Impedance Analysis at CESR

Jim Shanks, on behalf of the CESR Accelerator Group
2022.12.08
• General Comments

• Longitudinal Impedance
  – Formalism
  – Measurements
  – Application: Undulator Vacuum Chamber Damage

• Transverse Impedance
  – Formalism
  – Analytic Modeling
  – Numerical Modeling
  – Measurements
  – Application: CHESS-U Timing Mode
Introductory Remarks

• Formalism, modeling, data, and analysis shown here represent the work of many individuals over many years.

• A big THANK YOU to everyone who has contributed:

  • Mike Billing
  • Jesse Chandler
  • Antoine Chapelain
  • Jerry Codner
  • Mike Ehrlichman
  • Mike Ehrlichman
  • Walter Hartung

  • Stephen Poprocki
  • Laura Salo*
  • John Sikora
  • Michael Spiegel**
  • Suntao Wang
  • Laurel Ying

*REU / summer student
**Cornell undergrad
• Wakefields (time-domain) and impedances (frequency-domain) arise from the interaction of a bunch’s EM field with the surrounding vacuum structure

• Several important consequences:
  – Energy loss / turn
  – Tuneshift
  – Mode Coupling Instability

• Although closely related, examine transverse and longitudinal separately
Longitudinal Impedance
• Longitudinal self-wake for a vacuum structure:

\[ W_z(\tau) = \frac{1}{q} \int_{-\infty}^{\tau} \lambda(t) G_{||}(\tau - t)dt \]

- \( W_z(\tau) \) has units V/pC
- \( \lambda(t) \) = current distribution (longitudinal)
- \( G_{||} \) = Green’s function for wake, computed for \( \lambda(t) = \delta(t) \)
- \( q = \int_{-\infty}^{\infty} \lambda(t)dt \)

• The longitudinal impedance \( Z_{||}(\omega) \) is the Fourier transform of the delta-function wakefield \( G_{||}(\tau) \):

\[ Z_{||}(\omega) = \frac{1}{q} \int_{-\infty}^{\infty} e^{-j\omega\tau} G_{||}(\tau) d\tau \]

• Higher-Order Mode (HOM) loss parameter for self-wake \( W_z(\tau) \):

\[ k_{||} = \frac{1}{q} \int_{-\infty}^{\infty} \lambda(t)W_z(t)dt \quad \rightarrow \quad \Delta E = k_{||}q^2 \]

Energy loss / turn
Longitudinal Impedance (HOML)

- Following M. Billing documentation (CBN 01-6) [15]
- Loss factor $k_{HOM}$ and wake $W$ (as observed at one trailing bunch) are:

$$k_{HOM} = 2\pi f_{RF} < V > \sin \phi_{SR} \left( \frac{d\Delta t}{dq_{main}} \right) - \pi f_{RF} \left( \frac{R}{Q} \right) n_{cells} \exp \left[ -\frac{1}{2} \left( \frac{2\pi f_{RF} \sigma_z}{c} \right)^2 \right]$$

$$W = 2\pi f_{RF} < V > \sin \phi_{SR} \left( \frac{d\Delta t}{dq_{main}} \right) - k_{HOM}$$

$\rightarrow$ Focus on $k_{HOM}$

$f_{RF} =$ RF frequency  
$<V> =$ Total RF voltage  
$\phi_{SR} =$ Synchronous phase without beam loading*  
$q_{main} =$ charge in main bunch (see next slide)  
$(R/Q) =$ property of RF cavities  
$n_{cells} =$ # of RF cavities  
$\sigma_z =$ bunch length

*Over the past three years, we have had either 6, 7, or 8 CCUs installed at any given time. This was not always documented or tracked. However, this is less than a 1% effect on the term $\sin \phi_{SR}$.
Implementation

- Fill 3 adjacent 2ns buckets
- Vary current in second ("main") bunch
- Measure change in arrival time between:
  - Precursor and main bunch \( \rightarrow \) measures \( k_{HOM} \)
  - Main and witness bunch \( \rightarrow \) wake measurement at 2ns following main bunch
- Plot \( \Delta t \) vs. main bunch current (linear)
  - Slope \( d\Delta t/dI \) yields \( k_{HOM} \) and wake, per previous slide
HOML Measurements

