LOW IMPEDANCE BELLOWS FOR HIGH-CURRENT BEAM OPERATIONS*

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Abstract

In particle accelerators, bellows are commonly used to connect beamline components. Such bellows are traditionally shielded to lower the beam impedance. Excessive beam impedance can cause overheating in the bellows, especially in high beam current operation.

For an SRF-based accelerator, the bellows must also be particulate free. Many designs of shielded bellows incorporate rf slides or fingers that prevent convolutions from being exposed to wakefields. Unfortunately these mechanical structures tend to generate particulates that, if left in the SRF accelerator, can migrate into superconducting cavities, the accelerator's critical components.

In this paper, we describe a prototype unshielded bellows that has low beam impedance and no risk of particulate generation.

INTRODUCTION

In particle accelerators, bellows have deep varying convolutions. Without rf shield, the structure has high beam impedance that can generate strong wake field which can degrade the emittance of electron beam that passes through. The wakefield generated by passing beams can build up to heat the bellows to an unsustainable temperature. The thin walls of the bellows can also be damaged if illuminated by stray electron beams or intense synchrotron radiation. All the storage rings employ shielded bellows to eliminate those risks [1].

For an SRF-based accelerator, the bellows has an extra requirement to be particulate free. Many designs of shielded bellows use rf slides or fingers that shield bellows convolutions from being exposed to wakefields. Unfortunately those mechanical structures tend to generate particulates, that if left in the SRF accelerator, can migrate into the SRF accelerator's critical component: superconducting cavities. Since the components enclosing the beamline vacuum in a cryomodule for an SRF accelerator is non-serviceable, such a risk has to be mitigated when the cryomodule is being built.

Since the particulate-free condition cannot be met for many existing designs of shielded bellows, we decided to explore the possibility of an unshielded bellows that has low impedance to the beam, minimal rf heating, and large aperture in addition to the beam position interlocking to avoid the beam illumination. We illustrate such an example in a planned APS Short Pulse X-ray (SPX) cryomodule.

DESIGN REQUIREMENTS

In addition to the particulate free requirement, a successful bellows has to be mechanically flexible and strong. It allows cavities to be anchored while the cold mass in a cryomodule goes through thermal cycles that cause the bellows to extend or compress. Bellows should also provide flexibility for a transverse skew motion in case the cavities need to be aligned perpendicular to the beam travel direction. A bellows that is not shielded has to have shallow convolutions so a passing electron bunch does not generate a strong wakefield that could be accumulated to heat the beamline inner surfaces, which include bellows itself. These two properties are in conflict with each other; a trade-off has to be made depending on the specific application.

The SPX cryomodule requires a flexible bellows at three temperature zones. Figure 1 shows a schematic of a shortened SPX cryomodule [2]. It includes two deflecting cavities joined by a flexible bellows, and the cavities are operated at 2K. The bellows connecting the cavities is cooled by thermal conduction. Its cooling can be enhanced by extra thermal anchoring in the middle of the bellows. The other two bellows will be in the transition sections from 2K to 300K. These bellows are in close proximity to the cavities, and they are required to have minimal particulate generation during bellows flexing. A bellows at the end of the cryomodule will be completely at room temperature. Since its location is far away, its particulate-free requirement can be relaxed; hence a shielded bellows can be used.

For a bellows that connects neighboring cavities and room temperature valves, the heat generation from the wakefield has to be minimized to reduce unnecessary contribution to a cryogenic budget. For an SPX cryomodule, the heating of the bellows itself would be less than 0.5 W. It is preferable for the inter-cavity bellows to have high thermal conductivity to allow thermal strapping to be effective in removing heat from bellows. For the transitional bellows, a lower thermal conductivity would be preferred to reduce a conducting

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static heat load from high temperature components to cryogenic components. This suggests a copper-based inter-cavity bellows and a stainless steel (with copper coating inside)-based transitional bellows.

