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Summary of the production of the ACN cavities

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Summary

The LHC-ACN RF system consists of eight normal conducting cavities (four per beam) made of bulk copper and resonating at 200.4 MHz. CERN provided the forged copper parts to the contractor for the final machining and assembly (Ettore Zanon S.p.A., based in Schio, Italy). The contractor had to weld all the flanges to the body of the cavity, machine and weld the cooling channels, carry out the final machining to have the right geometry and the requested RF surface finish, and make the final assembly of all the components by electron beam welding. The precision required during the various steps is quite tight with respect to the dimension of the cavities and would have required a very time-consuming and costly quality check during production, with the constant presence of a CERN staff member at the contractor's and subcontractor's premises. It was therefore decided, in the engineering phase, to foresee a tuning procedure before the final weldings to allow the same final result (precision on fundamental mode frequency) using fewer resources. This report explains the procedure for final check and tuning and gives an overview of the results achieved.

1. The Tuning Procedure

The ACN cavity is composed mainly of three parts, the two end caps with the drift tubes and the central cylinder bearing all the flanges for the power coupler, the High Order Mode (HOM) couplers etc. [1], Fig. 1. These three parts are joined by EBW (Electron-Beam Welding) at the end of the manufacturing process. For the first cavity we asked the contractor to send the three parts to CERN in order to check the influence of the ancillary equipment (couplers, tuner etc.) on the fundamental mode frequency. All the equipment has been installed on the cavity assembled in vertical position, and its effect on the fundamental mode carefully measured [2]. The result is summarized in the following table, together with the results of the simulations for the effect of heating, water cooling and beam loading:

Tab. 1: Changes in the fundamental mode frequency due to the various accessories and to physical effects.

Equipment	Δf introduced	Remarks
Power coupler	0 kHz	No influence since its input reactance can be adjusted to compensate the frequency shift.
HOM couplers	-5 kHz ÷ +20 kHz	Depending on the orientation of the loop (see Fig. 2).

Tuner	+24 kHz ÷ +224 kHz	With extension sleeve of 20 mm (Fig. 3).
Damping Loop	0 kHz	With loop out of the cavity[*].
Vacuum	+62 kHz	Effect of N_2 relative dielectric constant (1.00061). No deformation is induced by atmospheric pressure.
RF Heating + water cooling	-45 kHz	Simulated by Ansys [1]
Beam loading	- 19 kHz	For half detuning with nominal beam [3]

From these values the frequency of the bare cavity can be deduced in order to obtain the nominal frequency, 200.394 MHz, with the tuner at its half stroke.

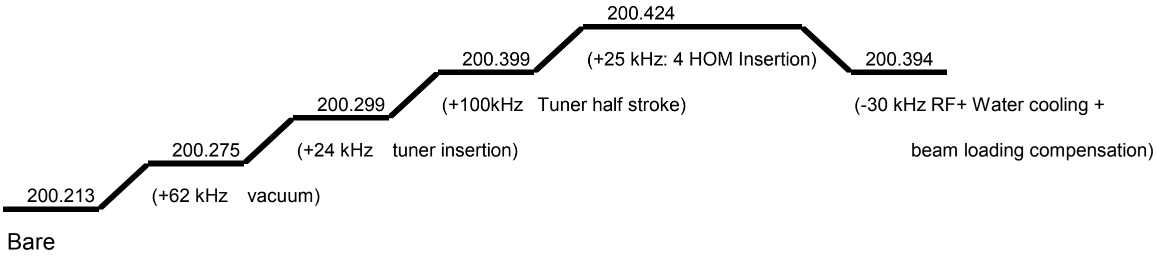

Fig. 1: Frequency change due to the different phenomena and equipment.

The goal is 200.213 MHz for the bare cavity without any equipment and filled with air at 20°C. In order to obtain this value with all the cavities, a procedure to check and adjust the frequency at the different stages of the production has been elaborated and implemented with the contractor. An overall length of 4 mm on each side with respect to the nominal dimension has been added to the central component of the cavity (see Fig. 2), in order to have enough margin to recover machining and welding tolerances in either direction. SUPERFISH simulations give a value of -125 kHz/mm[†]. (Frequency decreases when the length of the cavity diminishes). The frequency of the cavity was therefore 1 MHz (=8 mm * 125 kHz/mm) above the nominal value before welding the three components together.

