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Supplier capability assessment as a tool for product and process optimization

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Abstract
The Compact Linear Collider (CLIC) project is testing accelerating structure prototypes made of Oxygen Free Electronic (OFE) Copper. CLIC is looking to optimize the design and to reduce the manufacturing cost towards mass production. The fundamental unit, a disc of 83 mm, has sub-micrometre tolerances and therefore requires ultra-precision diamond turning and milling. This paper presents supplier's process capability on the production of four accelerating structures (118 parts). Moreover, these measurements together with a sensitivity analysis allow us to identify non-significant design parameters that were relaxed in a second production batch (138 parts). The changes on the design did not affect the accelerating capacity and reduced the unit price of 25%. The supplier performance of the second batch showed the expected good results.

Process capability index, ultra-precision, variability

1. Introduction

The CLIC project is one of the future projects under study at CERN to be built after the end of life of the Large Hadron Collider. At this stage of the project, CLIC is building accelerating structures prototypes made of OFE Copper which are then high power tested at CERN facilities. If CLIC is approved, 10184 structures will be needed at the first stage of construction [1]. The decision on the Go/No go of the project is approaching and it is fundamental the product/process optimization of the accelerating structures towards mass production.

CLIC technology is based on X-band (12 GHz), normal-conducting, high gradient acceleration (in the range of 70 - 100 MV/m), and low breakdown rates (3×10^{-7} m^{-1}) [2]. These high-level requirements make that the components of the accelerating structures have stringent tolerances (shape accuracy 4 µm, flatness 1 µm, dimensional tolerances 1 µm) and smooth inner surfaces (Ra 0.025 µm). Moreover, the assembly method, diffusion bonding, also needs similar flatness and roughness requirements. Polishing and other abrasive methods are banned for Radio Frequency (RF) applications (except if there is a chemical treatment afterwards). Thus, CLIC discs are produced exclusively by a combination of ultra-precision diamond turning and milling.

The Accelerating Structure (AS) fundamental unit is a copper disc of Ø83 mm by 8.3 mm height (Figure 1). Up to 2016 the production was limited to one or two accelerating structures and it was not possible to accurately evaluate the supplier capability. In the last years, it was decided to increase the number of structures in order to assess the reproducibility of the manufacturing and the geometrical changes caused by the assembly process.

In parallel, an effort to identify most significant design parameters was also carried on. The objective was to identify the contribution of each parameter to the frequency change.

This paper is organized as follows: in section 2 there is a brief description of the disc main design parameter. In section 3, the sensitivity analysis is presented. The process capability index and the measurements of the first production batch are presented in section 4. The analysis of the second order is resumed in section 5. Finally, conclusions are stated on section 6.

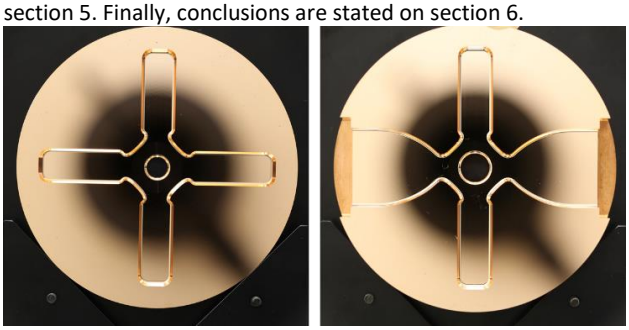

Figure 1. CLIC a) regular cell disc b) compact coupler cell

2. Design parameters

A CLIC disc is defined by 10 RF design parameters. Each of these parameters contributes differently to the accelerating gradient. Figure 2 shows a partial view of the technical drawing of a regular cell: where **a** is the iris aperture (1), **b** represents the inner radius, formed by the so called noses (2), **L** the height of the cell (3), **w** (5) and **HW** (4) width and length of the damping waveguide of the cell respectively. Furthermore, there are the flatness of the reference A (6), the flatness of the plane at 8.319 (7), the disc diameter (8), the shape tolerance of zone A (9) and zone B (10). Dimensions 1 to 5, 9 and 10 are related to the function of the part, while dimensions 6 to 8 have a critical impact on the assembly method (diffusion bonding).

3. Sensitivity analysis

A sensitivity analysis has been performed in order to identify the contribution of each of the parameters to the frequency change. Dimensions 6 to 10 cannot be simulated in this analysis. In a sensitivity analysis, each geometric parameter is varied slightly around the design value to determine the sensitivity of the return loss to that parameter.

