

HARMONIC CAVITY PERFORMANCE FOR NSLS-II

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Abstract

NSLS-II is a 3 GeV ultra-high brightness storage ring planned to succeed the present NSLS rings at BNL. Ultra-low emittance combined with short bunch length means that it is critical to minimize the effects of Touschek scattering and coherent instabilities. Improved lifetime and stability can be achieved by including a third-harmonic RF cavity in the baseline design. This paper describes the required harmonic RF parameters and the expected system performance.

INTRODUCTION

NSLS-II is an advanced 3rd generation storage ring that is under design at BNL [1,2]. The goal of the machine design is to achieve a brightness $\sim 10^{21}$ ph/sec-mrad²-mm²-0.1%BW in the 0.3-20 KeV photon energy range with ~ 20 insertion devices. To provide high brightness a 24 cell triple bend achromat (TBA) lattice has been adopted that provides ~ 1 nm horizontal emittance. In-vacuum permanent magnet type or superconducting Mini Gap Undulators (MGUs) make up the major fraction of the proposed IDs. At 3 GeV, hard x-rays must be generated from the higher harmonic undulator radiation.

A consequence of the very low emittance lattice is a small value of the momentum compaction, which results in a short bunch. The very small volume of the electron bunch yields a Touschek lifetime of a few hours. Although the ring and injector systems are designed to operate in a top-off mode, increasing the lifetime is still beneficial, relaxing the specs for the injector system and limiting user exposure to the injection transients.

Lifetime can be increased while maintaining the small transverse emittance by using a Landau higher-harmonic cavity to increase the electron bunch length. This approach is effectively employed in many light sources worldwide including the NSLS VUV-Ring, ALS, SLS, ELETTRA and others. We are proposing to include a third-harmonic RF system in the NSLS-II from day one.

Harmonic RF will also play a beneficial role for NSLS-II in the area of collective effects. For example, NSLS-II operation must be kept below the microwave instability threshold. An increase in energy spread would significantly reduce the brightness of the higher undulator harmonics. By lengthening the bunch, harmonic RF will significantly increase the microwave instability threshold as well as help with several other instabilities. In addition, lengthening the bunch will reduce the resistive wall heat

loads in the superconducting undulator vacuum chambers which may simplify the cryostat design.

In summary, the main benefits of harmonic RF are: (1) increased Touschek lifetime; (2) simplified top off injector design; (3) higher thresholds for certain coherent instabilities; (4) reduced resistive heat load on critical machine components, including Mini Gap Undulator chambers; and (5) ability to run in a compressed bunch mode for specific user timing experiments.

FUNDAMENTAL RF SYSTEM

The 500MHz fundamental RF system must provide 3.49MV for a 3% momentum acceptance assuming 1.127MW of radiation losses with a full expected complement of insertion devices.

Table 1: Relevant parameters of NSLS-II

Particle energy, GeV	3	
Momentum compaction	0.00016	
Beam current, mA	500	
Ring Circumference, m	630	
RF frequency, MHz	500	
R/Q, Ω	45 \times 2	
Bucket Height	3%	
Harmonic number	1050	
Ion clearing gap buckets	210	
	No IDs	All IDs
Synchrotron losses, kW	426	1127
Energy loss per turn, MeV	0.85	2.25
Total RF voltage, MV	1.87	3.49
Parameters w/o HRF		
RMS bunch length, mm	3.8	3.3
Synchrotron tune	0.004	0.005
Harmonic RF parameters		
Frequency, MHz	1500	
R/Q, Ω	45 \times 2	
Total voltage, MV	0.865	

To provide this voltage and power we are proposing to use CESR-B type Superconducting (SC) RF cavities. The lower R/Q made possible by the design of SCRF cavities reduces the total impedance of the RF system. The SCRF cavities can achieve a higher voltage per cavity than copper cavities resulting in fewer installed cavities. The CESR-B cavity at 500MHz is compact in size, has available high power klystrons and is compatible with injection system RF frequencies (both 2.99GHz linac and 500MHz booster frequencies). Two cavities placed back

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to back can be installed in a $\sim 5.2\text{m}$ length. It is a mature design which is available commercially, and a harmonic cavity at 1500MHz has already been produced for BESSY [3]. One limitation is the maximum power per coupler of $\sim 300\text{kW}$. To meet the NSLS-II requirement of 1127kW with the original coupler four cavities are needed. We are proposing to modify the CESR-B design to incorporate dual antennae couplers. The required voltage of 3.49MV can be easily met by two of the Cornell CESR-B cavities that can provide up to 2.4MV each. Modification to antennae couplers would take advantage of the progress made in at LEP, KEK and LANL in coupler power handling, as well as allow 2 couplers to be mounted in a single cavity. This would reduce the number of straight sections required for the fundamental RF systems from 2 to 1. Klystron power sources of up to 800kW are available at 500MHz, allowing both couplers to be driven from the same klystron, eliminating control complexities.