In order to reach the goal frequency after welding the following procedure was applied to all the cavities:

1. Assume that (values confirmed by measurements on the first cavity):

$$\frac{\Delta f}{\Delta \ell} = -125 \frac{kHz}{mm}; \qquad \Delta f_{Weld} = -200\ kHz$$

2. Measure the frequency f_{meas} of the bare cavity assembling the three components vertically. The RF contact is ensured by the quality of the surface, the weight of the components themselves and by an RF seal (see Fig. 3).
3. Compute the length to be removed on the first side with the formula:

$$L = \frac{1}{2} \frac{\left[200.213 MHz - f_{meas} - (2 \cdot \Delta f_{Weld})\right]}{\Delta f / \Delta \ell};$$

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[*] When the damping loop is inside the cavity, its RF performance can be mechanically adjusted to provide optimal damping. This has never been done on these cavities and must be checked before the high power test.

[†] A measurement on the first cavity has confirmed this value. The first time we machined away exactly 1 mm, which resulted in -125 kHz of detuning.

Fig. 1: a) The end-cap with the nose cone; b) the central part on the nose cone, c)the three pieces assembled vertically in order to perform the measurements.

4. Measure the frequency after machining (for all the cavities the length removed was within tolerances: ±0.3 mm, see Tab. 2);
5. Weld the first side;
6. Measure the frequency $f_{1stweld}$ of the cavity to check the shrinkage and decide the length to machine away with the following formula:

$$L = \frac{\left[200.213MHz - f_{1stweld} - \Delta f_{Weld}\right]}{\Delta f / \Delta \ell}$$

7. Check the frequency after the machining (results as for point 4: see Tab. 2);
8. Do the final welding;
9. Measure the final frequency.

The 2×4mm overall length was essential to compensate an underestimation of the welding shrinkage. In fact, the shrinkage observed on sample rings of the same diameter as the cavity at the level of the welding was only 0.4 mm on each welding. In reality, due to the good thermal conductivity of copper, and to the much larger mass of the different pieces of copper with respect to the sample rings (>600 kg vs. ~10 kg), a much larger energy was necessary to obtain full penetration of the welding. The first equatorial EB welding was in fact not fully penetrated and a second pass with a current 20% higher had to be done. For the remaining cavities the higher current was systematically applied with success. The temperature of the cavities, kept for some hours under vacuum in the welding vessel to reduce oxidation during cool-down to room temperature, was uniformly around 70˚C just after the welding, and the measured shrinkage above 1.6 mm per welding (see tab. 4).

This campaign of measurement, machining and welding was realized at the contractor premises. For the first two cavities we performed all the operations in one week for each, for the following ones, with the collaboration of the contractor, it was possible to apply the procedure to two cavities in parallel in one week. The results of the measurements are summarized in Tables 2 and 3.

