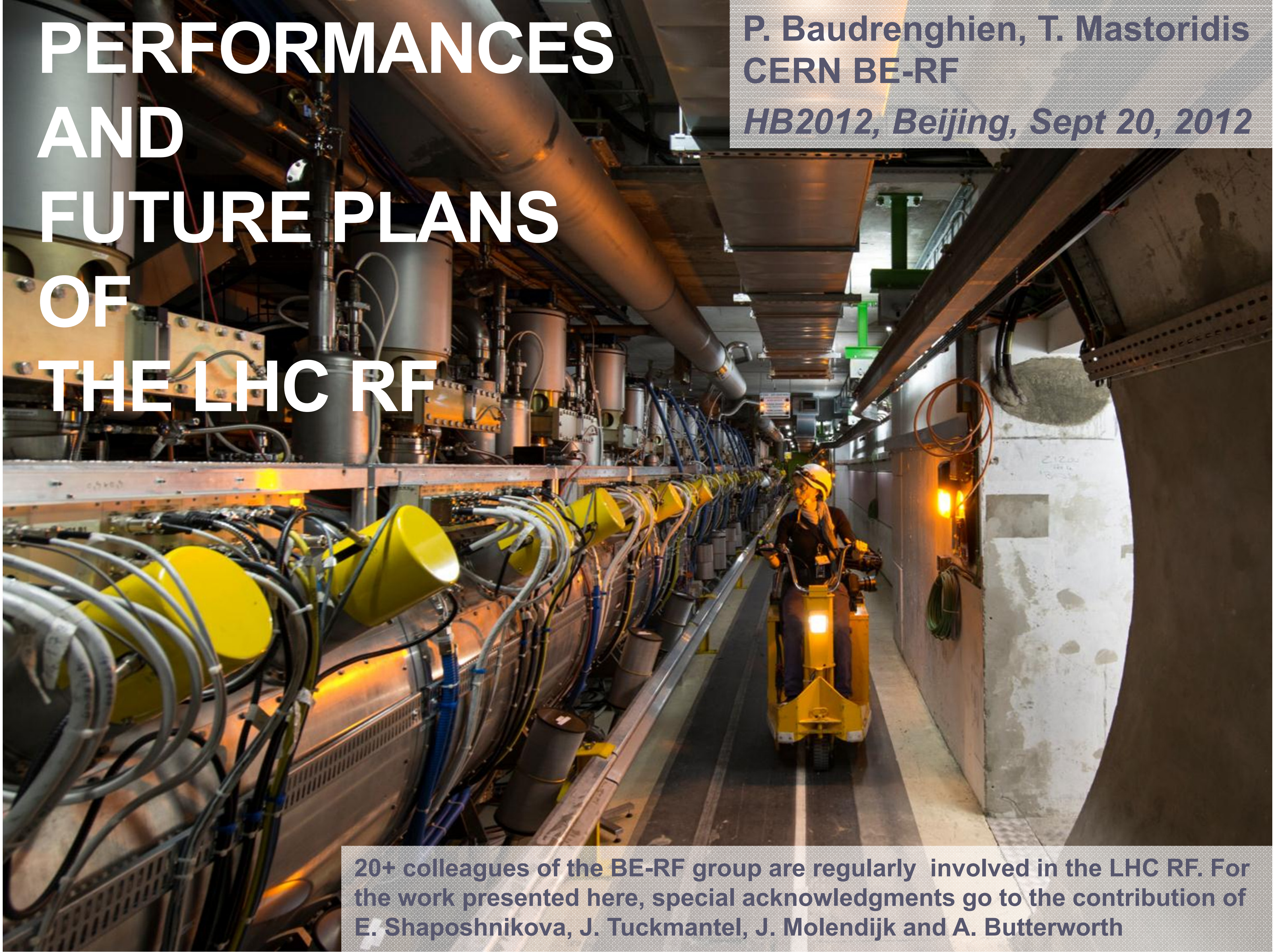


PERFORMANCES AND FUTURE PLANS OF THE LHC RF

P. Baudrenghien, T. Mastoridis
CERN BE-RF

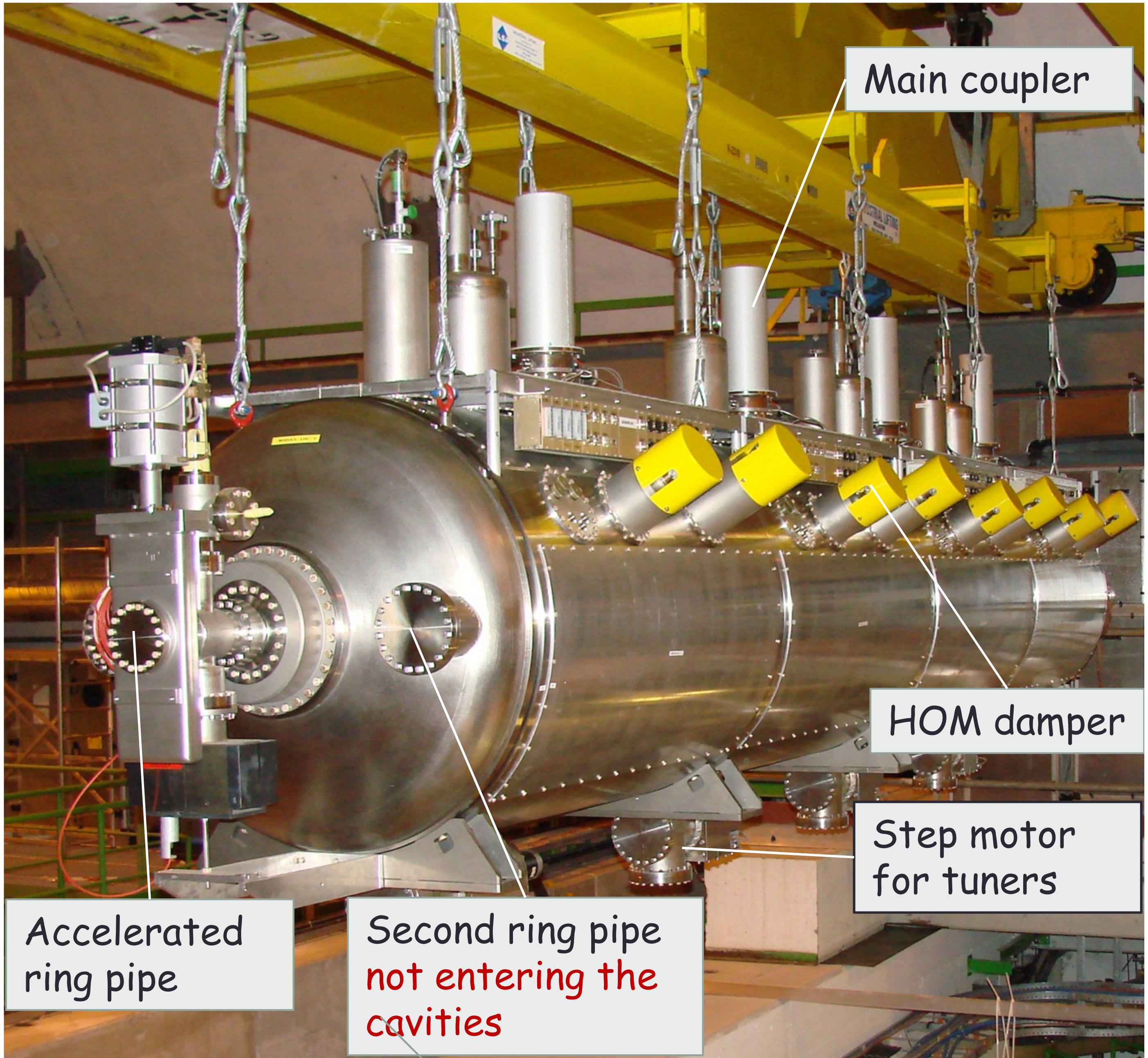
HB2012, Beijing, Sept 20, 2012

20+ colleagues of the BE-RF group are regularly involved in the LHC RF. For the work presented here, special acknowledgments go to the contribution of E. Shaposhnikova, J. Tuckmantel, J. Molendijk and A. Butterworth

