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FABRICATION AND SURFACE TREATMENT OF SUPERCONDUCTING RF SINGLE SPOKE CAVITIES FOR THE MYRRHA PROJECT

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Abstract

The MYRRHA project, based at SCK-CEN (Belgium), aims at coupling a 600 MeV proton accelerator to a sub-critical fission core operating at a thermal power of 60 MW. The first phase of the project, MINERVA, consists in realizing a 100 MeV superconducting linac in order to demonstrate the machine requirements in terms of reliability and fault tolerance. The MINERVA linac comprises several cryomodules, each containing two Single Spoke 352.2 MHz cavities made out of high RRR niobium and operating at 2 K. The fabrication and surface treatment of the Single Spoke RF Cavities have been completely undertaken by RI Research Instruments GmbH (Germany) and is currently ongoing; the first pre-series cavities were completed and delivered for cold testing. Main highlights of the fabrication include the deep-drawing of complex shapes, such as the central spokes and the outer caps of the cavities, which were successfully accomplished. As for the surface treatment, RI has commissioned, tested, and effectively started to use a new rotational buffered chemical polishing facility; this is required to polish the inner surface of the cavities, ensuring a uniform removal of material.

CAVITY FABRICATION

The Single Spoke RF cavity for MINERVA is a complete Electron-Beam (EB) welded structure made out of high RRR niobium, integrated into a helium tank in titanium grade 2 (Fig. 1). The main niobium parts of the bare cavity were fabricated starting from 3.4 mm thick sheets. The conceptual cavity design was performed by IJCLab [1].

The deep-drawing of the central half-spokes (Fig. 2) and the endcaps (Fig. 3) was entirely carried out at RI Research Instruments GmbH (RI) by means of a 100 tonnes hydraulic press. This represented a critical milestone for the fabrication and required a deep development effort due to the shape complexity. The conception and design of the deep-drawing process and tooling were supported by the FEM software AutoForm [2], focusing on the definition and the simulation of metal sheet forming processes. The accuracy of the numerical results as well as the functionality of the tooling were proven in parallel by performing trials on copper sheets. Finally, after the process validation, also the first niobium sheets were deep-drawn with satisfactory results. The so-validated processes were then extensively exploited for the serial production of the cavities.

Deep-Drawing of Central Half-Spokes

The spoke tooling design and the process definition were carried out according to RI's expertise and best practice. They were then supported and validated by means of numerical simulations and a test campaign on copper sheets.

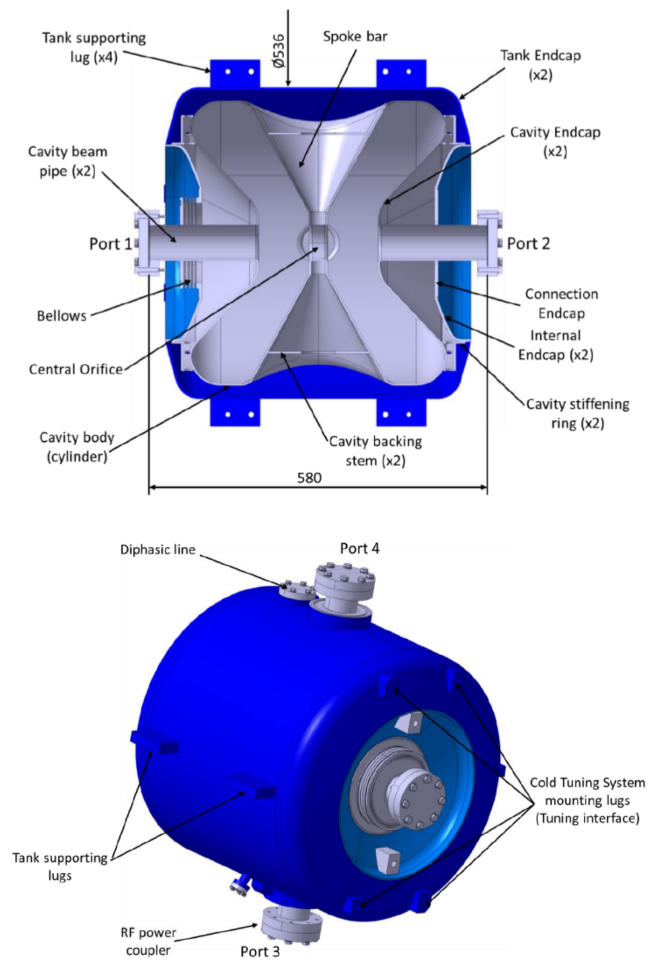

Figure 1: Cross-section and isometric overview of the Single Spoke RF Cavity for MINERVA; the niobium bare cavity is shown in grey, whilst the titanium helium tank is shown in light blue (Courtesy of IJCLab).

