First LHC Emittance Measurements at 6.5 TeV

Maria Kuhn[1,2] – September 16, 2015

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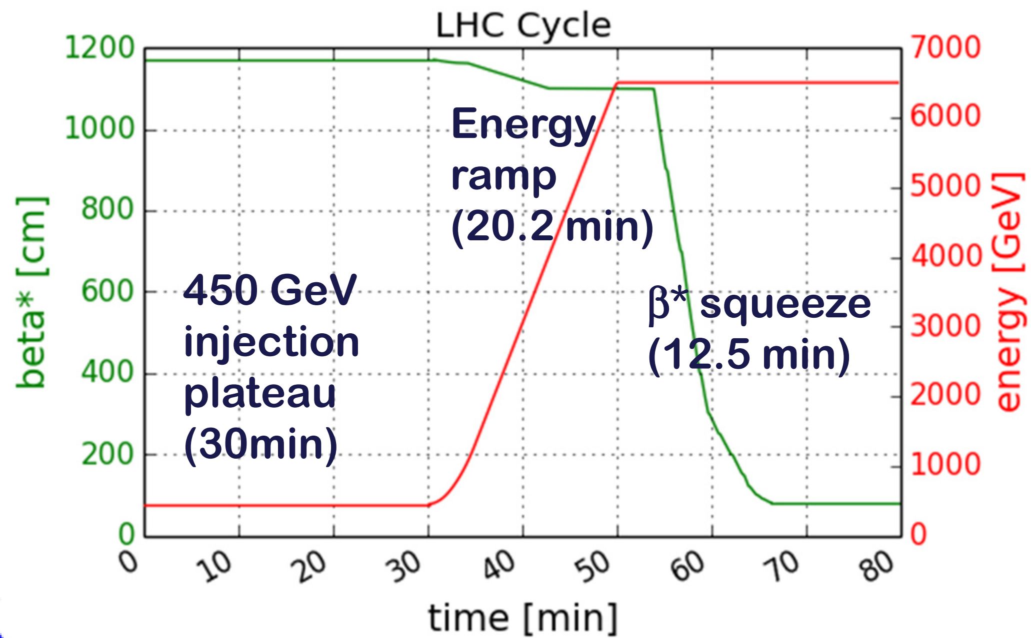
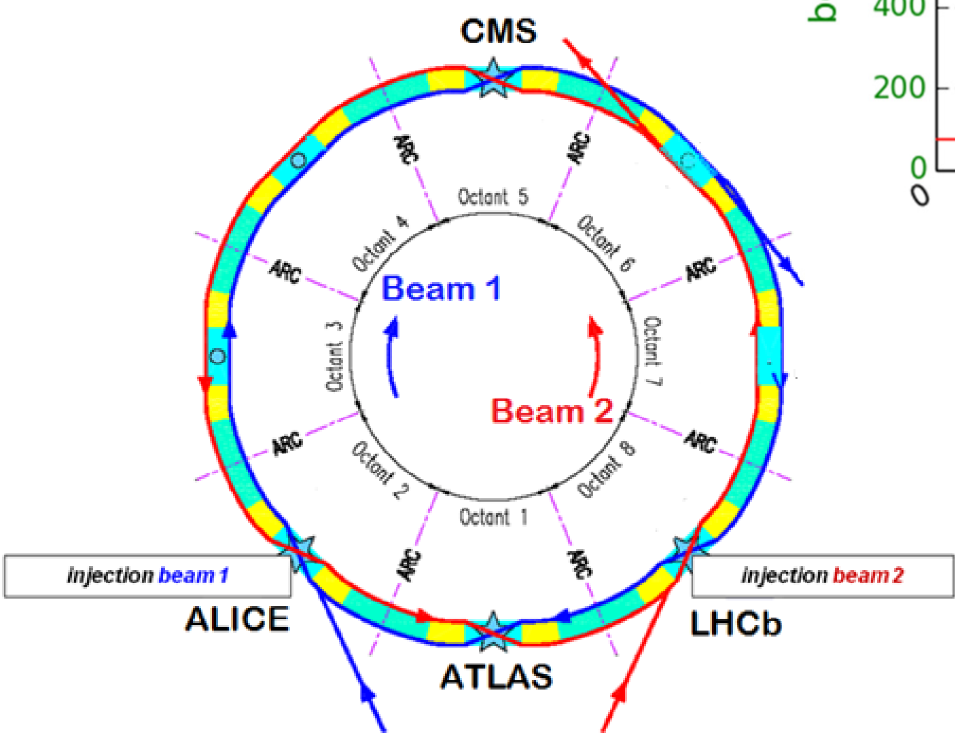
Introduction: LHC Cycle and Beam Parameters

- Injection
- Ramp
- Squeeze
- Collisions





- Two circulating beams.
  - Beam 1 rotating clockwise, beam 2 counter-clockwise.
- Collisions in four interaction points in the LHC.
  - ATLAS and CMS are the two large multi purpose detectors.

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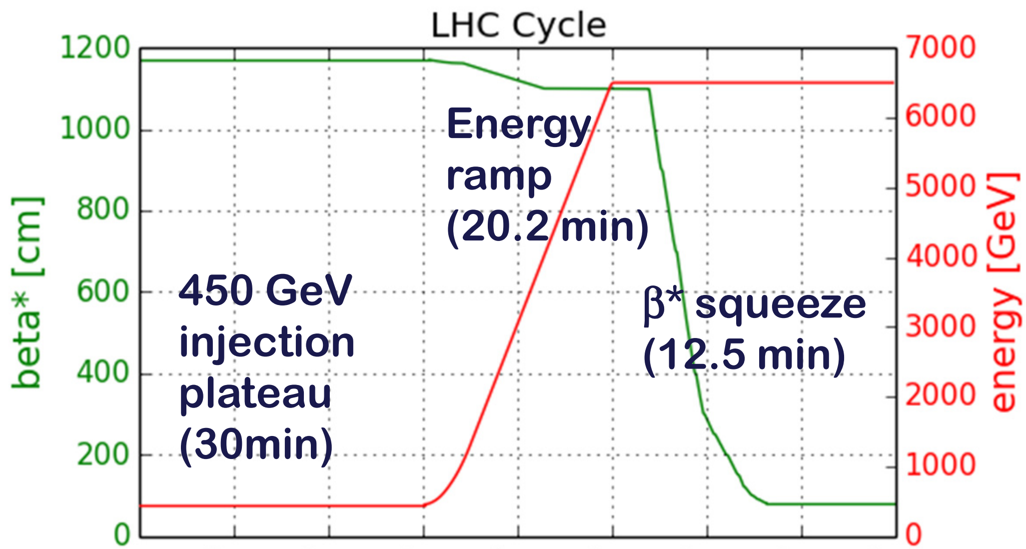
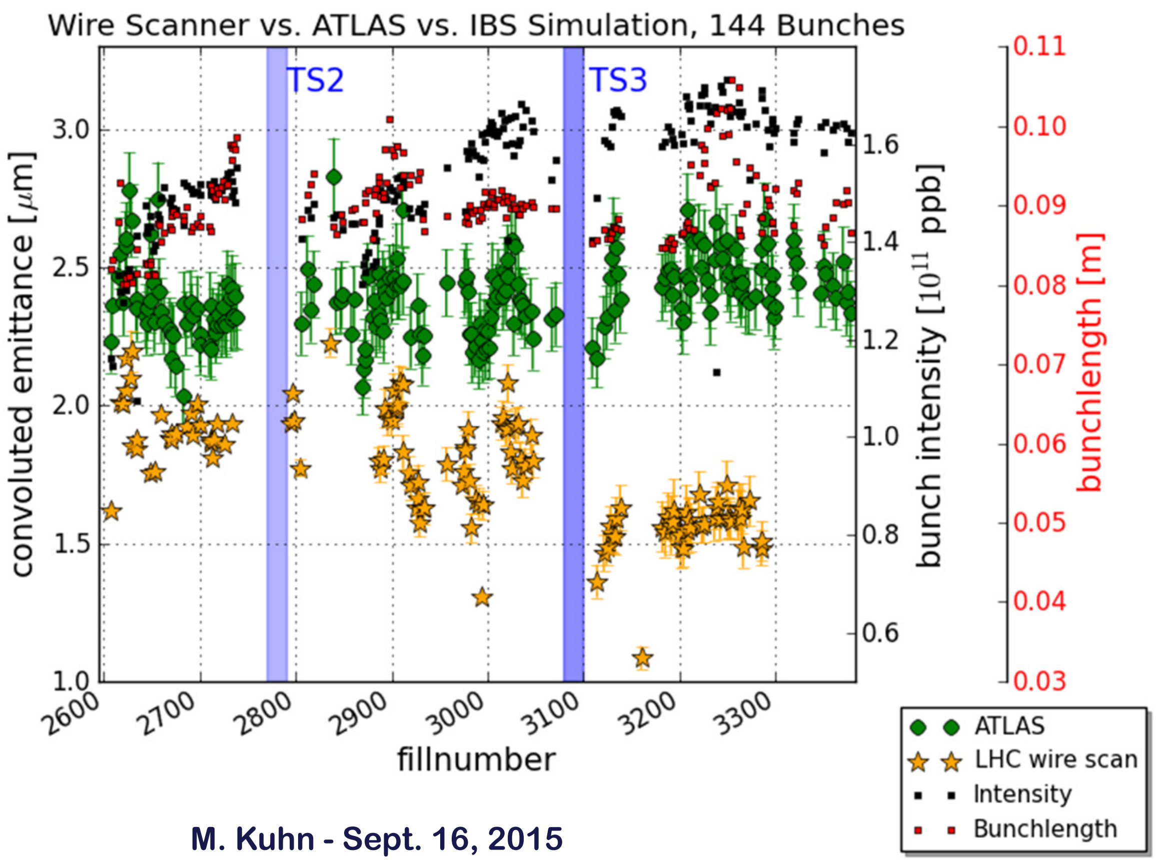


