Bunch length and particle distribution for (HL-) LHC

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Beam parameters: spread

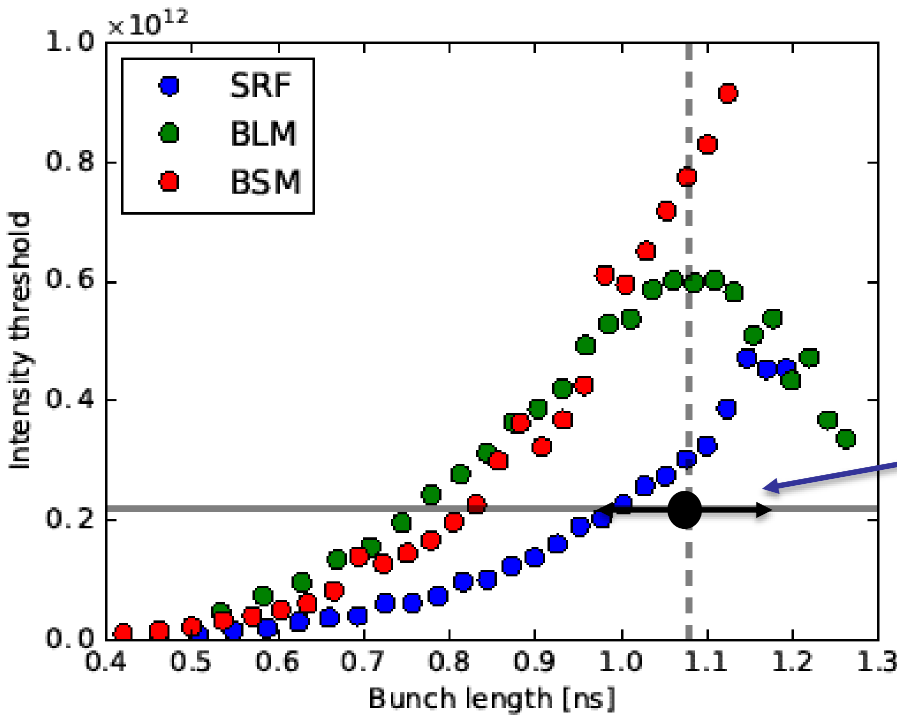
- Bunch-to-bunch variation (from injectors) leads to different synchrotron frequency shifts and therefore emittance blow-up (denser bunches are blown up less)

→ 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

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



E=7 TeV, V_{400} = 16 MV, V_{800} = 4 MV
For ImZ/n ~ 0.11 Ohm
→ 1.0 ns bunches are unstable

10% spread in bunch length

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

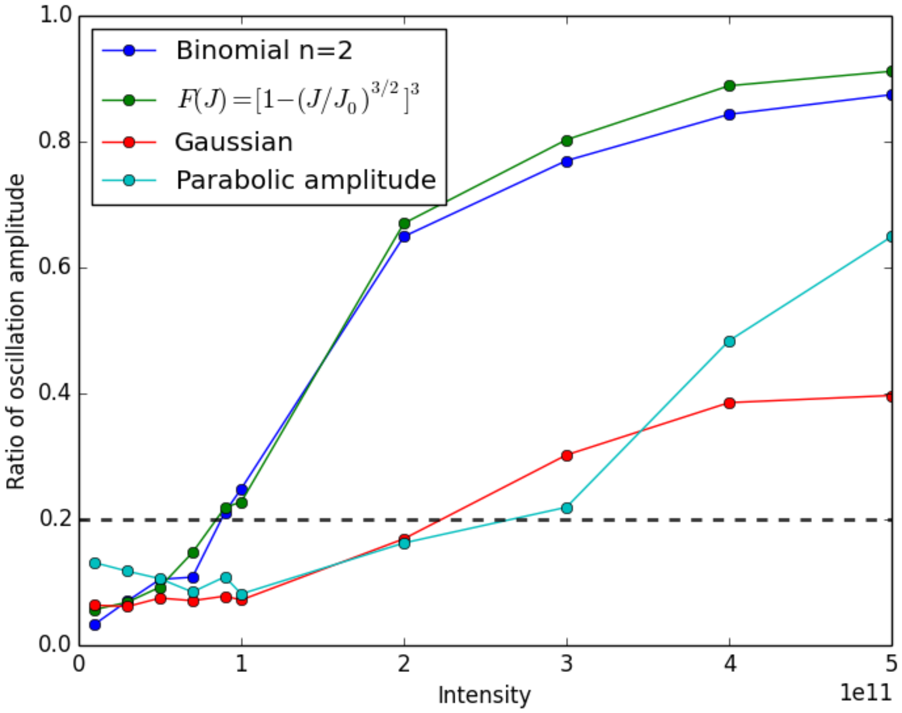
→ 1.2 ns nominal average bunch length in a single RF system

