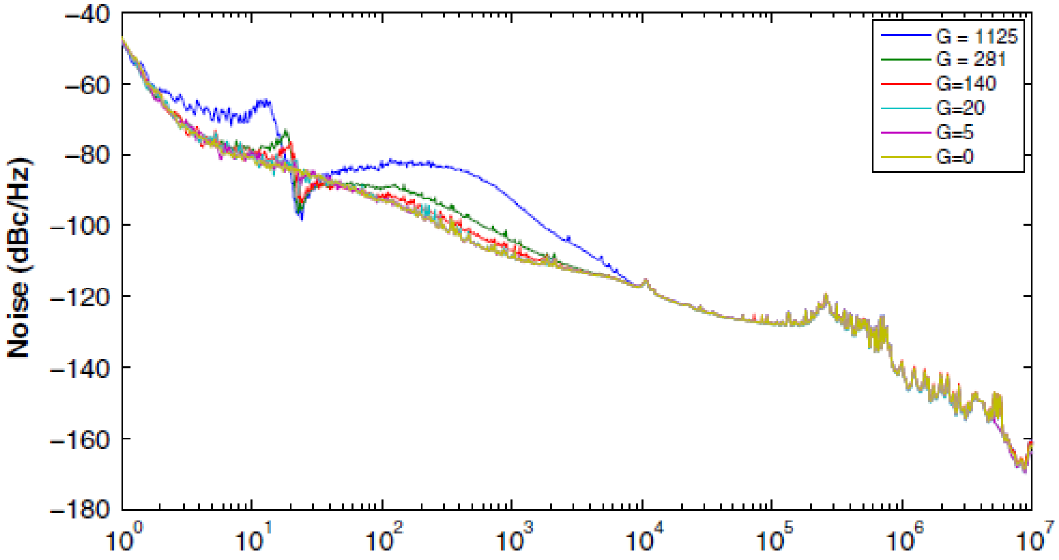
Phase noise PSD vs. frequency offset from carrier

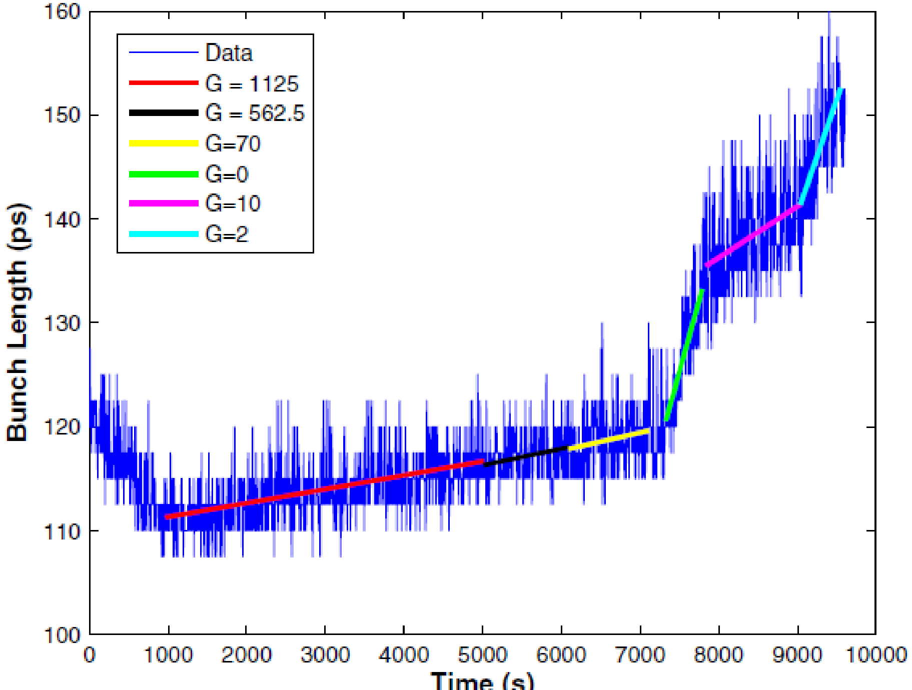


- Phase noise PSD with and without beam, measured in an LHC cavity at 3.5 GeV/c
- Reduction of noise PSD at f_s
- No effect at n $f_{rev} \pm f_s$

RF noise (3/3)

- Effect of phase loop gain [2]
  - Top: Phase noise PSD
  - Bottom: Bunch lengthening
- Relevance to FCC-hh
  - Higher energy -> more synchrotron radiation damping (0.54 h). Good!
  - But f_s= 3.4 Hz -> much larger PSD -> use high Q VCXO





2. LONGITUDINAL STABILITY

Effect of the cavity impedance at the fundamental.
Relevant to both hadron and lepton colliders

2.1. HADRON

Longitudinal Stability

Longitudinal Emittance blow-up

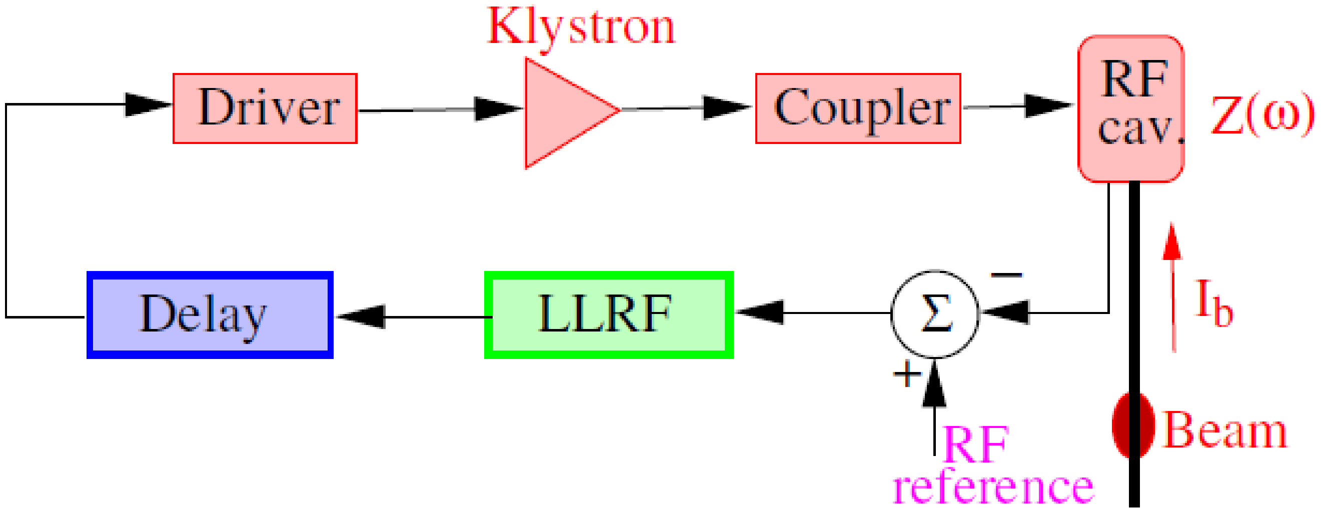
- Longitudinal stability is achieved by keeping a sufficient synchrotron tune spread (Landau damping)
- It will be lost during the ramp, following adiabatic bunch shortening

