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HE-LHC: Longitudinal beam parameters

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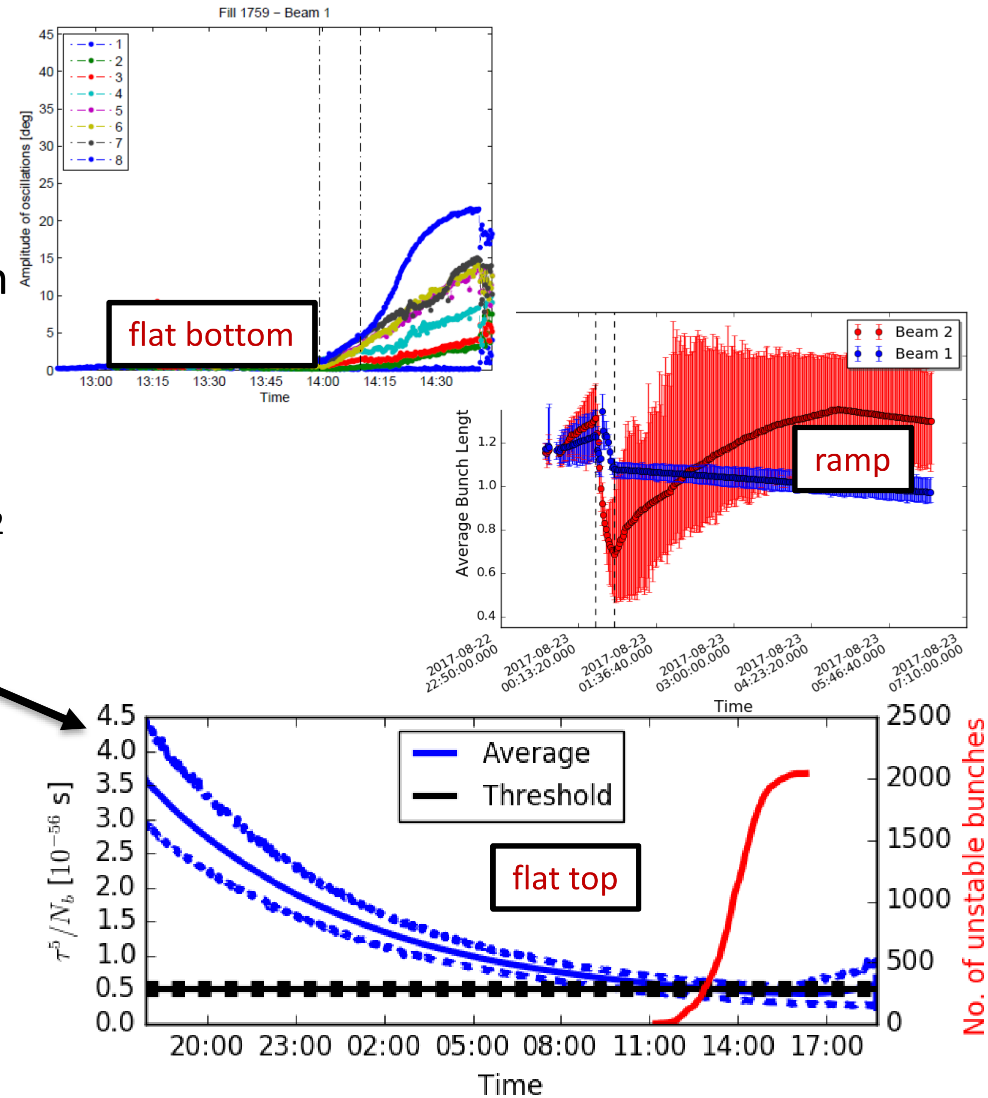
Outline

- Longitudinal beam stability in LHC, HL-LHC & HE-LHC
- Beam parameters at 13.5 TeV
- Injection at 0.45, 0.9 & 1.3 TeV
  - Beam parameters at injection
  - RF and beam parameters during acceleration
- Summary