Longitudinal beam parameters in 1 & 2 RF systems for stable operation @7 TeV with minimum (average) bunch length

RF system	V1 [MV]	V2 [MV]	N_{th} [10^{11}]	Bunch length (4σ) [ns]	Emittance (2σ) [eVs]	dE/E (2σ) [10^{-4}]
400 MHz	**16.0**	**0.0**	**2.2**	**1.2**	**3.0**	**2.36**
400 & 800 MHz (BSM)	**16.0**	**8.0**	**2.2**	**0.85**	**2.1**	**2.32**
400 & 800 MHz (BSM)	**16.0**	**4.0**	**2.2**	**1.0**	**2.5**	**2.34**
200 MHz	**6.0**	**0.0**	**2.4**	**2.3**	**4.85**	**1.97**
200 & 400 MHz (BSM)	**6.0**	**3.0**	**2.4**	**1.7**	**3.6**	**2.0**

Based on single-bunch stability threshold (loss of Landau damping) for beam with 10% spread in bunch length and assuming 10% margin (uncertainty in emittance blow-up and effect of SR damping)

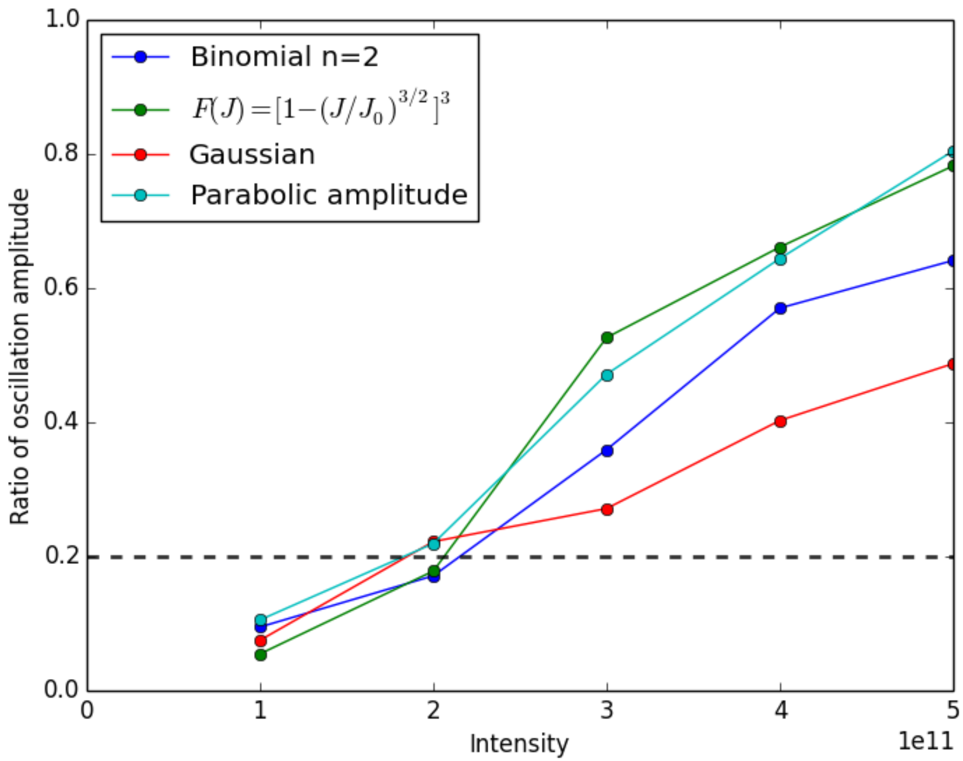
Threshold of LLD for particle distributions with same full bunch length (1 eVs emittance) @4.0 TeV



→Threshold amplitude

→ Different intensity thresholds for various distributions

Threshold of LLD for different particle distributions with same FWHM bunch length of 0.8 ns @4.0TeV