The Higher Order Modes (HOMs) are highly damped due to the large beam tubes incorporating ferrite dampers. ZAP calculations show that longitudinal coupled bunch instability growth rates are lower than the radiation damping rate, eliminating the need for longitudinal feedback systems. Preliminary studies of transverse coupled bunch growth rates are not as conclusive and this instability may require damping, but a transverse feedback damper is already required due to resistive wall wakes.

HARMONIC CAVITY CHOICES

A number of factors have influenced the choice of technology for the Higher-Harmonic Cavities (HHCs). SC cavities can sustain higher fields requiring fewer cavities and less ring circumference. Only two SC HHCs are required to meet the 860kV harmonic-voltage requirement. The voltage required is rather lower than inverse scaling with HHC harmonic due to the shallower main-cavity potential well at the synchronous phase. Although HOMs damping of Normal Conducting (NC) cavities is effective at reducing coupled-bunch mode problems, damping is superior in SC cavities, which have a very limited number of HOMs, for SC cavities, the need for coupled-bunch feedback systems is all but eliminated.

Powered operation of HHCs is superior because the cavity phase can be varied for best lifetime. But this improvement is only modest even for a uniform fill and, due to the transients associated with bunch trains, the improvement cannot be fully realized [5]. Passive operation of a NC cavity is superior in terms of lifetime to passive SC cavities if there is top-off operation and the impedance and number of cavities can be chosen to better approximate the ideal phase for stretching. But most of that gain cannot be realized when there is a bunch train. In SC cavities' favour, their lower R/Q ratio results in a smaller cyclic response to gaps in the ring's fill, which is a significant effect that would otherwise reduce the improvement in lifetime. This lower R/Q is a direct result

of the strategies applied to reduce the number and impedances of HOMs in SC cavities.

GAP TRANSIENTS AND LIFETIME

HHCs stretch bunches by flattening the bottom of the longitudinal potential wells [4]. In practice, the increase in bunch length is limited by cyclic distortions of the wells introduced by the transient associated with a gap in the fill pattern which is commonly employed to suppress ion trapping and to accommodate certain experimental programs [5]. Our working assumption for NSLS-II is to run with a 20% gap, i.e. 210 consecutive empty buckets. In this case, improvement in the lifetime is typically less than expected for a symmetric fill. It is necessary to provide a detailed accounting of bunch shapes to realistically estimate the beam lifetime.

This section presents results of calculations for potential well distortion due to gap transients and their impact on bunch shapes and lifetime. Machine parameters are given in table 1. In our calculation, both main- and harmonic-cavity transients are included; the main-cavity transient is rather less intense due to its scaling with frequency. The beam-induced fields have steady state components at their RF frequencies; these components are regarded as absorbed into the RF-system-induced fields leaving a residual field perturbation that is approximately antisymmetric about the center of the train [6]. For a cavity with frequency at harmonic number h and loss factor k , the perturbation (within the train) has the form

$$\delta V(t) = 2qk \cos(h\phi) \frac{t}{T_0},$$

where q is the effective charge [6] of the gap, the time variable t parameterizes bunch position along the train (centered at $t = 0$), and ϕ is azimuthal phase across each bunch. To a second approximation, where $\phi \ll 1$, this perturbation simply provides bunch-dependent shifts of field intensities seen by the bunches, and consequently shifts their synchronous phases. Each cavity (two main and two harmonic) contributes a perturbation term. The charge q , which represents the lack of charge in the gap, has opposite sign relative to the train charge, so leading bunches see increased field, synchronous phases are shifted ahead on the trailing half of the train, and behind on the leading half of the train. Furthermore, due to the greater main-cavity slope of the field on the trailing side of each bunch, the lagging buckets have deeper potential wells and contain bunches that are more sharply peaked. Figure 1 shows the profiles of bunches across the length of the bunch train.

Lengths and lifetimes of the individual bunches are strongly dependent on position along the bunch train; the leading bunches have less than 30% the lifetime of bunches near the center. Only a few of the bunches near the center of the train approximate the ideal shape. Note that, in top-off mode, maintaining a uniformly filled bunch train requires a non-uniform filling pattern.

The average lifetime as a function of single-gap fill fraction is shown in figure 2, and the bunch shape for the

uniformly filled case compared to the unstretched bunch is shown in figure 3. The obvious asymmetry of the stretched bunch in figure 3 is due to the passive operation of the cavity, which puts the harmonic-cavity phase at the non-optimal -90 degrees. In spite of this, the Touschek lifetime of the stretched bunch is still 3.8 times that of the unstretched bunch. Realizing this potential lifetime gain requires minimizing gap length. For comparison, the lifetime gain of the ideal stretched bunch is 4.8 times.

