COLD BEAM VACUUM INTERCONNECTS FOR THE LHC INSERTION REGIONS

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Abstract

The LHC machine is composed of arcs and insertion regions where superconducting magnets, working at temperatures of 1.9 K and 4.5 K, have flexibly interconnected beam vacuum chambers. These interconnects must respect strict requirements in terms of impedance, aperture, space optimization and reliability. A complete interconnect design was first developed for the arc regions, and from which a total of 20 variants have been created according to the different functional requirements of each pair of cryostats along the machine. All design features and manufacture processes were validated through extensive testing. Manufacture and assembly cost was minimised by using a modular interconnect design, with common components shared among different design variants. A detailed quality assurance structure was implemented in order to achieve the high level of reliability required. This paper presents the layout of cold beam vacuum interconnects along with details of development and testing performed to validate design and integration.

INTRODUCTION

The Large Hadron Collider (LHC) is a 7 TeV proton-proton collider currently under construction at CERN. Each of the 8 arcs of the machine will consist of a 2.5 km long continuous cryostat, operating at 1.9 K. The cryostat contains repeating half-cells comprising three twin-aperture dipole magnets and a 'short-straight section' (SSS) with lattice quadrupole and corrector magnets.

Between each arc is an insertion region consisting of two dispersion suppressors and a 'Long Straight Section', some 570 m long. This region contains a number of magnetic elements, some at 1.9 K, some at 4.2 K and some at room temperature that serve to steer and focus the beams. The cold magnets are joined by flexible 'interconnects' to ensure continuity of vacuum, along with local electrical and (where necessary) cryogenic services. A previous paper described the design of these cryogenic beam vacuum interconnects for the arcs [1]. However, the insertion regions are all in some way unique: designed for experimental collisions; beam cleaning; injection ejection etcetera. This results in a number of different interconnects with different apertures, beam separations, lengths and orientations.

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DESIGN DESCRIPTION

Functional requirements

The insertion region beam line interconnects of the LHC requires the same functionality as the beam arc interconnects. It has to maintain the continuity of beam vacuum between cryomagnets cold bores and the beamscreen He cooling lines. The electrical resistance between beam screens at operating conditions has to be ~100 μΩ to minimise transverse impedance, preventing beam instability. All connections will be welded by an automatic process wherever possible, with a maximum allowable leak rate of 10^{-11} Pa m^3s^{-1} [2]. The differential thermal expansions between cold masses and beam screens, as well as between adjacent cold masses need to be absorbed without endangering the performance.

Baseline design

A modular design, comprising three sub-assemblies, was developed in order to minimise the number of component variants and assembly operations underground (Figure 1). A fixed beam screen extremity that provides a fixation point relative to the cold mass; a movable beam screen extremity including a bellows expansion joint compensating the differential thermal expansion between cold mass and beam screen; and a shielded bellows expansion joint unit called a *plug-in module*. The movable side includes a pumping port interface in some cases. Furthermore, a beam position monitor (BPM) is also integrated into the beam interconnects in most quadrupoles. All welded and vacuum tight components are made from stainless steel 316 LN, with the exception of bellows in 316 L for reasons of manufacture.

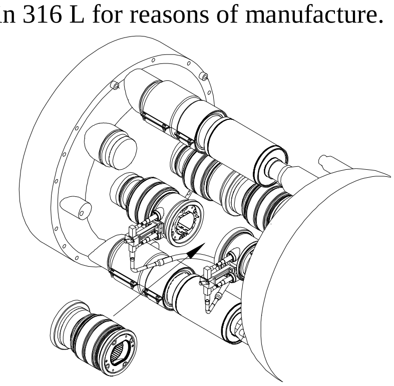

Figure 1 - Example of a twin-aperture cold beam vacuum interconnect. The plug-in module is installed in the tunnel.

The beam screen extremities hold the beam screen inside the cold bore with two conical bronze clamps. The cooling tubes attached to the beam screen are connected to the helium circuit (Figure 2). Feedthroughs, laser welded with partial penetration on the cooling tube extremities allow an assembly with no helium to beam vacuum welds. All flanges are designed to allow for repair, up to three times, in case of leak or poor weld thanks to 5 mm long welding lips.

