



# **LPA Scheme for the LHC Luminosity Upgrade**

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**Accelerator Division Seminar**

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Fermilab



# Outline



- Motivation
- Introduction
  - LHC luminosity upgrade scenarios
  - Colliding beams of Gaussian versus Flat bunches
- Recent Beam Studies on Flat bunches
  - Studies in the CERN PS and SPS
  - Flat Bunches in the Fermilab Recycler
- Prospects for the LHC
- Issues to explore
- Conclusions and Plans

# Motivation

- The LHC will be the highest energy collider in the world for at least one-two decades.

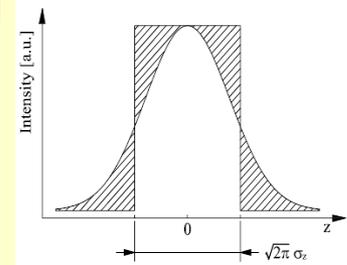
By design, the LHC luminosity =  $10^{34} \text{ cm}^{-2}\text{sec}^{-1}$ .

**The “Flat Bunch” or “Large Piwinski Angle” (LPA) scheme has a very high potential to achieve the goal of  $L \geq 10^{35} \text{ cm}^{-2}\text{sec}^{-1}$**

The Piwinski angle  $\phi_P$  is given by,

$$\phi_P = \frac{\theta_c \sigma_z}{2\sigma_x}$$

$\theta_c$  is crossing angle  
 $\sigma_z$  is RMS bunch length  
 $\sigma_x$  is RMS transverse beam size

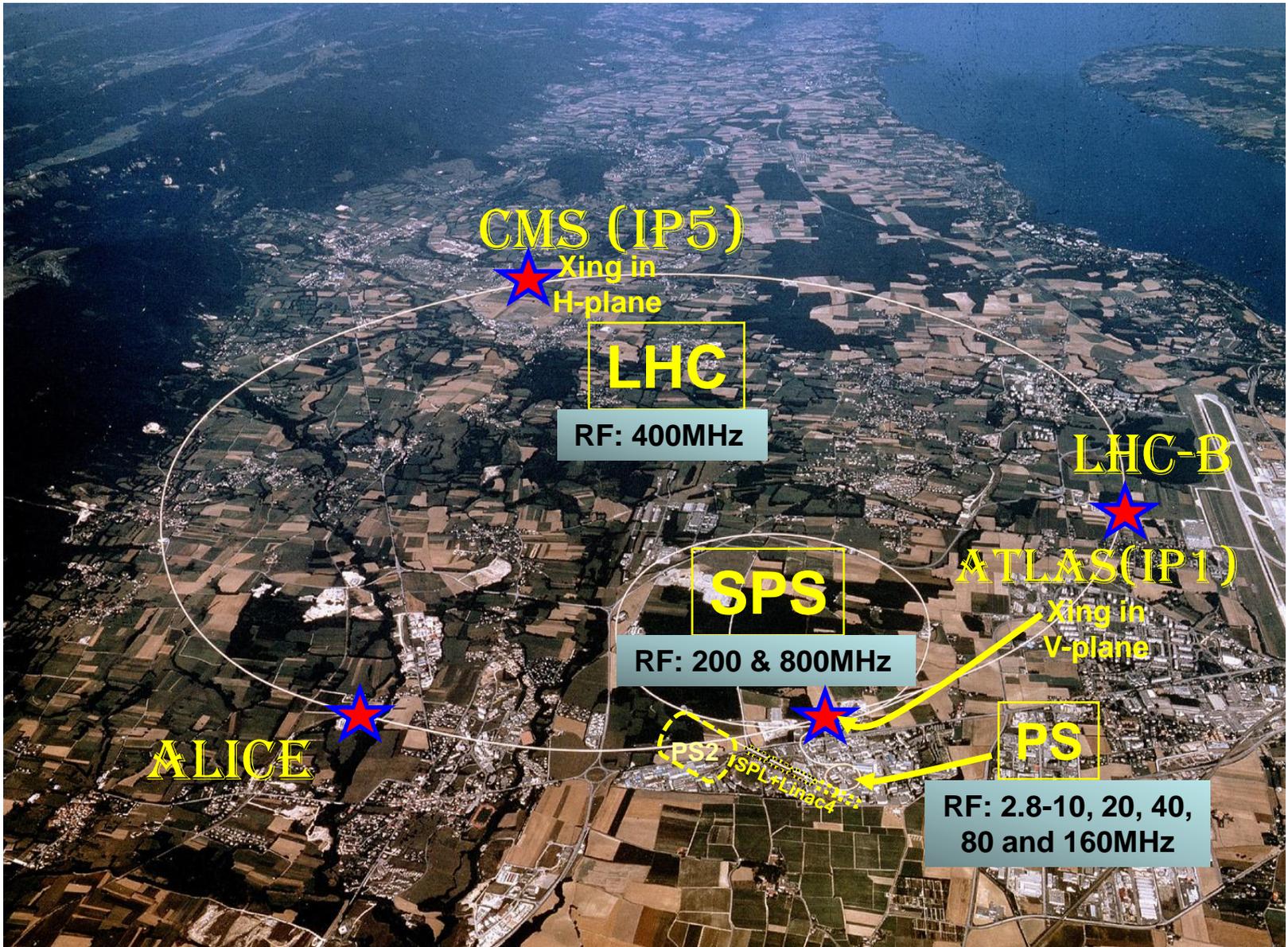


- ➔ In this scheme one can get ~40% higher luminosity than the standard scheme with Gaussian bunches even with the same bunch intensity and the total beam-beam tune shift if the flat-bunch line intensity is kept the same as that of Gaussian peak intensity. →(F. Ruggiero and F. Zimmermann (PRST-AB-Vol. 5, 061001 (2002)))

**Hence the interest in flat bunches in the LHC !**

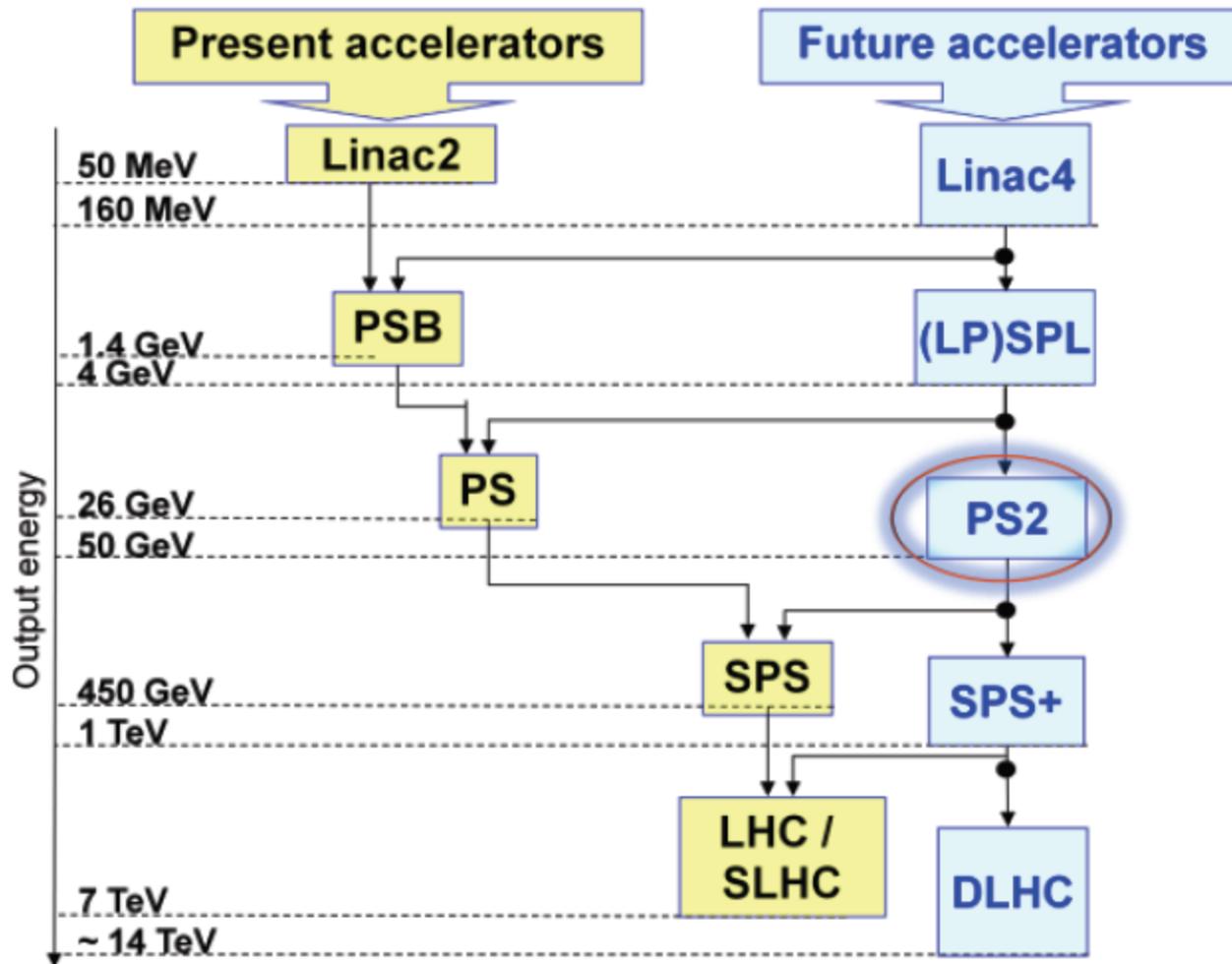


# CERN Large Hadron Collider





# CERN Complex Upgrade Path





# Present LHC Upgrade Paths



F. Zimmermann, CARE-HHH Workshop, 2008

$$\epsilon_{\perp} \text{ (Normalized)} = 3.75 \mu\text{m}, \text{ Allowed } \Delta Q_{\text{sum}} < 0.015 \text{ (LHC Design Rept. III)}$$

Parameter <b>Long. Profile</b>		<b>Nominal Gaussian</b>	<b>Ultimate Gaussian</b>	<b>ES &amp; FCC Gaussian</b>	<b>LPA Flat</b>
<b>Bunch Length (RMS)</b>	cm	7.55	7.55	7.55	11.8
bunch intensity	$10^{11}$	<b>1.15</b>	<b>1.7</b>	<b>1.7</b>	<b>4.9</b>
# of bunches		<b>2808</b>	<b>2808</b>	<b>2808</b>	<b>1404</b>
Average Current	I[A]	0.58	0.86	0.86	1.22
bunch spacing	ns	25	25	<b>25</b>	<b>50</b>
$\beta^*$ at IP1&5	m	0.55	0.5	0.08	0.25
crossing angle, $\phi_p$	$\mu\text{rad}, \text{Rad}$	285, 0.64	315, 0.75	0, 0	381, 2.01
hourglass factor		1	1	0.86	0.99
peak lumi $\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.0	2.3	<b>15.5</b>	<b>10.7</b>
average $\mathcal{L}$ (turnaround time 5h)	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	0.6	1.2	<b>3.6</b>	<b>3.5</b>
event pile-up		19	44	<b>294</b>	<b>403</b>

Note that ES and FCC scheme assume the  $\beta^*$  is 0.08m ☹️



# LHC upgrade paths with $L \geq 10^{35} \text{ cm}^{-2}\text{sec}^{-1}$

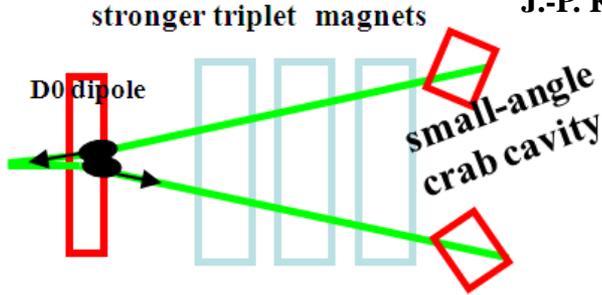


(F. Zimmermann, CARE-HHH Workshop, 2008)

L. Evans,  
W. Scandale,  
F. Zimmermann

## Early Separation (ES)

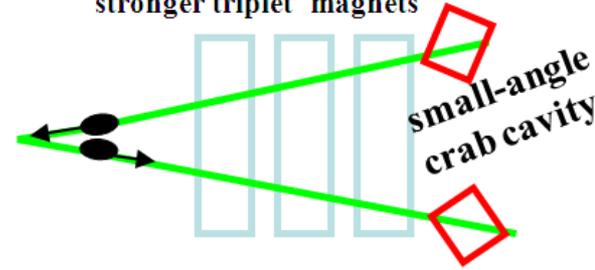
J.-P. Koutchouk



- ultimate beam ( $1.7 \times 10^{11}$  p's/bunch, 25 ns spacing),  $\beta^* \sim 10$  cm
- early-separation dipoles in side detectors, crab cavities  
→ hardware inside ATLAS & CMS detectors, first hadron crab cavities; off- $\delta$   $\beta$ ,  $\epsilon_{\perp} = 3.75 \mu\text{radian}$

## Full Crab Crossing (FCC)

stronger triplet magnets

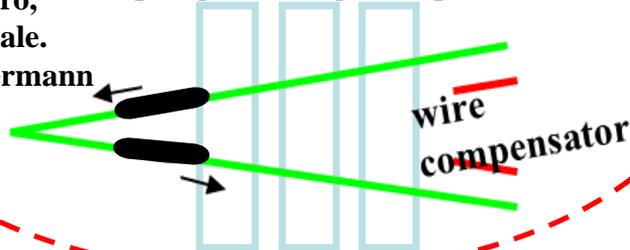


- ultimate LHC beam ( $1.7 \times 10^{11}$  p's/bunch, 25 ns spacing)
- $\beta^* \sim 10$  cm,  $\epsilon_{\perp} = 3.75 \mu\text{radian}$
- crab cavities with 60% higher voltage  
→ first hadron crab cavities, off- $\delta$   $\beta$ -beat

## Large Piwinski Angle (LPA)

F. Ruggiero,  
W. Scandale,  
F. Zimmermann

larger-aperture triplet magnets

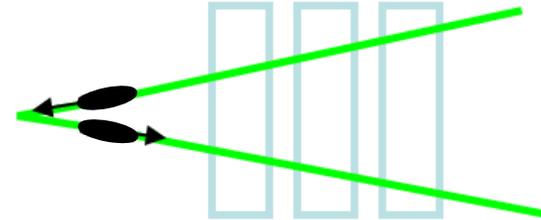


- 50 ns spacing, longer & more intense bunches ( $\sim 6 \times 10^{11}$  p's/bunch)
- $\beta^* \sim 25$  cm, no elements inside detectors,  $\epsilon_{\perp} = 3.75 \mu\text{radian}$
- long-range beam-beam wire compensation  
→ **novel operating regime for hadron colliders**, beam generation

## Low Emittance (LE)

R. Garoby

stronger triplet magnets



- ultimate LHC beam ( $1.7 \times 10^{11}$  p's/bunch, 25 ns spacing)
- $\beta^* \sim 10$  cm,  $\epsilon_{\perp} = 1 \mu\text{radian}$
- smaller transverse emittance  
→ constraint on new injectors, off- $\delta$   $\beta$ -beat