$$\tau \propto \frac{1}{\sqrt[4]{E\,V}}$$

- To preserve it, we apply controlled emittance blow-up (see Elena's presentation) [3]
  - Inject band-limited phase noise that selectively hit the core of the bunch
  - This technique is commonly used in the SPS and in the LHC since start-up

Cavity Impedance at the fundamental (1/3)

- Easily controlled by the LLRF
- Classic method [5]. Use a strong RF feedback to compensate for the beam induced voltage



Cavity Impedance at the fundamental (2/3)

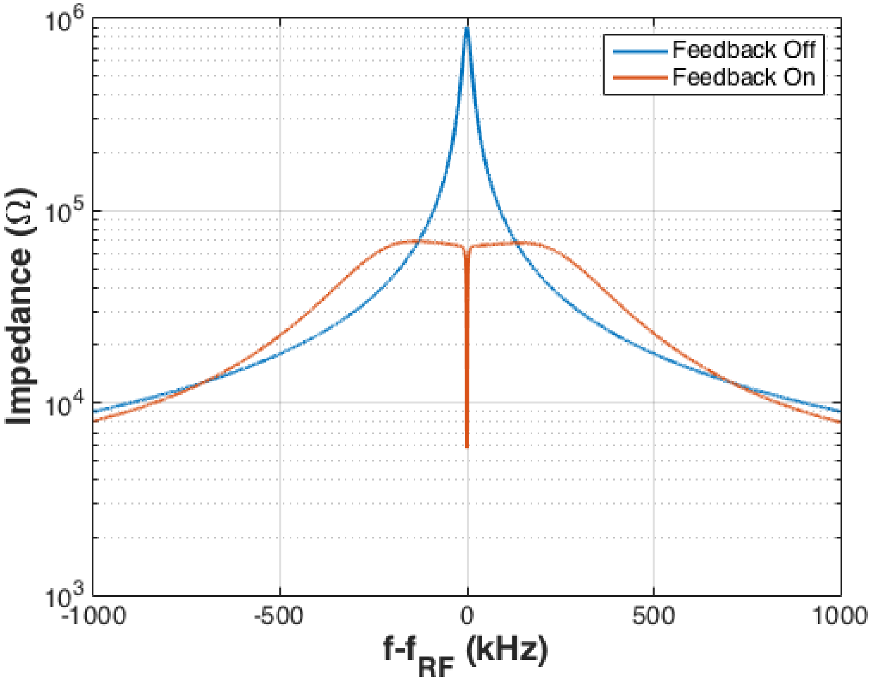
- Then the cavity impedance is effectively reduced by the loop gain

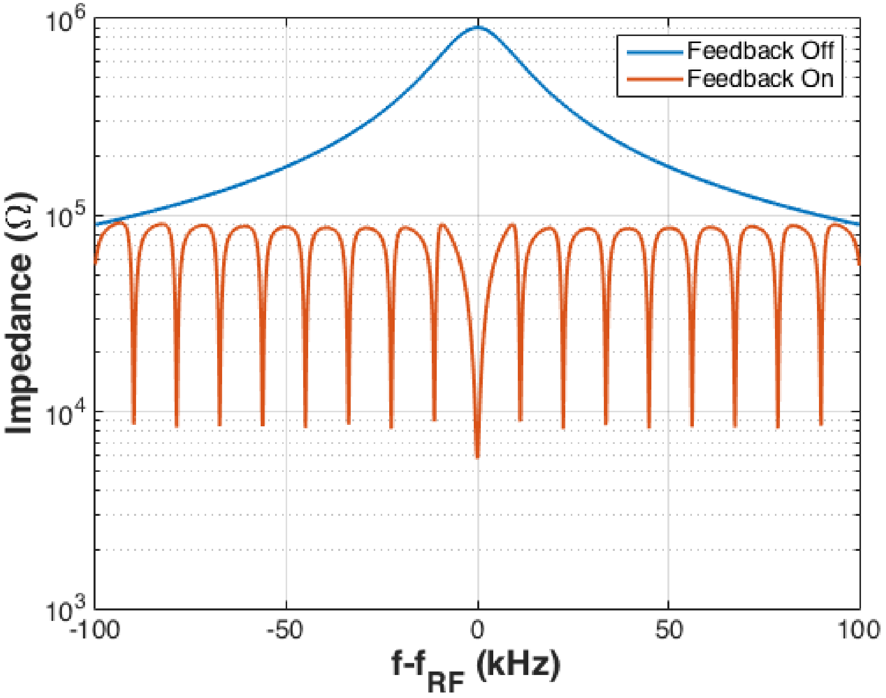
$$Z_{cl}(\omega) = \frac{Z(\omega)}{1 + e^{-i\tau\omega} G(\omega) Z(\omega) e^{i\phi}}$$

- With a proportional feedback, after optimization of the LLRF, the minimum value of the impedance seen by the beam is [5] $R_{\min} = \frac{2}{\pi}\tau\frac{R}{Q}\omega_{RF}$

- It is independent of the cavity loaded Q_L, but scales linearly with the loop delay τ (including amplifier group delay). It is essential to keep the loop delay short! A low *R/Q* geometry is also favorable.

