Beam stability with harmonic system

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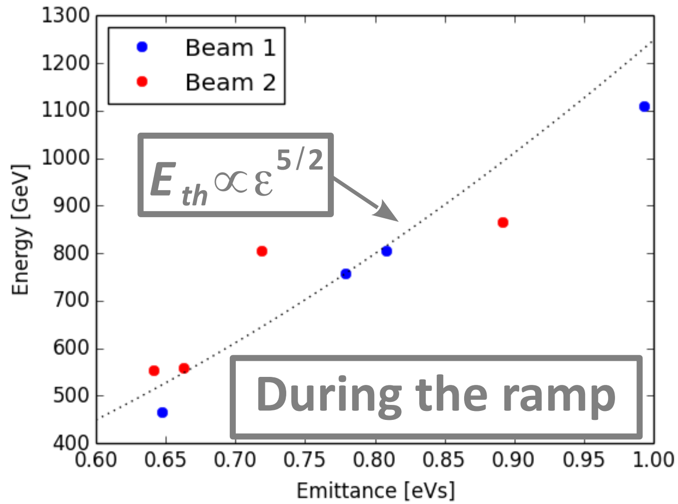
Outline

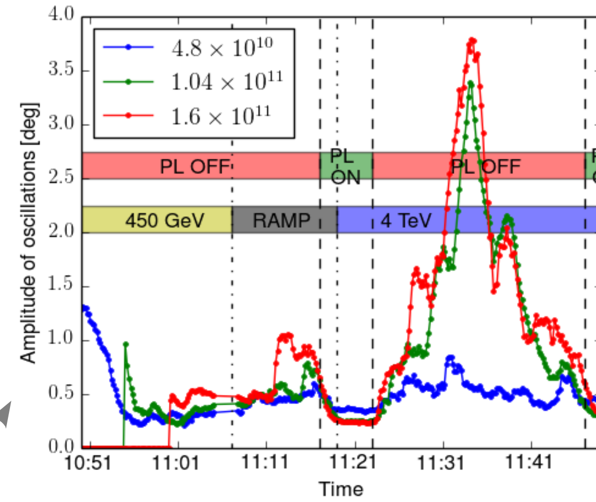
- Longitudinal stability of the bunch in the LHC
  - Measurements
  - Simulations
- HL-LHC longitudinal impedance model
- Longitudinal stability of the bunch in the HL-LHC
  - Injection
  - 7 TeV with harmonic system
  - Effect of a phase shift between the RF systems
  - Flat bunches in BSM
- Summary

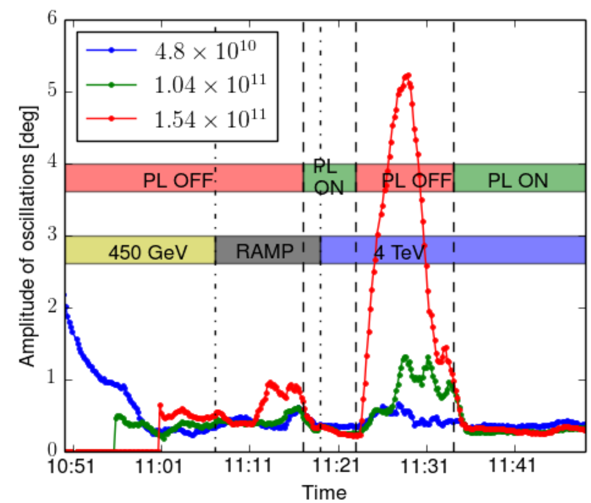
Measurements in the LHC during the ramp and at 4 TeV

- **Loss of Landau damping**
  - $$\Im Z/n < \frac{|\eta| E}{e I_b \beta^2} \left(\frac{\Delta E}{E}\right)^2 \frac{\Delta \omega_s}{\omega_s} f_0 \tau$$



At 4 Tev, 12MV and PL off with 1 eVs:
➔ $N_{th} \approx 1 \times 10^{11}$ (only one meas.)





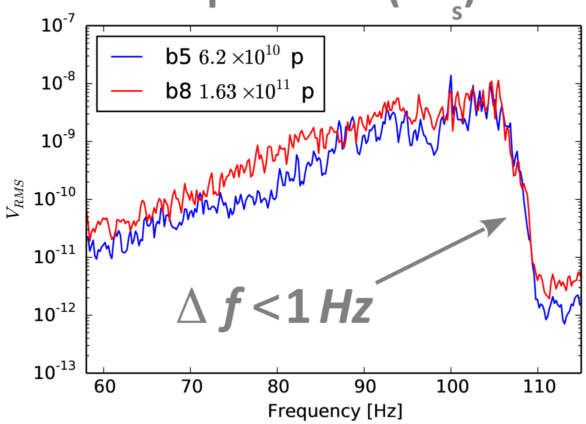
- **Coupled bunch instability: <u>not observed so far</u>**

