Impedance model of the LHC: summary of the present understanding of the measurements

X. Buffat, D. Amorim, S. Antipov, N. Biancacci, E. Métral,
N. Mounet, B. Salvant, C. Tambasco

WP2 meeting – 10.03.2020

Content

- List of experimental studies
- Coupled bunch instability rise time
- Single bunch instability rise time
- Single bunch real tune shift
  - Contribution of individual collimators
- Intrabunch motion
- Summary

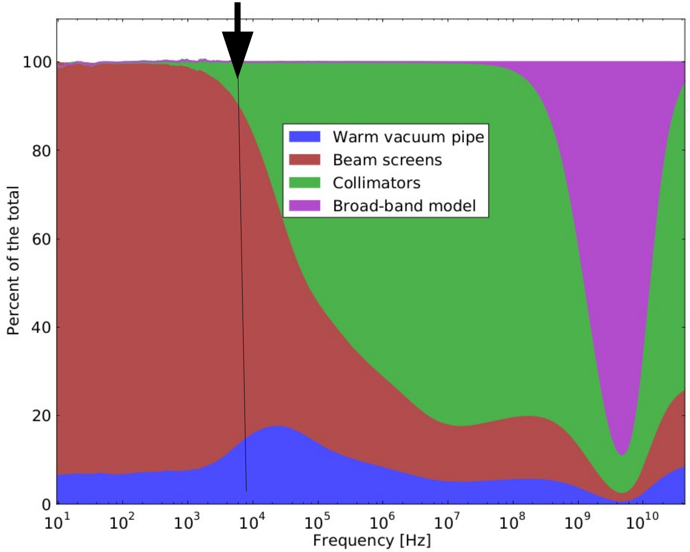
Experimental data available*

- Couple bunch instability rise time
  - 450 GeV and 3.5 TeV, 50ns, Q'~0, G=0
- Single bunch instability rise time
  - 450 GeV, -30<Q'<-5, G = 0
  - 3.5 TeV, Q'~2, G = 0.1
  - 6.5 TeV, Q'~15, G = 0.005, 0.01
- Single bunch real tune shift
  - 450 GeV, 3.5 TeV, Q'~0
  - 4 TeV, Q'~5
  - 6.5 TeV, Q' ~2 and 5

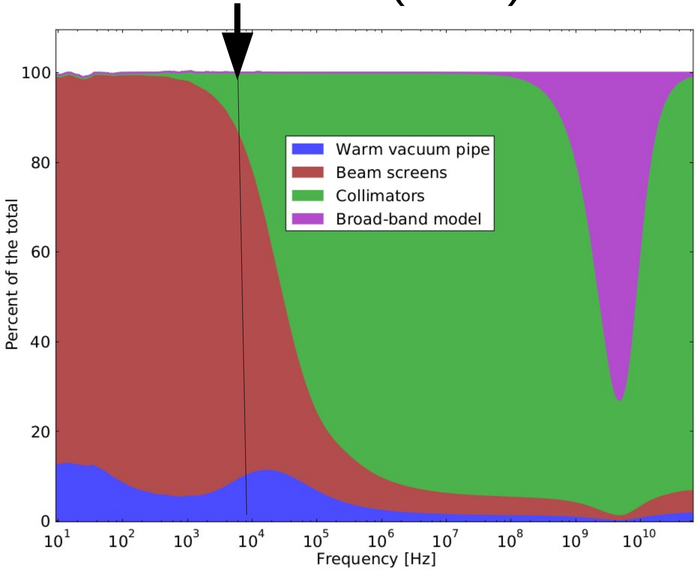
* Detailed list of references in appendix

Coupled bunch instability rise time

450 GeV (2011)



3.5 TeV (2011)



- The rise time of the most unstable coupled bunch mode (Q'~0, G=0) mostly depends on the real impedance of the beam screen around 8kHz

Coupled bunch instability rise time - Injection

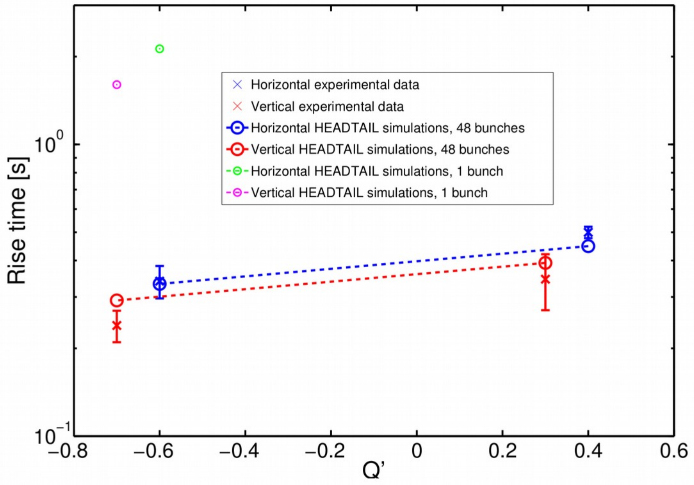


Figure 4.11: Rise times vs. Q' for beam 1 at injection: measurements and HEADTAIL simulations. Simulation results in the single-bunch case are also shown.

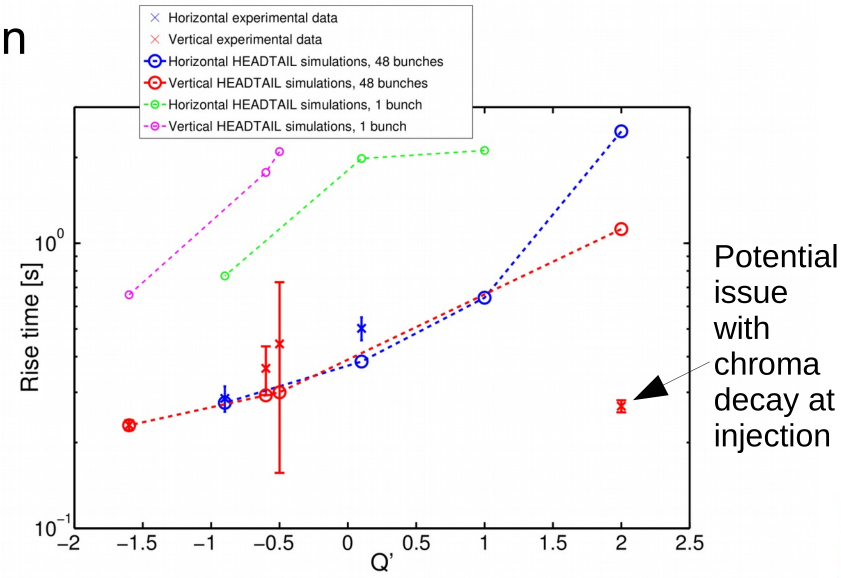
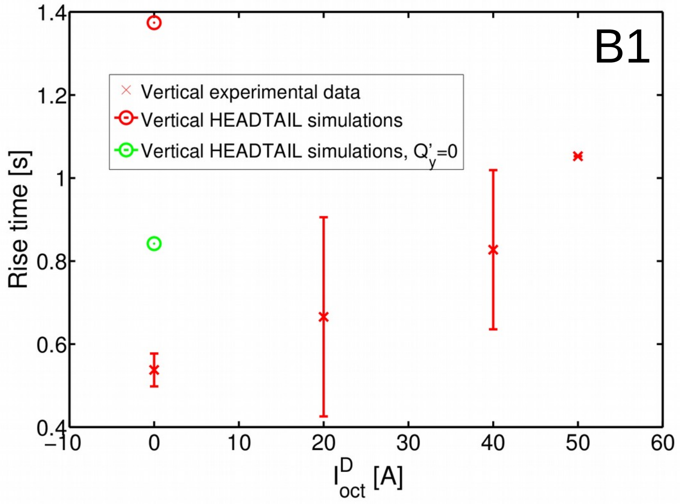


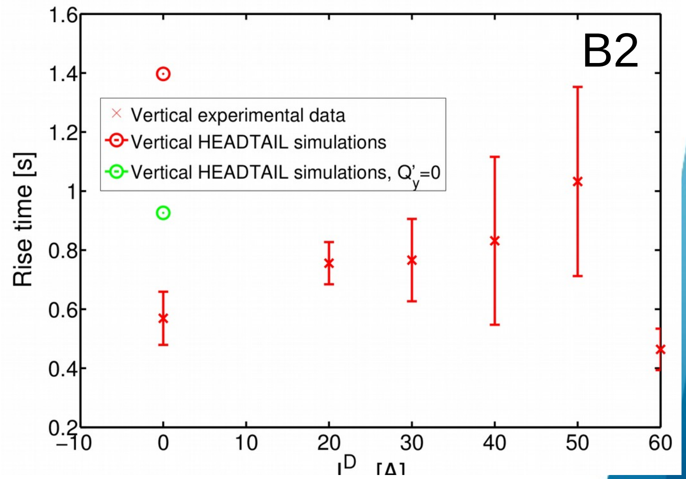
Figure 4.12: Rise times vs. Q' for beam 2 at injection: measurements and HEADTAIL simulations. Simulation results in the single-bunch case are also shown.

- No strong discrepancy (less than a factor 2) could be highlighted at injection with 48 bunch trains of bunches spaced by 50 ns
  - The ADT was switched off

Coupled bunch instability rise time – 3.5 TeV

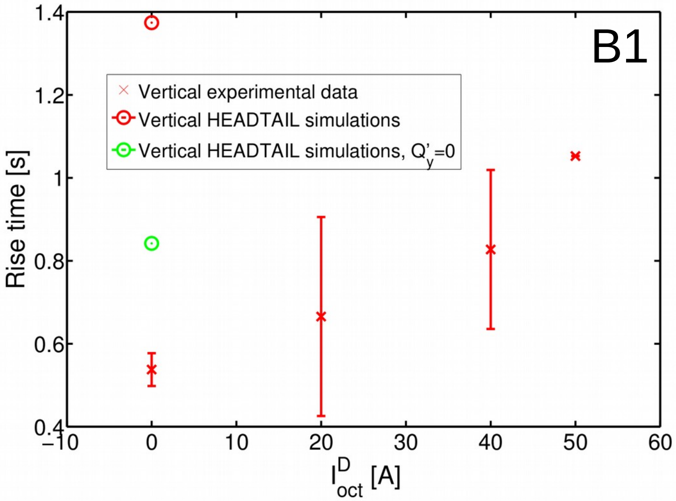
- With the same beam (48b, 50ns, G=0), coupled bunch instabilities were about twice as fast as expected at top energy

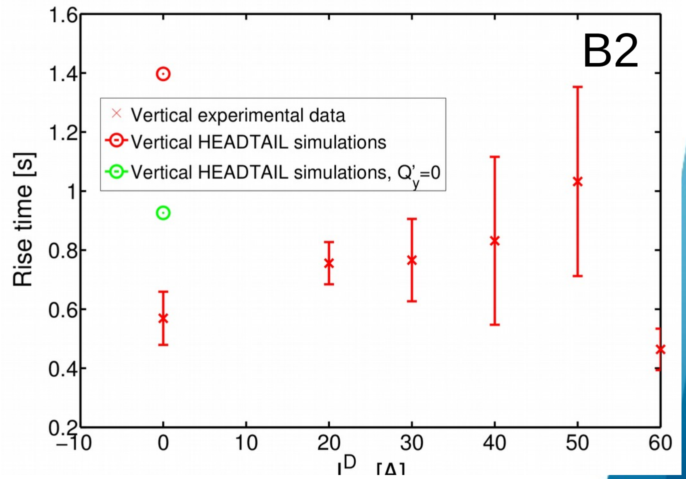




Coupled bunch instability rise time – 3.5 TeV

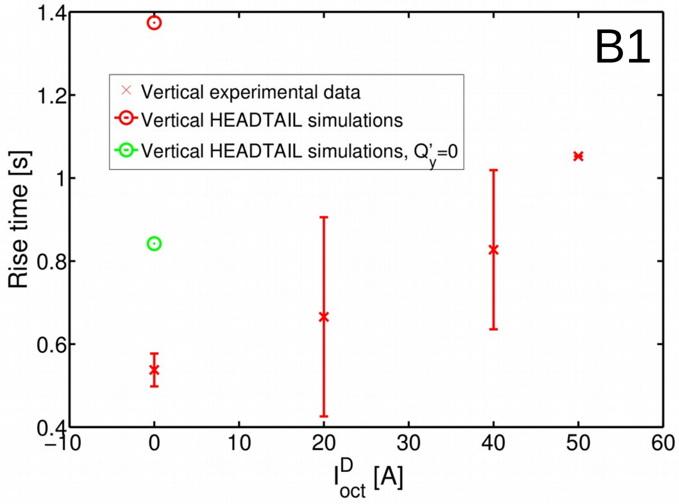
- With the same beam (48b, 50ns, G=0), coupled bunch instabilities were about twice as fast as expected at top energy
  - A difference between injection and flat top could indicate an additional unexpected contribution of the collimators or of the magneto-resistivity of the beam screen at low frequency.

