Harmonic system for LHC

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4th Joint Hi-Lumi LHC-LARP Annual meeting

Acknowledgements:

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E. Jensen, J. Esteban Muller, H. Timko

Outline

- Motivation for harmonic RF system in LHC
- Main options considered
  - Higher harmonic: 400 MHz (main) + 800 MHz
  - Lower harmonic: 200 MHz (main) + 400 MHz
- Is "down-selection" possible now?

History

Harmonic RF systems in LHC were considered for

- "LHC Luminosity and Energy Upgrade: A Feasibility Study", LHC Project Report 626, 2002, for capture losses (200 MHz)
- Longitudinal feedback (200 MHz)
- LHC Luminosity upgrade scenario with short bunches (F. Zimmermann et al., 2002; S. Fartoukh, 2011)
- LHC Luminosity upgrade scenario with flat long bunches (F. Zimmermann et al.)
- Beam stability (T. Linnecar, E. Shaposhnikova, 2007)
- Reduction of beam induced heating and e-cloud effect (C. Bhat et al., 2011)
- Reduction of the IBS effect and beam losses on FB (T. Mertens et al., 2011)
- Decrease of luminosity pile-up density (S. Fartoukh, R. Tomas, …)

=> double RF operation of LHC

Double RF system

Voltage in a double RF system:

$$V = V_1 \sin\varphi + V_2 \sin(\mathbf{n}\varphi + \mathbf{\Phi_2})$$

For non-acc. bucket above transition:

$\mathbf{\Phi_2 = 0}$ - bunch-lengthening (BL) mode

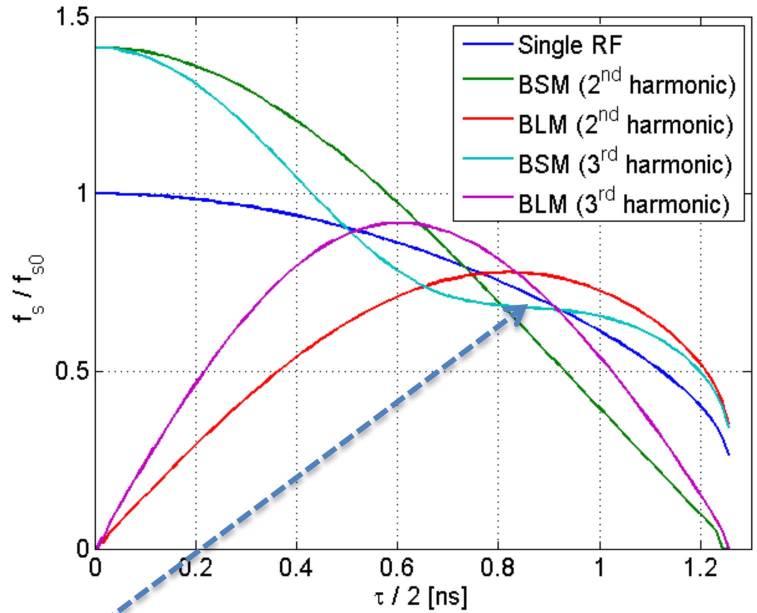
$\mathbf{\Phi_2 = \pi}$ - bunch-shortening (BS) mode

Usually is used to

- modify line density distribution ("flat" bunches in **BL-**mode)
- increase synchrotron frequency spread for beam stability (**BL-** or **BS-**mode)
- increase bucket size (only **BL-**mode)

Use of the **2nd harmonic** has advantages for beam stability (location of the flat region in fs(J))

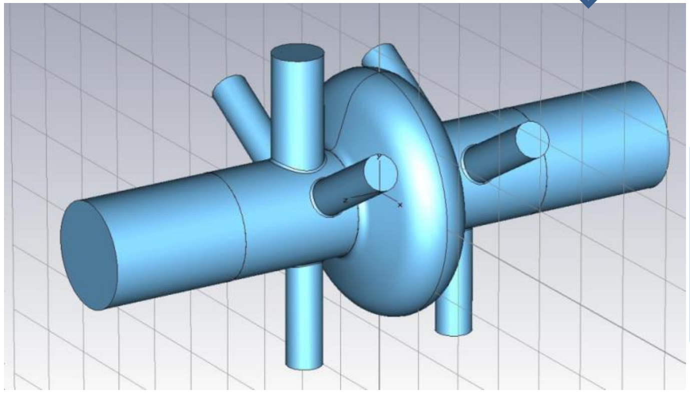
Synchrotron frequency distribution inside the bunch



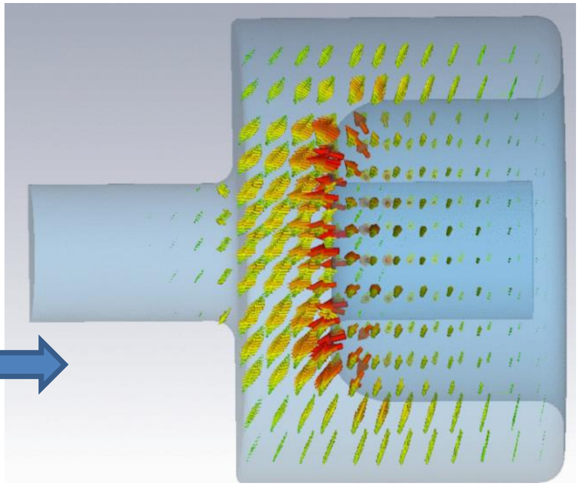
Present status of LHC cavities

"ACN capture RF system": 8 (4/beam) bare **NC 200 MHz** RF cavities (3 MV/beam, 240 kW/cavity) are stored in bld. 869 under dry Nitrogen. Design based on SPS **SWC** from 80's.