Proton beam parameters	LHC Design	2012 LHC	Early 2015 LHC
# bunches/ beam	2808	1374	3 - 458
Bunch spacing [ns]	25	50	25 and 50
Mean bunch length [ns]	1.3	1.2	1.2
Bunch intensity [10^{11} p]	1.15	1.1 - 1.7	1.0 – 1.2
Emittance at injection [μm]	3.5	1.5 – 2.0	1.5 – 3.0
Collision energy/beam [TeV]	7	4	6.5
Emittance at collision [μm]	3.75	2.4	1.5 – 4.0
β* at ATLAS/CMS [m]	0.55	0.6	0.8

Reminder: 2012 Emittance Blow-up

- In 2012 LHC was operated with high brightness beams.
  - Transverse emittance could not be preserved during the LHC cycle.
  - ~ 0.4 – 0.9 μm normalized emittance growth from LHC injection to start of collisions.
  - But emittance measurement precision during LHC Run 1 doubtful.

2012 LHC performance



LHC Wire Scanner Intensity Limitations

- Several types of beam profile measurement systems in the LHC.
  - The wire scanners are the most precise and versatile instruments.
  - Two operational wire scanners per beam.
    - Horizontal and vertical.
- Wire scanners cannot be used with high intensity physics fills.
  - Synchrotron light telescope (BSRT) is used for that purpose.
- BSRT cross calibrated with wire scanners.
- Currently, wire scanners are the only instrument to measure beam sizes through the LHC energy ramp.
  - Low intensity test fills (a few bunches) are measured to evaluate emittance preservation during the LHC cycle.

Run 2 LHC Wire Scanner Accuracy

- Transverse normalized emittance ε:
  - (For location with no dispersion)

Lorentz factor γ
(beam energy)

Wire scanner beam size σ accuracy

- Wire position measurement precision
  - Estimated position measurement potentiometer precision: 50 µm
- Wire position measurement calibration
  - Verified with beam by orbit bump scans at the wire scanner location

$$\boxed{\varepsilon_{x,y} = \gamma \frac{\sigma_{x,y}^{2}}{\beta_{x,y}}}$$

LHC Run 2 optics measured with k-modulation at 450 GeV and turn-by-turn phase advance method at 6.5 TeV.

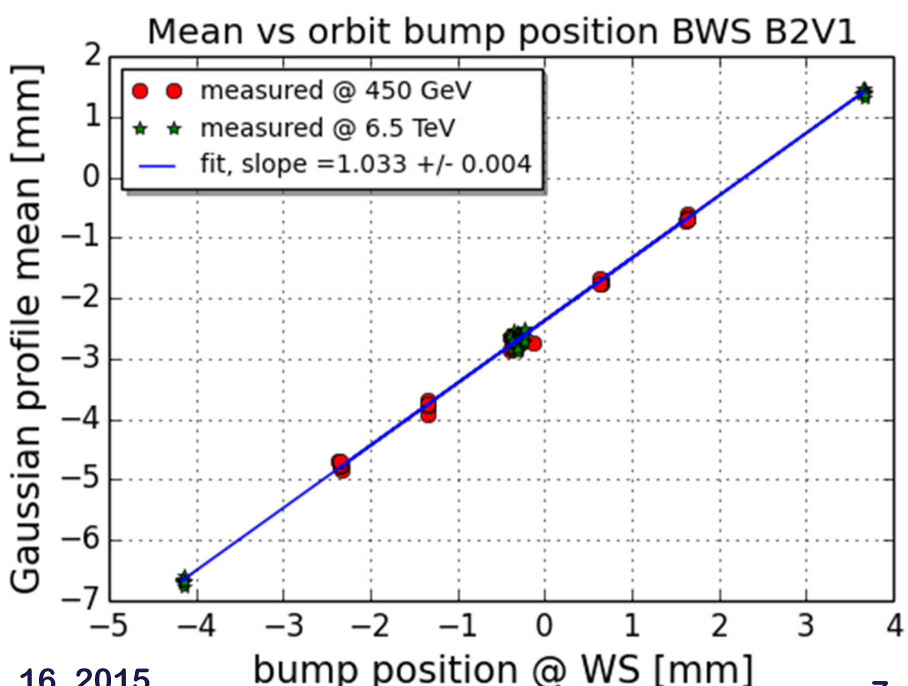
- β function accuracy better than 3 %.

Wire Position Measurement Calibration

- Using local orbit bumps to verify the wire position measurement calibration of the wire scanners.
  - Beam position measured with LHC orbit system and extrapolated to wire scanner.
  - Compared to mean position obtained from Gaussian fit to measured transverse beam profile.
  - Measurements at 450 GeV and 6.5 TeV are consistent.

Example B2V1: slope of linear fit shows + 3.3 % calibration error.

➔ Overestimating B2V emittances by 6.6 %.



Wire Scanner Emittance Measurement Errors

- Wire scanner position calibration verification results ($\Delta\varepsilon_{calibration}$):
  - Another set of orbit bumps foreseen for the near future to check reproducibility of obtained results.
  - The results in this talk do not include a correction of the calibration.
- All wire scanner measurements show large σ spread from scan to scan ($\Delta\varepsilon_{450GeV}$ and $\Delta\varepsilon_{6.5TeV}$).
  - Depending on scanner and energy.