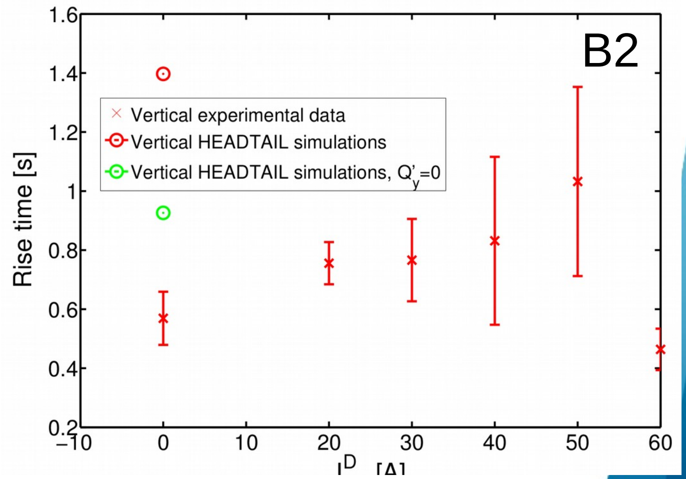




Coupled bunch instability rise time – 3.5 TeV

- With the same beam (48b, 50ns, G=0), coupled bunch instabilities were about twice as fast as expected at top energy
  - A difference between injection and flat top could indicate an additional unexpected contribution of the collimators or of the magneto-resistivity of the beam screen at low frequency.
- Yet, the accuracy of the flat top measurement is rather low due to :
  - The large uncertainty on the chromaticity (e.g. uncompensated feed-down from the octupoles)
  - The fact that the beams were stable without octupoles at flat top indicates the presence of another source of Landau damping (lattice NL, Q'')

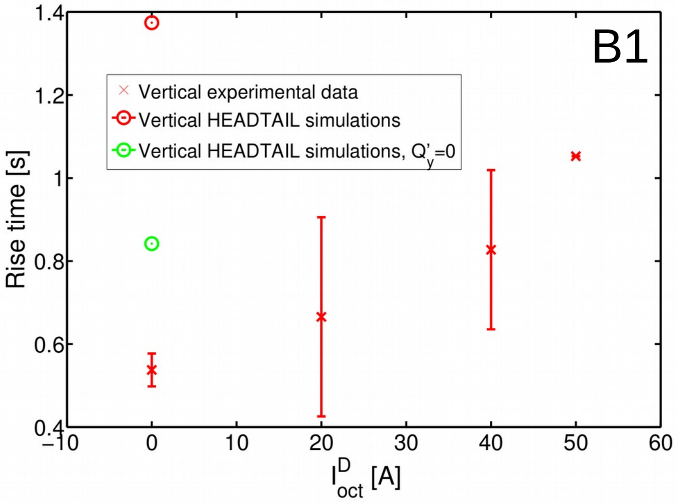


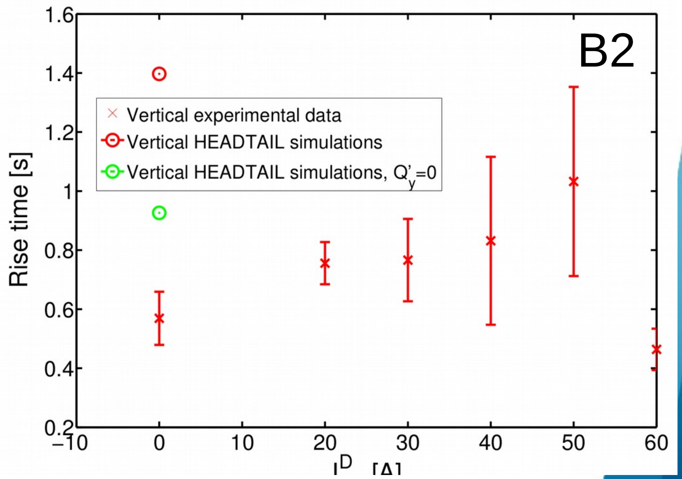


Coupled bunch instability rise time – 3.5 TeV

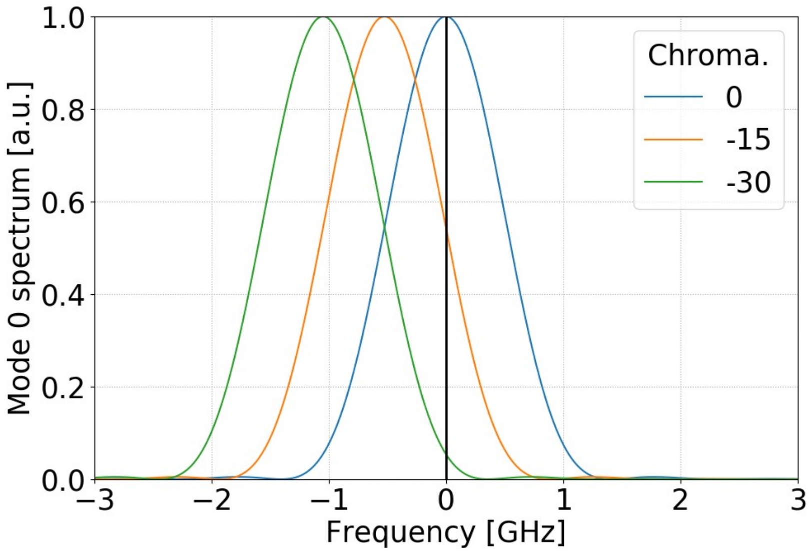
- With the same beam (48b, 50ns, G=0), coupled bunch instabilities were about twice as fast as expected at top energy
  - A difference between injection and flat top could indicate an additional unexpected contribution of the collimators or of the magneto-resistivity of the beam screen at low frequency.
- Yet, the accuracy of the flat top measurement is rather low due to :
  - The large uncertainty on the chromaticity (e.g. uncompensated feed-down from the octupoles)
  - The fact that the beams were stable without octupoles at flat top indicates the presence of another source of Landau damping (lattice NL, Q'')

→ A confirmation using new tools (long ADTObsBox buffers) and experience (control of linear coupling, lattice NL and feed-down) would be needed

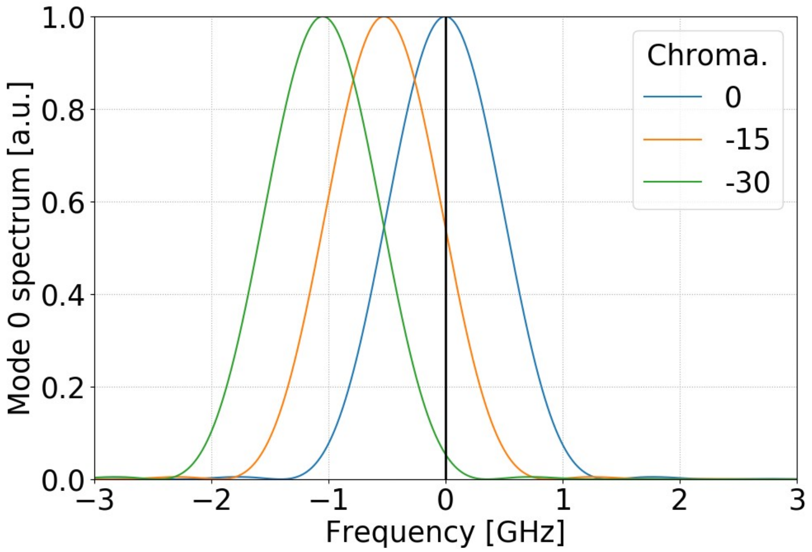


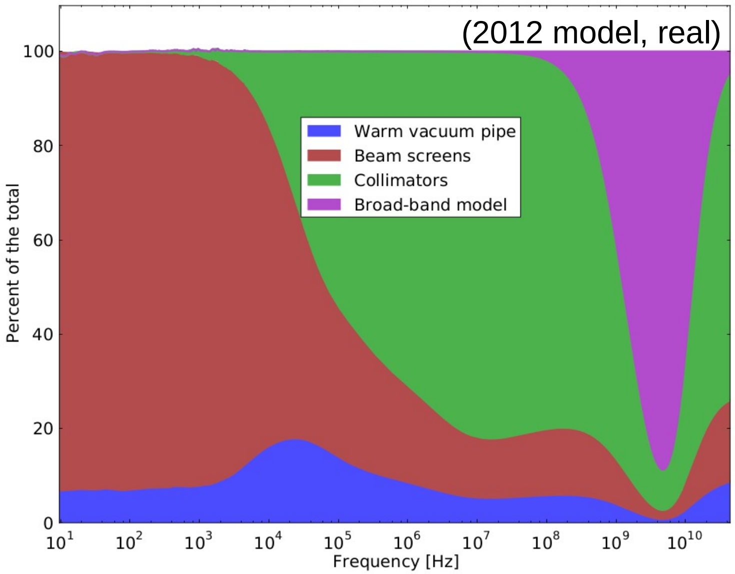


Single bunch instability rise time with a negative chromaticity



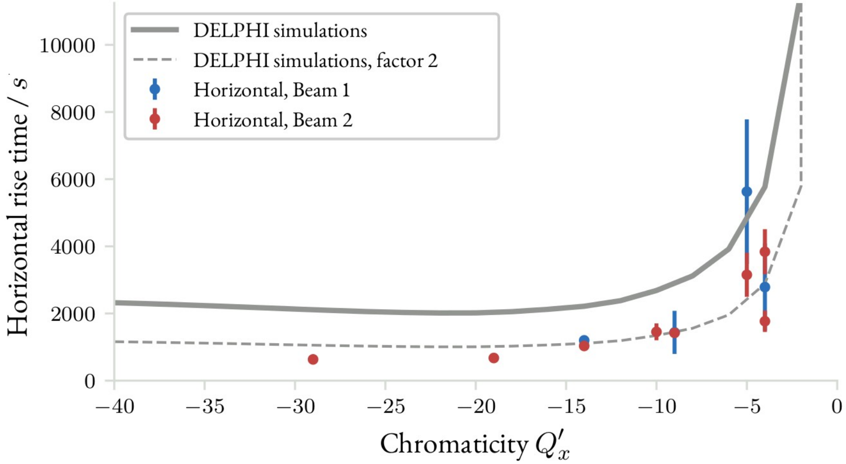
Single bunch instability rise time with a negative chromaticity

