CERN

Longitudinal parameters and beam induced heating

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Outline

- Introduction
- Longitudinal parameters
  - Landau damping
  - Particle losses
  - Synchrotron radiation
  - Intra Beam Scattering
  - Luminosity levelling
- Beam induced heating
  - Issues during LHC Run 1 and mitigation measures during LS1
  - Flat bunches
- Summary of bunch length reduction impact at 6.5 TeV
- Proposed strategy
- Conclusions

Longitudinal parameters

	Energy	RF Voltage [MV]	Bunch length [ns]	Emittance [eVs]
Design Report	450 GeV	8	1.5	0.8
	7 TeV	16	1.05	2.5

At the end of LHC run 1 (2012) → Lower emittance at injection than in DR

2012	450 GeV	6	1.2 (Q26) 1.15(Q20)	0.5 (Q26) 0.45 (Q20)
	4 TeV	12 (until 29/10)	1.25-1.3	2.2 - 2.35
	4 TeV	10 (from 29/10)	1.3-1.35	2.0 - 2.15

Voltage increased to 12 MV after 3-4 h to reduce bunch length and increase luminosity

But bunch length at 4 TeV had to be increased in several steps due to beam induced heating

For LHC Run 2: Is it interesting to reduce bunch length to profit from low β*?
→ Side-effects should be taken into account to optimize luminosity

Landau damping

- LHC beam: similar threshold at 6.5 TeV as at 4 TeV for V_{RF} = 10 MV if bl = 1.25 ns
- Single bunch instability: $N_b^{th} \propto \frac{\varepsilon^{5/2}}{E^{5/4}V^{1/4}}$

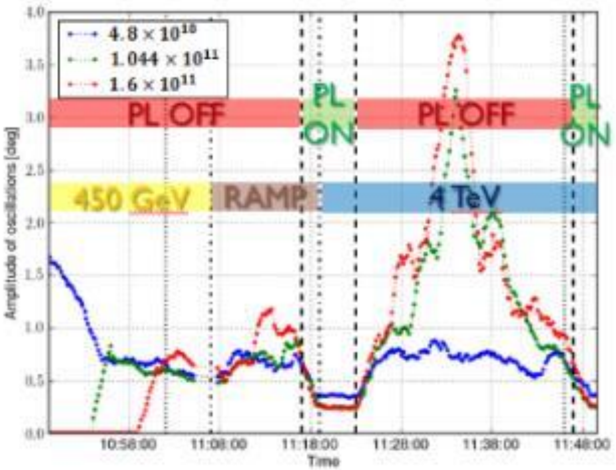
MD in 2012: N_b^{th} ~ 1.0 x 10^{11}, 1 eVs, 4 TeV, 12 MV
→ Scaling to 6.5 TeV, 10 MV:
  - 2.57 eVs (1.25 ns) → N_b^{th} ~ 6.0 x 10^{11}
  - 1.73 eVs (1.0 ns) → N_b^{th} ~ 2.2 x 10^{11}
  - 1.15 x 10^{11} → ε_{th} ~ 1.32 eVs (0.85 ns)

- Coupled-bunch instability: $I_T^{th} \propto \frac{\varepsilon^{3/2}V^{1/4}}{E^{3/4}}$

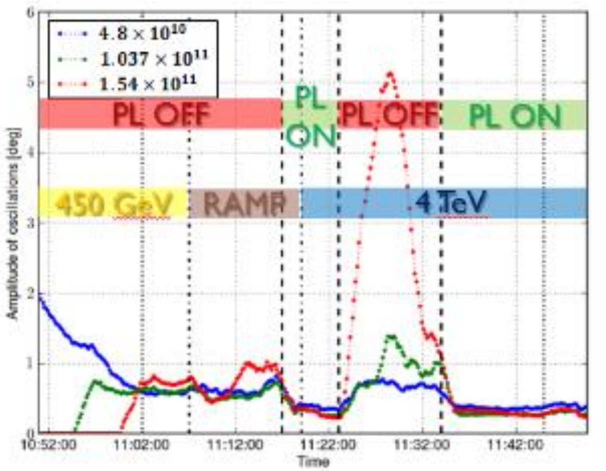
2012: I_T = 0.4 A, 450 GeV, 6 MV, 0.5 eVs
→ Scaling to 6.5 TeV, 10 MV:
  - 2.57 eVs (1.25 ns) → I_T^{th} > 0.83 A
  - 1.73 eVs (1.0 ns) → I_T^{th} > 0.46 A

