LTV Activity Report to LARP

LPA Scheme for LHC Upgrade

Progress and Plans

Chandra Bhat

Fermilab/CERN

LARP CM15 Collaboration Meeting

November 1-3, November

SLAC

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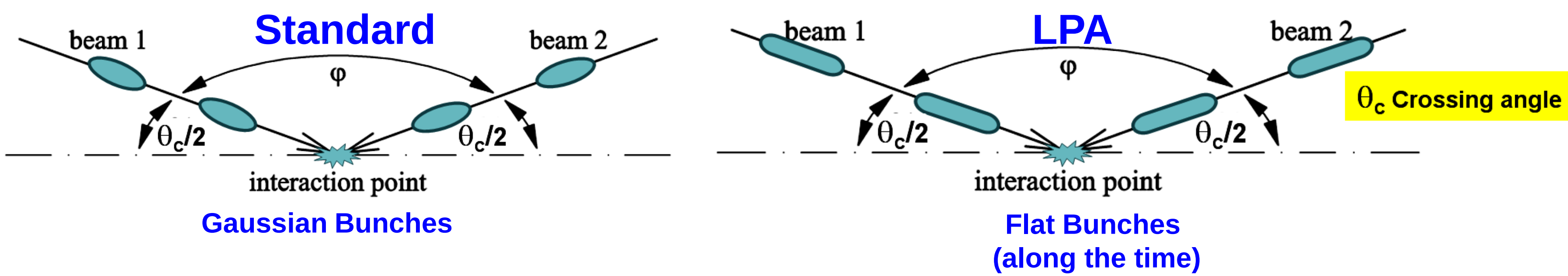
Outline

- Introduction
- Questions to be investigated for LPA scheme at LHC
- MDs studies at CERN
  - PS
  - SPS
  - LHC
- Simulation Studies on Flat Bunches
- Summary

The LPA scheme .. in a nutsell



- One can increase the LHC luminosity by √2 (!!) for the same number of particles and the same total beam-beam tune shift, **by simply flattening** the bunches (F. Ruggiero and Frank Zimmermann).

  ← Increasing the Piwinski angle $\phi = \theta_c \sigma_z / (2\sigma^*_x)$ (hence LPA-scheme)
- Merits: No elements in the detectors, Lower Chromaticity, reduced e-cloud issues, Less demands on the IR quadrupoles
- Challenges: Flat bunch production and Acceleration, High bunch charges (?) ….

Questions to be investigated for the LPA Scheme at LHC

- What are the parameter specifications and constraints?
- What is the optimal way to produce high-intensity flat bunches and where?
- If one produces bunches in one of the upstream accelerators, how can they be accelerated while maintaining their quality up to LHC top energy and during the store?
- What are the single-bunch and multi-bunch instability issues?
- Are there serious e-cloud effects? If so, how can they be mitigated?
- What are the rf requirements to handle such bunches?
- ~~How does this upgrade scenario fit within the current design of PS2~~?

2010: CERN (Steve Myers) has setup a team (headed by R. Garoby) which evaluates status for all of the existing injector machines for Luminosity upgrade.

Parameter Specifications & Constraints

- Recent changes of plan for LPA scheme assumes

Frank Zimmermann (Chamonix-2010)

- ❑ Ultimate Luminosity: a) ~7×10^{34} cm^{-2}sec^{-1} for 50ns bunch spacing with β*= 25cm, θc=381μrad
  or b) ~ 4×10^{34} cm^{-2}sec^{-1} for 25ns bunch spacing with β*= 50cm, θc=339μrad
- ❑ Beam Current: a) ~1.06A for 50ns bunch spacing
  or b) ~1.32A for 25ns bunch spacing

~ half of the projected peak luminosity

These changes are mainly driven by the number of acceptable number of interactions per collision at the interaction points.

Consequently, the specifications for the hardware like rf and feed-back systems can be bit more relaxed as compared with the previous projections.

Parameter Specifications & Constraints (Cont.)

$\varepsilon_\perp$ (Normalized) = 3.75 μm, Allowed ΔQ_{sum}<0.015 (LHC Design Rept. III)

	Nom./Ulti.	LPA-25ns	LPA-50ns	LPA-50ns 200MHz+400MHz/ 400MHz+800MHz
Long. Profile	Gaus	Flat	Flat	Dual-harmonic
bunch intensity x10^{11}	1.15/1.7	2.6	4.2	3.9/ 3.5
LE (4σ) (eVs) @7TeV	2.5/2.5	2.5	2.5	2.0/ 2.0
BL-RMS(cm)	7.55/7.55	11.8	11.8	16/ 9
Average Current[A]	0.58/0.86	1.32	1.06	1.0/ 0.88
bunch spacing [ns]	25	25	50	50/ 50
RF Combination[MHz]	400	Harmonic rf to be mentioned	Harmonic rf to be mentioned	200+400/ 400+800
β* at IP1&5 (m)	0.55/0.5	0.5	0.25	0.25/ .36
Xing angle, ϕ_P (μrad, Rad)	285, 0.64/ 315,0.75	339, 2	381, 2	381,2.7/ 381,1.3
Lpeak, $\mathcal{L}$ave. $10^{34}cm^{-2}s^{-1}$ (turnaround time 10h) $10^{34}cm^{-2}s^{-1}$	1.0, 0.45/ 2.3, 0.9	4.0 1.5	7.4 1.9	5/ 5

Where and how to produce flat bunches?

