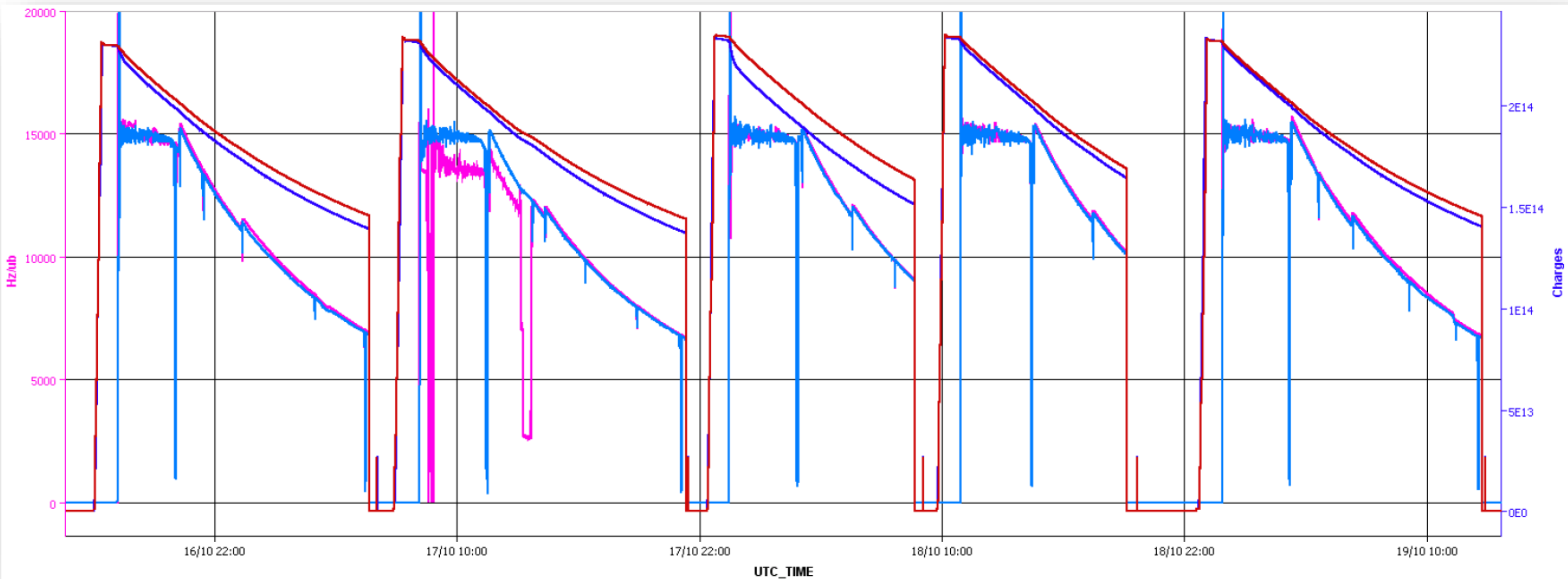
Levelling schemes (by separation, crossing angle, beta*): what have we learned and expectations for HL-LHC

Mirko Pojer, with material from Jorg Wenninger, Kajetan Fuchsberger and Michi Hostettler

7th HL-LHC Collaboration Meeting – CIEMAT, Madrid – 13-16 November 2017

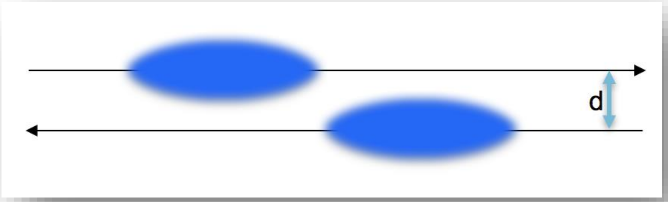
Is the HL-LHC era already started?



LHC operation from early October with luminosities above 2e34 $cm^{-2}s^{-1}$, with high luminosity experiments levelled at 1.5e34 $cm^{-2}s^{-1}$.

Contents

Levelling by offset



- Simplest method, based on local bumps at each IP.
- **Operational** since Run 1.
  - Routinely used in IP2 and IP8.
  - After some tests in 2016, now operational in IP1 and 5 as well.
- Beam stability not compromised *(see X. Buffat's talk on Stability)*.
  - The stability of the beams is reduced when colliding with an offset and some concern was raised before testing because of interplay of beam parameters, machine non-linearities, long range interactions, etc.
  - We have not observed problems of beam stability in the various fills where offset levelling was used between 2015-2017 with ATLAS and CMS.
  - Only a VdM fill for ALICE and LHCb gave some trouble in 2017 – up to 5 σ separation LRBB effect?
  - Losses observed during the first levelling test were mitigated profiting of the stability margins (chromaticity and octupole strength) and adjusting the tunes; no coherent instabilities observed, with sufficient margins in octupole and chromaticity.
- No (little) impact on collimators (TCT & TCLs) due to the smallness of orbit shifts.
- Possible future **improvement**: better integration with the orbit FB.
  - Orbit reference update at each levelling step (take over work done for x-ing levelling), cohabitation with OFB mitigated for the moment by 'gentle' OFB correction configuration.

Side effects of offset levelling

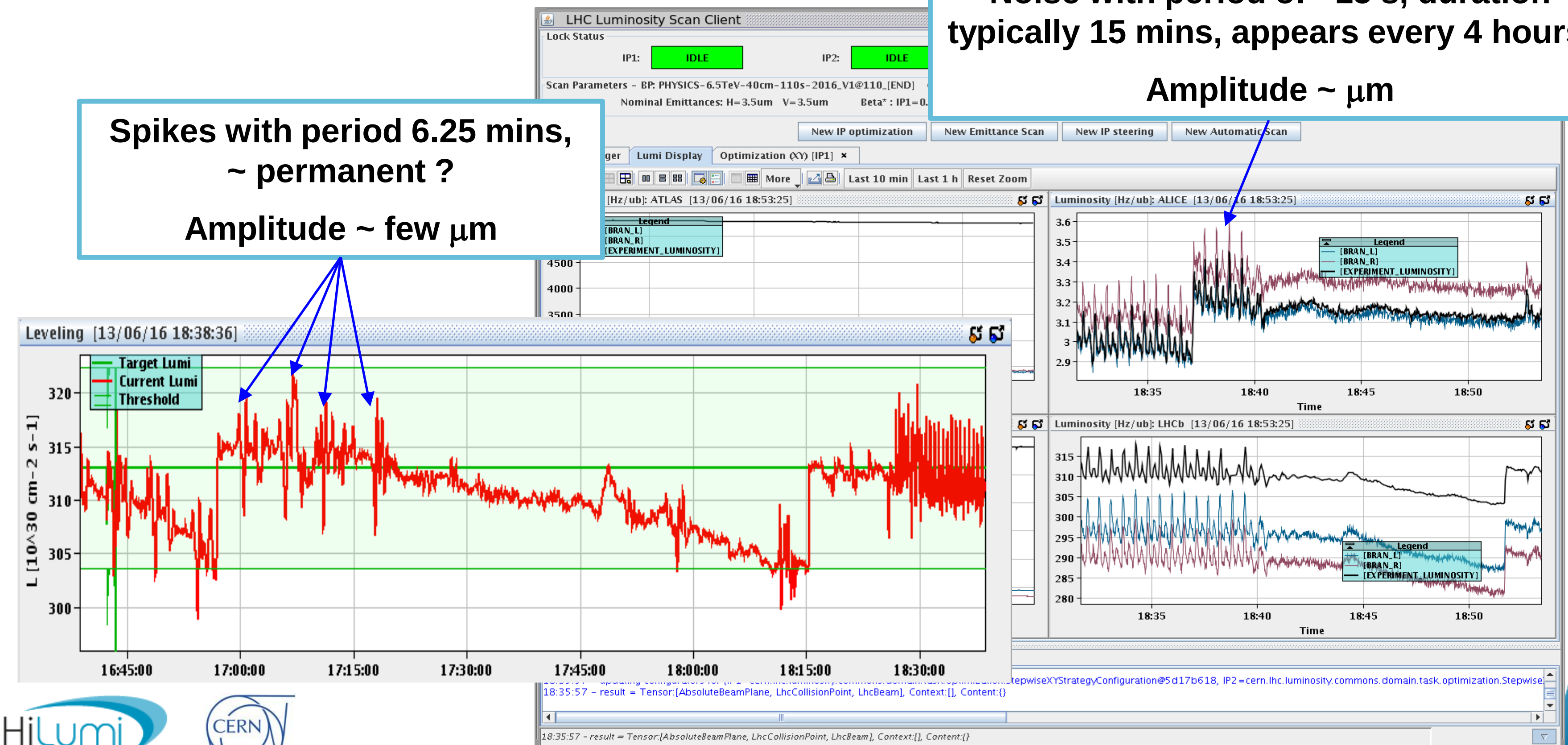
- A side effect of not colliding head on is the increased sensitivity to beam separation fluctuations induced by ‘orbit noise’ → L fluctuations.
- Periodic noise is clearly visible on the ALICE and LHCb luminosity
  - source not identified, but B2(H) is much more affected.

