Beam stability with harmonic system

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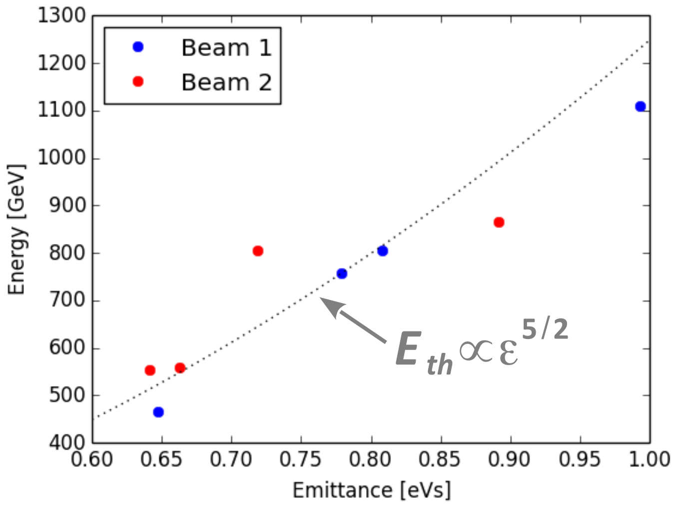
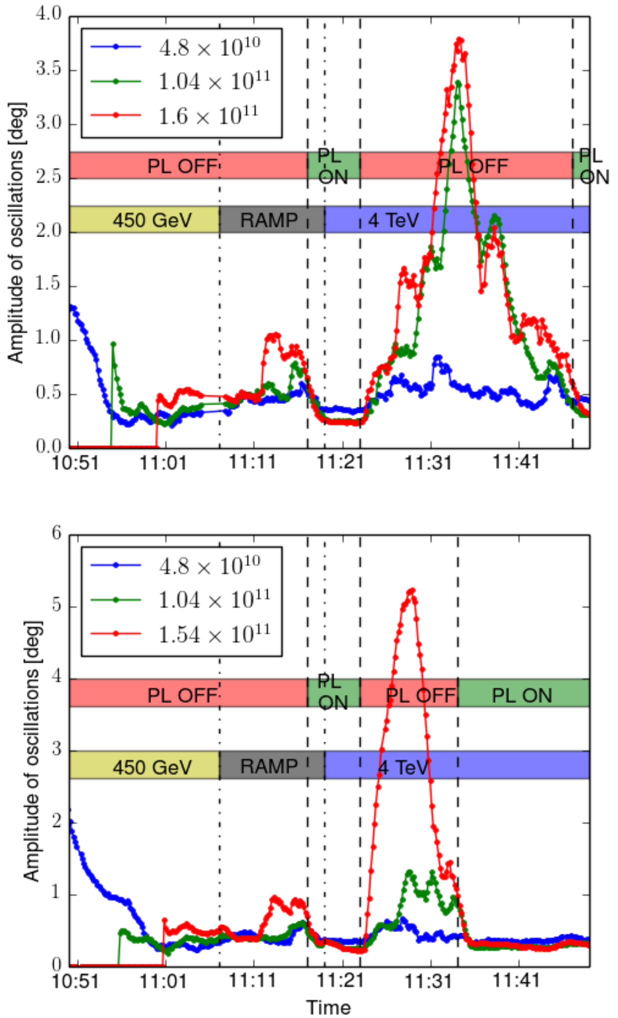
Outline

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

Beam stability in the LHC
Measurements

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





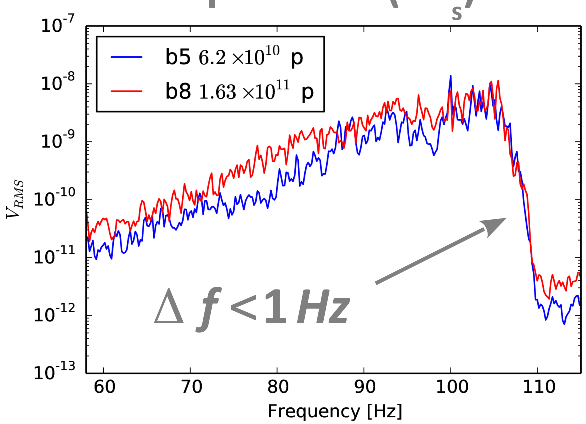
- **At 4 Tev, 12MV with 1 eVs:**
  - ➔ **$N_{th} \approx 1 \times 10^{11}$ (Only one meas.)**
- **Coupled bunch instability: <u>not observed so far</u>**

