BUNCH LENGTHENING HARMONIC SYSTEM FOR NSLS-II*

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Abstract

NSLS-II is a new ultra-bright 3GeV 3rd generation synchrotron radiation light source. The performance goals require operation with a beam current of 500mA and a bunch current of at least 0.5mA. Ion clearing gaps are required to suppress ion effects on the beam. The natural bunch length of 3mm is planned to be lengthened by means of a third harmonic cavity in order to provide a margin for the Touschek limited lifetime and for instability threshold currents. The paper presents the analysis of the bunch lengthening in this dual RF system consisting of a 500MHz fundamental and 1500 MHz harmonic system in presence of strong transient beam loading. A conceptual design of a 1500MHz SCRF cavity is developed and design performance is discussed.

INTRODUCTION

The NSLS-II will achieve sub-nm-rad emittance by using soft bends (large circumference) to enhance the effect of damping wigglers in reducing the emittance from a value of ~2nm for the bare lattice to 0.6nm with 54 m of 1.8 T damping wigglers. The lifetime of this low emittance beam is dominated by Touschek scattering and is of the order 3 hours. In order to replenish the Touschek scattered beam the injector must deliver 7.3 nC every three minutes to keep the average current variations less than 1 % and the bunch to bunch variations less than 20%. For some class of experiments the data must be blanked during the injection process, and there is a penalty to pay for the injection time. A passive superconducting 3rd harmonic RF system is proposed to lengthen the bunches and achieve a proportional increase in beam lifetime to either increase the time between injections, decrease the charge per injection or combination of the two.

The use of a gap in the fill for ion clearing is known to have an impact on bunch lengths across the train, and corresponding gains in lifetime [1, 2]. The next section discusses bunch lengths and their calculation for fills containing one or more gaps.

LONGITUDINAL BUNCH PROFILES WITH HHC

Bunch-lengthening higher-harmonic cavities have been shown to increase Touschek lifetime and suppress CB instabilities. Bunch lengths and lifetime are increased by a substantial factor in the absence of an ion clearing gap, more than a factor of four in the case of NSLS-II (Fig. 1).

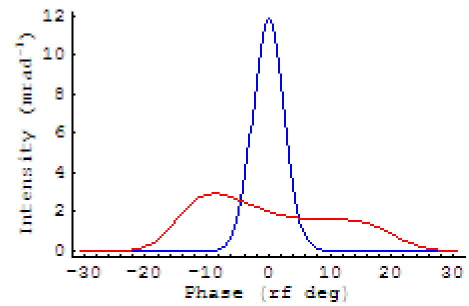

Figure 1: Unstretched (blue) and stretched (red) bunch profiles in a uniform fill. The bunch lengths are 14 and 60 ps rms, respectively. The HHC field intensity in the latter is 3% over that required for a flat-bottomed potential well. The asymmetry of the stretched-bunch profile is due to the non-optimum phase of the passively driven cavities.

But the use of a gap in the fill pattern for ion clearing has shown itself in some rings to introduce non-uniform bunch profiles, particularly shorter bunches on the ends of the train and variation of centroid phase over a wide range across the train [1, 2]. These effects reduce Touschek lifetime significantly, reducing the potential bunch-length and lifetime gains possible compared to uniform fills. Lower cavity R/Q (main and harmonic cavities) helps to reduce the problem, a fact that in part motivated the decision to use SC cavities.

To assess the impact of the ion-clearing gap for NSLS-II, two codes were use to calculate bunch profiles across the train. Two were written for the purpose of code validation. Without spelling out many details, both codes self-consistently calculate profiles by iterating two basic steps. The first step determines the profile $\rho_i(t)$ of each bunch given the RF potential $U_i(t)$ at that bunch,

$$\rho_i(t) \propto e^{-U_i(t)/\sigma^2} \tag{1}$$

where σ is an energy-spread parameter. $U_i(t)$ is proportional to the anti-derivative at bunch *i* of the sum of the RF fields in each of the modes included in the calculation.

The second step is the calculation of RF field intensities and phases from bunch profiles. In the time-domain code, the RF field in each mode and in each bucket is determined by the bunch profiles convolved with a 'periodic impedance' calculated at each bucket. The

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'periodic impedance' is the mode's impedance summed over turns, an approach that is possible because the profiles are static and so repeat on a turn-by-turn basis. In the frequency-domain code, the bunch profiles are fourier analyzed at a set of revolution harmonics on either side of the RF modes, and then multiplied by the impedance. The resulting fourier coefficients of the mode fields are then inverse fourier analyzed to get the time-domain fields, which are then used to calculate the potential wells. So these codes iteratively calculate profiles from fields, and fields from profiles. Fields and profiles are sampled in the time and/or frequency domains, depending on the code. Convergence requires a damping scheme. The RF modes ordinarily include main-cavity and HHC accelerating modes, and higher-order modes (HOMs) may be included as needed. Without a gap in the fill, the computed profile is simply the Haïssinski profile.