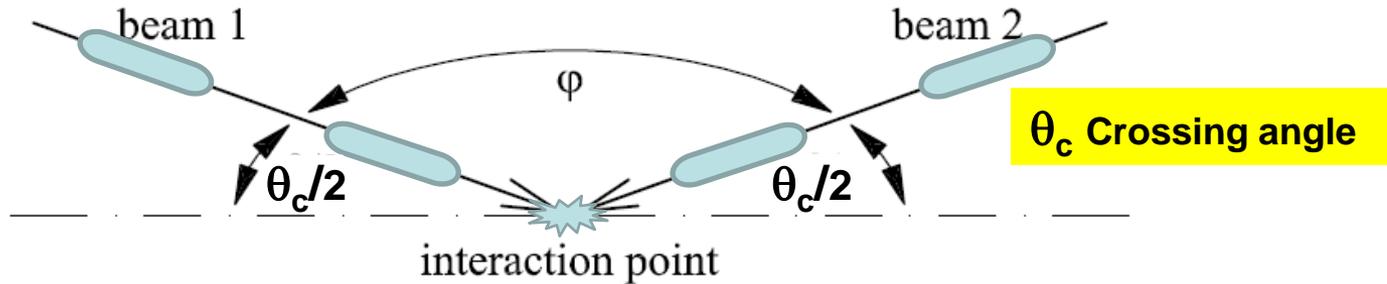


# Some History of Flat Bunches



- Used in ISR,CERN(1971-1983) ←  $\left\{ \begin{array}{l} L_{\text{peakmax}}=1.4\text{E}32/\text{cm}^2/\text{sec} \\ \langle I_{\text{max}} \rangle = 57 \text{ Amp} \\ E_{\text{cm}}=62 \text{ GeV} \end{array} \right.$
- Proposal to use FLAT bunches at LHC
  - Ken Takayama (PRL88,2002)
  - F. Ruggiero and F. Zimmermann (PRST-AB, 2002)
- Flat bunch applications worldwide
  - Fermilab Collider program: Recycler ← **2000-present.**  
Have used barrier rf system since its inception (~1982).
  - CERN-SPS Flat bunches with barrier buckets (2000).
  - KEK Induction Accelerator (~from 2000)
  - FAIR Project at Darmstadt is planning to use flat bunches ← **lots of theoretical work is being carried out**

# Luminosity and Beam-beam Tune-shifts for Colliding Beams



**Luminosity** for single crossing is given by,

$$L = 2cf_{rev} \cos^2 \left[ \frac{\theta_c}{2} \right] \int n_1 n_2 dV dt$$

**Incoherent beam-beam tune shift** due to additional focusing and defocusing EM force caused by one beam on the other beam is given by,

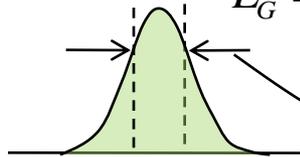
$$\Delta Q_{x,y} = \frac{1}{4\pi} \int \Delta k_{x,y}(z) \beta_{x,y}(z) dz$$

- Ref: 1. F. Ruggiero and F. Zimmermann PRST-AB-Vol. 5, 061001 (2002)) and  
 2. Heiko Damerau, Ph. D. Thesis 2005

# Luminosity Expressions

## Gaussian and Rectangular Colliding Beams

Luminosity for two colliding beams with **Gaussian** (RMS bunch length="  $\sigma_z$  ") line-charge distributions is,



$$L_G = \frac{2 f_{rev} n_b N_p^2}{(2\pi)^2 \sqrt{2} \sigma_z} \int_{-\infty}^{\infty} \frac{\cos\left[\frac{\theta_c}{2}\right]}{2\sigma_{\perp}(z)^2} \exp\left\{-z^2 \left[ \frac{\sin^2\left[\frac{\theta_c}{2}\right]}{\sigma_{\perp}(z)^2} + \frac{\cos^2\left[\frac{\theta_c}{2}\right]}{\sigma_z^2} \right]\right\} dz$$

Luminosity for two colliding beams with **Rectangular** line-charge distributions of bunch length " $l_b$ " is,



$$L_{Flat} = \frac{f_{rev} n_b N_p^2}{2\pi l_b} \int_{-\frac{l_b}{2\cos(\theta_c)}}^{\frac{l_b}{2\cos(\theta_c)}} \frac{\cos\left[\frac{\theta_c}{2}\right]}{2\sigma_{\perp}(z)^2} \exp\left\{-\frac{z^2 \sin^2\left[\frac{\theta_c}{2}\right]}{\sigma_{\perp}(z)^2}\right\} \left[1 - \frac{2|z| \cos\left[\frac{\theta_c}{2}\right]}{l_b}\right] dz$$

where,  $f_{rev}$ ,  $N_p$ ,  $n_b$ , and  $\sigma_{\perp}$  are revolution frequency, Number of protons/bunch, number of bunches/beam and RMS transverse size of the colliding beam, respectively.

## Gaussian and Rectangular Colliding Beams

The total beam-beam spread for colliding beams with two interaction points in the ring – one crossing **horizontally** and another crossing **vertically** but with similar values of crossing angles  $\theta_c$ .

$$\Delta Q_{GTotal} = \Delta Q_{GX} + \Delta Q_{GY} = -\frac{N_p r_p \beta^*}{\sqrt{2} \pi^2 \gamma \sigma_z} \int_{-\frac{l_{det}}{2}}^{\frac{l_{det}}{2}} \left(1 + \frac{z^2}{\beta^{*2}}\right) \exp\left(-\frac{2z^2}{\sigma_z^2}\right) G(\sigma_z, z) dz$$

$$\text{where } G(\sigma_z, z) = \frac{2}{\sigma_z^2} \left(1 - \exp\left[-\frac{\theta_c^2 z^2}{2\sigma_{\perp}^2(z)}\right]\right) + \frac{1}{\sigma_{\perp}^2(z)} \left(1 - \exp\left[-\frac{\theta_c^2 z^2}{2\sigma_{\perp}^2(z)}\right]\right)$$

Assuming  
no shielding  
inside the  
detector of  
length  $l_{det}$

The beam-beam spread for colliding rectangular beams is ,

$$\Delta Q_{FTotal} = \Delta Q_{FX} + \Delta Q_{FY} = \frac{N_p}{\pi \gamma} \frac{r_p \beta^*}{l_b} \frac{1 + \cos(\theta_c)}{2} \int_{-\frac{l_{det}}{2}}^{\frac{l_{det}}{2}} \left(1 + \frac{z^2}{\beta^{*2}}\right) F(z) dz$$

$$\text{where } F(z) = \left[ \left( \frac{\cos(\theta_c) - 1}{z^2 \sin(\theta_c)^2} \right) \left( 1 - \exp\left[ -\frac{\sin^2(\theta_c) z^2}{2\sigma_{\perp}^2(z)} \right] \right) - \frac{\cos(\theta_c)}{\sigma_{\perp}^2(z)} \exp\left[ -\frac{\sin^2(\theta_c) z^2}{2\sigma_{\perp}^2(z)} \right] \right]$$

with,  $r_p$  = classical radius of the proton.



# Special Cases of Beam-beam Tune-shifts



For Gaussian bunches with **small**  $\theta_c$  with  **$\sin(\theta_c) \approx \theta_c$**  &  **$\cos(\theta_c) \approx 1$**  and  **$\sigma_{\perp}^* \ll \sigma_z \ll \beta^*$**  at the interaction points, and  $1 + \left(\frac{\sigma_z \theta_c}{2\sigma^*}\right)^2 \approx \left(\frac{\sigma_z \theta_c}{2\sigma^*}\right)^2$  then one can show that,

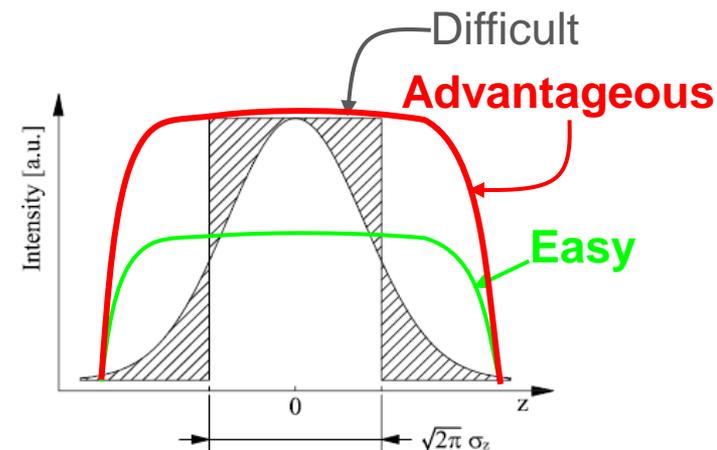
$$L_G \approx \frac{\pi}{2} \frac{f_0 \gamma^2 \sigma^* \sigma_z}{r_p^2 \beta^{*2}} \theta_c \Delta Q_{GTotal}^2 \quad \text{with} \quad \Delta Q_{GTotal} \approx -\frac{N_p r_p \beta^*}{\pi \gamma \sigma^* \sigma_z \theta_c}$$

Similarly, for the rectangular bunches with **small**  $\theta_c$  and  **$\sigma_{\perp}^* \ll \sigma_z \ll \beta^*$**  also with  **$\beta^* \theta_c / \sigma_{\perp}^* \gg 1$**

$$L_F \approx \frac{\sqrt{2}}{\pi} \frac{f_0 \gamma^2 \sigma^* l_b}{r_p^2 \beta^{*2}} \theta_c \times \Delta Q_{FTotal}^2 \quad \text{with} \quad \Delta Q_{FTotal} \approx \sqrt{\frac{2}{\pi} \frac{N_p r_p \beta^*}{\sigma^* \gamma \theta_c}}$$

Now, by taking the ratio of these two expressions one can show that, the Luminosity of rectangular bunch crossing is a factor of  $\sqrt{2}$  larger than that of a Gaussian bunch crossing if  $\Delta Q_{FTotal} = \Delta Q_{GTotal}$  and  $l_b = \sqrt{2\pi} \sigma_z$ .

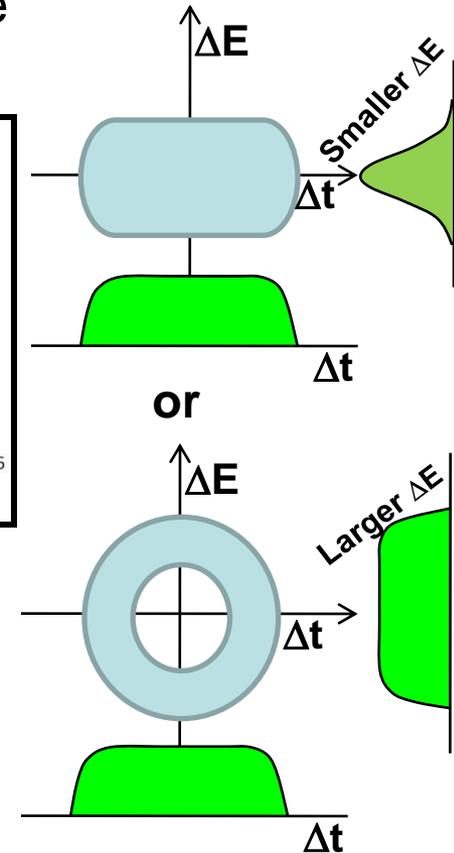
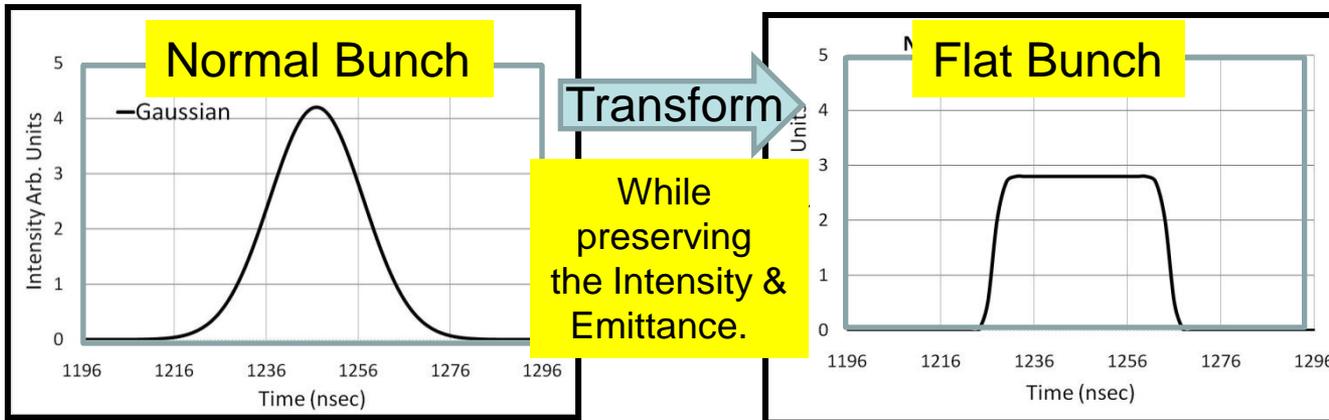
**However,**



# Generating Flat Bunches



- Bunches with uniform or nearly uniform line-charge distribution are “Flat Bunches”



- There are several ways to create flat bunches
  - Using resonant rf systems
    - Double, triple or multiple harmonic rf system
    - Longitudinal hollow bunches, Carli's technique
  - Barrier rf to generate Flat bunches



# Flat bunches with Double Harmonic RF



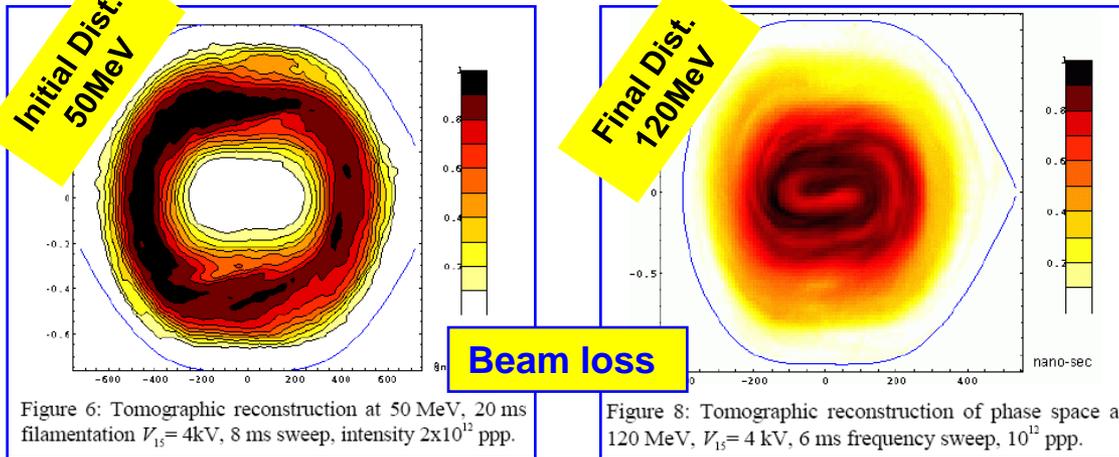
## ● References

- ★  2nd Harmonic debuncher in the LINAC, J.-P. Delahaye et. al., 11<sup>th</sup> 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)

# Past Effort at CERN (cont.): Flat Bunches Acceleration Experiment

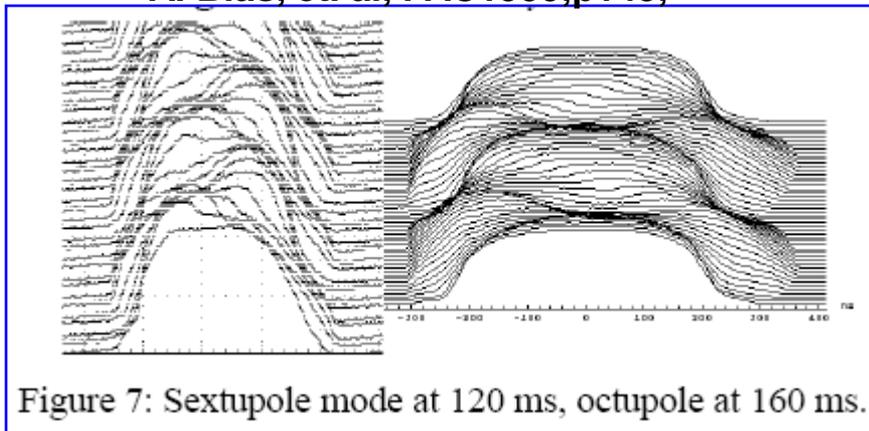


## Tomographic Reconstruction of Phase space



Subsequently, they perfected the technique of hollow bunch acceleration in PSB for bunches  $\sim 8E12/\text{bunch}$ . (PAC1999, p143)

A. Blas, et. al, PAC1999, p143,



However,

- by having small hollow did not give flat enough bunches
- large hollow led to double peaked bunches which were unstable.

