Impedance Estimates and Requirements for the PS2

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Tentative PS-2 parameters and Comparison to FNAL MI

	FNAL Main Injector		PS-2
	Present	New(project X)	
Injection kinetic energy, GeV	8		5
Extraction kinetic energy, GeV	120 (max. 150)		50
Circumference, m	3319.42		~1200
Number of particles per bunch	$7\cdot10^{10}$	$3.1\cdot10^{11}$	$4\cdot10^{11}$
Beam current at injection, A	0.49	2.45	2.5
Cycle duration, s	2.2	1.4	1.5 (3.3?)
Normalized 95% emittance, π mm mrad	15/15	25/25 †	18
Norm. acceptance at injection, π mm mrad	40/40	40/40	100‡
90% longitudinal emittance, eV s/bunch	0.4	0.5	0.5
Total number of particles	$3.4\cdot10^{13}$	$1.7\cdot10^{14}$	$6.5\cdot10^{13}$
γ-transition, γ_t	21.62	21.62	~12
Betatron tunes, Qx/Qy	26.42/25.41	26.45/25.46	~15
Maximum Coulomb tune shifts, ΔQx/ΔQy	0.033/0.038	0.043/0.046	0.07/012!!!
Harmonic number	588	588	160
Accelerating frequency, MHZ	53	53	40
Average beam power on the target, MW	0.3	2.3	0.37

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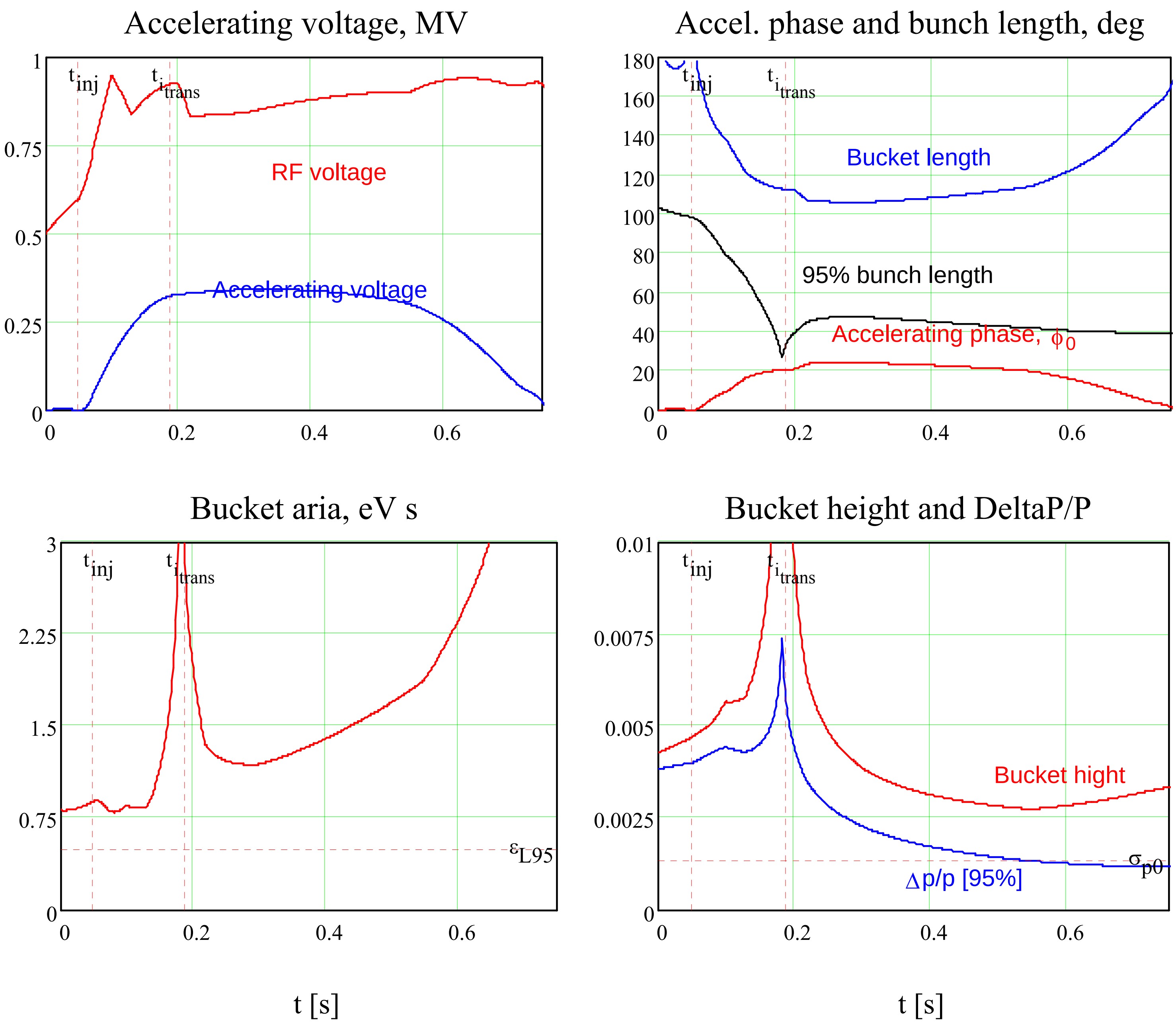
† KV distribution is implied

