

# PHASE TRANSIENTS IN THE HIGHER HARMONIC RF SYSTEM FOR THE ALS-U PROPOSAL\*

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## Abstract

The proposed upgrade of the ALS to a diffraction limited light source (ALS-U) requires lengthening the bunch by a factor up to four in order to limit the emittance growth due to intra-beam scattering, increase the Touschek lifetime to a value consistent with a on-axis swap-out period of about 30 seconds, improve beam stability, and lower the peak current with consequent reduction of high-frequency wakefields and beampipe heating.

To obtain the necessary bunch lengthening factor, a higher harmonic RF system will be used to flatten the total accelerating voltage seen by the circulating bunches. A fourfold increase of the bunch length requires operating the harmonic RF system near the optimum flat condition, which corresponds to cancellation of first and second derivatives of the main RF voltage waveform at the time of the bunch passage (i.e. at the synchronous phase). Such a situation presents particular challenges since a significantly stretched bunch covers a large interval of RF phases and it deviates considerably from the usual gaussian longitudinal density distribution. Furthermore, in the case of a passive harmonic system, gaps in the fill pattern may cause part of the bunch train to miss the lengthening target. At this time, two options, 500 and 100 MHz, are being evaluated for the main RF frequency and we have calculated the main parameters for a harmonic system in each case. The 500 MHz option requires gaps at least 10 ns long in the fill pattern for the rise time of the on-axis injection kickers, while with a 100 MHz main RF frequency it is possible to use a perfectly uniform beam. Since the first one is the favoured option for several reasons, ensuring that gaps are not a limiting factor in lengthening the bunch is necessary before committing to this solution. In this paper we present our studies, using both computer simulations and experiments on the ALS, that show that a 500 MHz main RF system, together with a 1.5 GHz harmonic system is a viable solution for the ALS-U requirements.

## INTRODUCTION

The ALS-U proposal envisions the upgrade of the present ALS synchrotron light source into a new ultra-low emittance machine for the production of diffraction-limited soft X-rays. The details of the proposal are reported in [1]. At our 2 GeV beam energy, intra-beam scattering becomes a serious limitation in achieving the desired ultra-low beam transverse emittance, of the order of 50 picometers, without decreasing the stored current.

Therefore harmonic RF cavities are included in the machine design, to lengthen the bunch. In addition to reducing intra-beam scattering, longer bunches have a longer Touschek lifetime, which allows to increase the interval between bunch train swap-outs. The spread in synchrotron frequency caused by the flattened accelerating voltage waveform introduces Landau damping, thus improving beam stability. Finally, the lower peak current reduces beam heating of vacuum chamber elements and the high-frequency components of the beam power spectrum are also eliminated. At present, we are investigating two different options for the main RF frequency, as detailed in [2]. Depending on the frequency chosen the harmonic system would operate at 1.5 GHz (third harmonic of 500 MHz), or at 500 MHz (fifth harmonic of 100 MHz). Fill patterns are also different between the two options: in order to allow 10 ns long gaps for the operation of the injection/extraction kickers, the 500 MHz main RF machine would store 11 trains of 26 bunches each, while in the 100 MHz main RF case all the 66 RF buckets would be filled. The RF main parameters are summarized in Table 1.

Table 1: Main RF Parameters

Parameter	Value	
Beam Energy ( $E_b$ )	2 GeV	
Circumference ( $L_R$ )	196.44 m	
Beam Current ( $I_b$ )	500 mA	
Main RF Frequency ( $f_{RF}$ )	500 MHz	100 MHz
Number of Bunches ( $N_b$ )	275	66
Energy Loss/Turn ( $U_0$ )	165 keV (260 keV with ID's)	
Energy Spread ( $\Delta\epsilon$ )	$8 \cdot 10^{-4}$	
Mom. Compaction ( $\alpha$ )	$2.69 \cdot 10^{-4}$	
Nat. Sync. Tune ( $Q_s$ )	0.002	
Main RF Voltage ( $V_{RF}$ )	760 kV	420 kV
Nat. Bunch Length ( $\sigma_b$ )	11 ps	35 ps
Higher Harm. Freq. ( $f_H$ )	1.5 GHz (3 <sup>rd</sup> harm.)	500 MHz (5 <sup>th</sup> harm.)
Req. Lengthening Factor	3-4	

