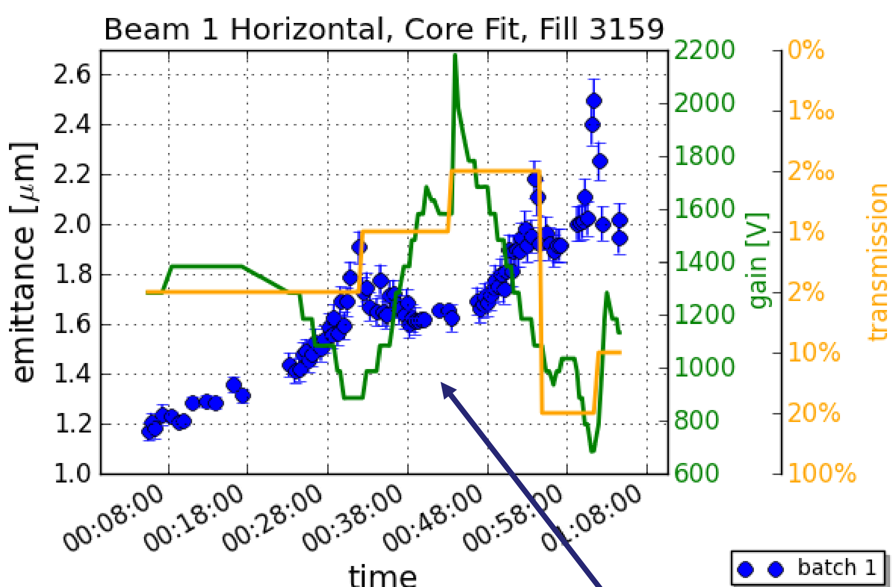
LHC Emittance Growth until Stable Beams

Maria Kuhn – 15 December 2015

Many thanks to V. Kain, G. Baud, E. Bravin, B. Dehning, J. Emery, M. Hostettler, E. Piselli, G. Trad.

Emittance Measurements Run 1

- Situation in 2012:
  - BSRT not available for second half of 2012.
  - Wire scanner: beam size strongly dependent on gain and filter of photomultiplier (PM).
  - Emittance from luminosity not consistent with emittance from wire scanners.



Wire scanner ε dependent on PM gain and filter

Example: ε from luminosity

Fill 3217	$\varepsilon_{conv,4\,TeV}$ [μm]
Wire scanner	1.84 ± 0.06
ATLAS	2.33 ± 0.12
CMS	2.63 ± 0.14

Beam Size Measurement 2015

- For BSRT upgrade see "Beam Profile Measurements", G. Trad, 16 December 2015, this workshop.
- Optics changes in IR4: same beam sizes at 6.5 TeV as in Run 1 at 4 TeV.
- Wire scanner upgrade:
  - Replaced broken photomultiplier of beam 2.
  - Upgraded power supply schematics.
  - Reduced photomultiplier gain dependency on light intensity.

➔ Beam size independent of wire scanner setting, no PM saturation!

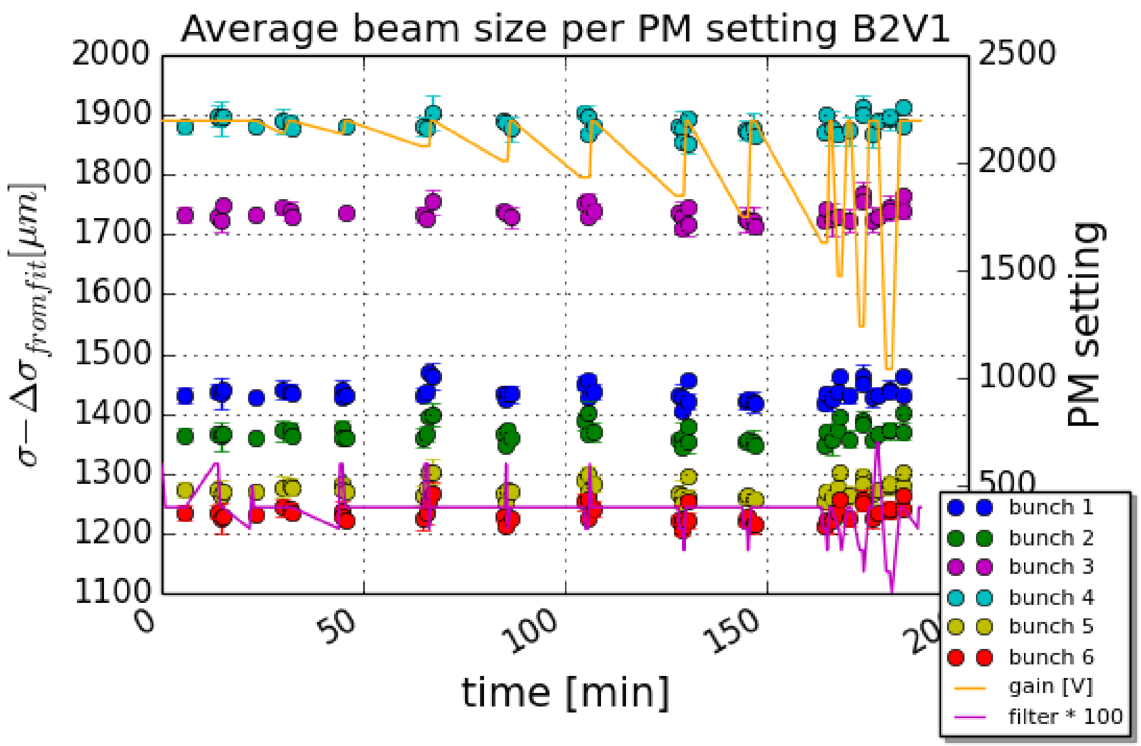
➔ Emittance from luminosity consistent with BSRT and wire scanners.