Beam stability in the LHC
Measurements

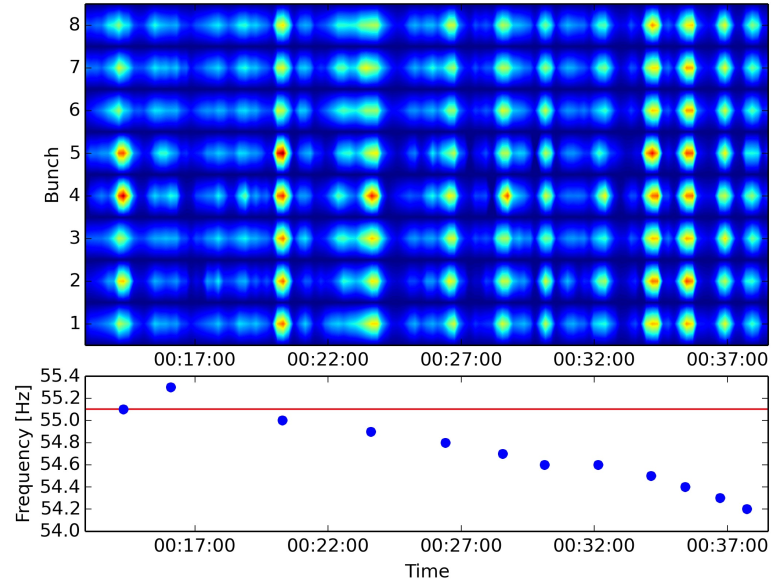
- **Reactive part of the longitudinal impedance validated from synchrotron frequency shift:**

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

Peak-detected Schottky spectrum (2 f_s)