Longitudinal beam stability in LHC

- Main limitation - loss of Landau damping due to longitudinal reactive impedance ImZ/n (0.09 Ω in LHC & 0.11 Ω in HL-LHC)
- No longitudinal wideband feedback, beam stability is provided by synchrotron frequency spread ~ $h^2\tau^2$ → controlled emittance blow-up
- Stability threshold N_{th} ~ τ^5 is well defined from measurements in LHC runs 1&2 *(PhD thesis J.E. Muller, 2016)*
- Single-bunch effect, coupled-bunch modes were not observed so far



Longitudinal beam stability in HL-LHC

- Increase in bunch intensity by factor 2 and in longitudinal inductive impedance ImZ/n by 20%

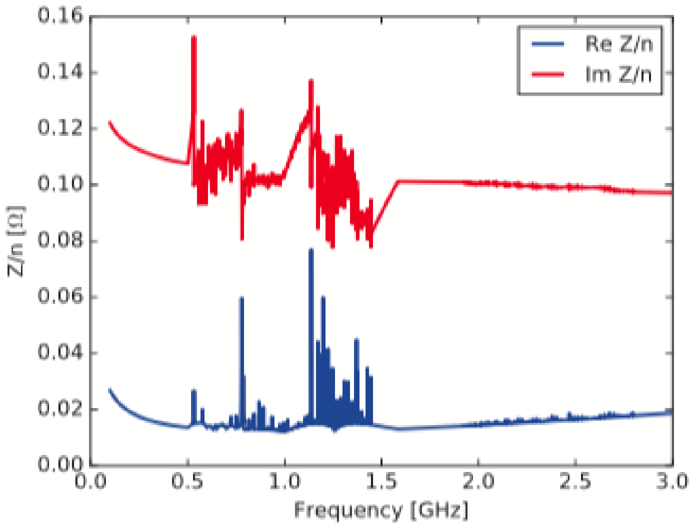
  → For longitudinal stability, the average bunch length on flat top (6.5 & 7 TeV) should be increased to 1.2 ns (± 10% spread)

- Different longitudinal parameters at injection (450 GeV) from 2021, after upgrades of the LHC injector chain (LIU)
  - Higher RF voltage and long. emittance on the SPS top energy

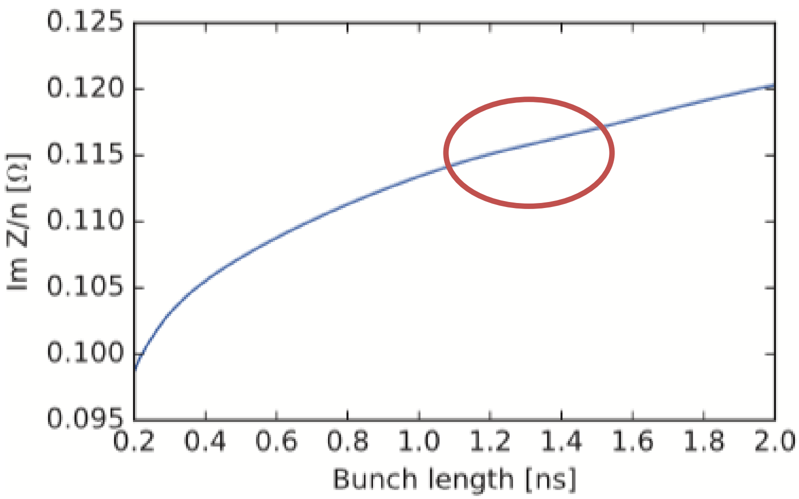
  → higher capture RF voltage in the LHC
  - Nominal voltage in HL-LHC DR is 8 MV – at the limit of available RF power

