Impedance Analysis at CESR

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Outline

- General Comments
- Longitudinal Impedance
  - Formalism
  - Measurements
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- 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 Forster
  - Walter Hartung
  - Stephen Poprocki
  - Laura Salo*
  - John Sikora
  - Michael Spiegel**
  - Suntao Wang
  - Laurel Ying

*REU / summer student
**Cornell undergrad

Introduction

- 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

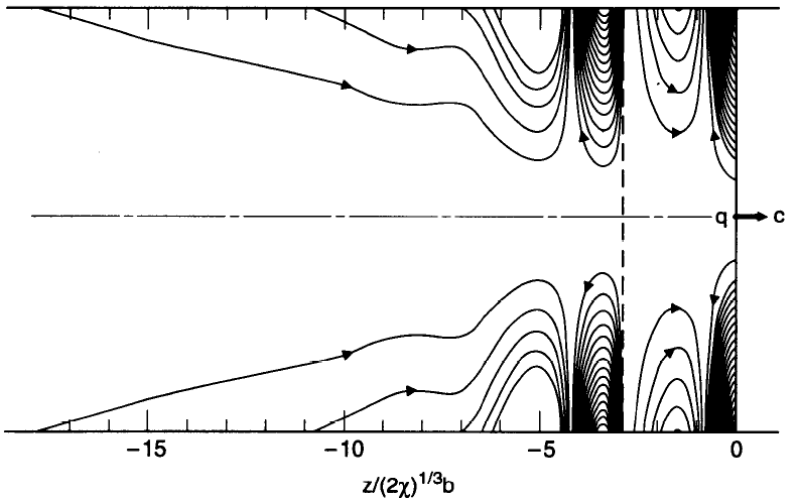


Figure 2.3. Wake electric field lines in a resistive wall pipe generated by a point charge q. The field pattern shows oscillatory behavior in the region $|z| \lesssim 5(2\chi)^{1/3}b$ (or $|z| \lesssim 0.35$ mm for an aluminum pipe with $b = 5$ cm). The field line density to the left of the dashed line has been magnified by a factor of 40. (Courtesy Karl Bane, 1991.)

Longitudinal Impedance

Formalism – Longitudinal

- 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 $W_z(\tau)$:

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

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:

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

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

→ Focus on k_{HOM}

f_{RF} = RF frequency

<V> = Total RF voltage

ϕ_{SR} = Synchronous phase without beam loading*

q_{main} = charge in main bunch (see next slide)

