Shielded and Unshielded Bellows
- Brief Review –
and some Numerical Analyses for so-called Low Impedance Bellows
(Status Oct. 2019)

F. Marhauser

U.S. DEPARTMENT OF ENERGY
JSA
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Bellows in High Current Machines

- Main problematic:
- Bellows convolutions will generate wakefields → impedance
- Not only degrades emittance, but will generate heat in thin walls
- Synchrotron radiation (or stray electrons) can damage bellows
- Storage rings usually employ **shielded bellows** to mitigate these issues
- Many designs use RF sliding fingers to shield wakefields from bellows convolutions
- One argument made against those designs, and when bellows are adjacent to SRF cryomodules/cavities, is that sliding contacts create particulates
  → major issue when particulates drift into SRF cavities
- Therefore the concept of **unshielded 'low impedance' bellows** was conceived several years ago, e.g. for APS Short Pulse X-ray (SPX) cryomodule

Bellows Impedance

Table 1: Loss factor comparison for a 3mm Gaussian bunch.

Bellows	κ_{loss}, mV/pC	
	Nominal	Offset 2mm
APS	64	-
SOLEIL	20	86
SPEAR3	67	-
NSLS-II	18	37

Note: Fingers in nominal position

PAC 2009

Impedance Calculations for the NSLS-II Storage Ring

A. Blednykh, M. Ferreira, S. Krinsky

Brookhaven National Laboratory, Upton, NY 11973-5000, USA

Large number of RF fingers, small transition angle inside bellows

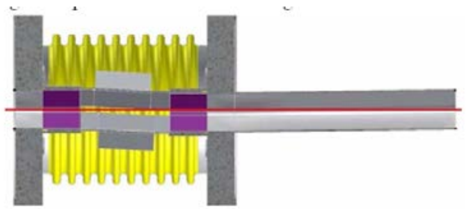


Figure 2: RF shielded bellows with a 2mm vertical offset.

IPAC 2012

Table 1: Comparison of Bellows in Storage Ring Accelerator Installations [1]

Accelerator	Bunch length [mm]	Kloss factor[mV/pC]	Bellows type
APS	3	64	shielded
SOLEIL	3	20	shielded
SPEAR3	3	67	shielded
NSLS-II	3	18	shielded
APS-SPX	3	455	unshielded
APS-SPX	10	1.517	unshielded

APS-SPX 'unshielded' bellows added

LOW IMPEDANCE BELLOWS FOR HIGH-CURRENT BEAM OPERATIONS*

G. Wu[1#], R. Rimmer[2], J. Feingold[2], H. Wang[2], J. Mammosser[2], G. Waldschmidt[1], A. Nassiri[1], J. H. Jang[3], S.H. Kim[3], K-J. Kim[1], and Y. Yang[4]
[1]ANL, Argonne, IL 60439, USA
[2]Jefferson Laboratory, Newport News, VA 23606, USA
[3]Pohang University of Science and Technology, Pohang, Korea
[4]Tsinghua University, Beijing 100084, China

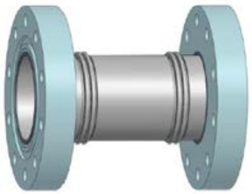


Figure 2: An unshielded bellows planned for use in the SPX cryomodule.

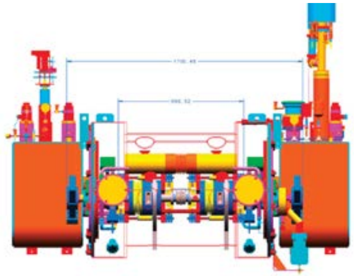


Figure 1: Front view of a shortened SPX cryomodule showing two deflecting cavities connected by a bellows. Transitional bellows at the ends of cryomodules are not shown.

Shielded Bellows

SPEAR 3 CDR, 1999

Shielded Bellows

Each straight section has a bellows module to allow for longitudinal expansion of the chamber. In order to minimize impedance, RF fingers will shield the bellows corrugations. To minimize interruption of the image current, the shields will be constructed of closely-spaced longitudinal strips. Each bellows assembly will have an inductance of 73 pH and a loss factor of 1.07×10^{-2} V/pC.

$\sigma_z = 4.9$ mm (10.7 mV/pC)

SOLEIL

Could not find any reference online
(citation link in paper is not working anymore)

EPAC 2006

FIRST RESULTS OF THE COMMISSIONING OF SOLEIL STORAGE RING

A Few Machine Physics Studies Results

The single turn capability of the BPMs has been very helpful during this early commissioning part. In addition to the very successful first turn correction, one of these BPMs revealed via a significant decrease of the intensity (sum signal) a suspicion of an obstacle in the machine. Systematic orbit bumps were then performed in order to locate precisely this obstacle. The machine was then opened around the indicated location and a distorted bellows RF finger was found.

NSLS-II

PAC2009

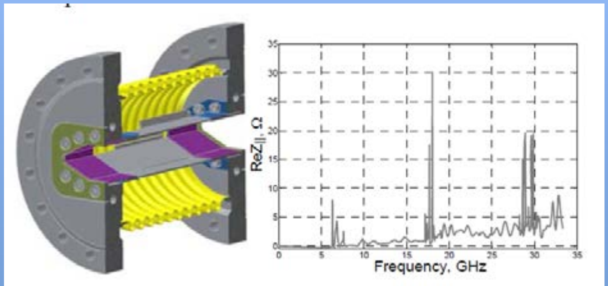


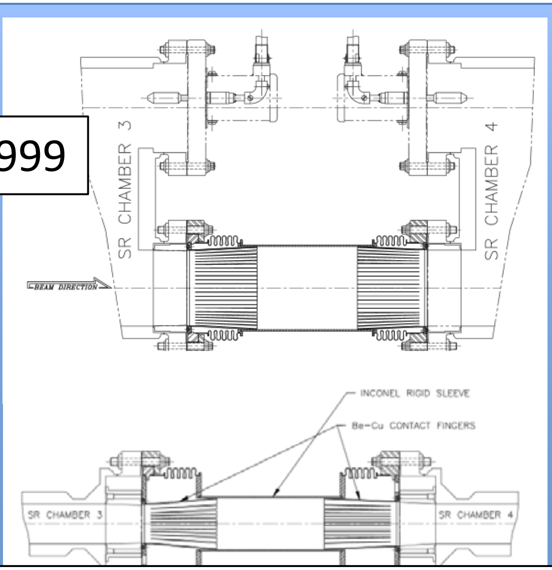
Figure 1: The NSLS-II RF shielded bellows.

Impedance optimization done considering

1) Location of the slots and their geometric dimensions
2) Generation of HOMs inside the bellows due to slots between RF metal and fingers
3) Vertical offset of RF spring fingers

APS

PAC1999



0.036" (0.91 mm) fingers made from quarter-hard Be-Cu sheets by wire EDM

Shielded Bellows

DAPHNE, EPAC 1999

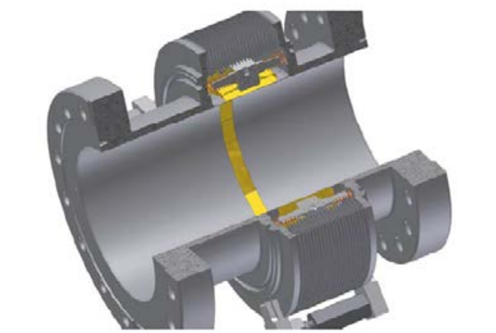


Figure 1: Section view of the RF shielded bellows (not cooled).

$ID_{b.t.}$ = 88 mm
$ID_{bellows}$ = 130 mm
$OD_{bellows}$ = 160 mm
L = 50 mm

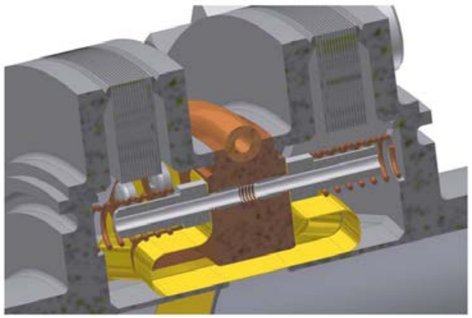


Figure 5: Detailed view of the RF cooled shielding.

