Beam Impedance and Heating for Several Important NSLS-II Components

A. Blednykh

Simulation of Power Dissipation and Heating from Wake Losses in Accelerator Structures

Mini-Workshop, DIAMOND, Jan. 30, 2013

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY

BROOKHAVEN SCIENCE ASSOCIATES

Acknowledgments

- NSLS-II/BNL:

  S. Krinsky, O. Singh, B. Kosciuk, C. Hetzel, H.-C. Hseuh, B. Bacha, W. Cheng, F. Willike, T. Shaftan, G. Bassi.

- CAD/BNL:

  I. Pinayev

- SLAC:

  M. Ferreira

- APS/ANL:

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

Outline

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

NSLS-II Current

N = number of electrons in single bunch (7.8×10^9)

Ne = Bunch Charge (1.25 nC)

M = number of bunches (1080)

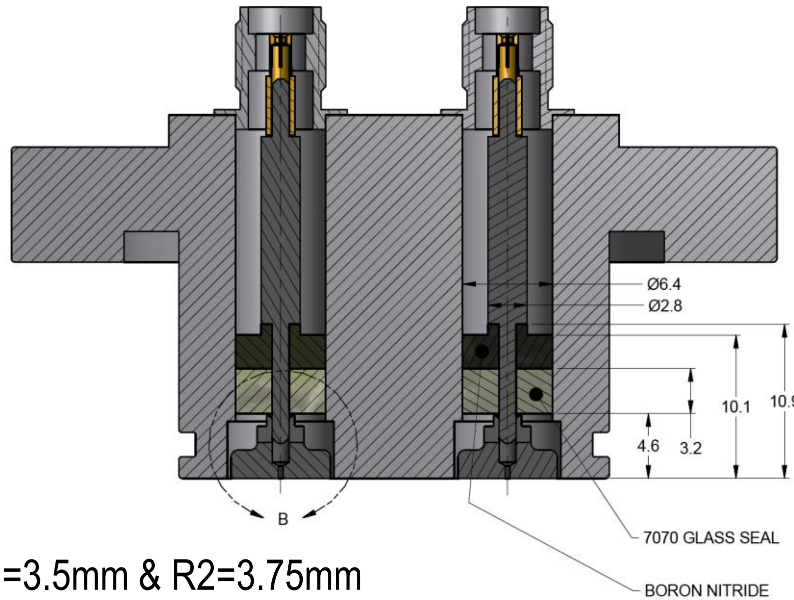
Single Bunch Current $$I_0 = \frac{N e}{T_0}$$ (.5 mA)

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

ignoring bunch lengthening

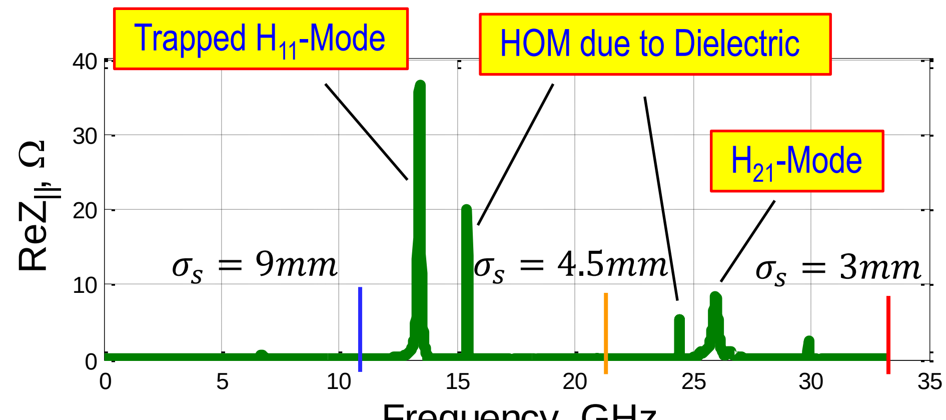
Average Current $$I_{av} = \frac{M N e}{T_0}$$ (500mA)

Large Aperture BPM (∅7mm)

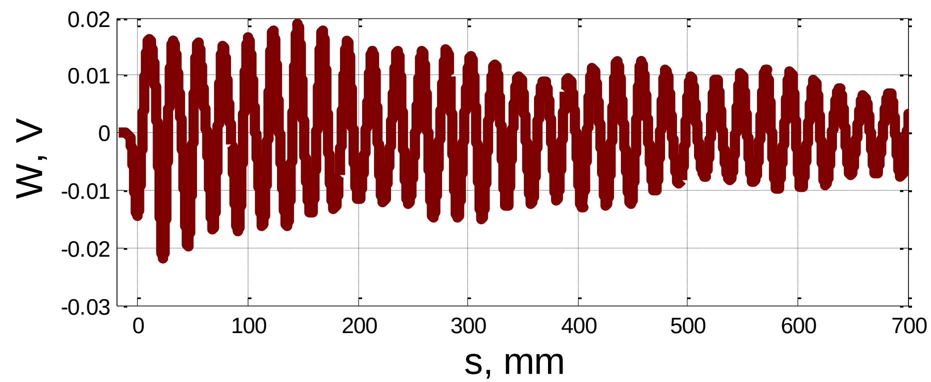


R1=3.5mm & R2=3.75mm

BPM Assembly



Real Part of the Longitudinal Narrow-Band Impedance



Longitudinal Wakepotential

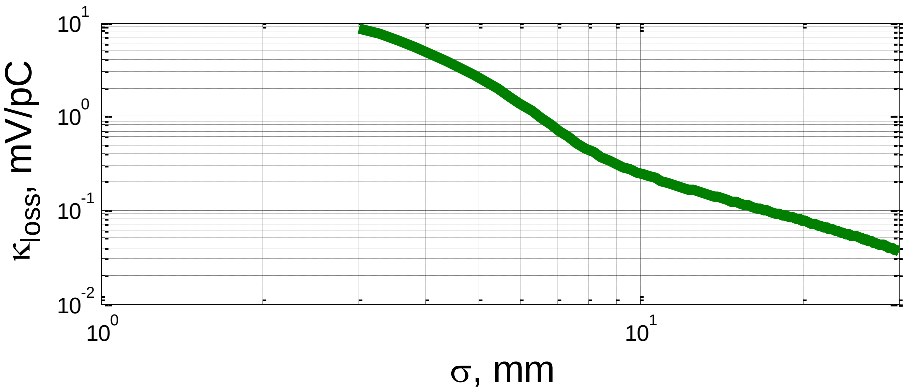
- The Cutoff Frequency of H_{m1}-Mode (ε_r=1)

$$f_c^{Hm1} \approx \frac{1}{\sqrt{\varepsilon_r}} \frac{c}{\pi} \frac{m}{(R1+R2)}, \quad where \quad m = 1,2,3,..$$

- f_{H11} & f_{H21}
- HOM's Due to Dielectric Are Seen by the Beam

Losses and Heating

Single Bunch Passing



Loss Factor as a Function of Bunch Length

500mA

$$P_{loss} = T_0 \frac{I_{av}^2}{h} k_{loss} = 492 \times k_{loss}$$

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

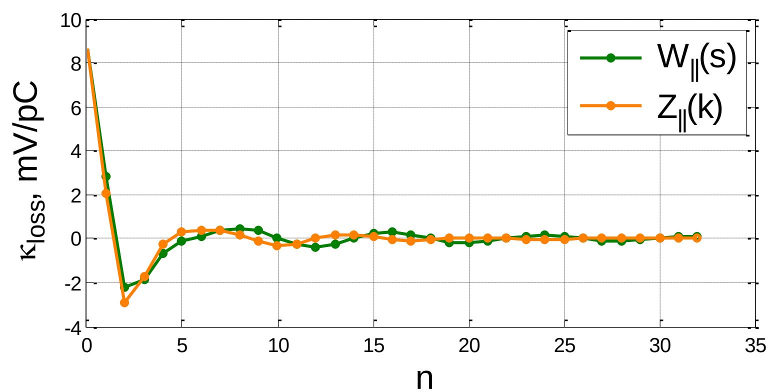
$$P_{loss} = 4.3W$$

Multi-Bunch Train (Equally Spaced)

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

$$= \sum_{n=0}^{\infty} \frac{c}{\pi} \int_0^{\infty} dk \left|\tilde{\rho}(k)\right|^2 \left[\operatorname{Re} Z(k)\cos(knl) + \operatorname{Im} Z(k)\sin(knl)\right]$$

Total Loss Factor

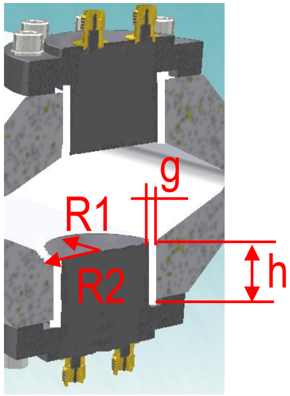


BPM Flange

g=100um and h=10mm

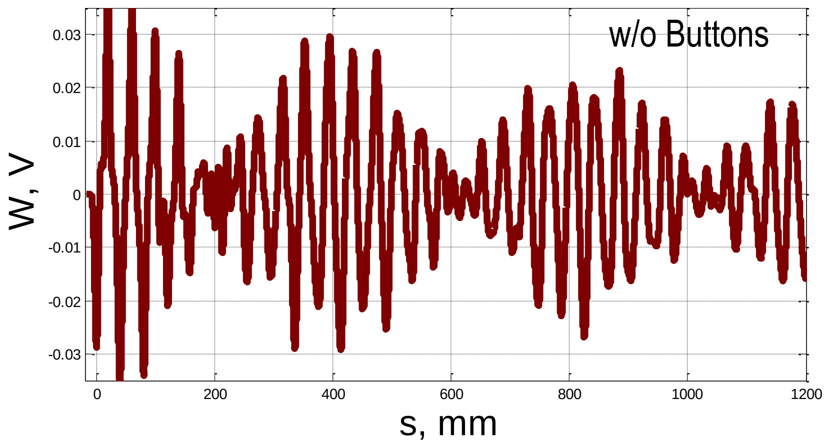
R1=30.5mm and R2=30.6mm

2a=76mm and 2b=25mm



- Single Bunch Passing (Geom.)