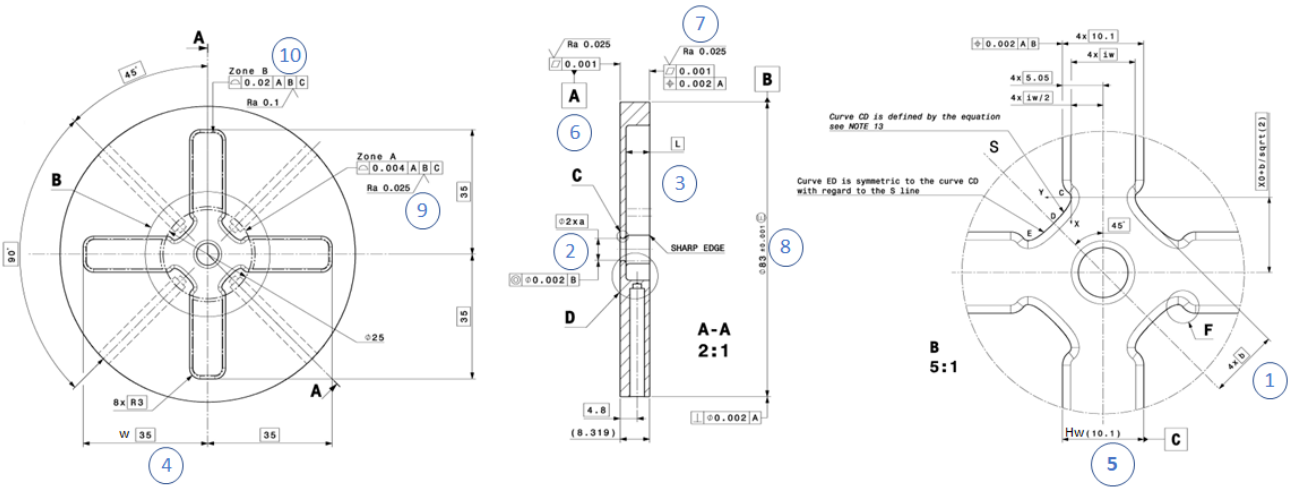

Figure 2. Main cell design parameters

The analysis on the CLIC TD26 prototype was performed using ANSYS High Frequency Structure Simulator (HFSS). The results include the first, middle and last cells (only middle cell is shown) with ±10 µm interval around the nominal design value (see Figure 3). According to the simulation results, the most sensitive geometrical parameter to the frequency change is the inner radius b for TD26 cells, followed by the iris diameter a. L, w and HW have almost no effect in this particular parameter while they are still critical to other functionalities of the accelerating structure.

3.1 Sensitivity analysis of the accelerating structure

A sensitivity analysis has been performed in order to identify the contribution of each of the parameters to the frequency change. Dimensions 6 to 10 cannot be simulated in this analysis. In a sensitivity analysis, each geometric parameter is varied slightly around the design value to determine the sensitivity of the return loss to that parameter. The analysis on the CLIC TD26 prototype was performed using ANSYS High Frequency Structure Simulator (HFSS). The results include the first, middle and last cells (only middle cell is shown) with ±10 µm interval around the nominal design value (see Figure 3). According to the simulation results, the most sensitive geometrical parameter to the frequency change is the inner radius **b** for TD26 cells, followed by the iris diameter **a**. **L**, **w** and **HW** have almost no effect in this particular parameter while they are still critical to other functionalities of the accelerating structure.

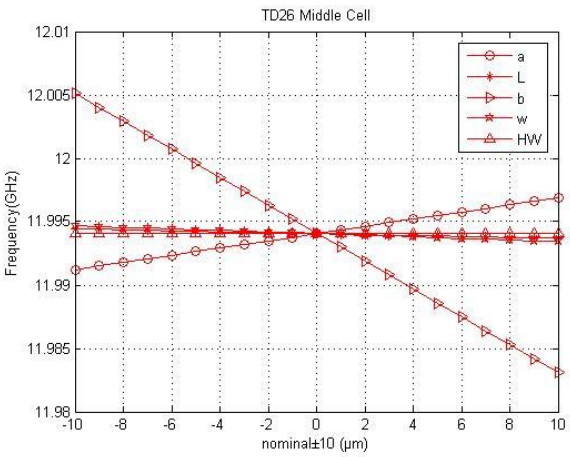

Figure 3. Frequency sensitivity of TD26 cell.

4. Process Capability

Among several supplier evaluation criteria one can find the quality, cost, delivery performance, sample inspection, factory visits, site survey and certifications (i.e. ISO standards certifications). According to Zhu [3], purchasing managers find the quality to be the most important criteria for supplier selection. Among several techniques, process capability is considered the most effective method in selecting quality products or parts [4]. Process capability compares the output of an in-control process to the specification limits by using capability indices [5]. Cpk is an index (a unitless number) which measures how close a process is running to its specification limits. The greater the Cpk index, the lesser is the process natural variation. As a reference, a Cpk > 1.33 indicates that the process is capable and meets the specification limits.

