

# FLAT BUNCH CREATION AND ACCELERATION: A POSSIBLE PATH FOR THE LHC LUMINOSITY UPGRADE

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## Abstract

Increasing the collider luminosity by replacing bunches having Gaussian line-charge distribution with flat bunches, but with same beam-beam tune shift at collision, has been studied widely in recent years. But, creation of “stable” flat bunches (and their acceleration) using a multiple harmonic RF system has not been fully explored. Here, we review our experience with long flat bunches in the barrier RF buckets at Fermilab. Present some preliminary results from beam dynamics simulations and recent beam studies in the LHC injectors to create stable flat bunches using double harmonic RF systems. The results deduced from these studies will be used to model the necessary scheme for luminosity upgrade in the LHC. We have also described a viable (and economical) way for creation and acceleration of flat bunches in the LHC. The flat bunch scheme may have many advantages over the LHC baseline scenario, particularly because of the reduced momentum spread of the bunch for increased intensities.

## I. INTRODUCTION

Considerable theoretical progress has been made over the years with regards to the choice of bunch length and crossing angle near the beam-beam limit in a storage ring in view of maximizing the collider luminosity [1,2]. It has been shown that [3,4] by using super-bunches in circular machines like the Large Hadron Collider (LHC) one can achieve pp collider luminosities in excess of  $10^{35} \text{cm}^{-2} \text{sec}^{-1}$ . One of the possible upgrade scenarios for the LHC is the use of bunches with flat line-charge distribution during collision in the place of nearly Gaussian bunches [5,6]. The peak luminosity at the interaction point for the colliding round beams with rms transverse size  $\sigma_{trans}^*$  and bunch length  $\sigma_z$  is given by,

$$L = \frac{n_b f_{rev} N_p^2}{4\pi \sigma_{trans}^{*2}} F \cong \frac{n_b f_{rev} N_p^2}{4\pi \sigma_{trans}^{*2}} \times \frac{1}{\sqrt{1 + \left[ \frac{\theta_c \sigma_z}{2\sigma_{trans}^*} \right]^2}} \quad (1)$$

where  $n_b$ ,  $f_{rev}$ ,  $N_p$  and  $\theta_c$ , are number of bunches, revolution frequency, number of protons per bunch and full crossing angle of the two beams at the interaction point, respectively. The quantity  $\theta_c \sigma_z / 2\sigma_{trans}^*$  is known as Piwinski parameter or “Piwinski angle”. To maximize the luminosity with a fixed number of beam particles per bunch one generally needs to choose the crossing angle and the bunch length as small as possible, i.e., minimize

the Piwinski angle. However, it is known that the total incoherent beam-beam tune shift for colliding beams is also reduced by a similar factor  $F$ , for a collider with crossing angle in alternating horizontal-vertical planes. Then, the Eq. (1) in terms of beam-beam tune shift  $\Delta Q_{bb} (\cong N_b r_p F / 2\pi \varepsilon_n)$  becomes [6],

$$L = \gamma \Delta Q_{bb}^2 \frac{\pi m_b f_{rev} \varepsilon_n}{r_p^2 \beta^*} \frac{1}{F} \quad (2)$$

with  $r_p$ ,  $\varepsilon_n$  and  $\beta^*$  are classical radius of the proton, average normalized transverse emittance of the colliding beams and lattice function at the interaction point in the ring, respectively. The overall beam-beam tune shift  $\Delta Q_{bb}$  is  $\sim 0.01$  [6,7] for the LHC by design. Consequently, at a fixed value of  $\Delta Q_{bb}$ , it is possible to increase the luminosity by increasing the crossing angle and/or bunch length.

Furthermore, assuming that a)  $\sqrt{\varepsilon_n / \gamma \beta^*} \ll \theta_c \ll 1$ , b)  $\sigma_{trans}^* \ll \sigma_z \ll \beta^*$ , but c) Piwinski parameter  $\gg 1$  it has been shown [2] that for the same bunch intensity and same beam-beam tune shift the luminosity can be enhanced by a factor of  $\sqrt{2}$  by simply transforming the longitudinal distribution of bunches from Gaussian shape to a uniform (‘flat’) distribution. Nonetheless, at increased bunch intensity and beam-beam limit at collision one can decrease the momentum spread of the bunch by flattening it; this in turn might help reducing the beam losses in the region of high dispersion of the ring but limited aperture. Hence, the large Piwinski angle scenario for the LHC upgrade may have high potential in terms of LHC performance and luminosity.