Excitation by RF phase modulation

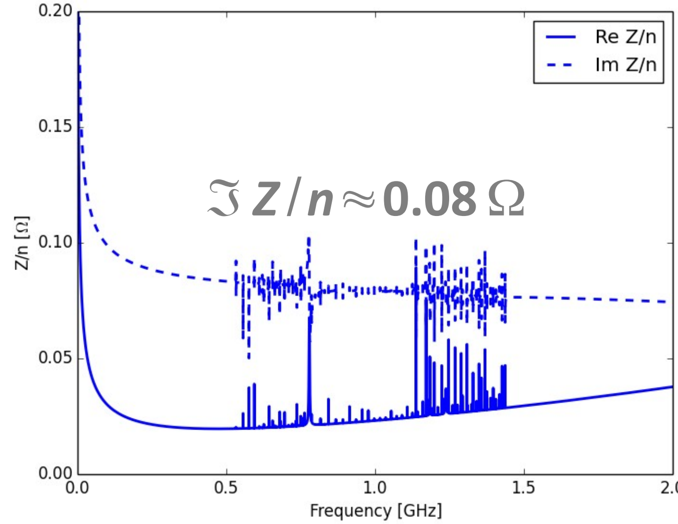


- **Measurements confirm that** $\Im Z/n < 0.1\,\Omega$

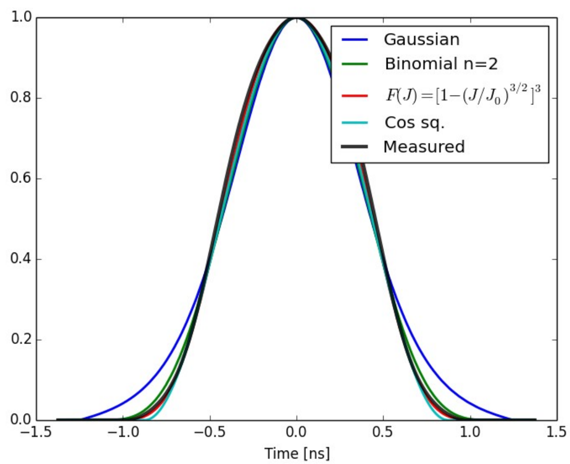
Beam stability in the LHC

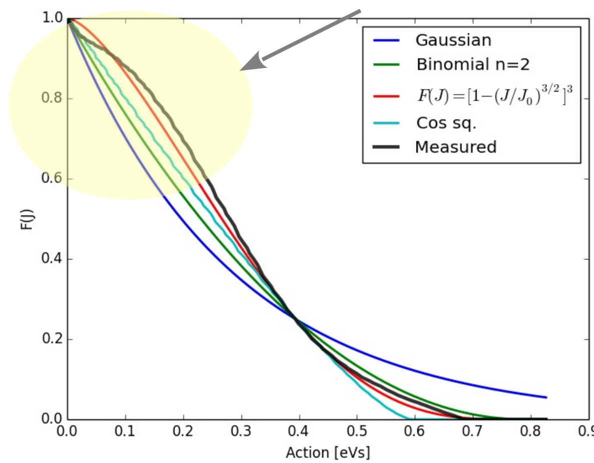
Simulations

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



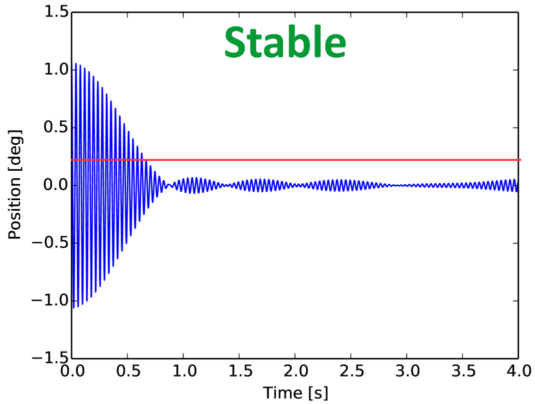
- **Bunch distribution: Best fit with $F(J) = [1 + (J/J0)^{1.5}]^3$ → Effect of controlled emittance BUP with PL on?**

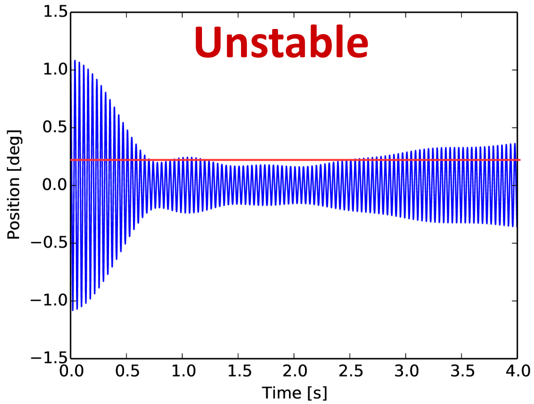


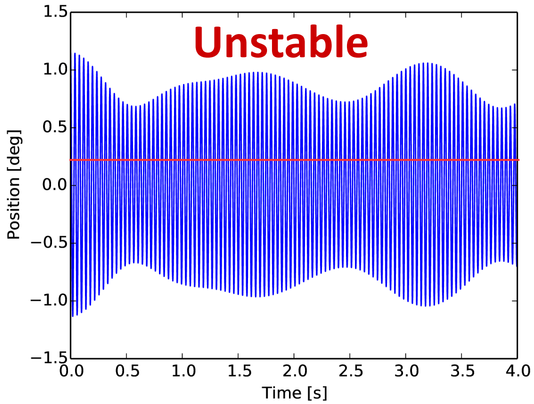


Beam stability in the LHC
Simulations

- **Method:**
  1) **Particles distribution matched in the bucket with intensity effects**
  2) **Phase kick of 1º**
  3) **Stability criterion: stable if oscillations amplitude is reduced below 0.2º**



