EXPERIENCES IN FABRICATING AND TESTING THE RF-SECTIONS OF THE MAINZ MICROTRON

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Summary

For the 840 MeV-setup of the Mainz Microtron cascade (MAMI B)[1] the fabrication of a total of 10 rf-sections is under way. Based on the experiences made with the 6m of structure built in-house for the 14 MeV- and 180 MeV-stages of MAMI, an optimized final design and an as far as possible simplified fabrication and testing procedure for these medium power on-axis-coupled structures have evolved[2].

The standard 29-cavity-structures are described with their simple cooling arrangement and the tuning plungers placed at the ends of the section. Some details for machining high-Q, high-precision cavity segments and tuning and brazing them are given. Finally, results from the test-procedure of the sections up to a power of 22KW/m (1.2MV/m) are reported: optimum conditioning, changes of the passband gap (permanent and with power) and observations done by a residual gas analyzer as well as by just looking into the structures under power.

The standard MAMI-section

The on-axis coupled structure[3] is successfully used for MAMI, their great advantages being compactness, simplicity of fabrication and easiness of fighting recirculative beam-blowup[4].

Fig. 1 shows the standard 2.45GHz-section. With their length of 29 accelerating cells (AC) and 28 pancake coupling cells (CC) it is well adapted to a 50KW TH2075-tube (dissipated power 15KW/m (1MV/m), beam load 15KW and some margin for steering the RF-amplitude to 10^{-3} by the klystron input power). The coupling is 4%; attempts to increase it by a larger slot angle θ ($k(\%) = 2.5 \cdot 10^{-7}\ \theta^4$(deg); slot-width 11.5, web thickness 6.2mm) were given up: mainly because the beam-blowup mode at 4.2GHz began to propagate[5], but also since a loss in shunt impedance of 6% occured going from $\theta = 63^0$ to 80^0.

The section is bolted together from three parts, the combined vacuum-rf-seals[6] at the joints working without any failure over the last four years on the two sections of the 180 MeV-microtron. The cooling manifold consists just of 20 channels of 6mm diameter drilled along the circumference, where every five channels can be fed separately. A high power experiment[7] showed that for a structure with thick webs such an arrangement is sufficient for powers up to 60KW/m. The diameter and number of the cooling channels first is a compromise between a high coolant flow velocity and a pressure drop sufficiently low ($\Delta p = 1.5 \cdot 10^5$ Pa at 80l/m) to allow the series connection of a section and a klystron collector. Second it fits for the five sections of MAMI B to a change of 18^0 of the angle α between adjacent pairs of coupling slots from section to section as beam-blowup countermeasure[5]. Pumping of the sections is done at each end and - the most important vacuum port - directly at the rf-vacuum-window. Here, a pressure of more than 10^{-3} Pa triggers an rf-power trip, because sometimes the 60KW-windows were cracked with only 10KW at some 10^{-2} Pa.

Fig. 2 shows the design of the tuning plungers. A critical dimension was the slot of 2.5mm between the plunger and the cylinder, with only 1.5mm width here strong multipacting occured. Two plungers on a section give a tuning range of 500KHz. One of the plungers is steered by a phase comparison between the rf-input and a section-cavity, the other one just follows him to the same depth of penetration. The position of the plungers at the ends of the section was chosen by practical considerations (see below). Each section carries six 50dB diagnostic probes with equal phase with respect to the input.

Fabrication

Machining

Since for the 600 cavity segments for MAMI B pre-forging of the profile turned out to be uneconomic, they were machined from full copper discs (total price DM 400,--/segment). To get vacuum-tight OFHC-copper, the prescriptions for the supplier were a forging-factor of at least three in diameter and a careful cut of the ends of the cast billets to prevent shrinkholes.