Currently, a number of upgrade paths are being investigated [5,8]. The Table I summarizes the relevant beam parameters for the various upgrade paths. Except for the LPA (large Piwinski angle) scheme, all others assume bunches with Gaussian line-charge distributions. In the LPA scheme one assumes the rms bunch length increase by about 60% and increase of bunch spacing from 25 nsec (nominal bunch spacing) to 50 nsec. Longitudinal beam dynamics for standard and flat bunches with 12.5 nsec and 75 nsec bunch spacing have also been investigated [9] for LHC upgrade. Furthermore, notice that the ES and FCC schemes require significant reduction in the  $\beta^*$  which could be a major technical challenge.

Recently, progress has been made at Fermilab [10-12] and at KEK [13] to store and accelerate proton and antiproton beams in flat super bunches created using

barrier buckets. The studies at the Fermilab Recycler [14] have shown that the flat super bunches of all different lengths had beam life-time  $>25$  hr at its operating beam intensity and are stable longitudinally. The transverse stability issues are addressed [15]. Currently, the Recycler is used as the main antiproton storage ring where the beam is stored in bunches with rectangular line-charge distributions for many hours. However, studies on flat bunch at the CERN PS Booster [16] using double (combination of 1<sup>st</sup> and 2<sup>nd</sup>) harmonic RF cavity displayed clear signature of longitudinal instability. Therefore, it is highly important to re-examine the issues related to the instabilities of the flat bunches and establish the conditions for beam stability [17] which is critical for the LHC high luminosity upgrade.

Table I: Parameters for nominal and other LHC upgrade paths. (ES: early separation scheme, FCC: full crab-cavity scheme, LPA: large Piwinski angle/flat bunch scheme)[8].

Parameter		Nominal	Ultimate	ES & FCC	LPA
Number of Bunches		2808	2808	2808	1404
Protons/bunch	$N_b(10^{11})$	1.15	1.7	1.7	4.9
Norm. Transv. Emit	mm	3.75	3.75	3.75	3.75
$\sigma_z$	cm	7.55	7.55	7.55	11.8
Bunch Spacing	nsec	25	25	25	50
$b^*$ at IP1 and IP5	m	0.55	0.5	0.1	0.25
$\theta_c$	mrad	285	315	0	381
Piwinski Angle		0.64	0.75	0	2
Peak and Average Lum. (10 hr turn around)	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	1	2.3	15.5	10.7
Event Pileup		19	44	294	403

In this report, we describe our latest studies on flat bunches related to the LHC upgrade. In Section II, various ways of flat bunch formation with some practical examples are given. Our recent experience with the double harmonic RF systems [18, 19] in the LHC upstream accelerators, namely SPS and PS, are explained in Section III. Section IV discusses the future prospects for the LHC luminosity upgrades with flat bunches.

## II. GENERATING FLAT BUNCHES

A “flat-bunch”, in general, may refer to either flatness in transverse coordinates or in longitudinal coordinates. In this report, we are interested in the latter type, i.e., bunches with uniform or nearly uniform line-charge distributions [10-13,20-26]. In general, one can get flat bunches either by simply re-shaping the RF waveforms (by adding higher harmonic components with proper weights) to have extended region with zero RF voltage in the middle of the bucket or creating a hole [22] in  $(\Delta E, \Delta t)$ -phase space. In both cases, we emphasize on preserving the longitudinal emittance (LE) of the bunch.

Yet another method to create flat bunch is by using barrier RF buckets [10-13, 25]. Figure 1 shows a schematic view of a normal bunch in a single harmonic RF bucket along with three different types of flat bunches namely, a flat bunch in a double harmonic RF with  $h=n \oplus 2n$  ( $n$  is an integer) and flat bunch obtained using barrier RF wave. The corresponding line-charge distributions are shown in the bottom pictures.

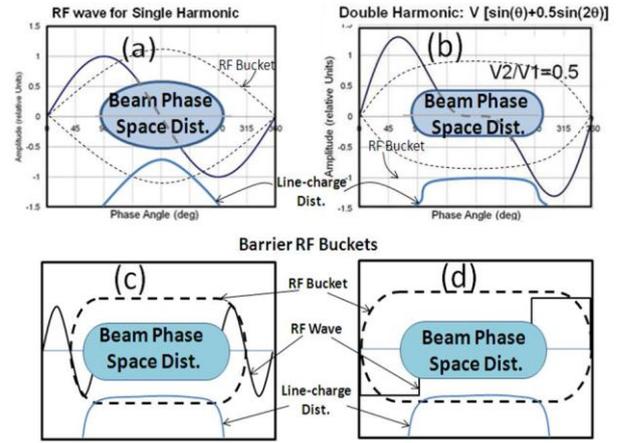


Fig.1: A schematics of bunch in a) single harmonic RF bucket (b) a flat bunch in double harmonic RF bucket.  $(\Delta E, \Delta t)$ -phase-space region of the beam particles and the RF waveforms. Similarly, barrier bunches (c) and (d) and the resulting line-charge distributions.