**Note: These bunches were not created with Carli's Technique**



# Recent Studies on Flat Bunches at CERN



## CERN Collaborators

- Frank Zimmermann,
  - Oliver Brüning,
  - Elena Shaposhnikova
  - Thomas Bohl
  - Trevor Linnecar
  - Theodoros Argyropoulos
  - Joachim Tuckmantel
  - Heiko Damerau
  - Steven Hancock
  - Edgar Mahner
  - Fritz Caspers
- } PS, SPS and RF
- Elias Metral, Giovanni Rumolo ← LHC Operation Group

→ J. MacLachlan (ESME simulations)

→ Humberto Maury Cuna, CINVESTAV, Mexico (e-cloud simulations)



# Flat Bunches with Double Harmonic RF during Recent MDs



## ● Studies in PS

### □ November 2008

- LHC-25 cycle, Flat Bunch at 26 GeV
- Beam Intensity:  $\sim 8.42E12$  ← Equivalent LHC nominal Intensity
- Bunch Emittance:  $\sim 1.4$  eVs ← Nominal emittance to LHC beam
- RF with  $V(h=21)=31kV$  and  $V(h=42)=16kV$  ←  $V42/V21 \sim 0.5, 0.0$

### □ July 2009

- PS Cycle and Emittance same as above, Intensity about 15% larger
- RF with  $V(h=21)=10kV$  and  $V42/V21=0.0$  to 1.0 in steps of 0.1

## ● Studies in SPS

### □ November 2008: Study on BLM and BSM

- Coasting beam at 270 GeV
- # Bunches =4, with bunch separation of 520 nsec
- Bunch intensity and emittances were similar to Nominal LHC beam
- RF with  $V(800MHz)/V(200MHz) = 0.25$ , with varieties of  $V(200MHz)$

### □ July 2009: Study on BLM and BSM

- Studies at 26 GeV
- # Bunch= 1, Varying Bunch Intensity and emittance (max. comparable to LHC beam)
- RF with  $V(800MHz)/V(200MHz) = 0.25$  and .1 , with  $V(200MHz)=1.7MV$

The data is being analyzed



## Beam Studies in the PS

- Create flat bunches using double/triple harmonic RF system with  $V_2/V_1 \sim 0.5$  above transition energy.
- Study beam instability ← **single and coupled bunch**
- Investigate beam-loading effects.



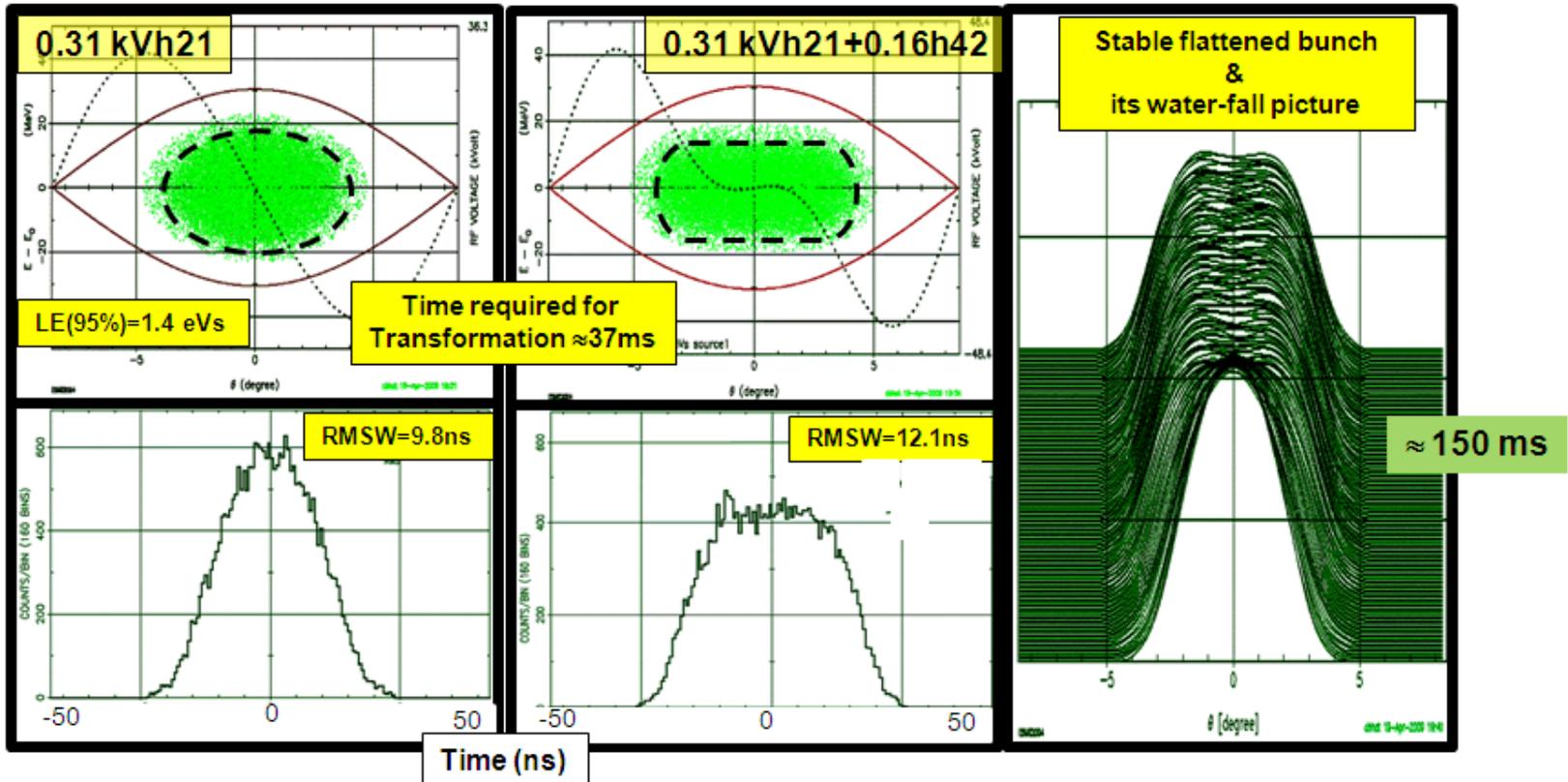
# Bunch Flattening in the PS at 26 GeV & its stability



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

ESME simulations

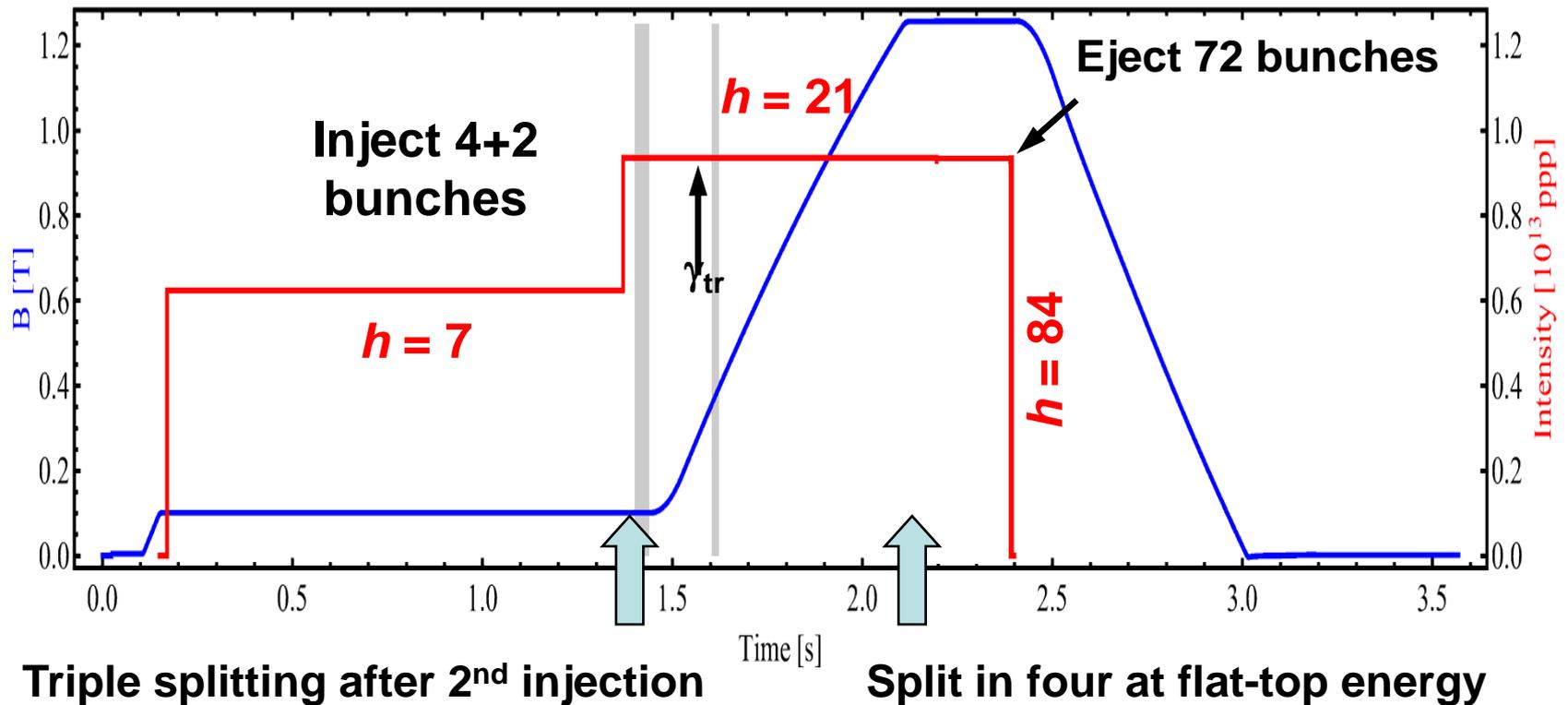
Using 10 and 20 MHz rf systems with bunch spacing = 100nsec



Predicted  $\approx 20\%$  increase in RMSW from beginning of rf manipulation to the flattened bunch



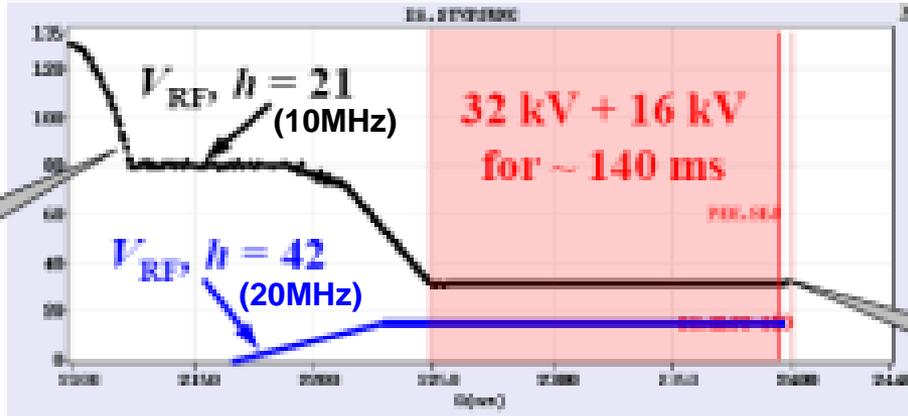
# LHC25(ns) cycle in the CERN PS





# PS Beam Studies using LHC25

RF ramp used in the transforming nominal bunches to flat bunches

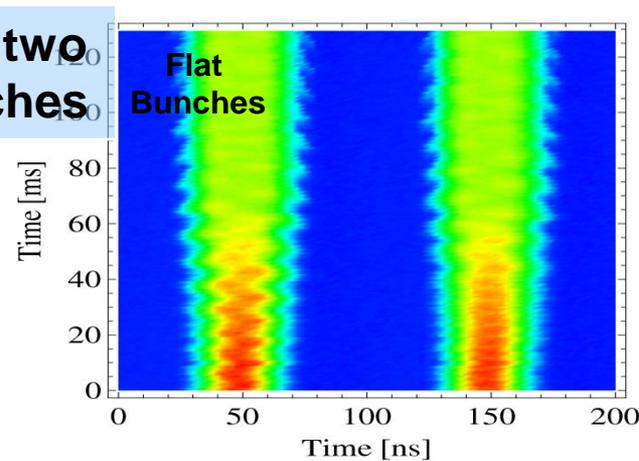
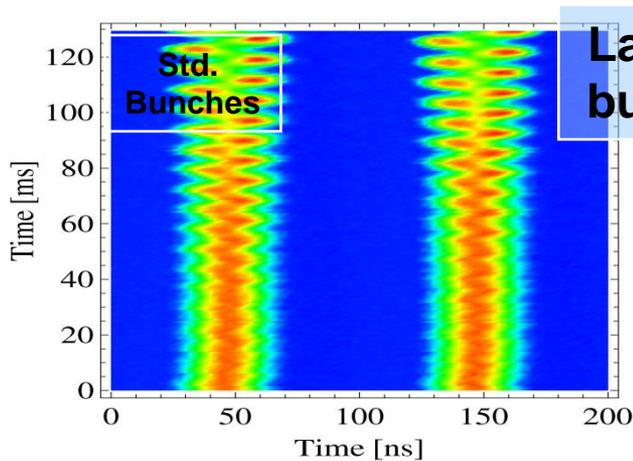