Measurements in the LHC at 450 GeV

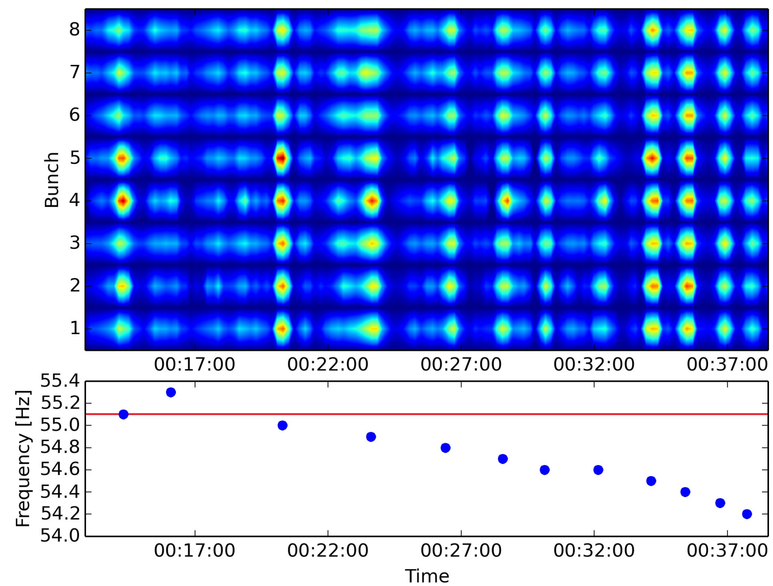
Reactive part of the longitudinal impedance estimated from synchrotron frequency shift:

$$\Delta f_s = f_{s0} \left(\frac{2}{\pi}\right)^{1/2} \frac{16 N e \omega_0 h^2}{V_{RF} (2\pi f_0 \tau)^3} \Im Z/n$$

Peak-detected Schottky spectrum (2 f_s)



Bunch excitation by RF phase modulation

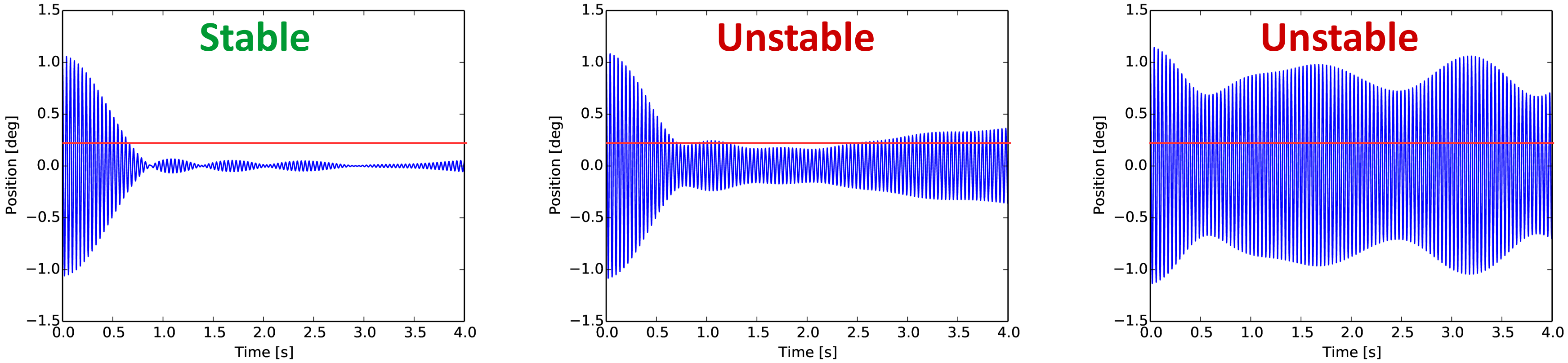


➔ **Measurements give: $\Im Z/n < 0.1\,\Omega$ (LHC DR 0.09 Ω)**

High Luminosity LHC

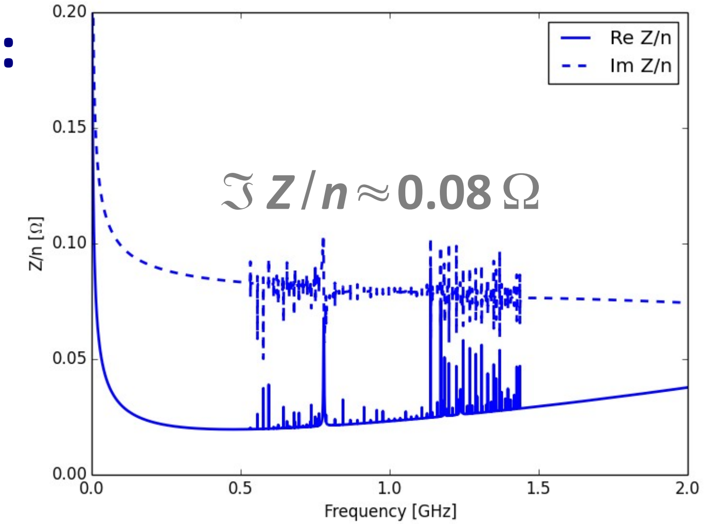
Simulations

- **Simulation code:** BLonD
- **Method:**
  1) Generation of particles distribution matched in the bucket with intensity effects
  2) Phase kick of 1º
  3) Stability criterion: stable if oscillations amplitude is reduced below 20 % of the initial amplitude

