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Cryogenic helium valves deflection and relaxation in ESS linac cryogenic distribution system

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Abstract. The commissioning of European Spallation Source linear accelerator cryogenic distribution system revealed valve deflections, partly combined with lack of valve tightness. An optical method of noninvasive measurement of long-stem cryogenic valve straightness has been elaborated and compared with direct deflection measurements. The allowable value of the valve deflection has been estimated on the basis of mechanical analysis and the procedure of the deformed valve relaxation has been proposed and successfully implemented. The paper presents the method, its validation by the opening of one of the valve boxes on the ESS Cryogenic Distribution System and provides the limits of the method's applicability.

1. Introduction

Large scientific facilities make extensive use of cold helium in different thermodynamic states for cryostating of superconducting cavities or magnets. The helium is supplied to cryomodules by cryogenic distribution systems which may contain tens of valve boxes and hundreds of cryogenic valves. Cryogenic control valves are considered a critical part of every cryogenic distribution system not only due to their importance for realization of different operation modes of the system, but also due to low mechanical stability of the valves resulting from their specific design. As the valves' actuators and positioners are located in room temperature, the valves create thermal bridges between room and low temperature elements. To protect these components from freezing and reduce undesirable, but unavoidable, heat inputs into the cryogenic temperature environment, the heat conduction through the valve's body and stem needs to be strongly reduced. This can be achieved by using low thermal conductivity materials such as stainless steel or G-10 (epoxy resin - glass fiber composite), reducing the cross-sectional area of the conduction path and increasing its length. These requirements are contradictory from the mechanical point of view as they imply a thin and elongated design of the valve stems and bodies, susceptible to lateral deformations. The valve deformations may result from stresses produced during their manufacturing, improper transport, welding of the valve to the valve box vessel and process pipes or cyclic thermal and pressure loads during the cool-down and warm up of the cryogenic system.

At several stages of a cryogenic system's life, especially during production, installation, factory acceptance tests, commissioning of devices, as well as during routine maintenance works, the straightness of cryogenic valves needs to be verified with a quick, but still reliable method. In a valve box assembly, the straightness measurement is additionally complicated by the fact that the valve exterior cannot be accessed without massive intervention to the valve box structure. If the valve deflection exceeds the allowable value, it should be relaxed with minimum intervention in the cryogenic system.

2. Optical method of valve deflection measurement

We treat the deflection measurement problem by employment of computer vision methods. To feed the computer vision algorithms with photographs we used a relatively simple and easily available hardware, together with a software based on the free and open-source OpenCV library. Our method is relatively simple and straightforward, and consists of two general steps:

1) collecting photographs of the valve interior and
2) compute the estimate of valve deflection using the software.

The hardware used to collect the photographs consists of a camera and a mounting sleeve, depicted in Figure 1a). Besides, we used a blue light emitting diode (LED), with a thin, long cable, inserted through a neighbouring pipe, to illuminate the bottom part of the valve, below the valve seat, such that the valve seat is visible and clearly recognizable, when seen by the camera.

