possible scenarios with high harmonic RF system for HL-LHC

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possible uses of higher harmonic RF

- **bunch shaping**
  - less peak density, **reduced component heating, reduced IBS**
- **bunch shortening or lengthening**
  - reduced component heating, varying luminous region, reduced bb tune shift, reduced IBS, leveling option, modulating e-cloud
- **beam stabilization** (more tune spread)
  - possibility of lower longitudinal emittance
  - **factor 3-4 increase in stability** for single-bunch & coupled-bunch instabilities (Elena S., Trevor L.)
- **scenarios with shorter bunch spacing?**
  - Stephane Fartoukh’s 5-ns scheme→**1.25 ns scheme!?** [better for electron cloud])
- off-momentum halo cleaning? (use “empty buckets”?)

success story of double RF systems

(e.g. SY Lee)

- 3rd harmonic cavity in Cambridge CEA, 1971, to increase Landau damping
- 6th harmonic cavity at the ISR to cure coherent instabilities, 1974/1977
- h=5/10 system in PS Booster increased beam intensity by 25-30%, 1983 & 1987
- beam intensity quadrupoled at IUCF, 1995, thanks to double RF system
- SPS reaches beyond nominal LHC bunch intensities, >5 times above single-RF coupled-bunch instability threshold with 4th harmonic RF system, 2002
- … LHC?

harmonic RF at the ISR

IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

LONGITUDINAL INSTABILITIES OF BUNCHED BEAMS IN THE ISR

P. Bramham, S. Hansen, A. Hofmann, E. Peschardt

CERN,
Geneva, Switzerland

Summary

Microwave instabilities occur in bunched beams in the ISR leading to a dilution of the phase space density and limiting the longitudinal density of the stacked beams. According to D. Boussard this instability can be described as a coasting beam instability inside bunches. Experimental investigations of this microwave instability support this theory and give a high frequency impedance $|Z_L|/n \approx 14$ ohms. Injecting large currents in bunches of large area increases the threshold of this instability. The larger currents can produce coupled bunch mode instabilities which can be cured by a higher harmonic cavity.

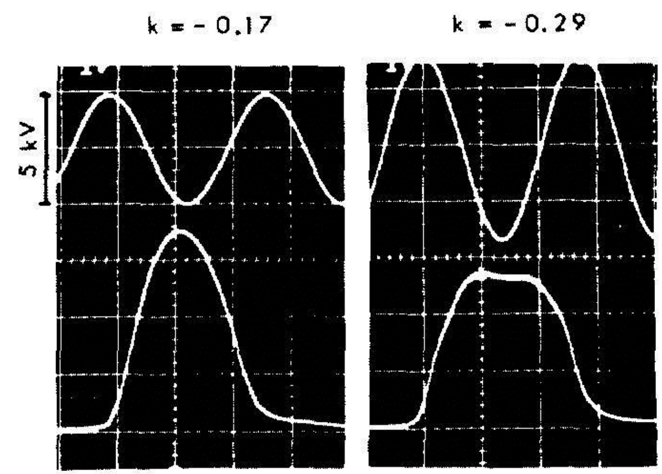


Fig. 5. Bunches (lower trace) stabilized by the higher harmonic voltage (upper trace). The phase of this voltage (not shown correctly on the picture) is chosen to reduce the phase focusing in the bunch centre.

beam dynamics in a double RF system

BEAM DYNAMICS IN A DOUBLE RF SYSTEM

A. Hofmann and S. Myers

CERN, Geneva, Switzerland

ABSTRACT

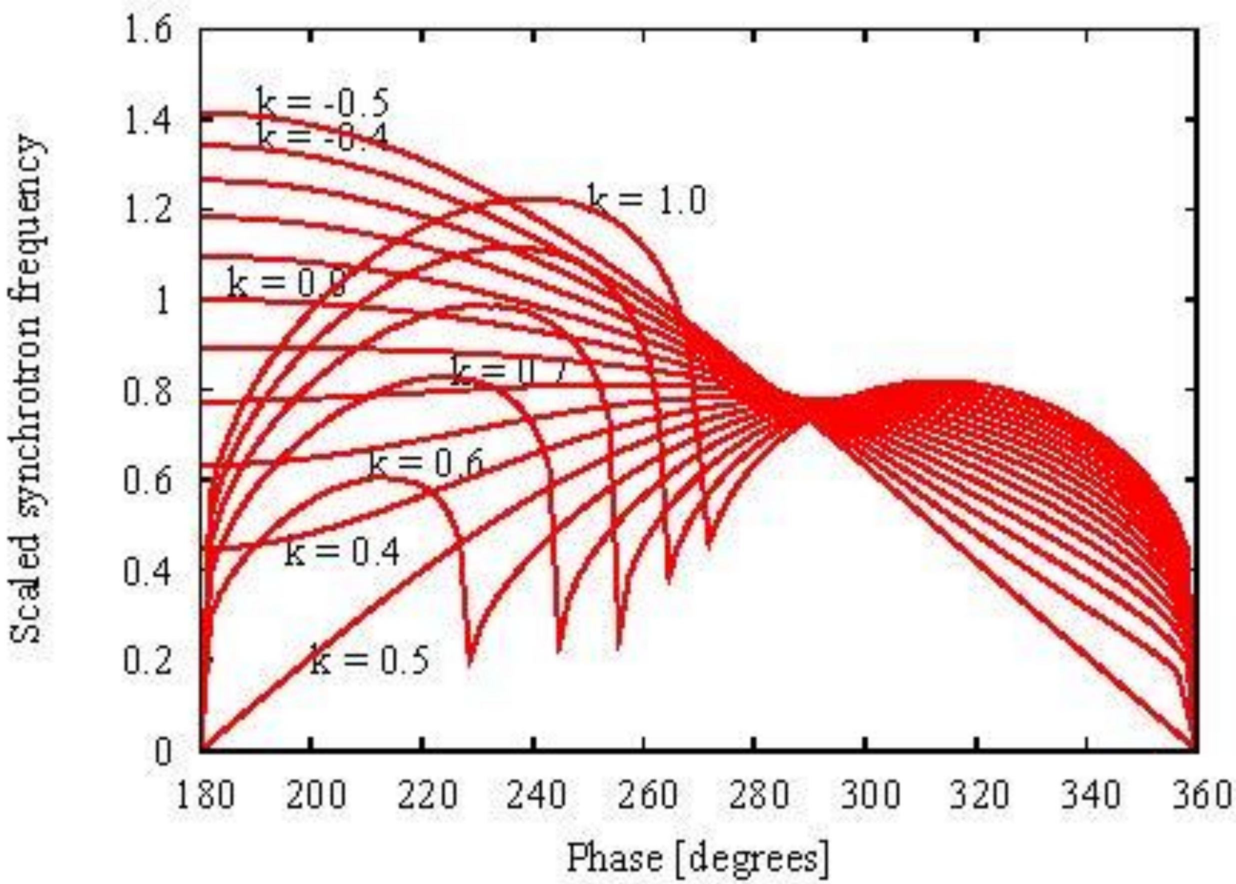
The addition of a higher harmonic RF system to the main system allows a control of the synchrotron frequency, the spread in synchrotron frequency and the bunch length. Adjustment of the higher harmonic system so as to reduce the slope of the RF wave to zero at the bunch centre leads to a longer bunch and a greatly increased spread in synchrotron frequency. This increases the Landau camping against longitudinal coupled bunch instabilities. The motion of single particles in this highly non linear potential is calculated numerically as well as analytically (by making some approximations). The dependence of the synchrotron frequency on amplitude and the forms of the synchrotron oscillations and the RF bucket are calculated. Finally the bunch shape and the distribution of particles in Q_s are calculated for electron bunches.