C. M. Bhat, et. al.,  
PAC2009 Vancouver

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

$V_{rf}(h=21)=31\text{kV}$  and  $V_{rf}(h=42)=16\text{ kV}$

h	Vrf
21	32kV
42	0



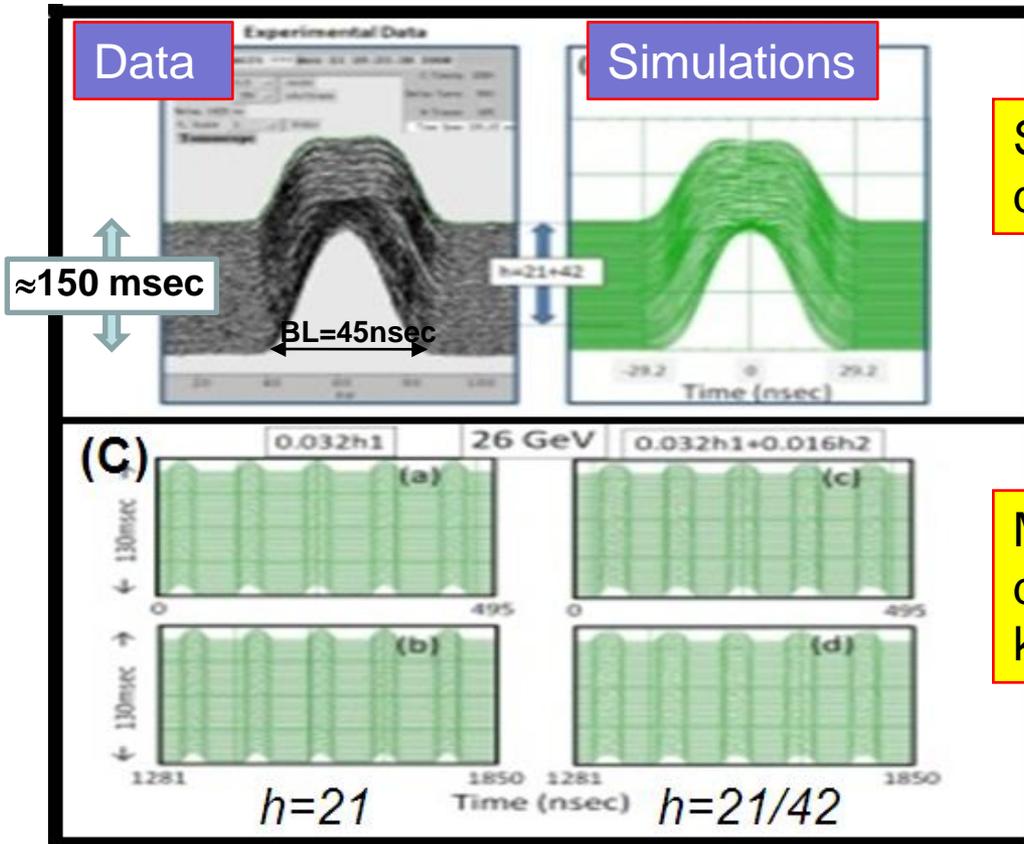
h	Vrf
21	32kV
42	16kV

LE(4 $\sigma$ ) = 1.45 eVs  
I=840E10/batch

- Beam showed coupled bunch oscillations while in  $h=21$
- Became unstable near extraction

- Beam was stable till extraction (~ 120 ms)
- Some oscillations seen when beam was in mostly  $h=21$

# Single-particle and Multi-particle Beam Dynamics Simulations



Single Particle Beam dynamics Simulations

Multi-Particle Beam dynamics Simulations with known cavity impedances

**Conclusions:** The observed coupled bunch instabilities in the PS with single harmonic rf system can not be accounted for by the known cavity impedances. ← **The new kickers in PS are suspected to be the possible source of impedances**



# Beam Stability Criterion



→ Large synchrotron frequency spread improves the stability.

→ If  $\frac{df_s}{dt} = 0$

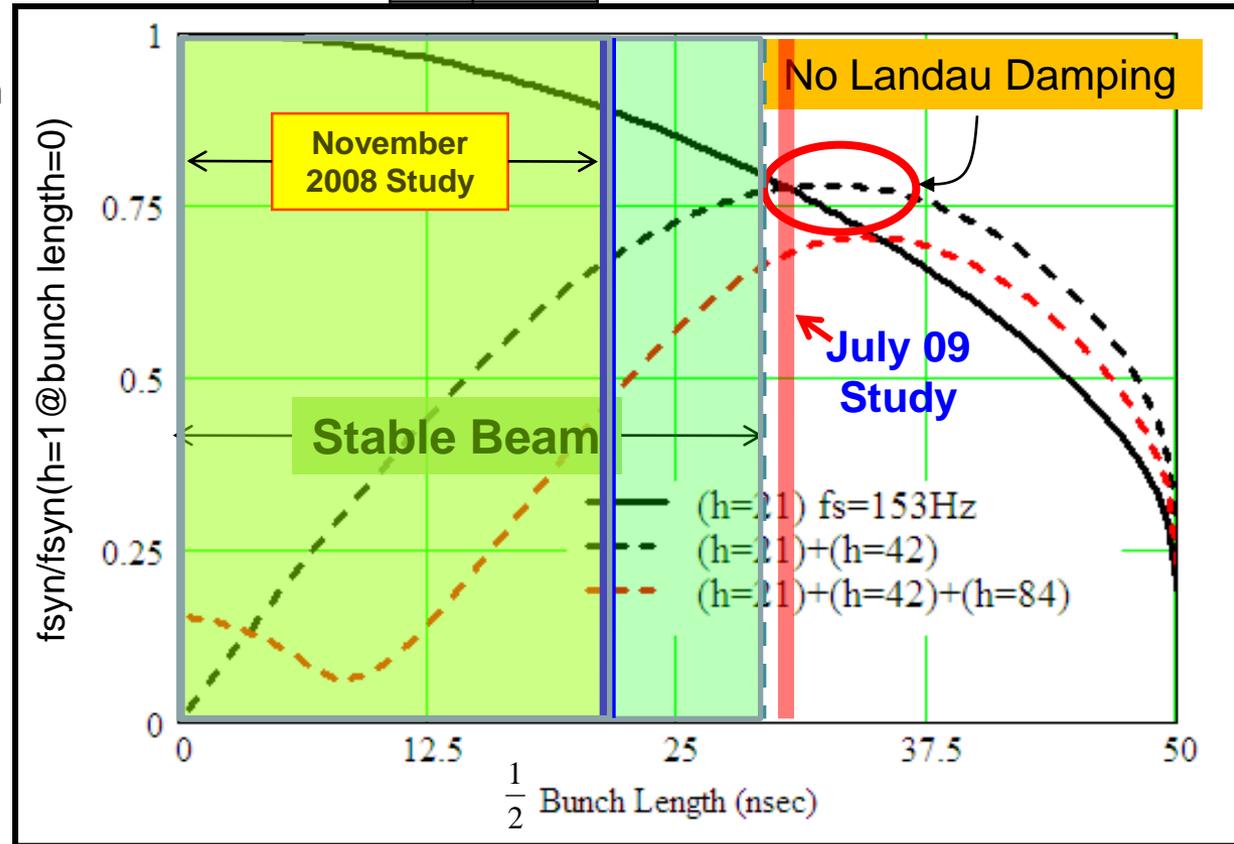
inside the bucket the particle in the vicinity of this region can become unstable against collective instabilities

V. I. Balbekov et.al., Vol. 62, No.2, pp. 98-104, 1987

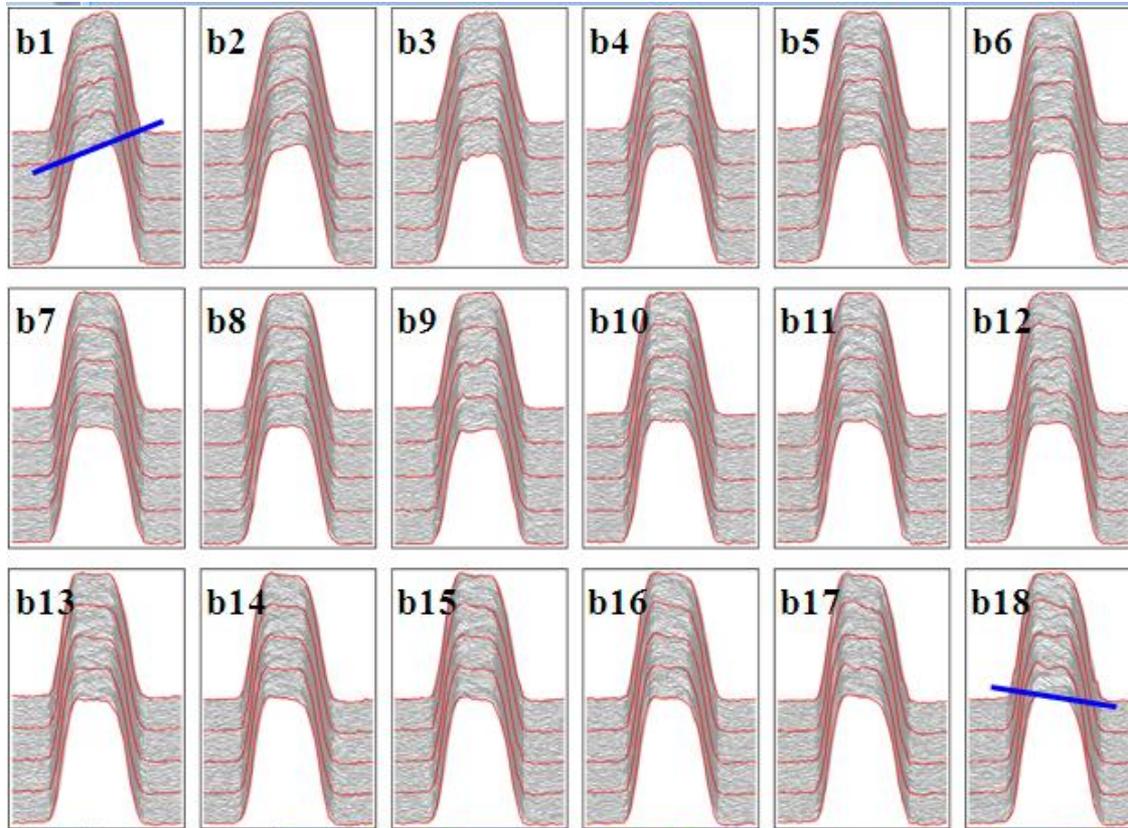
→ As the slope of the rf wave is reduced to zero at the bunch center, the bunch becomes longer and synchrotron frequency spread is greatly increased. This increases Landau damping against coupled bunch instabilities.

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

h	Vrf
21	32kV
42	16



# Flatness Along the Batch



By a detailed study, Heiko concluded that a small **phase errors ( $\sim 2^\circ$ ) between  $h=21$  and  $h=42$  lead to significant asymmetry** of bunches. Hence, we need transient beam loading compensation.

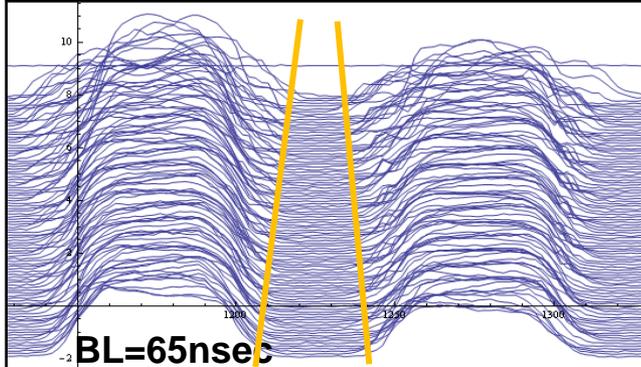


# July 2009 Studies: (A first look)

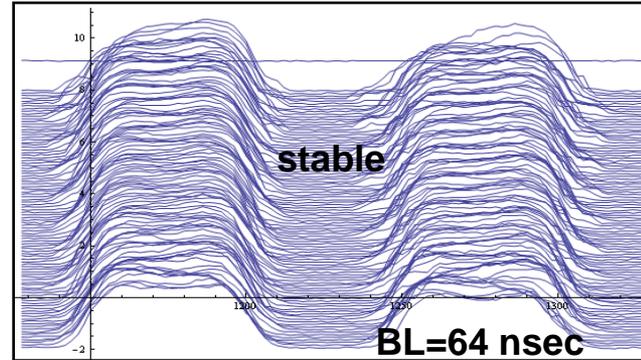


Beam ( $4\sigma$ ) Emittance = 1.45 eVs, Batch intensity=924E10

h	Vrf
21	10kV
42	5kV

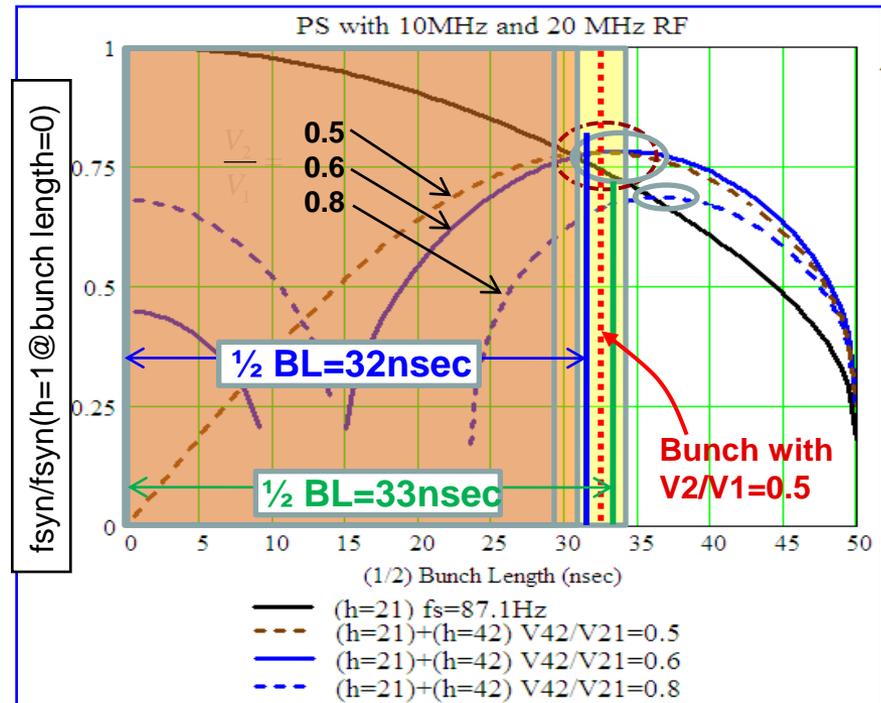


Beam became unstable near the end of the cycle



h	Vrf
21	10kV
42	6kV

**Conclusions:**  
The flat bunches created using double harmonic rf with harmonic ratio of 2:1 can be made stable if proper rf/beam parameters are chosen.



