Coupling Impedances in Accelerator Rings

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Fermilab

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Slides can be downloaded from
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Introduction

- A particle interacts with the vacuum chamber produces EM fields.
- The motion of a particle following is perturbed.

$$(\vec{E},\vec{B})_{\substack{\text{seen by}\\ \text{particles}}} = (\vec{E},\vec{B})_{\substack{\text{external, from}\\ \text{magnets, rf, etc.}}} + (\vec{E},\vec{B})_{\substack{\text{wake}\\ \text{fields}}}$$

where

$$(\vec{E},\vec{B})_{\substack{\text{wake}\\ \text{fields}}} \begin{cases} \propto & \text{beam intensity} \\ \ll & (\vec{E},\vec{B})_{\text{external}} \end{cases}$$

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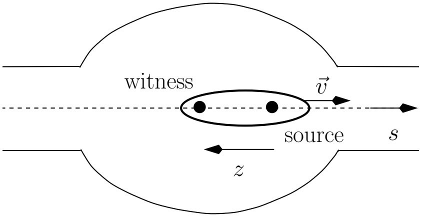
- Perturbation breaks down when potential-well distortion is large. Then, distortion has to be included into non-perturbative part.
- What we need to compute are the EM wake fields at a distance z behind the source particle.
- The computation of the wake fields is nontrivial.
- Two approximations lead to a lot of simplification.

1. Rigid-Bunch Approximation

- Motion of beam not affected during traversal through discontinuities.



Source particle at $s = \beta ct$

Witness particle at $s = z + \beta ct$

$z < 0$ for particle following.

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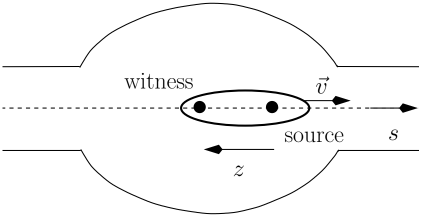

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2. Impulse Approximation

- We do not care about the wake fields $\vec{E}$, $\vec{B}$, or the wake force $\vec{F}$.
- We only care about the impulse

$$\Delta\vec{p} = \int_{-\infty}^{\infty} dt\ \vec{F} = \int_{-\infty}^{\infty} dt\ q(\vec{E} + \vec{v} \times \vec{B})$$

- We will see how the simplification evolves.

Panofsky-Wenzel Theorem

- Maxwell equation for witness particle at (x, y, s, t) with $s = z + \beta t$:

$$\vec{\nabla}\cdot\vec{E} = \frac{q\rho}{\epsilon_0} \qquad \text{Gauss's law for electric charge}$$

$$\vec{\nabla}\times\vec{B} - \frac{1}{c^2}\frac{\partial\vec{E}}{\partial t} = \mu_0 q\beta c\rho\hat{s} \qquad \text{Ampere's law}$$

$$\vec{\nabla}\cdot\vec{B} = 0 \qquad \text{Gauss's law for magnetic charge}$$

$$\vec{\nabla}\times\vec{E} + \frac{\partial\vec{B}}{\partial t} = 0 \qquad \text{Faraday's \& Lenz law}$$

- Want to write Maxwell equation for the impulse $\Delta\vec{p}$.

  First compute

with $\vec{F} = q(\vec{E} + \vec{v}\times\vec{B})$

$$\vec{\nabla}\cdot\vec{F} = \frac{q\rho}{\epsilon_0\gamma^2} - \frac{q\beta}{c}\frac{\partial E_s}{\partial t},$$

$$\vec{\nabla}\times\vec{F} = -q\left(\frac{\partial}{\partial t} + \beta c\frac{\partial}{\partial s}\right)\vec{B}.$$

$$\vec{\nabla} \times \Delta \vec{p}\,(x,y,z) = \int_{-\infty}^{\infty} dt\ \left[\vec{\nabla} \times \vec{F}(x,y,s,t)\right]_{s=z+\beta ct}.$$

this $\vec{\nabla}$ refers to x, y, z

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$$\underset{\substack{\uparrow\\ \text{this } \vec\nabla \text{ refers}\\ \text{to } x,y,z}}{\vec\nabla}\times\Delta\vec p\,(x,y,z)=\int_{-\infty}^{\infty}dt\;\Big[\underset{\substack{\uparrow\\ \text{this } \vec\nabla \text{ refers}\\ \text{to } x,y,s}}{\vec\nabla}\times\vec F(x,y,s,t)\Big]_{s=z+\beta ct}.$$

We obtain

$$\vec\nabla\times\Delta\vec p=-q\int_{-\infty}^{\infty}dt\;\left[\left(\frac{\partial}{\partial t}+\beta c\frac{\partial}{\partial s}\right)\vec B(x,y,s,t)\right]_{s=z+\beta ct}$$

$$=-q\int_{-\infty}^{\infty}dt\;\frac{d\vec B}{dt}=-q\vec B(x,y,z+\beta ct,t)\Big|_{t=-\infty}^{\infty}=0,$$

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- Cross product with $\hat s\Longrightarrow\dfrac{\partial}{\partial z}\Delta\vec p_\perp=\vec\nabla_\perp\Delta p_s.$ $\longleftarrow$ P-W Theorem

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$$= -q\int_{-\infty}^{\infty} dt\;\frac{d\vec{B}}{dt} = -q\vec{B}(x,y,z+\beta ct,t)\Big|_{t=-\infty}^{\infty} = 0,$$

- Dot product with $\hat{s} \Longrightarrow \vec{\nabla}\cdot(\hat{s}\times\Delta\vec{p}) \Longrightarrow \dfrac{\partial\Delta p_x}{\partial y} = \dfrac{\partial\Delta p_y}{\partial x}$
- Cross product with $\hat{s} \Longrightarrow \dfrac{\partial}{\partial z}\Delta\vec{p}_\perp = \vec{\nabla}_\perp\Delta p_s.$ $\qquad\longleftarrow$ P-W Theorem
- P-W theorem gives strong restriction between longitudinal and transverse.
- But it is very general. Does not depend on any boundary conditions. Even do not require $\beta=1$.

Supplement to Panofsky-Wenzel Theorem

$$\beta = 1 \implies \vec{\nabla}_\perp \cdot \Delta\vec{p}_\perp = 0.$$

Proof:

$$\vec{\nabla}\cdot\Delta\vec{p} = \int_{-\infty}^{\infty} dt \left[\vec{\nabla}\cdot\vec{F}(x,y,s,t)\right]_{s=z+ct} = q\int_{-\infty}^{\infty} dt \left[\frac{\rho}{\epsilon_0\gamma^2} - \frac{\beta}{c}\frac{\partial E_s}{\partial t}\right]_{s=z+ct}$$

$$\longrightarrow q\int_{-\infty}^{\infty} dt \left[\frac{\partial E_s}{\partial s}\right]_{s=z+ct} = \frac{\partial}{\partial z}\Delta p_s$$

Use has been made of

1. Space-charge term $\dfrac{q\rho}{\epsilon_0\gamma^2}$ omitted because $\beta \to 1$.
2. $\dfrac{\partial}{\partial t}E_s(s,t) = \dfrac{d}{dt}E_s(s,t) - \dfrac{ds}{dt}\dfrac{\partial}{\partial s}E_s(s,t).$

Maxwell equations now become

$$\vec{\nabla}\times\Delta\vec{p} = 0 \quad \text{and} \quad \vec{\nabla}\cdot\Delta\vec{p} = \frac{\partial}{\partial z}\Delta p_s$$ without any source terms.

Cylindrical Symmetric Vacuum Chamber

$$\begin{cases} \dfrac{\partial}{\partial r}(r\Delta p_\theta) = \dfrac{\partial}{\partial\theta}\Delta p_r \\ \dfrac{\partial}{\partial z}\Delta p_r = \dfrac{\partial}{\partial r}\Delta p_s \\ \dfrac{\partial}{\partial z}\Delta p_\theta = \dfrac{1}{r}\dfrac{\partial}{\partial\theta}\Delta p_s \\ \dfrac{\partial}{\partial r}(r\Delta p_r) = -\dfrac{\partial}{\partial\theta}\Delta p_\theta \quad (\beta = 1) \end{cases} \Longrightarrow \begin{cases} \dfrac{\partial}{\partial r}(r\Delta\tilde{p}_\theta) = -m\Delta\tilde{p}_r \\ \dfrac{\partial}{\partial z}\Delta\tilde{p}_r = \dfrac{\partial}{\partial r}\Delta\tilde{p}_s \\ \dfrac{\partial}{\partial z}\Delta\tilde{p}_\theta = -\dfrac{m}{r}\Delta\tilde{p}_s \\ \dfrac{\partial}{\partial r}(r\Delta\tilde{p}_r) = -m\Delta\tilde{p}_\theta \quad (\beta = 1) \end{cases}$$

- Cylindrical symmetry $\Longrightarrow$ expansion in terms of $\cos m\theta$ or $\sin m\theta$.

  We write $\Delta p_s = \Delta\tilde{p}_s \cos m\theta$, $\Delta p_r = \Delta\tilde{p}_r \cos m\theta$, $\Delta p_\theta = \Delta\tilde{p}_\theta \sin m\theta$,

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- For $m \neq 0$, $\dfrac{\partial}{\partial r}\left[r\dfrac{\partial}{\partial r}(r\Delta\tilde{p}_r)\right] = m^2\Delta\tilde{p}_r \Longrightarrow \Delta p_r(r,\theta,z) \sim mr^{m-1}\cos m\theta.$

Definition of Wake Functions

- Formal solution can be written as

$$\begin{cases} v\Delta\vec{p}_\perp = -q\mathcal{Q}_m W_m(z) m r^{m-1}\big(\hat{r}\cos m\theta - \hat{\theta}\sin m\theta\big), \\ v\Delta p_s = -q\mathcal{Q}_m W_m'(z) r^m \cos m\theta. \end{cases}$$

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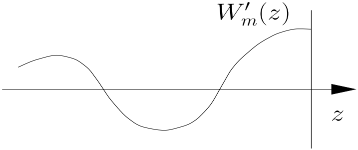
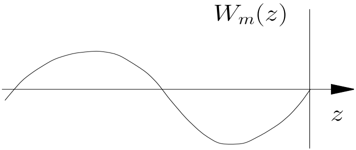
- Recall that solution of $\vec{E}$ and $\vec{B}$ reduces to solution of $W_m(z)$ only.
  Simplification comes from P-W theorem or rigid-bunch and impulse approximations.

- negative sign in front is a convention to make $W_m'(z) > 0$,
  since witness particle loses energy from impulse.

Some Properties of Wake Functions





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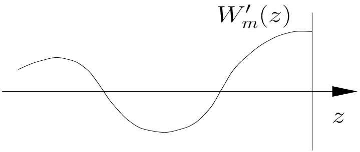

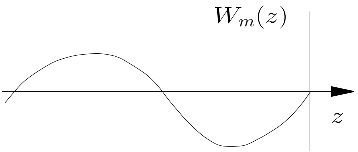

Fundamental Theorem of Beam Loading (P. Wilson)

A particle sees half of its wake, or $\frac{1}{2}W'_m(0_-)$.

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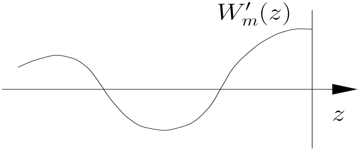

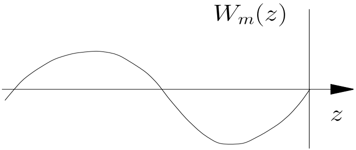

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A particle of charge q passes a thin lossless cavity, excites cavity.

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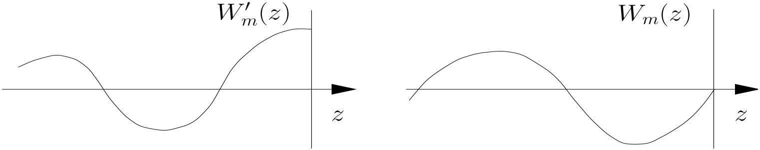

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Energy gained $\Delta\mathcal{E}_2 = -fq^2 W'_m(0_-) + q^2 W'_m(0_-)$.

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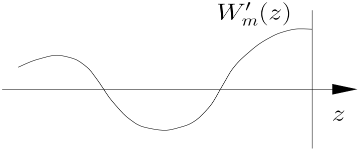

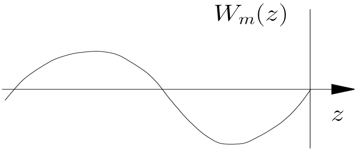

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Field inside cavity is completely cancelled.

$\Delta\mathcal{E}_1 + \Delta\mathcal{E}_2 = -2fq^2W'_m(0_-) + q^2W'_m(0_-) = 0 \Longrightarrow f = \frac{1}{2}$.

Properties of Wake Functions

- $W'_m(z) = 0$ for $z > 0$. (causality)
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  Total loss $q^2 W'(0_-) + q^2 W'_0(z) \geq 0$. Or $W'_0(z) \geq -W'_0(0_-)$.

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- $W'_m(-D) = W'_m(0_-)$ for some $D > 0 \implies$ wake is of period D.

Properties of Wake Functions

- $W_m'(z) = 0$ for $z > 0$. (causality)
- $W_m'(0_-) \geq 0$ (energy conservation)
- $|W_m'(z)| \leq W_m'(0_-)$.

  1st particle of charge q loses energy $\frac{1}{2}q^2 W'(0_-)$.

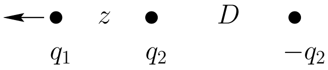
  2nd particle of charge q loses energy $\frac{1}{2}q^2 W'(0_-) + q^2 W_0'(z)$.