Expected enough margin on longitudinal stability

Beam 1



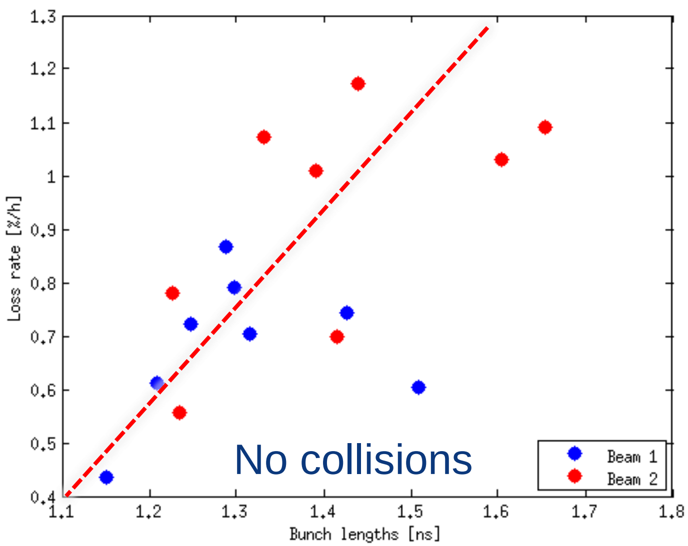
Beam 2



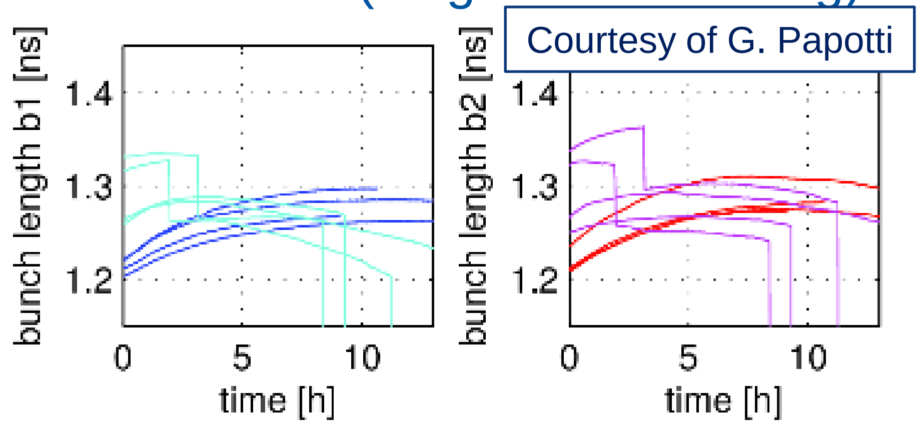
Particle losses

Two loss mechanisms:

Losses from the RF bucket

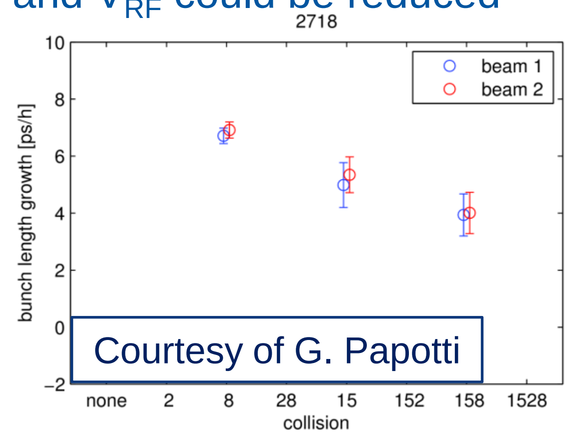


Beam-beam: maximum 1.3 ns at 4 TeV in 2012 (longitudinal shaving)



Dependence on Δp?

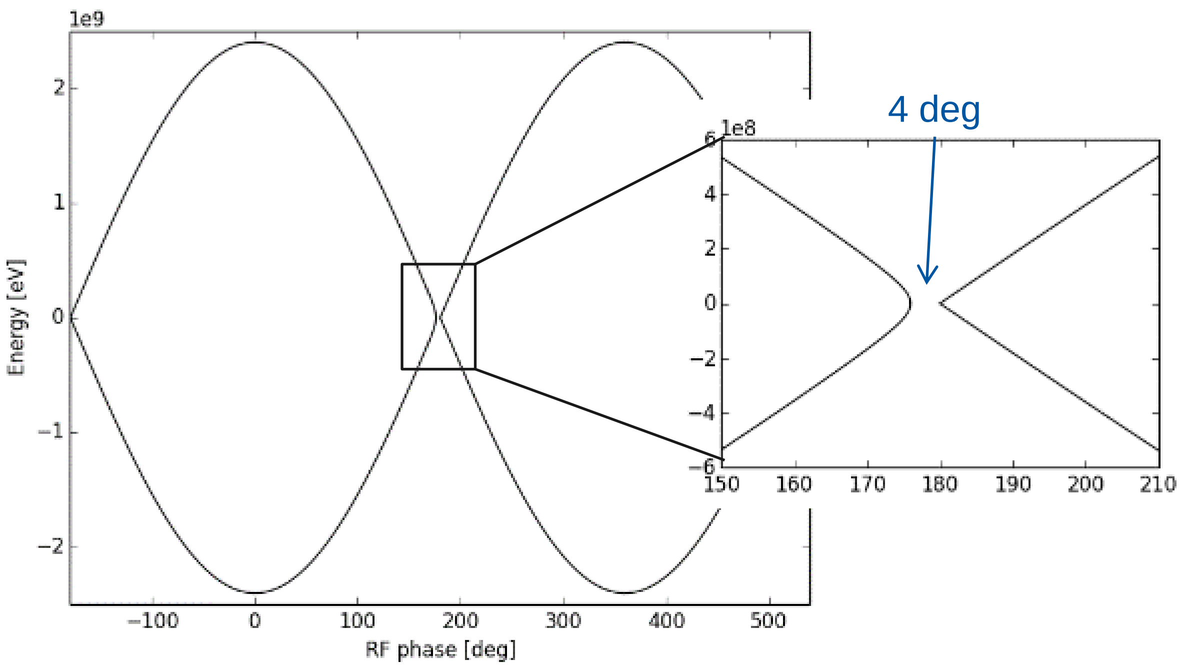
→ ε and V_{RF} could be reduced



In both cases, loss rate increases with bunch length!