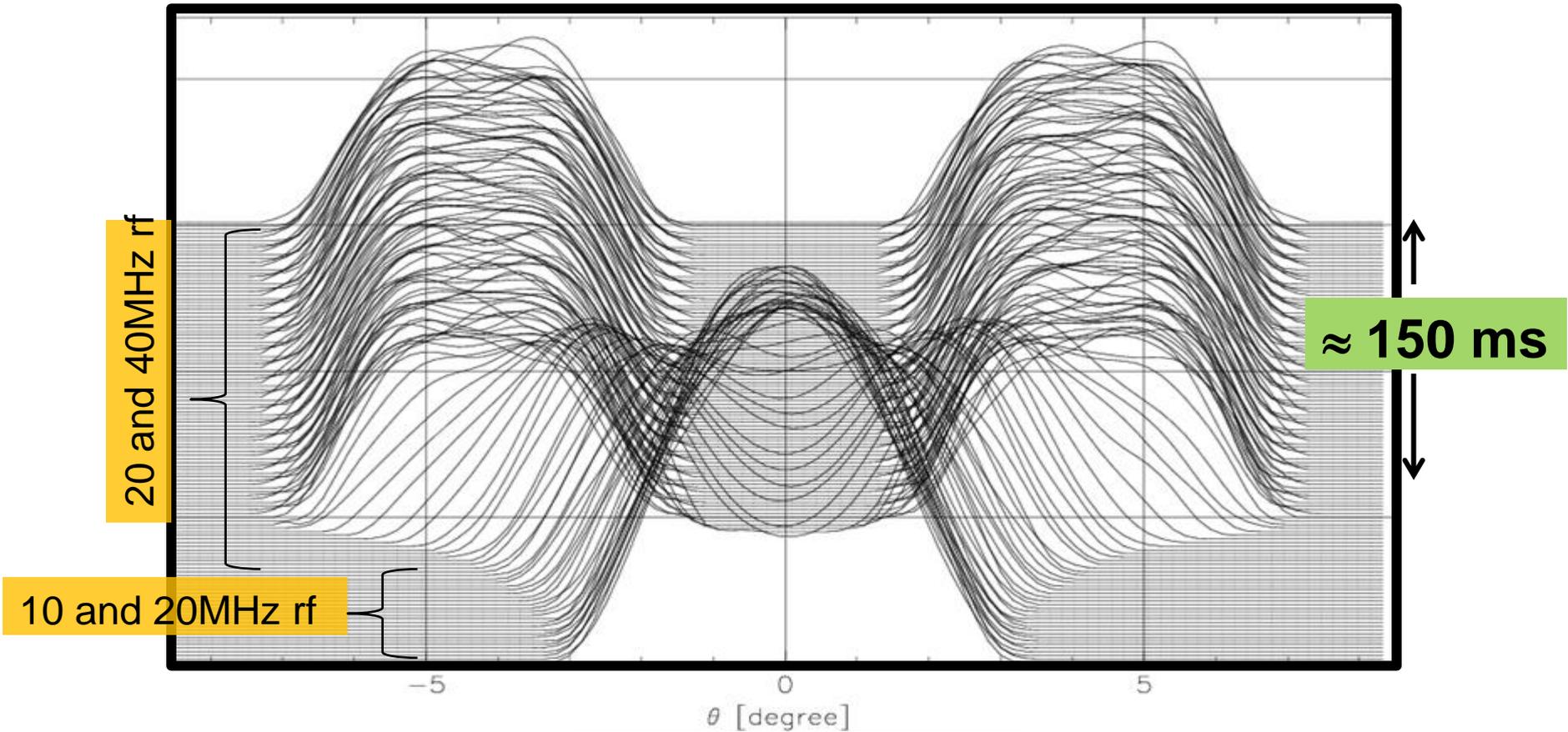


# Bunch Flattening in the PS at 26 GeV & its stability



(ESME simulations)

Using 10,20 & 40 MHz rf systems with bunch spacing = 50nsec



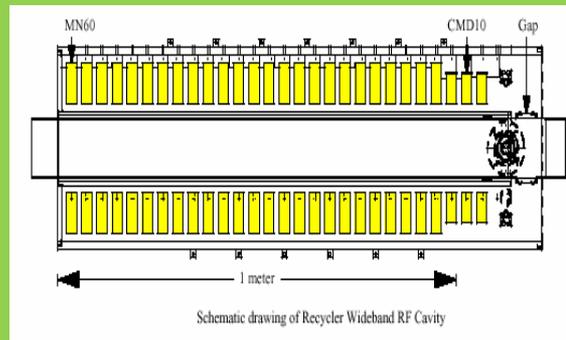
Work in Progress



# Flat Bunches in the Fermilab Recycler

# Recycler RF System to Produce Flat Bunches

Recycler  
Broad-band RF  
Cavities  
#of Cavities=4  
 $R_s \sim 50\Omega$   
10kHz-100MHz



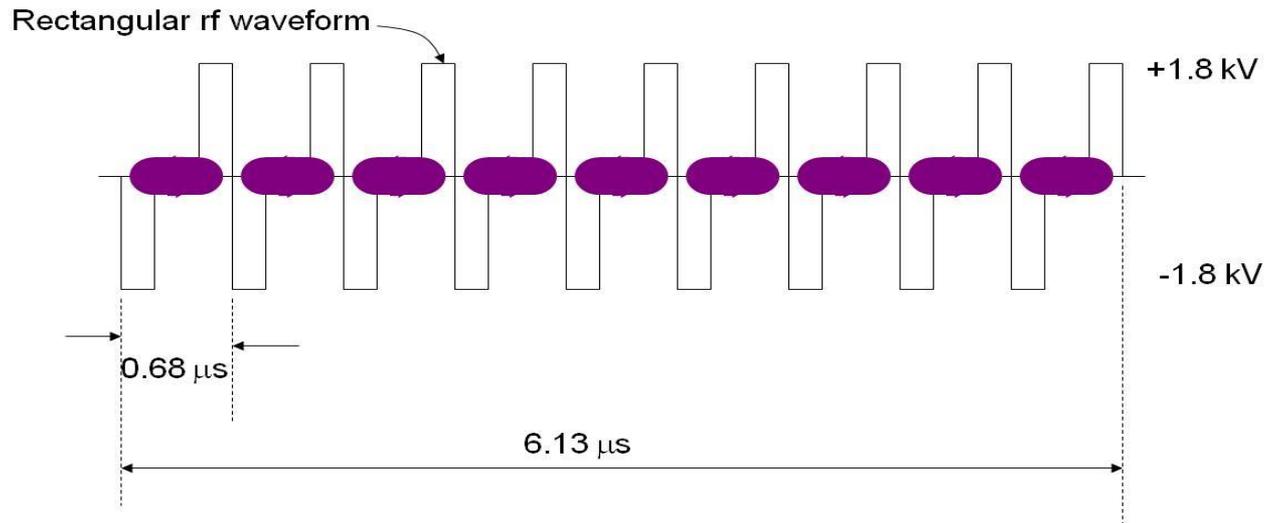
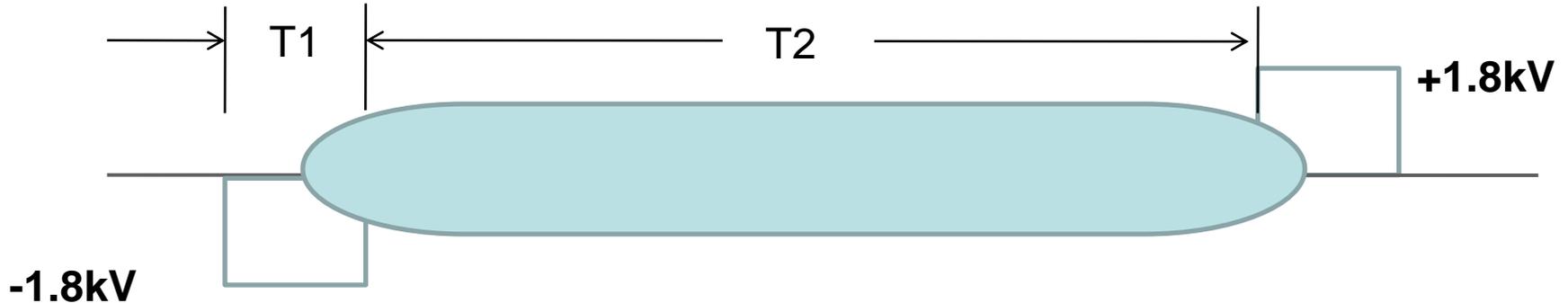
MI60 straight Section



Practically one can produce  
rf waveform of any shape

# Flat Bunches in the Recycler

Schematic of the RF profiles for the flat beam in the RR

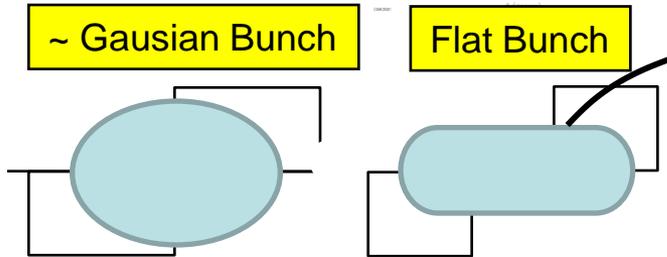
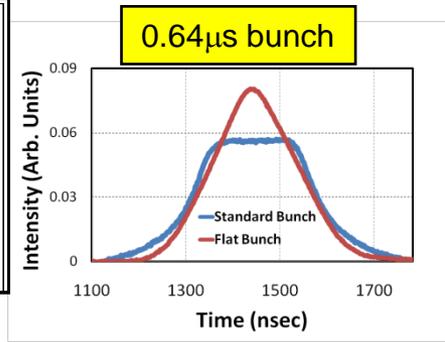
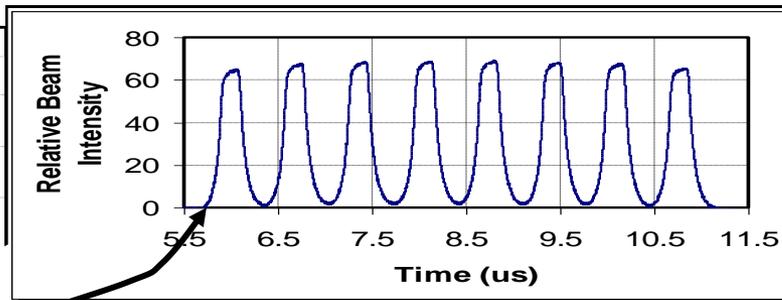
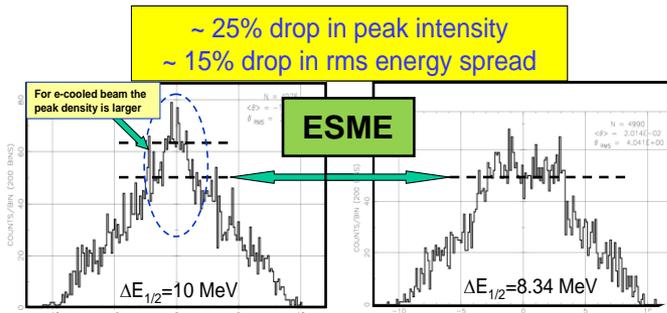
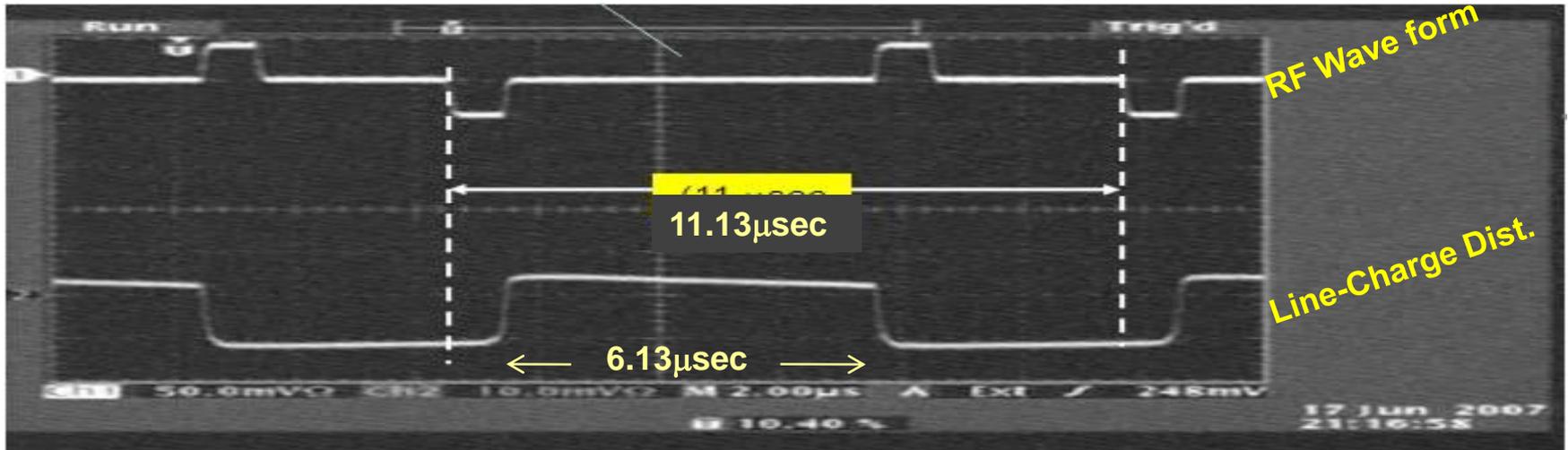


**or Flat bunches of any length  $< \sim 11 \mu\text{sec}$**



# Typical Flat Bunches in the Recycler

(2007 - Present)



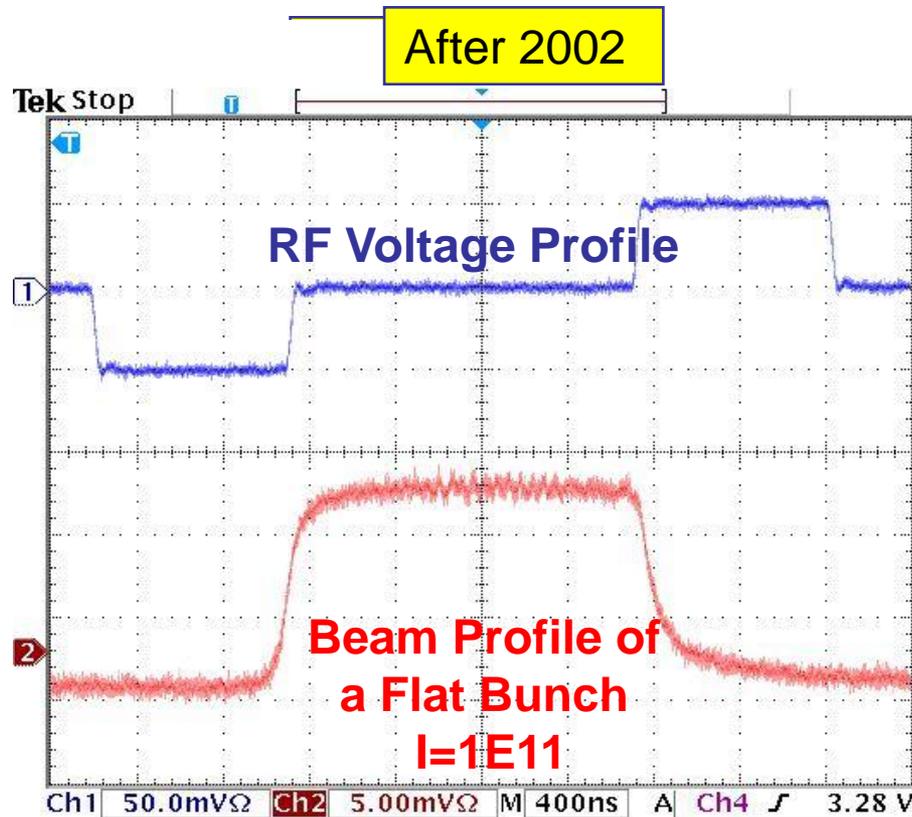
Experiment:

≈35% drop in peak intensity

≈25% drop in beam energy spread with flat bunches



# Removal of the Distortion of the Flat Bunches, the 1<sup>st</sup> Attempt



By using proper combination of filters the unwanted component was removed.