	σ_s, *mm*	κ_{loss}, *mV/pC*	P_{loss}, *w*
Impedance Budget	3	20	---
Average Current (300mA)	4.5	12	2.6
Average Current (500mA)	9	2	0.4



Longitudinal Long-Range Wakepotential

- Total Losses

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

	σ_s=3mm	σ_s=4.5mm	σ_s=9mm
Total loses, *mV/pC*	86	44(n=8)	---

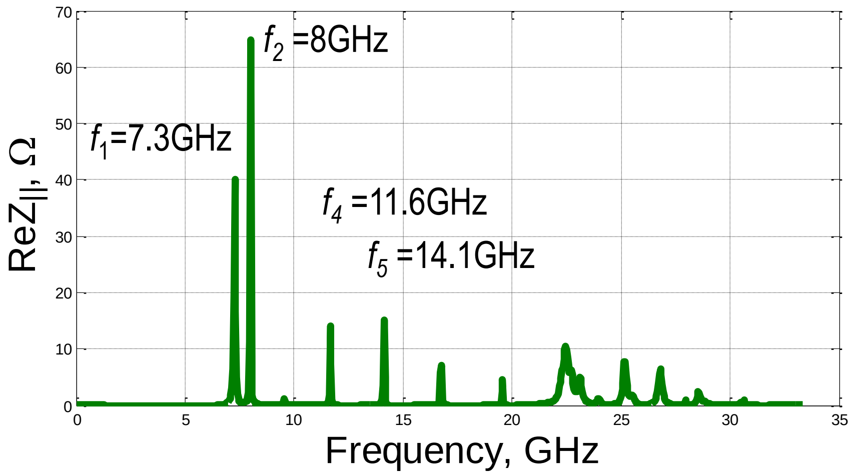
- Power Loss (@500mA)

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

Mode Classification

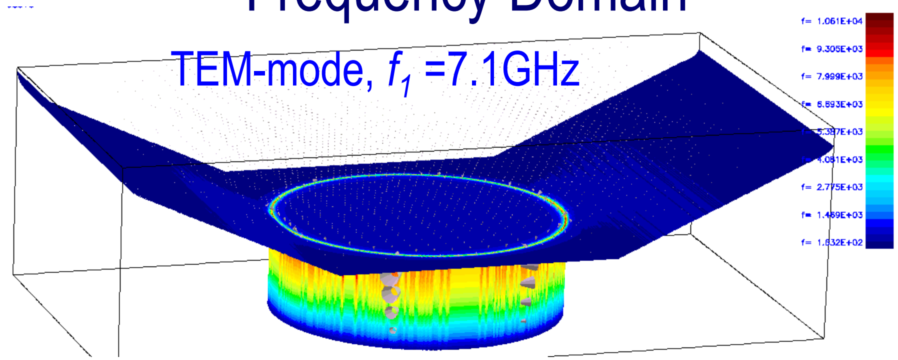
Time Domain

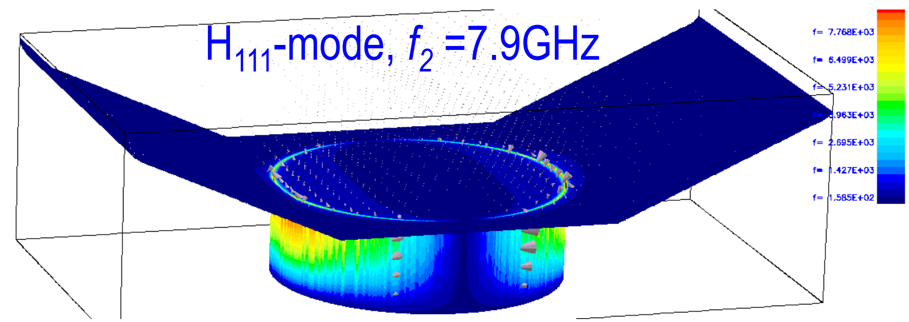
Real part of the longitudinal impedance

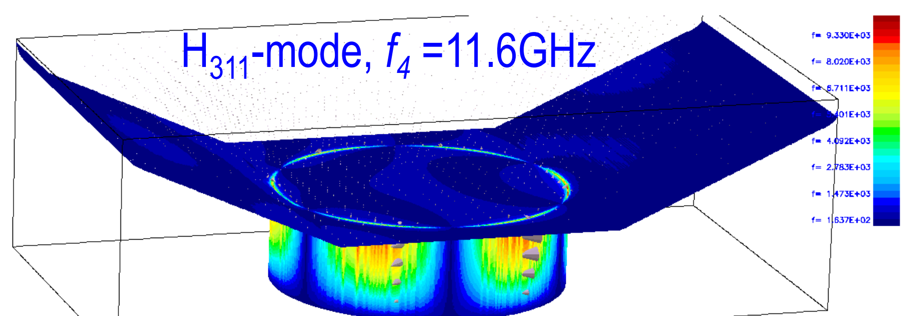


- Existence of trapped modes in a space between the vacuum chamber and the BPM flange
- Trapped modes have been classified
- Electric field distribution of TEM-mode and H_{m11}-modes are shown in figures

Frequency Domain







Frequencies Analysis

Frequencies of the Resonant Coaxial Cavity

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

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

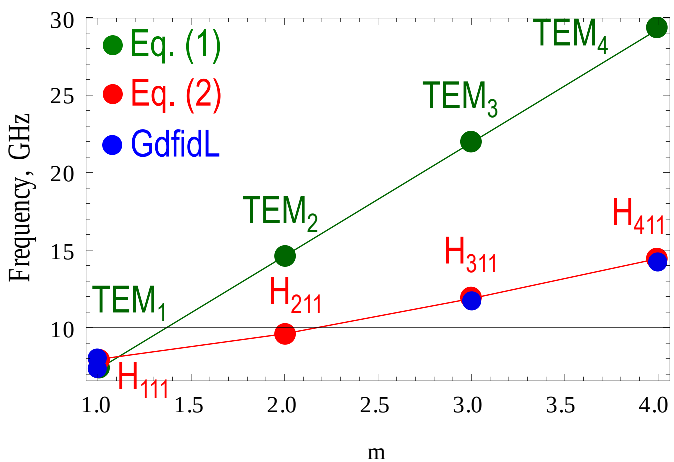
$$where \quad m = 1,2,3,.. \quad and \quad p = 1.$$

BPM Flange

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

f_{TEMm}^{Coax}: 7.1GHz, 14.3GHz, 21.4GHz and 28.6GHz

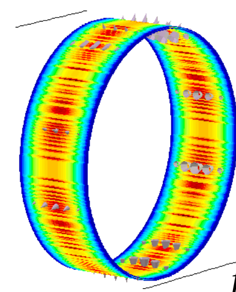
f_{Hm1p}^{Coax}: 7.8GHz, 9.5GHz, 11.8GHz, and 14.4GHz



Simulations of the Coaxial Cavity

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

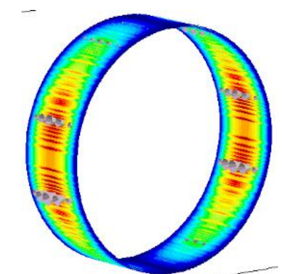
TEM$_1$-mode



$f_{TEM_1}^{Eq.1} = 15GHz$

$f_{TEM_1}^{Gdf} = 15GHz$

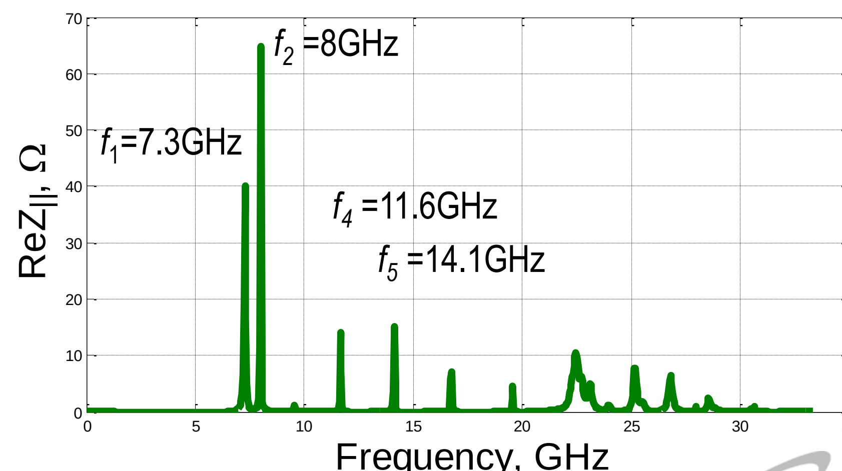
TE$_{111}$-mode



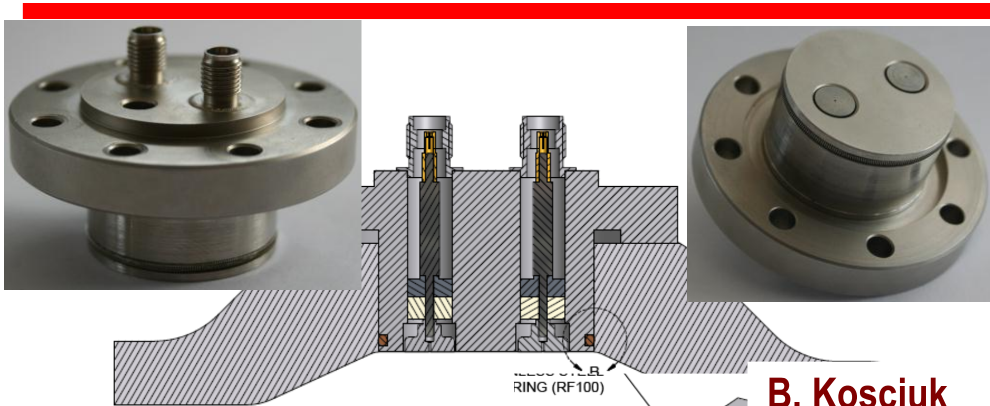
$f_{TE_{111}}^{Gdf} = 15.31GHz$

$f_{TE_{111}}^{Eq.2} = 15.28GHz$

Real part of the longitudinal impedance



RF Shielded BPM Assembly



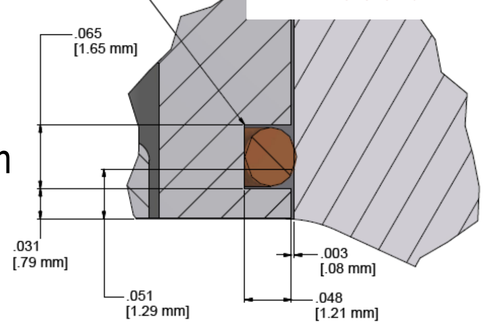
B. Kosciuk

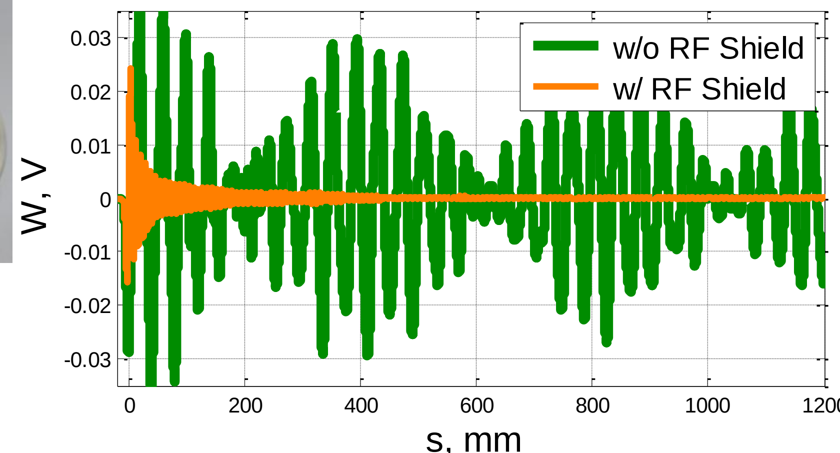
Geometric parameters:

g=100um and h=2mm

d1=30.5mm and d2=30.6mm

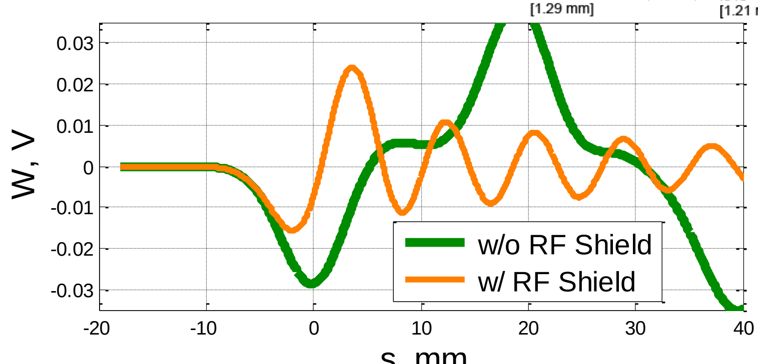
2a=76mm and 2b=25mm



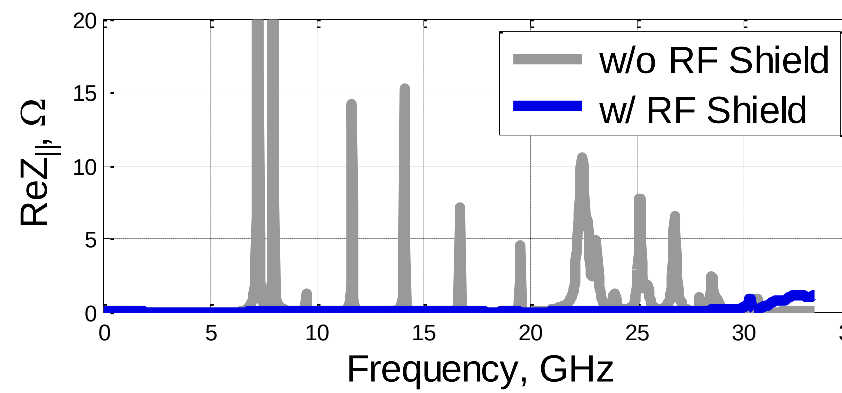


Longitudinal long-range wakepotential

$\kappa_{loss}(\sigma_s=3mm)$ = 0.7mV/pC (w/ RF Shield)



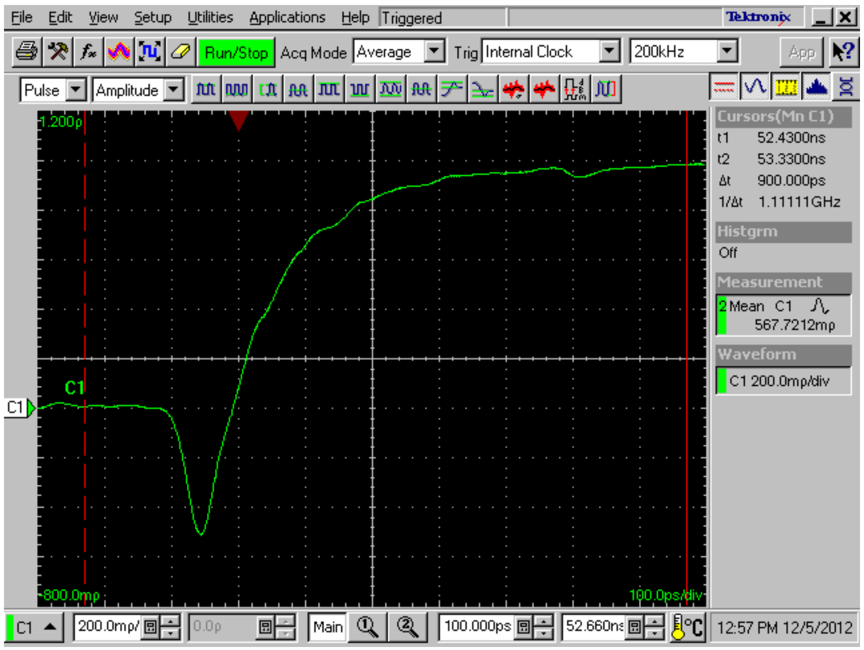
Longitudinal short-range wakepotential



Real part of the longitudinal impedance

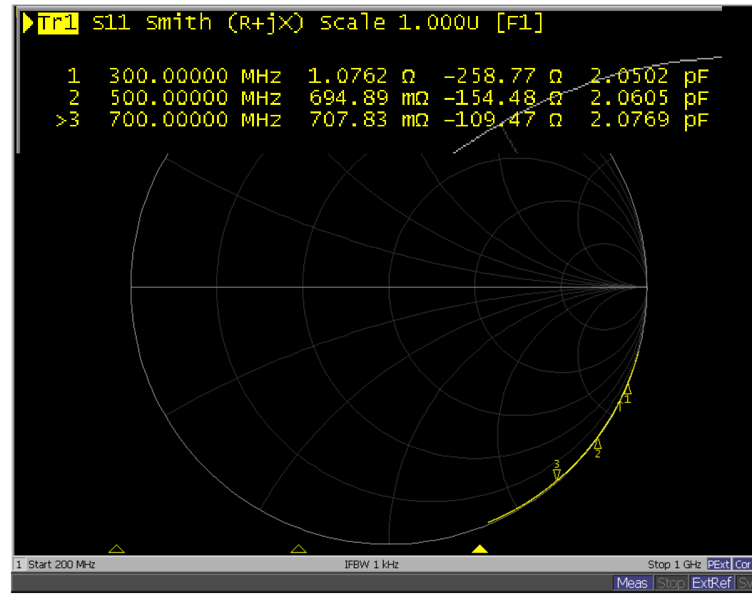
Measurements of the Button Capacitance

Tektronikx DSA 8200



TDR Measurements

Agilent E5071C Network Analyzer

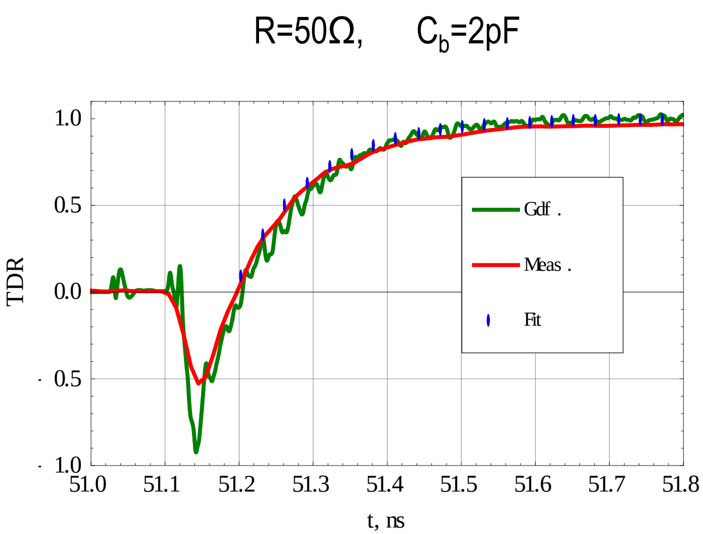


VPN (FDR) Measurements

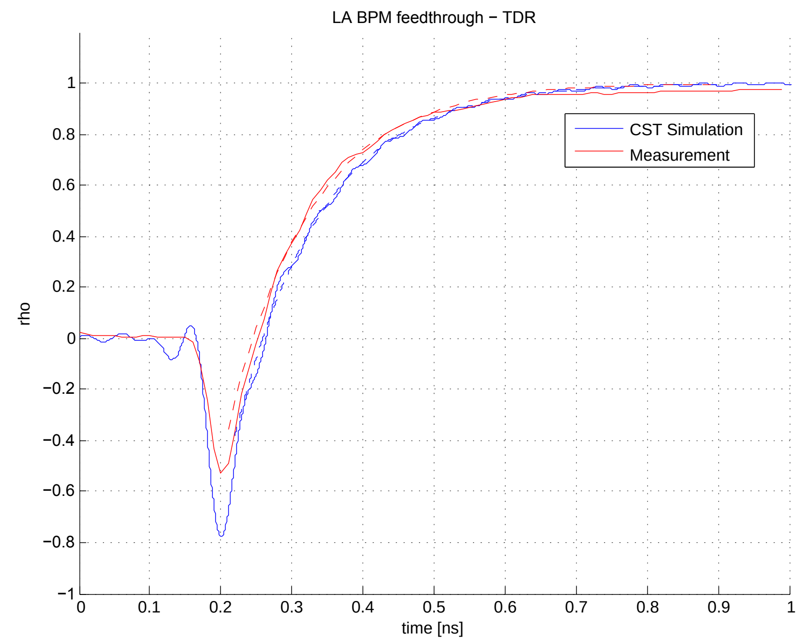
- Sensitive to Impedance Profile of the Transmission Line
- Sensitive to the Total Input Impedance Looking into the Tested Structure