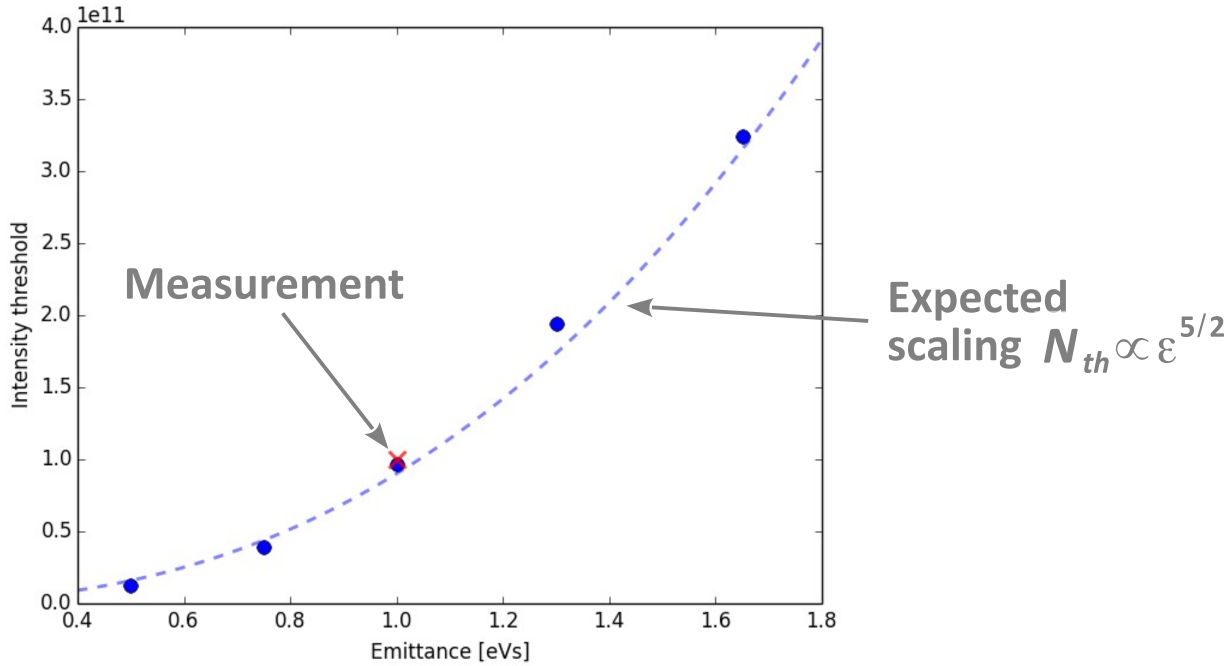




Beam stability in the LHC
Simulations

Scan of the intensity threshold for different emittances:

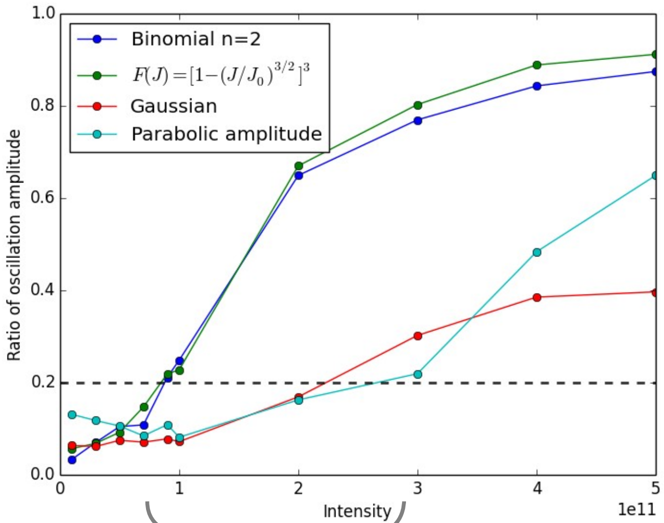
➔ **Good agreement between measurements and simulations**



Beam stability in the LHC
Simulations

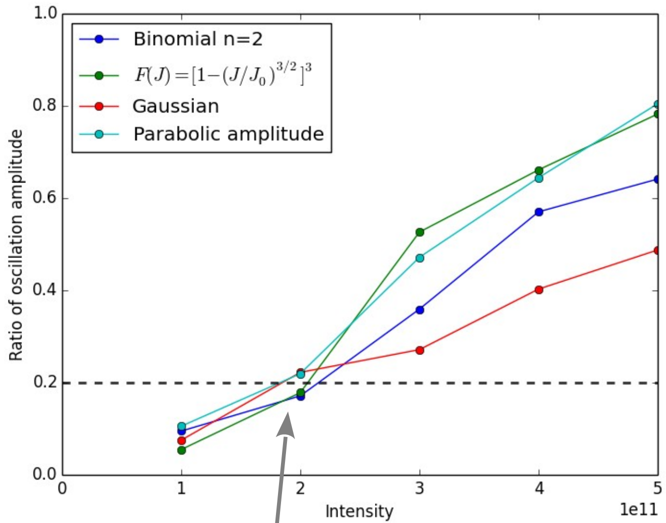
Effect of bunch distribution - dependence on the parameter chosen for the comparison:

1 eVs (0.8 ns) – full emittance



Large variation of the threshold

0.8 ns – from FWHM



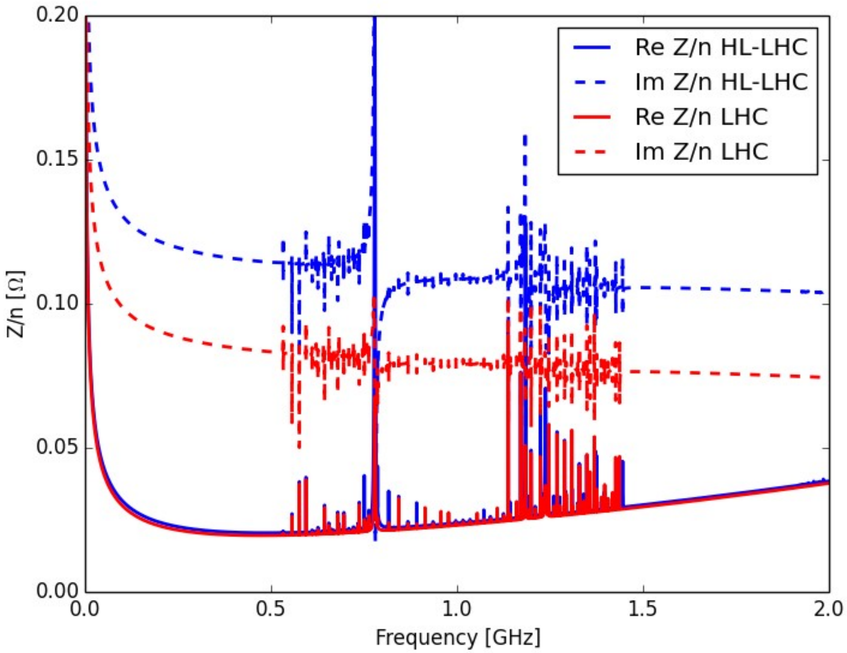
Almost independent on the distribution

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

HL-LHC longitudinal impedance model

Modifications wrt. LHC impedance model:

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

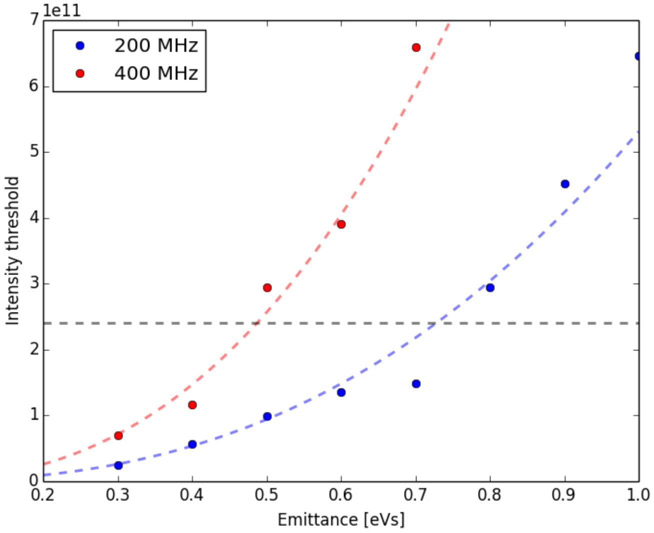


➔ **~40 % increase in Im Z/n:** $\Im Z/n \approx 0.11\,\Omega$

Beam stability in the HL-LHC

Injection

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



Simulations confirm the scaling:

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

Beam stability in the HL-LHC

7 TeV – Single RF

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

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

- **400 MHz, 16 MV, 2.5 eVs (1.05 ns) → N_{th} = 3.32 x 10^{11}**
  - ➔ **25 ns beam stable with 400 MHz system in single RF**
  - ➔ **High harmonic system would be needed for 50 ns beams (N_b 3.5 x 10^{11}) also with 400 MHz main RF system**
- **200 MHz, 6 MV, 2.5 eVs (1.57 ns) → N_{th} = 1.26 x 10^{11}**
  - ➔ **High harmonic system is needed in any case for stability with 200 MHz main RF system**