5/2018 (Before CHESS-U)

10/2021 (After CHESS-U)
• Use one of M. Billing’s Excel spreadsheets to compute $k_{\text{HOM}}$ analytically, including contributions from:
  – RF HOM loading, cells, and tapers
  – Ceramics, gate valves, sliding joints, separators, …
  – Resistive wall
  – Undulator tapers
  – Lumped pumps

• Compare $k_{\text{HOM}}$ before and after upgrade, analytic vs. measured:

<table>
<thead>
<tr>
<th>Date</th>
<th>MGB Analytic</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/2018 (arc pretzel)</td>
<td>2.66 V/pC</td>
<td>4.83 V/pC</td>
</tr>
<tr>
<td>10/2021 (CHESS-U)</td>
<td>1.87 V/pC</td>
<td>4.25 V/pC</td>
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</table>
Application: ID3 Damaged Chamber

- CHESS-U upgrade introduced a number of small-gap out-of-vacuum undulators
  - 7mm pole-to-pole
  - 0.5mm pole-to-chamber
  - 0.5mm wall thickness
  - $\rightarrow$ 5mm full-aperture
  - **4.6mm** due to vacuum deflection

- Discovered (the hard way) that thin-wall chambers conduct heat very poorly

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ID3B Chamber

April 2022

ID2B Chamber

Dissection

ID2B Chamber

October 2022

4.6mm due to vacuum deflection

2mm reduction in 4.6mm aperture
HOML – Damaged ID3 Chamber

- Historical measurements of $k_{\text{hom}}$ in CHESS-U (2019-2022): $-4.54 \pm 1.04 \text{ V/pC}$
- Damaged chamber is correlated with factor of approximately 2x larger HOML (!)
- After chamber replaced, $k_{\text{hom}}$ again in line with historical CHESS-U measurements

Prior to known damage
1/14/22: eLog #1990

ID3B aperture reduced by 2mm
10/25/22: eLog #2140

ID3 chamber replaced
11/15/22: eLog #2160

$k_{\text{hom}} = -3.069 \text{ V/pC}$
$w = 9.391 \text{ V/pC}$

$k_{\text{hom}} = -8.355 \text{ V/pC}$
$w = 22.645 \text{ V/pC}$

$k_{\text{hom}} = -3.760 \text{ V/pC}$
$w = 11.331 \text{ V/pC}$

2022.11.17
Longitudinal – Comments

- Longitudinal impedance is a useful diagnostic for identifying gross aperture issues
- Identified significant change (factor of 2x) in $k_{\text{HOM}}$ correlated with damaged Sector 3 ID chamber
  - May be able to use this as an earlier warning of problems, without having to remove undulator arrays
- Next steps:
  - Revisit analytic/numerical evaluation of longitudinal impedance
    - Presently relying on MGB Excel calculations
  - Improve automation of measurement
Transverse Impedance
• The second half of this talk draws heavily from CBN 20-01 “Characterization of Transverse Impedance for CHESS-U” [13]
  – CBN 20-01 in turn draws heavily from M. Billing’s internal documents on impedance analysis
  – Details and further discussion are available in CBN 20-01 and its references
Motivation – 4th-Gen Upgrades

• APS, PETRA-III upgrading to high-energy 4th-gen rings in the next few years
  – ESRF-EBS already implemented
  – SPring-8 also looking at upgrade options

• Multi-bend achromats (MBA) require strong focusing: > 80 T/m in many designs
  – Specialization enables ultra-low emittance: $\varepsilon_x < 0.2$ nm
  – Comes at a price:
    • Small apertures ($r \leq 16$mm) $\rightarrow$ resistive wall instability scales as $1/r^3$
    • Strong nonlinearities from chromatic correction $\rightarrow$ small dynamic aperture

  **Net effect: maximum per-bunch current is restricted**

• Example: APS-U will no longer be able to run “hybrid singlet” (60nC bunch)

• Proposed modes with highest bunch charge:
  – APS-U: 200mA across 48 bunches (15nC/bunch)
  – ESRF-EBS: 40mA across 4 bunches (28nC/bunch)