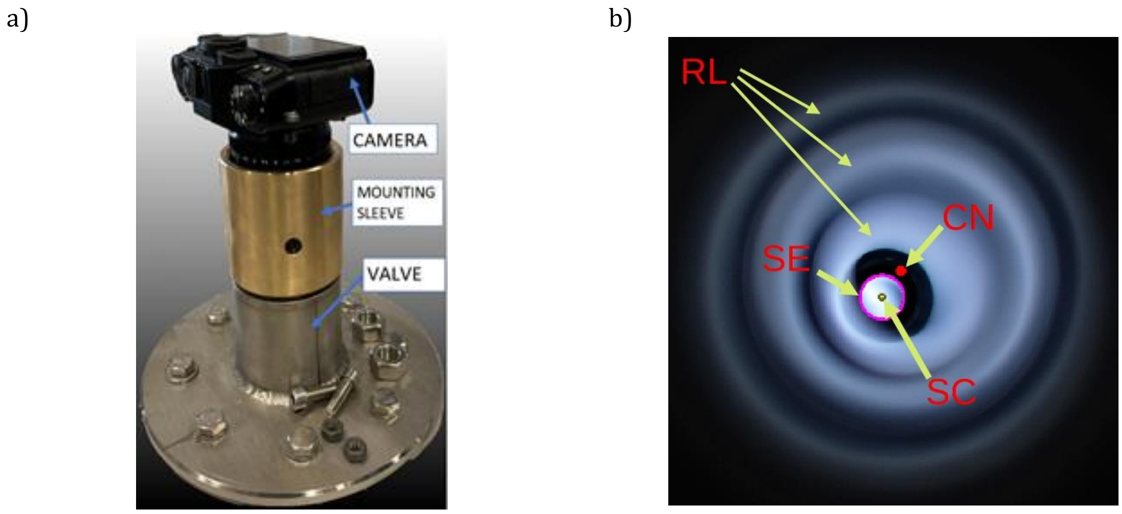

Figure 1. a) Hardware mounted on a valve for taking photographs of the valve interior [2], b) valve interior photograph extended with detected seat edges, where: CN – statistically estimated nominal (desired) position of valve seat centre, SC – estimated valve seat centre, SE – edge of valve seat, RL – rings of light projected on the valve interior [2].

The collected photographs are then used to estimate the valve deflection. Computer vision algorithm, namely Hough transform for circles [1], detects valve seat edges and calculates position SC of the seat centre. By processing photographs of many valves in this way (269 photographs collected from 60 valves of elliptical linac at ESS), we statistically estimated nominal position CN of the valves' seat centre. Then, our deflection metric is calculated as Euclidean distance between the points CN and SC. An example of a processed photograph is shown in Figure 1b).

Our method has been verified using a special validation platform, where a valve is deflected in a controlled manner, to compare the computer vision results with ruler-based measurements. When using the ruler measurements as the ground truth, Type A (statistically computed) uncertainty of measurement at the 99% confidence level computed using Student's t-distribution is no greater than 1.2 mm. Details about the optical straightness measurement method and its validation are given in [2].

3. Valve Box opening and valve body relaxation

The valve box with the deflected valve was opened from the bottom to assess the condition of the valves and pipes, as shown in Figure 2. Visual inspection revealed relatively small deflections of the valves, which were corrected after relaxing the valve's upper welds.

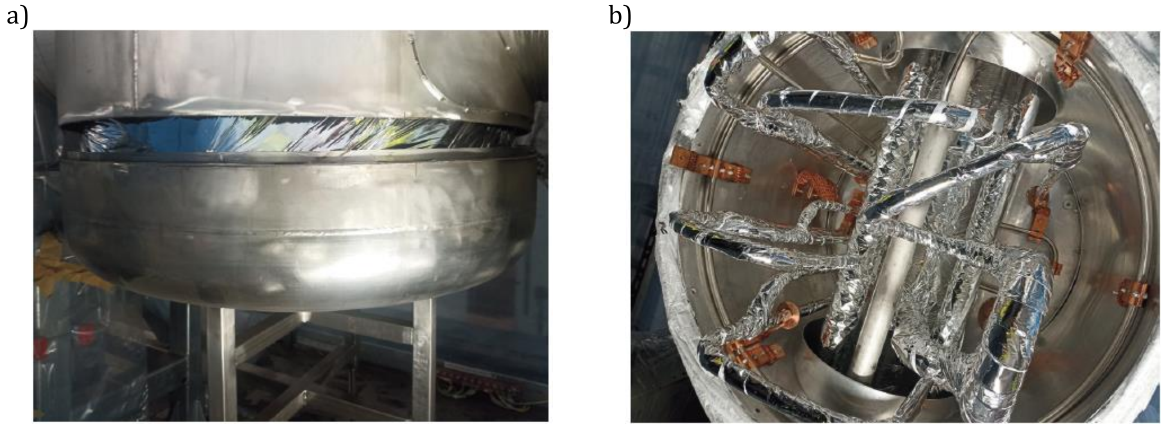

Figure 2. a) location of the cut in the valve box, b) interior of the valve box after removing the bottom plate, MLI, and radiation shield

Figure 3 presents a map of points derived from a 3D scan of the Valve Box overlaid onto its model, providing detailed information about any deviations. This scan allows observation of the shape of the valve deflections and the estimation of deviations from their nominal positions.