Synchrotron radiation

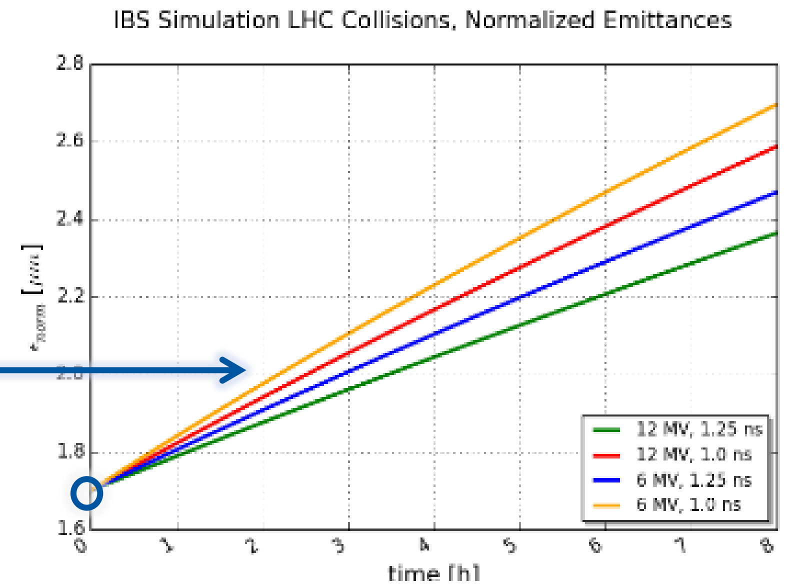
- At 6.5 TeV, SR energy loss per turn = 5 keV (0.7 keV at 4 TeV)
- Lost particles will move in the same direction much faster than at 4 TeV

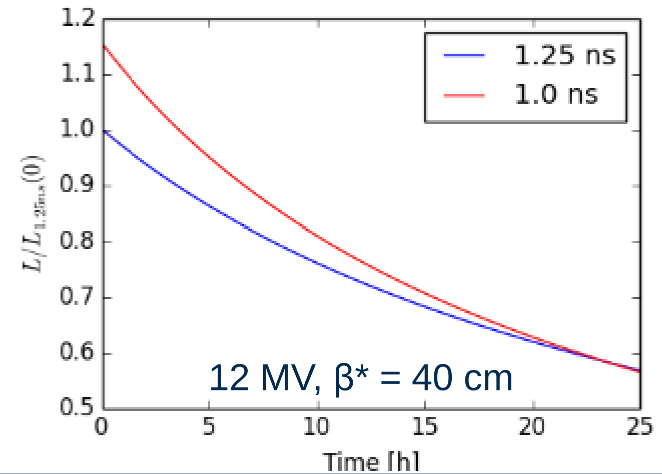


Intra Beam Scattering

IBS simulations (M. Kuhn):

- No vertical emittance growth
- Horizontal emittance:
  - Growth rate increases for shorter bunches
  - Strong dependence on initial transverse emittance ε_0 (slower growth for ε_0 = 3.75 μm)





→ Nevertheless higher integrated luminosity with 1.0 ns bunches than with 1.25 ns

Luminosity levelling (via τ)

Can be used in case heating is an issue or pile-up is too high (short bunches)

$$\tau \propto V^{1/4}$$

- Acceleration with 6 MV or increase to 8 MV
- Increase voltage to 16 MV during physics to reduce bunch length by ~20 %
  - From 1.25 ns (2.0 eVs) to 1.0 ns

  → Instantaneous luminosity increases by ~15%

Observe transverse stability: lower f_s (Q_s) could be detrimental

Beam induced heating

Issues during LHC Run1 and mitigation measures during LS1

Element	Problem	2011	2012	Expected situation after LS1
Double-bellow VMTSA	Damage		Replaced	All VMTSA removed
Injection protection collimator TDI	Damage		Still problems even if in parking position	Beam screen reinforced. Copper coating on the jaws abandoned
Injection kicker MKI	Delay (cold-down)		MKI8D (MKI8C after TS3)	Beam screen upgraded and attempt at increasing tank emissivity
Primary collimator TCP B6L7.B1	Few dumps		Interlock increased	Non-conformity should be removed (suspected cooling system issue)
Tertiary collimators TCTVB	Few dumps		Interlock increased	All TCTVBs have been removed. Situation with new TCTP should be followed up
Beam screen standalone Q6R5	Regulation at the limit		Since TS3, correlation with TOTEM?	Valves upgraded Neighboring TOTEM pot checked
ATLAS-ALFA roman pot	Risk of damage		Due to intensity increase	New design being installed
Synchrotron light telescope BSRT	Damaged		Damaged	New design being installed

- Significant efforts by all groups to protect their equipment
- Efficient monitoring of elements (potentially subject to heating) is needed:

→ Systematic logging of temperature data in LDB and on fixed display with alarms for fast reaction in CCC (in discussion with MPP)

Beam induced heating

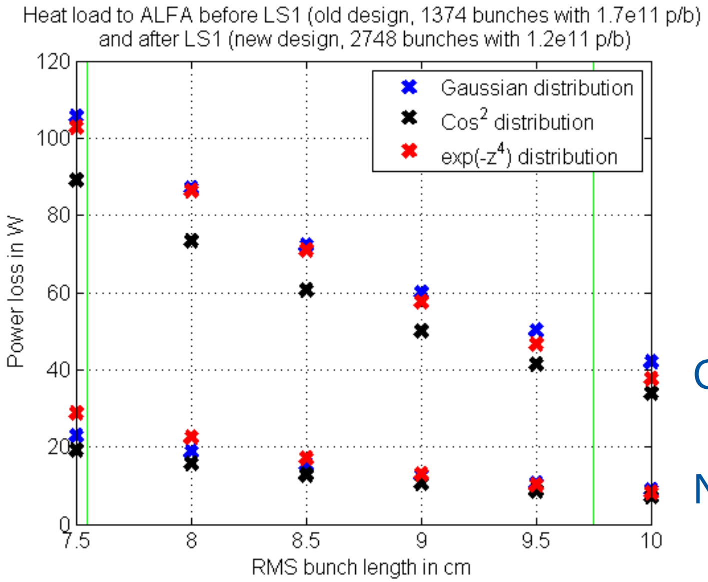
Different beam in 2015: M bunches at 25 ns (t_{bb}), bunch intensity N_b up to 1.3 x 10^{11}

$$P_{loss} = \sum_{k=-\infty}^{\infty} j_k^2 \operatorname{Re} Z_{\parallel}(\omega_k) \left[\frac{\sin(Mk\omega_0 t_{bb}/2)}{\sin(k\omega_0 t_{bb}/2)} \right]^2$$

