LPA Scheme for the LHC Luminosity Upgrade

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CERN

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Thanks also to
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Outline

- Motivation
- Introduction
  - Flat-bunch scheme, a short history and theory
  - LHC luminosity upgrade scenarios
- Flat bunch Studies at CERN
  - Beam studies in SPS and PS
- Flat Bunches in the Fermilab Recycler Ring
- Issues to explore
- Prospects for LHC
- Conclusions & Plans

Motivation

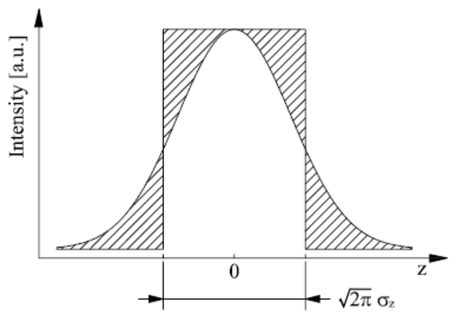
- The Large Piwinski angle or “Flat Bunch scheme” has the potential to yield 40% higher luminosity than Gaussian bunches for the same bunch intensity and the total beam-beam tune shift if the flat-bunch line intensity is kept the same as Gaussian peak intensity.

(F. Ruggiero and F. Zimmermann (PRST-AB-Vol. 5, 061001 (2002)

The Piwinski angle ϕ, is given by,

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

θ_c is crossing angle
σ_z is RMS bunch length
σ_z is RMS transverse size



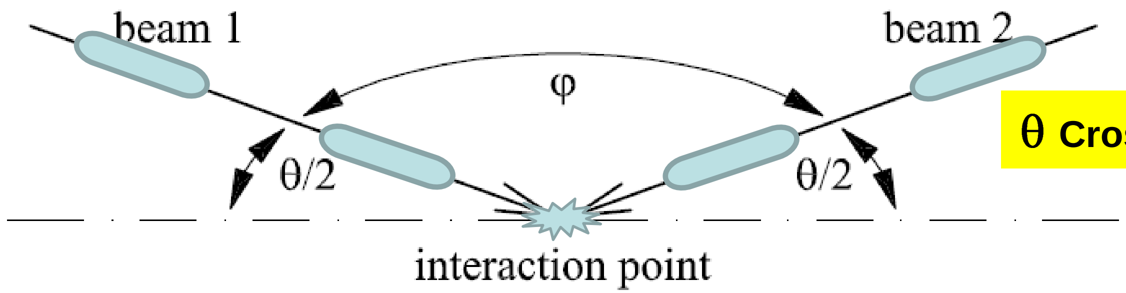
- Upgrade of the LHC luminosity towards 10^{35} $cm^{-2}sec^{-1}$ poses daunting challenges! It is, therefore, necessary to explore seriously all of the viable options.

Hence the interest in flat bunches in the LHC !

Some History Time-line

- Used in ISR (1972-1979)
- Flat bunch applications worldwide
  - ❑ Fermilab Collider program: Recycler (2000-present). We had barrier rf system since its inception (~1982).
  - ❑ CERN-SPS Flat bunches with barrier buckets (early 2000?)
  - ❑ KEK Induction Accelerator (~from 2000, Takayama's Group)
  - ❑ 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 the colliding beams



θ **Crossing angle**

The **luminosity** for single crossing is given by,

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

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

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

Luminosity and Beam-beam-tune shifts

Gaussian Beam

Luminosity for Gaussian Beams becomes,

$$L_G = \frac{2 f_{rev} n_b N_p^2}{\left(2\pi\right)^{\frac{3}{2}} \sqrt{2}\sigma_z} \int_{-\infty}^{\infty} \frac{\cos\left[\frac{\theta_c}{2}\right]}{2\sigma_\perp(z)^2} \exp\left\{ - z^2 \left[\frac{\sin^2\left[\frac{\theta_c}{2}\right]}{\sigma_\perp(z)^2} + \frac{\cos^2\left[\frac{\theta_c}{2}\right]}{\sigma_z^2} \right] \right\} dz$$

And the beam-beam tune spread,

$$\Delta Q_G = \frac{N_p r_p \beta^*}{\sqrt{2}\pi^{\frac{3}{2}} \gamma \sigma_z} \int_{\frac{-l\det}{2}}^{\frac{l\det}{2}} \left(1 + \frac{z^2}{\beta^{*2}}\right) \exp\left(-\frac{2z^2}{\sigma_z^2}\right) G(\sigma_z, z)\, dz$$

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

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

Luminosity and Beam-beam-tune shifts

Flat Rectangular Beam

Luminosity for two rectangular bunches of length "l_b" ,

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

And the beam-beam tune spread is,

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

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

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

Ref: 1. F. Ruggiero and F. Zimmermann PRST-AB-Vol. 5, 061001 (2002)) and

2. Heiko Damerau, "Creation and Storage of Long and Flat Bunches in the LHC", Ph. D. Thesis 2005

Present LHC Upgrade Paths

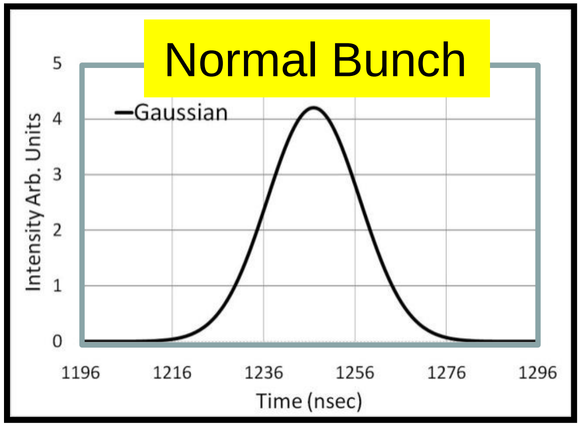
F. Zimmermann, CARE-HHH Workshop, 2008

Parameter		Nominal	Ultimate	ES & FCC	LPA
Bunch Length (RMS)	**cm**	**7.55**	**7.55**	**7.55**	**11.8**
bunch intensity	10^{11}	**1.15**	**1.7**	**1.7**	**4.9**
transv. emitt.	μm	3.75	3.75	3.75	3.75
bunch spacing	ns	25	25	**25**	**50**
beta* at IP1&5	m	0.55	0.5	0.08	0.25
crossing angle Piwinski parameter	μrad	285 0.64	315 0.75	0 0	381 2
peak lumi $\mathcal{L}$ average $\mathcal{L}$ (turnaround time 10h)	10^{34} $cm^{-2}s^{-1}$	1.0 0.46	2.3 0.91	**15.5** **2.4**	**10.7** **2.5**
event pile-up		19	44	294	403

Note that for ES and FCC scheme the β^* is 0.08m

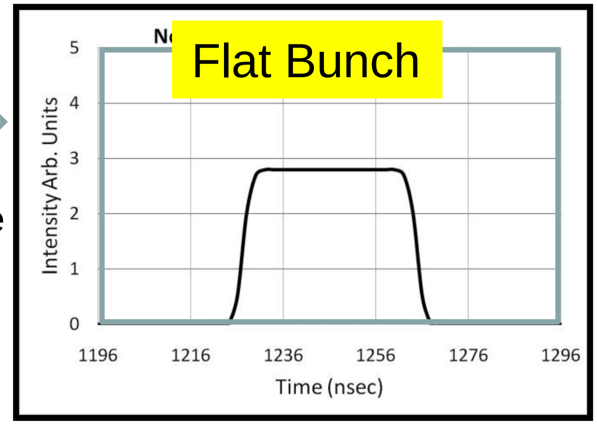
Flat Bunch Creation

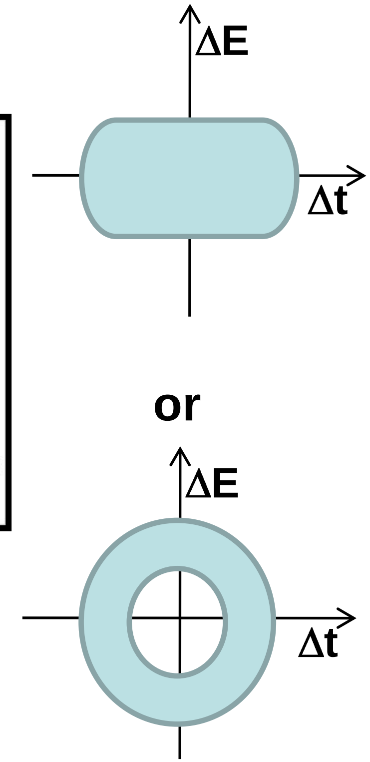
- Bunches with uniform or nearly uniform line-charge distribution are “Flat Bunches”



Transform

Preserving the Intensity & Emittance.





- There are several ways to create flat bunches
  - ❑ Using resonant rf system
    - ➢ 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., 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)

Recent Studies on Flat Bunches at CERN

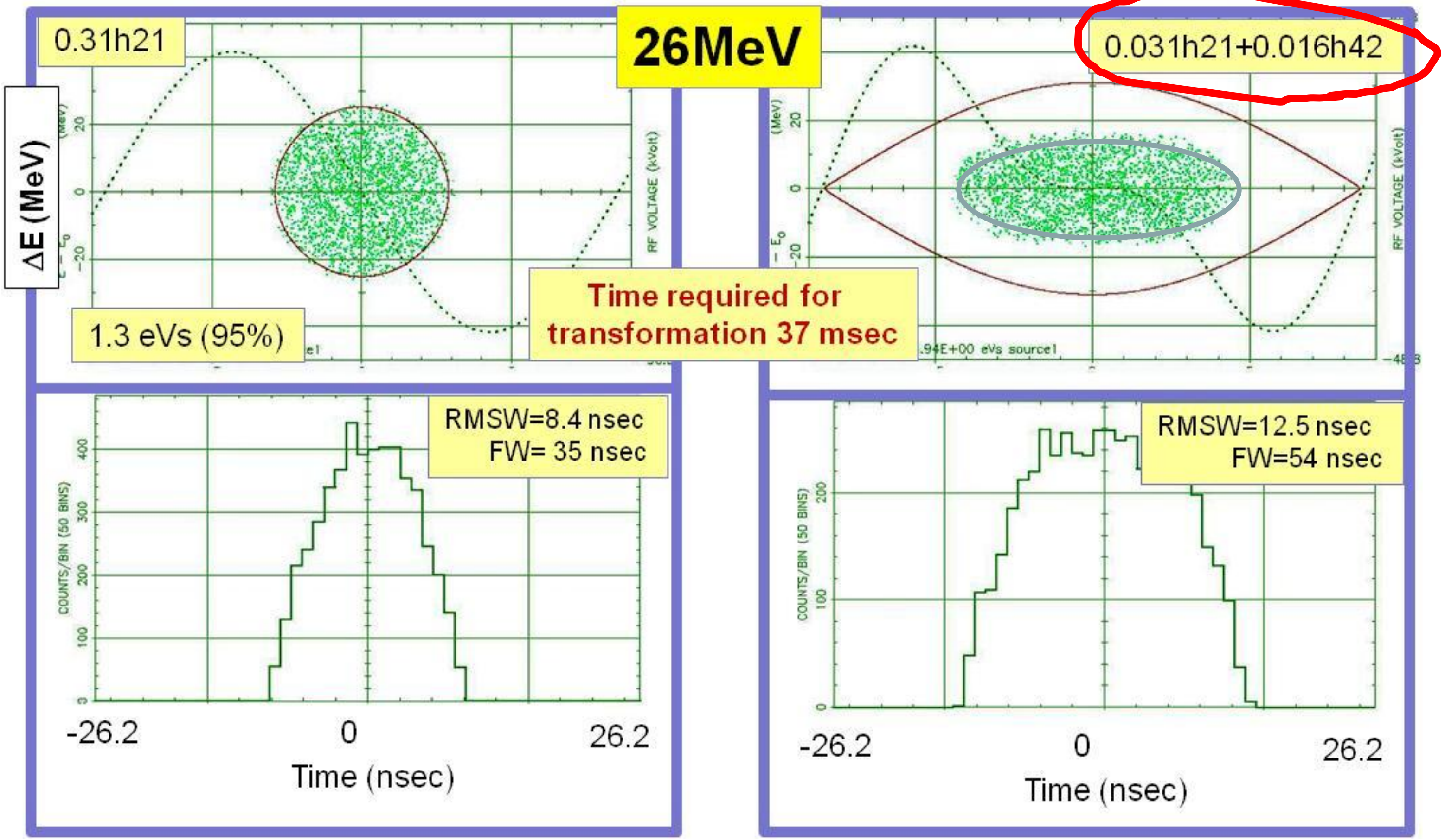
Recent Beam Studies on Flat Bunches with Double Harmonic RF

- Studies in PS
  - November 2008
    - LHC-25 cycle, Flat Bunch at 26 GeV
    - Beam Intensity: ~8.42E12 ← Equivalent LHC nominal Intensity
    - Bunch Emittance:~1.4 eVs ← Nominal emittance to LHC beam
    - RF with V(h=21)=31kV and V(h=42)=16kV ← V42/V21~0.5, 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