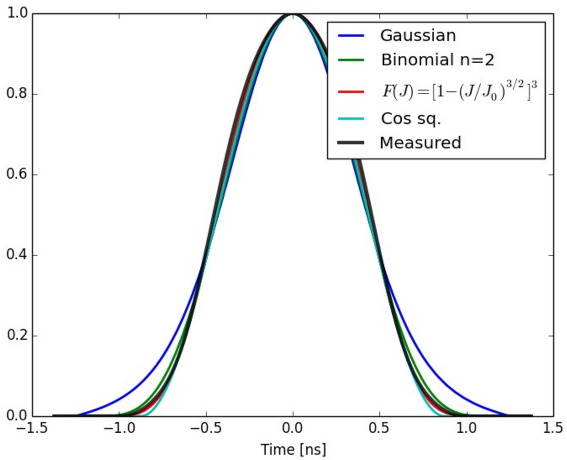


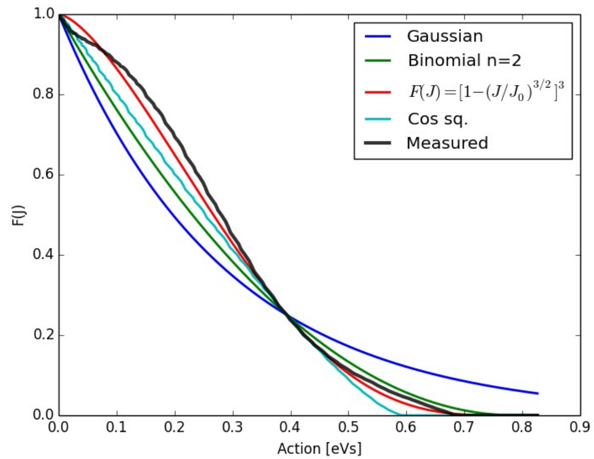
Beam stability in the LHC: Simulations

- **LHC impedance model (N. Mounet):**
  - Collimators
  - Beam screens
  - Vacuum pipe in warm sections
  - Broad-band (LHC DR)
  - Narrow-band:
    - RF cavities HOM
    - Experiments



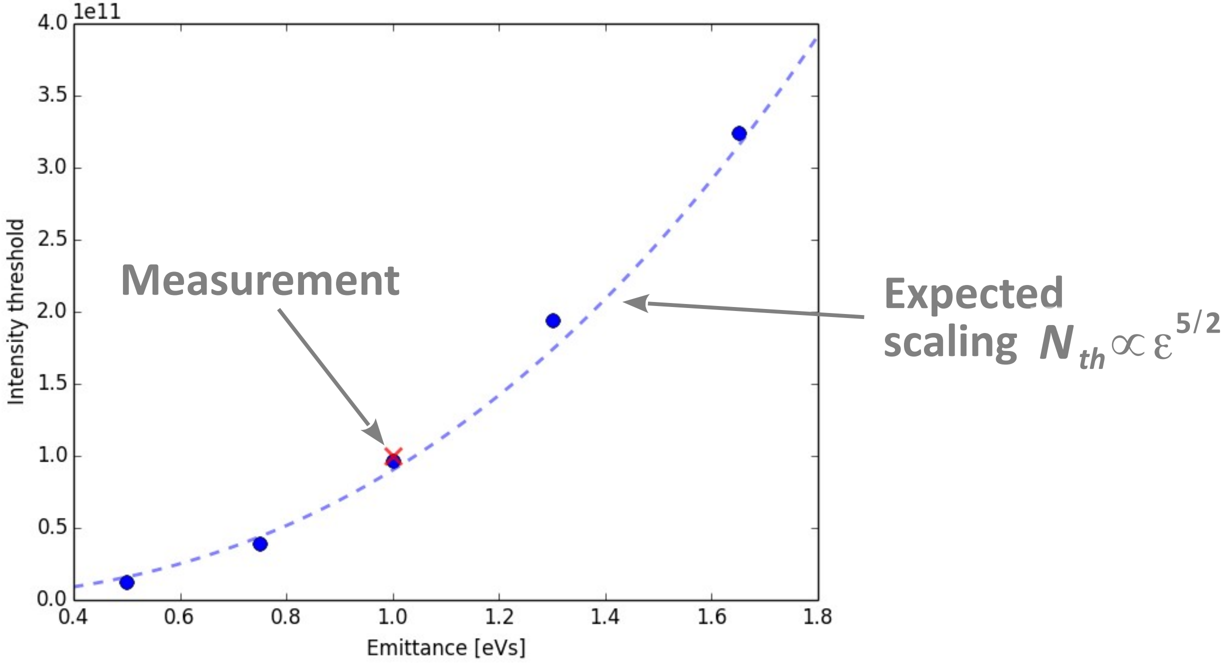
- **Bunch distribution:** Best fit with $F(J) = [1 + (J/J0)^{1.5}]^3$





Simulation results for LHC (1/2)

Intensity threshold for different emittances:



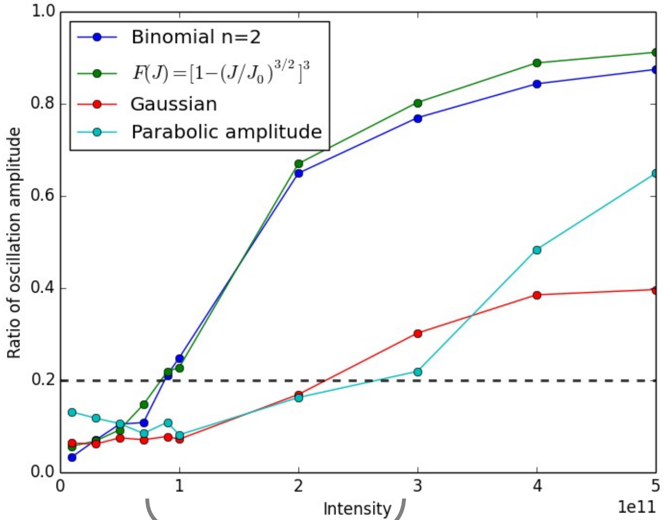
➔ **Good agreement between measurements and simulations**

