Longitudinal stability limits and bunch length specifications

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HL-LHC WP2 meeting

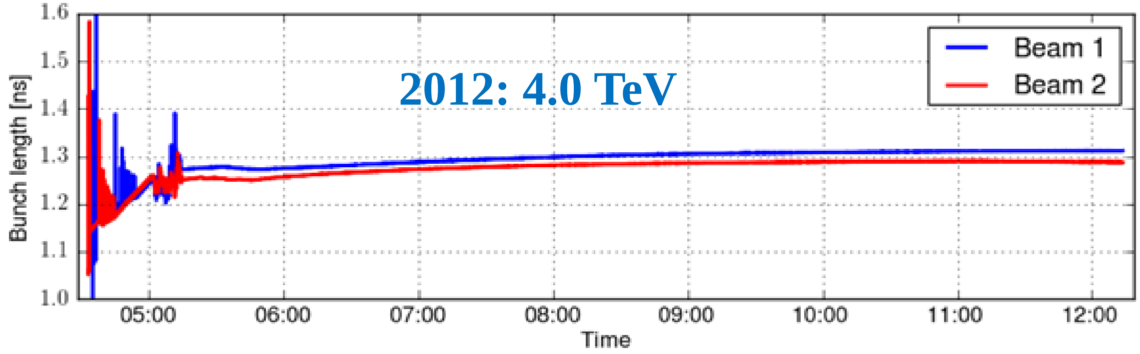
23 September 2016

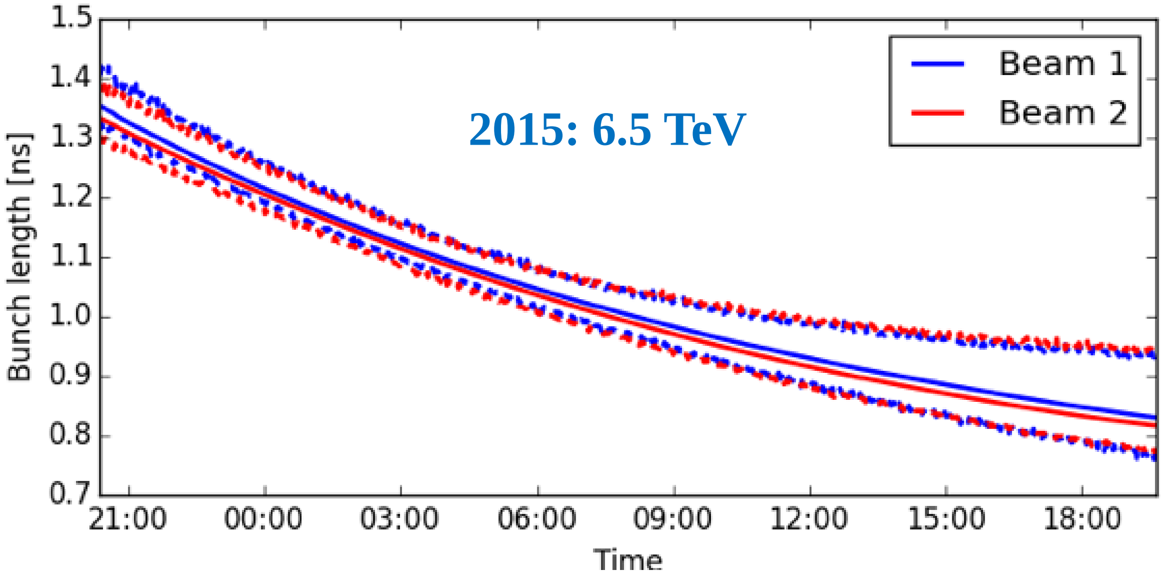
Outline

- Experience from present LHC operation
  - Bunch length
  - Stability
  - Longitudinal emittance blow-up
- HL-LHC
  - Single RF operation
  - Double RF operation
    - higher harmonic
    - lower harmonic