$j_k \propto N_b$, depends on bunch distrbution

Example: heating on ALFA roman pot

- Improved with new design → Less heating even for shorter bunches
- Bunch length reduction → Heating increases
- Expected behavior in several upgraded equipment

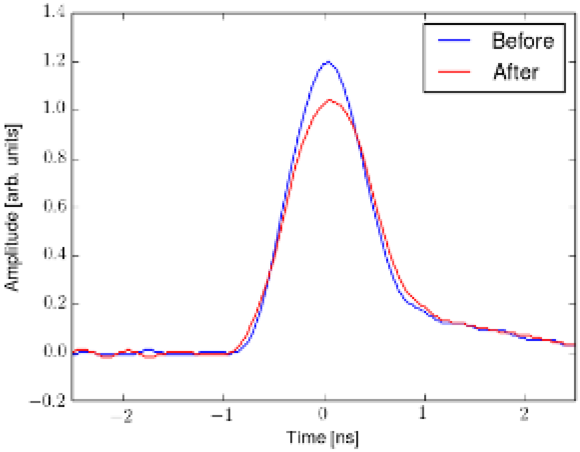


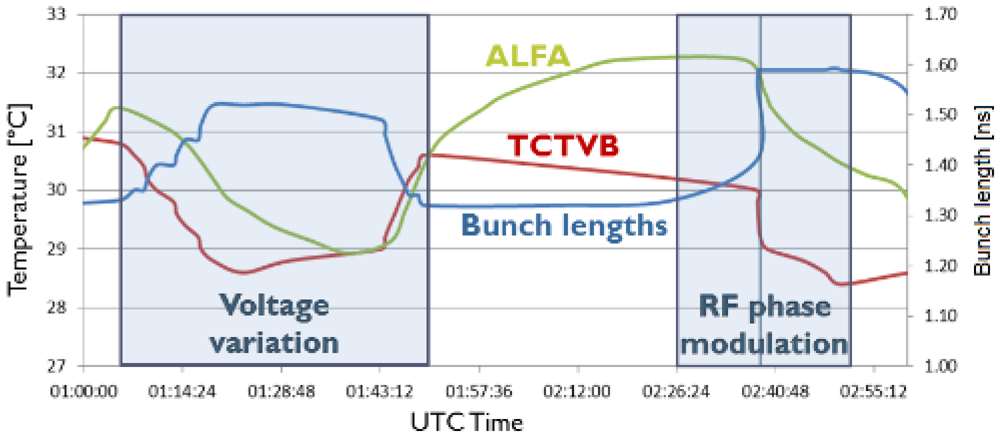
Old design before LS1

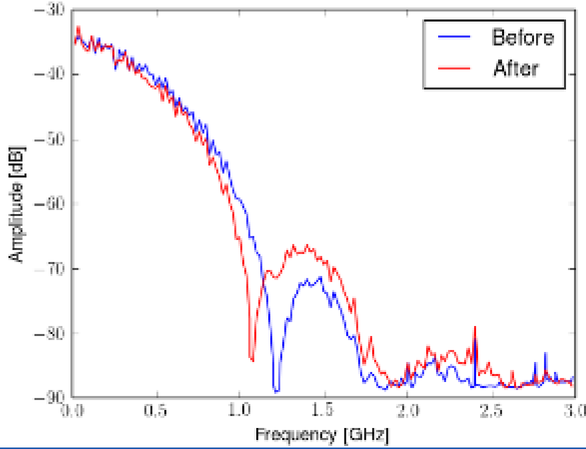
New design after LS1

Flat bunches

- Can reduce heating for devices with impedance below 1.2 GHz (for 1.25 ns bunch length)
- Can make luminous region more uniform
- Tested in 2012 LHC MD, with Phase loop off results as expected from simulations
  → More tests planned in 2015
- Possibility to improve bunch shape in operation (see P. Baudrenghien talk)







Summary of bunch length reduction impact at 6.5 TeV

Mechanism	Impact of reducing bunch length (1.25 ns to 1.0 ns)	50 ns	25 ns
Longitudinal stability	Loss of Landau damping threshold reduced by ~60 %	Not critical	Not critical
Particle losses	Decrease is expected	Beneficial	Beneficial
IBS	Horizontal emittance growth rate increases by ~20 %	Not critical	Not critical
Synchrotron radiation	No impact	No impact	No impact
Beam induced heating	More heat load expected on most equipment	Maybe critical	Maybe critical
Luminosity	Increase from 10 to 15%	Beneficial	Beneficial
Pile-up and pile-up density	Increase from 10 to 15%	Critical (without beta* levelling)	Not critical for standard Maybe for BCMS
Transverse stability	Small effect expected for Q' > 0	Maybe critical	Maybe critical
End of Squeeze Instability	Potential impact	Maybe critical	Maybe critical
Electron cloud	Decrease of multipacting threshold Increase of electron cloud induced heat load	Not critical	Maybe critical
Beam-beam effects	No impact expected on long range, increase of head-on tune spread, improvement of synchro-betatron resonance crossing	Not critical	Not critical