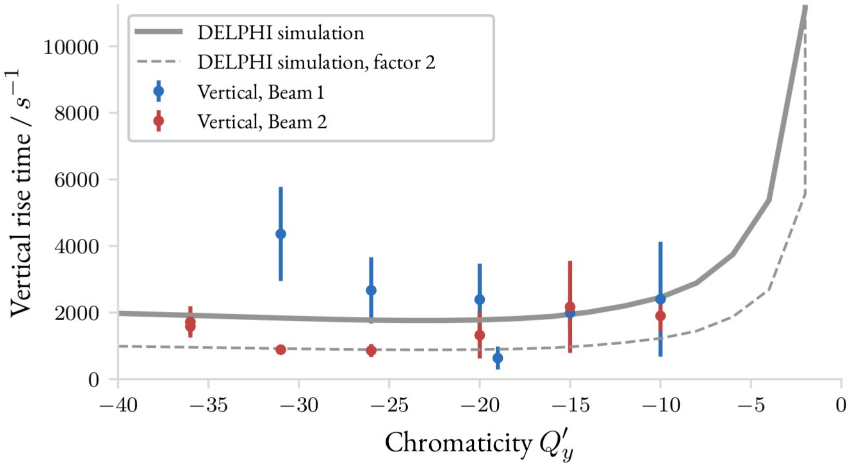




- At low chromaticity, the rise time is dominated by the contribution of the real part of the beam screen impedance
  - For high negative chromaticities, the collimator impedance dominates

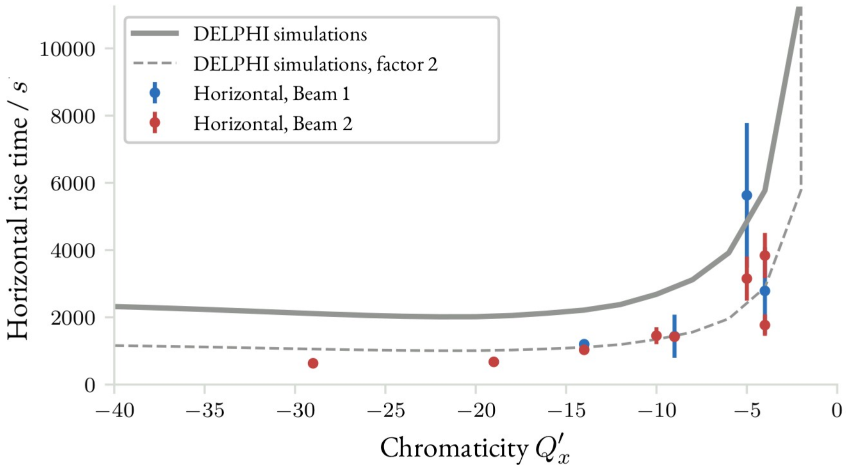
Single bunch instability rise time with a negative chromaticity (450 GeV)

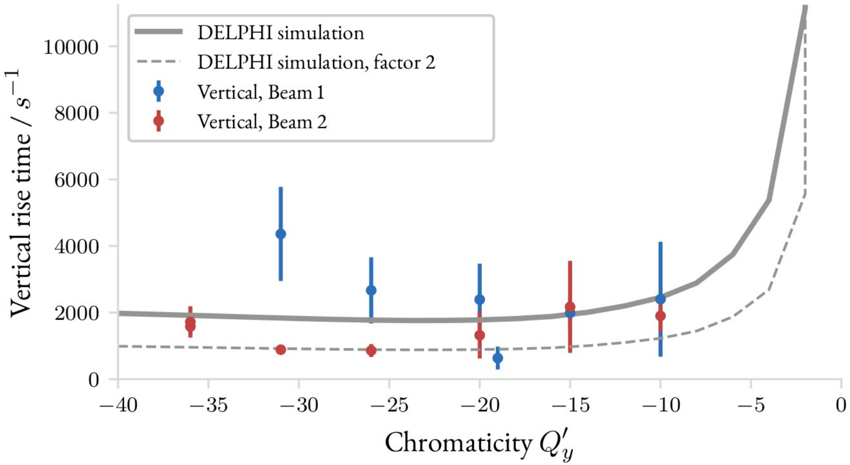




- Most measurements are compatible with an impedance between 1 to 2 times the model. Unfortunately the accuracy of the measurement is rather limited.
  - Only 2h were dedicated to this measurement (including setup)
  - First measurements at low chromaticities were affected by a residual ADT gain
  - The signal quality with a high chromaticity was low and would have required more setup time

Single bunch instability rise time with a negative chromaticity (450 GeV)

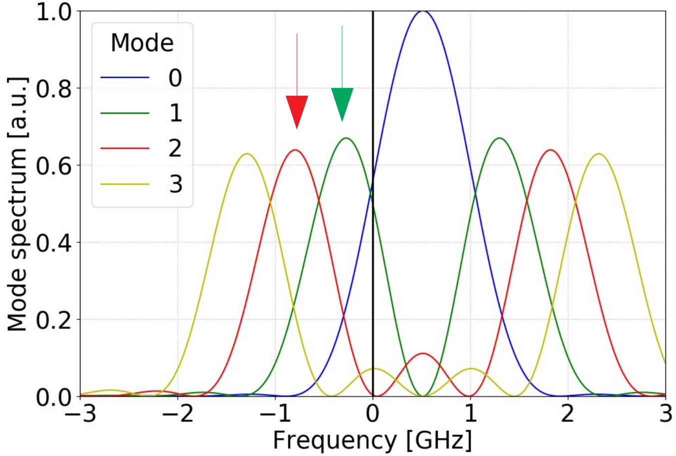


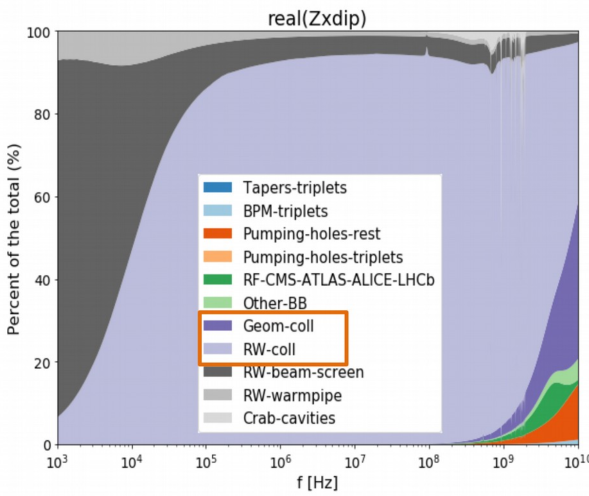


- Most measurements are compatible with an impedance between 1 to 2 times the model. Unfortunately the accuracy of the measurement is rather limited.
  - Only 2h were dedicated to this measurement (including setup)
  - First measurements at low chromaticities were affected by a residual ADT gain
  - The signal quality with a high chromaticity was low and would have required more setup time

→ Large potential for improvement

Single bunch rise time in operational conditions



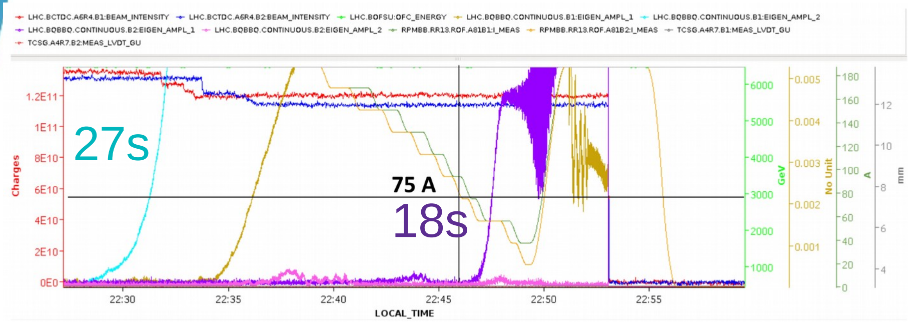


HL-LHC model

- Depending on the damper gain, mode 1 or 2 are the most unstable when operating with Q'~15
  - Both are dominated by the collimator impedance at top energy

Single bunch instability rise time – 6.5 TeV

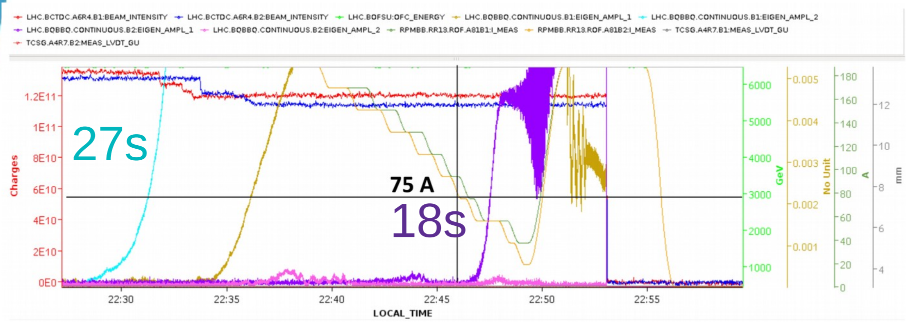
TCSG Impedance MD 2016. Expectation w/o Landau damping: **6s**



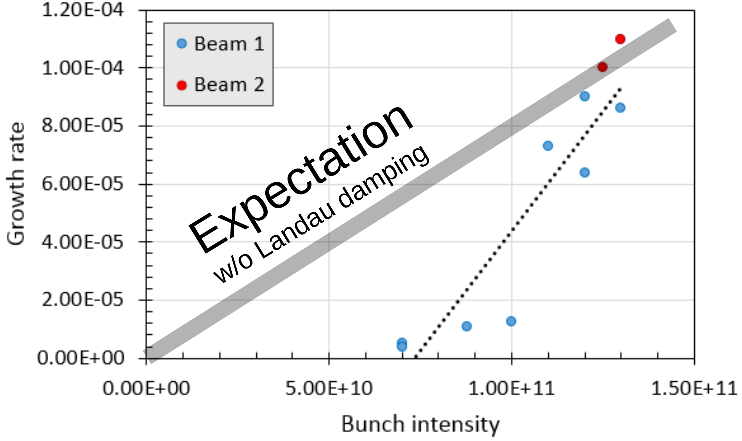
- Instabilities are mostly slower than expected (based on the linear model) due to Landau damping

Single bunch instability rise time – 6.5 TeV

TCSG Impedance MD 2016. Expectation w/o Landau damping: **6s**



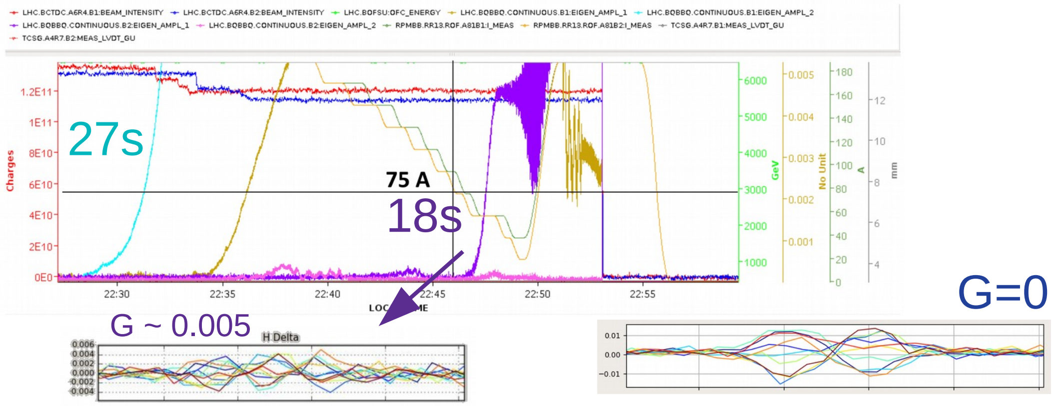
Complex tune shift MD (2018) : ADT switched off at end of fill