Preliminary design of the **SC 800 MHz** RF system:
HOM-free design: M. Zobov et al. → talk
L. Ficcadenti, R. Calaga, T. Roggen → talk



Preliminary design of **compact SC 200 MHz** ¼ wave cavity (R. Calaga)



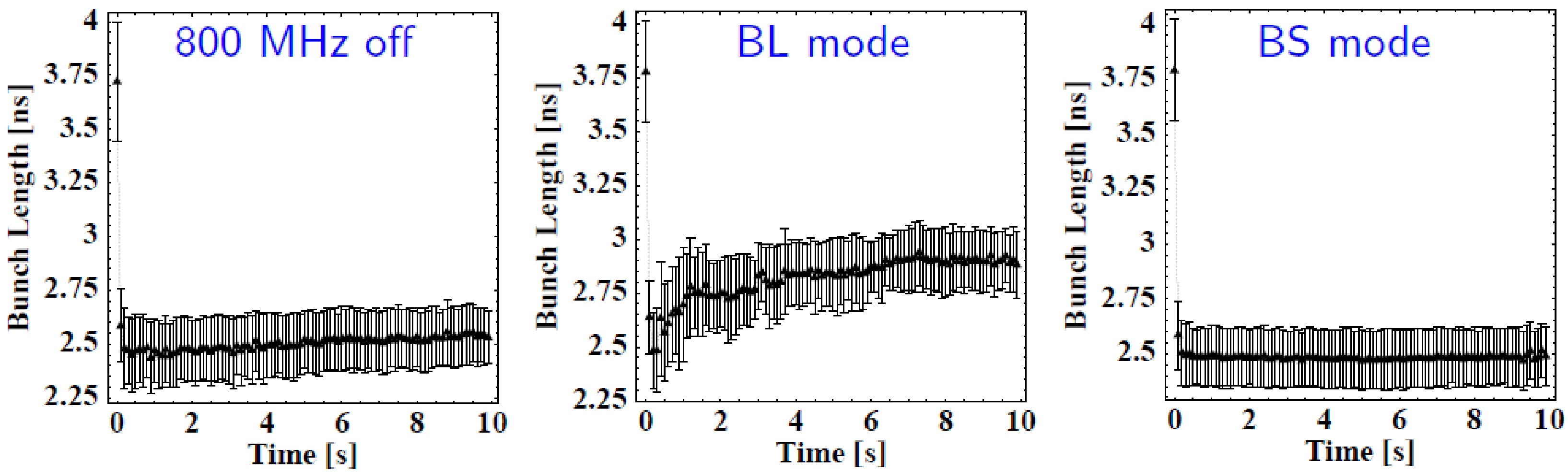
Motivation (1/2)

Longitudinal beam stability

- **Single bunch stability** is expected for HiLumi intensities in nominal 25 ns operation: single RF and 2.5 eVs emittance (more in talk of J. Esteban Muller)
- **No bunch-by-bunch longitudinal feed-back** (FB) in LHC => rely on "natural" Landau damping due to synchrotron frequency spread (D. Boussard et al., 1999).
- **Existing FB** can damp instabilities with frequencies (modes) inside system bandwidth (~200 kHz) – works for fundamental cavity impedance, but **not for HOM** outside
- In case of issues with **high intensity multi-bunch** (HiLumi) operation => increase synchrotron frequency spread in a double RF system => 800 MHz is the best choice

- **Transverse beam stability**:
  - some studies for LEP (S. Myers, Y. H. Chin)
  - complicated parameter space (simulations by K. Li) => E. Metral' talk

SPS double RF system (200+800) MHz: measurements for LHC beam in Q26 optics



The average bunch length at 26 GeV/c, 1.25×10^{11}/bunch, $V_1 = 3$ MV, $V_2 = 0.7$ MV, $h_2/h_1 = 4$ (T. Bohl, T. Linnecar, E. S. PAC'05)

$\Rightarrow$ **In a double RF (BS-mode) the instability threshold is increased by a factor 5!**

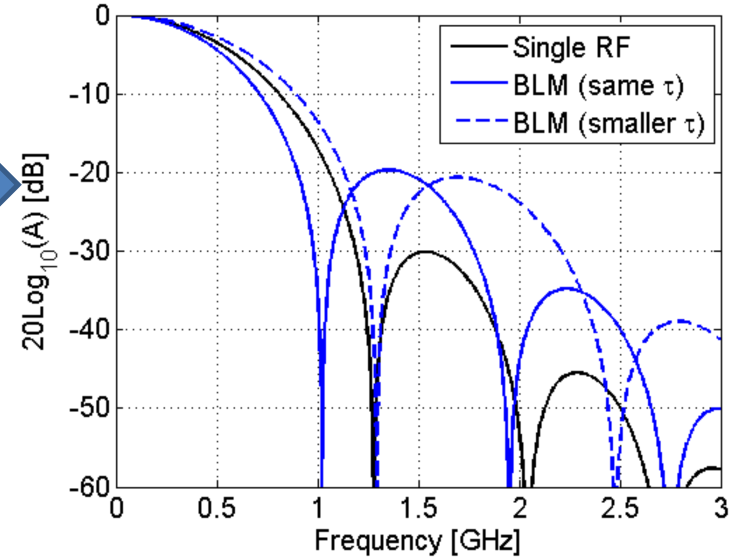
Motivation (2/2)

Flat bunches are reducing:

– Beam induced heating

– Pile-up

– Peak line density (e-cloud, beam-beam?)

