A CLAMPED Be WINDOW FOR THE DUMP OF THE HIRADMAT EXPERIMENT AT CERN

M. Delonca*, T. Antonakakis, D. Grenier, C. Maglioni, A. Sarrió Martínez,
CERN, Geneva, Switzerland

Abstract

At CERN, the High Radiation to Materials facility (HiRadMat) is designed to test accelerator components under the impact of high-intensity pulsed beams and will start operation in 2012. In this frame an LHC TED-type dump was installed at the end of the line, working in nitrogen over-pressure, and a 254μm-thick beryllium window was placed as barrier between the inside of the dump and the external atmosphere.

Because of the special loading conditions, a clamped window design was especially developed, optimized and implemented, the more standard welded window not being suitable for such loads. Considering then the clamping force and the applied differential pressures, the stresses on the window components were carefully evaluated thanks to empirical as well as numerical models, to guarantee the structural integrity of the beryllium foil.

This paper reports on choices and optimizations that led to the final design, presenting also comparative results from different solutions and the detailed results for the adopted one.

INTRODUCTION

The HiRadMat facility will use an extracted beam from CERN's Super Proton Synchrotron (SPS) to test accelerator components as well as raw material under controlled conditions [1]. An LHC TED-type dump was positioned at the end of the testing line to stop the incoming beam. The core of the dump is maintained in nitrogen (N2) over-pressure so that a window is required to separate it from the external atmosphere. Considering the beam loading, it appears that the only suitable material for the foil of the window is Beryllium [2]. Indeed, due to its low density, the punctual increase of temperature induced by the energy deposited remains well under its maximum service temperature and the induced stresses are considered as acceptable.

In order to fill the dump cavity with pure nitrogen, a preliminary vacuum is required. During this first phase, a pressure of 1 bar is applied on the Beryllium foil. Then, due to the nitrogen filling, the foil will be loaded by 0.1 bar over-pressure in the opposite direction.

The present paper describes the process which leads to the final design of the window, taking into account the leak tightness requirement as well as the specific load cases.

*melanie.delonca@cern.ch

DESIGN

A standard foil-to-flange welded design was firstly studied for this application, and subsequently discarded due to the double directional pressure.

Based on previous design of clamped windows, a first clamped configuration of the window was then specified. This first design made use of a 254 μm-thick Beryllium foil (diameter of 101 mm), clamped between two copper joints and two stainless steel flanges (solution 1, Fig.1). The leak tightness is ensured through knives in the flange penetrating in the copper joints and thanks to a chicane on the copper joints directly in contact with the Beryllium foil. Thanks to a 28 Nm torque applied on 16 clamping screws, the knives deform plastically the copper joints while the chicane stresses the Be foil over its yield limit [3].

A second configuration was defined with the same 254 μm-thick Beryllium foil and two stainless steel flanges. However, here the leak tightness is ensured through an Indium wire positioned on the nitrogen side of the window, between the Be foil and one of the flanges (solution 2, Fig.1). The torque applied on the screw is ~ 10 Nm.

In both cases, the geometry was optimized thanks also to the analytical results obtained as presented below. Firstly, a Carbon-Carbon (CC) plate is positioned on the N2 side to support the differential pressure of 1 bar due to the primary vacuum. The gap between the CC plate and the foil must be fixed at 0.2 mm, value estimated to effectively support the foil while being acceptable from a manufacturing standpoint. In order to ensure this gap, an adjustable stainless steel washer is placed between the CC plate and the lower flanges. Secondly, the inner diameter of the upper flange is reduced to 70 mm so that the free-bending diameter of the Beryllium foil is reduced when 0.1 bar over-pressure is applied.

Due to its fragility, the mechanical behavior of the Beryllium foil represents a major issue for both clamped solutions. The foil will be submitted to three phases of load: a first phase of clamping followed by an application of 1 bar of pressure and 0.1 bar of counter-pressure. The periphery of the foil is the most critical location since it is solicited during all three loading phases. The structural behavior of the foil in this location has been studied analytically using empirical formulae and is reported hereafter.