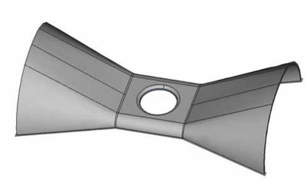

Figure 2: Central half-spoke.

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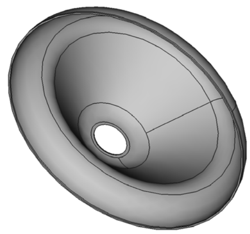

Figure 3: Cavity endcap.

Initially, a double-step process was foreseen (below referenced as Option A), which envisaged a preforming with a preliminary punch and a final forming with a nominal shape tool. The numerical simulation of this process showed that the pre-forming generates stiff corners at the extremities, which cannot be fully put into the desired shape after final forming with the nominal punch; this leads to residual wrinkles at the extremities (Fig. 4). These are also noticeable when looking at the geometrical deviation in the part (Fig. 5); moreover, it is highlighted that the process is not optimized for the shaping of the central region, where the part deviates due to local bending of the central surface. Figure 6 includes a plot of the final material thickness and shows a strong thinning at the four central top corners: residual thickness is 2.7 mm compared to a uniform starting sheet of 3.4 mm thickness. This corresponds to risks of local ripping, although the forming limit diagram confirms that these points do not exceed the forming limit curve for niobium (Fig. 7).

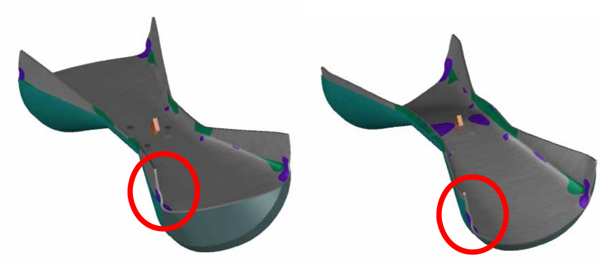

Figure 4: Simulation of the Option A process for half-spokes: initial preforming and final forming which leaves residual wrinkles at the extremities.

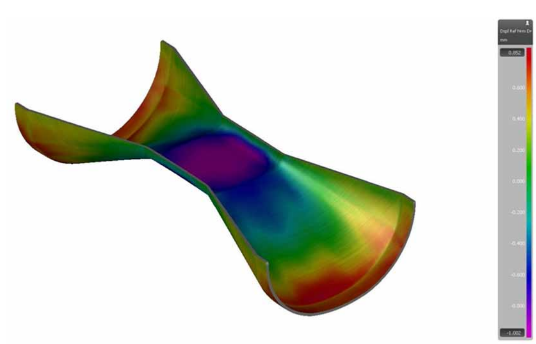

Figure 5: Absolute deviation in normal direction with respect to the nominal geometry after the final forming step of the Option A process: up to -1 mm in the centre and +0.8 mm at the extremities.

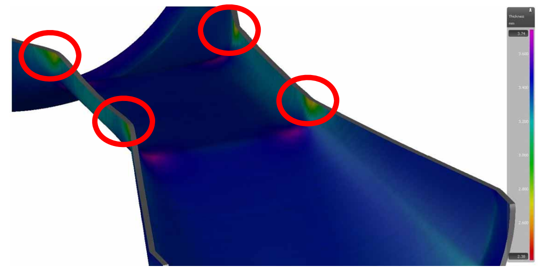

Figure 6: Material thickness after final forming: thinning up to 2.7 mm at the central top corners (yellow areas).