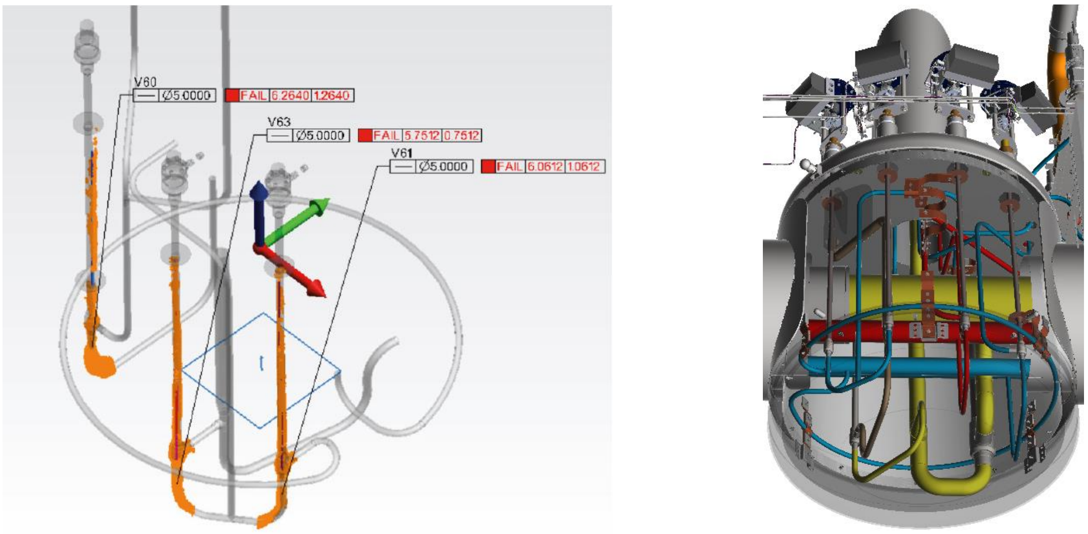

Figure 3. A map of points overlaid onto the 3D model of the opened valve box

To relax the stresses, the valve was dust-free cut in two places, allowing it to relax in all directions. The first cut was made on the ring and the second below the reduction – Figure 4.

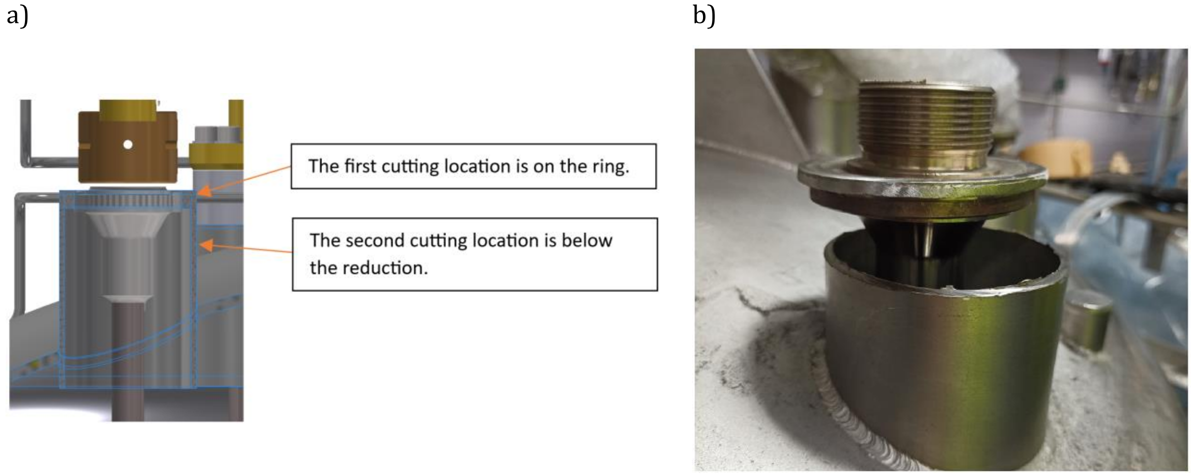

Figure 4. a) the cutting locations of the valve's vacuum jacket, b) view of the relaxed valve after cut-off from vacuum jacket.