9th HEACC, Geneva 1980

for LHC assume 800 MHz & ~8 MV

- availability of high-power power couplers
- compatibility with SPS system, synergies with SNS and LHeC
- voltage should be no more than 0.5 times 400-MHz RF Voltage to avoid multiple potential wells
- low harmonic ratio maximizes the bucket size

synchrotron tune in double harmonic RF system



for voltage ratio k>0.5 ϕ=0 becomes unstable,
two new fix points at $\phi \neq 0$ and inner separatrix appear

T. Sen et a;, IPAC2010, p. 2078

“flat” bunches with double harmonic RF

References from Chandra Bhat 2009

- 2nd Harmonic debuncher in the LINAC, J.-P. Delahaye et. al., 11th HEACC, Geneva, 1980.
- Diagnosis of longitudinal instability in the PS Booster occurring during dual harmonic acceleration, A.Blas et. al., PS/ RF/ Note 97-23 (MD).
- **Elena Shaposhnikova,** CERN SL/94-19 (RF) ← **Double harmonic rf system**; Shaposhnikova et. al., PAC2005 p, 2300.
- Empty Bucket deposition in debunched beam, A. Blas, et, al.,EPAC2000 p1528
- Beam blowup by modulation near synchronous frequency with a higher frequency rf, R. Goraby and S. Hancock, EPAC94 p 282
- a) Creation of hollow bunches by redistribution of phase-space surfaces, (C. Carli and M. Chanel, EPAC02, p233) or

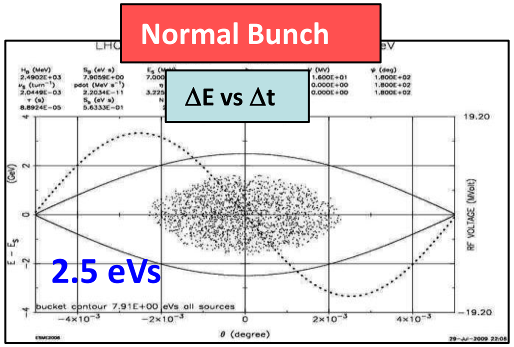
  b) recombination with empty bucket, C. Carli (CERN PS/2001-073).
- **Heiko Damerau, “Creation and Storage of Long and Flat Bunches in the LHC”, Ph. D. Thesis 2005**
- RF phase jump, J. Wei et. al. (2007)

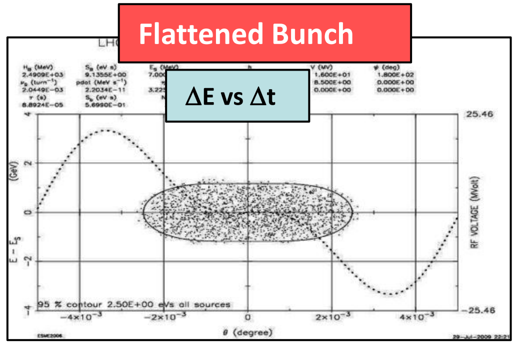
bunch flattening of the LHC beam at 7 TeV
(ESME Simulations)

