LHC Injectors Upgrade

Impact of RF power and LLRF settings (power, loops, noise)

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with the help and support of:

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CERN

Outline

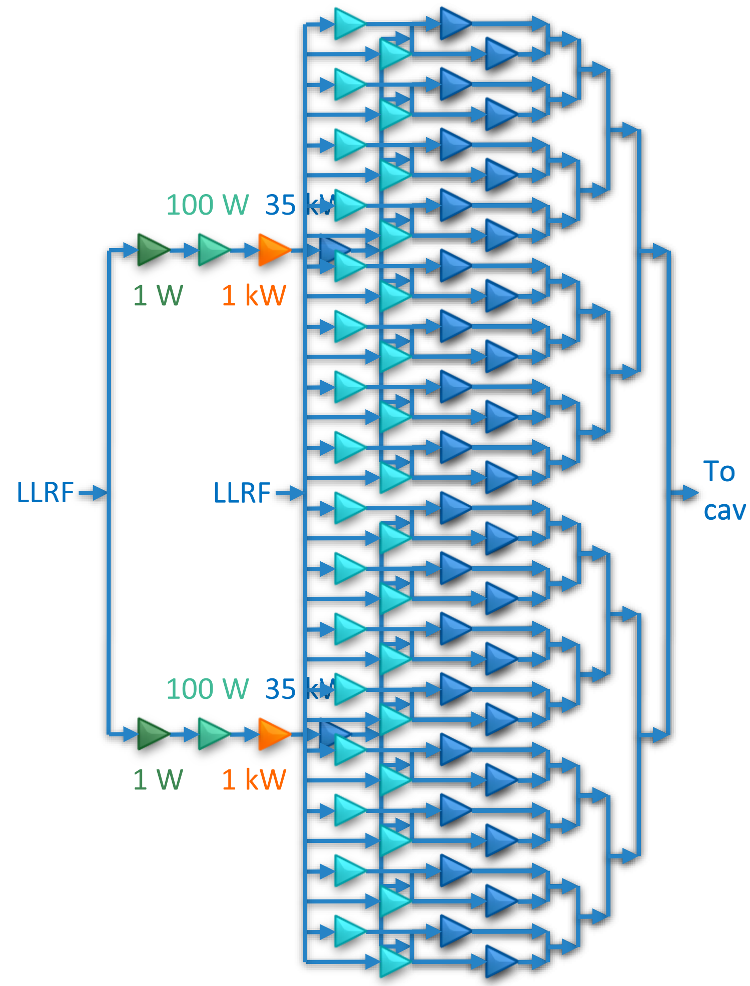
- **RF power in 2017**
  - configuration and limitations
- **SPS RF LL: cavity control**
  - feedforward and longitudinal damper on pLHC beam in 2017 (OP)
  - effect of long. damper (MD)
- **SPS RF LL: beam control**
  - phase sampling and 1-turn delay feedback (MD)
  - injection phase
    - operational spread (OP)
    - effect on losses (MD)
  - energy matching (OP, MD)
  - effect of RF noise (MD)
- **LIU SPS RF LL upgrade**

SPS RF power

1980-2016
2017

- **EYETS 2016-17: power plant for long cavities in LIU configuration**
  - tube amplifiers partly replaced by solid state amplifiers
  - learning period at the start of the year
    - many failures, investigations followed
    - identification of protection issues
    - negotiated improved bonding
  - clamp of power requested by LLRF
    - transients can damage the TTIs if overdrive requested
    - Switch&Limit module installed on 31 August

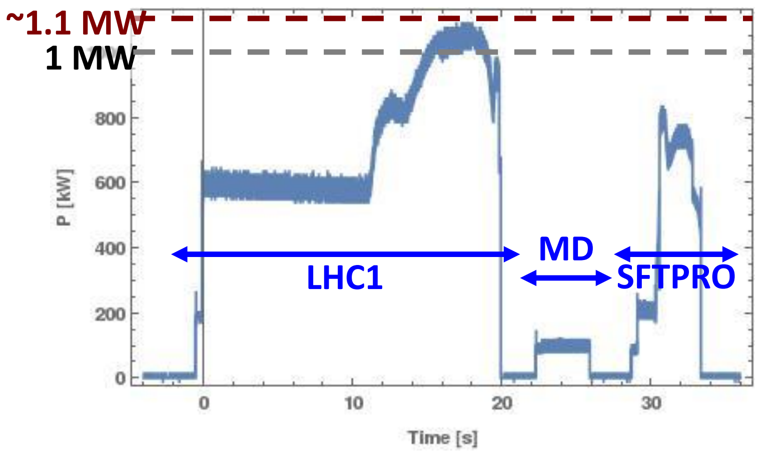
- **YETS 2017-18: no changes planned**
  - one more year of running to confirm the improved statistics on amplifier failures

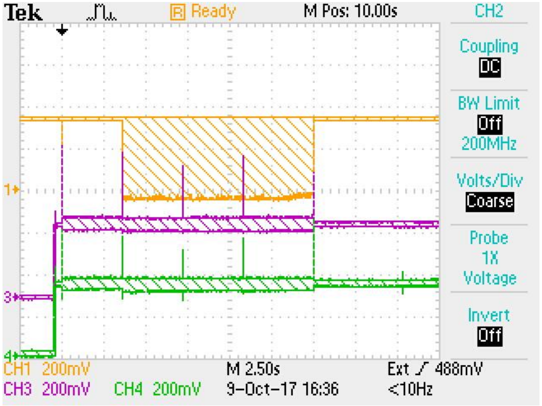


with E. Montesinos & team

power limitations

- **RF power not limiting operation at flat bottom presently**
  - can't increase voltage as the margin is needed later, in the ramp, both today and after LS2
- **but limited higher energy and during MDs**
  - e.g. Line 3 limiting (at last part of ramp, BCMS, 1 batch, 48 bunches, N = 1.25×10^{11}, 2017-09-12)
    - Line 4 not limiting for the same conditions
  - e.g. Line 3 & 4 limiting (high intensity run, BCMS, 4x48 bunches, N = 1.9×10^{11}, 2017-10-09)



