HL-LHC (and LHC) longitudinal collective effects with 1 RF system (400 MHz) or 2 RF systems

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HiLumi WP2 Task 2.4 meeting

26.03.2014

Longitudinal collective effects

- Single RF system
  - Single bunch instability during ramp for small longitudinal emittances => cured by controlled emittance blow-up
  - Beam measurements of impedance in 2010-2013
  - Beam loading for intensities > nominal (25 ns)

=> So far double RF system is not necessary for beam stability in the longitudinal plane

High harmonic RF system

Voltage in a double RF system:

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

(non-acc. bucket above transition):

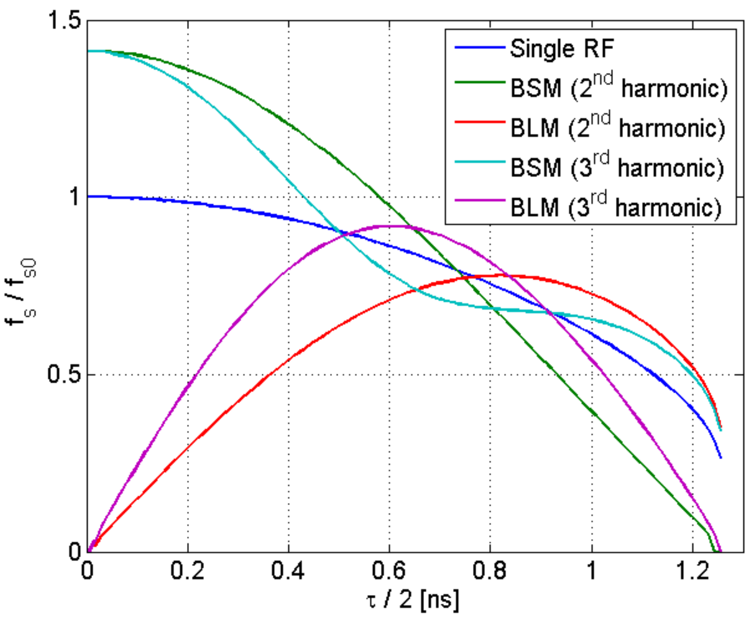
$\mathbf{\Phi_2 = 0}$ - bunch-lengthening (BL) mode

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

Usually is used to

- modify line density distribution ("flat" bunches in BL-mode) – can also be achieved in a single RF system but for a limited time (IBS, RF noise, SR)
- increase synchrotron frequency spread for beam stability (BL- or BS- mode)
- increase bucket size (only BL-mode)

Synchrotron frequency distribution inside the bunch



High harmonic RF system in LHC so far was considered for

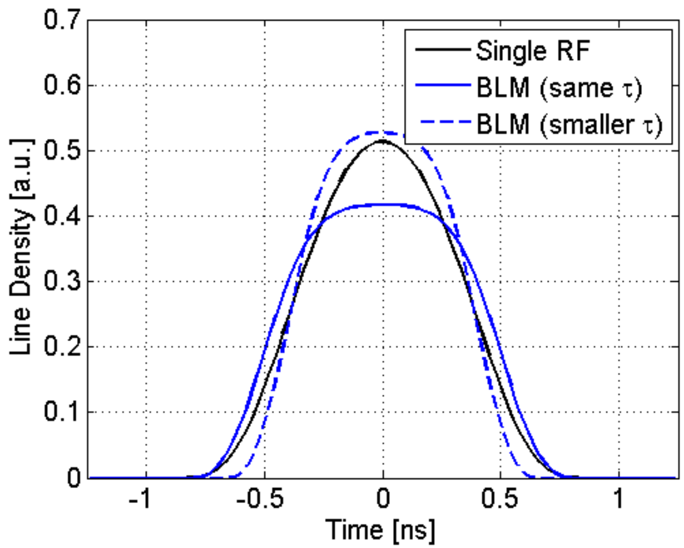
- "LHC Luminosity and Energy Upgrade: A Feasibility Study", LHC Project Report 626, 2002, O. Bruning et al.
- LHC Luminosity upgrade scenario with short bunches (F. Zimmermann et al., 2002; S. Fartoukh, 2011)
- LHC Luminosity upgrade scenario with flat long bunches (F. Zimmermann et al.)
- Beam stability (T. Linnecar, E. S., 2007)
- Reduction of beam induced heating and e-cloud effect (C. Bhat et al., 2011; S. Myers, LMC 2012)
- 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, …)

=> Preliminary cavity design of the 800 MHz RF system for LHC existed (L. Ficcadenti, R. Calaga, J. Tuckmantel, T. Roggen; M. Zobov et al.)