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J. Shanks - Impedance at CESR
• Single-beam operations with users at CHESS-U started in 2019
  – No more counter-rotating beams
  – No need to interleave trains of bunches
  – Significantly increases flexibility in bunch patterns
• Moderate-gradient quadrupoles (< 40 T/m)
  – Nonlinearities are significantly less than 4th-generation designs
  – Apertures remain reasonable (23 mm bore radius) → reasonable instability threshold
  – Allows for higher per-bunch current
• What would it take to enable Timing Mode at CHESS?
• What could users do with this?
Application: Timing Mode

- **Assumptions:**
  - Few bunches with high per-bunch current
  - Large separation between bunches
  - Preserve 200mA total beam current
  - Several potential modes of operation to enable different classes of experiments

- **Estimate of maximum bunch charge relies on impedance calculations**

- **Walk through theoretical evaluation of maximum bunch charge**
Simple estimates of impedance tuneshift are linear

- Will overestimate the instability threshold
- “Rule of thumb”: multiply linear approximation by 0.75 to estimate the instability threshold
Formalism – Transverse

- Transverse wake derived from longitudinal ($w_z$) via Panofsky-Wenzel theorem:

$$-\frac{1}{c} \frac{\partial}{\partial \tau} \bar{w}_\perp (\vec{r}_1, \vec{r}; \tau) = \vec{V}_\perp (\vec{r}_1, \vec{r}; \tau)$$

Driving charge $q_1$ at position $\vec{r}_1, z_1$
Witness charge $q$ at position $\vec{r}, z$

- Kick induced by the transverse wake:

$$\vec{r}'(\vec{r}_1, \tau) = \frac{eq}{E} \bar{w}_\lambda (\vec{r}_1, \tau)$$

$$\bar{w}_\lambda (\vec{r}, \tau) = \frac{1}{q} \int_0^\infty d\tau_d \int_V d\vec{r} \bar{w}_\perp (\vec{r}, \vec{r}_1, \tau_d) \lambda (\vec{r}, \tau - \tau_d)$$

$\tau_d = \text{delay between drive and witness particles}$
Via Joe Calvey:

\[
\bar{w}_\perp(r, r_1, \tau_d) = -c \int_{0}^{\tau_d} \left[ \left( \frac{\partial w_z}{\partial x} + \frac{\partial^2 w_z}{\partial x^2} x + \frac{\partial^2 w_z}{\partial x \partial y} y + \frac{\partial^2 w_z}{\partial x \partial x_1} x_1 + \frac{\partial^2 w_z}{\partial x \partial y_1} y_1 \right) \hat{x} \right.
\]

\[
+ \left( \frac{\partial w_z}{\partial y} + \frac{\partial^2 w_z}{\partial y^2} y + \frac{\partial^2 w_z}{\partial x \partial y} x + \frac{\partial^2 w_z}{\partial y \partial y_1} y_1 + \frac{\partial^2 w_z}{\partial y \partial x_1} x_1 \right) \hat{y} \right] d\tau
\]

\[
= (w_\perp x + w_\perp x^2 x + w_\perp x y y + w_\perp x x_1 x_1 + w_\perp x y_1 y_1) \hat{x}
\]

\[
+ (w_\perp y + w_\perp y^2 y + w_\perp x y x + w_\perp y y_1 y_1 + w_\perp y x_1 x_1) \hat{y}
\]
Multipole Expansion

- Via Joe Calvey:

\[
\vec{w}_\perp(r, \vec{r}_1, \tau_d) = -c \int_0^{\tau_d} \left[ \left( \frac{\partial w_z}{\partial x} + \frac{\partial^2 w_z}{\partial x^2} x + \frac{\partial^2 w_z}{\partial x \partial y} y + \frac{\partial^2 w_z}{\partial x \partial x_1} x_1 + \frac{\partial^2 w_z}{\partial x \partial y_1} y_1 \right) \hat{x} \\
+ \left( \frac{\partial w_z}{\partial y} + \frac{\partial^2 w_z}{\partial y^2} y + \frac{\partial^2 w_z}{\partial x \partial y} x + \frac{\partial^2 w_z}{\partial y \partial y_1} y_1 + \frac{\partial^2 w_z}{\partial y \partial x_1} x_1 \right) \hat{y} \right] d\tau
\]

\[
= \begin{pmatrix} w_{\perp x} + w_{\perp x^2} x + w_{\perp xy} y + w_{\perp x x_1} x_1 + w_{\perp x y_1} y_1 \hat{x} \\
+ w_{\perp y} + w_{\perp y^2} y + w_{\perp xy} x + w_{\perp y y_1} y_1 + w_{\perp y x_1} x_1 \hat{y} \end{pmatrix}
\]