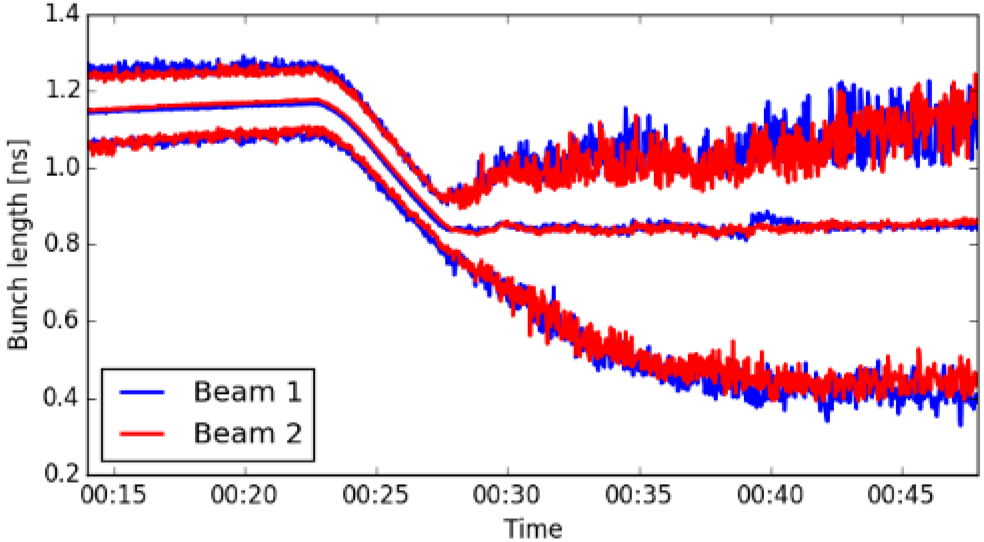
LHC

Bunch length during physics





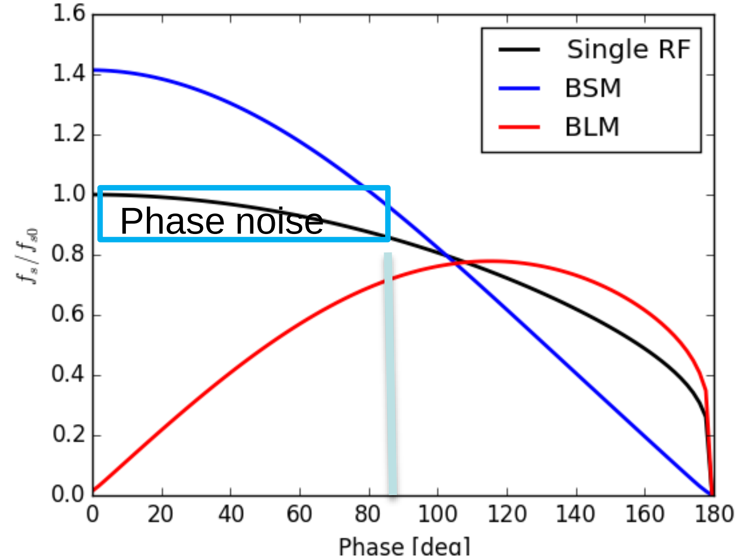
Controlled emittance blow-up



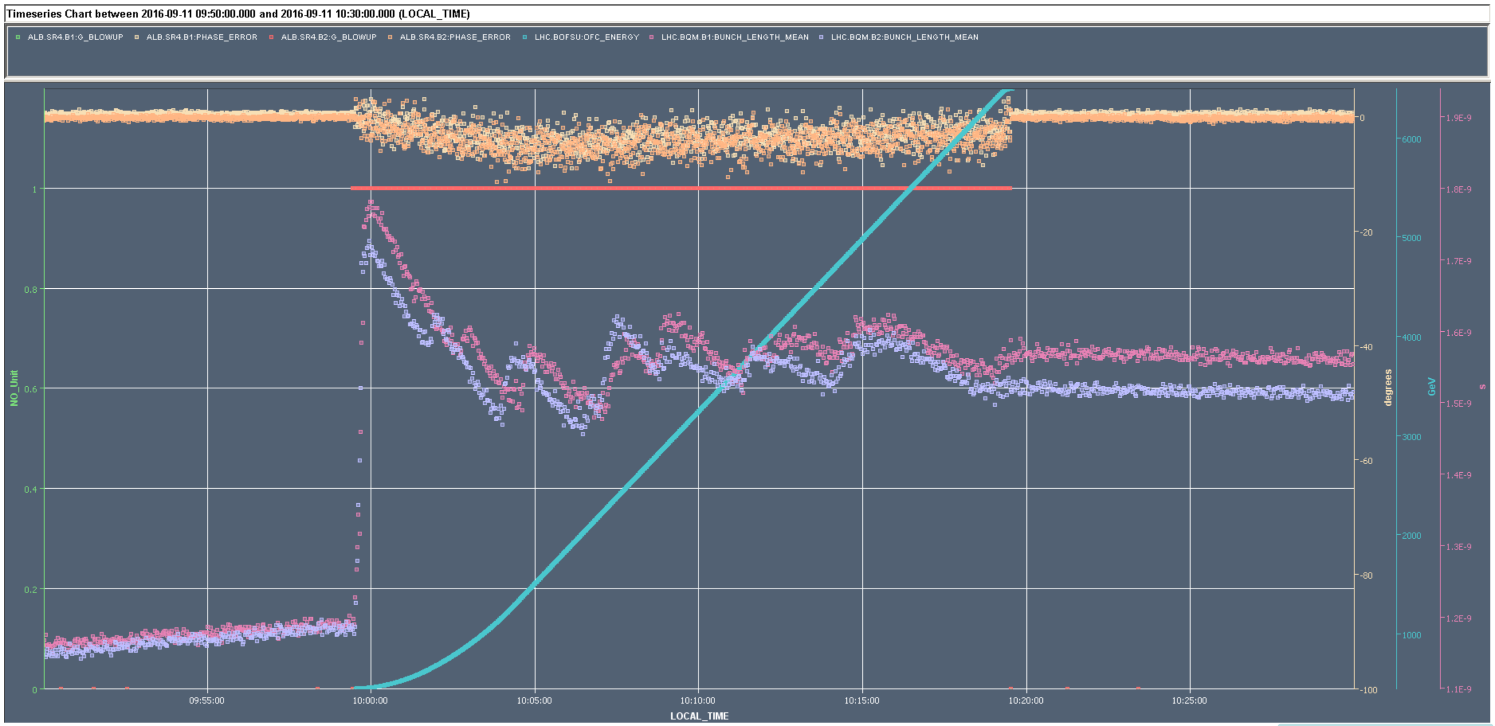
→ Bunch length bifurcation during emittance blow-up for 0.85 ns target length in 2015 MD (H. Timko et al., Evian workshop)