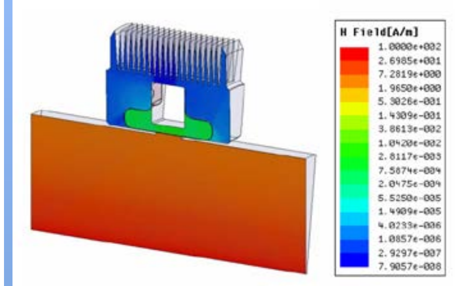


Figure 6: H field excited by the beam in the shielded bellows.

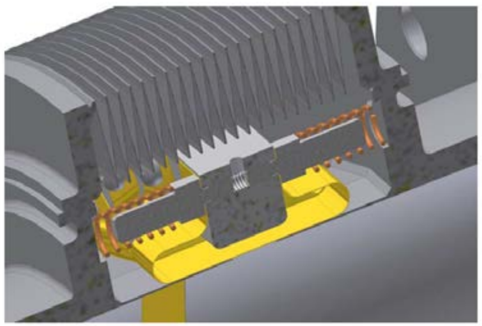


Figure 2: Detailed view of the RF shielding and centering system.

20 omega-shaped 0.15mm Be-Cu shielding strips (gold-coated, 10 um) centered and supported by Aluminum ring with 8 Be-Cu springs

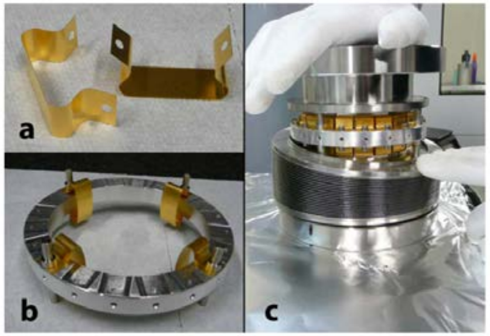


Figure 3: View of gold coated strip (a), supporting annular ring (b), RF shielded bellows assembly (c).

Shielded Bellows

KEKB, 1996

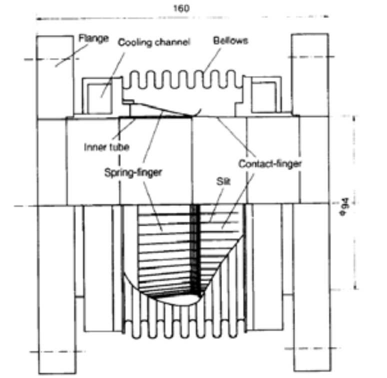


Figure 1. Schematic drawing of the bellows assembly designed for the KEKB.

Finger type RF shield
Expansion/extraction: 20 mm
Lifetime: 10^5 cycles with 1 mm stroke
$ID_{b.t.}$ = 100 mm, L = 160 mm

50 Contact fingers:
0.2 mm Be-Cu (C1720)
5.5 mm width, 0.5 mm gap
Spring fingers:
0.3 mm Be-Cu (C1720),
4.6 mm width, 2.4 mm gap
contact tip coated
With TiN (1 um)

Note: Several bellows near movable masks (collimators) suffered damages from excess heating (11 kW at 1.7 A)
Also: metal dust observed due to abrasion between contact fingers and inner tube of spring fingers

KEKB, PAC 2005

Comb-type vs. finger-type
higher thermal strength
lower impedance

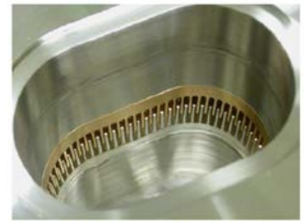


Figure 1: Racetrack bellows chamber with comb-type RF shield.

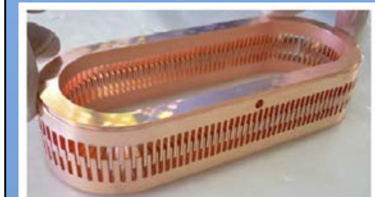


Figure 3: Trial model of racetrack comb-type RF shield without back fingers.

Racetrack bellows for IR region
W x H = 150 mm x 50 mm

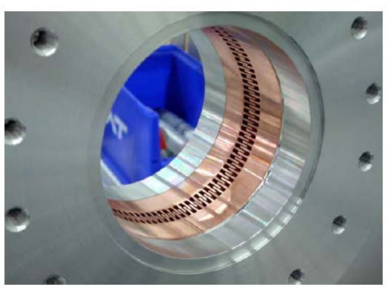


Figure 4: Comb-type RF shield for gate valve.

Circular bellows for movable mask
Comb-type RF shield
RF shield made from copper (C101
Flanges are made from SS316
$ID_{b.t.}$ = 94 mm, L = 160 mm

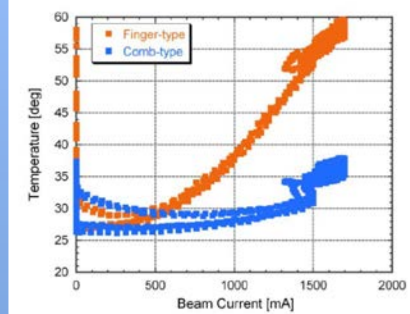


Figure 2: Average temperatures of corrugations of four bellows with comb-type and finger-type RF shield. The data include those during several beam injection cycles.

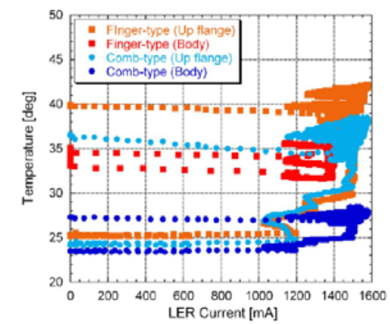


Figure 5: Temperatures at connection flange and body of gate valves with comb-type and finger-type RF shield. The data include those during several beam injection cycles. Small decreases of temperatures at low beam currents are due to the large heat capacity of gate valve.

Comb-type RF shield for gate valve
RF shield made from copper (C1011)
Flanges are made from SS316
$ID_{b.t.}$ = 94 mm, L = 95 mm

Shielded Bellows

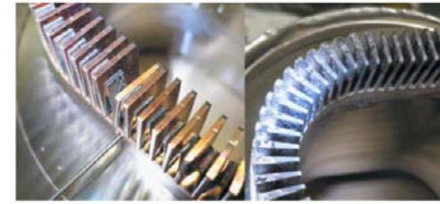


FIG. 7. Damage of teeth of the Comb-Ver.1. The teeth were slightly bent in order to check between them.

KEKB, PAC 2007

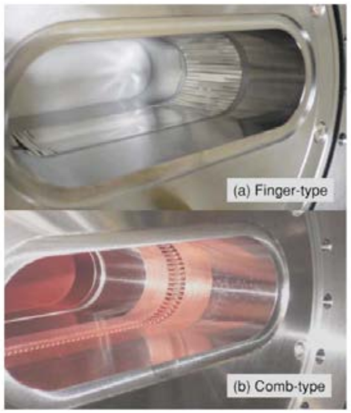


FIG. 11. Inside views of a racetrack gate valve with (a) a finger-type rf shield and (b) Comb-Ver.2.

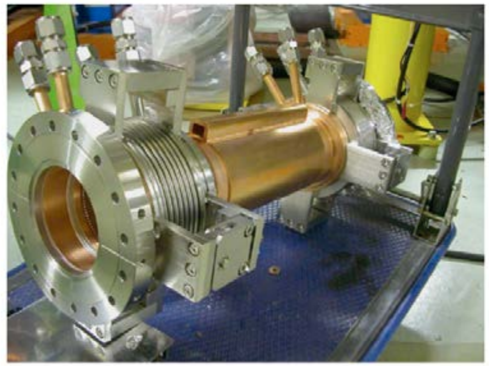


FIG. 4. Universal bellow chamber for a movable mask of KEKB LER.