=> Tests of effect of “flat” bunch distribution in a single RF system on beam induced heating was performed in LHC in 2012

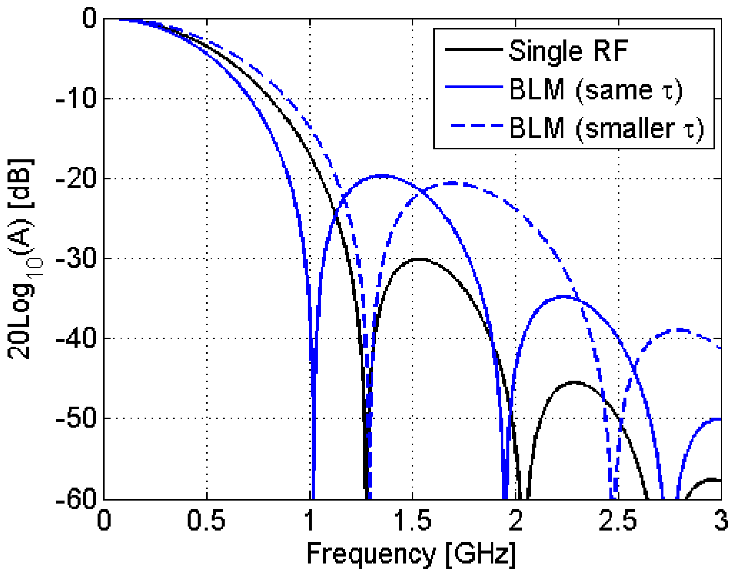
400 MHz + 800 MHz RF system ($V_1/V_2=2$): effect on beam induced heating

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

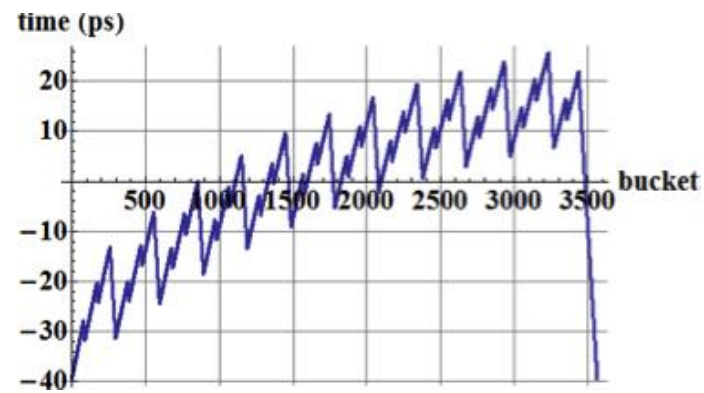
Power spectrum

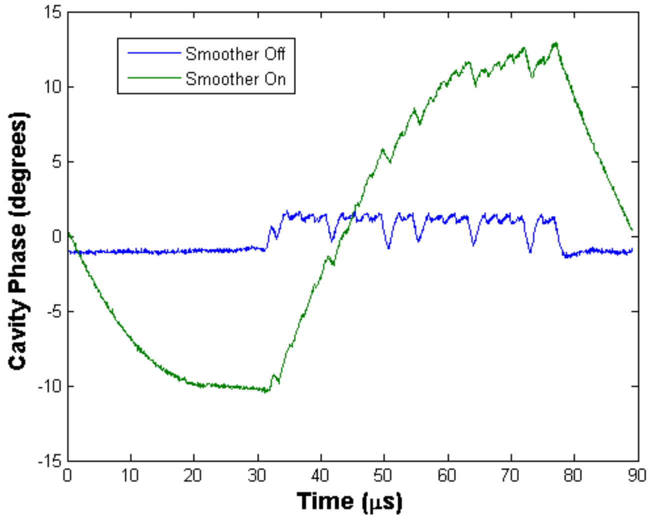


- The same bunch length: improvement < 1.1 GHz and degradation above
- Shorter bunches (1.2 ns): higher values at all frequencies