B. Bacha & I. Pinayev

TDR Simulations vs. Measurement



GdfidL



CST

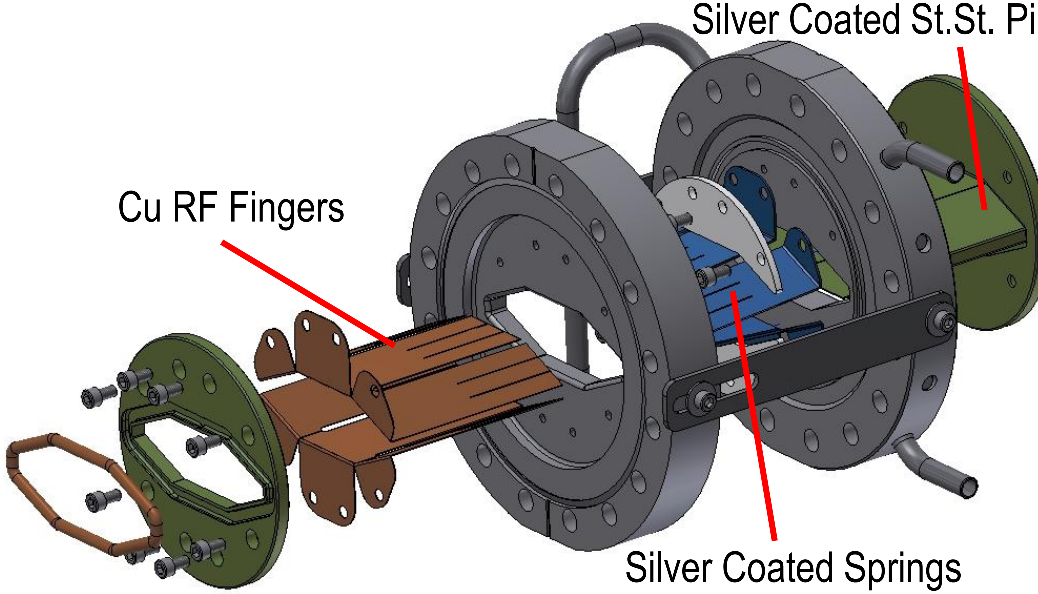
W . Cheng

U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY
BROOKHAVEN SCIENCE ASSOCIATES

NSLS-II Bellows

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

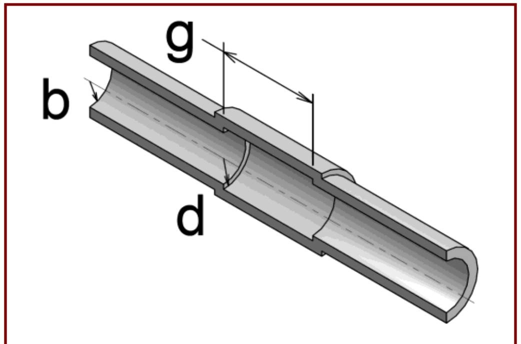


- Vacuum chamber aperture: 2a=25mm (V) and 2b=76mm (H)
- Bellows inner aperture: $2a_1$=25.5mm (V) and 2b=76.7mm (H)
- Water Cooled Flange
- Silver Coated Springs :

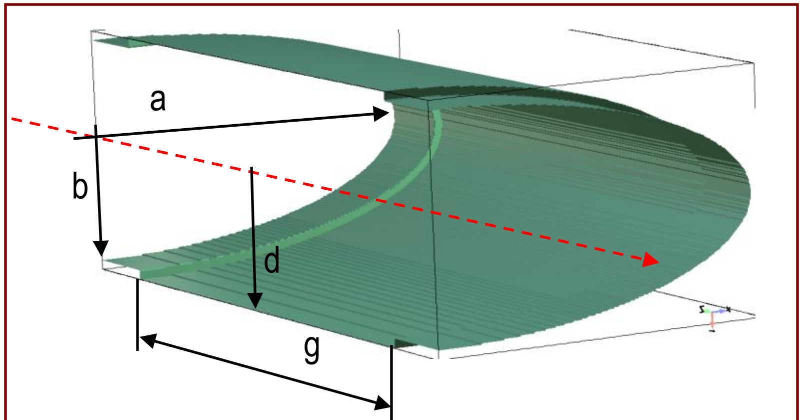
  1. Thermal Transition Improvement
  2. Significant Powder Reduction due to Mechanical Motion

M. Ferreira

Simplified Cavity Model (Loss Factor)



g=30mm and b=12.5mm



a=38mm, b=12.5mm and g=60mm

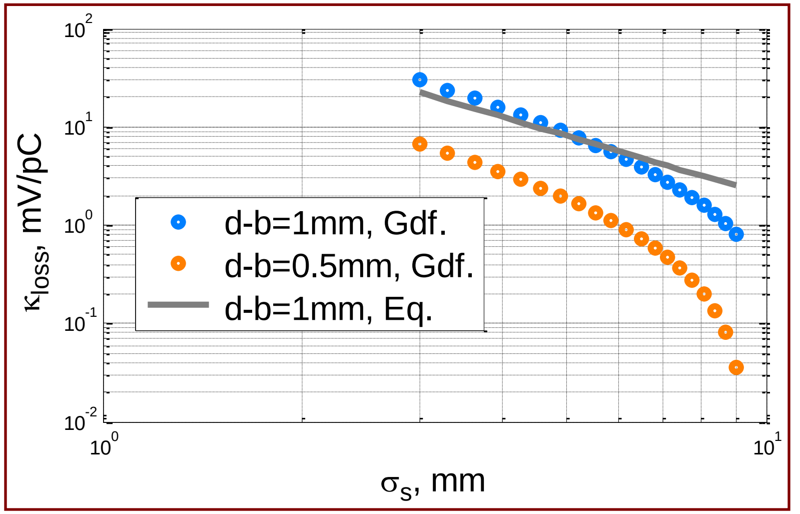
In the cavity regime, $b < g < b^2/\sigma$,

$$\kappa_{\mathrm{loss}} \approx \frac{1}{2\sqrt{\pi}}\frac{1}{b}\left(\frac{d-b}{\sigma}\right)^2 \qquad (d-b<\sigma).$$

A. Blednykh & S. Krinsky, PRSTAB 2010

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

  κ_{loss}= 7mV/pC (*d-b*=0.5mm)



Loss Factor

Loss Factor (Geometric):

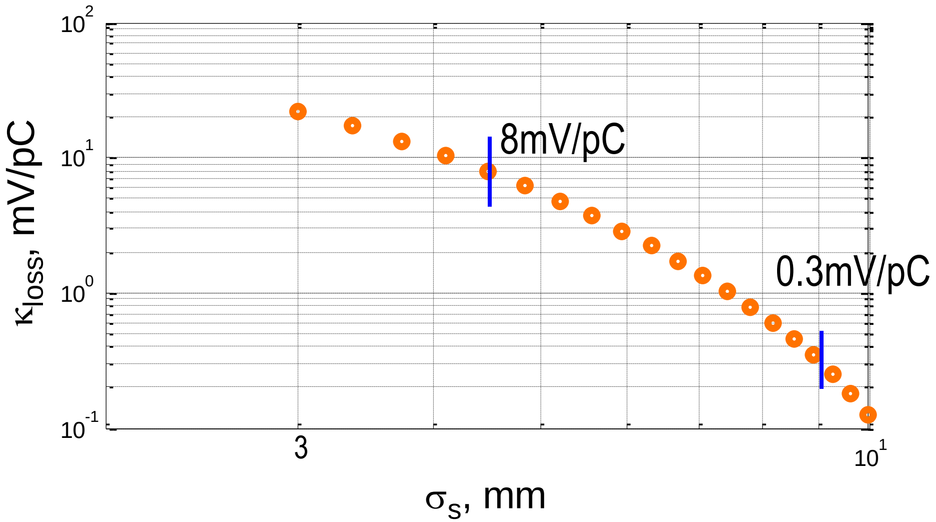
$$k_{loss}^{geom}(\sigma_s) = \int_{-\infty}^{\infty} \frac{c}{2\pi} \mathrm{Re}\, Z_{\|}(k) e^{-k^2\sigma_s^2} dk$$

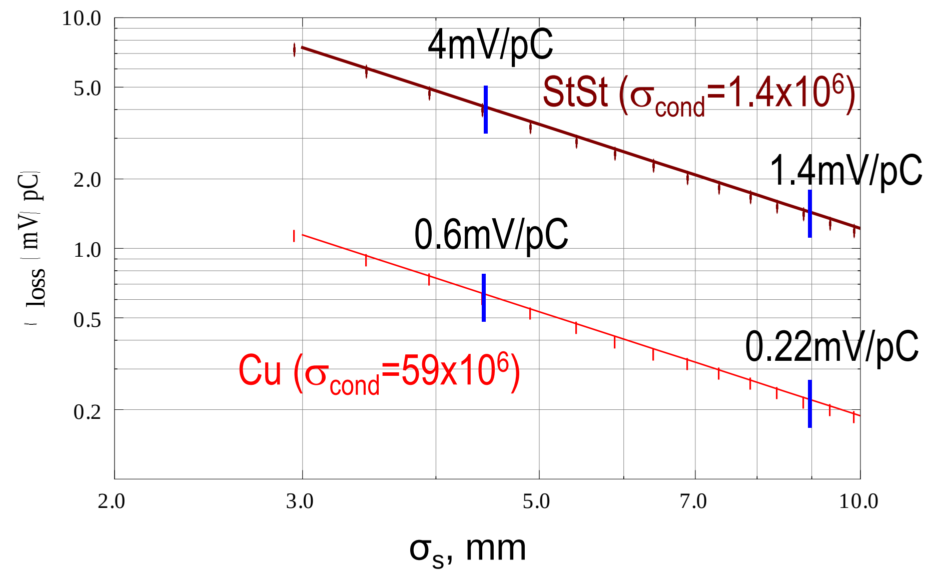
Loss Factor (Resistive Wall):

$$k_{loss}^{rw}(\sigma_s) = 1.2 \frac{cZ_0}{4\pi} \frac{L}{2\pi b^2} \left(\frac{s_0}{\sigma_s} \right)^{3/2} \qquad s_0 = (2b^2 / Z_0 \sigma_{cond})^{1/3}$$