Monopole
Via Joe Calvey:

\[
\vec{w}_\perp(r, r_1, r_d) = -c \int_0^{r_d} \left[ \left( \frac{\partial w_z}{\partial x} + \frac{\partial^2 w_z}{\partial x^2} x + \frac{\partial^2 w_z}{\partial x \partial y} y + \frac{\partial^2 w_z}{\partial x \partial x_1} x_1 + \frac{\partial^2 w_z}{\partial x \partial y_1} y_1 \right) \hat{x} \\
+ \left( \frac{\partial w_z}{\partial y} + \frac{\partial^2 w_z}{\partial y^2} y + \frac{\partial^2 w_z}{\partial x \partial y} x + \frac{\partial^2 w_z}{\partial y \partial y_1} y_1 + \frac{\partial^2 w_z}{\partial y \partial x_1} x_1 \right) \hat{y} \right] d\tau
\]

= \begin{align*}
\text{Quadrupole:} & \quad \left( w_{\perp x} + w_{\perp x^2} x + w_{\perp xy} y + w_{\perp xx_1} x_1 + w_{\perp xy_1} y_1 \right) \hat{x} \\
+ \left( w_{\perp y} + w_{\perp y^2} y + w_{\perp xy} x + w_{\perp yy_1} y_1 + w_{\perp yx_1} x_1 \right) \hat{y}
\end{align*}

\text{Monopole:}
Multipole Expansion

- Via Joe Calvey:

\[
\bar{w}_\perp(r, r_1, \tau_d) = -c \int_0^{\tau_d} \left[ \left( \frac{\partial w_z}{\partial x} + \frac{\partial^2 w_z}{\partial x^2} x + \frac{\partial^2 w_z}{\partial x \partial y} y + \frac{\partial^2 w_z}{\partial x \partial x_1} x_1 + \frac{\partial^2 w_z}{\partial x \partial y_1} y_1 \right) \hat{x} 
+ \left( \frac{\partial w_z}{\partial y} + \frac{\partial^2 w_z}{\partial y^2} y + \frac{\partial^2 w_z}{\partial y \partial x} x + \frac{\partial^2 w_z}{\partial y \partial y_1} y_1 + \frac{\partial^2 w_z}{\partial y \partial x_1} x_1 \right) \hat{y} \right] d\tau
\]

\[
= \begin{cases} 
\{ w_{\perp x} + w_{\perp x^2} x + w_{\perp xy} y + w_{\perp xx_1} x_1 + w_{\perp xy_1} y_1 \} \hat{x} \\
\{ w_{\perp y} + w_{\perp y^2} y + w_{\perp xy} x + w_{\perp yy_1} y_1 + w_{\perp yx_1} x_1 \} \hat{y}
\end{cases}
\]

- Monopole
- Quadrupole
- Skew
- Skew
Multipole Expansion

- Via Joe Calvey:

\[
\tilde{w}_\bot(r, r_1, \tau_d) = -c \int_0^{\tau_d} \left[ \left( \frac{\partial w_z}{\partial x} + \frac{\partial^2 w_z}{\partial x^2} x + \frac{\partial^2 w_z}{\partial x \partial y} y + \frac{\partial^2 w_z}{\partial x \partial x_1} x_1 + \frac{\partial^2 w_z}{\partial x \partial y_1} y_1 \right) \hat{x} \\
+ \left( \frac{\partial w_z}{\partial y} + \frac{\partial^2 w_z}{\partial y^2} y + \frac{\partial^2 w_z}{\partial y \partial x} x + \frac{\partial^2 w_z}{\partial y \partial y_1} y_1 + \frac{\partial^2 w_z}{\partial y \partial x_1} x_1 \right) \hat{y} \right] d\tau
\]

\[
= \left\{ \begin{array}{l}
 w_\bot x + w_{\bot x} x \\
+ w_{\bot y} y + w_{\bot y} y
\end{array} \right\} + \left\{ \begin{array}{l}
 w_{\bot x} y + w_{\bot x} y \\
+ w_{\bot y} y + w_{\bot y} y
\end{array} \right\} \hat{x} + \left\{ \begin{array}{l}
 w_{\bot x} x + w_{\bot x} x \\
+ w_{\bot y} y + w_{\bot y} y
\end{array} \right\} \hat{y}
\]