→ Similar observations in 2016 MDs and initial operation with reduced bunch length

Synchrotron frequency distribution inside the bunch



(Un)controlled emittance blow-up



H. Timko

→ Maximum bunch length ~1.5 ns limited by losses (~5%) from the RF bucket (recent ATS MD, ramp with target bunch length 1.2 s, maximum gain in BL FB)

Beam parameters

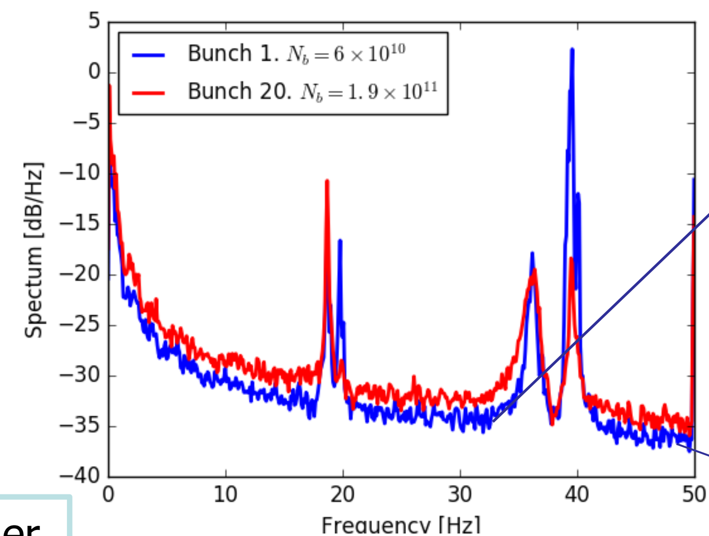
- Bunch-to-bunch variation (from injectors) leads to different synchrotron frequency shifts and therefore emittance blow-up (denser bunches are blown up less)

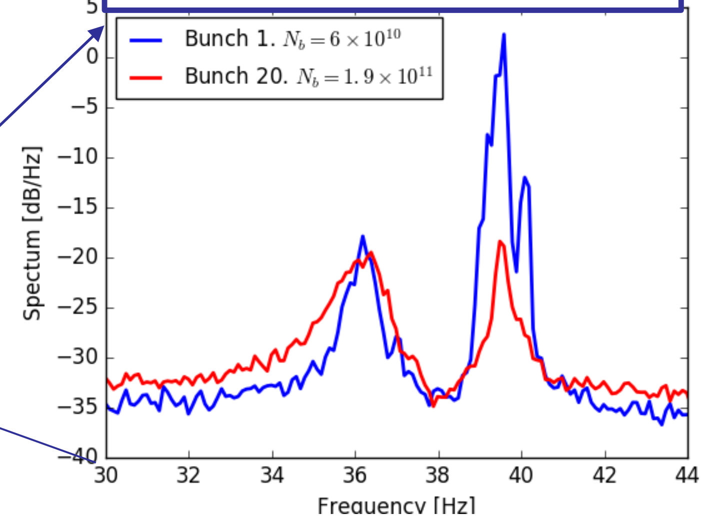
→ Bunch-to-bunch length variation after controlled emittance blow-up (BUP)

- Beam-to-beam and fill-to-fill variation (also due to action of bunch length feedback)

→ Variation in instability threshold

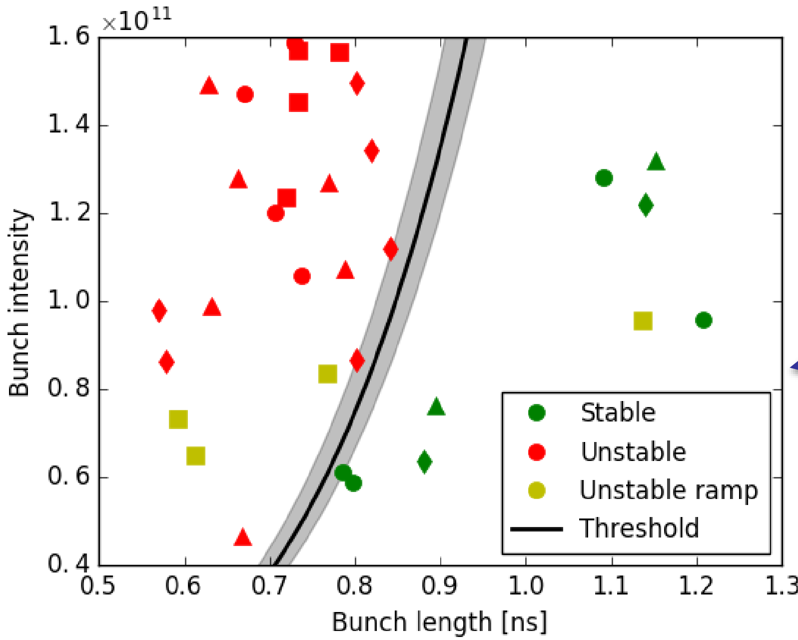
Synchrotron frequency distribution after BUP (PD Schottky spectrum)