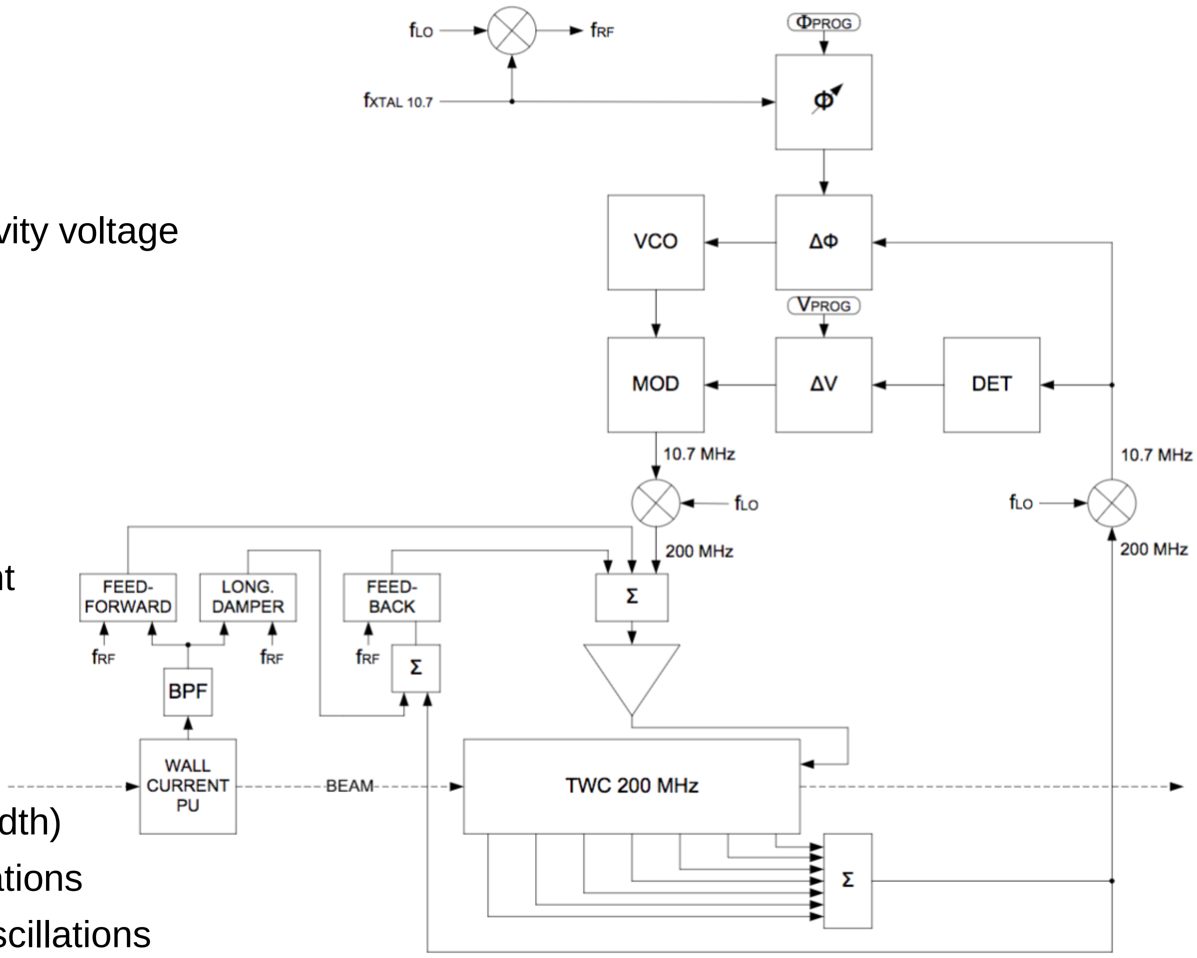


- **in 2018, log the Switch&Limit output**
  - for 2017, no logging available (need to look at one led on the card)
  - is logging once per cycle enough?
    - or require more precise time of clamping?

with T. Bohl

pLHC RF LL: cavity loops

- **cavity loop (slow)**
  - amplitude and phase loop for cavity voltage
- **1-turn delay feedback**
  - beam loading reduction
- **feedforward (ffwd)**
  - further beam loading reduction
  - uses WCM pick-up measurement
- **longitudinal damper**
  - designed for Q26
    - suboptimal for other fs
  - limited bandwidth (cavity bandwidth)
  - damping of 2-4th injection oscillations
  - suppression of coupled bunch oscillations



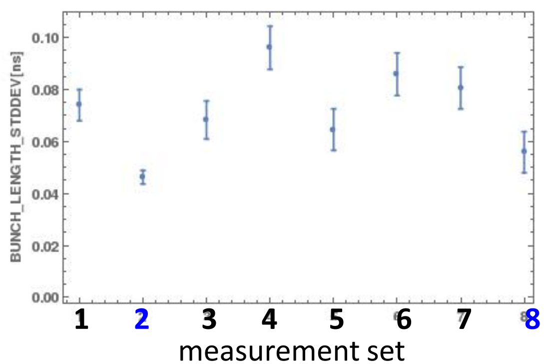
stabilization of operational pLHC

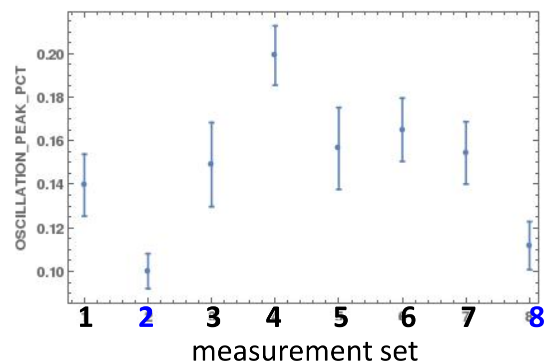
- **operated LHC beams in 2017 with the following configuration:**
  - 1-turn delay feedback on for all cavities
  - feedforward: on/off for short cavities, off for long cavities
  - long. damper: on for cavity 1; not setup for cavity 3
  - 800 MHz cavity 1 on (BSM), cavity 2 off
  - controlled emittance blow up during the ramp