  Total loss $q^2 W'(0_-) + q^2 W_0'(z) \geq 0$. Or $W_0'(z) \geq -W_0'(0_-)$.

  2nd particle of charge $-q$ loses energy $\frac{1}{2}q^2 W'(0_-) - q^2 W_0'(z)$.

  Total loss $q^2 W'(0_-) - q^2 W_0'(z) \geq 0$. Or $W_0'(z) \leq W_0'(0_-)$.
- $W_m'(-D) = W_m'(0_-)$ for some $D > 0 \Longrightarrow$ wake is of period D.

  Energy loss:



  1. $\frac{1}{2}q_1^2 W_0'(0_-)$.
  2. $\frac{1}{2}q_2^2 W_0'(0_-) + q_1 q_2 W_0'(-z)$.
  3. $\frac{1}{2}q_2^2 W_0'(0_-) - q_1 q_2 W_0'(-z-D) - q_2^2 W_0'(-D)$.

  Since total must be ≥ 0 and q_1 arbitrary, $W_0'(-z) \geq W_0'(-z-D)$.

  Change 3 charges to $(q_1, -q_2, q_2)$ to get $W_0'(-z) \leq W_0'(-z-D)$.

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- Higher azimuthals can be important for large transverse beam size compared with pipe radius.

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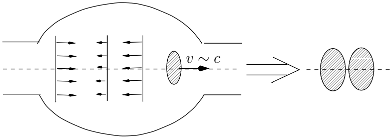
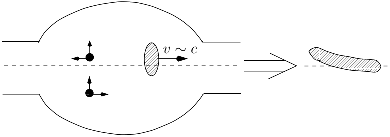


Particles in same vertical slice see same impulse. Can lead to longitudinal micro-bunching or microwave instability.



Particles in same vertical slice receive same vertical impulse independent of vertical position. Can lead to beam breakup.

Coupling Impedances

- Beam particles form current. Component with freq. ω is $I(s,t) = \hat{I} e^{-i\omega(t-s/v)}$.

- A test particle crossing a narrow discontinuity at s_1 gains energy from wake left by particles $-z$ in front ($z < 0$). Voltage gained is

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\begin{aligned}
V(s_1,t) &= -\int_{-\infty}^{\infty} [W_0'(z)]_1 \hat{I} e^{-i\omega[(t+z/v)-s_1/v]} \frac{dz}{v} \\
&= -I(s_1,t) \int_{-\infty}^{\infty} [W_0'(z)]_1 e^{-i\omega z/v} \frac{dz}{v} \equiv -I(s_1,t) \left[Z_0^{\parallel}(\omega) \right]_1
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- Unlike a current in a circuit, a beam has transverse dimension and therefore higher multipoles.

- When the beam is off-center by amount a, the current mth multipole is $\mathcal{P}_m(s,t)=I(s,t)a^m=\hat{\mathcal{P}}_m e^{-i\omega(t-s/v)}$.

Higher Azimuthal Impedances

- At location i, test particle density is $\rho = q\dfrac{\delta(r-a)}{a}\delta(\theta)\delta(s-s_i)$.

  Subject to the mth multipole element $\mathcal{P}(s_i, t+z/v)dz$ passes location i $-z$ earlier, voltage gained is

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V(s_i,t) &= -\int \frac{dz}{v}\mathcal{P}_m(s_i,t+z/v)[W_m'(z)]_i \int r dr d\theta \, r^m \cos m\theta \frac{\delta(r-a)\delta(\theta)}{a} \\
&= -\int \frac{dz}{v}\hat{\mathcal{P}}_m e^{-i\omega[(t+z/v)-s/v]}[W_m'(z)]_i a^m \\
&= -\frac{\mathcal{Q}_m}{q}\mathcal{P}_m(s_i,t)\int_{-\infty}^{0}\frac{dz}{v}\,[W_m'(z)]_i\, e^{-i\omega z/v} \qquad [\mathcal{Q}_m = qa^m]
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- Identify mth multipole longitudinal impedance across location i as

$$\left[Z_m^{\|}(\omega)\right]_i = -\frac{q\hat{V}}{\mathcal{Q}_m\hat{\mathcal{P}}_m} = \int_{-\infty}^{\infty}\frac{dz}{v}\,[W_m'(z)]_i\, e^{-i\omega z/v}.$$

- Summing up around the vacuum chamber: $Z_m^{\|}(\omega) = \sum_i \left[Z_m^{\|}(\omega)\right]_i$.

Transverse Impedances

- General defn. for long. imp.: $Z_m^{\parallel}(\omega) = \displaystyle\int_{-\infty}^{\infty} \frac{dz}{v} W_m'(z) e^{-i\omega z/v}$.
- If we replace W_m' by W_m, we obtain transverse impedances

  Defn. $\quad Z_m^{\perp}(\omega) = \dfrac{i}{\beta} \displaystyle\int_{-\infty}^{\infty} \frac{dz}{v} W_m(z) e^{-i\omega z/v} \qquad [W_m(z) = 0 \text{ when } z > 0]$
- Long. and transverse imp. are then related by $Z_m^{\parallel}(\omega) = \dfrac{\omega}{c} Z_m^{\perp}(\omega)$,

  so that both $\mathcal{R}e\, Z_m^{\parallel}$ and $\mathcal{R}e\, Z_m^{\perp}$ represent energy loss or gain.
- Transverse force, $F_{\perp} \propto -W_m$, must lag $\mathcal{P}_m$ by $\dfrac{\pi}{2}$ in order for $\mathcal{R}e\, Z_m^{\perp}$ to dissipate energy. Hence the factor i.
- The factor β is to cancel β in Lorenz force, just a convention.

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$$\begin{aligned}\langle F_1^\perp(s,t)\rangle &= -q\int_{-\infty}^{\infty} W_1(z) a\hat{I} e^{-i\omega[(t+z/v)-s/v]}\frac{dz}{v}\\ &= -qaI(s,t)\int_{-\infty}^{\infty} W_1(z) e^{-i\omega z/v}\frac{dz}{v} = \frac{i\beta q I(s,t) a}{L} Z_1^\perp(\omega).\end{aligned}$$

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- For transverse: $Z_1^\perp(\omega)=-\dfrac{i}{q\hat{I}a\beta}\langle\hat{F}_1^\perp\rangle$.
- For longitudinal: $Z_0^\parallel(\omega)=-\dfrac{1}{q\hat{I}}\langle\hat{F}_0^\parallel\rangle$.
- Other than from wake fcns, these are formulas employed to compute imp. directly from the long. and trans. forces seen by test particle.

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$$W_m(z) = -\frac{i\beta}{2\pi}\int_{-\infty}^{\infty} Z_m^{\perp}(\omega) e^{i\omega z/v} d\omega$$

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General Comments

- $W_m(z)=0$, $W'_m(z)=0$ when $z>0$ because of causality.
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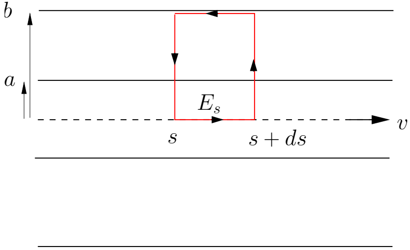
- All properties of the impedances remain unchanged, including no singularity in upper half ω-plane.
- Some may like to use j instead of i to denote imaginary value. Most of the time $j = -i$. Then $Z_m^{\parallel}$ and $Z_m^{\perp}$ have no singularity in lower half ω-plane instead.

Space-Charge Impedances

- Sp-ch imp. come from EM fields of beam even when beam pipe is smooth and perfectly connducting.
- Want to compute E_s due to variation of linear density $\lambda(s - vt)$. Assume small variation of trans. dist.



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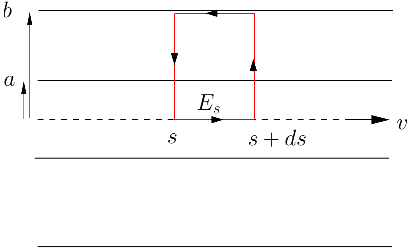

- Faraday law: $\oint \vec{E}\cdot\overrightarrow{d\ell} = -\frac{\partial}{\partial t}\int \vec{B}\cdot d\vec{A}.$

uniform dist. assumed

$$\oint \vec{E}\cdot\overrightarrow{d\ell} = E_s ds - \frac{e\lambda(s-vt)}{2\pi\epsilon_0}\left[\int_a^b \frac{dr}{r} + \int_0^a \frac{rdr}{a^2}\right] + \left\{s\to s+ds\right\}$$

- Geometric factor $g_0 = 2\left[\int_a^b \frac{dr}{r} + \int_0^a \frac{rdr}{a^2}\right] = 1 + 2\ln\frac{b}{a}.$

- Electric field or left side: $\oint \vec{E}\cdot\overrightarrow{d\ell} = E_s ds + \dfrac{eg_0}{4\pi\epsilon_0}\dfrac{\partial\lambda}{\partial s}\, ds.$
- Magnetic field or right side:

$$-\frac{\partial}{\partial t}\int \vec{B}\cdot d\vec{A} = -\frac{\partial}{\partial t}\frac{\mu_0 e\lambda(s-vt)v}{2\pi}\left[\int_0^a \frac{rdr}{a^2} + \int_a^b \frac{dr}{r}\right] ds = v^2\frac{e\mu_0 g_0}{4\pi}\frac{\partial\lambda}{\partial s} ds.$$

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- Consider a long. harmonic wave $\lambda_1(s;t) \propto e^{i(ns/R-\Omega t)}$ perturbing a coasting beam of uniform linear density λ_0.
- Voltage drop per turn is $V = E_s 2\pi R = \frac{ineZ_0 cg_0}{2\gamma^2}\lambda_1 = \frac{inZ_0 g_0}{2\gamma^2\beta}I_1.$
- The wave constitutes a perturbing current of $I_1 = e\lambda_1 v$.
- Imp. is $\left.\frac{Z_0^{\parallel}}{n}\right|_{\rm sp\ ch} = \frac{iZ_0 g_0}{2\gamma^2\beta}$ with $g_0 = 1+2\ln\frac{b}{a}.$ $\left[Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = \frac{1}{\epsilon_0 c} = \mu_0 c\right]$

Comments

- $\left.\dfrac{Z_0^{\parallel}}{n}\right|_{\rm sp\ ch} = i\dfrac{Z_0 g_0}{2\beta\gamma^2}$ is independent of freq., but rolls off when $\omega \gtrsim \dfrac{\gamma c}{b}$.
- $\left.Z_0^{\parallel}\right|_{\rm sp\ ch} \propto \omega$, resembling a neg. inductive imp. rather than a cap. imp.
- For a freq.-independent reactive imp. $\left.\dfrac{Z_0^{\parallel}}{n}\right|_{\rm sp\ ch}$, corr. wake is

$$W_0'(z) = \delta'(z)\left[-iRc\beta\frac{Z_0^{\parallel}}{n}\right]_{\rm reactive} = \delta'(z)\frac{Z_0 cRg_0}{2\gamma^2}.$$

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- Longitudinal reactive impedance results from a longitudinal reactive force $F_0^\parallel(s,t) = \frac{ie^2v}{2\pi}\left.\frac{Z_0^\parallel}{n}\right|_{\rm reactive}\frac{\partial\lambda(s,t)}{\partial s}$.

- This force modifies the bunch shape, called *potential-well distortion.* Below/above transition, capacitive force lengthens/shortens the bunch.

- Below/above transition, inductive/capacitive force can generate micro-bunching and eventual microwave instabilities.

Space-Charge Compensation at PSR

- Since $Z_0^{\|}|_{\rm sp\ ch}$ is just a negative inductance, an inductance can cancel the space-charge force. As an example, ferrite rings are placed in Los Alamos PSR to cancel space-charge force so as to shorten the bunch.

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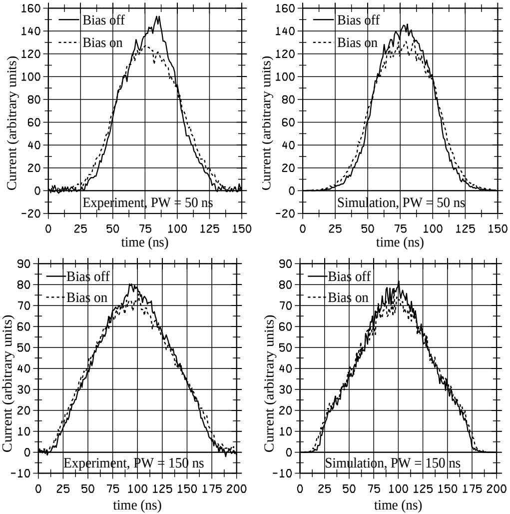


When 900-A bias is on, μ' of ferrite rings is reduced by 34%.

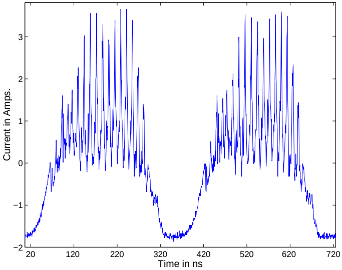
Bunches become longer when bias is on.

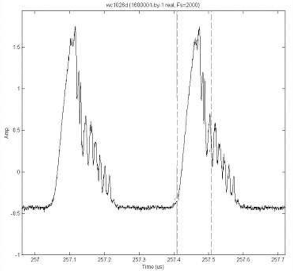
- However, resistive part of the ferrite, if too high, can generate microwave instabilities.

$\sim 500\ \mu$s

into PSR storage

with 3 ferrite tuners.