➔ Emittance can be measured with accuracy better than 10 %.

Fill 4585	$\varepsilon_{conv,6.5\,TeV}$ [μm]
Wire scan	2.12 ± 0.27
ATLAS	2.06 ± 0.28
CMS	2.33 ± 0.32
BSRT	2.32 ± 0.33

Example: PM Working Point Study

- Scan of beam size versus gain and filter setting @ 450 GeV.
- Measured beam size minus fitted growth from reference settings:



➔ **Beam size independent of PM settings. No sign of PM saturation.**

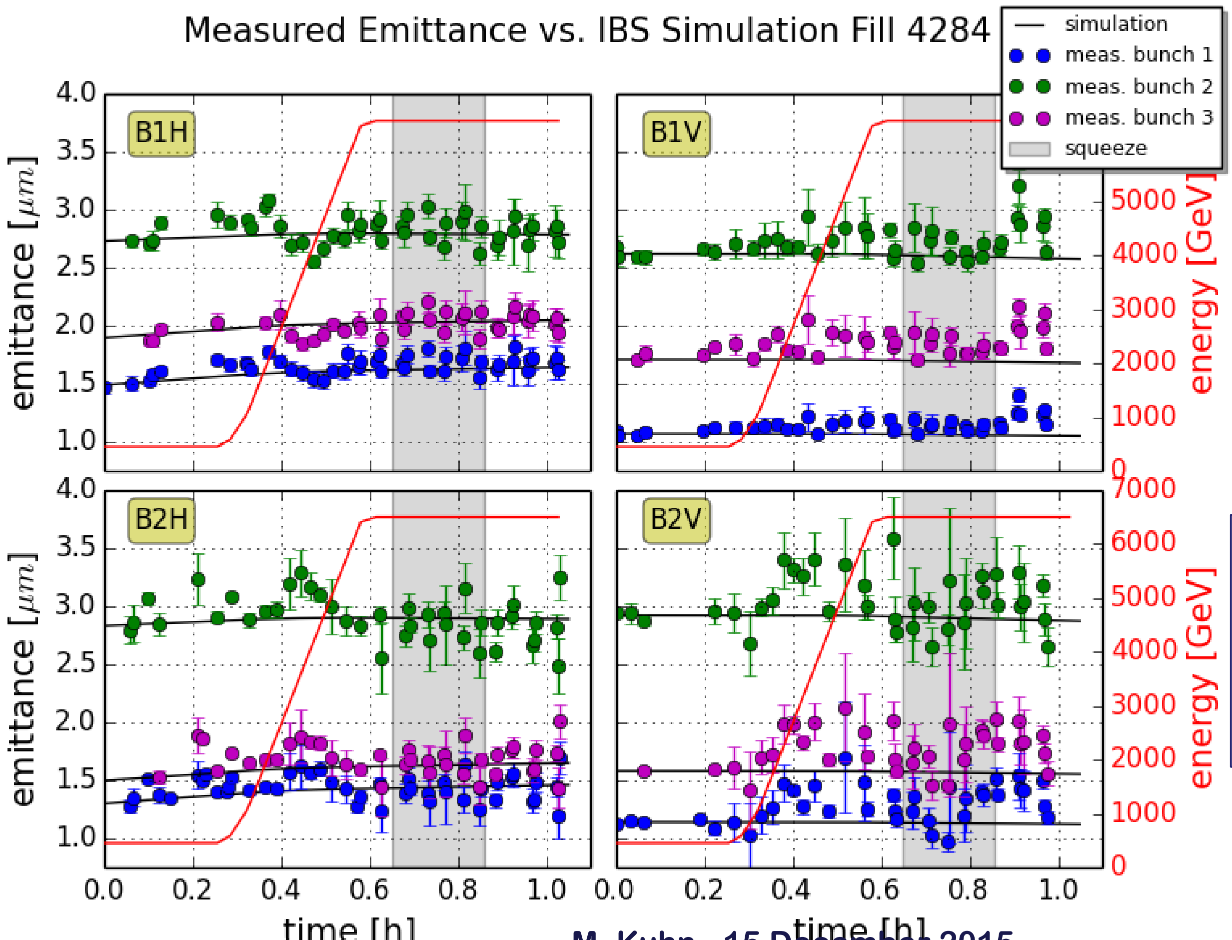
Emittance Preservation 2015: Overview

- Intra beam scattering (IBS) in horizontal planes.
  - Low ε growth due to reduced brightness 2015.
- 50 ns beams show very little ε blow-up, much smaller than during Run 1.
  - Average convoluted emittance blow-up: 10 %
- Large ε blow-up for 25 ns beams possibly due to electron cloud effects and beam instabilities.
  - Average convoluted emittance blow-up: 25 %
- Strong ε growth in the vertical planes for many test fills.