‡ Vacuum chamber size is set by this acceptance


Accelerating voltage, MV

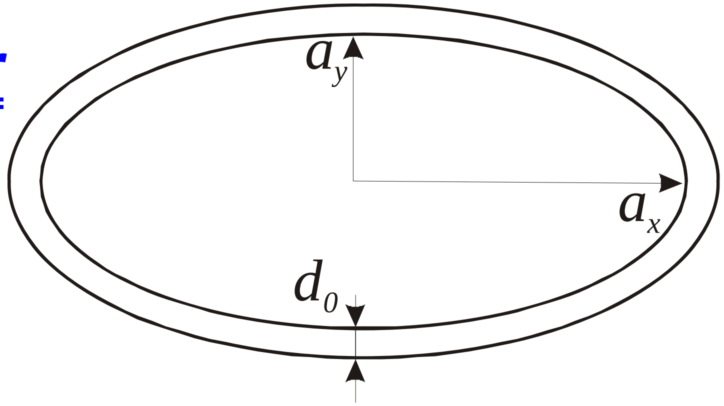
Accel. phase and bunch length, deg

Bucket aria, eV s

Bucket height and DeltaP/P

Beam parameters for single harmonic acceleration, f~40 MHz

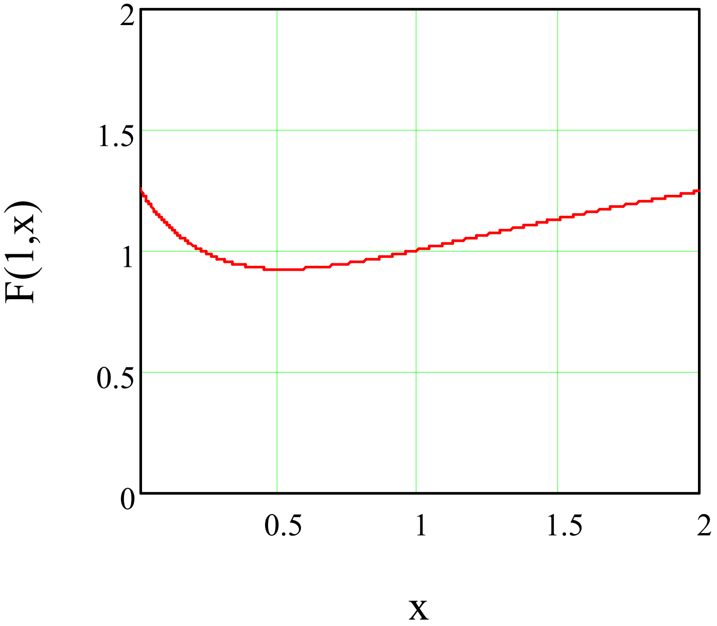
Field Screening by Vacuum Chamber



- Beam sizes are set by machine acceptance For $\beta_{max} \approx 40$ m and Normalized acceptances: $\varepsilon_{xn} \approx \varepsilon_{yn} \approx 100$ mm mrad one obtains sizes: $a_x \approx 6.2$cm, $a_y \approx 2.5$cm (the same sizes as for FNAL MI)
- Vacuum chamber thickness is limited by currents excited in walls by eddy currents

$$\frac{\delta B}{B} = i\frac{a_x d_0}{\delta^2}F(a_x,a_y), \qquad \delta = \frac{c}{\sqrt{2\pi\sigma\omega}} >> d_0$$

$$F(a_x,a_y)=\frac{4}{\pi}a_y\int_0^{\pi/2}\frac{\sqrt{a_x{}^4\sin\varphi + a_y{}^4\cos\varphi}}{\left(a_x{}^2\sin\varphi + a_y{}^2\cos\varphi\right)^{3/2}}(\cos\varphi)^2\,d\varphi$$



For stainless steel with d_0 = 1.3 mm (FNAL MI)

and f = 1 Hz ⇒ $dB/B \approx 2\cdot 10^{-4}$

For aluminum with d_0 = 3 mm (increased because of less rigidity)