Simulation results for LHC (2/2)

Effect of bunch distribution on threshold

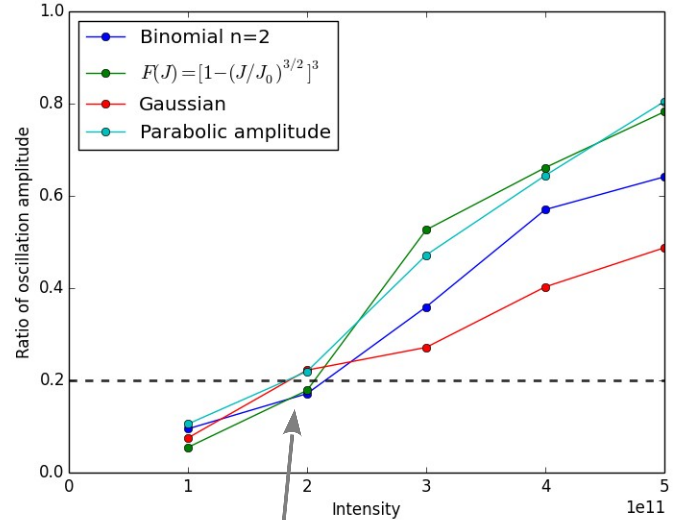
(for constant maximum bunch length or FWHM)

Full emittance – 1 eVs



Large variation of the threshold

Bunch length from FWHM – 0.8 ns



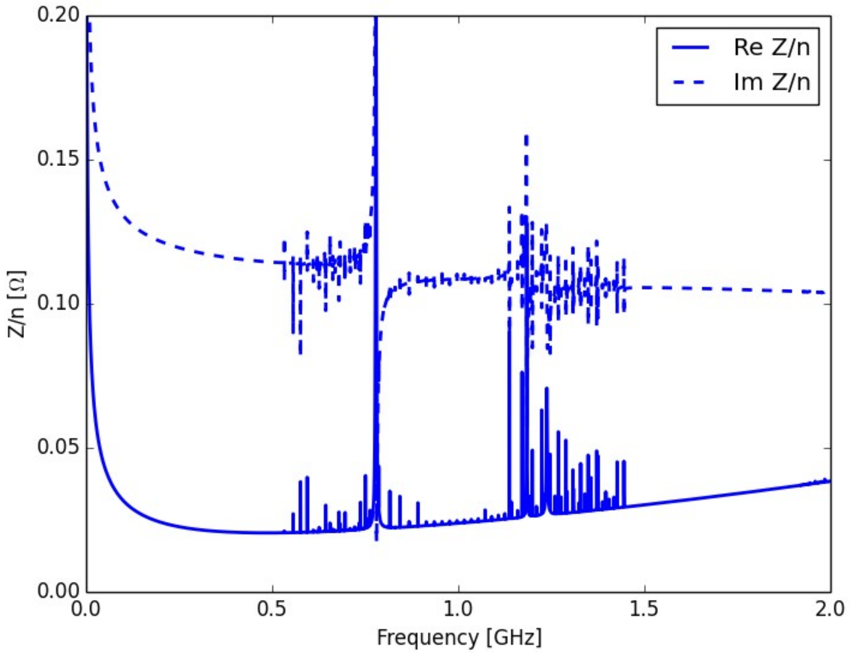
Almost independent on the distribution

<u>Note that LHC BQM is using FWHM!</u>

HL-LHC longitudinal impedance model

Modifications wrt. LHC impedance model (N. Mounet):

- Collimators
- Triplets
- HOM of experiments
- Crab cavities
- Pumping holes
- Wire compensator



➔ ~40 % increase in Im Z/n (≈ 0.11 Ω)

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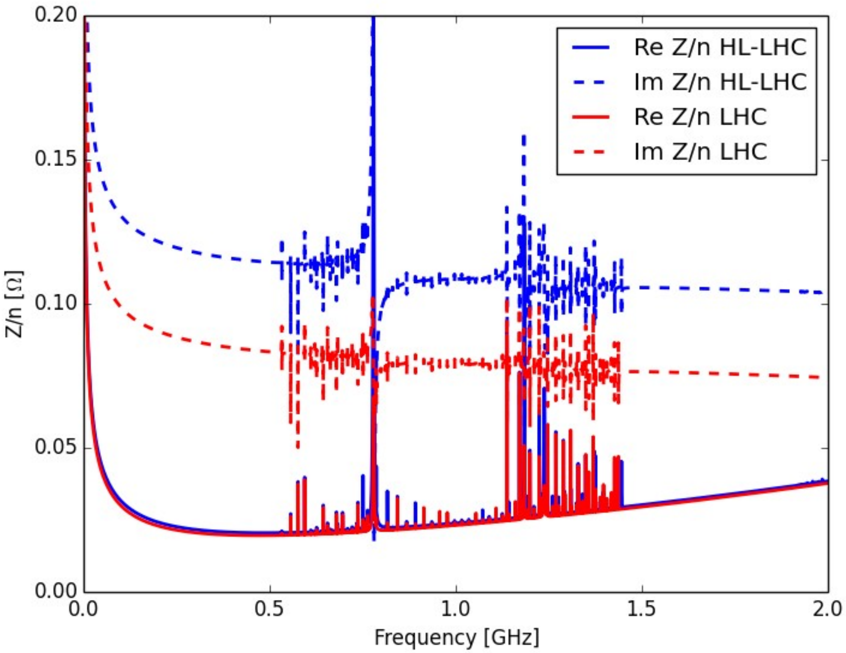