Noise with period of ~15 s, duration typically 15 mins, appears every 4 hours.

Amplitude ~ μm

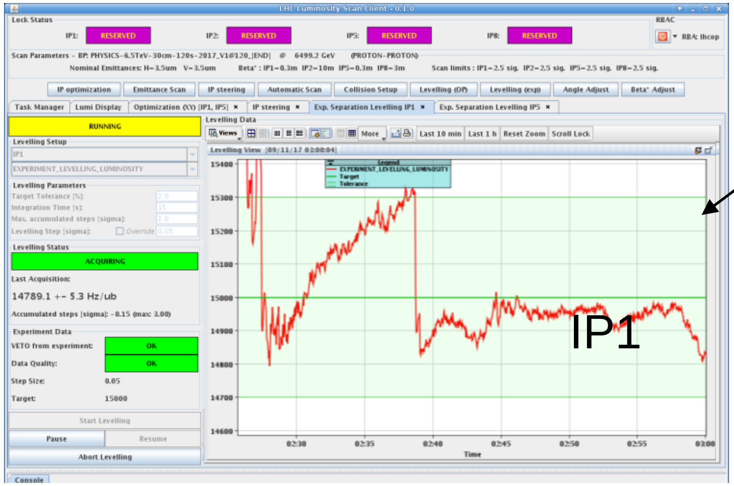
Spikes with period 6.25 mins, ~ permanent ?

Amplitude ~ few μm



Offset levelling: IPs difference

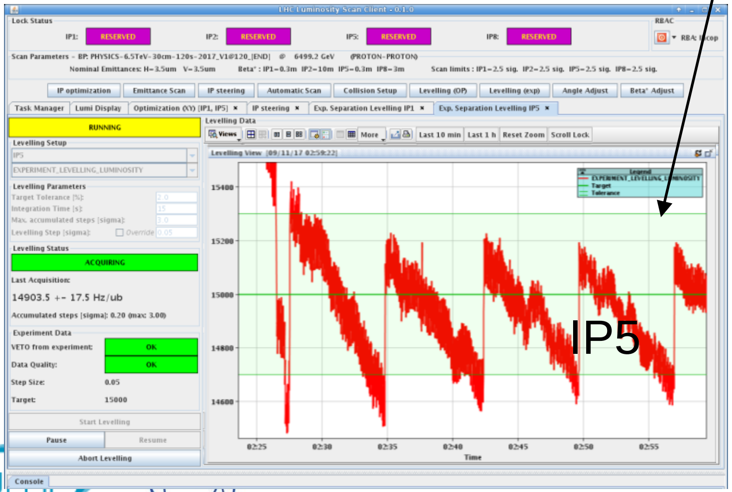
IP optimized and levelled in sep. plane (first steering by hand, than automatic)

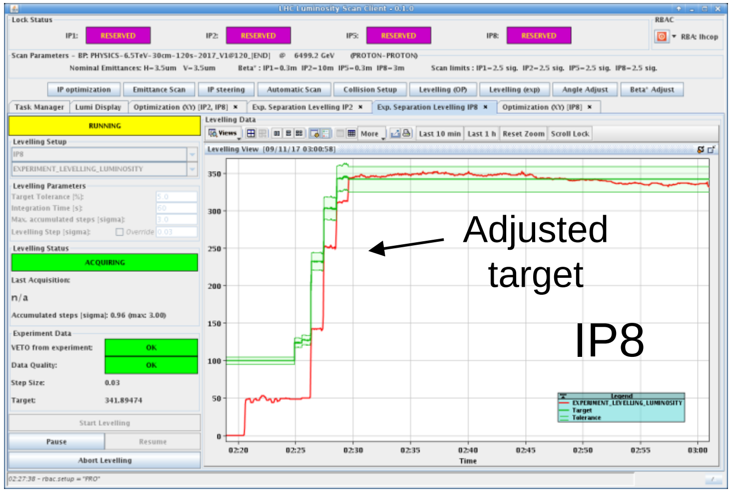


Fix target

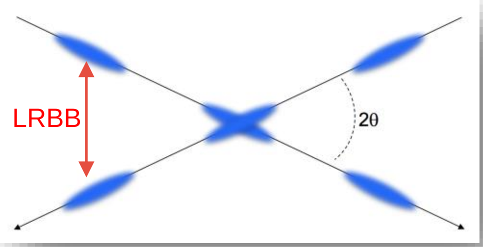
IP optimized only in x-ing plane and levelled automatically in sep. plane