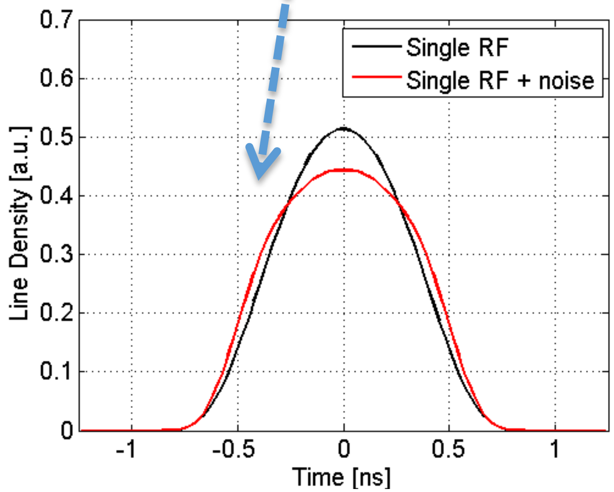


This shape can also be achieved in **a single RF system**:

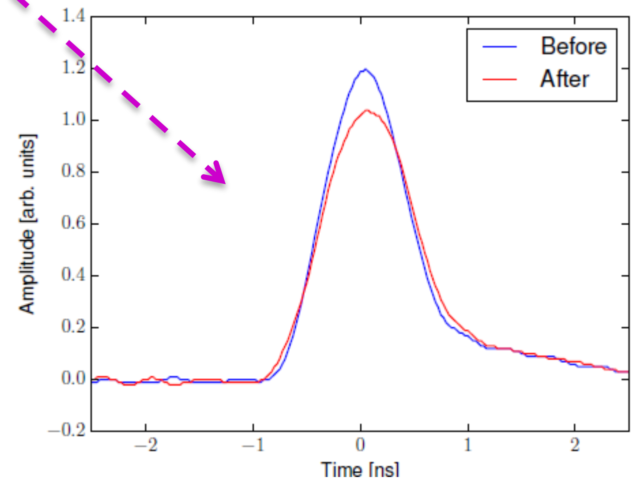
– Tested in LHC MD in 2012 => positive effect on beam induced heating (< 1.2 GHz) ("Flat bunches in LHC", IPAC'14)

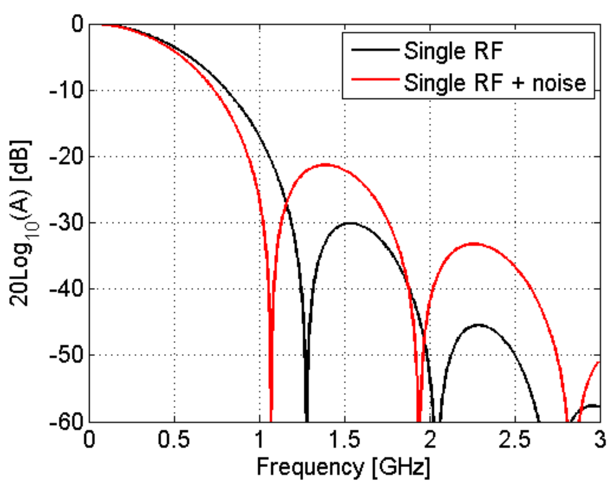
– For how long (IBS, RF noise & SR @ 7 TeV)? => future MD

Flat bunches in a single (400 MHz) RF system: simulations and measurements (LHC MD 2012)

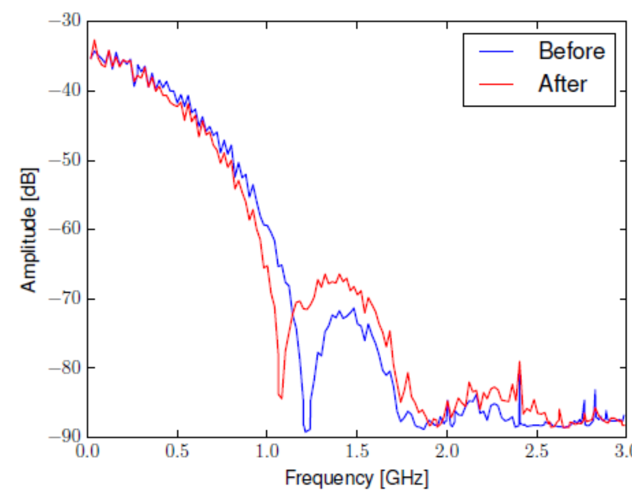


Bunch profile





Spectrum

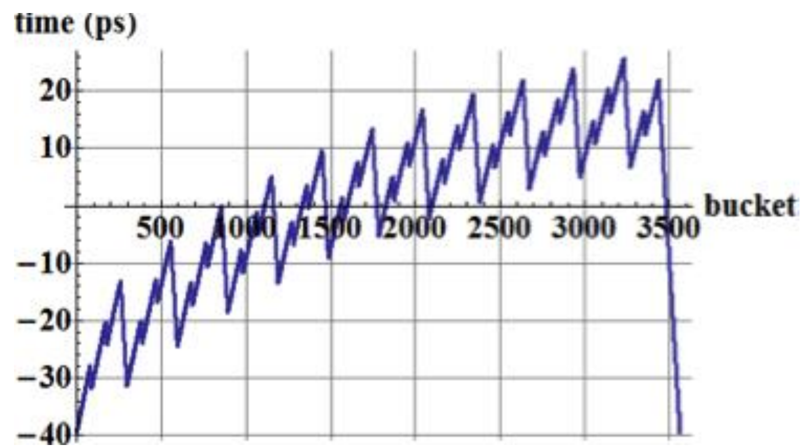


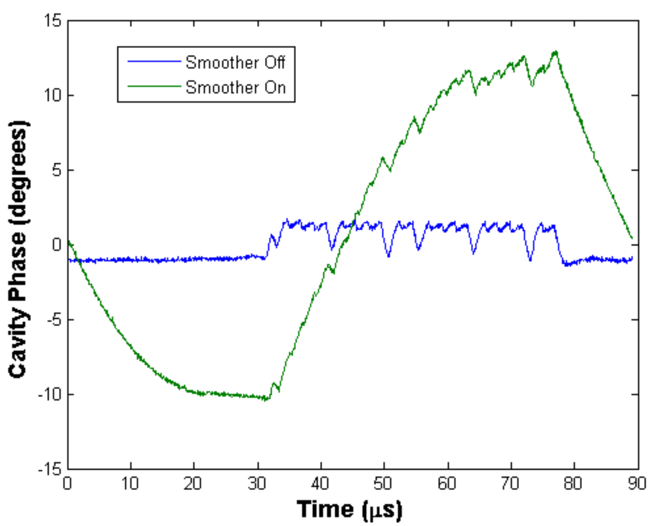
Simulations by T. Argyropoulos

⇒ **Good agreement between measurements and simulations**

High intensity operation with "full cavity detuning"