The segments were rough-machined to 0.2mm, annealed under vacuum for 4 hours at 400^{0}C and then, fine-machined to their final dimensions. The integral accuracy of this last step was such that the resonant frequencies showed approximately a Gaussian distribution with a standard deviation of 0.15MHz and 0.4MHz for the AC's and CC's, respectively. The quality factor Q of the AC's was rather sensitive to the conditions of machining. A diamond lathe tool (to our experience improving Q by 10 to 20% compared to a steel

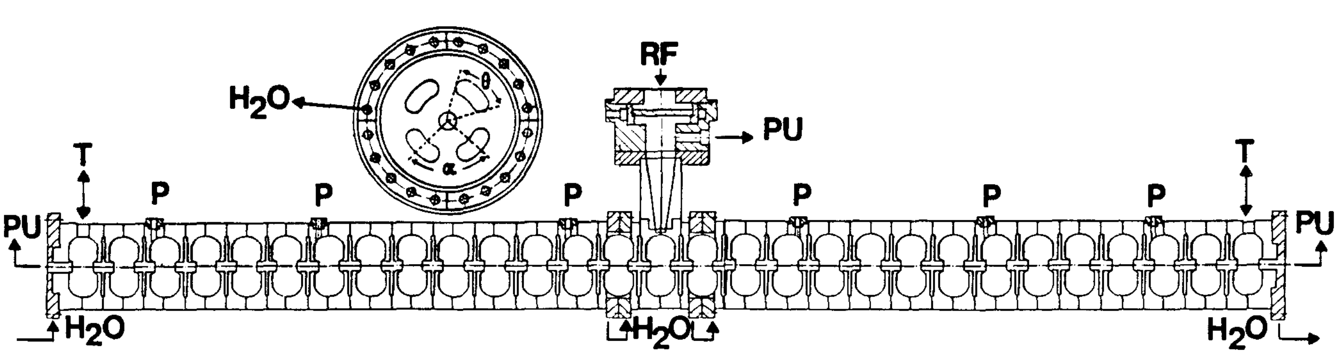

Fig. 1.: The standard MAMI-section (P-probe, PU-pump, T-Tuner)

tool) with a 0.5mm-radius semicircle profile was used and the lathe was run at 2100rpm with a feed of 0.03 mm/revolution. Then, a Q of 14500 to 15000 was always achieved (94% of SUPERFISH when accounting by 18% for the influence of the coupling slots). Just going down with the speed of the lathe to 1600rpm reduced the Q to about 12000, accordingly a surface roughness of 3µm instead of 1.8µm was measured. To get reliable frequency measurements on clamped cavity stacks (esp. for the CC's) a slightly convex profile of the circumferential end face of the segments was important, ensuring an electrical contact directly at the edge of the cavities.