THE SCENE

Cavities, klystrons, layout

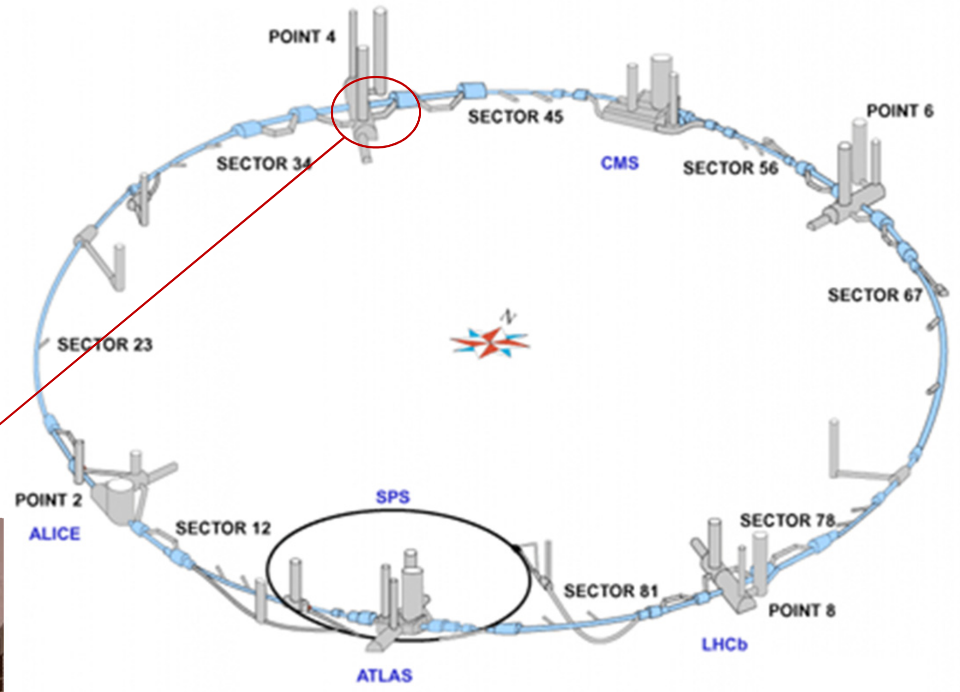
- 8 RF cavities per ring at 400.8 MHz
- Super Conducting Standing Wave type, single-cell, $R/Q = 45\ \Omega$, 2 MV/cavity maximum
- Movable Main Coupler: Q_L from 20000 to 180000
- 1 klystron per cavity, 330 kW max



Four independent cavities per cryostat

Layout

- Two independent rings (allows for p-Pb collisions)
- Klystrons and LLRF in a cavern ~150 m underground not accessible during operation



THE CHALLENGES…

- and our solutions…

MINIMIZING TRANSIENT BEAM LOADING AT INJECTION & CAVITY IMPEDANCE

- Superconducting cavity with low R/Q and high voltage per cavity
- Strong RF feedback and One-Turn feedback to prevent Coupled-Bunch instabilities

Transient Beam Loading during filling

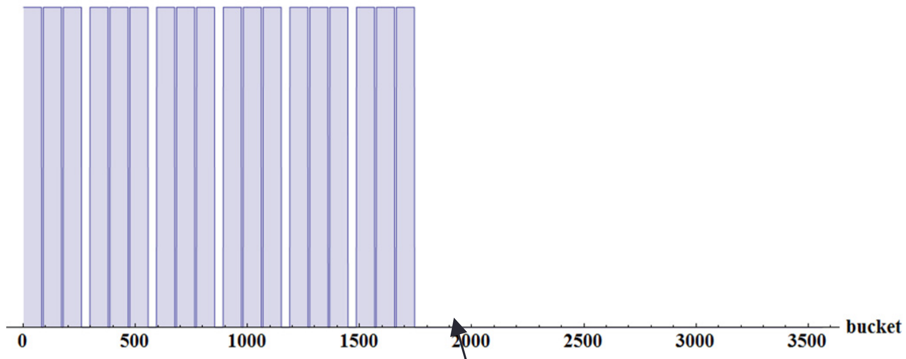
- Filling is done by the injection of twelve successive batches in each ring
- During filling, the field in the empty buckets is perturbed by the beam in the filled buckets
- This causes an injection phase error and then capture losses, if injection phase is kept constant
  - In the case of optimum detuning for the average beam current, and with a constant klystron drive, the peak phase modulation on the RF voltage caused be a beam gap is [1]

$$\Delta\phi \approx \frac{1}{2}\frac{R}{Q}\omega_0 \frac{I_{b,rf}}{V} t_{gap}$$

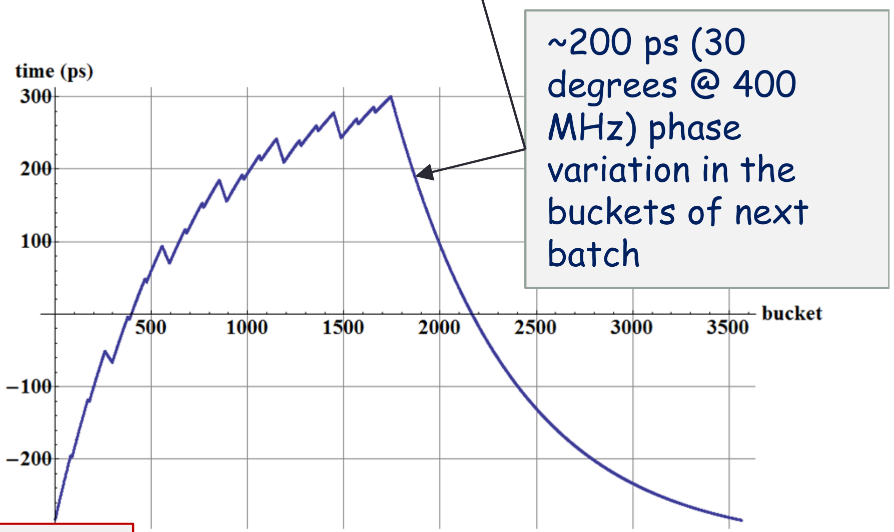
  - The effect is minimized with **superconducting cavities: low *R/Q*** (45 Ω) and **high voltage**

Hardware decision: Low R/Q superconducting cavities

Controls decision: Keep voltage constant over one turn, during filling. Strong RF feedback and One-Turn feedback



Situation half way during filling. One turn



Phase modulation of the cavity voltage half way during filling. Ultimate bunch current (1.7E11 p/bunch), 0.75 MV/cavity

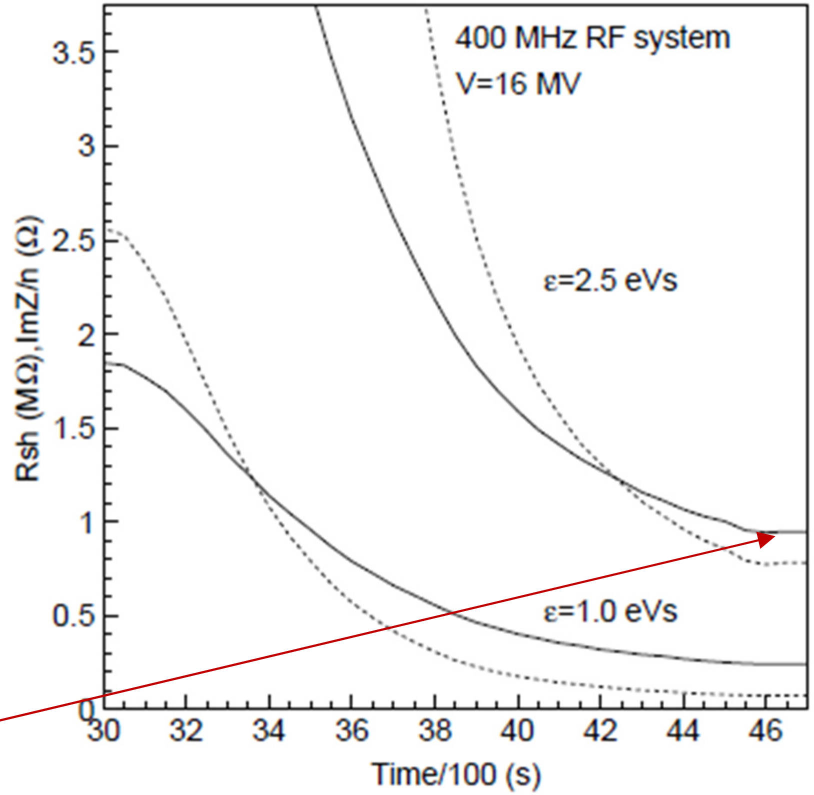
Coupled bunch instabilities

- Use of super-conducting cavities also minimizes the total impedance for a given RF voltage. A concern for a high intensity (>0.5 A DC) machine
- There is no longitudinal damper. We count on Landau damping for stability
- Narrow-band resonant impedance threshold

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

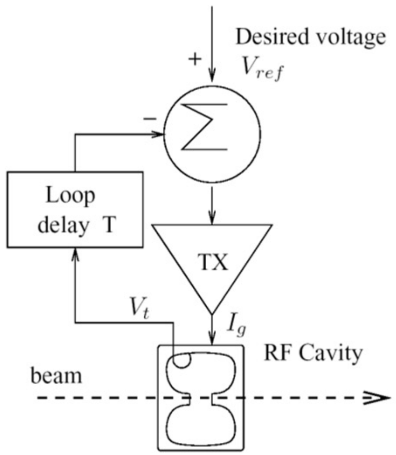
- Design target for nominal beam current: : At 7 TeV, the impedance must be below 1 MΩ (2.5 eVs=nominal)
- At fundamental, with Q_L=60000, the