Longitudinal impedance of HL-LHC

Reactive impedance ImZ/n



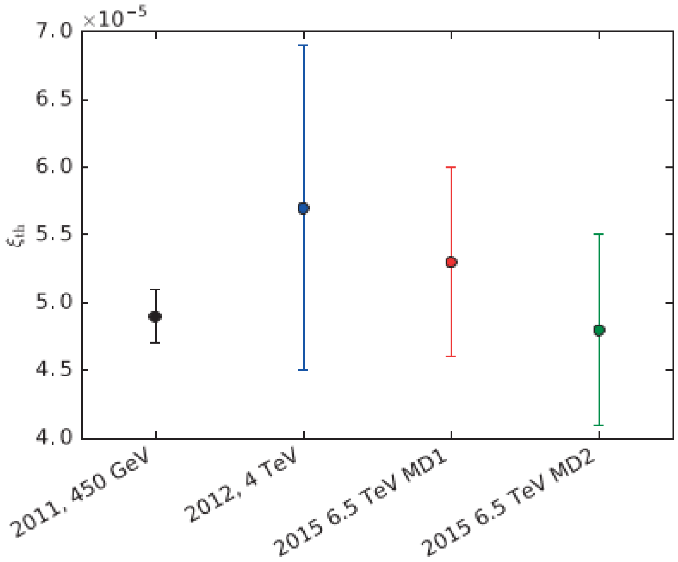
Effective impedance $(\mathrm{Im}Z/n)_{eff}$ for m=1



→ Higher effective impedance for larger bunch lengths (injection vs top energy)

Longitudinal beam stability in LHC & HL-LHC

Measurements in LHC: $\xi = \frac{\tau^5 V}{N_b}$



J.E. Muller et al.

Threshold impedance for loss of Landau damping

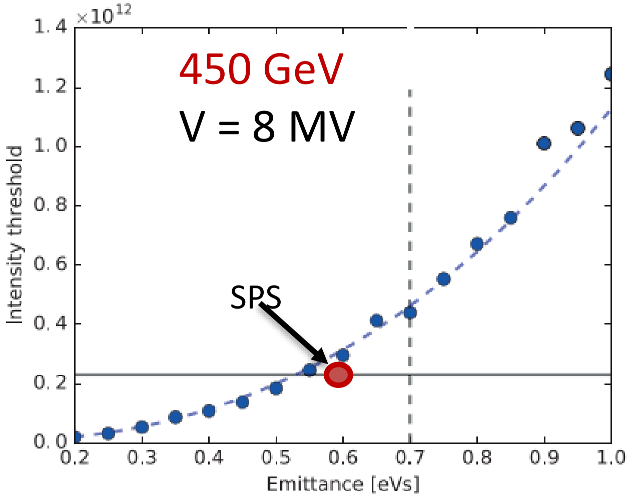
$$(\mathrm{Im}Z/n)_{\mathrm{th}} \propto \frac{\tau^5 V}{N_b} \rightarrow \quad \xi = \frac{\tau^5 V}{N_b}$$

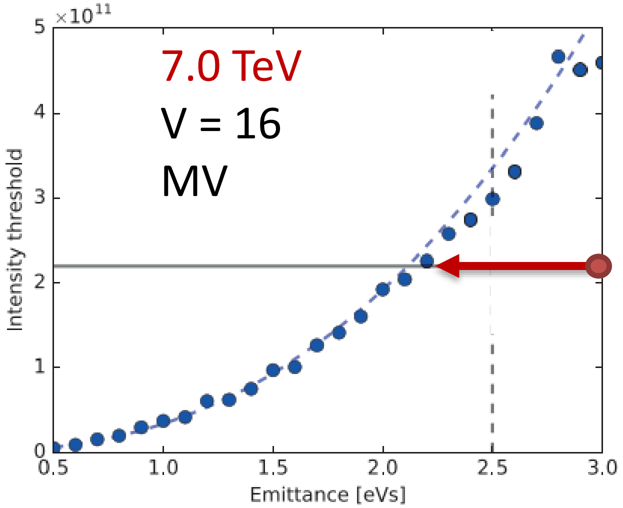
LHC: ξ_{th} = (5.0 ± 0.5) x 10^{-5} $(\mathrm{ns})^5$V

Due to 20% increase in impedance,
HL-LHC: ξ_{th} = (4.2 ± 0.4) x 10^{-5} $(\mathrm{ns})^5$V

Longitudinal beam parameters in HL-LHC

Thresholds for longitudinal single bunch stability (loss of Landau damping)





Bunch length spread of ± (10-15)% in run 2 → ± 25% in emittance

Longitudinal beam parameters in **HE-LHC**

- Various possible injection energies:
  - 0.45 TeV - present SPS
  - 0.9 TeV - upgraded SPS
  - 1.3 TeV - new "SPS"
- Higher top energy: 13.5 TeV vs 7 TeV in LHC
- Two different optics under consideration with
  - $\gamma_t = 53.8$ ($\alpha = 3.45 \times 10^{-4}$) - as in HL-LHC
  - $\gamma_t = 42.08$ ($\alpha = 5.646 \times 10^{-4}$)

