THE 4.9GHZ ACCELERATING STRUCTURE FOR MAMI C*

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Abstract

For the energy upgrade of the **MA**inz **MI**crotron (**MAMI C** [1], [2]) from 855MeV to 1500MeV a so called **H**armonic **D**ouble **S**ided **M**icrotron (**HDSM** [3]) is now under construction. To have a simple high power rf-distribution system, the two CW-linacs of this machine will consist of standing wave sections with a quite high number of accelerating cells (AC). One linac is operated at the MAMI frequency (2.45GHz) with an accelerating amplitude of 9.27MV and will have five 33AC-sections, each fed by one 50kW klystron. The other has to work at the first harmonic (4.90GHz) for 9.0MV and is made of eight 35AC-sections, each two of them powered by one 60kW klystron to be developed.

We report about the choice and optimisation process of the 4.90GHz accelerating structure and also present results of first model measurements on aluminium test cavities.

1 CHOICE OF STRUCTURE

For a standing-wave (SW) accelerating section with a large number of cells only biperiodic structures operated in $\pi/2$-mode should be considered [4]. Furthermore, at 4.90GHz the cell dimensions become already quite small (diameter ~ 46mm), so details of a precise and reproducible manufacturing process (machining and brazing), tuning tolerances as high as possible and a simple and efficient low pressure drop cooling manifold get relatively more important compared to e.g. a maximised shunt impedance R_s. Other important aspects to be considered are a loss free transmission of the 100µA beam and the beam blow up (BBU) properties of the structure.

A quite complete survey of advantages and disadvantages of the main four types of normal conducting SW-structures and of their optimisation was given in a LANL-paper [5]. Of these the DAW and the annular coupled ACS were not taken into consideration here because of their complicated mode spectrum. The side coupled structure (SCS) has, compared to the on axis coupled (OCS), the advantage of a 5 – 10% higher R_s (theoretically, only half the number of webs), but the disadvantages of a ca. by a factor of two lower achievable coupling coefficient (k~5%) and an altogether more complicated manufacturing. So the decision to stay with the OCS used in our RTMs was quite straightforward, naturally also because of the broad manufacturing and high power experience gained during the construction of MAMI A and B [6].

2 OPTIMISATION OF OCS-GEOMETRY

To reoptimise [7] the MAMI-OCS for the 4.90GHz HDSM-linac we use MAFIA [8] and, as far as the influence of a geometry parameter is evidently independent of the presence of coupling slots, the very fast, easy to use and precise URMEL [9].

The preconditions in this process are, that only circumference cooling as for the sections of our RTMs will be applied and that the structure will be operated at approx. the same power level as there, i.e. a dissipated power of ca. 14kW/m for a gradient of 1MV/m. Because the "maximum possible" values of these parameters scale with frequency only as ν^0 and $\nu^{1/4}$, we must stay with thick webs (3.09mm) and are thus fixed to a below optimum cell gap/length-ratio sacrificing ca. 5% of shunt impedance. Other parameter changes studied but rejected were (see Fig. 1): i) Smaller height h_S (6.0mm) of coupling slots for probably stiffer webs, but k is decreasing ~h_S^1. ii) Smaller radius of outer quarter circle r_q (9.13mm) in AC for more freedom to move the slots outward (see below, limited by diminishing radius of CC), but then one has a less stiff web, worse heat conductance to the outer wall and up to 10% loss in shunt impedance.

The seriously changed parameters are:

a) Diameter $\varnothing_B$ of beam hole: The parameter most influential on R_s; but the beam dynamical calculations for the HDSM [3] showed, that a scaled value of 7mm along an altogether 12m long linac would be dangerous for a relaxed machine operation. For values $\varnothing_B$ of 7/9/11/13mm the loss in R_s was calculated (with good agreement between MAFIA and URMEL) to 0/8/17/28%. Besides the decrease of R_s, an upper limit for $\varnothing_B$ was also given by the fact that beyond 10mm URMEL showed a quickly growing cell to cell coupling through the beam hole (ca. 0.6% at 13mm), which, because it is electric, would counteract the magnetic slot coupling. We took $\varnothing_B$=10mm, accepting a loss of 12% in R_s.