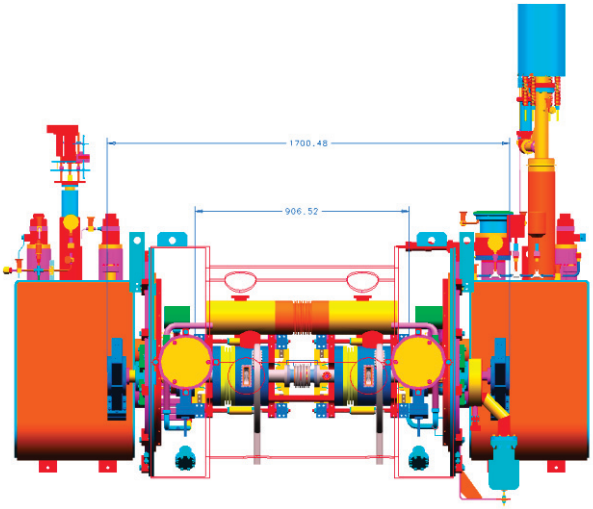

Figure 1: Front view of a shortened SPX cryomodule showing two deflecting cavities connected by a bellows. Transitional bellows at the ends of cryomodules are not shown.

Alignment parameters require the bellows to be flexible enough to allow transverse skew motion of 0.5 mm. Thermal contraction requires the bellows to allow a longitudinal motion of 1.0 mm.

The SPX cryomodule plans are to employ the same physics design for both inter-cavity bellows and thermal transition bellows.

OPTIMIZATION OF BEAM LOSS FACTOR

The design shown in Figure 2 has been adopted. A number of six shallow convolutions are divided into two groups to increase mechanical flexibility. The bellows inner diameter is 52 mm. The bellows convolution has an average spatial volume that is equal to a straight pipe of 52-mm inner diameter. The Bellows convolution starts inward. These careful considerations are important to keep the beam loss factor low with sufficient mechanical flexibility.

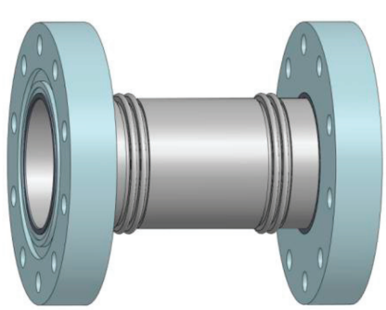

Figure 2: An unshielded bellows planned for use in the SPX cryomodule.

The beam loss factor was computed based on the APS beam structure that has a bunch length of 10 mm at an average 200-mA beam current. Figure 3 shows there would be no trapped mode except an excitation of high frequency wakefield around 11 GHz that is intrinsic to the bellows period, which we believe would be transparent in a bellows with such a large aperture.

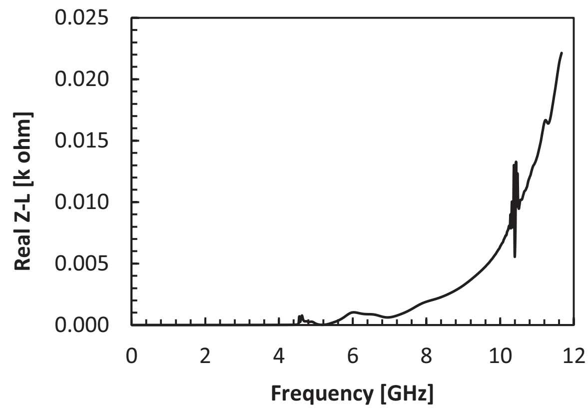

Figure 3: Real part of the longitudinal impedance of an SPX bellows.

Table 1 lists beam loss factors for bellows adopted in several storage ring installations around the world. For comparison purposes, 3-mm bunch length was used during the loss factor computation. The actual beam has a 10-mm bunch length for the SPX. Such a beam structure is considered friendly to an unshielded bellows as the comparison in Table 1 illustrates. A significantly lower beam loss factor will result in a smaller wakefield excitation in the bellows convolution. This directly translates to smaller electromagnetic surface heating of bellows' surfaces.