PS Studies

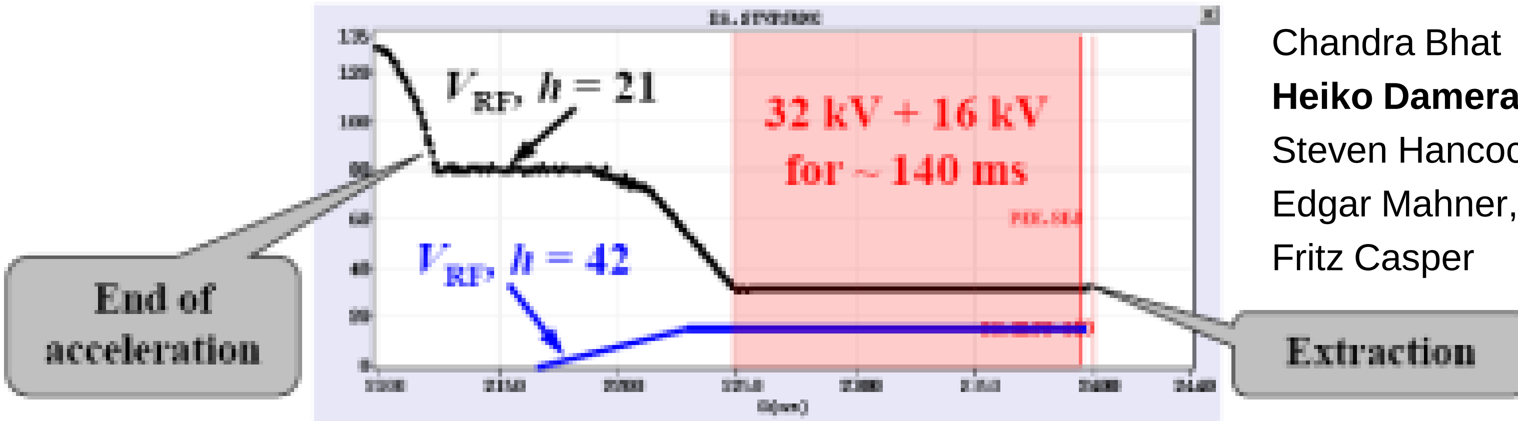
Evolution of RMSW of Bunches in PS while Flattening



Expected:-- About 50% increase in RMSW from beginning of rf manipulation to the flattened bunch

PS Beam Studies using LHC25

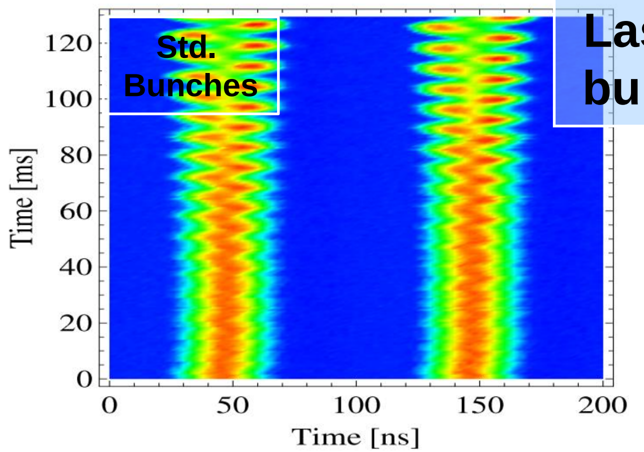
RF ramp used in the transforming nominal bunches to flat bunches



Chandra Bhat
Heiko Damerau,
Steven Hancock,
Edgar Mahner,
Fritz Casper

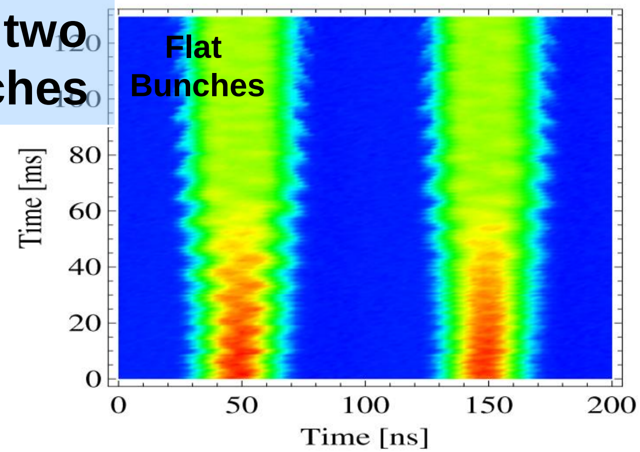
10 MHz RF system only, 32 kV at *h* = 21

h	Vrf
21	32kV
42	0



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

Last two bunches



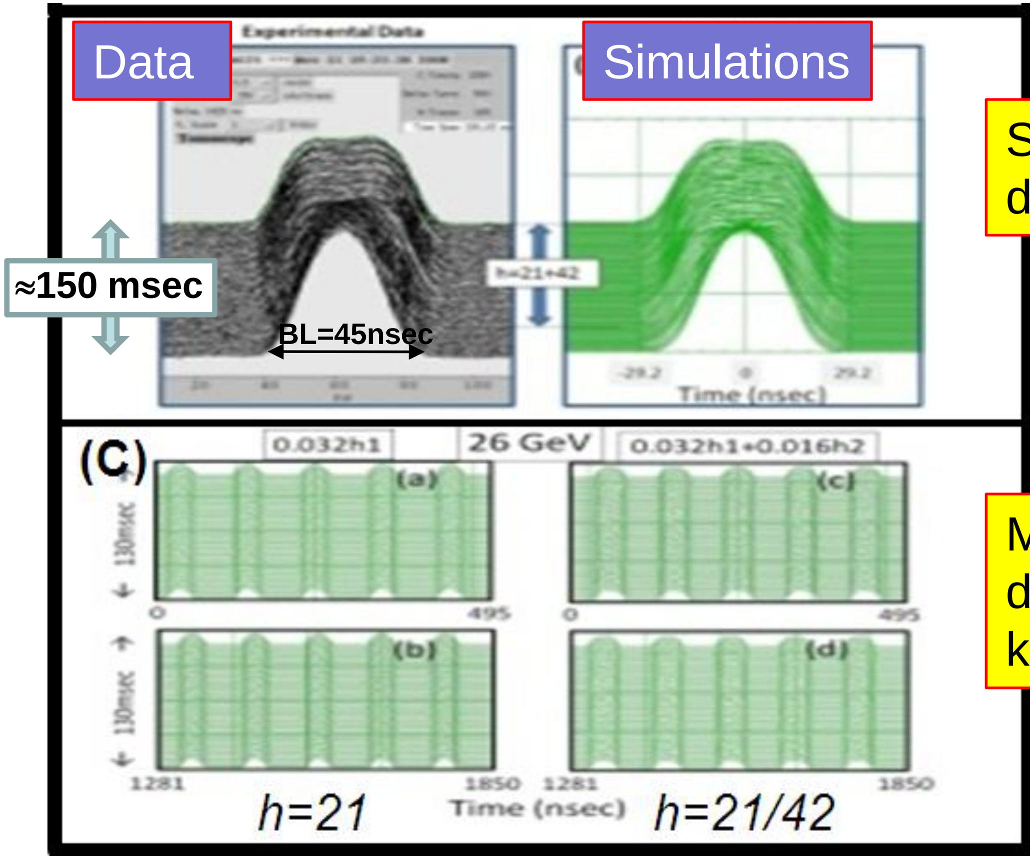
h	Vrf
21	32kV
42	16kV

LE(4σ)= 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

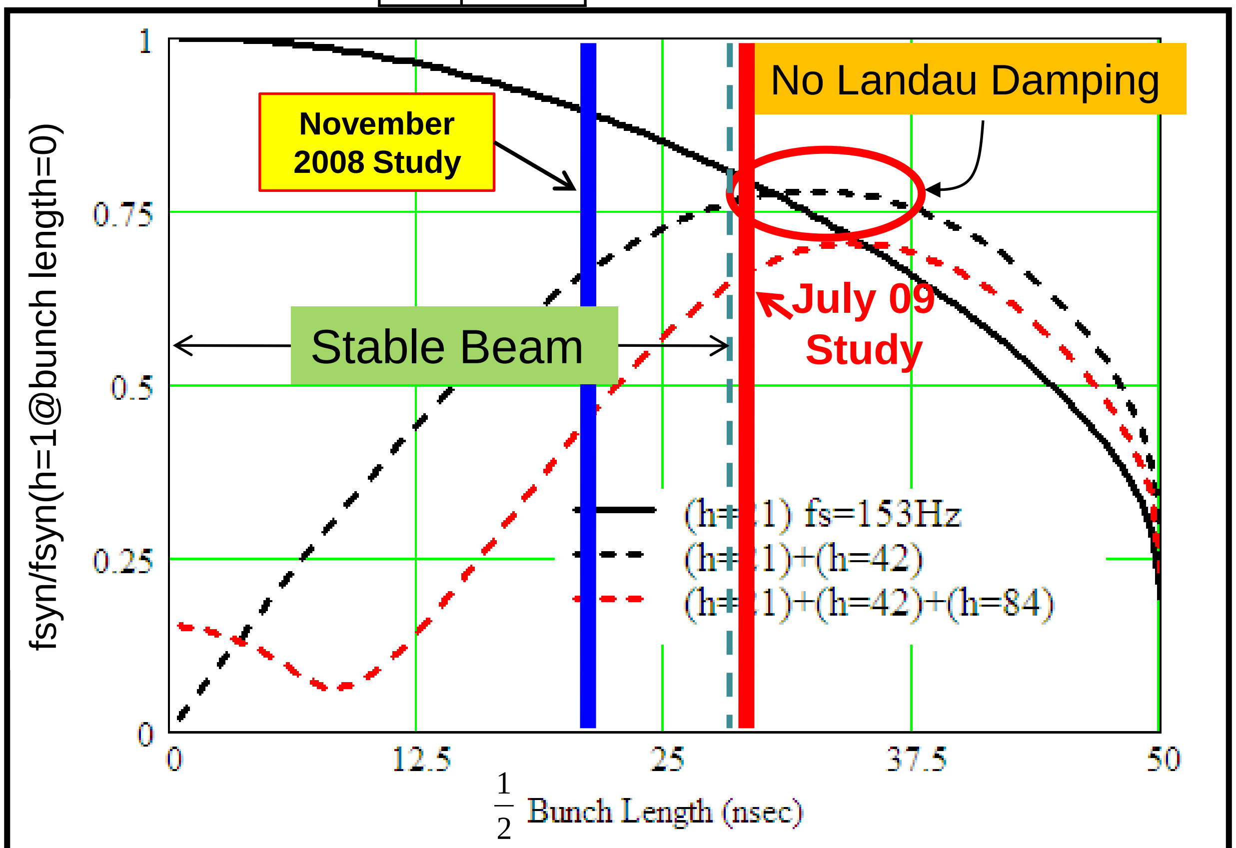
Multi-Particle Beam dynamics Simulations with known cavity impedances

PAC2009 Vancouver

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

h	Vrf
21	32kV
42	16



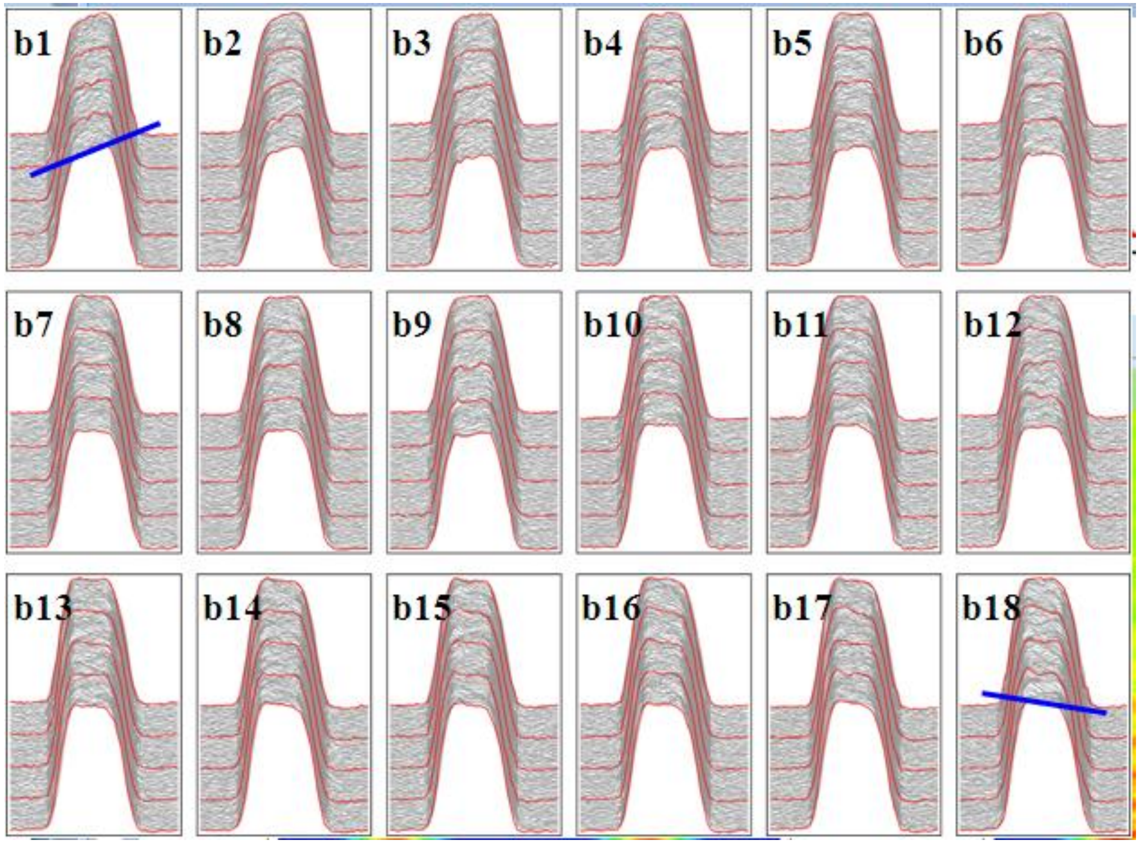
- ⇒ Large synchrotron frequency spread improves the stability.
- ⇒ If $\frac{df_s}{dt} = 0$ inside the bucket the particle in the vicinity of this region can become unstable against collective instabilities

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 11th Int. Conf. on HEA, ISR-Th-RF/80-26 (1980)

Flatness Along the Batch



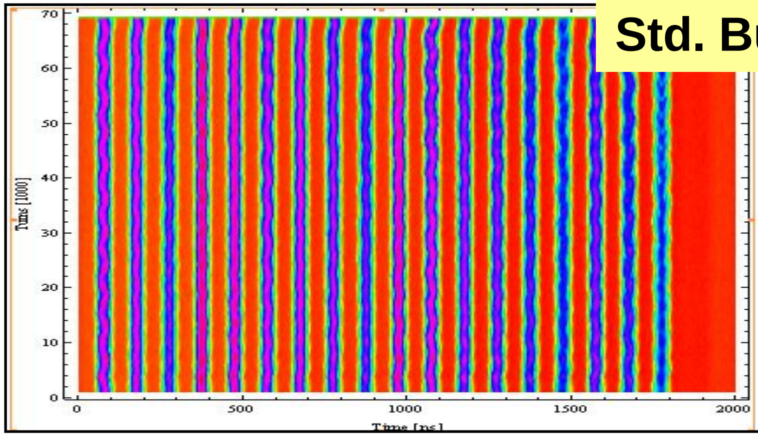
By a detailed study, Heiko concluded that a small phase errors (~ 2º) between h=21 and h=42 lead to significant asymmetry of bunches. Hence, we need transient beam loading compensation.

