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1.3 GHz SEAMLESS COPPER CAVITIES VIA CNC SPINNING TECHNIQUE

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Abstract

The spinning process is an established technology to produce seamless resonant cavities. The main drawback is that, so far, a manual process is adopted, so the quality of the product is subject to the worker's skills. The Compute Numerical Controlled (CNC) applied to the spinning process can be used to limit this problem and increase the reproducibility and geometrical accuracy of the cavities obtained. This work reports the first 1.3 GHz SRF seamless copper cavities produced by CNC spinning at the Laboratori Nazionali di Legnaro of INFN. For this purpose, metrological analysis were conducted to verify the geometrical accuracy of the cavities after different steps of forming and thermal treatments; axial profile and wall thickness measurements were carried out, investigating different zones of the cavity profile. The cavities were also characterized through mechanical and microstructural analysis, to identify the effect of the automatic forming process applied to the production process of the 1.3 GHz SRF seamless copper cavities.

INTRODUCTION

In the last decade seamless cavities were investigated to limit the decreasing of the Quality Factor at high accelerating fields given by the welded cavities [1]. The study of new sheet forming techniques has been a fundamental part of the research at LNL. This was made possible thanks to the European Social Fund (FSE), project in which this activity is part of. The pursuit to produce seamless cavities is a current challenge to face the problem of the cost and possible mass production. There are different techniques to produce a seamless cavity, as for example spinning, hydroforming, explosive forming, electroforming etc [2]. The spinning process for a single cell cavity starts with a circular disk of a certain diameter and thickness and consists in four steps. In the first step the sheet metal blank is clamped against a mandrel on a spinning lathe, and gradually preformed onto a frustum-shaped mandrel. In the second step the first half-cell is formed, and a cylindrical shape is given to the remaining part of the piece, by means of a second pre-mandrel. In the third step the second half-cell is obtained through the spinning of the manufact onto a collapsible mandrel, that has the same shape of the cavity interior to guide the material in the fourth stage of the spinning process [2] (Fig. 1).

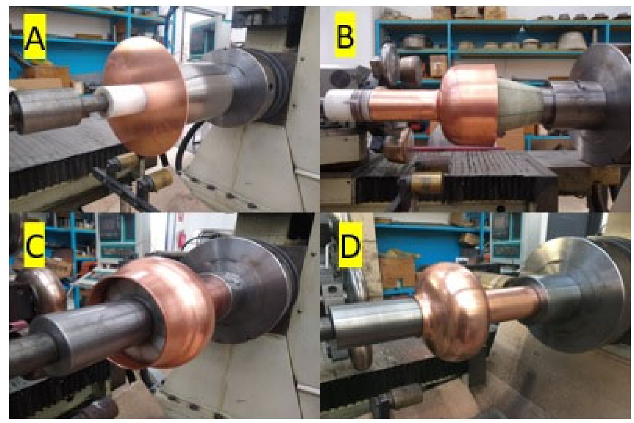

Figure 1: Spinning of a 1.3 GHz copper cavity via CNC A) Step 1, B) Step 2, C) Step 3, D) Step 4.

To reduce the variability due to the manual process of the operator and improve the reproducibility and geometrical accuracy of the cavities, the Compute Numerical Controlled (CNC) spinning process was applied.

The work shown in this document will deal with the study of the 1.3 GHz seamless copper cavities, through metrological and microstructural analysis, investigating the respect of dimensional tolerance, that is one of the challenges of this research for a large-scale production.

MATERIALS AND METHOD

The forming process starts from a 330 [mm] circular blank obtained from an Oxygen Free High Conductive (OFHC) Copper plate (Vickers micro hardness of 82±3 $HV_{0,5}$) through Wire EDM. Before the cold work, each blank is subjected to a first annealing in Ultra High Vacuum Furnace, to increase the ductility and reduce the contamination of the plate. To reach a desired vacuum value, a slow increasing temperature was applied to gradually degas the chamber. The thermal annealing was provided in the LNL UHV furnace following the thermal cycle reported in Table 1.

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Table 1: Thermal Cycle

Annealing	T_0	Heating Rate	T_1	Heating Rate	T_2	Heating Rate	T_3
	°C	°C/min	°C	°C/min	°C	°C/min	°C
●	25	0.5	200	10	300	10	500
○	25	0.5	200	10	300	10	400

A batch of cavities were produced through CNC spinning process, to investigate the reproducibility of the profile (Fig. 2).