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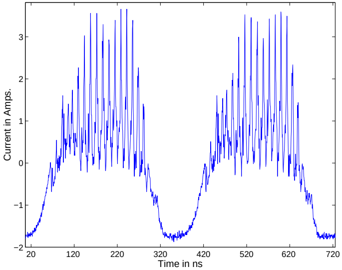

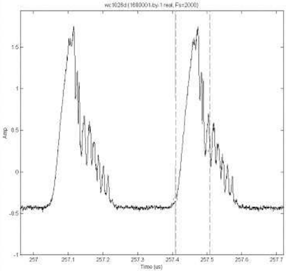

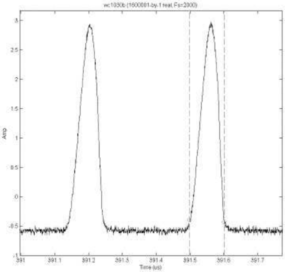

Heating ferrite increases μ' and decreases μ''. Using 2 instead of 3 of ferrite tuners and heating to 130° C alleviates the instabilities.

-

Other Transverse Beam Distribution

- The former geometric factor g_0 was computed according to uniform transverse distribution.
- It is easy to compute g_0 for any transverse distributions.
- We can also retain the form of g_0 for uniform distribution by introducing an effective beam radius $a_{\rm eff}$ such that $g_0 = 1 + 2\ln(b/a_{\rm eff})$.

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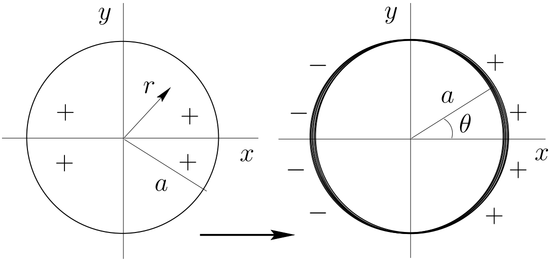
	Phase space distribution	g_0	$a_{\rm eff}$
Uniform	$\dfrac{1}{\pi\hat{r}^2}H(\hat{r}-r)$	$1+2\ln\dfrac{b}{\hat{r}}$	$\hat{r}$
Elliptical	$\dfrac{3}{2\pi\hat{r}}\left(1-\dfrac{r^2}{\hat{r}^2}\right)^{1/2}H(\hat{r}-r)$	$\dfrac{8}{3}-2\ln 2+2\ln\dfrac{b}{\hat{r}}$	$0.8692\hat{r}$
Parabolic	$\dfrac{1}{2\pi\hat{r}^2}\left(1-\dfrac{r^2}{\hat{r}^2}\right)H(\hat{r}-r)$	$\dfrac{3}{2}+2\ln\dfrac{b}{\hat{r}}$	$0.7788\hat{r}$
Cosine-square	$\dfrac{2\pi}{\pi^2-4}\cos^2\dfrac{\pi r}{2\hat{r}}H(\hat{r}-r)$	$1.9212+2\ln\dfrac{b}{\hat{r}}$	$0.6309\hat{r}$
Bi-Gaussian	$\dfrac{1}{2\pi\sigma_r^2}e^{-r^2/(2\sigma_r^2)}$	$\gamma_e+2\ln\dfrac{b}{\sqrt{2}\sigma_r}$	$1.747\sigma_r$

Transverse Impedance from Self-Field

- A uniformly distributed beam is shifted by Δ in x-direction. There is a horizontal opposing force. Hence the imp.
- Beam density

$$\rho(r) = \frac{e\lambda}{\pi a^2} H(a - r).$$



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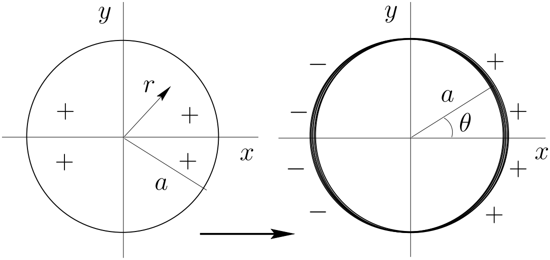

Shift to the right by $\Delta \to 0$

- Beam density

$$\rho(r) = \frac{e\lambda}{\pi a^2} H(a - r).$$

- Dipole density

$$\Delta\rho(r) = -\frac{\partial \rho(\vec{r})}{\partial x}\Delta = \frac{e\lambda\Delta\cos\theta}{\pi a^2}\delta(a - r).$$

- Dipole sees opposing electric force

$$F_{\rm elec} = \int_0^{2\pi} d\theta \int_0^{\infty} rdr \frac{e^2\lambda\Delta\cos\theta}{\pi a^2}\delta(a - r)\frac{\cos\theta}{2\pi\epsilon_0 r} = \frac{e^2\lambda\Delta Z_0 c}{2\pi a^2}.$$

- The shifted beam current $I = e\lambda\beta$ also generates a dipole current $\Delta I = e\beta\dfrac{\partial\lambda}{\partial x}\Delta$, and therefore a magnetic horizontal $F_x^{\rm mag}$.
- $F_x^{\rm mag} = -\beta F_x^{\rm elect}$. Total is $1-\beta^2 = 1/\gamma^2$,
  Total self-force $\displaystyle\int_0^C F_{\rm self}\,ds = \frac{e^2\lambda\Delta Z_0 cR}{\gamma^2 a^2}$.
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- The dependence on a^{-2} appears to resemble the incoherent self-field tune shift $\Delta\nu_{\rm self}$.
- Actually $Z_1^\perp\Big|_{\rm self}$ and $\Delta\nu_{\rm self}$ are even proportional to each other.

Coherent, Incoherent, and Impedance Forces

- Vertical force on a beam particle $\dfrac{d^2y}{ds^2}+\dfrac{\nu_{0y}^2}{R^2}\,y=\dfrac{F(y,\bar{y})}{\gamma m v^2}.$

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- Thus $\Delta\nu_{y\,\mathrm{inc}} \propto \dfrac{\partial F}{\partial y}\bigg|_{\bar{y}=0}$

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  $\Delta\nu_{y\,\mathrm{coh}}\propto\left.\dfrac{\partial F}{\partial y}\right|_{\bar{y}=0}+\left.\dfrac{\partial F}{\partial \bar{y}}\right|_{y=0}$
- But $Z_1^{\perp}\propto\left.\dfrac{\partial F}{\partial \bar{y}}\right|_{y=0}$,
- $\therefore$ Impedance Shift = Coherent Shift − Incoherent Shift.

- $\Delta\nu_{y\,\mathrm{coh}}$: result of all forces acting on center of beam at $\bar{y}$.
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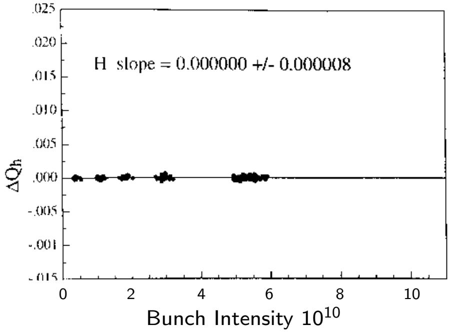
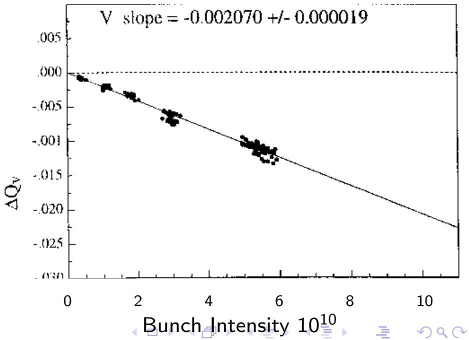
- Single bunch tune shift measurement at CERN SPS.





- Now let us come back to the self-field imp.
- Beam center moves with beam, does not see self-force, $\therefore \Delta\nu_{y\,\mathrm{coh}}^{\mathrm{self}} = 0$.
- Thus $\Delta\nu_y^{\mathrm{imp}} \propto -\Delta\nu_{y\,\mathrm{incoh}}^{\mathrm{self}}$.

  Or $Z_1^{\perp}\Big|_{\mathrm{self}}^{y,x} = -i\dfrac{2\pi Z_0\gamma\nu_{0y,x}}{Nr_0}\Delta\nu_{y,x\,\mathrm{incoh}}^{\mathrm{self}}$,

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  where N is the number of beam particles, r_0 is classical radius.
- As for the EM field inside the vacuum chamber,

  $Z_1^{y,x} = -i\dfrac{2Z_0R}{\gamma^2\beta^2}\dfrac{\xi_{1y,x} - \epsilon_{1y,x}}{h^2}$,

  where $\xi_{1y,x}/\epsilon_{1y,x}$ is *Laslett coherent/incoherent electric image coeff.*,

  h is vertical half gap in vacuum chamber.
- For circular beam pipe of radius b, $h = b$, $\xi_{1y,x} = \frac{1}{2}$, $\epsilon_{1y,x} = 0$.

  then $Z_1^{y,x} = -i\dfrac{Z_0R}{\gamma^2\beta^2b^2}$ is just vacuum chamber contribution to

  the trans. sp-ch imp.

Self-Field Impedance with Other Distributions

- Shifted dipole density is $\Delta\rho(r) = -\dfrac{\partial\rho(r)}{\partial y}\,\Delta = -\dfrac{d\rho(r)}{dr}\,\cos\theta\,\Delta.$
- Dipole electric force in the horizontal direction can be written more generally as

$$F_{\rm elec} = -\Delta\int_0^{2\pi} d\theta \int_0^\infty r dr\left[-e^2\frac{d\rho(r)}{dr}\right]\frac{\cos^2\theta}{2\pi\epsilon_0 r} = -\frac{e^2\rho(0)\Delta}{2\epsilon_0}.$$

- Self-field imp. $Z_1^\perp\Big|_{\rm self} = i\dfrac{Z_0 R}{\gamma^2\beta^2}\dfrac{\pi\rho(0)}{\lambda}.$ $\left[\text{uniform dist. } \rho(0) = \dfrac{e\lambda}{\pi a^2}\right]$

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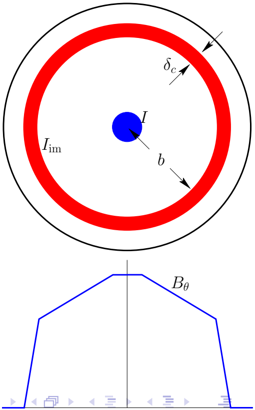
- If we write $Z_1^\perp\Big|_{\rm self} = i\dfrac{Z_0R}{\gamma^2\beta^2 a_{\rm eff}^2}$, same form as uniform distribution, equivalent beam radius is $a_{\rm eff} = \sqrt{\dfrac{\lambda}{\pi\rho(0)}}.$

  λ is linear density, $\rho(0)$ is volume density at beam center.

	Phase space distribution	$a_{\rm eff}$
Uniform	$\dfrac{1}{\pi\hat r^2}H(\hat r-r)$	$\hat r$
Elliptical	$\dfrac{3}{2\pi\hat r}\left(1-\dfrac{r^2}{\hat r^2}\right)^{1/2}H(\hat r-r)$	$\sqrt{\dfrac{2}{3}}\hat r$
Parabolic	$\dfrac{1}{2\pi\hat r^2}\left(1-\dfrac{r^2}{\hat r^2}\right)H(\hat r-r)$	$\frac{1}{\sqrt2}\hat r$
Cosine-square	$\dfrac{2\pi}{\pi^2-4}\cos^2\dfrac{\pi r}{2\hat r}H(\hat r-r)$	$\dfrac{\sqrt{\pi^2-4}}{\sqrt2\pi}\hat r$
Bi-Gaussian	$\dfrac{1}{2\pi\sigma_r^2}e^{-r^2/(2\sigma_r^2)}$	$\sqrt2\sigma_r$

Resistive Wall Impedance

- Consider a particle beam of current I in a cylindrical beam pipe of radius b.
- Want to compute resistive-wall impedance.
- Proper method: solve Maxwell equation in 2 media: vacuum and metal.
- We use here a simple model.



At freq. ω, skin depth: $\delta_c = \sqrt{\dfrac{2}{\sigma_c \mu_c \omega}}$.

Assume image current flows uniformly in one skin depth only;

i.e., within $b < r < b + \delta_c$

- $\mathcal{R}e\, Z_0^{\parallel}\Big|_{\rm RW} = \dfrac{2\pi R}{2\pi b \delta_c \sigma_c} = \dfrac{R}{b\delta_c\sigma_c}$.

- Now the image current generates magnetic flux.

  We have taken care of those inside the beam pipe as sp-ch imp.

  Need to take care of mag. flux inside beam pipe wall.

- Inside one skin depth of the pipe wall $B_{\theta\,\mathrm{av}} = \frac{1}{2}\left[\frac{\mu_c I}{2\pi b}\right]$.

  Factor $\frac{1}{2}$ occurs because B_θ decays linearly from $r = b$ to $b + \delta_c$.

- Total flux $\Phi = B_{\theta\,\mathrm{av}} 2\pi R\delta_c = \dfrac{\mu_c R\delta_c I}{2b}$.