High intensity operation
with scheme of "full cavity detuning"

Not possible to operate above nominal intensity with constant cavity voltage and phase over turn (actual half-detuning scheme) => use proposal of D. Boussard (1991): 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 => reduction in klystron forward power





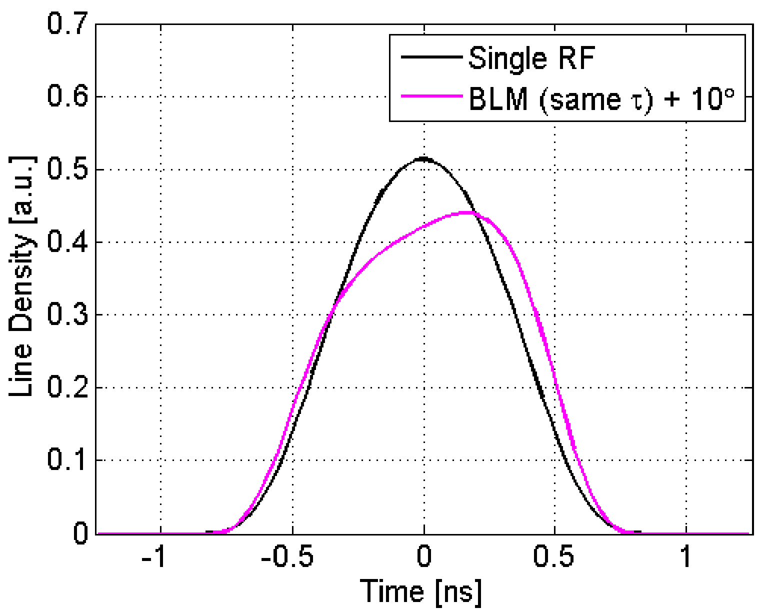
- in this scheme transient beam loading changes bunch positions;

effect ~ average beam current

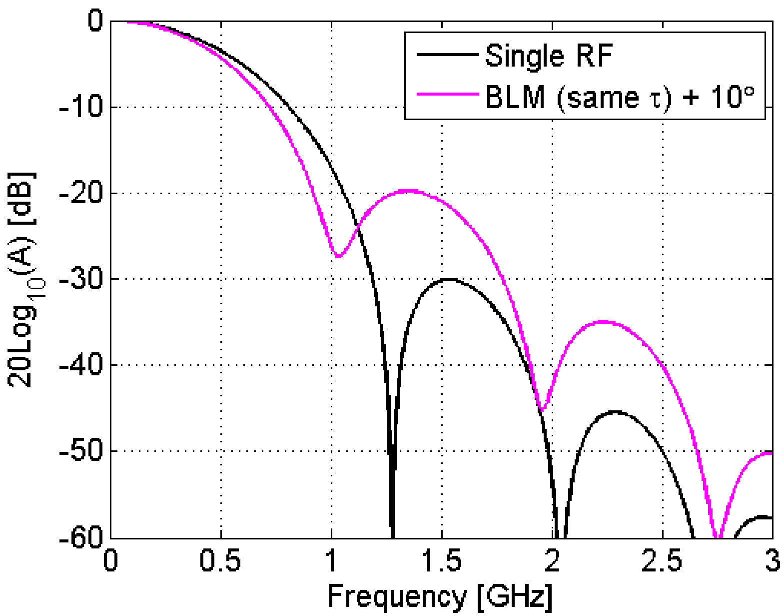
- +/- 35 ps bunch displacement => +/- 10 deg at 800 MHz
- similar effect in the SPS doesn't allow to operate in BL-mode => BS-mode