- **operation of ffwd and long. damper simultaneously degraded beam quality**
  - ffwd correctly compensates beam loading, confirmed that RF phase not heavily distorted by it
  - longitudinal damper: less efficient for Q20/Q22 than for Q26
  - speculation that some synchrotron frequency spread is needed to guarantee stability

2, 8: ffwd off

others: different combinations of ffwd on





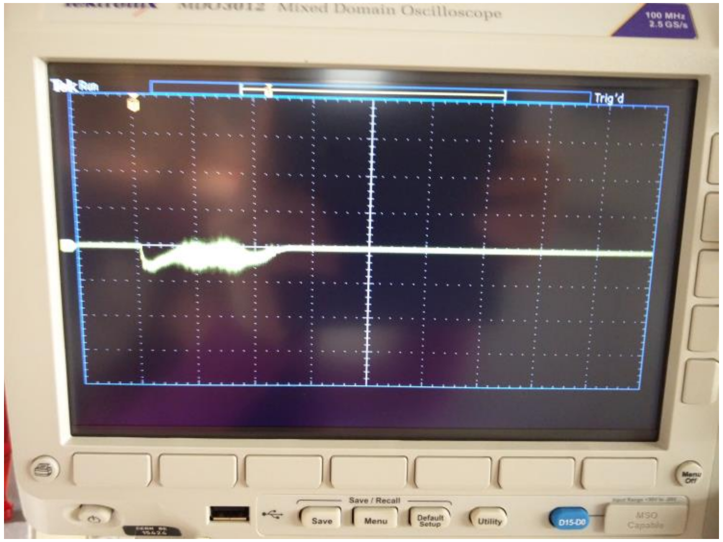
(OP 2017-07-14)

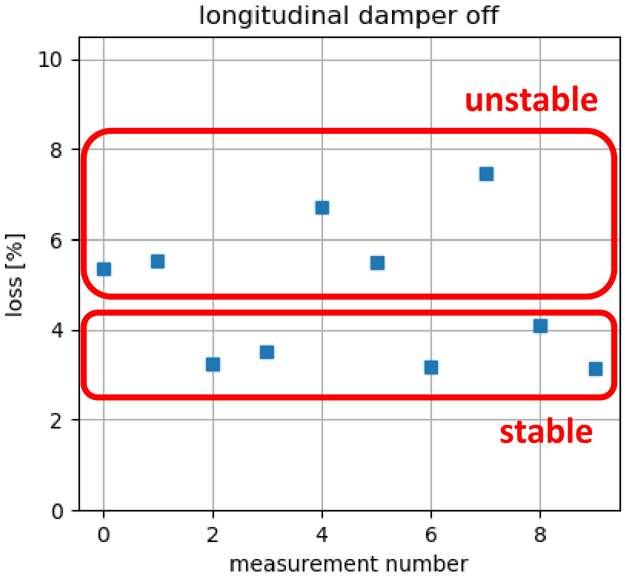
with T. Bohl

losses with long. damper off

(MD 2017-11-17)

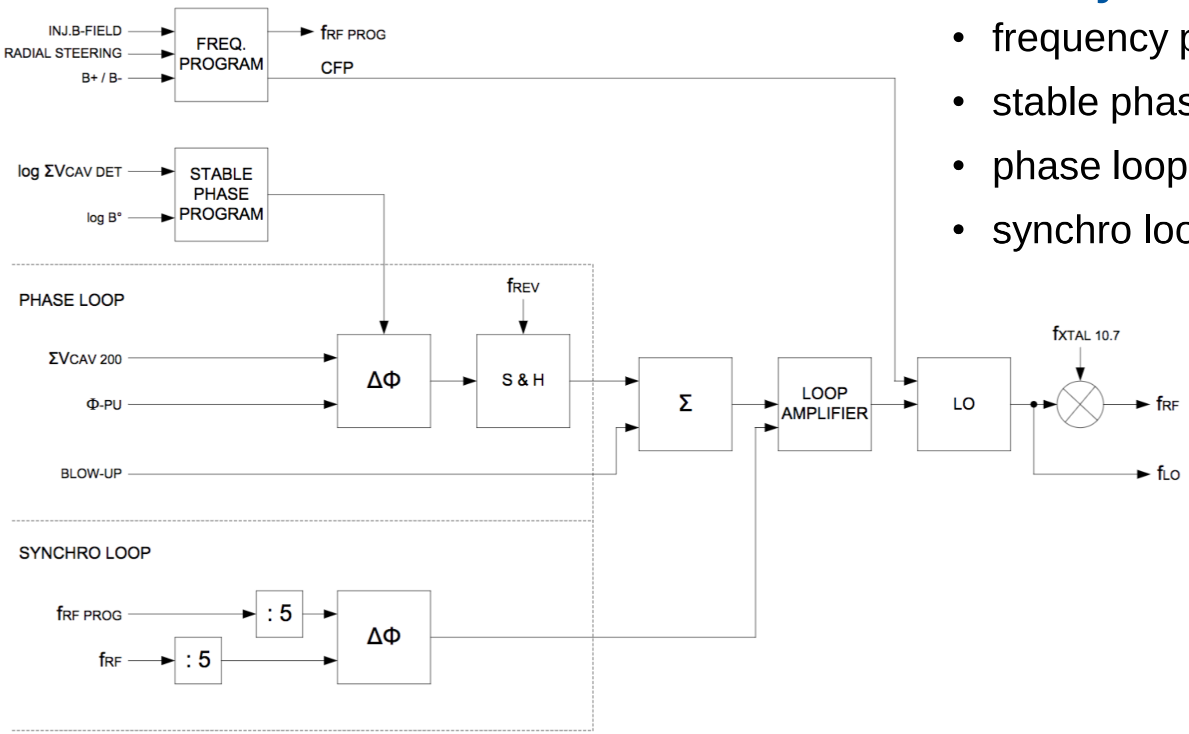
- **during MD session**
  - 72 bunches, 1.2-1.3e11 ppb
    - 2365 ms flat bottom, then start of acceleration
    - measure losses between 50 ms and 3000 ms
    - Q20
  - ffwd on, 1-turn delay fb on, 800 MHz off
    - other settings optimized (inj. phase, ref. phase)