- This problem is being addressed for some time
  - Beam dynamics simulations (C.Bhat)
    - Use of double harmonic rf systems for the LHC
      - Combo of 200MHz and 400MHz rf
      - Combo of 400MHz and 800MHz rf
  - Preliminary experiments in the PS (with Heiko et al)
    - To learn about the flatness of the bunches
    - Investigate the stability of flat bunches
  - Experiments in the SPS (with Elena et.al.)
    - Investigate the instability of bunches in double harmonic rf system

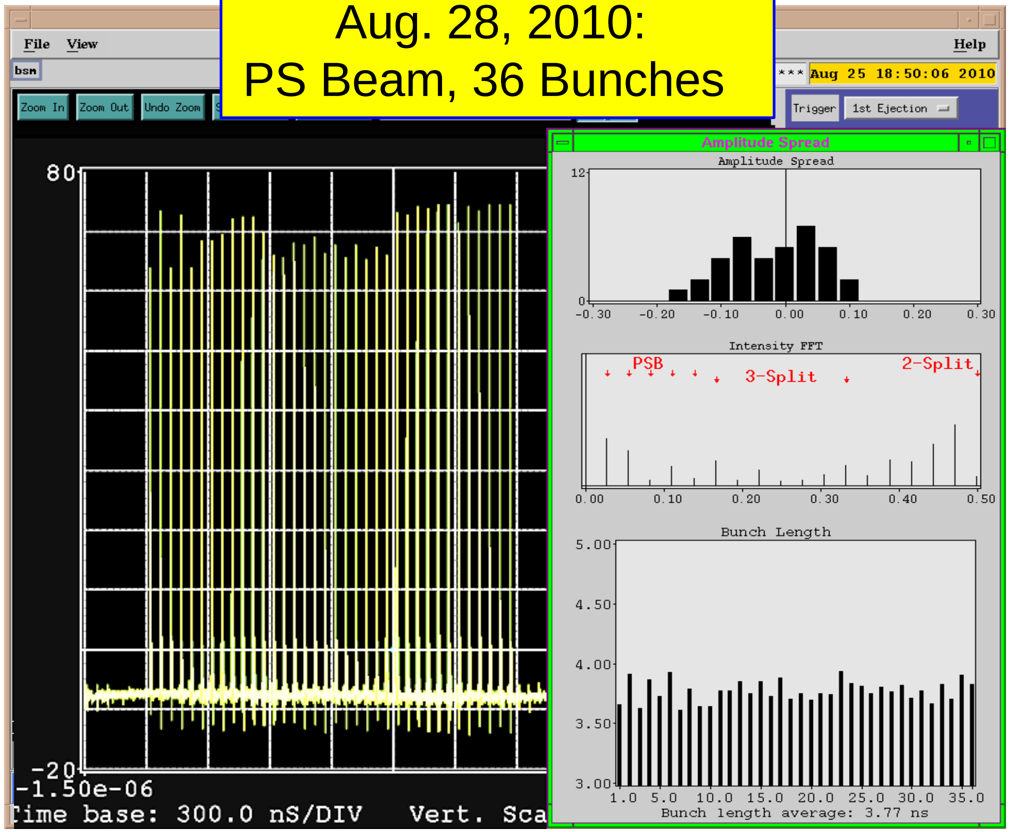
MDs in PS and SPS

(Gaussian Bunches of 50 ns spacing)

- Low emittance bunch trains with 50 ns bunch-spacing in the PS
  - Previously studied by H. Damerau et. al (MOPD52-HB2010), Hancock et at (CERN-ATS-2009-037/PAC09)
  - After I came to CERN, I participated in many of the parallel MDs on 50 nsec bunch preparation with Heiko and Steven, and acceleration in the SPS with Elena et. al.,
  - Eventually, since last Friday LHC had several stores with 50 nsec.