  - Mainly during injection plateau and beginning of ramp.

Example: Test Fill 4284

3 single bunches: I_b = 0.6 – 1.1 x 10^{11} ppb, bunch length = 1.0 – 1.25 ns

- ➔ IBS matches ε evolution in H.
- ➔ Stronger ε growth in V. However, less than usually.
- ➔ No measured optics during the ramp/squeeze included in analysis.



Wire scanner measurements versus MADX IBS simulations.

B2V very noisy measurement at flattop (use average of several values).

Example: Test Fill 4284 in Numbers

- IBS matches ε evolution in H.
- Stronger ε growth in V.

Emittance growth through the cycle of bunch 3 (purple)

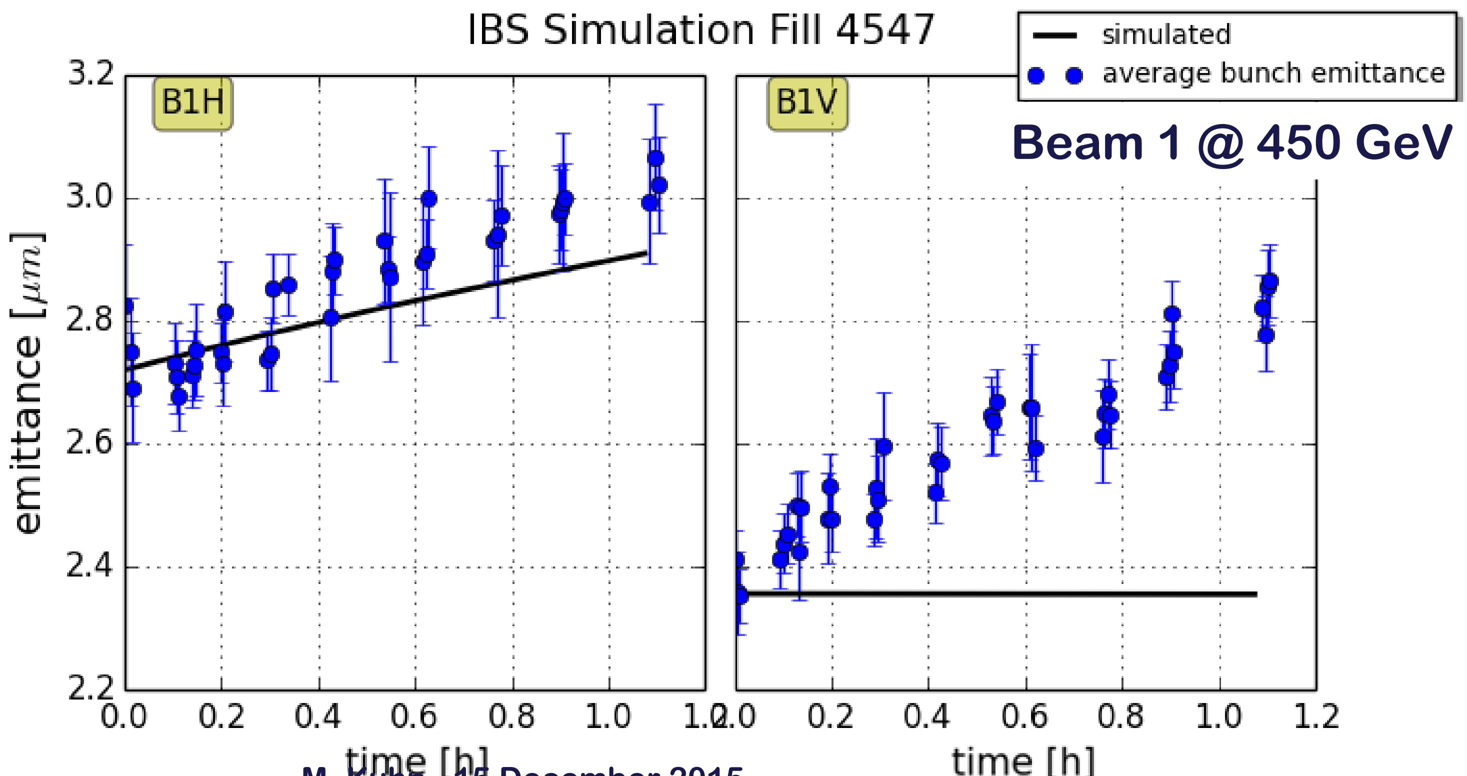
	ε_{450GeV} [μm]	$\varepsilon_{6.5TeV}$ [μm]	$\Delta\varepsilon$ [%]	$\Delta\varepsilon_{sim}$ [%]
B1H	1.90 ± 0.05	2.08 ± 0.12	9 ± 7	8
B1V	1.71 ± 0.04	2.04 ± 0.13	19 ± 8	-2
B2H	1.50 ± 0.10	1.65 ± 0.12	10 ± 10	10
B2V	1.58 ± 0.03	1.95 ± 0.17	23 ± 11	-2