- **losses depended on stability**
  - if beam stable, losses similar to when long. damper on
  - if beam unstable, losses worsen by few %
- ***we should take the stability into account when looking at losses!***

pLHC RF LL: beam control

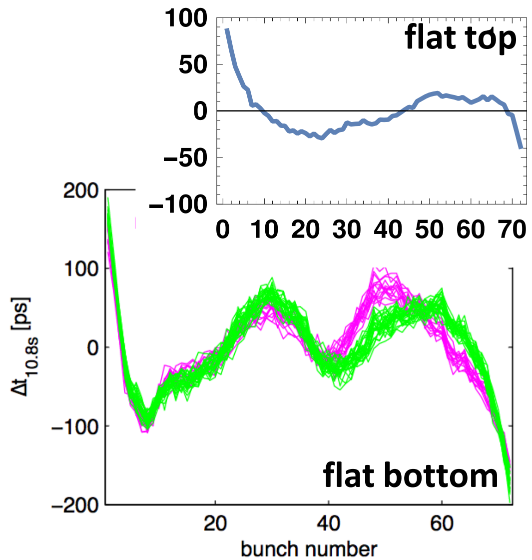


- **main systems**
  - frequency program
  - stable phase
  - phase loop (bring RF phase onto beam phase)
  - synchro loop (bring f_{RF} onto the freq. program)

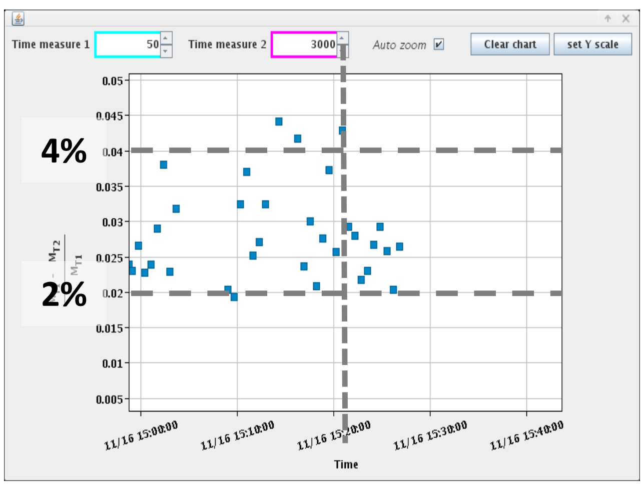
- **some knobs:**
  - phase loop gain, synchro loop gain: operationally optimized
  - MD to move phase sampling
  - MDs on injection phase, energy matching, reference phase (stable phase offset)

phase sampling and 1-turn delay feedback

(MD 2017-11-16)

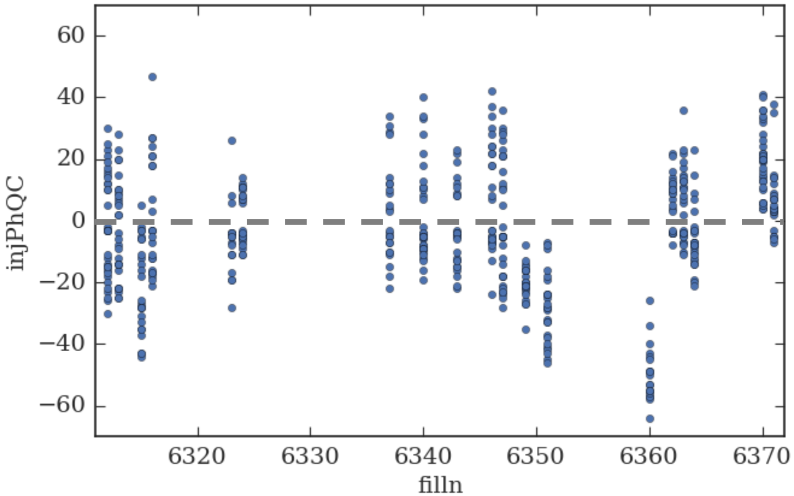


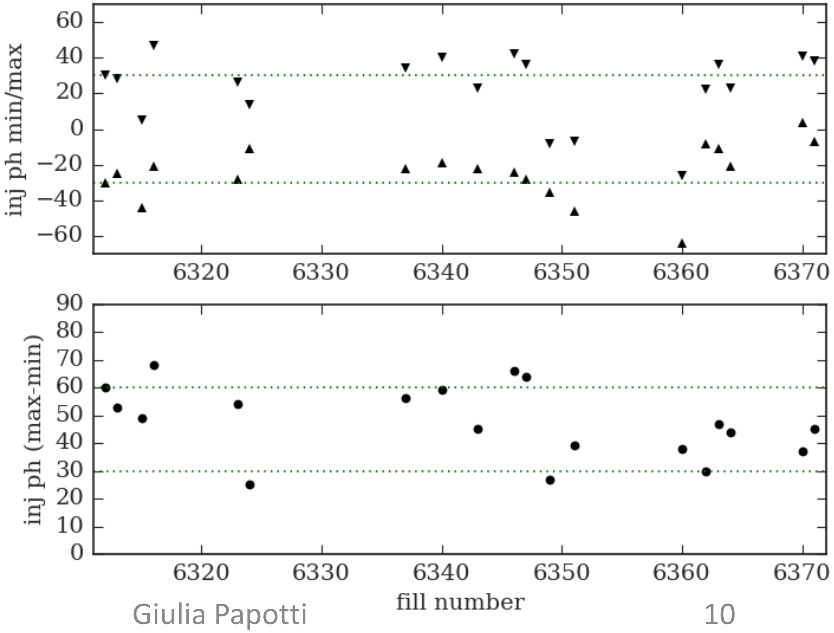
- **phase sampling is on the first 12 bunches**
  - not affected by beam loading, operationally easier
  - not always representative of the full batch due to beam loading
- **MD to set phase sampling to middle/end of 72-b batch**
  - even in the absence of injection phase error, an RF phase error is introduced by the 1-turn delay feedback
- **conclusion: for changing the phase sampling, expert support is needed**
- **negative effect on losses (+1-2%)**
  - equivalent to non-optimum setup of LL