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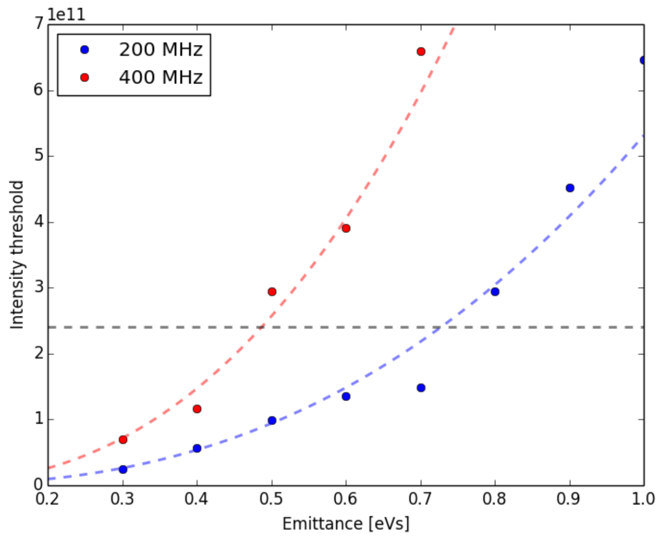
Beam stability at injection in the HL-LHC

- **Assuming the same particle distribution as in the LHC**
- **For N_b = 2.4 x 10^{11}, minimum emittance in single RF:**
  - **3 MV @ 200 MHz: 0.73 eVs (2.03 ns)**
  - **6 MV @ 400 MHz: 0.49 eVs (1.20 ns)**



Simulations confirm the scaling from loss of Landau damping:

$$\varepsilon_{th} \propto \frac{h^{7/10}}{V^{1/10}} \Rightarrow \left(\frac{h_{400}}{h_{200}}\right)^{\frac{7}{10}} \left(\frac{V_{200}}{V_{400}}\right)^{\frac{1}{10}} = 1.51$$

Beam stability at 7 TeV in the HL-LHC Single RF

Loss of Landau damping – scaling from LHC at 4 Tev:

$$N_{th} \propto \frac{\varepsilon^{5/2} h^{7/4}}{\Im Z/n \, E^{5/4} V^{1/4}}$$

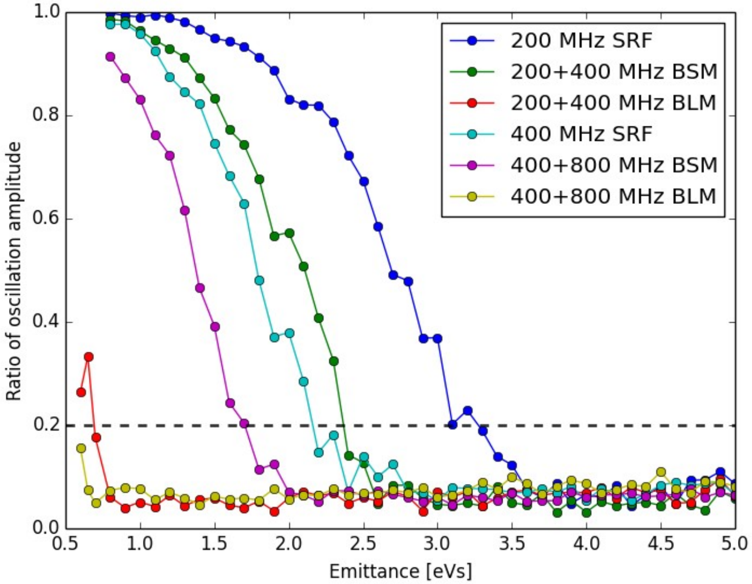
- **400 MHz RF:** 16 MV, 2.5 eVs (1.05 ns) → $N_{th} = 3.32 \times 10^{11}$
  - → HL-LHC 25 ns beam stable
  - → Unstable for HL-LHC 50 ns beams ($N_b = 3.5 \times 10^{11}$) → Larger emittance or high harmonic RF needed
- **200 MHz RF:** 6 MV, 2.5 eVs (1.57 ns) → $N_{th} = 1.26 \times 10^{11}$
  - Unstable for HL-LHC parameters → Larger emittance or high harmonic RF needed

Beam stability at 7 TeV in the HL-LHC Double RF (1/2)

Minimum emittance (and bunch length) for stability:

	N_b	Single RF	BSM	BLM
200 + 400 MHz 6 MV, 3 MV	2.4×10^{11}	3.25 eVs (1.8 ns)	2.38 eVs (1.31 ns)	0.70 eVs (1.25 ns)
400 + 800 MHz 16 MV, 8 MV	2.2×10^{11}	2.16 eVs (0.97 ns)	1.72 eVs (0.77 ns)	~0.45 eVs (0.65 ns)