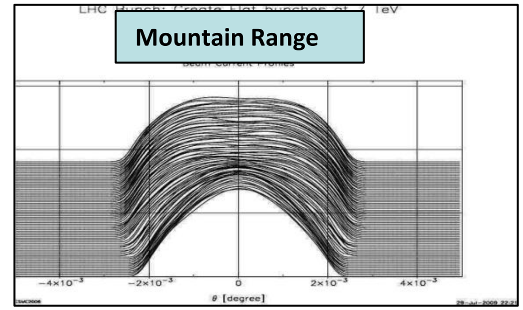
C. Bhat 2009

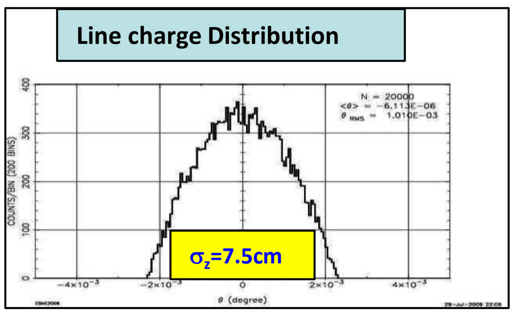
Vrf(400MHz)=16MV

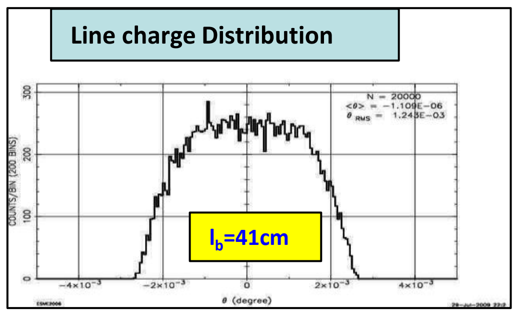
Vrf(400MHz)=16MV + Vrf(800MHz)=8.5MV

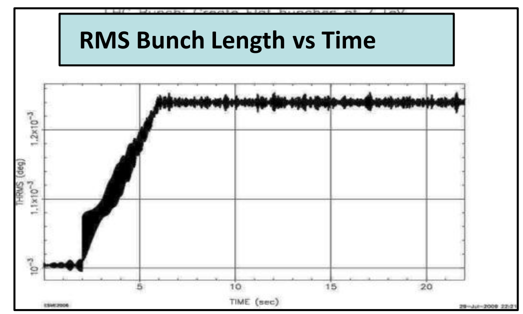


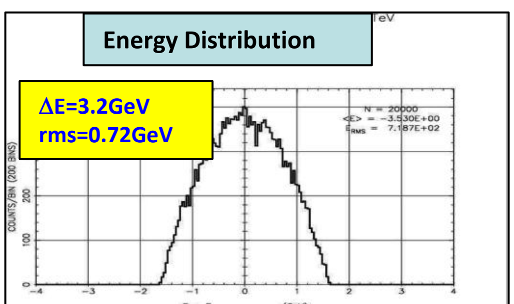


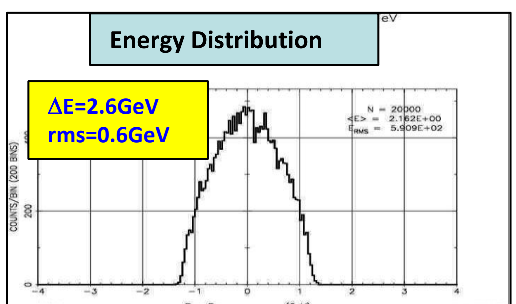


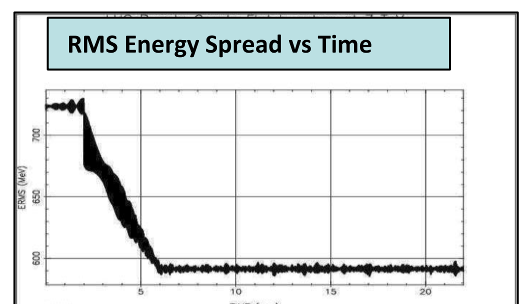










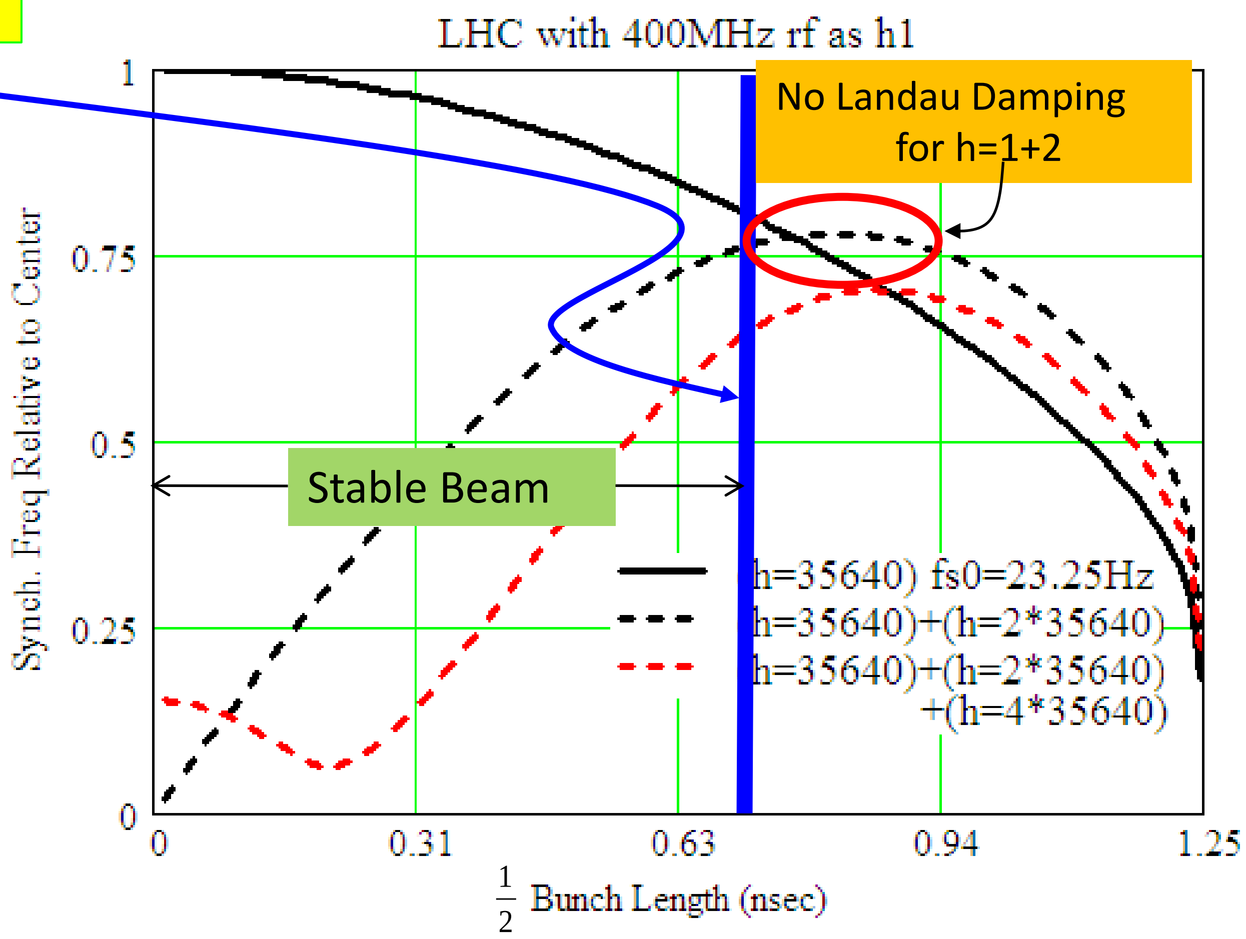


acceptable flat bunches at LHC

with 400MHz+800MHz RF

LE=2.5eVs, Lb=41cm

h	Vrf
35640	16MV
71280	8.5



Conclusions:

The 41 cm (11.8 cm rms) long flat bunches (2.5 eVs) with 400Mhz+800Mhz rf systems may be susceptible to beam instability.

