

# ANALYSIS OF REMAINING FATIGUE LIFE OF EDGE WELDED BELLOWS FOR LHC COLLIMATORS

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## Abstract

Following the detection of several leaks on edge-welded bellows (EWBs) in the Large Hadron Collider (LHC) collimators, an investigation campaign was initiated to better understand the fracture behaviour of EWBs subject to lateral movements. The campaign led to dedicated experimental fatigue tests performed on multiple EWB geometries, originating from different production batches and tested at various cyclic amplitudes. The effects of bake-out were also evaluated. Supported by metallographic analyses of membrane edge-weld fractures, the study revealed a wide spread in EWB fatigue life. Experimental results, combined with real movement data from the EWBs installed in the LHC, were used to estimate the remaining fatigue life of EWBs used in LHC collimators. This analysis enabled the optimization of the EWBs lateral movements during LHC operation to extend service life, the identification of collimators at risk of developing leaks, and the development of mitigation strategies to minimize operational impact. The findings highlight the importance of high safety margins when designing critical components whose service life is governed by fatigue mechanisms.

## INTRODUCTION

LHC collimators are essential devices with multiple functions, including the protection of sensitive LHC equipment (e.g. superconducting magnets), efficient beam-halo cleaning and background control of beam particles [1, 2].

Collimators intercept beam particles by means of movable jaws made of particle-absorbing material (cf. Fig. 1). Although these jaws are located inside the primary vacuum of accelerators, their actuation is performed from the outside of the vacuum. Motion is transmitted across the vacuum boundary through flexible edge-welded bellows (EWBs), which allow jaw displacement by lateral deformation.

For axial motions of EWBs, fatigue models have been developed [3–5]. Furthermore, manufacturers relying on semi-empirical methods are able to estimate EWB fatigue life with reasonable confidence. By design, purely lateral motions of edge-welded bellows (cf. Fig. 2) produce a non-uniform stress distribution across its membrane pairs (MPs), making it more complex to predict EWB fatigue life.

In 2022, the first leak occurred on an EWB. The leaking collimator provided the first evidence of limited life

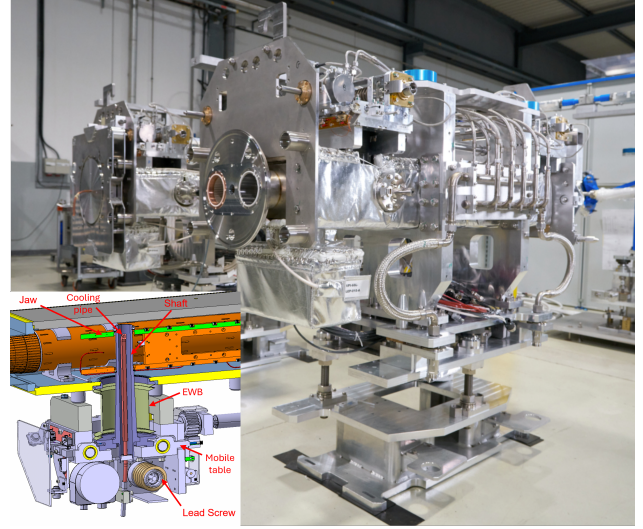


Figure 1: High Luminosity LHC prototype collimators with schematic of collimator jaw movement mechanism.

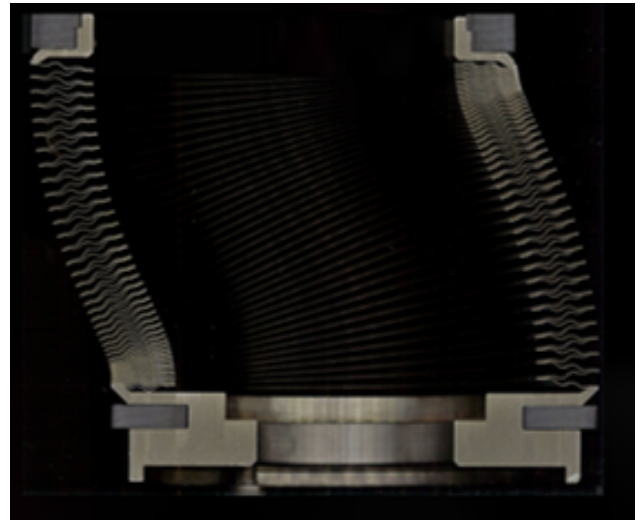


Figure 2: Cross section cut of an EWB performing a purely lateral movement.

expectancy of LHC EWBs. In 2023, a second EWB leak appeared on a critical collimator dedicated to injection protection (TDIS). The EWB leak was sealed with “vacseal” and the collimator EWB was blocked in a fixed position. A second EWB leak occurred on a collimator with the same function a week later requiring the LHC to operate in a de-

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graded configuration for several weeks until the collimator was replaced.

Following the incidents, it was discovered that manufacturers contracted by CERN had delivered a significant number of EWBs, produced that did not comply with CERN specifications. As a result, these EWBs were expected to fail before reaching the number of cycles required to cover the lifetime of LHC collimators. These EWBs were produced by two different suppliers but also came from different production batches, with batches progressively delivered during the 15+ years of LHC operation and new collimators production.