Cavity Impedance at the fundamental (3/3)





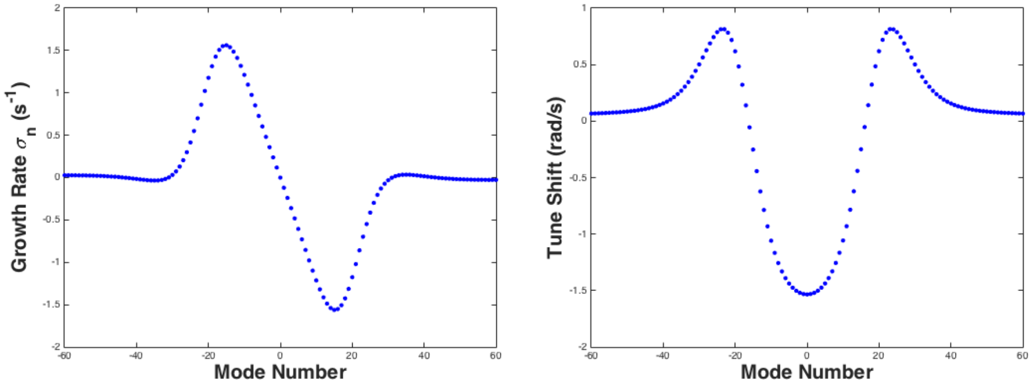
- Left: Modulus of the cavity impedance of an LHC cavity without and with RF feedback. Q_L=20000
- Extra impedance reduction can be achieved, around the revolution frequency sidebands (spectral components driving CBI), using a OTFB [6]
- Right: Enlargement of the cavity impedance with OTFB (red). LHC cavity at injection. f_{rev}=11 kHz

Growth rate vs. Landau damping (1/2)

- The growth rates can be computed from the reduced cavity impedance (at fundamental) and the longitudinal bunch profile. For a parabolic line density

$$\Lambda_n^m = \sigma_n^m + i\,\Delta\omega_n^m$$

$$= \frac{3}{2\sqrt{\pi}5^3}\,\frac{\Gamma\left(m+\frac{1}{2}\right)}{(m-1)!}\,\frac{\eta q I_0}{\omega_s E_0 \sigma_\tau^3}\left(\frac{Z(\omega)}{\omega}\right)_{eff}$$



Growth rate and tune shift vs. mode number

LHC cavity with HiLumi LHC parameters, injection energy, OTFB off

- Mode 1 (dipole, m=1) couples most strongly. Stability is preserved if the modulus of the growth rate is smaller than ¼ the synchrotron tune shift (Sacherer simplified stability criterion)

$$\left|\Lambda_n^m\right| < \frac{\Delta\omega_s}{4}$$

Growth rate vs. Landau damping (2/2)

- The analysis was done for the Hi-Lumi LHC showing large stability margin [7]
- Scaling to the FCC-hh
  - The synchrotron tune spread is 6 times smaller
  - Assuming that we double the number of cavities, the growth rate would be 4 times smaller (lower slippage factor, lower beam current, higher Z - doubled? -, higher energy, lower synchrotron frequency)
  - From the above (back of the envelope) “guesstimate”, the stability margin would be reduced by 50 %. Given the large margin for HiLumi, the result is re-assuring.

	FCC-hh	**HiLumi LHC**
p/bunch	1E11	2.2E11
Bunch spacing (ns)	25	25
RF freq. (MHz)	400.8	400.8
Energy (TeV)	50	7
Voltage (MV)	16-32	16
σ_z (cm)	8	8
f_s (Hz)	3.4	20
Nb Cav.	16 ?	8
γ_t	~100 (?)	~50

2.2. LEPTON

Longitudinal Stability

Growth Rate vs. Synchrotron Radiation damping

- Longitudinal stability is achieved if the growth rate caused by the longitudinal impedance minus the synchrotron radiation damping rate is kept below the damping available from dedicated feedback systems (active dampers) [11]
- Many cavities -> cavity fundamental-driven instabilities with growth time of 0.8 ms in HER, much faster than radiation damping time (30 ms)
- Instabilities caused by the cavity fundamental impedance has been a major limitation for PEP II [8]

	FCC-ee	PEP II HER
DC current (A)	1.45	2.1
RF freq. (MHz)	400.8	476
Energy (GeV)	45.6	9
Bunch spacing (ns)	2.5-7.5	2
Voltage (MV)	200-400	17.5
Rad. Damping time (ms)	0.4	30
Nb Cav.	100 ?	28

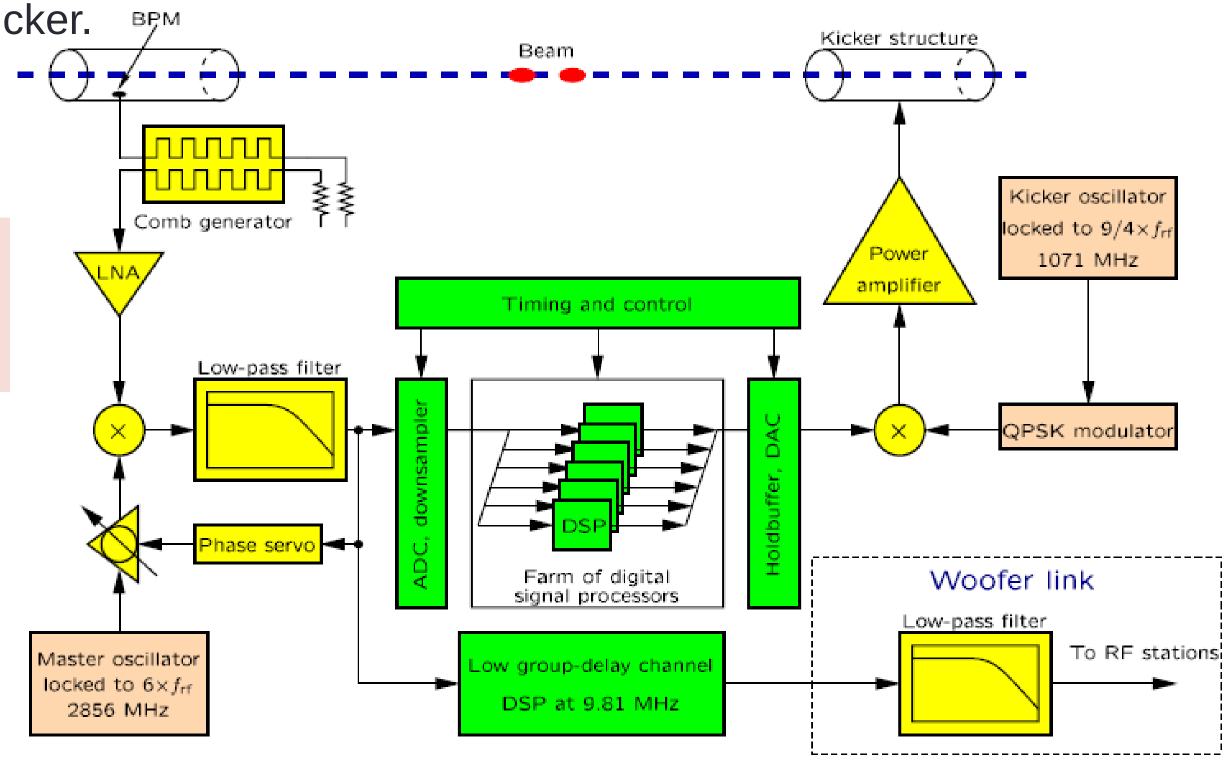
Comparison of FCC-ee (high current/low energy version) to PEP II-HER.