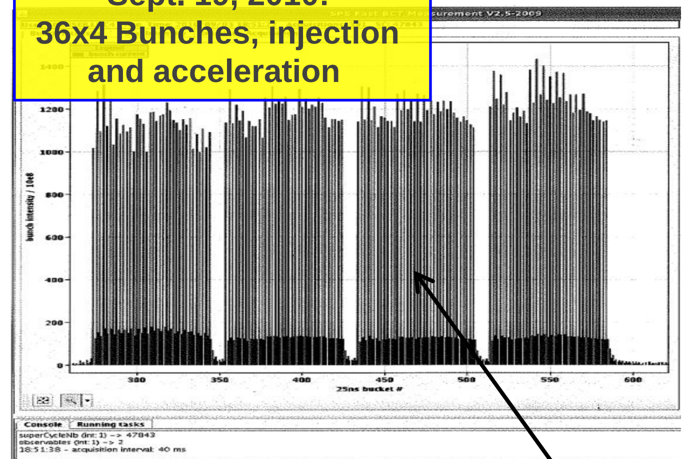
Some Examples of 50 ns Bunches

Aug. 28, 2010:
PS Beam, 36 Bunches



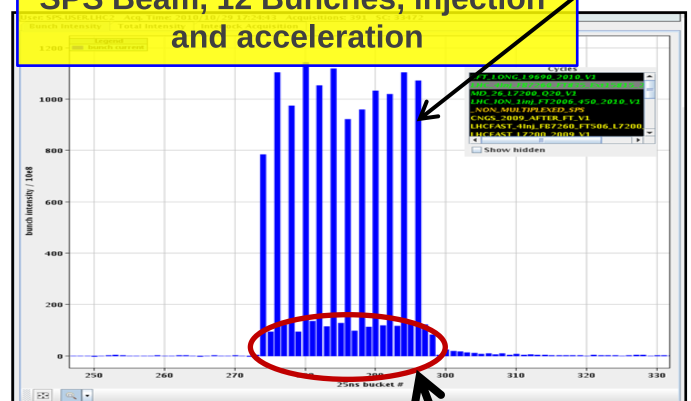
~1.9E11p/bunch

Sept. 19, 2010:
36x4 Bunches, injection and acceleration



~1.1E11p/bunch

Oct. 29, 2010:
SPS Beam, 12 Bunches, injection and acceleration

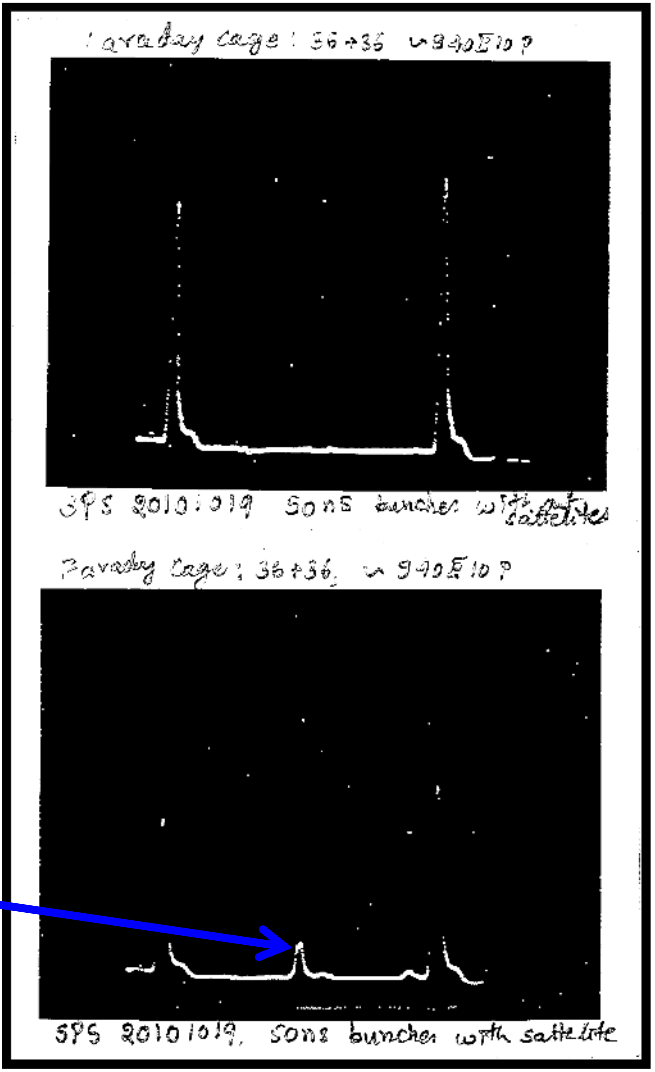


Are these satellite bunches?

LE(4σ)~0.35 eVs & e_T~3 μm

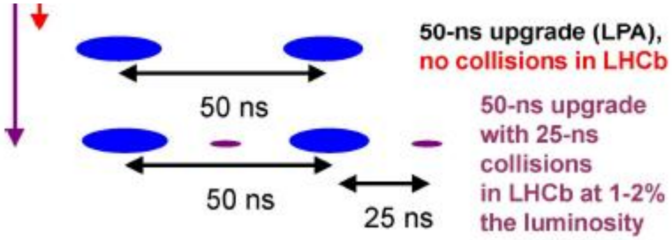
MDs in PS and SPS (cont.)

- Are there satellite bunches?
  - Yes, there were satellites with about 10% intensity of the main bunch in some cases. (Normally the satellite is <1%)
  - I had carried out simulations to create bunch train in the PS with 50 ns spacing and satellite bunches.
  - Also, have taken data in PS during “rebucketing”. A more systematic study will be done.



Satellite bunches

This was one of the issues to be addressed in the LHC for 50 ns high luminosity upgrade with 25 ns collisions in the LHCB at 1-2% the luminosity ← Oliver Bruning and Frank Zimmermann



MDs in PS and SPS (cont.)

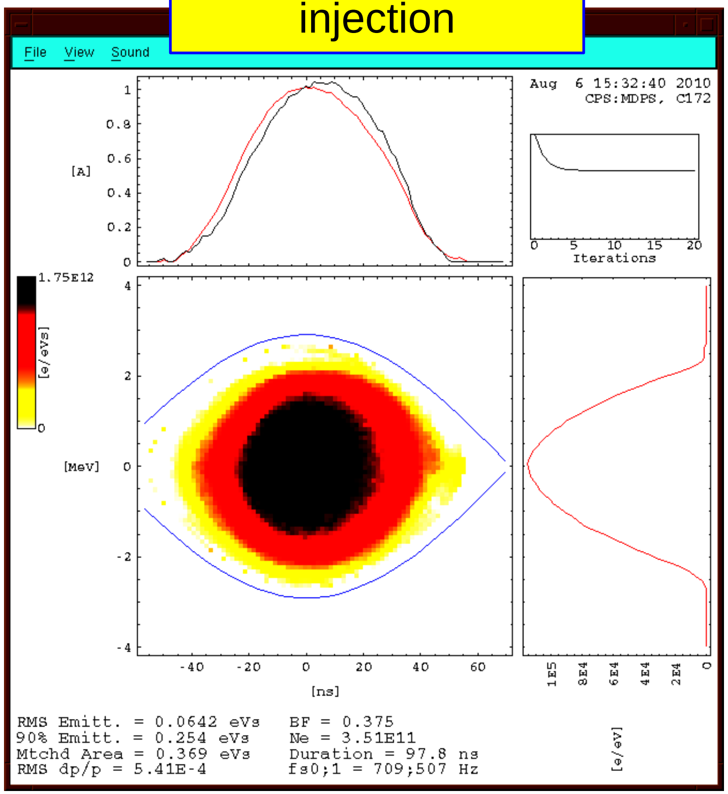
(High Intensity single Gaussian Bunch)

- Low emittance high intensity bunch in the PS
  - In the past lot of MD studies have focused on nominal intensity (~1.2E11p/bunch) single bunch.
  - A few months ago Heiko et. al., were able to produce high intensity single bunch of **~3.5E11**p/bunch, which is nearly a factor of three larger than the nominal LHC bunch intensity. This is of high interest for the LPA scheme.
  - The data taken in PS on the subsequent MD period is shown below.