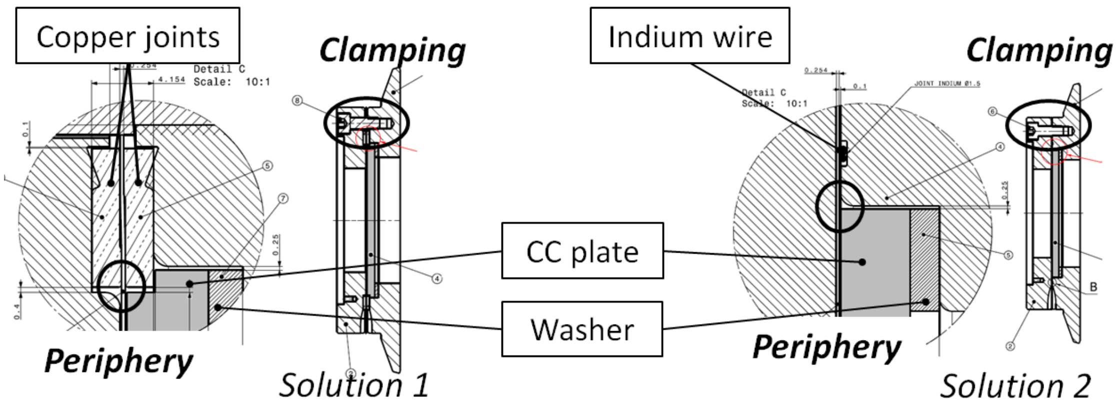

Figure 1: Design of the two studied solutions.

A precise evaluation has been done thanks to the development of numerical models and is presented in the last part of this paper. The centre of the foil where the beam deposits energy is not considered in this paper but was analyzed in a complementary study [2].

ANALYTICAL ESTIMATES

Clamping Phase

Due to the complex geometry, an analytical estimate of the stress induced by the clamping on the periphery of the foil can be done only if considering the clamping system itself (screws, knives/copper joints set and Indium wire) far enough from the location of interest. Indeed, in this case, the clamping stresses are estimated through surface to surface pressure contact between the foil and the Copper joint/flange. Thus, the foil can be considered as in a pure compressive state and the average stress due to the clamping can be calculated with [4]:

$$\sigma = \frac{C}{\left(\frac{P}{2\pi} + 1.166 R_t \mu_t + R_h \mu_h\right) S} \quad (1)$$

where C is the torque (Nm) applied on the clamping screws, σ (Pa) is the pure-compressive stress in the Be foil, S is the surface (m2) of compression, and P, R_t, μ_t, R_h and μ_h are the characteristics of the screws (respectively the thread pitch, the effective radius of thread contact, the coefficient of friction in threads, the effective radius of head contact and the coefficient of friction under head).

Application of Pressure

At the periphery of the foil, stresses are due to the clamping force (axial stress) and to the application of pressures (flexural and diaphragm stresses).

Roark's formulae allow the flexural and diaphragm stresses due to the differential pressure to be evaluated [5].

The foil is considered to be flat, of uniform thickness and made of a homogeneous isotropic material. All the forces are assumed to be normal to the foil and large deformations are also taken into account.

Finally, the results are valid only within the elastic limit of the foil material.

Considering these assumptions, the following equations can be used to evaluate the deflection and the stresses at the periphery of the foil:

$$\frac{qa^4}{Et^4} = K_1 \frac{y}{t} + K_2 \left(\frac{y}{t}\right)^3 ; \frac{\sigma a^2}{Et^2} = K_3 \frac{y}{t} + K_4 \left(\frac{y}{t}\right)^2 \quad (2)$$

where q is the applied pressure (Pa), a is the free bending-radius of the foil (m), t is its thickness (m), E the Young's modulus of the foil material, y is the deflection (m) and σ is the stress at the periphery of the foil (Pa).

The values of the coefficients K_i ($i = 1..4$) depend upon the boundary conditions at the edge (Table 1). The two solutions studied have the same edge conditions, fixed and held, which correspond to an embedded foil.

Table 1: K coefficients for Eq. 2

Edges conditions	K_1	K_2	K_3	K_4
Fixed and held	$\frac{5.33}{1-\nu^2}$	$\frac{2.6}{1-\nu^2}$	$\frac{2}{1-\nu}$	$\frac{4}{1-\nu^2}$

The total von Mises equivalent stresses [6] at the periphery of the foil can be then calculated by taking into account the direction of principal stresses. The flexural and diaphragm stresses (2) are radial whereas the clamping stresses (1) are axial.