Noisier signal in IP5, most probably due to the detector lumi

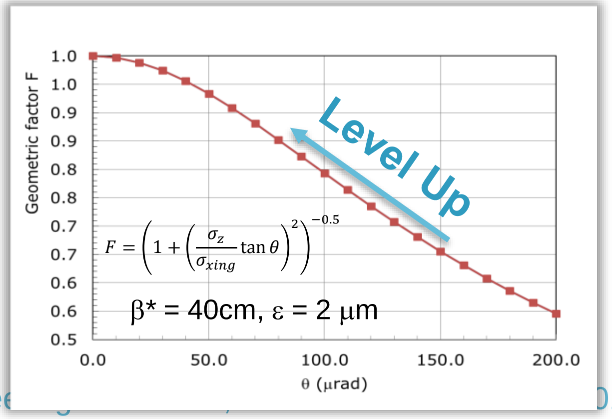




X-ing angle (anti-)levelling

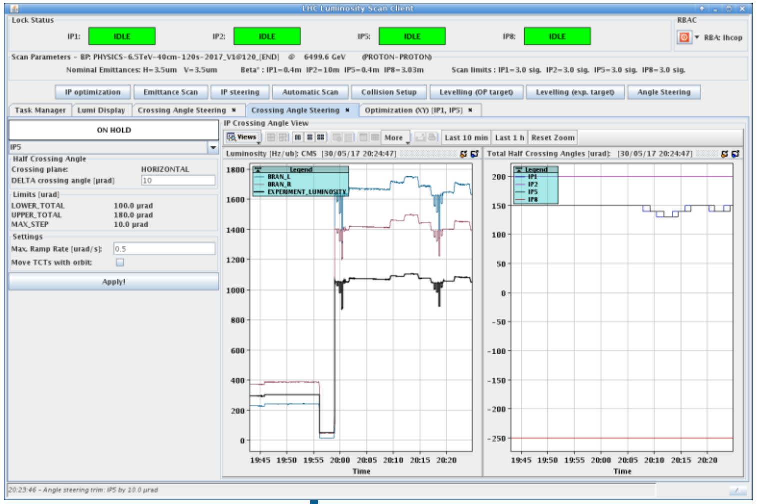


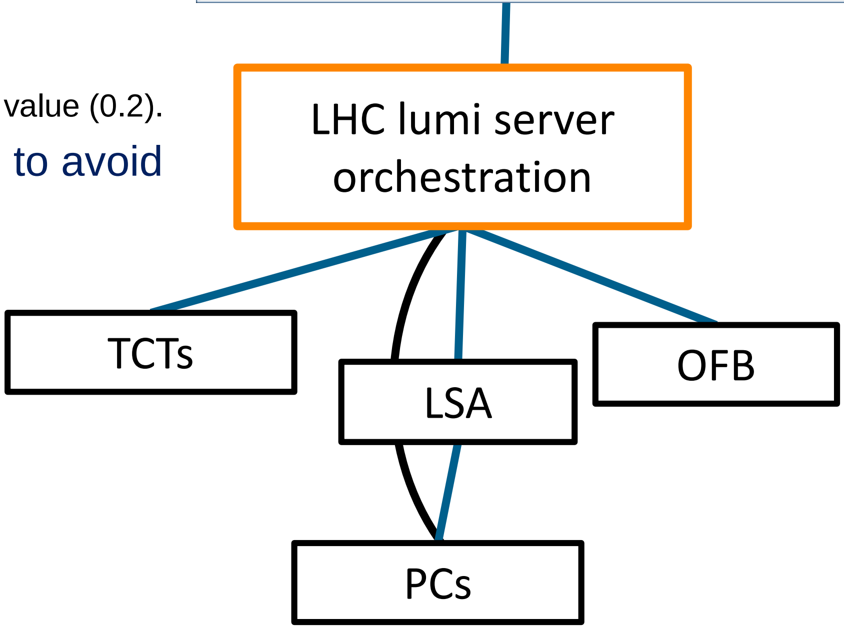
- Local in each IP, limited in range due to aperture (+ trims) and LRBB (- trims).
- **Operational** since June 2017.
- Challenges imposed by the larger bumps and impact of non-closures.
  - Collimators centre (TCT & TCLs) to follow the beam.
    - Collimator interlock limits to be opened to cover a range.
    - MPS validation at the tightest point (smallest X angle) done preliminarily.
  - Operation and synchronization with the orbit FB mandatory.
    - Mainly Controls challenge.
- Implemented in a simple 'trim' format through the luminosity client/server software.
- Possible future **improvements**: automated steps, trim speed and collimation.
  - Steps could be finer and linked to bunch intensity (currently not possible due to CTPPS).
  - Slow trim preparation (orbit FB reference and OFB data synchronization) could be improved.
  - Update of collimator interlock limits.
- Because of aperture limitations and trim limits, this is mostly favorable as **anti-levelling**.
  - Presently used in association with the separation levelling, once this is not effective any longer.



Levelling orchestration

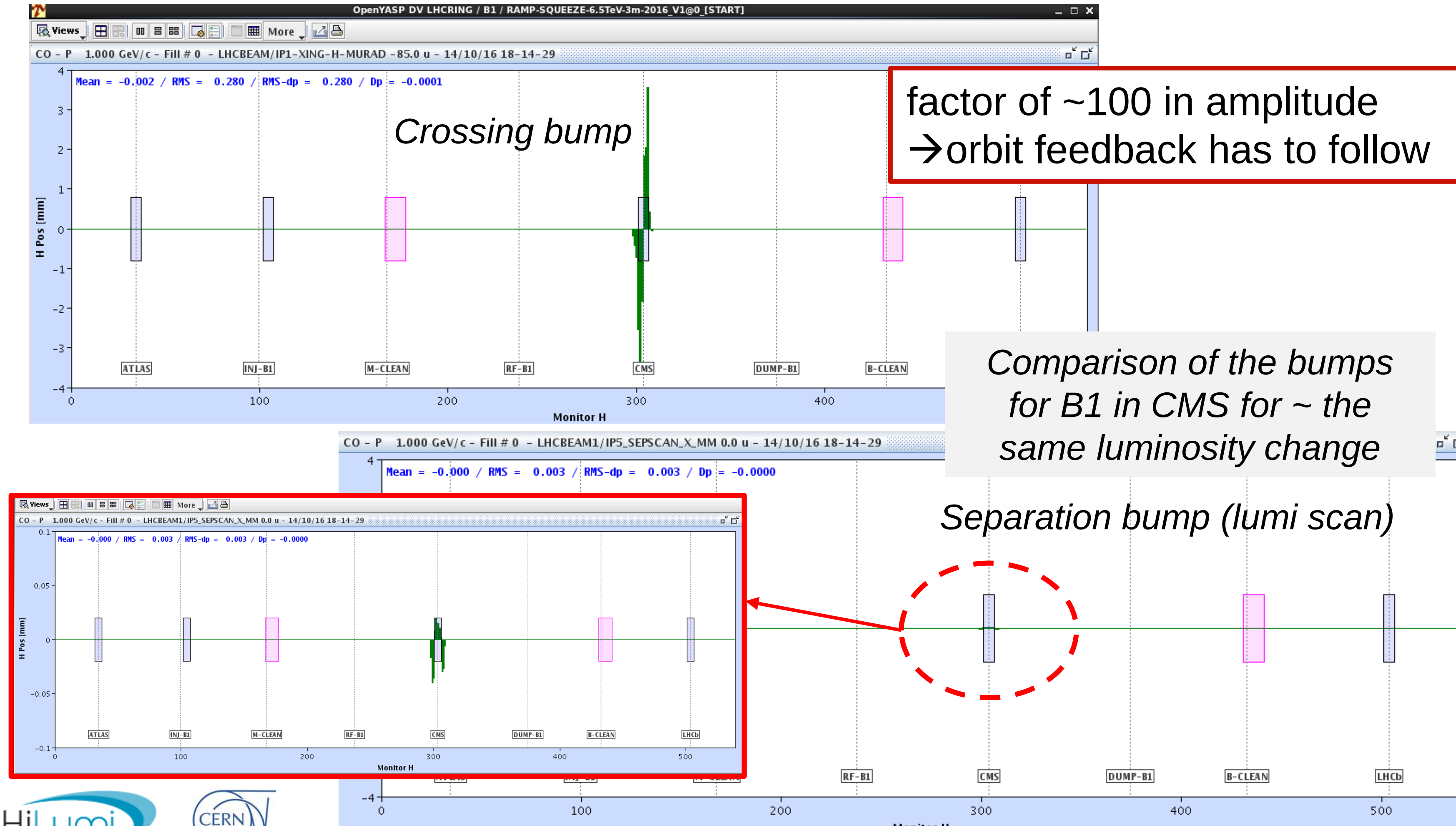
- The whole x-ing angle orchestration is managed through the lumi server.
- Settings changed for a crossing angle change.
  - Power converters (existing IP_CROSSING knobs).
  - Tertiary collimator positions (TCTs and TCLs).
    - Keep gap constant.
    - Move centre with the orbit change.
  - Orbit feedback to correct leakage.
    - Stays on during the change.
    - Must not counteract the changes.
    - Increase gain (0.5) w.r.t. Stable Beams value (0.2).
- The lumi server synchronizes systems to avoid transients.
  - Limit the ramp rate to ~0.5 urad/s.
    - “stretch” the trim period.





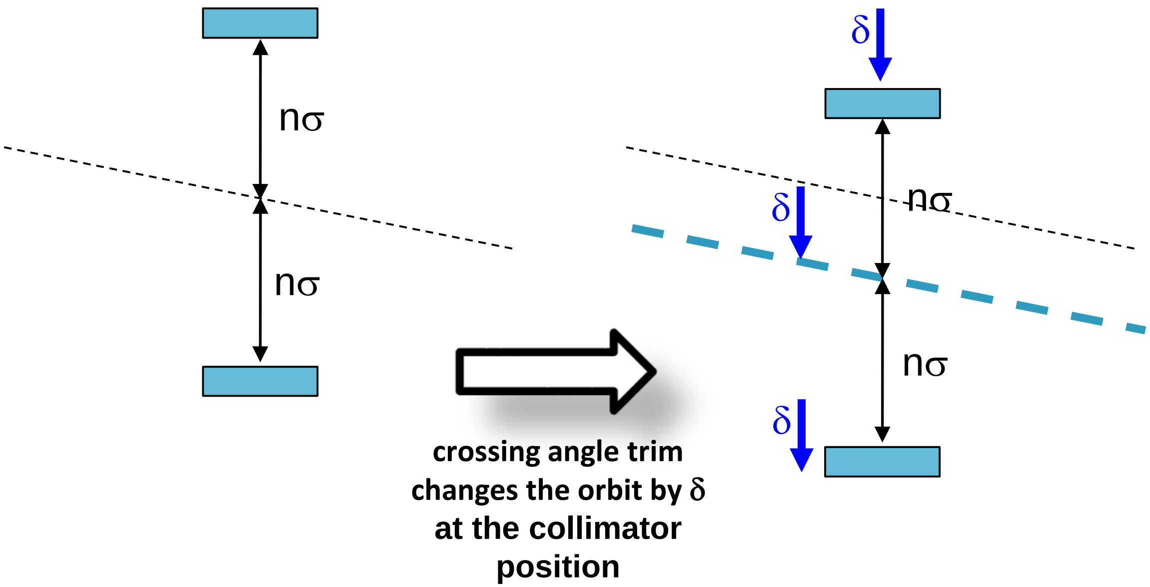
Separation versus crossing

- Separation and crossing levelling are both controlled with local orbit bumps. But the amplitudes differ vastly → **reason for the higher complexity of x-ing levelling**.