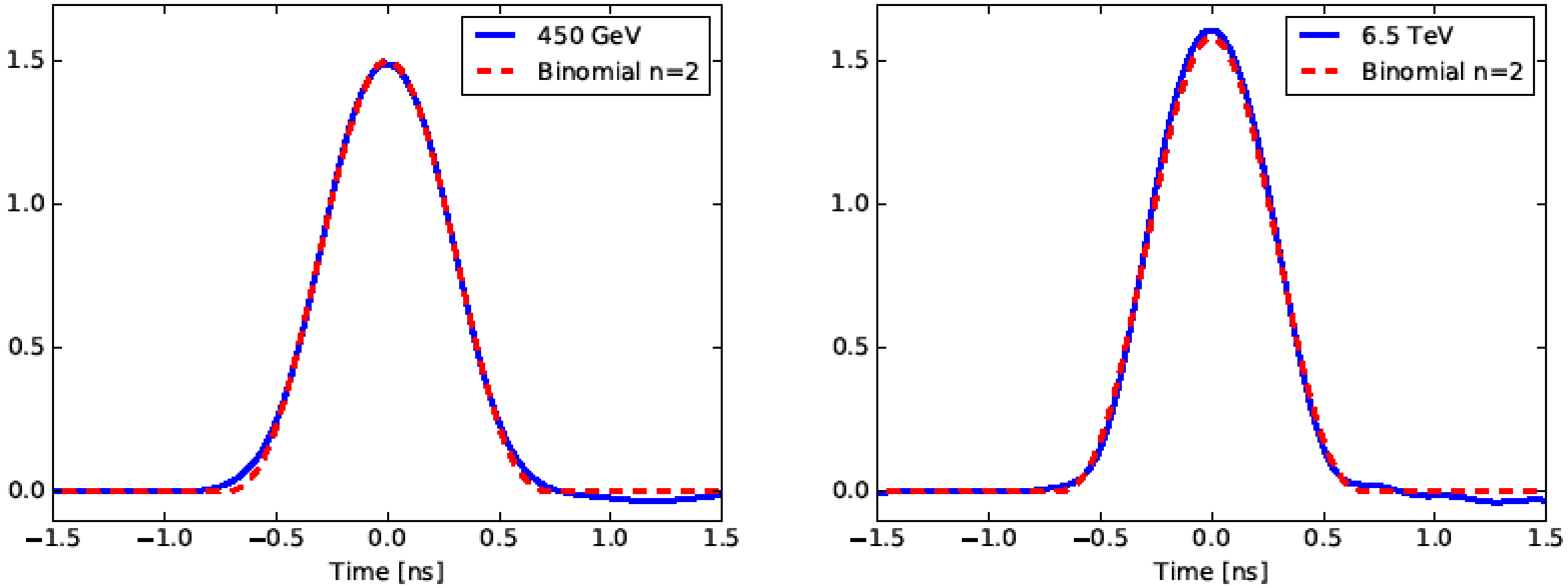


→Threshold amplitude

→ Similar thresholds for all distributions

Bunch profiles in a single RF system (measured and fitted)

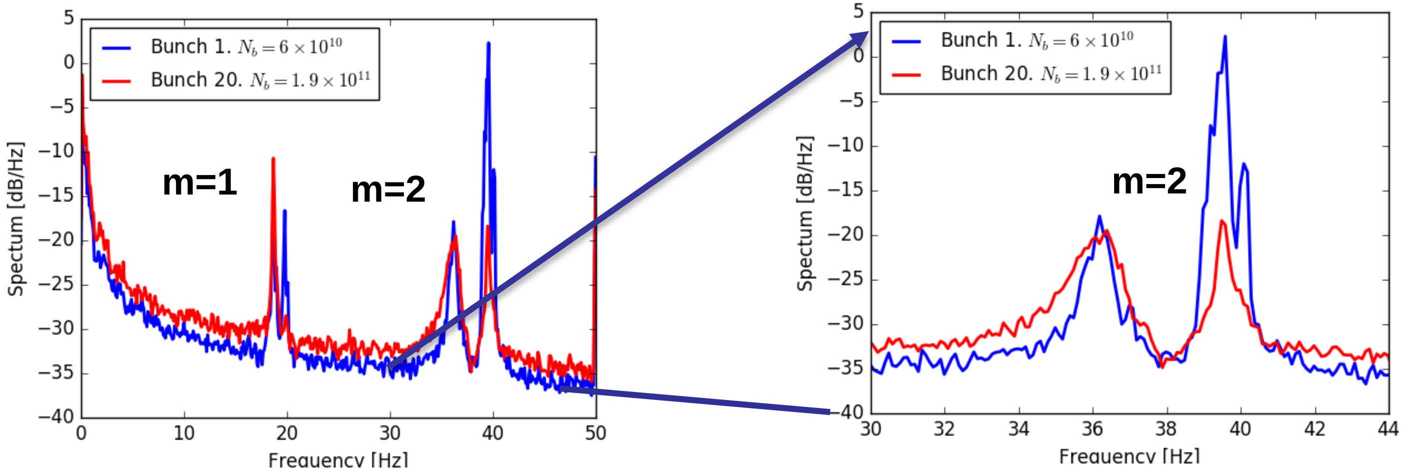
Binomial line density distribution $\lambda(t) = \lambda_0(1 - 4t^2/\tau^2)^{2.5}$ fits well present LHC bunches (in a single RF) on flat bottom and at beginning of flat top (after controlled emittance with band-limited noise during ramp)