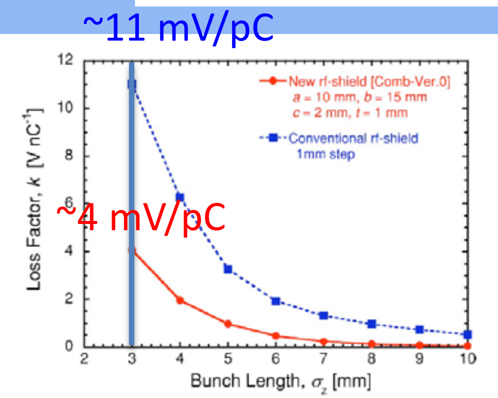


FIG. 3. Calculated loss factors for a typical comb-type rf shield (Comb-Ver.0) and a conventional finger-type rf shield.

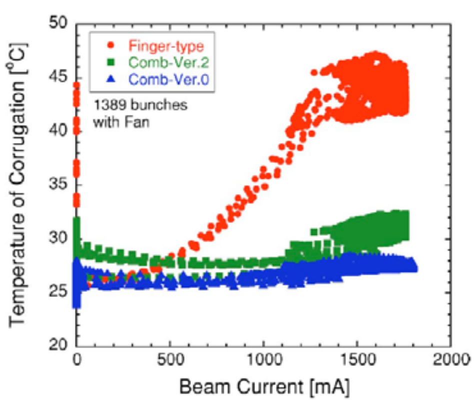


FIG. 8. Temperatures of corrugations of bellow chambers with a finger-type rf shield, Comb-Ver.2 and Comb-Ver.0 during beam operation.

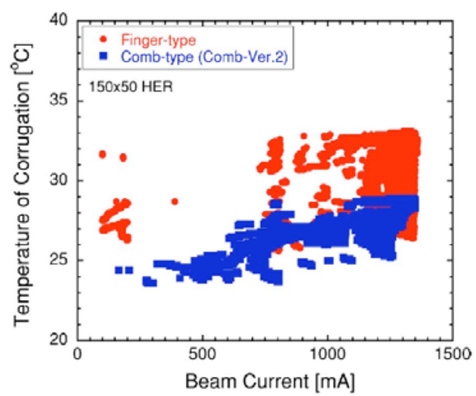


FIG. 12. Temperatures of bodies of a racetrack gate valve with a finger-type rf shield and that with Comb-Ver.2 during beam operation.

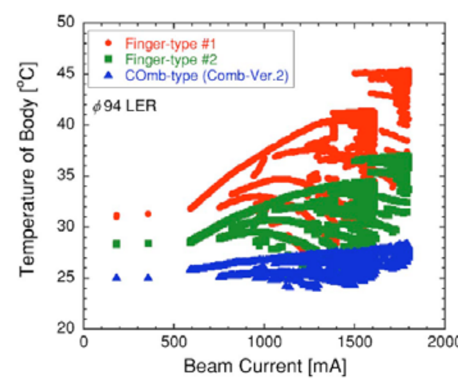


FIG. 10. Temperatures of bodies of two gate valves with a finger-type rf shield and that with Comb-Ver.2 during beam operation. Two gate valves, 1 and 2, are located under a similar condition.

Shielded Bellows

SLAC-PUB-95-6992, 1995

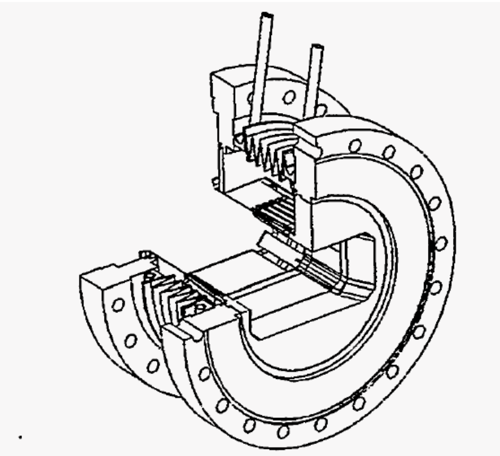


Figure 2: Bellows Module, Cut Away

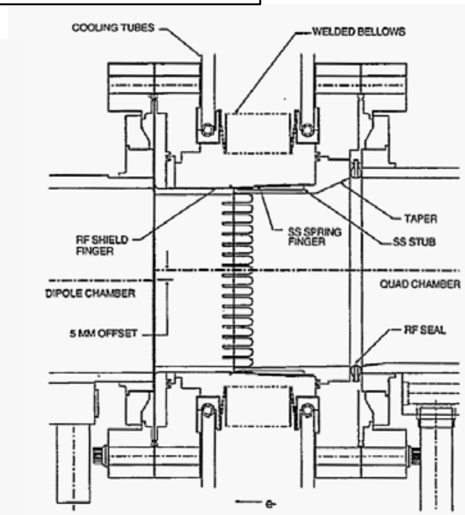
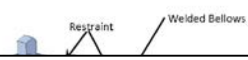


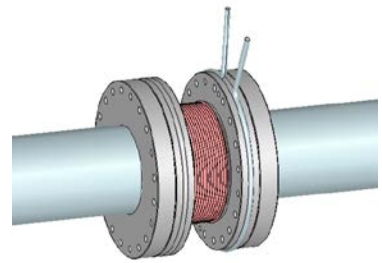
Figure 3: Plan View Cross-Section of Bellows Module

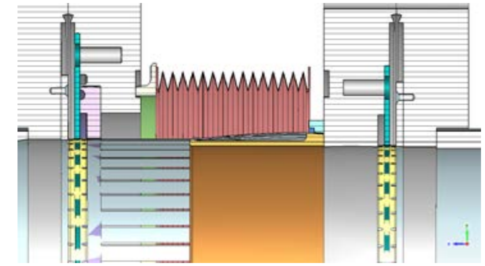
Alexander Novokhatski

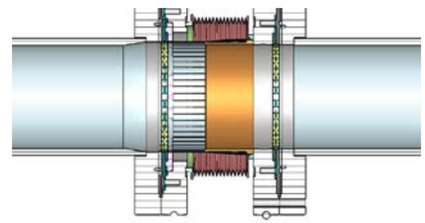
SLAC National Accelerator Laboratory

HOM absorber for IR of PEP-II









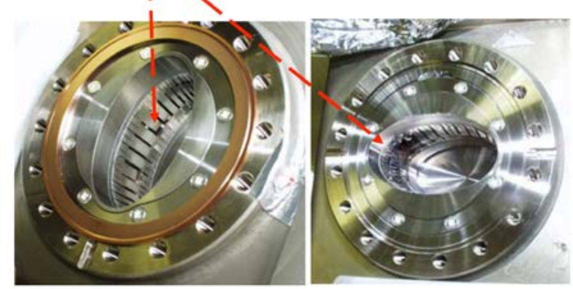
PEP-II Type shielded bellows
with round beam pipes
(engineering model from R. Lassiter, M. Wiseman)

Finger type RF shield
Expansion/extraction: 20 mm
Lifetime: 10^5 cycles with 1 mm stroke
$ID_{b.t.}$ = 100 mm, L = 160 mm

50 Contact fingers:
0.2 mm AL-15 GlidCop (x2 higher thermal conductivity than Be-Cu)
4 mm width

Wake fields discharge in shielded fingers of vacuum valves

- Shielded fingers of some vacuum valves were destroyed by breakdowns of intensive HOMs excited in the valve cavity.