Figure 2 shows bunch profiles for HHC detuning of 80 kHz. Although this detuning is approximately optimal for a uniform fill, the HHC field intensity with this fill factor is less than optimal, showing a great deal of spread of centroid phases and less than optimal bunch lengthening.

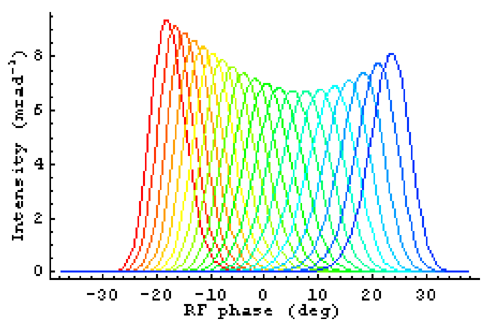

Figure 2: Bunch profiles across the train for an 80% fill, and +80 kHz HHC detuning. The unit of the vertical axis is 1/mrad of ring azimuthal angle with each profile normalized to 1 when integrated over that variable. The horizontal-axis unit is 500-MHz rf degree. The leading edge of each bunch is the right edge of each profile, and leading to trailing bunches of the trains vary in color from red to blue. Average rms bunch length is 4.3 rf degrees or 24 ps.

In most cases, rms bunch lengths increase with decreasing HHC detuning. With shorter gap and HHC detuning, the center bunches can become bimodal so that the rms bunch lengths are large while well depth and lifetime suffer. At the same time, bunches near the ends of the train can still remain peaked. ELETTRA seems capable (or nearly so) of operating in this regime [1].

At the other extreme with large ring, low fill fraction, or large impedance, the spread in centroid phases can out race the increase in HHC field intensity. When this happens, bunch lengths show rather little increase with decreasing HHC detuning and may even reverse. Figure 3 shows an example of this behavior.

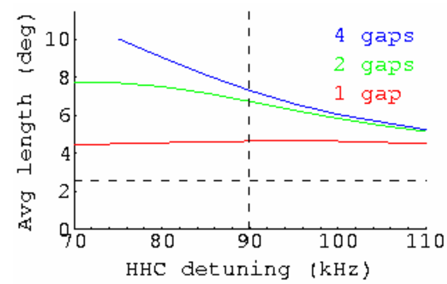

Figure 3: NSLS-II bunch lengths as a function of HHC detuning for one (red), two (green), and four (blue) symmetrically placed ion-clearing gaps. Net fill fraction is 90% in all cases. The vertical-axis unit is 500-MHz rf degree. The horizontal dashed line is the 14-ps unstretched bunch length, while the vertical dashed line is the detuning for nominal HHC field intensity in a uniform fill of unstretched bunches.

Even with SC cavities, NSLS-II is limited in its ability to lengthen bunches with HHCs when there is only one ion-clearing gap. When the one gap is split symmetrically into two or more gaps, the impact is greatly reduced. With four gaps, the average bunch-length gain is approaching the maximum 4:1 ratio in this machine (Fig. 4). So it may be useful in NSLS-II to employ multiple gaps in the fill to reach greater lifetime gains.

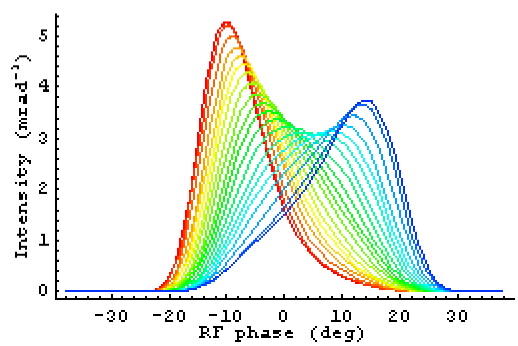

Figure 4: Bunch profiles with 80% net fill fraction in four symmetrical bunch trains, and +80-kHz HHC detuning. Average rms bunch length is 7.9 rf degrees or 44 ps.

Since ion instability and ion clearing are local effects, they are sensitive to gap duration and gap repetition rate and not directly sensitive to gap count and ring size. So there is a certain amount of sense to spitting up a gap in a large ring to the degree that gap duration and repetition rate are in line with other rings, such as ELETTRA, where gaps for ion clearing are used successfully.