Mitigations

- Cavity impedance at the fundamental was a large part of the longitudinal impedance at PEP II
- Mitigation: RF feedback and OTFB
  - In PEP-II, growth rates with the RF and OTFB ON, were measured much larger than expected. This was traced to the non-linearity of the klystron driver
  - IN PEP-II, the LLRF loops were fine-adjusted for beam stability at the expense of feedback loop stability margin, in the last years
  - RF feedback on multi-cell cavity is more difficult. For an N-cell cavity we have a cluster of N closely spaced resonances. Although the N-1 “parasitic” resonances are not affecting the beam (sum of accelerating kicks equal to zero), they can make the RF feedback unstable and must therefore be damped in the LLRF processing. Done with RF filters for the LEP cavity installed in the SPS in 1990s. More easy to-day with digital technology. Easier if distance between fundamental modes is kept much larger than feedback BW. To be looked-up for FCC-ee

Woofer and Longitudinal damper

- In PEP-II, the cavity fundamental-driven instabilities were controlled via a dedicated low-mode “woofer”, that is a low BW damper using the cavities as “kicker”. This provided a 0.33 ms damping time for the low-order modes
- HOM-driven instabilities were damped by a broadband bunch-by-bunch longitudinal damper. Similar longitudinal dampers have been used in DAFNE and ALS
- At 2.5 ns bunch spacing (FCC-ee), the LLRF part of such a longitudinal damper is “relatively easy” with to-day’s technology
- It requires a longitudinal kicker.



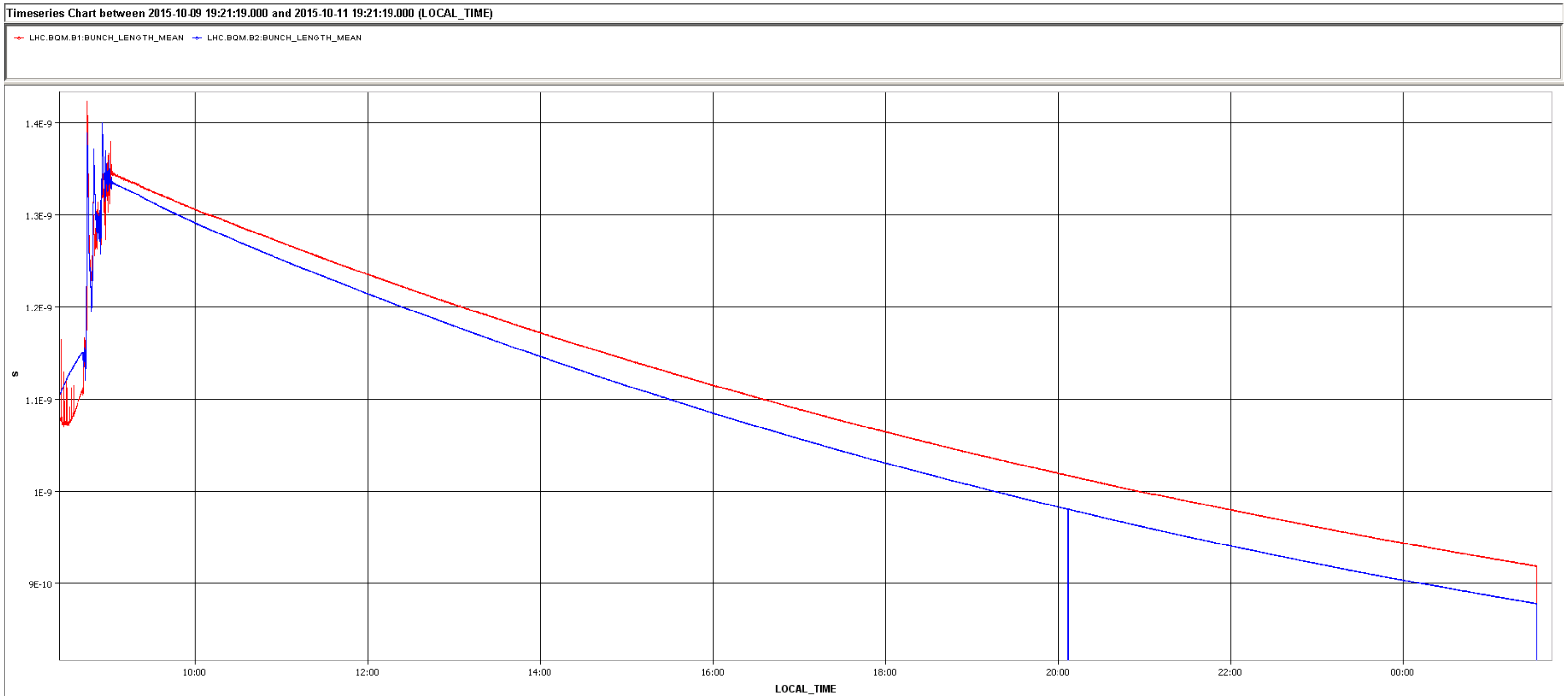
PEP II longitudinal damper and woofer. Reproduced from [8]