Quadrupole  Dipole
Monopole  Skew  Skew
• Via Joe Calvey:

\[
\bar{w}_\perp(r, r_1, \tau_d) = -c \int_0^{\tau_d} \left[ \left( \frac{\partial w_z}{\partial x} + \frac{\partial^2 w_z}{\partial x^2} x + \frac{\partial^2 w_z}{\partial x \partial y} y + \frac{\partial^2 w_z}{\partial x \partial x_1} x_1 + \frac{\partial^2 w_z}{\partial x \partial y_1} y_1 \right) \hat{x} \\
+ \left( \frac{\partial w_z}{\partial y} + \frac{\partial^2 w_z}{\partial y^2} y + \frac{\partial^2 w_z}{\partial y \partial x} x + \frac{\partial^2 w_z}{\partial y \partial y_1} y_1 + \frac{\partial^2 w_z}{\partial y \partial x_1} x_1 \right) \hat{y} \right] d\tau
\]

\[
= \left\{ \begin{array}{l}
\left\{ \begin{array}{c}
\bar{w}_\perp x + \bar{w}_\perp x_2 x + \bar{w}_\perp xy y + \bar{w}_\perp xx_1 x_1 + \bar{w}_\perp xy_1 y_1 \end{array} \right\} \hat{x} \\
+ \left\{ \begin{array}{c}
\bar{w}_\perp y + \bar{w}_\perp y_2 y + \bar{w}_\perp xy x + \bar{w}_\perp yy_1 y_1 + \bar{w}_\perp xy_1 x_1 \end{array} \right\} \hat{y}
\end{array} \right.
\]

\[
K = kL = \frac{eq}{E_b} \left[ w_\perp y^2 + w_\perp yy_1 \right] y_0
\]

\[
\Delta Q = \frac{1}{4\pi} K < \beta >
\]

Effective quadrupole gradient

Impedance tuneshift
To summarize – for every component in the accelerator:

- Calculate the dipole and quadrupole wakes
- Use these to determine tuneshift contribution from each component

\[ K \text{[m}^{-1}] = kL = \frac{eq}{E_b} \left[ w_{\perp}y^2 + w_{\perp}y_{y1} \right] y_0 \]

Effective quadrupole gradient

\[ \Delta Q = \frac{1}{4\pi} K < \beta > \]

Impedance tuneshift
Two categories of contributions to transverse impedance:

- **Resistive wall** – resistivity of vacuum chamber interacting with image current
- **Discontinuities** – cavities, sliding joints, tapers, etc.

Different analytic methods for each
Resistive wall wake calculated in Gluckstern, van Zeijts, and Zotter (GZZ) [6] for either elliptical or rectangular beam pipe of major axis half-width \( a \) and minor axis half-height \( b \) can be described using the same form:

\[
\frac{\partial^2 W_{\perp,i}}{\partial s \partial i}(z) = D_i \frac{c}{\pi^2 b^3} \sqrt{\frac{2Z_0 \rho}{\sigma_z}} \left\{ \frac{\pi}{4} \exp \left( -\frac{z^2}{4\sigma_z^2} \right) \sqrt{\frac{z}{\sigma_z}} \left[ I_{-1/4} \left( \frac{z^2}{4\sigma_z^2} \right) + I_{1/4} \left( \frac{z^2}{4\sigma_z^2} \right) \right] + \frac{1}{2\sqrt{2}} \exp \left( -\frac{z^2}{4\sigma_z^2} \right) \sqrt{-\frac{z}{\sigma_z}} K_{1/4} \left( \frac{z^2}{4\sigma_z^2} \right) \right\} \quad z > 0
\]