4.1 Supplier process capability (TD26)

A TD26 prototype is composed of 29 discs: 24 standard discs (Figure 1.a) and 5 compact couplers (CC) discs (Figure 1.b). The latter discs present a lateral pocket to allow the connection of the waveguides. The production of the first order included 4 accelerating structures, in total 116 discs (of which 20 coupler cells) plus 2 spares for metrology. The standard discs have the same shape, but the dimensions slightly change (few hundredths of mm) from one to another especially inside the zone A: iris and shape of the nose (see Figure 2).

Figure 4 shows the control chart of the external Ø83 mm of the total production. The graph shows 15 parts (12% of total production) out of the 1 µm tolerance. However, only one part is above 1.5 µm. Figure 5 shows the control chart of the iris diameter (a) of all the discs. Since the irises are different, the graph is presented as the measured value minus the nominal. It can be observed that all the parts are in tolerance with higher variability at the end of the production.

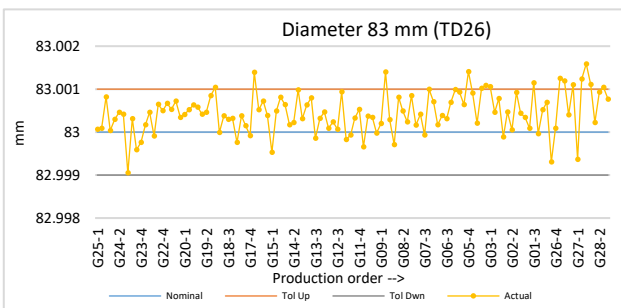

Figure 4. Control chart of Ø83 mm (TD26).

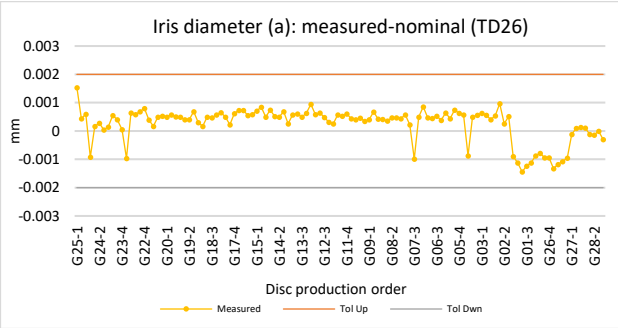

Figure 5. Control chart of iris diameter (a).

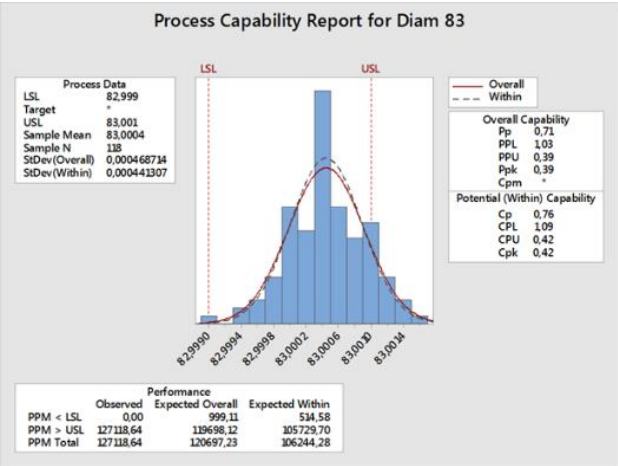

Figure 6. Process capability Ø83 mm.

In average, every disc had 20 dimensions measured using a CMM. Moreover, roughness (6 different measurements) and form measurements of zone A (at least one out of four sections of the internal shape and iris) and B (at least one out of four sections of the waveguides) were also performed. A visual inspection, looking for scratches and surface defects, was performed before the goods reception. From the more than 2000 dimensional measurements performed on the discs, only 53 were slightly out of tolerance. Roughness and shape tolerances were within the specifications.

The process capability of the iris diameter **a** has an impressive Cpk=2.40, hence 0 defectives Parts Per Million (PPM). The dimension of the inner radius **b** was not directly measured in this order, it was included in the shape tolerance. For this reason, it is not possible to calculate the indicator for this dimension. Nevertheless, all the shapes were within specifications. Figure 6 shows the process capability of the external Ø83 mm fabrication tolerance. The process has a Cpk = 0.42 which can be translated into 120697 PPM. The flatness of the reference A (number 6 on fig. 2) has a Cpk=0.77 (14306 PPM) and the flatness of the plane at 8.319 (number 7 on fig. 2) Cpk=0.76 (21090 PPM). The height of the cell **L**, linked to the flatness of the two mentioned planes, has a Cpk of 0.83 (6905 PPM).