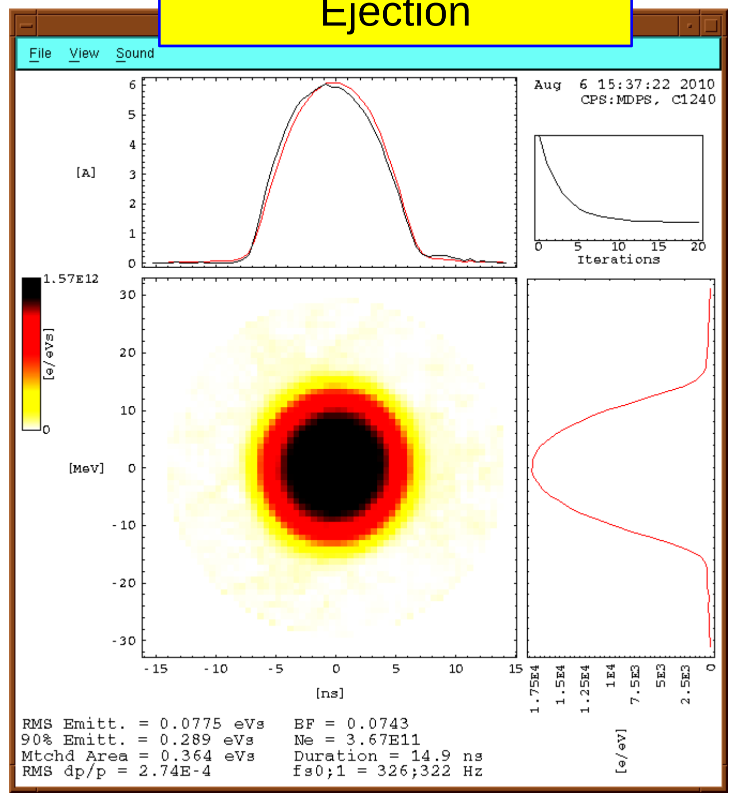
Examples of High Intensity Single Bunch in the PS

Aug. 6, 2010:
~3.5E11p/bunch

Bunch at 2ms after injection



Bunch at 20ms before Ejection



LE(4σ)< 0.3 eVs & e_T<3 μm

MDs in PS and SPS (cont.)

(High Intensity single acceleration)

- Single bunch injection and acceleration in the SPS is interesting from the point of view of study on
  - ❑ Longitudinal beam instability of
    - ➢ Single (and multi-bunch) in double harmonic rf buckets. In the case of SPS, we can study combo of 200MHz and 800MHz rf in very great detail.
      - – Have taken lots of data ←needs analysis and simulations

    T. Argyropoulos, C. Bhat and Elena et. al.
  - ❑ Transverse instability
    - ➢ Significant amount of research was carried out at CERN SPS to understand single bunch TMCI (Beniot Salvant and Elias Metral et. al.)
      - – We have taken lot more of data recently on different bunch intensities ←needs analysis and simulations

    Benoit Salvant, W. Hofle et. al.
- High intensity single and multi-bunch acceleration
  - ➢ During MD October of 25, we were able to accelerate a single bunch with 2.5E11p in the SPS with about 92% efficiency

Summary

- This is a very exciting time at CERN. Every week/every day a new record on the luminosity is reached. It has been a great opportunity to understand the issues for LHC luminosity upgrades beyond the nominal luminosity
- Attending a lot of informative and important meetings
  - LHC 8:30 AM Meeting (every day)
  - LHC Commissioning Meeting (LCM) (every week)
  - LHC Management Meeting by Steve Myers (~every week)
- Collaboration with PS & SPS groups has become very fruitful in understanding issues related to generating required bunches in the injector chain.
- Production of low emittance high intensity bunches with intensity>3.5E11 (single bunch intensity needed for LPA scheme as shown in the Table) in PS is really major accomplishment.
- Could not cover
  - Issues and prospects related to the LHC rf upgrade in view of the LPA scheme
  - Our present simulation work which being carried out in collaboration with Fermilab group.

Example LHC Upgrade paramenters

Chamonix-2010 (Chamonix-2010 Frank Zimmermann**)**

parameter	symbol	nom.	nom.*	ult.	β*=30 cm, HI	β*=30,cm , CC	β*=14, cm HI	β*=14 cm, CC	LPA – 25	LPA – 50
transverse emittance	ε [μm]	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75
protons per bunch	N_b [10^{11}]	1.15	1.7	1.7	2.3	1.6	2.3	1.6	2.6	4.2
bunch spacing	Δt [ns]	25	50	25	25	25	25	25	25	50
beam current	I [A]	0.58	0.43	0.86	1.16	0.81	1.16	0.81	1.32	1.06
longitudinal profile		Gauss	Gauss	Gauss	Gauss	Gauss	Gauss	Gauss	Flat	Flat
rms bunch length	σ_z [cm]	7.55	7.55	7.55	7.55	7.55	7.55	7.55	11.8	11.8
beta* at IP1&5	β* [m]	0.55	0.55	0.5	0.30	0.30	0.14	0.14	0.50	0.25
full crossing angle	θ_c [μrad]	285	285	315	348	(348)	509	(509)	339	381
Piwinski parameter	$\phi=\theta_c\sigma_z/(2*\sigma_x*)$	0.65	0.65	0.75	1.1	0.0	2.3	0.0	2.0	2.0
tune shift	ΔQ_{tot}	0.009	0.0136	0.009	0.01	0.01	0.006	0.01	0.01	0.01
peak luminosity	L [10^{34} cm^{-2}s^{-1}]	1	1.1	2.3	5.9	4.0	7.5	7.9	4.0	7.4
peak events per #ing		19	40	44	111	76	142	150	75	280
initial lumi lifetime	τ_L [h]	23	16	15	7.7	7.8	6.0	4.0	12.4	5.3
effective luminosity ($T_{turnaround}$=10 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	0.45	0.43	0.90	1.8	1.2	2.0	1.7	1.5	1.9
	$T_{run,opt}$ [h]	21.5	17.7	17.2	12.4	12.5	11.0	8.9	16.0	10.5
effective luminosity ($T_{turnaround}$=2 h)	L_{eff}[10^{34} cm^{-2}s^{-1}]	0.67	0.68	1.41	3.2	2.2	3.8	3.5	2.4	3.6
	$T_{run,opt}$ [h]	9.6	7.9	7.7	5.5	5.6	4.9	4.0	7.2	4.7
e-c heat SEY=1.3	P [W/m]	0.4	0.1	0.6	1.3	0.7	1.3	0.7	1.4	0.8
SR heat 4.6-20 K	P_{SR} [W/m]	0.17	0.13	0.25	0.34	0.24	0.34	0.24	0.38	0.31
image current heat	P_{IC} [W/m]	0.15	0.17	0.33	0.60	0.29	0.60	0.29	0.39	0.51
gas-s. 100 h τ_b	P_{gas} [W/m]	0.04	0.03	0.06	0.08	0.05	0.08	0.05	0.09	0.07
luminous region	σ_l [cm]	4.5	4.5	4.3	3.7	5.3	2.2	5.3	5.2	3.8
annual luminosity	L_{int}[fb^{-1}]	57	56	116	245	169	286	253	198	274

