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FINITE ELEMENT ANALYIS AND EXPERIMENTAL VALIDATION OF LOW-PRESSURE BEAM WINDOWS FOR XCET DETECTORS AT CERN

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Abstract

In the framework of the renovation and consolidation of experimental areas at CERN, a low-pressure design beam superimposed windows (250 µm Mylar and 150 µm polyethylene) for the Threshold Cherenkov counters (XCET) has been modelled and verified for its implementation. The XCET is a detector used to count the number of selected charged particles in the beam by adjusting the pressure that leads to the emission of Cherenkov photons only above certain pressure threshold. Simultaneously, the charged particles pass from a vacuum environment to the pressurized refractive gas vessel through a solid interface. Minimal material in this solid interface is therefore crucial to avoid interactions of the low-energy particles which may lead to beam intensity loss or background production. Hence, thin and low-density materials are required to mitigate multiple scattering and energy loss of the incoming particles while still allowing the needed pressures inside the counter vessel. A XCET validation methodology was conducted using Finite Element Analysis (FEA), followed by experimental validations performing burst pressure tests and using Digital Image Correlation (DIC).

INTRODUCTION

When a charged particle passes through an optically transparent medium with a velocity greater than the phase velocity of light in that medium, it emits prompt photons, called Cherenkov radiation, at a characteristic polar angle that depends on the particle velocity. Cherenkov counters are particle detectors that use this radiation. Particle identification using this detector is based on the fact that at a given particle momentum the number of emitted Cherenkov photons is a function of the particle mass and the refractive index n of the gas that is, in turn, defined by the radiator gas type and pressure [1, 2].

The XCET detector is composed of a horizontal tube filled with the required gas, thin entrance and exit windows that are traversed by the particle beam, a mirror and a conical body at 90º leading to an optical window followed by a photomultiplier as seen in Fig. 1. The Cherenkov light is produced inside the vessel by the interplay between the gas and the particles. At the end of the tube, the thin mirror reflects the light towards the conical body whose inner side is composed of a parabolic mirror beaming the photons through the optical glass window into the photomultiplier.

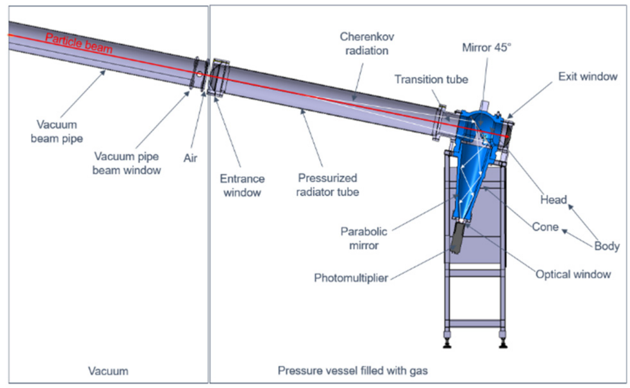

Figure 1: Layout of XCET components.

SCOPE OF ANALYSIS

There are a total of 16 XCET detectors installed in the Experimental Areas at CERN, 4 in the East Area and 12 in the North Area. Every XCET uses a different pressure in a range between 3.5 bar (g) to 15 bar (g) depending on the physics requirements of the experiments. For low pressure operations (3.5 bar (g)) two thin superimposed windows composed of a layer of Mylar and a layer of Polyethylene are installed to separate the surrounding environment from the gas used inside the Cherenkov detectors which is under pressure. The selection of the material was based on its low density, to mitigate multiple scattering. The lower the density and the thickness of the material chosen, the lower are the energy losses and multiple scattering when crossed by the particle beam, enhancing its quality.

The scope of this analysis was to ensure that the mechanical properties of the material were suitable for the intended loads and safe for the rest of the components in accordance with Directive 2014/68/EU. Different types of computational and experimental tests were performed to crosscheck results and validate the different materials used for low pressure operations.

GEOMETRY AND MATERIALS

This paper focus on the unique components for low-pressure operations of the Cherenkov Counter, two superimposed windows made of an inner layer of 250 µm Mylar to resist the mechanical stresses and an outer layer of 150 µm of black polyethylene to preclude external light entering the detector, and their respective flanges made of AW-6082 T6. The diameter of these elements may vary from DN150 mm to DN219 mm depending on the XCET configuration and it is possible to have two different dimensions in the same XCET as there is an entry and an exit window. However, if different dimensioned windows are

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installed in the same detector, they will share the same service loads, mechanical properties, the same number and size of bolted connections (20xM10 bolts), and geometrical characteristics, all but their external diameter. Yet, as they will share an identical volume of pressurized gas, the larger diameter window will be exposed to higher forces. Therefore, the DN219 window was taken as subject for all experimental and computational tests for this paper. Figure 2 shows the different elements of the window.

