*Towards Operational Leveling by β**

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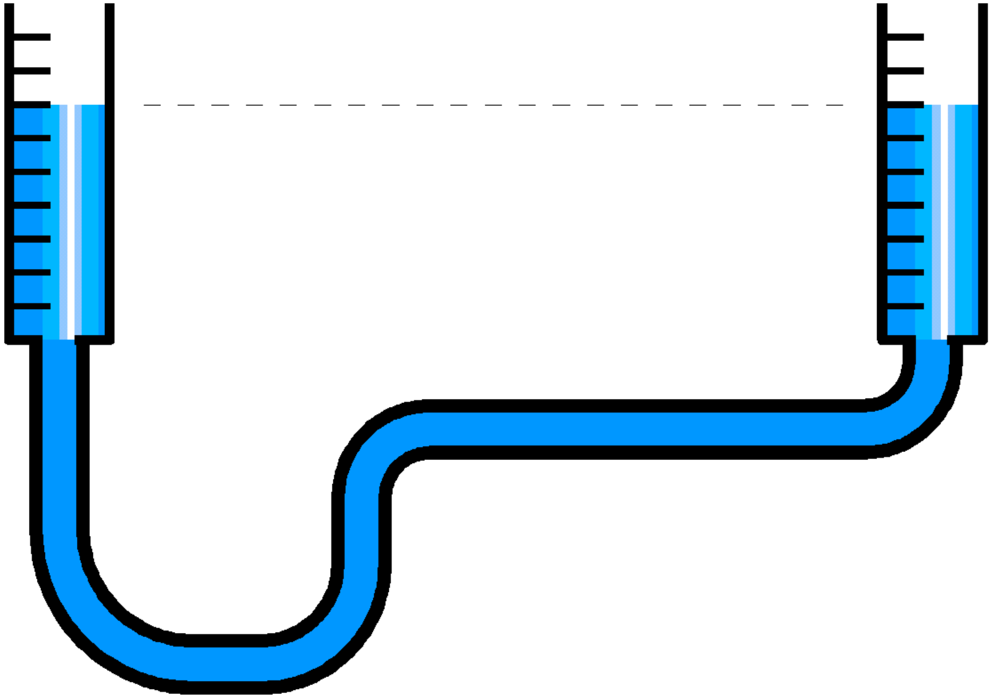
BE-OP-LHC



Levelling options

- Levelling by separation
- Levelling by crossing angle
- Levelling by β^*

Complexity scale

Existing levelling techniques: offset

Offset levelling:

- Extremely simple and local to each IP.
- Operational since run 1.
- No (little) impact on collimators (TCT & TCLs) due to smallness of orbit shifts.
- Baseline technique for ALICE and LHCb, driven by the experiments.
- Possible future **improvement**: better integration with the orbit FB.
  - Orbit reference update at each levelling step (take over work done for xing levelling), cohabitation with OFB mitigated for the moment by 'gentle' OFB correction configuration.
- 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 – 'positive' effect on LRBB?
  - We should keep offset levelling as a serious candidate also for HL-LHC, partly in combination with beta* levelling.