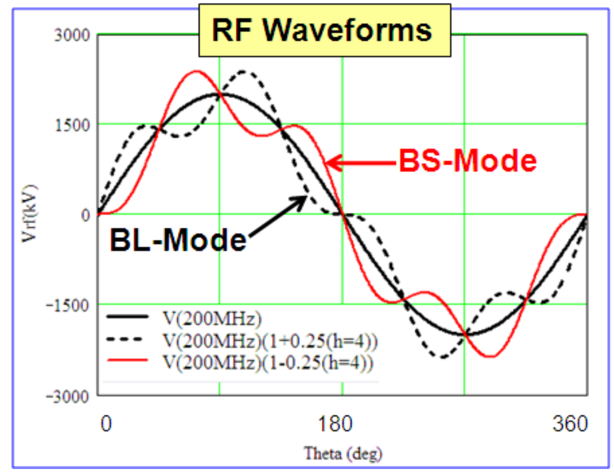
SPS Studies:
Single Bunch, Local Loss of Landau Damping

E. Shaposhnikova, T. Bohl, T. Linnecar, C. Bhat, T.Argyropoulos*, J.Tuckmantel

Range of Vrf in the Experiment

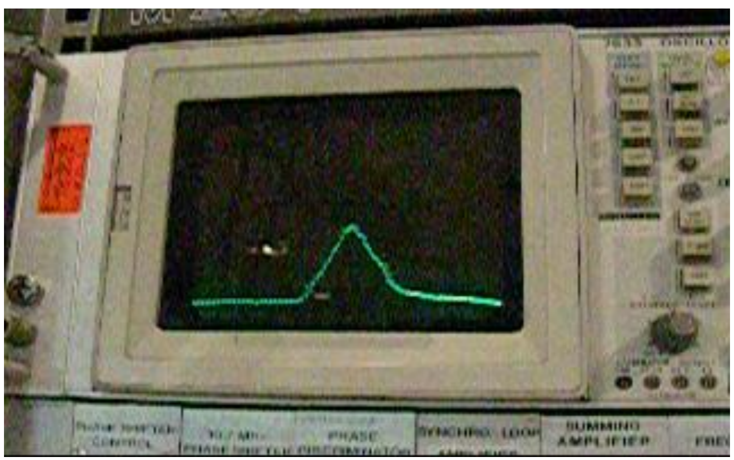
RF	h	Vrf(MV)	Ratio V4/V1
200MHz	4620	1-2	
800Mhz	18480	0.1-0.5	±0.25
E	26 GeV and 270 GeV		

$h_2/h_1=4$

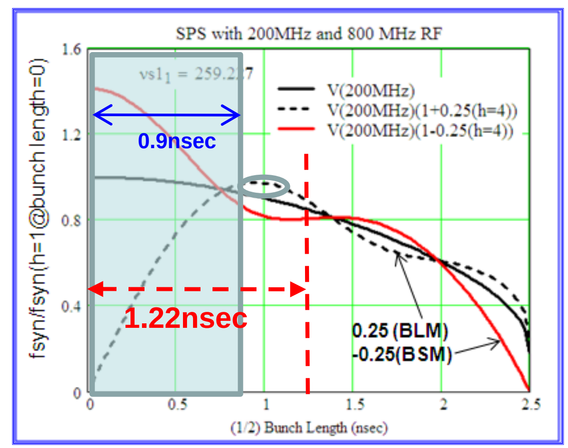


November 2008

BSM V4/V1=0.25, **Beam Energy = 270 GeV**
# of Bunches = 1-4, **Intensity≈1E11 (ε_L=0.4 eVs)**



Bucket Length=5 nsec



Conclusions (for h4/h1=4) :
- **BLM is unstable** under almost all time &
- **BSM is more stable** almost all time.

Experiment with a single harmonic rf wave also showed the signs of instability(?!?).
More studies are being carried out

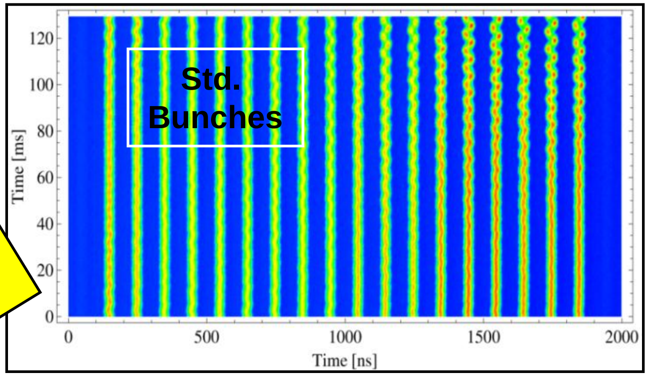
PS Studies at 26 GeV:
Stable Flat Bunches using Double-harmonic rf System