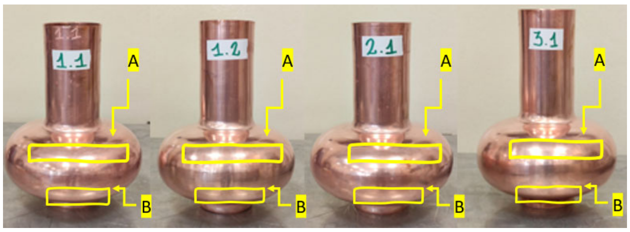

Figure 2: 1.3 GHz cavities produced through CNC process.

During the spinning process, cavities were treated at different annealing temperature (Table 2) to understand if this can affect the result.

Table 2: Annealing of the Cavities at Different Spinning Steps

Cavity	Step 1	Step 2	Step 3	Step 4
1.1	●	◊	◊	◊
1.2	●	◊	◊	◊
2.1	●	◊	●	◊
3.1	●	◊	◊	○

● Annealing 500°C; ◊ No Annealing; ○ Annealing 400°C;

Metrological analysis of the cavities (1.1, 1.2, 2.1, 3.1) was conducted at Unilab – Laboratori Industriali S.r.l - through Optical Measuring Machine (OMM)

Studies at LNL laboratory shows the relaxation of the internal stresses and recrystallization phenomena of the cavities during annealing [3].

In this work a series of samples were extracted (1.1.A, 1.1.B, 1.2.A, 1.2.B, 2.1.A, 2.1.B, 3.1.A, 3.2.B), at the first and the second half of the cavities, to analyse the microstructure of the material (Fig. 2). Samples were incorporate in a phenolic resin, ground with abrasive papers (500, 800, 1200,400 grit) and polished with clothes and diamonds suspension (6 µm and 1 µm). Once the sample was polished, the surface was chemical etched with 2,5g $FeCl_3$, 1ml HCl in 100ml of H_2O. The microstructure analysis was studied with the optical microscope, with Leica DMRE instrument. Hardness test was conducted with Micro durometer Vickers Leitz Wetzlar micro-hardness tester, with a load of 500gr.

RESULTS AND DISCUSSION

Metrological Analysis

Metrological analysis were made, and different measurements were taken in three different zones: 1st half of the cavity, the equatorial zone, and the 2nd half of the cavity. To investigate the reproducibility and dimensional tolerances, it was decided to make a comparison, through Optical Measuring Machine, using a digital 3D representation between:

- Cavities
- Die and CAD drawing
- Die and Cavities.
- Cavities and CAD drawing

Comparison between cavities (1.1, 1.2, 2.1, 3.1) respectively of the longitudinal and transversal axial profile, are shown in Figs. 3-5 (a, b). In all the analysis, the cavity thicknesses and their standard deviation were measured. The two cavities (1.1, 1.2) that have undergone the same annealing process show an almost identical profile, both longitudinal and transversal, demonstrating complete reproducibility.

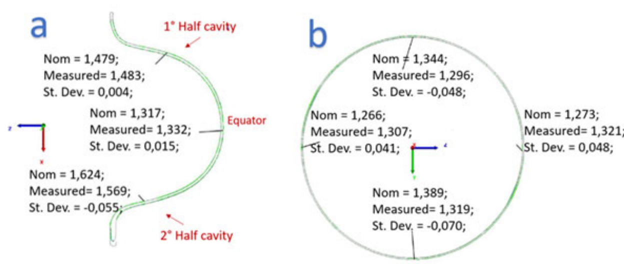

Figure 3: (a, b) Profile comparison and thickness variation between cavity 1.1 and 1.2.

Cavity 2.1 shows a slightly higher thickness of the longitudinal and transversal profile. The standard deviation in the first and second half of the cavity less than 0.2 [mm], taken as a reference limit for geometrical tolerances, while it reaches values of almost 0.3 [mm] in the equator zone. The intermediate annealing of the material and a micro hardness variation, which affects the ductility of the material, can cause this behaviour. Through these considerations we can state that parameters involved in the CNC process should be modulated as a function of the annealed material.