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Based on these parameters it is possible to calculate analytically the harmonic voltage and phase necessary for cancelling first and second derivatives of the main RF voltage waveform, and thus obtain the optimum flat total accelerating voltage, as seen by the center of mass of the bunches [3]. For the 1.5 GHz 3<sup>rd</sup> harmonic system these are

$$V_{h,opt} = 236 \text{ kV} \text{ and } \varphi_{h,opt} = 0.138 \quad (1)$$

while for the 500 MHz 5<sup>th</sup> harmonic system

$$V_{h,opt} = 65 \text{ kV} \text{ and } \varphi_{h,opt} = 0.165 \quad (2)$$

The above values have led us to planning passive cavities for the 1.5 GHz system and an active one for the 500 MHz system, due to the low voltage value required. In this second case the harmonic system would be more flexible, being able to be used even at the lowest currents, such as during commissioning. The passive system instead yields the design harmonic voltage and phase simultaneously, only at one specific value of the current. Furthermore, the phase specified in Eq.(1) can be obtained at that current only if the harmonic cavities total shunt impedance is

$$R_{s,opt} = \frac{V_{h,opt}}{2I_h \cos(\pi/2 - \varphi_{h,opt})} \quad (3)$$

where  $I_h = 465 \text{ mA}$  is the component of the beam current spectrum at the harmonic cavity frequency. From Eqs.(1) and (3) we find that  $R_{s,opt} \approx 1.85 \text{ M}\Omega$ , which is a value consistent with a normal-conducting copper cell.

Regardless of the active or passive nature of the harmonic system it is well documented [4] that beam loading effects can substantially affect their performance. In particular, large gaps in the fill pattern can induce a spread in the harmonic voltage and phases by the different bunches (phase transient), so that only a fraction of them is optimally lengthened, while in the most severe cases others can actually be shortened. Therefore, we investigated the effect of phase transients in the two configurations proposed for the ALS-U. In the following sections we show our results using simulation codes and beam measurements on the current ALS.

## SIMULATION CODE RESULTS

In order to simulate the effect of the harmonic cavities on the longitudinal beam dynamics in the ALS-U we made use of the code mbtrack [5], originally developed by R. Nagaoka and A. Rodriguez, which can track multiple bunches, composed of as many as 30 thousand macroparticles each, around a ring, calculating the 6D phase-space of each bunch turn by turn. Our own code, which instead represents each bunch by a single macroparticle and only tracks bunches in the longitudinal phase-space, although much faster, could only be used to

confirm the mbtrack results for smaller bunch lengthening factors, roughly up to two, since for longer bunches the actual longitudinal charge distribution over a substantial portion of the harmonic period is necessary to properly calculate the beam loading.

### 1.5 GHz 3<sup>rd</sup> Harmonic System

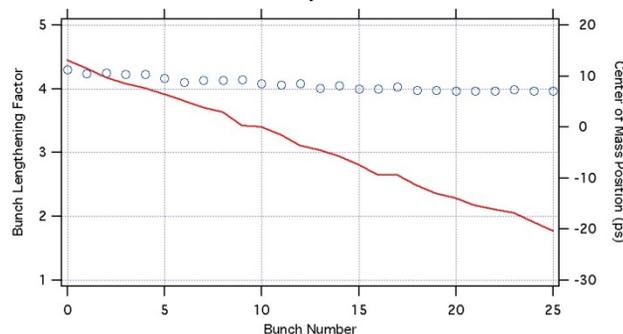


Figure 1: Bunch lengthening factor and phase transient for an ALS-U train, with a 500 MHz main RF frequency and a 3<sup>rd</sup> harmonic system.

Figure 1 shows the bunch lengthening factor calculated for the 26 bunches of one of the ALS-U trains when the passive 3<sup>rd</sup> harmonic system is designed to obtain the harmonic voltage and phase in Eq.(1). The passive harmonic cavities, with a  $Q = 20000$ , have to be detuned by 272 kHz at the design beam current of 500 mA. In the simulation all the bunches circulating in the machine have exactly the same current and therefore all the 11 trains are identical to each other. This would not be the case in an actual machine, but we can see from the measurements presented in the next section that even relatively large non-uniformities, randomly distributed, do not seem to affect significantly the phase transient, which in the idealized simulation is equal to about 30 ps, or about 16 angular degrees of the harmonic frequency.

### 500 MHz 5<sup>th</sup> Harmonic System

With this second option the filling pattern is completely uniform (neglecting non-uniformities generated by the injection process) and we don't expect any substantial phase transient

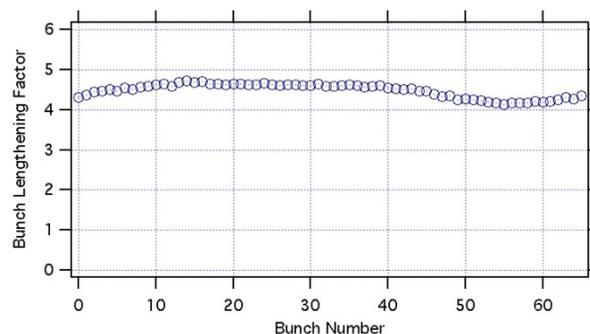


Figure 2: Bunch lengthening factor the ALS-U with a 100 MHz main RF frequency and a 5<sup>th</sup> harmonic system.