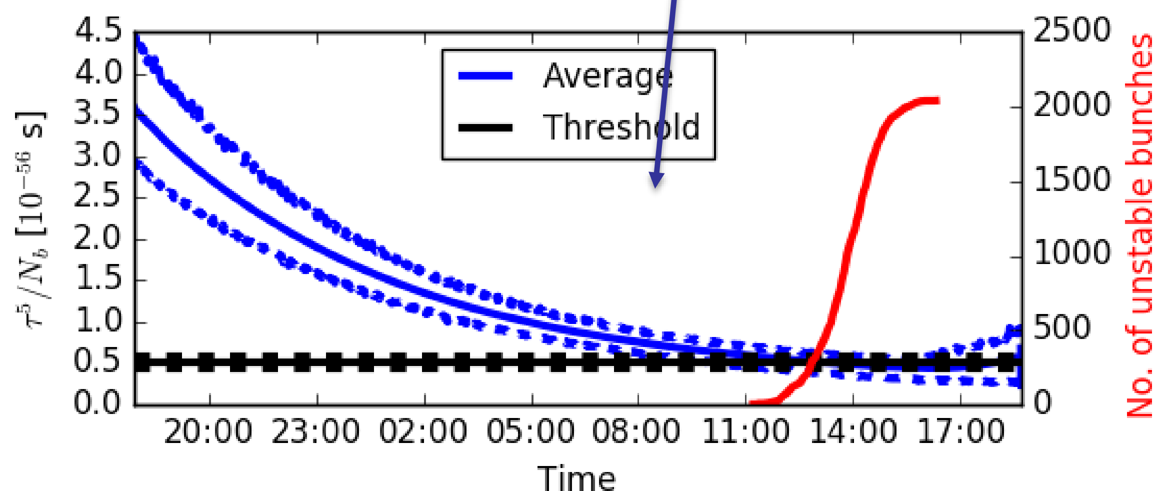
J. E. Muller

Longitudinal beam stability in LHC



J. E. Muller et al.

Single bunch stability threshold is well defined by measurements in MDs and operation (long fills)



No wideband FB in LHC → we rely on Landau damping

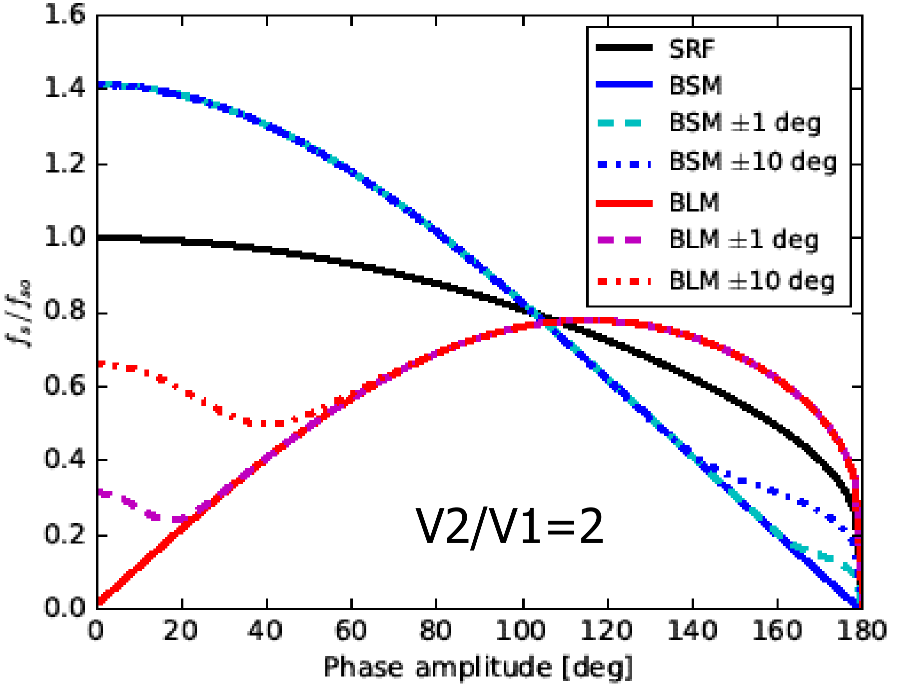
Single bunch instability, no coupled-bunch modes were observed so far