operational injection phase spread

- **injection phase jitters (shot-to-shot): look at the spread in operational conditions**
  - during LHC filling, only 32-128b trains (no 12s)
  - for each LHC fill, record SPS QC injection phase error for each injection
    - QC injection phase slightly overestimated
- **scatter in injection phase bigger than expected**
  - max-min ~25-30 deg on a good day, ~50 deg on a bad day; often max-min ~40 deg
  - not always centered around 0
    - will show to operators during shutdown lectures





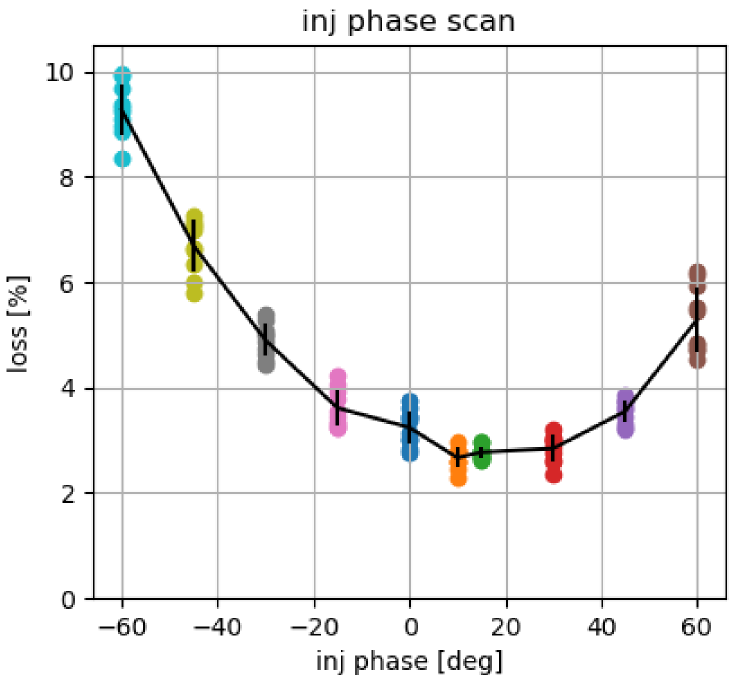
injection phase and losses

(MD 2017-11-17)

- **MD to check impact of inj. phase on losses**
  - scanned LSA knob in 15 deg steps, +/-60 deg around the optimum
    - optimized inj phase so to be around 0 on QC
    - LSA knob at -165 deg
  - 72 bunches, 1.2-1.3e11 ppb
    - measure losses at 3000 ms vs 50 ms

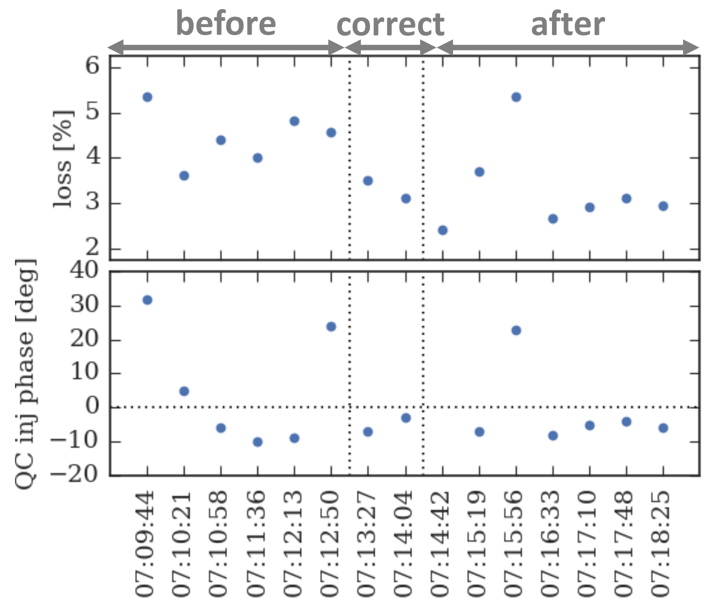
- **impact of ~1% already for operational phase scatter (+/-20 deg)**
  - shots off by 30 deg can be 1-2% worse

- **byproduct: calibration of QC inj. phase error**
  - knob at 60, detect 80
    - non-linear signal for large phase error
  - proper analysis to follow during YETS
    - additional data taken with independent measurement
    - could lead to improvement in SPS QC for 2018



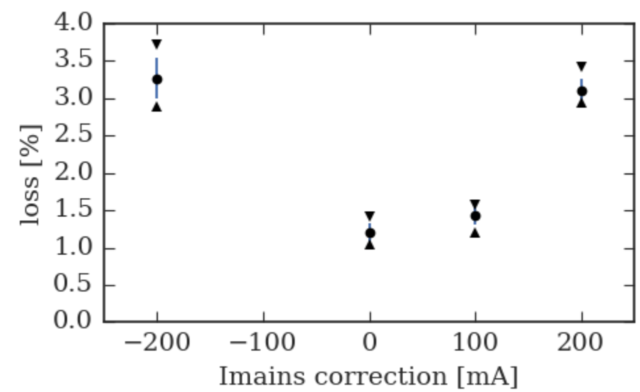
tuning of energy matching

- **3 sets of data**
  - LHC1 filling on 2017-11-12: recuperate 2% on losses
    - 25 mA on 301 A: 0.8 permil
  - (parasitic) parallel MD on 2017-11-24
    - few points, guess acceptable range is +/- 100 mA
  - tried again on 2017-11-27, “unsuccessful”
    - acceptable range only -25 mA to +200 mA
    - possibly transverse setup not optimized



