BEAM-BEAM LONG RANGE COMPENSATOR MECHANICAL DEMONSTRATOR

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Abstract

Beam-Beam Long-Range Compensators employing current-carrying wires are considered as valuable options in hadron colliders to increase dynamic aperture at small crossing angles. This paper presents a simple design proposal for application at CERN LHC. The preliminary design allows for a certain scalability of the number of modules, current flowing in the wire, and dimensions. It complies with two key requirements: (a) the use of a thin, bare metal wire that allows for movement as near to the beam as necessary while minimizing interactions with beam particles and meeting the specified DC current target; and (b) a wire support that is both an electrical insulator and a thermal conductor (ceramic). A molybdenum wire, vacuum brazed on an aluminium nitride support, is proposed, and the design is conceptually proved through the realization and extensive test of a demonstrator device. The wire brazing validation, as well as the system's heat management, which are the most critical aspects, are given particular regard.

INTRODUCTION

Beam-Beam Long Range (BBLR) interactions are well recognized as one of the machine performance restrictions in hadron colliders like the LHC [1]. Their influence decreases the beam lifetime and the collider integrated luminosity [2]. A BBLR Compensator (BBLRC) embedding a DC current carrying wire and movable in the transverse plane of the particle beam, represents a possible solution to counteract these effects [3]. A mechanical design for this device is proposed for the CERN LHC machine and its luminosity upgrade.

The envisioned BBLRC unit consists of three 1.15 m long independent modules per beam, each hosting a 1 mm diameter molybdenum wire. The three modules per beam are installed on a single support in two parallel assemblies. Each assembly features a dedicated actuation system. This allows moving the modules (therefore the wire) both in the vertical and horizontal planes.

The wire in each module has an active (straight portion) length of 1 m and carries a DC current up to 150 A. For each module, the estimated Joule-effect dissipated power is approximately 2.1 kW and, for this reason, the wire is vacuum brazed on three aluminium nitride (AlN) blocks. This system is used to mechanically support the wire and electrically insulate it from the copper components of the vacuum chamber. The AlN support is mechanically clamped to a copper housing featuring a water cooling channel. Given the good thermal conductivity of pure AlN, this allows to significantly cool down the molybdenum wire during operations. The described BBLRC module is shown in Fig. 1.

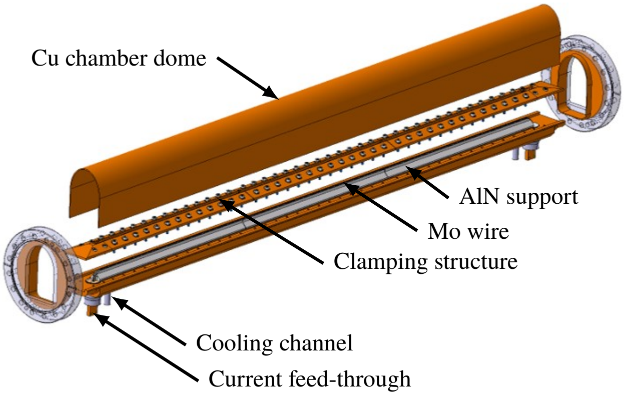

Figure 1: Exploded view of a single module of the BBLRC.

From preliminary thermal simulations, with a water flow of 1.5 m s^{-1} (i.e. 12 L min^{-1}) the wire reaches a temperature of around 90 °C in the straight section and up to 140 °C in the end transitions, where active cooling is less effective due to greater distance from the cooling channel.

The vacuum brazing represents the most critical step in the assembling process since, in case of bad contact between the wire and the support, a thermal runaway may occur. To validate the brazing procedure and design concepts a cost-effective, short (290 mm long), BBLRC demonstrator was built. This paper aims to describe this demonstrator device and show the results of the extensive thermo-mechanical test campaign executed on it.

THE MECHANICAL DEMONSTRATOR

The mechanical BBLRC demonstrator, shown in Fig. 2, has been designed to allow performing several tests. The device can be opened to mount/dismount the AlN support with the wire brazed on it, enabling the testing of two different wire diameters (0.8 mm and 1.0 mm). This version of the device can be tested in air and under vacuum at 0.01 mbar. Values of pressure for this configuration cannot go lower due to the fact that the device has to be opened. Moreover, thanks to optical viewports, it is possible to perform IR camera thermal measurements. A second welded version could be realised with limited modifications to the first one. This will be done in future studies to allow for Ultra High Vac-

