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DESIGN AND QUALIFICATION OF TRANSPARENT BEAM VACUUM CHAMBER SUPPORTS FOR THE LHCB EXPERIMENT

J.L. Bosch, P. Chiggiato, C. Garion, CERN, Geneva, Switzerland

Abstract

Three beryllium beam vacuum chambers pass through the aperture of the large dipole magnet and particle acceptance region of the LHCb experiment, coaxial to the LHC beam. At the interior of the magnet, a system of rods and cables supports the chambers, holding them rigidly in place, in opposition to the vacuum forces caused by their conical geometry.

In the scope of the current upgrade programme, the steel and aluminium structural components are replaced by a newly designed system, making use of beryllium, in addition to a number of organic materials, and are optimised for overall transparency to incident particles.

Presented in this paper are the design criteria, along with the unique design developments carried out at CERN, and furthermore, a description of the technologies procured from industrial partners, specifically in obtaining the best solution for the cable components.

INTRODUCTION

In the dipole aperture of the LHCb detector, the beryllium beam pipes undergo axial forces due to their conical geometry and the atmospheric pressure exerted on their external walls.

The two beam pipes in this region are named UX85/2 and UX85/3, with increasing nominal diameter, respectively. They are held in place at the two respective support points, S2F and S3F, as seen in Fig. 1.

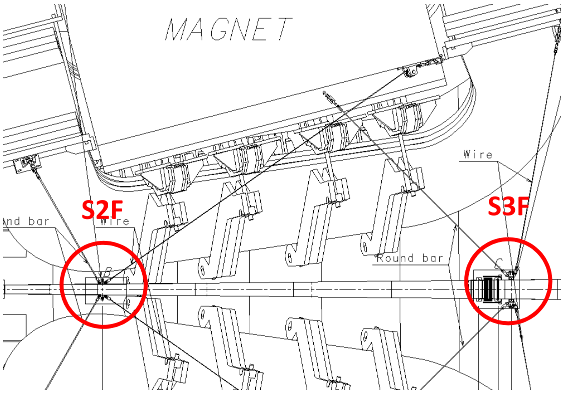

Figure 1: Fixed beam pipe support points, S2F and S3F inside the LHCb detector.

The concerning beampipes are particularly fragile since they are designed for maximum particle transparency and are therefore manufactured in thin-walled beryllium.

In this critical region of the LHCb experiment, the material mass has to be the lowest possible so that the particle transparency is the highest possible; this motivation drives the optimisation of material use [1]. The current beam-pipe support systems in this region were optimised using mainly metallic solutions, but left scope for improvement in the selection of advanced materials [2]. This optimisation work was begun and reported in 2011 [1].

A new system design extends the scope of various design choices already proposed, and is presented in the following paper.

Described here is the 'safe' optimisation of the beryllium collar (replacing the original aluminium version), the novel design of the carbon fibre rods and synthetic cables to replace the currently installed steel components, and the qualification and testing of all materials used.

COLLAR OPTIMISATION

The aluminium collars are redesigned in beryllium [3], and optimised with respect to mass in order to minimise the interaction with incident particles.

A further optimisation was necessary to account for the following factors: high temperature operation, brittle fracture failure criteria, certificated batch material properties, and exceptional loading scenarios [4]. Estimated real material properties were obtained by scaling the measured properties of the batch material against the high temperature data of other existing beryllium grades. Table 1 shows the resulting properties.

Table 1: Estimated Mechanical Properties of Certified be I-220H Batch at 150°C [4]

Properties	**Be I-220H**
Yield Strength (MPa)	421.4
Elastic Modulus (GPa)	301
Poisson's Ratio	0.08
Fracture Toughness	11.5 – 13.4

Mechanical Performance

Finite Element Analyses using Ansys were performed for both S2F and S3F collars. The exceptional loading condition refers to a maximum force application in the case of a cable failure, and additionally high temperature material properties are used, as described in Table 1. Figure 2 shows the Maximum Principal Stress (which is a suitable failure criterion for brittle materials) contours under such conditions.

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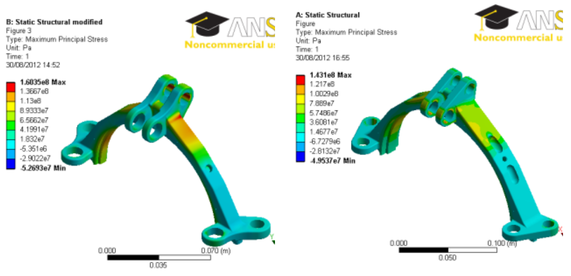

Figure 2: Maximum Principal Stress contours of S2F and S3F Collars (left to right, respectively) under exceptional and high temperature loading.

The obtained stress safety factors for the new design under the specified constraints is 3 or above.

Table 2 additionally shows the resulting safety factors for the new beryllium (Be) collars in comparison with the old aluminium (Al) design, under the same stress criteria.