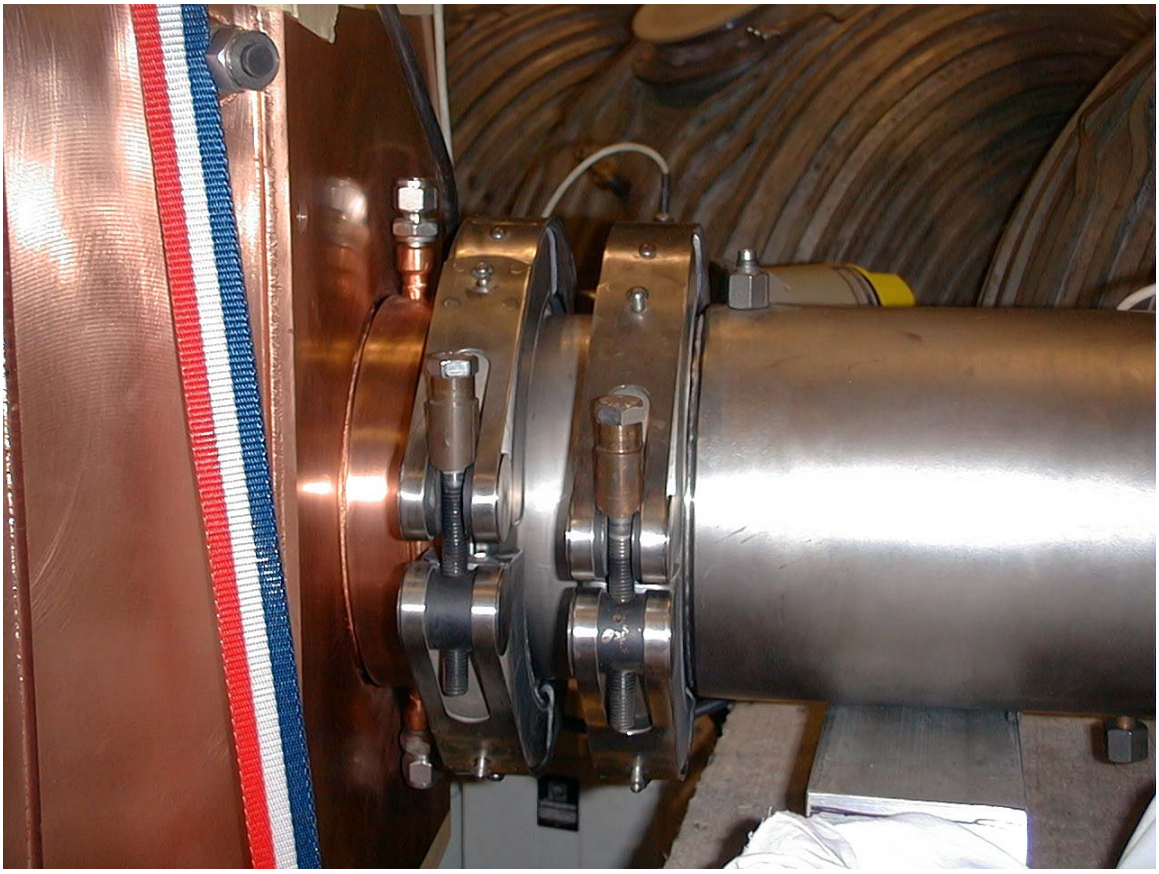

Fig. 3: A 40mm extension mounted on the tuner.

Tables 2 and 3 are extremely interesting since they show that the machining of the three separate components of the cavities was quite precise, even if in a few cases some dimensions were not fully respected. The deviation from the tolerance was within 0.2 mm, and we decided to go on with the standard procedure, since it was still possible to recover the error on the fundamental mode.

Tab. 2: Frequencies [MHz] measured on the eight cavities at the different stages.

Cavity	1	2	3	4	5	6	7	8
f_1	200.894	201.015	200.765	200.923	200.775	200.792	200.841	200.838
f_2	200.630[‡]	200.809	200.692	200.782	200.694	200.700	200.739	200.736
f_3	200.430	200.598	200.485	200.584	200.515	200.508	200.537	200.524
f_4	200.430[§]	200.420	200.423	200.416	200.417	200.430	200.436	200.429
f_5	200.210	200.218	200.206	200.211	200.198	200.214	200.212	200.213

[‡] Result of two machinings, the first of 1 mm to check the value of $\Delta f/\Delta \ell$, leading to an intermediate frequency of 200.767 MHz, and a second of 1.1 mm.

[§] No machining was done on the first cavity, since the measured welding shrinkage was surprisingly higher than that observed on the welding sample, due to the higher energy necessary to weld the massive pieces. For the second welding, the energy was even higher, leading to a slightly bigger shrinkage. For the following cavities, the level of current for the welding was the same for the two weldings.

Tab. 3: Statistics on the frequencies.