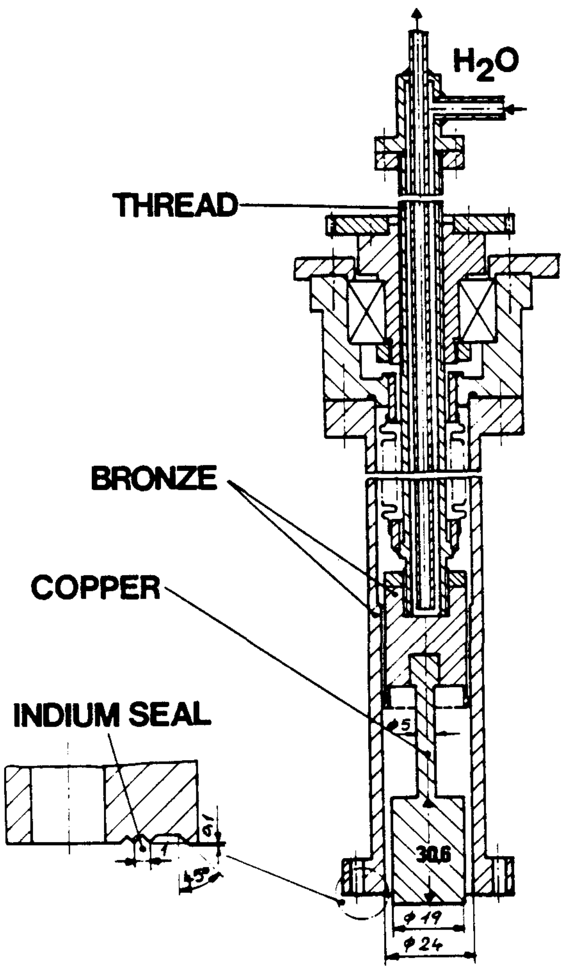

Fig. 2.: The tuning plunger

Tuning

The necessary standards for tuning the cells of a section were determined with the coupled-loop program LOOP[8]. The critical variable assumed was a detuning of the two end cavities by 7MHz (the plungers moving over their full range). The main result was (cf. fig. 3):

a) even with a very well tuned section one gets an additional unflatness in E_{AC} of 5% (compared to a power-flow-droop of 1.3%), a phase deviation $\Delta\phi_{AC}$ of $\leq 3^0$ and a deterioration in Q of 15% (caused by a field level in the CC's five times higher than from power flow only),

b) the tuning errors which just double this "zero-effect" are a random mistuning ($\Sigma\ \Delta f = 0$) of the AC's and CC's by 3MHz and 12 MHz, respectively and a passband gap $\delta = f_{CC} - f_{AC}$ of ± 0.7 MHz.

Therefore, after fine-machining, individual cells were mainly tuned to get the right resonant frequency for the whole section and a small δ. Tuning was done alternately by clamping individual AC's and CC's between tuned etalon-half-cells of the appropriate boundary type (π/2-mode) and by clamping half a section as a long stack. In the latter case a comparison was done for the gap δ determined by fitting a 4-parameter dispersion relation to the measured mode spectrum with DISPER[8] and by measuring the accelerating and coupling mode directly by appropriate boundary conditions: deviations up to 0.4MHz for absolute values and 0.15MHz for changes in δ occured between DISPER-results and directly measured gaps[10], just small enough to be tolerable.

The preset of the π/2-frequency for warm-up of the sections under power was with good success calculated by the semiempirical formula[2]

$$\Delta f = -0.041 \cdot P \cdot (7.17/D + 1.21/D^{1.2} + 0.23)$$

(Δf - MHz, P-power in KW, D-cooling-water flow in l/m). The first term is just the average warm-up of the cooling-water, the second describes the temperature jump at the water-copper boundary and the third (adjusted to measurements on the early MAMI-sections) gives the average warm-up of the structure itself.

As the final step of tuning a slot of a·b-11.5·38 mm^2 is cut into the mid cavity of the section (VSWR ~ $a^{1/2} \cdot b^5$) to give slightly overcritical coupling (VSWR = 1.17 for match at a beam load of 88·50µA). The flatness of E_{AC} was controlled to be better than 4% by a bead-pull measurement, no corrections on the coupling slots were done.

Brazing

The following brazing-alloys were used: for copper/copper-joints the eutectic Ag/Cu-72/28 (Cusil, 780^{0}C), for stainlees steel/copper-joints Ag/Cu/Pd-52/28/20 (Palcusil 20, 879^0-898^{0}C). The steel-copper brazings were done in a furnace with graphite heating elements and, therefore, a highly oxygen-free vacuum, thus, a nickel plating of the titanium-free stainless steel was not necessary. Small steel ports (e.g. the probe-flanges) were wettened with Palcusil 20, again finished and, then, brazed with Cusil together with the copper/copper-joints. As a support for repair of unsatisfactory brazings Ag/Cu/In-60/27/13 (Incusil 13, 605^0-710^{0}C) was sometimes used. The alloy Ag/Cu/Pd-58.5/31.5/10 (Palcusil 10, 824^0-852^{0}C) was unreliable, it softened during several Cusil-brazings at 790^0-795^{0}C and joints fell apart.

