High Current Effects at NSLS-II

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for
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Outline and Scope

• Scope of this talk
• Motivation
• Touschek lifetime – new regime
• IBS – results and questions
• Impedance budget (ID chambers)
• The rest & status review
• Summary and conclusions

Parameter Goals for NSLS-II
I = 500 mA ( 0.5 mA/bunch )
\( \varepsilon_x = 0.5-1 \) nm
\( \varepsilon_y = 1 \) Angstrom/4\( \pi \)
\( \delta E/E = 0.1 \% \)
Lifetime & Collective Effects

Become harder with higher brightness

- small bunch in all 6D
- high current
- many small gap IDs

Lower lifetime & instability thresholds

Known solutions

• Topoff injection (lifetime => radiation) ✓
• Harmonic RF ✓
• $Z(\omega)$ minimization (HOM-damped RF, BB minimization,…) ✓
• Multi-bunch feedback systems ✓

Challenges

• need $|Z/n| < 0.5 \, \Omega$ for MW threshold in multi-bunch
• TMCI due to resistive wall from small gap IDs

Baseline for NSLS-II:
1.5 GHz SC harmonic cav.

Single bunch instabilities become most challenging esp. at medium energy
Lifetime Limiting Mechanisms

- Quantum – not a problem
- Gas – Elastic
  Vertical acceptance due to MGUs (gap = 2b = 5mm, L = 5m) is $A \sim 1 \mu m$-rad

\[
\frac{1}{\tau_{\text{scat}}} = \frac{4r_e^2 Z^2 \pi n_c}{2 \gamma^2} \left[ \frac{\langle \beta_x \rangle \beta_{x,\text{max}}}{a^2} + \frac{\langle \beta_y \rangle \beta_{y,\text{max}}}{b^2} \right] \rightarrow \tau_{\text{scat}} \approx 24 \text{ hours @} 1 \text{ nTorr } N_2
\]

- Gas – Bremsstrahlung

\[
\frac{1}{\tau_{\text{brem}}} = \frac{16r_e^2 Z^2 n_c}{411} \ln \left[ \frac{183}{Z^{1/3}} \right] \left[ -\ln \varepsilon_{\text{acc}} - \frac{5}{8} \right] \rightarrow \tau_{\text{brem}} \approx 72 \text{ hours @} 3\% \varepsilon_{\text{acc}}
\]

Gas contributions to lifetime are small
It’s now all about Touschek
Touschek Lifetime Basics

• For flat and transversely non-relativistic beams (works well for NSLS-II)

\[
\frac{1}{\tau_{\text{tous}_1/2}} = \frac{\sqrt{\pi r^2 c N_b}}{\gamma^3} \frac{C(\zeta)}{\sigma' V \varepsilon_{\text{acc}}^2} \quad \zeta = \left[ \frac{\varepsilon_{\text{acc}}}{\gamma \sigma}' \right]^2
\]

Acceptance \( \varepsilon_{\text{acc}} \) is likely lattice limited

\[
V = 8 \pi^{3/2} \sigma_x \sigma_y \sigma_z
\]

Needs averaging over the ring

• Decay is non-exponential, but is assumed linear for frequent topoff

\[
N_b(t) = \frac{N_b(0)}{1 + t / \tau_{\text{tous}_1/2}} \quad \Rightarrow \quad \tau_{\text{total}} = 1 / (\tau_{\text{gas}}^{-1} + \tau_{\text{brem}}^{-1} + \tau_{\text{tous}_1/2}^{-1})
\]

• Energy spread dependence (through dispersion) is typically weak

• Touschek is peak current effect, i.e. \( \tau_{\text{tous}_1/2} \sim \sigma_z / N_b \)
Touschek Scaling with Emittance – New Regime

\[
\frac{1}{\tau_{\text{tous}}^{1/2}} = \frac{\sqrt{\pi r_e^2 c N_b C(\zeta)}}{\gamma^3 \sigma_x' V \varepsilon_{\text{acc}}^2} = \frac{\sqrt{\pi r_e^2 c N_b}}{\gamma^2 \varepsilon_{\text{acc}}^4} \sigma_x^4 V D(\zeta)
\]