Side effects of offset levelling

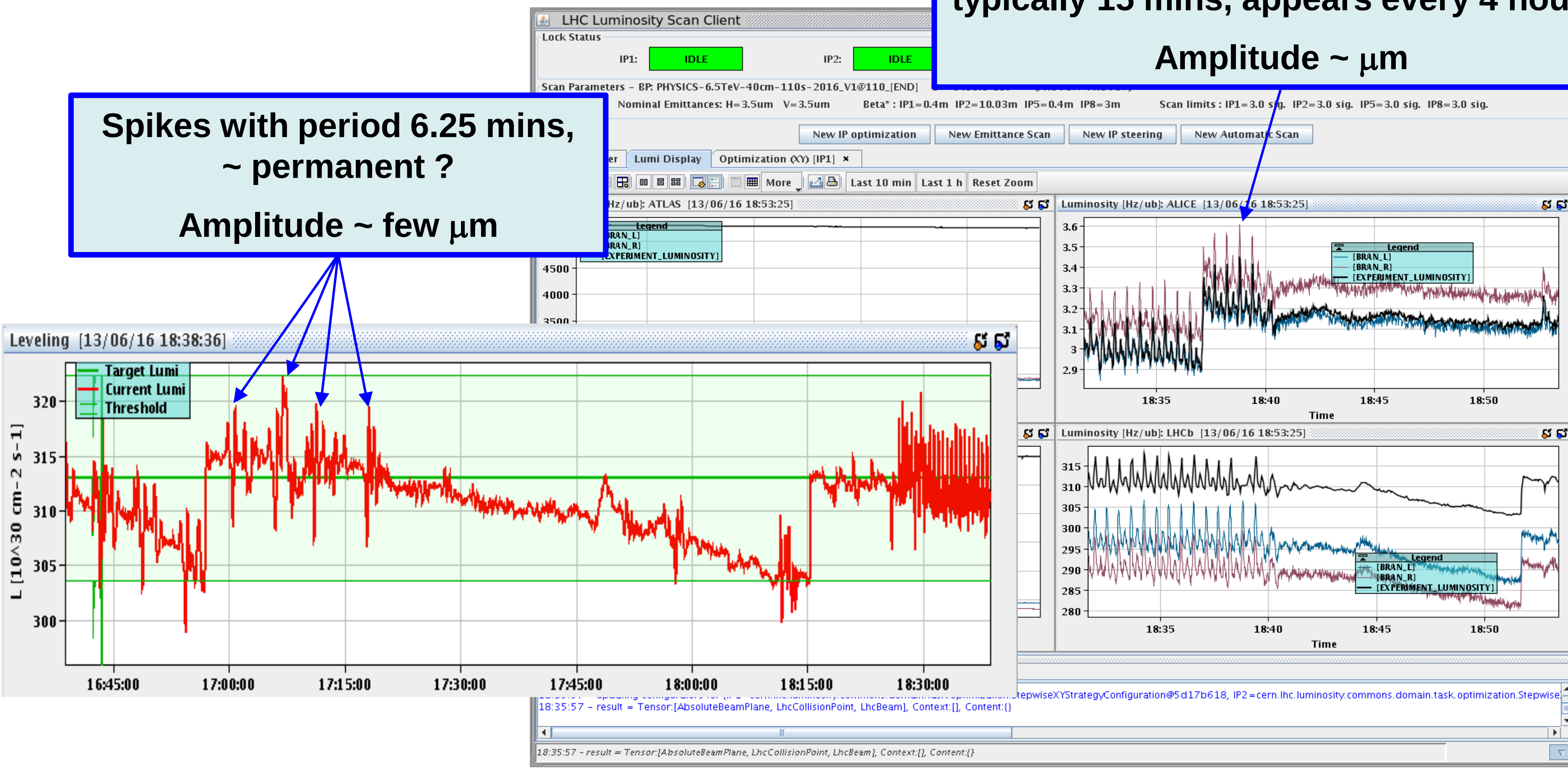
- A side effect of not colliding head on is the increased sensitivity to beam separation fluctuations induced by ‘orbit noise’ → L fluctuations.
- Periodic noise is clearly visible on the ALICE and LHCb luminosity.
  - *Source not identified, but B2(H) is much more affected.*

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

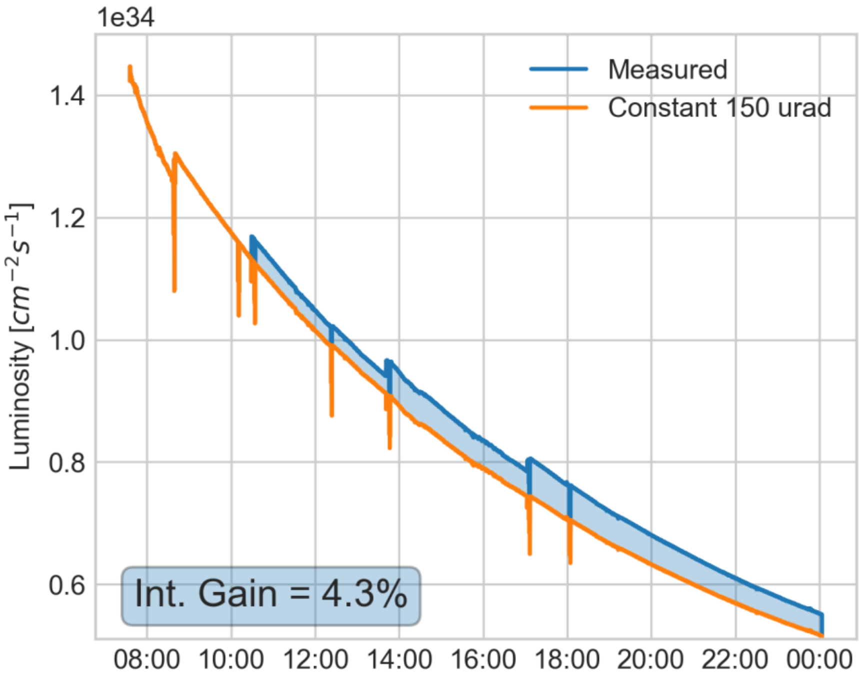


Existing levelling techniques: xing

Crossing angle anti-levelling:

- Local to each IP, limited in range due to aperture (+ trims) and LRBB (- trims)
- Operational since June 2017.
- Due to the larger bumps and impact of non-closures, operation and synchronization with the orbit FB is mandatory, collimator centre shifts are also integrated.
- 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.
- This is not an all-round levelling method, but rather an end of fill improvement.

- After each crossing levelling step:
  - the luminosity is optimized (imperfection of orbit tracking),
    - This would also apply to future beta* levelling.
  - the tunes are re-adjusted - could be automated if it would be fully reproducible.
    - Automatic tune re-adjustment poses however the question of where to store the trims.



Fill 5872
ATLAS Luminosity

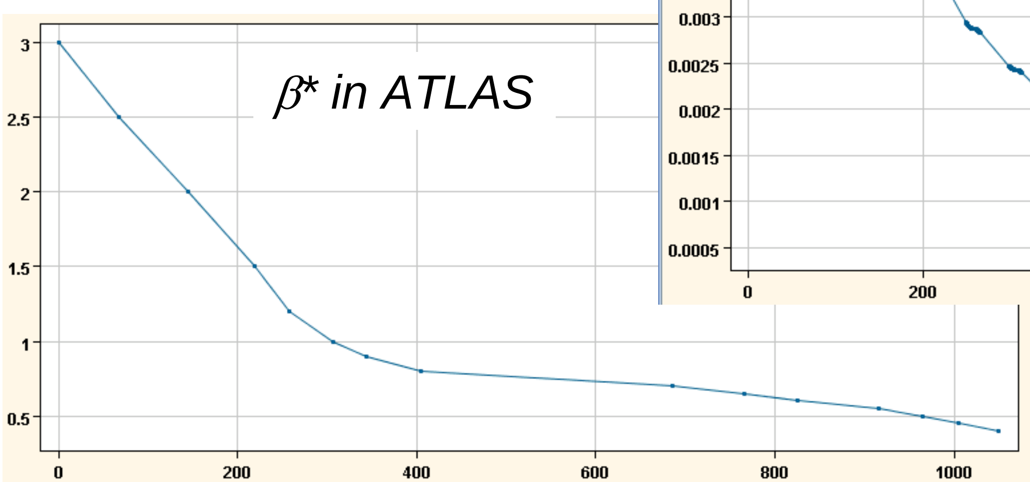
Levelling complexity

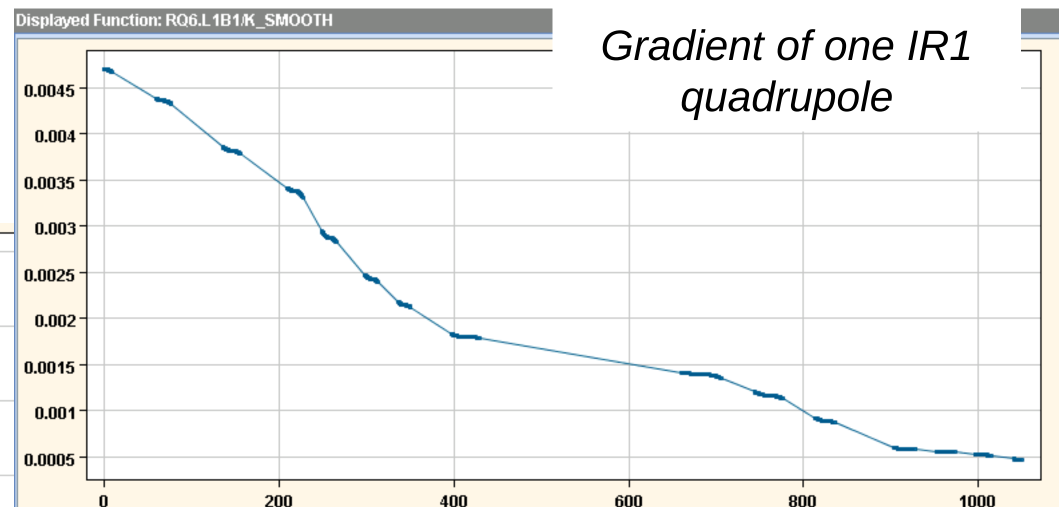
- Offset levelling:
  - Local orbit bump with **simple trim**.
- Crossing angle levelling:
  - Local orbit bump with **complex trim**:
    - Orbit bump, orbit FB reference, collimator shifts.
    - Synchronized action of bump, orbit FB and collimators.
- β^* levelling:
  - Local or global optics change – **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).
    - ….
  - And the beams should remain ~ in place at the IPs.