- **seems negligible for operational beams**
  - max correction on LHC1: 90 mA (0.3 permil)
  - max correction on LHC25NS: ~120 mA (0.4 permil)

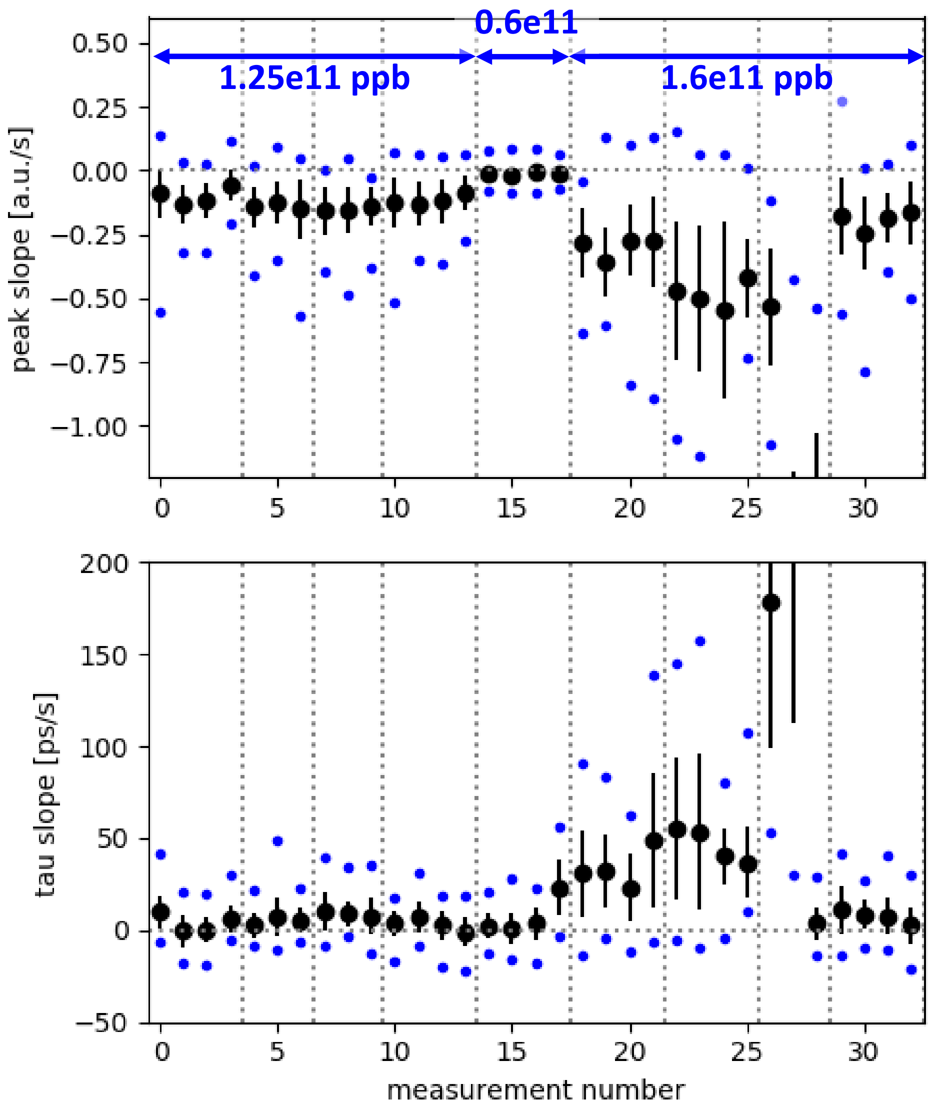
- **could imagine to add algorithm for suggested correction into SPS QC**



a look at RF noise

(MD 2017-11-14)

- **recall coast MD: less growth if 1-turn delay feedback off**
  - only possible for low intensity (0.3e11 ppb)
- **took some measurements during long. MD**
  - inject in low voltage and then increase it
  - 36 bunches, Q22, different intensities
    - tune kicker at 2000 ms
    - Hannes et Fanouria dixerunt: IBS negligible
- **very very preliminary: observations at different intensities and voltage programs**
  - 1.25e11 ppb
    - no bunch length growth
    - slight peak decrease (losses)
    - similar behaviour despite different voltage programs
  - 0.6e11 ppb
    - no bunch length growth, no peak decrease
  - 1.6e11 ppb
    - ffwd on: more bunch length growth and losses
    - ffwd off and 6.5 MV: beam unstable
    - ffwd off and 4.5 MV: stable, no growth, little losses
- **more time and data required**
  - confirms that feedforward is noisy



with J. Repond

RF noise on the long filling plateau

P. Baudrenghien, J. Galindo, G. Hagmann, G. Kotzian, L.Schmid, A. Spierer, T. Mastoridis

The RF noise is very damaging with full buckets. Diffusion does not only concern dipole mode (damped by the phase loop) but also higher modes where we have no damping. Increase of fs (Q20) is also unfavorable.

Existing LLRF	Post LS2 LLRF
• The longitudinal damper has low gain following the move to Q20 (fs 400 Hz ->800 Hz), and high noise (Digital electronics from 90s, 8-bits DAC)	• Improved with modern electronics and tuned to the exact fs
• Feedforward has high noise	• Improved with modern electronics
• Master RF (LO) has high noise. Very visible with the LHC ions beams	• Care to minimize LO noise. Experience from on-going CC design
• TX has high noise	• Will be reduced with the Polar Loop

Capture losses in the first tens of turns (1 ms)

P. Baudrenghien, J. Galindo, G. Hagmann, G. Kotzian, L.Schmid, A. Spierer, T. Mastoridis

Existing LLRF

- Transient Beam Loading is damped in 3 turns and reduced by 10 (linear)
- Dipole perturbation (triggered by PS-SPS injection error) reduced by 5
- Quadrupole perturbation (triggered by voltage mismatch) reduced by 3
- Large uncompensated phase error at head of batch, plus ripple along batch at cavity zero
- Phase loop measures first 12b only

Post LS2 LLRF

- 2-3 turns/20 linear but beam intensity doubled
- Dipole perturbation reduced by 10
- Quadrupole perturbation reduced by 10, plus quadrupole damping
- Compensation bandwidth increased, plus coupling between cavities of different lengths
- B-by-b phase measurement and any average possible. Not sure it will help

Reminder:

- The OTFB steady-state gain will be increased by 2 (minimum) but the beam intensity will be doubled. Instability threshold unchanged
- If the SPS bucket is full at injection, any imperfection leads to losses.