Proposed strategy

- Injection at 6 MV
- Ramp to 6.5 TeV with controlled longitudinal emittance blow-up
- Start with “safe parameters”:
  - Bunch length target 1.25 ns
  - Voltage linearly increased during the ramp to 12 or 10 MV (as in 2012)
- Two possibilities for luminosity increase:
  - Reduce ε, same V_{RF} → Reduce bunch length (to nominal)
  - Reduce ε and V_{RF} → Potential for luminosity levelling

Reduction of the blow-up target must be done in small steps and with careful monitoring of heating and transverse stability

Tests can be done during re-commissioning and MDs

Conclusions

- Margin in longitudinal stability → Lower emittances are tolerable:
  - Improved beam lifetime
  - Effect of IBS is expected to be not significant
  - Possibility of luminosity levelling

- Improvements in heating
  - Known issues expected to be solved
  - More temperature monitoring and alarms available after LS1
  - Flat bunches and bunch length levelling as possible mitigations

→ Shorter bunches (1.0 ns) are probably feasible

Are they interesting for experiments?

Spare slides

Longitudinal parameters for different scenarios

6.5 TeV

Tau [ns]	V_{RF} [MV]	f_s [Hz]	Q_s	ε [eVs]	Bucket area [eVs]	Δp/p
1.25	10	18.84	1.67×10^{-3}	2.57	6.04	2.07×10^{-4}
1.0	10	18.84	1.67×10^{-3}	1.73	6.04	1.72×10^{-4}
1.25	12	20.64	1.83×10^{-3}	2.81	6.61	2.27×10^{-4}
1.0	12	20.64	1.83×10^{-3}	1.89	6.61	1.89×10^{-4}
1.25	6	14.59	1.3×10^{-3}	1.99	4.68	1.6×10^{-4}
1.0	16	23.83	2.12×10^{-3}	2.19	7.64	2.2×10^{-4}

Maximum voltage using 250 kW klystron power (20% margin for regulation):

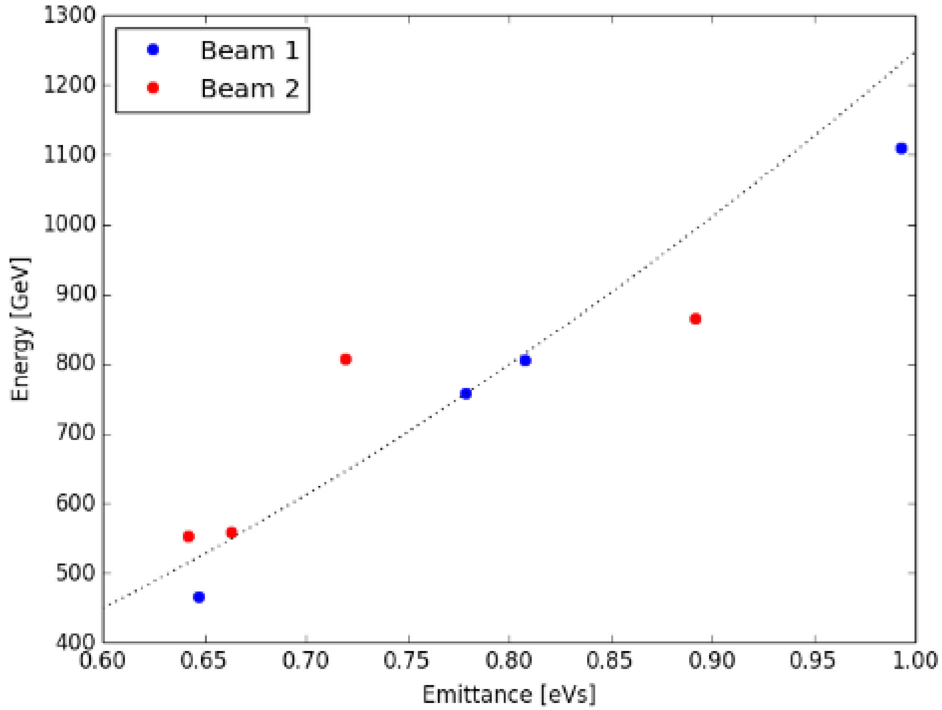
- 1.25 ns: 13.4 MV (0.55 A DC) and 14.9 MV (0.5 A DC)
- 1 ns:12.6 MV (0.55 A DC) or 14 MV (0.5 A DC)

Loss of Landau damping: Scaling

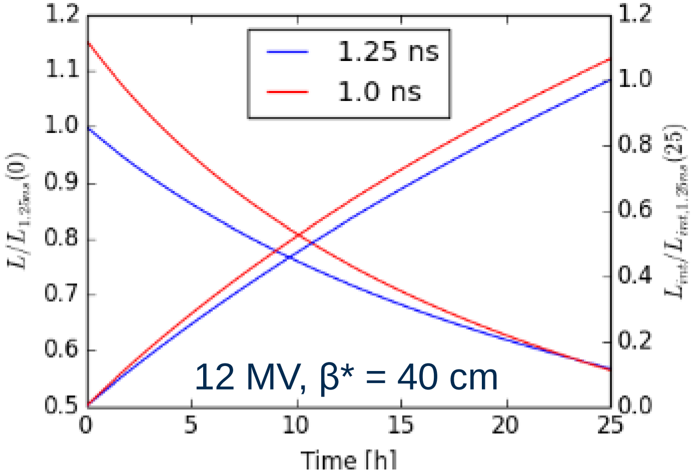
MD 2012:
Loss of Landau damping during the ramp