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

Loss factor as a Function of Bunch Length



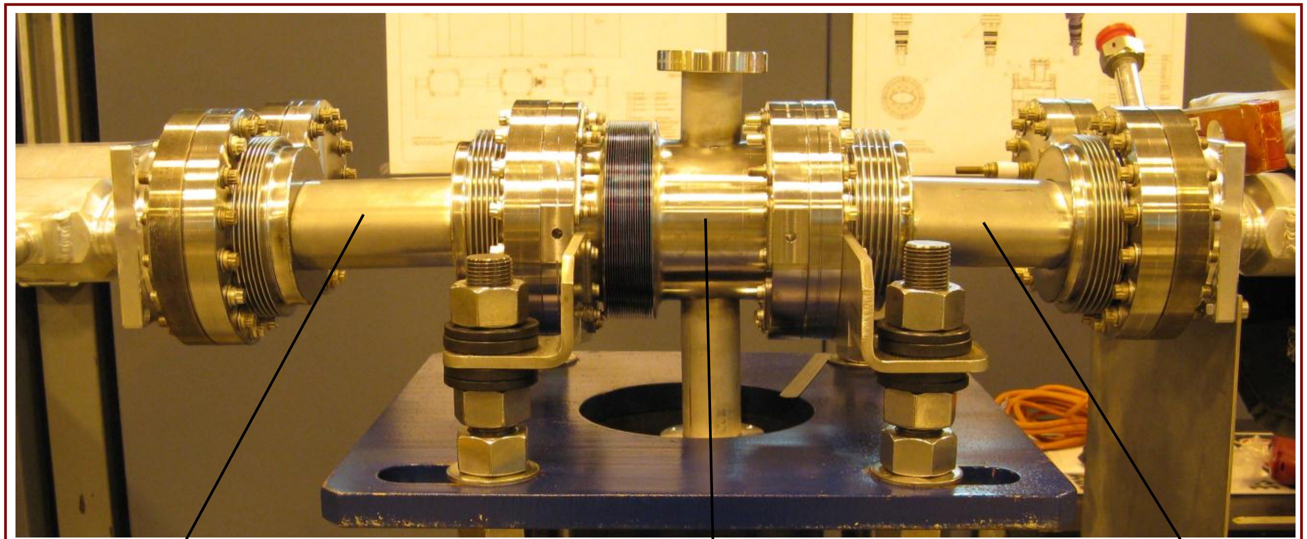


σ_s=4.5mm (I_{av}= 300mA) with ID's

σ_s=9mm (I_{av}= 500mA) with ID's & Landau Cavity

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

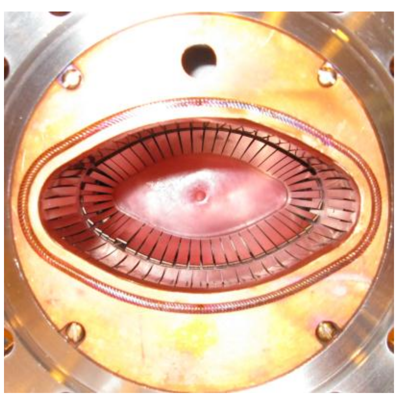
NSLS-II Bellows Under Beam Test in the APS Storage Ring

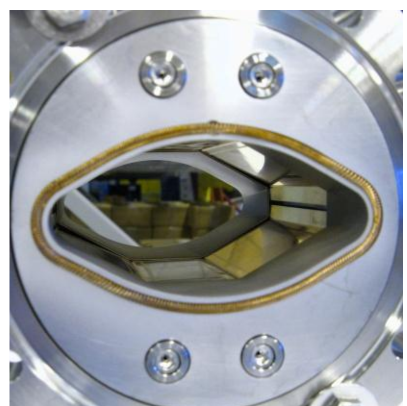


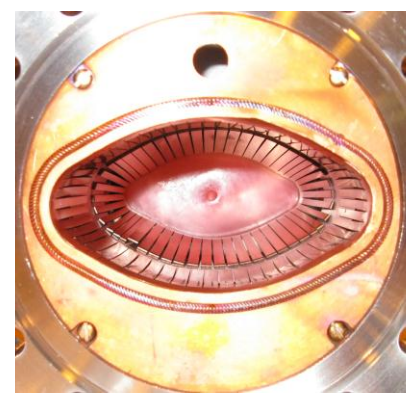
APS Bellows

NSLS-II Bellows adapted for the APS vacuum chamber profile

APS Bellows



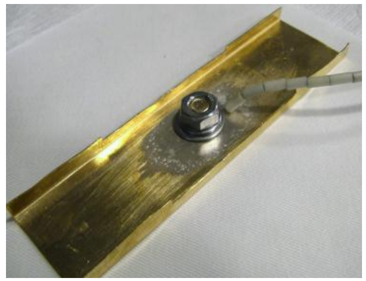




“Simulation of Power Dissipation and Heating from Wake Losses in Accelerator Structures”, Mini-Workshop, DIAMOND

Measurement of Temperature Rise in Adapted Bellows

NSLS-II Bellows Adapted for APS



RF Finger with Thermocouple

2a=40.7mm
2b=84.2mm
$2a_2$=43.8mm
h=0.75mm
gap=76mm
th=0.5mm (Fing.)
L_{tap}=38mm

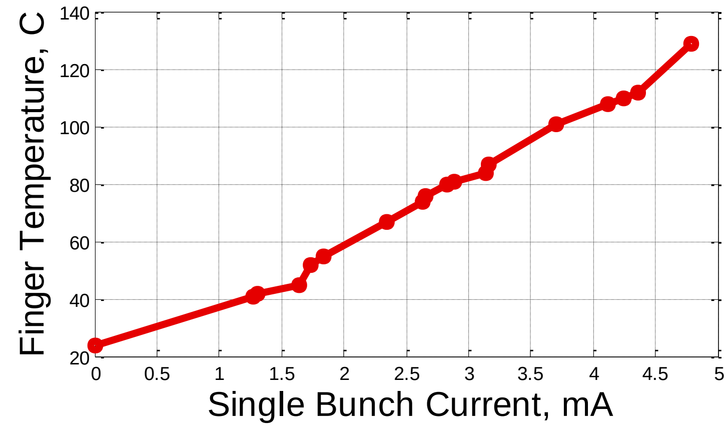
APS Ring Parameters:

I_{av}= 115mA

h_b = 24

T_0= 3.7μs

σ_s=10mm



Measured Temperature on RF Finger

- Direct measured temperature under the RF finger
- Upper temperature limit for RF fingers is 250 °C
- High current run: 150 mA in 24 bunches !
- I_0 = 6.3mA – T = 155 °C
- No damages and deteriorations was observed !

Data Comparison of Adapted & Regular NSLS-II Bellows

NSLS-II Bellows adapted for APS

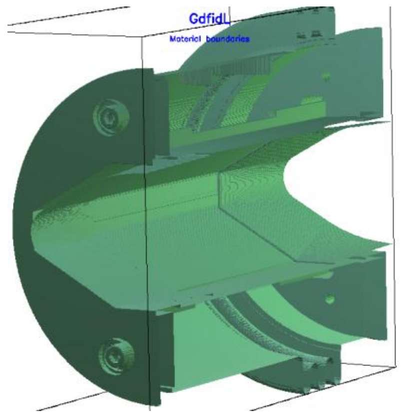
APS ring parameters:

I_{av}= 115mA

h_b =24

T_0=3.7μs

σ_s=10mm



NSLS-II Bellows

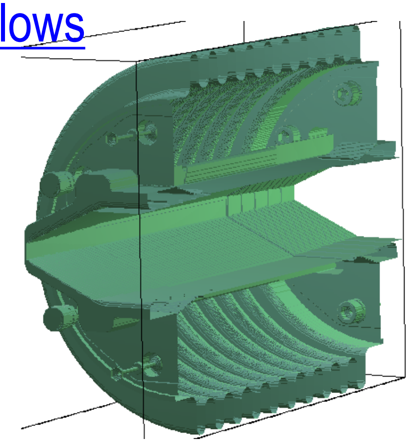
NSLS-II ring parameters:

h_b =1080

T_0=2.6μs

σ_s=4.5mm (I_{av}= 300mA)

σ_s=9mm (I_{av}= 500mA)



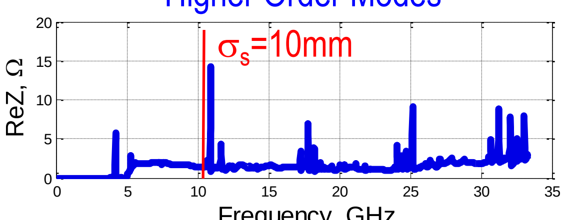
115mA

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

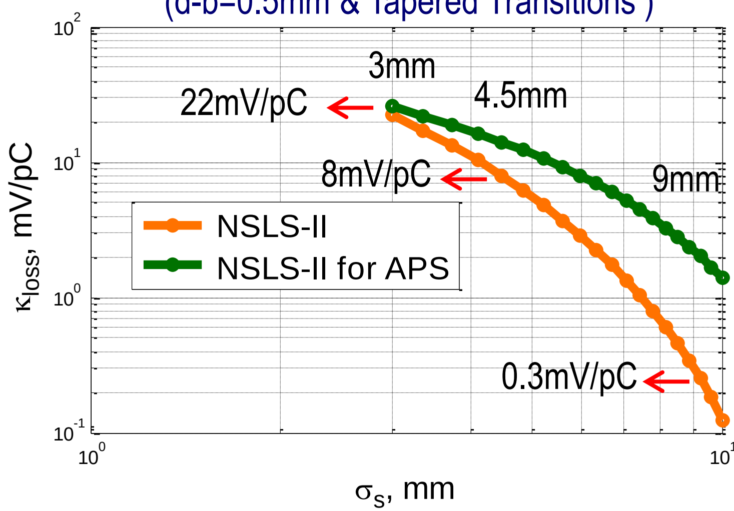
$$k_{loss}^{rw+geom}(\sigma_s = 10mm) = 1.5\, mV/pC$$

$$P_{loss}^{APS} = 3.1\ W$$

Higher Order Modes



(d-b=0.5mm & Tapered Transitions)



Geometric Loss Factor as a Function of Bunch Length.