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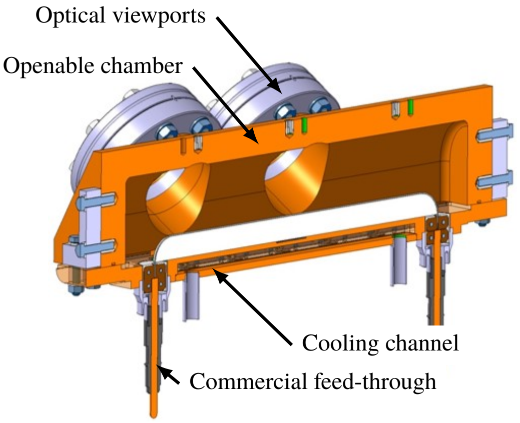

Figure 2: BBLRC demonstrator cut view.

uum (UHV) and material outgassing tests. The device was mounted on a test bench with: a thermal IR camera (FLIR E75), voltage taps, temperature sensors (PT100, placed with a contact force of 5 N-15 N) close to hot-spots (i.e. the inlet and outlet sections of the wire), temperature sensors at the inlet and outlet of the cooling channel, and a flowmeter. The wire was then connected to a DC power supply able to provide a maximum of 400 A and 15 V. This setup and, more specifically, the one used during in-air testing, is shown in Fig. 3.

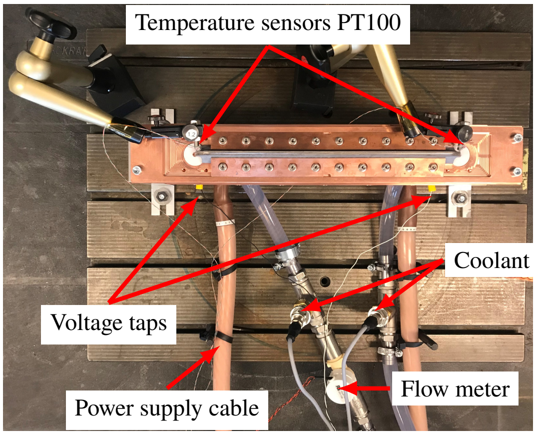

Figure 3: Top view of the test bench used during in-air measurements. The copper housing is unmounted. The IR camera is not shown in the figure but is present in the setup.

TESTING RESULTS

Fabrication of the demonstrator device and its testing were performed from October to December 2021 respectively in the CERN EN-MME main workshop and mechanical laboratory. Tests are divided in: in-air tests, for which the demonstrator Cu dome was removed, thus allowing to get better thermal IR images of the structure, under primary vacuum, and voltage drop tests both in-air and under vacuum.

In-Air Tests

In-air tests were performed both with step-wise (30 A increments per step) and single bursts of injected current.

With 150 A of injected current in the 1 mm diameter wire, the temperature measured with PT100 probes located close to the hot-spots is slightly below numerical predictions (the measured temperature is around 80 °C while the numerically predicted values are close to 100 °C). The temperature measured on the straight portion of the wire using an IR camera is in line with simulations and it is shown in Fig. 4.

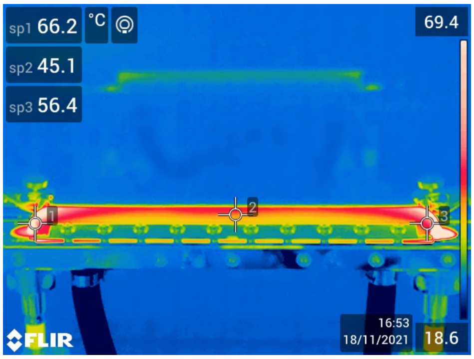

Figure 4: Lateral view picture taken with a FLIR E75 IR camera thermal measurements for in-air testing with 150 A injected in the 1 mm wire. All screws clamping the insulator in place have a 1 N m torque

After tests with 180 A of injected current, clear signs of oxidation were found mostly at the outlet-side transition between insulator and wire clamp, where a hot-spot (shown in Fig. 5) is created due to local lack of brazing. This phenomenon would not occur in an under vacuum environment.

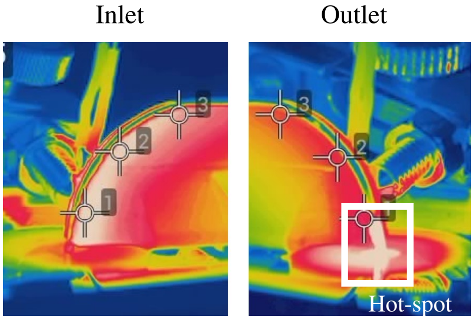

Figure 5: Close-up picture taken with the FLIR E75 IR camera showing a hot-spot in the outlet region where the ending of the wire is clamped to the feedthrough.