3. BUNCH SHORTENING DURING PHYSICS

Relevant to hadron colliders only

Bunch shortening…

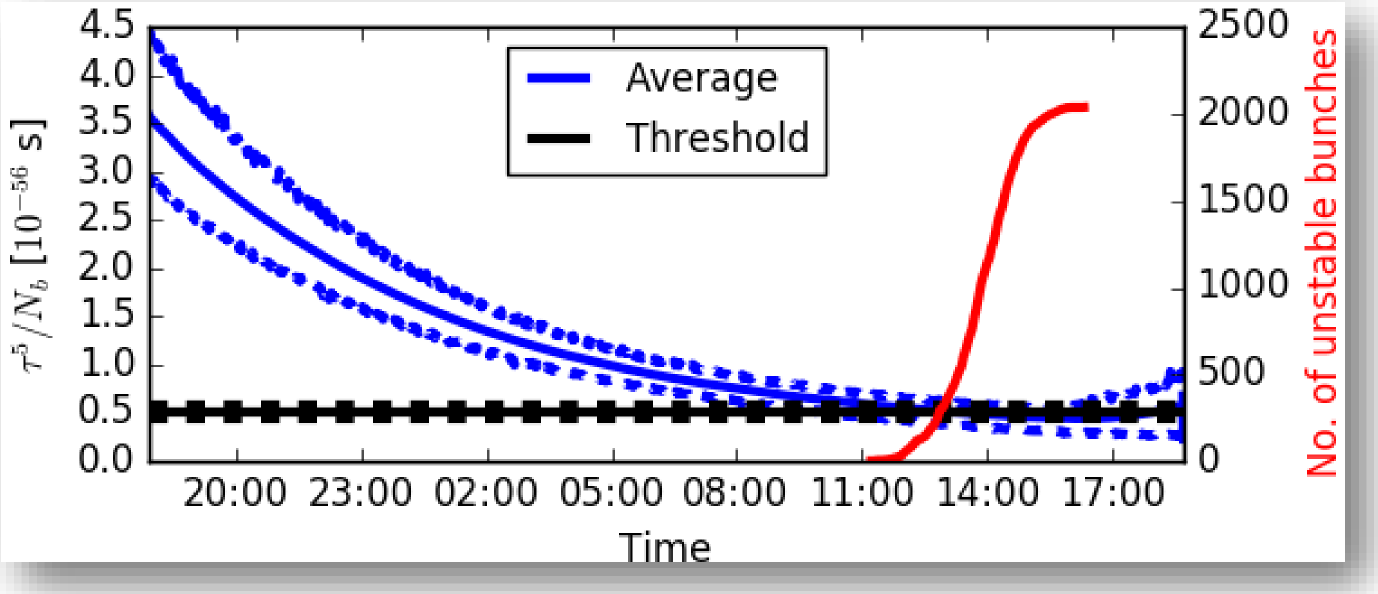
- Bunch shortening during physics is caused by synchrotron radiation damping



Bunch length evolution during a 24 hours long fill. From 1.35 ns down to 0.9 ns. LHC run 2 (2015) with ~2000 nominal intensity bunches.

Instability

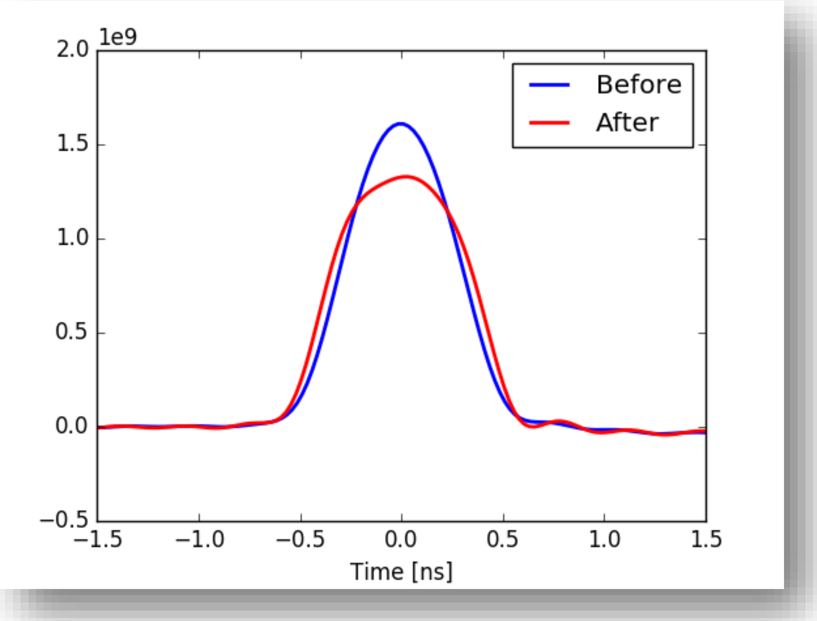
- Bunch shortening during physics can drive the bunch unstable as the bunch longitudinal emittance decreases and can reach the stability limit (loss of Landau damping)



At constant energy and voltage, the single-bunch instability growth rate scales as N/τ^5, with N the number of particles in the bunch and τ the bunch length [10]. When this ratio reaches the threshold (Im(Z/n) ~0.1 Ω), the bunch becomes unstable. LHC run 2 (2015) with ~2000 nominal intensity bunches.

Mitigation

- It cannot be compensated by reduction of phase loop gain. This creates longitudinal tails and particles are lost out of the bucket before significant lengthening of the bunch core
- It can be compensated by
  - Injecting band-limited RF phase noise that mainly excite the core of the bunch (method used for longitudinal emittance blow-up in the LHC ramp)
  - Brief coherent excitation of the bunch core with a single-tone signal [9]



Longitudinal profile of an LHC bunch before and after application of an RF phase excitation lasting for *10 s*, at the $0.965\, f_{s0}$ frequency [11].