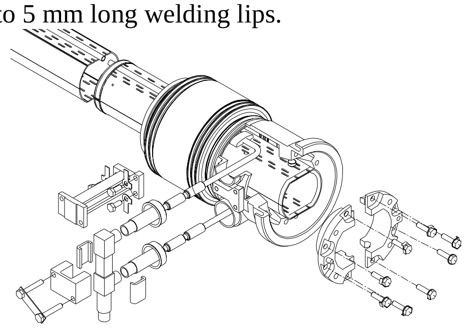

Figure 2 - Exploded view of a standard movable beam screen extremity.

The plug-in module connects the assembled beam screen extremities. It houses the RF-contact bridge and beam screen end transitions, ensuring a good electrical contact between beam screens. It will be installed in the tunnel after cryomagnet first alignment. The plug-in module compensates for relative movements due to thermal contractions, misalignment and mechanical tolerances between two adjacent cryomagnets (Figure 3). Copper beryllium fingers, Au coated with a 5 µm layer, and a copper transition tube with a 3 µm Rh coating on the extremity provide the optimum contact at operating temperature. The static contact between plug-in module and beam screen is made through copper beryllium C17200 strips with 1 µm thick Au coating and vacuum brazed below C17200 annealing temperature with indium to the RF-contact transition flange made of copper [3]. In addition, a ring 3 mm long and 3 µm thick, Au coated, is laser welded to the extremity improving the electrical contact of the assembly [4]. Measurements performed showed that such static contact assembly was still not enough to meet the impedance budget; to further reduce the contact impedance bronze belleville washers, mounted as shown in figure 3, ensured a local axial force of 800 N on each beam screen creating another effective contact surface between the beam screens and the plug-in module copper transitions [5]. Positioning pins guarantee a proper alignment during assembly to avoid strip damage by the sharp beam screen ends.

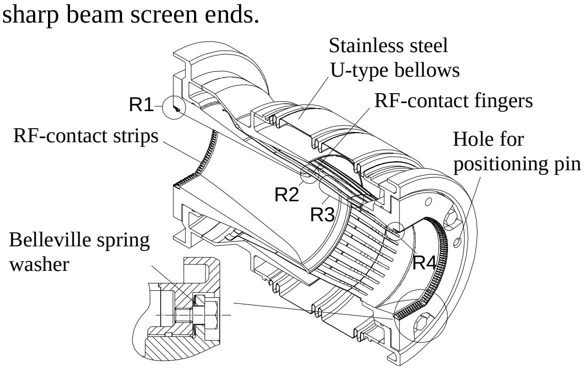

Figure 3 - Plug-in module.

Layout

Cold bores of inner diameters 50, 53, 63, 69 and 74 mm with their corresponding different beam screens have to be interconnected. The machine layout requires transitions between cold bores of 50/50 mm in the arc and dispersion suppressors, but also transitions of 50/63, 53/63, 63/63, 63/69, 63/74 and 74/74 mm in the long straight sections.

In addition, vertical aperture requirements for several cryomagnets, implied the introduction of extra interconnect variants with the beam screen flat surfaces either horizontal or vertical. This change in orientation, coming late in the design process, led to the design of many different assembly and component variants, as well as the development of new assembly techniques and tooling. Figure 4 presents one of these special designs for the inner triplet. This assembly allows its installation with the same radial clearance as the baseline design, although using more longitudinal space, maintaining the same level of global reliability.

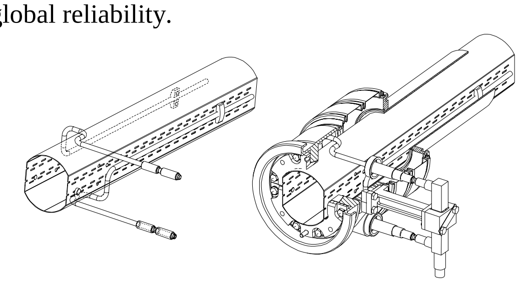

Figure 4 - Special beam screen extremity assembly for vertically oriented beam screens in the inner triplet.