J. Dey, D.Kubicki and J. Reid, PAC2003, 1204.

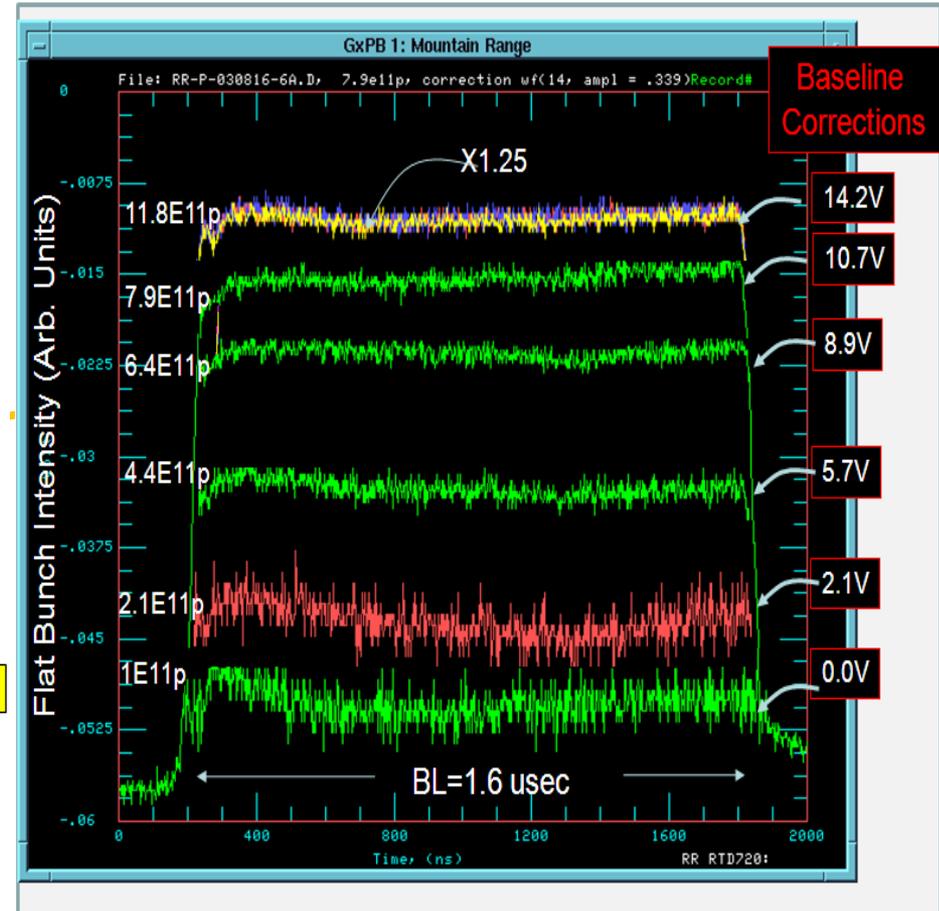
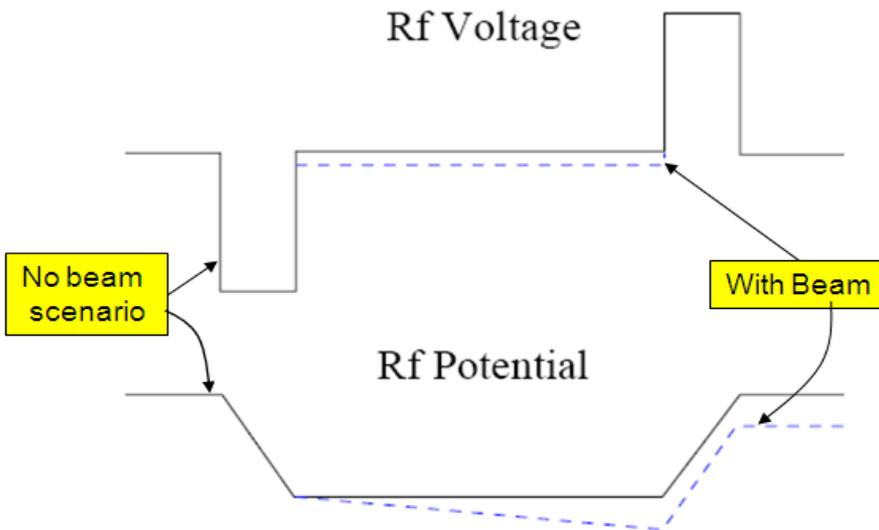


# Potential Well Distortion due to Beam Loading Effects:



## Bunch profile as a Function of Intensity

**Potential Well Distortion** due to the resistive part of the coupling impedance was observed by increasing the bunch intensity at a fixed bunch length (flat bunch) ← First observation of such effects in hadron machines (according to one of my theory friends, K. Y. Ng)



C. M. Bhat and K. Y. Ng, Proc. 30<sup>th</sup>  
Adv. ICFA Beam Dynamics.  
Workshop, 2003, Stanford, Oct. 2003

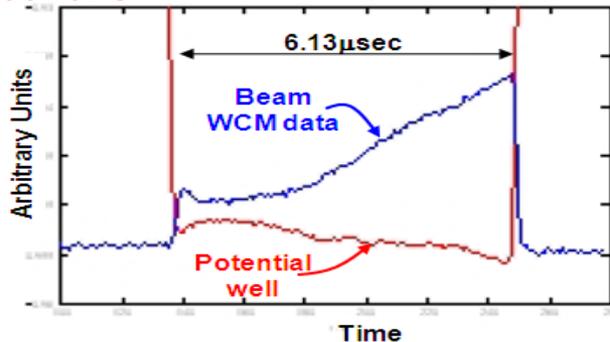
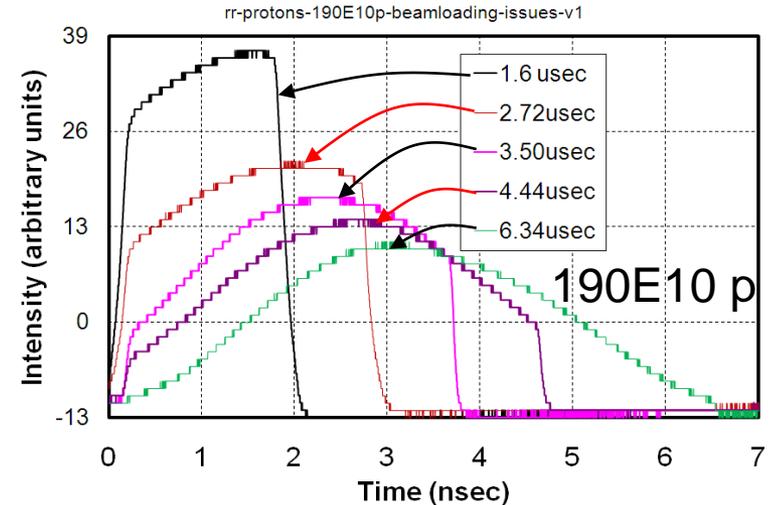


# Recycler Beam Loading Effect: Function of Bunch Length



By varying the bunch length on the same beam showed that it needs further improvements.

The inverse of the potential well and beam wall current monitor data are found to be strongly correlated (M. Hu) ← **Indicated necessity of rf corrections beyond the linear corrections**

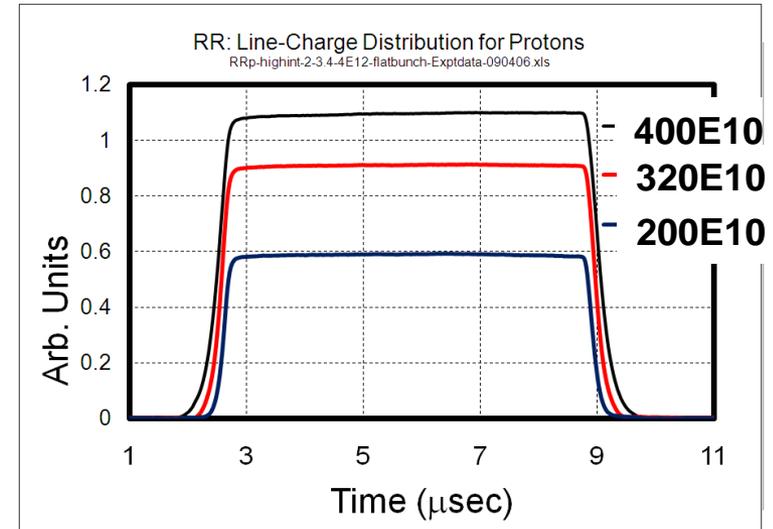


**Identification of RF Imperfections**

J. Crisp et al, HB2006 (2006) 244

**FPGA based adaptive correction system,**

M. Hu et. al, PAC2007,p458



**Conclusions: Beam loading issues of the RR flat bunches is taken care-off**



# Longitudinal Stability of Recycler Flat Bunches: Threshold for loss of Landau Damping



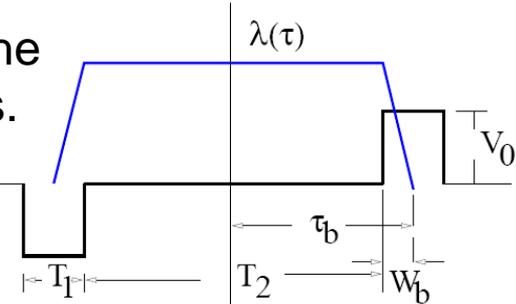
(T. Sen, C. Bhat and J.-F. Ostiguy, FERMILAB-TM-2431-APC, June 9, 2009)

- Revisited the longitudinal stability of the flat bunches in the Recycler barrier buckets for different density distributions.

With the line density  $\lambda(\tau)$ ,

$$\lambda(\tau) = \int_{-\Delta E_b(\tau)}^{\Delta E_b(\tau)} \rho(\Delta E, \tau) d(\Delta E) = \begin{cases} \lambda_0 [U(\tau) - U_b]^{p+\frac{1}{2}} & \text{Binomial dist.} \\ \lambda_0 [U(\tau) - U_b] & \text{Elliptic dist.} \\ \lambda_0 \exp\left\{-\frac{eU(\tau)}{H_0 T_0}\right\} & \text{Exponential dist.} \end{cases}$$

With  $U(\tau) = \int_{\tau}^{\tau} V(t) dt$



Non of the above distributions match with the observed beam profiles.

- The longitudinal distribution that describes the Recycler flat bunches is a *tanh* dist.

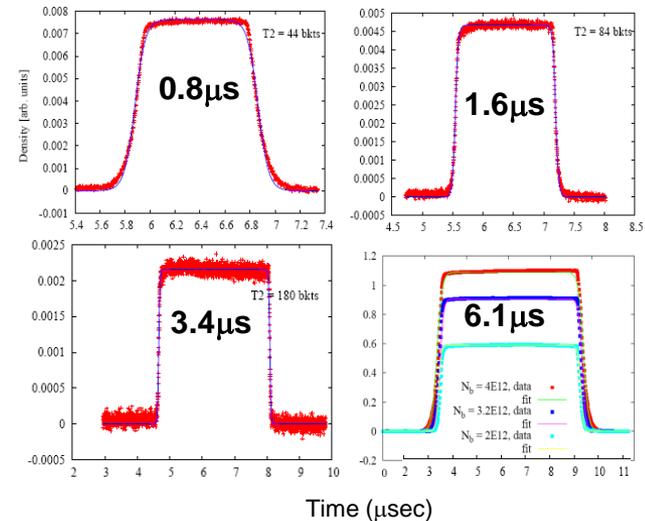
$$\lambda_{fit}(\tau) = N_b a \{ [1 + \tanh(b\tau + c)] \theta(-\tau) + [1 - \tanh(b\tau - c)] \theta(\tau) \}$$

$$\lambda_{fit}(0) = N_b a (1 + \tanh c)$$

$\theta$  is the step function,  $a$ ,  $b$  &  $c$  are three parameters from fit.

The intensity limit is estimated using this dist. for a **6.1  $\mu$ s flat bunch**, where the coherent dipole frequency is at the edge of the incoherent synchrotron frequency dist. in the presence of the space charge.

$$I_{limit} \approx 4E14 p$$





# Beam Studies in the SPS



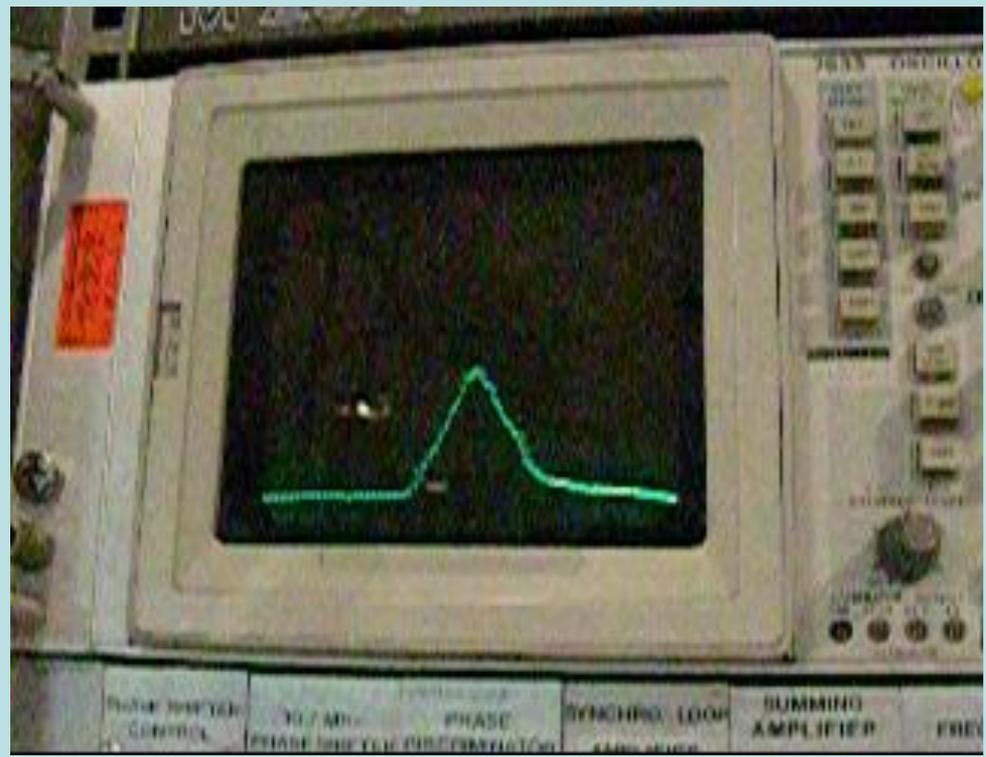
# Studies in the SPS



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

## November 2008

**BSM V4/V1=0.25**  
**Beam Energy = 270 GeV**  
**Number of Bunches = 4**  
**Intensity~1E11 (LHC type)**



**What is going on here?**

## Range of Vrf in the Experiment

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

We repeated the experiments with a single bunch during July –Aug, 2009 MD period in order to eliminate any multi-bunch effects. We found

- **BLM is unstable** under almost all time.
- To our surprise, bunch in a single harmonic was **showing a sign of instability** ← **this is disturbing**
- **BSM is more stable** almost all time.