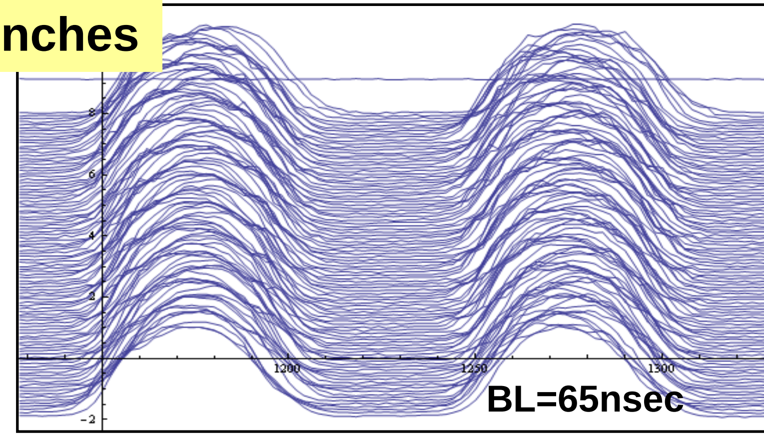
Samples from the July Studies in the PS:

A first look

Beam (4σ) Emittance = 1.45 eVs, Batch intensity=924E10

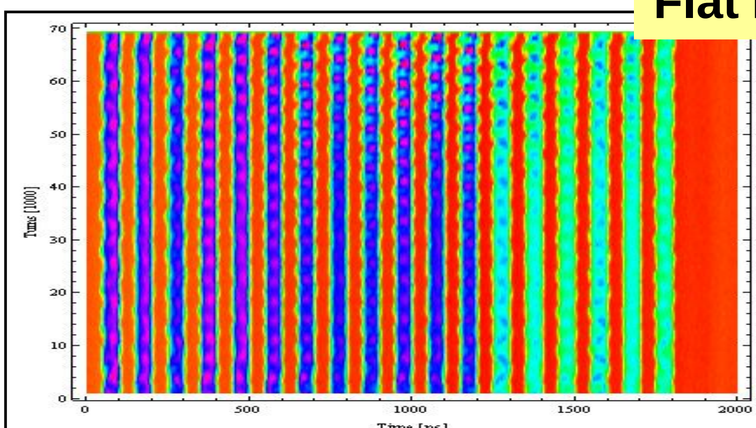
Std. Bunches

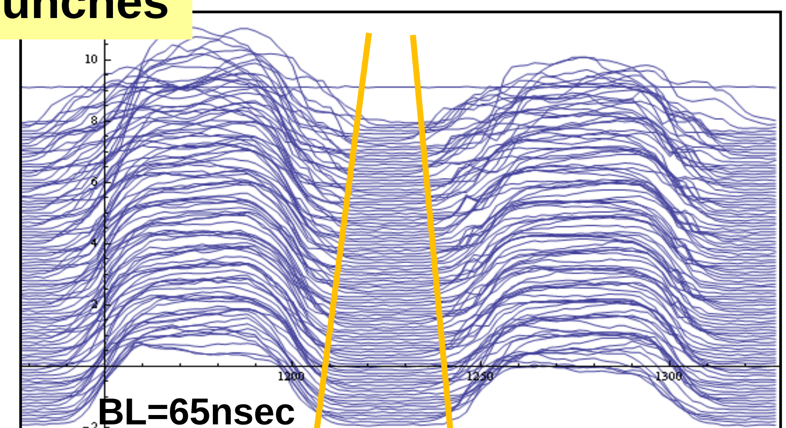




h	Vrf
21	10kV
42	0kV

Flat Bunches



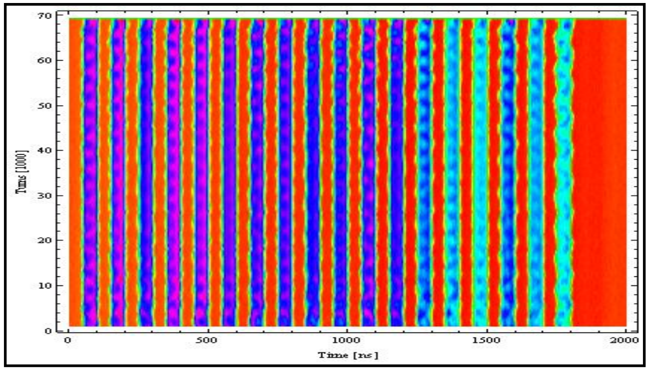


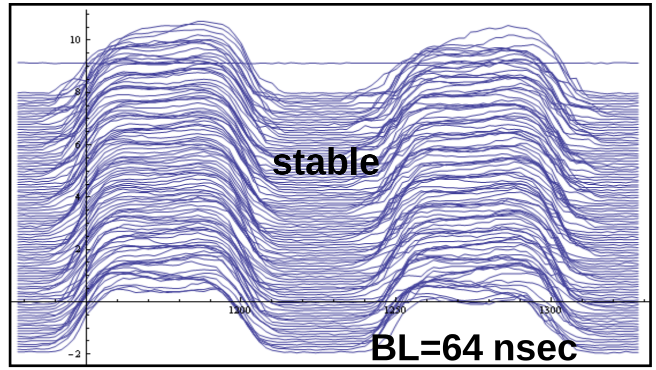
h	Vrf
21	10kV
42	5kV

Beam became unstable near the end of the cycle

July Studies in the PS: A first look (cont.)

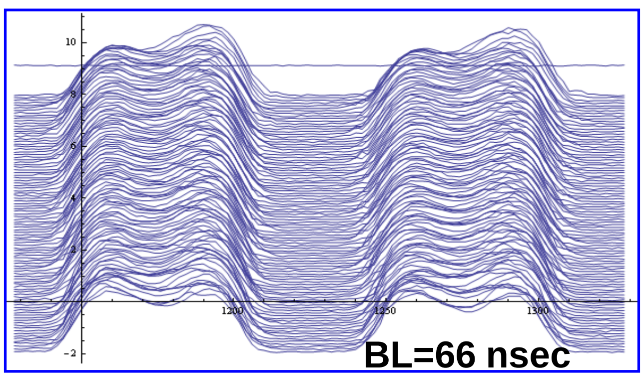
2009-07-14_LHC25_FlatTop_10kVh21_6kVh42_cb_18b_b



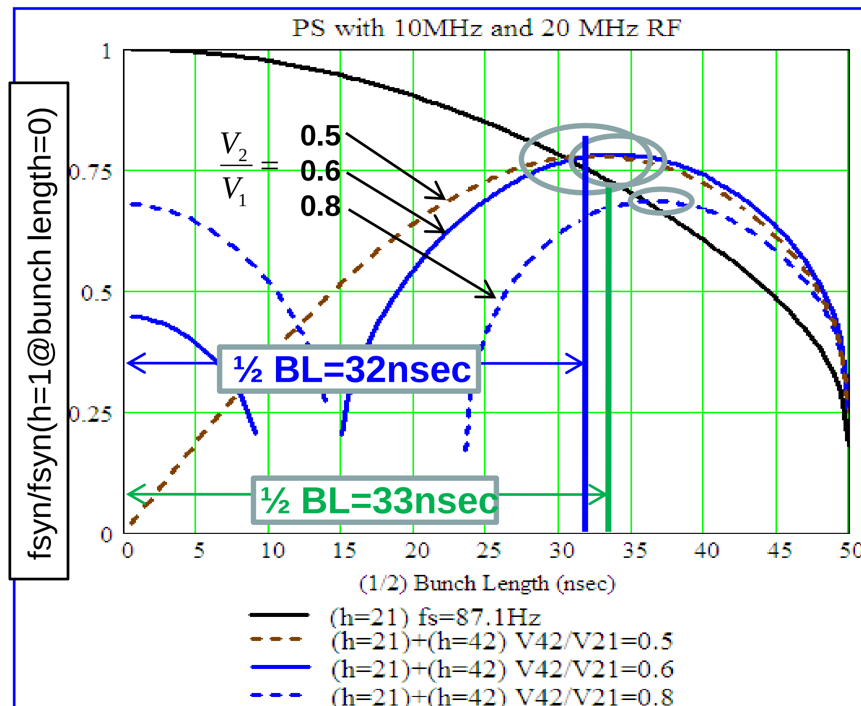


h	Vrf
21	10kV
42	6kV

h	Vrf
21	10kV
42	8kV



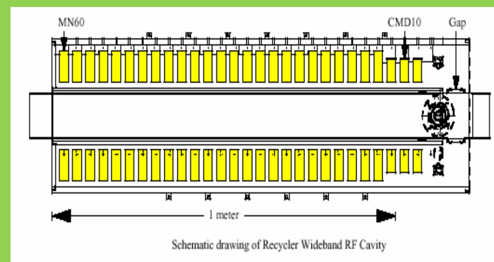
Beam is more stable

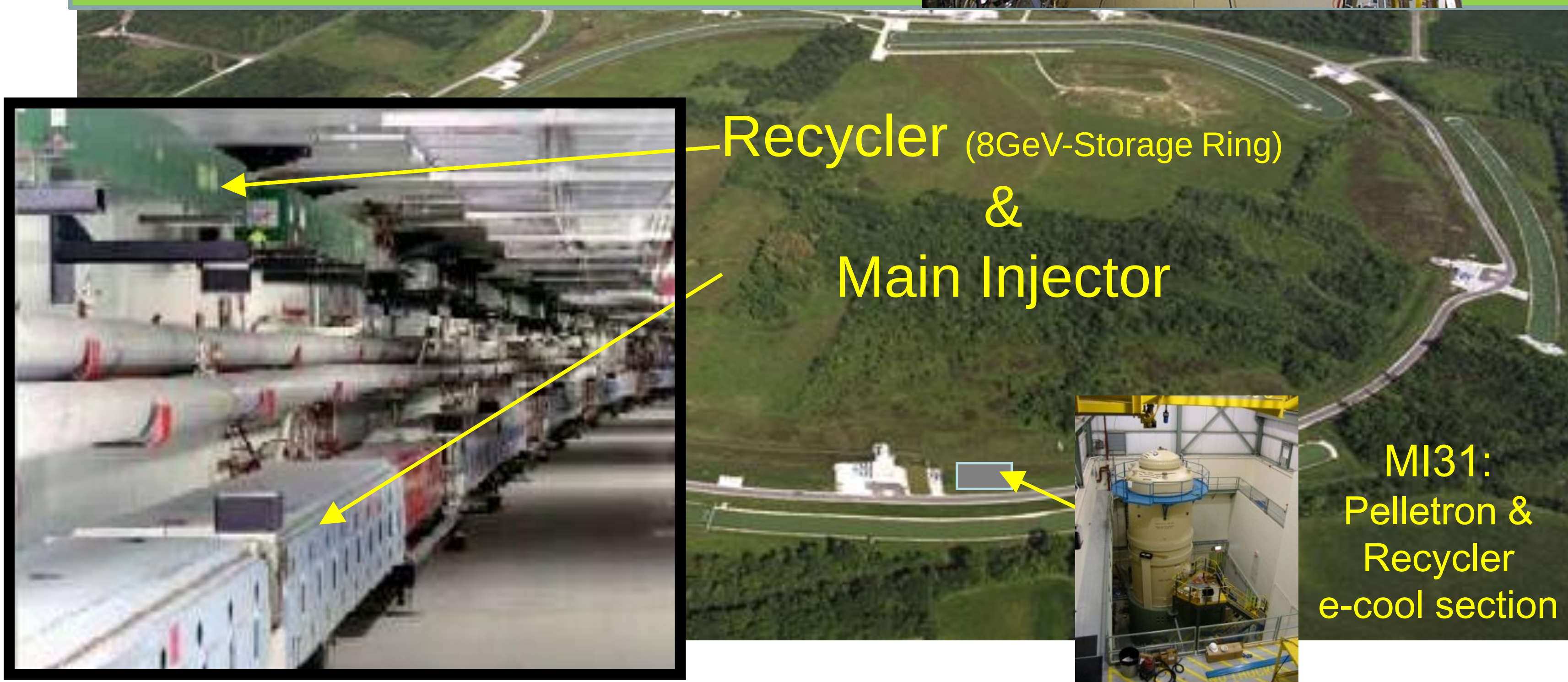


Flat Bunches at the Fermilab Recycler

Fermilab Accelerator Complex

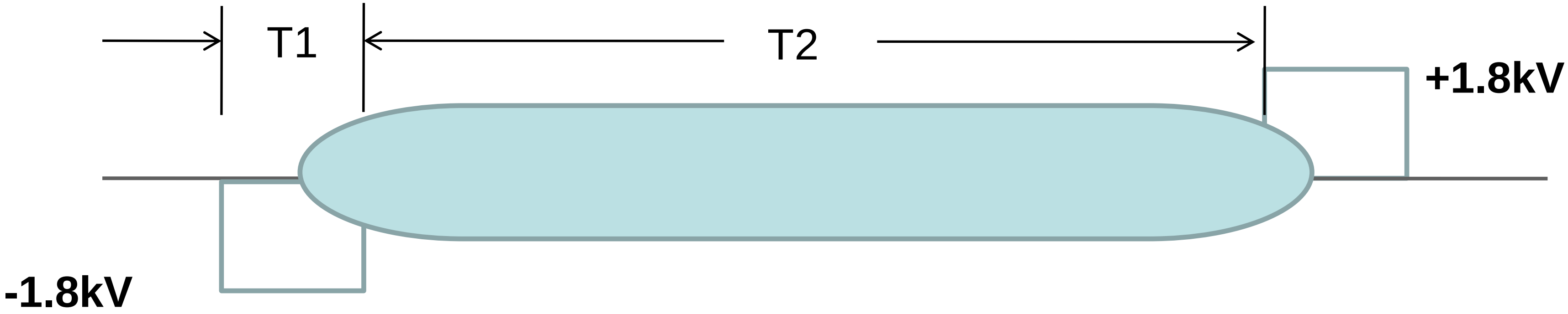
Recycler
Broad-band RF
Cavities
#of Cavities=4
Rs~50Ω
10kHz-100MHz