- Not possible to operate above nominal intensity with constant cavity voltage and phase over turn (actual "half-detuning" scheme)
- Keep klystron current constant and let beam gaps modulate the cavity phase => full cavity detuning (P. Baudrenghien et al., IPAC11); tested in MD in 2012 with nominal 50 ns beam, cavity phase modulation with 732 bunches



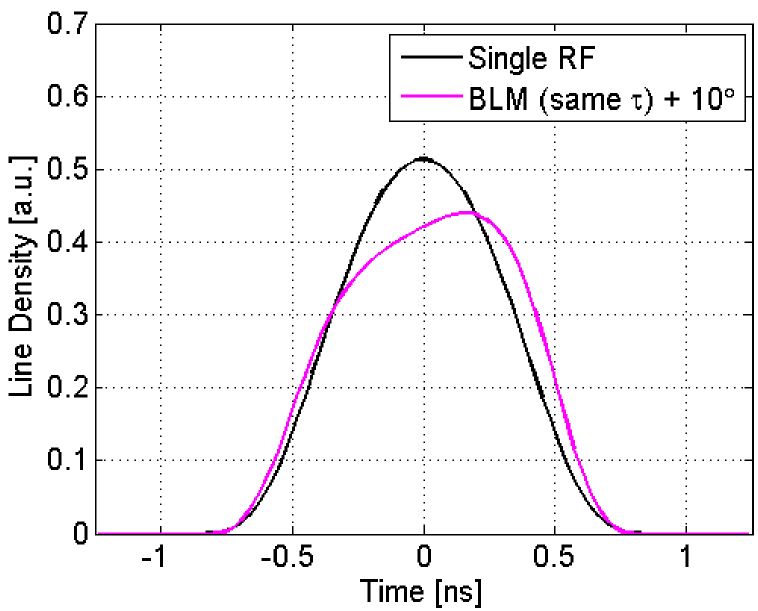


• in this scheme transient beam loading changes bunch positions;
effect ~ average beam current
+/- 35 ps bunch displacement =>
+/- 10 deg at 800 MHz **=> tilted bunches**

• similar effect (phase shift) doesn't allow to operate in BL-mode in SPS => BS-mode

Tilted bunches in a double RF system

Bunch profile

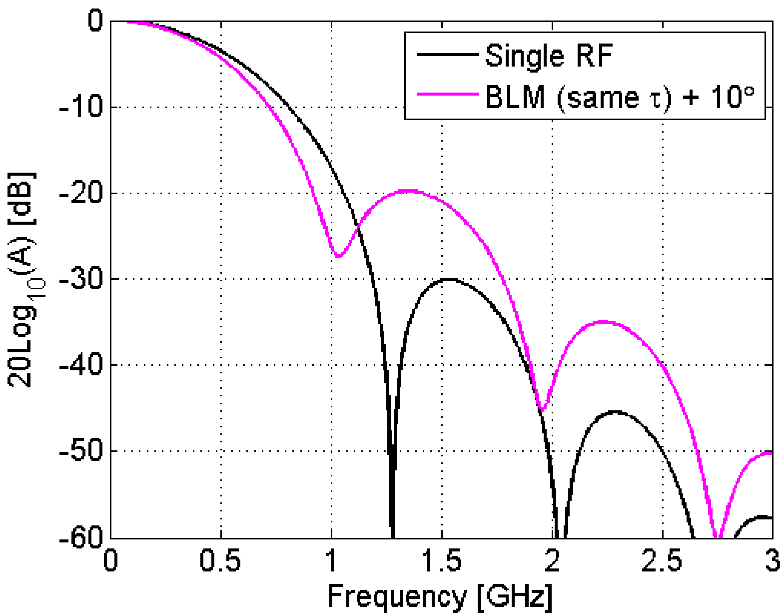


Single RF: τ =1.5 ns → ε = 4 eVs

Double RF: τ =1.5 ns → ε = 3.2 eVs

Simulations by T. Argyropoulos

Spectrum



→ **Smaller** improvement in spectrum for tilted bunches (for the same τ_{max})

→ Stability – in talk of J. E. Muller

Comparison of two operation modes of a double RF system

- **Bunch shortening:**
  - + good for beam stability
  - + very robust (large allowed RF phase shift)
  - + increased linear synchrotron frequency
  - - increased peak line density
  - - reduced (single RF) bucket size
- **Bunch lengthening:**
  - + reduced peak line density (flat bunch)
  - + increased bucket area
  - + for a given V_{800} (and $\Phi_2 = 0$) larger increase in frequency spread
  - - high sensitivity to RF phase shift (tilted bunches)
  - - flat region in f_s distribution (limitation on max bunch length)

Power requirements

- **400 MHz:** RF power limitation at 300 kW
  - ½ detuning scheme: V=*const*, P=*const* during beam passage and in the gaps
  - full detuning scheme: allow V (RF phase) modulation and reduce RF power (by ~ factor 3),
- **800 MHz:** $V_{800}=V_{400}/2=8$ MV
  - BL-mode: Power > 300 kW for 1 MV → 10 cavities with variable coupler
  - BS-mode: Power < 80 kW for 1 MV → 2-3 cavities with fixed coupler