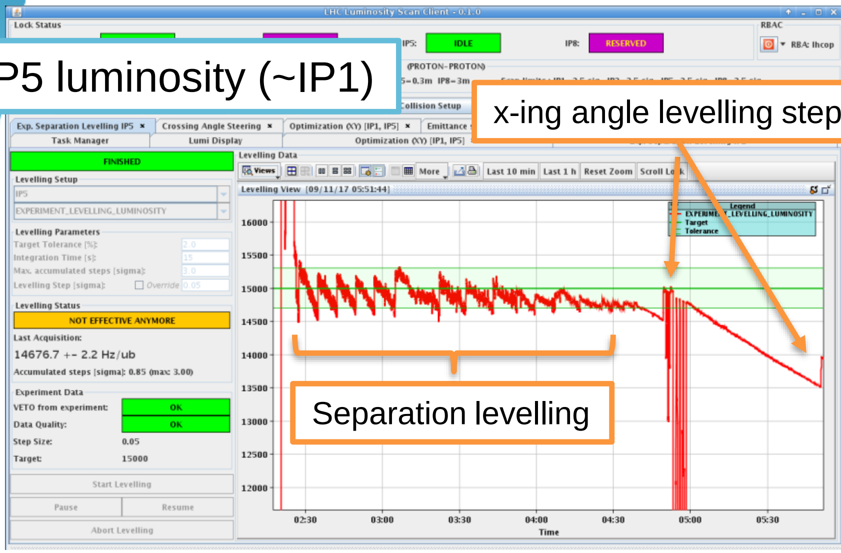
Strategy for moving the TCTs

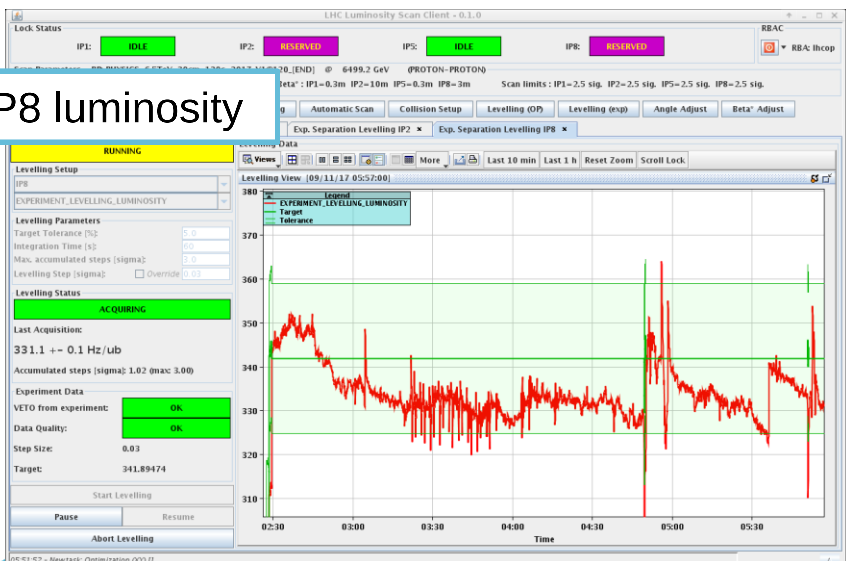
- Keep the **gap constant.**
- **Move the centre with the orbit change.**
  - Add a delta to all jaw positions.
  - Handle collimator specifics (coordinate system, 5μm round-off).

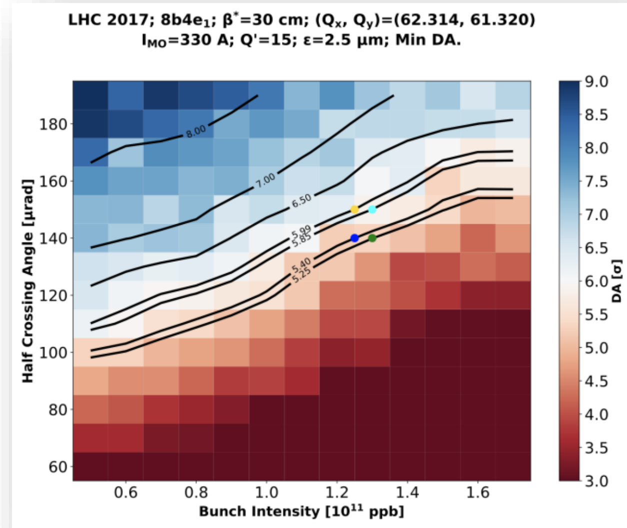


	δ per 10 μrad
TCT	94.8 μm
TCL	101.8 μm

Crossing levelling considerations





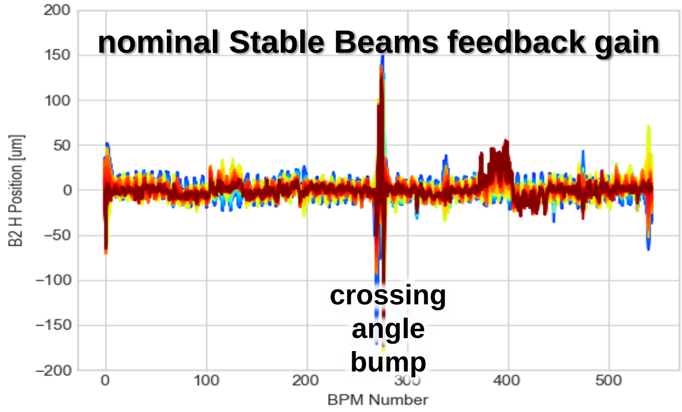


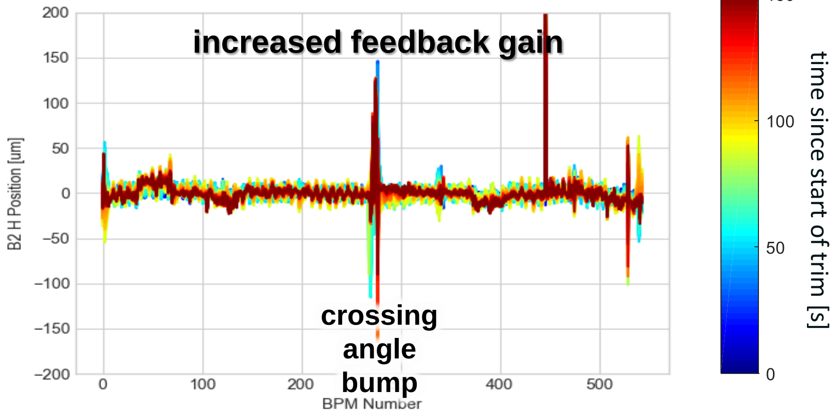
N. Karastathis @ LBOC #88

- x-ing angle levelling is routinely used since Summer.
- After each crossing levelling step.
  - The luminosity is optimized (imperfection of orbit tracking).
  - The tunes are re-adjusted - could be automated if it was fully reproducible.
  - Automatic tune re-adjustment poses however the question of where to store the trims.
- The gain is about 3% at each -10 μrad step, equivalent to a 0.05 σ separation.
- The number of steps is limited by dynamic range and instabilities (from 150 down to 110 μrad). *(see Y. Papaphilippou at LMC on 04/10/17)*
- At each x-ing angle change in IP1 and 5, large disturbance at the other IPs.

