

THE MECHANICAL DESIGN OF A COLLIMATOR AND CRYOGENIC BYPASS FOR INSTALLATION IN THE DISPERSION SUPPRESSORS OF THE LHC

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Abstract

A project to install collimators in the dispersion suppressor regions of the LHC was launched early 2010, aiming to reduce the power deposition in superconducting magnets by a factor of 10. To be placed in the continuous arc cryostat, the design of such collimators had to comply with challenging integration, functional and time constraints. A pre-study for a cold collimator solution was launched in parallel with an alternative design consisting of a room temperature collimator and a cryogenic bypass. The second was eventually preferred, as it was based on proven LHC technologies for cryogenic, vacuum, electrical and collimator material solutions, despite the increased difficulty on the mechanical integration and assembly. This paper presents the mechanical design of a cryogenic bypass for the LHC continuous cryostat and respective collimator unit, both made to comply with the functionality of existing LHC systems. The approach taken to achieve a reliable design within schedule will be explained alongside the measures adopted to validate new solutions, in particular, when dealing with welding distortions, systems routing, thermal loads and precision mechanics.

INTRODUCTION

Studies on the LHC multistage collimation system revealed that additional collimators installed in some of the dispersion suppressors were needed to reduce the power deposition on the superconducting magnets, as the beam intensity increases towards nominal. The introduction of two collimators on each side of insertion region 3, with 1 m long tungsten jaws, would result in a reduction of power deposition by a factor of 10 [1].

Since the dispersion suppressors are part of the LHC continuous cryostat, the integration of such collimators implies longitudinal shifting of magnets to create space. A first idea to minimise the required space was to build a cold collimator with active parts inside the cryostat cooled by the available 50 K-65 K helium header. When compared to a conventional room temperature collimator, the absence of cold to warm transitions would reduce the total length by at least one meter. However, operating a surface subjected to a direct impact of the beam halo inside the 3 km long cold beam vacuum sectors of the LHC was soon recognised as a major challenge, if not a showstopper. Moreover, as accessing the inside of the cryostat, currently without moving parts, implies warming up the full LHC sector, the introduction of the collimator would require extensive reliability testing. These two issues ruled out the possibility of installation of a cold

collimator in the next long LHC shutdown (2013-14). The solution was to design a cryogenic bypass providing cold to warm transitions, vacuum sectorisation and routing of both cryogenic lines and electrical busbars, creating the space for a dedicated room temperature collimator (Fig. 1). For an active collimator length of 1.0 m, the total additional length per collimator becomes 4.5 m, including 0.5 m for an additional interconnect.

The Dispersion Suppressor Collimator project was suspended following a review of the LHC collimation system held on June 2011, which assessed that for the luminosities projected until HL-LHC, the present collimation system would adequately protect the superconducting magnets. A prototype of the cryogenic bypass is currently under construction at CERN.

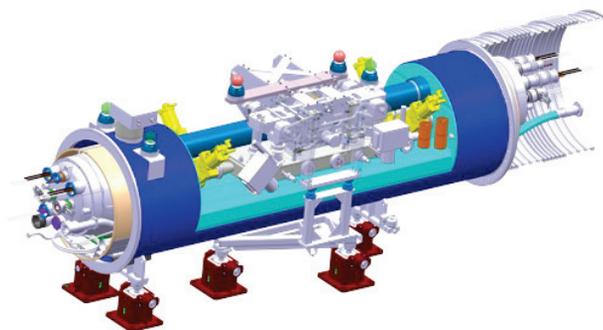


Figure 1: Assembly of cryogenic bypass and collimator, prior to interconnection with the magnet string.

INTEGRATION

Half of the longitudinal space can be obtained by shifting some magnets away from the interaction point and replacing the existing connection cryostat, which fills the empty space between the arc and the dispersion suppressors, with a shorter version. The remainder implies shifting magnets towards the long straight sections with consequent changes in the distribution feedboxes (DFBA), cabling and other equipment.

In the transverse plane (Fig. 2), the collimator and cryogenic bypass must be compatible with the clearance for transport in the tunnel on one side, and the cryogenic distribution line on the other. In addition, the two-phase helium heat exchanger line cannot be displaced, thus limiting the envelope available for the collimator. Existing collimators [2] are not compatible with these constraints; therefore a new design had to be developed.

Ultra-high vacuum (UHV) gate valves with RF-shielding installed on both ends of the collimator, allow for completely independent operation of the cold and

warm vacuum systems, currently the baseline throughout the machine. The remaining lines are routed through the cryogenic bypass without interruption, resulting in no changes for the operation of the continuous arc cryostat, especially regarding helium circuits and insulation vacuum. Independent supporting of the collimator and cryogenic bypass could be achieved, allowing to decouple their installation and alignment.