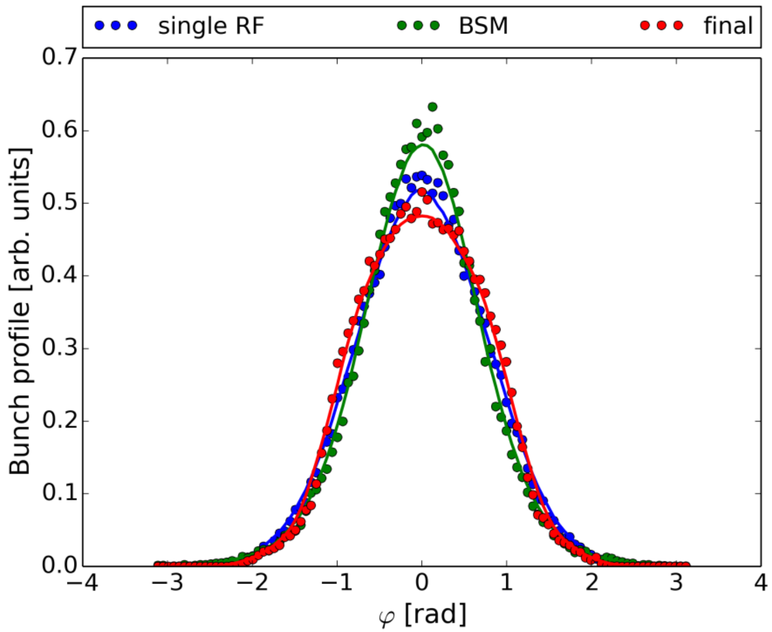
(P. Baudrenghien, WP4-HH Meeting; R. Calaga, Chamonix 2014)

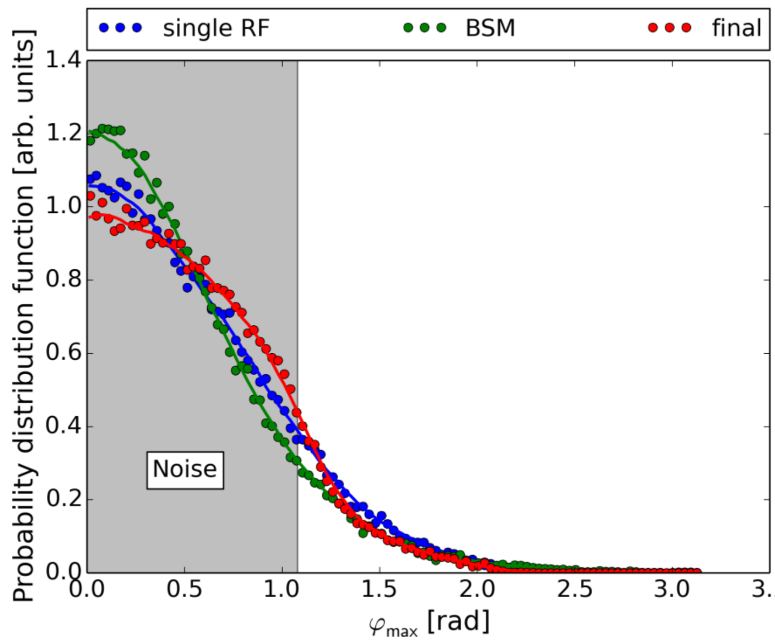
Flat bunches in the BS-mode?

Preliminary results

Phase noise applied in BS-mode in frequency band (√2 - 1.2) f_{s1}

V_{400}=16 MV → V_{400}=16 MV & V_{800}=8 MV (BSM) → + noise





BQM 4σ (FWHM): 1.13 ns → 1.34 ns

Simulations by H. Timko

→ Final bunch is flatter than the initial one in a single RF system!

Summary for (400+800) MHz

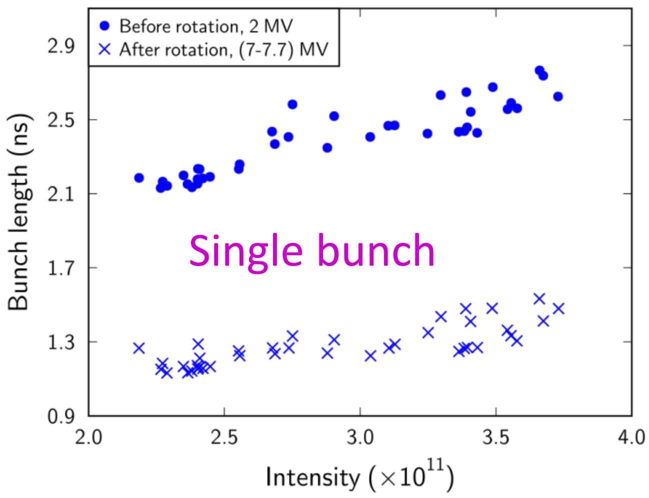
- From power requirements the BS-mode seems to be more reasonable (in full detuning scheme)
- Main application of BS-mode is longitudinal beam stability, but this could be also the most urgent case. No problems are expected for beam induced heating (flat distribution)
- Prototype (2 cavities) can be built in 5-6 years – to test in LHC with high intensity beams after LIU
- Transverse stability is also affected, but probably above considered intensities (K. Li simulations, more in talk of E. Metral)