- Vertical emittance growth not consistent with IBS.

Vertical Growth at Injection Plateau

- Typical ε growth: 5 % in 10 minutes in both vertical planes.
- Similar ε growth times with single bunches and 12 bunch trains.
  - Growth goes down with energy.
  - Does not depend on chromaticity/octupole settings (2 ≤ Q' ≤ 15).
  - Does not depend on brightness (for tested parameter range).

Wire scanner measurements versus MADX IBS simulations.



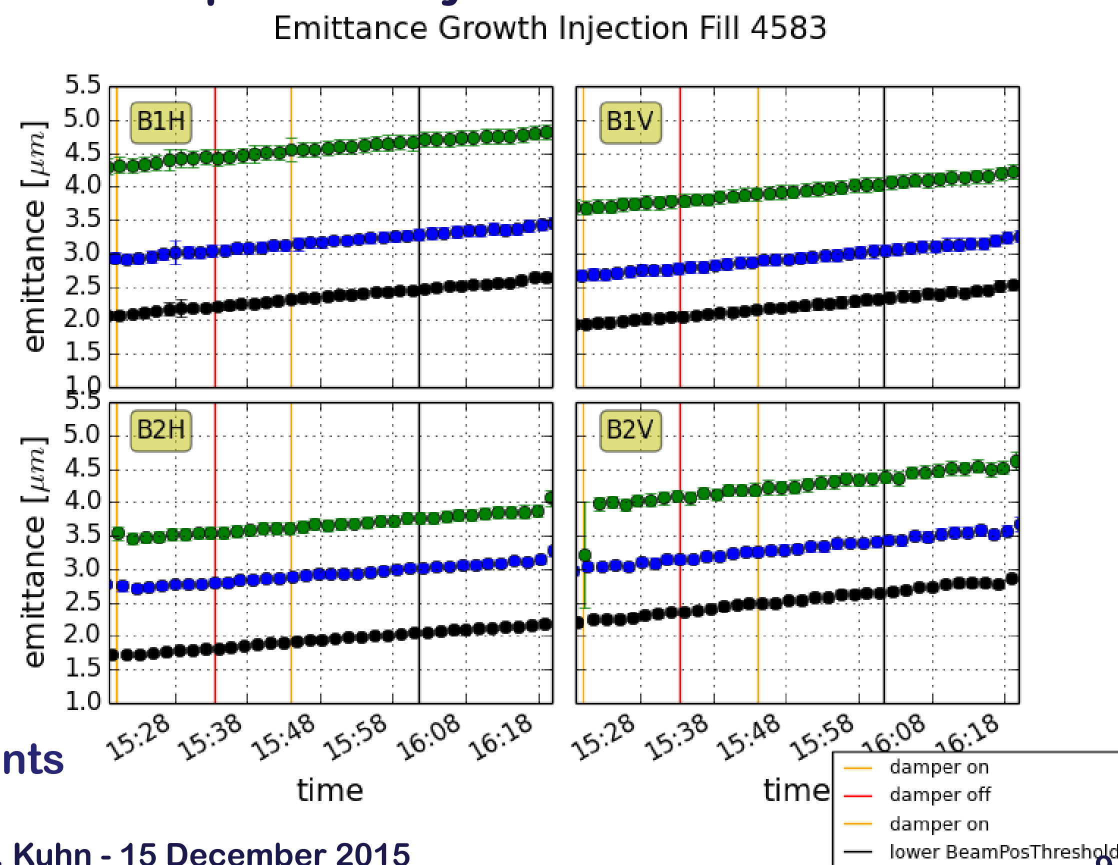
Vertical Growth Induced by Damper?