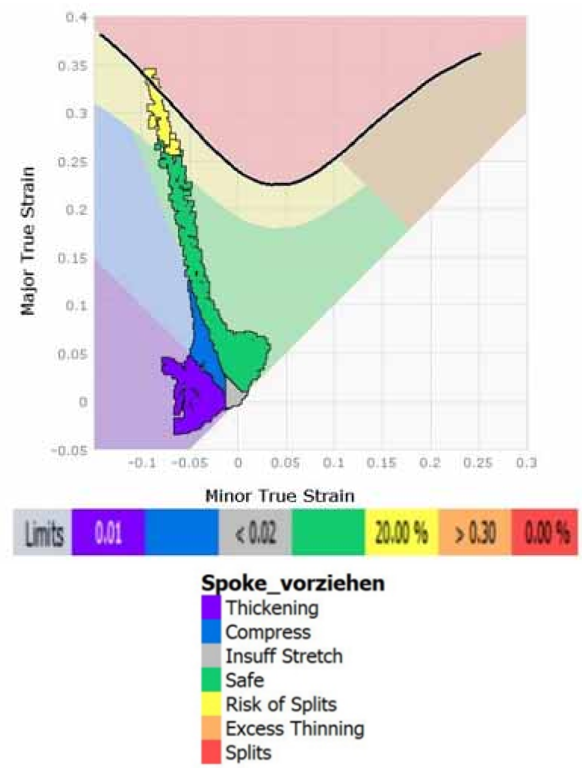

Figure 7: Formability assessment and forming limit diagram (black line representing the forming limit curve).

Copper trials were carried out to validate this process and fully confirmed the qualitative results of the numerical simulation (Fig. 8). It should be noted that only a qualitative comparison is possible due to the difference in the material properties between niobium (considered for the analysis) and the available copper grade for the trials (Cu-HCP / CW021A).

Following this return of experience, a new and simpler process was adopted (below referenced as Option B), which corresponded to the direct forming with the nominal shape punch (Fig. 9). The numerical results were very promising, showing that the generation of external wrinkles could be prevented (Fig. 10). The deviations in the central region could be drastically reduced as well; the local bending of the central surface initially created by the punch pressure on the half-spoke extremities is finally totally compensated when the punch reaches its standstill on the die.

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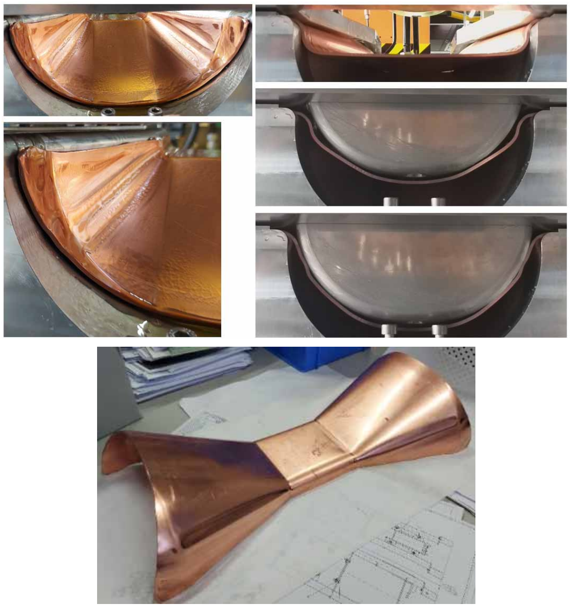

Figure 8: Option A process for half-spokes: copper trials.

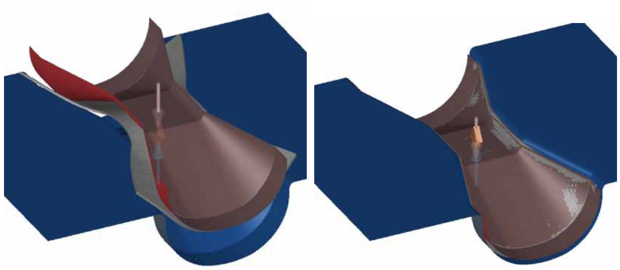

Figure 9: Option B process for half-spokes deep-drawing.

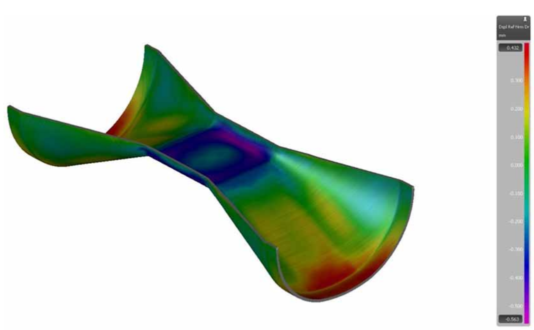

Figure 10: Absolute deviation in normal direction with respect to the nominal geometry after direct forming (Option B process): up to -0.6 mm in the centre and +0.4 mm at the extremities.