As lateral loading of EWBs is a non-standard operating mode, the manufacturer experience with the lateral movement collimator constraint is limited. Most EWB manufacturers contracted by CERN were not able to accurately estimate the fatigue life of manufactured EWBs as they lacked both experimental data and appropriate technical tools to predict EWB fatigue life under lateral loading.

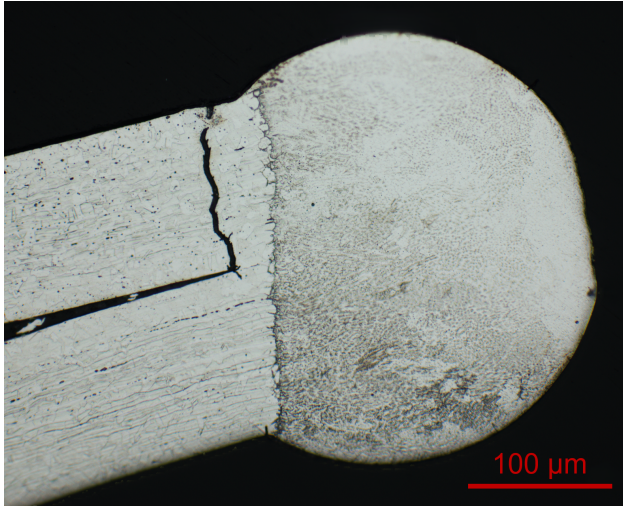


Figure 3: Microscopy of an EWB membrane fracture located in the heat affected zone of the inner laser beam weld of an EWB. MPs of EWBs, including MPs in this figure, are generally made out of 316L stainless steel.

During lateral motion, the MPs at the extremities of the bellows experience the most deformation, being separated the most on one side while remaining in contact on the opposite side (cf. Fig. 2). Consequently, these end MPs are subject to the highest levels of stress during lateral loading. Post-mortem examinations of EWBs further corroborated this behaviour, revealing that cracks and leaks developed consistently in these same MPs, near the inner beam-side welds of the bellows (cf. Fig. 3).

## EWB FATIGUE TESTS

Experimental fatigue tests on EWBs were performed at CERN and by a bellows' manufacturer to assess the fatigue life (defined as the number of cycles that a sample can sustain before failure) under repeated lateral displacements (i.e. cyclic loading). The study was initiated to understand the

fracture behaviour of EWBs and estimate the remaining service life of the bellows installed on LHC collimators.

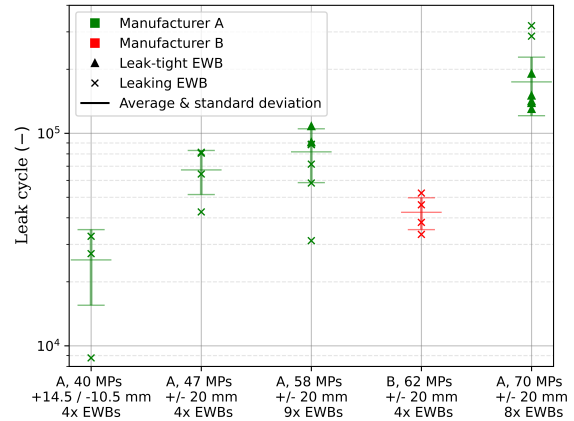


Figure 4: Experimental fatigue life measurements of LHC collimators EWBs as a function of the number of MPs on EWBs, lateral cycling amplitude or manufacturer. Leak-tight EWBs denote cycling tests that were stopped before EWB failure.

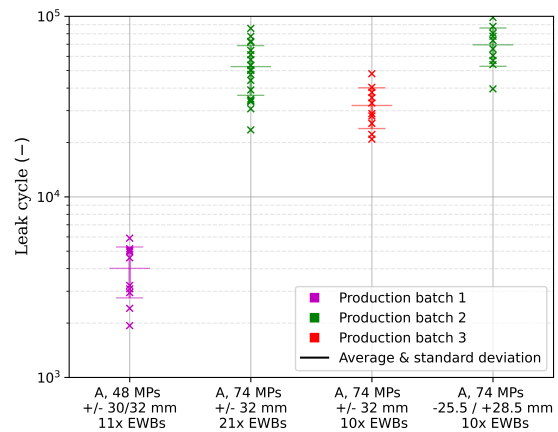


Figure 5: Experimental fatigue life measurements of LHC injection collimators (TDIS) EWBs as a function of the number of MPs on EWBs, lateral cycling amplitude.

The experimental fatigue results reveal that the number of MPs is one of the key parameter driving the fatigue life of EWBs. Figure 4 shows that increasing the number of MPs from 47 to 70 increases EWB fatigue life by a factor of 3. In Fig. 5, the increase of the number of MPs from 48 to 74 MPs for EWBs used for injection devices (TDIS) led to a 10× increase of fatigue life. This increased performance is directly correlating with the reduction of membrane separation during cycling and associated stress levels in these membranes.