HL-LHC

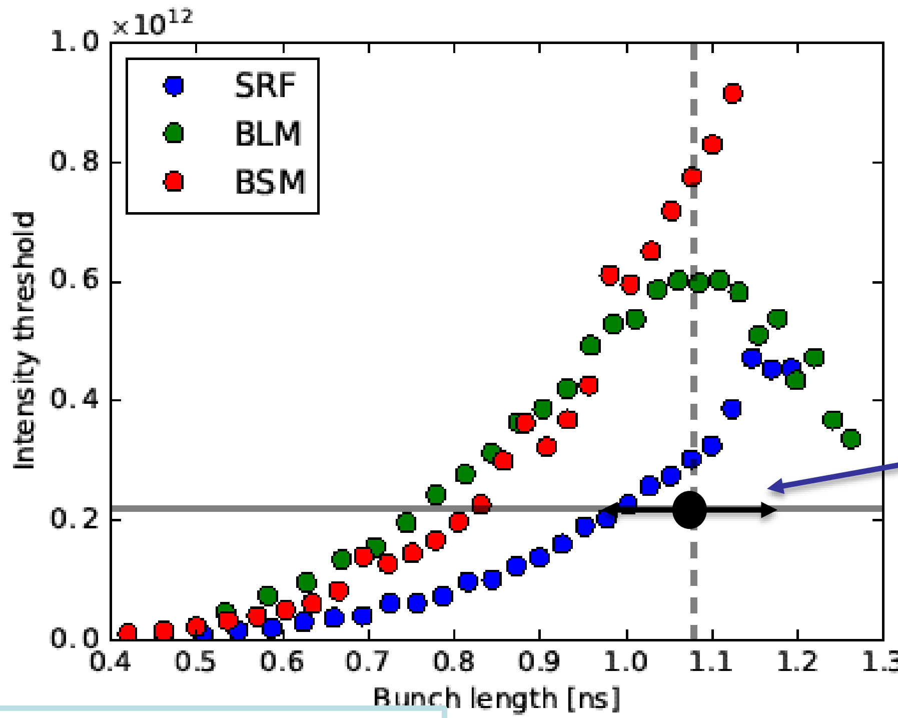
Double RF operation

Full detuning scheme will be used in operation for high intensity beams (P. Baudrenghien et al.)
leading to bunch displacements

→ Only bunch-shortening operation mode is really feasible in a double RF system



Longitudinal beam stability in HL-LHC
400 MHz & (400 MHz + 800 MHz) RF



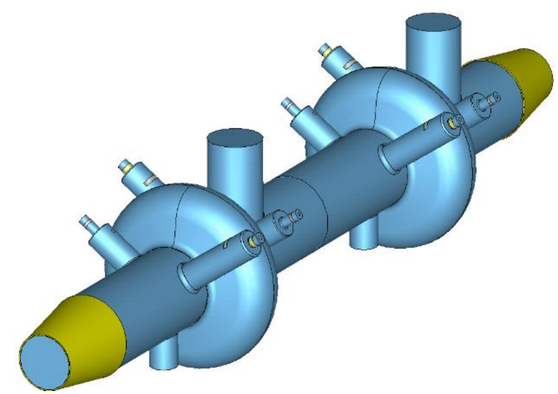
J. E. Muller, PhD thesis

E=7 TeV, V_{400} = 16 MV, V_{800} = 4 MV
ImZ/n ~ 0.11 Ohm (N. Biancacci et al.)

→ 1.0 ns bunches are unstable

→ Voltage of 4 MV @ 800 MHz would be sufficient for stability of bunches > 0.85 ns (as now)

10% spread in bunch length



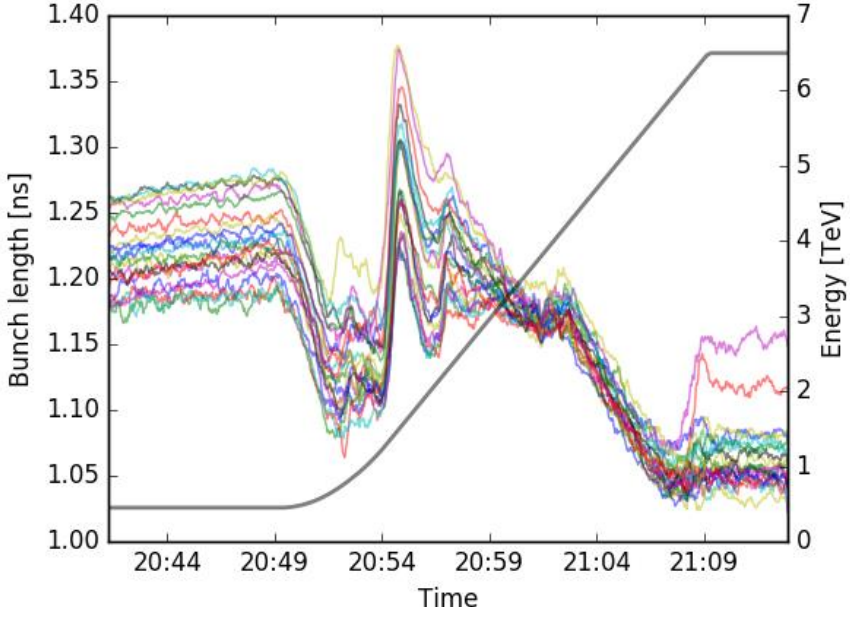
Cavity design: T. Roggen & Y. Shashkov

- Controlled longitudinal BUP, if done too close to instability threshold, may excite dipole motion
- SR leads to bunch shrinkage

