Collective Effects in the NSLS-II Storage Ring

Brookhaven National Lab

And

F. Wang
MIT-Bates, Middleton, MA

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Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

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COLLECTIVE EFFECTS IN THE NSLS-II STORAGE RING*


Abstract
A new high-brightness synchrotron light source (NSLS-II) is under design at BNL. The 3-GeV NSLS-II storage ring has a double-bend achromatic lattice with damping wigglers installed in zero-dispersion straights to reduce the emittance below 1nm. In this paper, we present an overview of the impact of collective effects upon the performance of the storage ring. Subjects discussed include instability thresholds, Touschek lifetime and intra-beam scattering.

INTRODUCTION
In this paper, we discuss the effect of multi-particle interactions on the electron beam in the NSLS-II storage ring as described in the Conceptual Design Report [1]. The storage ring has 500 MHz RF and a revolution period of $T_s=2.6$ μs. The baseline design configuration corresponds to filling 80% of the RF buckets and leaving a 20% gap to allow for ion clearing. In this case we have $M=1040$ bunches, each containing $N_e=7.8\times10^9$ electrons ($N_e^c=1.25$ nC) corresponding to a total average current $I_p=MN_e^c/T_0=500$ mA and a single-bunch current $I_0=N_e^c/T_0=0.5$ mA. For an RMS bunch duration $\sigma_t=15$ ps, the peak bunch current is $I_p=N_e^c/\sqrt{2\pi} \sigma_t=3.3$ A.

The most accurate approach to estimating the instability thresholds for NSLS-II is to carry out computer simulation tracking studies using the wakefields determined by numerical calculation for each component comprising the storage ring. This large effort is now underway [2]. Here, we shall estimate instability thresholds using a simplified model of the ring impedance, which has been developed based on impedance calculations performed to-date and on the experience at existing storage rings [3] as well as on impedance calculations we have performed to-date. The impedance model is presented in Table 1, and some key beam parameters are given in Table 2. Calculations show [1] that radiation damping is sufficient to stabilize coupled bunch motion in the presence of the long-range wakefields due to the longitudinal and transverse broadband resonators whose parameters are chosen based on experience at other storage rings [3].

INSTABILITY THRESHOLDS
We consider an approximate model of the storage ring impedance. The storage ring vacuum chamber is approximated by 720 m of aluminum with a half-aperture of 12.5 mm. We also include 20 in-vacuum undulators, each with 3 m copper chambers of vertical half-aperture 2.5 mm. The geometric impedance due to cross-section changes in the vacuum vessel is approximated by longitudinal and transverse broadband resonators whose parameters are chosen based on experience at other storage rings [3] as well as on impedance calculations we have performed to-date. The impedance model is presented in Table 1, and some key beam parameters are given in Table 2. Calculations show [1] that radiation damping is sufficient to stabilize coupled bunch motion in the presence of the long-range wakefields due to the longitudinal and transverse higher-order modes in CESR-B superconducting cavities.

### Table 1: Impedance Model

<table>
<thead>
<tr>
<th>CESR-B HOMs</th>
<th>$\beta_x=18\text{m}$</th>
<th>$\beta_y=3\text{m}$</th>
<th>$\eta=0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_x=4.0\text{V/pC}$</td>
<td>$\kappa_y=0.68\text{KV/pC/m}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$720\text{ m of aluminum with half-gap of 12.5 mm and } \beta_x=7.6\text{ m}:$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa_x=1.3\text{V/pC}$</td>
<td>$\kappa_y=5.6\text{KV/pC/m}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$60\text{ m of copper with half-gap of 2.5 mm and } \beta_x=2\text{ m}:$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa_x=19\text{KV/pC/m}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse broadband impedance with $f_s=30\text{GHz}, R_y=1\text{MO/m}, Q_x=1$, and $\eta=7.6\text{m} :$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa_x=19\text{KV/pC/m}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal broadband impedance with $f_s=30\text{GHz}, R_y=30\text{kΩ}$, $Q_x=1 :$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\left(\text{Im} Z_0/n\right)_0=0.4 \text{Ω}$</td>
<td>$\kappa_x=399\text{ V/pC}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 2: Parameters for threshold calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, $E[\text{GeV}]$</td>
<td>$3$</td>
</tr>
<tr>
<td>Revolution period, $T_s[\text{μs}]$</td>
<td>$2.6$</td>
</tr>
<tr>
<td>Momentum compaction, $\alpha$</td>
<td>$3.7 \times 10^4$</td>
</tr>
<tr>
<td>Energy loss, $U[\text{keV}]$</td>
<td>$1172$</td>
</tr>
<tr>
<td>RF voltage, $V[\text{MV}]$</td>
<td>$3.7$</td>
</tr>
<tr>
<td>Synchrotron tune, $\nu_s$</td>
<td>$0.0094$</td>
</tr>
<tr>
<td>Damping time: $\tau_c, \tau_t[\text{ms}]$</td>
<td>$13, 6.5$</td>
</tr>
<tr>
<td>Energy spread, $\sigma_{\varepsilon,0}[$%$]$</td>
<td>$0.09$</td>
</tr>
<tr>
<td>Bunch duration, $\sigma_{\sigma_0}[$ps$]$</td>
<td>$15$</td>
</tr>
</tbody>
</table>

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*krinsky@bnl.gov
Transverse Mode Coupling Instability (TMCI)