Low harmonic RF system in LHC: motivations

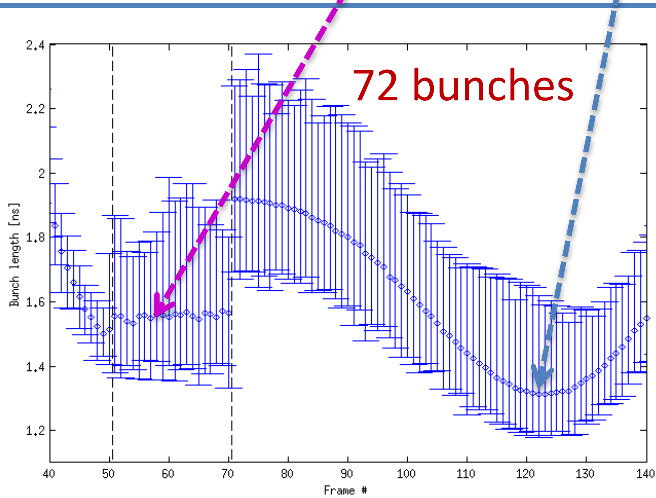
- Pushes up the limitation to the SPS intensity due to power limit in the SPS 200 MHz RF system (even after upgrade)
  - Alternative to bunch rotation on the SPS flat top
  - Doesn't remove limitation during the SPS ramp → $2xT_{acc}$
- Allows longer bunches for reduction of pile-up density (depending on future length of LHC experiments lumi-region)
- Luminosity leveling when used with existing 400 MHz RF
- Improve e-cloud effect, beam induced heating and IBS (R. Tomas Garcia et al., RLIUP)
- Beneficial for ions in LHC (J. Jowett, RLIUP) and momentum slip-stacking in the SPS (simulations of T. Argyropoulos)

Bunch rotation tests in the SPS

- Good results were achieved for a single bunch (AWAKE, 2012)
- MD on 4.11.2014: 1&2 batches of 72 bunches (1.1×10^{11}/b) (T. Bohl, J. E. Muller, E. S.): 7 MV ↘ 3 MV ↗ 7 MV



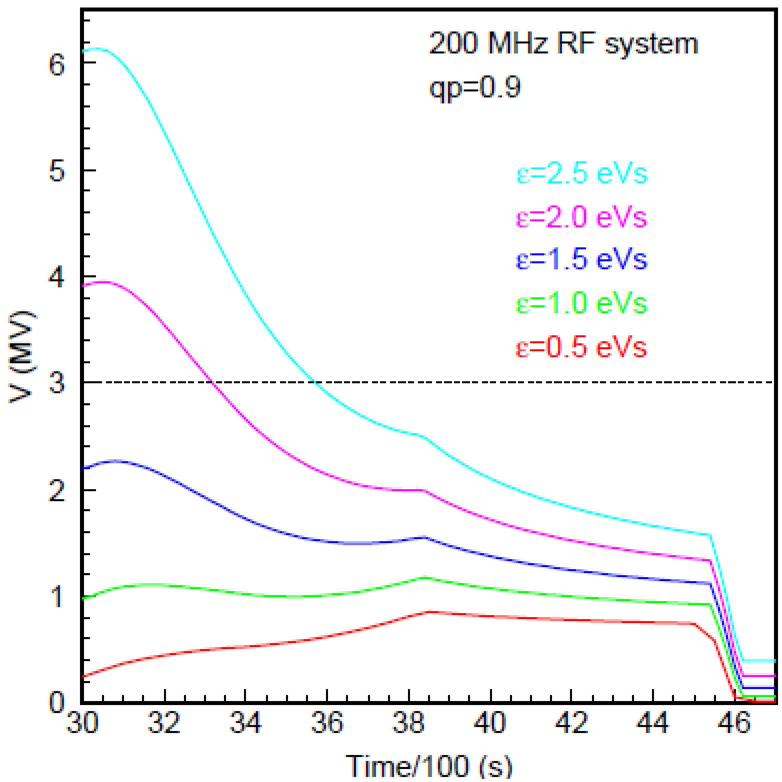
7 MV adiabatic: 1.55ns & step: 1.3 ns



- With adiabatic voltage increase bunches are 20% longer
- Uncontrolled longitudinal emittance blow-up, especially at low voltage (before rotation) due to instability → SPS impedance reduction would help

200 MHz RF system as a fundamental: Voltage program

Ramp



Flat top

- V=3 MV is enough to accelerate ε = 1.5 eVs and to transfer 3.0 eVs to 400 MHz at 7 TeV
- At 4 TeV with 12 MV we had ε=2.2 eVs (τ=1.25 ns)
- At 7 TeV to have the same bunch stability we need 3.0 eVs in 400 MHz and 4.0 eVs in a single 200 MHz RF

→ double RF system should be used for short bunches

Beam parameters at 7 TeV in (200 + 400) MHz RF system

emit. [eVs]	V@200 MHz [MV]	V@400 MHz [MV]	double RF operation	bunch length max or 4 σ [ns]	
3.0	0.0	16.0	-	1.17	
2.5	6.0	0.0	-	1.57	long bunches
2.5	6.0	3.0	BSM	1.35	
2.5	6.0	3.0	BLM - flat	2.0	
3.0	16.0	0.0	-	1.34	
3.0	16.0	8.0	BSM	1.14	“short”
3.0	16.0	8.0	BLM – flat	1.8	
0.9	16.0	8.0	BLM	1.15	
1.5	6.0	3.0	BSM	1.05	small
0.4	3.0	1.5	BLM	1.15	

Flat bunch with 10 cm rms corresponds in BL-mode to τ_{max}=1.15 ns

→ very small emittances for nominal bunch lengths (~1 ns)

Power requirements for 200 MHz SC RF system

R. Calaga, Chamonix 2014

- ½ detuning: 1.5 MV/cavity, P_{max} = 450 kW → 4 cavities for 6 MV
  - required for flat bunches
- Full-detuning: 3 MV/cavity → 2 cavities for 6 MV
- Power coupler: LHC type, fixed coupling
- Amplifier – Diacrode THALES 628: 500 kW CW