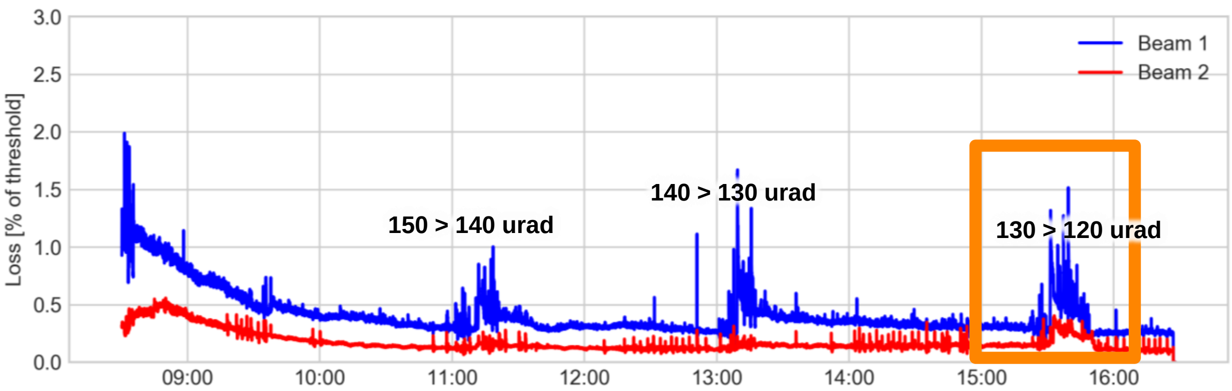
Positive aspects

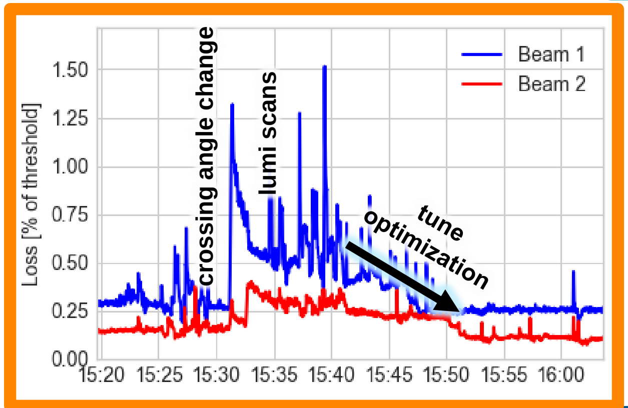
- **Leakage < 50 μm** per 10 μrad step: vanishes within ~ 30 s with increased FB gain.





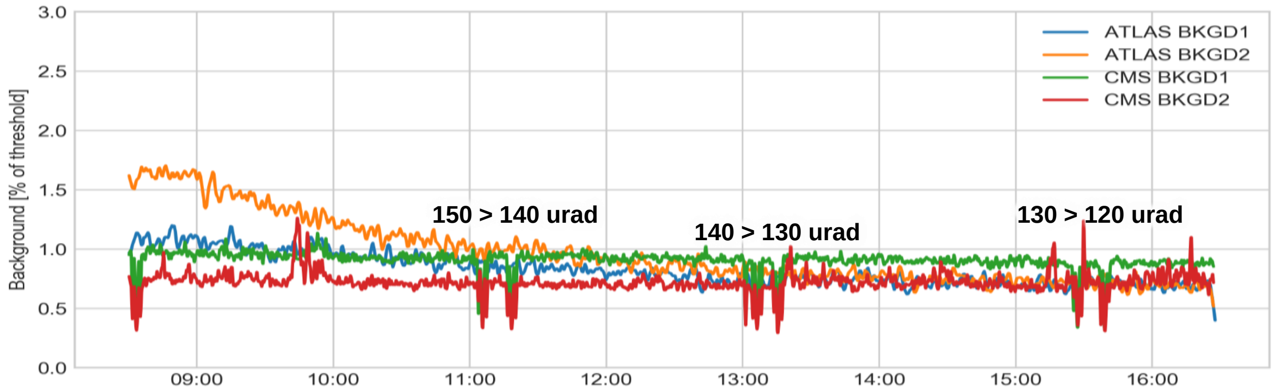
- No losses on the TCTs and small increase of TCP losses.
  - Spikes lower than during the first hour of Stable Beams, **few % of dump threshold.**
  - Losses stabilize on a slightly higher level after the steps.
    - Expected from decreased dynamic aperture (< 5 σ).
    - Last steps (130 urad -> 120 urad) usually the worst, B1 worse than B2.



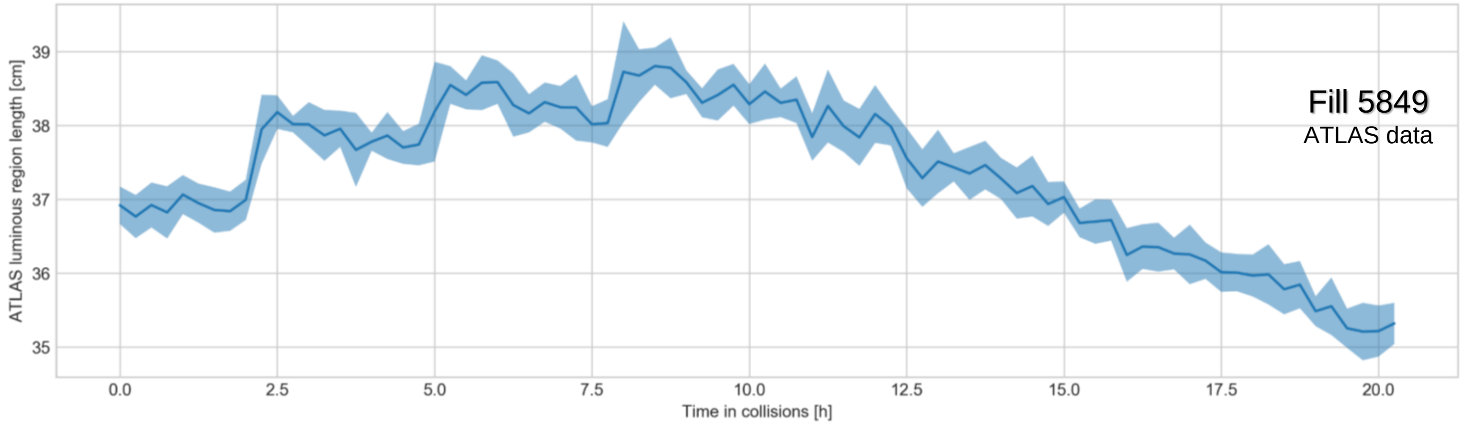


Seen from the experiments

- No increase of experiment background levels.



- Reduction of the geometric factor increases luminous length.
  - ~2.5% per crossing angle step.
  - Reduces pile-up density.
    - Compensates for the increased pile-up due to the higher luminosity.

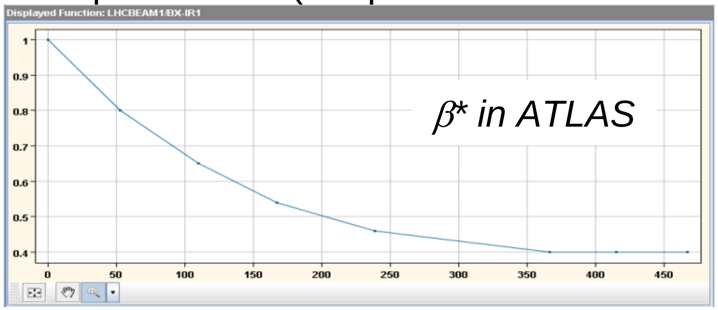


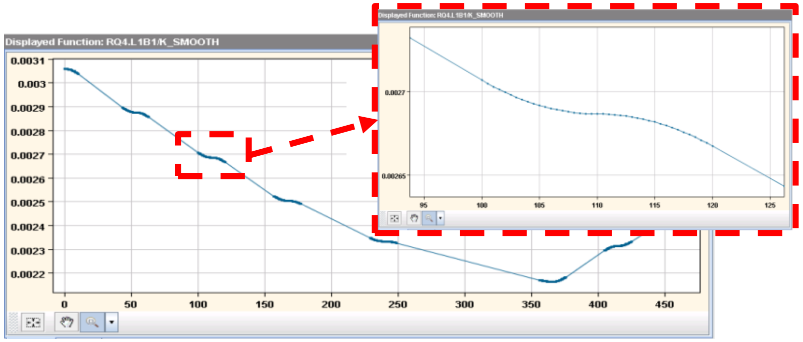
β^* levelling

- This is the most complicate method, but more favorable wrt x-ing angle levelling (larger dynamic range) and offset levelling (never loses the Landau damping due to the tune spread coming from head-on collisions).
- Not easy, mainly as squeezing the beams in ‘stable beams’ implies **local** (in leveled IP) or **global** (as per ATS nature) **optics change**.
  - With telescopic squeeze, no magnet strengths are in principle modified locally in IR1 and IR5, leveling in those two IRs is expected to be easier and smoother. On the other hand changing β^* in IR1 in this mode is obtained through gradient changes in IR2 and IR8 which could render the offset leveling in those IRs more delicate to maintain during a leveling step.
- This technique **involves close to all systems / settings**:
  - bumps at IP (shape and value), orbit corrections,
  - optics corrections,
  - Q, Q’ and coupling trims,
  - movement of TCTs (or TCTs preset for β^* range),
  - orbit control with the orbit feedback: maintain beam separation in offset levelled IPs, head-on collisions in β^* levelled IPs,
  - internal update of LSA DB (optics etc),
  - …. and the beams should remain ~ in place at the IPs.
- Transients, losses etc (as in squeeze) also appear during β^* levelling.

