Beam Impedance and Heating for Several Important NSLS-II Components

A. Blednykh
Simulation of Power Dissipation and Heating from Wake Losses in Accelerator Structures
Mini-Workshop, DIAMOND, Jan. 30, 2013
Acknowledgments

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• **CAD/BNL:**
  I. Pinayev

• **SLAC:**
  M. Ferreira

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  L. Emery, J. Hoyt, G. Goeppner, J. Gaglian
Outline

• Large Aperture BPM Button Analysis
• RF Shielding Design for the NSLS-II Bellows
• Test of the NSLS-II Bellows Under Beam in the APS Storage Ring.
• Stripline Beam Impedance
• Impedance of the NSLS-II Diagnostic Straight Section
• Summary
NSLS-II Current

N = number of electrons in single bunch (7.8x10⁹)

Ne = Bunch Charge (1.25 nC)

M = number of bunches (1080)

Single Bunch Current \[ I_0 = \frac{N \ e}{T_0} \] (.5 mA)

Peak Bunch Current \[ I_p = \frac{N \ e}{\sqrt{2\pi \sigma_t}} \] (33 A for \( \sigma_t=15 \) ps)

Average Current \[ I_{av} = \frac{M \ N \ e}{T_0} \] (500mA)
Large Aperture BPM (Ø7mm)

BPM Assembly

- The Cutoff Frequency of $H_{m1}$-Mode ($\varepsilon_r=1$)
  \[
  f^H_{c,m1} \approx \frac{1}{\sqrt{\varepsilon_r}} \frac{c}{\pi} \frac{m}{R1 + R2}, \quad \text{where} \quad m = 1, 2, 3, \ldots
  \]
- $f_{H11}$ & $f_{H21}$
- HOM’s Due to Dielectric Are Seen by the Beam

Real Part of the Longitudinal Narrow-Band Impedance

- Trapped $H_{11}$-Mode
- HOM due to Dielectric
- $H_{21}$-Mode

Longitudinal Wakepotential

$\sigma_s = 9 \text{mm}$
$\sigma_s = 4.5 \text{mm}$
$\sigma_s = 3 \text{mm}$

$R1=3.5\text{mm} \& R2=3.75\text{mm}$
Losses and Heating

Single Bunch Passing

Multi-Bunch Train (Equally Spaced)

\[ \kappa_{loss} = \sum_{n=0}^{\infty} \int_{-\infty}^{\infty} ds \int_{-\infty}^{s'} \rho(s') w(s' - s + nl) \rho(s') = \]

\[ = \sum_{n=0}^{\infty} \frac{C}{\pi} \int_{0}^{\infty} dk |\tilde{\rho}(k)|^2 \left[ \text{Re} Z(k) \cos(knl) + \text{Im} Z(k) \sin(knl) \right] \]

Loss Factor as a Function of Bunch Length

\[ P_{loss} = T_0 \frac{l_{av}^2}{h} k_{loss} = 492 \times k_{loss} \]

\[ k_{loss}^{\text{geom}} (\sigma_s = 3\text{mm}) = 8.7\text{mV/pC} \]

\[ P_{loss} = 4.3W \]

Total Loss Factor
BPM Flange

• Single Bunch Passing (Geom.)

<table>
<thead>
<tr>
<th></th>
<th>( \sigma_s ) mm</th>
<th>( k_{loss} ) mV/pC</th>
<th>( P_{loss} ) W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance Budget</td>
<td>3</td>
<td>20</td>
<td>---</td>
</tr>
<tr>
<td>Average Current (300mA)</td>
<td>4.5</td>
<td>12</td>
<td>2.6</td>
</tr>
<tr>
<td>Average Current (500mA)</td>
<td>9</td>
<td>2</td>
<td>0.4</td>
</tr>
</tbody>
</table>

• Total Losses

\[
\sum k_{loss}^{tot} = k_{loss}^{SB} + k_{loss}^{MB}
\]

<table>
<thead>
<tr>
<th>( \sigma_s ) = 3mm</th>
<th>( \sigma_s ) = 4.5mm</th>
<th>( \sigma_s ) = 9mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total loses, mV/pC</td>
<td>86</td>
<td>44 (n=8)</td>
</tr>
</tbody>
</table>