To place the filler at the joint wires of brazing alloy hidden in a groove were the preferred method, because thus, the inspection of light transmission before brazing was a very sensitive control of the flat contact of the joint surfaces. Brazing foil was avoided as far as possible. The joints were prepared by degreasing,etching with 25% acetic acid and rinsing with destilled water and acetone.

The only problem with brazing were rather unpredictable changes of the passband gap δ. With a statistics of brazing 17 cavity stacks they accured mainly by +0.9 and -0.5MHz. The annealing of the segments before fine-machining[9] did not reliably heal this effect. The positive change can be explained by a 0.05mm smaller diameter of the CC's (brazing alloy running in), but there is no convincing explanation for the negative change.

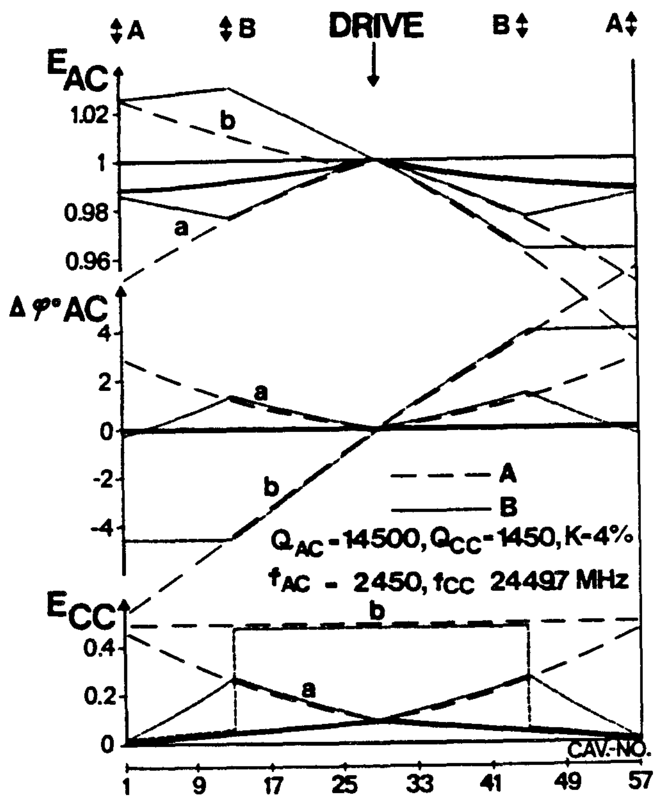

Fig. 3.: Field levels in the AC's and CC's and phases (mod. π) of the AC's in a standard section. Solid line: structure well tuned, dashed lines: plunger-cavities detuned (A-end tuners, B-middle tuners). Detuning was ++6.5MHz (a) and -+6.5MHz (b).

Power tests

Procedure of conditioning

RF-conditioning is done in the following way: with tuned-up end cavities the CW input power is slowly raised until vacuum trips begin to accumulate. Then, at about half this power, the end cells are detuned in opposite directions up to ±3.5MHz. This procedure is iterated with increasing power until 10KW can be instantaneously switched to the section and then, the power driven up to 35KW within a minute with the vacuum staying under 10^{-5} Pa. Normally, the first conditioning of a section took 10 to 16 hours, then - e.g. after opening the structure to air for inspection - one hour of conditioning after pump-down is sufficient.

The reason for the two-step conditioning-procedure can be seen from fig. 3: the first step cleans the AC's, then by moving the tuners in opposite directions one gets high "cleaning-field" levels in all the CC's with only moderate power input to the section. This was one of the reasons to put the plungers at the ends of the section, the other one was to place them - as the by far dirtiest part of a structure - as near as possible to the vacuum pumps.

Just looking at the unflatness effects and phase deviations of the AC's, fig. 3 shows a position of the tuners in the middle between input coupler and section end to be optimal ($\Delta Q/Q$ is reduced from -15% to -4%). For the injector linac of MAMI, where the sensitivity of the beam to these perturbations is much higher and the rf-power level only 7KW/m, this mid position will be realized[10].