\[
\frac{1}{2\sqrt{2}} \exp \left( -\frac{z^2}{4\sigma_z^2} \right) \sqrt{-\frac{z}{\sigma_z}} K_{1/4} \left( \frac{z^2}{4\sigma_z^2} \right) \quad z < 0
\]
Resistive wall wake calculated in Gluckstern, van Zeijts, and Zotter (GZZ) [6] for either round, elliptical or rectangular beam pipe of major axis half-width $a$ and minor axis half-height $b$ can be described using the same form:

$$i = x,y$$

$$\frac{\partial^2 W_{\perp,i}}{\partial s \partial i} (z) = \frac{D_i}{\pi^2 b^3} \sqrt{\frac{2Z_0 \rho}{\sigma_z}} \left\{ \frac{\pi}{4} \exp \left( -\frac{z^2}{4\sigma_z^2} \right) \sqrt{\frac{z}{\sigma_z}} \left[ I_{-1/4} \left( \frac{z^2}{4\sigma_z^2} \right) + I_{1/4} \left( \frac{z^2}{4\sigma_z^2} \right) \right] + \frac{1}{2\sqrt{2}} \exp \left( -\frac{z^2}{4\sigma_z^2} \right) \sqrt{-\frac{z}{\sigma_z}} K_{1/4} \left( \frac{z^2}{4\sigma_z^2} \right) \right\}$$

Excessively complicated geometric function of $b/a$

encapsulating chamber geometry (round, elliptical, or rectangular)

Longitudinal dependence

\[ z > 0 \]

\[ z < 0 \]

Note: This is still a function of longitudinal position within the bunch $z$, which is to say, particles in the tail of the bunch will be affected by the resistive wall wake from particles in the head of the bunch. The net effect must therefore be computed as a function of longitudinal action $J_z$, averaged over one synchrotron cycle, and convolved with the Gaussian particle distribution. The details of how this is done are covered in [4], Appendix C.
Stupakov [5] shows that one can approximate the kick factor $\kappa$ for a linearly tapered structure with half-width $a$ and half-height tapering at angle $\alpha$ to a minimum of $b$:

$$\kappa = \begin{cases} 
1/b^2 & \text{for } \sqrt{\frac{ab}{\sigma_z}} > 0.37 \\
2.7 \sqrt{\frac{\alpha}{\sigma_z} b^3} & \text{for } 0.37 > \sqrt{\frac{ab}{\sigma_z}} > 3.1 \frac{b}{a} \\
\sqrt{\frac{\pi \alpha a}{2\sigma_z b^2}} & \text{for } \sqrt{\frac{ab}{\sigma_z}} < 3.1 \frac{b}{a}
\end{cases}$$

Diffractive
Intermediate
Inductive

All tapers in CESR are designed to minimize impact to beam, and are in the inductive regime.

45mm $\rightarrow$ 10mm collimator

22mm $\rightarrow$ 5mm CCU taper
• Numerical modeling of wakes would be an entire talk in of itself
  – Briefly summarize process here
• Wakes can be modeled with Finite Element Analysis (FEA)
  – For CESR, we use ACE3P (namely, T3P)
• General procedure:
  – Generate a 3D “void” model based on CAD drawings
  – Convert void model to a mesh with Trelis ← the tricky part
  – Run T3P, which yields longitudinal wakes
  – Postprocess longitudinal wakes into transverse wakes
Putting It All Together

- Tally all significant contributions to transverse impedance
  - Resistive wall
  - Collimators
  - Tapers
  - Sliding joints

- Translate into vertical tuneshift/mA

- Known shortcomings of analytic/numerical impedance tally:
  - South Arc sliding joints
  - CHESS-U undulator tapers
  - CCU chamber deformation under vacuum
  - L3 90mm round chamber
  - Ceramic chambers