Roughly \( \varepsilon_x \) independent, for fixed \( \varepsilon_y \)

Similar to Le Duff

\[
\zeta = \left( \frac{\varepsilon_{\text{acc}}}{\gamma \sigma_x'} \right)^2 \approx \frac{\varepsilon_{\text{acc}}^2}{\gamma^2} \frac{\beta_x}{\varepsilon_x}
\]

Ignores dispersion

\( \beta_x = 7.2 \text{m, } \varepsilon_{\text{acc}} = 3\% \)

\( \star \) \( \zeta = 0.13 \text{ @ } \varepsilon_x = 1.4 \text{ nm} \)

\( \diamond \) \( \zeta = 0.38 \text{ @ } \varepsilon_x = 0.5 \text{ nm} \)

Lattice-averaged rates (\( \sigma_z = 4 \text{ mm, } \varepsilon_{\text{acc}} = 3\% \))

\( \tau_{\text{tous}} = 4 \text{ hours @ } \varepsilon_x = 1.4 \text{ nm} \)

\( \tau_{\text{tous}} = 4 \text{ hours @ } \varepsilon_x = 0.5 \text{ nm} \)

For \( \varepsilon_x \approx 1\text{-nm} @ 3 \text{ GeV} \) Touschek lifetime reaches minimum, and should grow at lower \( \varepsilon_x \). Experimental confirmation, anybody?
Touschek Lifetime vs. Acceptance and Total Lifetime

- Most calcs. for bare lattice w/o apertures. Effect of IDs included “by hand” in ZAP
- ZAP, SAD & MAD results agree
- Work in progress to consider other effects, i.e. lattice nonlinearities, $\alpha_2$, effects of IDs, errors & coupling correction, bunch lengthening, etc.
- Lattice-dependent momentum aperture being done by 6D tracking (Elegant and TRACY2)

\[ \tau_{\text{tous}_{1/2}} \approx \text{const} \times \varepsilon_{\text{acc}}^4 \]

\[ \tau_{\text{tous}_{1/2}} \approx 4 \text{ hours} @ 3\% \text{ RF acc.} \]

\[ \tau_{\text{total}} = \frac{1}{(\tau_{\text{gas}}^{-1} + \tau_{\text{brem}}^{-1} + \tau_{\text{tous}_{1/2}}^{-1})} \approx 3 \text{ hours} \]
Multiple Intra-Beam Scattering (IBS)

ZAP Calculations for I=500 mA

- $\varepsilon_x$, $\delta E/E$, $\tau_{rad}$, scaled “by hand” for radiation loss
- Bare lattice case agrees with SAD and Bane’s approx.
- Emittance blow-up: $< 50\%$ @ 3 GeV, $< 15\%$ @ 3.5 GeV
- Smaller $\varepsilon_x$ offset by shorter $\tau_{rad}$
- Will re-run with 3D code SAD with IDs and vertical $\eta$
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IBS with Bunch Lengthening

- ZAP calcs shown @ 1.4 MV loss/Trn
- Harmonic RF (HRF) x2-3 in $\sigma_z$
- Ignore PWD
- IBS is small
- Will re-run with 3D code SAD with IDs and vertical $\eta$

With realistic bunch lengthening IBS effect is small for NSLS-II
# NSLS-II Impedance Budget