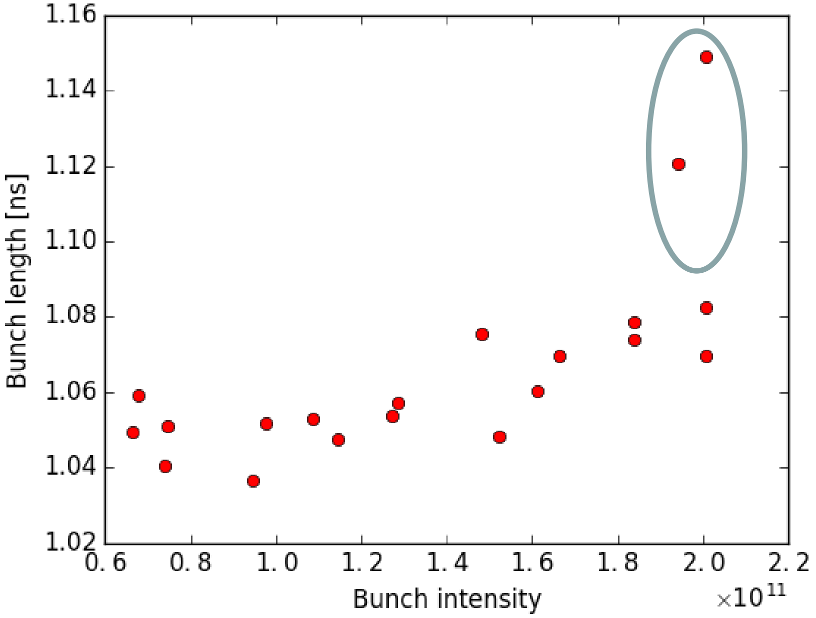
→ 1.3 ns nominal average bunch length in a single RF system

Longitudinal instability for HL-LHC intensity

Bunch length during ramp



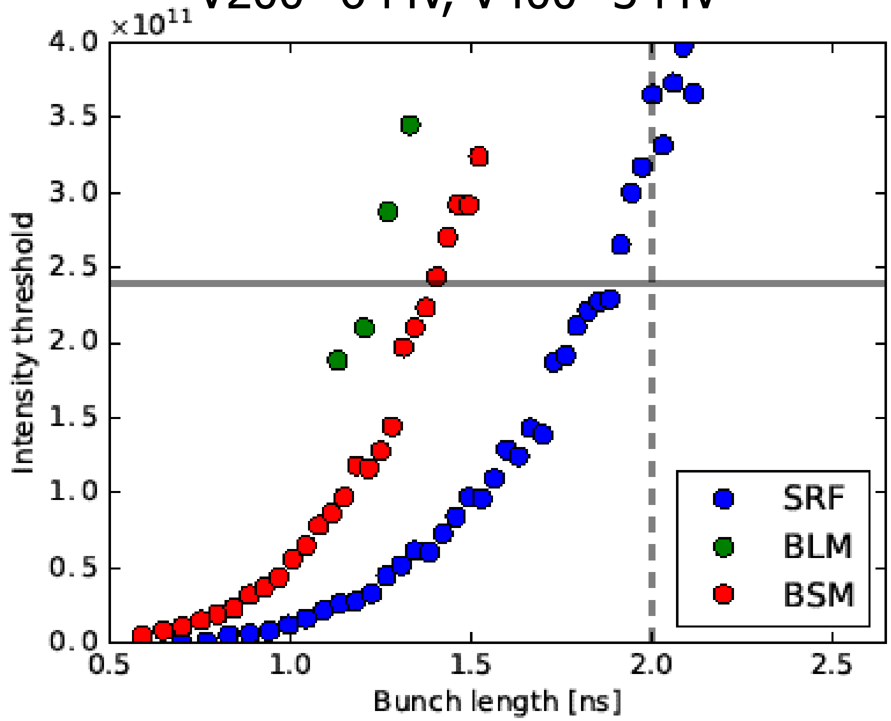
Bunch length on LHC flat top



RF MD on 25.08.2016, P. Baudrenghien, J. Muller, H. Timko, E. S.

Longitudinal beam stability in HL-LHC: 200 MHz & (200 MHz + 400 MHz) RF

V200=6 MV, V400=3 MV

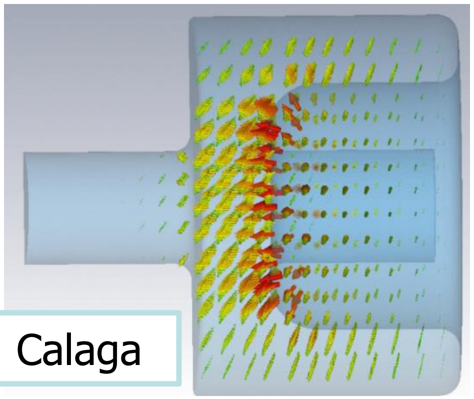


J. E. Muller, PhD thesis

→ Bunches with 2 ns length are at the limit of stability in a single RF and with 1.5 ns in a double RF system (BSM)