Shielded Bellows

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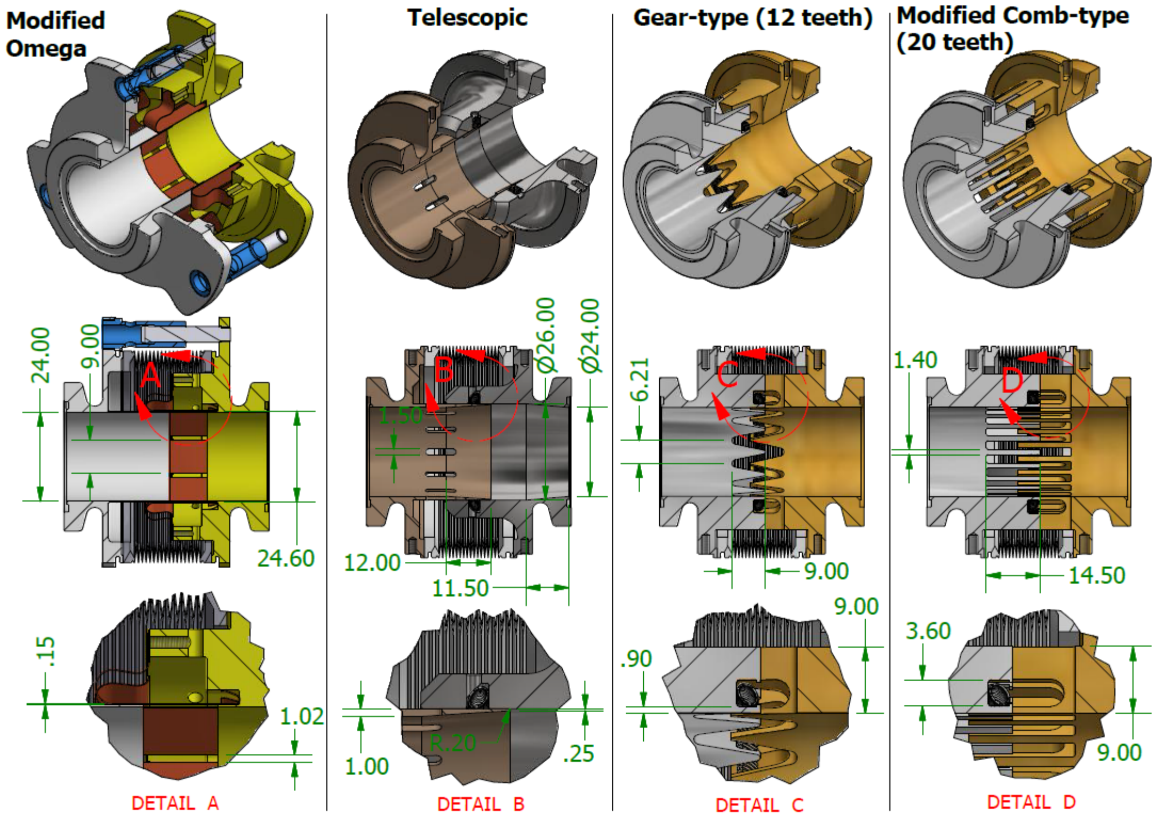
DESIGN REVIEW OF BELLOWS RF-SHIELDING TYPES AND NEW CONCEPTS FOR SIRIUS

H. O. C. Duarte*, R. M. Seraphim, T. M. Rocha, A. R. D. Rodrigues, P. P. S. Freitas
Brazilian Synchrotron Light Laboratory (LNLS), Campinas, Brazil

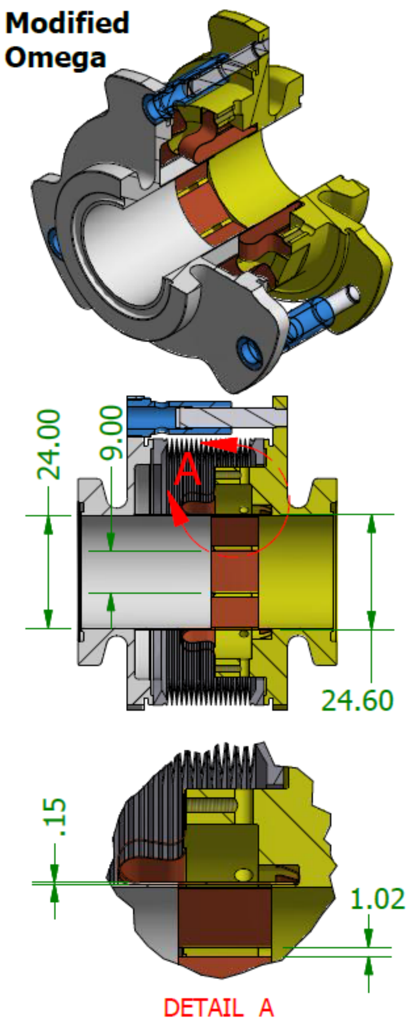


(1) <u>gap-independent</u>:
Designs that demand radial change in chamber profile, whose longitudinal gap variation does not strongly affect wakefields

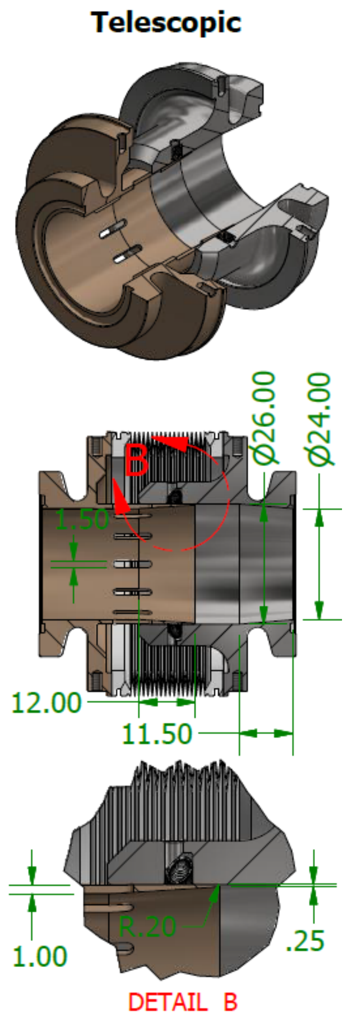
(2) ‘<u>gap-dependent</u>’:
Designs that do not demand radial changes except in a high capacitance gap, whose longitudinal variation strongly affects the wakefields

(2) Based on KEK design

Gap-Independent Designs



Be-Cu alloy strips



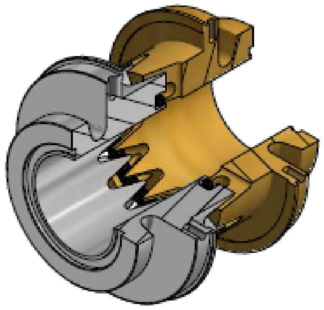
Silver-plated spring

based on Daphne design,
8 Be-Cu alloy strips
→ TEST done: difficulty to keep evenly distributed contact, and mainly with lateral displacement,
strip thermal resistance to softening with standard Be-Cu alloys was not satisfactory for bake-out cycles over machine lifetime

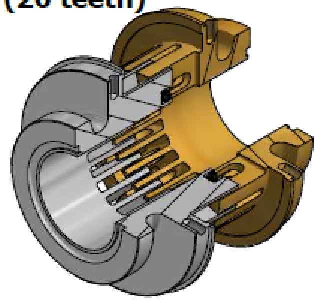
Silver-plated, lodged coil springs for axisymmetric electric contact

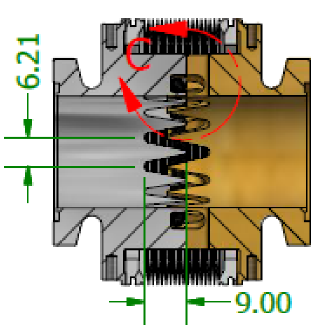
Gap-Dependent Designs

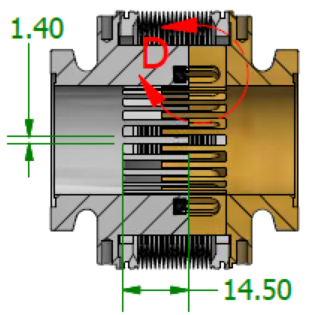
Gear-type (12 teeth)

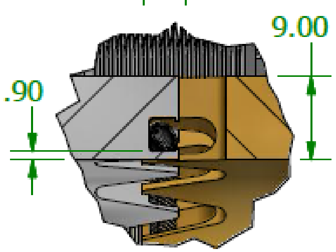


Modified Comb-type (20 teeth)

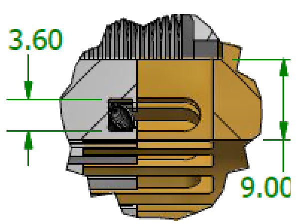








DETAIL C



DETAIL D

Spec.: 0.5 mm lateral gap between neighboring teeth, when fully compressed, spring-coil in an axisymmetric groove at tip of teeth provides electrical contact, opposite teeth have sliding groove almost along entire length

→ Shielding proved effective

→ 12 teeth provided good compromise between mechanical and electromagnetic aspects, but limited compression (requirement 9 mm)

→ 20 teeth no longer feasible with gear-type design with longer fingers

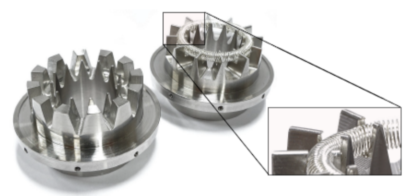


Figure 4: Gear-type bellows prototype: slider (left) and holder (right) parts, with the lodged coil spring in detail.