- Inductive imp. is

$$\mathcal{I}m\, Z_0^{\parallel}\Big|_{\mathrm{RW}} = -i\omega\frac{\mu_c R\delta_c}{2b} = -i\frac{\omega\mu_c R}{2b\delta_c}\underbrace{\left[\frac{2}{\sigma_c\mu_c\omega}\right]}_{\downarrow\, \delta_c^2} = \underbrace{-i\frac{R}{b\delta_c\sigma_c}}_{\downarrow\,\text{same as } \mathcal{R}e\, Z_0^{\parallel}\big|_{\mathrm{RW}}}.$$

- We can now write

$$Z_0^{\parallel}\Big|_{\mathrm{RW}} = [1 - i\,\mathrm{sgn}(\omega)]\,\frac{R}{b\delta_c\sigma_c} = [1 - i\,\mathrm{sgn}(\omega)]\sqrt{\frac{\omega\mu_c}{2\sigma_c}}\,\frac{R}{b}.$$

Comments

- We can now write $Z_0^\parallel\Big|_{\rm RW} = \big[1 - i\,{\rm sgn}(\omega)\big]\dfrac{R}{b\delta_c\sigma_c} = \mathcal{R}\dfrac{2\pi R}{2\pi b}$.

  where *surface impedance* is defined as $\mathcal{R} = \dfrac{1 - i\,{\rm sgn}(\omega)}{\delta_c\sigma_c}$.

- $Z_0^\parallel\Big|_{\rm RW} = \mathcal{R}\dfrac{\rm long.\,length}{\rm width}$. More accurate defn. $\mathcal{R} = \dfrac{E_s}{H_\perp}\Big|_{\rm surface}$.

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- One may wonder why $\mathcal{R}e\,Z_0^{\parallel}\Big|_{\rm RW} \to 0$ when $\omega \to 0$.

  One may expect a dc beam still sees the resistivity of the pipe wall.

- $\omega = 0$ implies no time dependency of $\vec{B}$ and $\vec{E}$.

  Then $\vec{B}$ and $\vec{E}$ are not related because there is no more Faraday's law.

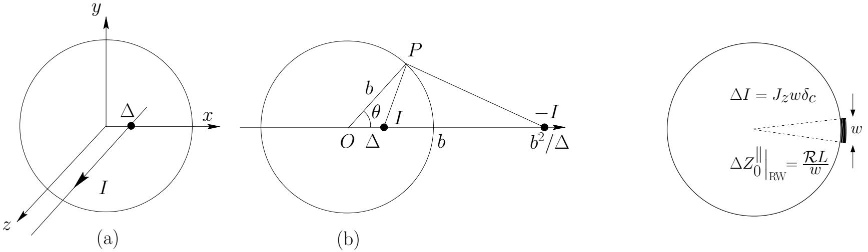
  $\vec{B}$ created by the dc current cannot generate $\vec{E}$ on surface or

  inside wall of beam pipe.

- Thus is no resistive loss at $\omega = 0$ and $\mathcal{R}e\,Z_m^{\parallel}\Big|_{\rm RW} \to 0$ for all $m \geq 0$.

Transverse Resistive Wall Impedance

- Compute image current distribution for an off-set beam.



- Dipole image current density ↓ monopole

$$\Delta J_z(\theta) = -\frac{I\Delta}{2\pi b}\left[\frac{2\Delta(b\cos\theta - \Delta)}{b^2 + \Delta^2 - 2b\Delta\cos\theta} - 1\right] \approx -\frac{I\Delta}{\pi b^2}\cos\theta.$$

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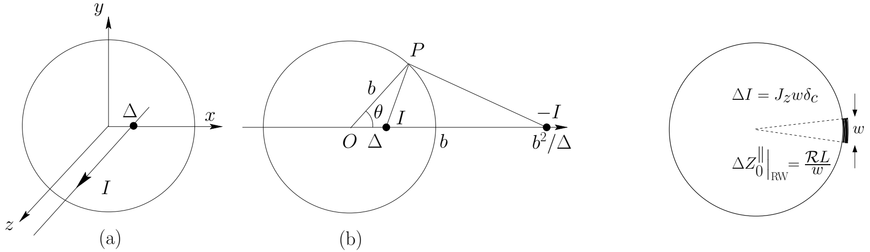

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- Voltage generated by image current element for length L at $\theta = 0$ is

$$V = \delta I\,\delta Z_0^{\parallel}\Big|_{\rm RW} = \left[-\frac{I\Delta}{\pi b^2}w\right]\left[Z_0^{\parallel}\Big|_{\rm RW}\frac{2\pi b}{w}\right] = -\frac{2I\Delta}{b}Z_0^{\parallel}\Big|_{\rm RW} = E_{z0}L,$$

where $E_{z0} = -\dfrac{2I\Delta Z_0^{\parallel}\Big|_{\rm RW}}{bL}$ is E_z on surface of beam pipe at $\theta = 0$.

- Because this is generated by a dipole beam, $E_z(x) = E_{z0}\dfrac{x}{b}$,

  Faraday law gives $i\omega B_y = -\dfrac{\partial E_z}{\partial x} \implies B_y = -\dfrac{iE_{z0}}{\omega b}$.

- B_y clinging the dipole current loop, creating a horizontal opposing force.

- $Z_1^x = \dfrac{i}{\beta I \Delta}\displaystyle\int_0^C \left[\vec{E} + \vec{v}\times\vec{B}\right]_x ds = \dfrac{2c}{b^2}\dfrac{Z_0^{\parallel}\Big|_{\rm RW}}{\omega}$.

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  Faraday law gives $i\omega B_y = -\dfrac{\partial E_z}{\partial x} \implies B_y = -\dfrac{iE_{z0}}{\omega b}$.
- B_y clinging the dipole current loop, creating a horizontal opposing force.
- $Z_1^x = \dfrac{i}{\beta I \Delta}\displaystyle\int_0^C \left[\vec{E} + \vec{v}\times\vec{B}\right]_x ds = \dfrac{2c}{b^2}\dfrac{Z_0^{\parallel}\Big|_{\rm RW}}{\omega}$.
- Note that $Z_1^{\perp} = \dfrac{2c}{b^2\omega_0}\dfrac{Z_0^{\parallel}\Big|_{\rm RW}}{n}$ [not P-W relation!!!!]

  $Z_1^{\perp}$ and $\dfrac{Z_0^{\parallel}\Big|_{\rm RW}}{n}$ are proportional for all frequencies.
- But as we will see below, this is not true at low frequencies.

Instabilities from Resistive-Wall Impedances

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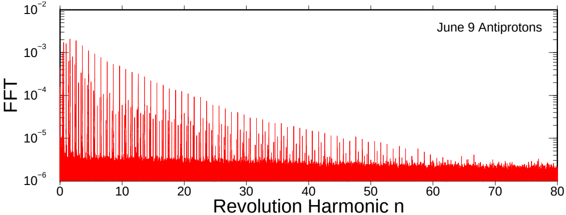
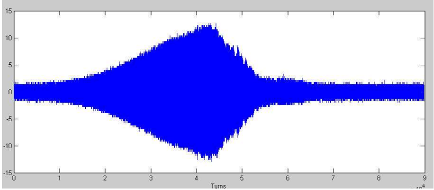
Examples in Recycler

Long $\bar{p}$ beam
$\tau = 3.5\ \mu$s
$N_b = 28 \times 10^{10}$
$\epsilon_{x,y95\%} = 3 \times 10^{-6}\ \pi$m
$\xi_y = -2 \rightarrow 0.$



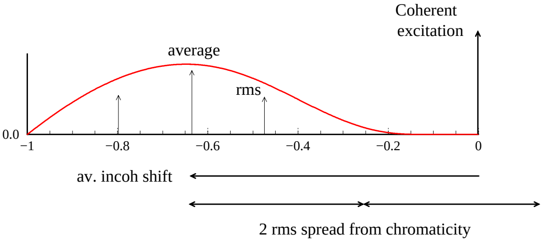
p beam unbunched
$N_b = 43.9 \times 10^{10}$
$\epsilon_{x,y95\%} = 6 \times 10^{-6}\ \pi$m
$\xi_y = -2 \rightarrow 0.$



time

- All modes become stable in the presence of $\Delta\nu_y^{\rm sp\,ch}$ when chromaticity $\xi_y = -2.53$.

$$\Delta\nu_y^{\rm sp\,ch}\Big|_{av} = 14.2\times10^{-4}$$
$\xi_y = -2.53$ produces
$$\sigma_{\Delta\nu_y} = 8.59\times10^{-4}.$$



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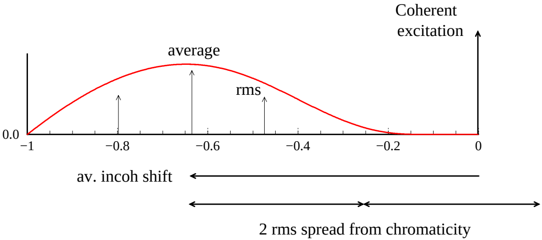

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Eventually a transverse kicker was built instead.

- Situation is different when beam is bunched. Driving impedance is

$$\mathcal{Z}_y = \sum_{p=-\infty}^{\infty} Z_1^y(\Omega + p\omega_0)h(\Omega + p\omega_0)$$

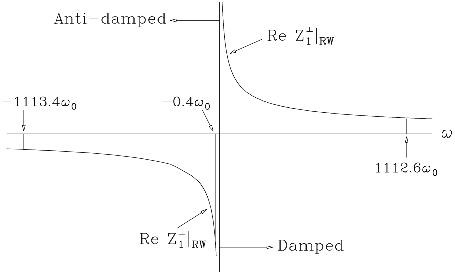
where h is bunch power spectrum and $\Omega = \omega_{y0} + \Delta\omega_{y\,\rm coh}$.

- Growth of many lower sidebands are cancelled by damping of upper sidebands, net growth will be much milder than for unbunched beam.

Transverse Coupled Bunch Instabilities

- For the Tevatron in target mode, if there are $M = 1113$ equally spaced bunches, there can be M modes of coupled motion.
- Each mode is driven by the imp. $\mathcal{Z}_{y\,m\mu} = \sum_q Z_1^y(\Omega + \omega_q) h_m(\omega_q - \chi/\tau_L)$, with $\omega_q = (qM + \mu)\omega_0 + \omega_\beta + m\omega_s$.

For each coupled mode μ, not all betatron sidebands contribute, but every Mth sideband contribute.



- Thus upper sidebands can no longer cancel growth from lower sidebands. Strongest drive is the sideband at negative freq. closest to $\omega = 0$, or at $\omega = -(1 - [\nu_y]_{\rm res})\omega_0$. It acts like a narrow resonance.

Remedy

- Change shape of bunch of power spectrum, like longer bunch, does not help much, because driving force is at very low freq.
- There are a few ways to minimize or avoid the instability:
- Chromaticity will certainly help by
  1. Widening tune spread to provide more Landau damping.
  2. Shifting driving betatron sideband to freq. with smaller power spectrum.
  3. Tevatron: $\eta = 0.0028$, $\tau_L = 5$ns, $f_0 = 47.7$ Khz.
     $\xi = +10$ shifts power spectrum by $\chi = \omega_\xi \tau_L = 2\pi f_0 \xi \tau_L/\eta = 5.4$.
  4. Power spectrum reduces by > 4 folds, and so is instability growth rate.
  5. But driving sideband hits $m = 1$ when $\omega_\xi \tau_L/\pi = 1.7$.
     Or high azimuthal modes become unstable.
- Octupole tune spread provide Landau damping.
- Coat beam pipe with copper to reduce resistive-wall impedance.
- Install wideband transverse kicker.

Scaling Law

- Apply to bunches that go from one accelerator ring to another, like the Booster, Main Injector, and Tevatron.
- Weiren Chou shows that this transverse coupled bunch instability growth rate is the same for all the rings, provided that
  1. same rf bucket width with all bucket filled,
  2. same beam pipe, meaning same radius b and wall conductivity σ_c
  3. same residual betatron tune.

  Roughly, beam current the same for completely filled ring,
  $\omega_0 \propto 1/R$, $E \propto R$, $\nu_\beta \propto \sqrt{R} \implies$ same growth rate
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- Typical growth time is a few or few tens ms.
- **Problem:** Booster bunches see laminated magnets, resistive impedance must be much larger.
- Transverse coupled bunch instability is very milder in Booster, where there is no dedicated transverse damper.
- Something must be wrong with the expressions for resistive-wall impedance, especially at small frequencies.

Problems with $Z_1^\perp$

- Recall that we derived $Z_1^\perp(\omega) = \dfrac{2c}{b^2}\dfrac{Z_0^\parallel}{\omega}$ and $Z_1^\perp \to \dfrac{1}{\sqrt{\omega}}$ as $\omega \to 0$.
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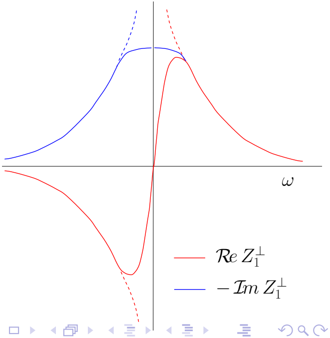
- We also showed that there is no resistive loss at $\omega = 0$. So we should expect $\mathcal{R}e\, Z_m^\perp(0) = 0$.
- $\mathcal{R}e\, Z_1^\perp(\omega)$ must bend back to zero.
- $\mathcal{I}m\, Z_1^\perp(\omega)$ will approach a fixed value instead of infinity as $\omega \to 0$.



$Z_1^\perp$ near $\omega = 0$

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- Flux is $\Phi_y = \displaystyle\int_{-b}^{b} B_y dx = 2bB_y = -\dfrac{\mu_0 I_{\rm im}\Delta}{\pi b} = -\dfrac{\mu_0}{2} I_d$.
- Inductance seen by $\pm I_d$ loop is $\mathcal{L} = \dfrac{\mu_0}{2}$.

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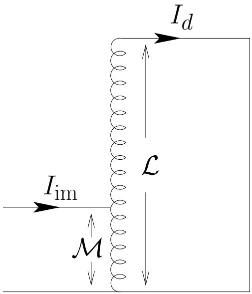
- Inductance seen by $\pm I_d$ loop is $\mathcal{L} = \dfrac{\mu_0}{2}$.
- But inductance seen by beam current I is different.
  There is some sort of transformer effect as a result of the shift Δ.