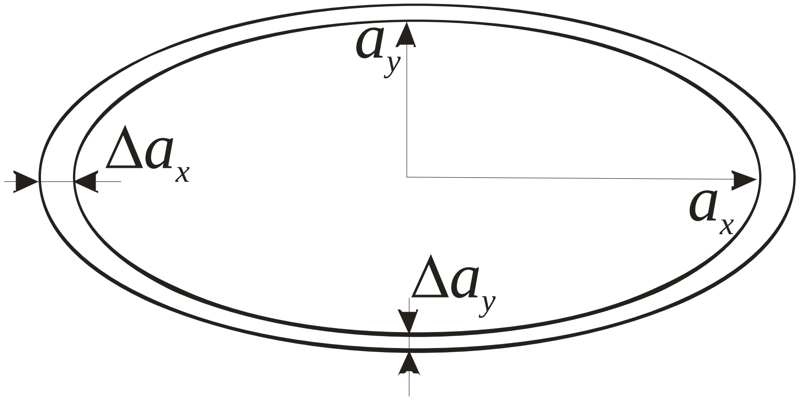
and f = 1 Hz ⇒ $dB/B \approx 10^{-2}$

Thus only stainless steel is suitable as the vacuum chamber material

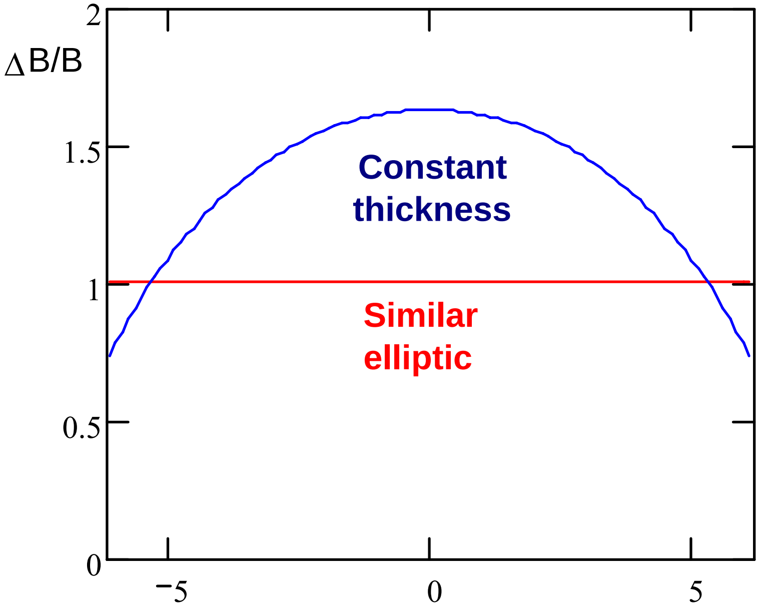
Elliptic vacuum chamber with similar boundaries

- Elliptic vacuum chamber with similar boundaries attenuates field uniformly

$$\frac{\delta B}{B} = i\frac{2a_x a_y \Delta a_x}{\delta^2 (a_x + a_y)}, \qquad \frac{\Delta a_x}{a_x} \equiv \frac{\Delta a_y}{a_y}$$



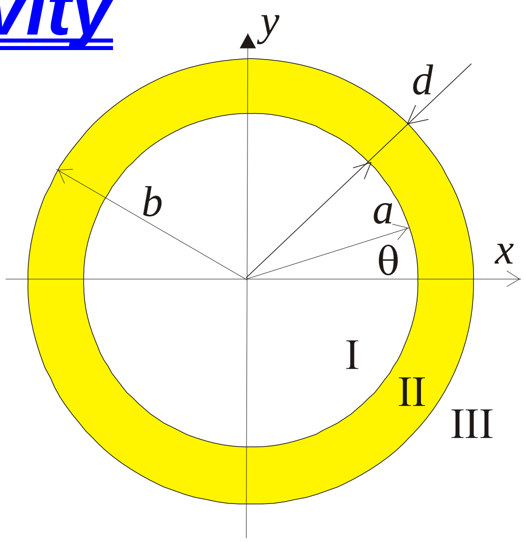
- That, in principle, allows one to use extruded aluminum vacuum chamber
  - High accuracy of the chamber profile
    - Time delay of bending magnetic field
  - Quads still have to be addressed separately
    - Disagreement between quads and dipoles
- This choice does not look attractive from operational points of view but if followed could significantly reduce resistive wall impedance



Dependence ΔBy(x,0) for similar elliptic and constant width vacuum chambers, arbitrary units, $\Delta a_x = d_0$

Transverse Impedance due to Wall Resistivity

For round vacuum chamber ($d \ll a,\ b = a + d$)

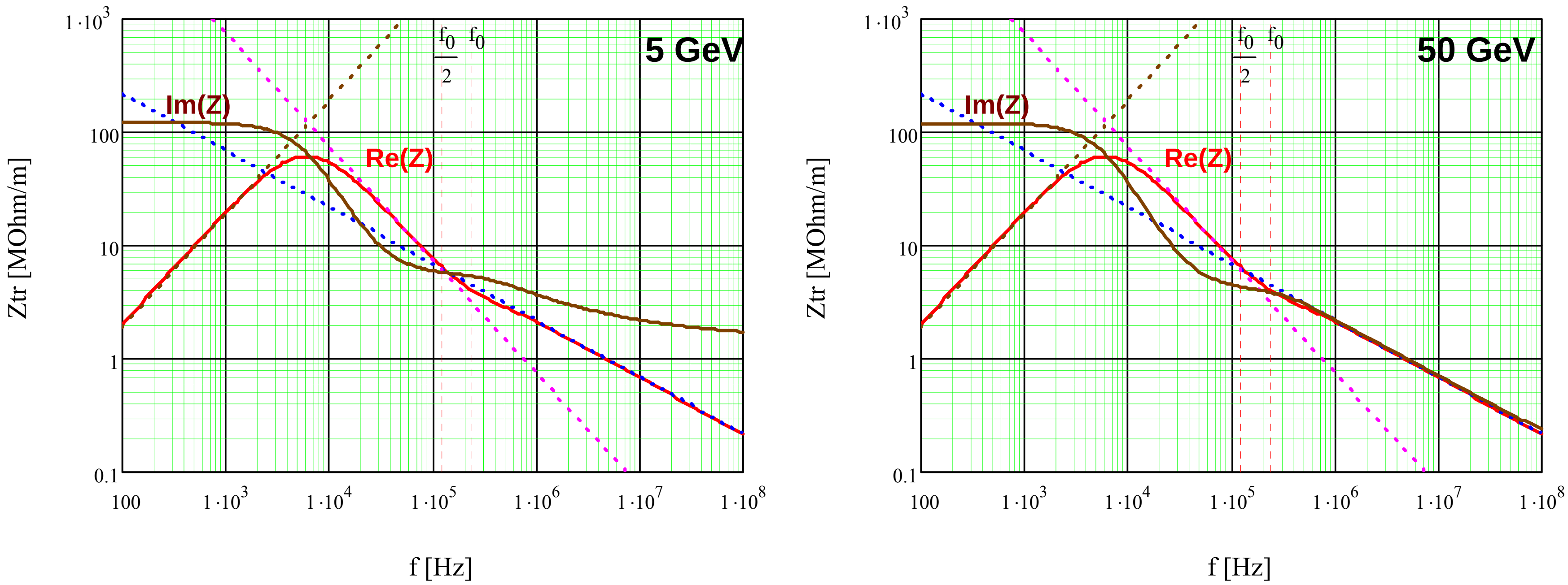


$$Z_\perp = -i\frac{Z_0(2\pi R)}{2\pi a^2}\left[2\frac{e^{kd}(1+kb)-e^{-kd}(1-kb)}{e^{kd}(1+ka)(1+kb)-e^{-kd}(1-ka)(1-kb)}+\frac{1}{\beta}-1\right]$$