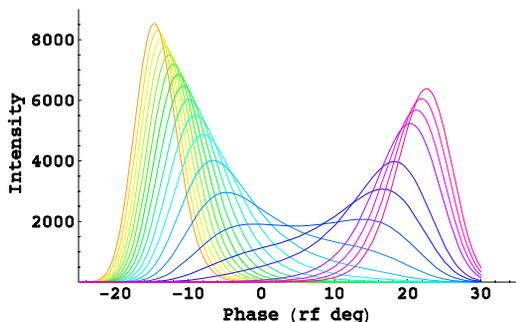


Figure 1: Line densities of bunches uniformly sampled along the length of an 80%-fill bunch train. The leading edge of each bunch is on the right and the progression of leading bunches to trailing bunches is from left to right. Each bunch is normalized to unity with respect to ring azimuthal angle.

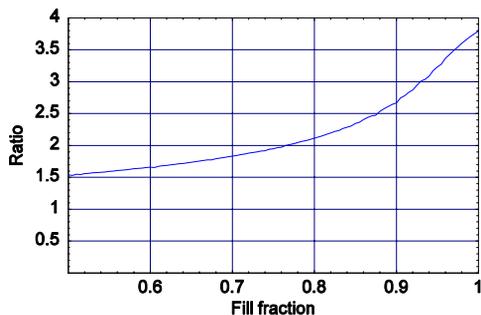


Figure 2: Touschek lifetime gain with respect to an unstretched bunch. The total current is held constant.

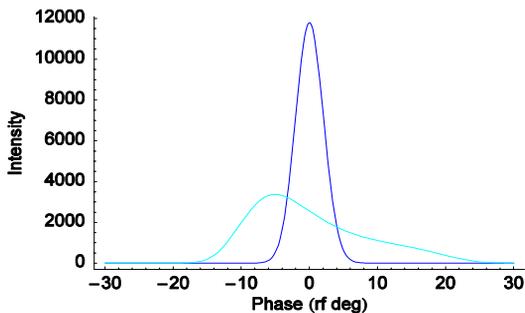


Figure 3: Line densities of unstretched (blue) and stretched (aqua) bunches in a uniform fill.

COHERENT INSTABILITIES AND HEAT

We also have estimated the effect of tripling the bunch length on the following three coherent instabilities: (1) the

longitudinal microwave instability threshold increases from $|Z_n/n| = 0.1\Omega$ to 0.3Ω , since the peak current is reduced by a factor of 3; (2) the threshold for the transverse coupled mode instability (TMCI) is proportional to the synchrotron tune ν_s . Since the Landau cavity reduces the synchrotron tune, it may decrease the TMCI threshold. There are two cases to consider. First, suppose the range of the wakefield is short compared to the bunch length. In this case, the threshold depends on the peak current, so lengthening the bunch counters the effect of reducing ν_s and the Landau cavity can be expected to result in only a small change in the TMCI threshold. On the other hand, if the range of the wakefield is long compared to the bunch length e.g. resistive wall, the threshold depends on the average current in the bunch, so lengthening the bunch (but still remaining shorter than the wakefield) can be expected to significantly reduce the threshold. (3) As for the coupled bunch modes, the threshold currents of the rigid dipole modes ($|m|=1$ for the longitudinal case and $m=0$ for the transverse case) due to long wavelength wake, such as the resistive wall wake and the RF-cavity parasitic wake with resonance angular frequency $\omega_r < 1/3\sigma_z$, are unchanged when the bunch is lengthened by a factor of 3. The threshold currents of the next higher modes (dipole mode, $|m|=1$, for the transverse case, and quadrupole mode, $|m|=2$, for the longitudinal case) decrease by a factor of $3^2 = 9$. Further calculations of couple bunch instabilities (CBIs) are in progress. The exact location of HOMs significantly depends not only on the cavity geometry but also the interface to the ring vacuum pipe.

Bunch stretching will also significantly reduce image current heat loads on ring components, including the most critical one – the superconducting MGU chamber. Assuming a Cu chamber in the extreme anomalous skin-effect regime, the power deposition scales as $I_{av}\sigma_z^{-5/3}$; so for NSLS-II parameters, tripling the bunch length reduces the heat load by about a factor of 6 from $\sim 5.4\text{W/m}$ to 0.8W/m . This is quite important for cryogenic design allowing heat removal with arrays of commercially available cryo-coolers, vs. a more expensive refrigerator option. Heat loads for (warm) in-vacuum permanent magnet undulators also reduce (this time $\sim I_{av}\sigma_z^{-3/2}$). But being quite low to begin with ($\sim 28\text{W/m}$ for unstretched bunch) they don't appear to present any problems.

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