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 each segment are determined by LSA from the circuit parameters (ramp & acceleration rates).

2016 IR1 & IR5 β* [m]:

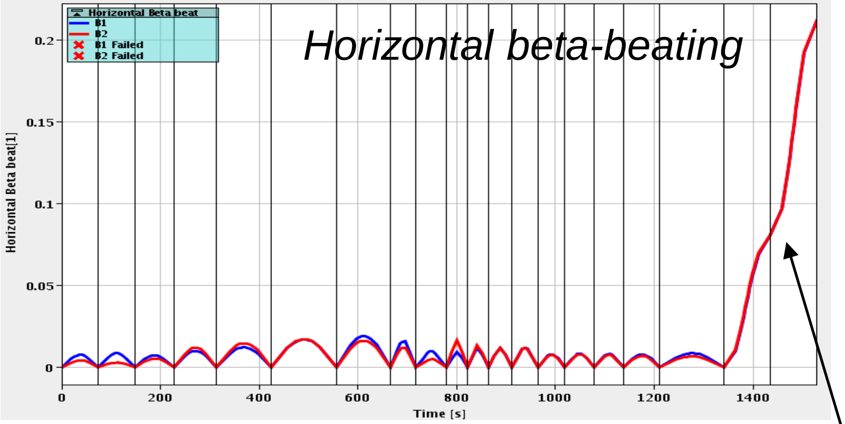


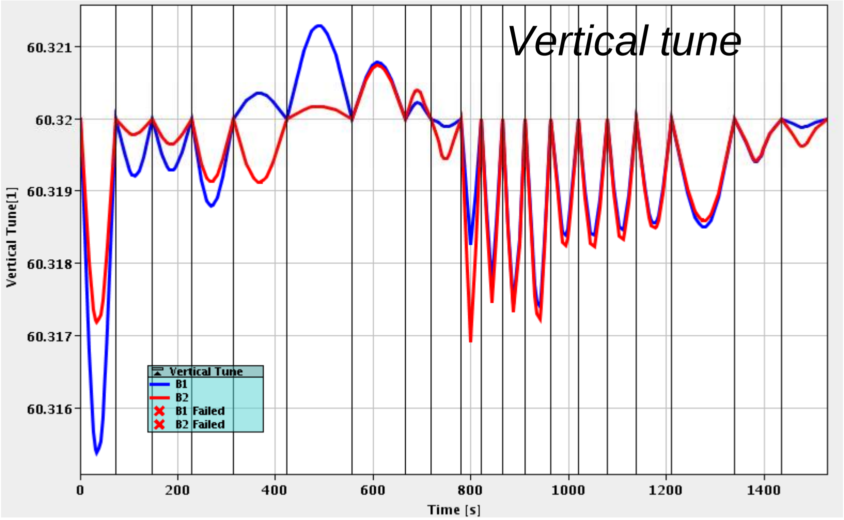


Optics handling in LSA

- 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.
- The density of β^* matched points is chosen to keep the transients reasonable.