RF voltage & longitudinal beam stability in HE-LHC

RF voltage needed for the given filling factor of the bucket area:

$$V \sim \varepsilon^2 \eta/E \sim \varepsilon^2 \alpha /E \sim \varepsilon^2/ (E \gamma_t^2)$$

→ 1.6 times more V for larger α and same emit., as @ 0.45 GeV

Emittance for longitudinal beam stability (Landau damping)

$$\varepsilon \sim (E/\eta)^{1/2} \sim E^{1/2} \gamma_t$$

→ larger emittance (controlled blow-up during ramp) @13.5 TeV, but similar voltage

→ at fixed energy E, voltage V is similar in two optics (γ_t)

→ keep the same bunch length as in HL-LHC

High energy: 13.5 TeV

HE-LHC at 13.5 TeV (during physics)

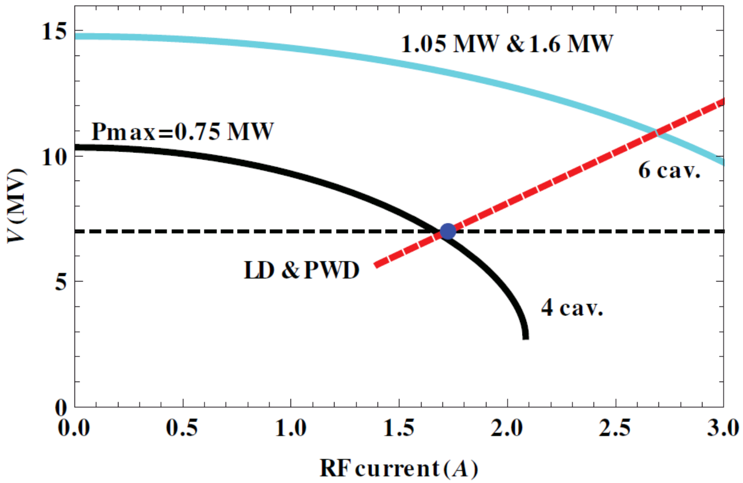
Energy TeV	Optics γ_t	Intensity/b $[10^{11}]$	400 MHz RF voltage [MV]	Bunch length (4 σ) [ns]	Emittance (2 σ) [eVs]	±Δp/p (2 σ) $[10^{-4}]$
7.0	53.8 HL-LHC	2.3	16.0	1.2	3.03	2.36
13.5	53.8	2.3	16.0	1.2	4.20	1.70
13.5	42.08	2.3	16.0	1.2	3.30	1.33

HE-LHC parametes obtained by scaling from values at 7 TeV for HL-LHC baseline (ImZ/n_{eff}=0.11 Ohm)

Present injection energy: 0.45 TeV (with SPS after LIU upgrade)

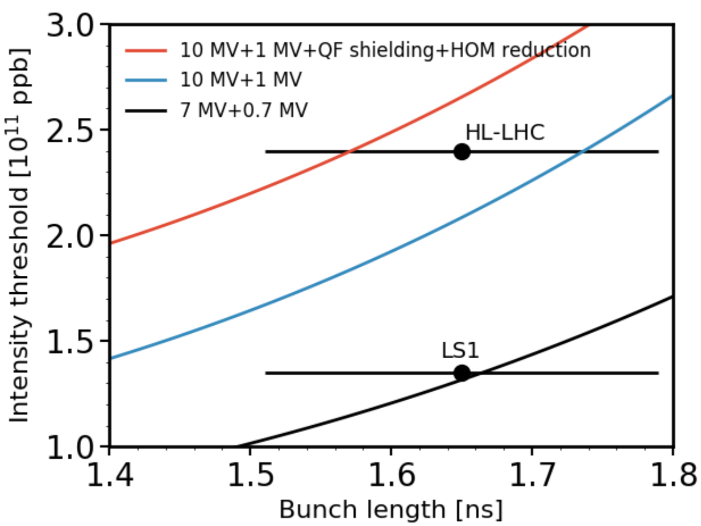
SPS after LIU upgrades (>2021)