$$k = \frac{1-i}{\delta}\quad,\quad \delta = \frac{c}{\sqrt{2\pi\sigma\omega}}\quad,$$

$$Z_0 = \frac{4\pi}{c} \approx 377\quad.$$

$$Z_\perp = (2\pi R)Z_0\begin{cases}\dfrac{c(1-i)}{2\pi a^3\sqrt{2\pi\sigma_R\omega}}-\dfrac{i}{2\pi a^2}\left(\dfrac{1}{\beta}-1\right) & ,\quad \delta \le d\\[2ex] \dfrac{c^2}{4\pi^2\sigma_R\omega a^3 d}-i(\ldots) & ,\quad \sqrt{ad}\ge\delta\ge d\\[2ex] \dfrac{\sigma_R\omega d}{c^2 a}-i\dfrac{1}{2\pi a^2\beta} & ,\quad \delta\ge\sqrt{ad}\end{cases}$$



Stanless steel, r=a=25 mm, d=1.3 mm;

(20-50)% correction at the lowest betatron sideband due to δ ~ d

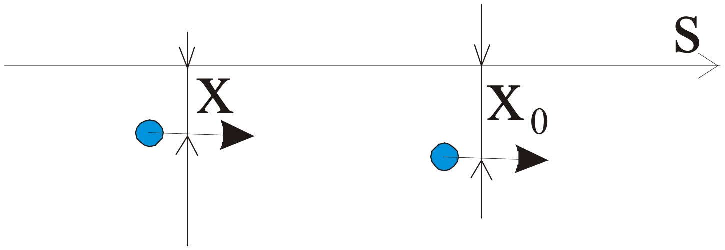
Transverse Impedance due to Wall Resistivity (continue)

Impedance of flat vacuum chamber

$$Z_y = \kappa Z_\perp \,, \quad Z_x = \frac{\kappa}{2} Z_\perp \,, \quad \kappa = \frac{\pi^2}{12} \approx 0.822$$

- ♦ Impedance of elliptic vacuum chamber is close to the flat one

Detuning Wake



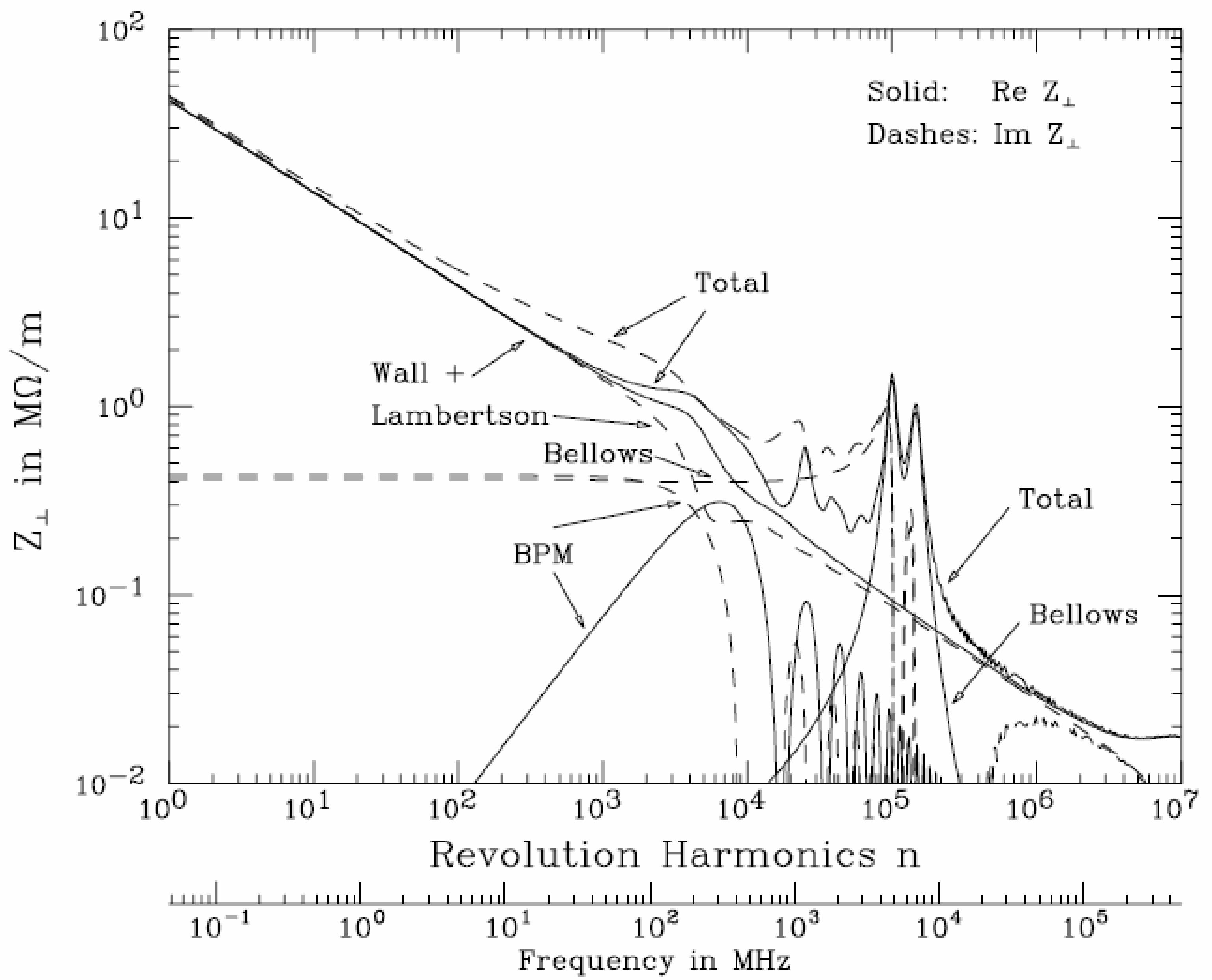
*A.Burov, V.Danilov "Suppression of transverse instabilities by asymmetries in the chamber geometry," PRL, **82**, 1999, p.2286.