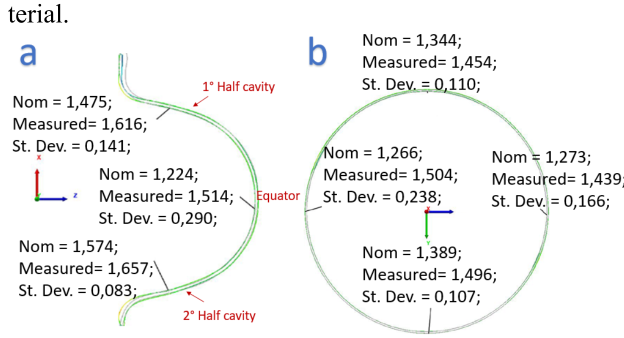

Figure 4: (a, b) Profile comparison and thickness variation between cavity 1.1 and 2.1

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The comparison between cavity 1.1 and 3.1 shows an almost identical profile, both longitudinal and transversal. The final annealing for the cavity 3.1 does not cause a dimensional change in the cavity. Furthermore, the reproducibility and the geometric tolerances are respected.

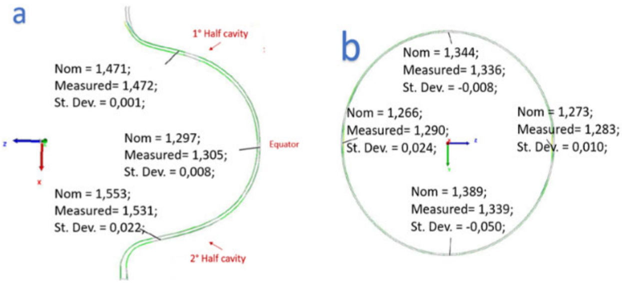

Figure 5: (a, b) Profile comparison and thickness variation between cavity 1.1 and 3.1.

Comparison between Die and CAD drawing, respectively of the longitudinal and transversal axial profile, are shown in Fig. 6 (a, b). The longitudinal and transversal profile of the Die shows some differences from the CAD drawing; this may be due to the geometry of the polymer Die built in sectors, each of which is fixed to the metal body, and to the wear of the latter.

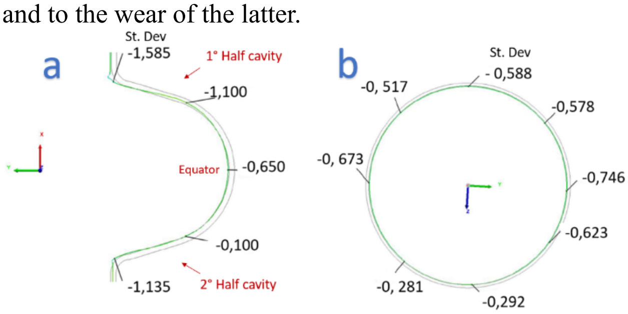

Figure 6: (a, b) Profile comparison and thickness variation between Die vs CAD drawing.

Comparison between Die and Cavities, respectively of the longitudinal and transversal axial profile, are shown in Figs. 7-9 (a, b). Longitudinal and transversal profile shows variation in standard deviation greater than the geometric tolerances required (0.2 [mm]) for the cavities 1.1 and 2.1; this may be due to an elastic return of the material after the spinning phase. A better trend is shown in the cavity 3.1; this can be due of the relaxation of the internal tension given by the final annealing of the cavity.

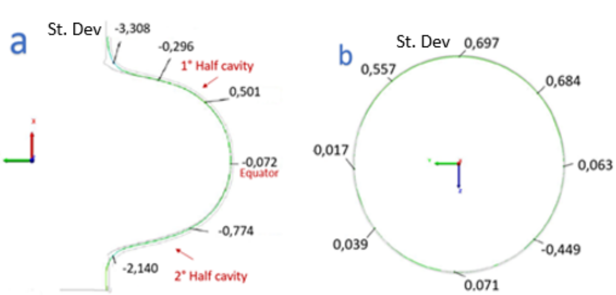

Figure 7: (a, b) Profile comparison and thickness variation between Die vs cavity 1.1.

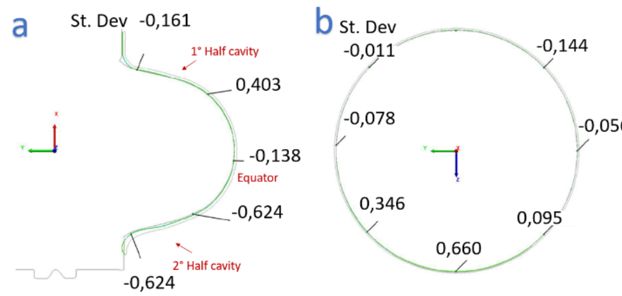

Figure 8: (a, b) Profile comparison and thickness variation between Die vs cavity 2.1.