C. Bhat 2009

parameter list for LHC LPA scheme at 7 TeV

V_{RF} (400 MHz)= 16 MV, V_{RF} (800 MHz)=8 MV

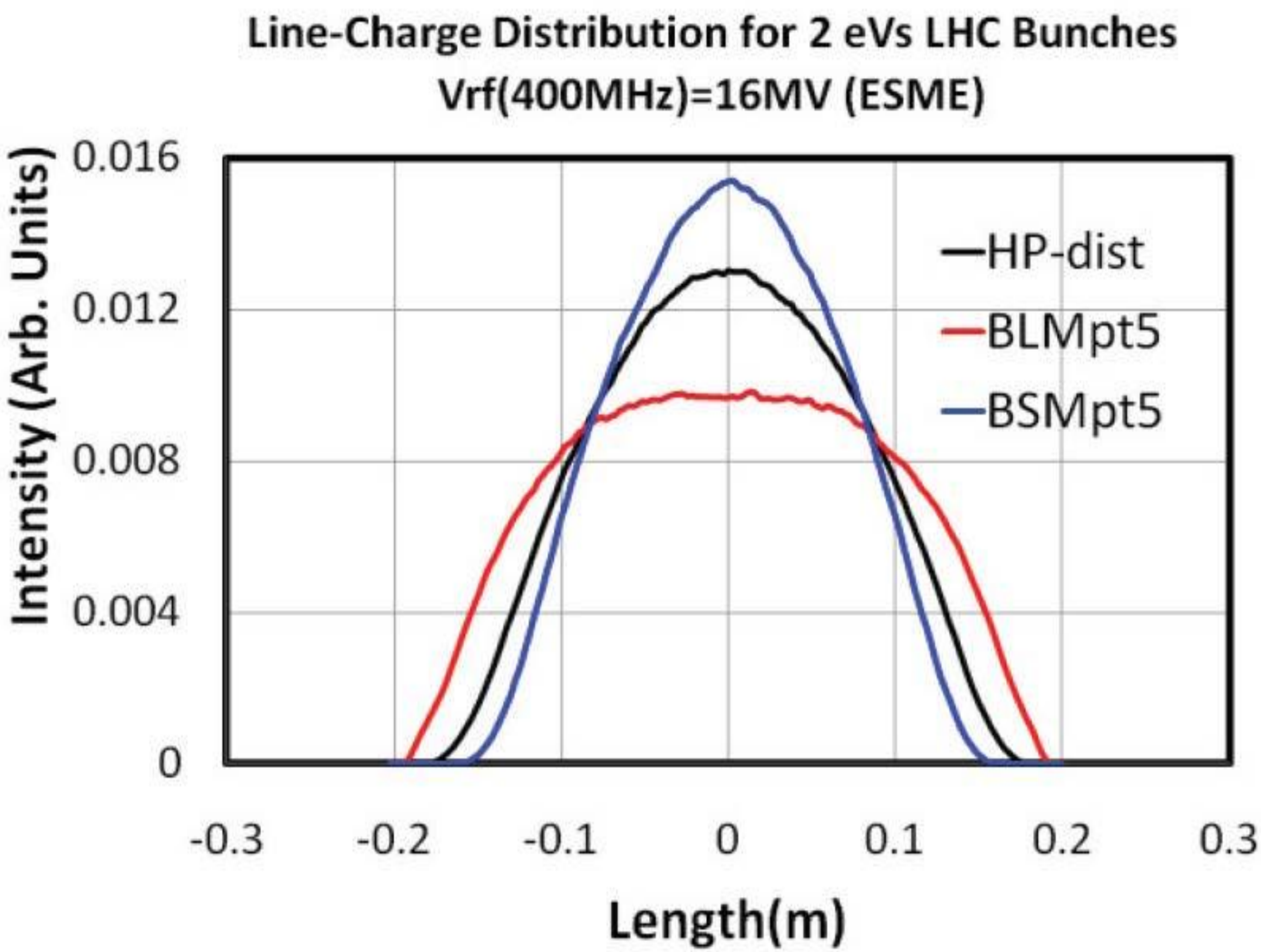
BLM & BSM 180 deg difference

Parameters		Nominal	Ultimate	LPA (200MHz+400MHz RF) BLMpt5 (A)	LPA (200MHz+400MHz RF) BSMpt5 (B)	LPA (400MHz+800MHz RF) BLMpt5 (C)	LPA (400MHz+800MHz RF) BSMpt5 (D)
Number of Bunches		2808	2808	1404	1404	1404	1404
Protons/bunch	$N_b(10^{11})$	1.15	1.7	3.9	3.3	3.5	3.1
Beam Current [A]		0.58	0.86	1	0.84	0.88	0.78
Norm. Transv. Emit	um	3.75	3.75	3.0-3.75	3.0-3.75	3.0-3.75	3.0-3.75
σz	cm	7.55	7.55	16	11	9	6
Bunch Spacing	nsec	25	25	50	50	50	50
β^* at IP1 and IP5	m	0.55	0.5	0.25	0.25	0.36	0.36
θ_c	urad	285	315	380	380	380	380
Piwinski Angle		0.64	0.75	3.03-2.71	2.08-1.86	1.42-1.22	0.963-0.862
ΔQbb		0.006	0.009	0.01-0.009	0.012-0.01	0.016-0.014	0.018-0.015
Peak and Average	$10^{34} cm^{-2} s^{-1}$	1	2.3	6-5.3	5.9-5.2	6.1-5.3	6.0-5.0
Lum. (10 hr turn around)		0.46	0.91	1.68-1.6	1.5-1.4	1.6 - 1.5	1.5 -1.4
Event Pileup		19	44	201-227	224-196	232-200	227-192

we can vary the rms bunch length between 6 and 9 cm using 8-MV 800-MHz system

C. Bhat 2011

LHC bunches with 2nd harmonic RF



$L \sim 1/\sigma_z$ (w.o crab); varying bunch length for L leveling?