using LHC25

C. Bhat, H. Damerau, S. Hancock, E.Mahner, F.Caspers

10 MHz RF system only, 32 kV at *h* = 21

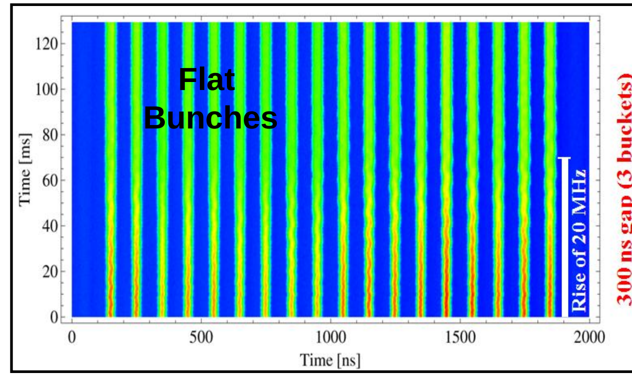
h	Vrf
21	32kV
42	0



Bunches in single harmonic RF

LE(4σ)= 1.45 eVs
I=840E10/batch

Vrf(h=21)=31kV and Vrf(h=42)=16 kV



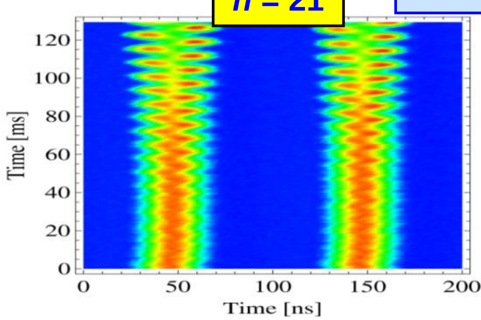
h	Vrf
21	32kV
42	16kV

$h_2/h_1=2$
$V_2/V_1=0.5$

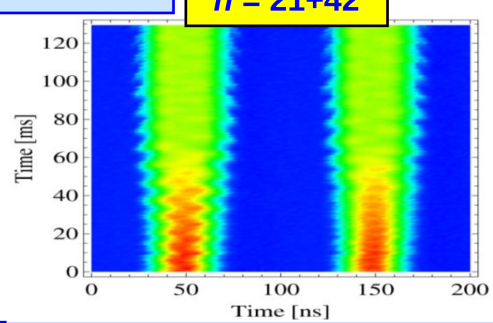
Bunches in Double harmonic RF

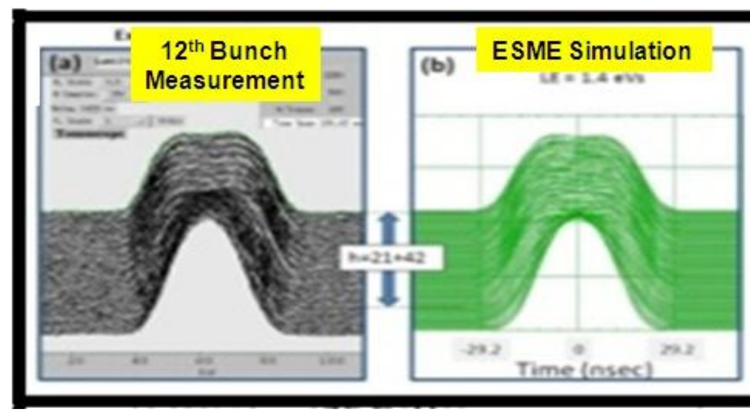
Last two bunches

h = 21



h = 21+42





Conclusions

- Beam in h=21 showed coupled bunch oscillations
- Beam in DOUBLE HARMONIC rf became stable (~for 120 ms)

C. M. Bhat, et. al., PAC2009

Beam Stability Criterion

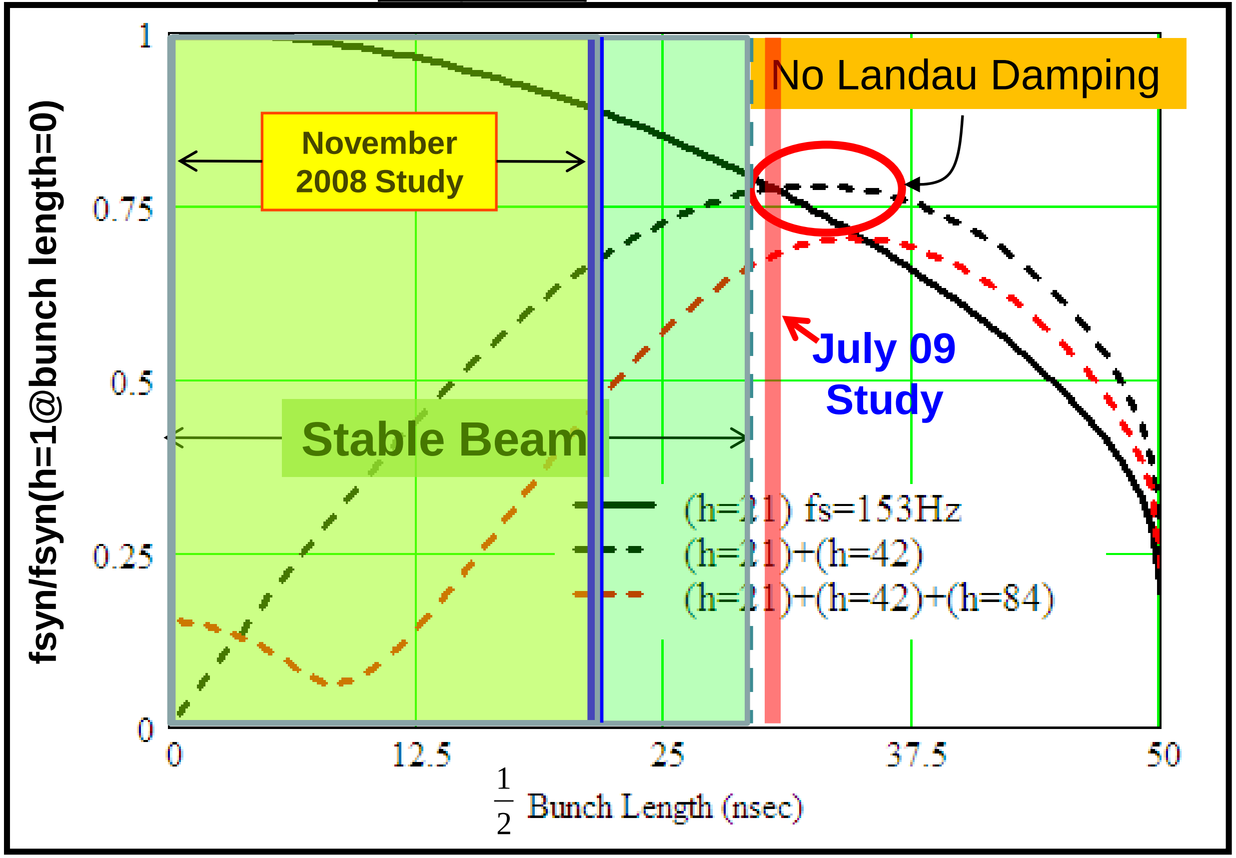
- ⇨ Large synchrotron frequency spread improves the stability.
- ⇨ If $\frac{df_s}{dt} = 0$ inside the bucket, particles in the vicinity of this region can become unstable against collective instabilities.