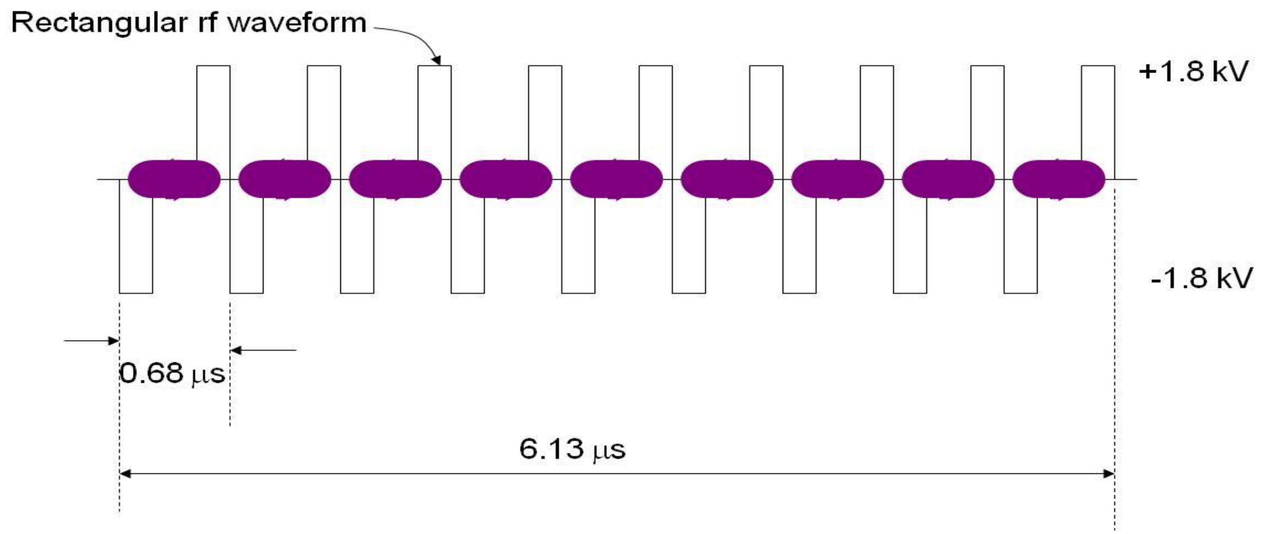




Flat Bunches in the Recycler

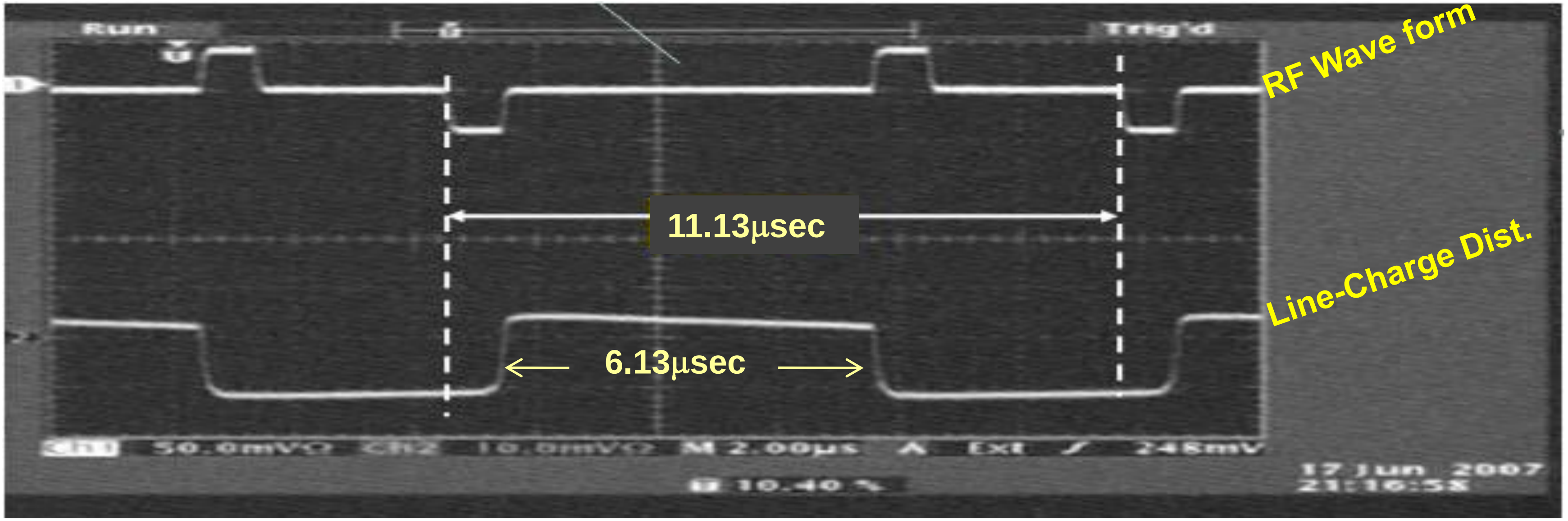
Schematic of the RF profiles for the flat beam in the RR



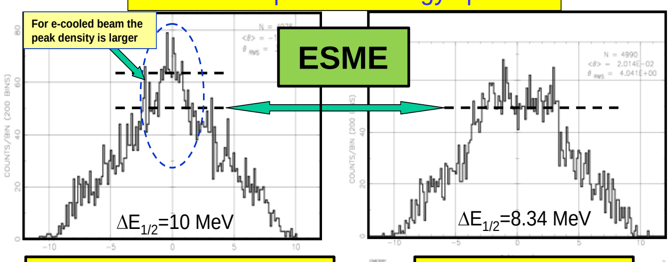


or Flat bunches of any length <~11 μsec

Typical Flat Bunches in the Recycler (Recent)

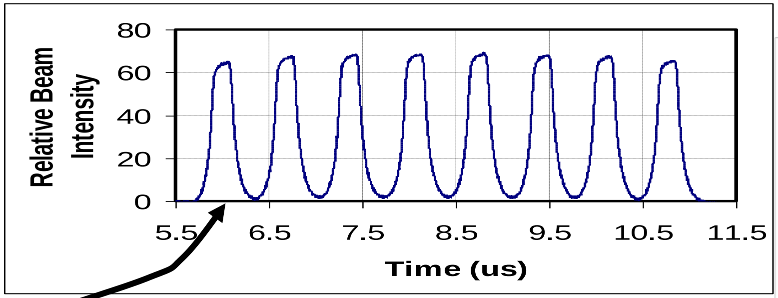


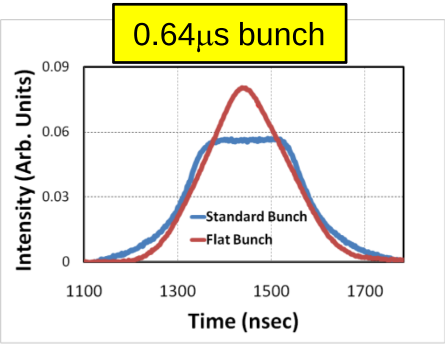
~ 25% drop in peak intensity
~ 15% drop in rms energy spread

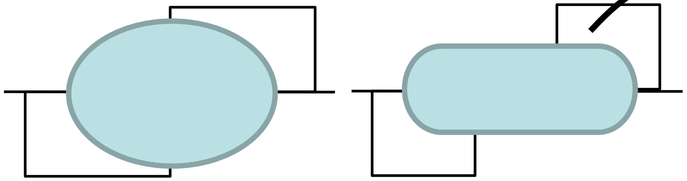


Standard Bunch

Flat Bunch







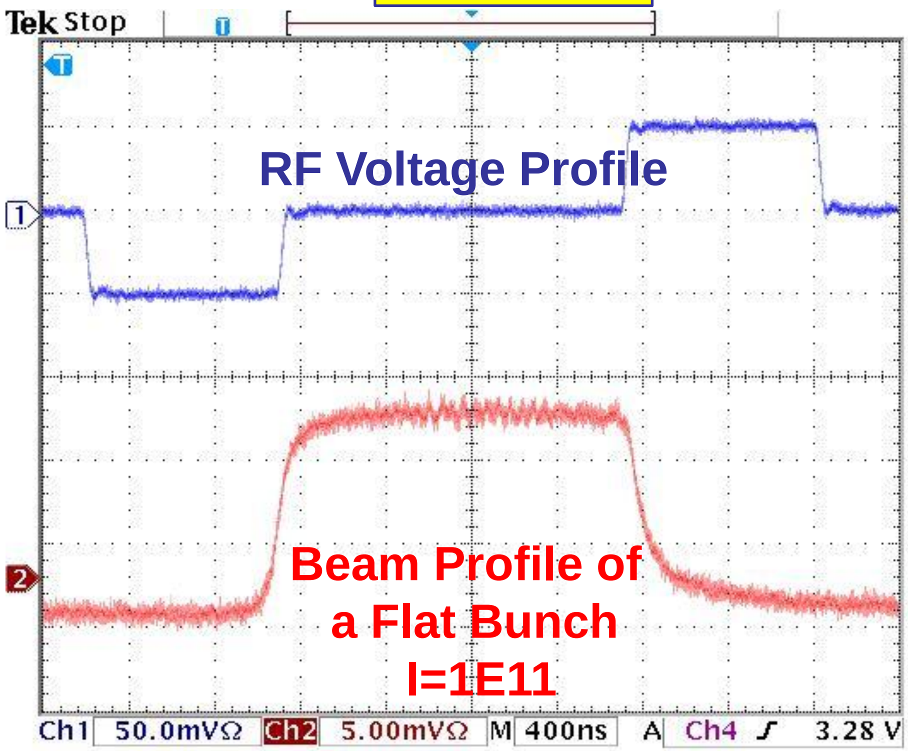
Experiment:

≈35% drop in peak intensity

≈25% drop in beam energy spread with flat bunches

Removal of the Distortion of the Flat Bunches, the 1st Attempt

After 2002



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

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

Potential Well Distortion in High Energy Storage Rings

The measured line charge distribution of the electron bunch was well explained as a solution to Haissinski Equation which states that in the presence of a **pure resistive impedance, *R*$_s$**, the linear density is given by,

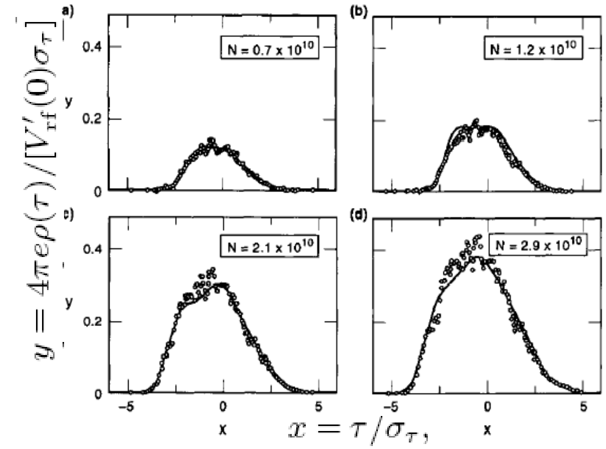
$$\rho(\tau) = \rho_0 \exp\left[-\frac{\tau^2}{2\sigma_\tau^2} + \alpha_R N \int_0^\tau \rho(\tau')d\tau' \right]$$

τ is arrival time,
+ve for head,
-ve for tail

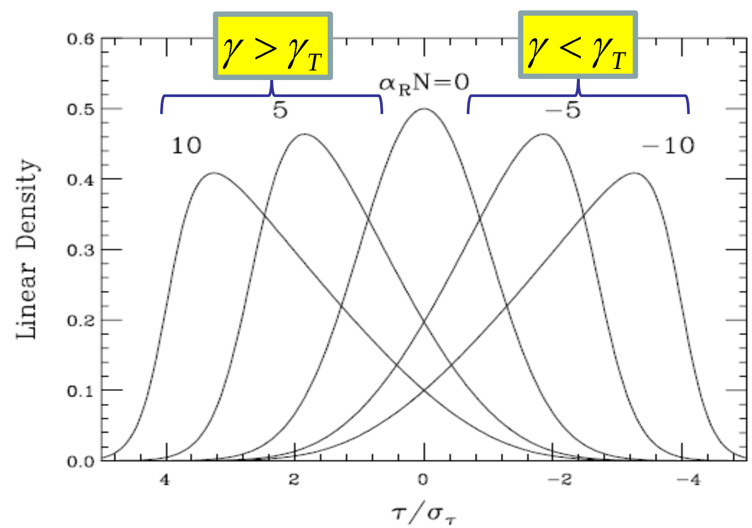
$$\text{Where } \alpha_R = \frac{e^2\beta^2 E_0 R_s}{\eta T_0 \sigma_E^2}$$

1st term in the exponent represents rf potential and is even in τ

2nd term gives perturbation to the rf potential but odd in τ ← giving rise to asymmetry, resulting in bunch lengthening or shortening.