Available RF voltage at 200 MHz



3.0 A → 2.3 × 10^{11} p/b, 25 ns bunch spacing

Threshold intensity per bunch



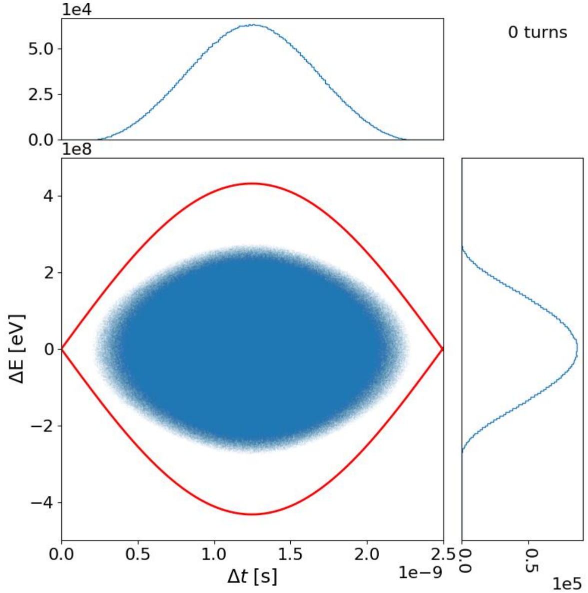
BLonD simulations at 450 GeV with 72 bunches using full SPS impedance model (J. Repond et al.)

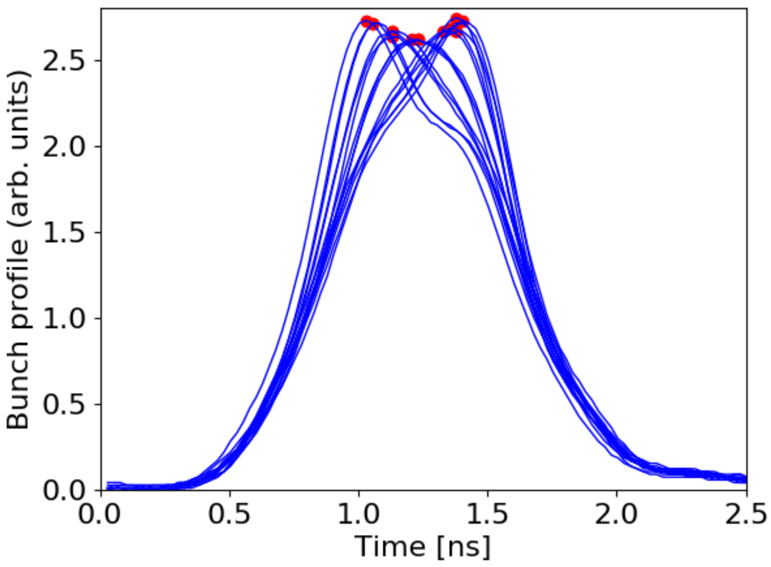
SPS at 0.45 TeV now and after LIU (> 2021)

Intensity/bunch [10^{11}]	200 MHz voltage [MV]	Bunch length 4 σ [ns]	Emittance 2 σ [eVs]	±Δp/p 2 σ [10^{-4}]	Comments
1.2	7.0 – max now	1.65	0.48	4.30	achieved
1.2	10.0	1.24 ns	0.35 – min	4.11	>2021
2.4	10.0 – max	1.65 ns	0.57	5.12	>2021

- Q20 optics (γ_t =18)
- LIU-SPS: 200 MHz RF upgrade plus impedance reduction
- Beam parameters in a double RF system (200 + 800 MHz) with V_{800}=0.1 V_{200}
- Additional stability margin with higher 800 MHz RF voltage (1.6 MV maximum)
- Bunch length is determined from FWHM bunch length assuming a Gaussian distribution
- Momentum spread and emittance are defined by particle trajectory corresponding to the 4-σ bunch length (without potential well distortion, ~ 2%)

Injection into the LHC





Longitudinal phase space at injection into LHC for nominal LIU-SPS (10 MV) and HL-LHC (8 MV) parameters without injection errors.
Unmatched voltage needed due to injection errors