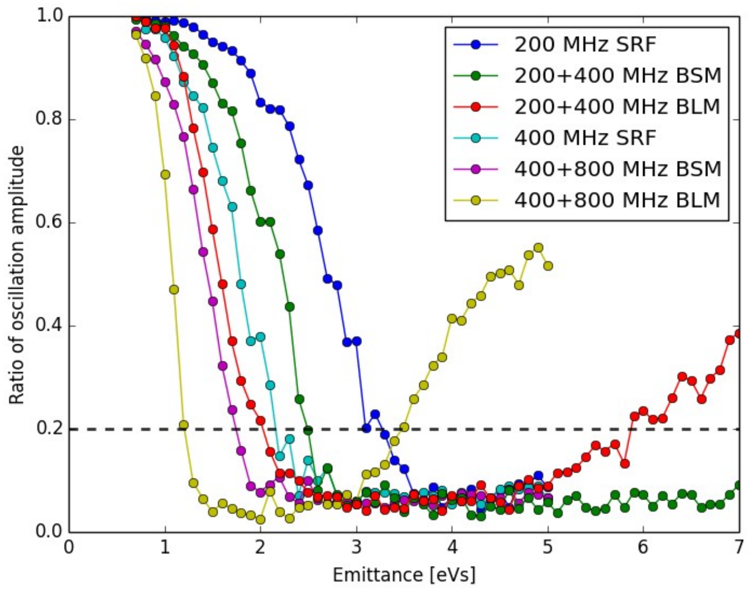
- **More stable with high harmonic:**
  - **BLM better than BSM for the same emittance, but similar for the same bunch length**
  - **~50 % larger emittance needed for 200 MHz compared to 400 MHz**



Beam stability at 7 TeV in the HL-LHC Double RF (2/2)

Voltage ratio: 0.25

- **In BSM, stability margin slightly reduced compared to ratio 0.5**
- **In BLM, stability margin is reduced substantially and there is also a limit to the maximum emittance:**
  - **200+400 MHz: 3.5 eVs (2.04 ns)**
  - **400+800 MHz: 5.9 eVs (1.77 ns)**



Minimum emittance (and bunch length) for stability:

	N_b	Single RF	BSM	BLM
200 + 400 MHz 6 MV, 1.5 MV	2.4×10^{11}	3.25 eVs (1.8 ns)	2.47 eVs (1.43 ns)	2.09 eVs (1.60 ns)
400 + 800 MHz 16 MV, 4 MV	2.2×10^{11}	2.16 eVs (0.97 ns)	1.76 eVs (0.80 ns)	1.21 eVs (0.80 ns)

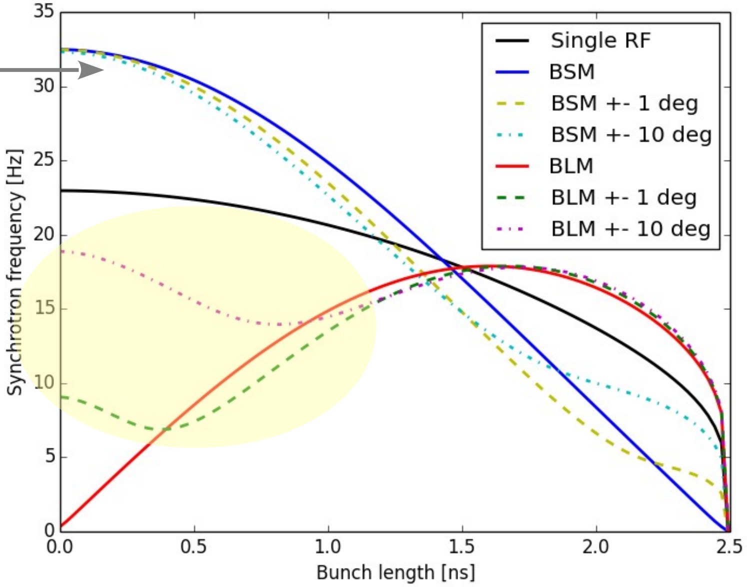
Beam stability at 7 TeV in the HL-LHC
Effect of a phase shift between the RF systems (1/2)

Beam loading introduces a phase shift between the RF systems (full-detuning scheme)

➔ **Synchrotron frequency distribution changes with a phase shift**

Small effect in BSM

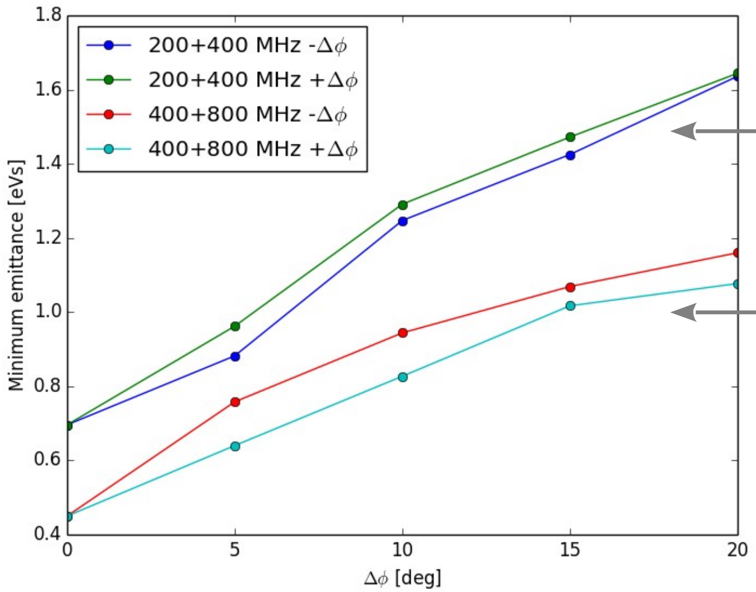
Very strong effect in BLM even for a small phase shift