The copper trials confirmed the suitability of the process to the half-spoke forming and a first trial with niobium was performed (Fig. 11). The 3D metrology measurement of the formed part shows very low deviations, acceptable in view of the cavity functional requirements (Fig. 12). It should be noted that the starting sheet geometry was also optimised by means of numerical simulations in order to define the amount of residual extra-material on the edges and prevent the part ripping during the process.

Figure 11: Deep-drawing of niobium half-spoke spoke: view from the side and the extremity during the process and finished part.

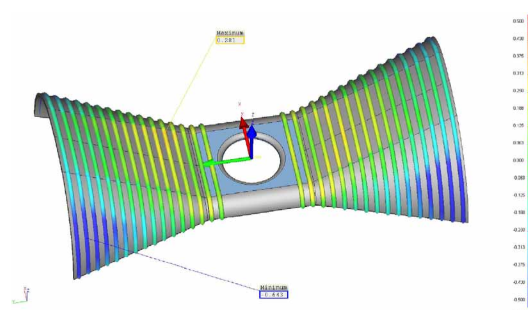

Figure 12: Metrology report of niobium half-spokes: deviations span from +0.3 mm at the outer-central surfaces to -0.6 mm at the side extremities.

Deep-Drawing of Endcaps

For the deep-drawing of the cavity endcaps, a double-step process was defined: forming of the inner region followed by the final forming of the outer diameter.

In a first step, a hold-down ring was foreseen on the outer diameter in order to prevent the development of wrinkles due to the external material thickening, as confirmed by the numerical simulations (Fig. 13 and Fig. 14). The inner radius in contrast showed a strong thinning – compared to a uniform starting sheet of 3.4 mm thickness - although the forming limit curve for niobium is not exceeded (Fig. 13). Parameters such as the total force applied by the press and the initial hold-down ring gap on top of the starting sheet were defined by combining RI's expertise and numerical analyses; the geometrical shaping and the material flow in the tooling were optimized in this way. The spring-back effect after tooling removal was also numerically evaluated (Fig. 15).

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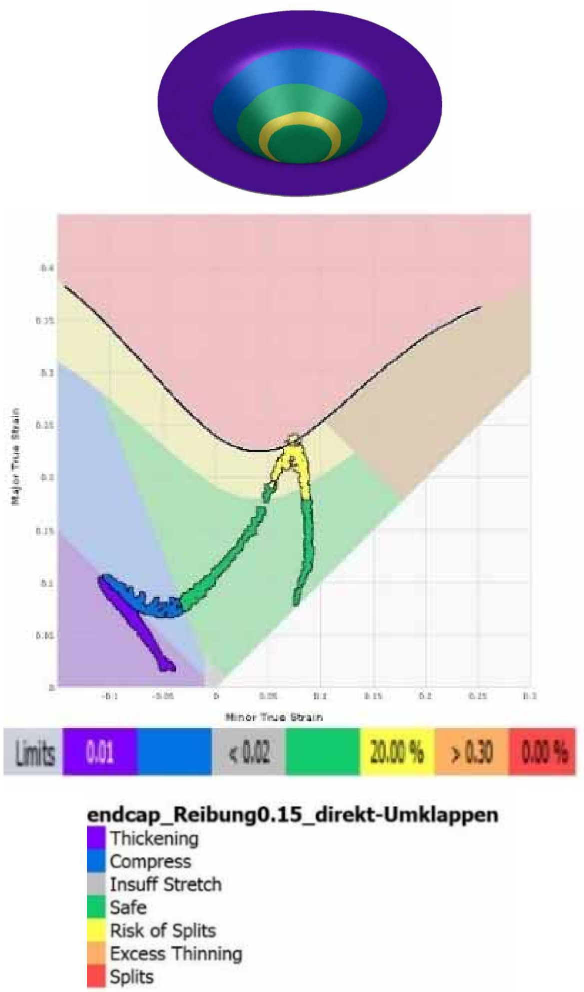

Figure 13: Numerical simulation of the first step of the endcap deep-drawing: forming limit diagram.

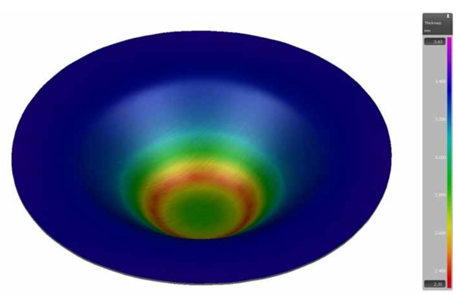

Figure 14: Material thickness after first step of endcap deep-drawing: light thickening in the outer region (around 3.5 mm) and strong thinning at the inner radius (2.5 mm).

