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PRESERVING MICROMETRE TOLERANCES THROUGH THE ASSEMBLY PROCESS OF AN X-BAND ACCELERATING STRUCTURE

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Abstract

The CLIC structures are designed for operating at X-Band, 2π/3 traveling wave mode with a loaded 100 MV/m gradient. Mechanical tolerances, at the submicron level, are required to satisfy the RF design constraints and beam dynamics and are reachable using ultra-precision diamond machining. However, inherent to the manufacturing process, there is a deviation from the nominal specifications and as a result; incorrect cavity dimensions produce a less efficient linac. Moreover, the assembly process increase the difference from the original geometry. As part of a cost and manufacturability optimization of the structures for mass production, this study aims to identify a correlation between frequency deviations and geometrical errors of the individual discs of the accelerating structures caused by the production process. A sensitivity analysis has been carried out to determine the most critical parameters. Cell frequency deviations have been monitored by bead pull measurements before and after bonding. Several accelerating structure prototypes have been tested to determine our assumptions and to assess if the assembly process preserves the tight tolerances achieved by machining.

INTRODUCTION

CLIC baseline accelerating structure (AS) stack is composed by a variable quantity of discs of the prototype being produced. The cavity formed by the disc represents the RF zone. The geometry of the disc depends on different parameters and each of these parameters contributes differently to satisfy the RF design. Sub-micrometre tolerances are needed to reach the accelerating gradient goal of 100 MV/m if no tuning is applied and if no temperature correction is allowed to the AS [1]. However, the normal variability of the manufacturing processes makes that the disc presents discrepancies with respect to the nominal design. This paper aims at identifying the most critical design parameters through the means of a sensitivity analysis of the geometrical effects on the AS regular cells. For this purpose, six AS of two different prototypes are analysed: T24 N4 and N5 (Figure 1.a) and TD26 N1 to N4 (Figure 1.b).

GEOMETRICAL PARAMETERS

RF designs of both T24 and TD26 discs has been completed by ANSYS High Frequency Structure Simulator (HFSS) software. The T24 prototype consists of 24 undamped cells with a weak tapering of the irises [2]. The geometry of the standard cell is illustrated in Figure 2.a: ***b*** represents the inner radius; ***a*** is the iris aperture and ***h*** the height of the cell. The TD26 prototype also consists of 26 tapered cells with integrated coupling cells [3]. The TD26 cells have more complicated RF design compare to T24 cells because they include damping waveguides as illustrated in Figure 2.b (design with symmetry plane) where ***a***, ***b***, ***L***, ***w*** and ***HW*** represents iris aperture, inner radius, height, width and length of the damping part of the cell.

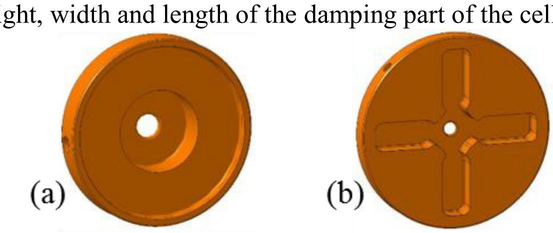

Figure 1: (a) T24 and (b) TD26 regular disc.

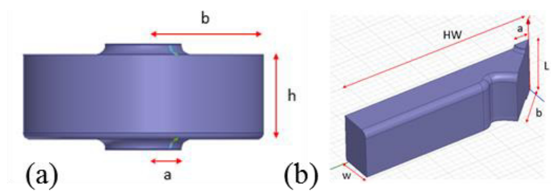

Figure 2: Geometrical parameters of (a) T24 and (b) symmetry plane of TD26.

SENSITIVITY 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 was performed using ANSYS HFSS. The results for both T24 and TD26 included the first, middle and last cells (only first cell is shown) with ±10 μm interval around the nominal design value. According to the simulation results, the most sensitive geometrical parameter to the frequency change is the inner radius ***b*** for T24 cells, followed by the iris diameter **a** (Figure 3).

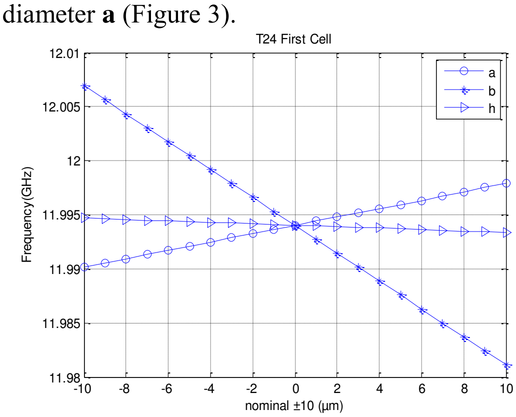

Figure 3: Frequency sensitivity of T24 cell.

The same behaviour of the cell parameters to frequency change is still valid for TD26 cells. The most sensitive geometrical parameter to frequency change is the inner radius ***b*** as T24, followed by the iris diameter (Figure 4).