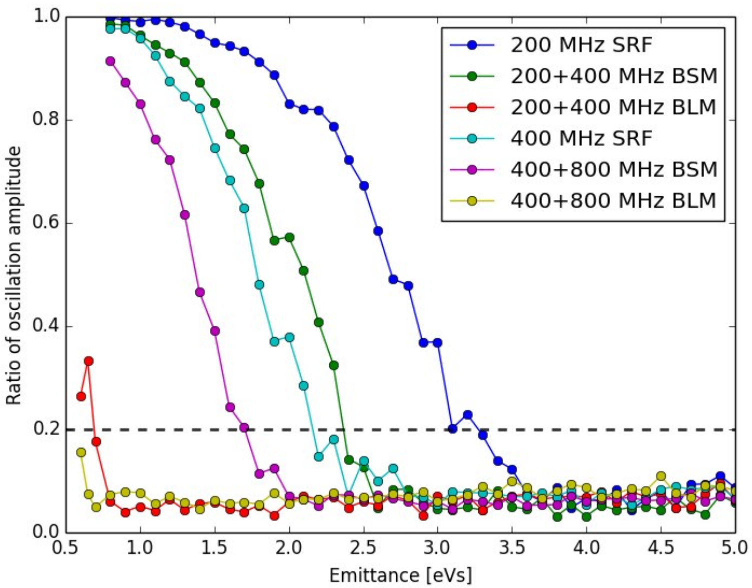
Beam stability in the HL-LHC

7 TeV with harmonic system

Minimum emittance (and bunch length):

	Single RF	BSM	BLM
200 + 400 MHz	3.25 eVs (1.8 ns)	2.38 eVs (1.31 ns)	0.70 eVs (1.25 ns)
400 + 800 MHz	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**
- **400 MHz single RF is more stable than 200+400 MHz in BSM**



Beam stability in the HL-LHC

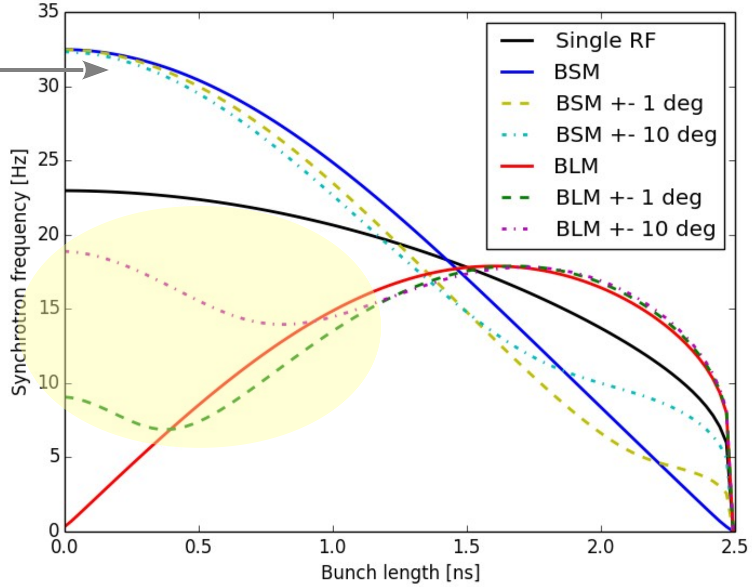
7 TeV – Effect of a phase shift between the RF systems

If the full-detuning scheme is used, too much power is required to keep a constant phase shift between the RF systems along the bunch trains