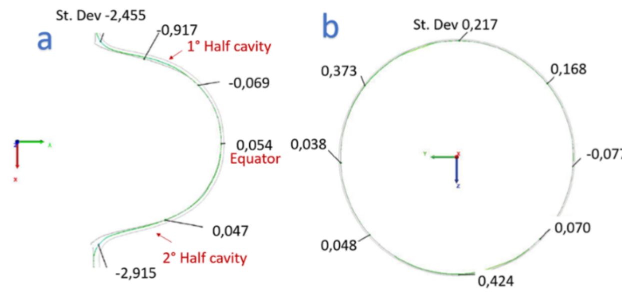

Figure 9: (a, b) Profile comparison and thickness variation between Die vs cavity 3.1.

Comparison between cavities and the CAD drawing, respectively of the longitudinal and transversal axial profile, are shown in Figs. 10-12 (a, b).

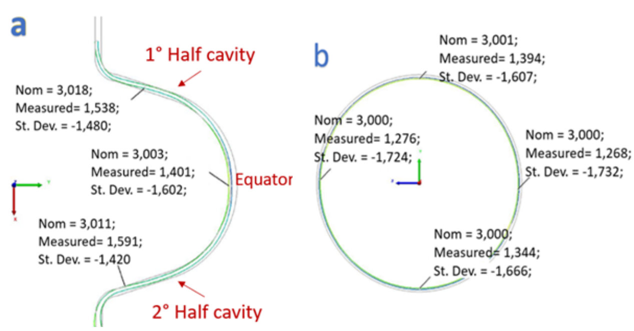

Figure 10: (a, b) Profile comparison and thickness variation between cavity 1.1 vs CAD drawing.

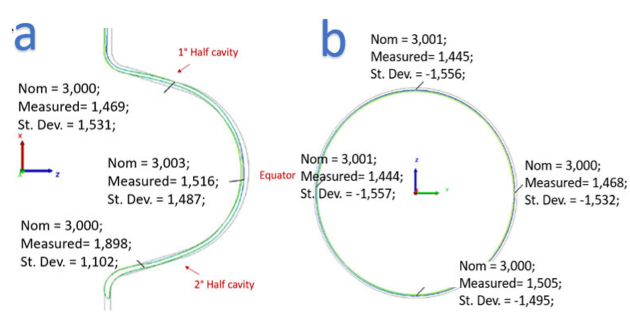

Figure 11: (a, b) Profile comparison and thickness variation between cavity 2.1 and CAD drawing.

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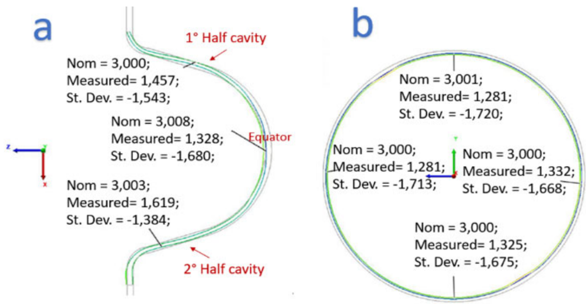

Figure 12: (a, b) Profile comparison and thickness variation between cavity 3.1 vs CAD drawing.

The longitudinal profile of the three cavities shows an average reduction of the thickness by the 50% respect of the CAD drawing. The value of the thickness shows a minimum in the equatorial zone (between 1.328 [mm] and 1.516 [mm]) while the second half of the cavities shows an ever-greater thickness than the first half (between 1.591 [mm] to 1.800 [mm] respect of 1.457 [mm] to 1.500 [mm]). The thickness trend along the profile obtained in this work is opposite to that obtained for the 400 MHz cavities [4]. This is due to a difference in the initial manufacturing process. The 400 MHz cavities shows a greater thickness in the first half cavity due to the initially deep drawn of the plate before spinning. It will be necessary to investigate this experimental difference in a FEM analysis to better understand the two processes. The transversal profile in the equatorial zone shows a negligible variation of thickness for each cavity (less than 0.2 [mm]) and an internal diameter for all the cavities is slightly smaller respect of the CAD drawing. To study the feasibility of the process, the standard deviation of the internal surface of the cavity were compared with the internal surface of the CAD drawing, at different geometrical point (Figs. 13-15).