• Power Loss (@500mA)

\[
P_{loss} = T_0 \frac{I_{av}^2}{h} k_{loss} = 42W
\]

\( g = 100\mu m \) and \( h = 10\) mm
\( R_1 = 30.5\) mm and \( R_2 = 30.6\) mm
\( 2a = 76\) mm and \( 2b = 25\) mm

Longitudinal Long-Range Wakepotential

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Mode Classification

Time Domain
Real part of the longitudinal impedance

$$f_1 = 7.3\text{GHz}$$
$$f_2 = 8\text{GHz}$$
$$f_4 = 11.6\text{GHz}$$
$$f_5 = 14.1\text{GHz}$$

Frequency Domain

TEM-mode, $$f_1 = 7.1\text{GHz}$$

$$H_{111}$$-mode, $$f_2 = 7.9\text{GHz}$$

$$H_{311}$$-mode, $$f_4 = 11.6\text{GHz}$$

- Existence of trapped modes in a space between the vacuum chamber and the BPM flange
- Trapped modes have been classified
- Electric field distribution of TEM-mode and $$H_{m11}$$-modes are shown in figures

“Simulation of Power Dissipation and Heating from Wake Losses in Accelerator Structures”, Mini-Workshop, DIAMOND
Frequencies Analysis

Frequencies of the Resonant Coaxial Cavity

(1) \[ f_{TEM}^{Coax} = \frac{c}{2} \times \frac{m}{L_{str}}, \text{ where } m = 1,2,3... \]

(2) \[ f_{Hm1p}^{Coax} = \frac{c}{2\pi} \sqrt{\left( \frac{2\pi \times m}{\pi (R1 + R2)} \right)^2 + \left( \frac{\pi \times p}{L_{str}} \right)^2}, \]

where \( m = 1,2,3... \) and \( p = 1 \).

BPM Flange

R1=15.3mm, R2=15.2mm and L_{str}=21mm (fitted)

\[ f_{TEM}^{Coax} : \ 7.1GHz, 14.3GHz, 21.4GHz \text{ and } 28.6GHz \]

\[ f_{Hm1p}^{Coax} : \ 7.8GHz, 9.5GHz, 11.8GHz, \text{ and } 14.4GHz \]

Simulations of the Coaxial Cavity

R1=15.4mm, R2=15.2mm and L_{str}=10mm

TEM_1-mode

TE_{111}-mode

\[ f_{Eq}^{TE_{111}} = 15.28GHz \]

\[ f_{Eq}^{Gdf} = 15.31GHz \]

Real part of the longitudinal impedance

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RF Shielded BPM Assembly

Geometric parameters:
g=100um and h=2mm
\(d_1=30.5\text{mm}\) and \(d_2=30.6\text{mm}\)
\(2a=76\text{mm}\) and \(2b=25\text{mm}\)

B. Kosciuk

Longitudinal long-range wakepotential
\[ \kappa_{\text{loss}}(\sigma_s=3\text{mm}) = 0.7\text{mV/pC (w/ RF Shield)} \]

Longitudinal short-range wakepotential

Real part of the longitudinal impedance

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Measurements of the Button Capacitance

TDR Measurements

- Sensitive to Impedance Profile of the Transmission Line

B. Bacha & I. Pinayev

VPN (FDR) Measurements

- Sensitive to the Total Input Impedance Looking into the Tested Structure

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TDR Simulations vs. Measurement

R=50Ω, C₀=2pF

GdfidL

CST

W. Cheng

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NSLS-II Bellows

- The minimum height of fingers support \( h \) limited mechanically
- Tolerance for misalignment of two consecutive vacuum chambers across the bellows is 2mm.
- “Beam pipe” - shaped RF shielding

- Vacuum chamber aperture: \( 2a=25\text{mm} \) (V) and \( 2b=76\text{mm} \) (H)
- Bellows inner aperture: \( 2a_1=25.5\text{mm} \) (V) and \( 2b=76.7\text{mm} \) (H)
- Water Cooled Flange
- Silver Coated Springs :
  1. Thermal Transition Improvement
  2. Significant Powder Reduction due to Mechanical Motion

M. Ferreira
Simplified Cavity Model (Loss Factor)

In the cavity regime, \( b < g < b^2/\sigma \),

\[
\kappa_{\text{loss}} \approx \frac{1}{2\sqrt{\pi}} \frac{1}{b} \left( \frac{d - b}{\sigma} \right)^2 \quad (d - b < \sigma).
\]