➔ Synchrotron frequency distribution changes with a phase shift

Small effect in BSM

Very strong effect in BLM even for a small phase shift

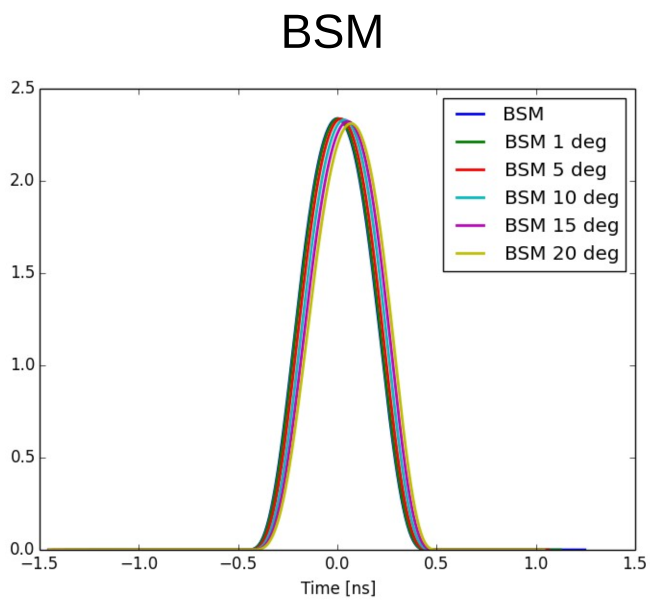


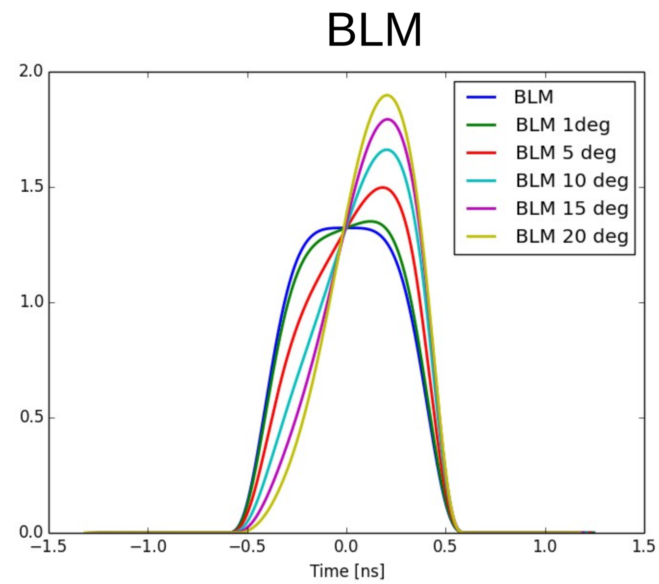
Beam stability in the HL-LHC

7 TeV – 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**



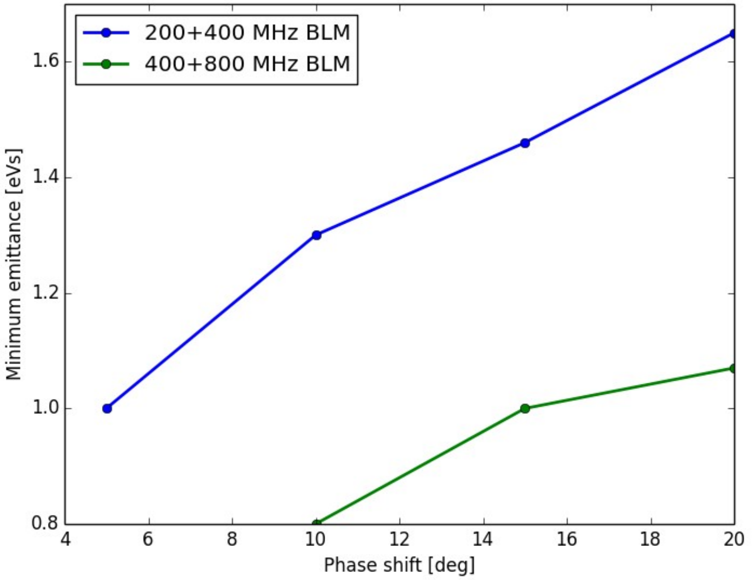


Beam stability in the HL-LHC

7 TeV – Effect of a phase shift between the RF systems

Minimum emittance required:

- **Doesn't change for BSM**
- **BLM: emittance increases with the phase shift, although corresponding bunch length is constant:**
  - **200+400 MHz: 1.35 ns**
  - **400+800 MHz: 0.73 ns**



Summary

- **Present LHC impedance model was tested in measurements and simulations**
- **Single bunch is stable in 400 MHz for the 25 ns baseline – High harmonic system needed for 50 ns**
- **Single bunch is more stable in 400 MHz than in 200+400 MHz in BSM**
- **BLM is very sensitive to a phase shift between the RF systems:**
  - **Stability is degraded**
  - **Bunch shape is distorted**
- **Coupled bunch instabilities were not studied**

High
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LHC

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