Considering the assumptions made for the Eq. 2, the analytical results do not take into account the behavior of the foil above the yield limit. Also, the clamping force and corresponding stresses are evaluated based on the total contact surface S, hence no concentration of stresses is taken into account.

NUMERICAL ANALYSIS

The mechanical behavior of both solutions has been analyzed numerically, to allow their complex geometries to be taken into account in details and the stresses in the entire foil and more precisely the clamping zone, to be evaluated.

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Two 2D-axisymetric models were developed, representing the full geometry of the two solutions.

Beryllium is assumed isotropic, and modeled with a multi-linear isotropic hardening behaviour [7], so that the plastic domain is taken into account.

For both solutions, the loading was implemented by following the three loading phases previously described. For each phase, the maximum von Mises equivalent stress at the periphery of the foil is reported in Table 2. For every maximum stress value, the safety factor is calculated based on the yield strength, which has been estimated at 345 MPa, while the ultimate strength is 496 MPa. The ultimate elongation is of 6.8 % [8].

Table 2: Summary of von Mises Equivalent Maximum Stresses in the Be Foil

Phase	Parameter	Units	Sol.1	Sol.2
Clamp	σ_{max}	MPa	436	71
	SF	-	*0.8*	*4.8*
1 bar	σ_{max}	MPa	453	324
	SF	-	*0.76*	*1.06*
0.1 bar	σ_{max}	MPa	437	165
	SF	-	*0.8*	*2.1*

For the clamping phase, in the case of solution 1, the numerical analysis shows a high risk of failure of the Be foil since the maximum stress is closed to the ultimate strength.

This happens when the knives of the flanges penetrate in the copper joints, creating a high concentration of stress in this region. Possible cracks there would certainly cause a degradation of the leak tightness of the window. For solution 2, the stresses induced by the clamping phase are much lower, since the clamping force required is smaller and the Indium wire induces a much lower concentration of stresses.

When 1 bar relative pressure is applied, the periphery of the foil is stressed beyond its yield limit in solution 1 so that the foil enters in plastic domain at the periphery, inducing a risk of failure once again. This does not happen with solution 2 where the stresses remain below the yield limit.

Finally, with 0.1 bar over-pressure in the opposite direction, the stresses are beyond the yield strength for solution 1 while for solution 2, they remain within the yield limit. In case of solution 1, the presence of an earlier plasticization of the periphery has a great influence on the final value of the stress.

TESTS

Tests were done for both solutions. The windows were assembled and the clamping force applied. Finally, a pressure of 1 bar was smoothly applied, followed by an overpressure of 0.1 bar.

After each pressure application, the leak tightness was controlled.

It appears that, for solution 1, the foil is already damaged during the clamping phase (even though not a clear failure), compromising the leak tightness but not its structural functionality (Fig. 2).

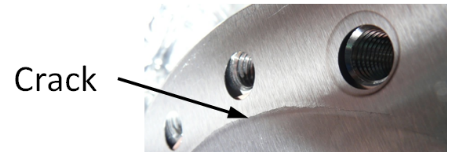

Figure 2: Crack on Beryllium foil after application of the clamping torque, solution 1.

For solution 2, the beryllium foil is not damaged, neither during the clamping phase or the application of pressure. The leak tightness is ensured up to 1.10^{-6} mbar.l/s.

These tests validated the numerical analysis and demonstrated the brittle behaviour of the Be foil.

CONCLUSIONS

Beryllium is the only possible candidate as foil material on a thermal point of view [2].

However, due to its brittle behaviour, the stresses in the foil have to remain lower than its yield strength.

Two different design solutions have been optimized and analysed in details.

Solution 2, which make use of an Indium wire, has been found to minimize stresses during the clamping phase and guarantee leak tightness in operational conditions.

Indeed, this design requires a smaller clamping torque, reducing the clamping stresses. Tests, in good agreement with simulations, demonstrates that the Be foil fails at some locations for solution 1.

Design solution 2 has hence been chosen for the window, manufactured and installed in front of the LHC TED-type dump in the HiRadMat facility.

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