A. Blednykh & S. Krinsky, PRSTAB 2010

- In the cavity regime, \( b < g < b^2/\sigma \), \( \kappa_{\text{loss}} \) does not depend on \( g \)
- The significant reduction of the loss factor can be performed due to \( d-b \) change
- Loss Factor (\( \sigma_s = 3\) mm): \( \kappa_{\text{loss}} = 30\text{mV/pC} \) (\( d-b=1\) mm)
  \( \kappa_{\text{loss}} = 7\text{mV/pC} \) (\( d-b=0.5\) mm)

\[ 10^0 \] \[ 10^{-2} \] \[ 10^{-1} \] \[ 10^0 \] \[ 10^{-1} \] \[ 10^2 \]

\( \kappa_{\text{loss}}, \text{mV/pC} \)

\( \sigma_s, \text{mm} \)

- \( d-b=1\) mm, Gdf.
- \( d-b=0.5\) mm, Gdf.
- \( d-b=1\) mm, Eq.
Loss Factor

Loss Factor (Geometric):

\[ k_{\text{geom}}^{\text{loss}}(\sigma_s) = \int_{-\infty}^{\infty} \frac{c}{2\pi} \text{Re} Z_{\parallel}(k) e^{-k^2 \sigma_s^2} \, dk \]

Loss Factor (Resistive Wall):

\[ k_{\text{loss}}^{\text{rw}}(\sigma_s) = 1.2 \frac{c Z_0}{4\pi} \frac{L}{2\pi b^2} \left( \frac{s_0}{\sigma_s} \right)^{3/2} \]

\[ s_0 = \left( \frac{2b^2}{Z_0 \sigma_{\text{cond}}} \right)^{1/3} \]

K. Bane & M. Sands “Short-Range Resistive Wall Wakefields”

Loss factor as a Function of Bunch Length

\[ \sigma_s = 4.5 \text{mm} \quad (I_{\text{av}} = 300 \text{mA}) \text{ with ID's} \]

\[ \sigma_s = 9 \text{mm} \quad (I_{\text{av}} = 500 \text{mA}) \text{ with ID's \\& Landau Cavity} \]

150mm of Cu vs. 150mm of St.St. with half-gap of 13mm

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NSLS-II Bellows Under Beam Test in the APS Storage Ring

NSLS-II Bellows adapted for the APS vacuum chamber profile

APS Bellows

APS Bellows

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Measurement of Temperature Rise in Adapted Bellows

NSLS-II Bellows Adapted for APS

APS Ring Parameters:

- $I_{av} = 115\text{mA}$
- $h_b = 24$
- $T_0 = 3.7\mu\text{s}$
- $\sigma_s = 10\text{mm}$

Measured Temperature on RF Finger

- Direct measured temperature under the RF finger
- Upper temperature limit for RF fingers is $250 \, ^\circ\text{C}$
- High current run: $150 \, \text{mA}$ in $24$ bunches!
- $I_0 = 6.3\text{mA} \quad \Rightarrow \quad T = 155 \, ^\circ\text{C}$
- No damages and deteriorations was observed!
Data Comparison of Adapted & Regular NSLS-II Bellows

**NSLS-II Bellows adapted for APS**

**APS ring parameters:**
- \( I_{av} = 115\) mA
- \( h_b = 24 \)
- \( T_0 = 3.7\) μs
- \( \sigma_s = 10\) mm

\[
P_{loss}^{APS} = T_0 \frac{I_{av}^2}{h} k_{loss} = 2039 \times \kappa_{loss}
\]

\[
k_{loss}^{rw+geom} (\sigma_s = 10\) mm\) = 1.5 mV / pC
\]

\[
P_{loss}^{APS} = 3.1 \) W
\]