(R/Q) = property of RF cavities

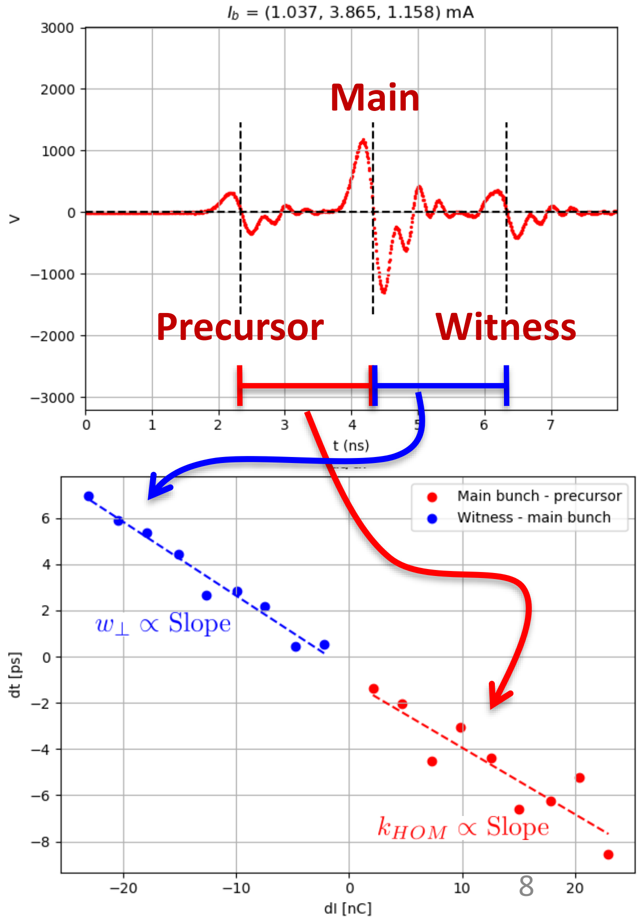
n_{cells} = # of RF cavities

σ_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 ϕ_{SR}

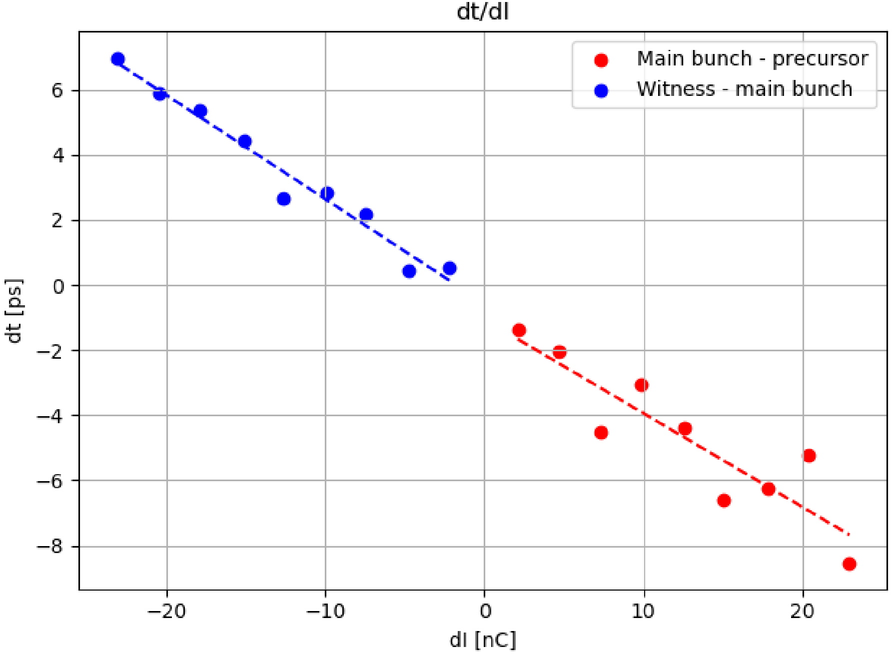
Implementation

- Fill 3 adjacent 2ns buckets
- Vary current in second (“main”) bunch
- Measure change in arrival time between:
  - Precursor and main bunch → measures k_{HOM}
  - Main and witness bunch → wake measurement at 2ns following main bunch
- Plot Δt vs. main bunch current (linear)
  - Slope dΔt/dI yields k_{HOM} and wake, per previous slide

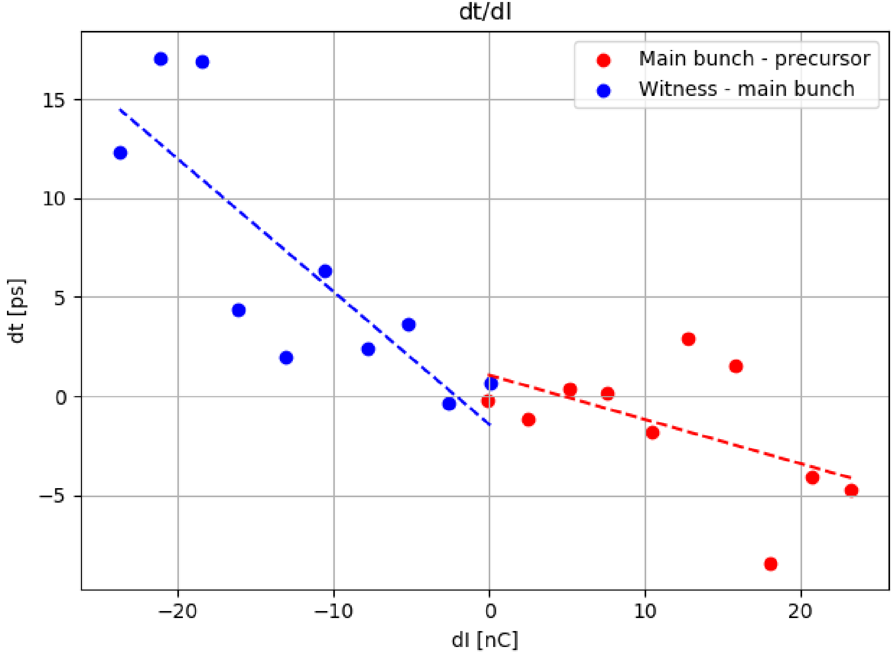


HOML Measurements

5/2018 (Before CHESS-U)



10/2021 (After CHESS-U)



