NEW WARM VACUUM INTERCONNECTION DESIGN FOR HL-LHC*

T. Silva†, V. Baglin, G. Bregliozzi, C. Garion, J. Hansen,
European Organization for Nuclear Research, Geneva, Switzerland

Abstract

Warm vacuum interconnections are critical components used to couple adjacent vacuum chambers in the warm sectors of the LHC. Their primary functions are to ensure vacuum tightness, to accommodate small radial misalignments between chamber flanges, to ensure electrical continuity via RF fingers, and to compensate for longitudinal thermal expansion and contraction of the Long Straight Sections during bakeout operations. Within the framework of the High Luminosity LHC (HL-LHC) upgrade, a new generation of warm vacuum interconnections has been developed. This design introduces a novel concept of RF contacts utilising a deformable radio-frequency contact bridge.

This contribution outlines the main design, manufacturing strategies and qualification of these new warm modules for the HL-LHC operation.

INTRODUCTION

Design Requirements

Warm vacuum interconnections couple adjacent vacuum chambers in the warm sectors of the Large Hadron Collider (LHC), providing vacuum tightness, radial misalignment compensation, and longitudinal thermal stroke accommodation during bakeout. Beyond mechanical compliance, they must also ensure reliable electrical continuity between beamline elements while maintaining low beam coupling impedance. The current standard design, based on RF fingers, accommodates radial misalignments of up to ±2 mm.

The High-Luminosity LHC project (HL-LHC) imposes more demanding geometric tolerances, driving the development of a new generation of interconnections built around a deformable radio frequency (DRF) contact bridge [1, 2]. This concept extends the misalignment compensation range to ±5 mm while enhancing mechanical robustness, avoiding buckling of RF bridges and reducing the probability of electrical contact loss under operational conditions. The design is presented in Fig. 1.

Components

These vacuum interconnections differ in aperture size according to their functional position within the LHC, while maintaining a common design philosophy. Each interconnection is composed of four primary elements.

The body is in stainless steel, constructed from welded assemblies of flanges, bellows, and tube sections, as can be seen in Fig. 2. It defines the structural envelope of the module and provides axial flexibility determined by the stroke of the bellows. Depending on requirements, modules may be

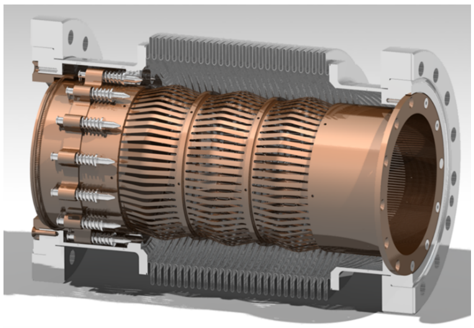

Figure 1: DRF Design of Vacuum Interconnections.

manufactured with zero, one, or two auxiliary ports. When the tube section serves as a support interface for additional components, a base plate is integrated into the design.

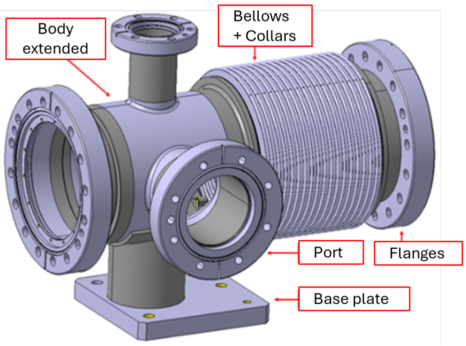

Figure 2: DRF Body.

The DRF insert is composed of a welded assembly integrating the DRF contact bridge, the flange, and a strip of RF contacts, as presented in Fig. 3. The flange is made of OFE copper, but the RF contacts and RF bridge are made of copper-beryllium (CuBe) because they need to withstand considerable mechanical stresses during installation and operation, even after bakeout at 250°C, while keeping excellent electrical continuity. The RF bridge has 3 convolutions, a length of 137.75 mm and a thickness of 0.1 mm.

The functional principle is based on the elastic deformation of the contact fingers, which compensates for the relative displacements arising during installation, nominal beam operation, and transient phases (e.g. thermal cycles or mechanical realignments). In the operational configuration, the convolutions are elongated, reaching an angle of 11° and forming a nearly linear profile. This straightened geometry minimises the contribution of the contact assembly to the longitudinal beam coupling impedance, thereby ensuring compatibility with HL-LHC impedance requirements [3].