**Table 1: Budget impedance of the NSLS-II ring components**

<table>
<thead>
<tr>
<th>Components</th>
<th>$\text{Im}Z'_0(\omega \rightarrow 0)$, $\Omega/m$</th>
<th>$\text{Im}Z'_1(\omega \rightarrow 0)$, $\Omega/m$</th>
<th>$\frac{\text{Im}Z'_1(\omega)}{\omega}$, $\Omega$</th>
<th>$\kappa_\text{G}$, V/pC/m</th>
<th>$\kappa_\text{S}$, V/pC/m</th>
<th>$\kappa_\text{BSB}$, V/pC</th>
<th>Estimated number of components</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Tapered elliptic vacuum chamber</td>
<td>$3 \cdot 10^3$ (75 $\mu$m)</td>
<td>$965$ (100 $\mu$m)</td>
<td>$30 \cdot 10^{-6}$ (100 $\mu$m)</td>
<td>86 (75 $\mu$m)</td>
<td>30</td>
<td>0.311 $\cdot 10^{-3}$</td>
<td>10</td>
</tr>
<tr>
<td>2. Room Temperature MGU</td>
<td>$58 \cdot 10^3$ (500$\mu$m)</td>
<td>$3.9 \cdot 10^3$</td>
<td>$130 \cdot 10^{-6}$ (500 $\mu$m)</td>
<td>505</td>
<td>112</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>3. Shielded RTMGU</td>
<td>$22 \cdot 10^3$ (500$\mu$m)</td>
<td>$3 \cdot 10^3$ (500$\mu$m)</td>
<td>$127 \cdot 10^{-6}$ (500$\mu$m)</td>
<td>245</td>
<td>73</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Dipole vacuum chamber</td>
<td>$1.1$</td>
<td>$17.6$</td>
<td>$0.073 \cdot 10^{-6}$</td>
<td>$4.6 \cdot 10^{-2}$</td>
<td>0.68</td>
<td>$0.240 \cdot 10^{-3}$</td>
<td>72</td>
</tr>
</tbody>
</table>

**GDFIDL Results**
## NSLS-II Impedance Budget (Cont.)

<table>
<thead>
<tr>
<th>Components</th>
<th>$\text{Im}Z_\phi(\omega \to 0), \ \Omega/m$</th>
<th>$\text{Im}Z_\phi(\omega \to 0), \ \Omega/m$</th>
<th>$\text{Im}Z_\phi(\omega), \ \Omega$</th>
<th>$k_{s}, \ W/(pC/m)$</th>
<th>$k_{r}, \ W/(pC/m)$</th>
<th>$k_{loss}, \ W/(pC)$</th>
<th>Estimated number of components</th>
</tr>
</thead>
<tbody>
<tr>
<td>5. Photons absorber</td>
<td>1.1</td>
<td>17.2</td>
<td>0.037 $\cdot 10^{-5}$</td>
<td>2.9 $\cdot 10^2$</td>
<td>0.43</td>
<td>0.139 $\cdot 10^{-3}$</td>
<td>120</td>
</tr>
<tr>
<td>6. BPM</td>
<td>54</td>
<td>42.1</td>
<td>1.1</td>
<td>0.87</td>
<td>19.97 $\cdot 10^{-3}$</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td>7. Elliptic bellows</td>
<td>8.9 $\cdot 10^3$</td>
<td>4.6 $\cdot 10^3$</td>
<td>126.2</td>
<td>74.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Transition from absorber to regular vacuum chamber</td>
<td>9.8 $\cdot 10^3$</td>
<td>77</td>
<td>1.14 $\cdot 10^6$ ($\text{bellows}$)</td>
<td>55</td>
<td>10.4</td>
<td></td>
<td>48</td>
</tr>
</tbody>
</table>

Alexei Blednykh
Geometric Impedance of Small Gap ID Chambers

- NSLS-II will have ~20 small gap ID chambers of 5mm full gap
- Many LS reported lower TMCI threshold with increased # of IDs
- Existing analytical solution (round x-section or very flat) don’t directly apply to NSLS-II
- Obtained analytical solution for $Z_\perp(0)$ for gradual confocal tapers
- Confirmed by GDFIDL

Impedance of NSLS-II ID tapers is <10 kΩ/m, and is less than Res. Wall. Need to understand higher measured numbers from some other LS.
**TMCI due to MGU Resistive Wall**