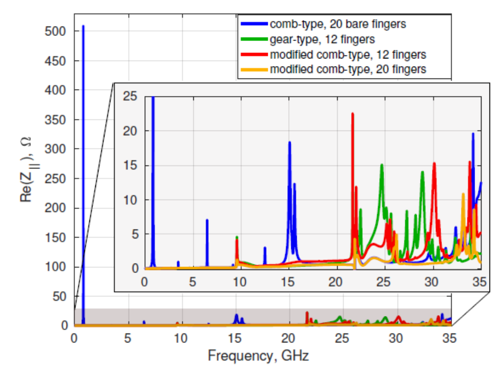


Figure 3: Real part of longitudinal impedance comparison between the studied gap-dependent designs with 9 mm long teeth and 6 mm longitudinal gap.

Jefferson Lab

Preference for Sirius Ring/Brazil

Choice: Telescopic bellows

Downside:

1) Tight fitting tolerances required to prevent locking of movement when subject to radial forces

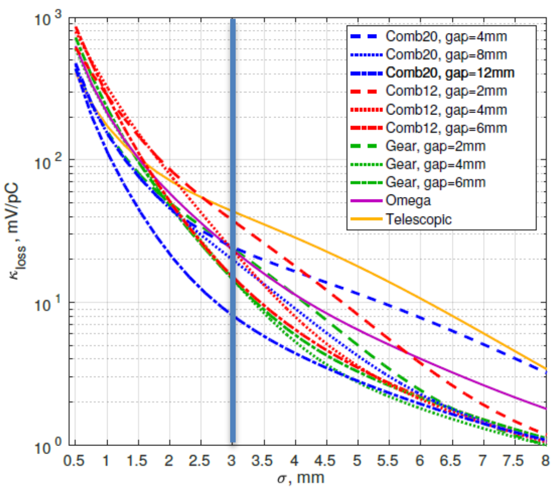
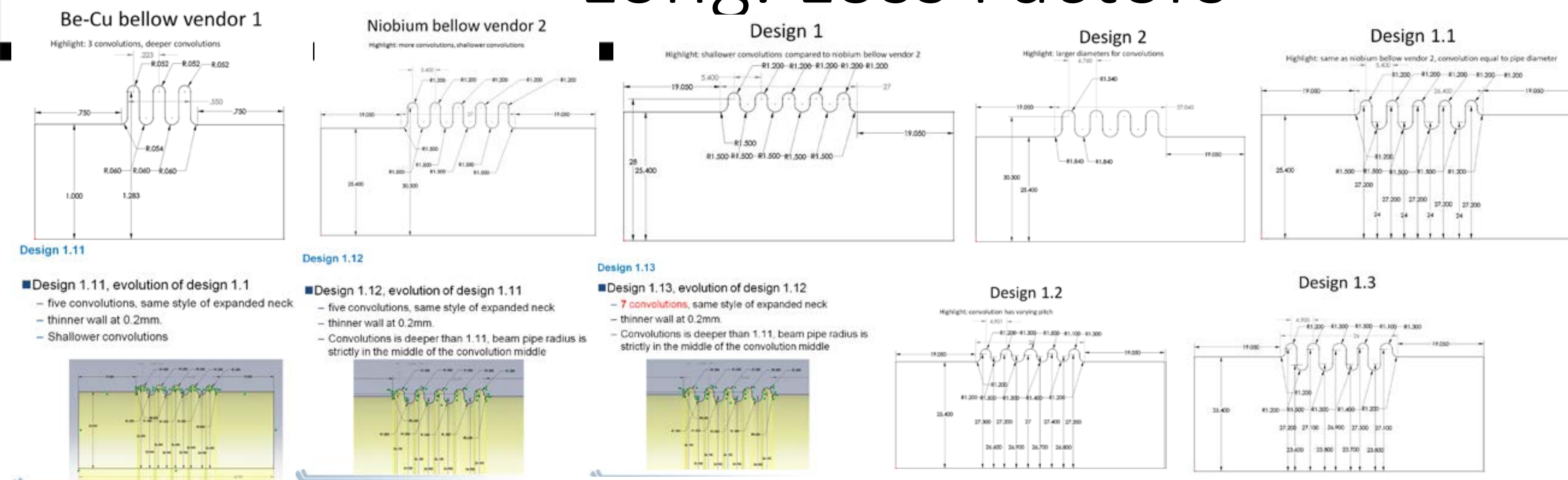


Table 1: Qualitative Comparison between the Four considered Designs from Fig. 1 in Terms of Mechanical Aspects

Mechanical Aspect	**Modif. Omega**	**Telesc.**	**Gear**	**Modif. Comb**
Fabrication complexity	+++	+++	++++	+++++
Assembly difficulty	++++	+	++	++
Est. Cost	+++	++	+++	++++
Bake-out resilience	++	+++	+++	+++
Ext. limiter requirement	++++	+	+++	+++
Design complexity	+++	++	+++	+++
Manuf. tol.	+++	++++	+++	+++