### Double/Multiple harmonic RF systems:

Flattening the bunches using double harmonic RF wave [16,20,24,26-28] is commonly suggested technique for high intensity operation of low energy synchrotrons. The technique has been employed to decrease the space-charge related intensity limitation by shaping the longitudinal distribution of bunches. This helps to enhance the Landau damping which is one of the necessary requirements to reduce collective beam instabilities.

Figure 2 shows the RF waveforms and the corresponding potentials for i)  $V_{rf}(h=1)$ , ii)  $V_{rf}(h=2)/V_{rf}(h=1)=0.51$ , iii)  $V_{rf}(h=4)/V_{rf}(h=1)=0.25$ , iv)  $V_{rf}(h=2)/V_{rf}(h=1)=0.67$  &  $V_{rf}(h=4)/V_{rf}(h=1)=-0.09$  and v)  $V_{rf}(h=2)/V_{rf}(h=1)=0.92$  &  $V_{rf}(h=3)/V_{rf}(h=1)=0.3$ . It is obvious that the combination of  $h=1, 2$  and  $3$  gives maximum bunching factor (i.e., the ratio of average beam-intensity to the peak beam-intensity). The procedure for generating flat bunches presented here, is either to start from a bunch captured in  $h=1$  or  $h=2$  RF bucket and adiabatically turn on the rest of the RF waves. In all these cases the relative phase of individual RF waveforms are held constant either at 0 or at 180 deg,

depending on the harmonic components. We illustrate the technique with some examples in the next two sections.

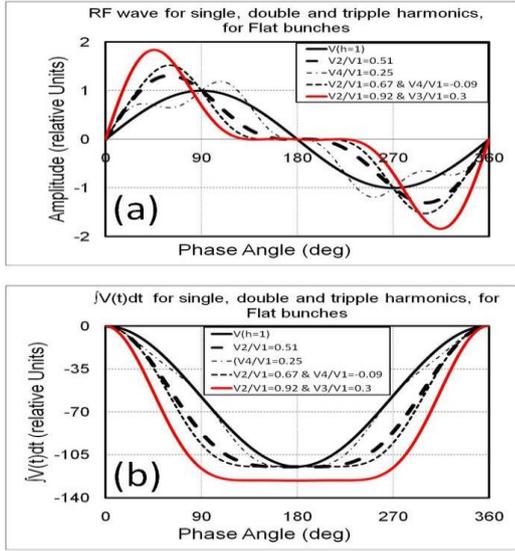


Fig.2: (a) Wave-forms and (b) potentials for various combinations of double and triple harmonics which can be used to generate flat bunches in synchrotrons ( $n=1$ ).

The Carli-technique [22] provides two elegant but distinct methods to produce flat bunches in synchrotrons via creation of hollow core in the longitudinal phase space of a bunch. These are 1) the recombination with an empty bucket and 2) the redistribution of phase space. The longitudinal emittance of the bunch is preserved in the latter method. Both of them use  $h=1$  and  $h=2$  RF systems during RF manipulations, although, the methods are not restricted to only these RF harmonics. The 2<sup>nd</sup> technique has been successfully demonstrated at the CERN PS Booster; hollow bunches have been obtained without significant blow-up of the total emittance. It is important to note that strongly double-peaked bunch shape results in an initial large space-charge tune shift before the blow-up has flattened the bunch [21]. Further, preservation of hollow distribution during coast was not obvious and these bunches in single harmonic RF buckets became unstable if RF phase loop is active [21]. Consequently, at higher intensities this technique is found to be of limited use.

### Barrier RF system:

In recent years, the barrier RF systems [29] have become important tools in a variety of beam manipulations at the synchrotrons. A barrier RF wave of an arbitrary shape in a circular accelerator is a result of superposition of several Fourier components of harmonics of fundamental rotational frequency. The barrier pulses are generated by a wide-band solid state power amplifier in conjunction with ferrite loaded wide band RF cavities. The modern barrier RF systems have operating bandwidth

in the range of tens of kHz to hundreds of MHz. The Fermilab Recycler is equipped with a broad-band barrier RF system and all of the beam manipulations in the longitudinal phase space are carried out using this RF [10-12]. One can confine beam particles between two barriers (positive and negative voltage pulses) to form a flat super bunch which can be accelerated using another rectangular RF pulse [11,13].

Figure 3 (lower trace) shows an example of a typical flat bunch occupying 55% of the Fermilab Recycler ( $6.13\mu\text{sec}$  out of  $11.11\mu\text{sec}$ ) with about  $4 \times 10^{12}$  antiprotons. The length of rectangular barrier pulse (top trace in Fig. 3(a)) was about  $0.9\mu\text{sec}$  each with a pulse gap of  $6.13\mu\text{sec}$ . In practice, this can be extended to occupy  $>83\%$  of the ring without any issues.