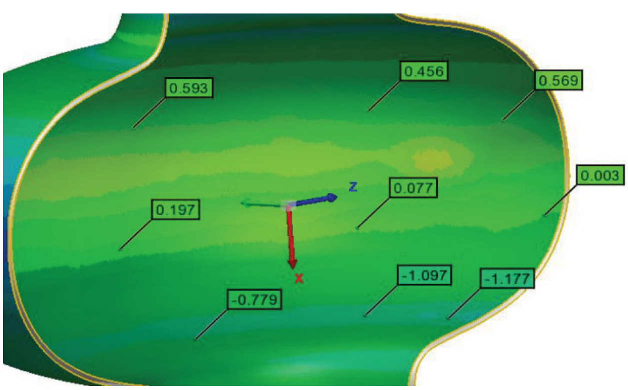

Figure 13: Standard deviation between internal surface of cavity 1.1 and CAD drawing.

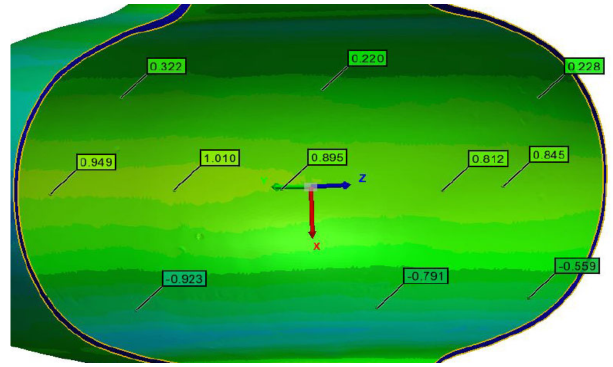

Figure 14: Standard deviation between internal surface of cavity 2.1 and CAD drawing.

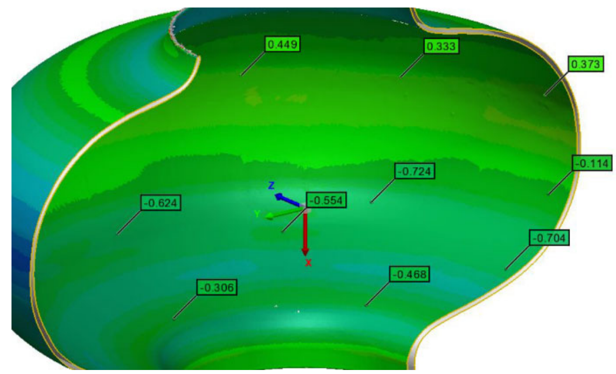

Figure 15: Standard deviation between internal surface of cavity 3.1 and CAD drawing.

A comparison of the internal profiles shows a standard deviation greater than 0.2 [mm], demonstrating that geometrical tolerances are not respected. Through these considerations, to improve the quality of the product, it is necessary to act on the geometry of the Die, modulating the operating conditions of the process according to the ductility of the material.

Microstructural Evolutions

The cavity 1.1 does not undergo any heat treatment during the process or at its end. In Fig. 16 the microstructure shows a strong elongation of the grains along the spinning direction, and it has also the higher hardness in both the half cells (Fig. 17) The intermediated annealing treatment of the cavity 2.1 recrystallised the microstructure releasing the stress and dislocation accumulate during deformation and permit to restore the ductility of the material, in Fig. 16 c, d in fact it is possible to observe equiassic grains characterized by recrystallization twins. The second half cell of the cavity 2.1 does not show, internally, a strong deformation of the microstructure and the hardness results are similar to the annealed one. Externally, the deformation process between the step 3 to 4, produce a slight work hardening that does not greatly influence the inner surface.