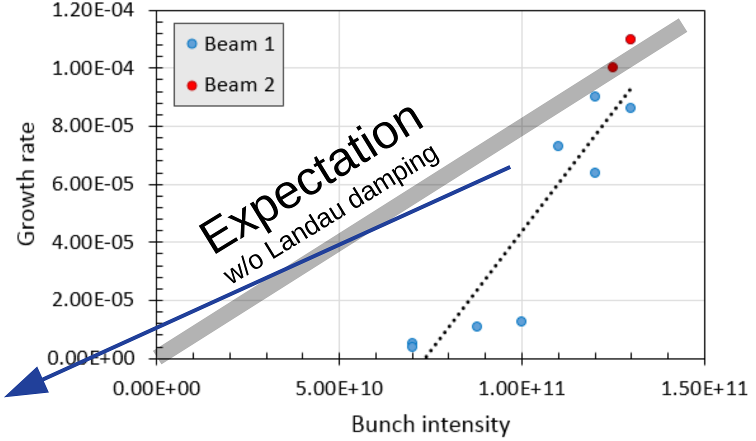
- Instabilities are mostly slower than expected (based on the linear model) due to Landau damping
  - Measurements taken close to the instability threshold seem most accurate

Single bunch instability rise time – 6.5 TeV

TCSG Impedance MD 2016. Expectation w/o Landau damping: **6s**



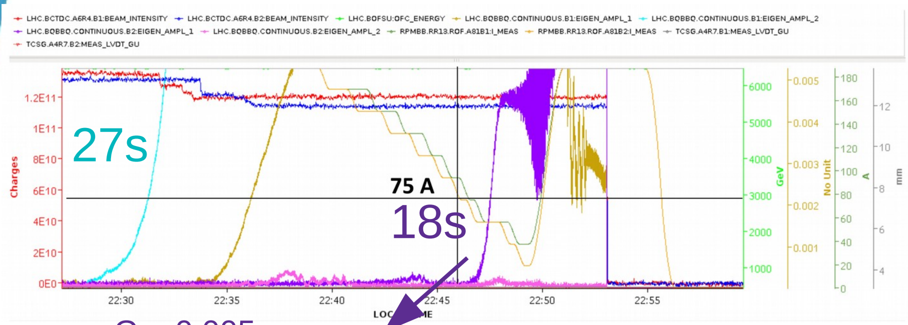
Complex tune shift MD (2018) : ADT switched off at end of fill



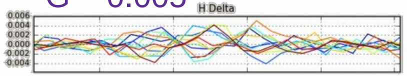
- Instabilities are mostly slower than expected (based on the linear model) due to Landau damping
  - Measurements taken close to the instability threshold seem most accurate
- The unstable mode type follows the expectations

Single bunch instability rise time – 6.5 TeV

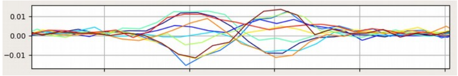
TCSG Impedance MD 2016. Expectation w/o Landau damping: **6s**



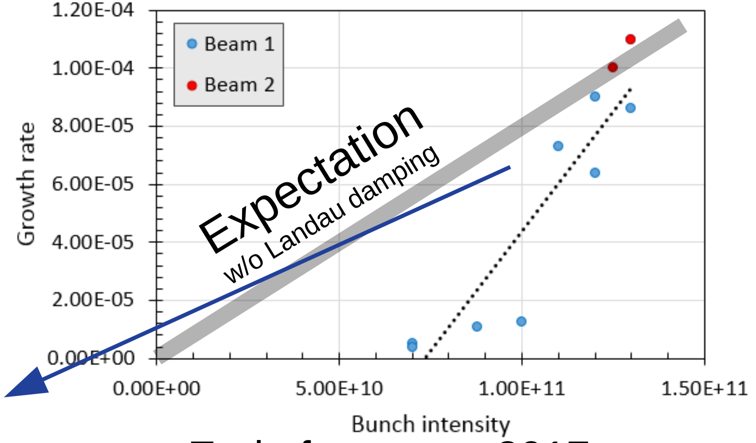
G ~ 0.005



G=0

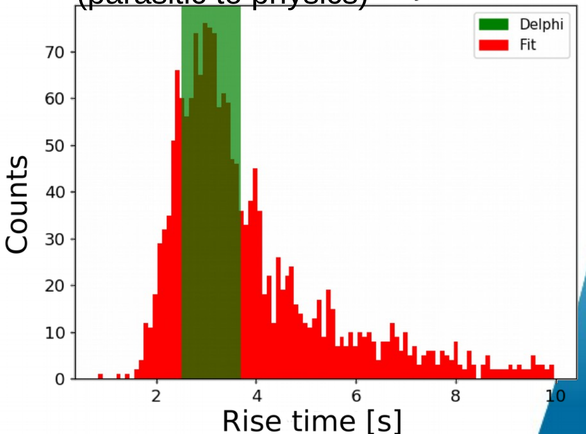


Complex tune shift MD (2018) : ADT switched off at end of fill



End of squeeze 2017

(parasitic to physics)



- Instabilities are mostly slower than expected (based on the linear model) due to Landau damping
  - Measurements taken close to the instability threshold seem most accurate
- The unstable mode type follows the expectations
- Automated analysis of ADT activity monitor data over several fills showed an average compatible with DELPHI predictions

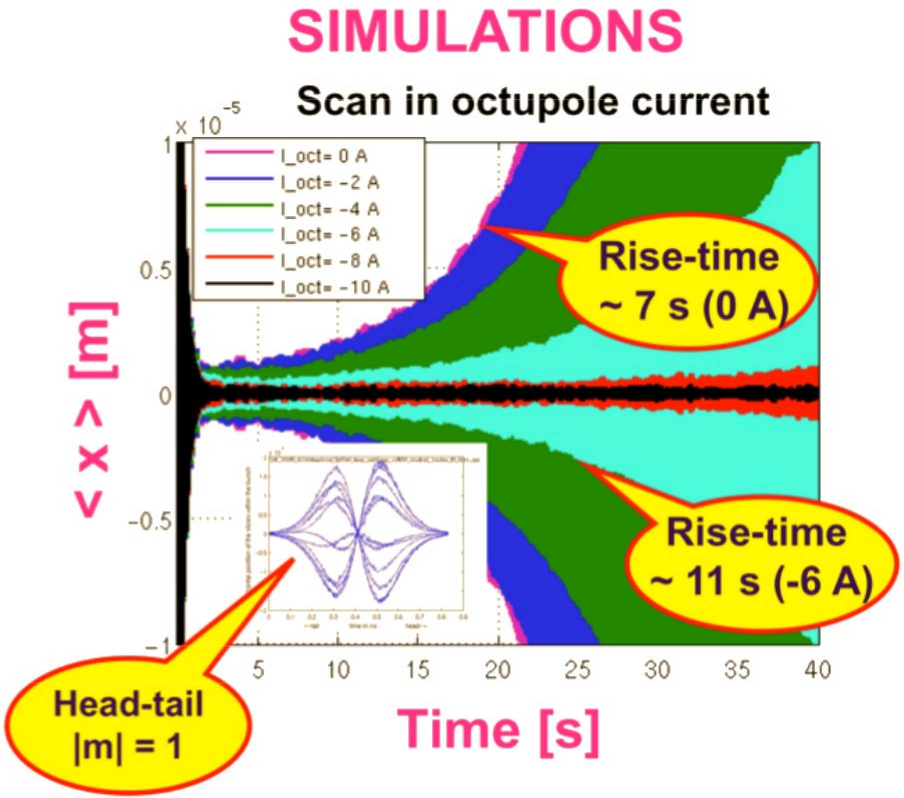
HiLumi HL-LHC PROJECT CERN

The issue with rise time measurment

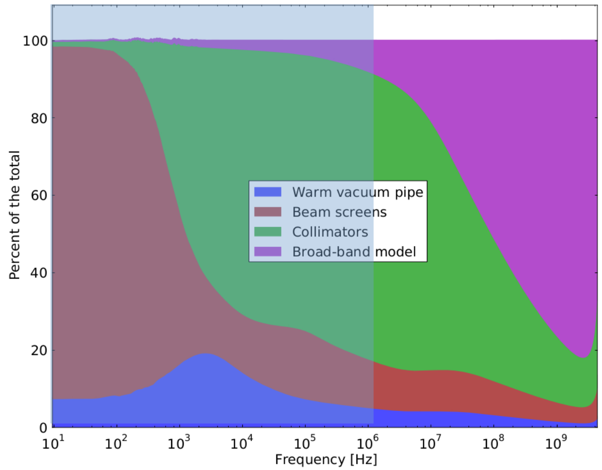
2010 measurement : 9.8s

- Similarly to octupole threshold measurements, the rise time measurements suffers from the uncertainty on Landau damping (i.e. knowledge of the emittance, tail distribution and non-linearities)

  → At flat top an experimental procedure that circumvents fully this issue was not found yet, as the octupoles are needed during the ramp and they can not be switched off fast enough



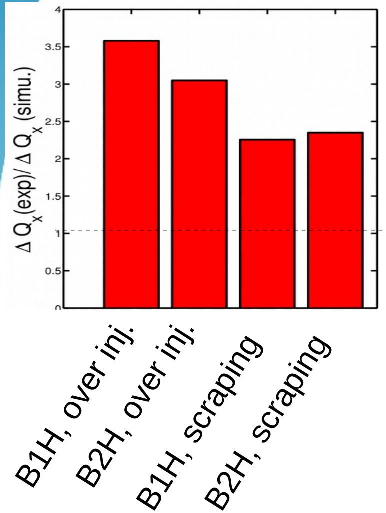
Single bunch real tune shift - injection

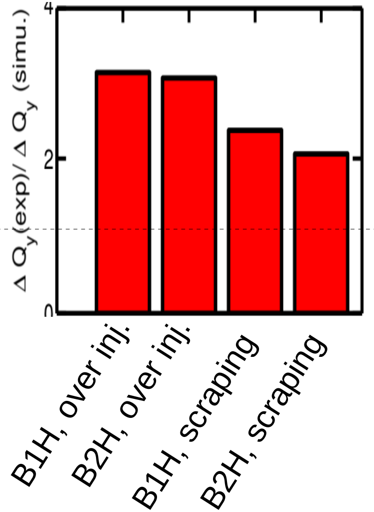


- The experiments were performed with Q'~0. The single bunch real tune shifts probes mostly the imaginary part of the collimators' impedance

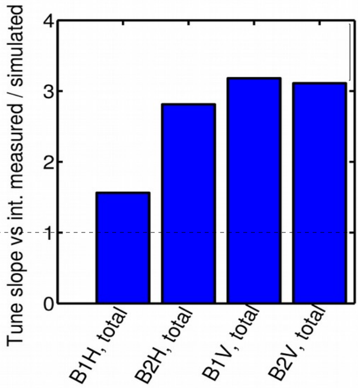
Single bunch real tune shift - injection

2010

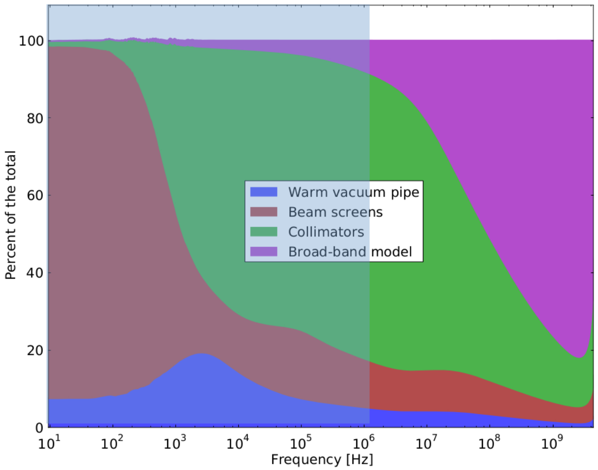




2012



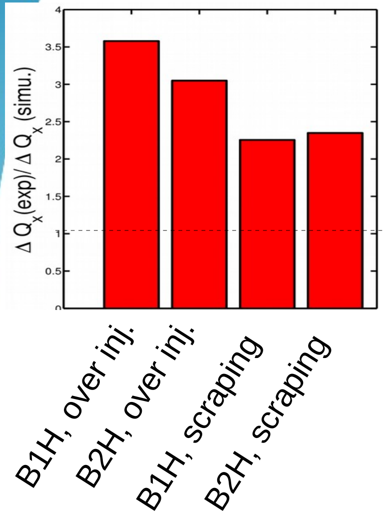
Multiple bunches with different intensities