- For round vacuum chamber the beam excites dipole field behind him.
  That corresponds to the normal wake field, *W*(*s*).
- For non-round vacuum chamber there are quadrupole field and higher multipoles.
  Contribution corresponding to quadrupole field is described by detuning wake *D*(*s*):

$$\int_L F_x ds' v = e^2 \left(x_0 W_x(s) + x D(s) \right)$$

$$\int_L F_y ds' = e^2 \left(y_0 W_y(s) - y D(s) \right)$$

- Detuning wake changes betatron tunes for tail particles
  - ♦ For the round vacuum chamber: $D(s) = 0$.
  - ♦ For the flat vacuum chamber: $W_x(s) = W_y(s)/2 = -D(s)$



Tevatron transverse impedance estimate at the Run II beginning, Run IIA handbook (B.Ng), 2001

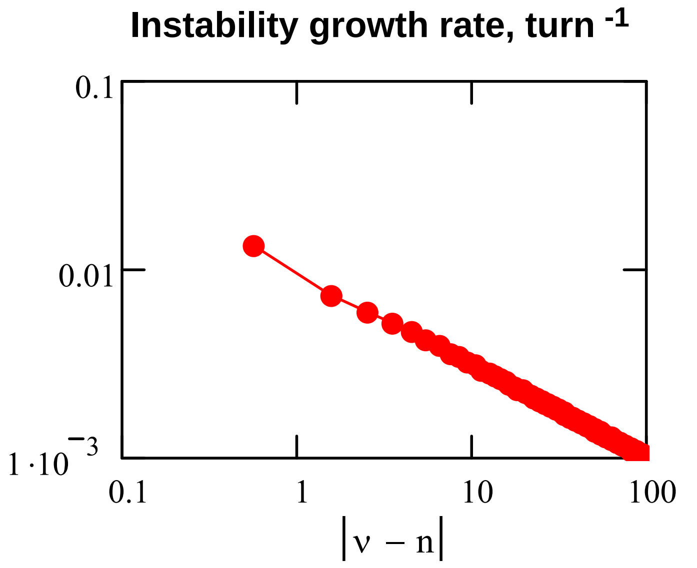
- Tevatron has stainless steel vacuum chamber
  - Wall resistivity dominates $Z_\perp$ at frequencies below 100 MHz

Transverse Instability at the Lowest Betatron Sidebands

- Resistive wall impedance is dominating at low frequencies
- For a flat vacuum chamber the coherent tune shift is

$$\Delta\nu_{y_n} = -\frac{1+i}{96\pi}\frac{eI_0C^{5/2}}{mc^2\gamma\beta^2\nu a_y{}^3\sqrt{\sigma_R c(n-\nu)}}$$

  - Assume
    - zero tune spread ($d\nu/dp = 0$)
    - $d \gg \delta$
- For FNAL Project-X the instability due to resistive wall impedance has growth time of 10 turns



Instability growth rate at injection for different transverse modes

- It is not a problem for PS-2 due to smaller ring size (smaller energy)
  - Growth time ~ 30 turns
- Present bunch-by-bunch damper at FNAL MI damps betatron motion during ~70 turns
  - There should not be a problem to do something similar for PS-2
- Landau damping damps high frequency modes

Ways to Reduce Resistive Wall Impedance, $Z_\perp$

- If required there are 2 ways to reduce impedance
  - Thin conductive layer on the inner wall of vacuum chamber
  - Larger aperture
- Both methods increase screening of the alternate bending field
- At the lowest betatron sideband the thin conductive layer equally affects screening and impedance
  - but it does much better job at high frequencies
- Larger aperture affects the impedance much stronger ($a^3/d \sim a^2$) than the shielding (~a)