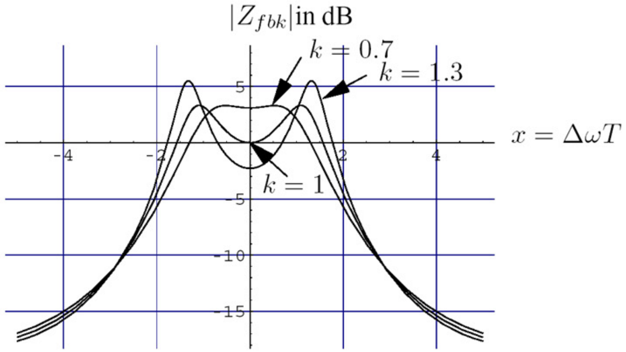
Target: Reduce effective cavity impedance by 100 minimum on resonance

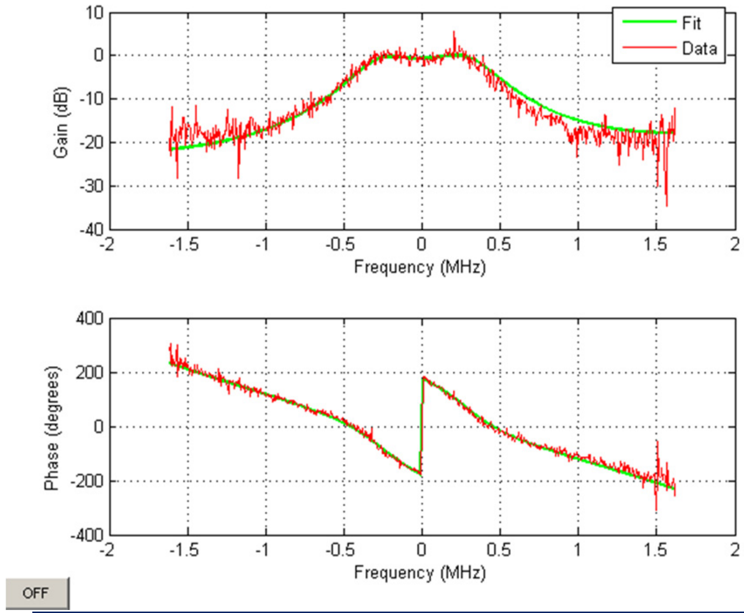


Narrow-band impedance threshold Rsh (solid line) and imaginary part of the broad-band impedance threshold Z/n (dotted line) during the acceleration ramp with constant 16 MV for different longitudinal emittances. Reproduced from [3]

Strong RF feedback







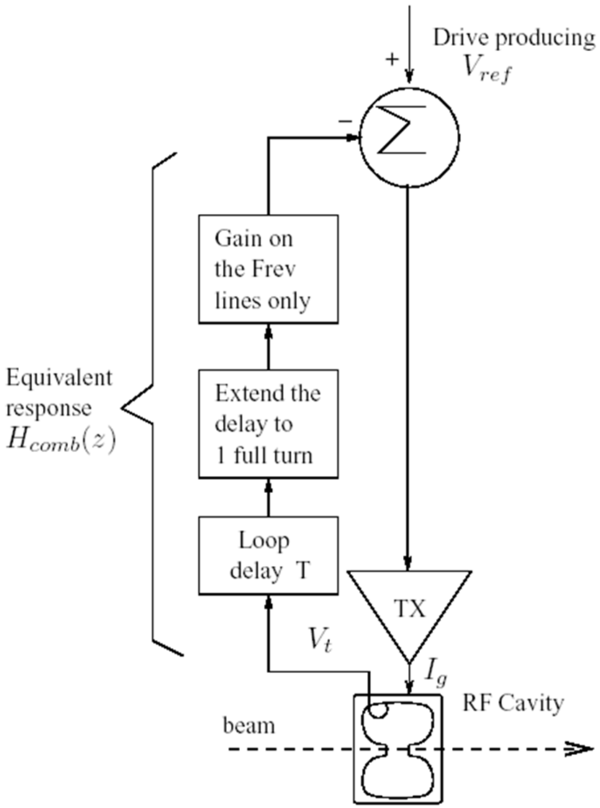
With an RF feedback the minimal effective impedance

With the RF feedback we reduce the cavity impedance at resonance by ~35 linear (Q_L=60k). The 21.6 MΩ are reduced to 0.6 MΩ. A bit risky if instability threshold is 1 MΩ

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 ~ 35. 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.

The loop delay T was kept low in the LHC

One-Turn delay feedback (OTFB)



- The One-Turn delay Feedback (OTFB) produces gain only around the revolution frequency harmonics
- It further reduces the transient beam loading and effective cavity impedance (factor of 10)

With the One-Turn delay feedback we gain another factor 10 in impedance reduction on the revolution sidebands resulting in a 350-fold reduction (Q_L=60k). The 21.6 MΩ are now reduced to 0.06 MΩ. Comfortable margin compared to the 1 MΩ threshold.

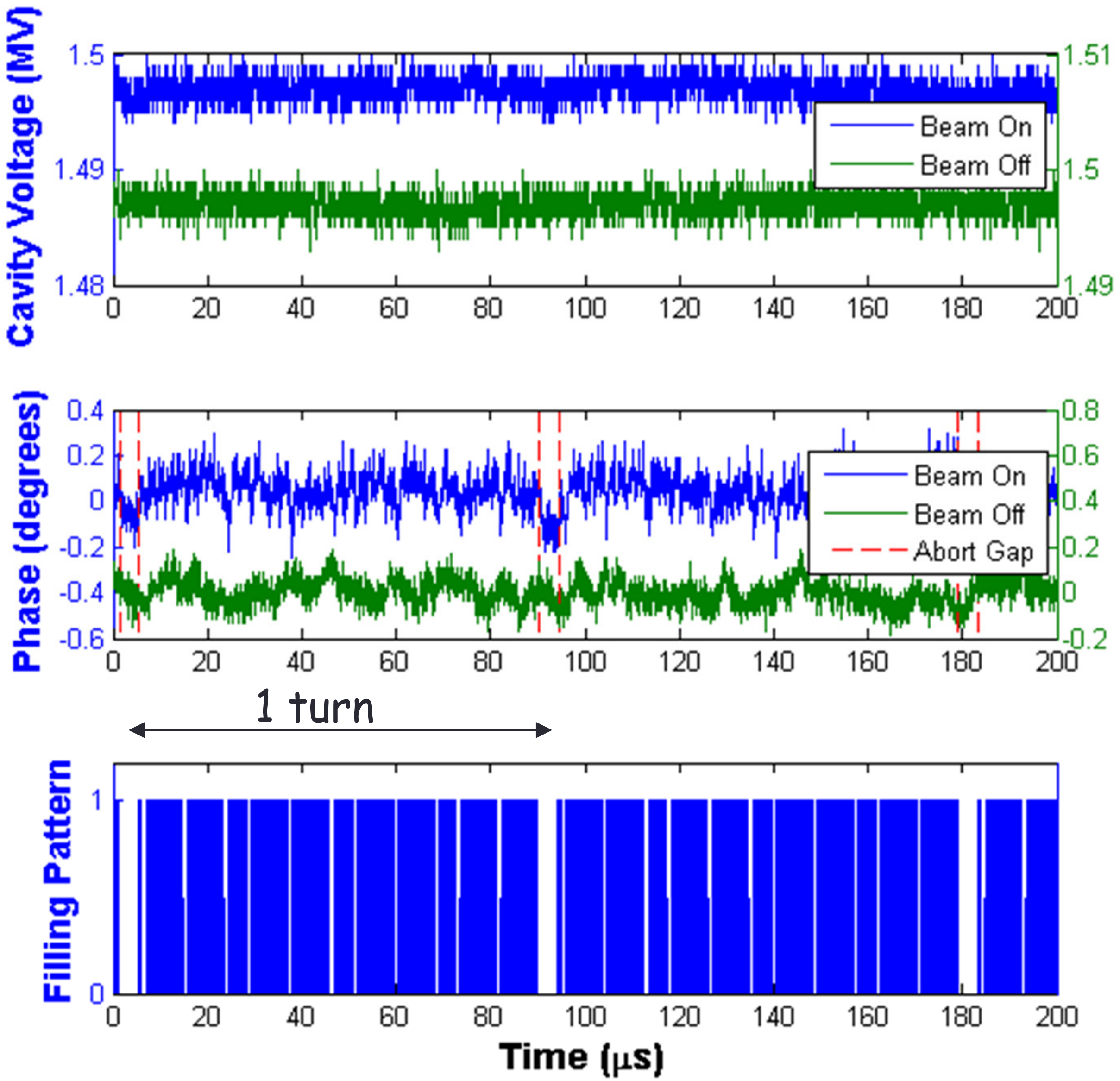
Effective Cavity Impedance with RF feedback alone (smooth trace) and with the addition of the OTFB (comb). The cavity centre frequency is 400.789 MHz. We look at a band offset by +200 kHz to +300 kHz. Frev= 11 KHz. The OTFB provides ~ 20 dB additional impedance reduction on the Frev lines.