- Last LHC MD block: tested effect of abort gap cleaning, injection slot cleaning, and transverse damper itself on emittance growth.
  - Single bunches at 450 GeV.

→ Abort gab cleaning: no effect.

→ Injection slot cleaning: blows up close-by bunches in horizontal planes.

→ Transverse damper on/off: no effect on vertical ε blow-up.
  - Damper cannot suppress ε growth, could be incoherent (no BBQ activity).



BSRT measurements

BCMS Beams in the LHC

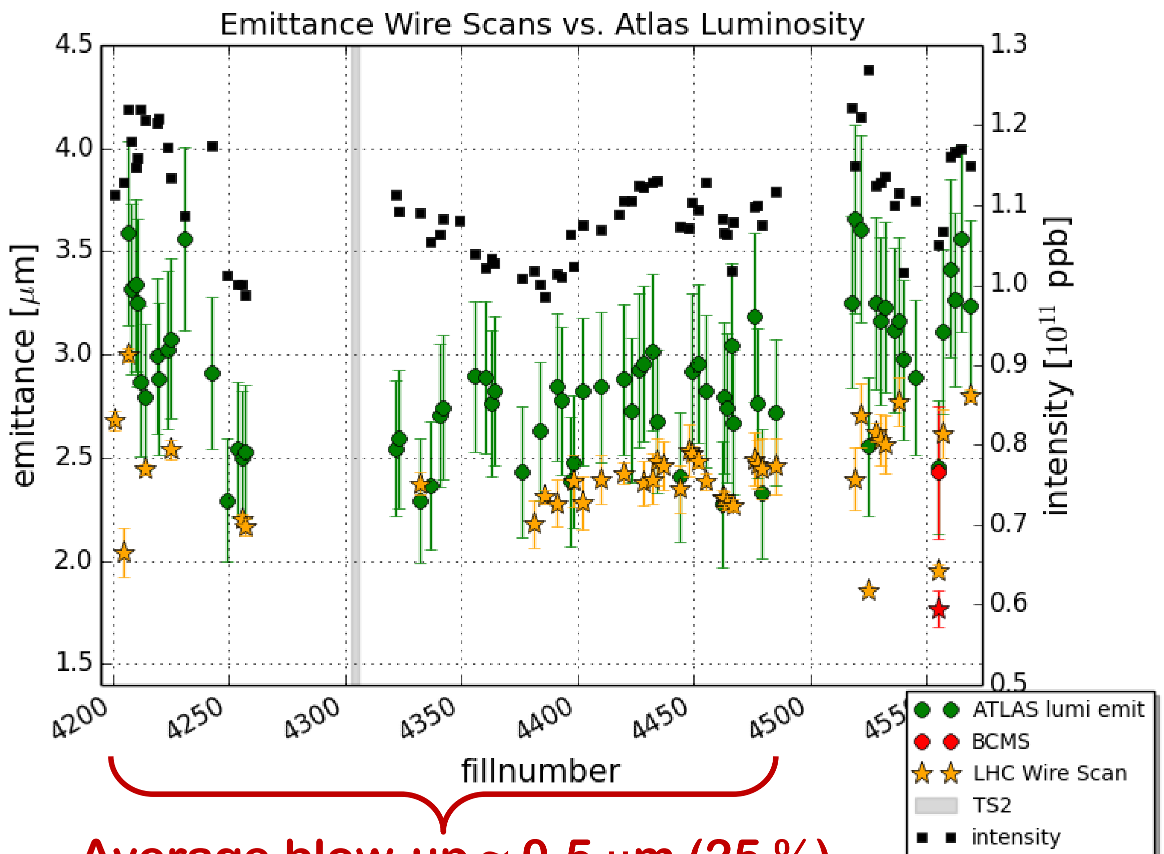
- Tested two 25 ns BCMS fills in the LHC in 2015: low statistics
  - Fill 4555 with nominal bunch intensity: 1.1 x 10^{11}ppb and 589 bunches.
    - Brightness ~ 0.62 x 10^{11}ppb/μm.
  - Fill 4585 with reduced bunch intensity: 0.9 x 10^{11}ppb and 12 bunches.
    - Brightness ~ 0.48 x 10^{11}ppb/μm.

Fill	ε_{450GeV} [μm]	$\varepsilon_{6.5TeV,ATLAS}$ [μm]	$\varepsilon_{6.5TeV,CMS}$ [μm]	$\Delta\varepsilon_{ATLAS}$ [μm]	$\Delta\varepsilon_{CMS}$ [μm]
4555	1.77 ± 0.09	2.43 ± 0.32	2.55 ± 0.35	0.66 (37 %)	0.78 (44 %)
4585	1.89 ± 0.10	2.06 ± 0.28	2.33 ± 0.32	0.17 (9 %)	0.44 (23 %)

- Large emittance growth for Fill 4555.
  - However, many instabilities at injection and start of squeeze.
- Growth for Fill 4585 comparable with standard 25 ns fills.
  - But also similar brightness.