Following the cutting process, the curvature of the valves was assessed using the optical method described above and the valve supplier's gauge– Figure 5a). It was confirmed that the valves were free from curvature after stress relaxation. In the next step the special designed adapters were welded between the valve flange and vacuum jacket in a manner that did not introduce additional stresses on the valve – Figure 5b).

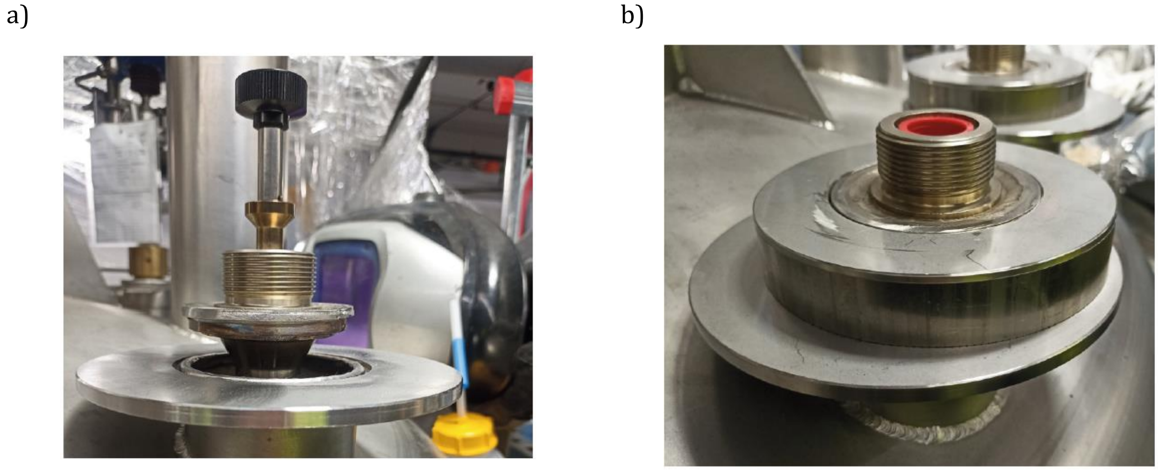

Figure 5. a) one of the methods for checking the correctness of the valve installation, b) the relaxed valve with the adapter.

4. Modelling of valve body tube deformation

Thanks to the optical method described above, it is possible to determine the valve deflection, but in order to determine whether the obtained deflection value is at an acceptable level, it is necessary to calculate the value of the stresses that the determined deformation generates and compare them to the yield stress. In order for the valve to return to its original shape after the load-causing deflection is removed, the stresses must not exceed the yield stress. The relationship between deformation and stress in the elastic range is described by Hooke's law, which assumes that body deformations, in response to forces, occur instantaneously and completely disappear when the applied forces stop acting. The above assumption is true for stresses lower than the yield strength. Once the yield point is exceeded, the material is permanently deformed and does not return to its original shape even when the load is completely removed. The relationships between the strain value, stress and bending moment are described by the following equations:

$$F = \frac{3EJ_Z y}{L^3} \tag{1}$$

$$\sigma = \frac{M}{W_Z} = \frac{FL}{W_Z} \tag{2}$$

where: F – force acting on the valve, N, E – Young Module, kN/mm^2, (for stainless steel E = 205 000 kN/mm^2 [3]), y – valve deflection, mm, L – valve length, mm, (815 mm), M – bending moment, Nmm, and σ – maximum bending stresses, N/mm^2. The geometric moment of inertia J_z, mm^4, and bending strength index W_z, mm^3, for tubes are expressed with equation (3) and (4), respectively:

$$J_z = \frac{\pi(D^4 - d^4)}{64} \tag{3}$$

$$W_z = \frac{\pi(D^4 - d^4)}{32D} \tag{4}$$

where D and d, mm, are the external and internal tube diameter, respectively.