Transformer Ratio

- Introduce mutual inductance $\mathcal{M}$: $-i\omega\mathcal{M}(I_{\rm im}-I_d)=-i\omega(\mathcal{L}-\mathcal{M})I_d$,
- Get $\dfrac{\mathcal{M}}{\mathcal{L}}=\dfrac{I_d}{I_{\rm im}}=\dfrac{2\Delta}{\pi b}$,
  This is a geometric relation.
- Force at beam: $F_x=e(E_x-\beta cB_y)$.
  Imp.: $\dfrac{Z_1^\perp}{L}=\dfrac{(F_x/e)_{\rm mag}}{i\beta I\Delta}=-\dfrac{cB_y}{iI\Delta}=\dfrac{c\mu_0 I_d}{i4\Delta b\,I}=i\dfrac{Z_0}{2\pi b^2}$.
  capacitive ↑



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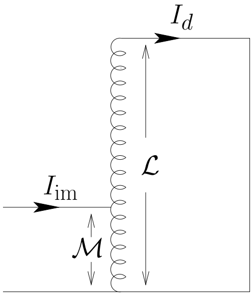

- This is the familiar imp. from magnetic image.
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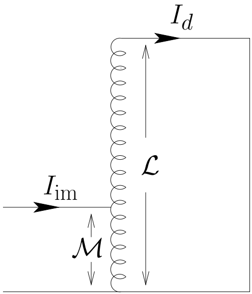

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- Here we wish to emphasize that task of above is two-fold:

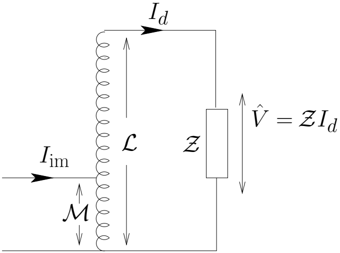
  1. contributes to sp ch imp.
  2. contributes to transformer ratio.

Inclusion of Resistivity

- Recall $\dfrac{Z_0^{\|}\big|_{\rm RW}}{L} = \dfrac{\mathcal{R}}{2\pi b}$, $\mathcal{R}$ is surface imp.
- For a length L, voltage generated:

$$V(\theta) = 2\left[\frac{\mathcal{R}L}{w}\right]\left[w\Delta K_z(\theta)\right] = \frac{\mathcal{R}LI_d}{b}\cos\theta.$$

- $\dfrac{\hat{V}}{L} = \dfrac{\mathcal{R}I_d}{b} = 2\pi\dfrac{Z_0^{\|}\big|_{\rm RW}}{L}I_d = \mathcal{Z}I_d.$



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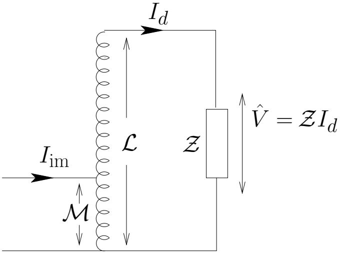

- On pipe wall surface $\hat{E}_z = \frac{1}{2}\dfrac{\hat{V}}{L} = \frac{1}{2}\mathcal{Z}I_d$. (Note factor $\frac{1}{2}$)
- Now compute impedance: $\dfrac{F_x}{e} = E_x - vB_y = \dfrac{v}{i\omega}\dfrac{\partial E_z}{\partial x} = \dfrac{v\mathcal{Z}I_d}{i2\omega b}$.
$$\frac{Z_1^H\big|_{\rm RW}}{L} = \frac{F_x/e}{i\beta I\Delta} = -\frac{c\mathcal{Z}I_d}{2\omega bI\Delta} = -\frac{c\pi}{\omega b}\frac{I_d}{I\Delta}\frac{Z_0^{\parallel}\big|_{\rm RW}}{L}.$$

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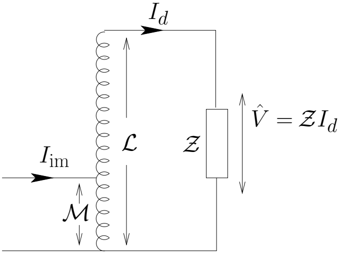

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$$\frac{Z_1^{H}\big|_{\rm RW}}{L} = \frac{F_x/e}{i\beta I\Delta} = -\frac{c\mathcal{Z}I_d}{2\omega b I\Delta} = -\frac{c\pi}{\omega b}\frac{I_d}{I\Delta}\frac{Z_0^{\parallel}\big|_{\rm RW}}{L} .$$

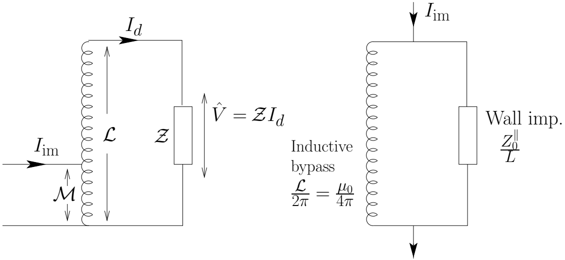
- What is left is to compute the ratio I_d/I in presence of resistivity.

  Although $\dfrac{\mathcal{M}}{\mathcal{L}} = \dfrac{2\Delta}{\pi b}$ is unchanged, $\dfrac{I_d}{I}$ has changed and $\neq -\dfrac{2\Delta}{\pi b}$.

$$-i\omega\mathcal{M}(I_{\rm im}-I_d)$$
$$=[-i\omega(\mathcal{L}-\mathcal{M})+\mathcal{Z}]\,I_d\,.$$

obtain

$$\frac{I_d}{I_{\rm im}}=\frac{2\Delta}{\pi b}\,\frac{-i\omega\mathcal{L}}{-i\omega\mathcal{L}+\mathcal{Z}}$$



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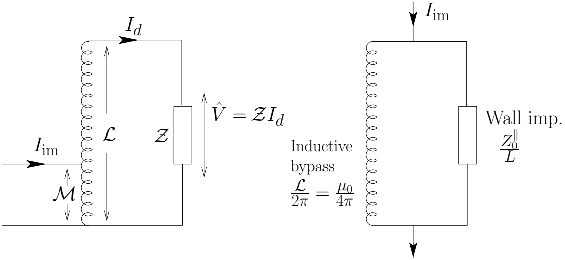

- Finally the imp. $\dfrac{Z_1^H\big|_{\rm RW}}{L} = \dfrac{2c}{\omega b^2}\dfrac{\dfrac{-i\omega\mathcal{L}}{2\pi}\,\dfrac{Z_0^{\parallel}\big|_{\rm RW}}{L}}{\dfrac{-i\omega\mathcal{L}}{2\pi}+\dfrac{Z_0^{\parallel}\big|_{\rm RW}}{L}}.$ $\longleftarrow$ 2 imp. in parallel

- Thus Z_1^H is just 2 impedances in parallel: $\dfrac{-i\omega\mathcal{L}}{2\pi}$ and $\dfrac{Z_0^{\parallel}\big|_{\rm RW}}{L}$.

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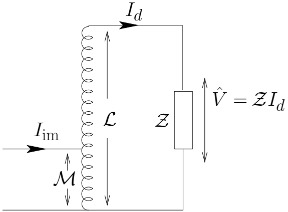

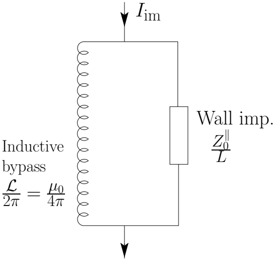

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- Thus Z_1^H is just 2 impedances in parallel: $\dfrac{-i\omega\mathcal{L}}{2\pi}$ and $\dfrac{Z_0^\parallel\big|_{\rm RW}}{L}$.
- Large ω, go thru $\dfrac{Z_0^\parallel\big|_{\rm RW}}{L}$ and $\dfrac{Z_1^H\big|_{\rm RW}}{L} \to \dfrac{2c}{b^2}\,\dfrac{Z_0^\parallel\big|_{\rm RW}}{\omega L}$. $\longleftarrow$ classical region
- Small ω, go thru $\dfrac{-i\omega\mathcal{L}}{2\pi}$ and $\dfrac{Z_1^H\big|_{\rm RW}}{L} \to \dfrac{-ic\mathcal{L}}{\pi b^2} = \dfrac{-iZ_0}{2\pi b^2}$. $\longleftarrow$ inductive bypass

Results of Maxwell Equations

- Tevatron: $R = 1$ km, pipe radius $b = 3$ cm, wall thickness $t = 1.5$ mm. s.s. wall $\sigma_c = 1.35 \times 10^6$ $(\Omega\text{-m})^{-1}$.
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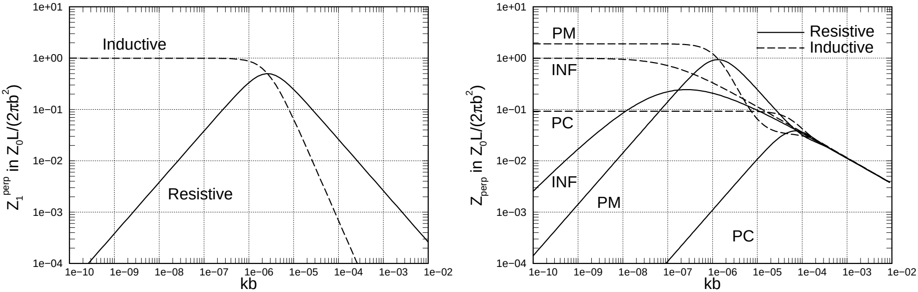
- Bend-around between $kb \sim \dfrac{4}{Z_0\sigma_c b} = 2.6\times10^{-7}$ ($f \sim 0.4$ kHz)

$$\text{and } kb \sim \frac{2}{Z_0\sigma_c t} = 2.6\times10^{-6} \quad (f \sim 4.2 \text{ kHz})$$

- $\nu_y = 19.6$ and $(1-Q)$ line at 19.1 kHz ($kb = 1.2$).



thin-wall model ($t \ll \delta_c$) thick-wall model

Comments

- It appears that $f_{\rm bend}$ depends on σ_c, b, and t only, and not on size and energy of ring.

  $f_{\rm bend} \sim 0.4$ to 4 kHz.

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- Will show later that low-ω region is important to Booster.

- First let us review some measurement of $Z_1^\perp$ at low ω by Mostacci *et al.* Measurement was performed to understand low ω effect to LHC.

Direct Measurement of $Z_1^{\perp}(\omega)$

- Current I was passed into a N-turn loop $L_w = 1.25$ m long and $\Delta = 2.25$ cm wide, inside a s.s. beam pipe of length $L = 50$ cm and radius $b = 5$ cm, wall thickness $t = 1.5$ mm.

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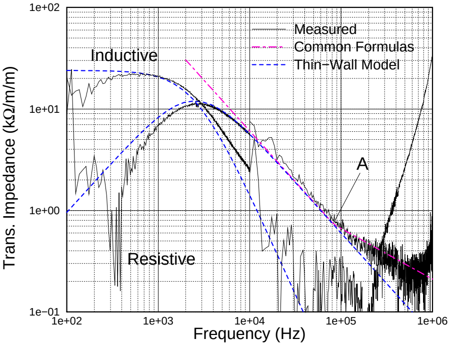
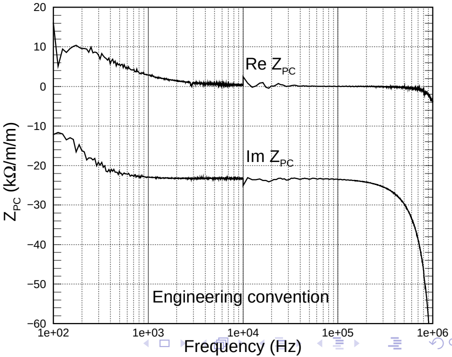
- $I_{\rm im} \to B \to V$ on loop thru imp. $Z_{\rm pipe}$ of pipe.

Then $Z_1^\perp\Big|_{\rm RW} = \dfrac{c}{\omega}\dfrac{Z_{\rm pipe} - Z_{\rm PC}}{N^2\Delta^2}$, where $Z_{\rm PC}$ is same as $Z_{\rm pipe}$

but with a perfectly conducting pipe instead.





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- A dipole particle beam sees both magnetic and electric images in wall. The two cancelled when $\gamma \to \infty$.
- The dipole current loop sees only magnetic image but not electric. This magnetic contribution must be subtracted, leaving us with the $Z_1^\perp$ we are after.
- A perfectly (PC) conducting pipe will just produce this magnetic contribution. So such a subtraction is necessary.
- Actually a copper pipe was used as PC.
  $\sigma_{c\,\mathrm{Cu}} = 5.88 \times 10^7\ (\Omega\mathrm{m})^{-1}$
  $\sigma_{c\,\mathrm{SS}} = 1.35 \times 10^5\ (\Omega\mathrm{m})^{-1}$ $\qquad (\sigma_{c\,\mathrm{Cu}}/\sigma_{c\,\mathrm{SS}} = 44)$
- Measured impedance for copper pipe:
  $\mathcal{R}e\, Z_1^\perp$ almost zero because of small resistivity.

$$\frac{\mathcal{I}m\, Z_1^\perp}{L} = \frac{iZ_0}{2\pi b^2} = i23\ \Omega/\mathrm{m}/\mathrm{m}. \qquad \text{(capacitive)}$$

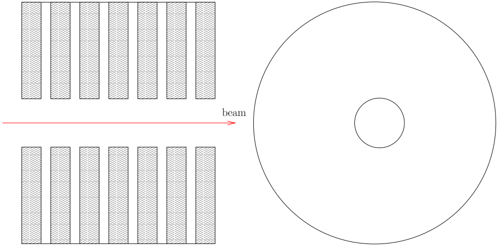
Laminations

- The beam sometimes sees a laminated surface rather than a smooth one, like Lambertson magnets and laminated combined-fcn magnets.
- These surfaces can be approximated as

  2 parallel laminated plates

  or

  a laminated annular ring.