200 MHz RF system in LHC: possible issues (to be studied)

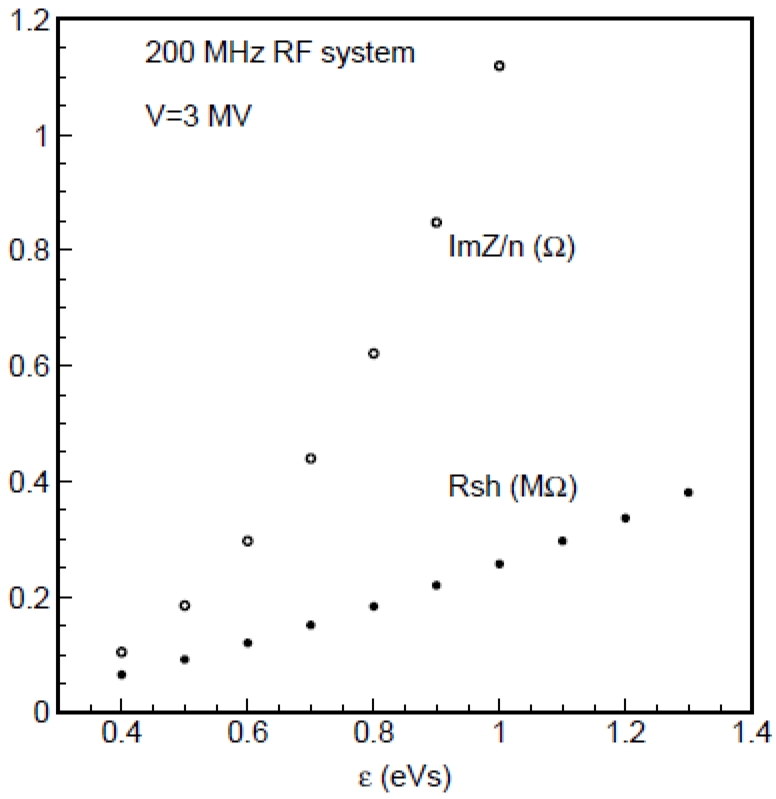
- Possible issues with stability for short bunches (for the same emittance stability threshold ~ h^2 → 4 times lower) → double RF operation
- In both single and double RF systems (BLM): limit on minimum achievable bunch length (longitudinal emittance) with reasonable 200 MHz voltage
- Crab cavities at 400 MHz (for long bunches)
- Transverse beam stability to be studied - smaller synchrotron tune than in (400+800) MHz

Summary

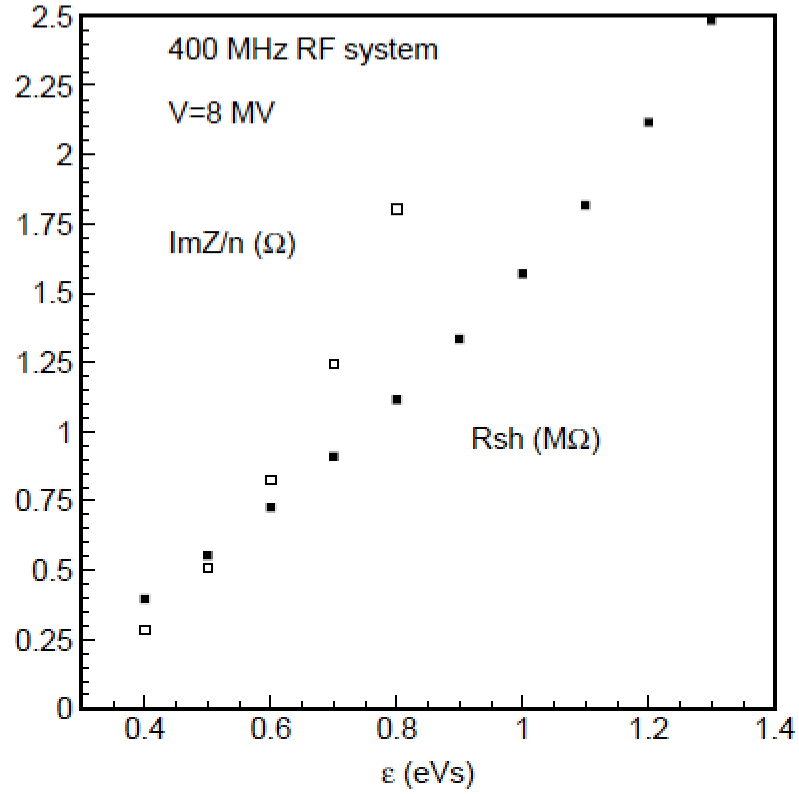
- Two possible options of the 2nd RF system (200 MHz or 800 MHz) for HL-LHC scenarios with main applications:
  - 800 MHz: beam stability
  - 200 MHz: long bunches (e-cloud, pile-up)
- Low harmonic RF system can be used only in a double RF operation
- Beam stability, both longitudinal and transverse, in a double RF system, in particular (200+400) MHz, should be studied in detail
- Flat bunches in a double RF system are difficult to obtain (power for HH or emittance for LH) → rely on RF phase modulation
- 5-6 years are required to be ready → start the 800 MHz prototype now
- Start design of the compact SC 200 MHz RF system
- Finally, expected benefits should be weighted against impedance increase and reduced reliability

200 MHz RF system as a fundamental RF: comparison of beam stability in a single RF system (450 GeV/c, nominal bunch and beam intensity)