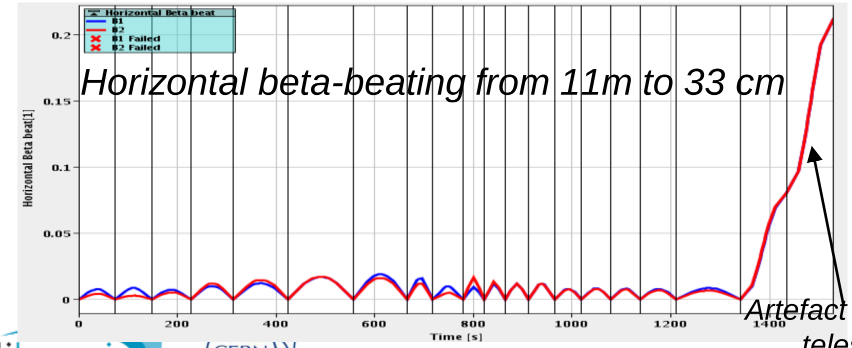
Optics handling in LSA

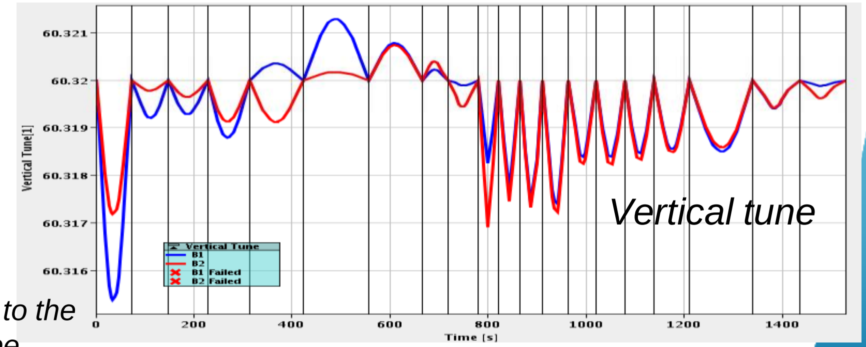
- During the squeeze, we transit from one matched optics (matched point) to the next. Each optics corresponds to a β* combination of the 4 IRs.
- Between 2 points the settings are interpolated and follow a parabolic-linear-parabolic change to be able to stop at both end points (dI/dt = 0).
  - The duration and parameters of each segment are determined by LSA from the circuit parameters (ramp & acceleration rates).





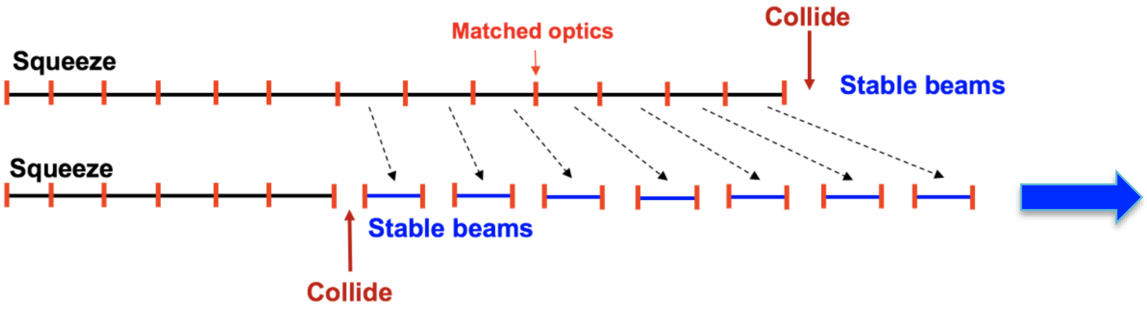
- By construction, transient optics errors (tune, chromaticity, beta-beating, orbit) appear between two matched optics points.
  - Transients can be observed on losses; the tune transients are corrected by feed-forward.

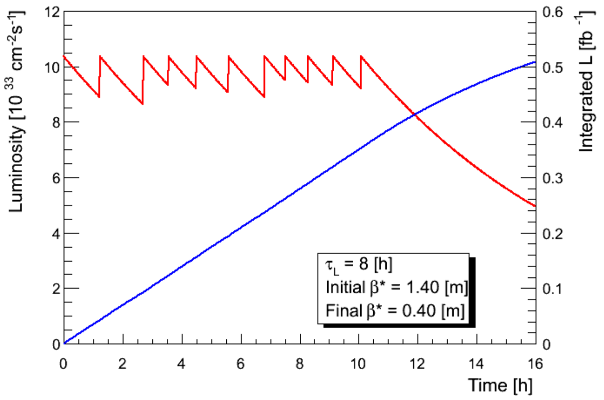




β* levelling in practice

- Currently, a β* levelling scheme has to be built on top of the existing settings structure.
  - Start from a squeeze segment with N matched points.
  - Execute the squeeze segments one by one during stable beams at regular time intervals.

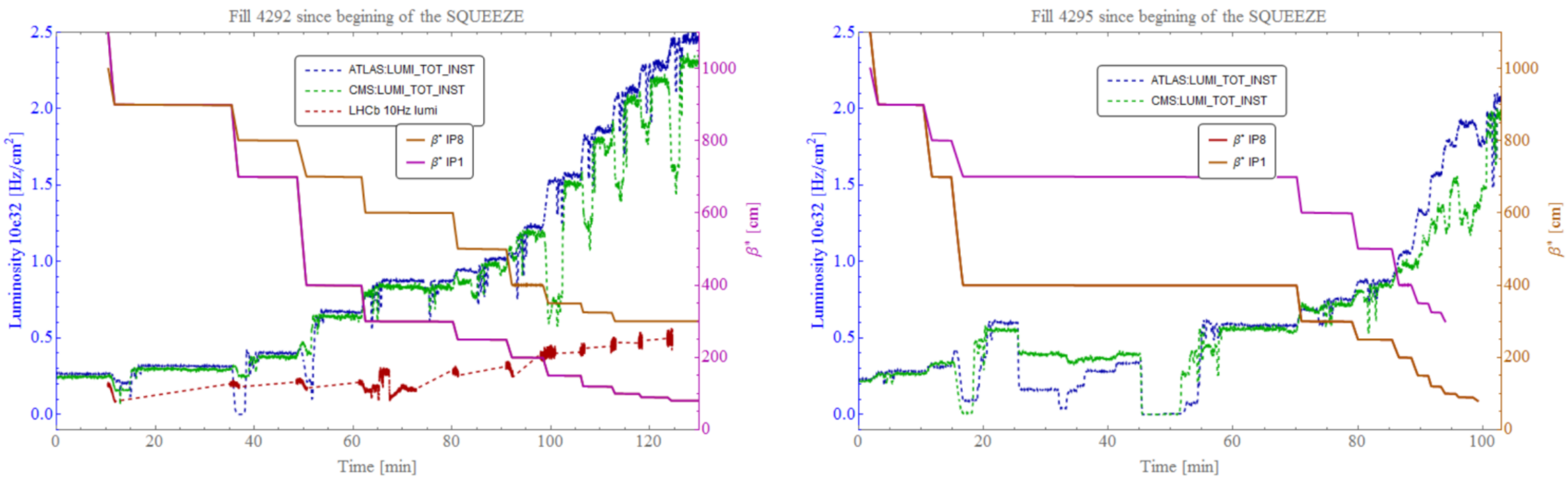




- Ideally: β* steps of arbitrary size, independently in each IP.
  - Requires significant changes in the control system.
  - Alternatively, break up squeeze beam process into individual beam processes to be played in stable beams.
  - An increase of the number of matched points could partially do the job.