- Real bunch tails are more populated (also visible from the PD Schottky)
- Profiles become Gaussian after a few hours due to IBS and SR

Particle distribution after controlled emittance blow-up in LHC

Particle distribution in synchrotron frequency Ω after blow-up from Peak Detected Schottky spectrum for low and high intensity bunches



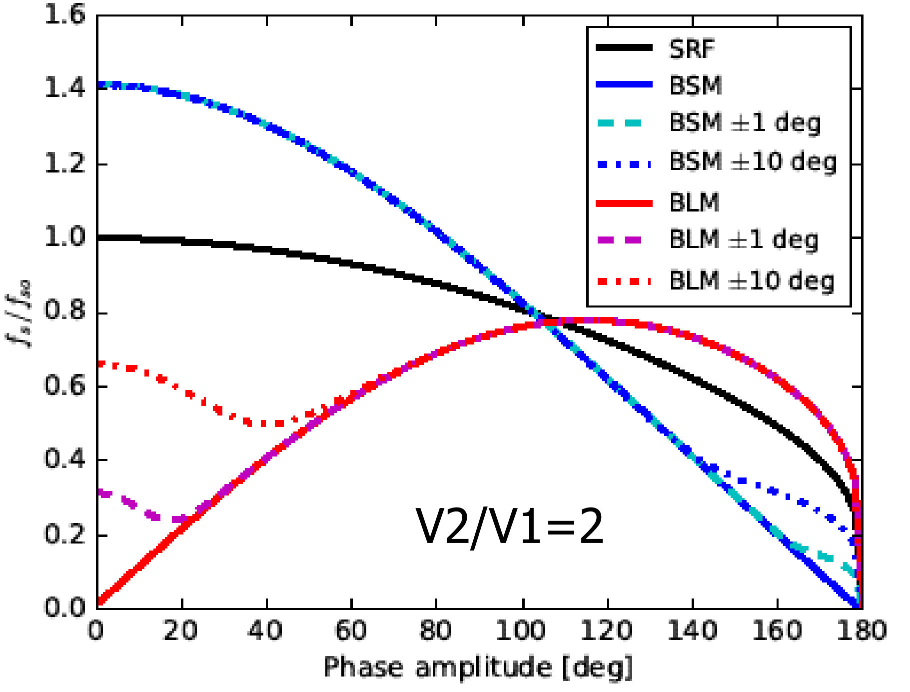
→ After controlled emittance blow-up the distribution function in synchrotron frequency F(Ω) (or in action F(J)) has a hole

Particle distribution function F(Ω) = dN/dΩ = F(J)/Ω'(J)

Double RF operation

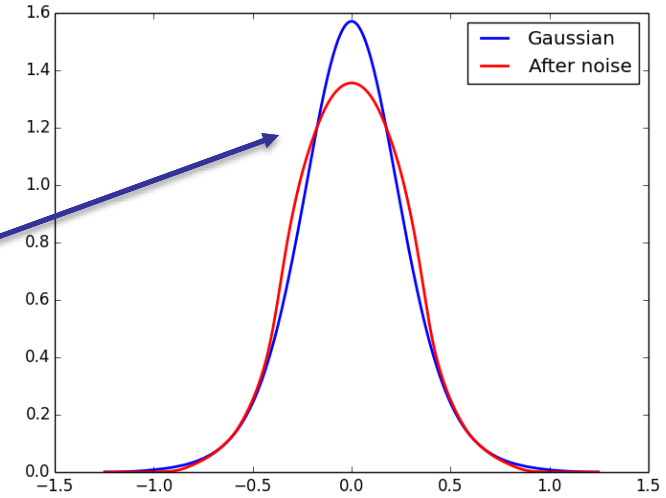
Full detuning scheme will be used in operation for high intensity beams (P. Baudrenghien et al.) leading to bunch displacements