300mA

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

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

$$P_{loss}^{NSLS-II} = 1.9\ W$$

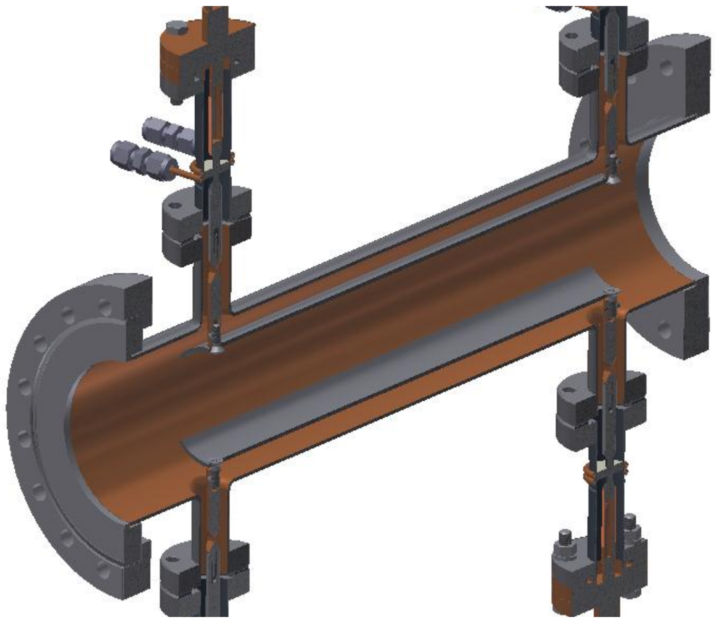
500mA

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

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

$$P_{loss}^{NSLS-II} = 0.3\ W$$

NSLS-II Stripline



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

W. Cheng & B. Kosciuk

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

Stripline Beam Impedance

A. Blednykh, W. Cheng, S. Krinsky, “Stripline Beam Impedance” BNL, NSLS-II Tech. Note, 2012

- Longitudinal Beam Impedance

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

$g_{\parallel}$ – *longitudinal geometric factor*, $Z_{ch,\parallel}$ – *longitudinal characteristic impedance*, L – *longitudinal length of electrodes*

- Transverse Beam Impedance

$$Z_{\perp}(k) = (g_{\perp}^2 Z_{ch,\perp}/kb^2)[\sin^2(kL) + j\sin(kL)\cos(kL)]$$

$g_{\perp}$ – *transverse geometric factor*, $Z_{ch,\perp}$ – *transverse characteristic impedance*, k – *wave number*
b – *distance between the beam axis and the electrodes*

- Lambertson’s Definition of Shunt Impedances for Stripline

D.A. Goldberg and G.R. Lambertson, “Dynamic Devices: A Primer on Pickups and Kickers,” LBL-31664, 1991

$$R_{sh,\parallel} = 2Z_L g_{\parallel}^2 \sin^2\Theta \quad (8.11)$$

Z_L – *characteristic impedance of a single electrode*

$Z_{ch,\parallel} = Z_L/2$ – *For two electrodes*

$$R_{sh,\perp} = 2Z_{L,\perp}\left(g_{\perp}\frac{2}{k_B h}\right)^2 \sin^2\Theta \quad (8.17)$$

$Z_{ch,\perp} = Z_{L,\perp}/2$ – *For two electrodes*

$h = 2b$

$R_{sh,\perp} \to \Omega$

- Relation Between Beam & Shunt Impedances

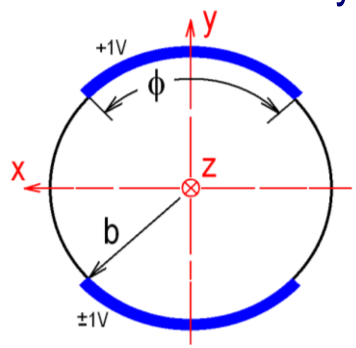
$$\mathrm{Re}\, Z_{\parallel}(k) = R_{sh,\parallel}/4 \qquad \mathrm{Re}\, Z_{\perp}(k) = R_{sh,\perp} \times k/4$$

$$Z_{\parallel} = R_{sh,\parallel}/4 \quad (8.21)$$ G.R. Lambertson

Characteristic Impedances and Geometric Factors

- Simplified Geometries (Analytically)
- POISSON Code (Numerically)

Circular Geometry



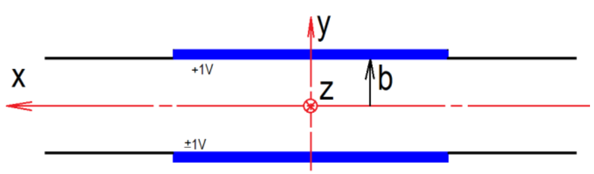
Longitudinal

$$g_{||} = \frac{\phi}{\pi}$$

Transverse

$$g_{\perp} = \frac{4}{\pi} sin \frac{\phi}{2}$$

Rectangular Geometry



Longitudinal

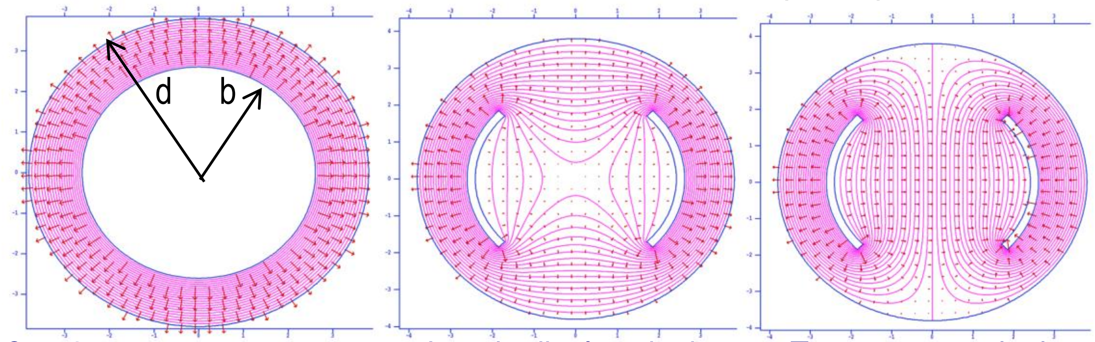
$$g_{||} = \frac{2}{\pi} tan^{-1} \left(sinh \frac{\pi a}{2b} \right)$$

Transverse

$$g_{\perp} = tanh \frac{\pi a}{2b}$$

G.R. Lambertson

b=26.1mm & d=38mm $\phi = \pi/2$



Coaxial:

$$Z_{ch}^{CXL} = \frac{Z_0}{2\pi} Log(d/b)$$

Longitudinal excitation

+1V

Transverse excitation

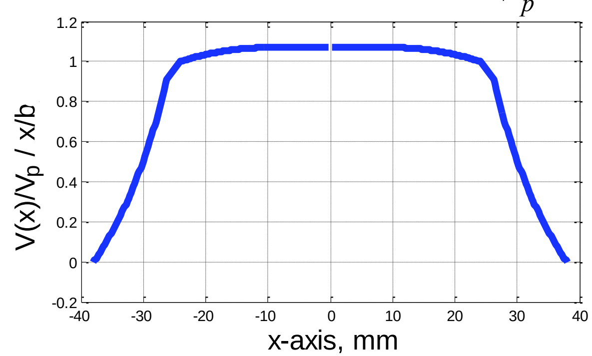
±1V

Characteristic Impedance

$$Z_{ch} = \frac{1}{cC}$$

Capacitance of Stripline

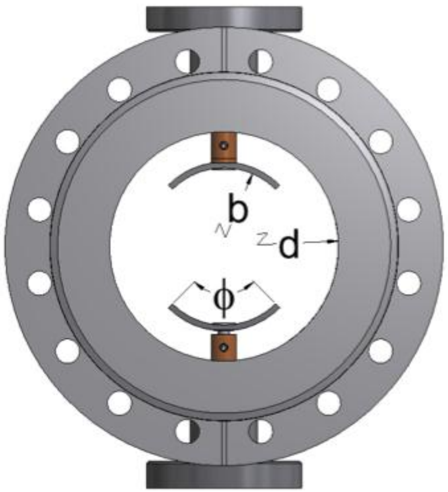
$$C = \frac{2W_e}{V_p^2}$$



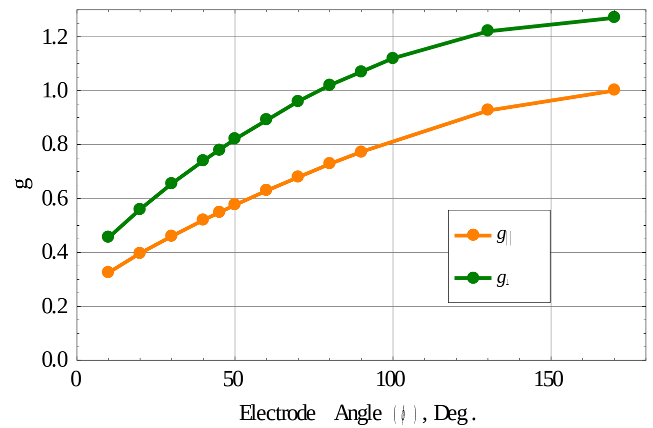
The ratio of beam to electrode voltages $V(x)/V_p$ divided by x/b. For x~0, $g_{\perp}$=1.1

Numerically Calculated "g" & "Z_{ch}"

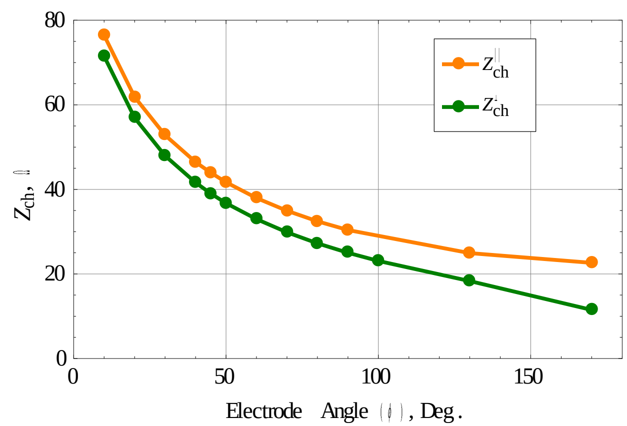
- Circular Geometry With Two Electrodes Inside



b_{min}=26.1mm & d=38mm



Geometric Factor

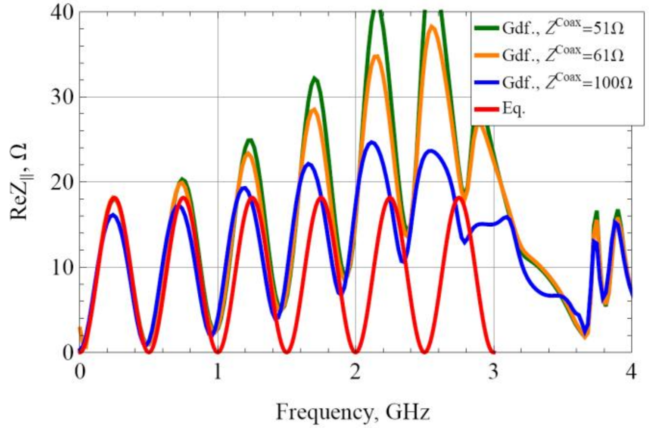


Characteristic Impedance

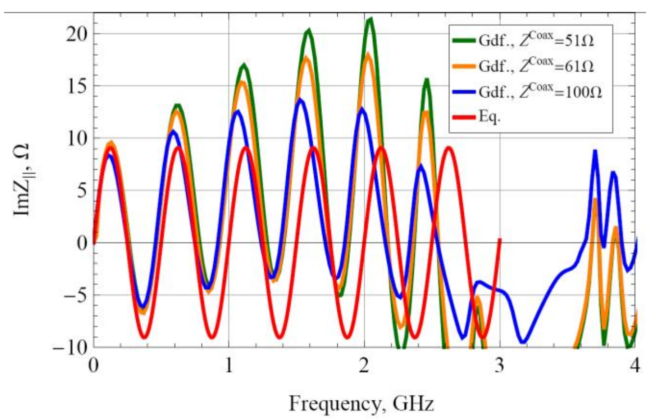
Beam Impedance At Low Frequencies ($\phi=\pi/2$)