Uncompensated transient beam loading

Beam induced modulation of the cavity voltage and phase in physics (blue). 1380 bunches, 1.3E11 p/bunch, 50 ns spacing.

We observe 0.2 degree phase modulation caused by the abort gap.

The situation without beam is shown in green for comparison.



MINIMIZING DEMANDED KLYSTRON POWER

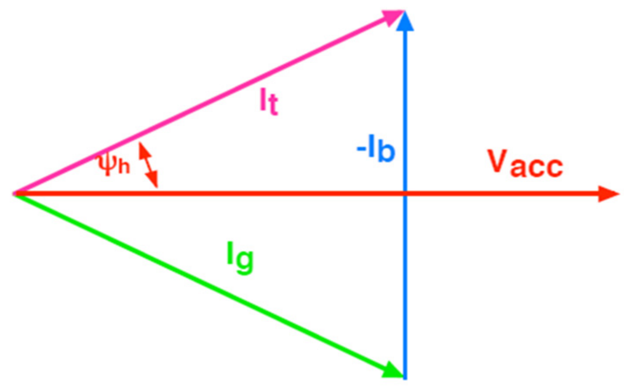
- Half-detuning

Half detuning [2]

- For a constant RF voltage (amplitude and phase), the klystron demanded power will be different in the beam-on segments and in the no-beam segment
- This power depends on the cavity tune. The "Half detuning" scheme makes the demanded power equal during beam and no-beam portions

$$\left[\frac{\Delta f}{f}\right]_{half} = -\frac{1}{4}\, R/Q\, \frac{I_{b,rf}}{V}$$

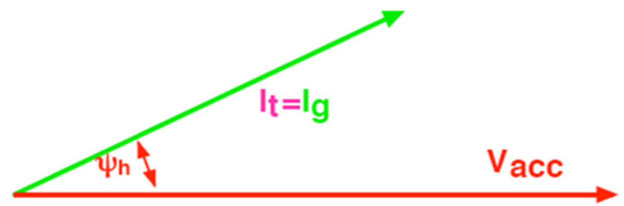
Half-detuning: beam current present



- Once the half-detuning policy is enforced, klystron power is uniquely dependent on the RF voltage, beam current and cavity loaded Q

$$P = \frac{1}{8}\frac{V^2}{Q_L\, R/Q} + \frac{1}{2} Q_L\, R/Q \left[\frac{I_{b,rf}}{4}\right]^2$$

Half-detuning: beam current absent



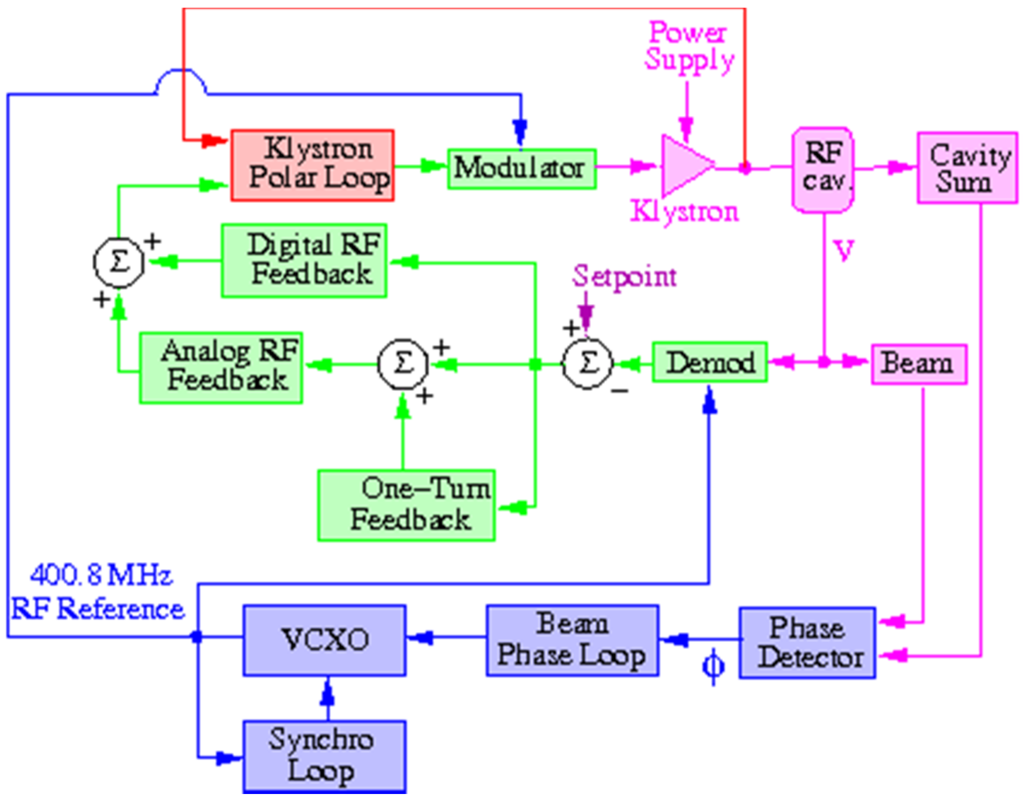
- We can optimize the loaded Q to minimize power at injection and in physics

RF NOISE

Emittance growth caused by RF noise should remain below the synchrotron radiation damping time: 13 hours at 7 TeV

- Klystron polar (amplitude/phase) loop
- RF feedback and OTFB
- Beam Phase Loop

RF noise [6]



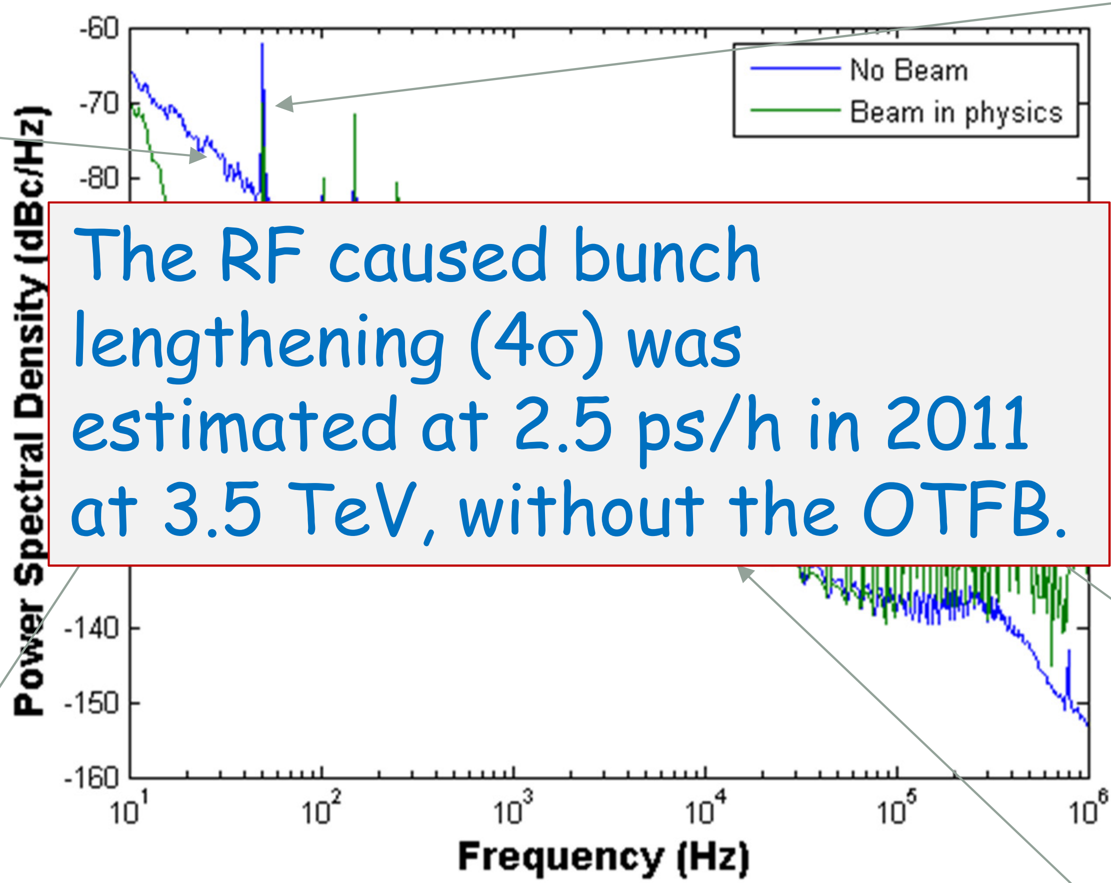
Three LLRF loops

- The Klystron Polar loop (in red) is an amplitude/phase loop that reduces the effect of HV ripples. One loop per klystron
- RF feedback and OTFB are cartesian loops (I/Q) to regulate the cavity field (green). One loop per cavity
- The Beam Phase Loop (BPL) damps the common mode synchrotron oscillation (blue). It uses a PU to extract beam phase (averaged over all bunches) and feeds back to the VCXO input. One loop per ring

Cavity Sum phase noise with beam (green) and without beam (blue)

Noise in the 10Hz-1kHz range is caused by the VCXO (-20 dB/decade slope)

50 Hz and harmonics come from the klystron HV ripples. The klystron loop reduces them by 50 dB up to 600Hz. Fs crosses 50 Hz during the ramp [55 Hz-26 Hz].