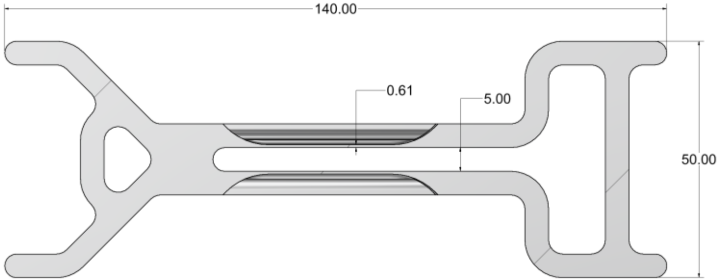
Analytic vs. Measured

- Use one of M. Billing's Excel spreadsheets to compute k_{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_{HOM} before and after upgrade, analytic vs. measured:

	MGB Analytic	**Measured**
5/2018 (arc pretzel)	2.66 V/pC	4.83 V/pC
10/2021 (CHESS-U)	1.87 V/pC	4.25 V/pC

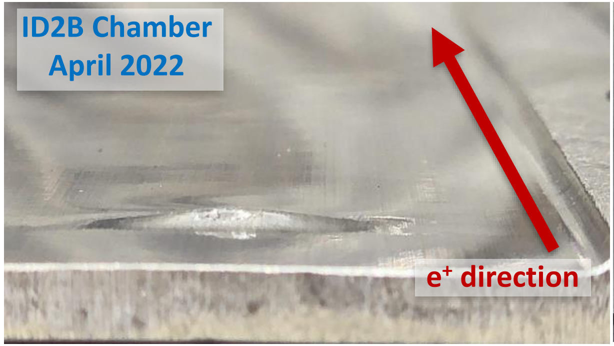
Application: ID3 Damaged Chamber

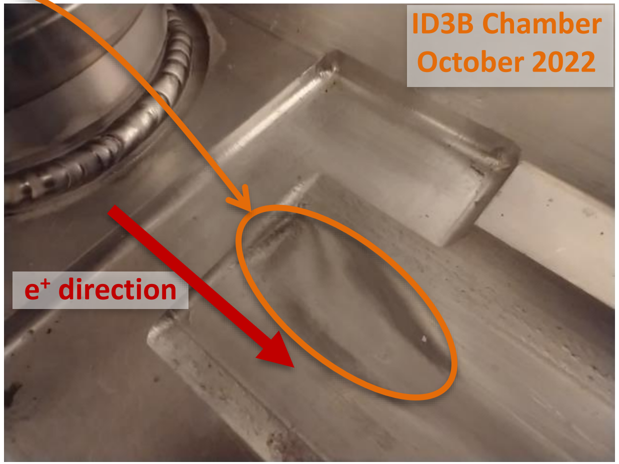
- CHESS-U upgrade introduced a number of small-gap out-of-vacuum undulators
  - 7mm pole-to-pole
  - 0.5mm pole-to-chamber
  - 0.5mm wall thickness
  - → ~~5mm~~ full-aperture
    4.6mm due to vacuum deflection