This last identified issue of oxidation has been particularly detrimental for the 0.8 mm wire. Specifically, the molybdenum oxide that forms tends to peel off, reducing the effective wire cross section, hence decreasing its electrical conductance. Ultimately, in this scenario, it resulted in the wire breakage (See Fig. 6). It is worth highlighting that, even tough the 0.8 mm diameter wire failed during tests, the major root cause (oxidation) is absent under vacuum. Yet this indicates that too small cross sections could present risks.

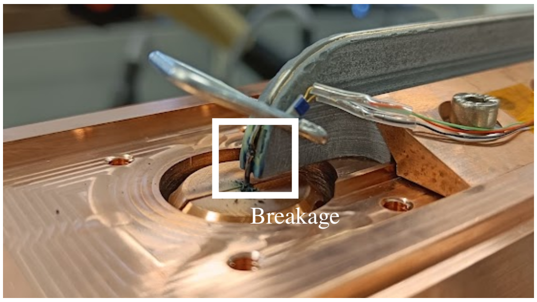

Figure 6: Breakage of the 0.8 mm diameter wire during in-air tests.

Under Vacuum Tests

Similar testing as the one conducted in-air and previously reported was carried out under primary vacuum (0.01 mbar) on the 1 mm thick wire. The wire was cleaned from the oxide that had formed in the preceding tests. Moreover, one additional temperature sensor was placed at the middle of the insulator to allow a better thermal mapping of the structure. Under primary vacuum, other than not having oxidation issues, temperature measurements indicate values lower than in-air testing. This is because, despite the lack of natural convection, thermal diffusion is improved by the additional mass of the copper dome. As a comparison and to sum up the results from the temperature PT100 probes, in Fig. 7, stationary temperatures measured at different injected currents are shown.

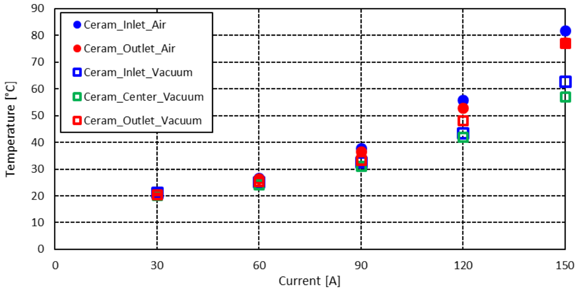

Figure 7: Measured temperature points on the aluminium nitride support with PT100 probes for the 1 mm thick wire during in-air and under vacuum tests.

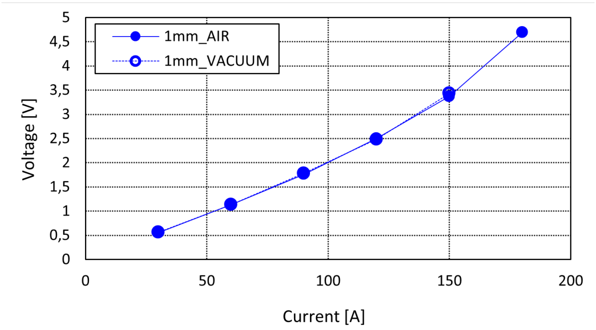

Figure 8: Measured voltage drop for every current step.

Voltage Drop

Thanks to the voltage taps, it was possible to measure the voltage drop. In the case of the ⌀1 mm wire, the drop is around 3.5 V with a current of 150 A. With a rough extrapolation the expected drop for a 1 m long wire is around 12 V. This value is slightly lower than predictions (around 14 V) and this discrepancy can be related to the contribution of the conductive brazing alloy. In Fig. 8 the voltage drops for each current step is reported both for in-air and under vacuum tests.

CONCLUSION

In this paper a simple, cost-effective, modular design for realizing a BBLRC was presented. The design employs a 1 mm thick molybdenum naked wire brazed onto a ceramic insulator and has shown promising results. A demonstrator was manufactured and tested to validate the concept, in particular the vacuum brazing. The studies showed that the 1 mm diameter wire is viable, with measured temperatures in line with or lower than expectations provided by numerical simulations. The 0.8 mm diameter wire failed under testing due to oxidation. It is worth to point out that this issue will not be present under vacuum. Still the 1 mm diameter wire was preferred.

The absence of any major showstoppers during the preliminary study indicates that this concept has significant potential for further development.

However, the preliminary design did not consider several key aspects, such as beam and RF losses, fabrication tolerances, UHV and secondary electron yield compliance, ceramic charging effect, etc. These factors should be the object of a proper design study to ensure the viability of the concept.

Overall, the results suggest that the concept is ready for a full-fledged design that includes interfaces, motorization, integration, RF and electromagnetic optimization, and other factors that were not considered in the preliminary study. This will help to fully validate the concept and ensure its viability for further development.

ACKNOWLEDGEMENTS

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