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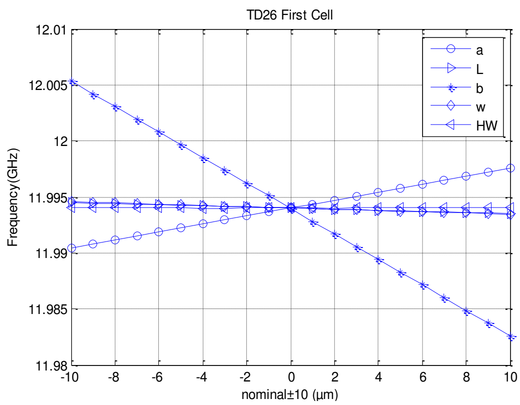

Figure 4: Frequency sensitivity of TD26 cell.

PRODUCTION AND METROLOGY

All discs of both prototypes were produced by ultra-precision diamond machining. In the case of the T24 by turning while TD26 by a mix of turning and milling. They were produced by two different companies. All discs were re-measured at CERN with an optical (non-contact) microscope (accuracy 4 µm).

In general, the ***b*** parameter was always smaller for all discs of both prototypes. The quality of all discs is homogeneous with maximum variability between discs of the same structure up to 5 µm (see Table 1). This range is smaller than the ±10 µm used for the simulation. Figure 5 and Figure 6 presents the b measurements of T24 and T26 structures respectively.

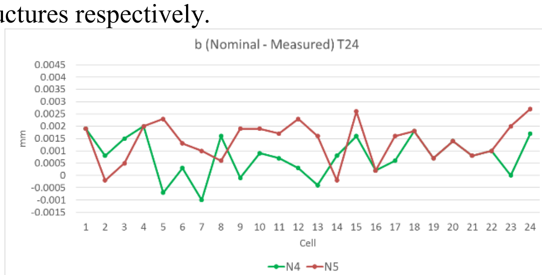

Figure 5: T24 structures (b measurement).

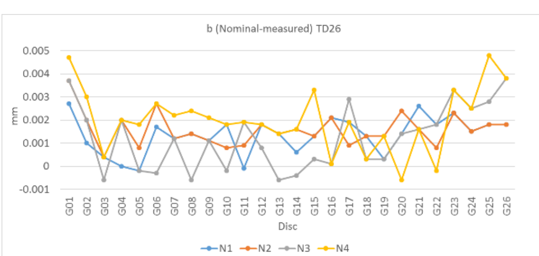

Figure 6: TD26 structures (b measurement).

BEAD PULL MEASUREMENTS

The individual frequency deviations of the accelerating discs were obtained by bead pull measurement and analysed by tuning software [4]. The bead-pull method measures in a single bead passage the amplitude and phase advance of the accelerating mode and allows determining the frequency error of each individual cell. The bead pull measurements were done for all T24 and TD26 disc stacks before bonding (Figure 7 and Figure 8) and T24 structures after bonding (Figure 11). Frequency deviation are uniform with reduced variability.

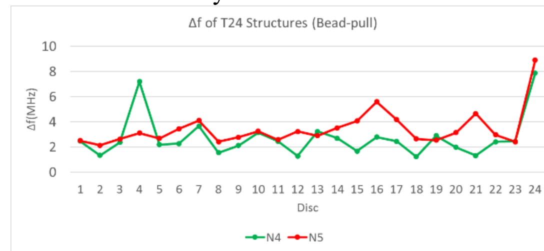

Figure 7: Bead pull measurement T24 before bonding.

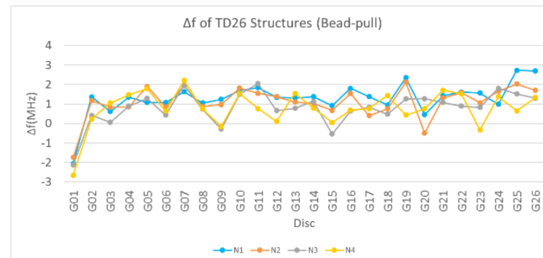

Figure 8: Bead pull measurement TD26 before bonding.

Table 1. Range and Correlation of ***b*** Parameter Before Bonding.

Structure	Min value (mm)	Max value (mm)	Range (mm)	Correlation coefficient (r)
T24 N4	-0.001	0.003	0.004	-0.038
T24 N5	-0.001	0.002	0.003	-0.069
TD26 N1	0	0.002	0.002	-0.193
TD26 N2	0	0.003	0.003	-0.59
TD26 N3	0	0.004	0.004	-0.09
TD26 N4	0	0.005	0.005	-0.4

CORRELATION RESULTS

The linear correlation represents the strength of relationship between two different datasets and identified by a coefficient r. The coefficient value ranges from +1.0 (strong positive correlation) to -1.0 (strong negative correlation), being 0 no correlation at all. According to the inverse proportion between frequency change and inner radius dimension, a negative correlation is expected.