The transition tube is made of OFE copper and has a thickness of 5 mm. To ensure low-resistance current transfer and long-term stability, the contact interface on the tube is rhodium-coated (see Fig. 4). Depending on the installa-

* Research supported by the HL-LHC project
† tomas.h.silva@cern.ch

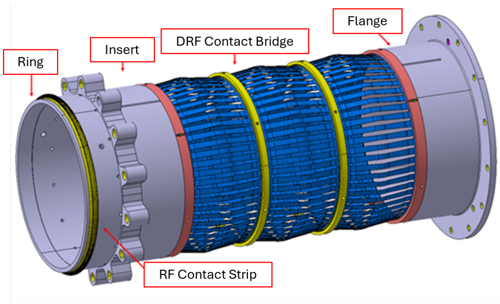

Figure 3: DRF Insert.

tion location, the inner surface may be treated with a non-evaporable getter (NEG) coating, an amorphous carbon (aC) coating, or left uncoated. In addition, the tube can be manufactured with or without pumping slots.

A minimum number of pumping slots must be present in the transition tube to ensure equal conductance between the tube and pumping ports. For this, the total surface of the pumping slots must equal the surface of a pumping port, which has an internal diameter of 60 mm. The dimensions of each pumping slot is shown in Fig. 5, and the conductance requirement is achieved with 76 slots. These are distributed in 19 rows, with 4 slots per row.

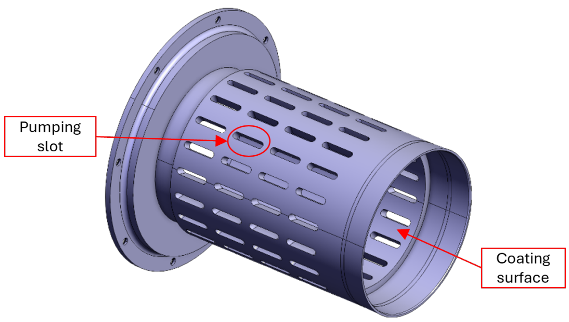

Figure 4: DRF Transition Tube.

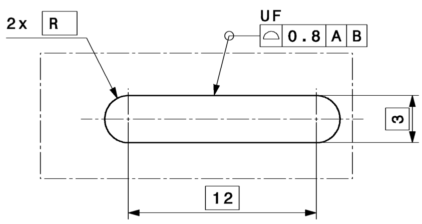

Figure 5: Dimensions of a pumping slot in mm unit.

The spring and shoulder pin assembly comprises Inconel 718 helical springs combined with shoulder pins, as shown in Fig. 6. It provides the mechanical linkage between the insert and the module body. During interconnection extension, the springs are compressed, storing elastic energy that restores the assembly to its nominal length once the module is back to the nominal position. The number of springs installed scales with the nominal aperture of the interconnection, ensuring that the total restoring force exceeds the sum of the forces comprising the force to extend the RF bridge and the sliding friction generated between the transition tube and the RF contact strip. For example, a DRF module with an aperture of 80 mm has 14 pre-loaded springs.

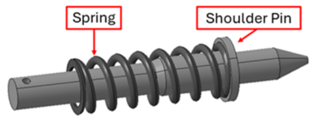

Figure 6: Spring and Shoulder Pin Assembly.

WORKING CONDITIONS FOR THE DRF TUBE AND RF FINGERS

Geometry

The primary objective during the installation of DRF modules is to ensure they are set at a nominal predefined length (T), which is measured between the external vacuum Con-Flat (CF) flanges. The height (H) and length (L) of each DRF convolution, together with the RF contact opening gap (G), define T. These dimensions are presented in Figs. 7 and 8.

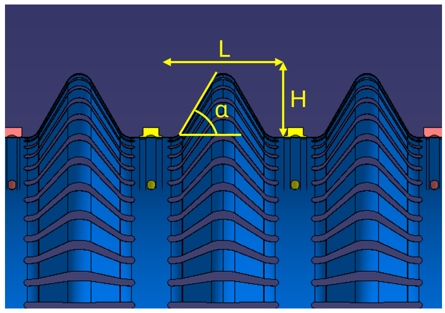

Figure 7: Geometry parameters of DRF Insert convolutions.

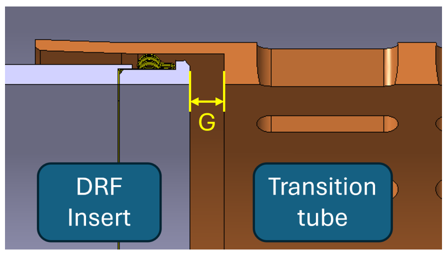

Figure 8: Gap between DRF Insert and Transition Tube.