200 MHz RF

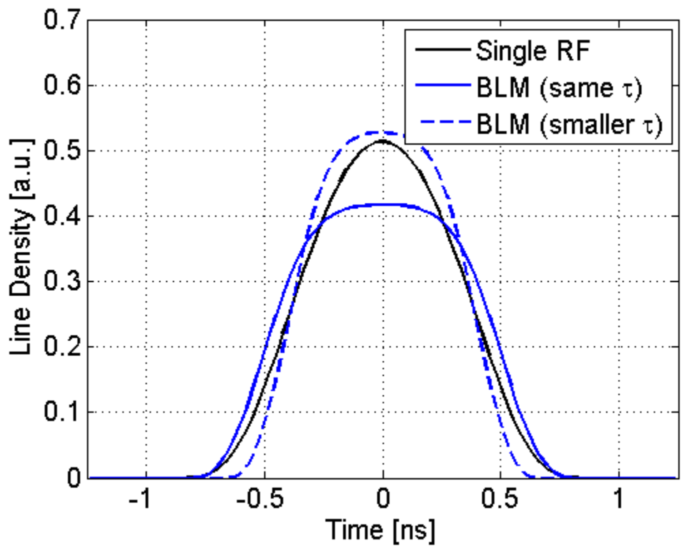


400 MHz RF



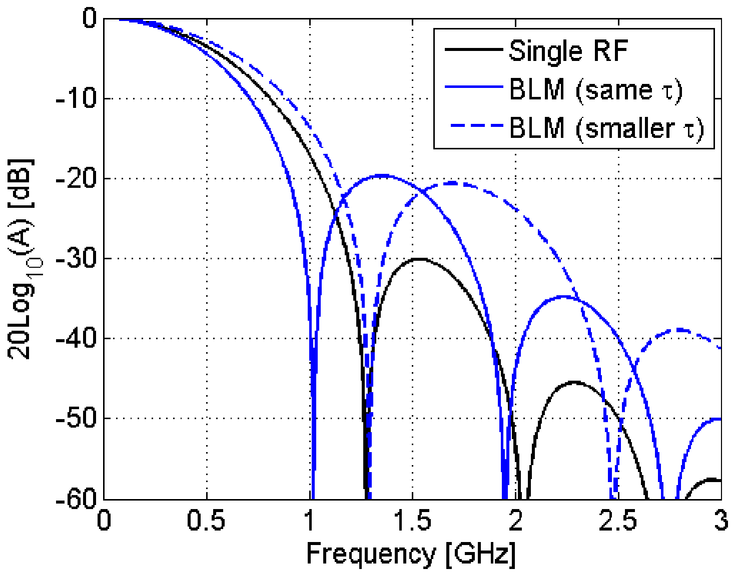
400 MHz + 800 MHz RF system (V_1/V_2=2): effect on beam induced heating

Bunch profile



Single RF: τ =1.5 ns, ε =4 eVs
Double RF: τ =1.5 ns, ε =3.2 eVs
τ =1.25 ns, ε =1.65 eVs

Power spectrum

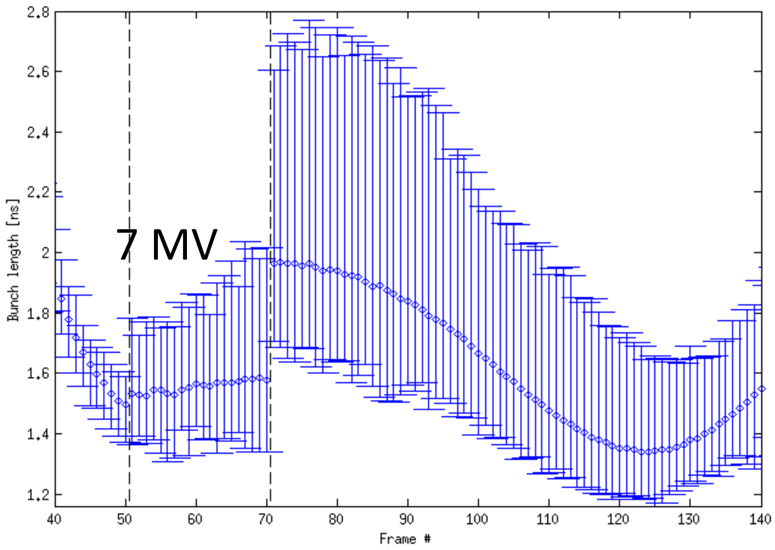


- The same bunch length: improvement < 1.1 GHz and degradation above
- Shorter bunches (1.2 ns): higher values at all frequencies

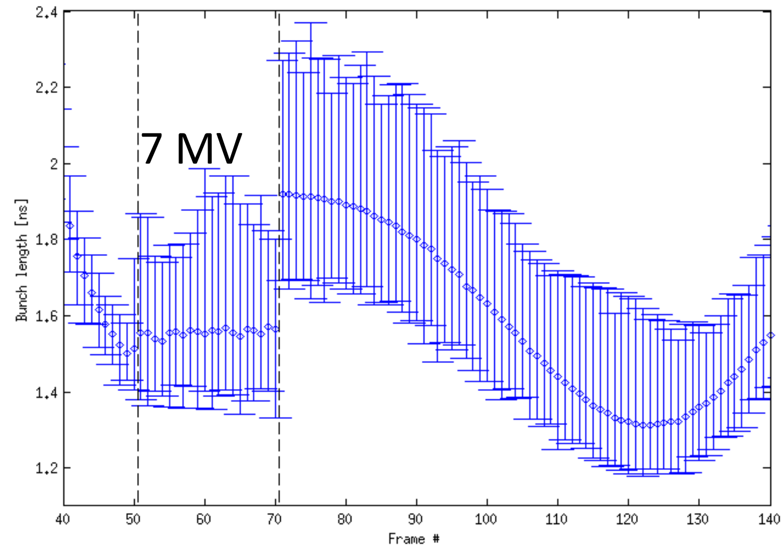
Emittance blow-up on the SPS flat top

Bunch length measurements

3 MV↗ 7 MV



3 MV↗ 7 MV



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