Long. Loss Factors

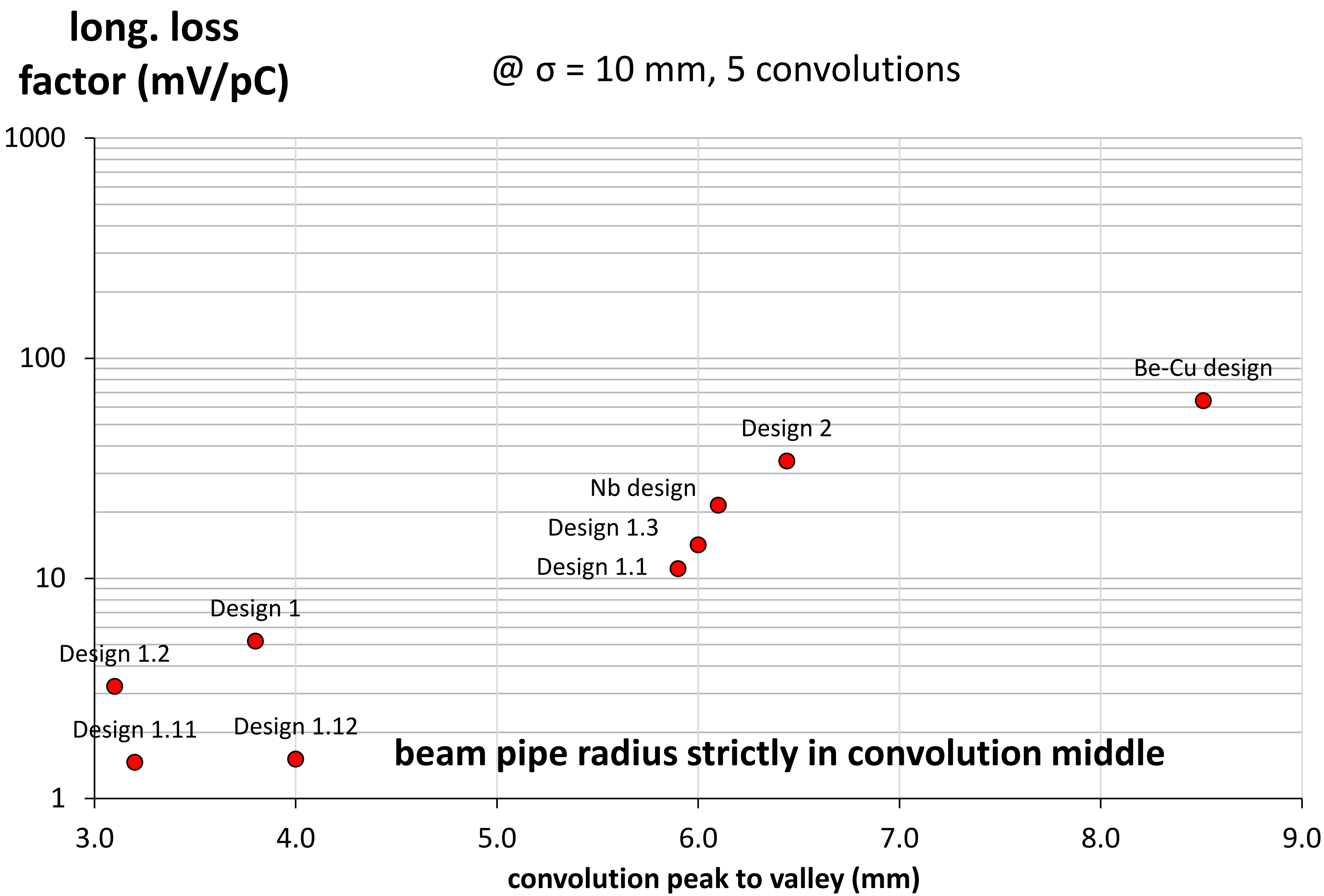


Machine	Bellows type	Beam tube radius (mm)	Bunch length (mm)	Convolution peak to valley (mm)	κ_z GdfidL 3D (mV/pC) 2011	κ_z CST 3D (mV/pC) 2011	κ_z ABCI 2D (mV/pC) 2011	κ_z ABCI 2D (mV/pC) Frank 2019
Be-Cu design	unshielded, 3 conv.	25.4	10	8.51	-	33.5		34.7
Nb design	unshielded, 5 conv.	25.4	10	6.1	-	19.8		21.5
Design 1	unshielded, 5 conv.	25.4	10	3.8	6.0	4.2		5.19
Design 2	unshielded, 4 conv.	25.4	10	6.44	27.6	23.7		25.8
Design 1.1	unshielded, 5 conv.	25.4	10	5.9	12.9	5.0		11.07
Design 1.11	unshielded, 5 conv.	25.4	10	3.2	-	-		1.46
Design 1.12	unshielded, 5 conv.	25.4	10	4.0	2.53 ?	-		1.51
	unshielded, 5 conv	25.4	**3**	4.0	436 ?	-		342.8
Design 1.13	ditto, 7 conv.	25.4	10	4.0	4.47 ?	-		2.70
Design 1.2	unshielded, 5 conv.	25.4	10	3.1	4.0	2.9		3.23
Design 1.3	unshielded, 5 conv.	25.4	10	6.0	15.3	8.0		14.2

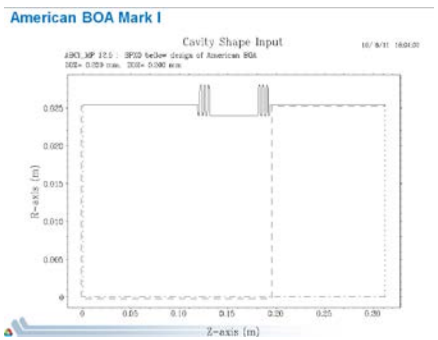
Bellows (PS/GdfidL)
Slides received from Haipeng W
Part of ANL Bellows Developme
2011

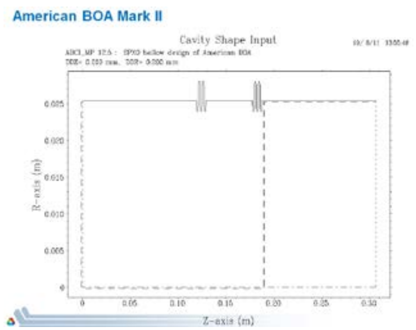
Bellow Design Consideration
Genfa Wu,
SPX mini-workshop, July 2011
Incl. loss factors with from G. W
Feingold

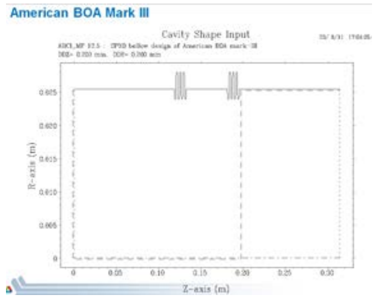
Long. Loss Factors

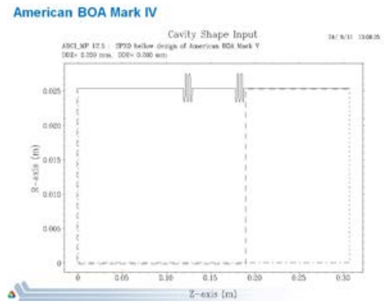


Long. Loss Factors









Bellows Status and Plans
Genfa Wu,
SPX design reviews, August 2011

Machine	Bellows type	Beam tube radius (mm)	Bunch length (mm)	k_z GdfidL 3D (mV/pC)	k_z CST 3D (mV/pC)	k_z ABCI 2D (mV/pC)
APS-SPX (SPX0 American BOA Mark IV)	unshielded, 2 x 2.5 conv.	25.4	10	1.517	-	-
APS-SPX (SPX0 American BOA Mark III)	unshielded ,2 x 3.5 conv.	25.4	10	1.851	-	-
APS-SPX (SPX0 American BOA Mark II)	unshielded, 2 x 2.5 conv.	25.4	10	0.920	-	-
APS-SPX (SPX0 American BOA Mark I)	unshielded ,2 x 3 conv.	25.4	10	4.177	-	-
Design 1.2	unshielded, 5 conv.	25.4	10	1.97	-	-
Design 1.3	unshielded, 5 conv.	25.4	10		-	-

Unshielded 'Low Impedance' Bellows

IPAC 2012

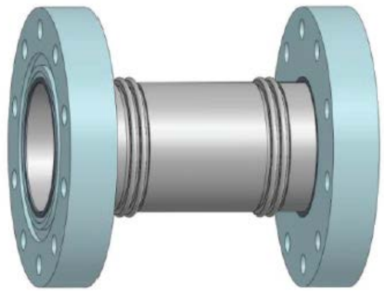


Figure 2: An unshielded bellows planned for use in the SPX cryomodule.