The RF caused bunch lengthening (4σ) was estimated at 2.5 ps/h in 2011 at 3.5 TeV, without the OTFB.

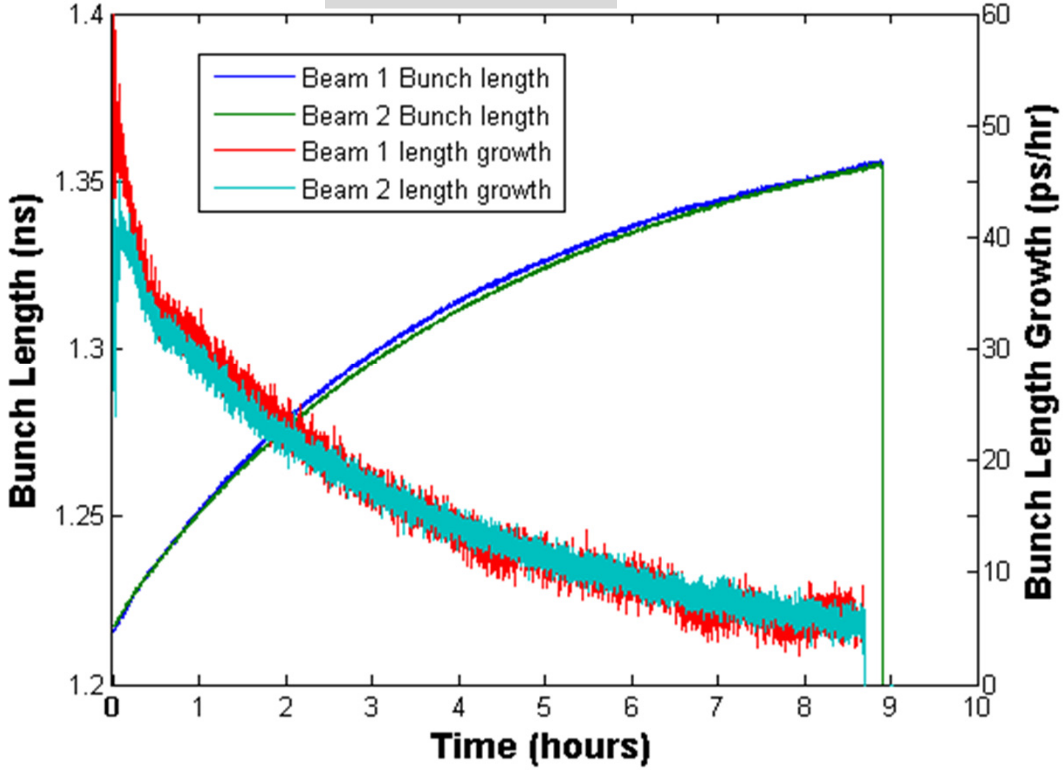
The Beam Phase Loop reduces the noise spectrum at the synchrotron frequency (26 Hz in physics). Without it bunch lengthening at injection is 300 ps/h

The lines at harmonics of the revolution frequency (11 kHz) come from the uncompensated transient beam loading

The dips at multiple of Frev are the action of the OTFB that increases regulation gain and decreases noise level

Bunch length evolution in Physics

Aug 2011



Bunch length (ns) and growth (ps/hour). Calculated from FWHM of bunch profile.

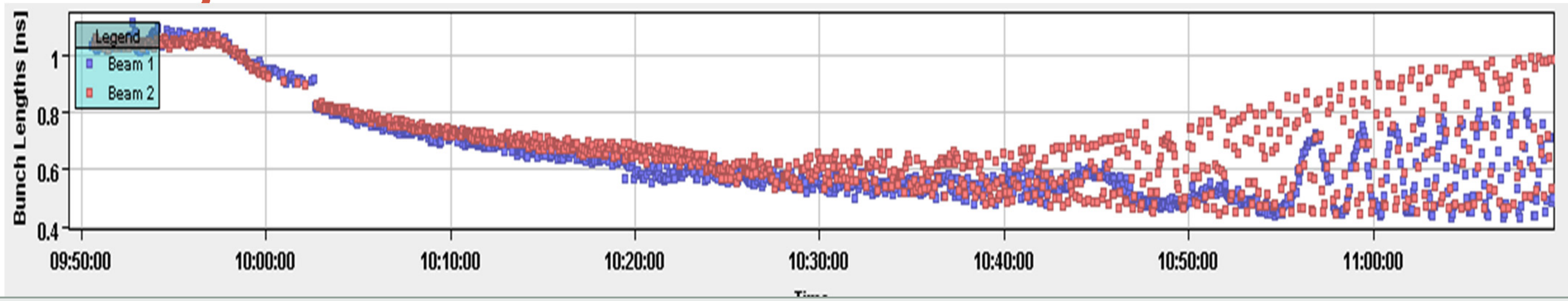
Longitudinal emittance growth caused by RF noise was a major concern during the LHC design. It has been successfully reduced to a level that is no more an issue for LHC operation

BROADBAND LONGITUDINAL STABILITY

No dedicated longitudinal feedback system -> stability must be provided by Landau damping. Sufficient synchrotron tune spread at high energy is necessary.

- Longitudinal blow-up

Ramping nominal bunch intensity without blow-up…unstable



May 15th 2010. First attempt to ramp nominal intensity single bunch. Bunch length during ramp. The longitudinal emittance is too low (<0.4 eVs). The bunch becomes unstable

- Broadband stability criteria

$$\frac{\left|\operatorname{Im} Z\right|}{n} < \frac{|\eta| E}{e I_b \beta^2} \left(\frac{\Delta E}{E}\right)^2 \frac{\Delta \Omega_s}{\Omega_s} f_0 \tau$$

- The RHS is proportional to

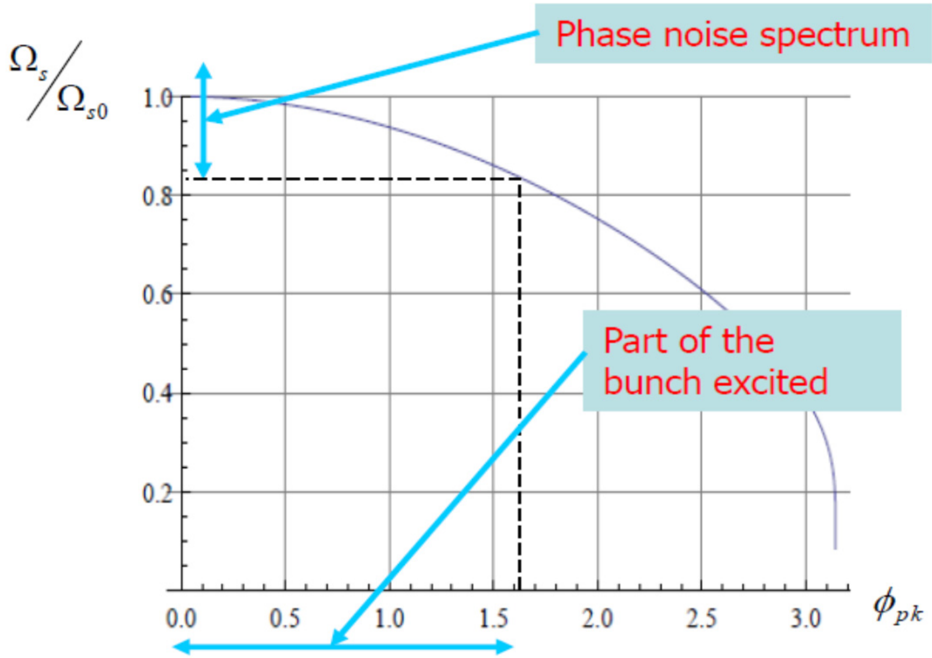
$$\frac{\left|\operatorname{Im} Z^{thr}\right|}{n} \propto \frac{\varepsilon^{5/2}}{E^{5/4} V^{1/4} I_b} \propto \frac{\tau^5 V}{I_b}$$

- Without blow-up the threshold quickly decreases during the acceleration ramp
- With a blow-up that keeps bunch length constant, the threshold increases linearly with the RF voltage
- The offending impedance is the 0.06 Ω inductive impedance