→ Stable operation with bunches longer than 1.5 ns

Good for reduction of e-cloud, beam-induced heating, pile-up density…



Cavity design: R. Calaga

LHC bunch emittance and stability @7 TeV in single & double RF systems for 1 ns bunches

	V1 [MV]	V2 [MV]	Emittance [eVs]	N_th
400 MHz SRF	16	0	2.19	**2.19 x 10^11**
400+800 MHz BSM	16	8	2.74	**8.13 x 10^11**
400+800 MHz BLM (no phase shift)	16	8	1.44	**> 10^12**
200 MHz SRF	6	0	1.01	**1.05 x 10^10**
200+400 MHz BSM	6	3	1.39	**4.55 x 10^10**
200+400 MHz BLM (no phase shift)	6	3	0.35	**~1 x 10^11**

N_th - threshold for loss of Landau damping for 1 ns long bunches (BLonD simulations of J. E. Muller)

"Possible beam parameters in double RF operation of the CERN LHC" in Proc. IPAC'16

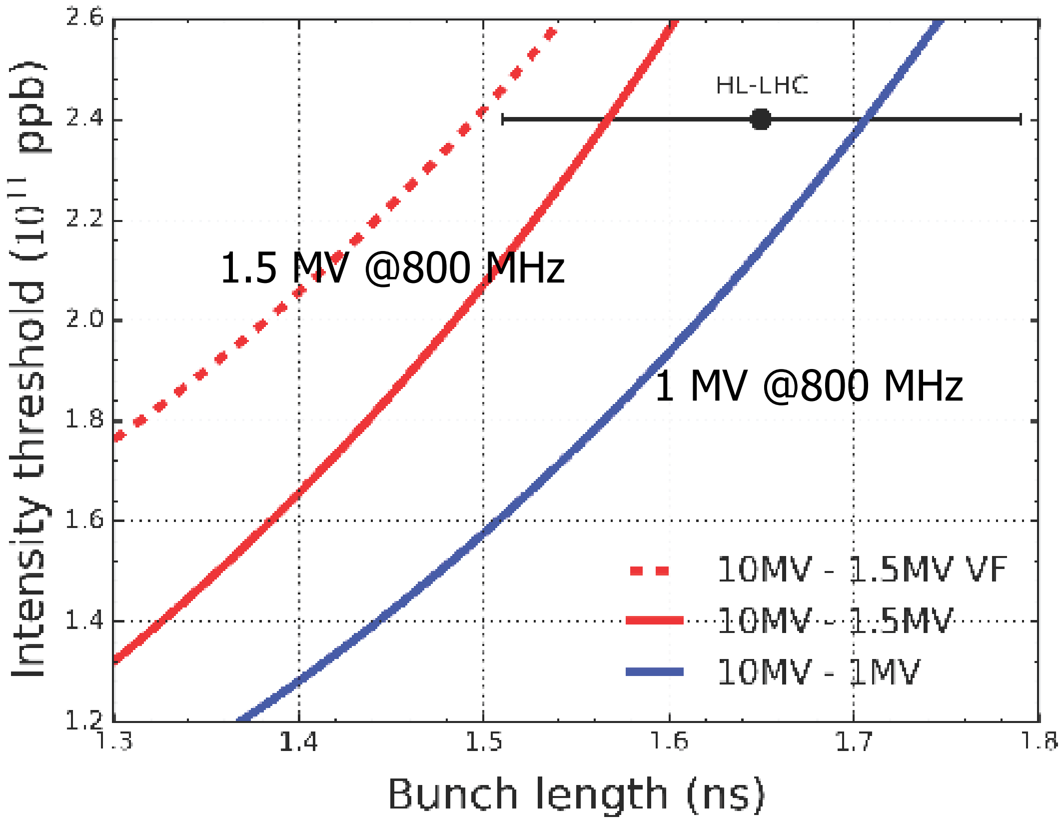
Summary I: HL-LHC

- In the 400 MHz RF system longitudinal stability of bunches with nominal HL-LHC length of 1.08 ns is at the limit. Some margins are required due to bunch-to-bunch and beam-to-beam (BUP) variation and SR shrinkage. Stability is recovered for 1.3~ns long bunches in single RF operation or with 4 MV at 800 MHz
- Possible uncertainties due to increased HL-LHC impedance in multi-bunch operation (coupled bunch instabilities?)
- Beam lifetime for bunch length more than 1.5 ns in the 400 MHz RF is reduced: → narrow operation range of (1.3 - 1.5) ns
- New operation regime with long (> 1.5 ns) bunches in 200 MHz (+ 400 MHz) RF system has many advantages
- Double RF system should make emittance blow-up more reliable

SPARE SLIDES

Capture 200 MHz RF system: needs from the SPS

Impedance reduction of vacuum flanges:
72 bunches 2RF systems (1 MV @ 800 MHz)



With 1.5 MV at 800 MHz
the threshold increase
is already sufficient,
but margin is still small