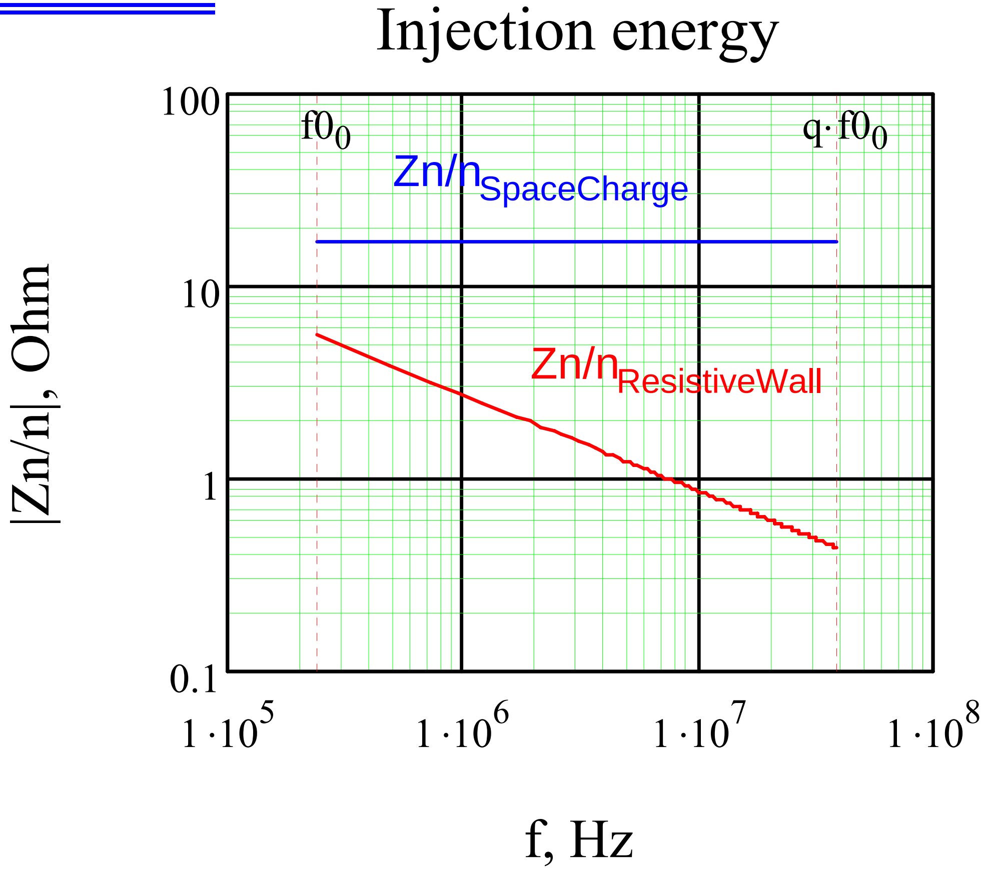
Wideband Longitudinal Impedance

- At low energy and transition crossing the impedance is dominated by the space charge

$$\frac{Z_n}{n} = i\frac{Z_0}{\beta\gamma^2}\ln\left(\frac{a_y}{1.06\sigma}\right)$$

- Resistive wall makes the second largest contribution at small frequencies, f ≤ 100 MHz

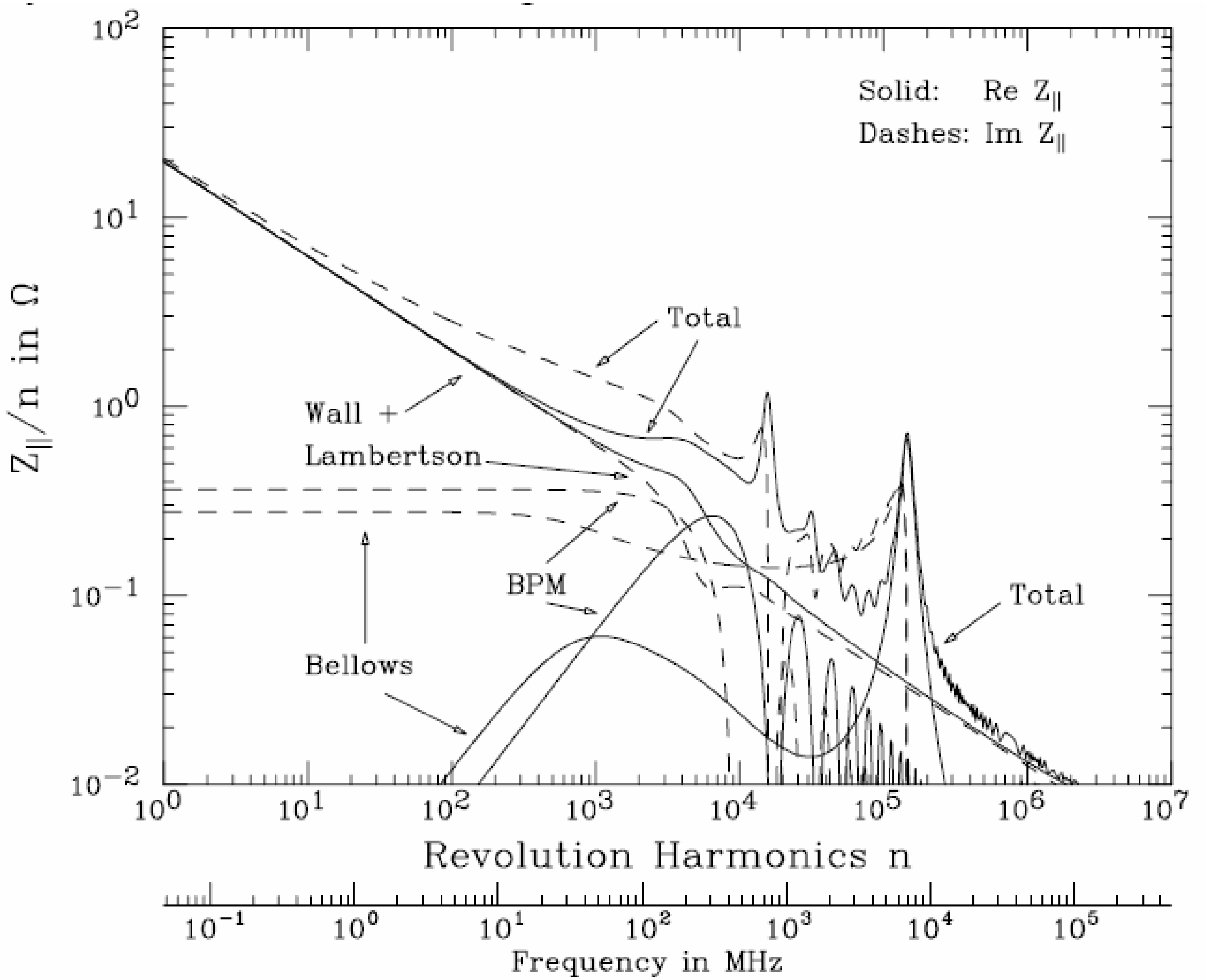
$$\frac{Z_n}{n} = (1-i)\kappa\frac{Z_0}{4\pi a_y}C\sqrt{\frac{n\omega_0}{4\pi\sigma_R}}$$