LONGITUDINAL COUPLED-BUNCH INSTABILITIES

Since the HOMs of the SC cavities are well damped, the impedances of these modes are relatively small compared to undamped modes or damped HOMs in NC cavities. The possibility of instability of stretched bunches in the longitudinal plane is further lessened by

Landau damping. Nevertheless, the possibility of instability was checked by calculating threshold impedances as a function of HOM frequency via multi-bunch Vlasov simulations [4]. The results are shown in Fig. 5. The simulated thresholds are well above the expected damped impedances of the HOMs of the SC cavities, and well above the short-bunch thresholds [3]. Instability of unstretched or compressed bunches is not excluded, however.

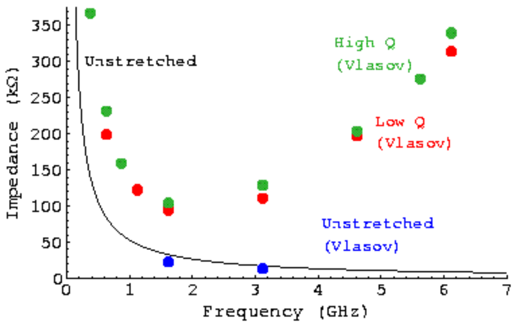

Figure 5: CB instability thresholds for the lowest-lying stretched- coupled-bunch mode for a model high-Q HOM (green points) and a model low-Q HOM (red points). The two model impedances test for sensitivity to details of the impedance. The solid line and blue dots for unstretched bunches are from an analytic formula [3] and Vlasov simulations [4], respectively.

PASSIVE SUPERCONDUCTING CAVITY

Requirements

In order to create zero slope in the accelerating voltage with a dual RF system the second RF system must provide a voltage ~ proportional to the inverse of the harmonic number times the fundamental. For a NSLS-II third harmonic system 1.1 MV is required. This is beyond what can be reliably maintained in a single cell cavity structure, and so two cavities are necessary. In order to save space two cells in a single cryostat like the Super3HC [5] cavity is proposed.

Table 1: Cavity parameters

NSLS-II Design Parameters	
Frequency (MHz)	1500
Overall length, 2 cells (m)	<1.5
RF voltage (1500MHz, MV)	1.1
Q	3 x10^8

It has been shown that the stretched bunches have significantly higher coupled bunch instability thresholds than un-stretched bunches. In the design of a new light source one can not preclude operation with normal bunches or using the harmonic cavity to shorten the bunches. The fundamental 500MHz cavities are highly damped with large beam-pipes and ferrite absorbers. The same approach is being taken with the harmonic cavity design to minimize its HOM impedances so as not to preclude operation with short bunches. Preliminary results using a cavity profile like the Super-3HC, except with ferrite beam-pipe dampers looks promising but has not sufficiently damped the TE110 like mode. Further work will concentrate on increasing the beam-pipe diameter to propagate this mode to the ferrite.

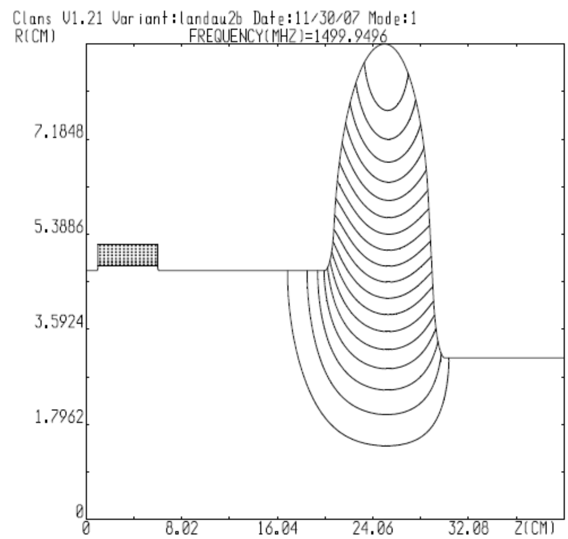

Figure 6: Preliminary cavity design with ferrite HOM damper.

CONCLUSION

Bunch length calculations show that the size of the ring in NSLS-II is a serious impediment to bunch lengthen using HHCs when there is a single 20% gap for ion clearing. This limitation can be reduced if the fill fraction can be increased, the cavity impedances reduced, and/or the 20% gap broken up into two or more symmetrically place gaps with similar net fill fraction. The quality of the final vacuum will ultimately determine the average bunch lengthing that can be achieved.

Preliminary cavity design studies have shown promising results in the design of a two cell ferrite damped HOM cavity, although further work needs to be done to damp the TE110 like mode to acceptable levels.

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