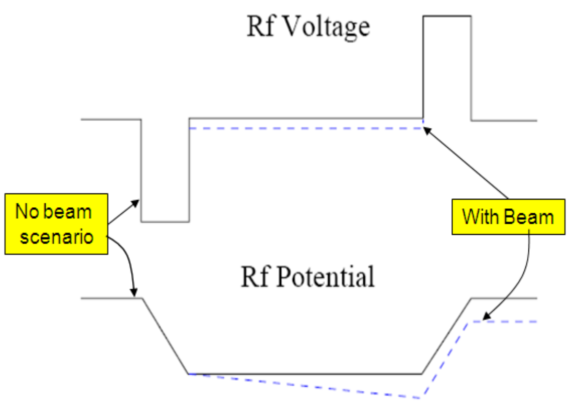


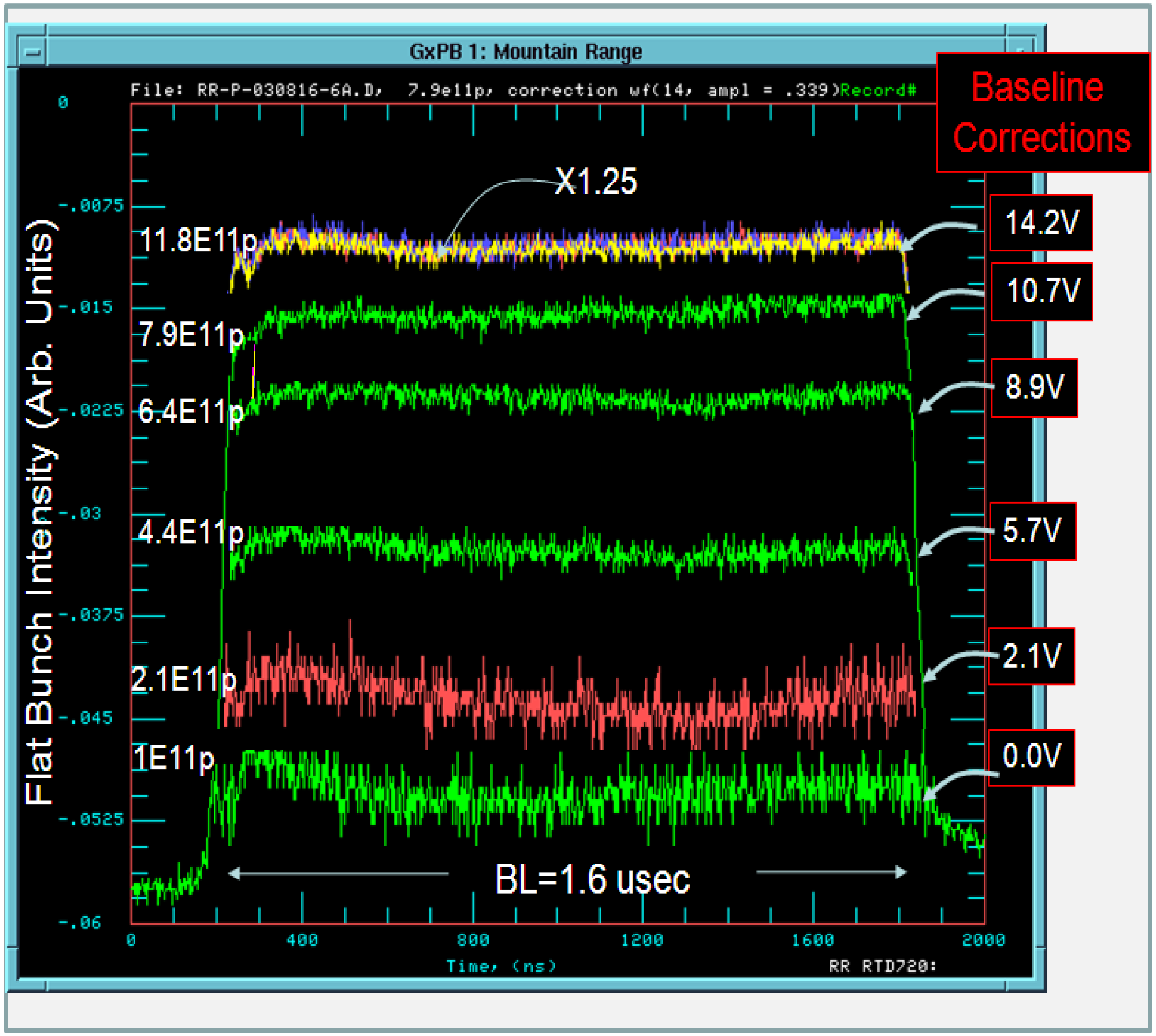
K.L.F. Bane & R.D. Ruth, PAC1989, 789 (SLAC SLC)
(beam is going from left to right)



Recycler Beam Loading Effects:
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, Bill Ng)

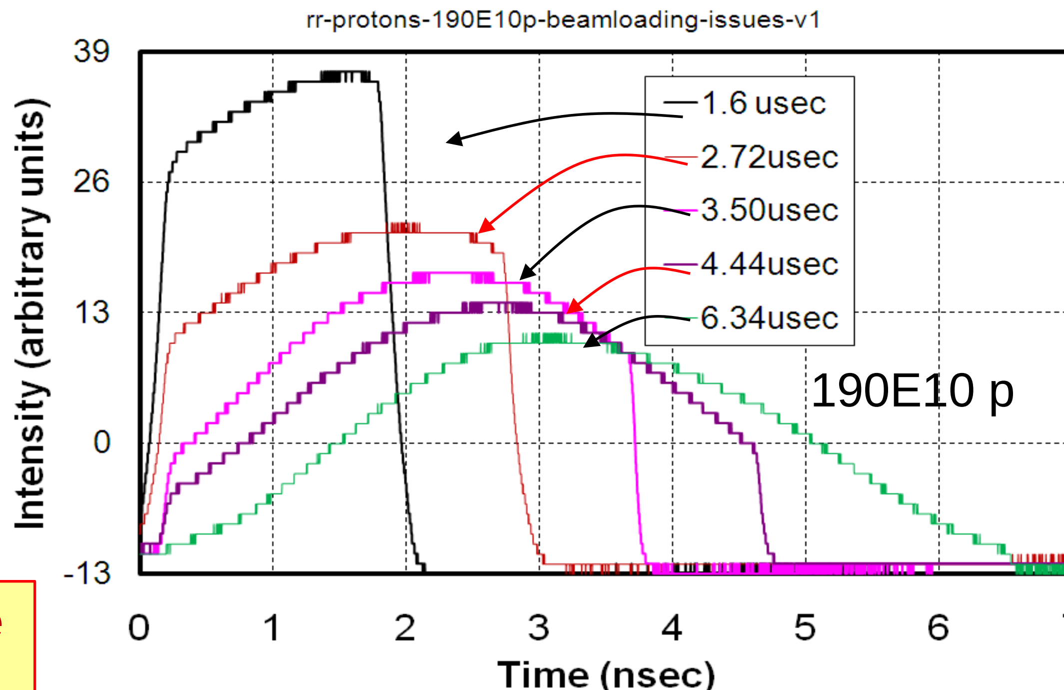




Bhat and Ng, Proc. 30th Adv. ICFA Beam Dynamics. Workshop, 2003, Stanford, Oct. 2003

Recycler Beam Loading Effect:
Function of Bunch Length

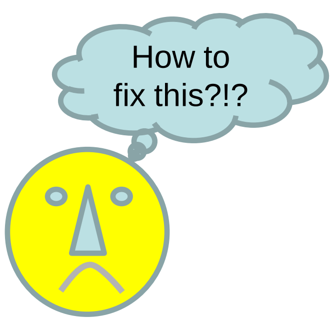
By varying the bunch length on the same beam showed that the solution to the problem requires further improvements.

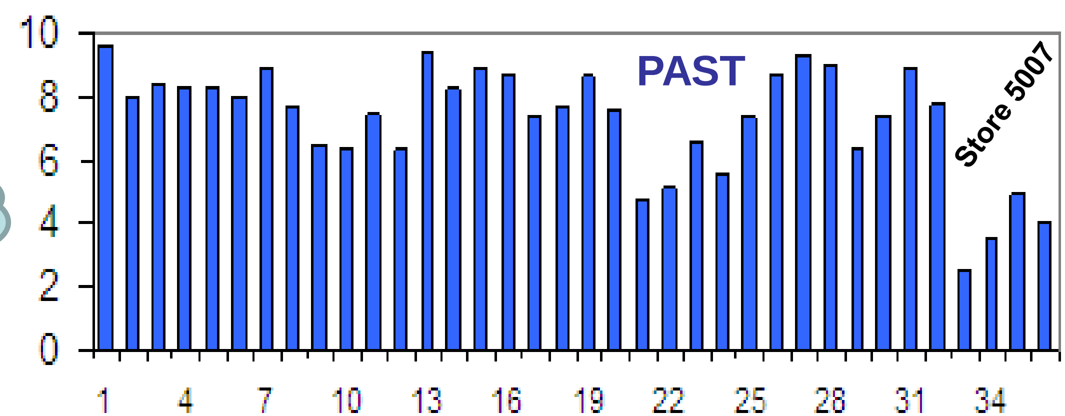


Consequence of this issue on the Tevatron Collider Program was

Bunch to bunch Luminosity variation >200%

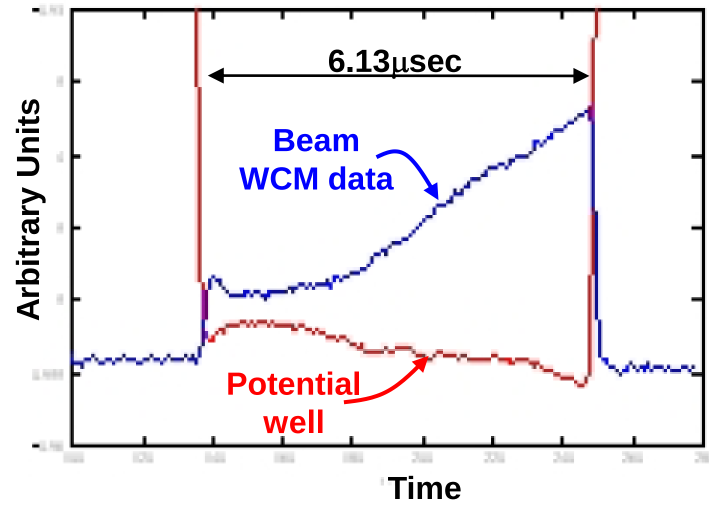
Goal: <15%





RF Imperfections and FPGA based Adaptive Corrections

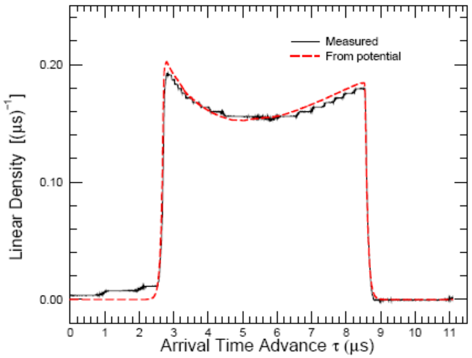
The inverse of the potential well and beam wall current monitor data are found to be strongly correlated ← **Indicated necessity of rf corrections beyond the linear corrections**



To understand this behavior analyses have been made using **Haissinski equation**, assuming ΔE distribution to be Gaussian,

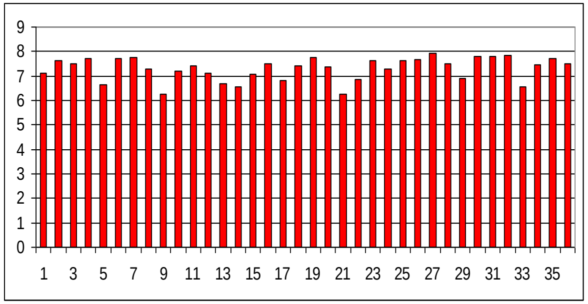
$$\rho(\tau)-\rho(0)=\frac{|e|\beta^2 E_0}{|\eta| T_0 \sigma_E^2}\,\rho(0)\int_0^{\tau} V_{eff}(\tau')\,d\tau'$$

where $V_{eff}(\tau')$ =measured fan-back voltage



Identification of RF Imperfections

J. Crisp et al HB2006 (2006) 244

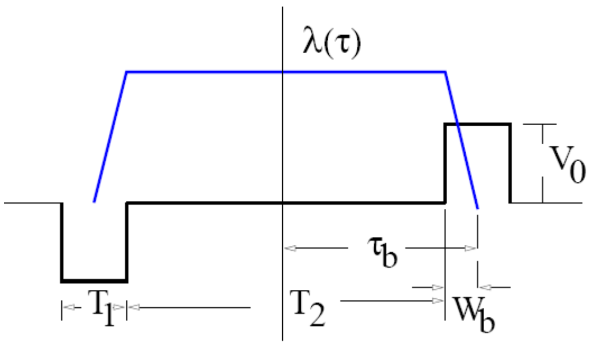


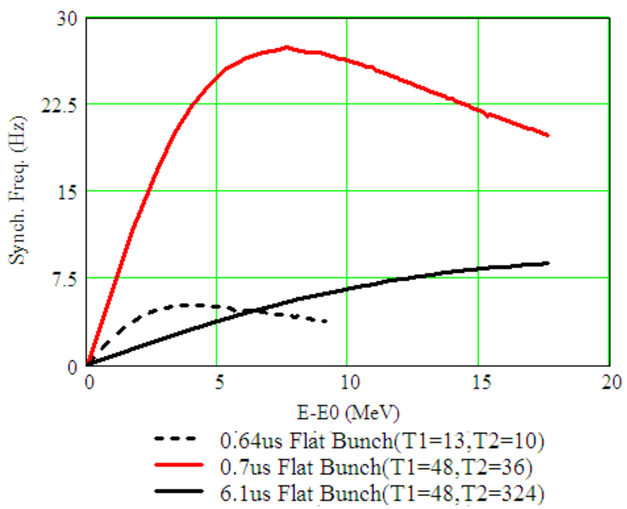
Bunch-by-bunch Luminosity variation ~15% HEP Experimenters are Happy

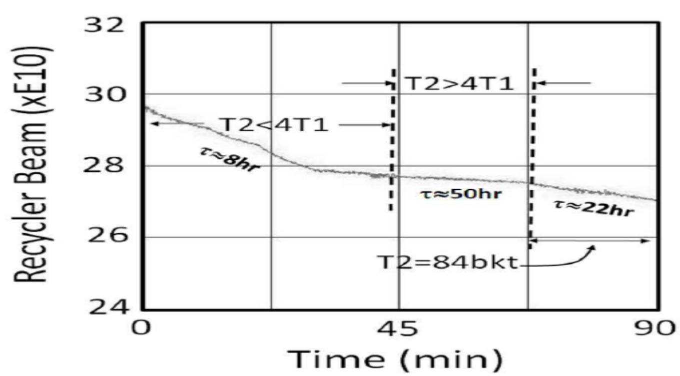
Longitudinal Stability of Recycler Bunches: Threshold for loss of Landau Damping

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

- We have examined the stability of intense beam in barrier buckets of the Recycler. We include space charge effect in this model to predict the bunch intensity at which Landau damping would be lost.