Blow-up [4][5]

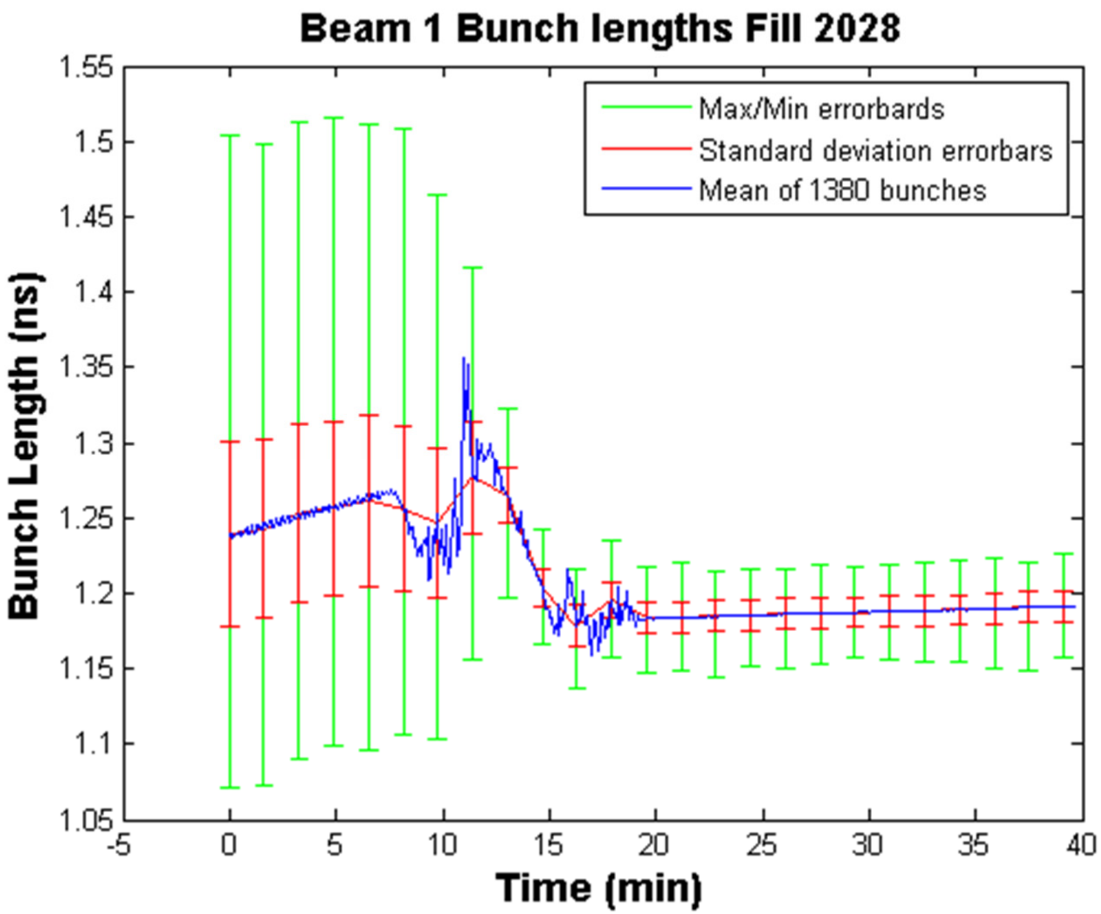
- We inject band-limited RF phase-noise in the main accelerating cavities
- The noise-band extends from 0.85 fs to 1.1 fs, to limit the excitation to the core of the bunch
- The noise spectrum tracks the synchrotron frequency change
- The noise amplitude is controlled by feedback using the measurement of the average bunch-length

$$\Omega_s(\phi_{pk}) \approx \Omega_{s0}\left[1-\left(\frac{\phi_{pk}}{4}\right)^2\right]$$



Ω_s/Ω_{s0} as a function of the maximum phase deviation in radian.

Bunch length evolution in the ramp with blow-up



Bunch length mean (averaged over the 1380 bunches), and spread statistics (Min/max and standard deviation) during the acceleration ramp. 1.3E11 p/bunch

WHAT COMES NEXT

- 2.2E11 p/bunch single bunch intensity
- 25 ns spacing -> higher beam current (1.12 A DC)
- Preserve transverse emittance during filling (batch per batch blow-up)
- Reduce the sensitivity to energy matching (longitudinal damper)
- Asymmetric beams: proton-Lead collisions

High single-bunch intensity: bunch stability

- In 2012, two bunches per ring, 3E11 p/bunch, were successfully ramped to 4 TeV, with longitudinal blow-up and Beam Phase Loop ON
- Small transmission loss in ramp (< 2 %)
- At 4 TeV we had 2.6 eVs to 2.9 eVs longitudinal emittance

Tentative conclusion: no single-bunch problem with up to 3E11 p/bunch

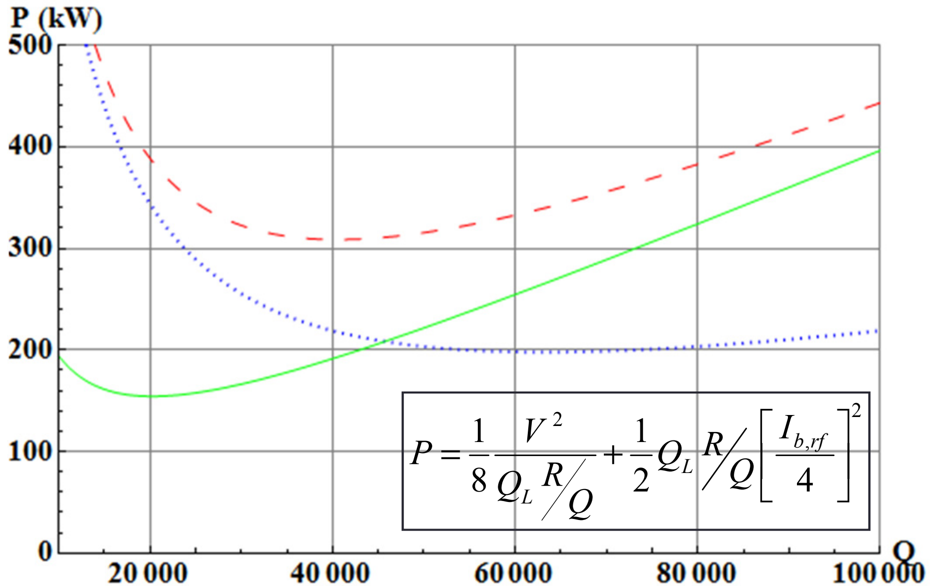
Higher beam intensity: stability

- The cavity impedance at the fundamental is modified much by the RF feedback and OTFB
- Coupled-bunch instability growth rates have been computed for the high-intensity LHC case: 2835 bunches, 2.2E11p/bunch, 25 ns spacing, 1.25 ns long bunches (1.12 A DC)
- With the strong RF feedback and OTBF, the cavity impedance at the fundamental can easily accept 2.2E11 p/bunch, 25 ns spacing
- The growth rate, maximum over all orders n are
  - at injection 0.06 s^{-1} with half detuning, for a Landau damping ($\Omega_s/4$) equal to 13.3 s^{-1}
  - at the end of the ramp 0.07 s^{-1} with full detuning, for a Landau damping ($\Omega_s/4$) equal to 13.3 s^{-1}
  - at 7 TeV/c, 0.01 s^{-1} with full detuning, for a Landau damping ($\Omega_s/4$) equal to 4.8 s^{-1}
- *So far* we have not observed destabilizing effects of other narrow-band impedances…

Higher beam intensity: RF power

- We now operate with a cavity voltage (amplitude and phase) constant over one turn
- This requires large klystron power to compensate for the transient beam loading

Above nominal (1.15E11 p/bunch, 25 ns) the 300 kW+ klystron power demanded in physics is too big. We cannot keep the "constant RF voltage" scheme.