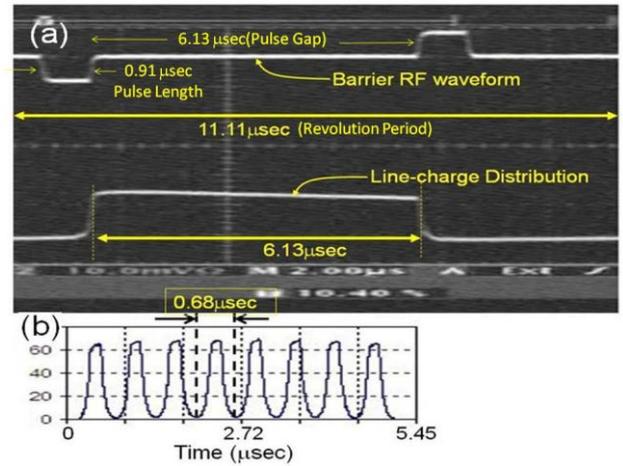


Fig.3: Experimental data of typical flat bunches in the Fermilab Recycler produced using the barrier RF: a) RF wave form (top) and line-charge distribution (bottom) as indicated, b) Eight smaller flat bunches created using barrier buckets of length equal to about  $0.68\mu\text{sec}$ .

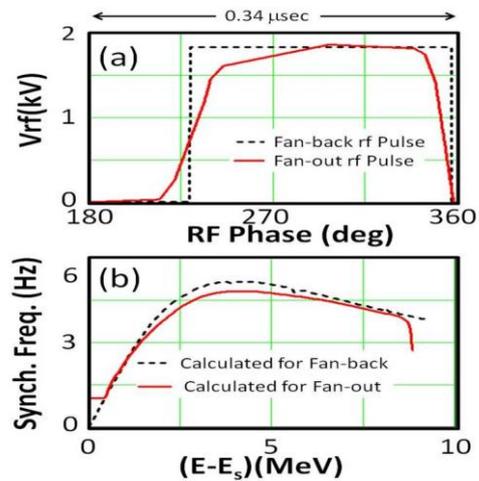


Fig.4: (a) Fan-back and fan-out RF wave-forms and (b) the calculated synchrotron frequency as a function of  $\Delta E$  of the beam particle in the bucket.

Figure 3(b) illustrates beam particle distribution after dividing the 6.13  $\mu\text{sec}$  long super bunch shown in Fig 3(a) into eight bunches. These are about 0.68  $\mu\text{sec}$ /bunch. Figure 4(a) shows half of the fan-back (dashed line) and fan-out (solid line) RF signals (along with the negative signal, not shown) used to create each one of the eight bunches shown in Fig. 3(b). Figure 4(b) shows the calculated synchrotron frequency as a function of  $\Delta E$  for beam particles in the 0.68  $\mu\text{sec}$  long bucket. It has been pointed out [30, 31] that the beam may be subjected to collective instability when the synchrotron oscillation amplitude of the beam particles reaches the region where synchrotron frequency is maximum or where the tune spread is small. The synchrotron frequency is maximum at about 4 MeV for the data shown in Fig. 3(b). On the other hand, for the super bunch (Fig. 3(a)), the maximum synchrotron frequency was at the bucket boundary. The intensity thresholds for the instability against the rigid coherent dipole oscillations for these cases are being investigated [32]. During the normal operation of the Recycler the beam brightness parameter  $D=N \times 10^{10}/6\epsilon_n/LE$  [33], is monitored and held to be  $<4$  to prevent beam from reaching transverse instability limit [15]. In our experience, none of the bunch display any sign of longitudinal instability. Besides, these bunches had lifetime in excess of 600 hrs with transverse dampers and beam cooling on. Experiments on protons with the dampers and beam cooling turned off showed the limit on  $D$  to be  $\sim 0.8$  and beam life time  $>25$  hr. Thus, our experience at the Fermilab Recycler is that the flat bunches can be stable with properly selected RF and beam parameters.

### III. RECENT EXPERIMENTS AT CERN

Recently machine development (MD) studies have been carried out in the LHC upstream accelerators, viz., SPS and PS separately, to investigate beam instability in double harmonic RF systems. In both of the experiments the beam parameters were chosen as per the LHC nominal operation. But, the harmonic components of the double RF system were different in these two studies. For example, the studies in the SPS was done with  $h=4620$  and  $h=4 \times 4620$  (i.e., 200 MHz and 800 MHz) RF systems [18] and that in the PS was with  $h=21$  and  $h=42$  (i.e., 10 MHz and 20 MHz) RF systems [19]. It is important to note that the experiments have been carried out well above the transition energy in both cases.