flat bunches & beam-beam

LHC Project Report 627 (2002)
F. Zimmermann et al

$$L^{Gauss} \approx \frac{1}{2} \frac{f_{coll}\gamma}{r_p \beta^*} \Delta Q_{tot} N_b$$

luminosity for Gaussian or flat bunches

$$L^{flat} \approx \frac{1}{\sqrt{2}} \frac{f_{coll}\gamma}{r_p \beta^*} \Delta Q_{tot} N_b$$

for the same bunch charge and the same beam-beam tune shift, the luminosity of a uniform (or 'flat') longitudinal distribution is exactly $2^{1/2}$ times higher

flat bunches & IBS

LHC Project Report 627 (2002)

$$\frac{1}{\tau_{IBS,flat}} = \frac{2\sqrt{\pi}\sigma_z}{l_{\mathrm{flat}}} \frac{N_{\mathrm{flat}}}{N_{\mathrm{Gaussian}}} \frac{1}{\tau_{\mathrm{IBS,Gaussian}}}$$

for equal bunch populations, $N_{\mathrm{flat}}=N_{\mathrm{Gaussian}}$, and $l_{\mathrm{flat}}= (2\pi)^{1/2}\sigma_z$ both the luminosity and the IBS growth rate for a uniform (super-) bunch are $2^{1/2}$ times larger than for a Gaussian bunch, and for the same reason

flat bunches & IBS

LHC Project Report 627 (2002)

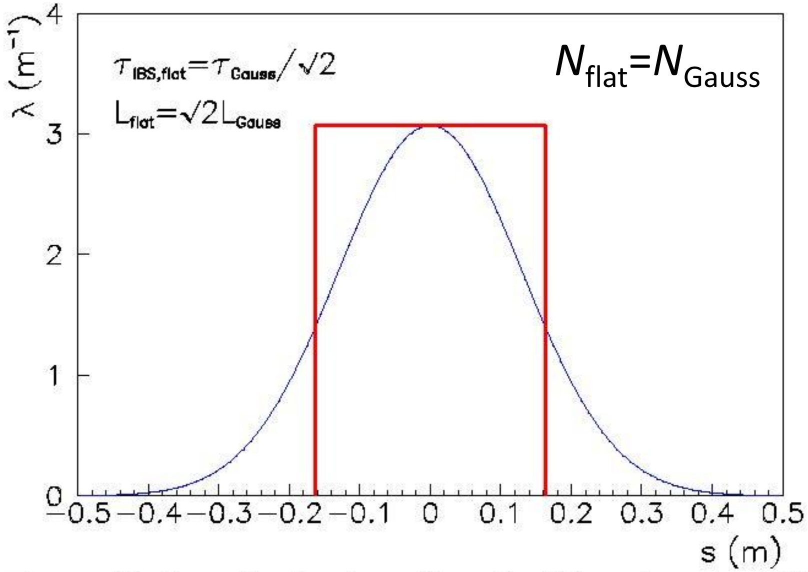


Figure 29: Longitudinal profile of uniform bunch yielding a factor of $\sqrt{2}$ higher luminosity and IBS growth rate than the Gaussian bunch.