Undamped bunch oscillations after injection into mismatched voltage.
Lower instability threshold

HL-LHC and HE-LHC at 450 GeV

- For HL-LHC, the situation at injection (450 GeV) was revisited recently due to potential RF power limitation (with half-detuning scheme for transient beam loading compensation)
  - Matched RF voltage at 400 MHz is ~2.3 MV for SPS Q20 optics
  - Mismatched voltage (6 MV) was used most of run2 to accommodate phase and energy errors, but it also leads to lower instability threshold
  - In 2018 voltage was decreased in operation to 4 MV (batches of 48 bunches with nominal LHC intensity)
  - Worse for the Q22 optics in the SPS (not considered anymore)

→ Solution found for Hl-LHC will be adapted for HE-LHC

LHC & HL-LHC at 450 GeV: beam after filamentation

- Beam parameters after filamentation depend on RF voltage in LHC
- Maximum emittance after filamentation is similar to the injected one, but particle distribution is different
- Potential well distortion (intensity effect) gives < 5% smaller $\Delta p/p$

	Intensity/bunch [10^{11}]	400 MHz RF voltage [MV]	Bunch length (4σ) [ns]	Emittance (2 σ) [eVs]	±Δp/p (2 σ) [10^{-4}]
Run 2	1.15	6.0	1.21	0.48	5.77
End 2018	1.15	4.0	1.34	0.48	5.24
HL-LHC	2.3	8.0	1.24	0.58	6.81
HL-LHC	2.3	6.0	1.35	0.58	6.31

Higher injection energy: 0.9 & 1.3 TeV (with new injector)

HE-LHC with γ_t = 53.8 (α = 3.45x10^{-4}): beam parameters after capture for 2.3E11 ppb

Beam energy [TeV]	400 MHz RF voltage [MV]	Emittance (2 σ) [eVs]	Bunch length (4 σ) [ns]	±Δp/p (2 σ) [10^{-4}]
0.45	8.9	0.7	1.35	7.6
0.9	9.1	1.0	1.35	5.44
1.3	9.1	1.19	1.35	4.52

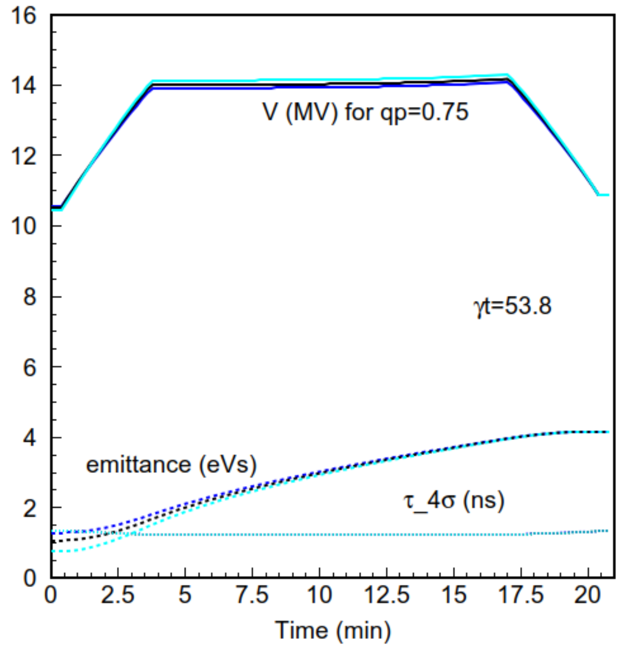
- All emittances are defined by longitudinal stability in LHC (and scaled from the 0.45 TeV value) taking into account 20% spread in emittance
- The SPS (after LS2) cannot produce 0.7 eVs with 1.65 ns bunch length (288 bunches) in Q20
- RF voltage is calculated for 0.75 bucket filling factor in momentum
- Bunch length is after capture and filamentation