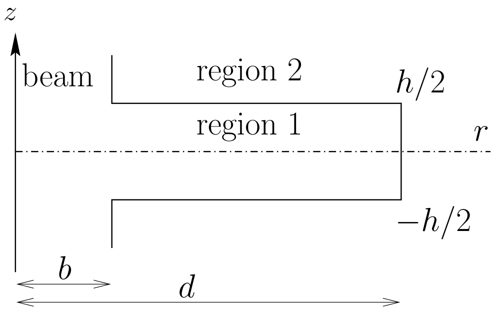


- Want to compute the impedance seen by the beam.

	crack	lamination
Width or thickness	$h = 0.000375''$	$\tau = 0.025''$
Relative mag. suseptibility	$\mu_{1r} = 1$	$\mu_{2r} = 100$
Relative dielectric	$\epsilon_{1r} = 4.75$	$\epsilon_{2r} = 1$
Conductivity	$\sigma_{c1} = 1.0 \times 10^{-3}$ $(\Omega\text{-m})^{-1}$	$\sigma_{c2} = 0.5 \times 10^{7}$ $(\Omega\text{-m})^{-1}$

Crack Impedance

- Solve Maxwell eq.
  $$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E_z}{\partial r}\right)+q^2E_z=0$$
  to get E_z across crack
  and then surface imp. $\mathcal{R}_c$.



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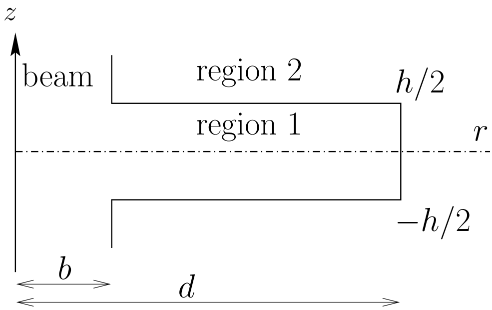

- Solution for annular-ring model

$$\frac{\mathcal{R}_c}{Z_0}=-\frac{E_z(b)}{Z_0H_\theta(b)}=\frac{jqc}{\epsilon_{1r}\omega}\,\frac{J_0(qb)N_0(qd)-N_0(qb)J_0(qd)}{J_1(qb)N_0(qd)-N_1(qb)J_0(qd)}\,,$$

  with $q^2=k_i^2+g_i^2, \quad i=1,2.$

- q is trans. wave numbers, $k_1^2=\omega^2\mu_1\epsilon_1, \quad k_2^2=\omega^2\mu_2\epsilon_2=\dfrac{2i}{\delta_{2c}^2}$.

- Longitudinal decrement: $g_1=(1+i)k_1^2\dfrac{\mu_2}{\mu_1}\dfrac{\delta_{2c}}{h}, \quad g_2\sim\dfrac{1-i}{\delta_{2c}}$.

Low-Frequency Behavior

- At low $\omega > 0$, use small-argument expansion to get
$$\frac{\mathcal{R}_c}{Z_0} \to (1-i)\frac{\omega\delta_{2c}b}{ch}\mu_{2r}\ln\frac{d}{b}$$
- This can be shown to be imp. seen by $I_{\rm im}$ going in and out of crack penetrating δ_{2c} into laminations.
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- For bend-around of $Z_1^\perp$, compare with bypass ind. $Z_{\rm bypass} = \dfrac{\omega Z_0}{4\pi c}$,
  or $\left|(1-i)\dfrac{2\delta_{2c}\mu_{2r}}{\tau}\ln\dfrac{d}{b}\right| \sim 1.$
- For $b = 1.25''$ and $d = 6''$, get $f_{\rm bend} \sim 250$ MHz.
  ($\sim$ 100 MHz in actual computation).
- Small-argument expansion good for $f \ll 5\ MHz$.

High-Freqency Behavior

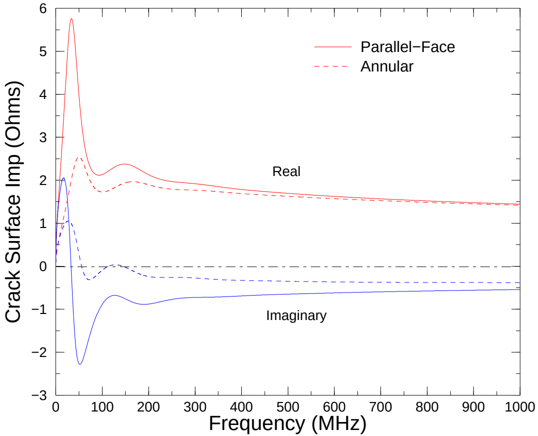
At high ω, large-argument expansions of $H_0^{(1),(2)}$ and $H_1^{(1),(2)}$ give

$$\frac{\mathcal{R}_c}{Z_0} = \frac{jqc}{\epsilon_{1r}\omega} \tan q(d-b).$$

Like a cavity, but filled with dissipative medium.

Resonances will be damped, except maybe the first one.

The crack also acts like a capacitance in parallel with surface impedance.

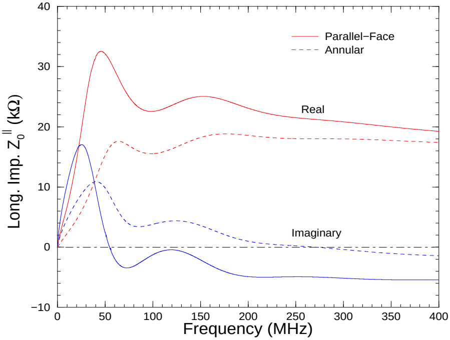


High ω, $I_{\rm im}$ flows across crack as displacement current more easily.

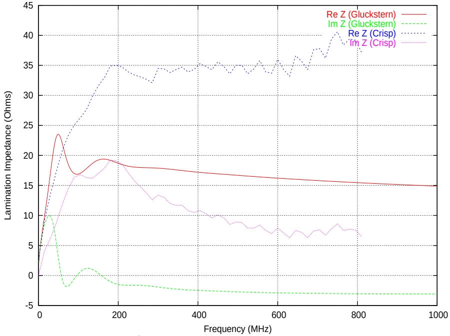
But at low ω, $I_{\rm im}$ has to flow thru surfaces of each crack; expect large imp.

Application to Booster

- Booster consists of 48 F and 48 D laminated magnets.
  Vertical gap: $2b = 1.64''$ (F) and $2b = 2.25''$ (D).
  Magnet height: $2d = 12''$.
- Calculation and Measurement of $Z_0^{\|}$ of 96 Booster magnets:



Theory

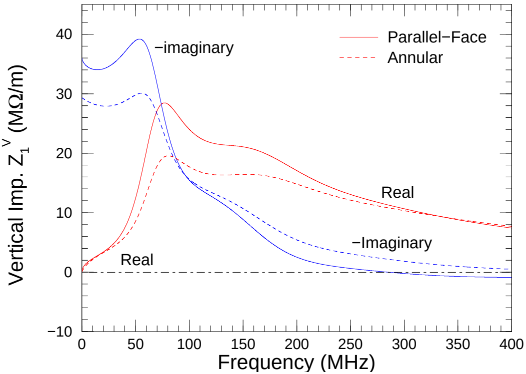


Crisp's Measurement

- Measurement was made by Crisp using a current in a wire.

Z_1^V of Booster Lamination Magnets

- See inductive bypass at low freq.
- $\mathcal{R}e\, Z_1^V$ bends around $\sim$ 70 MeV
- No $\omega^{-1/2}$ behavior at low freq.
  Broad-band from 70 MeV to 200 MHz.



- Relatively high bend-around freq. is result of high lamination imp.
- Will not drive trans. coupled bunch instabilities.
- Since $|Z_1^V|$ is large ($\sim 20\ \mathrm{M\Omega/m}$), will drive head-tail instabilities.

Beam Pipe Contribution

- Lamination magnets cover $\sim 60\%$ of the Booster ring, leaving $\sim 40\%$ with beam pipes.
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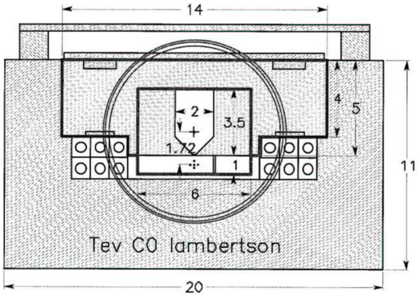
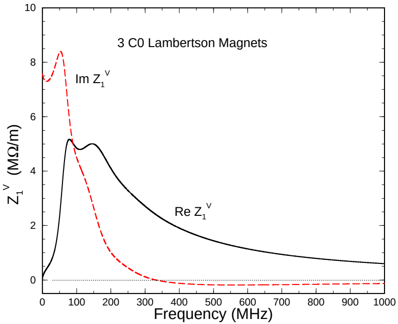
- Chromaticity is ineffective in shifting power spectrum because of large $\eta = -0.458$.
- However, during the ramp, growth rate decreases (with E^{-1}) $|\eta|$ becomes smaller, making chromaticity more effective.
- Thus transverse coupled-bunch instabilities can only be appreciable near injection.

Lambertson Magnets in Tevatron

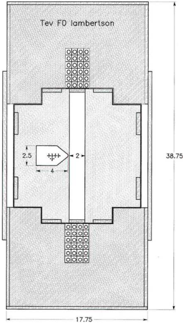




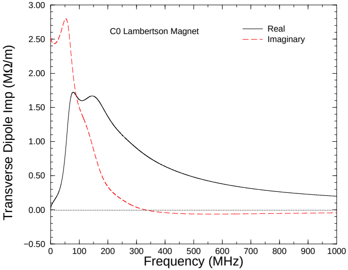
- During 2003 shutdown, 3 C0 Lambertsons for fixed target beam extractions were removed.
- These magnets served as dipoles with beam passing thru the narrow 1” gap.
- They will not drive transverse coupled-bunch instabilities, but head-tail instabilities.

Lambertson Magnets F0 in Tevatron

- There are 4 F0 Lambertsons in Tevatron.
- Unlike the C0's, beam is in field-free region during storage (vertical gap$\sim 2.5''$).
- Can compute Z_1^V by approx. as annular magnet.
- Result is an order of mag. less than the C0's.
- Z_1^V had been measured by Crisp and Fellenz.



- Attenuation S_{21} was measured along 2 parallel wires driven differentially.
- The wires, $\Delta = 1.0$ cm apart, form a TEM balanced transmission line, matched to 100 Ω with resistive L-pads and driven with a 100 Ω broadband 180° hybrid splitter.
- Imp. computed from $Z_1^V = -\dfrac{c}{\omega\Delta^2} 2Z_c \ln S_{21}$



- Agreement of $\mathcal{I}m\, Z_1^V$ are good, but much smaller for the plateau region.

Betatron Tune Shift in Booster

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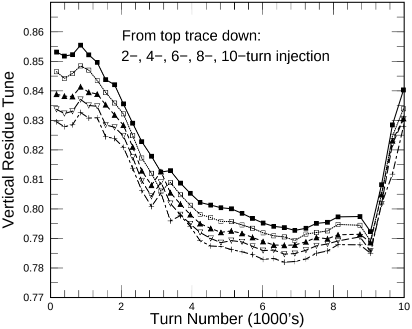
- Betatron oscillation modes were solved using ICA, and ν_y was computed from FFT.
- ICA routine increases accuracy of measurement because all BPM data are used.
- Only data up to transition are used, because of lack of H-V coupling while pinger kicks horizontally.



What Should be Included in $\mathcal{I}m\, Z_1^V$?

- Assuming Gaussian distribution, $\Delta\nu_y\Big|_{\rm dyn} = \dfrac{e^2 N_b R}{8\pi^{3/2}\beta E_0 \nu_y \sigma_\tau}\, \mathcal{I}m\, Z_1^V\Big|_{\rm eff}$.
- Effective imp.: $\mathcal{I}m\, Z_1^V\Big|_{\rm eff} = \dfrac{\displaystyle\int_{-\infty}^{\infty} \frac{d\omega}{2\pi} Z_1^V(\omega) e^{-\omega^2\sigma_\tau^2}}{\displaystyle\int_{-\infty}^{\infty} \frac{d\omega}{2\pi} e^{-\omega^2\sigma_\tau^2}}$.

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- Consider $\mathcal{I}m\, Z_1^V\big|_{\rm SC} = \dfrac{Z_0}{\pi\beta^2\gamma^2}\displaystyle\sum_i L_i \left[\frac{\epsilon_{sc}^V}{a_{vi}^2} - \frac{\xi_1^V - \epsilon_1^V}{h_i^2}\right]$.
- Self-field part is cancelled by adding $\Delta\nu_y\big|_{\rm incoh}^{\rm self}$.
  ϵ_1^V-part is cancelled by adding the incoherent part.
- So only ξ_1^V-part should be included.
  This is the coherent wall image contribution.