Impedance and RF Contact Benefits

The physical dimensions of the convolutions (H and L) and the gap (G) determine the module's contribution to beam impedance. The RF contact bridge carries the beam image current between adjacent vacuum chambers, electromagnetically shielding the outer bellows and substantially reducing the overall impedance. At the nominal convolution angle α of 11°, electromagnetic simulations confirm that no modes are trapped within the DRF structure, validating the compatibility of this design with HL-LHC impedance requirements [3].

Operational Parameters

Under standard operating conditions, the module is designed to maintain specific mechanical states: the bellows should be in free state length; the DRF convolution nominal height is 2.68 mm and the nominal length is 32.944 mm ; the springs should be pre-compressed 3 mm; and the gap should be null.

To balance mechanical flexibility with acceptable beam impedance, the design is operated at a nominal angle of 11°. This configuration allows for a total working range of 46.3 mm, consisting of an 8.3 mm extension and a 38 mm compression. Additionally, the modules can handle a lateral offset of ±5 mm when the bellows are at free length, which reduces to ±2.5 mm when compressed by 25 mm.

PROTOTYPE TESTING

Axial Force to Slide RF Contacts

During testing, the prototype module was extended to the maximum length and offset to the maximum on the transversal axes, as indicated in Fig. 9. When the modules are extended above the nominal installation length, the RF contacts slide on the rhodium-coated surface of the transition tube, compressing the inconel springs. The main function of the springs is to return the RF contacts to their nominal position when the module is back to its nominal length.

The force needed from the springs was experimentally verified by manually pulling and pushing the DRF insert to make it slide. The force needed in function of the extension of the module is presented in the Fig. 10, for a DRF module with a diameter of 80 mm.

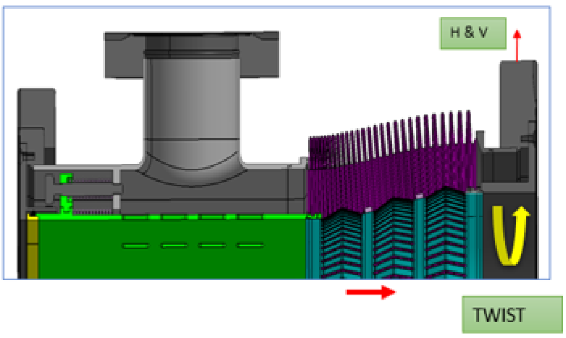

Figure 9: Longitudinal, radial and torsional displacements during prototype testing.

Bakeout and Mechanical Tests of Springs

During operation, the maximum spring compression will be 10 mm. During testing, springs were compressed by 12 mm and baked to the maximum bakeout temperature of 250°C for 24 hours. The first design of springs, made of Titanium, showed plastic deformation after bakeout. Therefore, it was decided to change the material to Inconel 718. The test was repeated and no plastic deformation was observed within the specified working range.

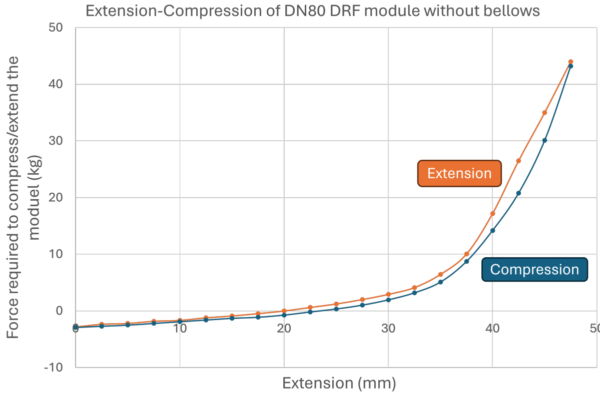

Figure 10: Friction test of RF Contacts.

CONCLUSION

A new generation of warm vacuum interconnections has been developed for the HL-LHC upgrade, introducing the deformable radio frequency contact bridge concept. The DRF design extends the radial misalignment compensation range to ±5 mm while maintaining compatibility with HL-LHC impedance requirements at the nominal convolution angle of 11°. The modular architecture, combining a common design philosophy with aperture-specific variants, accommodates the diverse installation requirements across the Long Straight Sections of the two high luminosity Insertions of the ATLAS and CMS experiments.

Prototype testing has validated the key mechanical parameters of the design. The axial force required to slide the RF contacts was experimentally characterised, and the spring subassembly was qualified for bakeout conditions at 250°C. These results support the progression towards series production of the DRF modules for HL-LHC installation.

A total of 83 DRF modules with nominal diameters of DN63, DN150, DN212, and DN250 are designated for installation in the critical regions of LSS1 and LSS5. With the exception of the bellows, all components were produced in-house at the CERN Main Workshops, making full use of its machining and surface treatment capabilities.

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