Wire Scanner	$\Delta\varepsilon_{calibration}$ [%]	$\Delta\varepsilon_{450GeV}$ [%]	$\Delta\varepsilon_{6.5TeV}$ [%]
B1H2	+ 7.2	25	20
B1V2	- 5.2	20	10
B2H1	+ 9.0	25	15
B2V1	+ 6.6	15	10

Photomultiplier Working Point Investigations

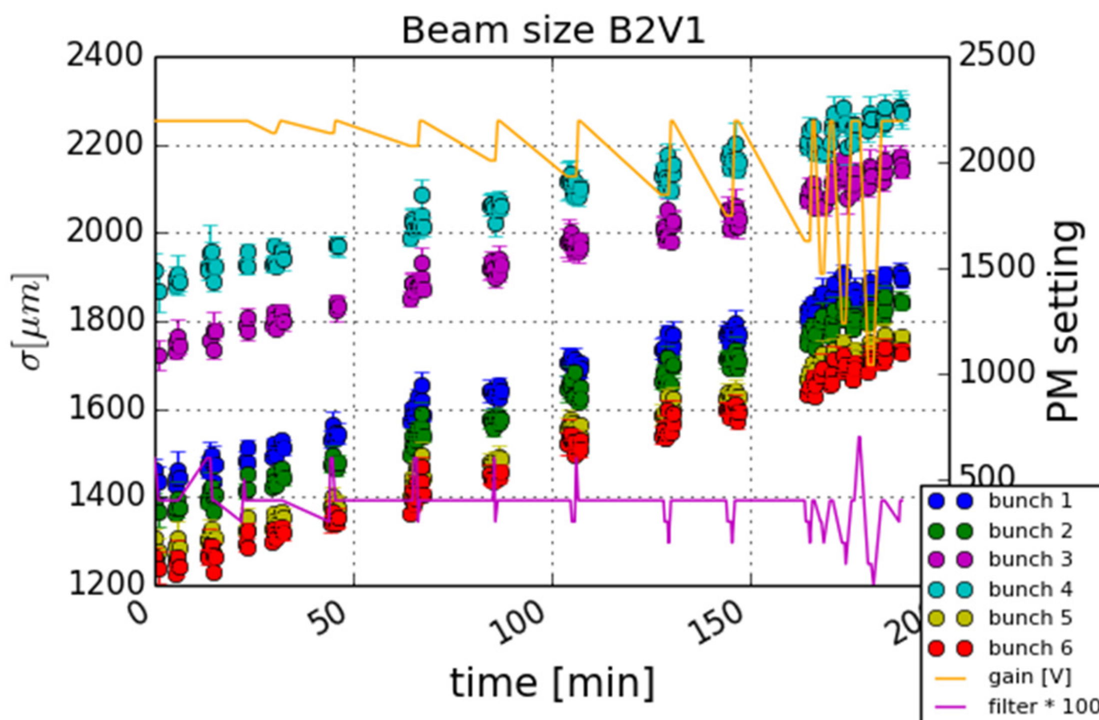
- Wire scanner shower product amplified by photomultiplier (PM).
  - Amplification settings (gain + filter) can alter obtained beam profile.
- LHC Run 1: strong dependence of measured σ on PM settings.
- **Optimum PM working point has to be established!**
  - Scan through all available gain and filter setting combinations.

Bunches with different beam sizes were injected.

To remove natural ε growth, scans with fixed reference settings done after each settings change.

➔ Exponential fit

Example: B2V1 at 450 GeV



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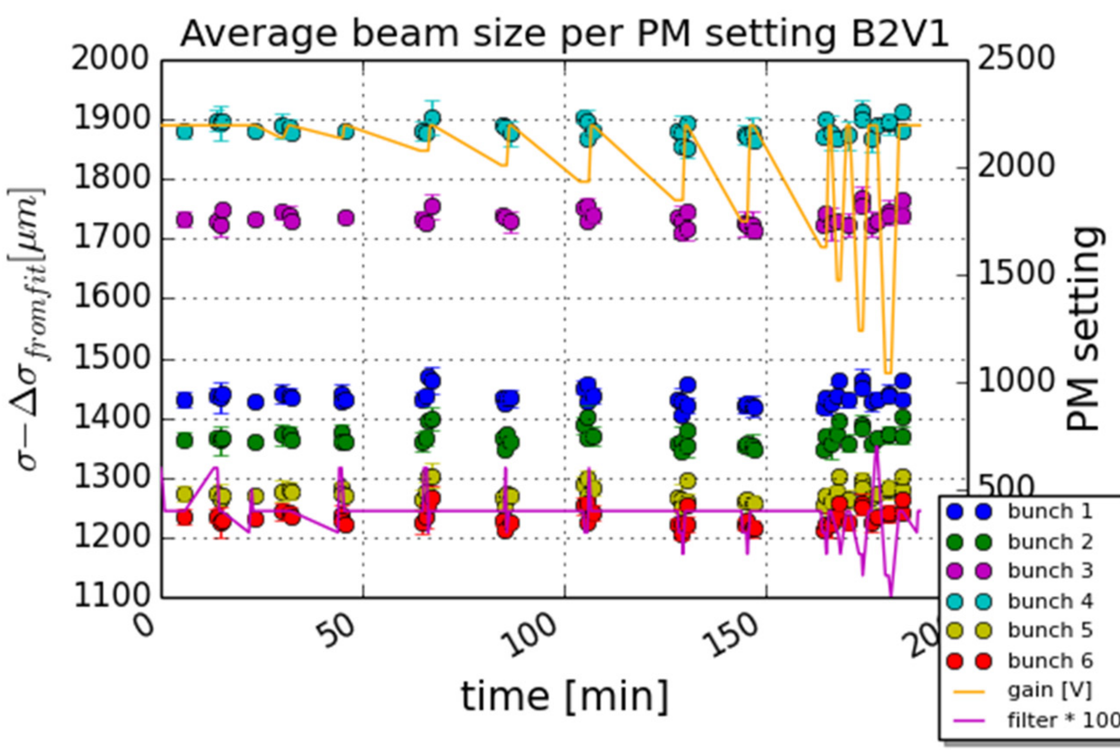
- **Optimum PM working point has to be established!**
  - Scan through all available gain and filter setting combinations.

Measured beam sizes minus the fitted growth.

Measurements with same gain + filter settings are averaged.