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

$$ReZ_{||}(k) = g_{||}^2 Z_{ch,||} sin^2(kL)$$

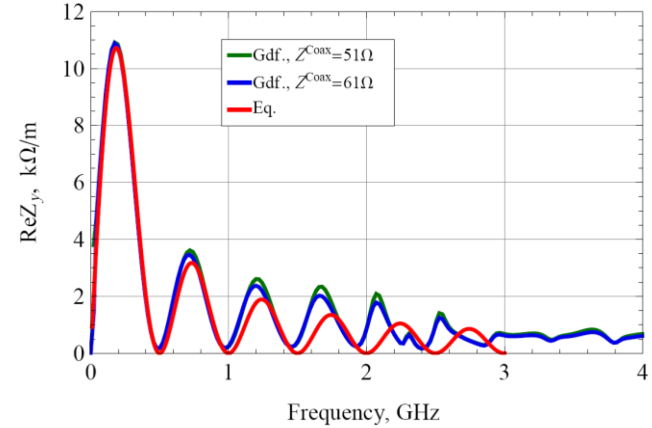


$$\mathrm{Im}\, Z_{||}(k) = g_{||}^2 Z_{ch,||} \sin(kL)\cos(kL)$$

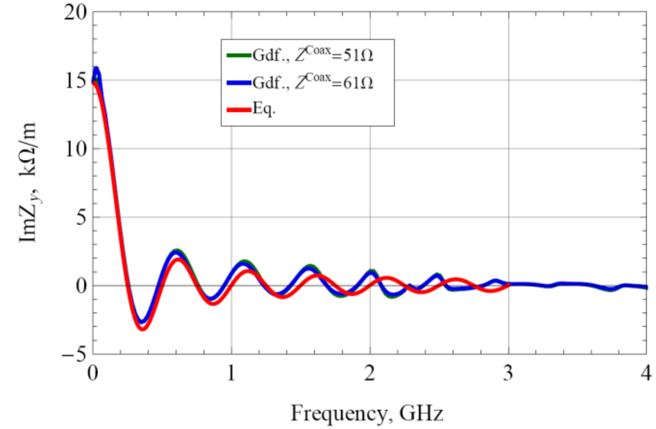


Transverse Impedance ($g_{\perp} = 1.1$ & $Z_{ch,\perp} = 25\Omega$)

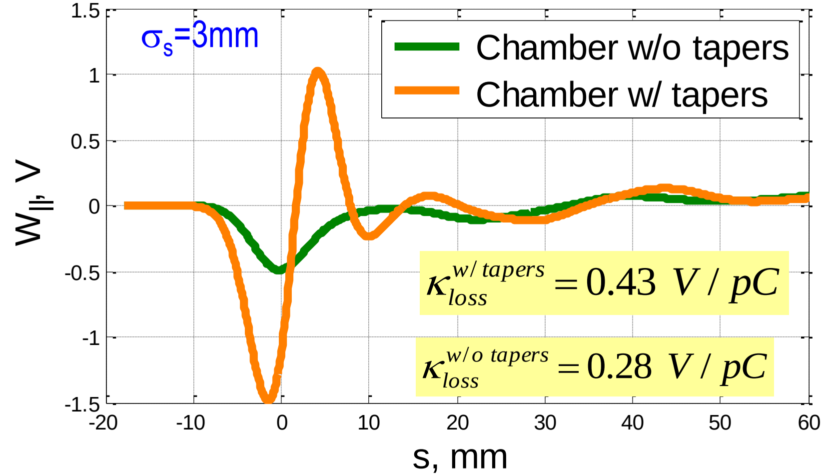
$$ReZ_{\perp}(k) = \left(g_{\perp}^2 Z_{ch,\perp}/kb^2\right) sin^2(kL)$$



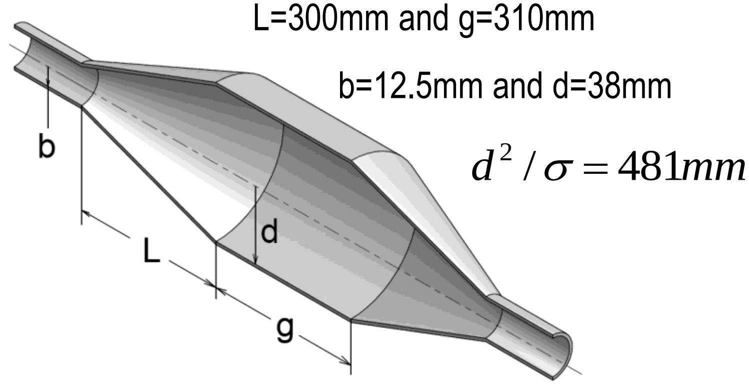
$$ImZ_{\perp}(k) = \left(g_{\perp}^2 Z_{ch,\perp}/kb^2\right) sin(kL)\cos(kL)$$



Tapered Cavity



Longitudinal Short-Range Wakepotential



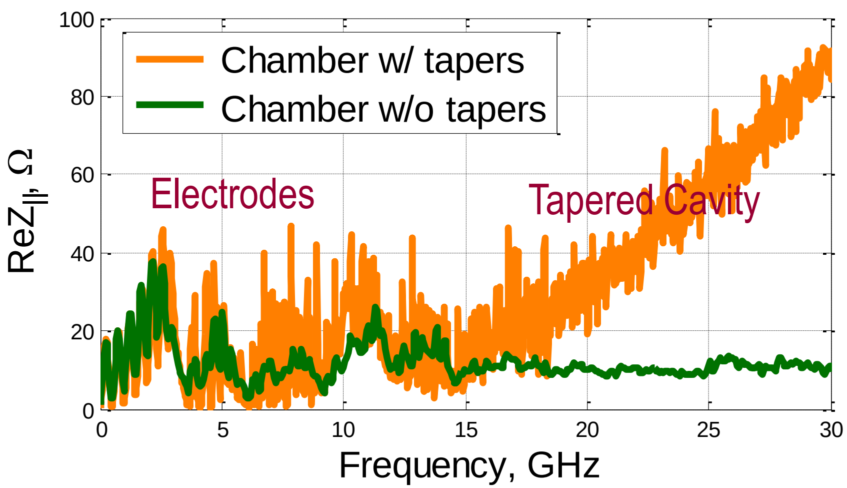
- ECHO code: $\kappa_{loss} = 0.16\,V/pC$
- Tapered Cavity with

$$g > d^2/\sigma \quad and \quad d - b > b$$

$$\kappa_{\text{loss}} \approx \frac{2}{\sqrt{\pi}} \frac{\log(d/b)}{\sigma} \left[\frac{2}{\pi} \arctan\left(\frac{0.2 d^2}{\sigma L} \right) \right]^2$$

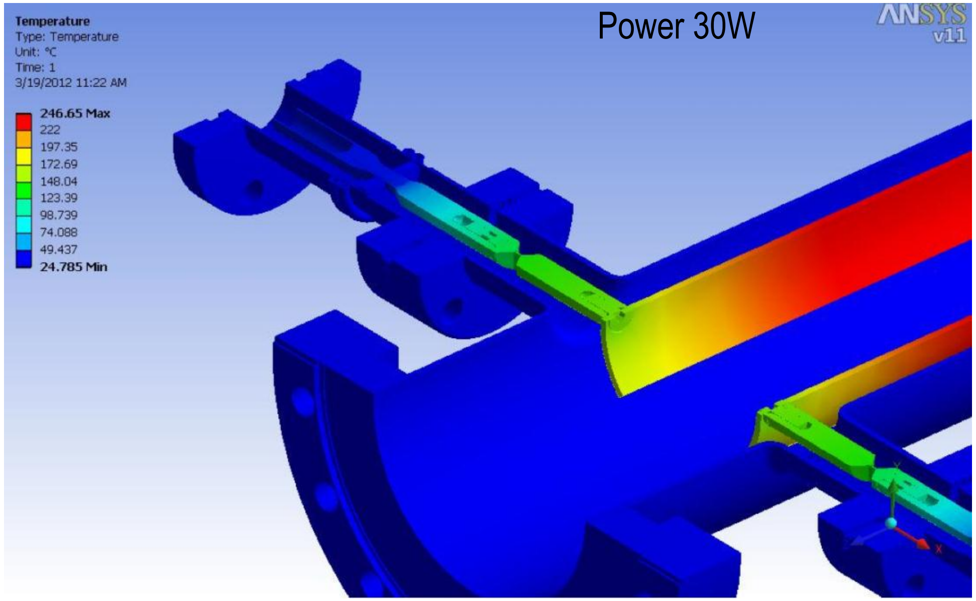
A. Blednykh & S. Krinsky, PRSTAB 2010

$$\kappa_{loss} = 0.15\,V/pC$$



Real Part of the Longitudinal Impedance

Temperature Distribution (ANSYS)



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

B. Kosciuk

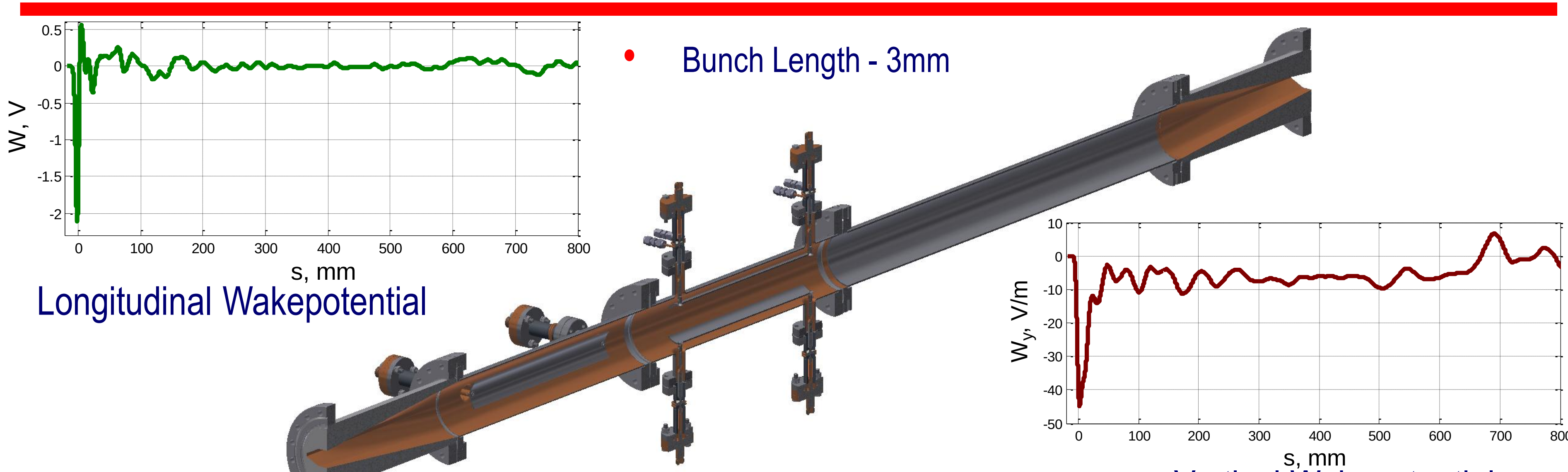
Geometric Loss Factor:

- k_{loss}=0.38V/pC (Two Electrodes) -> 4.5mm bunch length
- k_{loss}=0.15V/pC (Two Electrodes) -> 9mm bunch length

Loss Power:

- P_{loss}=30W per electrode @ 300mA in 1080 bunches
- P_{loss}=44W per electrode @ 500mA in 1080 bunches

NSLS-II Diagnostic Straight Section

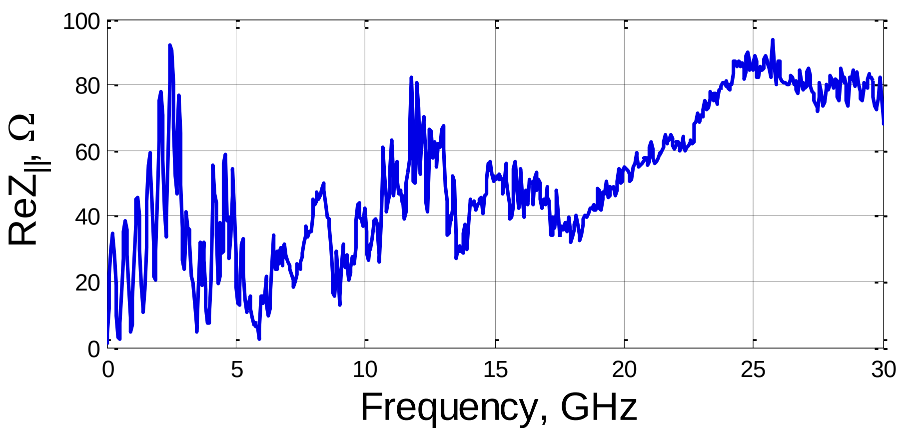


Longitudinal Wakepotential

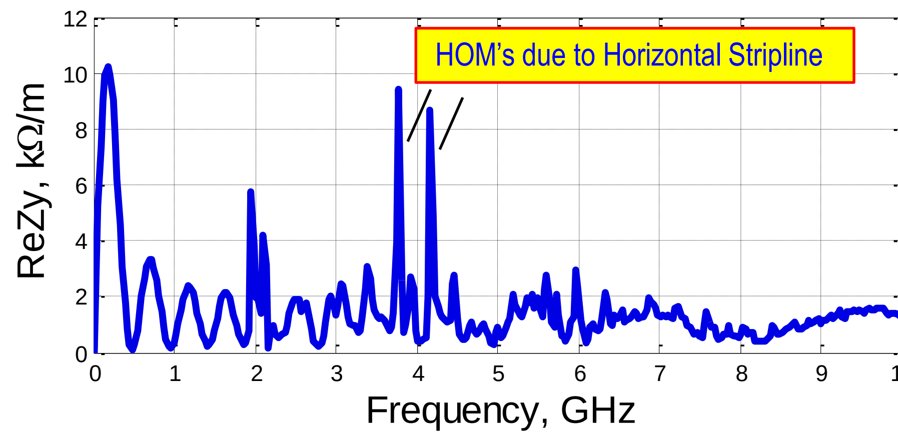
- Bunch Length - 3mm

Diagnostic Straight Section (Cell 16)

Vertical Wakepotential



Longitudinal Narrow-Band Impedance



Vertical Narrow-Band Impedance

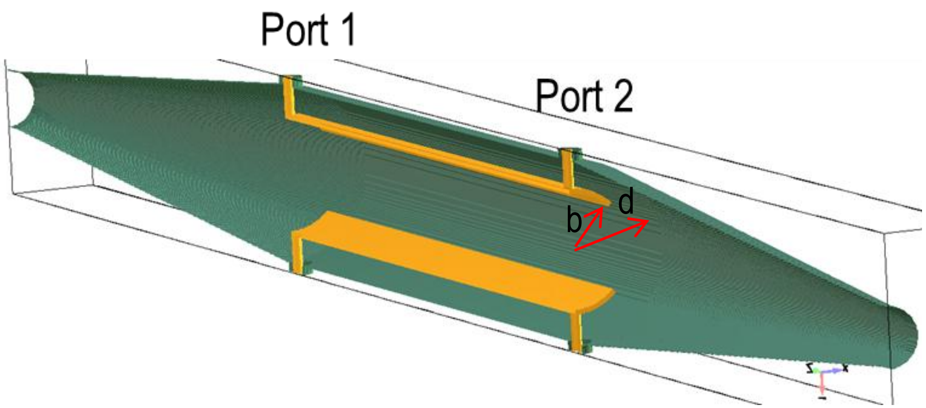
Summary

- RF shielding of the NSLS-II Bellows has been well adapted for the octagonal shape of the NSLS-II vacuum chamber.
- NSLS-II Bellows passed beam-test in the APS storage ring at high current without damages and deteriorations. The next step is temperature measurements in the NSLS-II storage ring under beam condition.
- Successful Implementation of RF Shielding for Large Aperture BPM Assemblies.
- Stripline Heating Concern. Close monitoring of temperature rise using outside-body thermocouples. Designed water-cooled feedthrough.

- Back-Up Slides

Comparison of Two Striplines

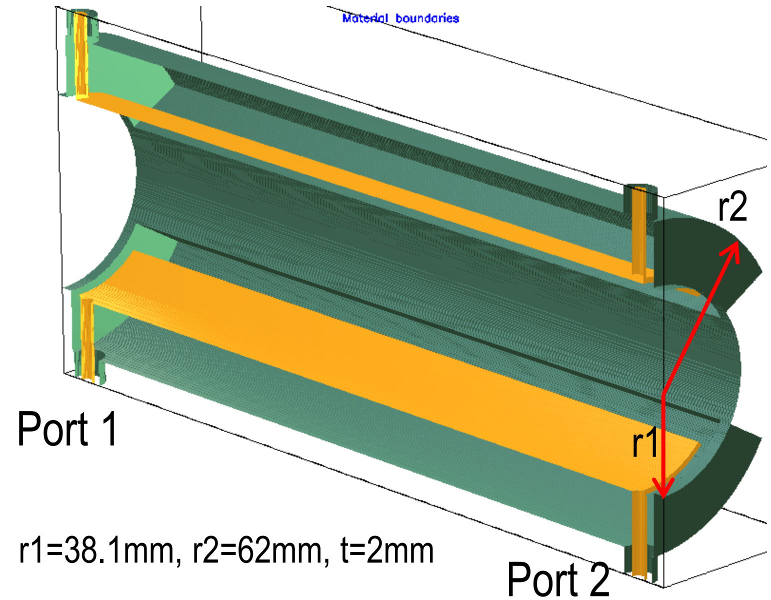
Option A



Electrode: $\phi=\pi/2$, b=24.1mm, d=26.1mm, L=300mm

Port: r3=3mm, r4=7mm

Option B



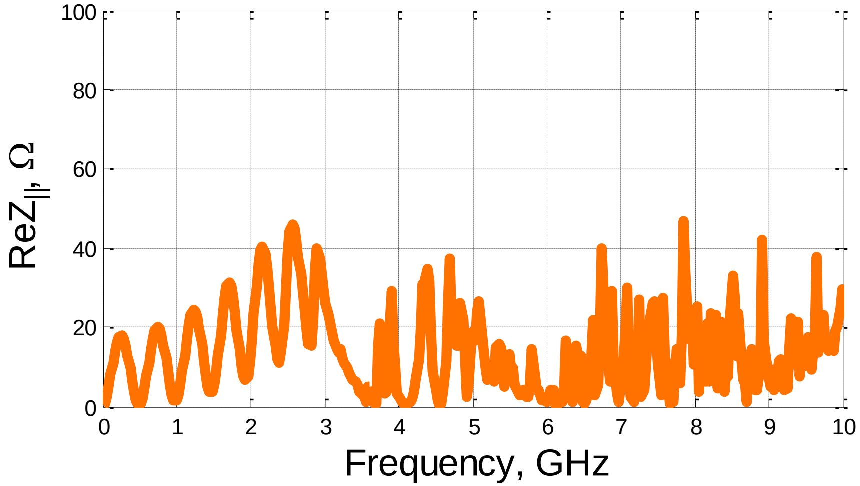
r1=38.1mm, r2=62mm, t=2mm

- Calculated w/o Tapered Transition

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

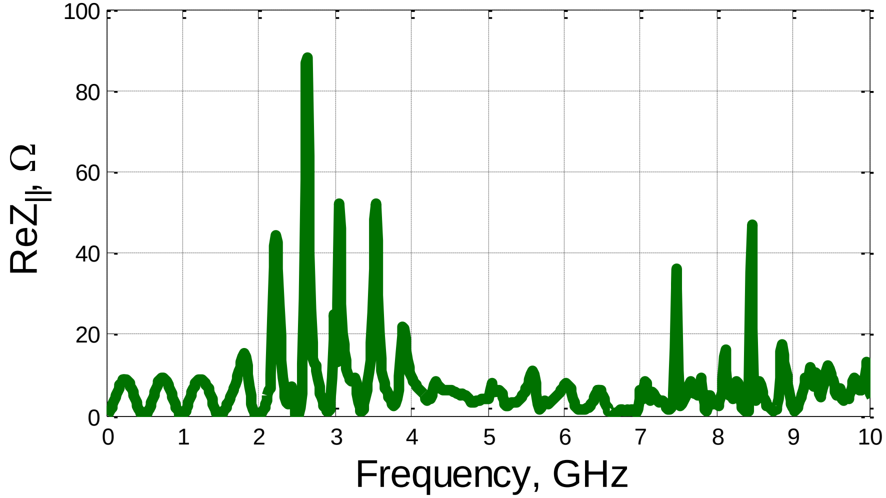
Narrow-Band Impedance

Option A



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

Option B



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