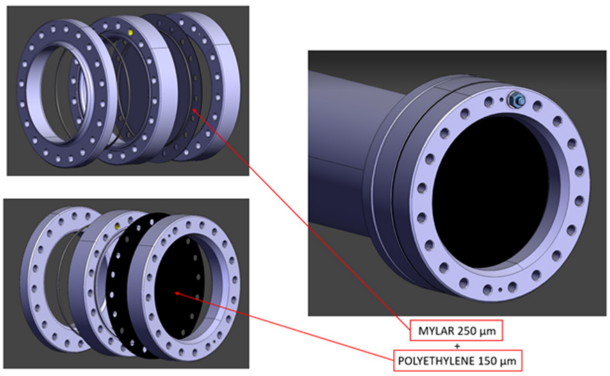

Figure 2: XCET window components: radiator tube, flanges, O-rings, and the two superimposed windows (on the inner part the Mylar window and on the outer, the black polyethylene window).

Load Cases

The windows were evaluated according to section 7.4 of Directive 2014/68/EU of the European Parliament which states that for proof tests of pressure vessels, and for our study case, the pressure of the proof test shall be no less than the maximum allowable pressure multiplied by a coefficient 1,43.

The loads applied to the windows are defined by the maximum allowable pressure of each Cherenkov detector. This internal pressure generated from a specific compressed gas like CO_2, N_2, He, R134a or R218 will vary depending on the momentum of the particle to be detected and will be maximum at 3.5 bar (g). Thus, there are three load cases analysed in the experimental tests and Finite Element Analysis:

- First step pressure of 2 bar (g)
- Maximum allowable pressure of 3.5 bar (g)
- Validation pressure of 5 bar (g)

VALIDATION METHODS

Finite Element Analysis

The goal of the FEA was to predict the stress, strain and deformation of the different aforementioned components. Hence, a 2D axisymmetric static structural simulation using ANSYS Workbench 2020 was performed. The 2D axisymmetric model, created for a less expensive computational simulation, was converted later in 3D models, enabling direct comparison with the experimental technique of Digital Image Correlation (DIC): the concerned surface in the FEA 3D models was extracted and compared with the analogous surfaces measured with DIC. Strain/stress readings were obtained from large surface areas allowing the identification of the regions where the highest stress developed and evolved into the critical regions that lead to failure. The identification of these regions and measured burst pressure is strictly linked to the boundary conditions (contacts and their type) in the FEA models.

Hydraulic Pressure Tests

To validate the window at 1,43 times the maximum allowable pressure as the European Directive states, as well as to corroborate the FEA results, a total of ten different burst tests were performed with distinct objectives and configurations. First, six hydraulic pressure tests using Digital Image Correlation (DIC) were performed, obtaining strain and deformations data for different pressure inputs. Yet, this experimental validation could not be achieved due to undesired fluctuations in the pressure readings. These were caused by the low sensitivity of the sensor and the insertion of an incompressible fluid using a manual pump as consequence of the absence of an automatic regulator for such low-pressure inputs.

Digital Image Correlation (DIC)

To accurately benchmark the FEA models, measurements of the development of displacements, strains and deformations during the tests in the surface of the window were made (see Fig. 3). For this purpose, DIC was used. An optical technique for full field non-contact and three-dimensional measurement of shape, displacement and strains. It uses a stereoscopic multi camera set up to acquire several images that track the relative displacements suffered by a stochastic pattern imprinted in the material and compares it from a reference state to subsequent deformed states [3]. Typically, this is done by painting a white background and dusting on top with black paint. Considering the materials under test, extremely high elongations were to be expected. For this reason, HeBoCoat® was selected to produce a white background, and GRAPHIT 33® to produce the black dusting. In the case of the black polyethylene windows, no white background was needed, instead a white dusting was made with HeBoCoat®. Finally, the reference undeformed image is discretized in subsets and correlated with their analogous deformed versions to provide vector length and directions of each cell of the imprinted surface within sub pixel accuracy. Lastly, special software performs the calculation for the conversion of the vector fields into high-resolution strain data.

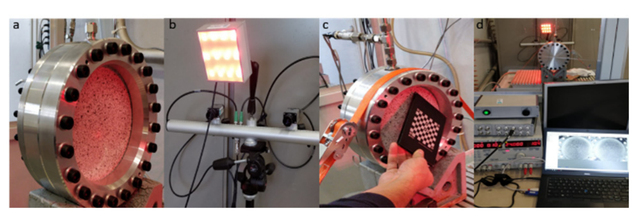

Figure 3: Test set-up: a) Mylar window with stochastic painting; b) DIC Manta MG-505B cameras; c) DIC calibration; d) DIC Image acquisition system.