An approximate relation [5] determining the threshold of the TMCI at zero chromaticity is given by

$$\Delta V_y = \frac{e I_0^R}{2E V_s \omega_0} \sum_j \beta_{y,j} \kappa_{y,j} = 0.7,$$

(1)

where $I_0^R$ is the threshold bunch current, $\beta_{y,j}$ is the average value of the vertical beta function in the $j^{th}$ element, and $\kappa_{y,j}$ is its kick factor. $E = \gamma mc^2$ is the electron energy and $V_s$ is the synchrotron tune. Consider a bunch current of 0.5 mA. Using the NSLS-II parameters as described in Table 2, we find that to be below the TMCI threshold requires

$$\sum_j \beta_{y,j} \kappa_{y,j} < 180 \text{ KV/pC}.$$  

(2)

Using the values of the kick factors and beta functions as specified in Table 1, we find that

$$\sum_j \beta_{y,j} \kappa_{y,j} = 160 \text{ KV/pC}.$$ Therefore, 0.5 mA bunches are below the TMCI threshold for zero chromaticity.

Longitudinal Microwave Instability

At very low single-bunch current, the longitudinal density is determined by the equilibrium between radiation damping and quantum fluctuations. As the bunch current increases, the longitudinal charge distribution is modified by the wakefield. Below the threshold of the microwave instability, the energy distribution remains unchanged, and the longitudinal charge distribution is determined by the time-independent solution of the Haissinski equation [6].

Once the current exceeds the microwave instability threshold, both the energy distribution and the charge distribution are modified and are no longer time-independent. In the case of a broadband resonator with shunt impedance $R_s$, resonant frequency $\omega_s$, and quality factor $Q_s = 1$, Oide and Yokoya [7] have shown that the single-bunch current threshold is given by

$$I_0^R = \frac{E V_s \sigma_e}{\epsilon R_s (\omega_s / \omega_0)} S(\omega_s, \sigma_r).$$

(3)

From tracking studies using the program ELEGANT [8], we have found that in the regime $x > 0.2$ a useful fit to the scaling function is given by

$$S(x) = 11 + 9.4(x - 0.7)^2.$$  

(4)

In Fig. 1, we show the dependence of the bunch length and the energy spread as calculated using the program ELEGANT [8]. This shows that 0.5 mA bunches will suffer negligible increase in energy spread due to the longitudinal microwave instability. These estimates we made without including the effect of a third-harmonic cavity. Including it will increase the microwave threshold.

Particle tracking [9] has been used to estimate transverse stability thresholds for coupled bunch modes. In these calculations we include both the long-range and short-range resistive wall wakefields as well as the short-range longitudinal and transverse wakefields, as described in Table 1. To keep the problem manageable, we assume that all RF buckets contain identical bunches interacting via a single coupled bunch mode. A single bunch is tracked and the effect of other bunches is obtained by appropriate phase shifts under the assumption that the coherent frequency shift is small compared to the characteristic frequency width in the long-range transverse impedance. This should be an excellent approximation for the resistive wake impedance, which dominates the long-range transverse wake. The resistive wall impedance as well as the longitudinal and transverse broad band resonator parameters are as given in Table 1.

Three cases were simulated. Case 0 is a "stripped" case with no longitudinal wakes, no quadrupolar wakes (also referred to as detuning wakes), and no third-harmonic RF. Case 1 has the full suite of collective effects but no third harmonic cavity. Case 2 includes a perfect third harmonic cavity. The single-bunch threshold current as a function of vertical chromaticity is shown in Fig. 2. In cases 1 and 2, a chromaticity of 4 allows for an average bunch current of about 0.5 mA and hence for an average
stored current of 500 mA. This demonstrates the importance of running at positive chromaticity. Note also that bunch lengthening and enhanced synchrotron frequency spread introduced by the longitudinal wakefield and the third-harmonic cavity increase the effectiveness of positive chromaticity to stabilize the beam. Operating with large positive chromaticity can increase the instability threshold; however, it can reduce energy acceptance and shorten Touschek lifetime. Therefore, transverse feedback is included in the NSLS-II design.

**Intrabeam scattering (IBS)**

The NSLS-II emittance is strongly dominated by the IDs and damping wigglers. We have calculated IBS effects [11] as a function of radiation losses in the machine, having $\varepsilon_0$ vary from the $\sim$2 nm bare lattice value down to about 0.4 nm. The zero-current vertical emittance $\varepsilon_0$ was fixed at the diffraction limit for 1 Å x-rays (8 pm-rad), corresponding to coupling varying from $\sim$0.5% for bare lattice to about 2% for $\varepsilon_0 = 0.4$ nm.

Calculations have been performed with the code ZAP [12]. We assumed 500 mA average ring current uniformly distributed into 80% of the 500 MHz RF buckets. As we changed the amount of radiation losses, the RF voltage was adjusted to keep the RF energy acceptance constant at 3%. Electron beam parameters in the absence of IBS, used as input to ZAP (such as horizontal emittance, energy spread, bunch length, and radiation damping times) were calculated analytically by scaling bare lattice values by the amount of radiation losses. As the emittance w/o IBS is reduced, the damping time is also decreased. In Fig. 4, we see that IBS increases the horizontal emittance by $\sim$20% for all values of the energy loss per turn. These estimates were done without harmonic RF. Adding it reduces the peak density and alleviates the IBS effect.

**References**

[5] See e.g., S. Krinsky, BNL-75019-2005-IR.