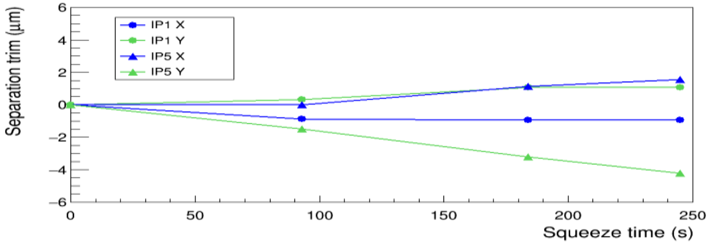
β* levelling MDs - past

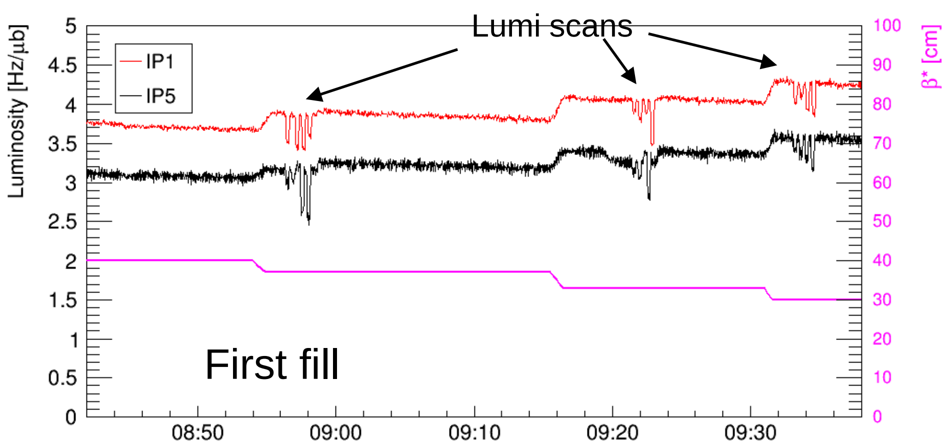
- Up to 2015, β* levelling MDs used the standard squeeze (in ATS language, pre-squeeze) to gain some experience with setup and reproducibility.
  - The advantage of the pre-squeeze is that it is fully local to a given IP, at least from the point of view of the theoretical strength changes: reduces the coupling between IPs.
  - The transients from one step to another were however quite important in particular above β* of 1-2m: the beam separation trims varied a lot along the squeeze.
  - Once setup, the reproducibility was good, sufficient to maintain beams well in collision (~1σ) even a few months later.

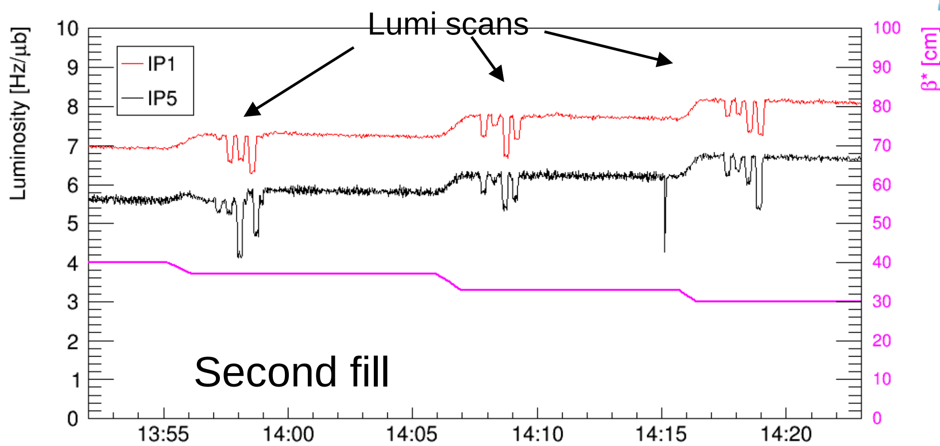


β* levelling MD in 2017

- In 2017, after TS#2, the ATS telescopic squeeze from 40cm to 30cm was introduced, which offered a good opportunity for β* MD. *See MD note CERN-ACC-NOTE-2017-0052*
  - Telescopic squeeze was confirmed to ease life for IR1 & IR5 – no local settings change (in theory) – and possibly make life more difficult in IR2 and IR8 – local settings changes in critical IRs.
  - Opened the door for tests of new levelling software.
- 2 fills were executed; three β* steps were performed to 37, 33 and 30 cm.
  - The orbit FB was on for every step, with updated reference orbit functions to take into account changes of the luminosity scan knob settings as well as shape changes of the IP knobs (high gain scaling factor and low number of eigenvalues).
  - At each step luminosity optimization scans.
  - Small relative beam separation trims were observed, confirming the good stability of the optics corrections.

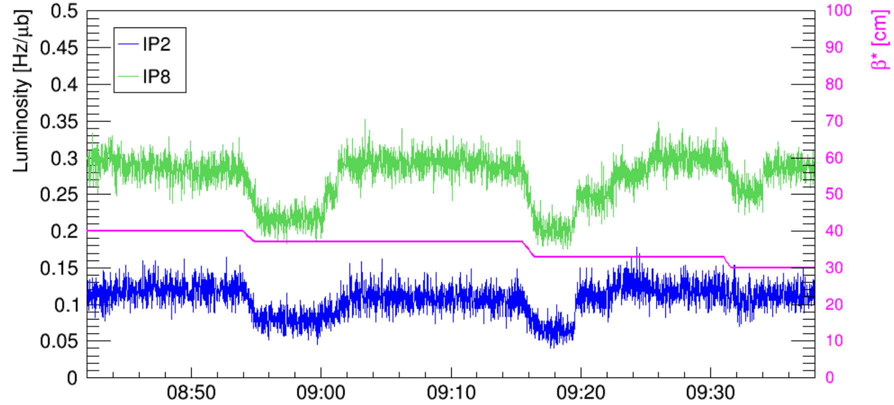




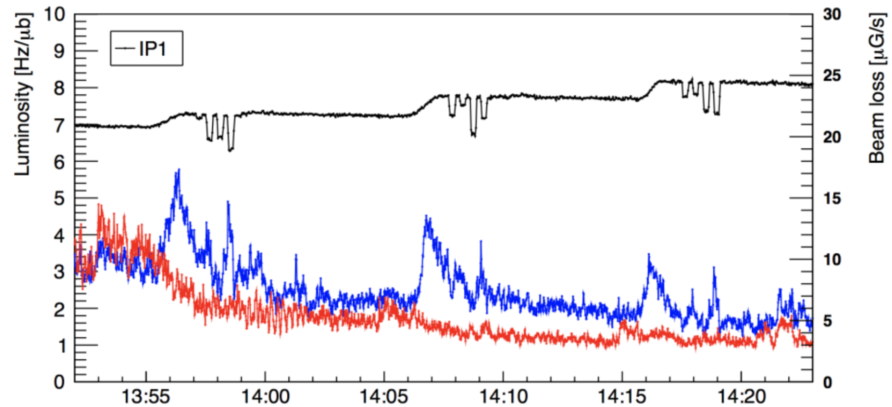


β* levelling MD in 2017_cont.

- After optimizing the luminosity in all IPs, the beams were separated by 1 σ in ALICE and LHCb (based on a nominal emittance of 3.5 μm) to simulate a situation with leveling and to render the luminosity of those two IPs sensitive to orbit perturbations.



- Between steps the separation had to be corrected by up to 0.3σ (~10-15 μm) at certain steps – not a real surprise as not prior orbit setup (→ feed-forward) was made.
  - The telescope makes life more difficult in IR2 and IR8. Reproducibility?
- Unfortunately in the second fill the separation was much smaller (by accident) and the reproducibility could not be tested – next MD.
- Small loss spikes were visible on the BLMs of the TCPs of both beams, but well below a worrying level.