- TMCI driven by small undulator gaps is a concern: $Z_{\perp}(\omega) / L \sim a^{-3}$
- Threshold: $\Delta \nu_y = \frac{I_{th} W_{\perp}^{\text{max}} \beta_y^* L}{2 \omega_{rev} E / e} = \nu_s$
- NSLS-II undulators: 
  - assume 100 m of Cu pipe 5 mm $\varnothing$
  - $I_{th} \approx 1 \text{ mA} / \text{ bunch} \quad \text{warm}$
  - $I_{th} \approx 4 \text{ mA} / \text{ bunch} \quad \text{cryo}$
  - $\beta_y^* = 5 \text{ m}, \sigma_z = 3.3 \text{ mm}, \nu_s = 0.005$
- Also confirmed by simulations (MOSES, tracking)
- This does not change significantly with harmonic RF

\[ W_{\perp} \left[ \frac{\nu}{\text{pC/m}^2} \right] \]

\[ \rho \left[ \text{arb} \right] \]

At operating value of 0.5 mA/bunch, we are below TMCI threshold
Other Issues Studied

• RF cavity and resistive wall driven coupled bunch instabilities
• Damping of transverse couple bunch inst. with positive chromaticity
• Beam dynamics with harmonic RF
• TMCI particle tracking with harmonic RF included
• Micro-Wave instability (Tracking, Oide-Yokoya method, Fokker-Plank solver)
• Coherent synchrotron radiation instability
• Resistive heat of (SC) undulator chambers

None of these presently appear showstoppers for NSLS-II design
Summary and Conclusions

• NSLS-II is optimized for nominal multi-bunch operation, and uses many known solutions to ease high current effects
• NSLS-II single bunch and high current goals appear to be achievable
• Touschek lifetime of a few hours is in the new regime, experimental confirmation would be welcome. Tracking (Elegant, TRACY2) in progress for momentum acceptance, loss distribution, etc.
• (Multiple) IBS appears insignificant
• Transverse couple bunch instability may require feedback
• Impedance budget work is ongoing. Results will feed into Elegant and other codes, as well as will be re-evaluated analytically
• Would like collaboration with other facilities on understanding measurement results due to small gap ID chambers
EXTRA
Concluding Remarks

• Single bunch and average current goals appear to be achievable
• Transverse coupled bunch instability may require feedback
• We are facing a theoretical puzzle in regard to microwave instability threshold, which we are working to resolve. However, the threshold is above the 0.4ma required.
• At the moment we are estimating instability thresholds based on the impedances observed at ESRF and APS.
• We are calculating the NSLS-II impedance budget. Once this is done, we will estimate the instability thresholds using the calculated impedance.
• Realistic calculation of the Touschek lifetime is of critical importance. Work on this problem is underway using both TRACY2 and ELEGANT.
• TMCI and/or TMW instabilities are observed at many synchrotrons and may limit single bunch current

• Generally both the geometric (transitions) and resistive wall wakes contribute

• For typical short, warm, MGUs the geometric wake exceeds the resistive wall

Geometric wake will be made small with shallow taper and optimal transition design to minimize the geometric contribution to the impedance and avoid the TMCI instability
Resistive Wall for Normal and Anomalous Skin Effect Regimes

- **(Warm) Permanent Magnet MGUs (Cu @ 300 K)**
  
  Normal Skin Effect: \( l/\delta_{sk} \ll 1 \implies Z_{s\_normal}(\omega) = \sqrt{\frac{\omega \mu}{2 \sigma_{\text{cond}}}} (1 - i) \)

- **(Cold) Superconducting SCUs (Cu @ 4.2 K)**
  
  Extreme Anomalous Skin Effect:
  
  \( l/\delta_{sk} \gg 1 \implies Z_{s\_extreme}(\omega) = A\omega^{2/3} (1 - i\sqrt{3}) \)

  with \( A = 0.033 \text{ ps}^{5/3} \text{ V/pC} \) for Cu, independent of \( \sigma_{\text{cond}} \) (RRR)

We derived most resistive wall related quantities (short/long range wakes, loss/kick factors, instability thresholds, etc.)
Resistive Wall Heating

• (Warm) Permanent Magnet MGUs (Cu @ 300 K)
  \[ \frac{P}{L} = 5.6 \times 10^{-5} \frac{I_{av}^2 \lambda_{RF}}{a \sigma_z^{3/2}} \]