#### Studies in SPS [18]

The primary goal of this study was to revisit the beam instability issues in double harmonic RF system in the SPS. Earlier attempt on BLM (“Bunch Lengthening Mode”) in the SPS [34,35] with the  $V_4/V_1=0.25$  (e.g., dash-dot curve in Fig. 2) indicated the bunches becoming highly unstable. During current study, both BLM as well

as BSM (“Bunch Shortening Mode”, where the relative RF phase between  $h=4620$  and  $h=4 \times 4620$  systems was at 180 deg off relative to BLM case) were investigated in detail for various conditions of  $V_4/V_1$  ratios, phase loop and longitudinal dampers.

Figure 5 illustrates some representative data from the study on BSM on the first of four bunches in the SPS at 270 GeV. First, the beam is accelerated from 26 GeV to 270 GeV using BSM (normal operation) to form a coasting beam. At the top energy the ratio  $V_4/V_1$  was varied in steps. The development and growth of the shoulder (indicative of beam instability) at various times

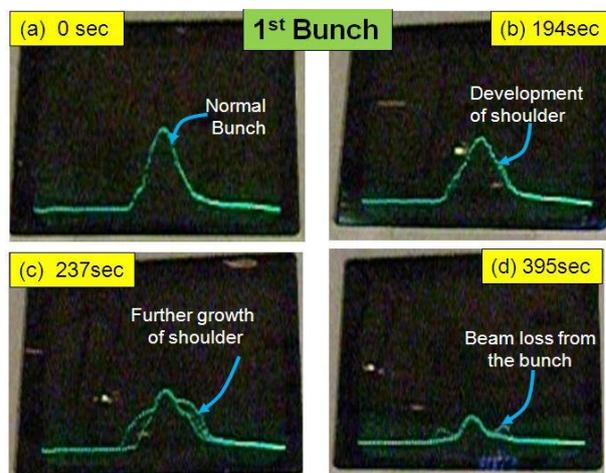


Fig. 5: The line-charge distribution for the first bunch out of four in the SPS for bunch shortening mode with  $h=4620$  and  $4 \times 4620$  at 270 GeV beam coasting condition. (These data will be presented and discussed in detail in a different document by E. Shaposhnikova, T. Bohl, T. Linnecar, J. Tuckmantel, and C. M. Bhat [ref. 18]).

in the cycle are shown in the Fig 5(b)-(d). The time  $t=0$  sec is very close to the end of the beam acceleration. Preliminary examination of the data indicated that the bunch became very unstable when the voltage ratio was approaching 0.25. Detailed data analysis is in progress.

#### Studies in PS [19]

The PS, being one of the earliest proton synchrotrons, has very complex RF system to enable many different beam manipulations in longitudinal phase space. The current beam study in PS with  $h=21$  and  $h=42$  was primarily motivated by some of the recent beam dynamics simulations carried out by the author related to LPA scheme for LHC luminosity upgrade and to address the instability of flat bunches produced in the double harmonic RF system with  $V_2/V_1 \sim 0.50$ .

Figure 6 shows the results from longitudinal beam dynamics simulations for a single bunch in  $h=21$  RF system with  $V_1=31\text{kV}$  and in  $h=21 \oplus 42$  with  $V_2/V_1=0.51$

with a fixed RF phase difference of 180 deg. The simulations were carried out using ESME [36] at 26 GeV without including intensity, feed-back or any cavity higher order mode effects. We find that a bunch in single harmonic RF bucket can be transformed to a flat bunch in about 35 ms (about six synchrotron period;  $1/f_s=6.5$  ms) with virtually no emittance growth. Figure 7 shows the calculated synchrotron frequency of the beam particle in the RF bucket as a function of phase coordinate of the particle relative to the center of the bunch (180 deg represents the center of the bunch) for different combinations of harmonic components. The voltages as well as the corresponding harmonic numbers are also indicated in the figure. The calculations show that the maximum for the synchrotron frequency occurs at 117 deg from the bunch center for  $V_2/V_1=0.51$  (e.g., curve marked “31kVh21+16kVh42”). The simulation shown in Fig.6 (which was attempted to reproduce the experimental data shown in Fig. 8) shows that the maximum extent of the bunch is about 104 deg. Hence, the beam particles are well below the maximum of the synchrotron tune. Therefore, the bunches were expected to be longitudinally stable.