b) Angle α_s and position r_s of the coupling slots: For the tiny and long 4.90GHz-sections a large coupling is very important because i) for a certain quality (and price) of manufacturing the achievable absolute machining accuracy goes only with approx. the dimensions$^{1/2}$ and ii) the coupled loop models [10] for biperiodic structures

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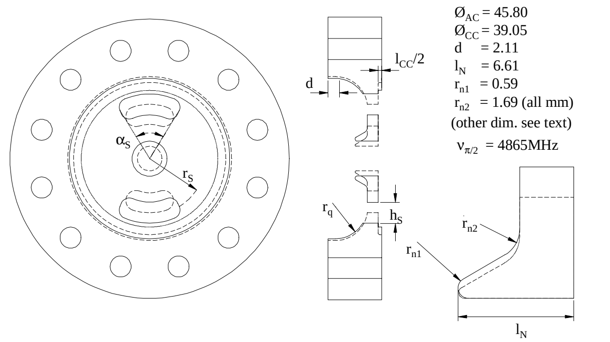

Figure 1: Comparison between a 4.90GHz-cell design and the MAMI 2.45GHz-cell scaled by ½ (dotted lines).

show an improvement in stability with k^2 or at least k (e.g.: power flow drop $\sim 1/(k^2 \cdot Q_{AC} \cdot Q_{CC})$; tilt sensitivity $\sim \Delta\nu_e \cdot \delta/(k^2 \cdot \nu^2)$ when detuning end cells by $\Delta\nu_e$ with a plunger, where δ is the passband gap; field level in very flat coupling cells $\sim 1/(k \cdot Q_{AC})$). Because the quality factors $Q_{AC,CC}$ go down (at least) with $1/\nu^{1/2}$, an increase of the coupling k=-4% of the 2.45GHz RTM-structures by more than a factor $\sqrt{2}$ is necessary. The most sensitive parameter to increase k is α_s ($k \sim \alpha_s^{3...4}$); clearly for larger α_s one has to pay by a worse heat conductance from the interior cell region (where 20-25% of power is dissipated) to the outside. Another means to increase k is to shift the slots outward to a larger radius r_s (Fig. 1), thus getting a purer magnetic coupling instead of the somewhat mixed coupling when they are positioned near the nose cones. A limit here is given by the increase of eff. web thickness with increasing r_s due to the rounded outer profile and by the coupling cell diameter $\varnothing_{CC}$ getting smaller for a closed gap. For several slot geometries the coupling factors calculated by DISP-fits [11] to the MAFIA-spectra are given in Tab.1. The geometry taken for our Al-models was α_s=63.9° at r_s=15.5mm, where with the difference of 1mm between outer slot radius and the edge of the CC one has enough freedom to tune them by diameter. The loss in R_s for this parameter set compared to a scaled MAMI-OCS would be 4%.

c) Length l_{CC} of coupling cells: ν_{CC} is quite sensitive to this parameter, $\partial\nu_{CC}/\partial l_{CC} \approx$ +90MHz resp. +160MHz for r_s=12.5mm resp. r_s=15.5mm around l_{CC}=1.94mm. Larger l_{CC} gives a loss of R_s ca. linear by percentage of cell length, the influence on k is still under investigation.

Table 1: MAFIA/DISP results for diff. slot geometries and positions. Upper part for slots at r_s=12.5mm, lower for r_s=15.5mm. **S**,**R**-slots with **S**harp edges resp. by radii of 2.5mm **R**ounded edges. For $\nu_{\pi/2} \approx$4899MHz gap always closed to < ±5MHz. Between 154k and 1070k gridpoints for normally 3 cells (½AC/CC/½AC) with 6 mode frequencies; but some checks also with 5 cells and 10 frequencies. Coupling k and k_2 from 4 parameter fits with DISP (the same spectra fitted by 5 par. always showed a nearly identical k and $(k_2+k_3)_5=(k_2)_4$, e.g. seventh row: –8.19/-0.54% → -8.15/-0.81/+0.26%).