Tilted bunches in a double RF system

Bunch profile



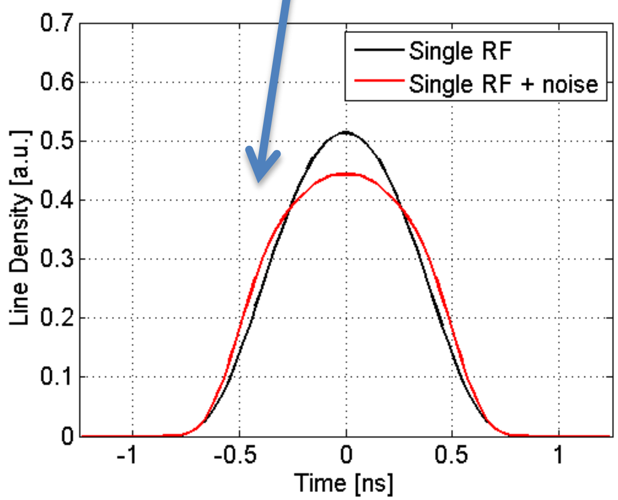
Spectrum



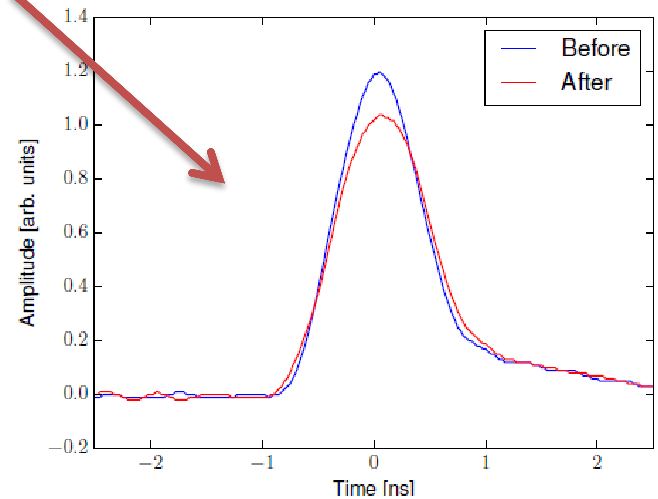
Single RF: τ =1.5 ns => ε = 4 eVs
Double RF: τ =1.5 ns => ε = 3.2 eVs

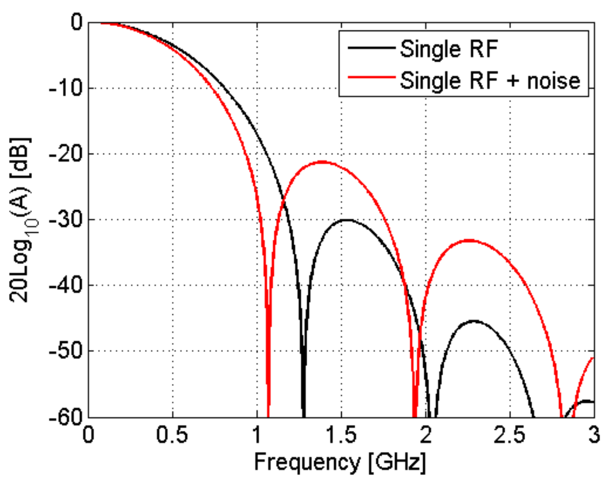
No improvement in spectrum for tilted bunches even for the same τ