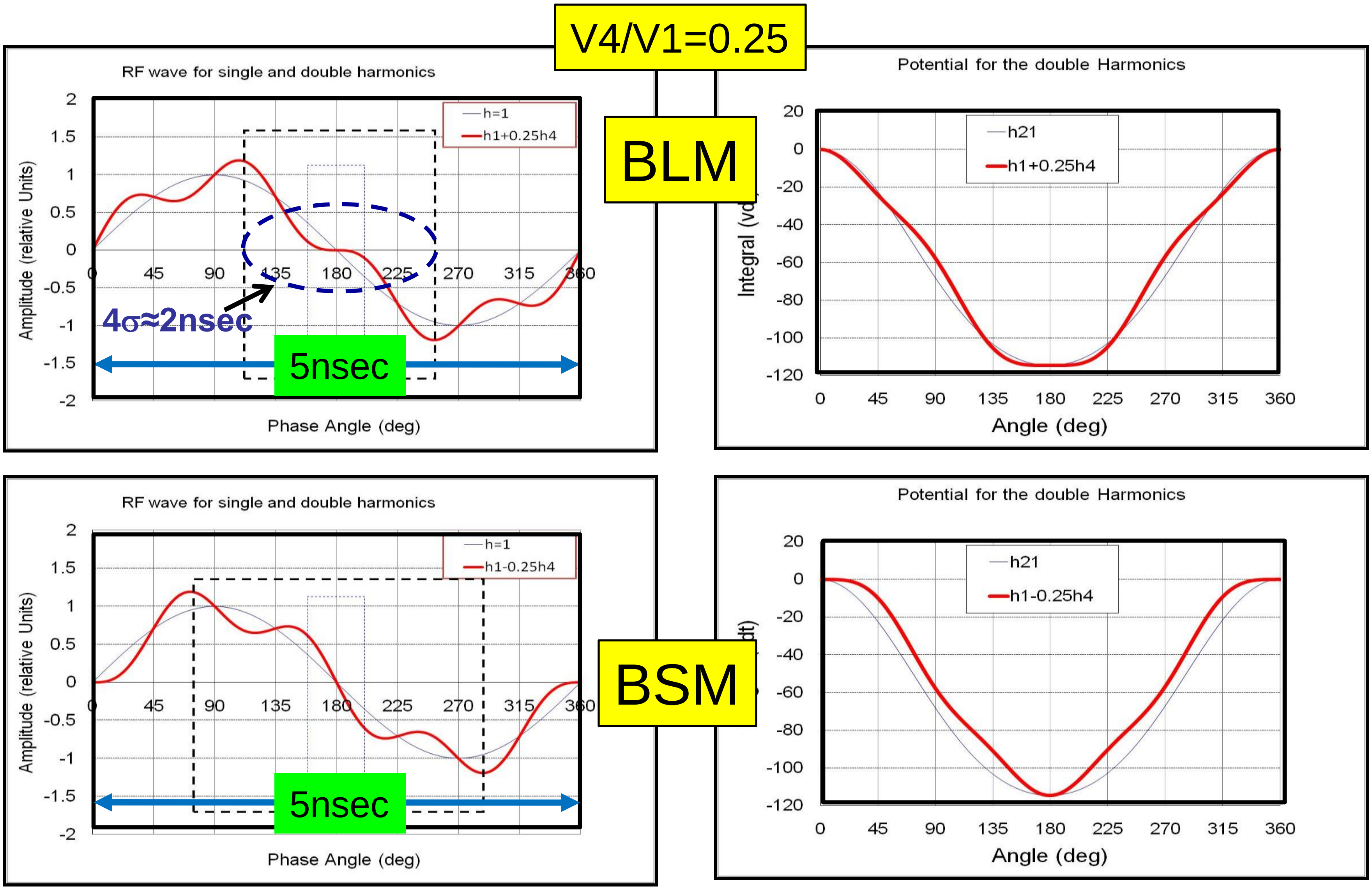




Beam Studies in the SPS

Double RF used in SPS Studies

(wave forms & Integral(Vdt)



Chandra Bhat

Prospects for the LHC

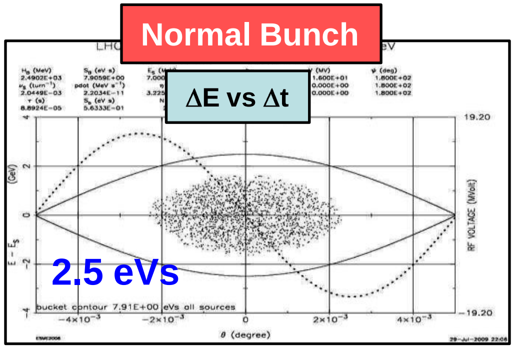
Flat Bunch Prospects for LHC

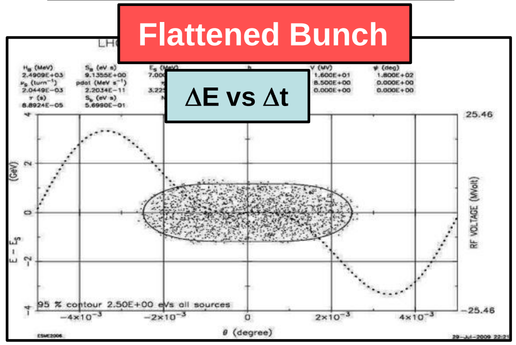
- Two scenarios for creating flat bunches at LHC are investigated
  - Flat Bunches creation at 450 GeV and acceleration
  - Flat Bunches at the Top energy
    - Using the 200 MHz (R. Losito et. al, EPAC2004, p956) and 400MHz RF systems in the Ring.
    - Using 400 MHz and 800 MHz RF ← **This gives 41 cm long flat bunches, BUT!?!**

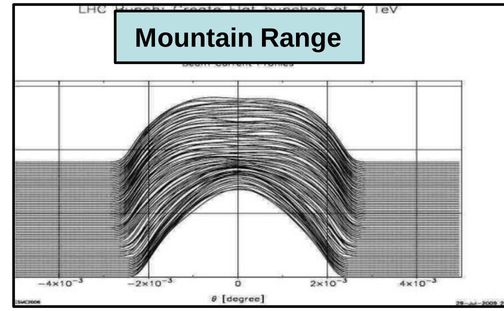
Bunch Flattening of the LHC Beam at 7 TeV
(ESME Simulations)