Transient beta-beating for the 2017 squeeze 11m-33cm



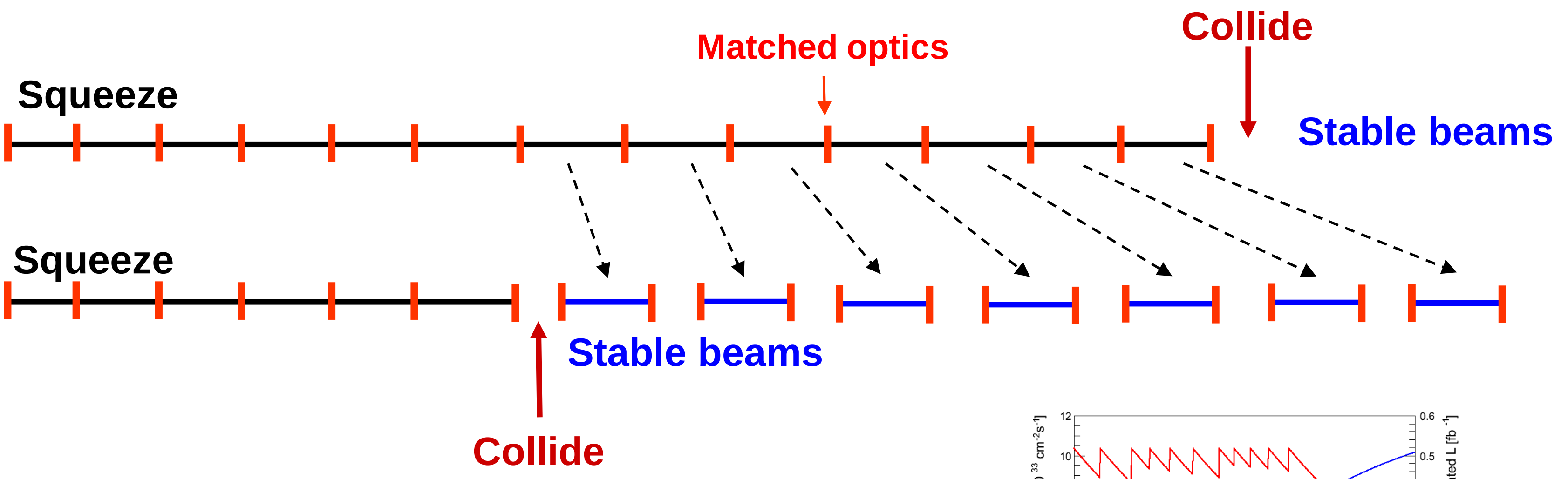


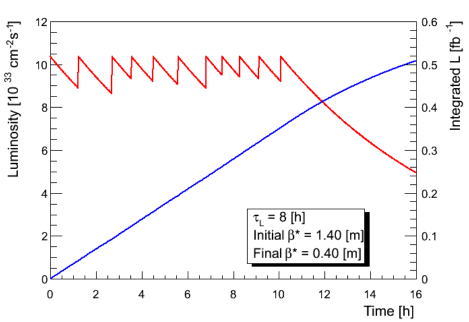
At small β^* the transient error is ~1%.

Artefact due to the telescope

Beta* In practice

- Currently (and probably also for run 3) 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.*