For the second step, a simple forming with the final shape tool was initially foreseen and tested. When pressing on the outer region, massive wrinkles are generated (Fig. 16). These wrinkles are eventually flattened when the punch reaches its standstill on the die, although they are not completely eliminated and deviations are still appreciable (Fig. 17). Copper trials confirmed these results, although the residual wrinkles are much bigger on copper due to the material's stronger mechanical properties and lesser formability with respect to niobium (Fig. 18).

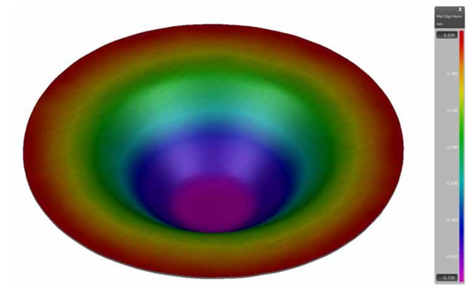

Figure 15: Spring-back effect after first step of endcap deep-drawing, spanning from +0.6 mm in the outer region to -0.7 mm in the centre.

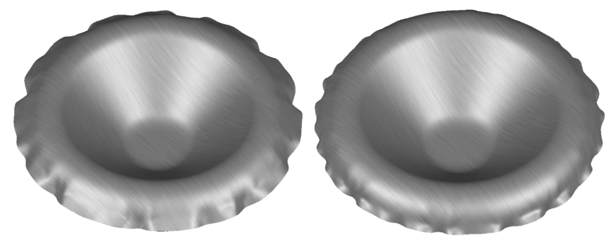

Figure 16: Numerical simulation of the second step of the endcap deep-drawing.

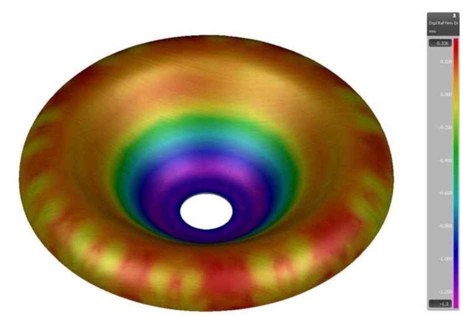

Figure 17: Absolute deviation in normal direction with respect to the nominal geometry after deep-drawing.

Figure 18: Copper trials of endcap deep-drawing.

Based on these results, the second step of the process was optimized by introducing an external clamping ring. This additional tool maintains the sheet clamped all around in order to minimize the wrinkle generation while driving the main punch downwards, whilst allowing the sheet sliding and the material flow during shaping (Fig. 19); parameters such as ring gap and clamping force were also optimized via numerical analyses. The wrinkle elimination and the improvement of the geometrical deviations were proven numerically and, subsequently, by means of successful trials with copper and finally with niobium (Fig. 20 and Fig. 21).

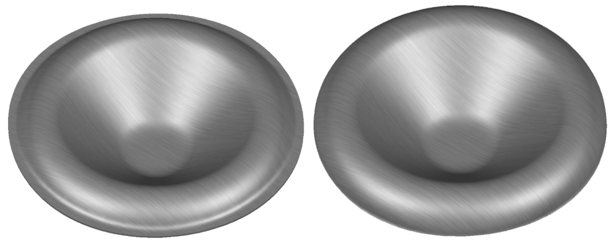

Figure 19: Numerical simulation of the second step of the endcap deep-drawing with an external clamping ring (not shown in the pictures).

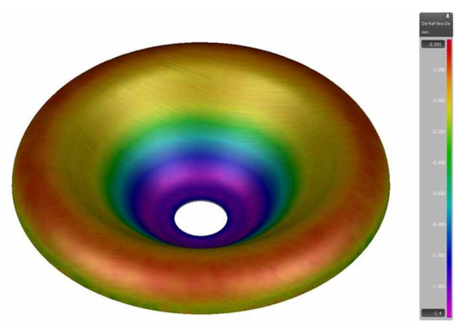

Figure 20: Absolute deviation in normal direction with respect to the nominal geometry after deep-drawing with the external clamping ring.

Figure 21: Successful deep-drawing of a niobium endcap.