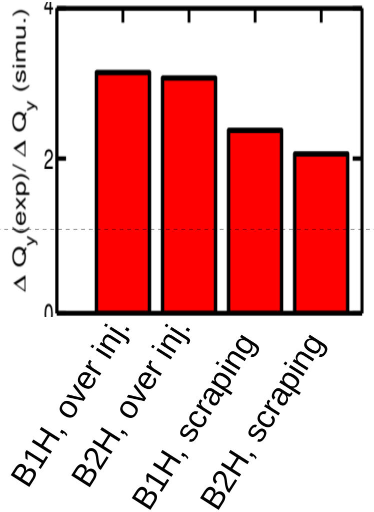


- The experiments were performed with Q'~0. The single bunch real tune shifts probes mostly the imaginary part of the collimators' impedance
    - → The results from Run 1 are compatible with a discrepancy of a factor ~3

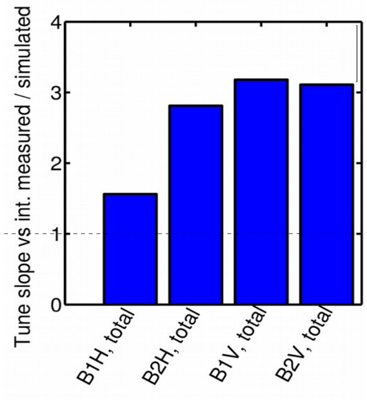
Single bunch real tune shift - injection

2010

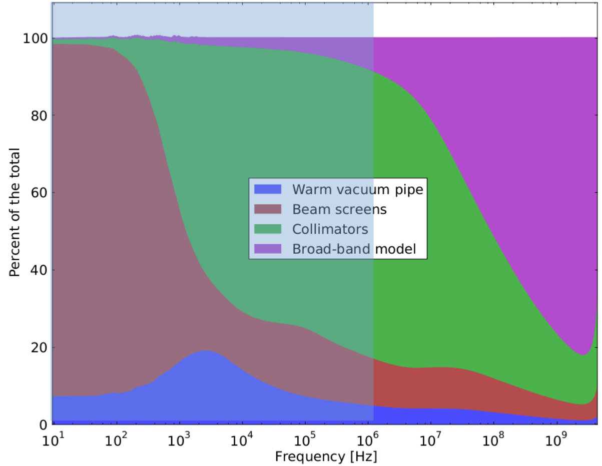




2012



Multiple bunches with different intensities



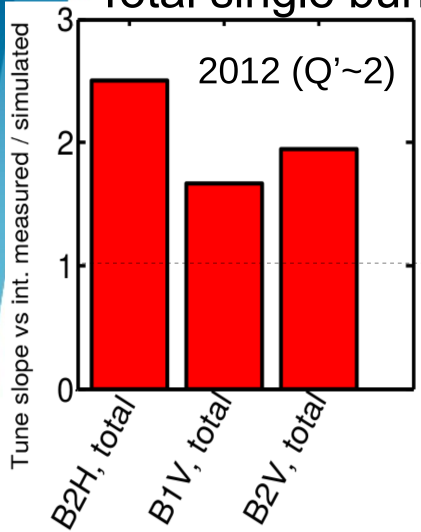
- The experiments were performed with Q'~0. The single bunch real tune shifts probes mostly the imaginary part of the collimators' impedance

  → The results from Run 1 are compatible with a discrepancy of a factor ~3

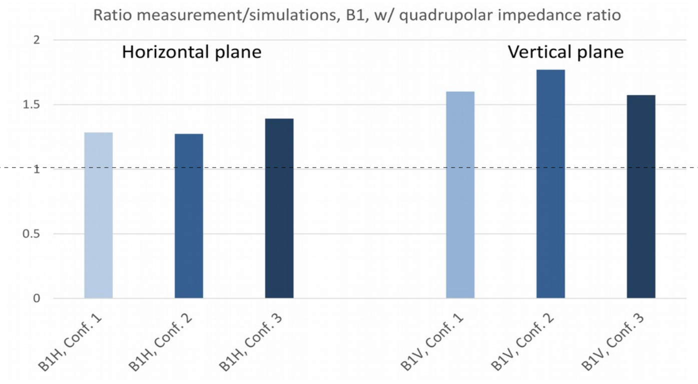
- The total tune shift at injection was not re-measured in Run 2

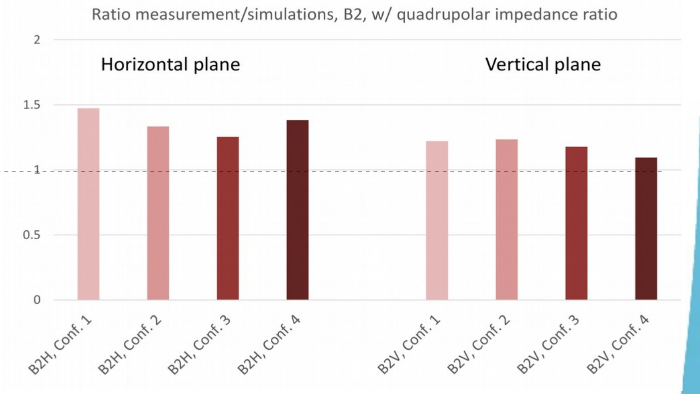
Conf. 1	TCP7@5sig, TCSG7@14sig
Conf. 2	TCP7@5sig, TCSG7@6.5sig
Conf. 3	TCP7@5sig, TCSG7@6sig
Conf. 4	TCP7@4.5sig, TCSG7@6sig

Total single bunch real tune shift – 4 TeV and 6.5 TeV



2017 (tight coll. Settings, Q’~5)

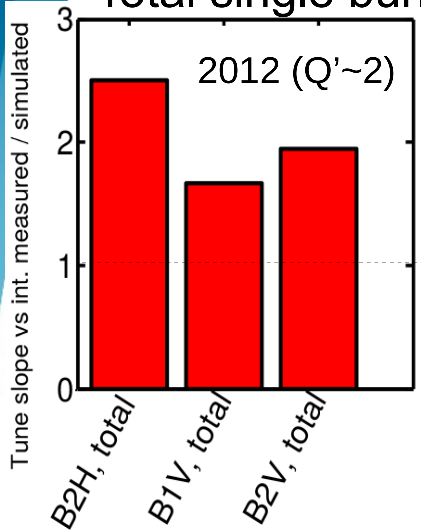




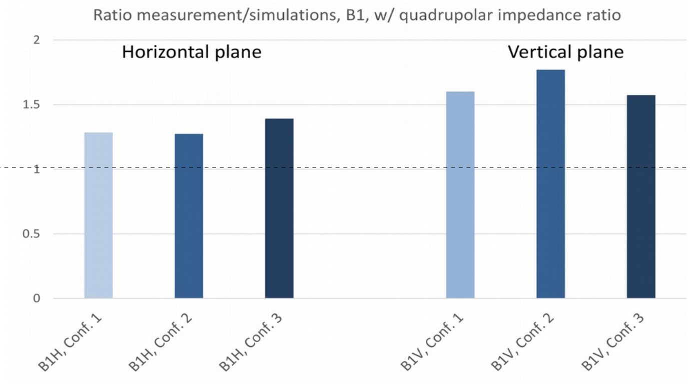
- Over the years the total real tune shift at flat top was measured about 1.5 times higher than modelled

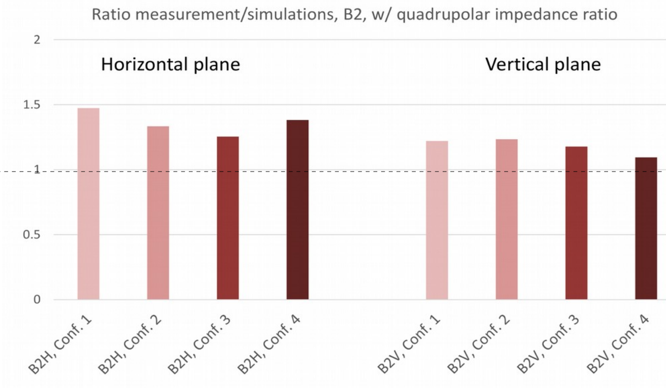
Total single bunch real tune shift – 4 TeV and 6.5 TeV

Conf. 1	TCP7@5sig, TCSG7@14sig
Conf. 2	TCP7@5sig, TCSG7@6.5sig
Conf. 3	TCP7@5sig, TCSG7@6sig
Conf. 4	TCP7@4.5sig, TCSG7@6sig



2017 (tight coll. Settings, Q'~5)





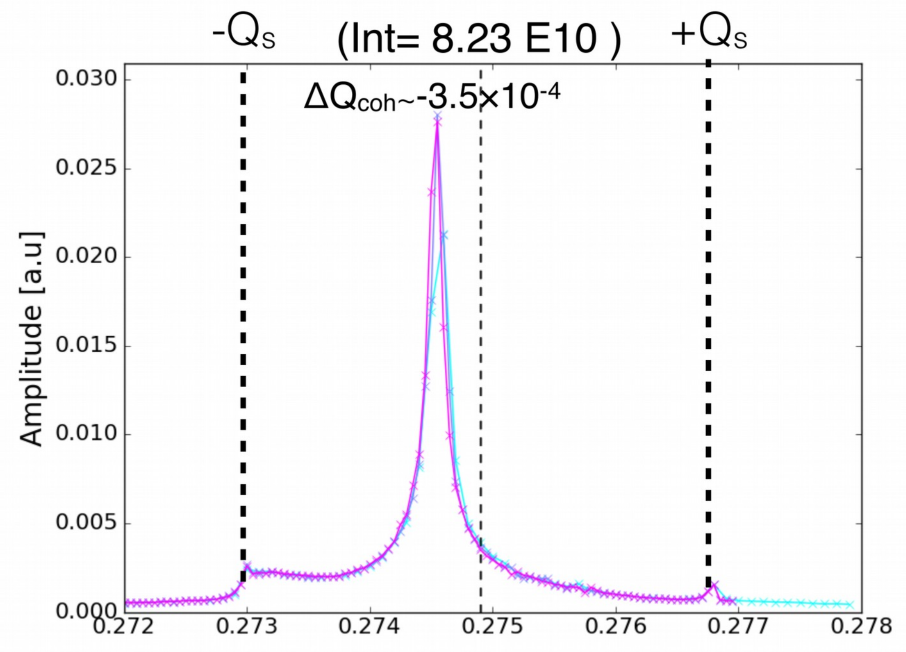
- Over the years the total real tune shift at flat top was measured about 1.5 times higher than modelled
- The discrepancy was slightly reduced in Run 2 w.r.t. Run 1, which may be attributed to
  - → The refinement of the impedance model
  - → Improvement of the measurement technique

Total single bunch real tune shift – 6.5 TeV

- In COMBI, a multiplication of the wake by a factor 1.5 was needed to reproduce the measured shift in B1H during a BTF measurement

→ Slightly higher than measured with kicks (1.3)