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

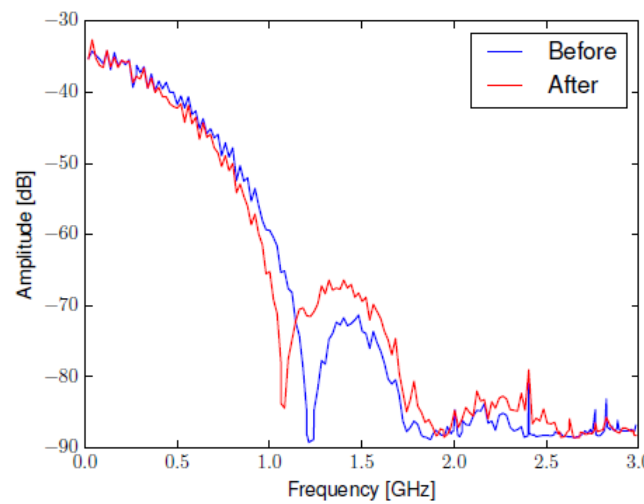


Bunch profile





Spectrum

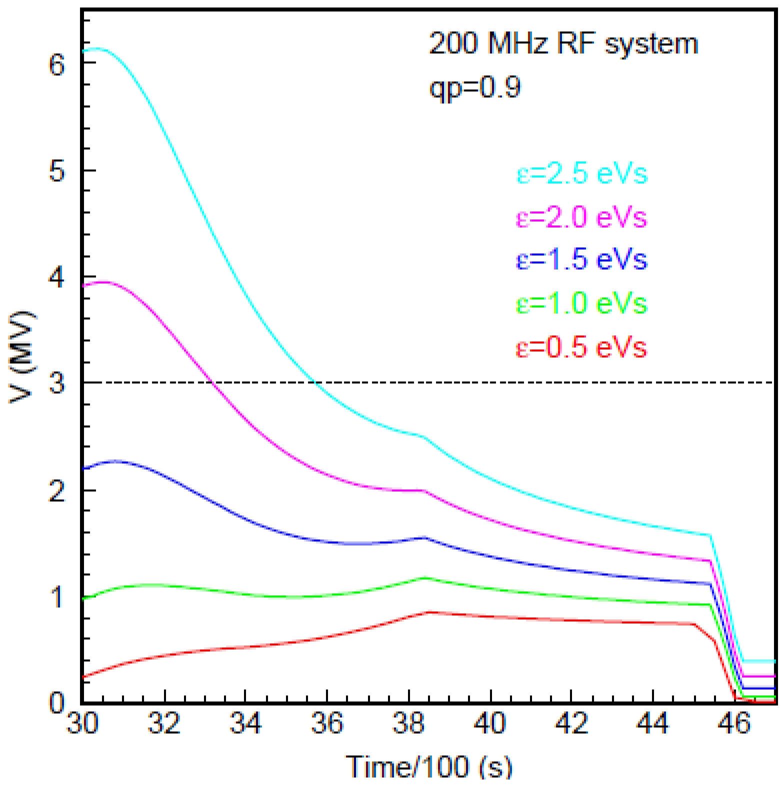


Low harmonic RF system in LHC as a fundamental RF: motivations

- Provide longer bunches for reduction of pile-up density in LHC
- Together with existing 400 MHz RF can be used for luminosity leveling
- Push up the limitation to injected intensity from power limit in SPS 200 MHz RF system (after upgrade)
- Improve IBS, beam induced heating and e-cloud effect (R. Tomas Garcia et al., RLIUP)
- Beneficial for ions and momentum slip-stacking scheme in the SPS (J. Jowett, RLIUP)
- New proposal for compact SC cavity design (R. Calaga)

200 MHz RF system as a fundamental: Voltage

Ramp



Flat top

(1) V=3 MV is enough to accelerate max inj. ε = 1.5 eVs and to transfer 3.0 eVs to 400 MHz @7TeV

(2) Bunch length @7 TeV :

In 2012 in 12 MV we had ε=2.2 eVs with 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 system => double RF system should be used for short bunches

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

emit. [eVs]	V@200 MHz [MV]	V@400 MHz [MV]	double RF operation	bunch length 4 σ [ns]
3.0	0.0	16.0	-	1.17
3.0	3.0	0.0	-	2.1
3.0	3.0	1.5	BSM	1.83
3.0	3.0	1.5	BLM - flat	2.41
3.0	16.0	0.0	-	1.34
3.0	16.0	8.0	BSM	1.14
3.0	16.0	8.0	BLM – flat	1.8
2.0	6.0	0.0	-	1.68
2.0	6.0	3.0	BSM	1.44
2.0	6.0	3.0	BLM	2.07

long bunches

“short”