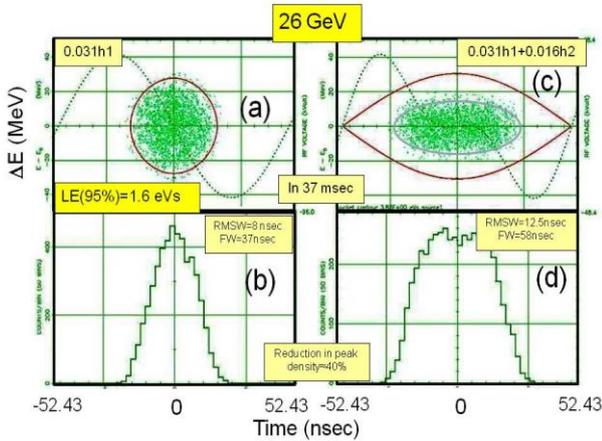


Fig.6: Simulations for the flat bunch creation at 26 GeV. in the CERN PS (a)  $(\Delta E, \Delta t)$ - phase space distribution for beam particles, (b) the line-charge distribution for the bunch, in single harmonic RF bucket, (c) and (d) are similar distributions after forming the flat bunches.

Some representative data taken during PS study at 26 GeV flat-top is shown in Figure 8, illustrating the transformation of proton bunches in 10 MHz RF buckets to a flattened bunch produced with the superposition of 20 MHz RF wave with voltage ratio used in our simulations (Fig. 6). There is good agreement between the predicted mountain range and the measured data. Further, a preliminary examination of the data shows that the flattened bunches in double harmonic RF buckets (Fig. 8(d)) are more stable towards coupled bunch instability as compared with bunches in the single harmonic RF buckets (Fig. 8(c)). Note that the limitations of the

magnets and the power supplies in the PS precluded the study of flat bunch beam stability beyond 145 msec. Detailed data analysis is presented elsewhere [19].

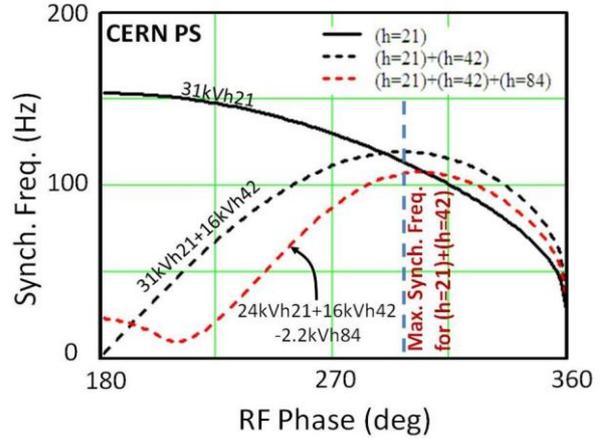


Fig.7: The calculated synchrotron frequency as a function of phase coordinate of the particle for three different cases of harmonic combinations.

Thus, the results from our recent experiments carried out above the transition energy in PS using double harmonic RF system are very promising. More detailed studies are planned in both SPS and PS. These would help us to model the RF manipulations to create flat bunches for the LHC and address their instabilities.

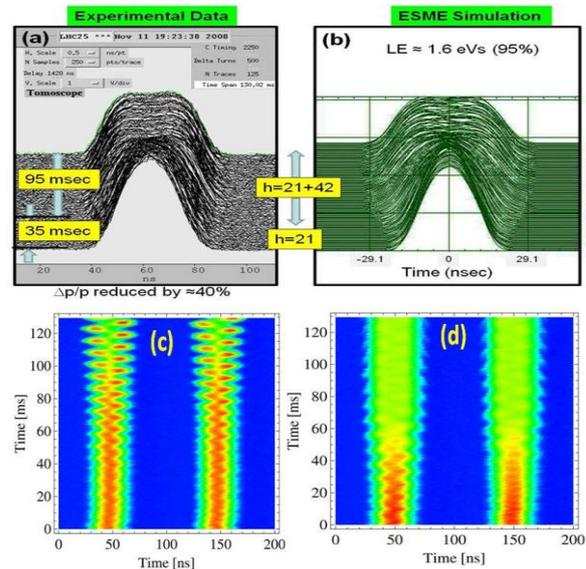


Fig.8: PS Data on flat bunches at 26 GeV: a) experimental data on mountain range plot on the 12<sup>th</sup> bunch during the creation of flat bunch, b) ESME prediction of the experimental data. Experimental data on the contour plots for bunch number 17 and 18 with c) single harmonic RF and d) double harmonic RF buckets. The experiment was conducted with bunch intensity  $\sim 46 \times 10^{10}$  ppb. (These data will be presented elsewhere [19]).

#### IV. FUTURE PROSPECTS AT LHC WITH FLAT BUNCHES

Two scenarios for the LHC upgrades with LPA scheme are proposed here: a) flat bunch creation at the collision energy and b) flat bunch creation at injection energy of 450 GeV and acceleration to the collision energy. Both of them need additional RF systems. By design, the LHC uses 400 MHz RF systems for its beam acceleration as well as for coasting during collision. For the scenarios discussed here, we need 200 MHz RF systems in the LHC ring which can provide a minimum of 3 MV RF per beam (with a safety margin of ~25% is better). If beam acceleration is also considered then we also need capabilities for tuning the frequency of the cavity to match the momentum of the particle.