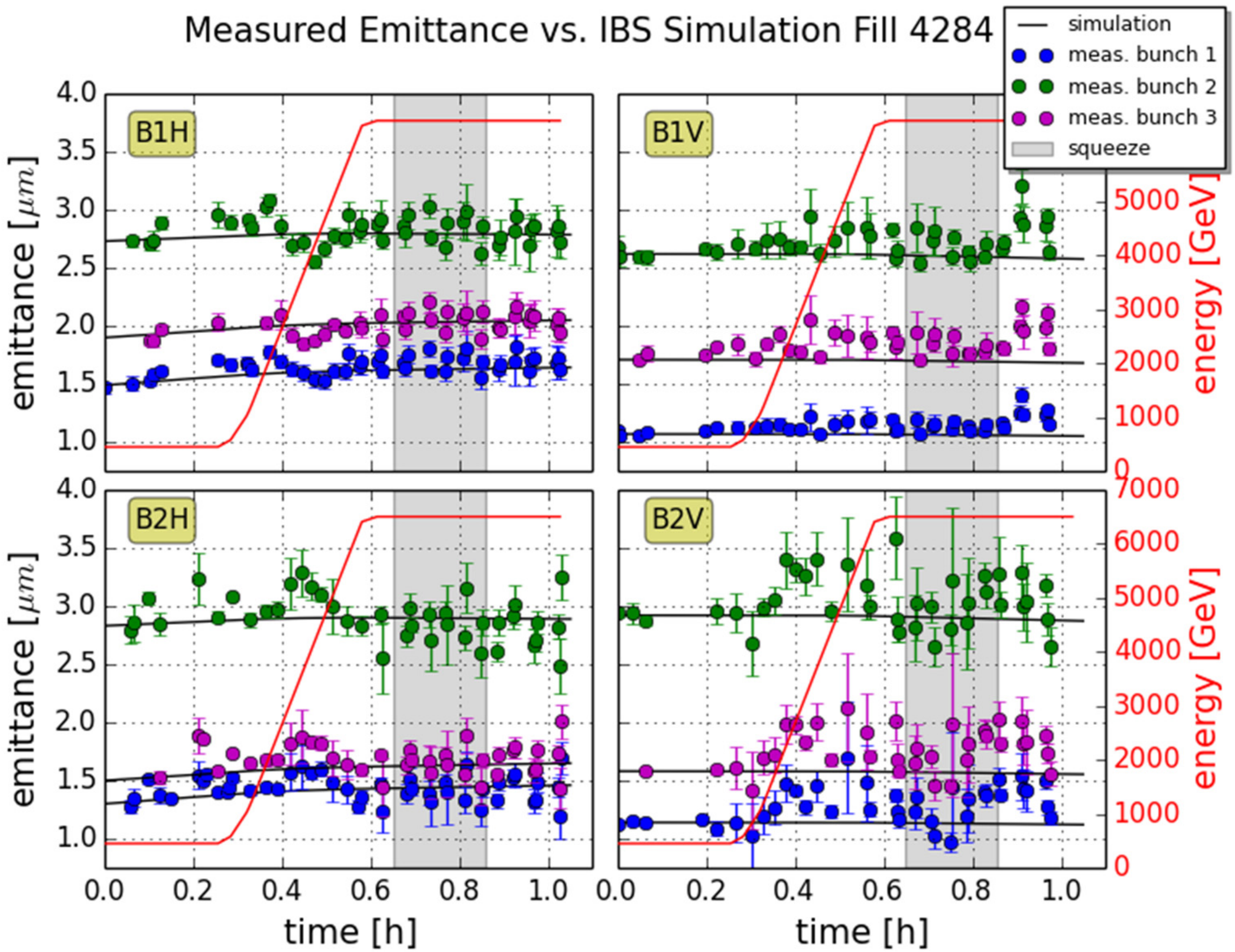
➔ No sign of PM saturation at 450 GeV could be detected.

➔ Same for 6.5 TeV.



First Emittance Measurements (1)

- Example Fill 4284 (August 28, 2015):
  - 3 bunches with different initial emittances, intensities (0.6 – 1.1 x 10^{11} ppb) and bunch lengths (1.0 – 1.25 ns).



IBS simulations with MADX IBS module include measured initial beam parameters, dispersion, and radiation damping.

➔ Measurements in the horizontal planes match IBS simulation.

First Emittance Measurements (2)

- **Example Fill 4284 (August 28, 2015):**
  - 3 bunches with different initial emittances, intensities (0.6 – 1.1 x 10^{11} ppb) and bunch lengths (1.0 – 1.25 ns).

IBS simulations with MADX IBS module include measured initial beam parameters, dispersion, and radiation damping.

→ Measurements in the horizontal planes match IBS simulation.

Emittance growth through the cycle of bunch 3

	ε_{450GeV} [μm]	$\varepsilon_{6.5TeV}$ [μm]	$\Delta\varepsilon$ [%]	$\Delta\varepsilon_{sim}$ [%]
B1H	1.90	2.08	9	8
B1V	1.71	2.04	19	-2
B2H	1.50	1.65	10	10
B2V	1.58	1.95	23	-2

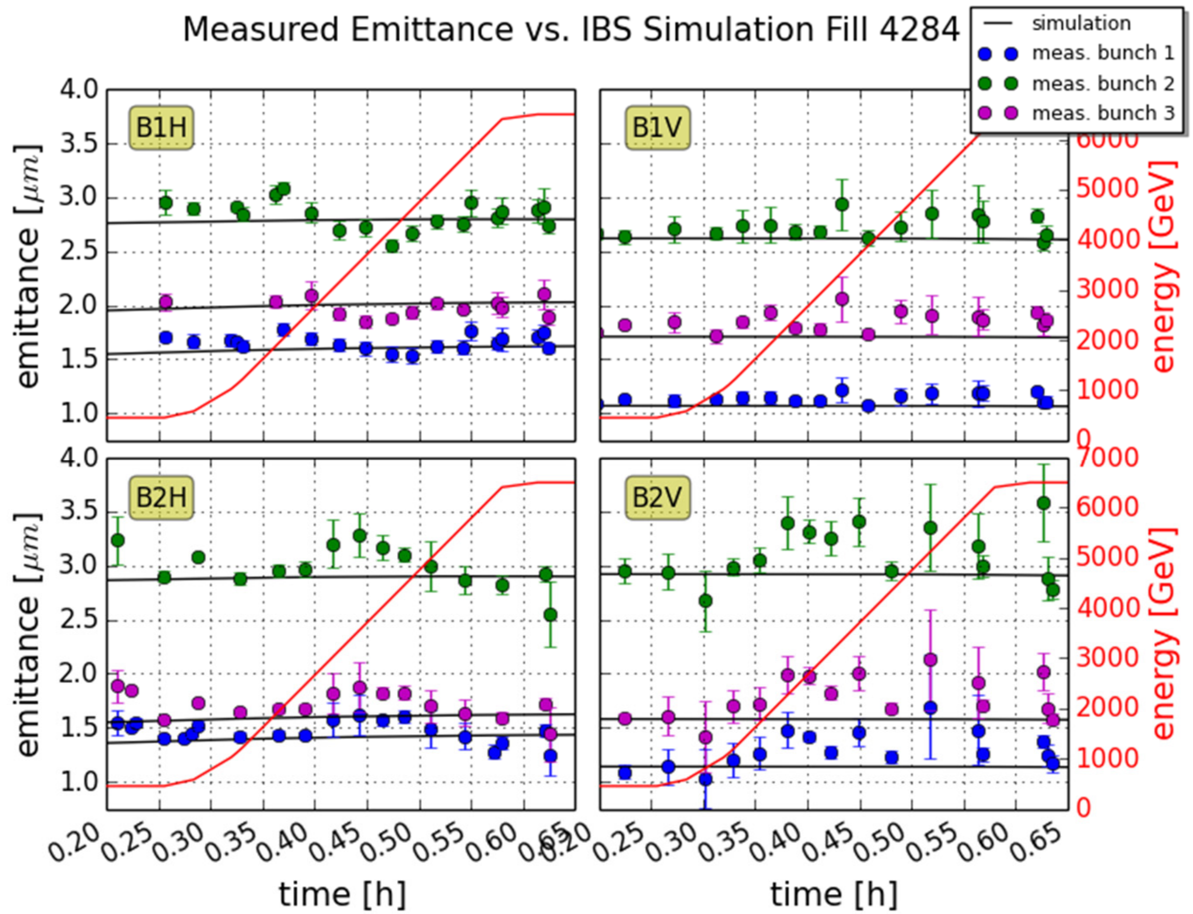
Vertical emittance growth through the cycle could not be reproduced with IBS simulations.

Emittance Growth during the LHC Ramp

- o **Measured β during ramp not yet available.**
  - – **Using linear interpolation of measured β at injection + flattop.**
- o **Current β knowledge results in unphysically growing/shrinking ε.**
  - – **Run 1 experience: non-monotonically changing β functions during the ramp.**

Measurements in the horizontal planes consistent with IBS simulations during the ramp.