The geometry of the CC cells is different compared to the regular cells; therefore, it will be advisable to calculate the capability index separately. The flatness of the planes of the CC is more difficult to control since the shape of the disc is not completely closed. Nevertheless, the index calculation was done considering the whole production (worst case).

5. New order (TD31)

After the successful fabrication of the TD26 prototype, the CLIC project decided to optimize the design of the baseline for the 380 GeV machine, the TD31 prototype. From the point of view of the manufacturing, the new design posed the same challenges than the TD26. However, the TD31 has five regular cells more. The objective was to produce again 4 accelerating structures and, consequently, the number of discs passed from 118 to 138 with the increment of order cost. The initial price enquiry was 25% more expensive than the TD26 prototype. This increment was higher than expected and for this reason, the production team decided to relax some of the tolerances to reduce the price with the final objective of not affecting the part quality and function.

On one hand, from the previous analysis, it was clear that the supplier had difficulties on maintaining flatness of planes and disc diameter, all parameters affecting the assembly of the structure. On the other hand, the company was capable of maintaining the most sensitive parameters: iris diameter and shape of the nose. Thus, the relaxation of the tolerance for the flatness and disc diameter was accorded. The bid was won by the same supplier of the TD26 with a similar price (less than 1% difference).

5.1 Supplier process capability (TD31)

Figure 7 shows the control chart of the external disc diameter (83 mm) with the relaxed tolerance (±2 µm). It can be observed that all the discs are now in tolerance. The Cpk is now 0.93 (8180 PPM). The average diameter is still under the 1 µm but the variability is bigger than previously seen.

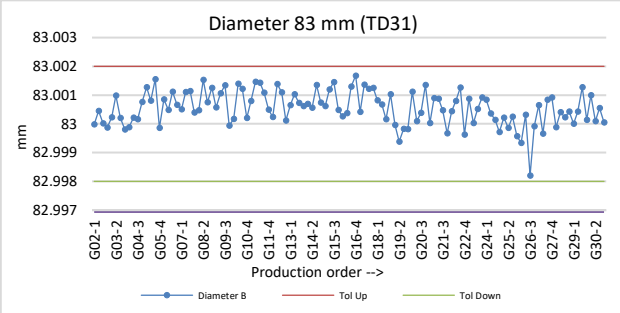

Figure 7. Control chart of Diameter 83 mm (TD31)

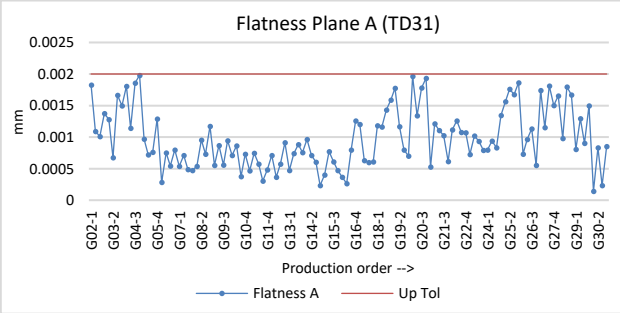

Figure 8. Control chart of flatness of reference A (TD31)

Moreover, Figure 8 shows the control chart of the flatness of reference A. Again, all the discs are in tolerance even if there is a bigger variability (Cpk 0.98 - 33017 PPM). In this case the sample mean is 0.9 µm.

For the TD31 it was demanded to the supplier to include the dimensional measurements of the b parameter (4 measurements for every disc). Figure 9 shows the process capability report of the b parameter. All the measurements are in tolerance. However, it is visible a tendency to the upper level of the tolerance. The process reaches a Cpk of 0.88 (6957 PPM). The iris diameter Cpk has been an outstanding 3.60.

Again, the roughness and shape measurements of all discs were all within the tolerance limits. The visual inspection performed before the goods reception was satisfactory and the measurement on sample disc was also conform to the specifications.