Emittance Blow-up vs Brightness 2015

- 25 ns fills: standard and BCMS
- Comparison of emittance from luminosity and convoluted emittance measured at injection with wire scanners.
  - Errors include measured β*, crossing and 10 % lumi uncertainty.



Average blow-up ~ 0.5 μm (25 %)

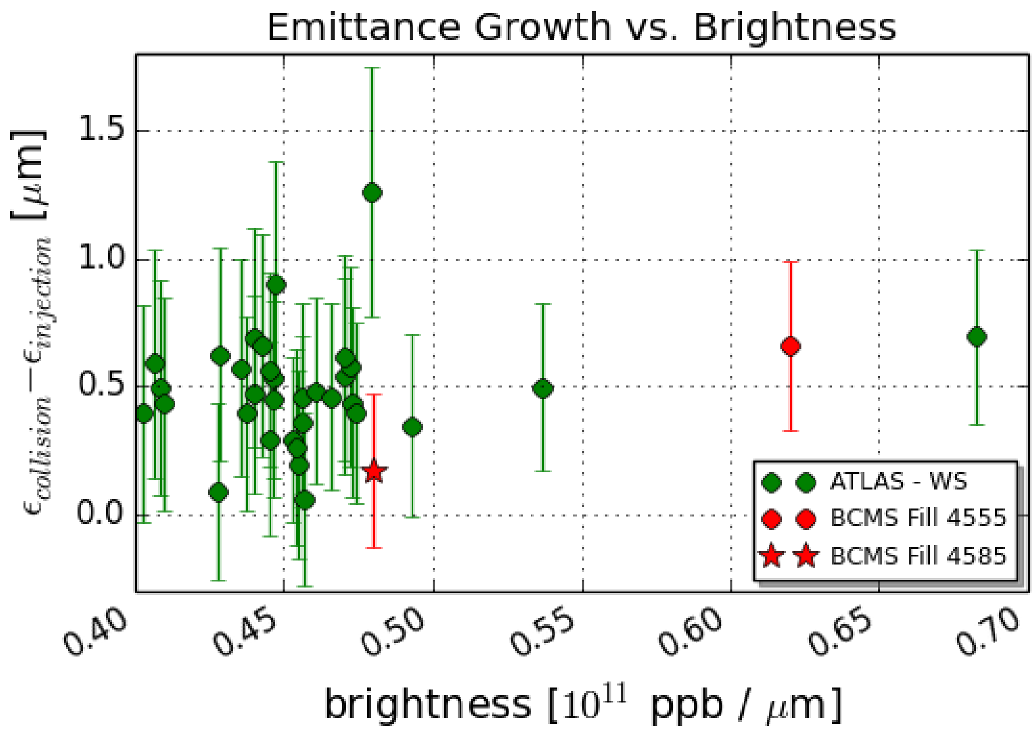
<u>Convoluted ε:</u>

- Collision values from ATLAS luminosity
- Injection values from LHC wire scanners

$$\varepsilon = \frac{1}{2}\sqrt{(\varepsilon_{1x} + \varepsilon_{2x})(\varepsilon_{1y} + \varepsilon_{2y})}$$

Emittance Blow-up vs Brightness 2015

- **25 ns fills: standard and BCMS**
- **Comparison of emittance from luminosity and convoluted emittance measured at injection with wire scanners.**
  - **Errors include measured β*, crossing and 10 % lumi uncertainty.**
- **Only two fills with significantly higher brightness and higher ε blow-up.**
  - **Not enough statistics to conclude whether BCMS/ high brightness lead to more growth like IBS.**



Convoluted ε:

- **Collision values from ATLAS luminosity**
- **Injection values from LHC wire scanners**

$$\varepsilon = \frac{1}{2}\sqrt{(\varepsilon_{1x} + \varepsilon_{2x})(\varepsilon_{1y} + \varepsilon_{2y})}$$

Summary & Conclusion

- LHC beam profile measurement systems in the LHC in much better shape after LS1.
- Emittance can be measured with accuracy better than 10 %.
- IBS well describes ε growth measured in the horizontal planes for low intensity fills.
- Unknown source of ε growth in the vertical planes.
- Overall ε growth through the cycle for 25 ns beams:
  - 25 % on average (~ 0.5 μm).
  - IBS predicts ~ 5 % ε growth (0.1 μm) for 2015 beam parameters.
    - Assuming 15 min average injection plateau length.
- High brightness BCMS fill showed more overall ε blow-up than standard 25 ns.
  - But only data for only one fill.