The 200 MHz RF system is not new to the LHC. Originally, this was part of the baseline design. The necessary cavities and part of the subsystem have already been built and tested [37]. Later it was decided to use 400MHz RF instead of 200 MHz RF and use the latter system in the LHC when the losses at high intensities become significant.

##### *Flat Bunch Creation at Collision Energy:*

Possibility of creation of flat bunches in the LHC for luminosity upgrade using Carli-technique and double harmonic RF systems were addressed earlier [2,9]. The former technique was abandon because of the reasons described in Section II. Here we revisit the 2<sup>nd</sup> technique assuming that the beam parameters can be held below instability limits. The longitudinal emittance margin for individual bunches at peak energy in the LHC is about 2.5 eVs (4-sigma) by design [38]. The maximum bucket area from the 400 MHz RF system at 7 TeV is about 7.9 eVs (at  $V_{rf}=16MV$ ) with a bucket to bunch ratio of 3.2. Figure 9 shows the results from simulation for a 2.5 eVs

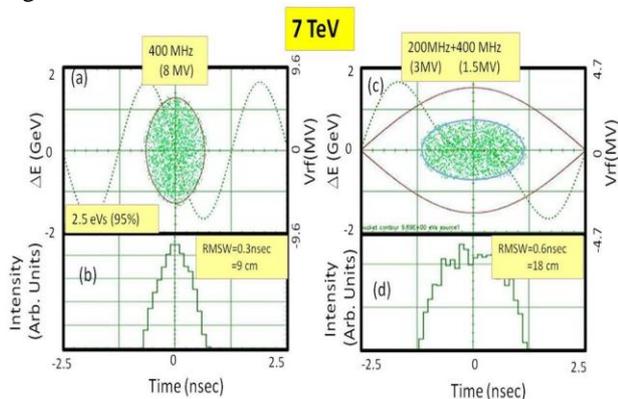


Fig.9: ESME simulations for the flat bunch creation at 7 TeV in LHC. For details see the caption for Fig. 6.

proton bunch in single harmonic RF bucket and a flat bunch in double harmonic RF bucket formed using 200 MHz and 400 MHz RF waveforms. In this scenario the

injected bunch is accelerated from 450 GeV to 7 TeV using 400 MHz RF system as designed. At peak energy, the RF voltage of the 200 MHz RF system is adiabatically increased to 3 MV with bucket center (of 200 MHz) aligned with beam center. At the same time, the voltage on 400 MHz RF is reduced adiabatically to 0 volts followed by a phase jump of 180 deg, and then the voltage is increased back to 1.5 MV. The final RF waveform will be similar to that shown in Fig. 2 for  $V_2/V_1=0.5$ . The simulation shows the time required for the transformation of a bunch in single harmonic RF bucket to a flat bunch is about 10 sec (<70 synchrotron period) without any longitudinal emittance growth and beam loss. For the case shown here the rms width of the bunch increased by nearly a factor of two.

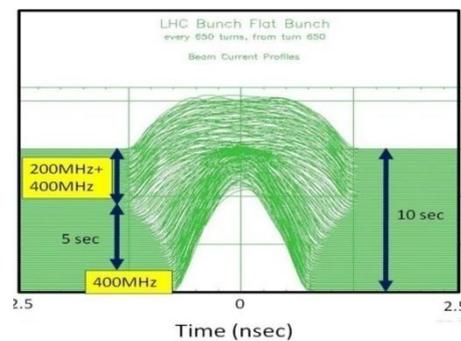


Fig.10: Simulation for mountain range during transformation of a bunch in a 400 MHz RF bucket to a flat bunch as explained in the text.

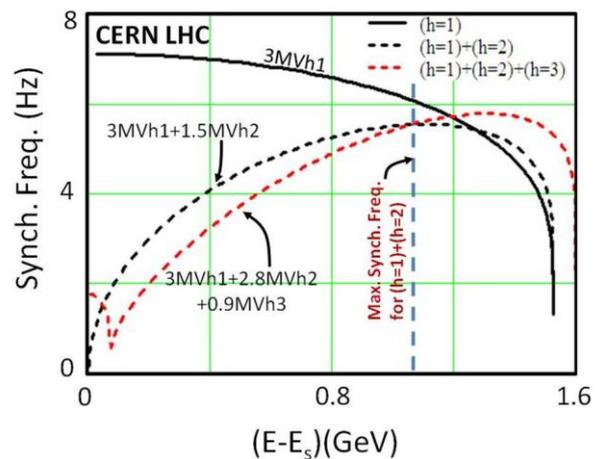


Fig.11: The calculated synchrotron frequency as a function of  $\Delta E$  for the beam particle in the bucket at  $E_s=7$  TeV. In this case,  $h=1$  implies 17820 (with the 200 MHz RF system).