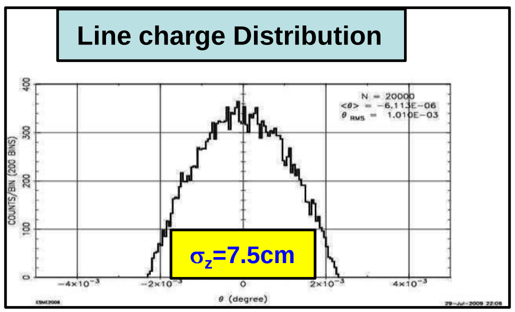
Vrf(400MHz)=16MV

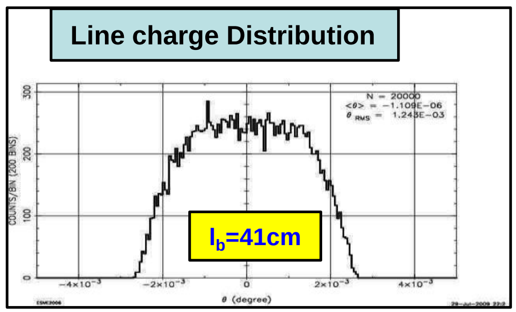
Vrf(400MHz)=16MV + Vrf(800MHz)=8.5MV

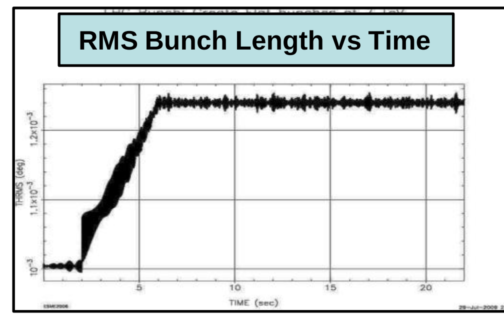


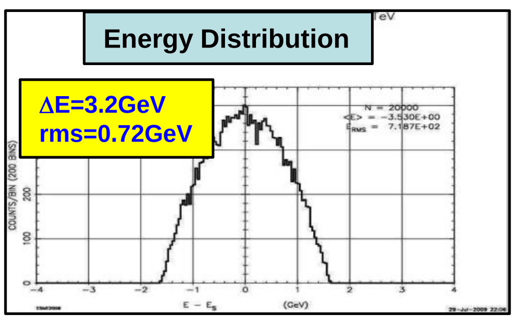


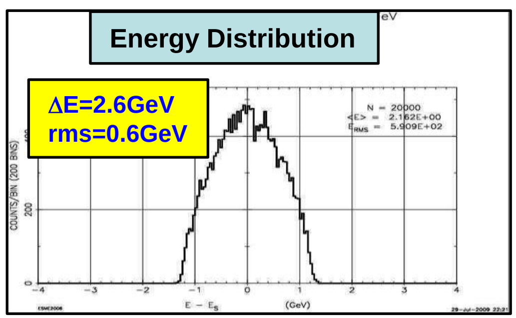


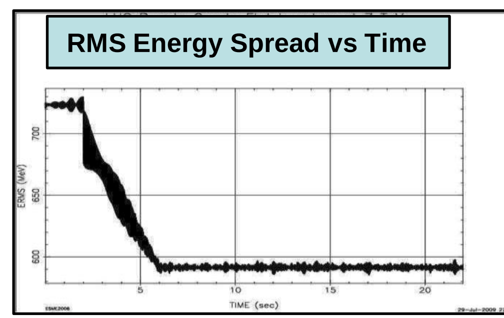










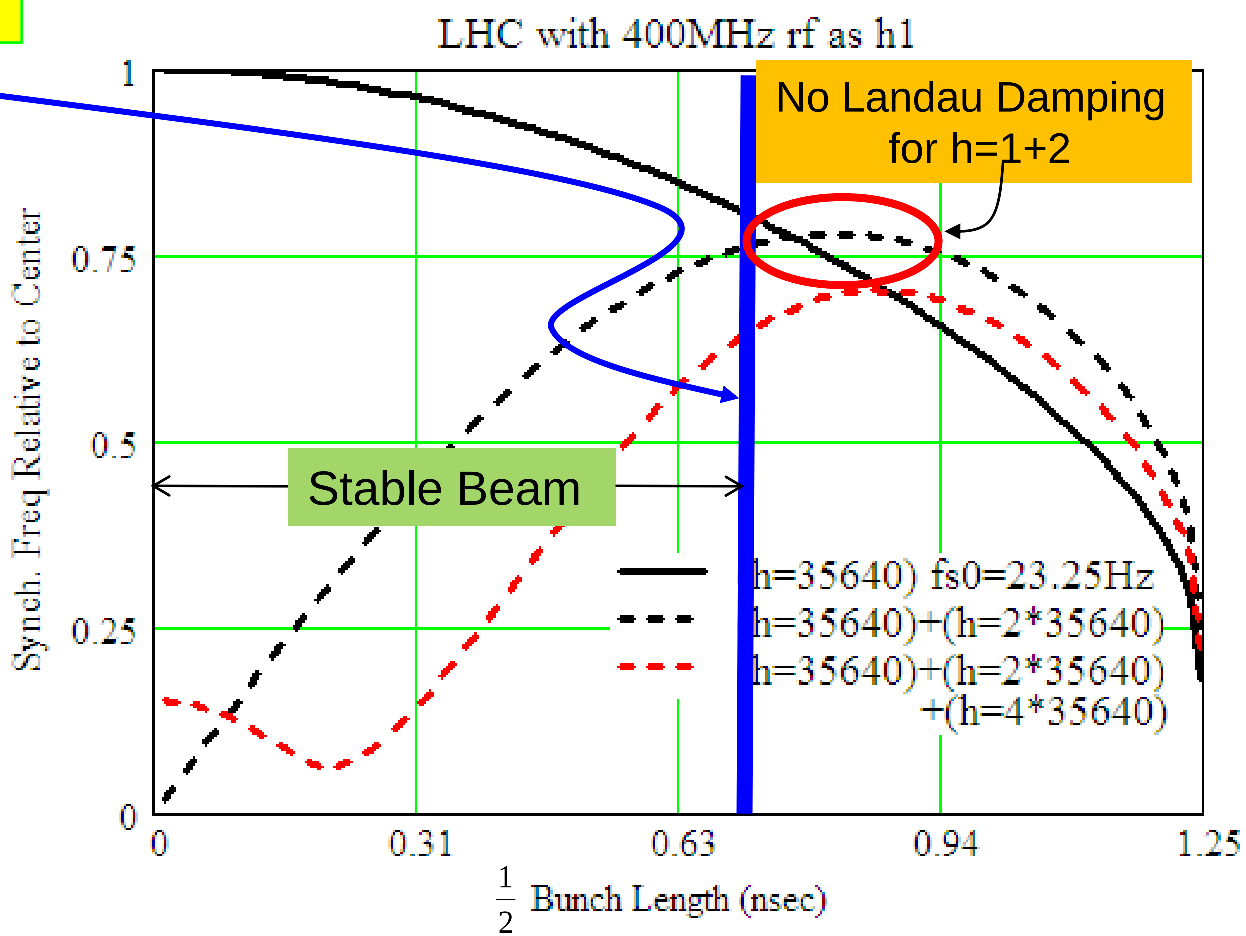


Acceptable Flat Bunches at LHC

with 400MHz+800MHz RF

LE=2.5eVs, Lb=41cm

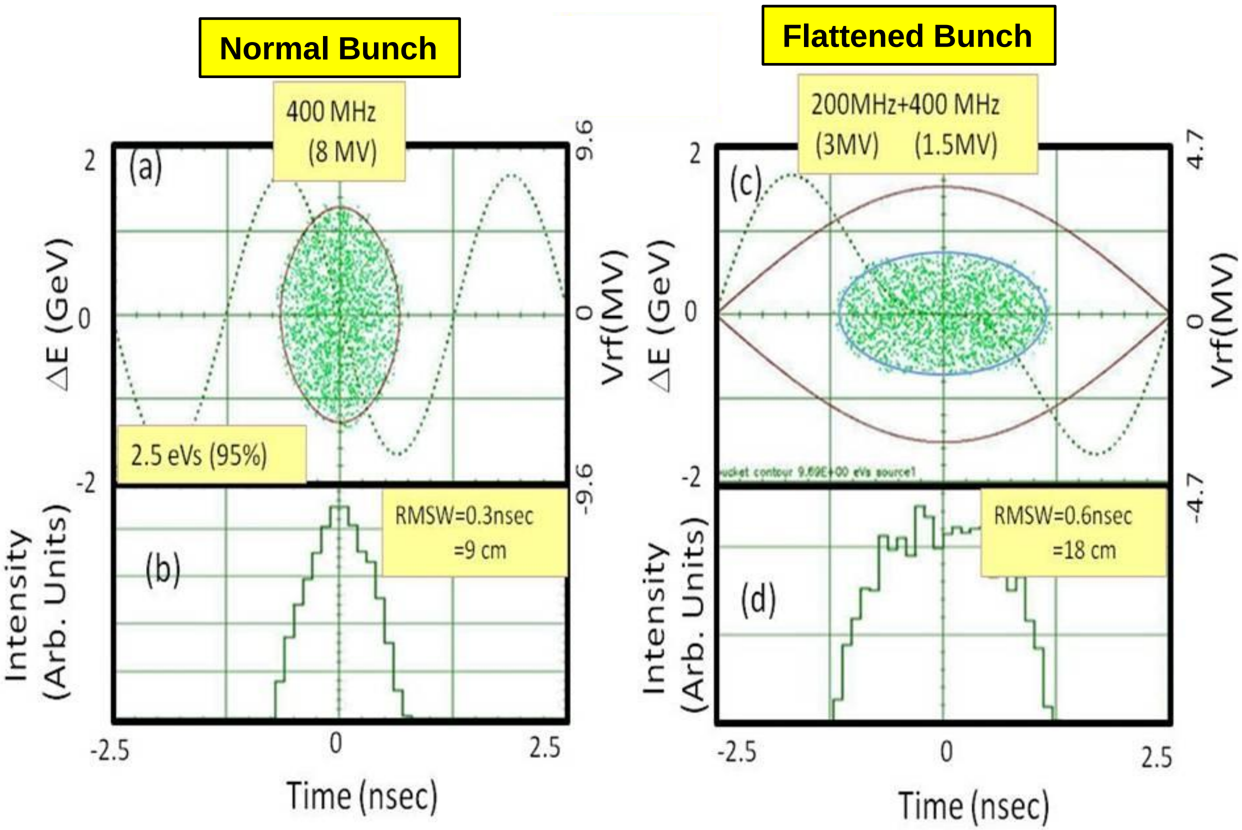
h	Vrf
35640	16MV
71280	8.5

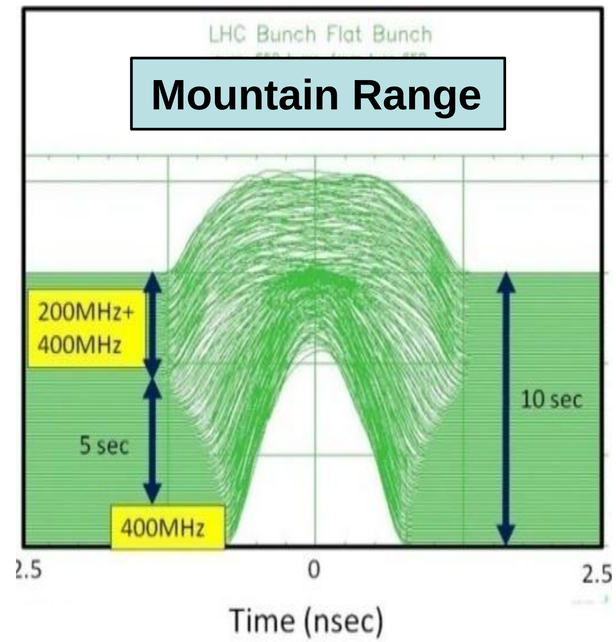


Conclusions:

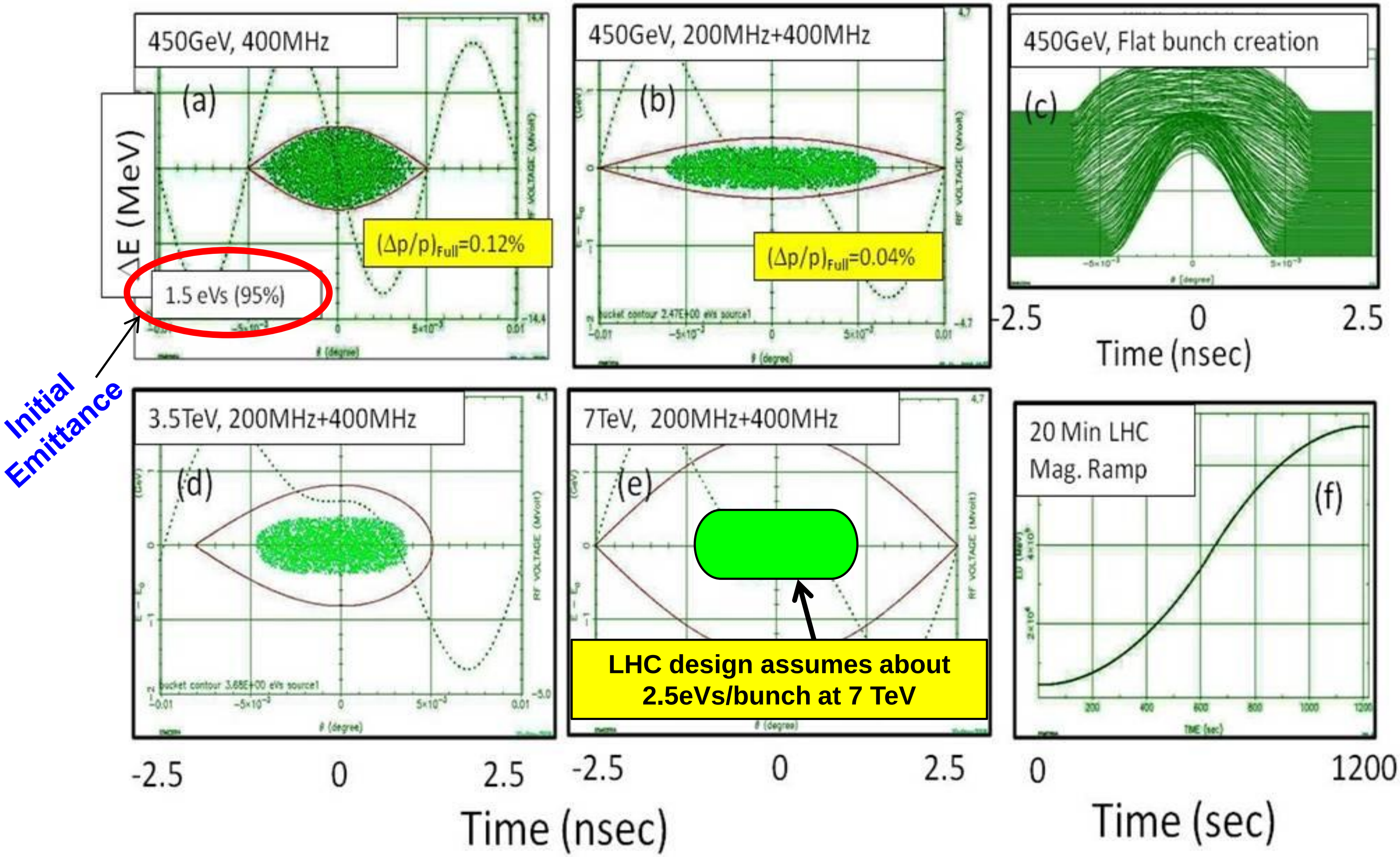
The 41 cm long flat bunches (2.5 eVs) with 400Mhz+800Mhz rf systems may be susceptible to beam instability.