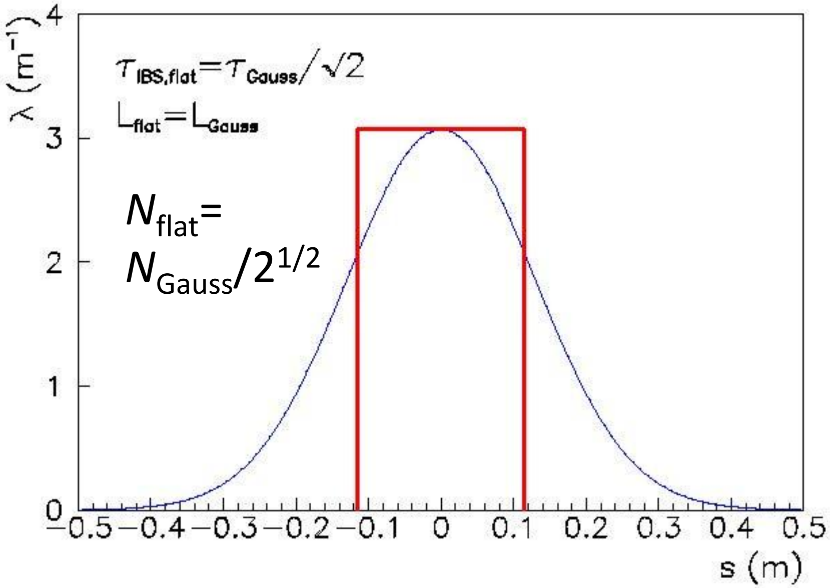


Figure 30: Longitudinal profile of uniform bunch yielding equal luminosity as, and a factor $\sqrt{2}$ higher IBS rate than, the Gaussian bunch.

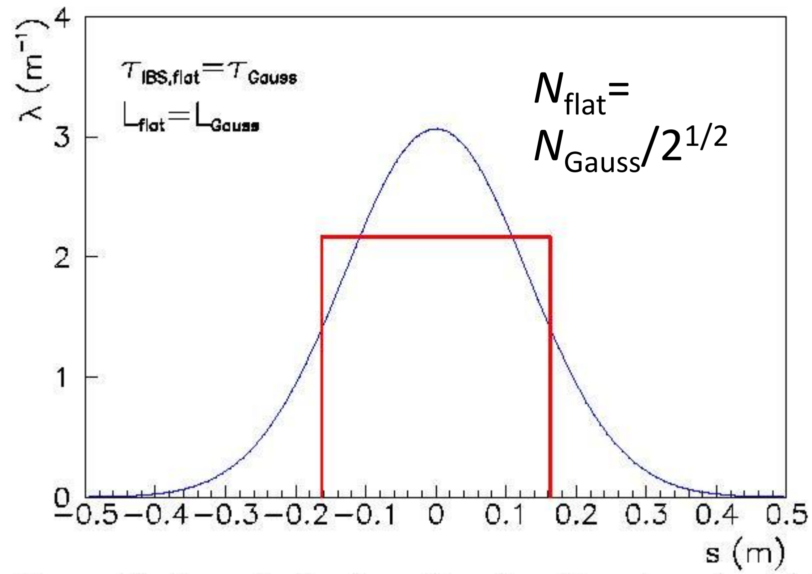
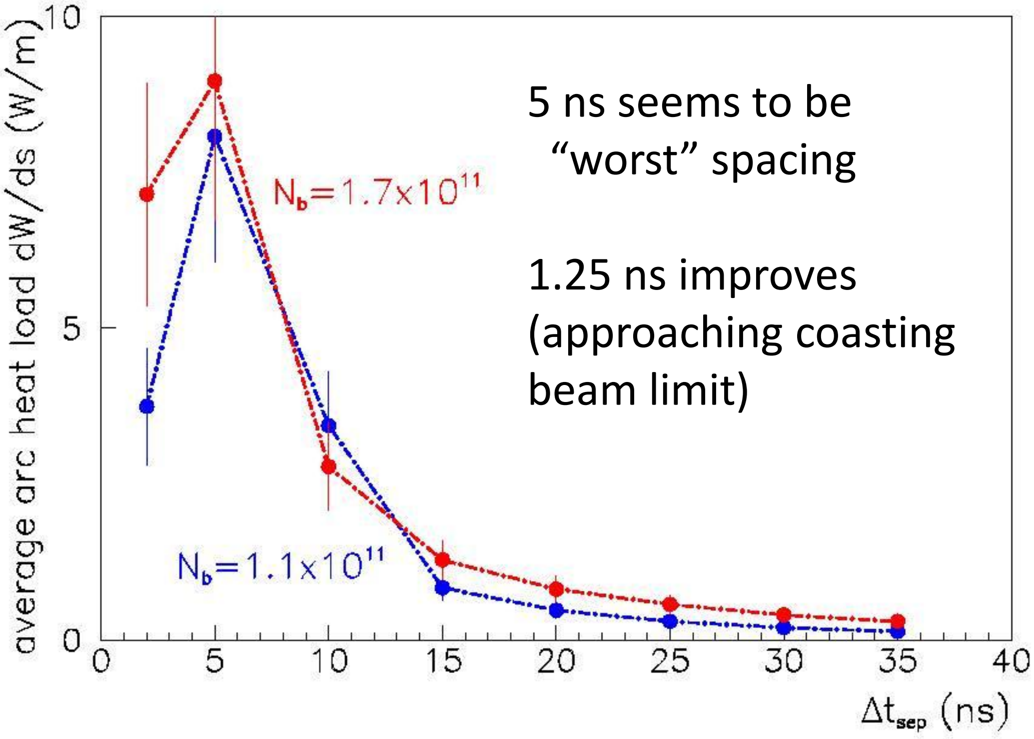


Figure 31: Longitudinal profile of uniform bunch yielding the same luminosity and IBS rate as the Gaussian bunch.

e-cloud heat load



5 ns seems to be "worst" spacing

1.25 ns improves (approaching coasting beam limit)

Figure 22: Average arc heat load as a function of bunch spacing, for $\delta_{max} = 1.1$ and various bunch populations.