**Higher Order Modes**

\( \sigma_s = 10\) mm

**Geometric Loss Factor as a Function of Bunch Length.**

- \( 22\) mV/pC
- \( 8\) mV/pC
- \( 0.3\) mV/pC

\( \sigma_s, \) mm

**NSLS-II Bellows**

**NSLS-II ring parameters:**
- \( h_b = 1080 \)
- \( T_0 = 2.6\) μs
- \( \sigma_s = 4.5\) mm \((I_{av} = 300\) mA\)
- \( \sigma_s = 9\) mm \((I_{av} = 500\) mA\)

\[
P_{loss}^{NSLS-II} = T_0 \frac{I_{av}^2}{h} k_{loss} = 217 \times \kappa_{loss}
\]

\[
k_{loss}^{rw+geom} (\sigma_s = 4.5\) mm\) = 8.6 mV / pC
\]

\[
P_{loss}^{NSLS-II} = 1.9 \) W
\]

\( \sigma_s, \) mm

**500mA**

\[
P_{loss}^{NSLS-II} = T_0 \frac{I_{av}^2}{h} k_{loss} = 602 \times \kappa_{loss}
\]

\[
k_{loss}^{rw+geom} (\sigma_s = 9\) mm\) = 0.5 mV / pC
\]

\[
P_{loss}^{NSLS-II} = 0.3 \) W
\]
NSLS-II Stripline

- Two straight sections (Cells 16 & 29) are occupied by striplines.
- Bunch-by-bunch transverse feedback system built in Cell 16 to stabilize the electron beam against the coherent transverse oscillations driven by the resistive wall.
- The geometric parameters specified to provide enough high transverse shunt impedance 10 kΩ.
- Since the regular NSLS-II vacuum chamber has an octagonal shape 25mm x 76mm two smooth transitions are applied on both side of the section to minimize the longitudinal and transverse beam impedances.

One half of the stripline kicker geometry. Two electrodes are located inside of the round pipe with a $d=38mm$ radius. The length of electrodes is 300mm.

W. Cheng & B. Kosciuk
Stripline Beam Impedance

- **Longitudinal Beam Impedance**
  \[
  Z_\parallel(k) = g_\parallel^2 Z_{ch,\parallel}[\sin^2(kL) + j \sin(kL)\cos(kL)]
  \]
  
  \( g_\parallel \) - longitudinal geometric factor, \( Z_{ch,\parallel} \) - longitudinal characteristic impedance, \( L \) - longitudinal length of electrodes

- **Transverse Beam Impedance**
  \[
  Z_\perp(k) = (g_\perp Z_{ch,\perp}/kb^2)[\sin^2(kL) + j\sin(kL)\cos(kL)]
  \]
  
  \( g_\perp \) - transverse geometric factor, \( Z_{ch,\perp} \) - transverse characteristic impedance, \( k \) - wave number, \( b \) - distance between the beam axis and the electrodes

- **Lambertson’s Definition of Shunt Impedances for Stripline**
  
  
  \[
  R_{sh,\parallel} = 2Z_L g_\parallel^2 \sin^2 \Theta \quad (8.11)
  \]
  
  \( Z_L \) - characteristic impedance of a single electrode, \( Z_{ch,\parallel} = Z_L/2 \) - For two electrodes
  
  \[
  R_{sh,\perp} = 2Z_L g_\perp \left( \frac{2}{k_B h} \right)^2 \sin^2 \Theta \quad (8.17)
  \]
  
  \( Z_{ch,\perp} = Z_{L,\perp}/2 \) - For two electrodes, \( h = 2b \)

- **Relation Between Beam & Shunt Impedances**
  
  \[
  \text{Re} Z_{\parallel}(k) = R_{sh,\parallel} / 4
  \]
  
  \[
  Z_\parallel = R_{sh,\parallel} / 4 \quad (8.21)
  \]
  
  G.R. Lambertson

  \[
  \text{Re} Z_\perp(k) = R_{sh,\perp} \times k/4
  \]
Characteristics Impedances and Geometric Factors

- Simplified Geometries (Analytically)
  - **Circular Geometry**
    - Longitudinal: \( g_{||} = \frac{\phi}{\pi} \)
    - Transverse: \( g_{\perp} = \frac{4}{\pi} \sin \frac{\phi}{2} \)

- POISSON Code (Numerically)
  - **Rectangular Geometry**
    - Longitudinal: \( g_{||} = \frac{2}{\pi} \tan^{-1}\left(\sinh\frac{\pi a}{2b}\right) \)
    - Transverse: \( g_{\perp} = \tanh\frac{\pi a}{2b} \)
  - **Coaxial:**
    - Longitudinal: \( Z_{ch}^{cxl} = \frac{Z_0}{2\pi} \log(d/b) \)
    - Transverse: \( \phi = \pi/2 \)