Beam 2 vertical emittances grow 20 % (~ 0.3 μm).

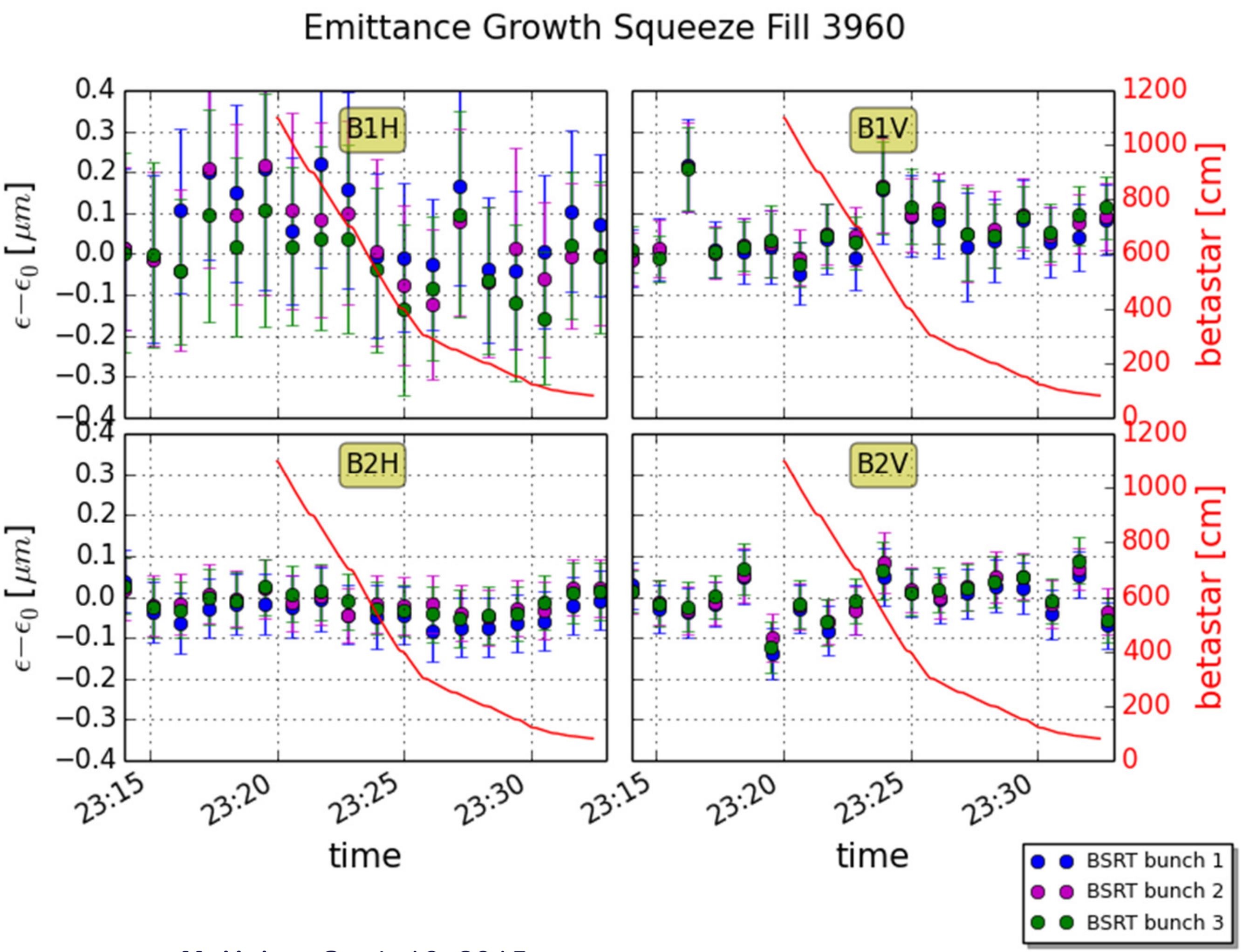


Emittance Preservation during the Squeeze

- Within measurement accuracy emittances are conserved during the β* squeeze.
  - Result is reproducible.

Emittances measured with BSRT and averaged over several hundred measurements.

Also need measured β functions during the squeeze.



Emittance at Start of Collisions

- Comparison of emittance from wire scans and luminosity:
  - Fill 3954 (July 4, 2015), one bunch in collision.
  - According to experts ATLAS luminosity low by ~10 % with uncertainty $\pm$10 %.
    - 5 % error on crossing angle
    - $\pm$1 cm error on measured bunch length.
    - β^* measured with k-modulation with 1 % uncertainty.

$$L = \frac{k\, N^2\, f\, \gamma}{4\,\pi\,\beta^*\,\varepsilon} \cdot F$$

L .... Luminosity
k .... # bunches
N .... # protons / bunch
f .... Revolution freq.
F .... Luminosity reduction factor

	Injection	Collision	Growth	
WS ε [μm]	2.51 ± 0.10	2.75 ± 0.20	0.24	10 %
ATLAS ε [μm]	n.a.	2.97 ± 0.36	0.46	19 %

- Preliminary: ATLAS and wire scanner results agree within errors.
  - Better than during Run 1.

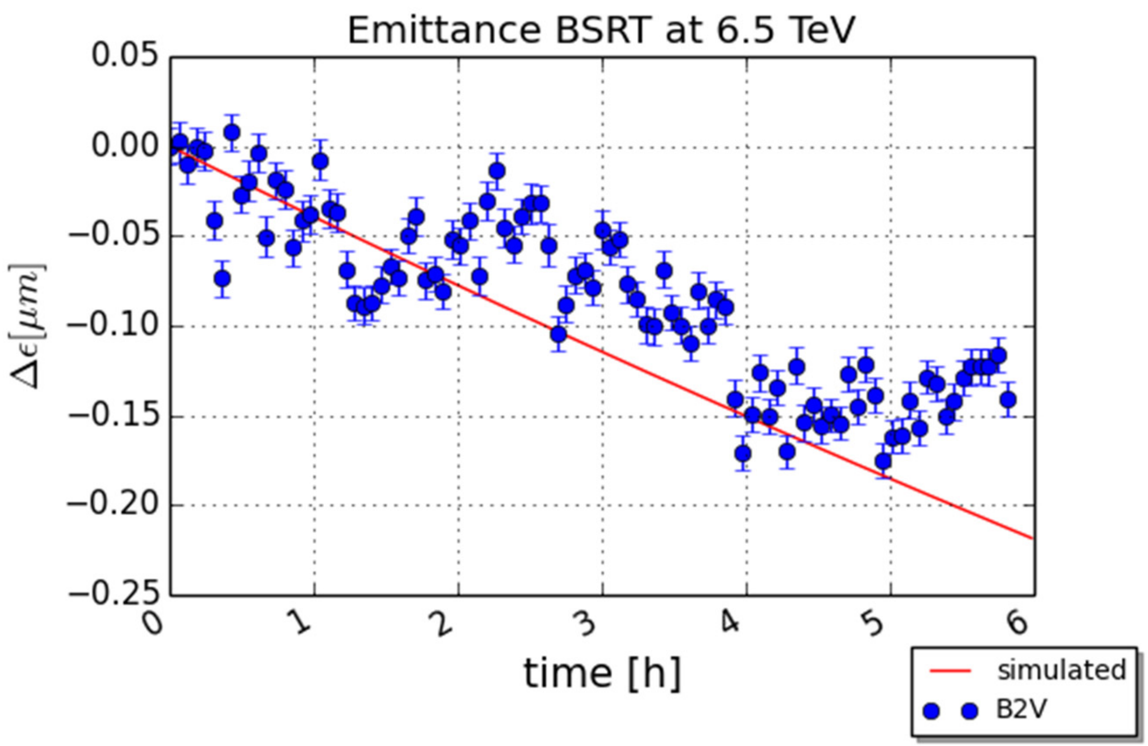
Radiation Damping at 6.5 TeV

- At high energies protons circulating in the LHC emit enough synchrotron radiation to modify the beam parameters
  - First observed during LHC Run 2
  - Counteracts IBS: reduction of vertical emittance

Simulations with MADX IBS module.