Table 2: Stress Safety Factor Comparison of Old and New Collar Designs Based on a Von Mises Stress Criterion

Component	**Stress Safety Factor**
S2F Collar (Al/Be)	2.1/**3.5**
S3F Collar (Al/Be)	2.5/**3.9**

Non Destructive Testing

The beryllium collars, manufactured from a certified batch of hot-isostatically-pressed (HIP) material, were tested using non-destructive techniques in order to ensure inclusions and/or critically sized porosity are not found; namely x-ray radiography. Figure 3 shows an example of two such images. In addition, a thorough visual inspection of the surface, specifically in the highly stressed regions shown in Fig. 2 is conducted, to rule out imperfections at the critical crack length [4].

The radiographic testing highlighted no inclusions or porosity, but did conclude that small indications of less than 0.5 mm depth cannot be detected because of the low density of beryllium (1848 kg/m^3) [5].

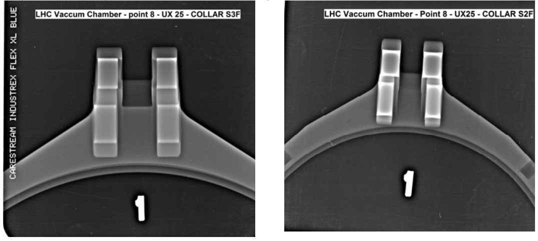

Figure 3: 2D X-Ray Radiography results sample of S3F and S2F Collars (left to right respectively).

CABLE SYSTEM OPTIMISATION

Design development was exhaustive in the case of the cable support system. An initial study identified carbon fibre reinforced plastic (CFRP) and Technora-Aramid fibres as suitable materials for the rigid and flexible components of the system, respectively [6]. The high radiation length of the materials was the main benefit of the proposed solution. However, an initial study into glued aluminium-to-CFRP terminations and Technora spliced ropes were replaced with the current novel designs.

Novel Cable Design

The commercially procured cables are constructed by a protected manufacturing process, designed by Future Fibres (Valencia, Spain).

The main innovation is the winding of the carbon fibre, and Aramid tows around each end fitting in a continuous loop until the desired cable diameter is achieved (after consolidation). In this fashion, maximum strength and stiffness figures can be reached with the smallest diameter. Figure 4 shows an example of the CFRP cable in its finished form.

Figure 4: Carbon fibre cable manufactured by continuously wound tows of carbon fibre and consolidated with epoxy. Uniball end fitting are made of PBI engineering plastic.

Mechanical Performance

The constraints of the cable system were set by those achieved by the previous steel system. Allowable beampipe displacement, during operation and under failure scenarios, is the major constraint. The design loads include axial loads of 1875 and 7488 Newtons on the S2F and S3F support points, respectively.

Estimated properties of the composite fibres could be used in the analysis because all strands are oriented along the length of the cable. The chosen diameters ensure the abovementioned maximum displacements and also acceptable stress safety factors as proved by an Ansys analysis. Table 3 summarises the modelled performance of the new cable system to the measured performance of the old system.

Table 3: Summary of Cable System Performance (Measured Values of the Old System vs. Computed Values of New System) [7]; SF is Safety Factor

Component	**Axial force (N)**	**Axial disp. (mm)**	**Stress SF**
S2F (old/new)	1533/1875	1.2/1.4	25/37
S3F (old/new)	7045/7488	0.79/0.89	2.9/13

In addition to the system analysis a test of the manufactured cables was carried out, yielding both indicative stiffness and breaking load values. The real results vary from the modelled solutions in that a pin-to-pin cable stiffness includes the stiffness of the bulk cable and the end effects where the fibres separate to form around the toggle. Table 4 shows the results and confirms the suitability of the system design for the intended application. The failure mode is generally a rupture of the plastic end toggle as opposed to a break of the cable.

Table 4: Summary of Composite Cable Performance: Stiffness Measured in Design Ranges and Maximum Load at Failure [8]

Cable Type	**Stiffness [MN] (150-250kg)**	**Stiffness [MN] (850-950kg)**	**Max load [kN]**
HM Carbon	-	9.0	23.3
Technora	0.70	-	18.5

Material Qualification

The lifetime of the composite solution, with respect to Technora fibres and PBI plastic, may be limited, so testing them under irradiation conditions to ensure sufficient resistance to LHCb total doses is important.

Both materials were tested to an absorbed dose of 10MGy in a gamma radiation environment, and to 1MGy in a proton beam. The breaking strength and stiffness values were not significantly affected by the gamma exposure [7]. The proton exposed samples were tested only up to operation loads, but no significant increase in brittleness was detected [7].

The PBI plastic used for the cable toggles and for the collar-to-beampipe interface rings, showed good resistance to proton radiation, maintaining its elastic modulus after irradiation, but demonstrating a 16% decrease in tensile strength. The sample size was not sufficient however to draw a definitive conclusion, but the lower strength was used as a design parameter, nevertheless [9].

Detrimental creep behaviour of the Technora cables is not expected [10]. The literature shows strain to be linear with log-time in the secondary strain phase at ABLs (Absolute Breaking Load) below 50%. The cables will however be monitored with force gauges during operation, and tension can be adjusted during technical stops of the machine if necessary.

CONCLUSIONS

The new support system design firstly allows a significant increase in particle transparency. The beryllium collars were optimised with respect to Maximum Principal Stress, and inspected using radiology techniques before installation.

The composite cables have employed a novel and safe design concept and have been optimised in material choice and volume. Furthermore the employed materials have been qualified for use in a high particle flux region.

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