Beam stability at 7 TeV in the HL-LHC
Effect of a phase shift between the RF systems (2/2)

Minimum emittance needed for stability:

- **No change for BSM (up to 20 deg at main RF frequency)**
- **BLM: minimum emittance increases with the phase shift**



$N_b = 2.4 \times 10^{11}$
200 MHz: 6 MV
400 MHz: 3 MV

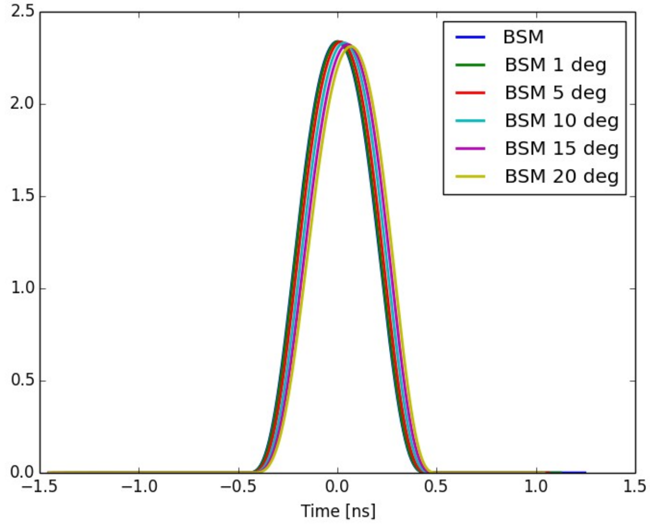
$N_b = 2.2 \times 10^{11}$
400 MHz: 16 MV
800 MHz: 8 MV

Effect of a phase shift between the RF systems

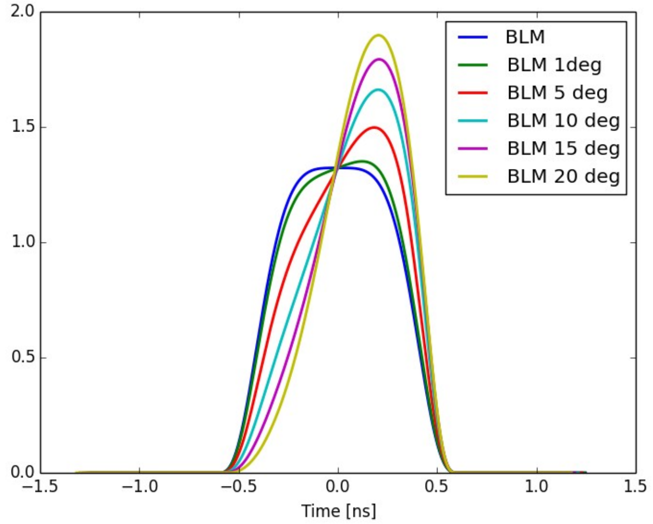
Bunch shape is also modified by the phase shift:

- **Slightly tilted in BSM**
- **Strongly distorted in BLM – flat shape is lost**

BSM



BLM



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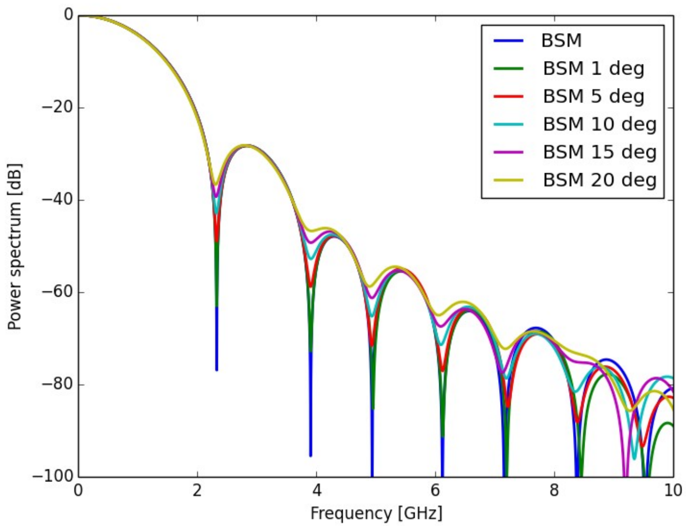
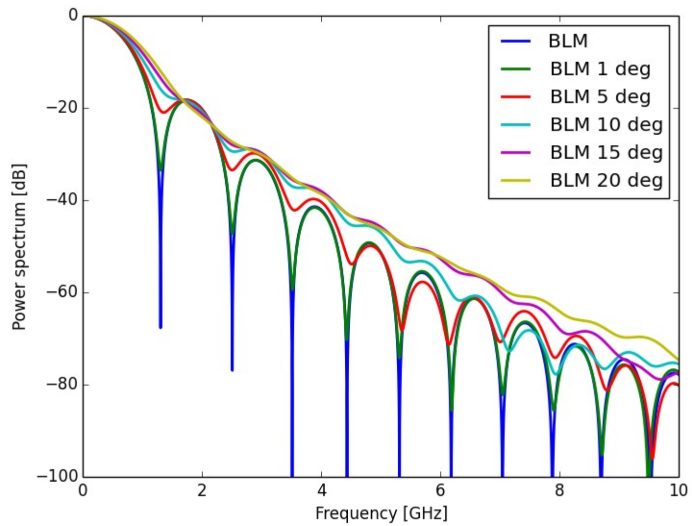
BSM