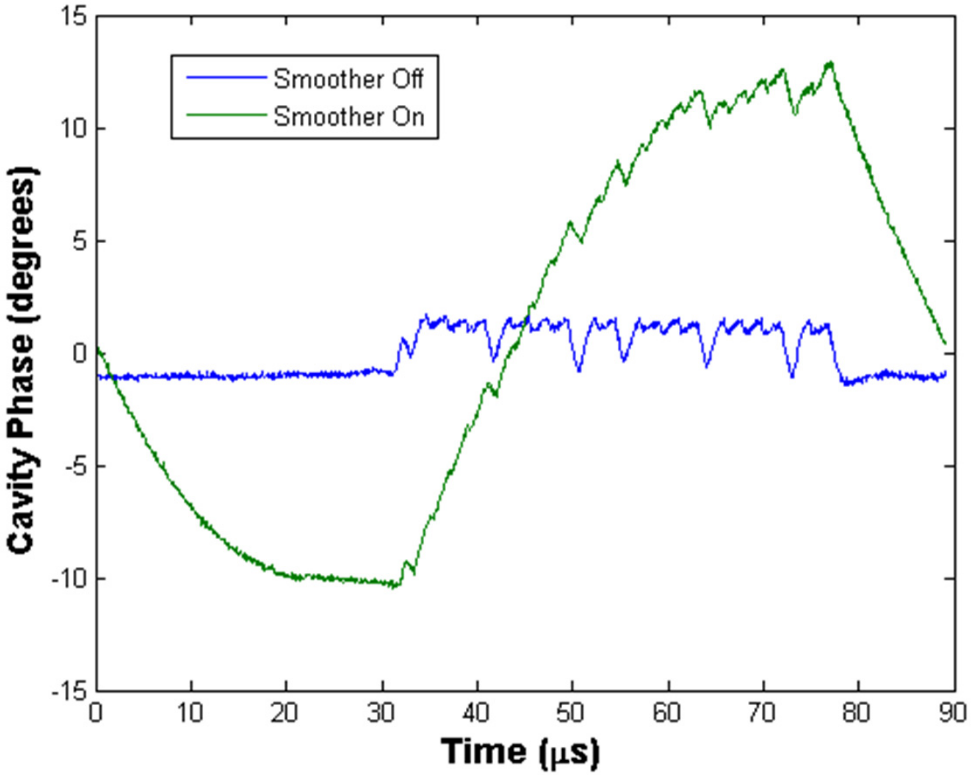


Klystron power vs. QL with half detuning. Dotted blue trace: physics conditions, nominal beam current (0.56 A DC). Dashed red trace: physics conditions, ultimate beam current (1.7E11 p/bunch, 0.86 A DC). Solid green trace: injection conditions, ultimate beam current.

RF phase modulation [7]

- **In physics**
  - We will accept the modulation of the cavity phase by the beam current (transient beam loading) and adapt the voltage set point for each bunch accordingly
  - The klystron drive is kept constant over one turn (amplitude and phase)
  - The cavity is detuned so that the klystron current is aligned with the average cavity voltage
  - Needed klystron power becomes independent of the beam current. For Q_L=60k, we need 105 kW only for 12 MV total
  - Stability is not modified: we keep the strong RFfdbk and OTFB
  - The resulting displacement of the luminous region is acceptable
- **During filling** it is desirable to keep the cavity phase constant for clean capture. Thanks to the reduced total voltage (6 MV) the present scheme can be kept with ultimate.

First results



Results from MD, June 22-23rd, 2012

Cavity Phase with ring half full (12b+144b +144b+72b+144b+144b+72b)

The blue trace shows the situation with the present scheme: we try to keep the RF voltage phase constant over one turn. The OTFB was switched off to enhance voltage transients

The green trace shows the proposed scheme: the phase is allowed to vary as a consequence of the transient beam loading

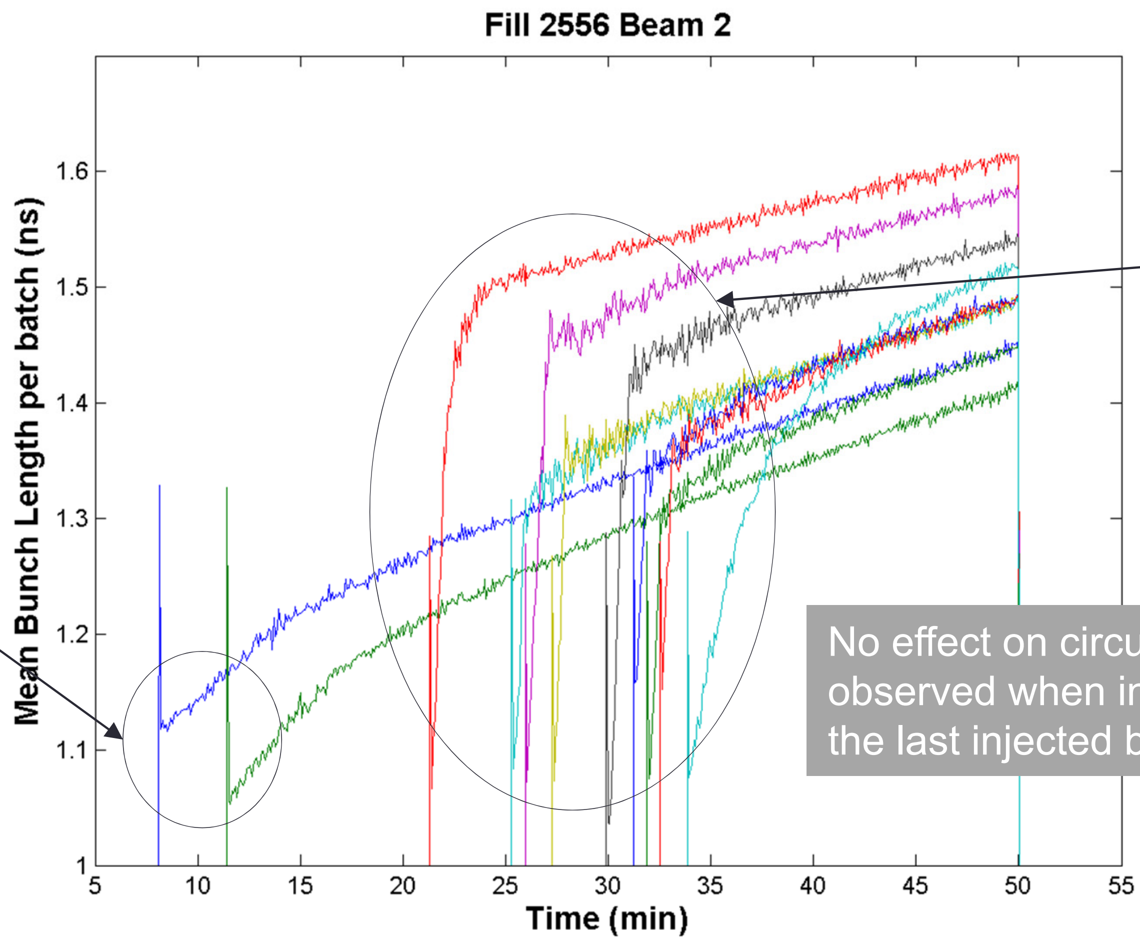
Test done at injection, with ~half ring full, resulting in 22 degrees or 150 ps modulation over one turn

Batch per batch blow-up at injection

- 30 minutes are needed to fill both rings, 12 batches per ring
- The batches injected first suffer from transverse emittance growth (caused by IBS) resulting in a reduced luminosity when put in collision
- The transverse effect of IBS can be reduced if we increase the longitudinal emittance of the newly injected batch after each injection
- Becoming more important with the new low gamma-transition optic in the SPS resulting in smaller longitudinal emittance injected into the LHC

First results

First two batches injected without blow-up. 0.6 eVs, growing fast in the following 5 minutes



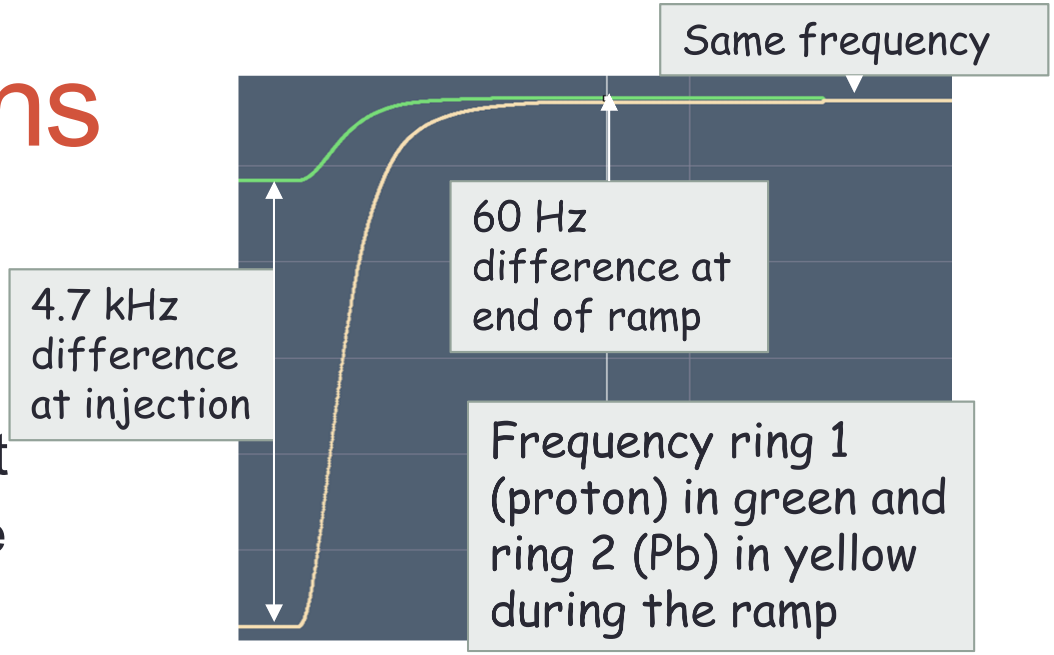
Following nine batches injected with blow-up just after injection. Different emittances (bunch length) set points and blow-up strengths