ROTATIONAL BCP

The Buffered Chemical Polishing (BCP) process is a necessary part of the inner surface treatment of superconducting RF cavities in preparation of cold testing (if an electropolishing in lieu of BCP cannot be applied given the complex geometry of the cavity). It allows to remove a material layer from the cavity inner surface and subsequently polishes it, so that the cavity may achieve sufficiently high RF fields depending on performance requirements. A stationary BCP facility is already available at RI and extensively used on superconducting RF cavities. For the MINERVA project, a new rotational BCP facility was developed by RI (Fig. 22). Through continuous rotation of the cavity during the chemical process, rotational BCP helps to ensure a much more uniform niobium removal than achievable with a stationary BCP facility, especially when complex shapes have to be treated, such as Single Spoke cavities. It also avoids the creation of defects on the inner surface, which can be caused by gas bubbles sticking to the wall during a stationary BCP process.

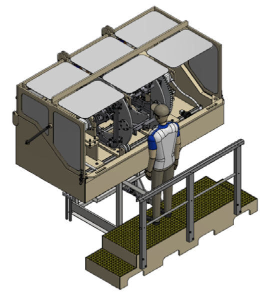

Figure 22: Overview of rotational BCP facility.

BCP Parameters

The main parameters for the BCP process were defined based on RI's expertise. The acid mixture is pre-cooled to 5-10 °C before the BCP start; the acid temperature during the process is kept between 10 to 15 °C and shall not exceed 15 °C in order to prevent excessive hydrogen contamination. The facility includes a spraying system on the top part, so that the cavity might be sprayed with cold water to keep the acid temperature below 15 °C if necessary. For monitoring purposes, temperature sensors are available in the acid circuit and are installed on the cavity itself.

Slightly more than half of the cavity inner volume is filled with acid during the BCP; the rest of the volume is flushed with a backflow of nitrogen. Target flow for the acid is around 10 litre/minute. Content of the acid mixture is as follows:

- 1 part nitric acid (65% concentration);
- 1 part hydrofluoric acid (48% concentration);
- 2 parts phosphoric acid (85% concentration).

The rotational speed of the cavity is around 1 RPM (Rotation Per Minute). This rotation is obtained through a motor and sliding contacts on the heads allowing to maintain a leak-tight connection during the rotation. For safety reasons, the facility integrates an external cage which shall be locked when the process runs. Moreover, when the process is stopped, the facility allows the full system, including the cage, to rotate by 90 ° in vertical position, so that the acid can be easily and quickly drained.

The actual material removal can be evaluated by means of Ultra-Sound (US) measurements of the thickness on the cavity wall. In the specific case of the MINERVA cavity, both bulk BCP (150 µm target) and final BCP (30 µm) are performed on the jacketed cavity; hence, this measurement is only feasible on the end pipes, which are not covered by the titanium He tank. The material removal can be also cross-checked by measuring the weight loss after BCP.

Facility Commissioning

Following the delivery and assembly, the rotational BCP facility was commissioned and tested by running the process on a 1.3 GHz single-cell cavity (Fig. 23). The system functionality and the compliance of the process parameters were confirmed. Moreover, the cavity inner surface was inspected and the niobium removal was measured in order to ensure that well uniform and regular removal is applied.

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Finally, the first MINERVA cavity was installed in the facility and then successfully processed (Fig. 24).

Figure 23: Rotational BCP facility commissioning with a single-cell cavity.

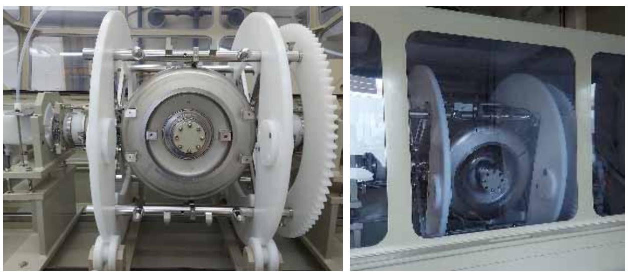

Figure 24: Rotational BCP of the first MINERVA cavity: installation of cavity in the facility (left) and during the process (right).

CONCLUSION

Process and tooling for the deep-drawing of half-spokes and endcaps, developed and validated via numerical simulations and copper trials are currently being extensively used for the series fabrication of Single Spoke RF cavities for MINERVA. The new rotational BCP facility was commissioned and tested; it is now effectively operational at RI's premises.

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