For the sake of simplicity, we studied a passive system using a cavity with a  $Q = 20000$  and optimal shunt

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impedance  $R_{s,opt} = 430 \text{ k}\Omega$  and the lengthening factor for the 66 bunches is shown in Fig. 2

The spread in bunch lengthening factors, even for a completely symmetric filling pattern, might be due to numerical errors deriving from using only 30 thousand macroparticles, the effect of which is amplified when the total accelerating voltage is maximally flat.

## BEAM MEASUREMENTS

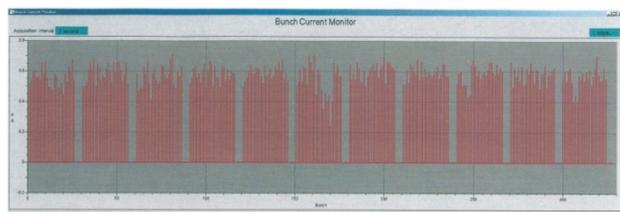


Figure 3: ALS experiment fill pattern.

The ALS is presently operating with RF parameters quite close to those described for the ALS-U in the 500 MHz main RF configuration. RF frequency and beam current are the same, the ALS has a passive 3<sup>rd</sup> harmonic system with a total shunt impedance of 5.1 M $\Omega$ , and its harmonic number is 328. The only substantial difference is the main RF voltage, which is normally set at 1.25 MV, but can be lowered below 1.1 MV during our experiment. In such conditions, we cannot achieve maximally flat total accelerating voltage, due to the total shunt impedance of the harmonic cavities being below the required 6.4 M $\Omega$ . It is nonetheless possible to get closer to the optimal harmonic voltage  $V_{h,opt} = 378 \text{ kV}$ , but with a phase different from  $\phi_{h,opt}$ . Therefore, we ran a series of experiments injecting the ALS-U fill pattern in the ALS.

Figure 3 shows the fill pattern measured by the ALS bunch current monitor used during our experiment. Due to the harmonic number being 328, two of the trains consist of 25 bunches instead of 26. This adds to the asymmetries contributing to the phase transient.

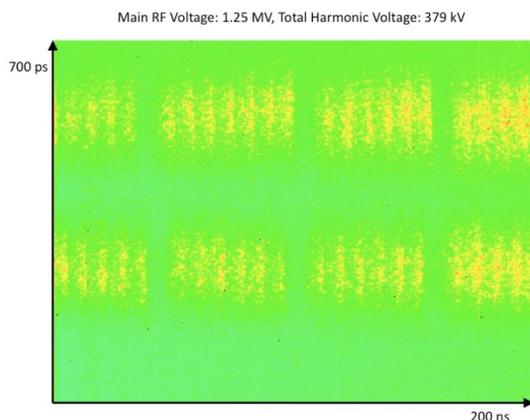


Figure 4: Streak camera measurement of 4 bunch trains at the standard ALS RF voltage and 379 kV harmonic voltage.

A streak camera measurement of bunch length and phase transient taken with close to optimal harmonic voltage is shown in Fig.4. The phase transient along a train is in good agreement with the about 10 ps obtained by running our simulation code with the ALS parameters.

The bunch lengths measured at various harmonic voltages and also at a reduced main RF voltage of 1.09 MV are shown in Fig. 5. Bunch lengthening factors, up to a value of about four, are consistent with lifetime measurements and with our expectations.

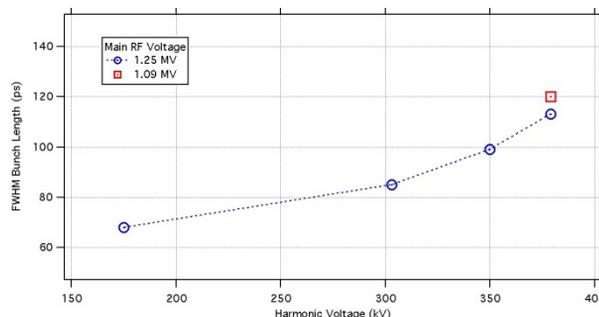


Figure 5: Measured bunch lengths with ALS-U fill pattern in the ALS for various harmonic and main RF voltages.

## CONCLUSIONS

In this paper we have discussed the two options for a harmonic system to lengthen the ALS-U bunches by a factor of around four. We have used tracking codes to simulate the performance of the harmonic systems obtaining adequate bunch lengthening in both cases. Since for the 1.5 GHz 3<sup>rd</sup> harmonic system, gaps in the fill pattern could induce significant phase transient, we have also carried out experiments injecting into ALS-U like fill patterns in the ALS, which has similar RF parameters.

These measurements show that the 10 ns long gaps between trains in the ALS-U are short enough to limit the amplitude of phase transient, so the 3<sup>rd</sup> harmonic system performance is close to the optimal condition and the bunch lengthening targets can be achieved.

## REFERENCES

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