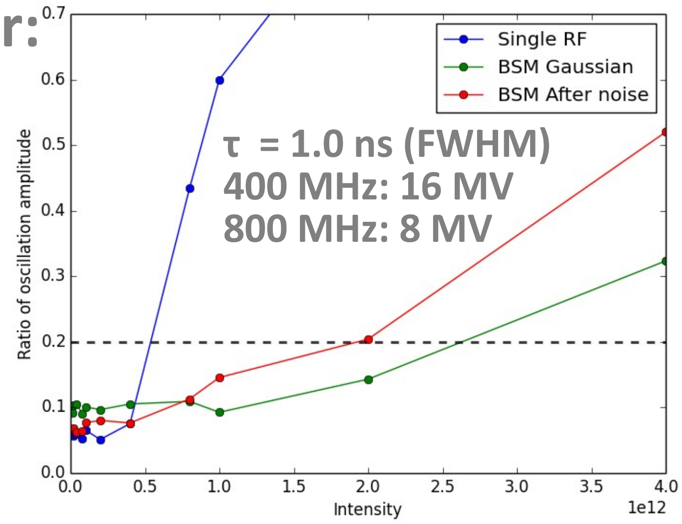


BLM

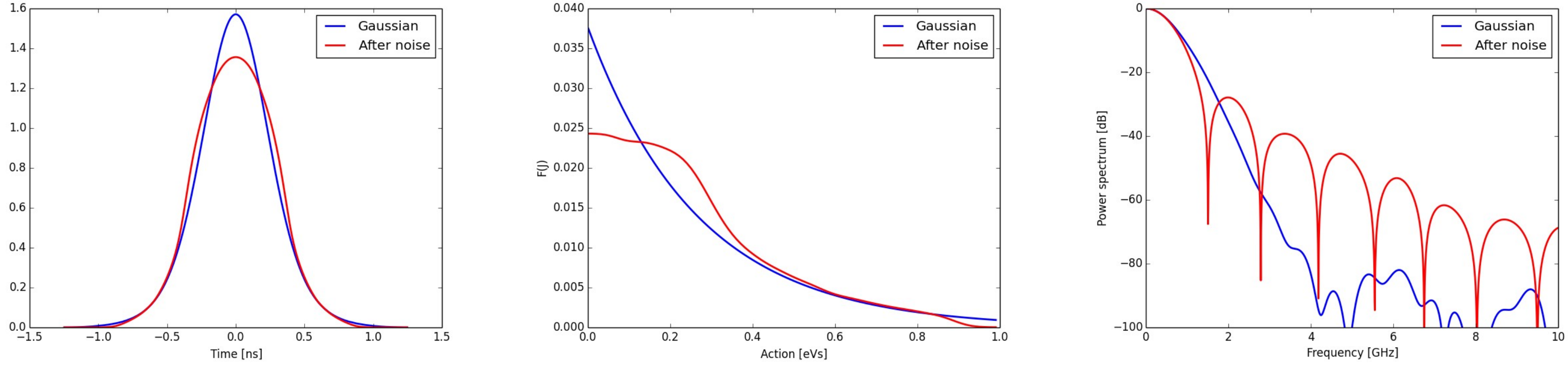


Stability of "flat" bunches in BSM
(HL-LHC at 7 TeV)

- **Flatter bunches could be beneficial for:**
  - **Beam induced heating (low freq.)**
  - **Pile-up in experiments**
- **Stability threshold slightly reduced, but 4 times higher than in single RF**



Flatter bunch produced with controlled longitudinal emittance blow-up with band limited noise (courtesy of H. Timko)



Summary

- Present LHC impedance model was tested in single bunch measurements and simulations
- Single bunch is stable in 400 MHz for HL-LHC 25 ns, but unstable for HL-LHC 50 ns → Larger emittance or high harmonic RF
- ~ 50 % larger emittance needed for stability in 200 MHz compared to 400 MHz (and longer bunches)
- BLM is very sensitive to a phase shift between the RF systems:
  - Stability is degraded
  - Bunch shape and spectrum are distorted
- Flatter bunches in BSM are slightly less stable, but still acceptable for HL-LHC intensities
- Coupled bunch instabilities were not studied

References

[1] F. J. Sacherer *et al.*, "A longitudinal stability criterion for bunched beams," IEEE Trans. Nucl. Sci. NS-20, p.825 (1973)

[2] E. Shaposhnikova *et al.*, "Loss of Landau damping in the LHC," IPAC'11, San Sebastian, Spain (2011)

[3] J. F. Esteban Müller *et al.*, "Beam measurements of the LHC impedance and validation of the impedance model," IPAC'14, Dresden, Germany (2014)

[4] "LHC Design Report," CERN-2004-003, Geneva, Switzerland, 2004

[5] N. Mounet, "The LHC transverse coupled-bunch instability," PhD Thesis, 2012

[6] T. Argyropoulos *et al.*, "Thresholds of longitudinal single bunch instability in single and double RF systems in the CERN SPS," IPAC'12, New Orleans, USA

[7] E. Shaposhnikova *et al.*, "Flat bunches in the LHC," IPAC'14, Dresden, Germany (2014)

[8] B. Salvant *et al.*, "Beam induced RF heating," LHC operation workshop, Evian, France (2012)

High Luminosity LHC

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