<table>
<thead>
<tr>
<th>Component</th>
<th>Analytic</th>
<th>Numerical (T3P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sector 2 CCU - RW</td>
<td>-9.6 Hz/mA</td>
<td>n/a</td>
</tr>
<tr>
<td>Sector 2 CCU - tapers</td>
<td>-11.2 Hz/mA</td>
<td>-12.9 Hz/mA</td>
</tr>
<tr>
<td>Sector 3 CCU - RW</td>
<td>-9.3 Hz/mA</td>
<td>n/a</td>
</tr>
<tr>
<td>Sector 3 CCU - tapers</td>
<td>-11.2 Hz/mA</td>
<td>-12.6 Hz/mA</td>
</tr>
<tr>
<td>Sector 4 CCU - RW</td>
<td>-9.3 Hz/mA</td>
<td>n/a</td>
</tr>
<tr>
<td>Sector 4 CCU - tapers</td>
<td>-11.2 Hz/mA</td>
<td>-8.9 Hz/mA</td>
</tr>
<tr>
<td>Sector 7 CCU - RW</td>
<td>-10.5 Hz/mA</td>
<td>n/a</td>
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<tr>
<td>Sector 7 CCU - tapers</td>
<td>-11.9 Hz/mA</td>
<td>-13.4 Hz/mA</td>
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<td>50 mm to 22 mm tapers</td>
<td>-1.4 Hz/mA</td>
<td>n/a</td>
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<td>43W collimator at 10 mm</td>
<td>-100.5 Hz/mA</td>
<td>-117.8 Hz/mA</td>
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<tr>
<td>43E collimator at 10 mm</td>
<td>-89.3 Hz/mA</td>
<td>-104.7 Hz/mA</td>
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<tr>
<td>Sliding Joints - North Arc</td>
<td>n/a</td>
<td>-8.5 Hz/mA</td>
</tr>
<tr>
<td>North Arc RW</td>
<td>-9.4 Hz/mA</td>
<td>n/a</td>
</tr>
<tr>
<td>South Arc RW</td>
<td>-4.5 Hz/mA</td>
<td>n/a</td>
</tr>
<tr>
<td>Total</td>
<td>-297.8 Hz/mA</td>
<td>-332.8 Hz/mA</td>
</tr>
</tbody>
</table>
Transverse – Measurements

• Straightforward to measure tuneshift vs. bunch current, using spectrum analyzer

• Measurement reproducibility, based on first half of 2022:

\[
\frac{df_x}{dl} = -47.4 \text{ Hz/mA} \quad \sigma = 7.6 \text{ Hz/mA} \\
\frac{df_y}{dl} = -418.8 \text{ Hz/mA} \quad \sigma = 14.1 \text{ Hz/mA}
\]

→ Measured vertical tuneshift is 25% larger than T3P estimates
Transverse – MCI Limit

• Linear estimate of mode coupling instability: \( I_b \frac{df_y}{dI_b} = 0.75 \times f_s \)
  - \( f_s = 13.2 \text{ kHz}, \frac{df_y}{dI_b} = -418.8 \text{ Hz/mA (measured)} \)
  \[ \Rightarrow I_b^{\text{max}} = 31.6 \text{ mA} \]

• Maximum per-bunch current needed for CHESS-U Timing Mode: 22.2 mA/b
  - Corresponds to 200 mA across 9 equally-spaced bunches

• On paper, seems like we’re good to go

• **Experimental verification**: One-off high-bunch-current test reached 20 mA in a single bunch with no signs of mode coupling instability
  - Going above 20 mA in a single bunch requires further consideration of instrumentation protection
Transverse – Comments

• Transverse impedance measurements yield an estimate of the maximum per-bunch current consistent with requirements for CHESS-U Timing Mode
  – Necessary for vetting Timing Mode bunch pattern viability

• Next steps:
  – Continue resolving discrepancies between analytic, numerical, and measurements
  – Interpreting transverse damping measurements (not shown here)
Summary and Conclusions

• Impedance measurements provide valuable diagnostic information
  – Vetting our understanding of vacuum chamber apertures
  – Gross aperture issues
  – Estimating maximum per-bunch current due to mode-coupling instability

• Still much to be done
  – Refine analytic/numerical models for both longitudinal and transverse
  – Revisit phase-measurement-based transverse impedance measurement (MPE) for localizing impedance contributions [15]
  – Automating HOML measurement to include in regular characterizations
References

Transverse Impedance:


HOML:

16. M. Billing, “Measuring Higher Order Mode Loss Factors and Wake Voltages Using the Change in Phase of Two Bunches”, CBN 01-06