➔ Simulation predicts slightly faster emittance decrease than measured with BSRT.

➔ Additional emittance growth from proton collisions + beam–beam effects not included in the simulation.

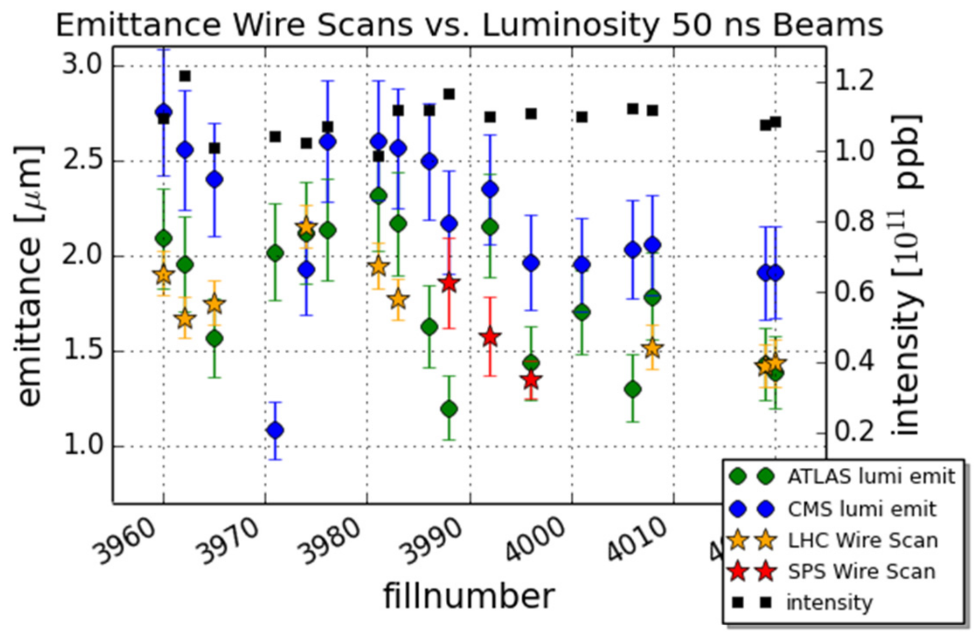


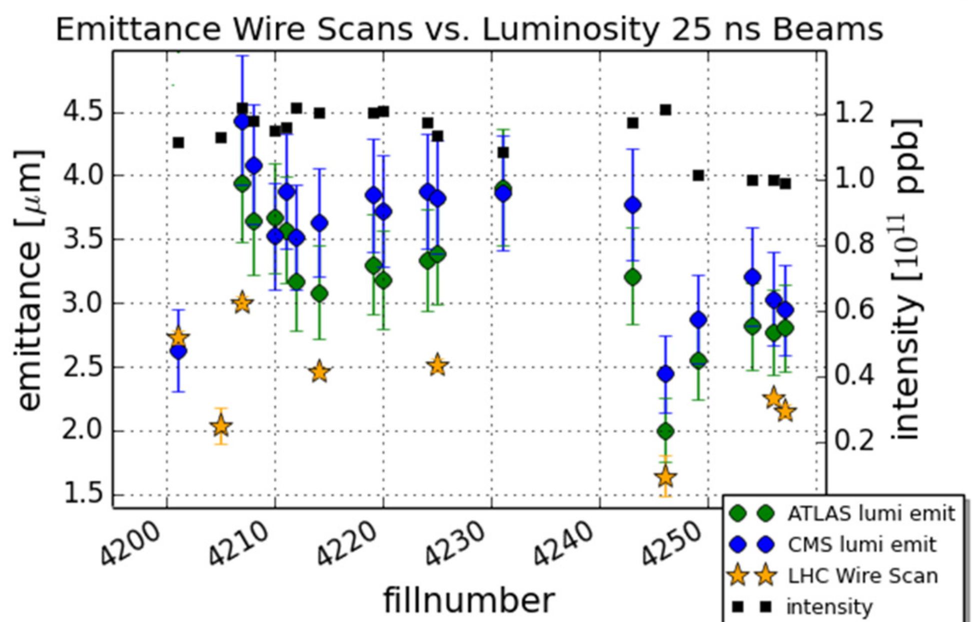
Current Performance of the LHC

- Emittance in collisions derived from luminosity.
- Injection emittance of first batch measured with SPS and LHC wire scanners.

Emittance blow-up through the cycle:

- 50 ns beams show very little blow-up (~ 10 %), much smaller than during Run 1.
- Large blow-up for 25 ns beams (25 % for most recent fills).
  - Electron cloud effects
  - Beam instabilities





Summary & Conclusion

- Good progress in understanding wire scanner emittance measurements for LHC Run 2.
  - Wire scanner calibration verified, no PM saturation effects detected.

Emittance growth during the LHC cycle:

  - Horizontal emittance growth matches IBS simulations.
  - Small growth in the vertical planes not yet understood.
    - Caveat: single bunch fills.
  - Synchrotron radiation damping observed for the first time at 6.5 TeV.
  - With still not fully calibrated luminosity data: emittances from wire scans and ATLAS luminosity agree within errors.