Conclusions

- **for loss studies at the % level, many settings need to be optimized**
    - injection phase shot-to-shot variation can be 1% easily
    - energy matching well corrected operationally
    - reference phase seems negligible for 1 injection (but worse for multiple injections)
  - the first injection is "easier" than the next ones
  - beam stability, slow drifts and discrete changes can affect the measurement
    - e.g. unstable beam suffers a few % more losses (from longitudinal damper off)

- **on the present system vs upgrade**
  - changes on accelerating structures:
    - shorten to reduce beam loading per structure
    - increase total number to increase available voltage
    - new couplers for 630 MHz HOM damping (factor 3 gained)
  - many advantages from the new LLRF
    - improved damping at different frequencies for beam loading, bunch-by-bunch phase sampling, …
    - lower noise, long. damper tuning to fs

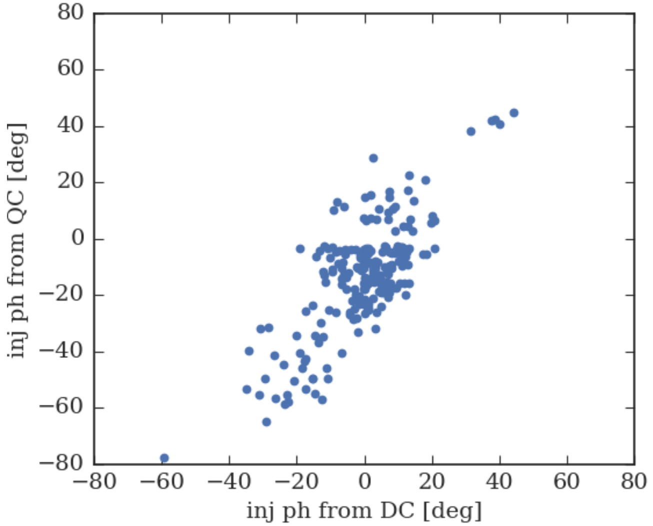
- **for 2018**
    - calibrate QC injection phase error calculation, possibly add algorithm for tuning of energy matching
    - switch&limit to be logged

phase sampling and 1-turn delay feedback

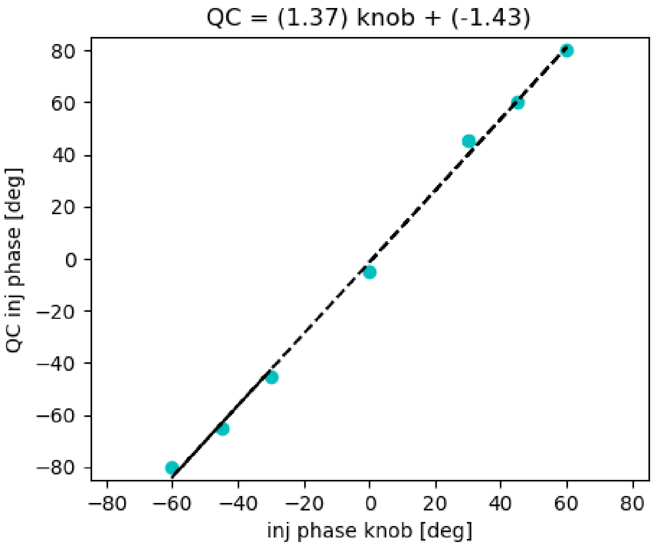
(MD 2017-11-16)

QC injection phase calibration

- **compared counter time measurements with QC inj phase**
  - good agreement even though not perfect
    - sign and magnitude of correction are in agreement (+/-10 deg accuracy)
  - QC overestimates the actual error when big
    - phase loop error signal is not linear!



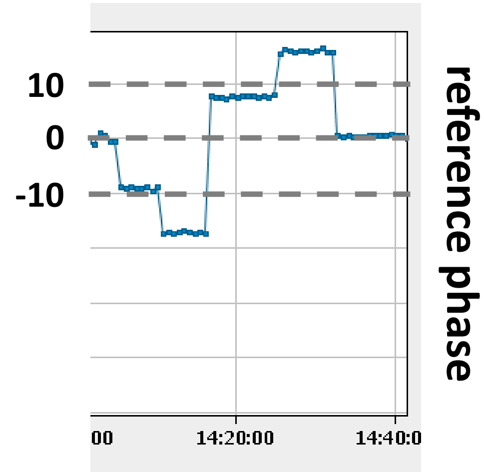
- **compared QC proposed correction with inj. phase knob trim**
  - fit factor 1.4
    - 30 deg read as 40 deg
    - 45 deg read as 60 deg
    - 60 deg read as 80 deg
  - error bars to come during the YETS