Table 1: Comparison of Bellows in Storage Ring Accelerator Installations [1]

Accelerator	Bunch length [mm]	Kloss factor[mV/pC]	Bellows type
APS	3	64	shielded
SOLEIL	3	20	shielded
SPEAR3	3	67	shielded
NSLS-II	3	18	shielded
APS-SPX	3	455	unshielded
APS-SPX	10	1.517	unshielded

LOW IMPEDANCE BELLOWS FOR HIGH-CURRENT BEAM OPERATIONS*

G. Wu[1#], R. Rimmer[2], J. Feingold[2], H. Wang[2], J. Mammosser[2], G. Waldschmidt[1], A. Nassiri[1], J. H. Jang[3], S.H. Kim[3], K-J. Kim[1], and Y. Yang[4]
[1]ANL, Argonne, IL 60439, USA
[2]Jefferson Laboratory, Newport News, VA 23606, USA
[3]Pohang University of Science and Technology, Pohang, Korea
[4]Tsinghua University, Beijing 100084, China

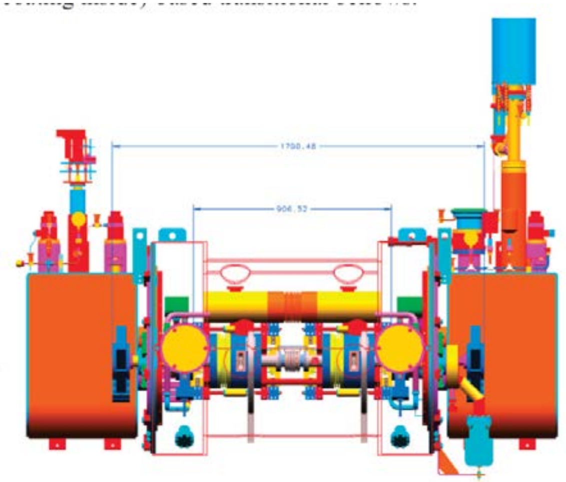
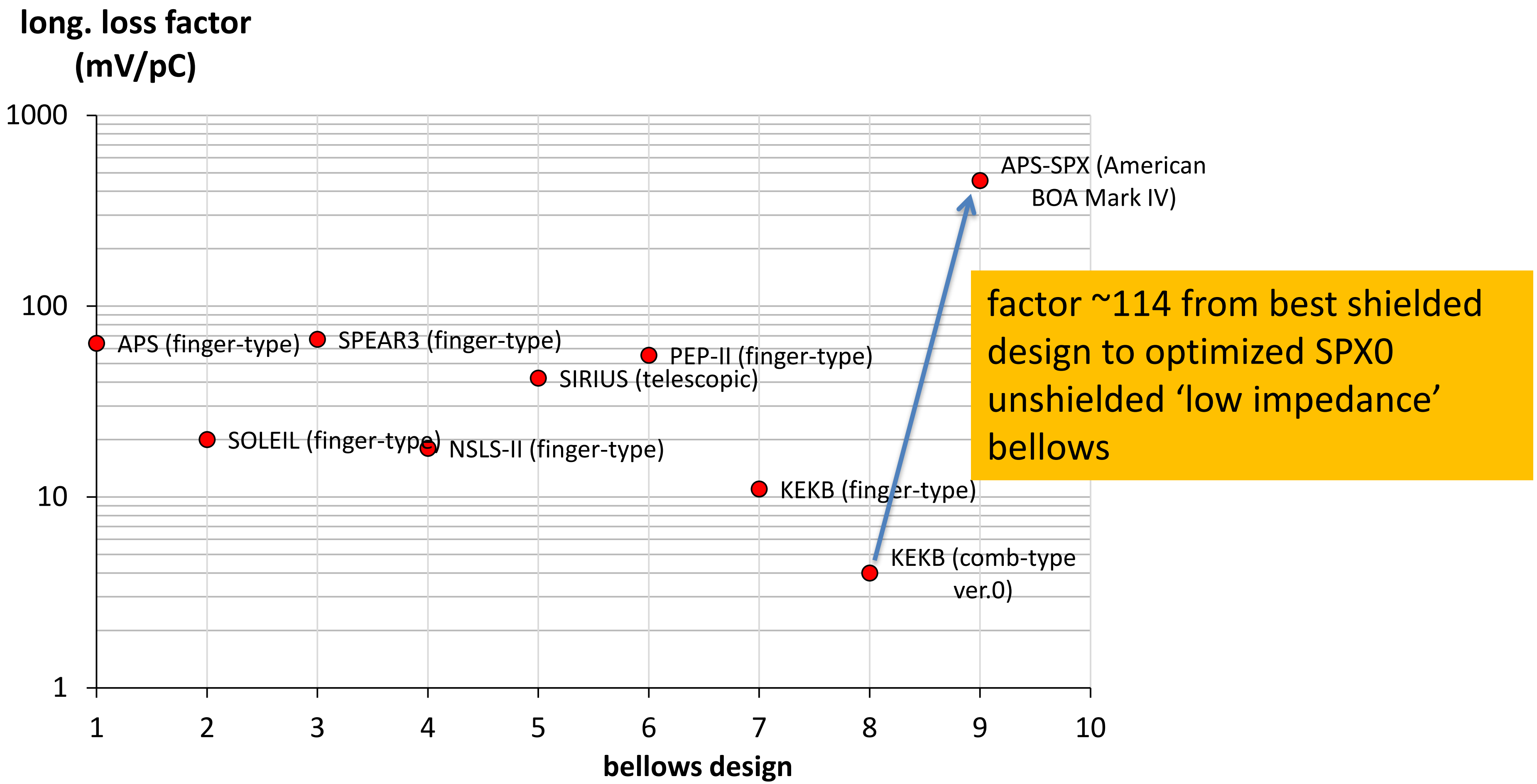


Figure 1: Front view of a shortened SPX cryomodule showing two deflecting cavities connected by a bellows. Transitional bellows at the ends of cryomodules are not shown.

Long. Loss Factors

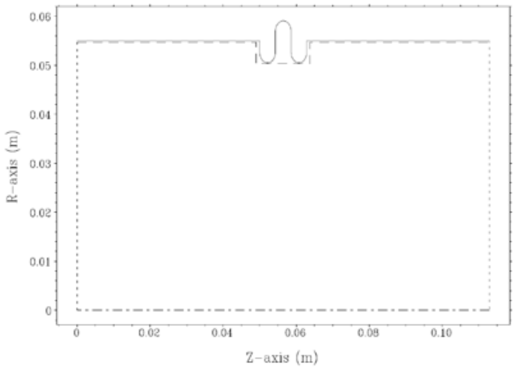
Machine	Bellows type	Beam tube radius (mm)	Bunch length (mm)	κ_z various codes ~2011 (mV/pC)	κ_z ABCI 2D Frank 2019 (mV/pC)	κ_z CST 3D Frank 2019 (mV/pC)
APS	shielded (finger type)		3	64	-	-
SOLEIL	shielded (finger type)		3	20	-	-
SPEAR3	shielded (finger type)		3	67	-	-
NSLS-II	shielded (finger type)		3	18	-	-
SIRIUS	shielded (telescopic)		3	~42	-	-
KEKB	shielded (finger type)	47	3	~11 (MAFIA no gaps)	-	-
KEKB	shielded (comb-type Ver. 0)	47	3	~4 (MAFIA no gaps)	-	-
PEP-II round	shielded (finger type)	45.06	3		-	55.3
PEP-II octagonal	shielded (finger type)	W x H = 90 mm x 50 mm	3		-	48.4
APS-SPX (SPX0 American BOA Mark IV)	unshielded, 2 x 2.5 conv.	25.4	3	455	438.6	436.6
APS-SPX (SPX0 American BOA Mark IV)	unshielded, 2 x 2.5 conv.	25.4	10	1.517	1.419	1.777
APS-SPX (SPX0 American BOA Mark III)	unshielded ,2 x 3.5 conv.	25.4	10	1.851		
APS-SPX (SPX0 American BOA Mark II)	unshielded, 2 x 2.5 conv.	25.4	10	0.920		
APS-SPX (SPX0 American BOA Mark I)	unshielded ,2 x 3 conv.	25.4	10	4.177		
APS-SPX Design 2.2	unshielded ,2 x 2.5 conv.	25.4	10	1.97	1.952	