	Average [MHz]	Standard Deviation [kHz]	Meaning
f_1	200.855	85.1	Frequency of the three bodies detached
f_2	200.740	43.6	Frequency after the machining of the first side
f_3	200.523	53.3	Frequency after the first welding
f_4	200.425	7.18	Frequency after machining of the second side
f_5	200.210	6.0	Final frequency (after second welding)

However the position of the HOMs will have to be measured carefully once the cavities are fully equipped, since it may differ slightly from one cavity to the other. Cavity no. 1 should be the most affected, since it has been machined only on one side. Its symmetry plane is therefore displaced by more than 1 mm. It is anyway worth stressing that the spread in frequency of the three separate parts was below 1%, a remarkable result for components of these dimensions, and that the spread for the final frequency is negligible (0.002%).

For sake of completeness, Tables 4, 5 and 6 present the same results expressed in length (they have been calculated by difference from the frequencies with the known value of $\Delta f/\Delta\ell$).

Tab. 4: Lengths [mm] calculated on the different cavities at the different stages.

Cavity	1	2	3	4	5	6	7	8
$\Delta\ell_1$	2.18	1.6	0.6	1.2	0.6	0.7	0.9	0.9
$\Delta\ell_2$	2.11	1.65	0.58	1.13	0.65	0.74	0.82	0.82
$\Delta\ell_3$	1.6	1.69	1.66	1.58	1.43	1.53	1.62	1.7
$\Delta\ell_4$	0	1.45	0.5	1.3	0.75	0.7	0.9	0.8
$\Delta\ell_5$	0	1.42	0.5	1.34	0.78	0.62	0.8	0.76
$\Delta\ell_6$	1.76	1.62	1.74	1.64	1.75	1.73	1.79	1.73

Tab. 5: Meaning of the preceding values.

$\Delta\ell_1$	Length to be removed from the first side (from formula)
$\Delta\ell_2$	Length really removed
$\Delta\ell_3$	Shrinkage for the first welding
$\Delta\ell4$	Length to be removed from the second side (from formula)
$\Delta\ell_5$	Length really removed
$\Delta\ell_6$	Shrinkage for the second welding

Tab. 6: precision of machining

Cavity	1	2	3	4	5	6	7	8
$\Delta\ell_1$-$\Delta\ell_2$	0.07	-0.05	0.02	0.07	-0.05	-0.04	0.08	0.08
$\Delta\ell_4$-$\Delta\ell_5$	-	0.03	0.0	-0.04	-0.03	0.08	0.1	0.04

From Table 6, the precision of machining at the contractor premises showed results always better than 0.1 mm, with an average of the absolute error of 0.06 mm and a standard deviation of 0.02 mm.

2. Non-conformities

Two non-conformities were encountered during manufacturing on cavities no. 5 and no. 7.

On cavity no. 5 by error one of the ports foreseen to mount the damping loops was welded with a shorter cylinder (25 mm instead of 27 mm). As a result, the two ports are in different planes, still parallel but 2 mm distant. It was decided to proceed without repairing this because there should not be an important effect on the damping efficiency for that damping loop, and no influence on the integration in the machine.

On cavity no. 7, due to an error of machining, the outer diameter of the end beam tube of one of the two ends caps was machined to 109.5 mm instead of 112 mm. This was a major mistake because this surface is one of the walls of the water-cooling circuit of the endcap. In order to correct this, the cavity was re-machined in order to allow the insertion of an additional sleeve with a geometry that allowed two weldings. The result was excellent, the weldings were done properly and the leak test revealed no leaks in the water circuit.

3. Conclusions

The eight copper cavities purchased under the contract F358 have been delivered to CERN and satisfy to all the specifications (in particular: Nominal frequency = 200.213 MHz ± 40 kHz). Minor non-conformities have been observed during the production but in no case was it necessary to reject the cavity concerned, since no effect on the required performance will be seen.

4. Ackknowledgements

We wish to thank Dr E. Zanon, Dr. Corniani, Mr. Festa and all their team from Zanon S.p.a. for the collaborative and pleasant spirit that they always showed during the tuning procedure and over the duration of whole contract, which eased our work in following it up.

5. References

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3. J. Tückmantel, private communication.