small

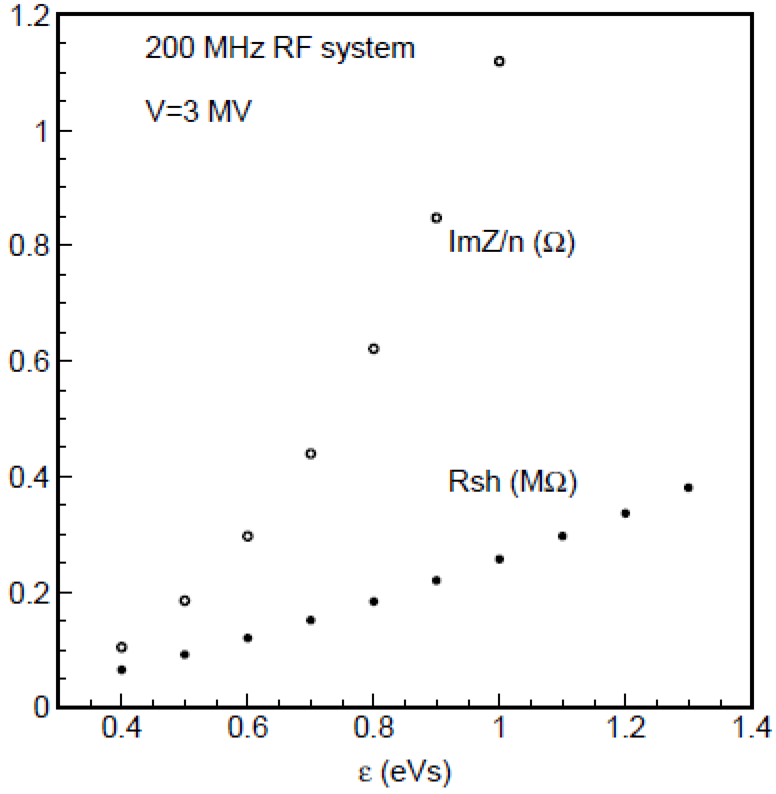
Flat bunch with 10 cm rms corresponds to 1.15 ns bunches in BLM => emittance reduction: 0.4 eVs in 3 MV (+1.5 MV) and 0.9 eVs in 16 MV (+8 MV),

Low harmonic RF system in LHC: possible issues (to be studied)

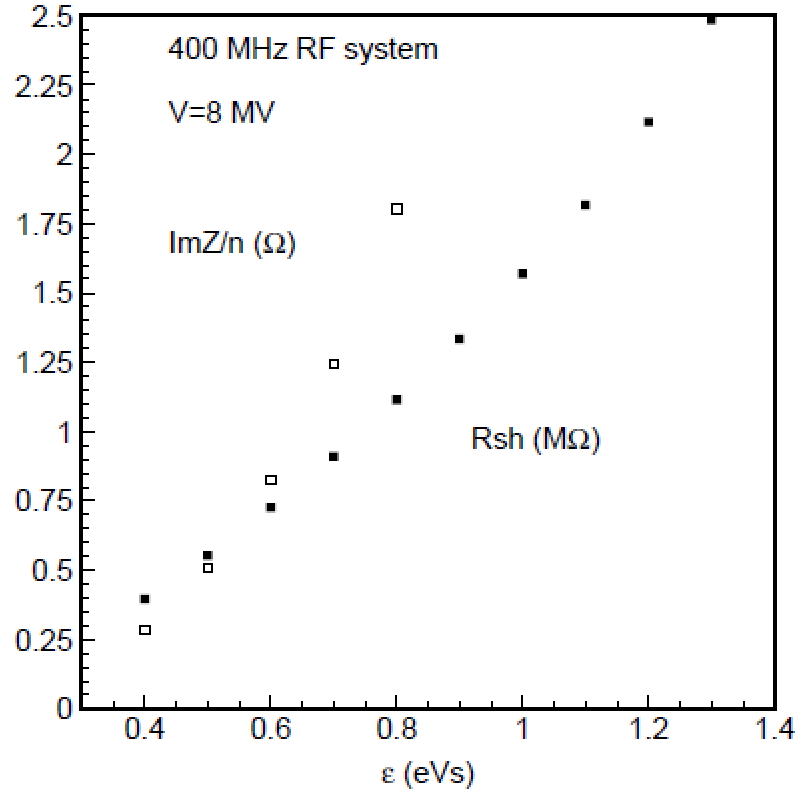
- Need to be used together with the 400 MHz RF (as a high harmonic system) to preserve beam stability (for the same longitudinal emittance stability threshold ~ h^2 => 4 times lower)
- In a double RF system (BL-mode): limit on the bunch length (3.4 ns) to avoid loss of Landau damping
- Full-detuning scheme most probably would also be needed => tilted bunches (if required bunch positions are not the same) and reduced beam stabilisation
- Crab cavities at 200 MHz (?)
- Transverse beam stability in a double RF system

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



Summary

- Two possible options of the 2nd RF system (200 MHz and 800 MHz) for HL-LHC scenarios
- Low harmonic RF system most probably cannot be used alone (as a single RF) => double RF operation
- Beam stability in a double RF system will be different and should be analysed using a realistic LHC impedance model
- Expected benefits should be weighted against impedance increase and reduced reliability
- More studies for a single RF system needed