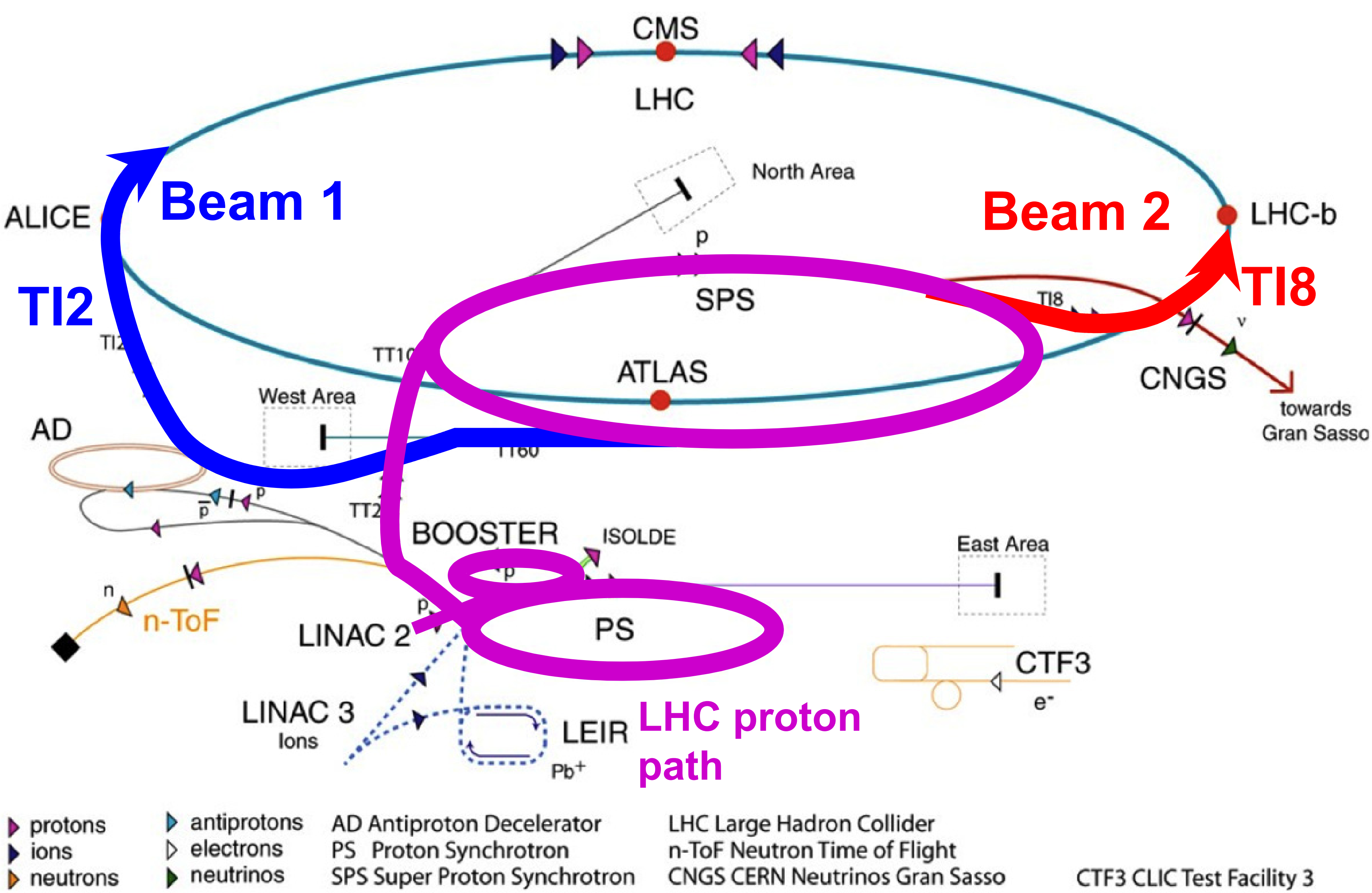
- Smaller emittance blow-up (~ 10 %) through the cycle than during Run 1 for 50 ns beams.
- 25 ns physics beams show much larger growth.
  - Electron cloud effects and beam instabilities.

APPENDIX

Outline

- LHC cycle and beam parameters
  - LHC Run 1 transverse normalized emittance blow-up
- LHC wire scanner intensity limitations
- Run 2 LHC wire scanner accuracy
  - Wire position measurement calibration
  - Photomultiplier working point investigations
- First transverse normalized emittance measurements
  - Emittance growth during the LHC ramp
  - Emittance preservation during the squeeze
  - Emittance at start of collisions
  - Radiation damping at 6.5 TeV
- Current performance of the LHC

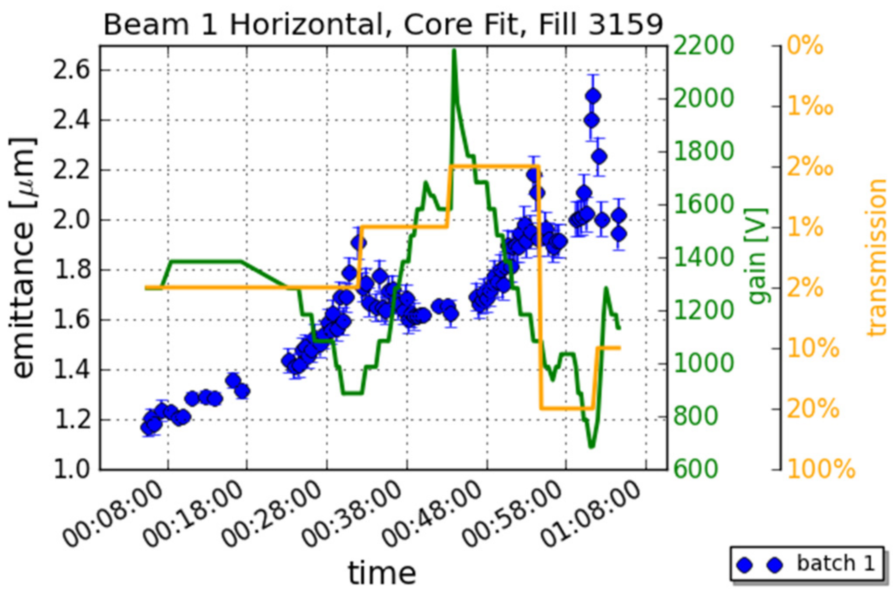
CERN Accelerator Complex



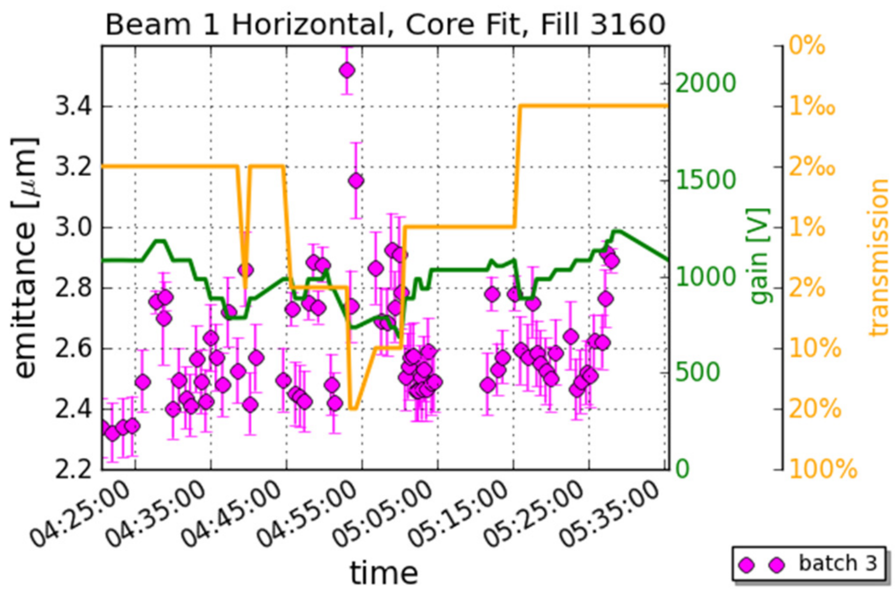
Photomultiplier Saturation Studies Run 1

- Photomultiplier (PM) gain and filter can have a strong influence on measured beam size
  - See measurements of 2012

Observed strong gain dependence at 450 GeV and 4 TeV during Run 1!



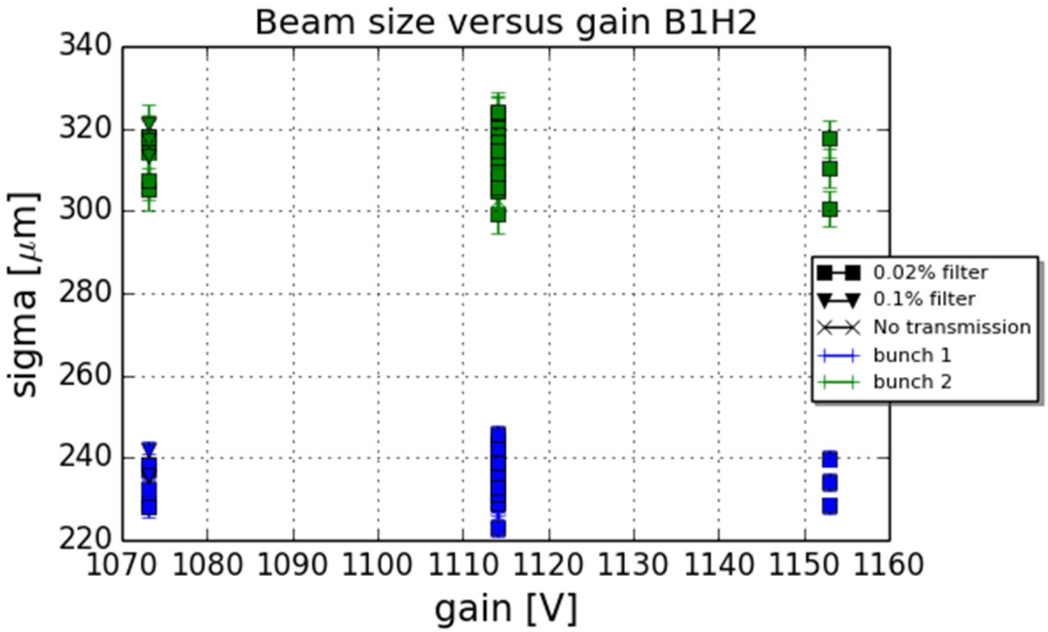
PM saturation studies at 450 GeV in 2012.