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

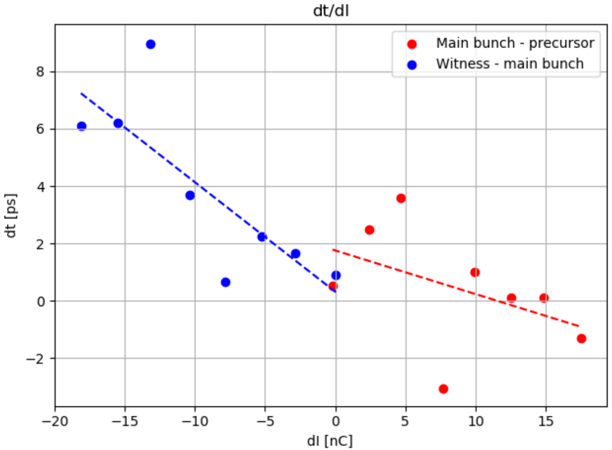
2mm reduction
in 4.6mm aperture





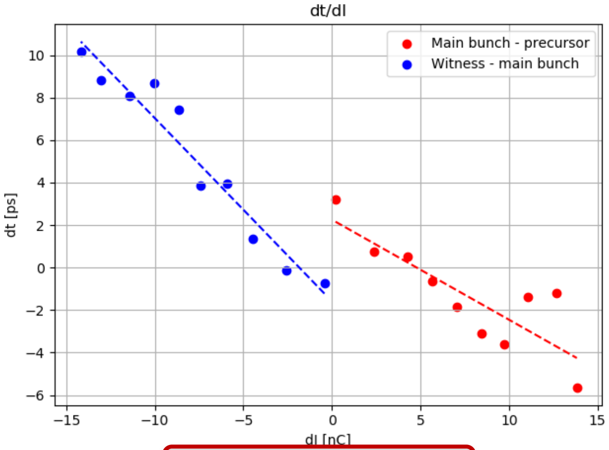
HOML – Damaged ID3 Chamber

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



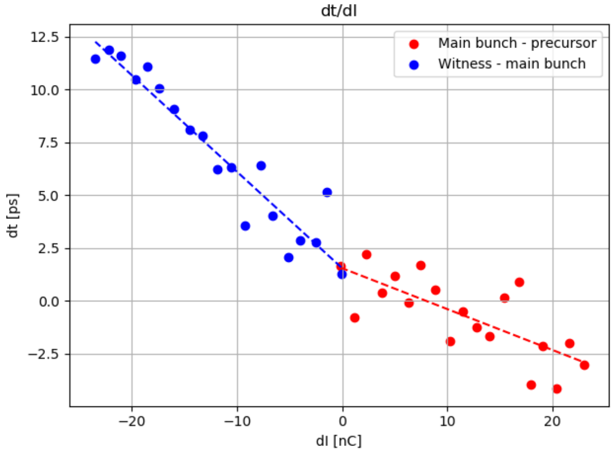
k_hom = -3.069 V/pC
w = 9.391 V/pC

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



k_hom = -8.355 V/pC
w = 22.645 V/pC

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



k_hom = -3.760 V/pC
w = 11.331 V/pC

- Historical measurements of k_hom in CHESS-U (2019-2022): **-4.54 ± 1.04 V/pC**
- Damaged chamber is correlated with factor of approximately 2x larger HOML (!)
- After chamber replaced, k_hom again in line with historical CHESS-U measurements

Longitudinal – Comments

- Longitudinal impedance is a useful diagnostic for identifying gross aperture issues
- Identified significant change (factor of 2x) in k_{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 ($r \le 16$mm) → resistive wall instability scales as $1/r^3$
    - Strong nonlinearities from chromatic correction → 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)

Meanwhile…

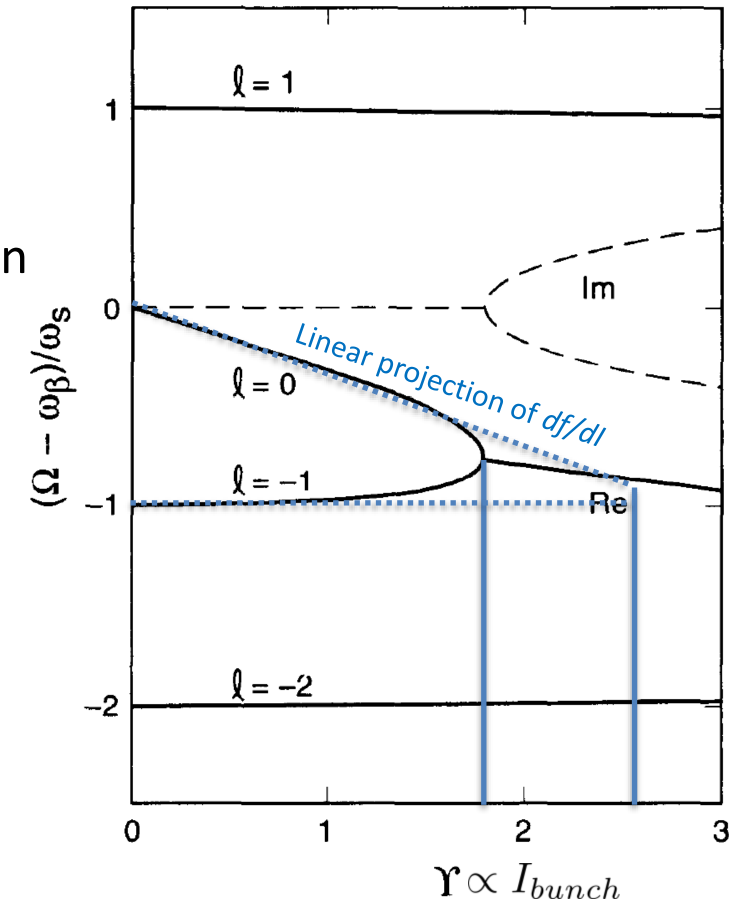
- Single-beam operations with users at CHESS-U started in 2019
  - No more counter-rotating beams
  - No need to interleave trains of bunches
  - Significantly increases flexibility in bunch patterns
- Moderate-gradient quadrupoles (< 40 T/m)
  - Nonlinearities are significantly less than 4th-generation 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