The last test on a section is done by changing the cooling water pressure between zero and $6 \cdot 10^5$ Pa while observing the height of the water peak with a residual gas analyzer to detect any micro water-vacuum leak.

Measurements and observations

The change of the passband gap δ with input power was determined with the method described in ref. 7. Fig. 4 shows three typical measurements and the range of measured slopes (average: -28KHz/KW/m). The reason for the significant deviations between different sections (e.g. -37KHz/KW/m for MAMI A1[9] (fig. 4: x) in good agreement with a computer model[11], and -22KHz/KW/m (fig. 4: Δ) for section 1 of MAMI B) is not quite clear: the cavity profile was the same, only the different thickness of the outer wall of the structure (11mm for MAMI A1, 18mm for MAMI B) and a change in copper quality may account for a different stiffness of the webs. One should note that the slope of $\delta(P)$ changes sign[7] when going beyond 20KW/m.

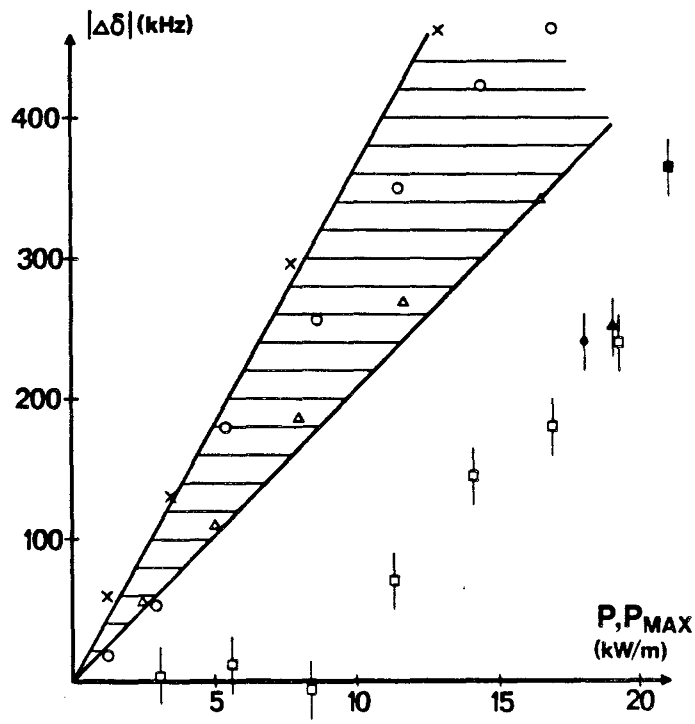

Fig. 4.: Range of slopes of reversible change of the passband gap δ with power (P,-$|\Delta\delta|$) and permanent changes measured at zero power after cycling to P_{MAX} (+$|\Delta\delta|$).

Already at low power levels, where the thermal stresses in the webs do not exceed the yield strength of copper[7,11], a permanent but stable change of the gap δ occurs. Fig. 4 shows this for four MAMI-sections (points with error bars).

The structures under power were open to optical inspection by glass windows at the ends. Although fabricated as clean as possible, lots of glowing particles were observed on their walls, absorbing some ten watts. The overall brightness of this glow decreased by a factor of 30 during the about 20 hours of the power test. The mechanism for this decrease is probably a reaction of the carbonized particles with the water-vapor in the section ($C+H_2O \rightarrow CO+H_2$ and $CO+H_2O \rightarrow CO_2+H_2$), as observed with the residual gas analyzer. The performance of the sections is not diminished by this glow, showing the sturdyness of normal conducting CW-structures.

The maximum possible power input was 39KW (22KW/m), this limit given by the cooling design of the tuners (fig. 2): at 43 KW their copper-head was molten, indicating an absorbed power of more than 160W. Guiding the cooling water further down would allow a factor of 2-3 higher power levels[7].

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