BLonD simulations
A. Lasheen & J. Repond

Possible uncertainties

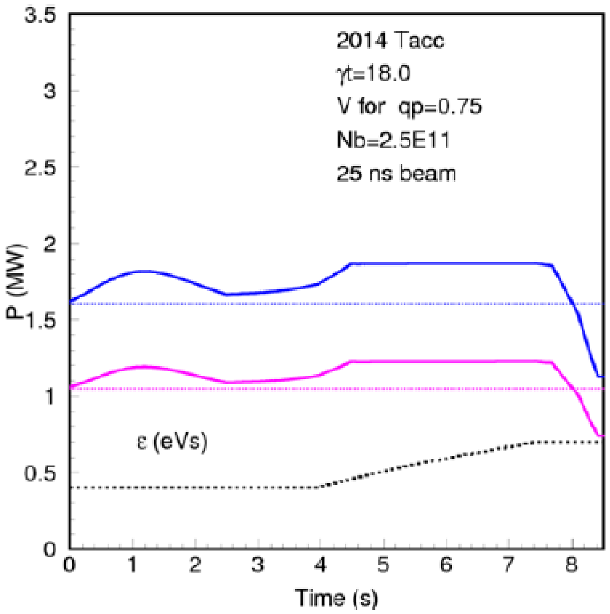
- Available voltage (very high RF power, main power couplers, LLRF: pulsing mode of operation)
- SPS impedance model
  - still some impedance missing (synchrotron frequency shift)…
- Simulations
  - Done for 1 batch of 72 bunches on the flat top
  - Stability during ramp (work in progress)
  - Don’t include longitudinal damper, phase loop, phase error,…

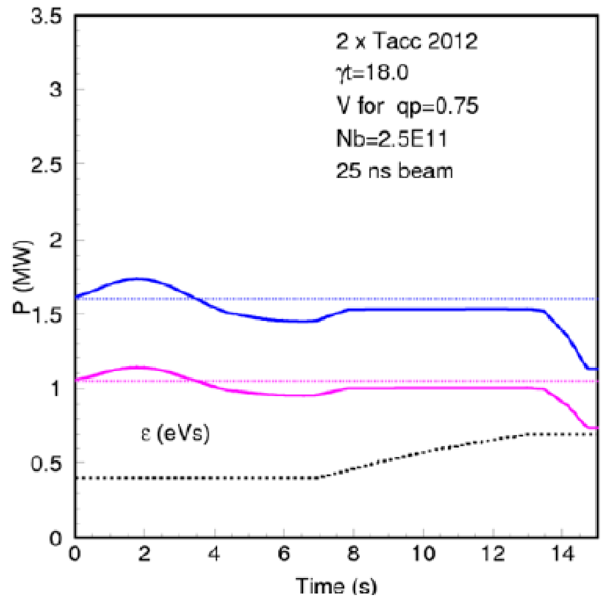
Possible additional means

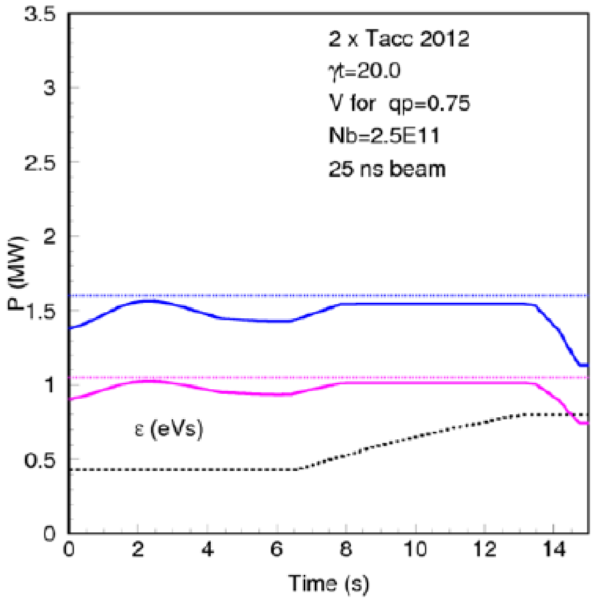
- Bunch rotation on the SPS flat top
  - tests are limited by instability (without impedance reduction < LS2)
- Longer bunches injected into the LHC
  - MDs during run2
  - SPS-LHC transfer simulations for realistic beam distribution
- Additional impedance reduction (HOMs, MKP…)
- 200 MHz RF system in LHC

E. S. et al., Removing known SPS intensity limitations for high Luminosity LHC goals – Proc. of IPAC'16

Nominal injected emittance & BUP: RF power for longer cycle and Q22







Summary - SPS

- From the RF point of view we should be able to obtain HL-LHC parameters after the 200 MHz RF upgrade and LIU baseline longitudinal impedance reduction
- We rely on simulations and it is difficult to take into account all possible uncertainties
- Extra margins can come from
  - bunch rotation on the SPS flat top
  - 5% longer bunches at injection into the LHC
  - 200 MHz RF system in the LHC
- Further longitudinal emittance increase in the SPS is limited by beam loading in the 200 MHz RF during ramp