The Coherent Wall Image Contribution

- Coherent wall-image consists of $\dfrac{\xi_1^v}{h_i^2\gamma^2} = \dfrac{\xi_1^v}{h_i^2} - \beta^2\dfrac{\xi_1^v}{h_i^2}$ the electric and magnetic contributions.
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- We write $\dfrac{\xi_1^V}{h_i^2\gamma^2} \rightarrow \dfrac{\xi_1^V}{\bar{h}_i^2} + \beta^2\dfrac{\xi_2^V}{h_i^2}$.
- $\xi_1^V \rightarrow \xi_2^V, \ \ -\beta^2 \rightarrow +\beta^2$ because of image in magnetic surface.
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- We have then $Z_1^V\big|_{\mathrm{mag}} = \dfrac{Z_0\xi_2^v}{\pi}\displaystyle\sum_i \dfrac{L_i}{h_i^2}$.
- This still has problems, since laminated surface is not perfect magnetic surface. Cracks and laminations become more apparent at high freq.
- More appropriate representation is what we have computed of Z_1^V for laminated surface. When $\omega \to 0$, beam sees bypass inductance. Higher frequency, beam sees laminations.

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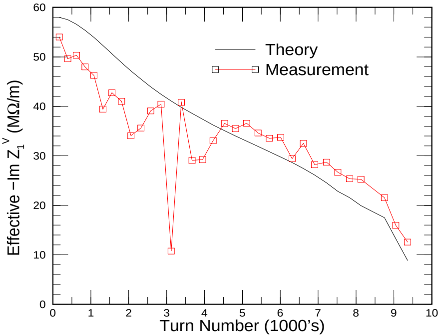
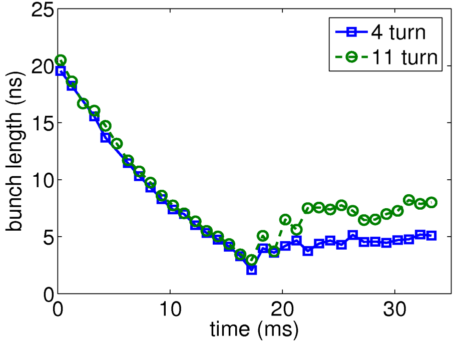
- $\mathcal{I}m\, Z_1^V$ is computed from tune-shift measurement and compared with calculated dipole imp.

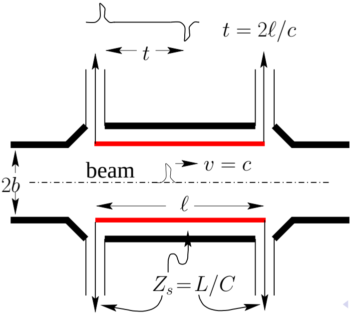


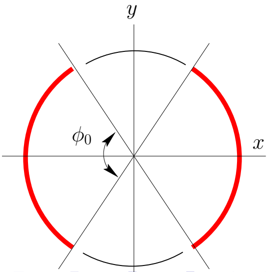


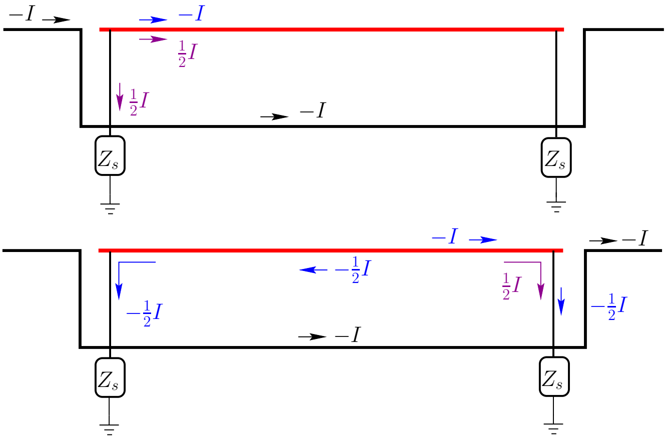
- Data point near 3000 turns involves error and should be excluded.
- Agreement is satisfactory, although not perfect.

Strip-Line BPM

- Tevatron is equipped with strip-line BPM's terminated at both ends.
- Strip line and extruded beam pipe forms a transmission line of $Z_s = 50\ \Omega$.
- 2 terminations are also of Z_s.
- We will see, for a short pulse ($\ll \ell$),
  - front termination registers a positive pulse followed by by a negative pulse
  - rear termination registers nothing
- Then $Z_0^{\parallel}$ and $Z_1^{\perp}$ are derived.







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β is particle velocity
β_s is transmission line velocity

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- For vertical impedance, offset current in y-direction.
  There is not net dipole image current on horizontal strip-lines.
  No dissipation, therefore $Z_1^V = 0$.

- There are $M = 216$ sets of BPM's in the Tevatron.

  Radius $b = 3.5$ cm, $\ell = 18$ cm, and $\phi_0 = 110^\circ$, $Z_s = 50\ \Omega$.

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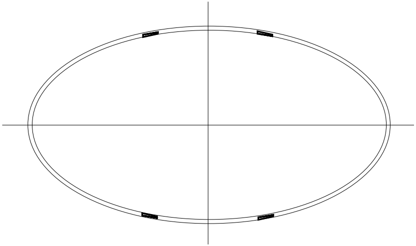

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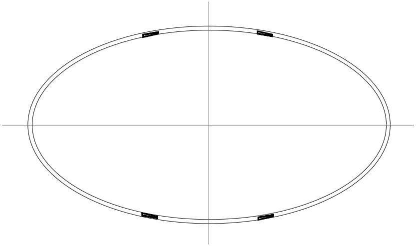

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- f_x and f_y can be computed via POISSON or directly measured.
- For all BPM's at low freq., $Z_1^H\Big|_{BPM} = -i2.66\ \mathrm{k\Omega/m}$, $Z_1^V\Big|_{BPM} = -i5.15\ \mathrm{k\Omega/m}$.

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  $Z_0^{\parallel} \to k^{-3/2}$ for an infinite array of cavities.
- Shunt impedance is responsible to resistive loss and beam loading.
- High shunt impedance and high Q are responsible for coupled-bunch instabilities.

Closed Pill-Box Cavities

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- From Jackson, for example,

  resonant freq.: $k_{mnp}^2 = \dfrac{x_{mn}^2}{d^2} + \dfrac{p^2\pi^2}{g^2}$.

  shunt impedance:

$$\left[\frac{R_s}{Q}\right]_{0np} = \frac{Z_0}{x_{0n}^2 J_0'^2(x_{0n})} \frac{8}{\pi g k_{0np}} \begin{cases} \sin^2 \dfrac{g k_{0np}}{2\beta} \times \dfrac{1}{1+\delta_{0p}} & p \text{ even} \\ \cos^2 \dfrac{g k_{0np}}{2\beta} & p \text{ odd} \end{cases}$$

$$\left[\frac{R_s}{Q}\right]_{1np} = \frac{Z_0}{J_1'^2(x_{1n})} \frac{2}{\pi g d^2 k_{1np}^2} \begin{cases} \sin^2 \dfrac{g k_{1np}}{2\beta} & p \neq 0 \text{ and even} \\ \cos^2 \dfrac{g k_{1np}}{2\beta} & p \text{ odd} \end{cases}$$

- Resonant freq. $\omega_{mnp} = k_{mnp} c$.
  x_{mn} is nth zero of Bessel function $J_m(x)$.

Numerical Computation and Measurement

- Only impedances of cavities of simplest shape, like the pill-box, can be computed analytically.
- For the actual cavities, numerically computation is necessary, using codes like SUPERFISH, URMEL, etc.
- Calculation gives resonant freq. f_r, R/Q and R for the lower modes.

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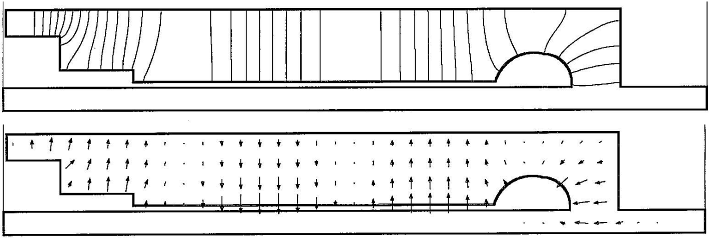

constant rH_ϕ

$\vec{E}$

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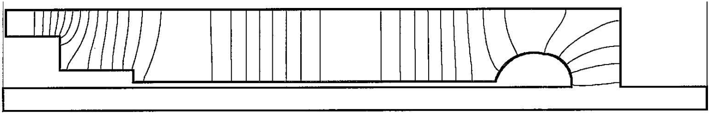

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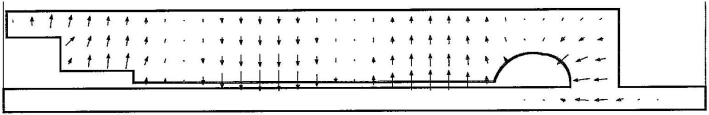

$\vec{E}$

- Tevatron cavity has also been measured Sun and Colestock using method of delectric bead-pull and wire measurement.

Longitudinal Modes of Tevatron Cavity

Mode Type	URMEL Results Frequency (MHz)	 R/Q (Ω)	 Q	Sun's Measurements Frequency (MHz)	 R/Q (Ω)	 Q
TM0-EE-1	53.49	87.65	9537	53.11	109.60	6523
TM0-ME-1	84.10	22.61	12819	56.51	18.81	3620
TM0-EE-2	166.56	18.47	16250	158.23	11.68	6060
TM0-ME-2	188.94	10.83	18235			
TM0-EE-3	285.94	7.53	20524	310.68	7.97	15923
TM0-ME-3	308.46	4.07	22660			
TM0-EE-4	402.69	4.93	25486	439.77	5.23	13728
TM0-ME-4	431.34	1.72	26407	424.25	1.28	6394
TM0-EE-5	511.69	5.57	25486	559.48	6.73	13928
TM0-ME-5	549.57	1.36	29453			
				748.18	10.90	13356
				768.03	2.47	16191

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- Agreement is not bad except for quality factors Q, which are much higher in URMEL computation.
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Transverse Modes of Tevatron Cavity

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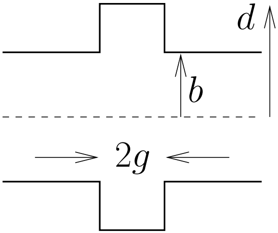
- There are many de-Q structures not taken into account in URMEL.
- The transverse of dipole modes have never been measured. Below are the URMEL results:

Mode Type	Frequency (MHz)	R/Q (Ω/m)	Q
1-EE-1	486.488	229.80	31605
1-ME-2	486.864	148.95	31487
1-EE-2	513.370	117.38	33262
1-ME-3	518.317	117.93	34008
1-EE-3	561.727	81.62	33029
1-ME-4	575.298	3.84	35810
1-EE-4	625.123	61.00	32598
1-ME-5	650.853	35.21	37592
1-EE-5	699.723	54.76	33407

Bellows

- Bellows may be approximated by a series of small pill-box cavities.
- The imp. of one single cavity has been worked out by Vos via field matching.
- The imp. is much simplied when $g \ll b$,



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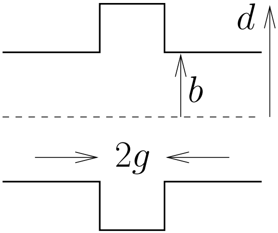

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$$Z_\parallel(\omega) = \frac{-igZ_0}{\pi b I_0^2(kb/\beta\gamma)D}$$

$$D = \frac{R_0'(kb)}{R_0(kb)} + 2k\left[\sum_{s=1}^{S}\frac{1}{\beta_s^2 b}\left(1 - e^{i\beta_s g}\frac{\sin\beta_s g}{\beta_s g}\right) - \sum_{s=S+1}^{\infty}\frac{1}{\alpha_s^2 b}\left(1 - e^{-\alpha_s g}\frac{\sinh\alpha_s g}{\alpha_s g}\right)\right].$$

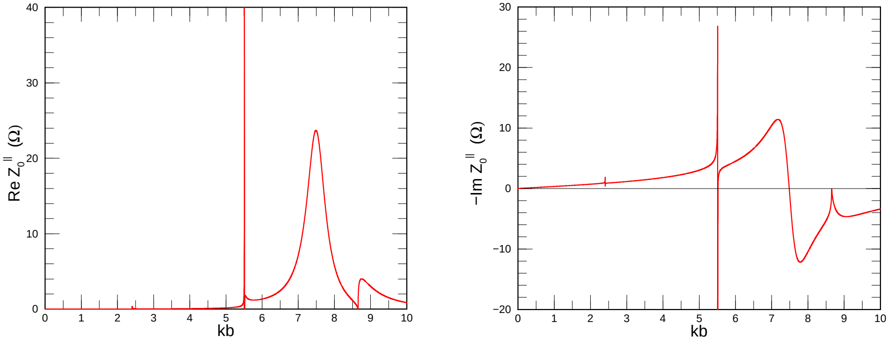
$\beta_s b = \sqrt{k^2b^2 - j_{0s}^2}, \qquad \alpha_s b = \sqrt{j_{0s}^2 - k^2b^2},$

j_{0s} is sth zero of the Bessel function J_0

j_{0S} is the zero that is just larger than or equal to kb.

$R_0(kb) = J_0(kb)Y_0(kd) - J_0(kd)Y_0(kb)$, with $d = b + \Delta$.

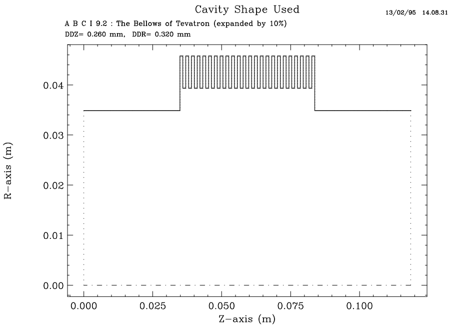
- As an example, consider a bellow convolution of the Tevatron with $\Delta = 0.64$ cm, $2g = 1.04$ mm, $b = 3.5$ cm.