**Capacitance of Stripline**
\[ C = \frac{2W_e}{V_p^2} \]

The ratio of beam to electrode voltages \( V(x)/V_p \) divided by \( x/b \). For \( x \sim 0 \), \( g_{||} = 1.1 \)
Circular Geometry With Two Electrodes Inside

$b_{\text{min}} = 26.1\text{mm} \& d = 38\text{mm}$
Beam Impedance At Low Frequencies ($\phi=\pi/2$)

Longitudinal Impedance ($g_\parallel=0.77 \& Z_{ch,\parallel}=30.5\,\Omega$)

\[ ReZ_\parallel(k) = g_\parallel^2 Z_{ch,\parallel} \sin^2(kL) \]

\[ ImZ_\parallel(k) = g_\parallel^2 Z_{ch,\parallel} \sin(kL)\cos(kL) \]

Transverse Impedance ($g_\perp=1.1 \& Z_{ch,\perp}=25\,\Omega$)

\[ ReZ_\perp(k) = \left(g_\perp^2 Z_{ch,\perp}/kb^2\right)\sin^2(kL) \]

\[ ImZ_\perp(k) = \left(g_\perp^2 Z_{ch,\perp}/kb^2\right)\sin(kL)\cos(kL) \]
Tapered Cavity

- ECHO code: \( \kappa_{\text{loss}} = 0.16 \text{ V} / \text{pC} \)

- Tapered Cavity with
  \[ g > \frac{d^2}{\sigma} \quad \text{and} \quad d - b > b \]
  \[ \kappa_{\text{loss}} \approx \frac{2}{\sqrt{\pi}} \frac{\log(d/b)}{\sigma} \left[ \frac{2}{\pi} \arctan\left(\frac{0.2d^2}{\sigma L}\right) \right]^2. \]

\( \kappa_{\text{loss}} = 0.15 \text{ V} / \text{pC} \)
Temperature Distribution (ANSYS)

- Heating of Electrodes Due To Passing Bunch (Geometrical Loss Factor)
- Thermal Expansion Can Cause Significant Stress In The Ceramic Seals
- The Risk Of Vacuum Leak
- KEK Stripline design is similar to the NSLS-II design.

Geometric Loss Factor:
- $k_{\text{loss}} = 0.38\text{V/pC (Two Electrodes)} \rightarrow 4.5\text{mm bunch length}$
- $k_{\text{loss}} = 0.15\text{V/pC (Two Electrodes)} \rightarrow 9\text{mm bunch length}$

Loss Power:
- $P_{\text{loss}} = 30\text{W per electrode @ 300mA in 1080 bunches}$
- $P_{\text{loss}} = 44\text{W per electrode @ 500mA in 1080 bunches}$

B. Kosciuk
NSLS-II Diagnostic Straight Section

- Bunch Length - 3mm

Longitudinal Wakepotential

Diagnostic Straight Section (Cell 16)

Vertical Wakepotential

Longitudinal Narrow-Band Impedance

Vertical Narrow-Band Impedance

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Summary

• RF shielding of the NSLS-II Bellows has been well adapted for the octagonal shape of the NSLS-II vacuum chamber.
• NSLS-II Bellows passed beam-test in the APS storage ring at high current without damages and deteriorations. The next step is temperature measurements in the NSLS-II storage ring under beam condition.
• Successful Implementation of RF Shielding for Large Aperture BPM Assemblies.
• Back-Up Slides
Comparison of Two Striplines

Electrode: \( \phi = \pi/2 \), \( b = 24.1\text{mm} \), \( d = 26.1\text{mm} \), \( L = 300\text{mm} \)

Port: \( r_3 = 3\text{mm} \), \( r_4 = 7\text{mm} \)

- Port boundary condition is applied for both geometries (PML)

- Calculated w/o Tapered Transition
Narrow-Band Impedance

Option A

- Low Impedance vs. Option B
- Is it still low enough?

Option B

- Gap at both ends is 10mm
- Strong HOM at high frequencies
- What is the minimum gap mechanically achievable?
- Further analysis with minimum gap can be done
- Small gap – possible HOM elimination