FCC-hh

- Bunch shortening is a major concern
- It will be much faster in the FCC-hh as the radiation damping time is 0.54 h (compared to ~20 h in LHC)
- Bunch length control in physics will be tested in the LHC in 2016 and later years
- It will hopefully have become routine operation by the start of FCC-hh …

4. Beam loading compensation: Constant cavity voltage phase vs. phase modulation

Relevant to both hadron and lepton colliders

Beam loading compensation

- Control of cavity voltage (including beam induced) is essential
  - We want to keep the voltage sensed by all bunches equal so that they have equal parameters (length, momentum spread)
  - We must compensate the beam-induced voltage at fundamental to avoid CBI caused by cavity impedance at fundamental (section 2.)
- We can derive a simple relation between I_g, V, I_b and the cavity detuning $\Delta\omega$ [13]

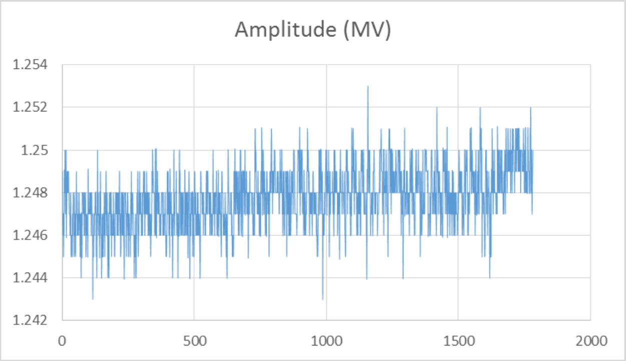
$$I_g(t) = \frac{V(t)}{2R/Q}\left[\frac{1}{Q_L} - 2j\frac{\Delta\omega}{\omega}\right] + \frac{dV(t)}{dt}\frac{1}{\omega R/Q} + \frac{I_b(t)}{2}$$

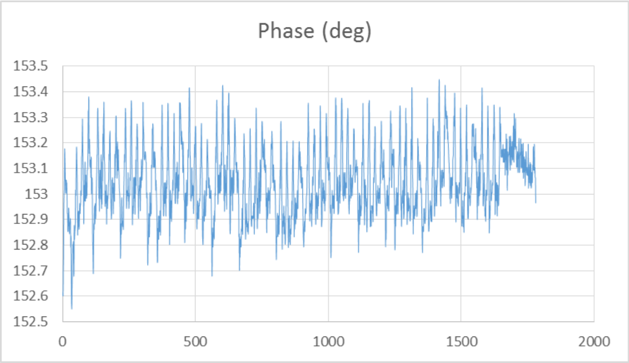
- The modulation in beam current $I_b(t)$ is imposed by the filling pattern: presence of small gaps for kicker rise time (hadron collider) or ions clearing gaps (lepton collider)

Beam loading compensation. LHC to-day

- So far we have operated the LHC RF for full compensation of the transient beam loading in the ACS cavities: $V(t) = V_0$
- The results are excellent: beam-loading invisible in amplitude, barely visible in phase (0.5 deg pk-pk)

Nov 2nd, 2015.
Fill 4565.
2244 b, 1.1E11 p/bunch.
Cav4B1





- But that calls for huge RF power. The klystron current must “toggle” according to

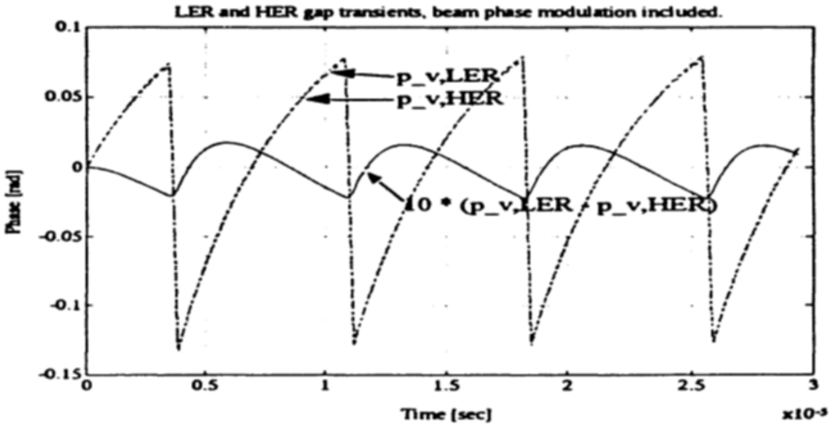
$$I_g(t) = \frac{V}{2\,R/Q}\left[\frac{1}{Q_L} - 2j\frac{\Delta\omega}{\omega}\right] + \frac{I_b(t)}{2}$$

- After optimization of Q_L, and detuning, the required power is then proportional to voltage and peak RF component of beam current (neglecting acceleration and synchrotron radiation losses) [14]

$$P_g = \frac{V\ I_{b,pk}}{8}$$

Beam loading compensation. A better scheme: cavity phase modulation

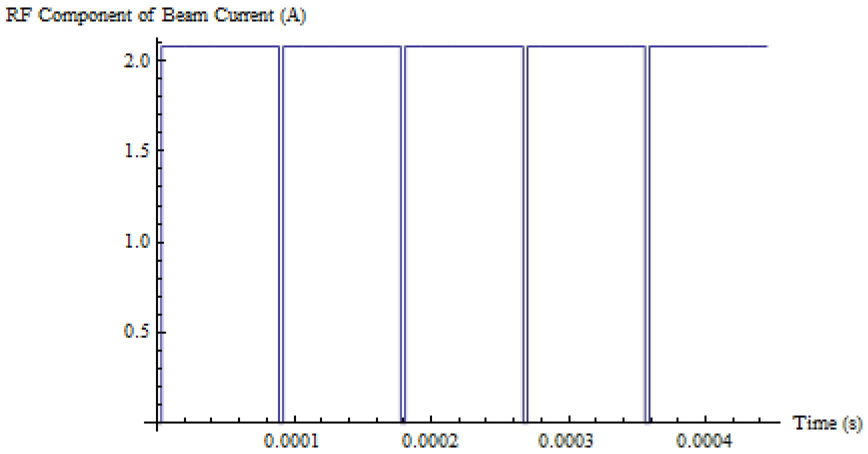
- Why do we care about voltage in turn segment where there is no beam?
- Alternative:
  - We keep the voltage *amplitude* constant over one turn
  - BUT we accept to modulate the voltage *phase* during the turn. This results in
    - A modulation of the distance between bunches. **To be accepted by experiments**
    - A required RF power **independent of beam intensity** (neglecting losses and radiation damping)
- The attractiveness of this scheme is evident: It was proposed for the LHC in 1991 [14], was operational at PEP-II [15], used in an SPS test of the 400 MHz LHC cavity in 1995 [16].