By testing comparable EWBs from different manufacturers, it was further observed that the fatigue life varies significantly between manufacturers. This variability is likely related to factors such as the choice of cold-rolled steel sheets (materials properties including yield strength

and ultimate tensile strength), the tolerances achievable by manufacturing equipment, and laser beam welding capability and experience. Based on additional tests on EWBs from another manufacturer, which are not reported here, the variation in fatigue life from one manufacturer to another can be estimated to be as large as a factor of four.

Additionally, more severe discrepancies were observed when one of CERN's manufacturers tested EWBs with unusual discolouration appearing after a 300 °C bake-out. Discussions with the supplier led to the assumption that laser beam welds had not been performed correctly. Without bake-out, the defect may not have been noticed, leading to the installation of defective EWBs on LHC devices. This weld manufacturing issue resulted in a reduction in fatigue life by a factor of approximately six.

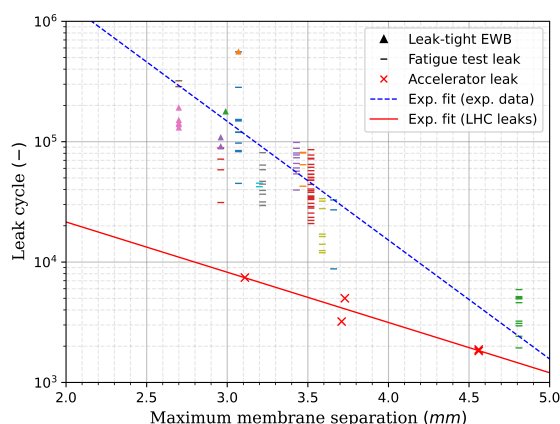


Figure 6: Comparison of EWB fatigue tests with LHC collimators EWB leaks. With differences in the number of MPs on EWBs installed on LHC collimators or tested, the lateral stroke was converted into simulated maximum membrane separation during cycling.

Maximum membrane separation during regular cycling movements, which can be simulated via finite element analysis accurately, was chosen as a correlation parameter to evaluate the remaining life expectancy of EWBs installed on LHC collimators. This parameter also directly correlates with the level of stress in the EWB membranes.

In Fig. 6, the recovered cycling data of leaking collimators is compared to all the fatigue tests conducted. Membrane separation is a parameter that allows one to compare different EWB geometries with different numbers of MPs with relative simplicity.

## Discussion

From the EWB fatigue tests and microscopic analysis of cracks next to edge beam welds, it is expected that the fatigue life variation depends on a range of factors including stainless steel properties, quality of the laser beam welds, amplitude of cyclic loading, dimensions of the EWB, number of MPs, etc. The fact that EWBs used in the LHC were manufactured 15 years ago at most, from material batches with unknown properties, has made it nonetheless non-trivial

to extrapolate the experimental results of EWBs from recent productions to the fatigue properties of EWBs installed on LHC collimators. The LHC EWB leaks were always reported to appear at much earlier stages than the leaks on EWBs tested with regular cyclic loading. The significant difference (cf. Fig. 6) may partially be explained by the different leak detection capabilities differences on the EWB test bench and in the LHC. On the EWB test bench, only leaks exceeding  $10^{-5}$  mbar L s<sup>-1</sup> can be detected, whereas in the LHC He leak rates below  $10^{-6}$  mbar L s<sup>-1</sup> are usually detected. Finally, the repetitive bake-outs and irradiative environment in the LHC may have also contributed to the fatigue life of EWBs on LHC collimators. A single bake-out (300 °C, 48 hours) of EWB prior to fatigue testing was found to not have any discernible effect on the EWB fatigue life, yet repetitive bake-out in the LHC (up to 30) may have had a measurable effect on EWB fatigue life. Studies are still ongoing to evaluate at best the remaining life of collimators in order to maintain the LHC collimation system and allow the LHC to run with limited interruptions until its planned end of life in 2041. Efforts were already conducted to limit the lateral stroke of EWBs during LHC operation by optimizing the movement of jaws, notably during beam injection.

## CONCLUSIONS

The main conclusions are the following:

- EWBs fatigue life is strongly dependant on the number of MPs when performing lateral strokes. Increasing the number of MPs on EWBs for this type of application reduces stress levels in membranes and improves significantly the life expectancy of EWBs.
- Significant variation of fatigue life was observed across EWB production batches and manufacturers. These differences may be explained by differences in material properties, manufacturing tolerances, EWB geometry and laser beam weld expertise.
- Observed differences between the fatigue life of EWBs obtained experimentally and from the post-processing of the cycling history of EWBs installed on LHC collimators may possibly be explained by differences in production year, manufacturer capabilities, material properties, and differences of leak detection thresholds.
- Given large uncertainties on EWB fatigue life, EWBs performing lateral movements and which are designed to last decades without maintenance or repairs, should rely on significant EWB fatigue safety factors ( $\sim 20$ ).

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