Between Q4 and D2, the interconnect components also provide a smooth transition between both cryomagnets with an offset of 3 mm in their corresponding beam axes. This offset is accommodated by the plug-in module, in the copper transition piece and the fixed beam screen extremity components. Those components, difficult to manufacture due to their complicated geometry, will be produced by machining and wire erosion in sub-components assembled by vacuum brazing. A non-circular cross section cold bore is foreseen in the Undulator magnet for the synchrotron radiation profile monitor [6]. This cryomagnet will be installed with a beam screen presenting cooling tubes welded on the curved surfaces. This solution maximises the aperture in the vertical plane but requires one extra interconnect variant for each of the two D3/Undulator interconnects. In addition, an offset of 3 mm is required in these interconnects. The number of plug-in module design variants also had to take into account the different thermal displacements resulting from 36 combinations of magnet lengths and fixed cold mass support positions. Given so many variations of the interface parameters, a design optimization was imperative to reduce costs. As the most complex element of the interconnects is the plug-in module, all variants were designed to be grouped into 4 main designs, in which only the beam screen transitions change. The arc U-type and nested bellows used in the arc could not be used for interconnects of cold bore diameter bigger than 50 mm. To avoid high costs related to production of small series, only one extra type of bellows will be installed.

TESTING

Cryotests

The plug-in modules of 50/50 mm design type were cryogenically tested. It was deemed not to be needed further tests for other designs since the solutions were identical and its behaviour at cryogenics temperatures learnt. The choice of Au/Rh coatings for the RF bridge gave the lowest contact impedance between different material combinations with no risk of cold welding because of the immiscibility of both elements at operating temperatures [1]. The RF contacts were designed to provide a force of 0.5 +/- 0.2 N/finger considering all possible offsets from the nominal at operating conditions (+/- 6 mm longitudinal and +/2 mm lateral). The impedance was shown to be proportional to the contact force ranging for those values between 1.8 to 0.9 mΩ per finger. In addition, a safety factor 5 against buckling of the RF contacts was calculated [7]. At cryogenic conditions, the impedance measured for the arc plug-in module was 125 μΩ. This value can be considered as the result of 4 impedances in a serial connection (see Figure 3). R1 and R4 would correspond to the RF strips contact with the Au coated beamscreen ends and present an impedance of ~15 μΩ each at operating conditions. R2 is constant in all temperature range and its value is ~1.3 mΩ/finger if 0.5 N are applied. R3 was measured to be 120 μΩ/finger at nominal position. Measurements of the RRR of the finger (CuBe C17410 with 5 μm Au coating) resulted to be 2.5. For the other designs, a similar impedance is expected; presenting slightly lower values for the cases where a larger cold bore dimensions allows a bigger number of fingers.

String 2 measurements

Measurements of the thermal displacements were carried out in the cool-down and warm-up operations during String 2 testing campaign [8]. The values of the bellows offsets showed that the thermal contraction coefficients of each independent material, used as reference in the initial calculations, do not exactly correspond to the real behaviour of the beam screen and the cold mass assemblies. The beam screen bellows compression and the plug-in module expansion, during temperature transitions when cold mass and beam screen follow different temperature profiles, were very close to the maximum design values [9]. However, the tested 50/50 mm interconnects were validated thanks to the margin saved during the design phase for possible deviations on the input data. New contraction coefficients presented in Table 1 were derived and used in the subsequent designs.

Table 1 - Thermal contraction coefficients between 293 K and 2 K.

	From references for the predominant material of the assembly [mm/m]	As derived from String 2 [mm/m]
Cold mass	2.93 (316LN)	3.13
Beam screen	2.57 (P506)	2.59

FABRICATION AND PLANNING

The components will be fabricated at the Budker Institute for Nuclear Physics (BINP) in Novosibirsk with materials provided by CERN. The pre-series components are expected to arrive by October 2004 and the series fabrication will begin after their provisional acceptance, expecting the first batch in January 2005.

CONCLUSIONS

The LSS interconnects are designed for the operation of the LHC at its ultimate luminosity. To achieve this, a big effort has been carried out adapting the designs to increase the beam aperture. The delivery of the components according to the agreed planning [10] will ensure the installation of the LHC on time. Nonetheless, a lot of organization work is remaining to achieve the difficult task of interconnecting the cryomagnets due to the different existing designs.

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