Impedance Tuneshift

- 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:

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

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:

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

$$\begin{aligned}\vec{w}_\lambda(\vec{r},\tau) &= \frac{1}{q}\int_0^\infty d\tau_d \int_V d\vec{r}\,\vec{w}_\perp(\vec{r},\vec{r}_1,\tau_d)\lambda(\vec{r},\tau-\tau_d) \\ \tau_d &= \text{delay between drive and witness particles}\end{aligned}$$

Multipole Expansion

- Via Joe Calvey:

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

$$
\begin{aligned}
&= \left(w_{\perp x}+w_{\perp x^2}x+w_{\perp xy}y+w_{\perp xx_1}x_1+w_{\perp xy_1}y_1\right)\hat{x}\\
&+ \left(w_{\perp y}+w_{\perp y^2}y+w_{\perp xy}x+w_{\perp yy_1}y_1+w_{\perp yx_1}x_1\right)\hat{y}
\end{aligned}
$$

Multipole Expansion

- Via Joe Calvey:

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\begin{aligned}
\vec{w}_\perp(\vec{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}\right. \\
&+ \left.\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
\end{aligned}
$$

$$
\begin{aligned}
&= \left(w_{\perp x}+w_{\perp x^2}x+w_{\perp xy}y+w_{\perp xx_1}x_1+w_{\perp xy_1}y_1\right)\hat{x} \\
&+ \left(w_{\perp y}+w_{\perp y^2}y+w_{\perp xy}x+w_{\perp yy_1}y_1+w_{\perp yx_1}x_1\right)\hat{y}
\end{aligned}
$$

Monopole

Multipole Expansion

- Via Joe Calvey:

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

Quadrupole

$$\begin{aligned}&= \left(\boxed{w_{\perp x}}+\boxed{w_{\perp x^2}x}+w_{\perp xy}y+w_{\perp xx_1}x_1+w_{\perp xy_1}y_1\right)\hat{x}\\ &+ \left(\boxed{w_{\perp y}}+\boxed{w_{\perp y^2}y}+w_{\perp xy}x+w_{\perp yy_1}y_1+w_{\perp yx_1}x_1\right)\hat{y}\end{aligned}$$

Monopole

Multipole Expansion

- Via Joe Calvey:

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

Quadrupole

$$
\begin{aligned}
&= \left(\boxed{w_{\perp x}}+\boxed{w_{\perp x^2}x}+\boxed{w_{\perp xy}y}+w_{\perp xx_1}x_1+\boxed{w_{\perp xy_1}y_1}\right)\hat{x} \\
&+ \left(\boxed{w_{\perp y}}+\boxed{w_{\perp y^2}y}+\boxed{w_{\perp xy}x}+w_{\perp yy_1}y_1+\boxed{w_{\perp yx_1}x_1}\right)\hat{y}
\end{aligned}
$$

Monopole Skew Skew

Multipole Expansion

- Via Joe Calvey:

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

$$
\begin{array}{cccccccccccc}
 & & & \textbf{Quadrupole} & & & & \textbf{Dipole} & & & & \\
= & (w_{\perp x} & + & w_{\perp x^2} x & + & w_{\perp xy} y & + & w_{\perp x x_1} x_1 & + & w_{\perp x y_1} y_1) & \hat{x} \\
+ & (w_{\perp y} & + & w_{\perp y^2} y & + & w_{\perp xy} x & + & w_{\perp y y_1} y_1 & + & w_{\perp y x_1} x_1) & \hat{y} \\
 & \textbf{Monopole} & & & & \textbf{Skew} & & & & \textbf{Skew} &
\end{array}
$$

Multipole Expansion

- Via Joe Calvey:

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

$$\begin{array}{ccccccccccccc} & & & \text{Quadrupole} & & & & \text{Dipole} & & & & \\ = & (& \boxed{w_{\perp x}} & + \boxed{w_{\perp x^2}x} & + & \boxed{w_{\perp xy}y} & + & \boxed{w_{\perp xx_1}x_1} & + & \boxed{w_{\perp xy_1}y_1} &) & \hat{x} \\ + & (& \boxed{w_{\perp y}} & + \boxed{w_{\perp y^2}y} & + & \boxed{w_{\perp xy}x} & + & \boxed{w_{\perp yy_1}y_1} & + & \boxed{w_{\perp yx_1}x_1} &) & \hat{y} \\ & & \text{Monopole} & & & \text{Skew} & & & & \text{Skew} & & \end{array}$$

$$\boxed{K[\mathrm{m}^{-1}] = kL = \frac{eq}{E_b}\left[w_{\perp y^2}+w_{\perp yy_1}\right]y_0} \longrightarrow \boxed{\Delta Q = \frac{1}{4\pi}K<\beta>}$$

Effective quadrupole gradient

Impedance tuneshift

Multipole Expansion

To summarize – for every component in the accelerator:

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

$$\boxed{K[\mathrm{m}^{-1}] = kL = \frac{eq}{E_b}\left[w_{\perp y^2} + w_{\perp yy_1}\right] y_0} \longrightarrow \boxed{\Delta Q = \frac{1}{4\pi} K < \beta >}$$

Effective quadrupole gradient

Impedance tuneshift

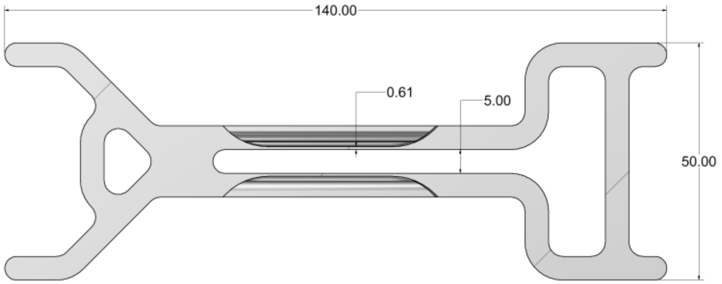
Transverse – Analytic

- 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 – Analytic

- 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:

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



CHESS Compact Undulator (CCU) chamber with *b* = 2.3mm half-height

Resistive Wall – Analytic

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:

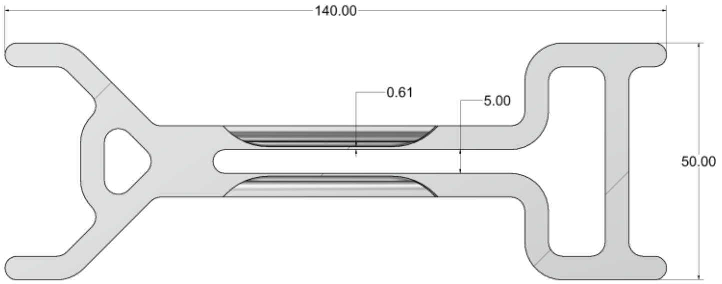
i = x,y

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

Excessively complicated geometric function of b/a encapsulating chamber geometry (round, elliptical, or rectangular)

Longitudinal dependence

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.



CHESS Compact Undulator (CCU) chamber with *b* = 2.3mm half-height

Discontinuities – Analytic

Stupakov [5] shows that one can approximate the kick factor κ for a <u>linearly</u> tapered structure with half-width *a* and half-height tapering at angle α to a minimum of *b*:

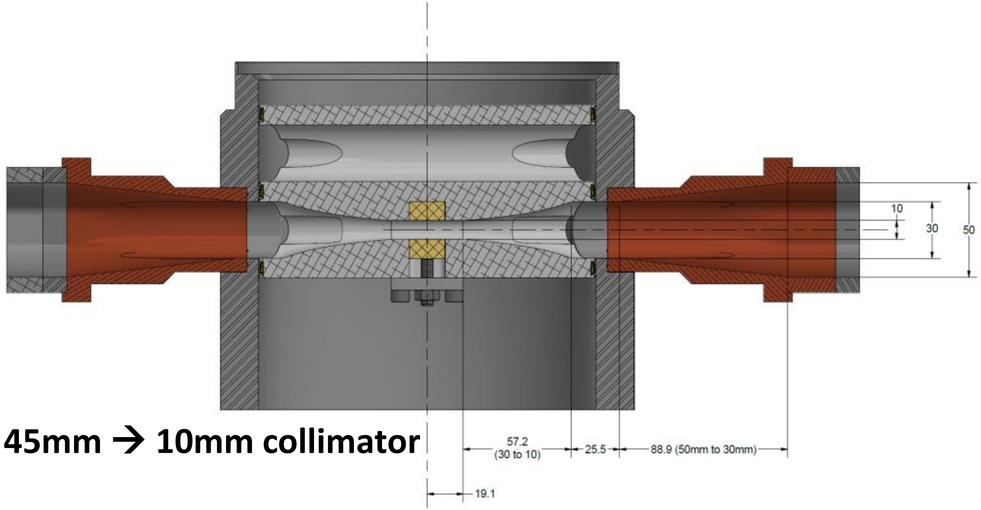
$$\kappa = -\begin{cases} 1/b^2 & \text{for } \sqrt{\dfrac{\alpha b}{\sigma_z}} > 0.37 \\ 2.7\sqrt{\dfrac{\alpha}{\sigma_z b^3}} & \text{for } 0.37 > \sqrt{\dfrac{\alpha b}{\sigma_z}} > 3.1\dfrac{b}{a} \\ \boxed{\dfrac{\sqrt{\pi}\alpha a}{2\sigma_z b^2}} & \text{for } \sqrt{\dfrac{\alpha b}{\sigma_z}}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