**More studies are being carried out**



# Prospects for the LHC



# Flat Bunch Prospects for LHC



● Two scenarios for creating flat bunches at LHC are investigated

## □ Flat Bunches at the Top energy

- Using 400 MHz and 800 MHz RF ← This gives 41 cm long flat bunches, BUT!?!
- Using the 200 MHz (R. Losito et. al, EPAC2004, p956) and 400MHz RF systems in the Ring.

## □ Flat Bunches creation at 450 GeV and acceleration

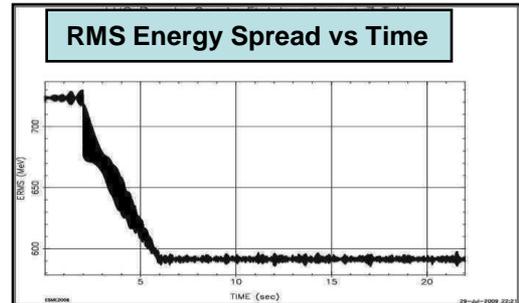
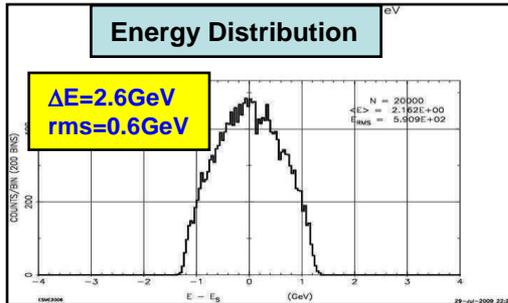
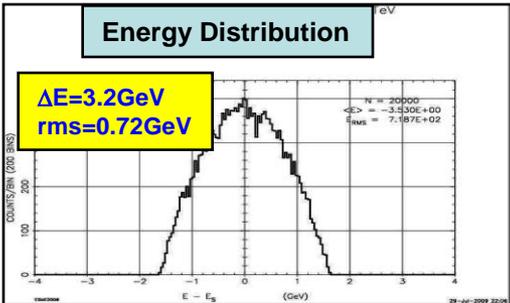
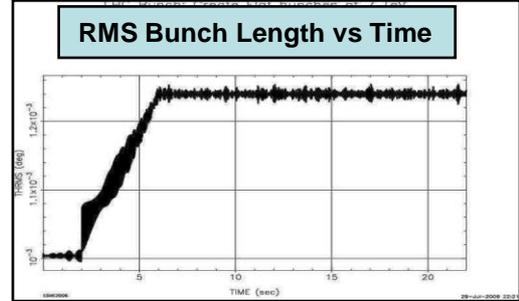
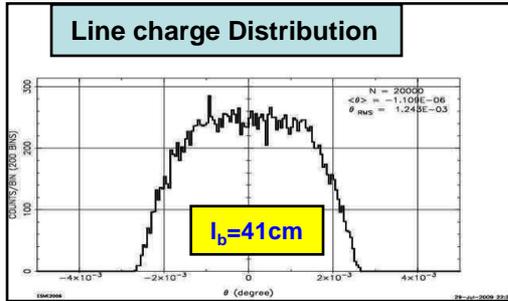
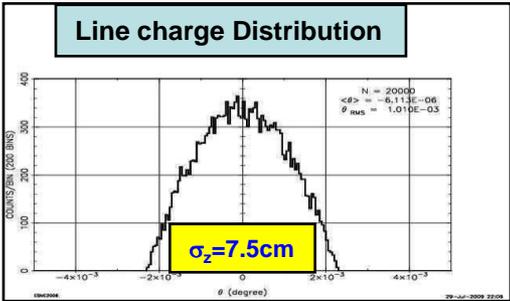
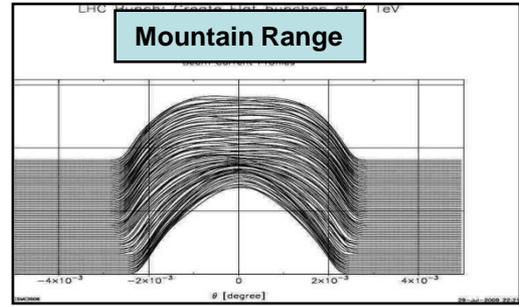
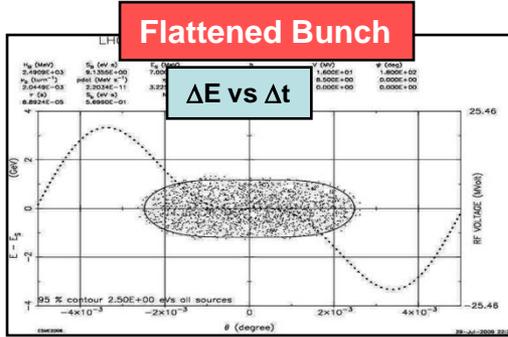
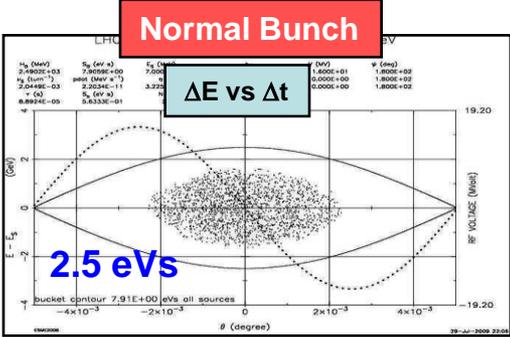


# Bunch Flattening of the LHC Beam at 7 TeV with 400 MHz and 800MHz rf



**Vrf(400MHz)=16MV**

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





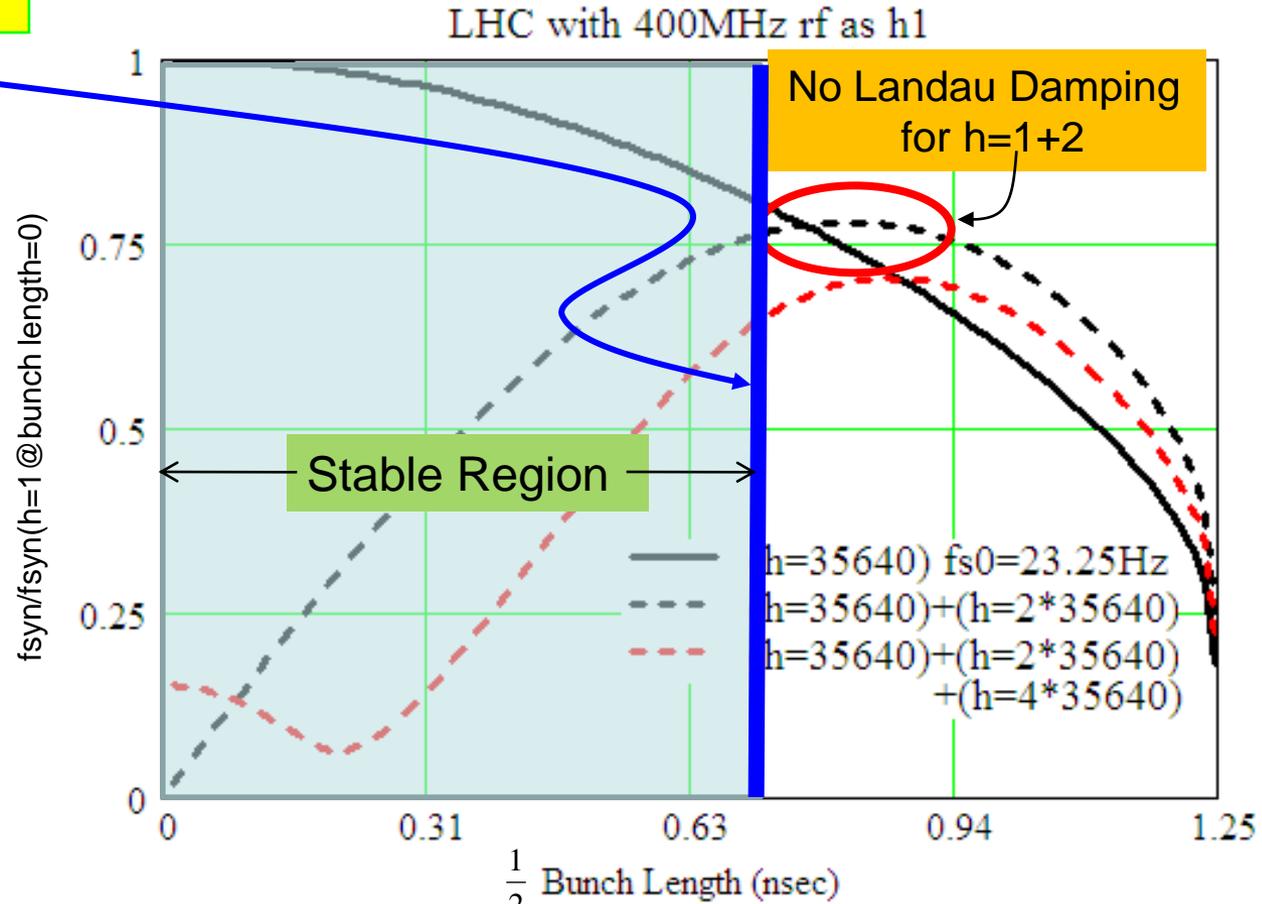
# Acceptable Flat Bunches at LHC

with 400MHz+800MHz RF



LE=2.5eVs, Lb=41cm

h	Vrf
35640	16MV
71280	8.5



**Conclusions:**  
 The 41 cm long flat bunches (2.5 eVs) with 400MHz+800MHz rf systems may be susceptible to beam instability.



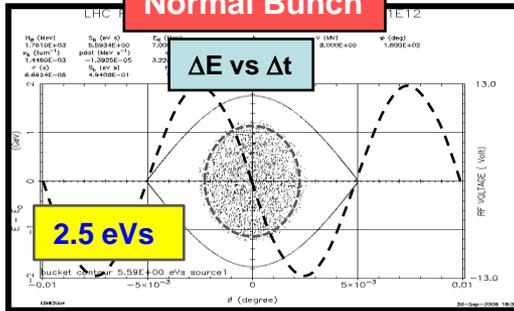
# Bunch Flattening of the LHC Beam at 7 TeV with 200 MHz and 400MHz rf



