Design of a 94 GHz Accelerating Structure

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Abstract

Recently accelerating structures at 120 GHz have been proposed. The choice of frequency was due to the availability of gyrotron power sources and the structure depth achievable by deep X-ray lithography (LIGA). In the meantime, progress allows for a somewhat lower frequency of 94 GHz where gyrotrons and medium power klystrons are more readily available. The paper presents the design of an accelerating structure which is planar double-sided and suited for fabrication by lithography. Since the structure is foreseen for high gradient operation, a side-coupled standing-wave muffin-tin was chosen in order to garantee a flat temperature profile while still having reasonable mode separation. Endcells and input power coupler are matched numerically by means of a new code GdfidL. The main RF parameters are also determined numerically as well as temperature distributions. Finally, first ideas for the full engineering of the structure are given.

1 INTRODUCTION

High aspect ratio microstructure technology (HARMST) provides means for fabricating high precision submillimeter components like actuators, gears, electrostatic motors, pumps etc. [1]. The same technology can be used for fabricating very high frequency accelerator components as proposed first in 1993 [2]. In this paper a planar (two dimensional) traveling wave structure was designed which consists of two metallic slabs supporting match-box like cavity resonators. Such a structure can be closed on the sides or open (Fig. 1) where, however, the fields decay exponentially in the open sides.

Since it will be very difficult to tune these tiny structures, the fabrication by deep x-ray lithography and subsequent etching and electroplating (LIGA) was chosen. This technique allows for very high precision, in the micron region, and perpendicular walls with good surfaces. However, at that time the feeling was that the structure depth is limited to about $500\,\mu m$. Therefore, as a compromise, the structure was designed for 120 GHz. In the meantime, progress in technology allows for deeper structures where the frequency can be lowered to 94 GHz (a satellit band) which is somewhat relieved but still high enough to explore a new regime. Also a new technique of electroforming in micro-structured glass has been proposed by Hülsenberg and others, see [1]. In this case UV-lithography on glass is used which is appreciably cheaper than x-ray lithography and which is better suited for deeper structures. Certainly for standard technology and frequency, the disk-loaded constant-gradient wave guide structure is an optimal solution with respect to performance and costs. At very high frequencies and using fabrication by lithography, the optimal solution is different. Here the losses are higher for a given gradient and the structure length is shorter. Since constant-gradient structures are very difficult to make, the temperature gradient along the structure may become prohibitive. On the other hand, adding any device to the structure, e. g. side-coupling cells, does not increase the costs as long as everything stays planar. Therefore, we have adopted a confluent side-coupled standing-wave structure [3] which has been modified slightly in order to have equal depth for all parts. The endcells of the structure and the input power coupler have been designed and matched numerically by means of a new code GdfidL [4]. The same code also allows for a steady-state temperature analysis. Finally, first ideas for the engineering of a complete unit are given.

2 STUCTURE GEOMETRY AND RF PARAMETERS

The structure corresponds to geometry (1) in [3]. It is a standing-wave structure which is side-coupled and confluent at the π-mode. The coupling cells have been enlarged in order to increase the coupling. The partial cuttings into the side-walls have been suppressed such that the whole structure has equal depth and height. The length of main cells follows from the π-mode as

$$L = \pi/\beta = \lambda/2 = 1.595\,mm \tag{1}$$

and the iris thickness was fixed to $t = 0.25\,mm$. The aperture for the beam is in principle a free parameter and influences the bandwidth, shunt impedance and wakefields. As a trade off between the different requirements $2a = 0.75\,mm$ was chosen. All the other dimensions were calculated with GdfidL and are shown in Figure 1. The main RF parameters are given in Table I.

$$\begin{aligned}
r\,/\,Q_0 &= 81.5\,k\Omega/m \\
Q_0 &= 3620\ (\kappa = 56 * 10^6\,\Omega^{-1}m^{-1}) \\
r &= 295\,M\Omega/m \\
v_g/c_0 &= 0.0113 \\
\alpha &= 24\,m^{-1}\ attenuation\,length \\
k_0 &= 12 * 10^3\,\frac{V}{pCm}\ \text{fundamental mode loss factor}
\end{aligned}$$

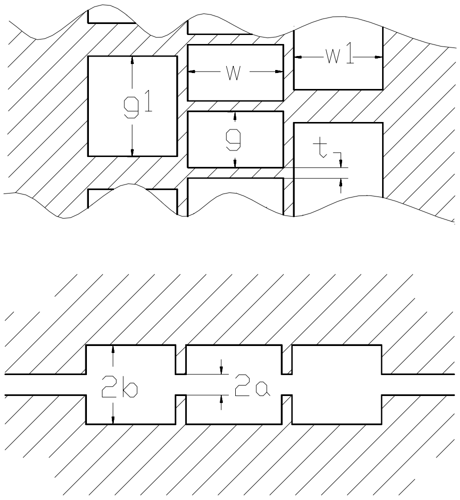

Figure 1: Geometry of the structure: $g1 = 2.40$, $w = 2.29$, $g = 1.34$, $t = 0.25$, $w1 = 2.14$, $2b = 2.29$, $2a = 0.75$ (in mm)

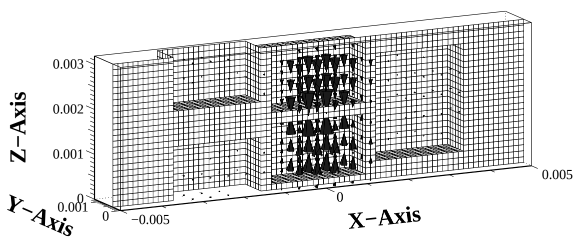

Figure 2: Field pattern of the confluent π-mode.