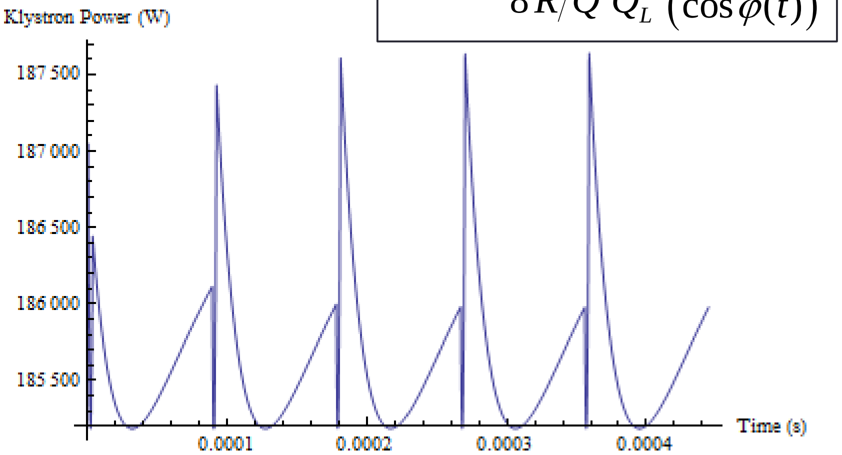


Phase slippage of the High and Low energy rings of PEPII, plus their difference. The pk-pk slippage was 70 ps.

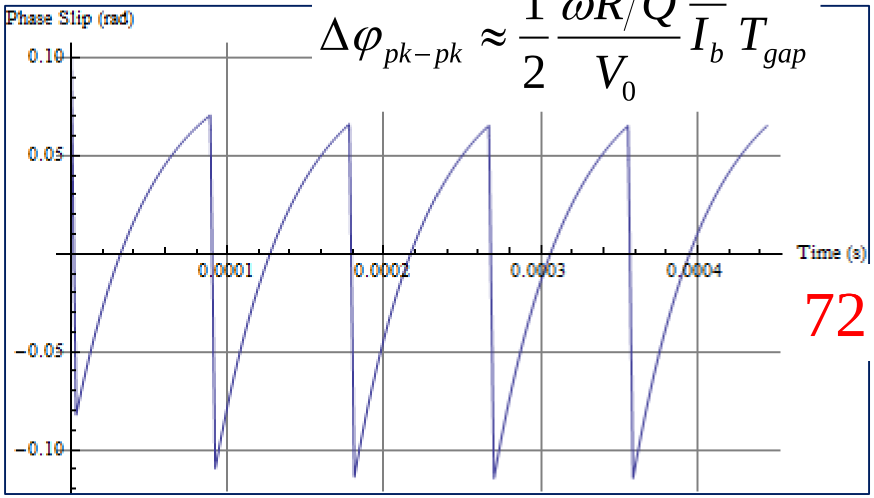
- The following figures consider the **HighLumi case**: 2808 bunches, 2.2E11 p/bunch, 1.11 A DC, $\cos^2$ longitudinal bunch profile, 1 ns base length, bunching factor 0.9, 2 MV/cavity, Q_L=60000, R/Q =45 Ω. The cavity is at the optimum detuning (-9039 Hz). We consider the **3.2 μs long abort gap only**.

$$P_g(t) = \frac{V^2}{8\,R/Q}\,\frac{1}{Q_L}\,\frac{1}{(\cos\varphi(t))^2}$$





$$\Delta\varphi_{pk-pk} \approx \frac{1}{2}\,\frac{\omega R/Q}{V_0}\,\overline{I_b}\,T_{gap}$$



72 ps

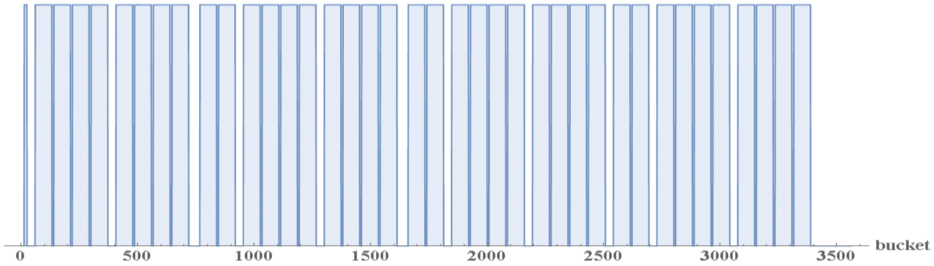
Top left: Component $i_b(t)$ of beam current at 400 MHz. 3.2 μs long abort gap.

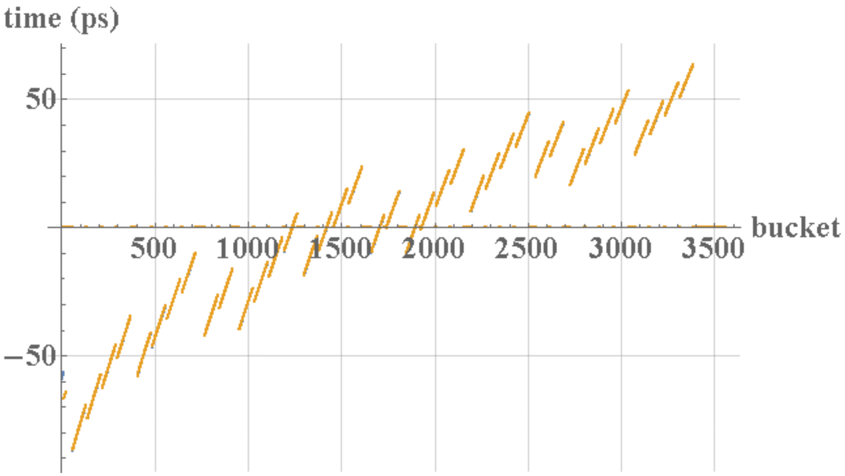
Top right: Klystron power, almost independent of beam current

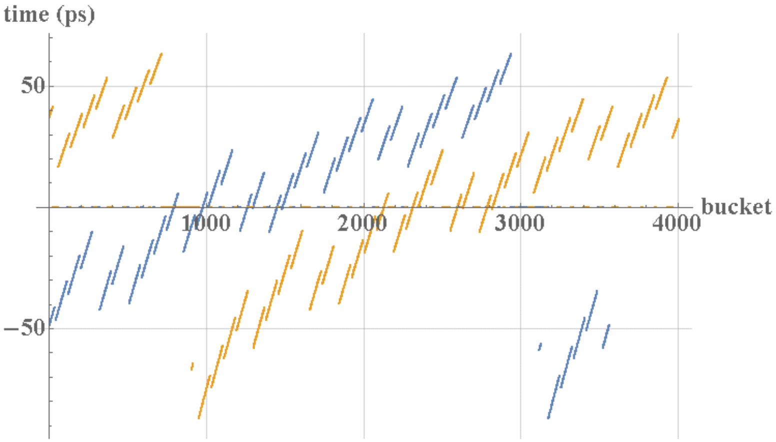
Bottom left: Phase modulation at 400 MHz. We get 0.180 rad pk-pk (10.3 degrees) at 400 MHz equal to 72 ps pk-pk.