Bunch Flattening of the LHC Beam at 7 TeV
with 400MHz and 200MHz RF systems





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

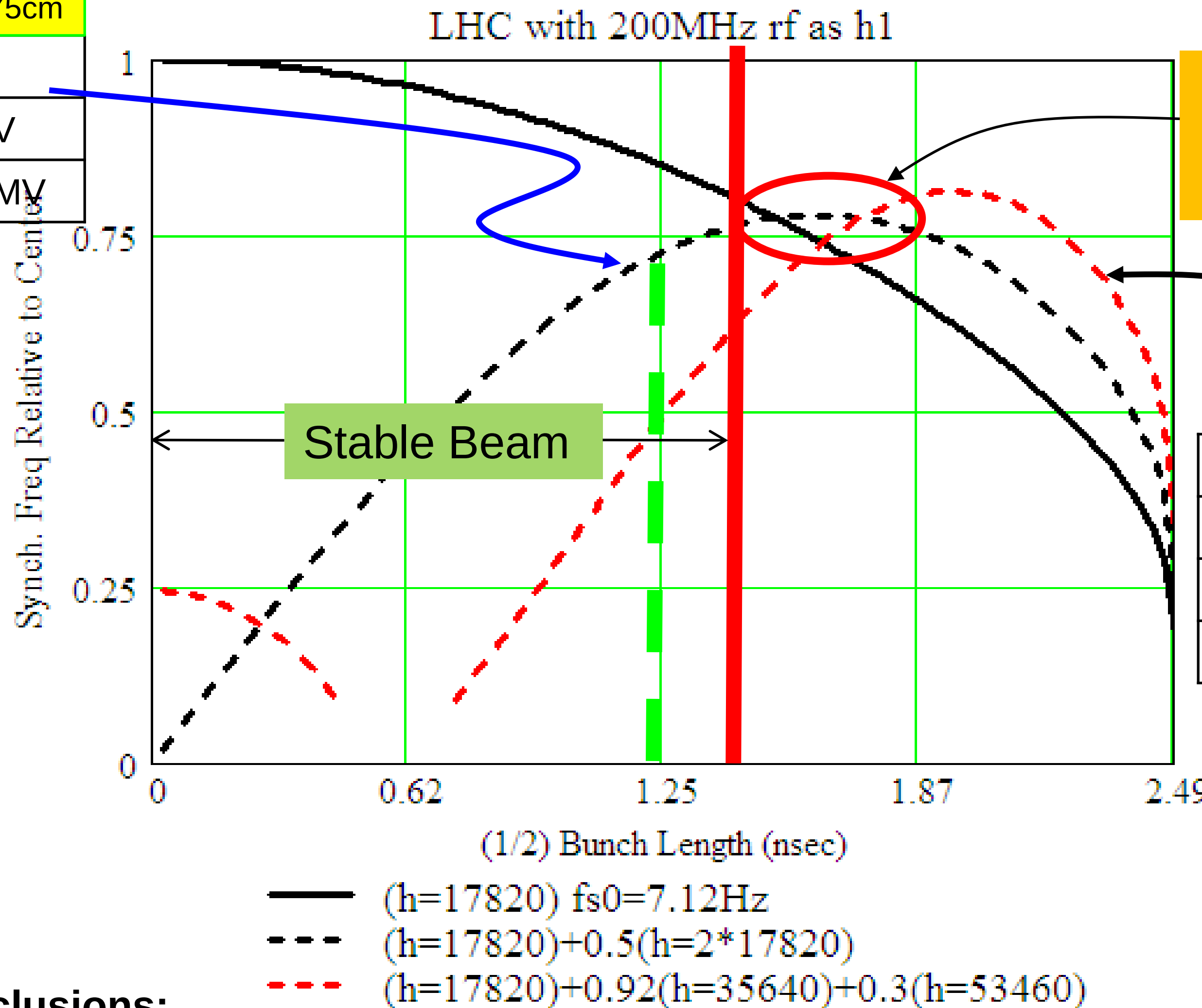


Acceptable Flat Bunches at LHC

with 200MHz+400MHz RF

LE=2.5eVs, Lb=75cm

h	Vrf
17820	3MV
35640	1.5MV



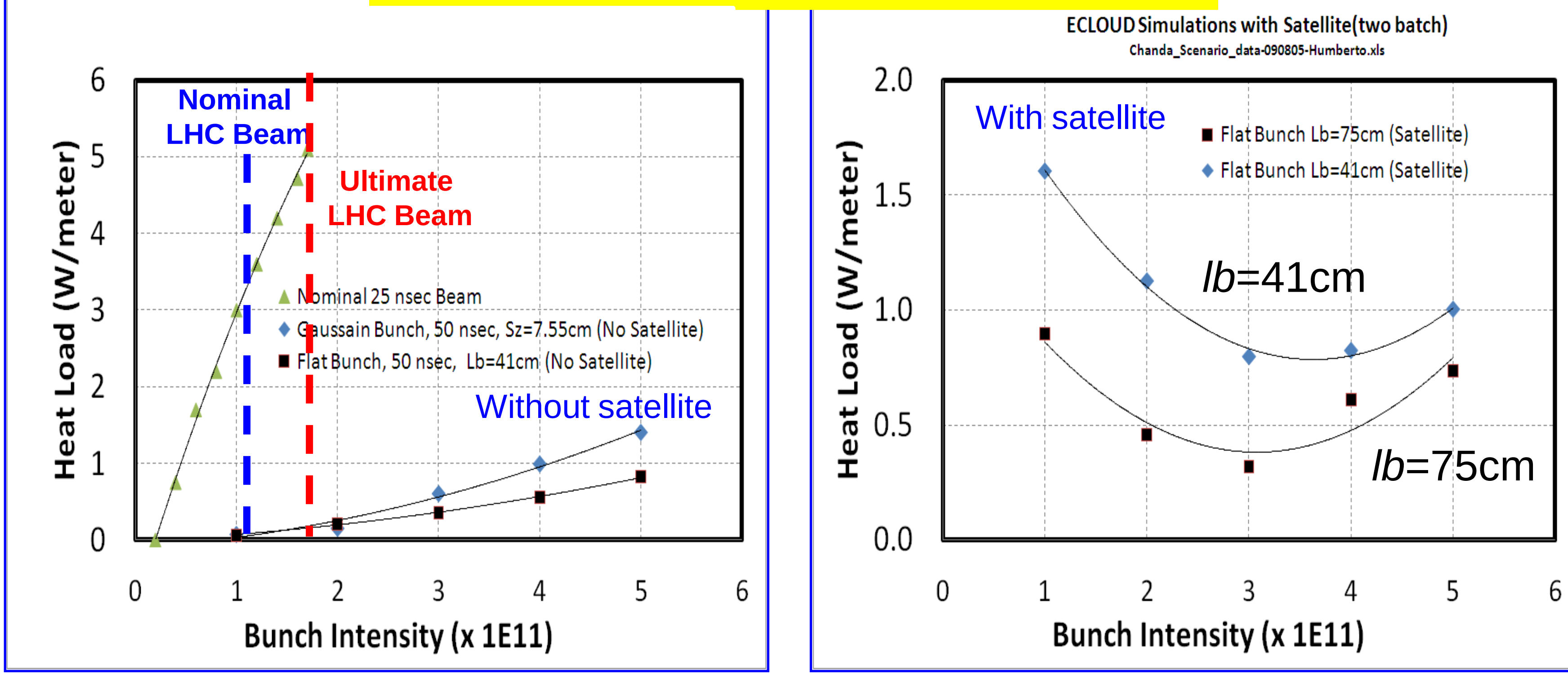
h	Vrf
17820	3MV
35640	2.76MV
53460	0.3MV

Conclusions:

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

ECLOUD Simulations
for Nominal and Flat bunches

Average Heat Load 2nd Batch



Humberto Maury Cuna, CINVESTAV, Mexico

Conclusions:

The estimated e-cloud effect with flat bunches is many times smaller than that with Gaussian bunches.

Summary and Conclusions

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

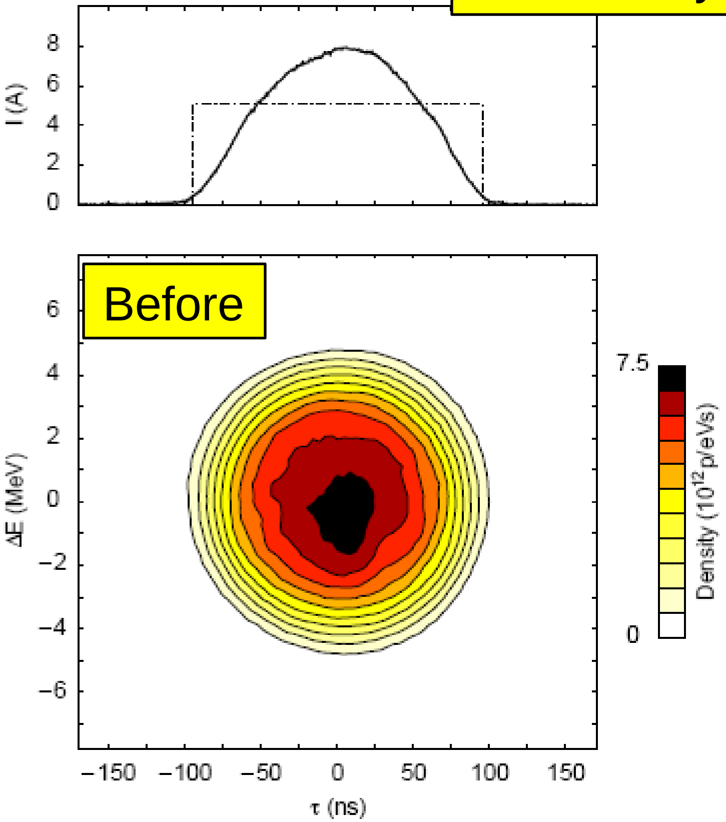
Flat bunch scenario for the LHC is a very promising path for the Luminosity upgrade.

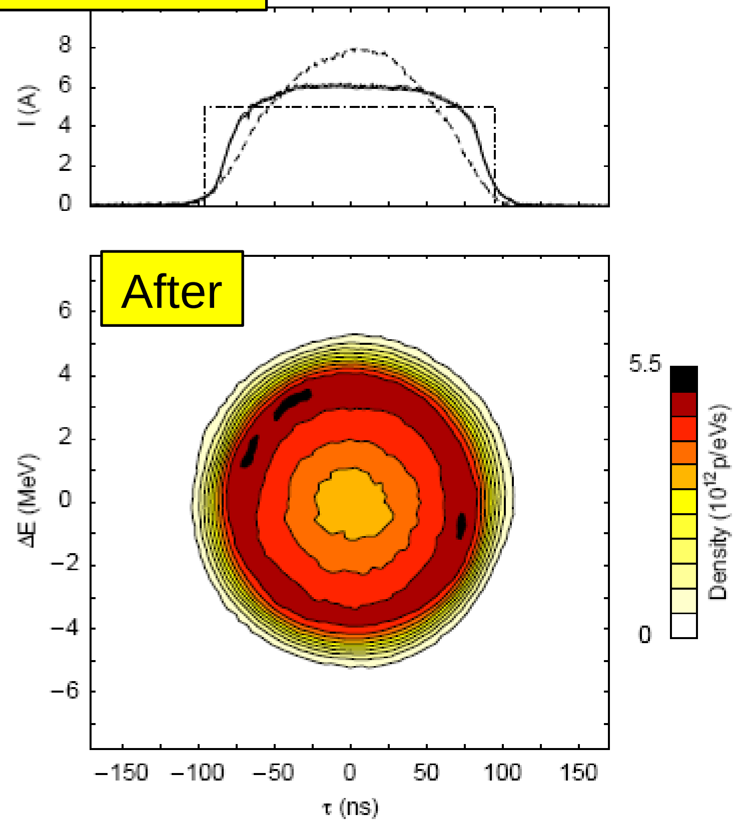
THANKS

Carli's Hollow Beam Technique
(EPAC2002, p233)
Experimental Demonstration at CERN PSB

Beam Tomography : Before and After redistribution of phase-space

At intensity of **$6x10^{12}$/bunch**





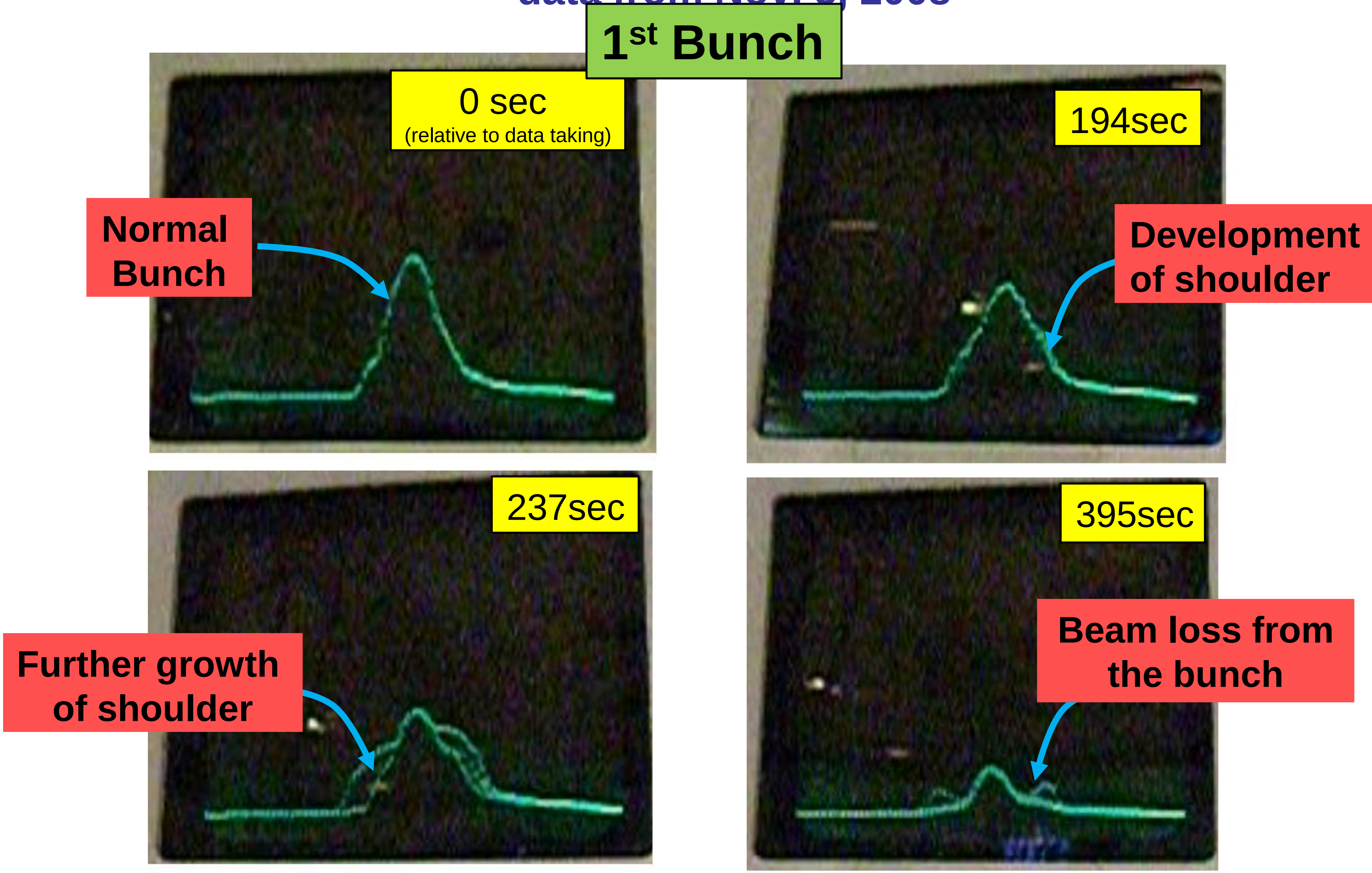
The beam studies were carried out up to beam intensity of **$8x10^{12}$/bunch**

SPS: Beam Studies with double harmonic rf

(E. Shaposhnikova,T. Bohl, T. Linnecar, J. Tuckmantel and C. Bhat)

- During the last MD studies (Nov. 5, 2008), we have carried out beam studies in the SPS to revisit the beam instability issues in 200MHz+800MHz, (i.e., h=1+h=4) double harmonic rf system.
  ←During 2006 study (at 120GeV/c) development shoulder in bunches were seen (E. Shaposhnikova et. al.,)
- Studies were conducted under various conditions at 270GeV Flat top on a coasting beam
  - Four LHC type (intensity and Long. emitt.) bunches, separated by 550nsec
  - Different RF voltage ratios for V4/V1, **(V4(100-500kV), V1(1-3MV)**
  - Long. damper and Phase-loop ON and OFF
  - Bunch lengthening and shortening mode (BLM and BSM)

SPS Beam Studies(cont.): BLM
(a first look, Preliminary)
data from Nov. 5, 2008



SPS Beam Studies(cont.): BSM and BLM
(Preliminary)

- Both BSM and BLM scenarios showed beam blowup
- The instability kicked in between 0-350 sec.
- The order in which a bunch becomes unstable was quite random
- Even though initial bunch parameters are nearly the same, they stabilized at different bunch properties