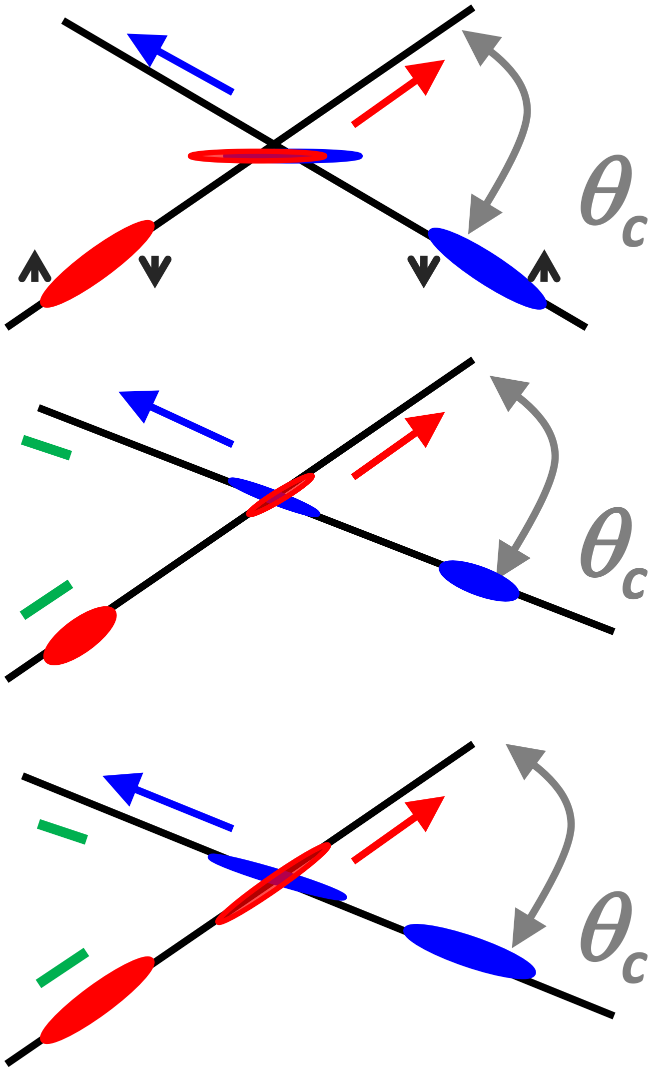
LHC Project Report 626 (2002)
(my simulation)

possible issues of higher harmonic RF

- beam loading effects at high intensity (with cavity phase modulation of the fundamental RF system)
  - can one apply the same modulation for the harmonic RF system?

approaches to boost LHC luminosity

- low β* & crab cavities (80 MV)
- low β* & **higher harmonic RF (7.5 MV @800 MHz)** + LR compensation
- large Piwinski angle + LR-BB compensation



always pushing intensity to “limit”

Chamonix 11

Higher-Harmonic RF Cavity

“octupoles for the longitudinal plane”

LHC Project Note 394

2007-02-16

Trevor.Linnecar@cern.ch

An RF System for Landau Damping in the LHC

T. Linnecar and E. Shaposhnikova / AB-RF

Keywords: RF Systems, Landau Damping, Longitudinal Beam Stability

Summary

A Landau system in the LHC could significantly increase the longitudinal stability of the LHC beam in the absence of wide-band longitudinal feedback and provide more freedom to define the bunch parameters even during the initial stages of LHC operation. This technique for stabilizing beams, used already in many accelerators, has proven to be very useful in the SPS, raising the instability thresholds by a factor five. One of the luminosity upgrade paths for LHC requires an RF system at 1.2 GHz with ~ 60 MV per beam for bunch shortening. A much smaller RF system at this frequency with ~3 MV per beam would be sufficient to provide Landau damping. This Note analyses the possible benefits and recommends that an R & D programme, leading to one prototype cryostat per ring to be installed in the LHC machine, be launched as soon as possible.

800-MHz system;
stability gain > factor 3
e.g. lower longitudinal
emittance (no blow up
in LHC), short bunches,
higher intensity

example HL-LHC parameters, β*=15 cm

parameter	symbol	**nom.**	nom.*	**HL crab**	**HL sb + lrc**	**HL 50+lrc**
protons per bunch	N_b [10^{11}]	**1.15**	1.7	**1.78**	**2.16**	**3.77**
bunch spacing	Δt [ns]	**25**	50	**25**	**25**	**50**
beam current	I [A]	**0.58**	0.43	**0.91**	**1.09**	**0.95**
longitudinal profile		**Gauss**	Gauss	**Gauss**	**Gauss**	**Gauss**
rms bunch length	σ_z [cm]	**7.55**	7.55	**7.55**	**5.0**	**7.55**
beta* at IP1&5	β^* [m]	**0.55**	0.55	**0.15**	**0.15**	**0.15**
full crossing angle	θ_c [μrad]	**285**	285	**(508-622)**	**508**	**508**
Piwinski parameter	$\phi=\theta_c\sigma_z/(2^*\sigma_x^*)$	**0.65**	0.65	**0.0**	**1.42**	**2.14**
tune shift	ΔQ_{tot}	**0.009**	0.0136	**0.011**	**0.008**	**0.010**
potential pk luminosity	L [10^{34} cm^{-2}s^{-1}]	**1**	1.1	**10.6**	**9.0**	**10.1**
events per #ing		**19**	40	**95**	**95**	**189**
effective lifetime	τ_{eff} [h]	**44.9**	30	**13.9**	**16.8**	**14.7**
run or level time	$t_{run,level}$ [h]	**15.2**	12.2	**4.35**	**4.29**	**4.34**
e-c heat SEY=1.2	P [W/m]	**0.2**	0.1	**0.4**	**0.6**	**0.3**
SR+IC heat 4.6-20 K	P_{SR+IC} [W/m]	**0.32**	0.30	**0.62**	**1.30**	**1.08**
IBS ε rise time (*z*, *x*)	$\tau_{IBS,z/x}$ [h]	**59, 102**	40, 69	**38, 66**	**8, 33**	**18, 31**
annual luminosity	L_{int}[fb^{-1}]	**57**	58	**300**	**300**	**300**