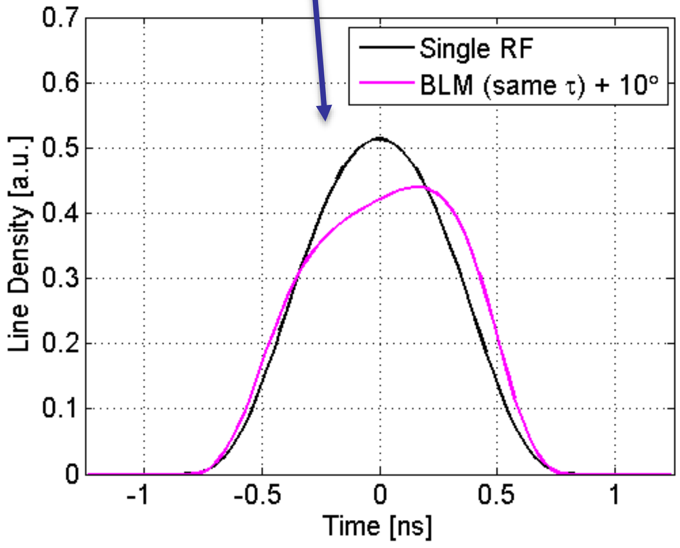
→ Only bunch-shortening operation mode is really feasible in a double RF system (at least for 400 + 800 MHz)

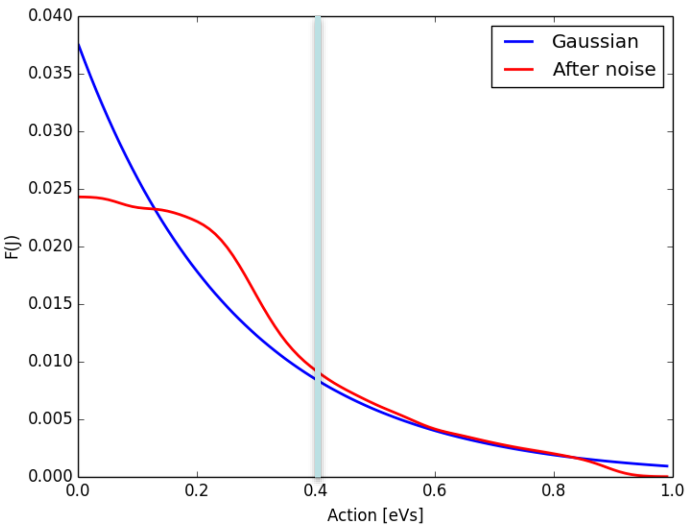


Bunch profiles in a double RF system

- Example for a double RF system with V_2/V_1=0.5 in BSM (BLonD simulations H.Timko). Band-limited noise applied to the bunch centre flattens the profile
- BLM: simulations (T. Argyropuolos)







Summary (1/2)

- During the LHC fill the bunch distribution is changing from binomial line density with n=2.5 to Gaussian (due to the SR damping) and again back to binomial after bunch flattening.
- The LHC DR report refers to the rms value of Gaussian bunch, FWHM value is used in operation.
- In operation in all cases the FWHM value is used multiplied by coefficient for the Gaussian distribution: $\tau = (2/\ln 2)^{1/2} \ \tau_{FWHM}$.
- Scaling to 4-sigma Gaussian length is useful to have comparison with the bucket size.
- The results of simulations show that the instability thresholds scale with the FWHM values and not with maximum bunch length. So in practice it makes sense to use in all cases the FWHM value (or multiplied by some constant coefficient, chosen in our case for a Gaussian bunch).

Summary (2/2)

- The future (HL-LHC) bunch length of 1.2 ns is presently defined by longitudinal beam stability (loss of Landau damping) and use of (scaled) FWHM value is again well justified.
- We can also assume that bunch distribution after blow-up will be similar to the present one (in single RF between binomial with n=2.5 and Gaussian). For the HL-LHC DR this value can be translated to the rms for a Gaussian bunch.
- Distribution in a double RF system will depend on operation mode (BSM or BLM) and controlled emittance blow-up. In BLM bunch profile is very sensitive to even small phase shift (tilt).