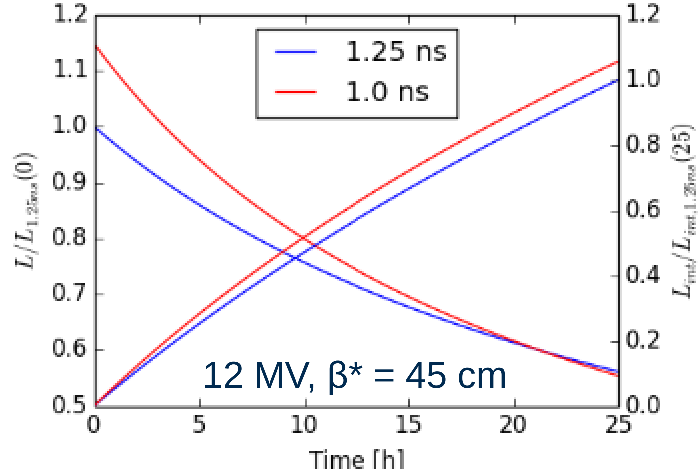
Bunch intensity ~2.3 x 10^{11}

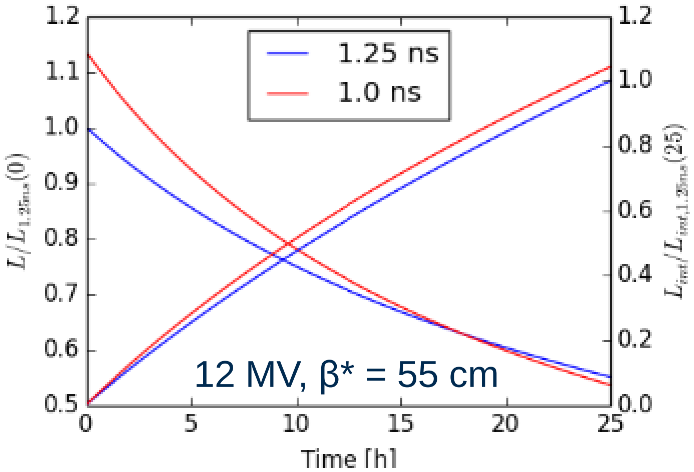
$$E^{5/4} \propto \frac{\varepsilon^{5/2}}{V^{1/4}}$$

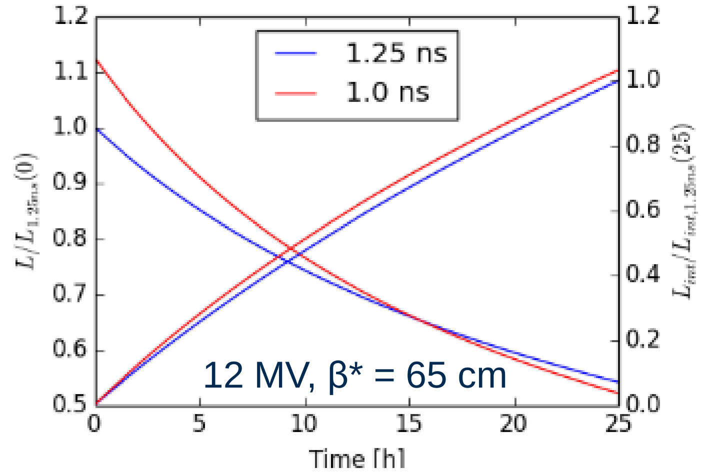


IBS - Luminosity









Predicted impact of consolidations and changing bunch length on heating (ongoing work)

Element	Before LS1 (1.7e11 p/b – 1374 bunches- 1.25 ns)	Consolidation of design during LS1	After LS1 (1.2e11 p/b – 2748 bunches -1.25 ns)	After LS1 (1.2e11 p/b – 2748 bunches -1 ns)
TDI (resistive wall at 55 mm)	36 W	Yes (but not on the jaw)	36 W (~)	48 W (+33%)
Arc beam screens	186 mW/m	No	215 mW/m (+15%)	300 mW/m
Triplet beam screens (Q1/Q2-Q3)	286/360 MW/m	No	331/419 mW/m (+15%)	460/590 mW/m
MKI	75 W (*)	Yes	tbc	36 W to 55 W (-25% to -50%)
MKD	22 W	No	22 W (~)	30 W (+35%)
TCP collimator	62 W	No	60 W (~)	92 W (+48%)
TCTP (at +/-5 mm)	-	-	3 W	5W
TOTEM** at 40 mm at 2 mm	10 W 57 W	Yes for some	5 W (-50%) 10 W (-80%)	13 W (+30%) 27 W (-32%)
ATLAS-ALFA at 40 mm	37 W	Yes	7 W (-80%)	20 W (-45%)
BSRT*** (broadband)	30 W	Yes	1 W	4 W
BGV (potential modes)	-	-	50 W (potential)	1 kW (potential)

(*) for conform MKI with 15 screen conductors (**) resistive wall not included (***) assuming no mode on beam line

Luminosity

Calculated using R. Tomás García and G. Arduini scripts

	Start-up scenario			Intermediate scenario			Pushed scenario		
ε [μm]	3.75	3.75		2.5	2.5		2.5	2.5	
N_b [10^{11}]	1.3	1.3		1.3	1.3		1.3	1.3	
β* [cm]	65	65		55	55		40	40	
Crossing angle [μrad]	320	320		340	340		300	300	
T [ns]	1.3	1.0		1.3	1.0		1.3	1.0	
Pile-up	24.9	27.2	+ 9.24 %	41.5	46.1	+ 11.08 %	50.0	57.0	+ 14 %
Pile-up density	0.188	0.243	+ 29.26 %	0.33	0.43	+ 30.30 %	0.46	0.59	+ 28.26 %
Luminous region	0.053	0.0448	- 15.47%	0.05	0.043	- 14.0 %	0.044	0.039	- 11.36 %