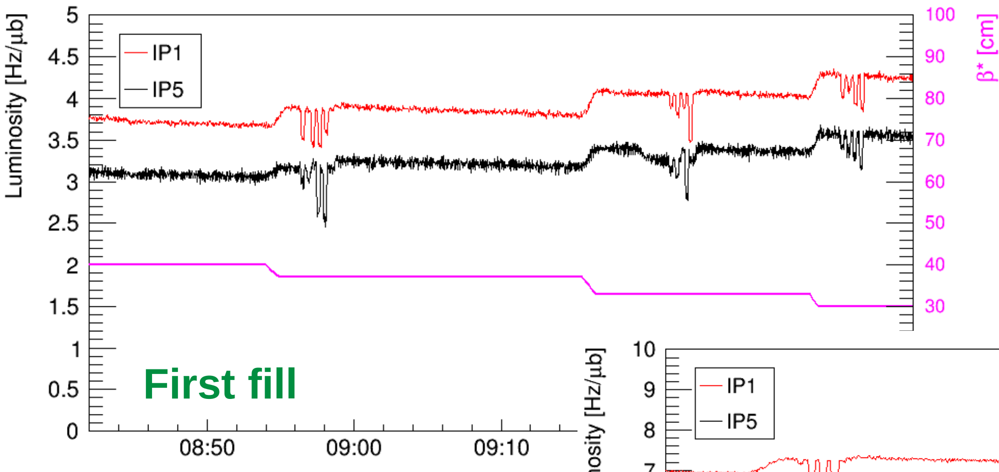


Beta* levelling MDs - past

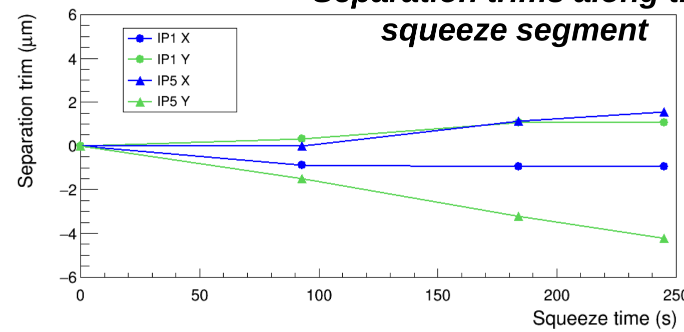
- Up to 2015 β* levelling MDs used the standard squeeze (in ATS language pre-squeeze) to gain some experience with setup and reproducibility.
  - The advantage of the pre-squeeze is that it is fully local to a given IP – at least from the point of view of the theoretical strength changes: reduces the 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.
    - Partly due to the fact that MDs took over standard squeeze setups where orbit control at the micron is not an issue.
  - Once setup, the reproducibility was good, sufficient to maintain beams well in collision (~1σ) even a few months later.
    - A by-product of the MD: development of better software for orbit FB references, generated from the knob settings (separation, xing, lumi scans etc).
- In 2017 the ATS telescopic squeeze from 40cm to 30cm offered a good opportunity for β* MD.
  - Telescopic squeeze should ease life for IR1 & IR5 – no local settings change (in theory) – and possibly make like more difficult in IR2 and IR8 – local settings changes in critical IRs.
  - If successful this could be a potential option for operation in 2018.
  - Open the door for tests of new levelling software.

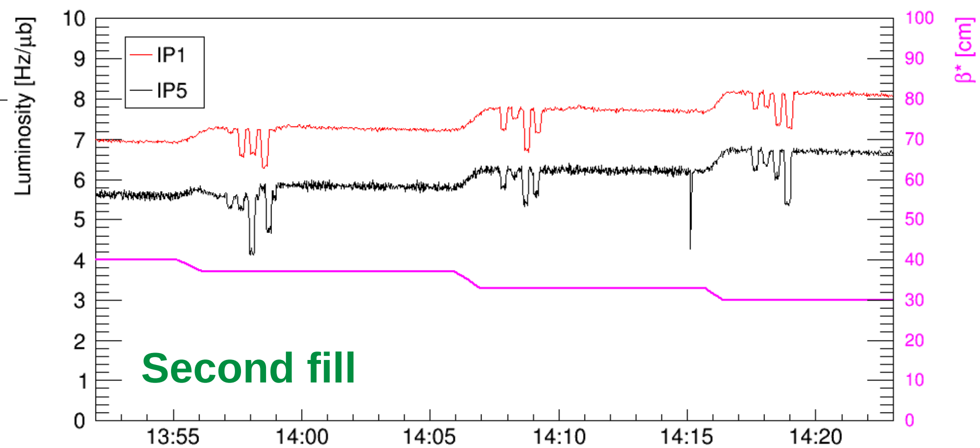
Beta* levelling MD

- Last week's MD on β* levelling in telescopic mode is based on executing a squeeze segment step-wise with collisions. It confirmed that when β* is changed with the telescope the transients are 'easy' to cope with in IR1&5.
  - In practice there are small changes due to optics corrections.
    - Small but measureable trims on the beam separations.
  - Levelling worked well in IR1 and IR5 at the first attempt without any setup !