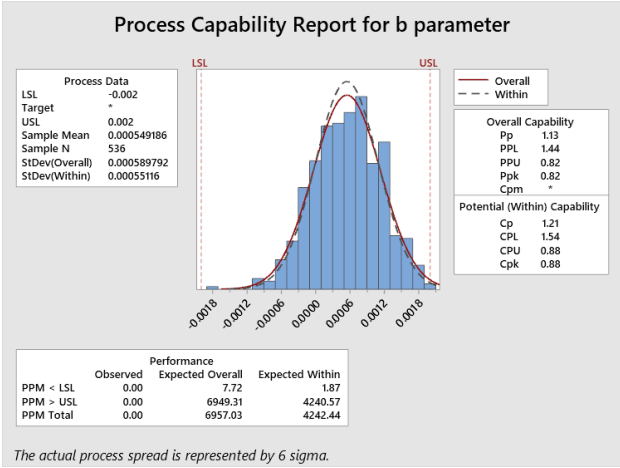

Figure 9. Process capability report of b parameter (TD31)

In order to check the quality of the produced cells, a functional measurement on the discs is performed before assembling the structure. The bead-pull method measures the frequency error of each individual cell by passing a dielectric bead through the axis of the structure and evaluating the amplitude and phase advance of the electric field in the accelerating mode [6]. Figure 10 shows the bead-pull measurement before assembly of the TD31-N1. The nominal phase advance of this prototype is 120°±1° and this value is reached by the structure after the individual tuning of the cells (normal variability is ±6°). In this case, however, the structure almost reached the goal without the need of tuning. This is a confirmation of the high quality achieved by the manufacturer.

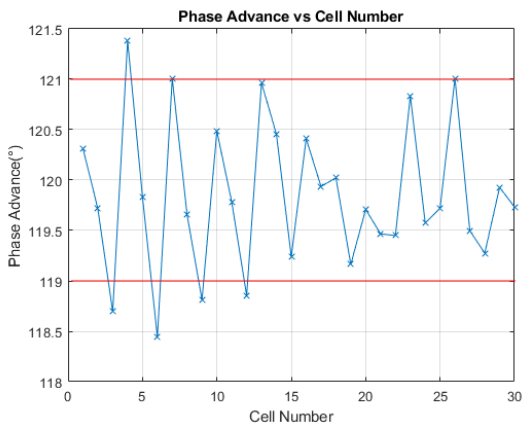

Figure 10. Bead-pull quality check after production.

At the moment of writing this paper, two structures TD31 have been assembled by diffusion bonding. Both structures are leak tight (helium leak rate 10^{-12} mbar l/s). The average straightness of the structure TD31-N1 is 35 µm (tolerance limit is 20 µm). Unfortunately, there was a displacement of one disc during transport from the assembly table to the oven causing the misalignment of the structure. If the measurements do not include the shifted disc, the straightness reaches 15 µm. The condition was identified and corrected on the assembly of the structure TD31-N2. The straightness was improved to the required 20 µm. Thus, the flatness relaxation of both planes and disc diameter had not affected the assembly process. The two structures are now finished, and they will be tested in high power in the following months.

6. Conclusions

A CLIC disc is defined by 10 principal design parameters. Each of them affecting in a different way the accelerating gradient and the assembly process. Through a sensitivity analysis, two main parameters have been identified: the inner radius **b** and the iris **a**. By analysing the production of four prototype structures (TD26) it was possible to understand that the supplier was challenged to maintain the flatness tolerances of 1 µm and the disc diameter (83mm ± 1 µm) while, at the same time, the principal parameters (a and b) were under control. Afterwards, the price enquiry of the TD31 prototype was launch and since it had more cells, the price of the order was higher. It was decided then to relax some of the tolerances to reduce the order price and maintain the same quality.

By analysing the process capability of the tolerances, it was decided to increase the flatness tolerance to 2 µm and the disc diameter (83mm ± 2 µm). With these changes, the price of the order was reduced 25%. The analysis of the second production batch shows a general improvement in the capability index. The Cpk of the disc diameter increased from 0.42 to 0.93, the flatness of reference A was originally 0.77 and it was improved to 0.98. On one hand, it has to be considered that the tolerance was doubled and an increase in the index is normal. On the other hand, the tolerances that were not relaxed, were still maintained at the same quality level. The iris diameter even increased from an already good Cpk 2.40 to an outstanding 2.69. The b parameter has been measured for the first time and it has a Cpk 0.88. The roughness measurements, shape measurements, quality inspection and measurements repeated at CERN were largely within the specification limits.

After the preliminary functional measurements, it can be stated that the capability of the accelerating structures fabrication has been maintained. The phase advance of the structure N1 is already as good as after tuning structures. Moreover, after the assembly of two structures TD31, it is possible to confirm that the relaxation of the tolerances (disc diameter and flatness) has not affected the assembly process. Both structures are leak tight and the straightness of the disc stack was 20 µm for the structure N2. The structures are fully assembled and waiting to be tested in high power.

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