κ = 1 and $\kappa \approx$ 0.8 are for round and flat vacuum chambers, correspondingly

C – machine circumference

σ_R – wall conductivity

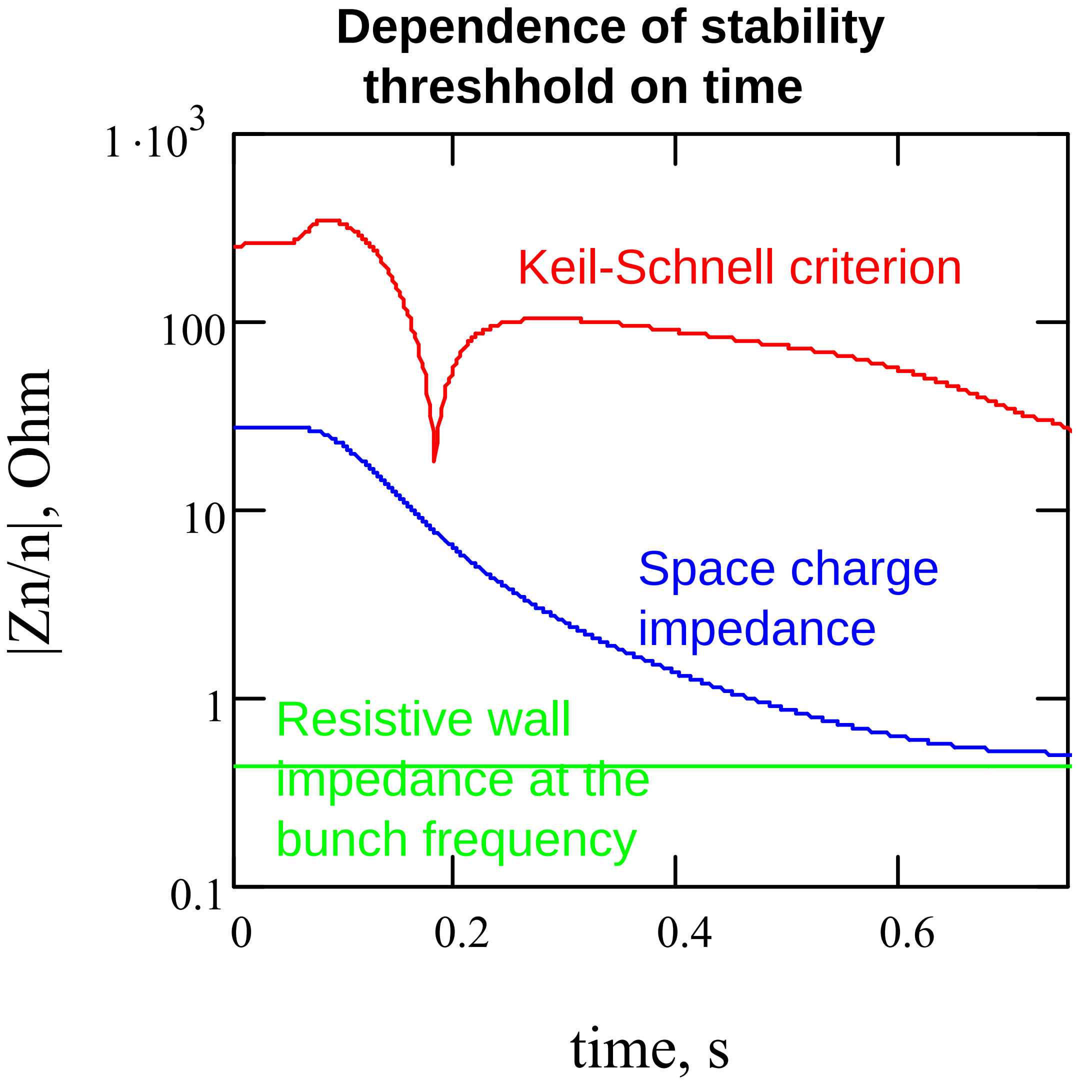


Tevatron longitudinal impedance estimate at the Run II beginning, Run IIA handbook (B. Ng), 2001

- At high frequencies (f ≥ 100 MHz) vacuum chamber interruptions begin dominating the impedance

Longitudinal beam stability

- Wide band longitudinal impedance is sufficiently small and should not be a problem
- Interaction with RF cavities can cause beam instability
  - ♦ Bunch-by-bunch damper can address the problem