Roadmap for HiLumi LHC

$$\Delta\varphi_{pk-pk} \approx \frac{1}{2}\frac{\omega R/Q}{V_0}\overline{I_b}\,T_{gap}$$







HiLumi conditions: 2,2E11 p/bunch, 12 MV, QL=60k

Top: Filling pattern. Note that the "abort" gap is 5 microsec long (including the 12b batch)

Bottom left: Phase modulation at IP1 and IP5

Bottom right: Phase modulation at IP8 and IP2

- CAUTION: this scheme results in modulation of the bunch distance that would result in **modulation of the z-vertex** except if filling patterns are symmetric **w.r.t. all collision points**

5. EXTRAPOLATIONS…

Relevance to FCC-hh and FCC-ee

Extrapolations…

FCC-hh

- **RF noise** should **not be a problem**. VCXO should however be selected with very high Q so that noise in the 1-4 Hz zone is small
- **Stability margin** for low order CBI (caused by cavity impedance at fundamental) is **not much worse** than HiLumi LHC
- **Bunch shortening** during physics is a **big issue**. Hopefully solved for HiLumi in the meantime
- Use of phase modulated cavity voltage can be considered if z-vertex modulation is acceptable by the experiments.

FCC-ee

- **CBI growth rates** likely **much larger** than synchrotron radiation damping->**active damping required**
  - Woofer for low order modes
  - **Bunch-by-bunch longitudinal feedback**
- **Phase modulated** RF voltage likely **required**. Compatibility with experiments to be checked.

Thank you for your attention

Comments? Questions?

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SPARE SLIDES

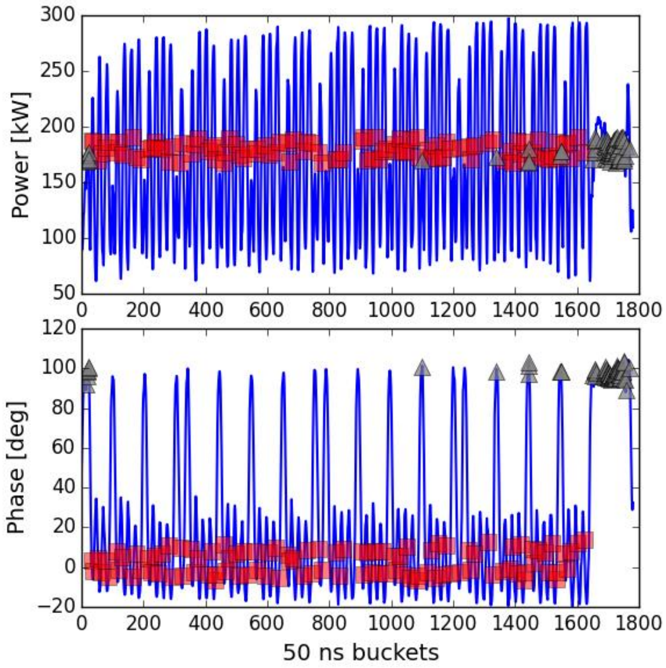
Beam loading compensation. To-day (2)

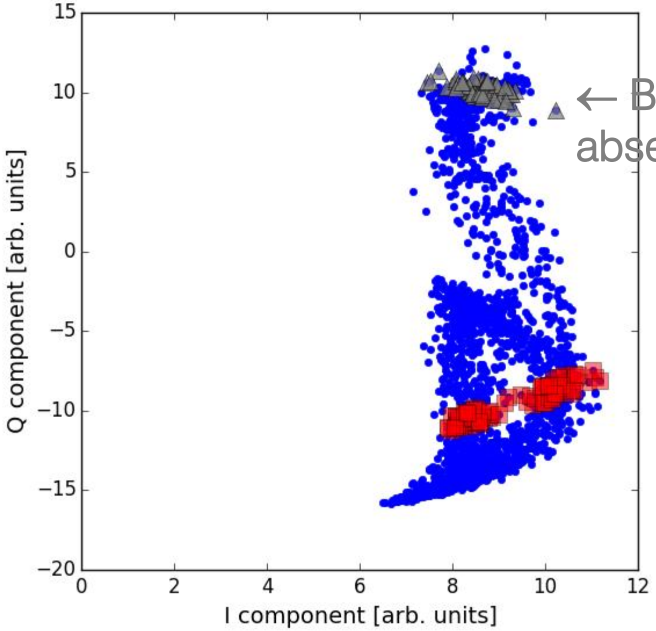
- The klystron current must “toggle” according to

$$I_g(t) = \frac{V}{2R/Q}\left[\frac{1}{Q_L} - 2j\frac{\Delta\omega}{\omega}\right] + \frac{I_b(t)}{2}$$

- After optimization of Q_L, and detuning, the required power is then simply proportional to voltage and peak RF component of beam current. Theory says 150 kW (10 MV, 1.2 A peak RF current), but we see large transients

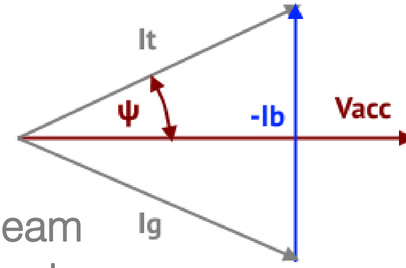
↓ Beam present ↓ Beam absent





← Beam absent

← Beam present



$$\boxed{P_g = \frac{V\, I_{b,pk}}{8}}$$

D. Boussard, RF Power Requirements for a High Intensity Proton Collider, PAC 1991