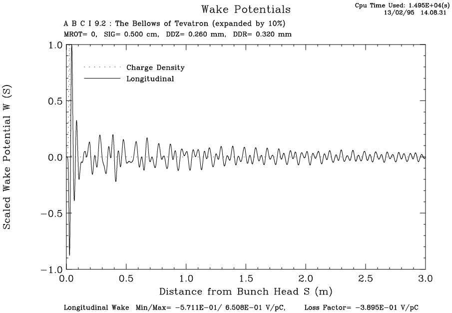


- Main peak at $f_r = 10$ GHz above cutoff, broadband with $Q \sim 12$.
- $Z_{\rm sh}/n \sim 1.15 \times 10^{-4}\ \Omega$.
- For N convolutions in bellows system, an estimate is to multiply by N.
- In Tevatron, there are 1000 bellows each with 24 convolutions, giving $Z_{\rm sh}/n \sim 2.8\ \Omega$ and low freq. $\mathcal{I}m\, Z_{\rm sh}/n \sim -i0.28\ \Omega$.

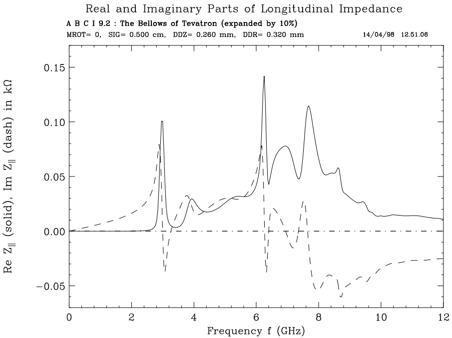
Numerical Computation

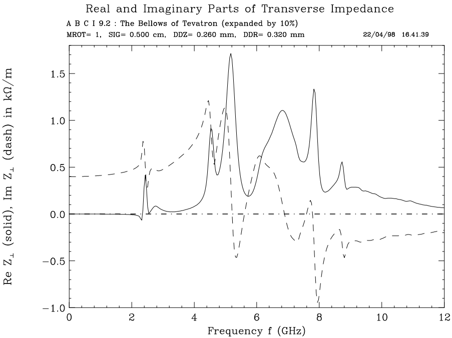
- Bellow convolutions are closed to each other and therefore talk to each other. Resonance freq. will be lower.
- Sometimes bellows are not so simple to have just convolutions on top of beam pipe. Usually need to resort to numerical computation.
- Codes TBCI or ABCI computes the wake behind a Gaussian bunch passing thru a cylindrical symmetric structure.
- Apply to the Tevatron bellows.





- Fourier transform is performed to the wake to obtain the impedance.





- The resonance freq. is at ~ 7 GHz for both $Z_0^{\|}$ and $Z_1^{\perp}$ lower than what Vos' prediction, and more broadband ($Q \sim 1$).
- We see more structure in imp. spectrum. Here even without convolutions, the bellows structure acts as a cavity.
- Result: $Z_{\rm sh}^{\|}/n \sim 0.68\ \Omega$ and low freq. $\mathcal{I}m\, Z_{\rm sh}^{\|}/n \sim -i0.34\ \Omega$.

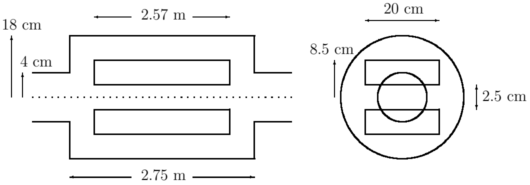
  $Z_{\rm sh}^{\perp} \sim 1.1\ \mathrm{M\Omega}/\mathrm{m}$ and low freq. $\mathcal{I}m\, Z_{\rm sh}^{\perp} \sim -i0.40\ \mathrm{M\Omega}/\mathrm{m}$.

Comments on Bellows Numerical Computations

- Exit pipe length is an issue, since all fields are assumed to drop to zero on both sides.
- Need to extend pipe length until results do not change by much. It is best to have exit pipe length $>$ pipe radius.
- Time step has to be much less than width of convolution.
- Incident beam is not a point charge, but is a short Gaussian bunch. The wake is not the point-particle wake fcn. Reduction to point-particle wake fcn. is possible, but with uncertainty.
- Wake must terminate at a certain length in calculation. Fourier transform will exhibit $\dfrac{\sin x}{x}$-behavior. This can be minimized by ending the wake at a point where wake is zero. Or add a filter to Fourier transform.
- A 2D code is always faster and easier to use than 3D code like MAFIA.

Separators

- There are 27 separators in Tevatron to separate p and $\bar{p}$ bunches.
- Simplified model:



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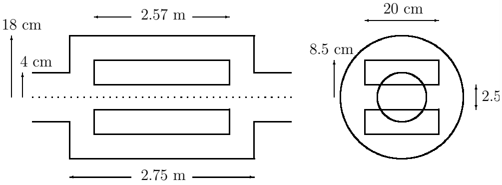
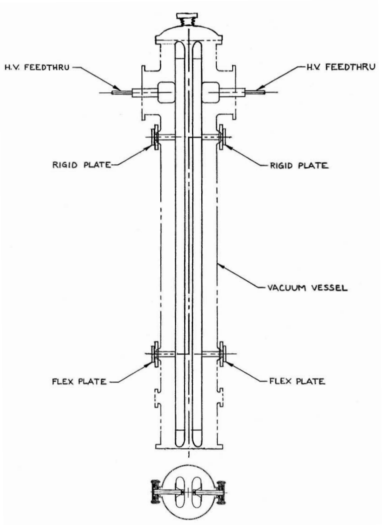
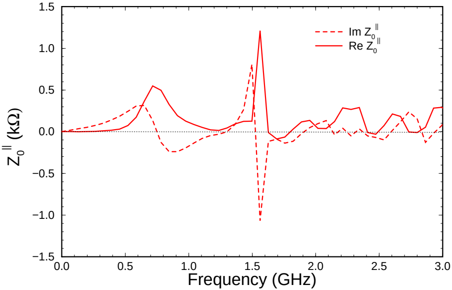
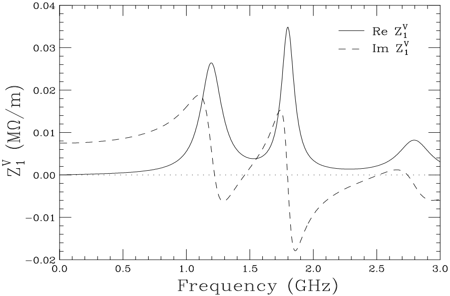




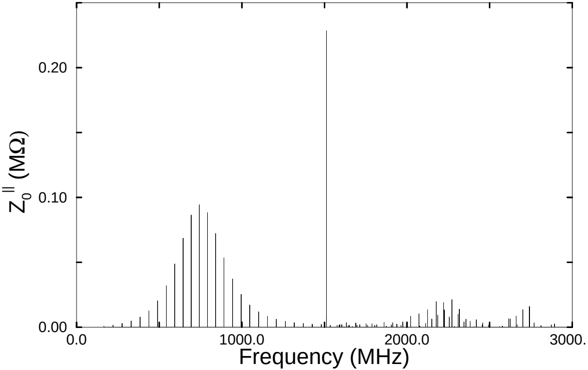
- Each separator consists of 2 thick plates, 2.57 m long.
- A beam particle can excite resonances at the upstream and downstream gaps.
- Space between plate and enclosure forms a transmission line.
- Use MAFIA to compute wakes and FFT to obtain imp.

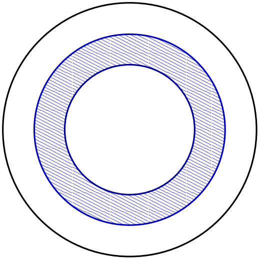
MAFIA Results





- At low freq., for each separator, $Z_0^{\|}/n \sim -i0.019\ \Omega$, $Z_0^V/n \sim -i0.0075\ \mathrm{M}\Omega/\mathrm{m}$.
- For 27 separators, $Z_0^{\|}/n \sim -i0.51\ \Omega$, $Z_0^V/n \sim -i0.20\ \mathrm{M}\Omega/\mathrm{m}$.
- These are very small.
- We would like to understand more about the impedances.
- Instead of MAFIA, which is a 3D code, we use the 2D code URMEL in the frequency domain.





- First 50 resonant modes are shown.

  They are narrow because well below $f_{\rm cutoff} = 4.59$ GHz.

- In 2D representation, upstream and downstream gaps can be viewed as 2 cavities, connected by a coaxial waveguide.
- Waveguide resonates when $\ell = \frac{1}{2}n\lambda$, with lowest mode $f = c/2\ell = 54.5$ MHz. Successive modes are also separated by 54.5 MHz.

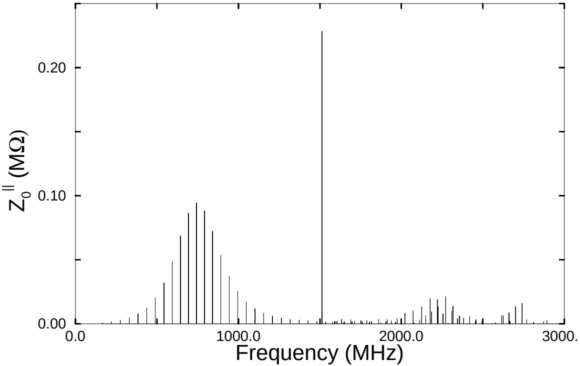
- These modes will be excited most when cavities are excited, with 1st pill-box (18-cm-deep) mode at $\sim$ 637 MHz.

  We see coaxial transmission line mode peaks there.

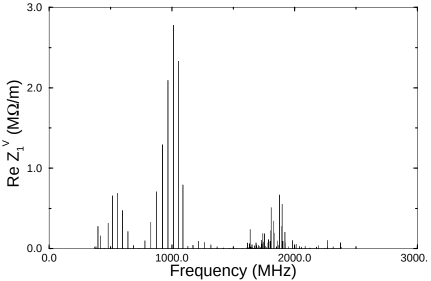
- 2nd pill-box mode at 1463 MHz with radial node at 7.84 cm, at the side edge of separator plate.

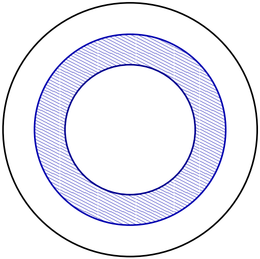
- Since it is not perturbed by coaxial guide.

  This mode is very strong.

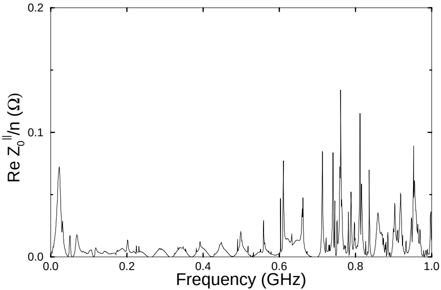


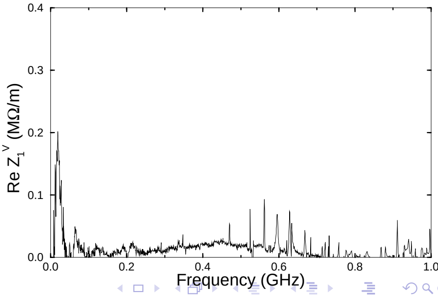
- Similar analysis applies to the trans. dipole modes.
- The lowest 50 dipole modes are shown.
- First 2 pill-box dipole modes: 1016, 1860 MHz.
- There is a special mode when one wavelength wraps around "cylindrical plates" at $r = 8.5$ to 18 cm. Or freq. between 265 and 562 MHz.
- This is seen in URMEL result (1st cluster).
- This is not seen in MAFIA result, because there is no cylindrical symmetry.





- Impedances of separator has been measured by Crisp and Fellenz, using a current-carrying wire for $Z_0^{\|}$ and a current loop pad for $Z_1^{\perp}$.
- Attenuation S_{21} was measured and the imp. calculated according to
$$Z_0^{\|} = 2Z_s\left(\frac{1}{S_{21}} - 1\right), \quad Z_1^V = \frac{2Z_s c \ln S_{21}}{\omega\Delta^2},$$
$\Delta = 1$ cm is current loop separation.
- We do see similar imp. structures as predicted by MAFIA and URMEL, except for a resonance near 22.5 MHz.
- The resonance is due to the absorption of 1st waveguide mode by power cables, connected to plates thru a 50 Ω resistor.





Comments on Separators

- The 2-m power cables increases the effective length of plates and shifts 1st resonant mode down from 54.5 to 22.5 MHz.
- This resonance contribute $\dfrac{\mathcal{R}e\, Z_0^{\parallel}}{n} = 0.82\ \Omega, \quad \mathcal{R}e\, Z_1^{\perp} = 2.1\ \mathrm{M}\Omega/\mathrm{m},$ which are appreciable.
- There are several ways to alleviate the effect:
  - Smooth out the resonance by increasing the 50 Ω damping resistor to 500 Ω.
  - Increase length of power cables to further lower resonant freq.
  - Maintain short Tevatron bunches to $\sigma_\ell = 37$ cm, so as to increase lowest head-tail mode to 82.8 MHz.

Separators vs. Strip-line BPM's

- Separator resembles stripline BPM.
  Why is separator imp. so much lower?
- In BPM, image current created at strip-lines eventually flows into terminations, which carry 50 Ω.
- But image currents created on upper and lower sides
  of separator plate at upstream gap,
  annihilate each other at downstream gap.
- Since no terminations to collect and dissipate image currents,
  the loss is small.
- Strip-line BPM does not exhibit resonances.
  But there will be resonances at separator assembly,
  which can contribute impedances.
- So we must de-Q these resonances or shift them to frequencies
  not harmful to the beam.