Diffractive

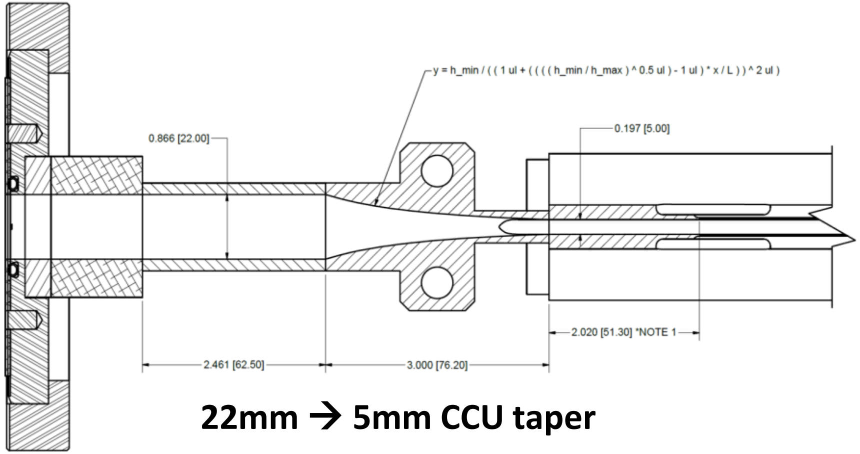
Intermediate

Inductive

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



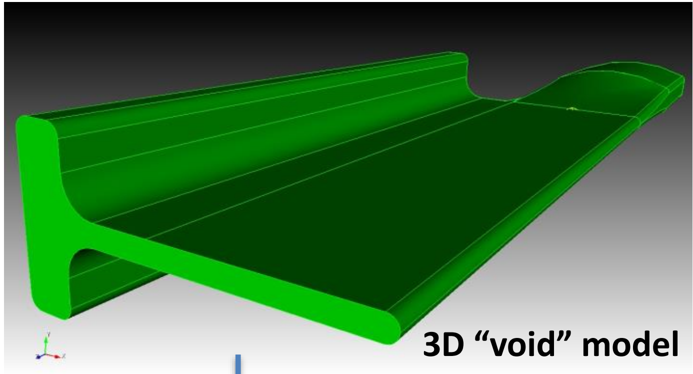
45mm → 10mm collimator

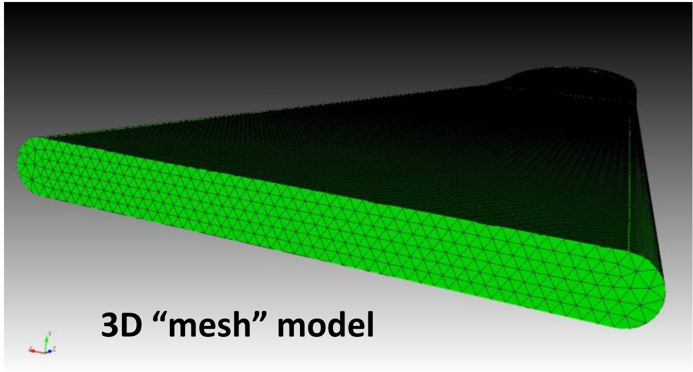


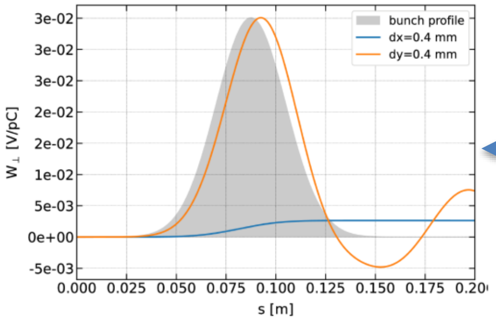
22mm → 5mm CCU taper

Discontinuities – Numerical

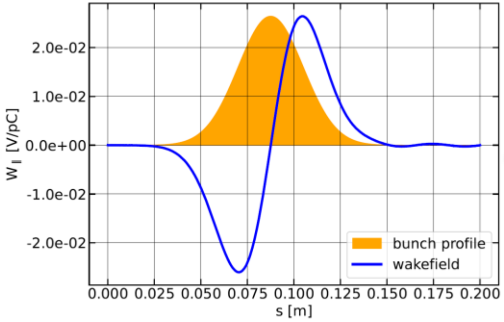
- Numerical modeling of wakes would be an entire talk in of itself
  - Briefly summarize process here
- Wakes can be modeled with Finite Element Analysis (FEA)
  - For CESR, we use ACE3P (namely, T3P)
- General procedure:
  - Generate a 3D “void” model based on CAD drawings
  - Convert void model to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







Transverse wake (dipole)



Longitudinal wake

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

Component	Analytic	Numerical (T3P)
Sector 2 CCU - RW	-9.6 Hz/mA	n/a
Sector 2 CCU - tapers	-11.2 Hz/mA	-12.9 Hz/mA[a]
Sector 3 CCU - RW	-9.3 Hz/mA	n/a
Sector 3 CCU - tapers	-11.2 Hz/mA	-12.6 Hz/mA
Sector 4 CCU - RW	-9.3 Hz/mA	n/a
Sector 4 CCU - tapers	-11.2 Hz/mA	-8.9 Hz/mA[b]
Sector 7 CCU - RW	-10.5 Hz/mA	n/a