example HL-LHC parameters, β*=30 cm

parameter	symbol	**nom.**	nom.*	**HL crab**	**HL sb + lrc**	**HL 50+lrc**
protons per bunch	N_b [10^{11}]	**1.15**	1.7	**2.28**	**2.47**	**4.06**
bunch spacing	Δt [ns]	**25**	50	**25**	**25**	**50**
beam current	I [A]	**0.58**	0.43	**1.15**	**1.25**	**1.03**
longitudinal profile		**Gauss**	Gauss	**Gauss**	**Gauss**	**Gauss**
rms bunch length	σ_z [cm]	**7.55**	7.55	**7.55**	**5.0**	**7.55**
beta* at IP1&5	$\beta*$ [m]	**0.55**	0.55	**0.30**	**0.30**	**0.30**
full crossing angle	θ_c [μrad]	**285**	285	**(359-462)**	**359**	**359**
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	**0.65**	0.65	**0.0**	**0.71**	**1.07**
tune shift	ΔQ_{tot}	**0.009**	0.0136	**0.0145**	**0.0128**	**0.0176**
potential pk luminosity	L [10^{34} cm^{-2}s^{-1}]	**1**	1.1	**8.69**	**8.32**	**9.41**
events per #ing		**19**	40	**95**	**95**	**189**
effective lifetime	τ_{eff} [h]	**44.9**	30	**17.8**	**19.3**	**15.8**
run or level time	$t_{run,level}$ [h]	**15.2**	12.2	**4.29**	**4.33**	**4.29**
e-c heat SEY=1.2	P [W/m]	**0.2**	0.1	**0.6**	**0.7**	**0.3**
SR+IC heat 4.6-20 K	P_{SR+IC} [W/m]	**0.32**	0.30	**0.93**	**1.65**	**1.23**
IBS ε rise time (*z*, *x*)	$\tau_{IBS,z/x}$ [h]	**59, 102**	40, 69	**30, 52**	**7, 29**	**17, 29**
annual luminosity	L_{int}[fb^{-1}]	**57**	58	**300**	**300**	**300**

preliminary conclusions

three alternative scenarios for 300 fb^{-1} / year:

- crab cavities
- **higher harmonic RF (shorter bunches) + LR compensation**
- 50 ns bunch spacing, large Piwinski angle, + LR compensation

decreasing β^* from 30 to 15 cm is equivalent to 10-20% beam current increase (scenario -dependent)

proposed roadmap & branching points

- ***LHC MDs*** for HL-LHC – starting in **2011**
  - ATS optics ingredients (beta wave, phase changes)
  - LR beam-beam limits
  - effect of crossing angle on HO b-b limit
  - electron cloud limits
  - "flat beam" optics [S. Fartoukh, LHCMAC19, e.g. r~2, Δn_1~1
  - effect of crossing plane (H-V, V-V, H-H)

several MDs may be done regardless of HL-LHC and also benefit nominal LHC performance

- ***install LR-BB compensators in LHC*** (**2013**)
- develop & prototype ***compact crab cavity (2011-16) for beam test in (SPS+) LHC (2017)***
- develop&install ***LHC 800-MHz system*** (**2016**?)

conclusion

higher harmonic RF system will give **greatly enhanced operational flexibility** & provide **much larger HL-LHC parameter space**, e.g. for

- reducing heating of components
- reducing IBS emittance growth
- increasing beam stability
- luminosity leveling (w/o crab cavities)
- optimizing the luminous region (w crab cavities)
- supporting shorter bunch spacings

we should build and install it!

appendix

estimating integrated luminosity

assumptions

- two high-luminosity collision points
- beam & *L* lifetime from *p* consumption
- 200 physics days of proton run per year

(w/o restart, w/o TS's, w/o MD periods)

- 5 h turnaround time
- 75% machine availability

[Nov. 2010: 80%, W. Venturini, Evian]

useful leveling formulae

	w/o leveling	*L*=const	ΔQ_{bb}=const
luminosity evolution	$L(t)=\frac{\hat{L}}{(1+t/\tau_{eff})^2}$	$L=L_0\approx const$	$L(t)=\hat{L}\exp(-t/\tau_{eff})$
beam current evolution	$N(t)=\frac{N_0}{(1+t/\tau_{eff})}$	$N=N_0-\frac{N_0}{\tau_{eff}}t$	$N(t)=$ $N(0)\exp(-t/\tau_{eff})$
optimum run time	$T_{run}=\sqrt{\tau_{eff}T_{ta}}$	$T_{run}=\frac{\Delta N_{max}\tau_{eff}}{N_0}$	$T_{run}=\tau_{eff}$ $\min\left[\ln\left(\sqrt{1+\phi_{piw}(0)^2}\right),\right.$ $\left.\ln((T_{ta}+T_{run}+\tau_{eff})/\tau_{eff})\right]$
average luminosity	$L_{ave}=\hat{L}\frac{\tau_{eff}}{(\tau_{eff}^{1/2}+T_{ta}^{1/2})^2}$	$L_{ave}=\frac{L_0}{1+\frac{L_0\sigma_{tot}n_{IP}}{\Delta N_{max}n_b}T_{ta}}$	$L_{ave}=\frac{\tau_{eff}}{T_{ta}+T_{run}}\left(1-e^{-T_{run}/\tau_{eff}}\right)$

ΔQ_{bb}=const→ exponential *L* decay, w decay time τ_{eff} ($\neq \tau_{eff}/2$)