α_s [°]	$\varnothing_{CC}$ [mm]	-k [%]	-k_2 [%]
64.0 / S	44.6	5.81	0.21
68.9 / R	44.1	6.21	0.24
72.9 / R	42.3	7.69	0.36
51.6 / S	42.7	5.27	0.24
64.0 / S	37.5	9.38	0.73
60.5 / R	40.7	6.88	0.39
63.9 / R	**38.9**	**8.19**	**0.54**
68.5 / R	37.0	9.88	0.78

d) For a good shunt impedance at a quite large beam hole (14mm) the nose cones of the 2.45GHz-structure were very sharp. Scaled down by ½ these noses would put difficulties to the shape of a lathe tool for machining a high quality surface of the whole AC in one stage. We therefore thickened the nose cones (Fig.1) while holding their angle of 30° and nearly their length. The loss in R_s is only 2.5%.

3 THERMOMECHANICAL BEHAVIOUR

In addition to achieving a coupling as high as possible a passband gap $\delta=\nu_{CM}-\nu_{AM}$ (CM, AM – coupling resp. accelerating mode) near zero is most important for a stable operation of a SW-structure even under some mistunings, be it statistical or e.g. caused by tuners in the end cells. In the OCS the asymmetric rf-current loading of the AC- and CC-side of the webs deforms them and causes a change of δ with rf-power. For many of the 2.45GHz MAMI-sections this change has been experimentally determined [6] as $\Delta\delta$=-21 to –37 kHz/kW/m. The measurement error was not more than ±10%, therefore the reason for the larger span of data is not totally clear till now: only the thickness of the outer wall cylinder changed between 11 and 18mm and the amount of forging of the copper at the supplier (before brazing!) was different.

To get an estimation of $\Delta\delta$ for our new profiles at 4.90GHz, we carried out an investigation [12] with the 2D program package PRUD/HAST [13]. PRUD calculates accurate frequencies and rf-current distributions with a very flexible mesh and HAST, with identical mesh, gives a deformed geometry back to PRUD. Because at 10kW/m the deformations are less than 2-3µm, they were multiplied by a factor of 10 to get the frequency changes, after a test that one stays within the linear perturbation range with this. We do not expect better results with e.g. MAFIA+ANSYS, where the coupling slots could be modelled, if one has to stay below several 10^6 mesh points. It was also tried to 2D-simulate the slots by a ring notch of equal volume at their radius. The calculations where done for an on axis field of 1MV/m, a heat exchange coefficient copper/water of 17500 W/m^{2}K (corresponding to a cooling water flow of ca. 60l/min at 2.9m/s) and as non trivial copper-constants a young modulus of $1.12 \cdot 10^{11}$ N/m^2 and a poisson ratio of 0.385.

As test a calculation for the 2.45GHz-profile [6] was done, without (P) and with ring notch (P+RN), and the results are compared with the empirical data (E) in Table 2 (the geometry parameters for this test were: $\varnothing_{out}$=114mm, $\varnothing_{AC}$=93.6mm, $\varnothing_{CC}$=88.9mm and $\varnothing_B$=14mm).

Table 2: Comparison of the exper. high power behaviour of the MAMI 2.45GHz-structure with thermomechanical PRUD/HAST calculations. All data normalised to 1kW/m.

	E	P	P+RN
$\Delta\nu_{AC}$ [kHz]	-23	-17	-31
ΔT_{Nose} [°C]	1.1	0.84	1.60
$\Delta\delta$ [kHz]	-21 to -37	-36	-61

The overestimation of the measured data by P+RN, shows that the simple model with unperturbed web is nearer to the truth.

The results for different 4.90GHz-profiles are given in Table 3. Here the parameter changed from a 2.45GHz-scaling is $\varnothing_B$=10mm and this alone reduces $\Delta\delta$ by a factor of 2. In addition also an influence of the thickness of the outer cylindrical wall can be seen (first 3 cases), which may perhaps explain the large range of measured values $\Delta\delta$ for the 2.45GHz profile. The most interesting fact, however, is the change of sign of $\Delta\delta$ with diminishing $\varnothing_{CC}$. A positive $\Delta\delta$ has the right sign to be safe against the very high power "thermal runaway". PRUD/HAST gives also a time development for the temperatures. Assuming a $(1-e^{-t/\tau})$-curve we got τ=5.0/1.9s for the 2.45/4.9GHz-profile respectively.