  V. I. Balbekov (1987)

- ⇨ As the slope of the rf wave is reduced to zero at the bunch center, the bunch becomes longer and synchrotron frequency spread is greatly increased. This increases Landau damping against coupled bunch instabilities.

  A. Hofmann & S. Myers, Proc. Of 11th Int. Conf. on HEA, ISR-Th-RF/80-26 (1980)

h	Vrf
21	32kV
42	16



Flat Bunch Prospects for LHC

(Simulation Studies with ESME)

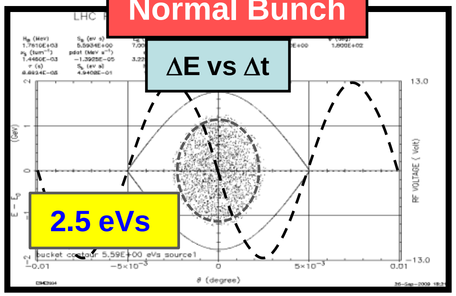
- Two scenarios for creating flat bunches at LHC have been investigated
  - Flat Bunches at 7 TeV using
    - 400 MHz + 800 MHz RF
    - 200 MHz + 400 MHz RF systems in the Ring
  - Flat Bunches creation at 450 GeV and acceleration

Flat Bunches in the LHC at 7 TeV

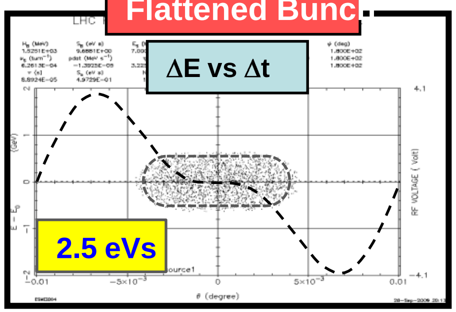
with 200 MHz and 400MHz rf

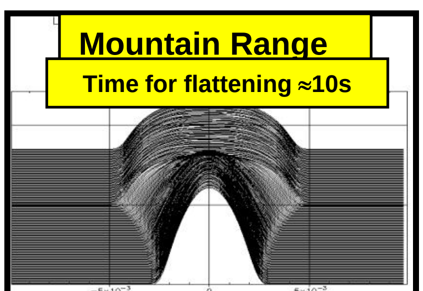
ESME Simulations

Vrf(400MHz)=8MV



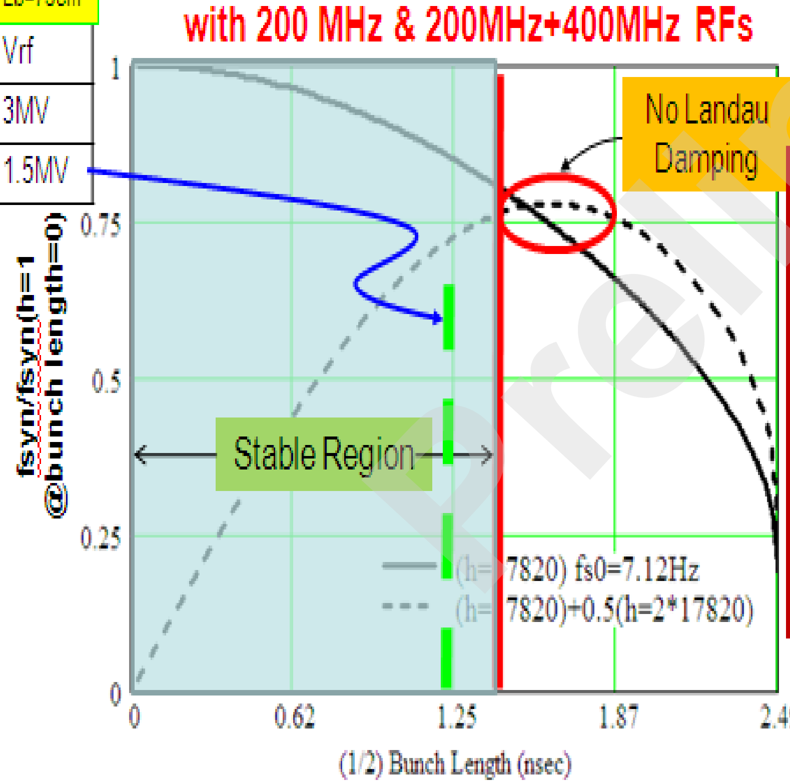
Vrf(200MHz)=3MV
Vrf(400MHz)=1.5MV





LE=2.5eVs, Lb=75cm

h	Vrf
17820	3MV
35640	1.5MV



Conclusions:

The flat bunches are stable for $\varepsilon_l \leq$ 2.5 eVs

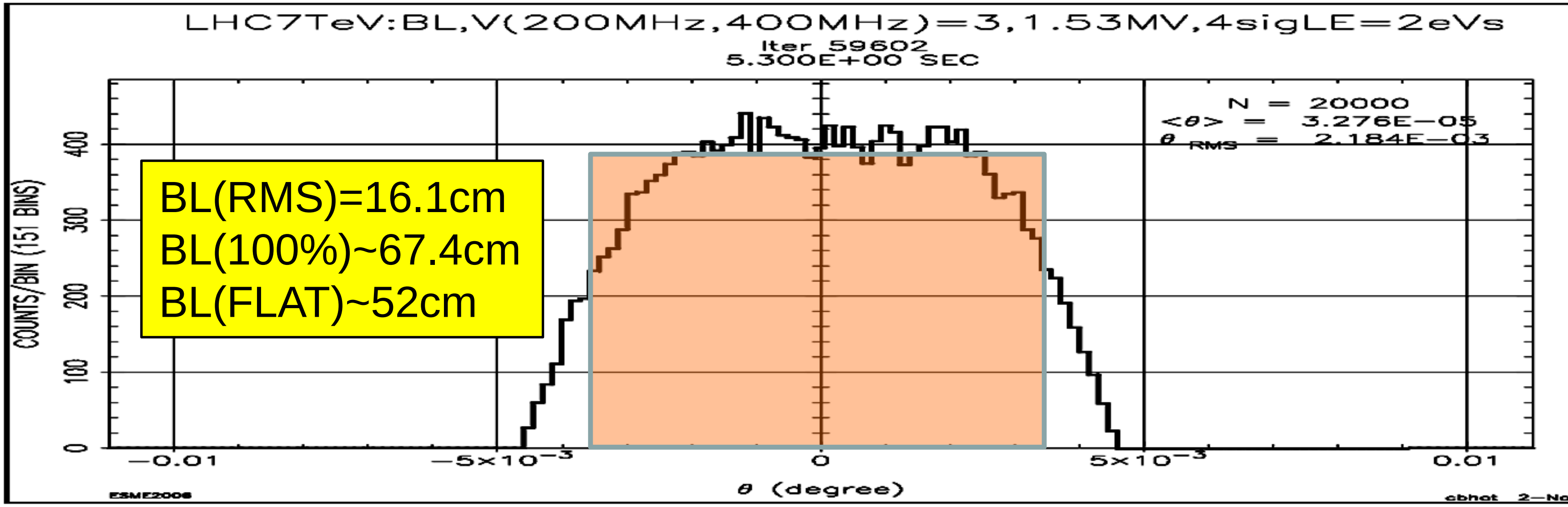
- $l_b \leq$ 75 cm in the case of 200MHz+400MHz rf.
- $l_b \leq$38 cm in the case of with 400MHz +800MHz rf.
- Calculated drop in
  - Peak int. ≈25%
  - ΔE ≈15%

Remark:

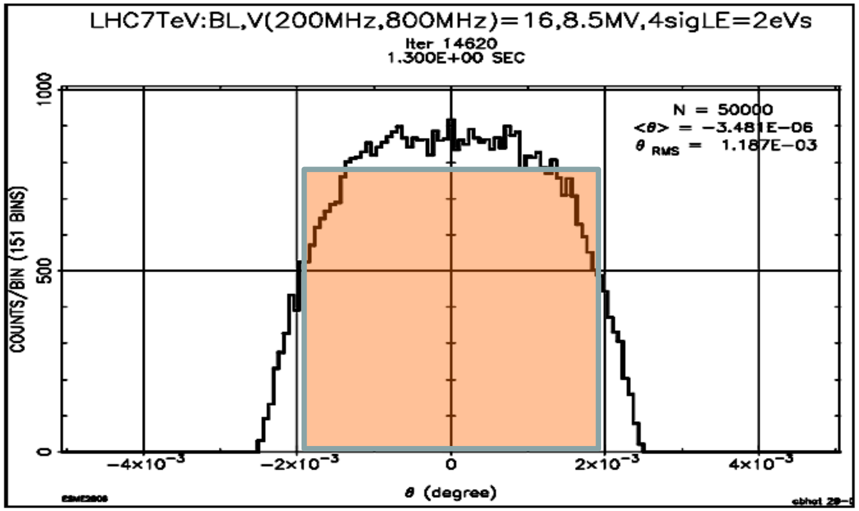
Required 200 MHz rf cavities exist.

R. Losito et. al., EPAC2004

Simulated Flat Bunch Profiles from ESME



BL(RMS)=8.8cm
BL(100%)~37cm
BL(FLAT)~30cm



Proposal
Theoretical Investigations of Flat Bunch Scenarios for the LHC Luminosity Upgrade

(November 4, 2009)

C. Bhat, H-J. Kim, F.-J. Ostiguy, T. Sen

Issues for Theoretical Investigations

Proposing to do theoretical investigations on the following issues --

- For creation of flat bunches, investigate the use of
  - ❑ multiple harmonic cavities (perhaps 2 to 3 harmonics) and
  - ❑ barrier bucket system

  Specify
    - ➢ Optimal RF parameters
    - ➢ Beam intensity limits
    - ➢ Reevaluate impedance budget and constraints
- If flat bunches are to be produced in one of the LHC upstream machines, explore beam instability issues for acceleration up to 7 TeV.
- Single-bunch and multi-bunch instability issues.

Issues for Theoretical Investigations (cont.)

- What are the optimal bunch and beam parameters for the LPA scheme with due consideration of the following
  - Integrated luminosity (i.e. luminosity and lifetime)
  - Emittance growth from beam-beam interactions, IBS
  - Instability growth rates
  - Beam loading compensation
  - Event pile-up: number, space and time resolution of events per bunch crossing
  - Beam losses
- Investigate possible locations and effects due the cavities in the machine lattices.
- **A hybrid scheme that would allow the FCC scheme to benefit from some of the advantages of flat bunches. This would be worth exploring.**
  - **Lower peak intensity decreases the e-cloud effect and space-charge effects**
  - **Lower momentum spread**
  - **Possibly better event resolution (spatial and time) in the detectors**

Existing Simulation Tools

- ESME
  - This is a 2D code to study longitudinal beam dynamics in (ΔE, Δt)-phase space in synchrotrons. We will use it to address
    - Flat bunch creation and acceleration with single and multiple harmonic rf systems,
    - Beam in barrier buckets,
    - Longitudinal single and multi-bunch instability
    - Beam loading issues.

  I have already shown some ESME simulation results. More to come

  Currently, a lot of bench-marking is going on in this case.
- Beam-beam code BBSIM
  - This code will be used to study the impact of beam-beam interactions on the emittance growth. Comparisons between a longitudinal Gaussian profile and a flat profile will be made for the LPA and for the FCC schemes.
- Vlasov solver
  - This will be used to investigate long term beam stability and particle losses. Also, 1) extract spectral information and 2) help establish the optimal ratio of harmonic amplitudes and bunch length, in the presence of realistic impedances.

  A code is developed at Fermilab and being compared with ESME