Beam induced heating: one of the LHC performance limitations

Machine elements with heating problems before LS1

Element	Problem	2011	2012
Double-bellow VMTSA	Damage		replaced
Injection protection collimator TDI	Damage		Still problems even if in parking position
Injection kicker MKI	Delay		MKI8D (MKI8C after TS3)
Primary collimator TCP.B6L7.B1	Few dumps		Interlock increased
Tertiary collimators TCTVB	Few dumps		Interlock increased
Beam screen standalone Q6R5	Regulation at the limit		Since TS3, correlation with TOTEM?
ATLAS-ALFA roman pot	Risk of damage		Due to Intensity increase
Synchrotron light telescope BSRT	Damage		Damage

Beam induced heating

Beam induced heating issues during LHC Run 1:

- Damage to equipment (RF fingers of VMTSA double bellow modules, BSRT mirror, TDI beam screen, TDI jaw deformation, damage came a few degrees close for ALFA detector)
- Beam dumps (due to interlock on TCP and TCTVB collimator temperatures, and maybe also vacuum interlock next to TOTEM pot)
- Delay to re-inject (MKI temperature)
- Believed to have affected temperature regulation of Q6R5 standalone (due TOTEM pot heating)

=> Bunch length was increased a few times to reduce heating

Beam induced heating

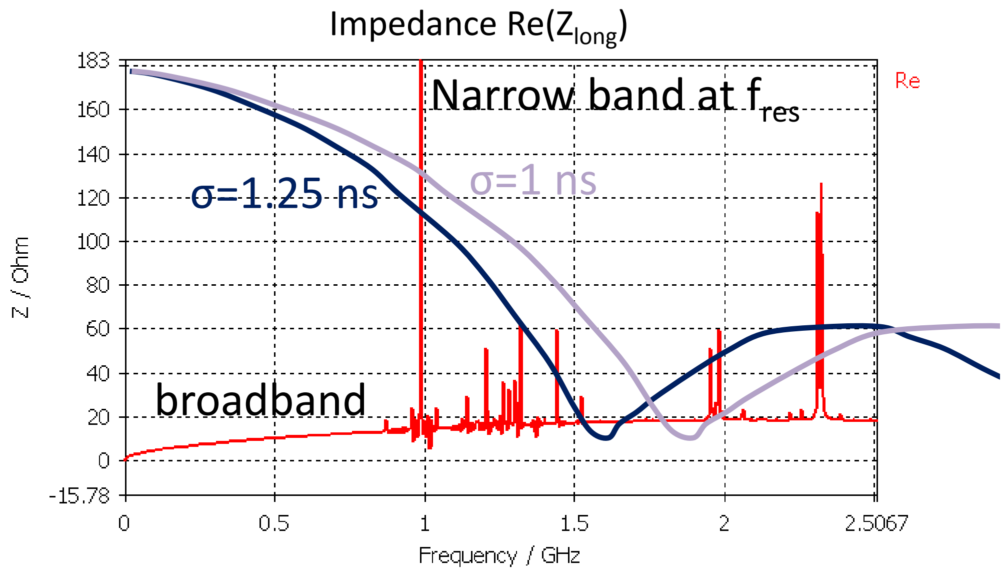
Mitigations put in place by equipment groups before and during LS1:

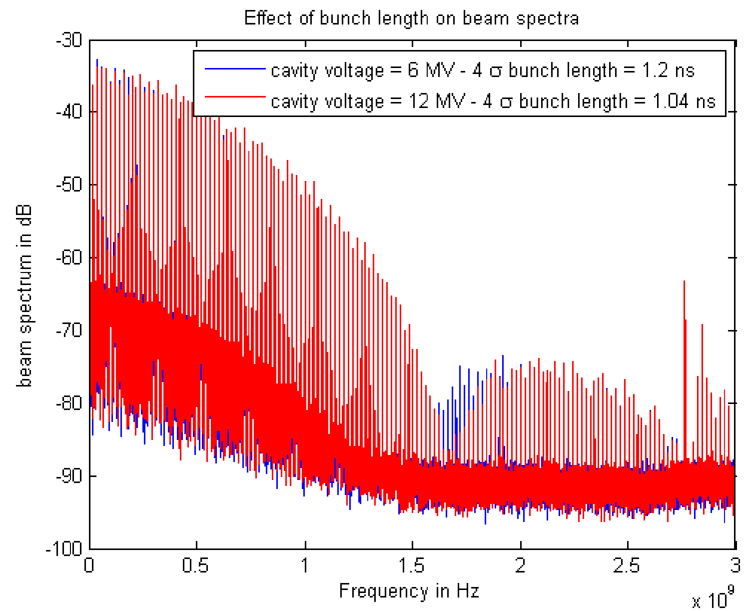
- VMTSA double bellows were all removed in 2012 → TE-VSC
- All non conform RF fingers were repaired during LS1 → TE-VSC and LRFF task force (also working on new design)
- 2-beam-collimators TCTVBs were all removed (half in 2012, half in LS1)→ EN-STI
- TCP.B6L7.B1 that was heating was exchanged during LS1 (investigations to know what happened will be performed in September with EN-STI to allow sufficient radiation cooldown) →EN-STI
- New design of the BSRT mirror during LS1 to reduce heating was installed → BE-BI
- The TDI beam screen was stiffened and more support was installed during LS1 → EN-STI/TE-ABT
- Copper coating on TDI jaw was planned but had to be abandoned at the last moment due to technical issues → EN-STI/TE-ABT
- Installed shielding on ATLAS-ALFA and TOTEM detectors during LS1 are planned to reduce heating, however TOTEM plans to approach high luminosity beams may increase heating
- MKI screening was significantly improved and the two non-conform magnets that were causing heating problems were repaired (MKI8C and in particular MKI8D) → TE/ABT