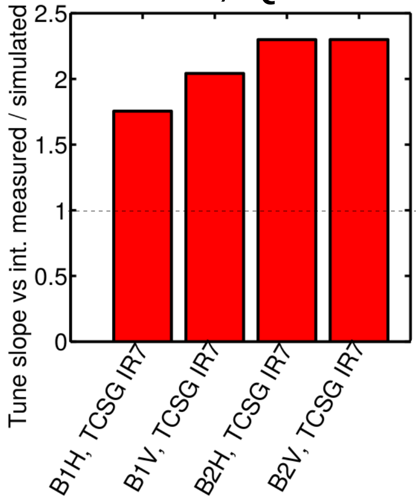
2018 BTF MD



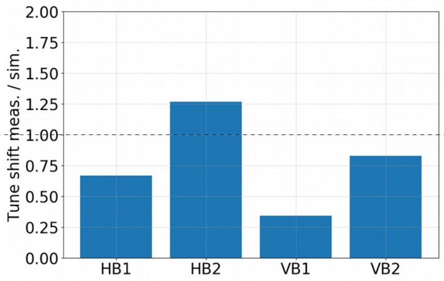
Conf. 1	TCP7@5.5sig, TCSG7@6.5sig
Conf. 2	TCP7@5.5sig, TCSG7@6.0sig

Single bunch real tune shift – IR7's TCSGs

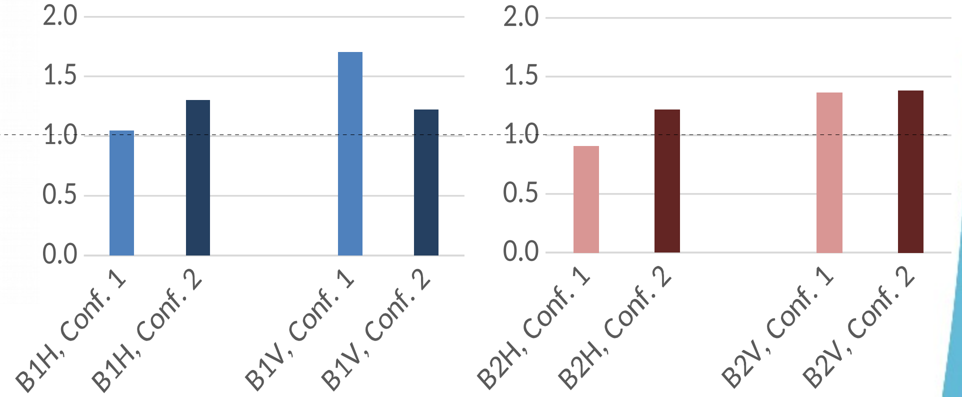
2012, Q'~2



2016 (Q'~15)



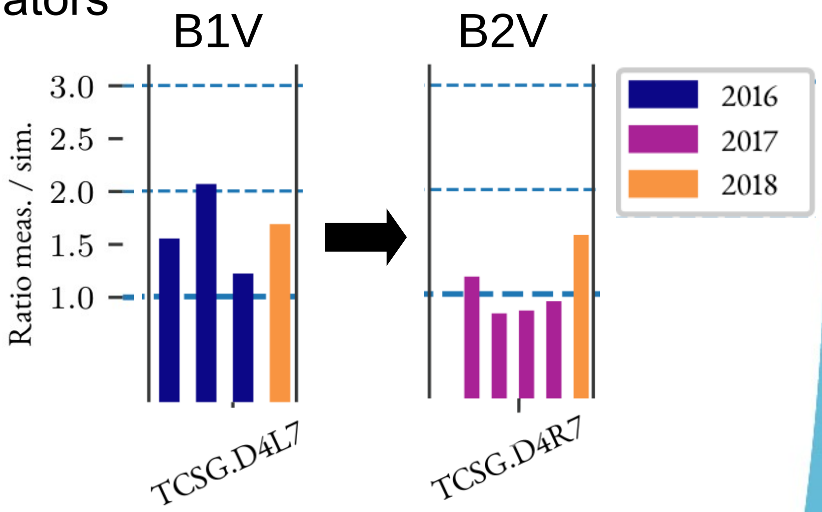
2018 (Q'~5)



- Thanks to the possibility to perform multiple kicks with collimators moving in and out, their contribution can be singled out with much higher precision than global quantities
- The contribution of the TCSGs is closest to prediction in 2018
  - → The refinement of the impedance model
  - → Improvement of the measurement technique

Single bunch real tune shift – Individual collimators

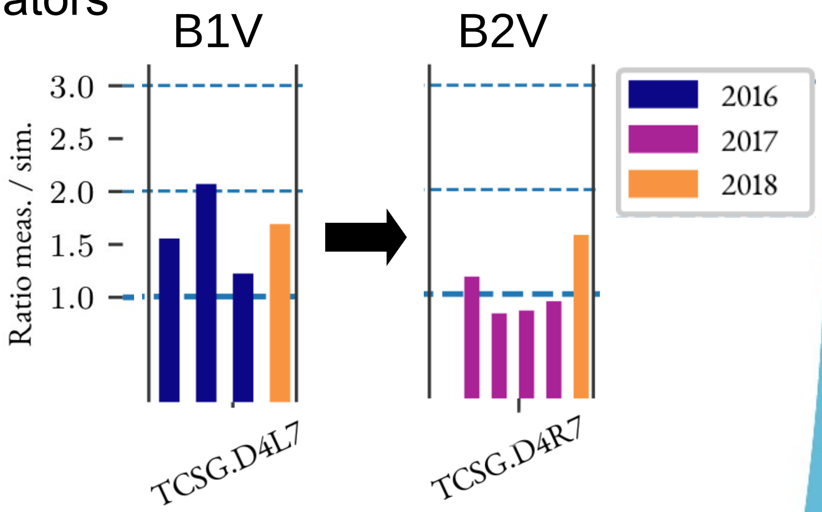
- The variability of the measurement was greatly reduced since the first measurments in 2016 thanks to
  - Experience with machine and beam setup (minimising decoherence while maintaining the beam stability)
  - Usage of multiple low amplitude kicks avoiding scraping and contributions from amplitude detuning
  - Fast cycling of the collimator position to average out the machine tune jitter

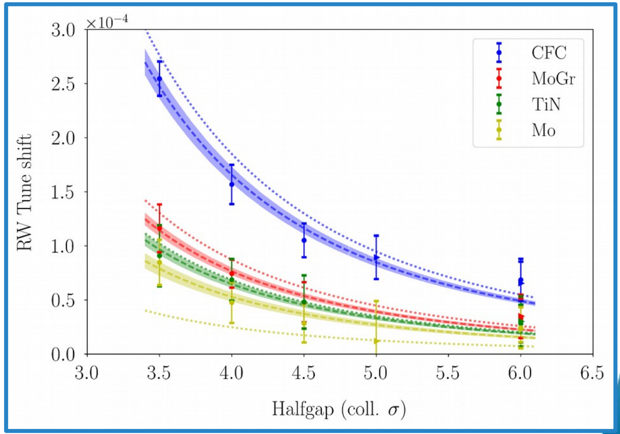


Single bunch real tune shift – Individual collimators

- The variability of the measurement was greatly reduced since the first measurments in 2016 thanks to
  - Experience with machine and beam setup (minimising decoherence while maintaining the beam stability)
  - Usage of multiple low amplitude kicks avoiding scraping and contributions from amplitude detuning
  - Fast cycling of the collimator position to average out the machine tune jitter

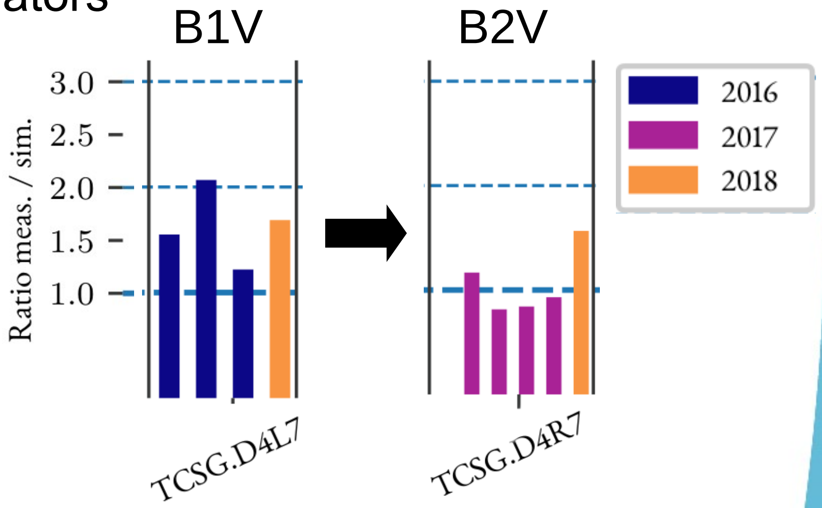
- A remarkable agreement was obtained between model and measurement for the prototype low impedance collimator in 2017
  (in spite of the small tune shift induced)





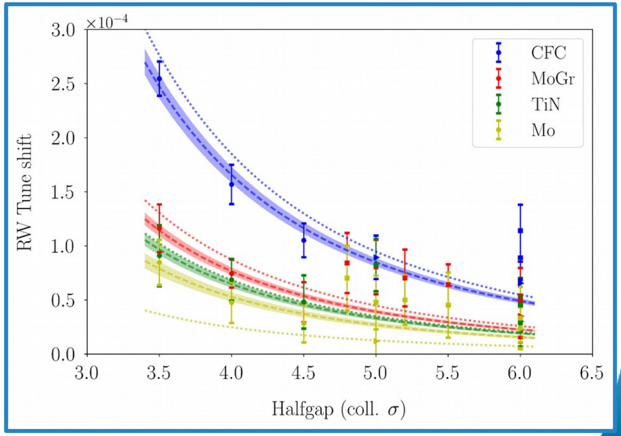
Single bunch real tune shift – Individual collimators

- The variability of the measurement was greatly reduced since the first measurments in 2016 thanks to
  - Experience with machine and beam setup (minimising decoherence while maintaining the beam stability)
  - Usage of multiple low amplitude kicks avoiding scraping and contributions from amplitude detuning
  - Fast cycling of the collimator position to average out the machine tune jitter

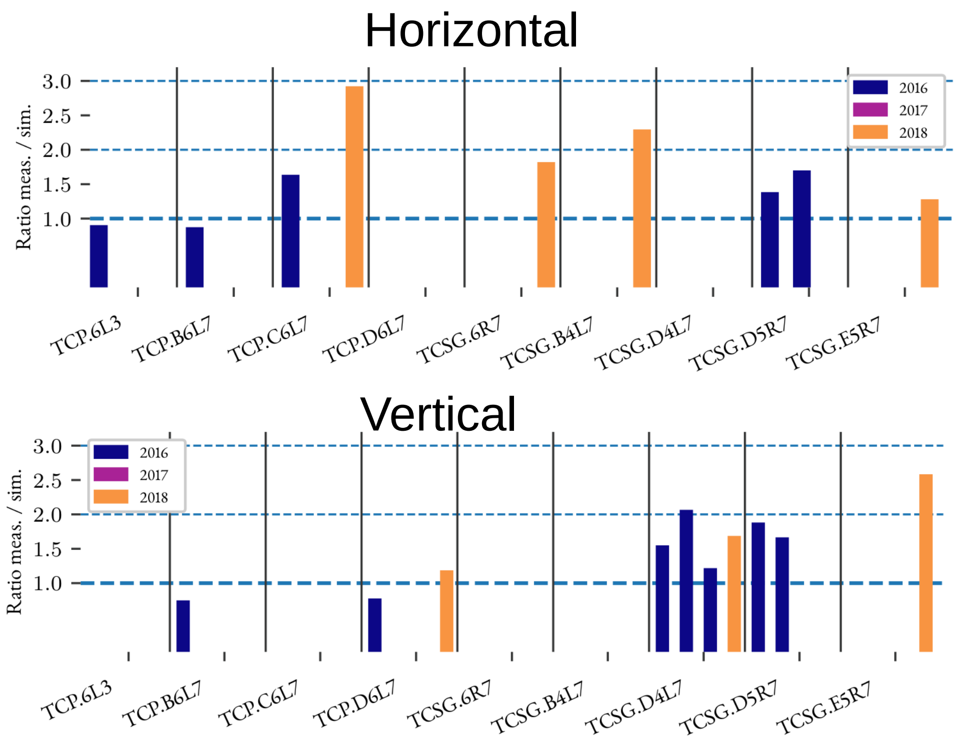


- A remarkable agreement was obtained between model and measurement for the prototype low impedance collimator in 2017 (in spite of the small tune shift induced)
  - The tune shift was measured significantly higher in 2018