PM saturation studies at 4 TeV in 2012.

Photomultiplier Working Point at 6.5 TeV

- Measurements at 6.5 TeV more difficult.
  - Smaller range of possible PM settings before ADC saturation.
- No evident sign of PM saturation at 6.5 TeV could be seen.



- Run 1 investigations showed significant dependency of measured beam size on PM settings.

➔ LHC wire scanner upgrade during Long Shutdown 1:
  - One broken wire scanner replaced (beam 2).
  - Power supply schematics upgraded.
  - PM gain dependency on light intensity reduced.

LHC Optics Measurements

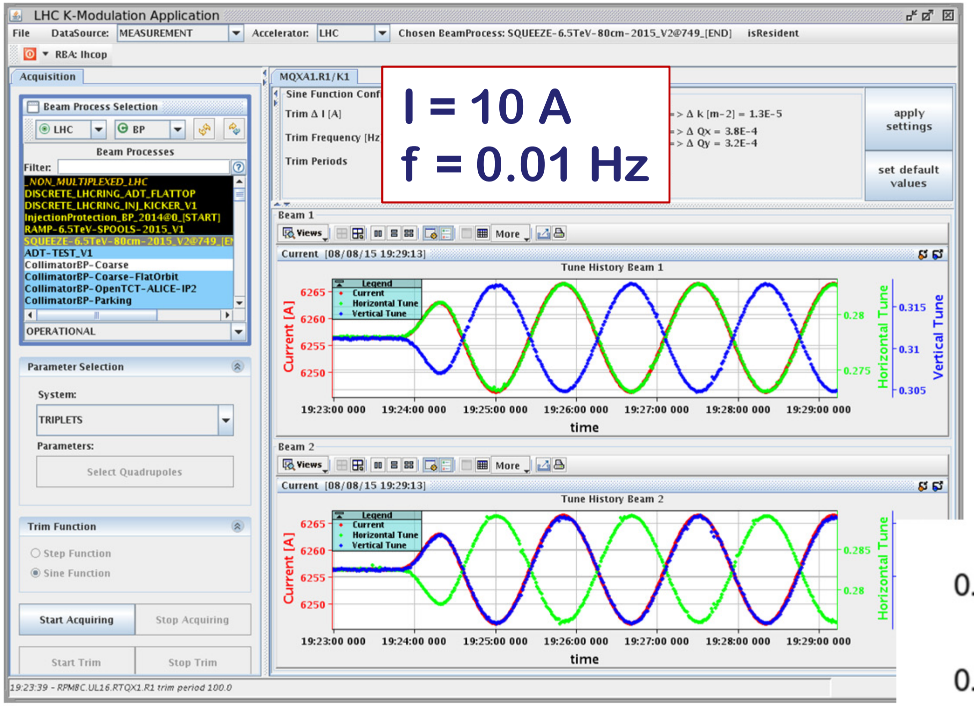
- Can use results from optics measurements with the turn-by-turn phase advance method and k-modulation for:

	IR4				IP1/2/5/8
	Injection	Ramp	Flattop	After Squeeze	β*
K-modulation	x				x
Turn-by-turn			x	x	

- Outstanding measurements:
  - K-modulation at 6.5 TeV and after the squeeze
  - Turn-by-turn phase advance measurements at 450 GeV (repeated) and during the ramp!
- For emittance plots: using measured β where possible
  - β function measurement error < 3 %
  - Maximum measured beta beat is 5 % at the wire scanners
  - Linear interpolation during the ramp and squeeze

β* Measurements

- Sinusoidal k-modulation in IP1/5 on August 8, 2015



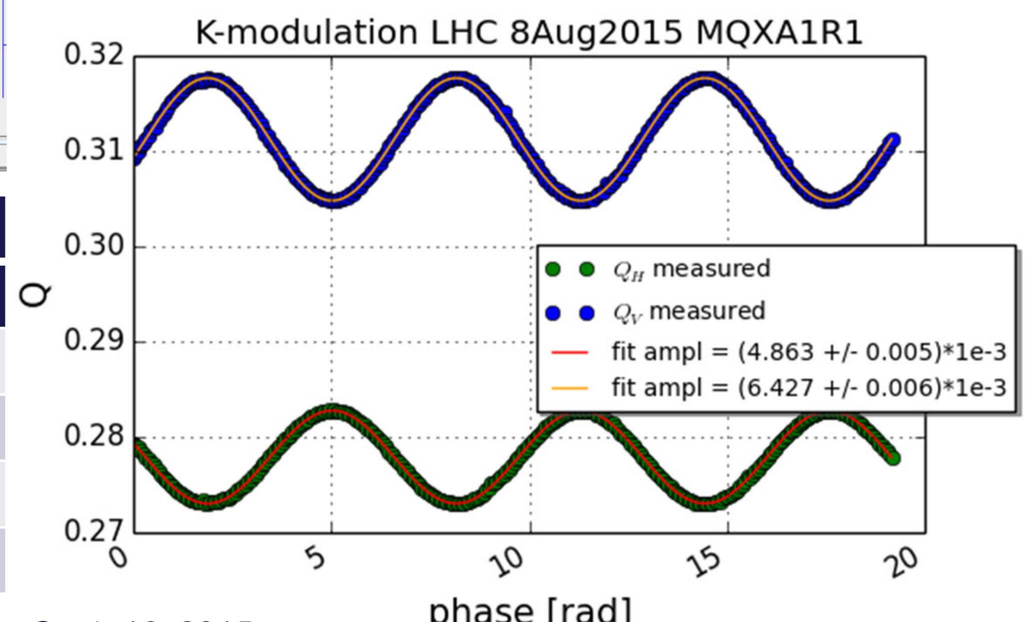
Measurement error on tune oscillation amplitude in sub-percent level

➔ β* meas. uncertainty ≤ 1 %

➔ Beta beat ≤ 1 %

➔ Compatible with turn-by-turn measurements

Preliminary!	IP1 [m]		IP5 [m]	
	B1	B2	B1	B2
β* H	0.81	0.79	0.80	0.80
ΔβH	0.01	0.004	0.001	0.01
β* V	0.81	0.79	0.79	0.79
ΔβV	0.01	0.01	0.01	0.002



Bunch Length Measurement

- Longitudinal bunch shape not Gaussian at 6.5 TeV
  - Due to controlled longitudinal RF blow-up at flattop energy
- But LHC bunch length monitor publishes 4σ bunch length values based on FWHM algorithm assuming Gaussian profiles

➔ **Bunch length error ±1 cm!**

➔ "True" emittance from luminosity should be larger by 0.1 μm