→ Very significant effort by all groups to protect their equipment

General consideration on power loss for HL-LHC parameters (2/3)

→ Decreasing bunch length from 1.25 to 1 ns.





$$P_{loss} = 2\left(eMN_b f_{rev}\right)^2 \left(\sum_{p=1}^{\infty} \mathrm{Re}\left[Z_{long}(2\pi pMf_{rev})\right] \times Powerspectrum(2\pi pMf_{rev}) \right)$$

→ switching to lower bunch length for broadband:

in general regularly increases (depends on broadband resonant frequency)

→ switching to lower bunch length for narrow band:

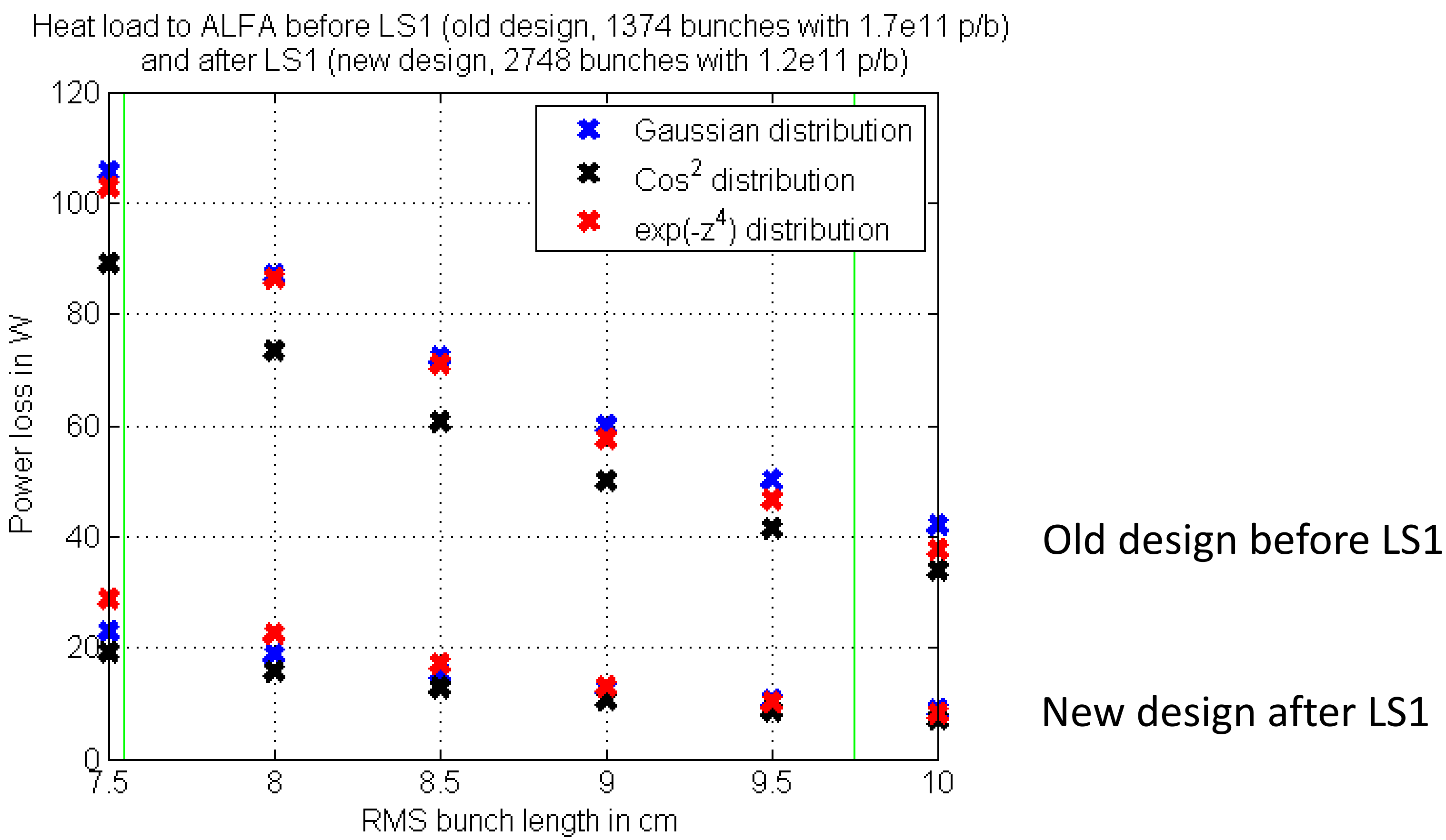
enhances some resonances , damps others, excites higher frequency resonances

→ Nominal bunch length should be more critical for most cases.

→ For most cases studied here (broadband): ~40 % increase

→ OP test in 2012 at injection energy did not reveal showstoppers to go to 1 ns with 50 ns beam at 1.5e11 p/b.

ATLAS-ALFA Roman pot



→ Heating on ATLAS-ALFA Roman pot increases by a factor 2 to 4 when decreasing bunch length from 1.25 ns to nominal (1.05 ns)

→ Heating is however predicted to be ~40% lower after LS1 than in 2012. In addition the location of the heating is further away from the detector (critical part) and easier to cool from outside.