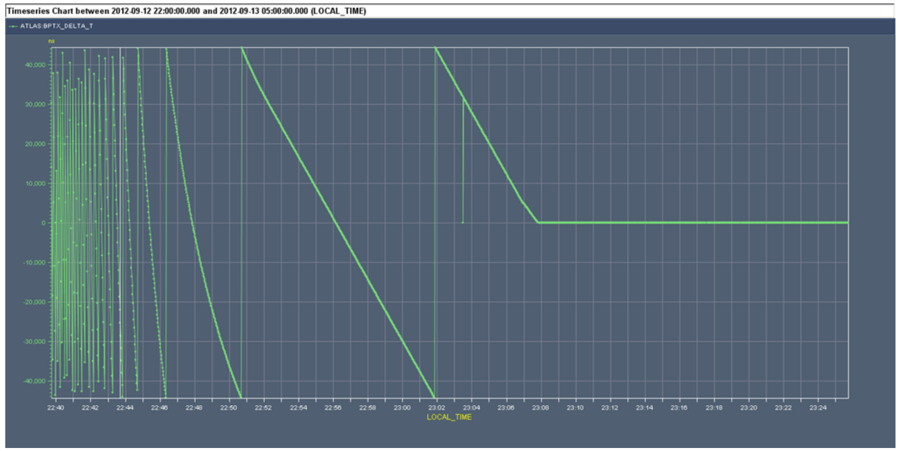
No effect on circulating batches observed when injecting RF noise on the last injected batch

Results from MD, April 22nd, 2012. 11 batches injected (144b per batch). The figure shows the mean bunch length (average over the corresponding 144b) for each batch. Longitudinal blow-up of the injected batch (except first two).

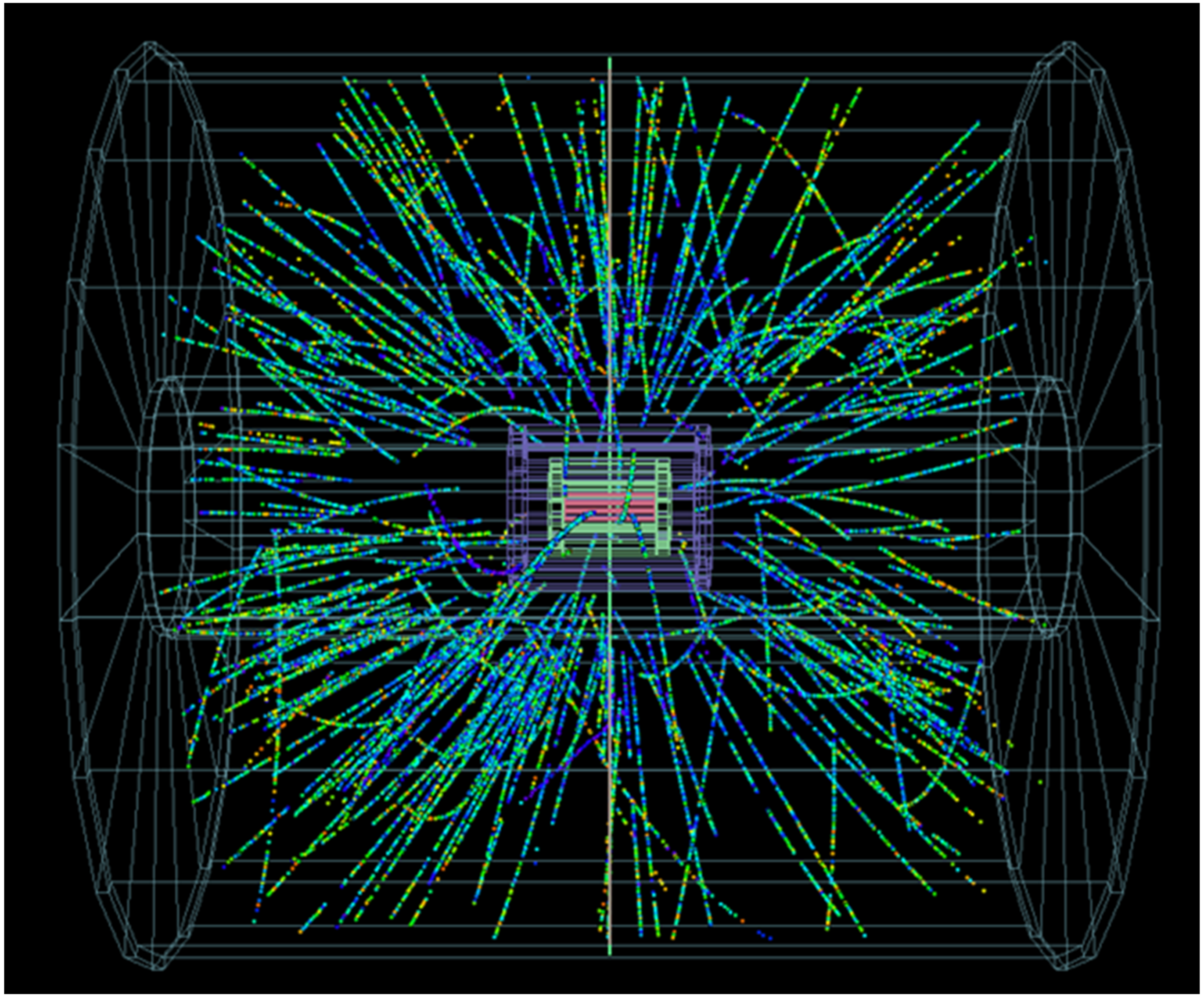
Proton-Lead collisions

- The two LHC rings see identical strength but opposite sign magnetic field
- The two RF systems are independent
  - At injection we have 4.7 kHz difference between the two rings (at 400 MHz)
  - At the end of the 4 TeV ramp the difference is 60 Hz only
- On flat top we lock the two rings on the same frequency, resulting in a +0.3 mm offset of the p ring and -0.3 mm offset of Pb ring
- We then gently cog the two rings to achieve crossing in the detector. It takes 11 minutes maximum for the 27km long ring. The intersection point travels the *Pays de Gex* at ~150 km/h!





ATLAS BPTX from end-ramp to end-rephasing. Measures the time interval between passage of bucket 1 of both rings in the detector



p-Pb collision in the ALICE detector, Sept 13th, 2012
Courtesy of H. Wessels, ALICE collaboration

CONCLUSIONS

- Very good first three years 2010,2011,2012
  - The compensation of transient beam loading is near perfect. Factor 350 impedance reduction at the fundamental
  - The contribution of RF noise to luminosity lifetime reduction is well below the one of IBS
  - The longitudinal blow-up is successful in preserving longitudinal stability
- A promising future
  - We are optimistic concerning single-bunch long. stability up to 3E11 p/bunch
  - For multi-bunch, 25 ns spacing and 2.2E11 p/bunch, we anticipate no stability problem with the cavity impedance at the fundamental. e- cloud issue?
  - We are developing an RF phase modulation scheme to keep the needed klystron power within the capacity of the present system
- Some questions (for the WG discussion?)
  - Why is the evolution of bunch length in physics different in 2012 compared to 2011?
  - How does the Main Phase Loop affect multi-bunch stability?
  - What causes the long-lasting (> 30 minutes) small amplitude (few degrees) dipole oscillations observed at injection?

….but these issues do not affect present machiine operation

A break on Sept 11, 2008, around midnight, to celebrate the capture of the very first few of a long series of circulating and colliding protons and ions…

REFERENCES

- LHC design
  - [1] D. Boussard, T. Linnecar, The LHC Superconducting RF System, 1999 Cryogenic Engineering and International Cryogenic Materials Conference, July 12-16, 1999, Montreal, Canada
  - [2] D. Boussard, RF Power Requirements for a High Intensity Proton Collider, PAC91
- Longitudinal stability
  - [3] E. Shaposhnikova, Longitudinal beam parameters during acceleration in the LHC
- Longitudinal Blow-up
  - [4] P. Baudrenghien, T. Mastoridis, Longitudinal Emittance Blowup in the LHC, submitted to PRST AB
  - [5] P. Baudrenghien et al., Longitudinal Emittance Blow-up in the LHC, IPAC 2011
- RF Noise
  - [6] T. Mastoridis et al., Radio Frequency noise effects on the CERN Large Hadron Collider beam diffusion, PRST AB, 14, 092802 (2011)
- Voltage modulation
  - [7] P. Baudrenghien, T. Mastoridis, Proposal for an RF roadmap towards ultimate intensity in the LHC, IPAC 2012