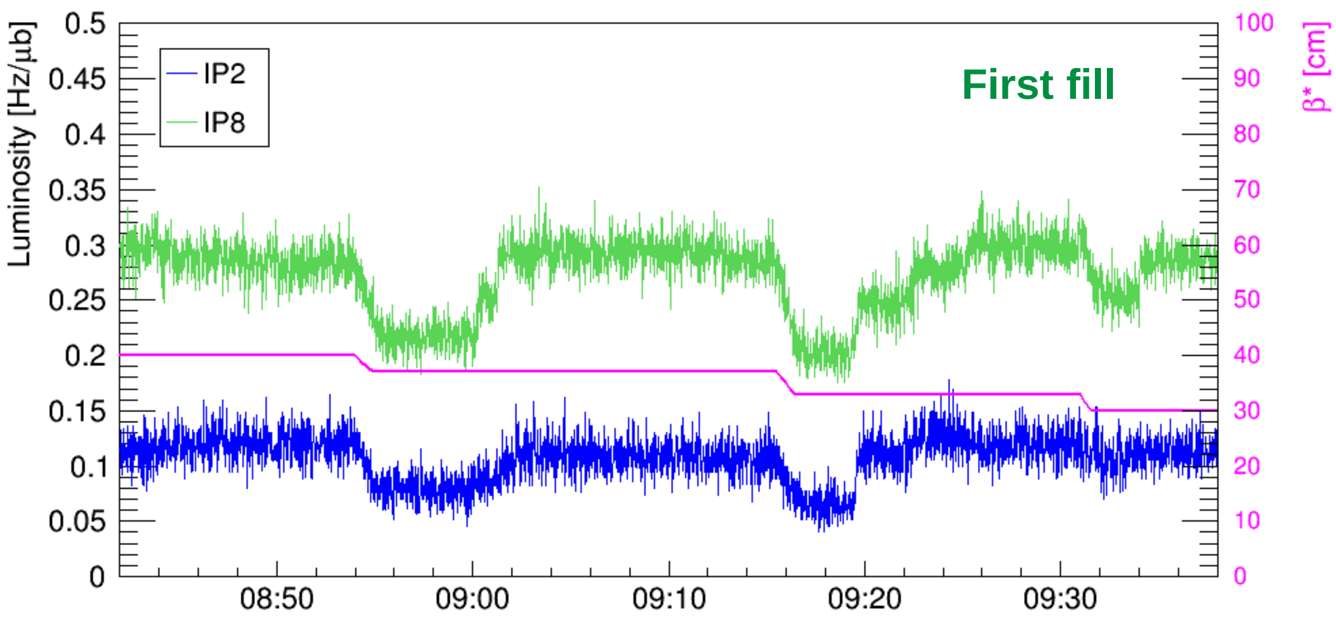
Separation trims along the squeeze segment





Beta* levelling MD

- During the MD IR2 and IR8 were setup with a 1σ separation (~ max. sensitivity to separation drifts).
- 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.

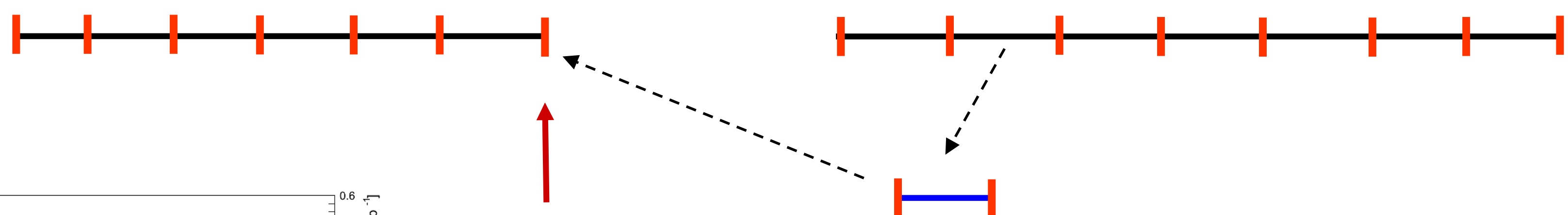


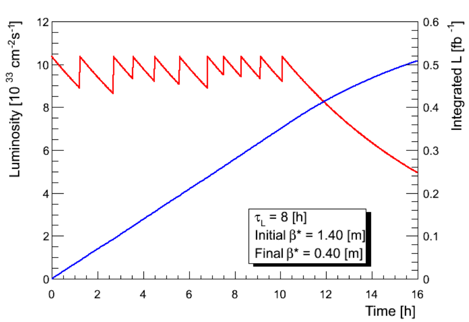
Next steps – twisting LSA a bit

- To ease levelling in the near / pre-HL future we are trying to implement β^* levelling as a trim based on a function beam process.
  - *A function BP is generated with fixed matched points. It is used to store the settings and corrections (Q, Q', coupling, orbit, optics, beam separation etc) and to track the evolution.*
  - *The segments between matched points are loaded and applied as a '**mega-trim**' through the luminosity server using the stored function pieces.*
  - *The **mega-trim** must involve the **orbit FB** (drive reference change, relative or absolute?), the **collimators** (may be more complex than for crossing leveling), the **PC interlocking** and an update of **LSA internals**, for example the optics (→ knob definitions).*
    - *Mega-trim may be stretched to make it smoother etc…*