A novel β^* leveling controls technique

- To ease levelling in the near / pre-HL future, we tried to implement β^* levelling as a trim based on a function beam process, generated with fixed matched points.
- In the 'classical' way of driving a squeeze in steps, a different *actual BP* is generated for each step, which leads to the complication of settings trimmed on the actuals, like lumi scans, tune optimization trims, etc → you would need to forward incorporate every time.
- The lumi server beta* changes are **(big) trims**, hence they don't make other BPs resident, re-generate or incorporate into any BPs.
  - The new reference orbit for the OFB is automatically calculated by the lumi server from the orbit bumps in the machine, the old and the new optics. The change is applied as a delta, so it is compatible with the usual measured orbit we're using in Stable Beams. With the 'classical' approach, you would need to always regenerate the RefPosition settings for all BPMs (which takes a lot of time), and it would not be possible to apply the changes as delta to the actual reference.
  - The collimator positions are dynamically calculated as delta.
- The parameters which are trimmed are divided in:

Parameters trimmed in absolute - the value in the actual BP has to match the first point of the function

BETA-STAR, Beta
BETA-BEATING, KNOB
MATCHING QUADRUPOLE, K
TRIPLET, K
TRIPLET CORRECTION, K
WARM QUADRUPOLE, K

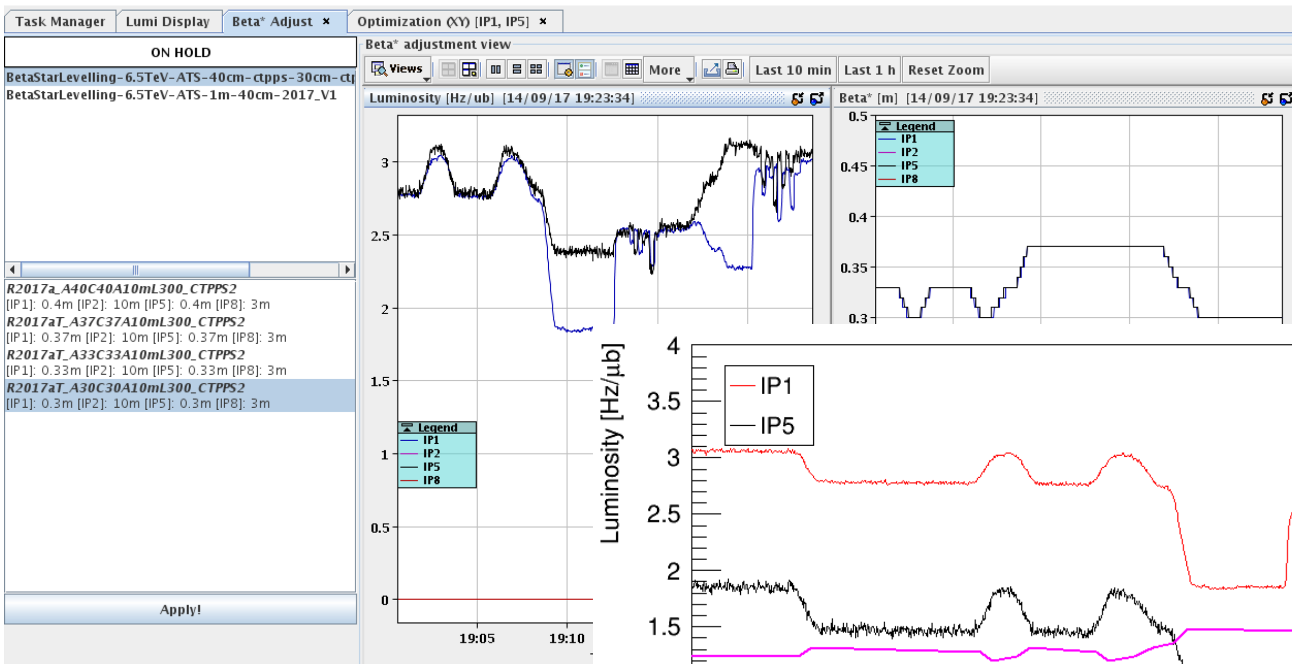
Parameters trimmed in relative - like if you did a constant incorporation every time

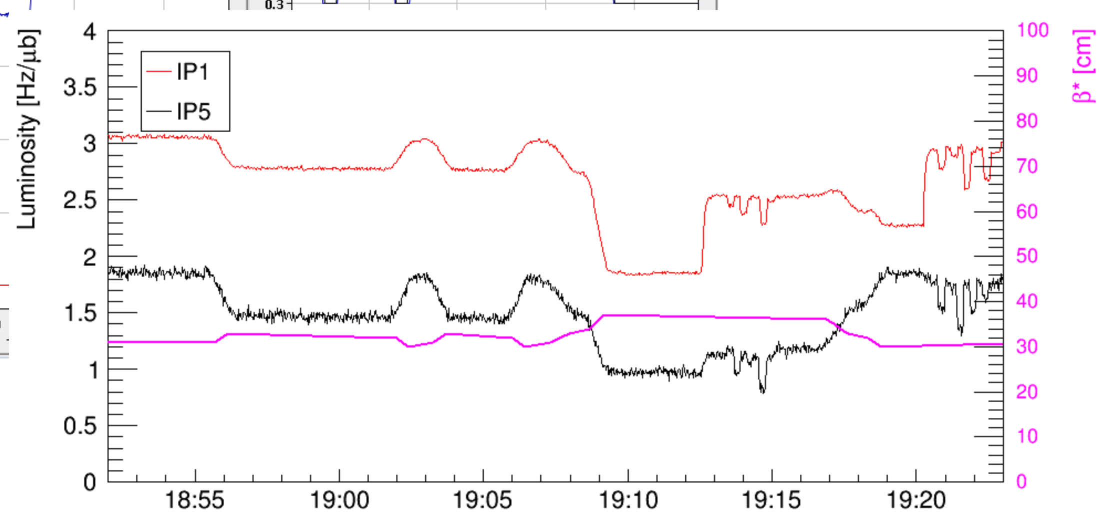
LUMI-SCAN, KNOB
IP_ANGLE, KNOB
IP_CROSSING, KNOB
IP_OFFSET, KNOB
IP_SEPARATION, KNOB
IP_SPECTROMETER, KNOB
TUNE_TRIM, KNOB
COUPLING, KNOB
CHROMATICITY, KNOB

TUNE_TRIM, K
COUPLING, K
CHROMATICITY, K
ORBIT-H, K
ORBIT-V, K
ORBIT-TRIPLET, K
WARM MAGNET, K
SKEW SEXTUPOLES, K

New control technique test

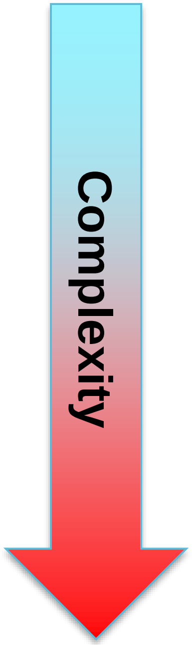
- During September MD, a first test was made of the trims method, but it only involved the PC settings – no orbit FB, no collimators.
- Given the prototyping state of this work, the results are very encouraging.
- The plan is to use the settings established in MD3 (essentially separation corrections) for a more advanced test of the big trims in MD4.





Summarizing

- Offset levelling.
  - Fully operational since years.
  - Local orbit bump with **simple trims**.
- Crossing angle levelling.
  - Fully operational since few months.
  - Local orbit bump with **complex trims**.
    - Orbit bump, orbit FB reference, collimator shifts.
    - Synchronized action of bump, orbit FB and collimators.
- β^* levelling.
  - Still some work to do, but promising results already obtained.
  - Local or global optics change – **complexity of a ramp or a squeeze step**.
  - This technique involves close to all systems / settings:
    - bumps at IP (shape and value), orbit corrections,
    - optics corrections,
    - Q, Q' and coupling trims,
    - collimators,
    - beam feedbacks – orbit,
    - internal update of LSA DB (optics etc).



Concluding remarks and outlook

- Two levelling schemes (offset and x-ing angle) are already successfully used in the LHC.
  - offset levelling is a **serious candidate also for HL-LHC**, partly in combination with beta* levelling.
  - The potential of x-ing angle levelling is limited.
- The good results obtained with β^* levelling make of it a potential option for operation in 2018.
- The new scheme of beta* 'big-trim' could bring us to a point where **β^* levelling can be considered for operation** based on a sequence of discrete matched optics.
  - Steps of 5-15% in luminosity seem reasonable.
  - This could be combined with offset-levelling in the same IRs to flatten the lumi curve (but some small humps will remain – unlikely to be of any relevance for the experiments).
- This could be sufficient up to and including the beginning of the HL area – then the real requirements may become clearer.
- Requiring independent beta* for IR1 and IR5 opens a Pandora box for settings, machine setup and operation.
- To improve control at the IP, one can consider in the longer term to build another feedback loop inside the orbit FB to maintain the IP positions with DOROS.
  - Requires a reliable and available DOROS system – not yet !
  - Very large impact on the orbit FB design – important and heavy changes.

Thank you for the attention!