  \( \frac{P}{L} \sim 28 \text{ W/m (warm Cu), or 140 W for 5 m undulator, easily handled} \)

• (Cold) Superconducting SCUs (Cu @ 4.2 K)
  \[ \frac{P}{L} = 4.2 \times 10^{-6} \frac{I_{av}^2 \lambda_{RF}}{a \sigma_z^{5/3}} \]

  Conservative Estimate*: \( \frac{P}{L} \sim 5 \text{ W/m (cold Cu), or 25 W for 5 m undulator, exceeds off-the-shelf single cryo-cooler capacities but could be handled by individual refrigerator. Harmonic RF may reduce this a factor of ~ 6.} \)

*Ignore bunch lengthening, ignore chamber ellipticity, allow for \( \Delta \) by \( a \to a - \Delta \), 4/5 RF buckets filled \( \to +25\% \)

average current \( I_{av} \) 500 mA
rms length \( \sigma_z \) 3.3 mm
RF wavelength \( \lambda_{RF} \) 60 cm
half ID gap \( a \) 2.5 mm
off-center error \( \Delta \) 0.5 mm
Synchrotron Radiation Heat Load on Undulator

- Undulator radiation has finite opening angle
- Small fraction hits the cold bore
- $P \sim 40 \text{ W}$ for 5 m undulator

![Graph showing power deposited in undulator vs. undulator length.]

- Warm MGU – easily handled
- Cold SCU - exceeds off-the-shelf single cryo-cooler capacities but could be handled by individual refrigerator.
Longitudinal Single Bunch Instabilities

- Microwave $\frac{\lambda_{\text{inst}}}{\sigma_z} << 1$
  - Boussard criterion $|Z_n/n| < ~0.1 \ \Omega \ < \text{low!}$
  - Lower $|Z_n/n|$ are believed achievable (i.e. ILC DR)
  - However, Boussard criterion is conservative
  - Harmonic RF (and PWD) increases the threshold $\sim \sigma_z$

- Mode-Coupling $\frac{\lambda_{\text{inst}}}{\sigma_z} > \sim 1$
  - Scaling NSLS ring $Z(\omega)$ gives $I_{\text{total}} > 1$ A
  - Scaling is very simplistic
    $\Rightarrow Z(\omega)$ budget is needed
  - Harmonic RF increases the threshold but slower than $\sim \sigma_z$

- Tight impedance control will be required

- Self-stabilize through increase in $\delta E/E$
- Not significantly driven by MGUs
Use of a bunch lengthening Landau cavity can increase Touschek lifetime, raise microwave instability threshold and decrease intrabeam scattering. Initial estimates indicate we can increase bunch length by factor of ~2.5
Geometric Impedance of Axially Symmetric Tapers

- At low frequency shallow taper impedance is imaginary and small
  \[ Z(\omega) \sim i\theta, \quad (\sigma_z \gg a\theta) \]
- Analytical expressions exist for impedance in this (Yokoya) regime

NSLS-II 0.5 m (\(\theta=25\) mrad) MGU tapers result in sufficiently low impedance to avoid MW and TMCI instabilities

\[ |Z_{\|}/n|=0.2 \text{ m}\Omega \quad Z_{\perp}=1 \text{ k}\Omega/m \]

Estimates confirmed by simulation

Also considered elliptical chambers

\(Z_y\) grows factor of \(\sim6\) but still low enough for TMCI
New Results (Convex Structure)

First order PT $Z_{x,y}$ and New GDFIDL Results

- GDFIDL & 1st order PT agree well for weakly elliptical case $Z_y$
- Perfect agreement for $Z_x$
- $Z_y$ growth saturates for very flat tapers at $\sim 10*Yokoya$
- $Z_x$ is $Yokoya/2$ for flat tapers

• PAC-05 Conjecture: PT clearly breaks down for flat structures
  Example: $Z_x$ should be 0 (not 0.5) for a flat structure
  • To confirm needed to extend the PT to higher orders

<= Not for $Z_x$
<= wrong