Squeeze

'Colliding' squeeze





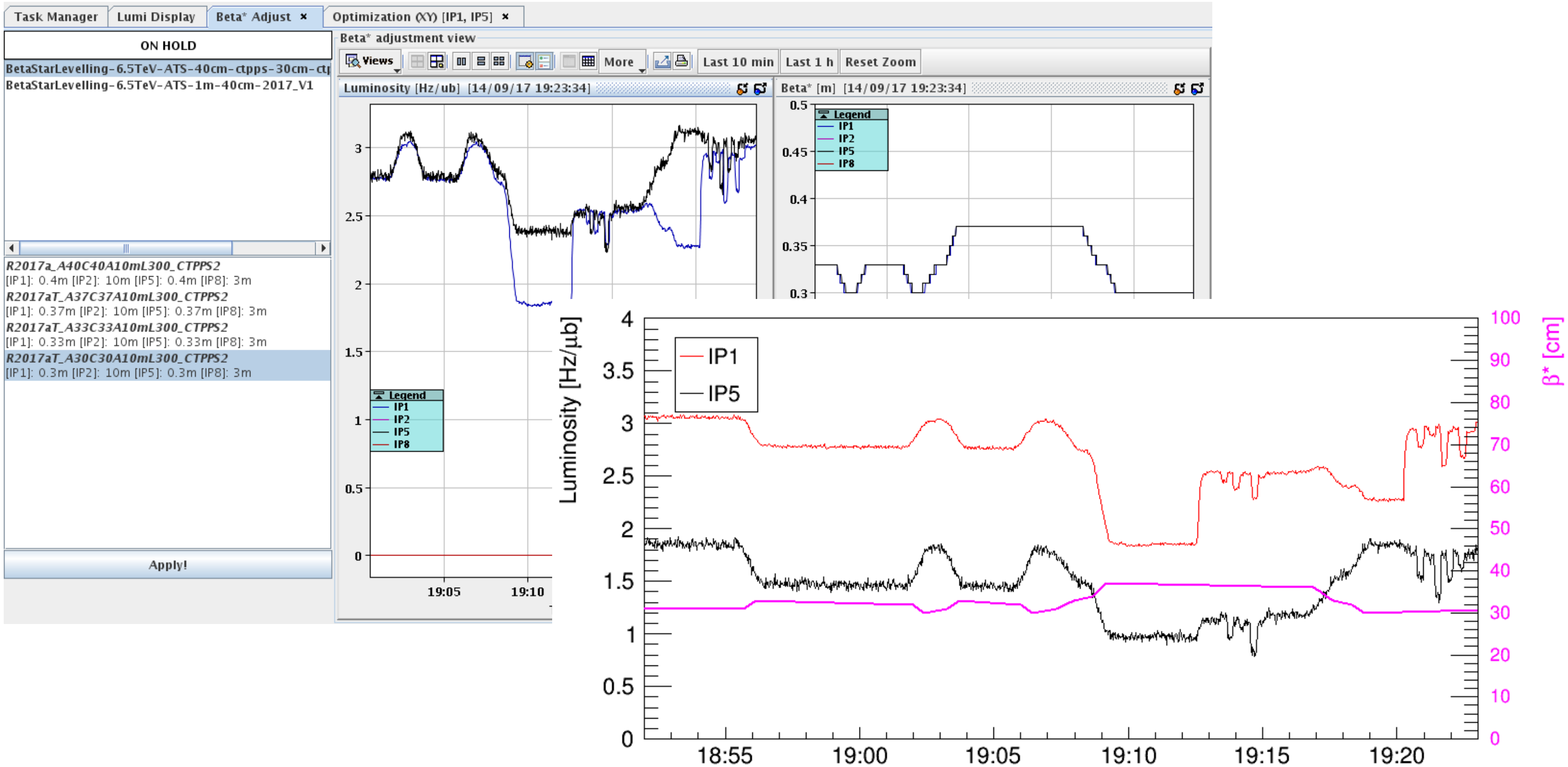
Collide

Take a segment and apply as trim

Can go backward and forward !

Twisting test

- During last week's MD a first test was made of the mega-trim, 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 mega-trim in MD4.



Outlook

- The new scheme of beta* ‘mega-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 well 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.
  - Non-linear knobs to trim β^* cannot be used directly as mapping to corrections can currently only be done through a BP (i.e. versus time).
  - Such a scheme requires **orthogonal corrections**, and may lead to an important increase in setup and testing time (playing back in different orders…).
  - Currently I see no real need since both experiments either operate at the maximum or at very low pile-up, special fills for tests at lower luminosity are handled well with offset levelling.
- 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.

Separation versus crossing

Separation and crossing levelling are both controlled with local orbit bumps. But the amplitudes differ vastly → <u>reason for the higher complexity of xing levelling</u>.

Comparison of the bumps for B1 in CMS for ~ the same luminosity change