Figure 10 displays the simulated mountain range data for the generation of flat bunch in the LHC. Figure 11 shows the calculated synchrotron frequency as a function

of  $\Delta E$  for  $V(200\text{MHz})=3$  MV (solid line),  $(V(200\text{MHz})=3\text{ MV})+(V(400\text{MHz})=1.5\text{ MV})$  (black dashed line). We have also carried out calculations including 3<sup>rd</sup> harmonic component which gives a very promising result and has high potential from the beam stability point of view [39]. In this case the synchrotron frequency reaches its maximum at a much higher value of  $\Delta E$ . As illustrated in Fig. 2 the bunches become much flatter as compared to any other double or triple harmonic case illustrated here.

### **Flat Bunch Creation at 450 GeV and Flat Bunch Acceleration:**

The RF manipulation involved in flat bunch creation at 450 GeV is very similar to that at 7 TeV. In the simulation we have assumed the  $LE=1.5$  eVs ( $\sim 50\%$  more than that used in the design [38]).

Figure 12 shows various stages of beam manipulation for flat bunch creation at 450 GeV and its acceleration to 7 TeV. The acceleration of the flat bunches is achieved by shifting the higher harmonic RF wave by about 25-30 deg relative to that used for creating it so that about 0.5MV/turn acceleration is reached. The simulation shows that the total acceleration time in this technique can be kept at about 20 min, similar to that planned in normal operation [38].

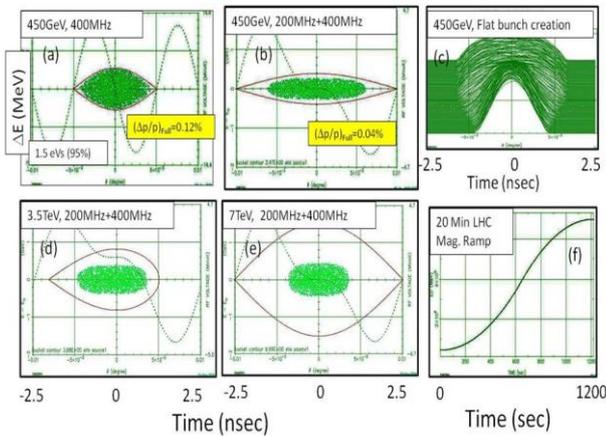


Fig.12: Simulations for the flat bunch creation and acceleration in the LHC. The  $(\Delta E, \Delta t)$  phase space distribution of particles at a) injection ( $LE=1.5$  eVs bunch), b) after flat bunch creation, c) mountain range picture of flat bunch creation, d) flat bunch acceleration e) the bunch at top energy and f) the LHC acceleration ramp of about 20 min long

Out of two methods proposed here for the LHC, the flat bunch creation at flat top energy is quite compelling. In this case, the 200 MHz RF cavity will be at constant frequency. The 2<sup>nd</sup> approach involving flat bunch acceleration needs additional software and hardware developments. Further, there is about 4% reduction in the

ratio of bucket area to bunch area during acceleration with dual harmonic RF. But, the advantage of this method is the reduced beam loss throughout the LHC operation, because, the momentum spread of the bunch is smaller than that for nominal acceleration case. This may be critical for high intensity operation of the LHC in future.

## **V. SUMMARY**

We have presented a discussion and simulation results on creation of flat bunches in the LHC supported by some recent beam experiments in the CERN SPS and PS. A preliminary analysis of the data shows that the proton bunches with appropriate beam parameters can be made stable in buckets of double harmonic RF system, in particular, with the harmonic voltage ratio of  $V2/V1 \sim 0.5$  and bunches extending below  $\pm 100$  deg. In the case of LHC, preliminary simulations at 7 TeV indicate that the particles in flat bunches with  $LE(95\%) \leq 2.5$  eVs in a double harmonic RF bucket made of 3 MV of 200 MHz RF and 1.5 MV of 400 MHz RF have their synchrotron tune well below the instability limit. In reality, one may need at least about 25% more RF voltage power (note that 400 MHz RF system has already more than enough RF power). Addition of 3<sup>rd</sup> harmonic RF component can provide further improvements. All of the simulations presented here are carried out without including HMO, impedances of the cavities and space-charge effects. Furthermore, to take full advantage of a  $\sqrt{2}$  increase in luminosity without increasing the bunch intensity one may need a new RF manipulation technique. Detailed study is in progress. Large Piwinski angle scheme by using flattened bunches at collision is a very promising path for the LHC luminosity upgrade. This becomes a very compelling case especially at higher bunch intensity and running very close to the beam-beam tune shift limit.

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