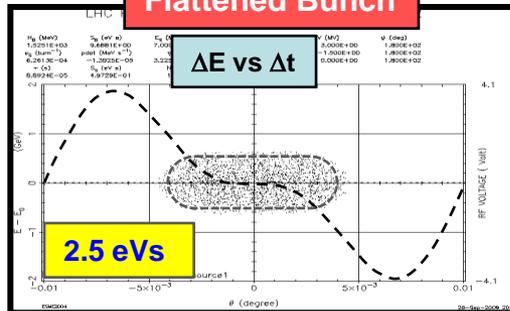
Vrf(400MHz)=8MV

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

Normal Bunch



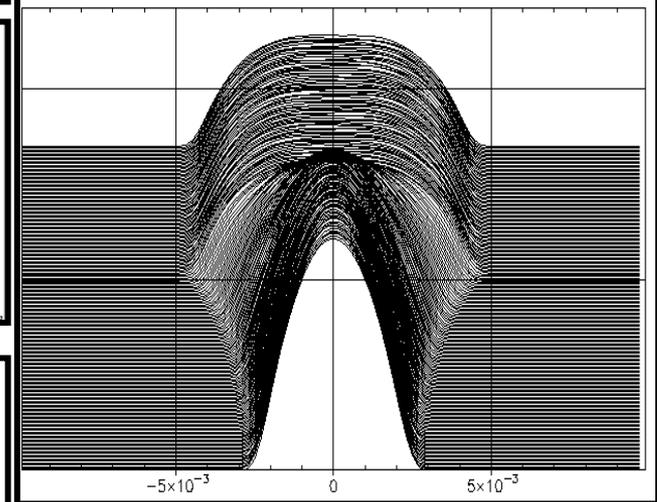
Flattened Bunch



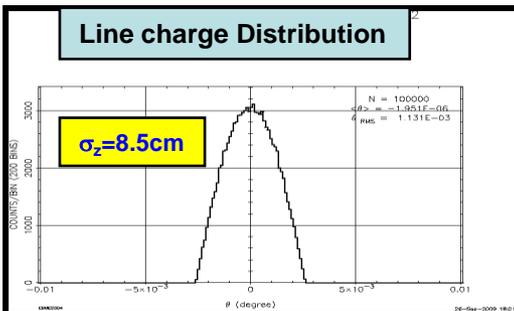
Mountain Range

LHC Flat Bunch at 7TeV(NoSC,BB),2.5eVs,1E12  
every 650 turns, from turn 650

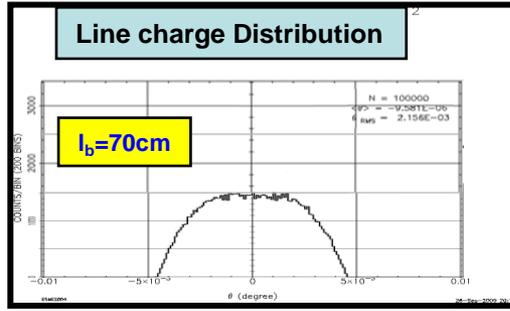
Time for flattening  $\approx 10$  sec



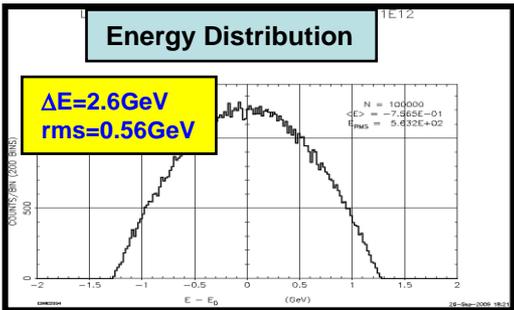
Line charge Distribution



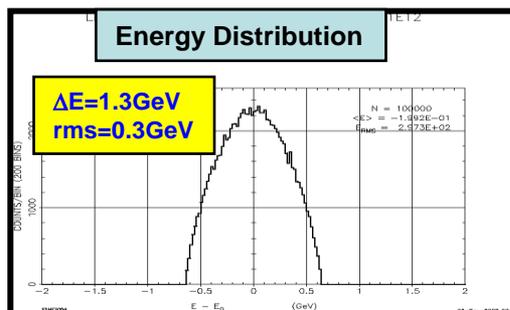
Line charge Distribution



Energy Distribution



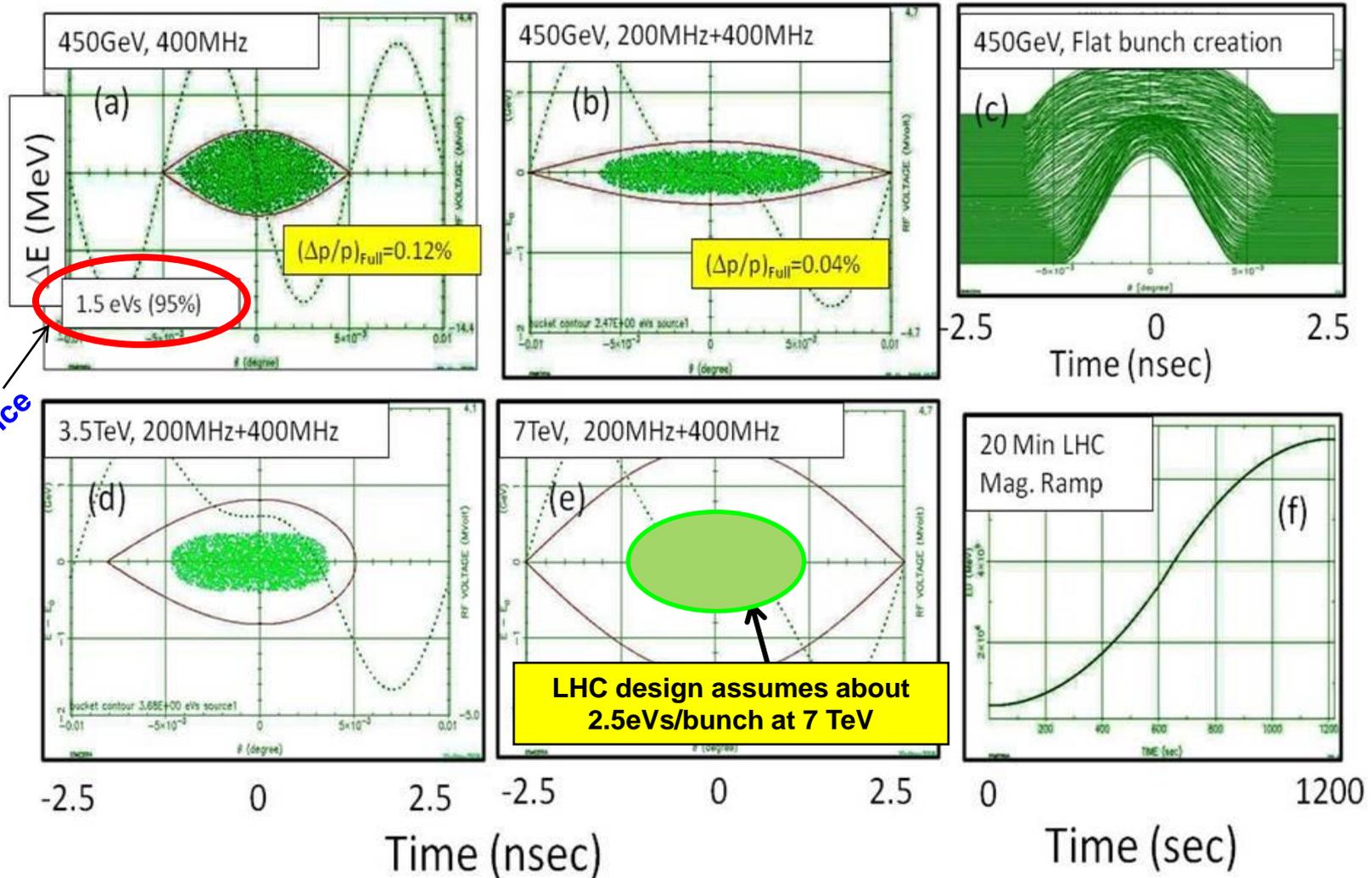
Energy Distribution



Comments: Required 200 MHz rf  
cavities exist.



# Flat Bunches at Injection & Acceleration using 400MHz and 200 MHz rf systems





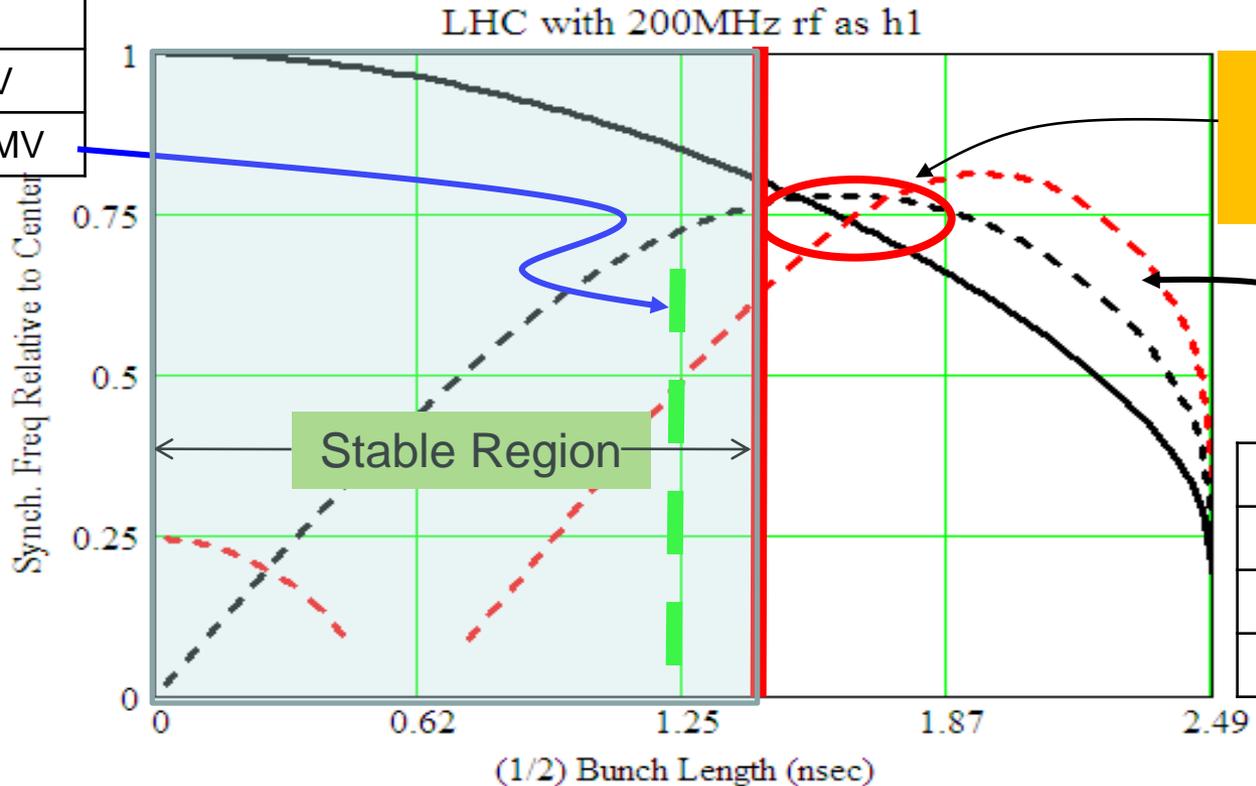
# Acceptable Flat Bunches at LHC



with 200MHz+400MHz RF

LE=2.5eVs, Lb=75cm

h	Vrf
17820	3MV
35640	1.5MV



h	Vrf
17820	3MV
35640	2.76MV
53460	0.3MV

- (h=17820)  $f_{s0}=7.12\text{Hz}$
- - - (h=17820)+0.5(h=2\*17820)
- . - . (h=17820)+0.92(h=35640)+0.3(h=53460)

**Conclusions:**  
 The <75 cm long flat bunches (2.5 eVs) with 200Mhz+400Mhz rf systems are stable.



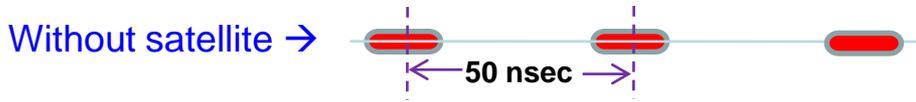
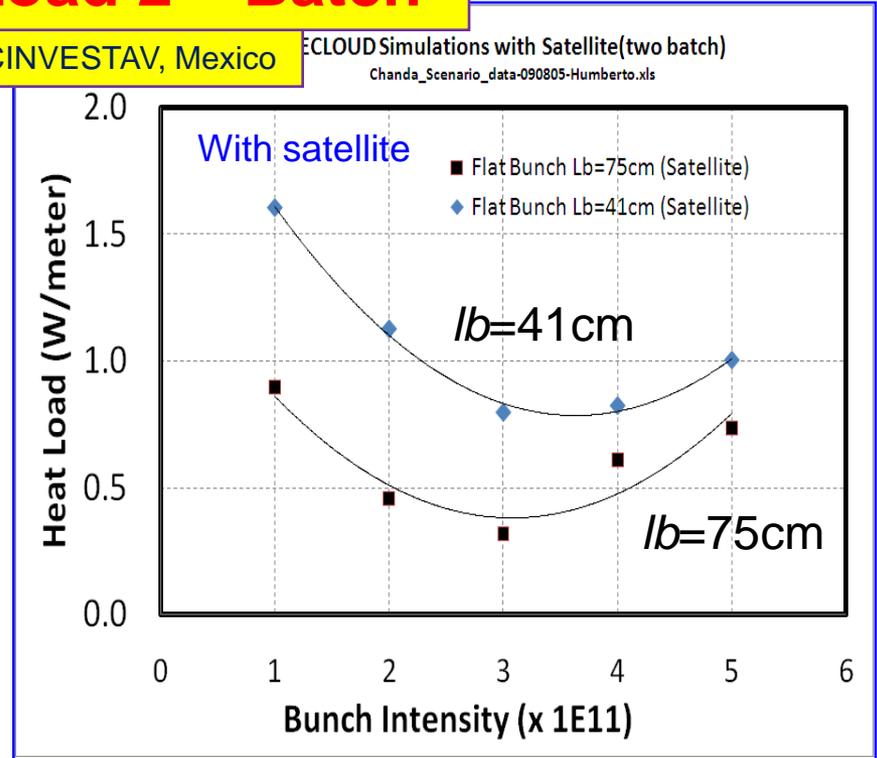
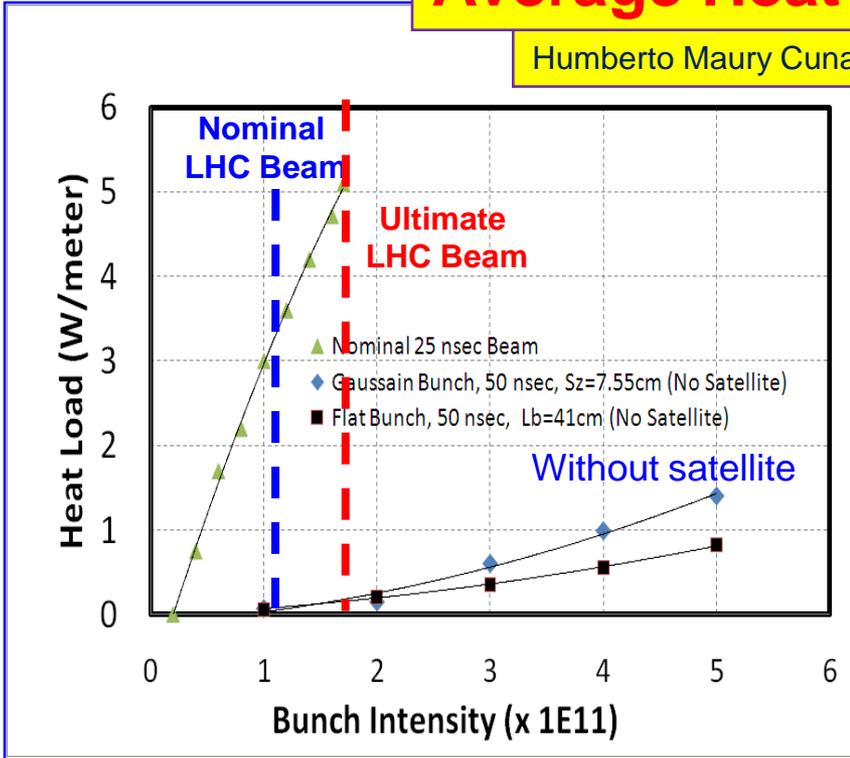
# ECLLOUD Simulations for Nominal and Flat bunches



## Average Heat Load 2<sup>nd</sup> Batch

Humberto Maury Cuna, CINVESTAV, Mexico

ECLLOUD Simulations with Satellite (two batch)  
Chanda\_Scenario\_data-090805-Humberto.xls



**Conclusions:**  
**The estimated e-cloud effect from flat bunches is many times smaller than that with Gaussain bunches.**



# LPA Scheme – Some Options



$\epsilon_{\perp}$  (Normalized) = 3.75  $\mu\text{m}$ , Allowed  $\Delta Q_{\text{sum}} < 0.015$  (LHC Design Rept. III)

Parameter Long. Profile		Nominal Gaussian	LPA Scheme Bunches with Harmonic RF		
Bunch Length (RMS)	cm	7.55	11.5	22	17
bunch intensity	$10^{11}$	1.15	4.9	6.3	5.7
LE ( $4\sigma$ )	eVs	2.5	2.5	2.5	1.5
Average Current	I[A]	0.58	1.22	1.6	1.42
bunch spacing	ns	25	50	50	50
RF Combination	MHz	400	400+800	200+400	200+400
$\beta^*$ at IP1&5	m	0.55	0.25	0.25	0.25
crossing angle, $\phi_p$	$\mu\text{rad}$ , Rad	285, 0.64	381, 2.01	381, 3.7	381, 2.9
peak lumi $\mathcal{L}$	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	1.0	10.7	10	10
average $\mathcal{L}$ (turnaround time 5h)	$10^{34}\text{cm}^{-2}\text{s}^{-1}$	0.6	3.5	3.8	3.6
event pile-up		19	403	??	??



# Issues and Future Plans



## Questions to answer:

● **What are the optimal beam parameters for the LPA scheme?**

★ ● What is the optimal way to produce such flat bunches? And where to produce?

★ ● **What rf capability is needed to handle such bunches?**

★ ● What are the single-bunch & multi-bunch instability issues? In addition, are there serious e-cloud effects and, if so, how can these effects be mitigated?

● **How to address the beam loading issues?**

● How does this upgrade scenario fit within the current design of PS2 ?

● **Is the number of interactions per collision going to be a problem for experiments?**

★ **Some have been partly addressed. Others being studied.**



# Summary and Conclusions

- The large Piwinski angle scheme is a viable path for the LHC luminosity towards  $10^{35} \text{ cm}^{-2}\text{sec}^{-1}$ . ← I am optimistic this can be done!  
But, there are a number of issues, may be unique to the LHC, that need to be investigated.
- The results from studies in the PS and SPS are very encouraging.
- I have discussed flat bunch creation at 450 GeV and its acceleration with 200MHz+400MHz systems. Some problems need to be overcome.
- I have discussed two scenarios for LHC flat bunch creation at the top energy.
  - 400MHz+800 MHz can be used to produce flat bunches with  $l_b = 41 \text{ cm}$ . But this is not suitable from the point of view of beam stability at  $LE = 2.5 \text{ eVs}$ .
  - Combination of 200MHz+400MHz system seems more promising.
- It will be useful to have a test 400MHz rf cavity ( $V_{\text{min}} \sim 2\text{MV}$ ) in the SPS to conduct dedicated studies on the beam instability on flat bunches.

Flat bunch scenario is a very promising and viable path for the Luminosity upgrade at the LHC.