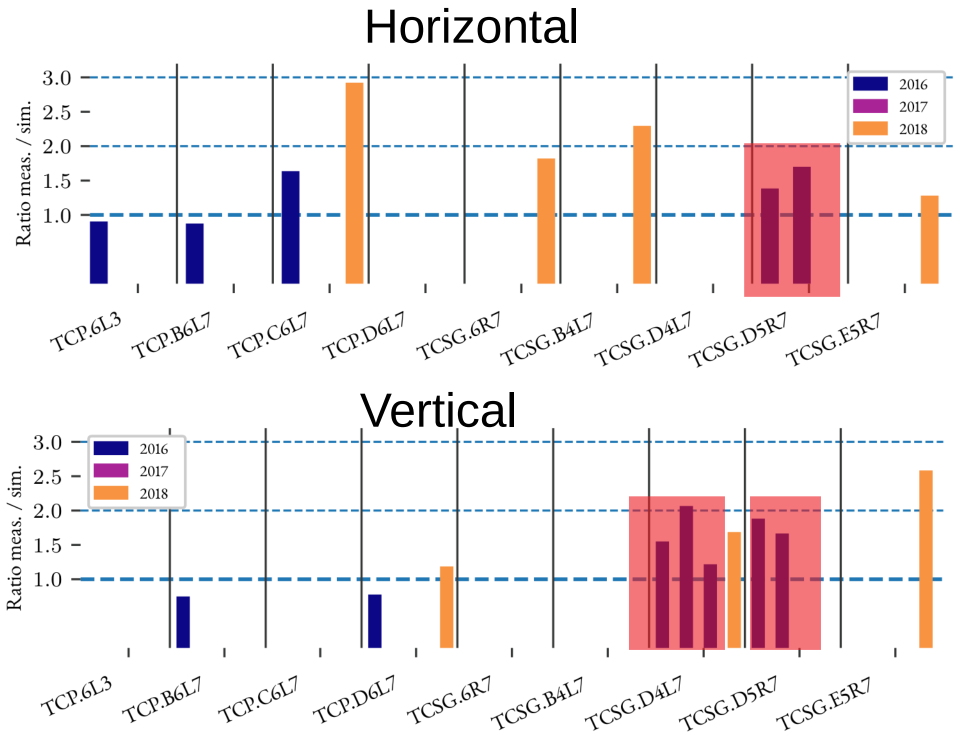
    → Irradiation ? misalignment ?



Single bunch real tune shift – Individual collimators, B1



Single bunch real tune shift – Individual collimators, B1



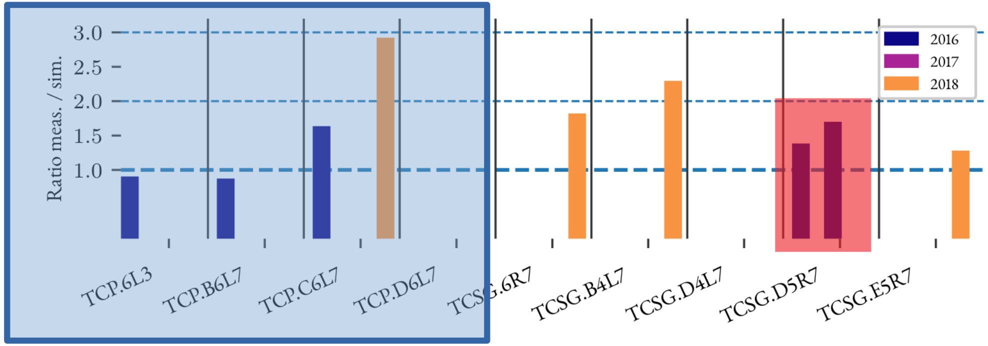
Measurements affected by intensity losses with too large kicks

Single bunch real tune shift – Individual collimators, B1

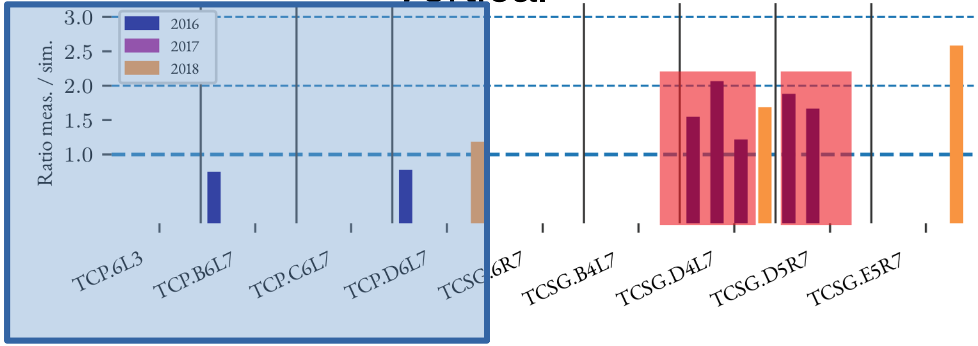
- The TCPs were measured together in 2012 and yielded 1.1 times the predictions (V only)

  → Compatible with 2016 data

Horizontal



Vertical



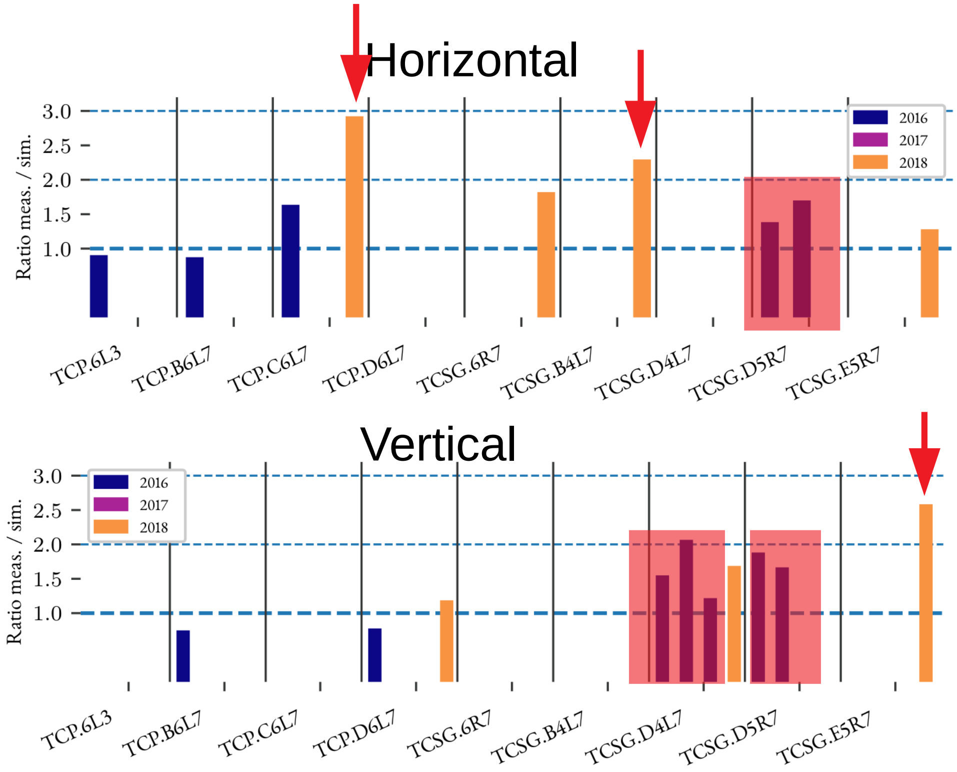
Measurements affected by intensity losses with too large kicks

Single bunch real tune shift – Individual collimators, B1

- The TCPs were measured together in 2012 and yielded 1.1 times the predictions (V only)

  → Compatible with 2016 data

- Some collimators (including one TCP) induced a tune shift more than twice the expected one



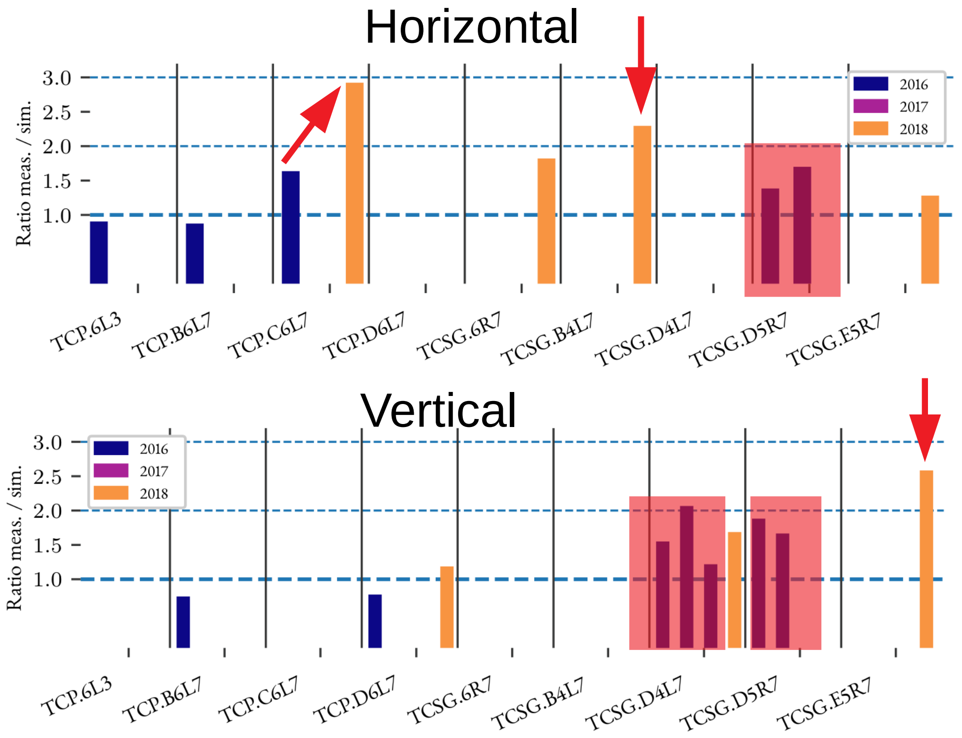
Measurements affected by intensity losses with too large kicks

Single bunch real tune shift – Individual collimators, B1

- The TCPs were measured together in 2012 and yielded 1.1 times the predictions (V only)

  → Compatible with 2016 data

- Some collimators (including one TCP) induced a tune shift more than twice the expected one
  - A significant degradation of the TCP.C6L7 is observed between 2016 and 2018



Measurements affected by intensity losses with too large kicks

Single bunch real tune shift – Individual collimators, B1

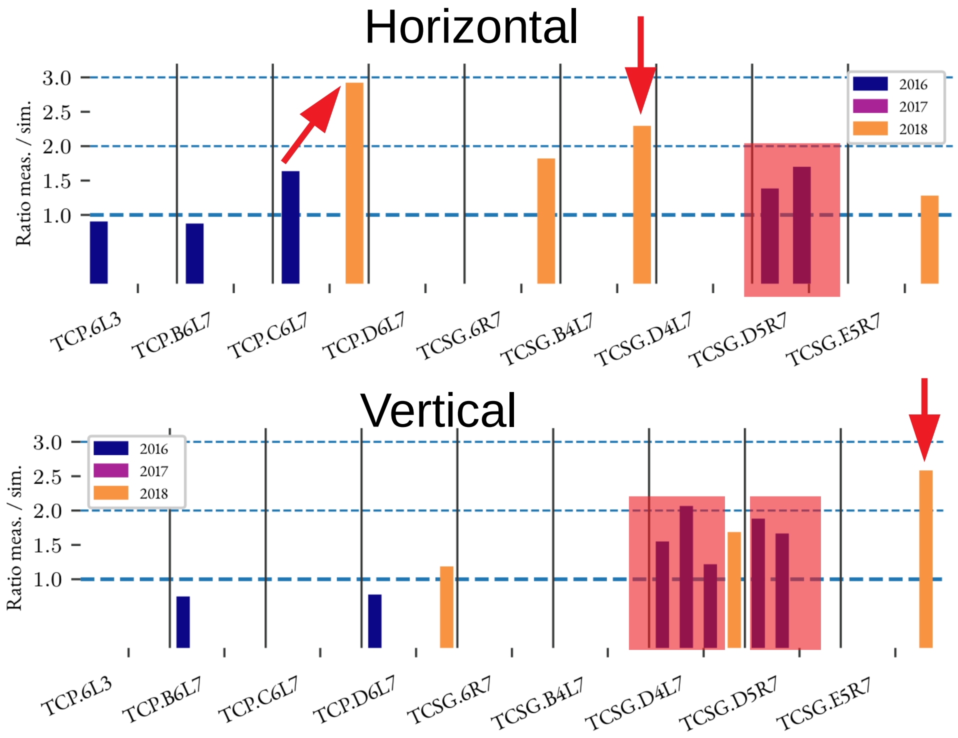
- The TCPs were measured together in 2012 and yielded 1.1 times the predictions (V only)

  → Compatible with 2016 data
- Some collimators (including one TCP) induced a tune shift more than twice the expected one
  - A significant degradation of the TCP.C6L7 is observed between 2016 and 2018
- The total tune shift might be affected by few collimators exhibiting a larger impedance

  → Non-conformities ?