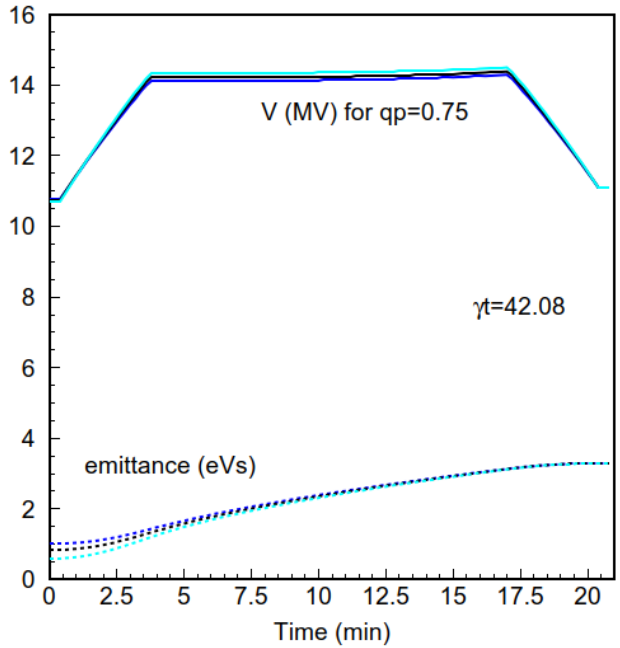
HE-LHC with γ_t = 42.08 ($\alpha = 5.646 \times 10^{-4}$): beam parameters after capture for 2.3E11 ppb

Beam energy [TeV]	400 MHz RF voltage [MV]	Emittance (2 σ) [eVs]	Bunch length (4 σ) [ns]	±Δp/p (2 σ) [10^{-4}]
0.45	9.0	0.55	1.35	5.98
0.9	9.1	0.78	1.35	4.24
1.3	9.1	0.94	1.35	3.54

- All emittances are defined by longitudinal stability in LHC (and scaled from 0.45 TeV value) taking into account 20% spread in emittance
- RF voltage is defined by 0.75 bucket filling factor in momentum
- Bunch length at injection energies is after bunch capture and filamentation

Emittance and RF voltage during ramp with different injection energies in two HE-LHC optics





→ For fixed bucket filling factor in momentum of qp = 0.75, max RF voltage is 14 MV

Summary

- Beam parameters in HE-LHC have been found for different optics from scaling from the LHC and choices made for the HL-LHC (7 TeV).
- At injection energy of 0.45 TeV, longitudinal parameters (emittance) are defined by the present SPS. In this case, more RF voltage will be required in the HE-LHC optics with higher α
- At 1.3 TeV (or 0.9 TeV) minimum longitudinal emittance should be determined by beam stability in HE-LHC
- The present SPS cannot produce beam with average emittance, required for stability in the HE-LHC, and nominal bunch length of 1.65 ns

Spare slides

HE-LHC with $\gamma_t = 53.8$ ($\alpha = 3.45 \times 10^{-4}$): beam parameters after capture for 2.3E11 ppb

Beam energy [TeV]	400 MHz RF voltage [MV]	Emittance (2 σ) [eVs]	Bunch length (4 σ) [ns]	±Δp/p (2 σ) [10^{-4}]
0.45	10.4	0.76	1.35	8.27
0.9	10.5	1.08	1.35	5.84
1.3	10.6	1.29	1.35	4.86
13.5	10.9	4.16	1.34	1.52

- All emittances are defined by longitudinal stability in LHC and scaled from the 7 TeV value (25% spread in emittance)
- The SPS (after LS2) cannot produce 0.76 eVs with 1.65 ns bunch length (288 bunches) in Q20
- RF voltage is calculated for 0.75 bucket filling factor in momentum
- Bunch length is after capture and filamentation

HE-LHC with γ_t = 42.08 (α = 5.646x10^{-4}): beam parameters after capture for 2.3E11 ppb

Beam energy [TeV]	400 MHz RF voltage [MV]	Emittance (2 σ) [eVs]	Bunch length (4 σ) [ns]	±Δp/p (2 σ) [10^{-4}]
0.45	10.7	0.60	1.35	6.53
0.9	10.8	0.85	1.35	4.61
1.3	10.8	1.02	1.35	3.84
13.5	11.0	3.29	1.34	1.2

- All emittances are defined by longitudinal stability in LHC and scaled from 7 TeV values (25% spread in emittance)
- RF voltage is defined by 0.75 bucket filling factor in momentum
- Bunch length at injection energies is after bunch capture and filamentation