Table 3: PRUD/HAST calculations for different 4.90GHz geometries. $\varnothing_{AC}$=45.9mm, $\varnothing_B$=10mm, $\varnothing_{out}$=diameter for coolant flow. All data normalized to 1kW/m. The temperature rise at the nose cone was always 1.0°C/kW/m.

$\varnothing_{out}$ [mm]	57	78	68	68	68
$\varnothing_{CC}$ [mm]	44.0	44.0	44.0	40.8	39.0
$\Delta\nu_{AC}$ [kHz]	-52.4	-49.3	-52.1	-55.8	-58.0
$\Delta\nu_{CC}$ [kHz]	-80.4	-85.5	-80.4	-47.9	-29.9
$\Delta\delta$ [kHz]	-28.0	-36.2	-28.3	+7.9	+28.1

Naturally the permanent change of δ we noted for the 2.45GHz-sections [6] can only be determined experimentally.

4 MODEL MEASUREMENTS

To get an experimental verification of the MAFIA/URMEL calculations and for first experiences with machining, thirty 4.90GHz segments (½AC / ½CC) were fabricated according to Fig. 1. For more robustness compared to soft pure copper (e.g. for test-mounting input couplers, tuners etc.) they were made from aluminium (AlCuMgPb, $\sigma_{Al}=20.3 \bullet 10^6$ A/V 1/m, measured to ±1%). The disadvantage clearly is an uncertainty for the finally achievable Q_{Cu}: the skin depth in this Al is 1.59µm compared to 0.94µm in Cu and also the higher weight of Cu-segments can give a rougher surface for a given lathe-concentricity. The lathe worked at a speed of 2400min^{-1} with a feed of 0.008mm/turn, a R=0.2mm hard metal tool was used.

A first measurement was done before machining the coupling slots. The 30 half Al-AC's were within a full range of 1.3MHz and the average frequency combining them statistically to full cells was ν_0=4970MHz, compared to an URMEL prediction of 4964MHz (20k grid-points). Within ±2-3% we measured Q=6960 and R_s/Q=7.788kΩ/m (by the dielectric rod method, including the corr. $a_1^2/\Sigma a_\nu^2$=0.98 for space harmonics by a Fourier analysis of the calc. axial E-field); a pleasant result compared to URMEL values (corr. for σ_{Al}) of Q=7030 and R_s/Q=7.656kΩ/m. So the surface roughness must be distinctly less than the skin depth of 1.6µm. After machining the coupling slot pairs, $\nu_{\pi/2}$, Q and R_s were measured at stacks of different lengths with the results of $\nu_{\pi/2}$=4865.2MHz, R_s/Q=7.762kΩ/m and Q=5820. That can be compared with MAFIA [8] results: $\nu_{\pi/2}$=4866MHz, R_s/Q= 8.234kΩ/m and Q=6880 (4×270k gridpoints, corr. for σ_{Al}). The couplings measured were –8.15/-0.54% as predicted by MAFIA (Tab.1).

When closing the passband gap δ by adjusting the diameter of the CC ($\partial\nu_{CC}/\partial\varnothing_{CC}\approx$-90MHz/mm) we found, that the angle φ_{AC} between the two pairs of coupling slots in the ACs is important (φ_{CC} must evidently be 90° to prevent strong second coupling): with $\delta\approx$0MHz made for φ_{AC}=0° the gap opens up to δ=+18MHz for φ_{AC}=90°, while ν_{AM} changes only by –3MHz. Disp-fits gave couplings of k/k_2=-8.15/-0.54% resp. –8.43/-0.02% for the two cases. (and MAFIA 5 cell-calculations confirmed this behaviour [7]). A renewed measurement on the 2.45GHz-profile (k=-4%) showed the same effect, but a factor of 5 weaker.

The HDSM-sections will be built with φ_{AC}=0° / φ_{CC}=90°, thus raising the calculated BBU threshold current of 0.24mA ([2], [14]) by a factor of two. For the TM_{110}-like BBU-mode a passband was found at 8397 – 8439 MHz; this mode is split by 70MHz for the two polarisation's relative to the slot pairs.

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