  → Incomplete model ?

  → Impact of the orbit ?

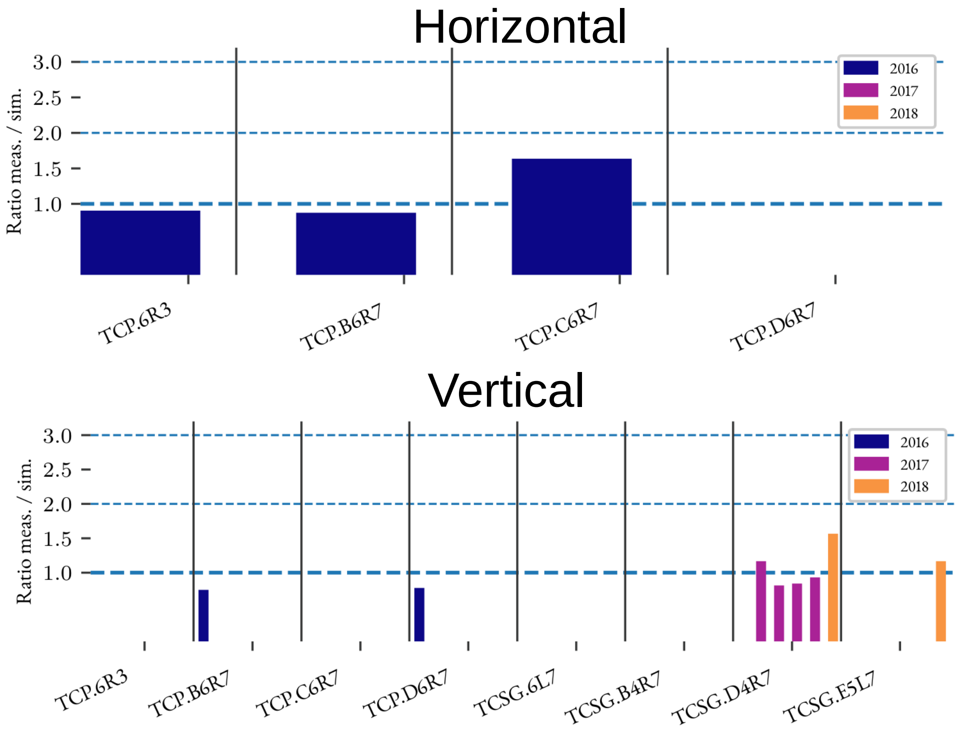


Measurements affected by intensity losses with too large kicks

Single bunch real tune shift – Individual collimators, B2

- The TCPs were measured together in 2012 and yielded 1.8 times the predictions (V only)

  → The incompatibility with 2016 measurements may be attributed to the measurement technique



Summary – Real impedance

- The coupled bunch instability rise times observed at 3.5 TeV could indicate an unknown source of impedance at low frequency but should be confirmed profiting from the new tools and experience
  - The agreement obtained at injection suggest a good modelling of the beam screen impedance at low frequency

Summary – Real impedance

- The coupled bunch instability rise times observed at 3.5 TeV could indicate an unknown source of impedance at low frequency but should be confirmed profiting from the new tools and experience
  - The agreement obtained at injection suggest a good modelling of the beam screen impedance at low frequency
- The quality of single bunch rise time measurement with negative chromaticity at injection do not allow for an assessment of the model better than a factor 2

  → More investment (in MD time) is needed to improve the uncertainty

Summary – Real impedance

- The coupled bunch instability rise times observed at 3.5 TeV could indicate an unknown source of impedance at low frequency but should be confirmed profiting from the new tools and experience
  - The agreement obtained at injection suggest a good modelling of the beam screen impedance at low frequency
- The quality of single bunch rise time measurement with negative chromaticity at injection do not allow for an assessment of the model better than a factor 2

  → More investment (in MD time) is needed to improve the uncertainty
- Single bunch instability rise time measurements at flat top are usually affected by Landau damping. The corresponding uncertainty usually shades the contribution from the impedance

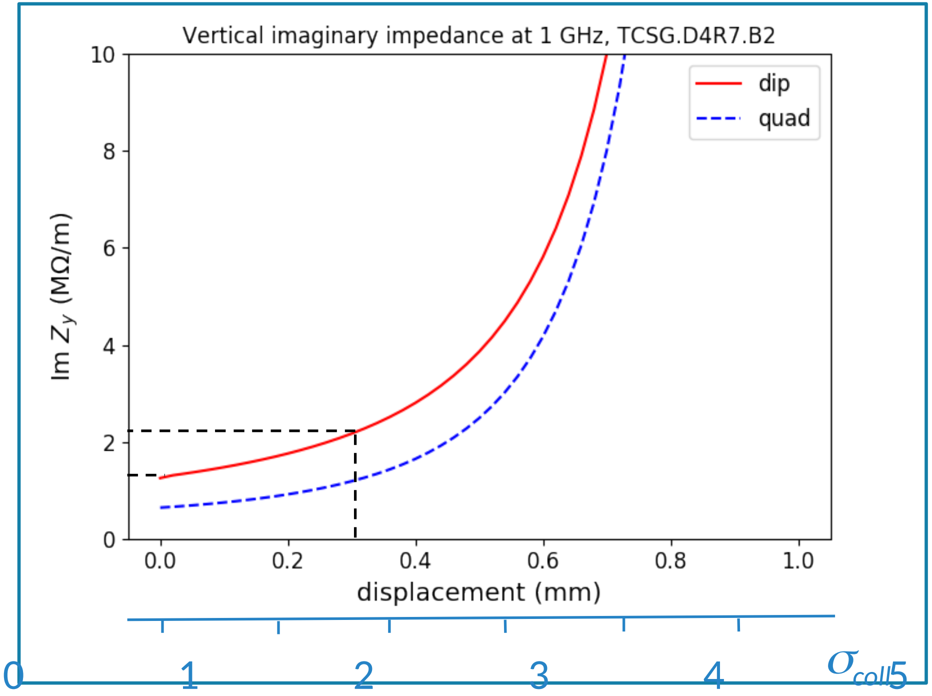
Summary – Imaginary impedance

Year	Measurement	B1H	B1V	B2H	B2V
2016	Tune shift vs. IR7 secondary collimators gaps[1]	1.3	1.4	1.1	1.4
2017	Tune shift vs. bunch intensity[2]	1.2	1.4	1.3	1.1
	Tune-shift vs. bunch intensity[3]	1.4	1.6	1.4	1.2
2018	Full machine tune shift at flat-top[4]	1.5	-	-	-
	Growth-rate vs. negative chromaticity	1.4	1.6	1.4	1.2

- Currently the real tune shift is the most accurate beam-based measurement of the impedance available
- Total real tune shifts are in the order of 1.5 times larger than expected
- The tune shift induced by individual collimators ranges from a perfect agreement with the model to 3 times larger. The cause for these differences is not known and should be further investigated

Detailed references

- E. Métral, et al., STABILIZATION OF THE LHC SINGLE-BUNCH TRANSVERSE INSTABILITY AT HIGH-ENERGY BY LANDAU OCTUPOLES, IPAC'11
- N. Mounet, et al., Transverse coupled-bunch instability rise times in the LHC atinjection and top energy, (MD in May 2011, CERN-ATS-Note-2011-035 MD)
- J.F. Esteban Müller, et al., Probing the LHC impedance with single bunches, (MD in Jun. 2012, CERN-ATS-Note-2013-001 MD)
- **N. Mounet, PhD thesis** and **N. Mounet, et al. Evian 2012**
- A. Mereghetti, et al., β*-Reach – IR7 Collimation Hierarchy Limit and Impedance, (MD314 in Aug. 2015, CERN-ACC-NOTE-2016-0007)
- L. Carver, et al., MD 755: Instability threshold and tune shift study with reducedretraction between primary and secondary collimators in IR7 (MD in Aug. 2015, CERN-ACC-NOTE-2016-0005)
- A. Mereghetti, et al., MD1447 - β*-reach: IR7 Collimation Hierarchy Limit and Impedance (MD in Jul. 2016, note in prep.)
- A, Mereghetti, et al., MD1446 - Impedance contribution of primary collimators (MD in Sep. 2016, note in prep.)
- D. Amorim, et al., MD1787 – LHC TDI tune shift measurement at injection, (MD in Oct. 2016 ,CERN-ACC-NOTE-2020-0015 MD)
- D. Mirarchi, et al., MD1878: Operation with primary collimators attighter settings, (MD in Oct. 2016, CERN-ACC-NOTE-2017-0014)
- A. Mereghetti, et al., MD1875 – Impedance Contribution of Single IR7 Secondary Collimators (MD in Oct. 2016, note in prep.)
- N. Biancacci, et al., Outcome of TCSG single collimator impedance and instability measurements, HSC meeting 22.08.2016
- **N. Biancacci, et al., 1/2-day internal review of LHC performance limitations (linked to transverse collective effects) during run II (2015-2016)**
- A, Mereghetti, et al., MD2191 : β*-reach: IR7 Collimation Hierarchy Limit and Impedance (MD in Sep. 2017, note in prep.)
- MD2490: Measurement of the TMCI Threshold at Flat-Top. Results reported in D. Amorim's PhD thesis
- S.A. Antipov, et al., SINGLE-COLLIMATOR TUNE SHIFT MEASUREMENT OF THE THREE-STRIPE COLLIMATOR AT LHC, IPAC'18
- D. Amorim, et al., MD3308 – growth rate versus chromaticity measurement at injection, (MD in Sep. 2018, note in prep.)
- D. Amorim, et al., MD3318 – Impedance Contribution of Secondary and Tertiary Collimators, (MD in Oct. 2018, note in prep.)
- MD3310: Complex tune shift as a function of the intensity for single bunches at top energy. Results reported in D. Amorim's PhD thesis
- C. Tambasco, et al., Instability threshold measurements in the presence of a controlled external excitation (MD in Jun. 2018 ,CERN-ACC-NOTE-2019-0044) and HSC meeting 10.12.2018
- **D. Amorim, PhD Thesis** and **D. Amorin, et al. HSC meeting 04.03.2019**



- A 100 μm orbit offset might increase impedance by 10-20%