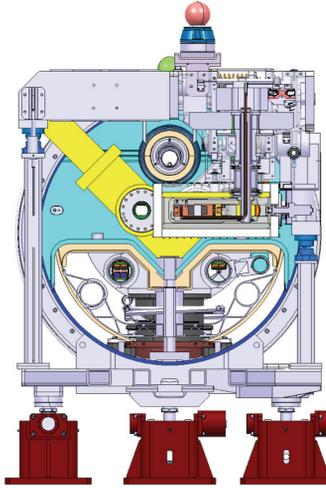


Figure 2: Transverse cross section of the cryogenic bypass and collimator.

CRYOGENIC BYPASS

The cryogenic bypass (Fig. 3) shall route the 1.9 K, 5-20 K and 50-65 K helium circuits and the magnet powering busbars of the LHC continuous cryostat, such as to create the space required for the installation of the collimator independently from the operation of the cryogenic and insulation vacuum systems of the LHC arcs [3]. A vacuum insulated inner vessel containing the superfluid 1.9 K helium bath also acts as pressurised vessel in the event of a magnet quench. An active thermal shield at 50-65 K intercepts the radiation heat load. Glass fibre reinforced epoxy support posts, thermalised at 50-65 K and 5-20 K, hold the inner vessel with minimum thermal losses. In order to allow a possible installation in the following LHC long shutdown, the design was made around proven solutions making use of components available from the stock of LHC spares. This includes the cold support posts, aluminium extrusions for the thermal shield, instrumentation feedboxes, beam vacuum components, cold mass end covers, etc. Interconnect interfaces are mostly the same as in the neighbouring magnets, for standardisation of tooling and procedures.

Superfluid Helium Vessel and Busbar Routing

The solution adopted for the helium vessel consists of two small volumes connected by three pipes. The upper pipe houses the two-phase heat exchanger and the two lower pipes are used for busbar routing. This configuration provides both a free cross section of 79 cm² for heat transfer by conduction through the superfluid

helium and low hydraulic impedance. Moreover, it forms a balanced structure avoiding end effects from the internal pressure. The two volumes are used to route the three pairs of 13 kA busbars from the standard interconnecting positions to the bypass lines. They also house the busbars fixed point and the flexible lyras for compensation of thermal contraction. The vessel is designed for a maximum allowable pressure of 20 bar, and meets both the requirements of EN 13458 and EN 13455 [4]. Given the geometry of the vessel, which falls out of the scope of the formulas in construction codes, design by analysis procedures had to be followed. The structural checks included also the interconnect forces generated in the bellows, resulting from potential misalignments at the interfaces. In general, the design is driven by stiffness requirements and not by strength. The only exception is the interface between the beam tubes and the flat covers on the cold to warm transition side. Here, membranes designed to be longitudinally flexible whilst behaving rigidly to transverse loads were introduced in order to accommodate the 0.5 mm deflection of the flat plates, without overstressing the welds to the beam tubes. The volumes are made from 316LN with specified maximum inclusion content to prevent leaks across the material. The tubes are seamless and made from 316L. All expansion joints are from the stock of LHC spare components.

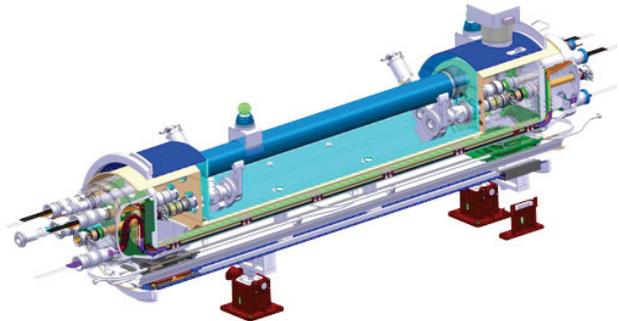


Figure 3: Cut view of the cryogenic bypass.

Radiation Shielding

As in the LHC magnet cryostats, the mechanical stiffness of the thermal shield is provided by an aluminium 6061 extrusion, which includes the pipe for active cooling with helium gas. Aluminium 1050 sheets 2.5 mm thick, joined by welding over 25% of the seam length, ensure enough thermal conductance to prevent hot spots. The maximum expected temperature gradient is 11 K, with the hottest spot at the centre of the conduction cooled tube shielding the heat exchanger line. Additional passive insulation is wrapped around the inner vessel and the thermal shield, consisting of 10 and 30 layers of multilayer insulation (MLI), respectively.