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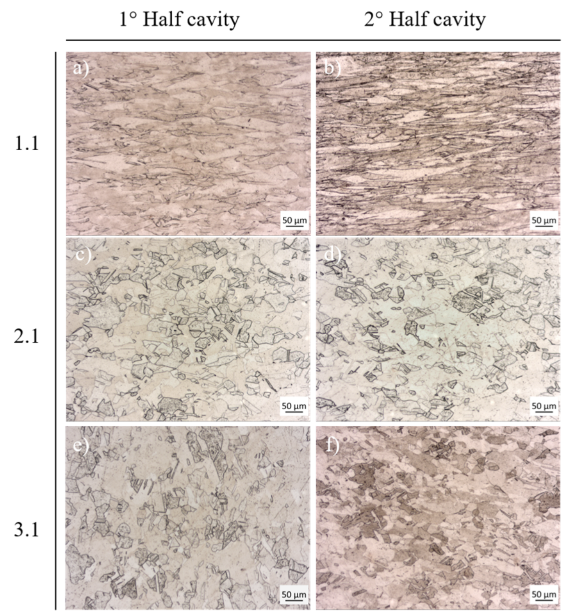

Figure 16: Microstructure of the inner surface of copper cavities 1.1, 2.1 and 3.1 in the first half cell respectively a, c and e, and in the second half cell respectively b, d and f.

The more homogeneous results is obtained with the 3.1 cavity with a final annealing, also in this case the material is characterized by a fully recrystallized microstructure. Both the half-cells have a reduce hardness typical of annealed copper.

Micro-hardness Test

In Fig. 17 the effect of annealing temperature on micro-hardness was tested.

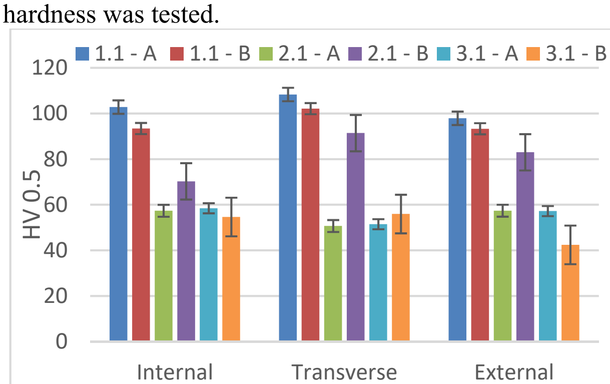

Figure 17: Micro-hardness test for cavities 1.1, 2.1, 3.1.

Starting from the annealed plate all the cavities were formed regardless on the heat treatment performed. Cavity 1.1 shows comparable micro-hardness values both in the first and second half. As expected, cavity 2.1 shows a lower micro-hardness values in the first half due the recrystallization of the microstructure. In the second half there is an increase in micro-hardness value due to the internal stresses given by the cold work. Cavity 3.1 shows low micro-hardness value, due to the final annealing process. These results are in accordance with the metallographic analysis. Moreover, the effect of copper microstructure on the subsequent polishing and final sputtering needs to be investigated.

CONCLUSION

The feasibility to produce a 1.3 GHz seamless cavity through CNC spinning process was demonstrated. Metrological analysis carried out have shown a good reproducibility for the cavities having the same thermal history. The initial annealing of the copper plate led to the formation of the cavities without the presence of defects or breaks. Intermediate annealing helped the workability of the spinning process, without bringing advantages in terms geometric tolerances, while final annealing did not modify the geometrical shape of the cavity. Through these considerations we can assume that an intermediate annealing produces an asymmetry property not contemplable with the fine-tuning process. On the other hand, the final annealing produce a homogeneous state stress in the whole cavity. Further developments are necessary to improve the geometrical accuracy, acting on the geometry of the Die and modulating the operating conditions of the CNC spinning process, according to the ductility of the material.

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REFERENCES

[1] W.V. Delsolaro, "Thin film research: CERN experience and possible future applications", presented at TESLA Technology Collaboration (TTC) Meeting, Milano, Italy, Feb. 2018.

[2] V. Palmieri, "Seamless Cavities: the Most Creative Topic in RF Superconductivity", in *Proc. 8th Int. Conf. RF Superconductivity (SRF'97)*, Padova, Italy, Oct. 1997, paper SRF97C18, pp. 553-589.

[3] F. Sciarrabba *et al.*, "Search on 1.3 GHz seamless cavities for the improvement of spinnability process", National Institute of Nuclear Physics Reports (2021).

[4] O. Azzolini *et al.*, "400 MHz seamless copper cavity in the framework of FCC study", in *Proc. 19th Int. Conf. RF Superconductivity (SRF'19)*, Dresden, Germany, June-July 2019, pp. 36-38. doi:10.18429/JACoW-SRF2019-MOP007