Sector 7 CCU - tapers	-11.9 Hz/mA	-13.4 Hz/mA
50 mm to 22 mm tapers	-1.4 Hz/mA	n/a
43W collimator at 10 mm	-100.5 Hz/mA	-117.8 Hz/mA
43E collimator at 10 mm	-89.3 Hz/mA	-104.7 Hz/mA
Sliding Joints - North Arc	n/a	-8.5 Hz/mA
North Arc RW	-9.4 Hz/mA	n/a
South Arc RW	-4.5 Hz/mA	n/a
Total	-297.8 Hz/mA	-332.8 Hz/mA

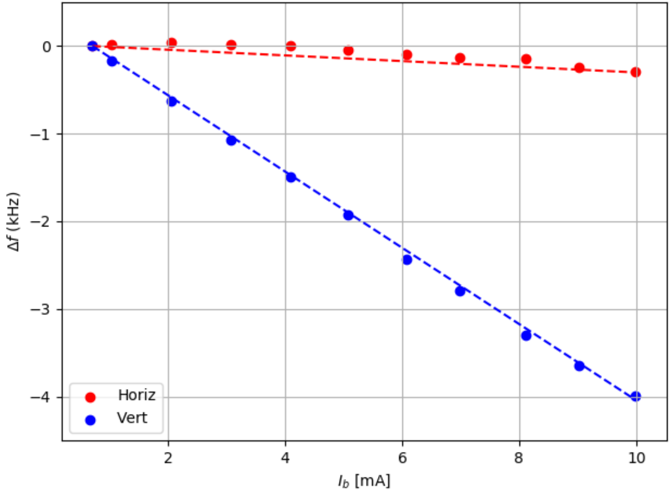
Transverse – Measurements

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

- Measurement reproducibility, based on first half of 2022:

df_x/dI = -47.4 Hz/mA σ = 7.6 Hz/mA
df_y/dI = -418.8 Hz/mA σ = 14.1 Hz/mA

Tuneshift vs. Bunch Current



→ 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 kHz, df_y/dI_b = -418.8 Hz/mA (measured)

$$\rightarrow I_b^{max} = 31.6 \text{ mA}$$

- Maximum per-bunch current needed for CHESS-U Timing Mode: **22.2mA/b**
  - Corresponds to 200mA across 9 equally-spaced bunches
- On paper, seems like we're good to go
- **Experimental verification**: One-off high-bunch-current test reached 20mA in a single bunch with no signs of mode coupling instability
  - Going above 20mA 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

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