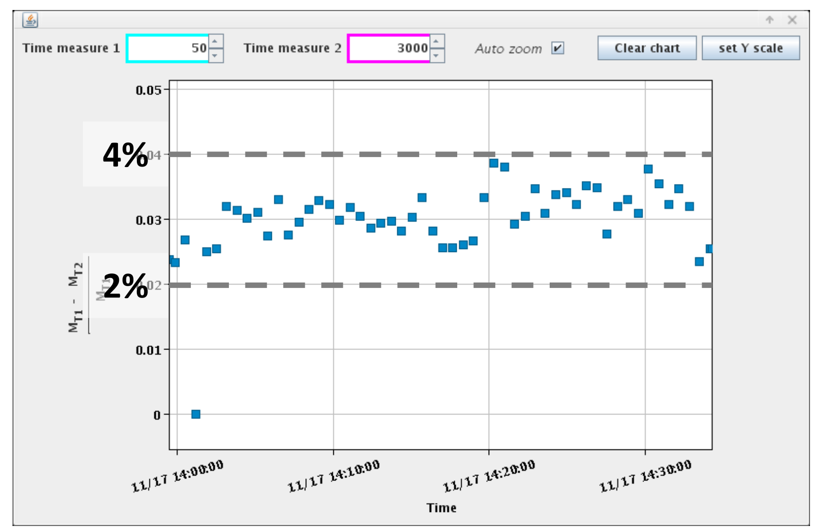
reference phase and losses

(MD 2017-11-17)

- **reference phase is the stable phase offset**
  - should be optimised when changing voltage, beam intensity, number of bunches
  - generally well optimised in operation (off by 1-2 deg)
    - observed 1-2 deg steps/drifts without setting changes
  - at times error up to ~10 deg during MD sessions



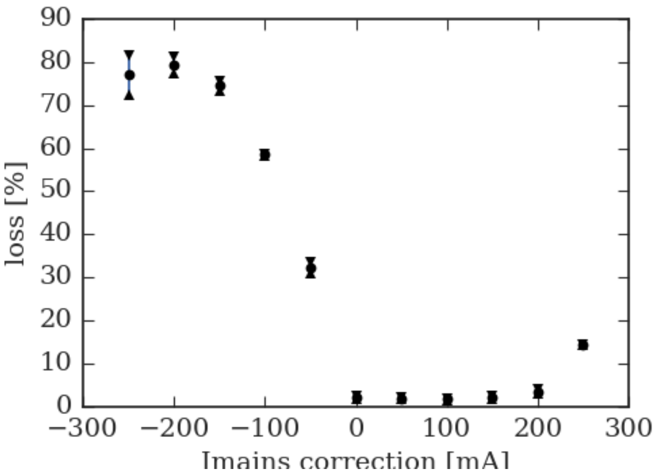
- **scanned +/-7 and +/-14 around optimum in MD**
  - 72 bunches, 1.2-1.3e11 ppb
    - measure losses at 3000 ms vs 50 ms
  - injection phase within +/-20 deg

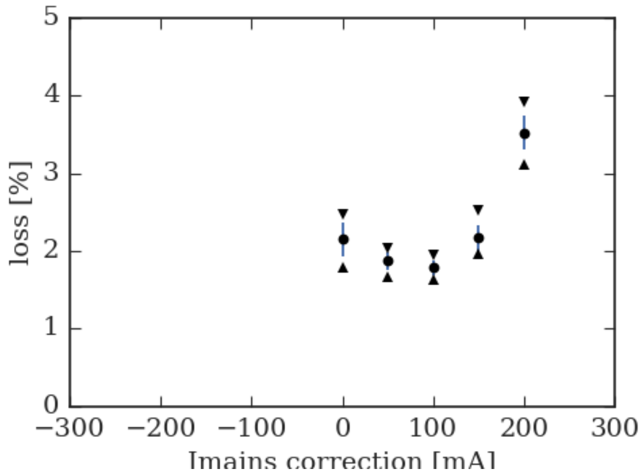


- **for first inj. impact on losses very small**
  - most likely worse for multiple injections

more on energy matching

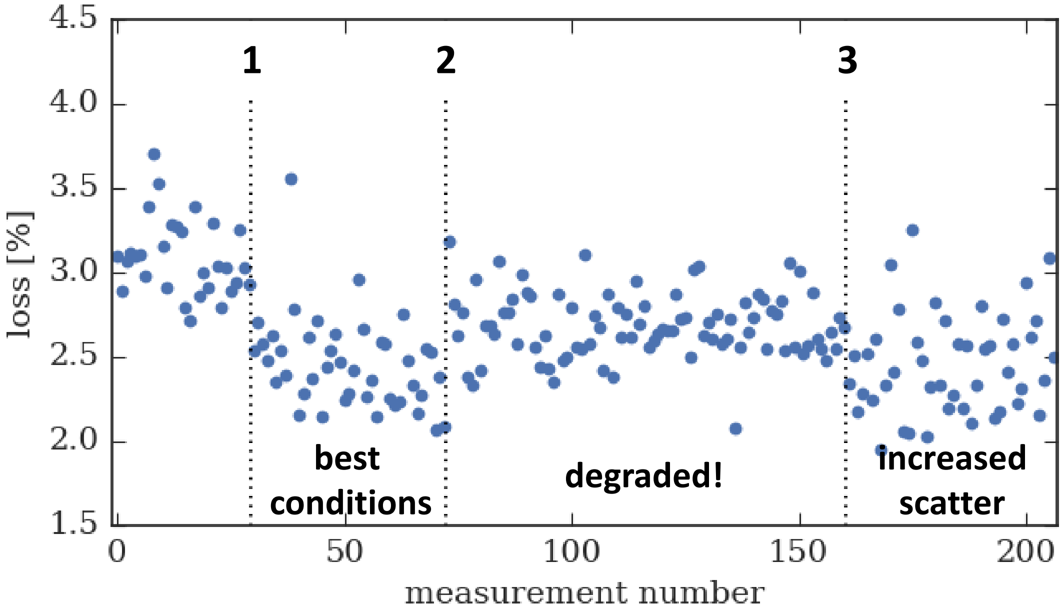
- **the other energy matching attempt**





effect of drifts on losses

(MD 2017-11-16)



- **at start of MD**
  - 72 bunches, 1.2-1.3e11 ppb, Q20
    - start of acceleration at 2365 ms
    - losses at 3000 ms vs 50 ms

- **loss observations**
  1. Q'V decrease (0.4 -> 0.1)
  2. added user at PS (???)
  3. reference phase corrected

- **conclusions:**
  - 1% shot-to-shot variation (at least)
  - slow drifts and discrete changes (elsewhere) can impact at the 1% level
    - can't control the whole accelerator complex