Before Bonding

The correlation coefficients between imperfections in inner radius and frequency deviations of individual cells is presented in Table 1. There is no visible correlation for both T24 structures (only N4 is shown on Figure 9). For TD 26, on one hand, N1 and N3 structures have no visible correlation. On the other hand, N2 and N4 show negative moderate correlation (only N2 is shown on Figure 10).

After Bonding

After bonding, the straightness of the structure and the disc diameter were measured in a CMM. Since the discs are bonded, neither optical nor mechanical measurements can be done at the interior of the RF cavity. The disc diameter is the only accessible surface. It has been observed in

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several structures that after bonding the external disc diameter reduces in average 8 µm. The only way to assess ***b*** modification after bonding is to cut the structure immediately after with the consequent loss of the structure. Moreover, it is necessary to keep in mind that cutting means also measurement references losses. Therefore, the established hypothesis is that copper sublimation creates a smaller disc and a bigger ***b*** and therefore a reduction on the frequency.

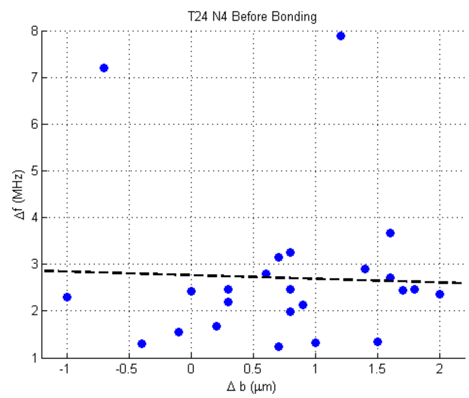

Figure 9: Scatterplot for T24 N4 before bonding.

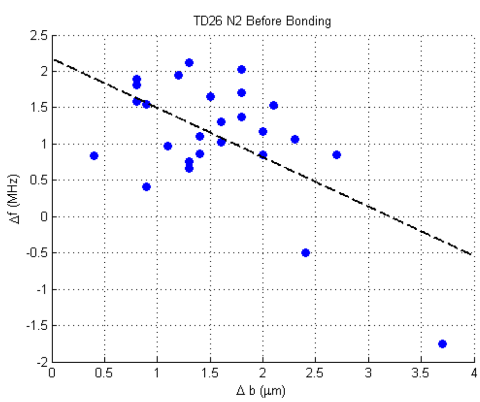

Figure 10: Scatterplot for TD26 N2 before bonding.

Unfortunately, for T24 N4, the diameter after bonding was not measured. The straightness of the structure after bonding was 15 µm. For the N5, there was a diameter reduction of 7 µm on average and a straightness of 30 µm. Frequency deviations of the cells before and after bonding obtained for T24 N4 and N5 have a similar general trend (Figure 11). On both structure there is a reduction of the frequency deviation. It is then clear that there has been a change on the geometry of the cells as expected confirming the hypothesis. The assembly method and bonding temperature curves were almost identical for both structures though two different suppliers perform the heat treatment. Moreover, another source of variation could be that other parameters of the disc were also affected (i.e. iris) and, as a result, they have also impact on the frequency reduction.

At the moment of writing this paper, TD26 structures were not yet bonded, and for this reason, the analysis could not be extended to those structures.

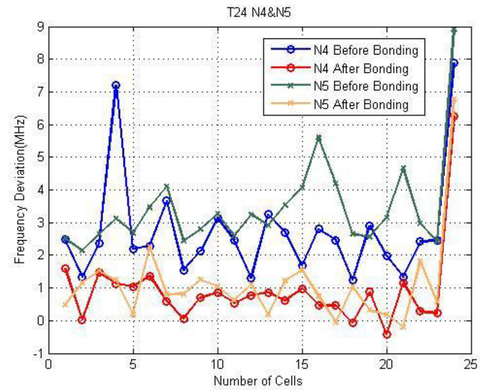

Figure 11: Frequency deviation before and after bonding.

CONCLUSION

The sensitivity analysis found that, among several parameters, the inner radius ***b*** contributes the most to the frequency change for both prototypes. According to the same analysis, a negative correlation between the two factors was expected. Parameter ***b*** measurements of all the discs for both prototypes are homogenous with reduced variability (maximum data range 5µm). As seen from the correlation analysis, before bonding there is no visible linear correlation except of TD26 N2 and N4: both structures show negative moderate correlation. The lack of correlation may be the effect of the low accuracy of the measurements processes: the accuracy of the microscope is worse than the tolerances at stake; frequency deviations before bonding are affected by the mechanical contact of the disc stack. Consequently, both measurement processes have to be greatly improved in order to get reliable data. The ***b*** parameter measurement is now an important requirement for suppliers. Another possibility is that the data follows another type of correlation or the combined effect of more than one parameter.

Finally, there is evidence of a geometry change in the cells after bonding since there is a reduction of frequency deviation. Nevertheless, it is not possible to numerically assess the change due to the inaccessibility of the RF cavity. Other possible causes need to be further investigated.

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