Cold Supports

Two carbon fibre reinforced composite cylindrical tubes act as support posts for the helium vessel, supporting both the weight and interconnect loads [5]. Since the welding work of the vacuum vessel can only be

finished with the inner vessel and thermal shield already in place, the resulting welding deformations may displace the support bases, thus imposing a re-alignment. The support bases were designed aiming for a quasi-isostatic support scheme during alignment, after which they are blocked, providing the reaction to the transversal interconnect forces.

Vacuum Vessel

The high current flowing through the busbars is enough to generate a magnetic flux density around the collimator a factor of 30 above the specified 0.06 mT limit for the high accuracy linear position sensors (LVDT), used in the jaw position control. This was solved by making the vacuum vessel from mild steel instead of stainless steel, which is enough to create a magnetic shielding effect, lowering the magnetic flux density outside the cryostat down to acceptable levels. The selected steel grade is P355NL2, a normalised fine grade steel for pressure purposes with specified minimum Charpy energy of 27 J in all directions, when tested at -50 °C.

COLLIMATOR

Despite the efforts to design a cryogenic bypass which maximises the space around the beam lines, the volume left for the collimator still meant a major integration challenge. The supports for the tungsten, the cooling and the actuation system had to be built around the beam lines and heat exchanger line, without entering the volume reserved for transport in the tunnel (Fig. 2).

Collimator Jaws and Cooling

Each of the two 1 m long active parts is composed of five tungsten blocks 200 mm in length, 30 mm height and 20 mm width (Fig. 4). The tungsten alloy is Inermet IT180®, with chemical composition 95% W, 3.5% Ni and 1.5% Cu. These are bolted to Glidcop® C15715 (0.15% Al₂O₃ dispersion strengthened copper) bars on the back of which a Cu-Ni alloy cooling circuit is vacuum brazed. A 1.5 MPa contact pressure between the tungsten blocks and the Glidcop bars ensures adequate thermal conductance for cooling. A back stiffener in Glidcop provides additional rigidity to the assembly.

The cooling tubes are routed out of the vacuum chamber along the support shafts. Electrical pick-up buttons at the jaw extremities (four in total) have been introduced to allow the calibration of the positioning system directly with the beam, significantly reducing the setup time. Welded bellows are used to transfer the movement across the 304L stainless steel vacuum barrier. The design heat loads per jaw are 40 W in steady state operating conditions and 200 W in transient conditions, the latter corresponding to 0.2 hours beam life time. From thermo-mechanical simulations, they are expected to yield a deflection of 12 µm and 20 µm, respectively, well below the specified value of 50 µm. Two PT100 transducers are installed for temperature diagnostics.

Actuation System

Each jaw is controlled in position within a maximum stroke of 25 mm. Stepper motors are operated in an open-loop control scheme with a resolution of 5 µm. Three LVDT position transducers are used for interlock and calibration purposes (one per jaw plus one for direct check of collision between jaws and redundancy). A reversible roller screw, pre-loaded with a spring to eliminate the play, converts the rotational motion into translation. The same spring gives the possibility of auto-retraction of the jaws in certain cases of motor failure, and in all situations prevents undesired movement towards the beam. Linear ball bearings installed on Ø40 mm cylindrical shafts, dry lubricated with graphite, support the weight of the jaws and precision guide the movement.

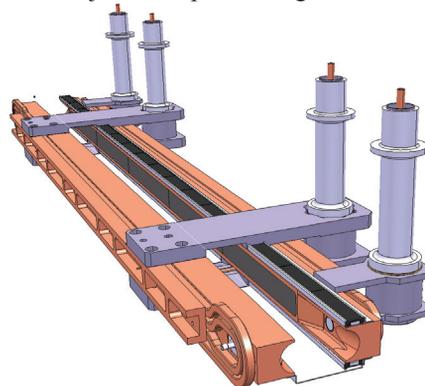


Figure 4: Collimator jaw assembly with cooling circuit and cantilevered support shafts.

CONCLUSION

Installing additional equipment in the continuous cryostat of the LHC presents a major integration challenge. The design presented here provides the means to install collimators operating at room temperature, thus remaining accessible for intervention. This is achieved by interrupting the cold beam vacuum chamber and creating new warm sectors. It was possible to reduce the total length required per collimator to 4.5 m with a design that adopts proven technological solutions and many standard LHC components. Other applications may be envisaged for the cryogenic bypass, such as the installation of new detectors.

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