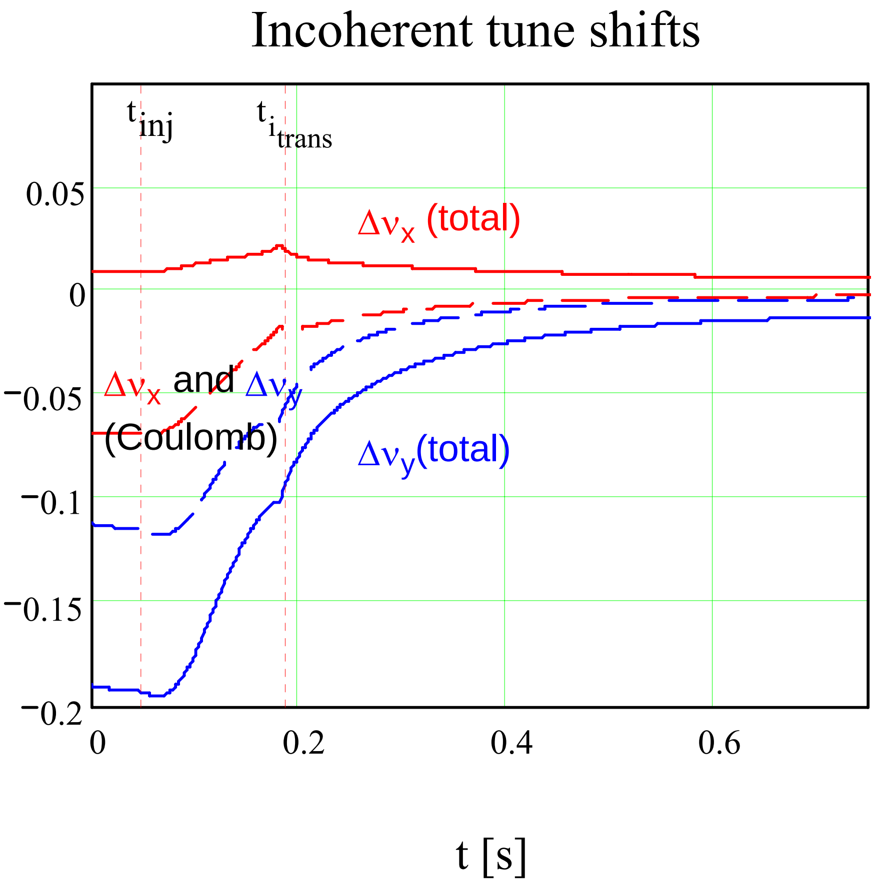
Other concerns

- Coulomb tune shifts look too large
  - Larger dispersion (smaller tunes) can increase horizontal beam size and partially alleviate the problem

    For equal tunes and emittances in smooth approximation

$$\Delta\nu_y = \frac{r_p N}{2\pi\beta^2\gamma^3\varepsilon}\frac{1}{\left(1+\sqrt{1+\frac{R\sigma_p^{\,2}}{\varepsilon\nu^3}}\right)}$$

$$\Delta\nu_x = \frac{r_p N}{2\pi\beta^2\gamma^3\varepsilon}\frac{1}{\sqrt{1+\frac{R\sigma_p^{\,2}}{\varepsilon\nu^3}}\left(1+\sqrt{1+\frac{R\sigma_p^{\,2}}{\varepsilon\nu^3}}\right)} \quad ,$$



$\Delta\nu_y$ still will be a problem but vertical resonance driving terms will be reduced if $\sigma_x \gg \sigma_y$

- Incoherent tune shifts due to interaction with the vacuum chamber can be corrected by machine quads (we use it in MI)

Limitations on the RF system

- RF frequency is chosen to coincide with LHC bunch frequency
    - Similar to the FNAL Project-X
    - May be not the best choice from ep multipactoring
    - RF gymnastics can be used to shorten bunches before extraction so that they could be caught by 200 MHz of next machine
    - Second harmonic RF would be helpful to reduce peak long. density at injection and achieve better Landau damping

Harmonic number	160
Frequency, injection to extraction, MHz	39.6–40.2
Total RF voltage, MV	1
Number of cavities	6
Shunt impedance per cavity, (R/Q)*Q, kΩ	100
Loaded Q	4000
Peak RF power, MW	1.6
Max. power transferred to the beam, MW	0.9
Voltage induced by the beam, MV	1.5

- Power and voltage are set by the acceleration and the number of particles
- Feed forward system will be required to suppress abort gap influence on RF parameters

Conclusions

- To ensure reliable operation of PS-2 with beam current of ~2.5 A one needs to minimize the machine impedances
- For comparatively short cycle time of ~(1 – 3) s the eddy currents limit the vacuum chamber conductivity. Taking into account the mechanical stability of the vacuum chamber the elliptical stainless steel vacuum chamber looks as a preferable choice
  - Covering it with thin layer of better conducting material (gold, silver of copper) would be helpful but is rather a question of choice than a necessity. To prevent the domination of bending field screening by this layer its thickness should not exceed 30-50 μm
    - σ_1/σ_2 gain in the impedance will be only for high enough frequencies, ≥20 MHz
    - Impedance at revolution frequency will be set by limitation on the bending field screening

- To keep the impedance at minimum
  - Good electromagnetic screening of bellows and other interruptions of the vacuum chamber
  - Do not use septum magnets with laminations seen by the beam
    - We fixed this problem with Tevatron. MI is next in line
- There are no fundamental limitations on the vacuum chamber impedance for PS-2 parameters
  - Use of transverse and longitudinal dampers is the must