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Pneumatic Pressure Tests

In view of the aforementioned issues trying to validate the window experimentally using an incompressible fluid, the methodology was modified, switching from liquid H_2O to compressed air. This time it was possible to reach the validation of the windows according to the European Directive as four pressure tests were performed with satisfactory results with the aid of a high sensitivity sensor in the studied pressure range and using an automatic pneumatic pump. Thus, it was feasible to maintain the pressure at 5 bar for over 90 minutes during the four tests. In Fig. 4 one of the plots obtained from the pneumatic bursts pressure tests is shown.

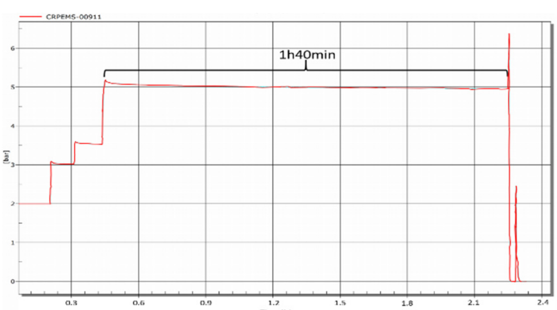

Figure 4: Pressure over time during pneumatic burst test. The spike around 2.25h shows the time when the pressure rose to failure reaching 6.5 bar before bursting.

FEA AND EXPERIMENTAL RESULTS

The Equivalent von-Mises stress results confirmed that the inner window made of Mylar was the one holding the stresses produced by the fluid pressure as shown in Table 1. However, during the experimental burst tests it has been proven that the existence of the black polyethylene window helped the Mylar layer maintain minor deformations for all of the different pressure ranges studied.

Table 1: FEA Maximum Stress and Utilisation Ratio for Different Pressure Inputs

	Mylar			Polyethylene		
P [bar]	2	3.5	5	2	3.5	5
σ_{max} **[MPa]**	110	161	204	1.8	2.5	3.2
$UR = \frac{\sigma_{UTS}}{\sigma_{max}}$	1.82	1.24	0.98	5	3.6	2.8

As it was expected, the maximum deformation for the Mylar occurred at the centre of the window as well as the maximum stress. However, this did not happen for the polyethylene layer which showed the maximum stress in the region of contact with the flange. Furthermore, with the utilisation ratio, created from the maximum stress readings from the FEA and the ultimate tensile strength, obtained from several traction tests performed in both materials, which are not included in this paper, it was shown that the polyethylene window is at all times under safe values for the pressure inputs studied under the premise of an unbreakable Mylar layer. On the other hand, the Mylar window would not crack at the maximum allowable pressure, but FEA predicted that it would at some point near the validation pressure. Nonetheless, the experimental results demonstrated the reliability of the components up to 5 bar. For low pressure inputs up to 3.5 bar the FEA results regarding deformations and maximum principal strains were similar to the results obtained using Digital Image Correlation technique as shown in Fig. 5. However, for higher pressures of up to 5 bar, the relative difference between FEA analysis and experimental significantly increased as shown in Table 2. The reason for this discrepancy is not clear but may be due to different causes, like changes in mechanical properties of the material due to long-term and inadequate storing, material and geometric nonlinearities, large plastic deformations or combinations of the above.

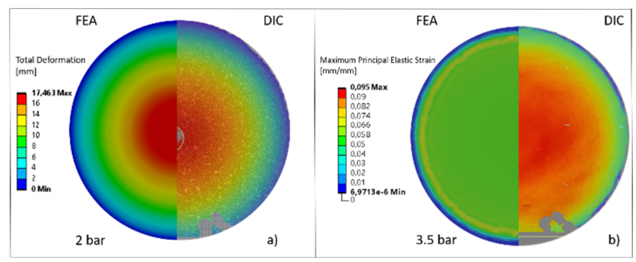

Figure 5: Static structural fully elastic plot comparison between FEA and DIC for Mylar and polyethylene window: a) Total deformation at 2 bar; b) max. principal strain at 3.5 bar.

In spite of the difference of the displacement results between the two methods, the FEA results showed the material reliability around 5 bar and the experimental results demonstrated that the material did crack at this pressure, and it was not until reaching higher pressures about 6 bar that the window burst.

Table 2: FEA and DIC Results for Different Pressure Inputs

	ΔL [mm]			ε [%]		
P [bar]	2	3.5	5	2	3.5	5
2D	17.6	23.7	27	3.5	6.1	7.8
3D	17.4	19.2	21.2	2.9	4.1	5.8
DIC	17.2	28.1	47.2	4.7	9.5	55.8

CONCLUSIONS

This paper presented a summary of the performed Finite Element Analysis and experimental tests using Digital Image Correlation technique for the beam windows installed in the Threshold Cherenkov Monitor. The safety of the Mylar and polyethylene window configuration for low-pressure applications of up to 3.5 bar has been demonstrated using the validation pressure set at 1.43 times the maximum allowable pressure by the European Directive 2014/68/EU. As such, they can be deemed valid for operation at 3.5 bar in the Experimental Areas at CERN.

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