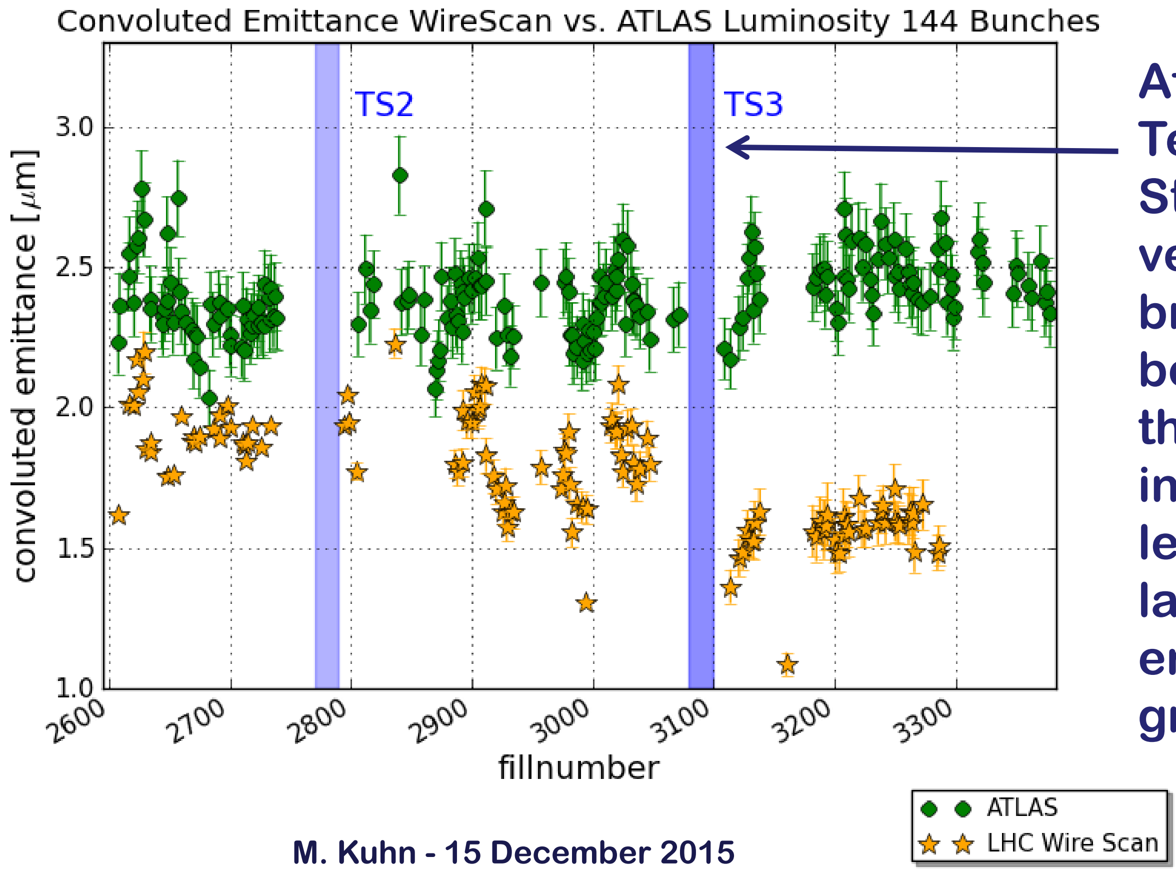
BACK UP

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 for 50 ns physics beams.
  - But emittance measurement precision during LHC Run 1 doubtful.

Convoluted ε:

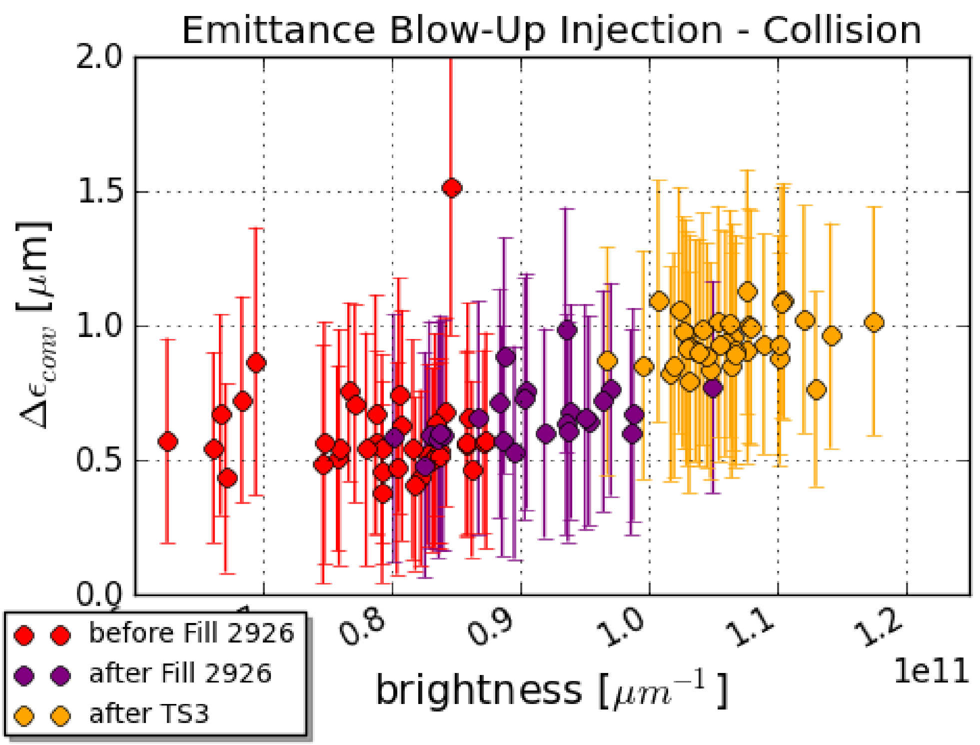
- Collision values from ATLAS bunch luminosity (similar for CMS values)
- Injection values from LHC wire scanners
- Average of first 144 bunch batch



After Technical Stop 3 (TS3): very high brightness beams from the LHC injectors lead to even larger emittance growth!

Emittance Blow-up vs Brightness 2012

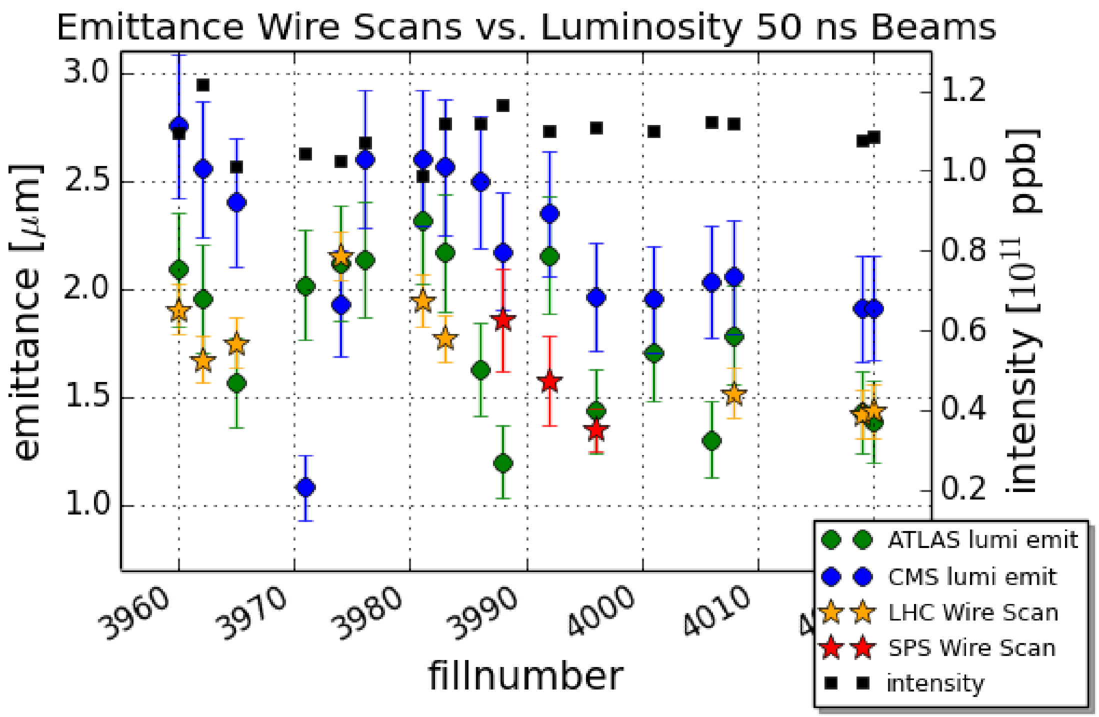
- 50 ns standard fills (only stable bunches)
- Comparison of emittance from luminosity and convoluted emittance measured at injection with wire scanners.
  - Errors include measured β* and crossing angle uncertainty.
- Brightness larger than for the 25 ns standard beams in 2015.
  - Emittance growth brightness dependent.



2015 LHC Performance with 50 ns Beams

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

➔ 50 ns beams show very little ε blow-up through the cycle (~ 10 %), much smaller than during Run 1.



Damping/ Decoherence Times

- Measured damping and decoherence times during MD3
  - With chromaticity 15 and octupoles 20 A

Time/Turns	B1H	B1V	B2H	B2V
decohrence	59	65	105	98
damping	25	21	35	27

G. Kotzian