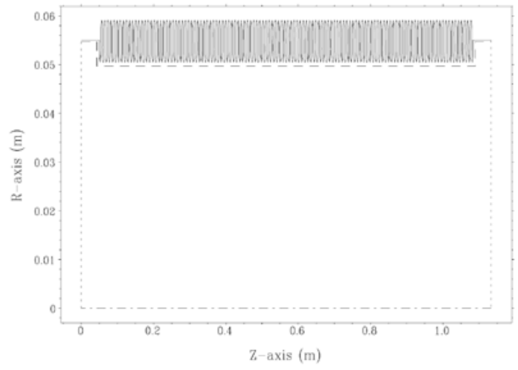
Long. Loss Factors @ σ = 3 mm

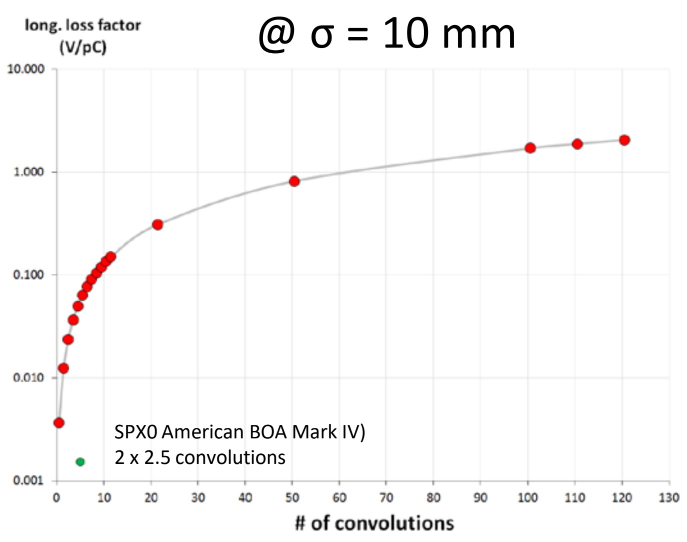


Re-evaluation of Unshielded Bellows Concept for JLEIC

- 953 MHz cavities have 55 mm beam tube radius
- Starting point: Scale APS-SPX (IV) design to radius

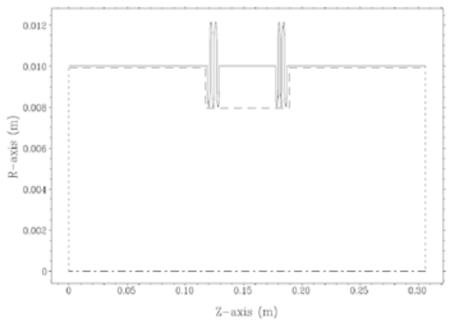


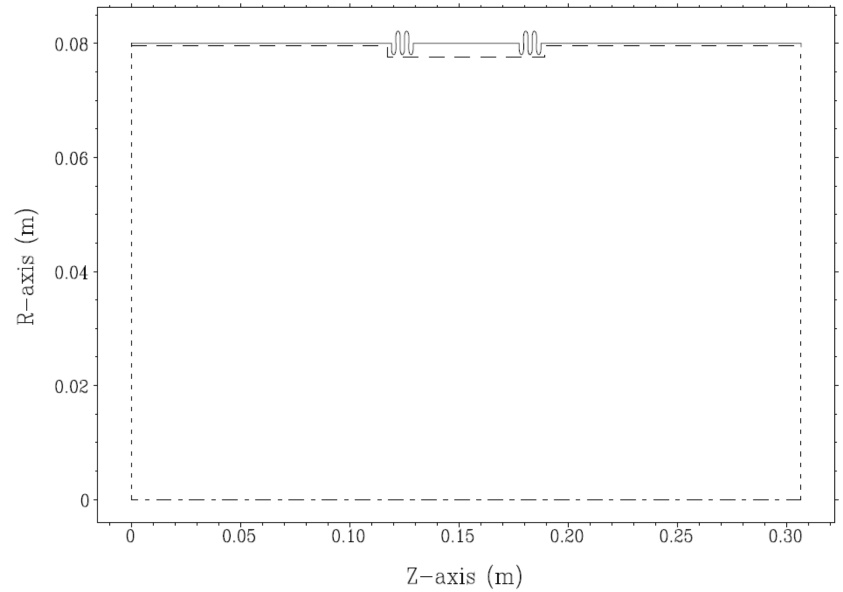


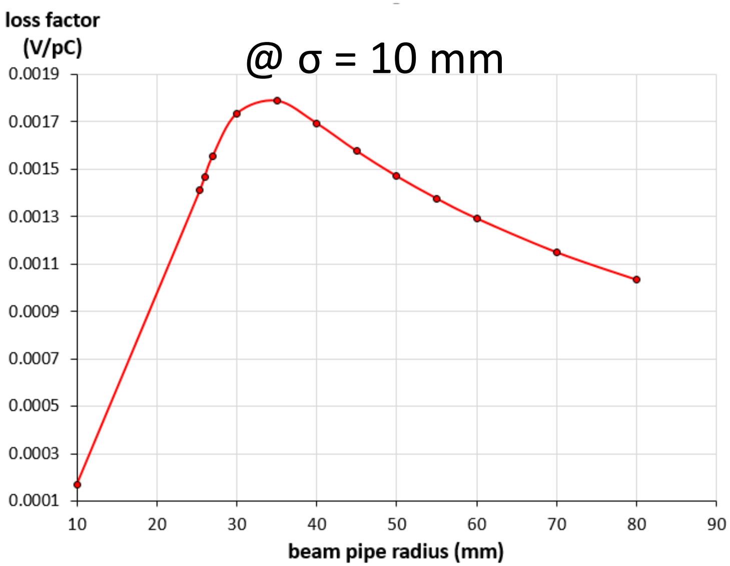


Re-evaluation of Unshielded Bellows Concept for JLEIC

- Double-Bellows Design
- Increase radius of APS-SPX (IV) desigr







appr. resonant frequency
b = beam pipe radius
Δ = corrugation depth

$$k_r b = 1.37 \left(\frac{\Delta}{b}\right)^{-0.948} \quad \text{for } \Delta/b < 0.5$$

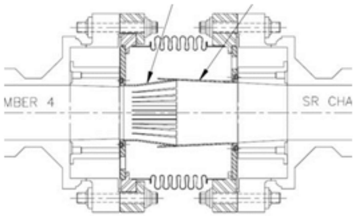
$$\Delta > 0.25 \text{ cm}$$

Here: ~14 GHz

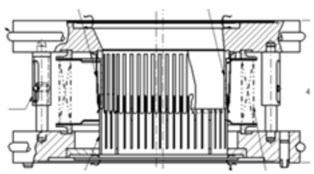
Choice of RF Shielded Bellows

Choice of RF Shielded Bellows

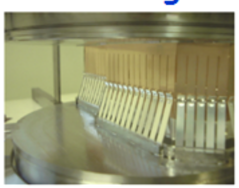
M. Ferreira



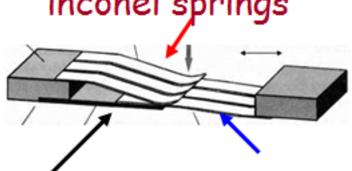
inside fingers



outside fingers



inconel springs



Solid sleeve

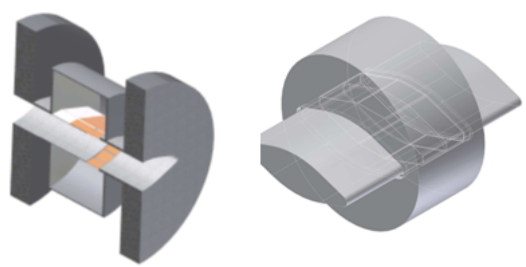
Be-Cu fingers

RF Bellows Requirements:

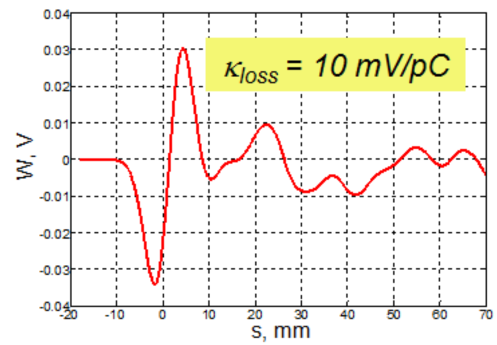
Max mis-alignment: 2 mm; Max comp/extension: ± 12 mm;

Max angle deviation: 15 mrad

Inside fingers	Outside fingers
(APS, LNLS)	(Soleil, Diamond, etc)
Simple, reliable	Lower impedance
$$	$$$



3D model for impedance simulation



Outside fingers

Wider fingers

Fewer fingers

Inside or outside fingers?

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