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

RF HEATING OF BELLOWS

Assuming a perfect match of bellows end ports, a simple calculation of surface heat flux integrated over the entire surface of the bellows in Figure 2 was found to be less than 0.674 W. Figure 4 shows instant power dissipation over the bellows inner surfaces for a stainless steel surface at room temperature.

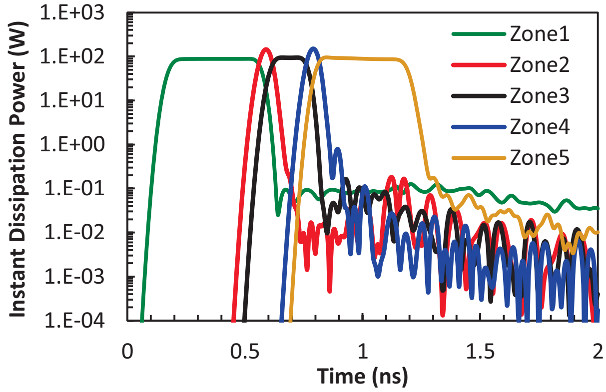

Figure 4: Surface instant power dissipations for a SPX bellows. Zones 1 and 5 are two straight sections from flanges to bellows convolutions. Zones 2 and 4 are two bellows convolutions, and Zone 3 is the centre section that connects to two bellows convolutions.

The APS bunch structure has bunch spacing that is beyond 10 nano seconds. The surface power dissipation does not need to consider multi-bunch effect as an image current in the bellows quickly decreases once an electron bunch passes, as shown in Figure 4.

Table 2 lists the surface power dissipation that would be useful for thermal calculations.

Table 2: Surface Power Dissipation for SPX Bellows

Zone in bellows	Dissipated Energy per Bunch (nJ)	Average Heating Power (W)	Average Heat Flux (W/m^2)
Zone 1	35	0.23	13
Zone 2	8.7	0.057	13
Zone 3	15	0.1	13
Zone 4	8.6	0.056	13
Zone 5	36	0.23	12

MECHANICAL FLEXIBILITY

A solid model has been constructed to understand the mechanical flexibility of bellows design. A very dense finite element model is shown in Figure 5. A maximum stress of 316 MPa was found to be in the bellows as a tensile stress, as shown in Figure 6. Careful selection of certain stainless steel may be sufficient to be used as a base material.

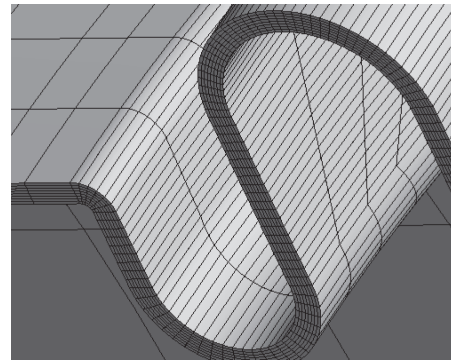

Figure 5: Meshes of a bellows solid model.

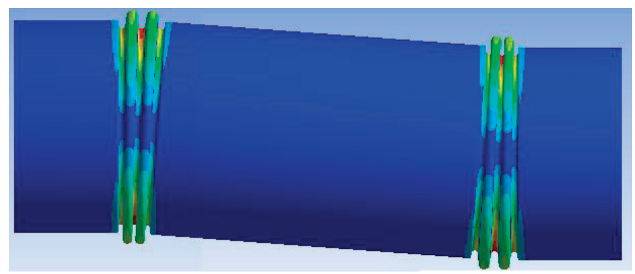

Figure 6: Equivalent (von-Mises) stress of SPX bellows.

CONCLUSION

Low-impedance-formed bellows is the preferred option for particulate-free operation and ease of cleaning as required for SRF applications. The final design requires a tradeoff between beam physics, SRF requirements, and mechanical flexibility.

Prototypes of SPX bellows made of stainless steel 316 and phosphor copper have been pursued. Further tests of a prototype will include stress measurement and fatigue testing. Once mechanical flexibility is proven, a beam test with actual storage beam will be conducted.

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