Figure 6a) shows the valve model with characteristic dimensions. Due to the significant stiffness of the upper part of the valve, it was assumed that only the pipe part was deformed, as a result, the force acting arm was shortened by 60 mm and the bending stresses increased – Figure 6b). The presented approach is more conservative, and at the same time the obtained results are characterized by higher stress values.

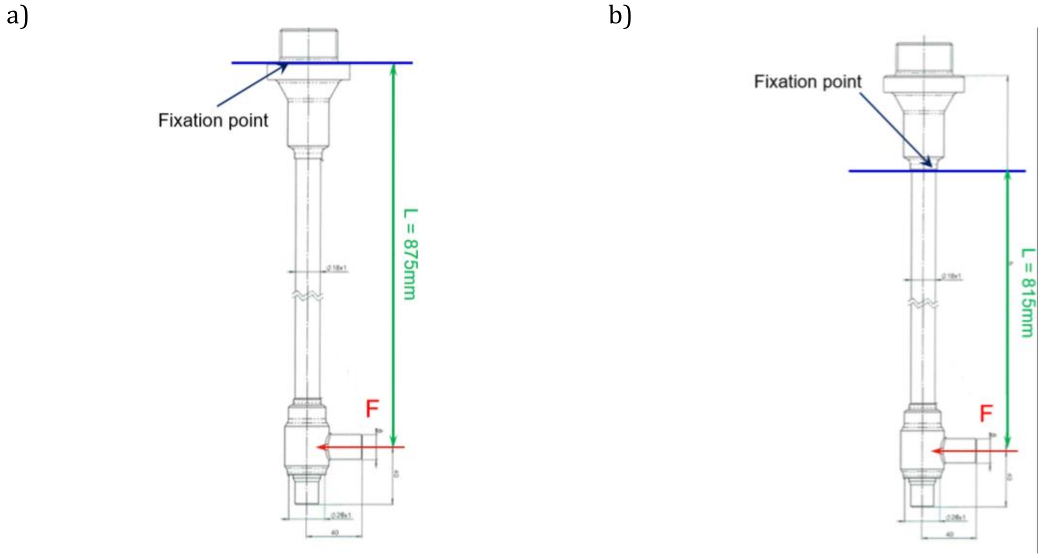

Figure 6. The valve model with characteristic dimensions, a) total length of the valve, b) lengths taken into account during calculations.

The calculation input data were taken from the valve manufacturer catalogue [3]. The stresses were determined for three cases of DN10 valve tube deformation. The calculation results are presented in Table 1. In three of analysed cases, the value of bending stresses is below or at the limit of the yield strength $R_{p0.2}$= 200 MPa, for 1.4404 steel of which the valve body tube is made. Only in the case of the largest deformation of y=25 mm the conventional yield $R_{p0.2}$ was slightly exceeded. Taking into account the shortening of the valve length assumed for calculations by 60 mm (7%) in relation to the actual valve length, it can be concluded that in the case of a DN10 valve the valve body deformation should not exceed 25 mm. The relaxed valves fulfilled this requirement.

Table 1. Summary of calculation results for a DN10 valve for three different values of valve body tube deformation.

	D mm	g mm	y mm	J_z mm^4	W_z mm^3	F N	M Nmm	σ N/mm^2
DN10	18	1.0	3.0	1936.0	215.1	6.60	5378	25.0
DN10	18	1.0	11.0	1936.0	215.1	24.19	19718	91.7
DN10	18	1.0	24.0	1936.0	215.1	52.79	43020	200.0
DN10	18	1.0	25.0	1936.0	215.1	54.99	44813	208.3

D – external diameter of valve body tube; g- wall thickness of valve body tube; y – deflection of valve body tube.

5. Conclusions

The deflected valves with the deformations not exceeding the plasticity limit can be relaxed with a relatively simple method requiring only a limited intervention into the valve box structure. The proposed repair method has been successfully implemented on the ESS Cryogenic Distribution System. The valve repair was preceded by optical measurement of deflection and modelling analysis of the bending stresses confirming its value below the yield point. The optical method allowed for non-invasive valve straightness measurement with sufficient precision, using cost efficient and generally available means.

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