Table I: RF parameters of the structure

As can be seen, the group velocity is uncomfortably low a consequence of the side-walls which are not cut down in this geometry. Nevertheless, due to its ease of fabrication, we keep this geometry for the moment and try to remedy this problem later. The field pattern of the confluent π-mode is shown in Figure 2. An estimate of the number of cells which can be coupled together gives

$$N < \frac{\pi v Q_o}{4 c_o} \approx 31, \tag{2}$$

which was lowered to 21 for a reasonable mode separation. Two structures are positioned on one wafer and powered via a power splitter from a single feed line (Figure 4).

3 FULL STRUCTURE WITH ENDCELLS AND POWER COUPLER

Special care has to be taken to get a flat π-mode distribution. This requires a detuning of the endcells and, in our case, of the end-coupling-cells. The final configuration of the end parts (Figure 3) was found with a numerical optimization procedure. The next step was the design of a power input coupler. Clearly, for standing wave operation with a relative large number of cells it is preferrable to couple symmetrically. The feed line couples, therefore, to the mid-cell via the side-wall. The coupling strength was matched by a $\lambda/4$ stub-line. The whole device consists of a central feed line, a power splitter, two bends and the input couplers, Figure 4. Again, power splitter, bends and couplers were numerically optimized with GdfidL.

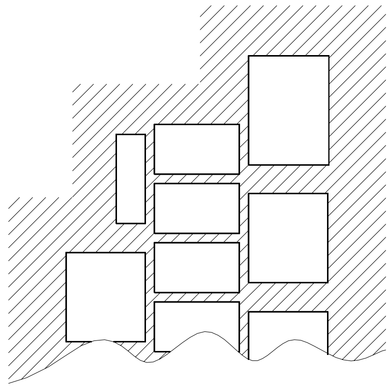

Figure 3: End configuration of the structure tuned to a flat π-mode.

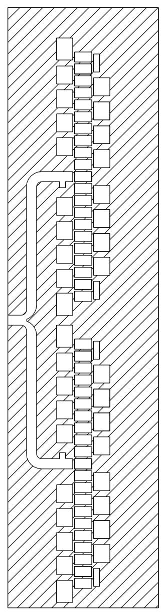

Figure 4: Two structures with central feed line, power splitter and couplers.

4 THERMAL ANALYSIS AND VACUUM TANK

With a 10 MV/m accelerating gradient the dissipated power will be 340 kW/m corresponding roughly to a heat flux of 3.4 $\mathrm{W/mm^2}$ averaged over the structure. Although such a heat flux can be cooled with advanced cooling devices like microchannels, there is probably no need to operate the structure in CW. Therefore, we assumed, for the moment,

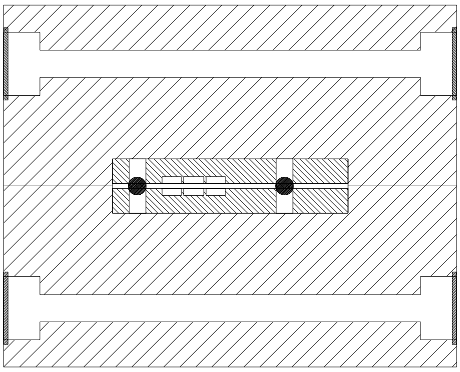

Figure 5: Cross-section of the RF structure with integrated cooling channels.

a duty cycle of 1 % and a repitition rate of 100 Hz which leads to a relative constant temperature distribution. Under these circumstances the heat flux is only 3.4 $\mathrm{W/cm^2}$ and straight forward cooling is possible. The heat analysis was done with GdfidL, where the RF power absorbed in the structure surface was calculated and used as the heat flux input for a steady state analysis. With a thermal conductivity of 3.84 $\mathrm{W/cm^\circ C}$ and a 1 cm thick copper slab, a temperature increase of 7 ^{o}C was found in the iris center. Finally, a first attempt was made to design a proper vacuum vessel. We believe it best to separate the vessel from the high precision structure, Figure 5 and Figure 6. In that way, several structures together with beam position pick-ups and if wanted, integrated quadrupoles can be prealigned, plumbed and mounted in a single vessel. The structure itself is open and does not need special devices for pumping.

5 CONCLUSION

At very high frequencies, around 100 GHz, RF structures have to be fabricated by lithography and, therefore, must be planar. Two technologies are available: Deep X-ray lithography and UV-lithography. Both seem to meet the requirements for an RF structure. The electrical behaviour of a planar structure is totally different to axis-symmetric structures. Now taking advantage of the higher geometrical degree of freedom and of the fact that costs are roughly independent of the complexity of the structure one can find attractive solutions to particular problems. A first design may be a straight forward traveling-wave structure as proposed in [2] or the above presented standing-wave structure. Both approaches are possible. Preference to one or the other may stem from an operational point of view or from cooling requirements in case of high gradient operation.

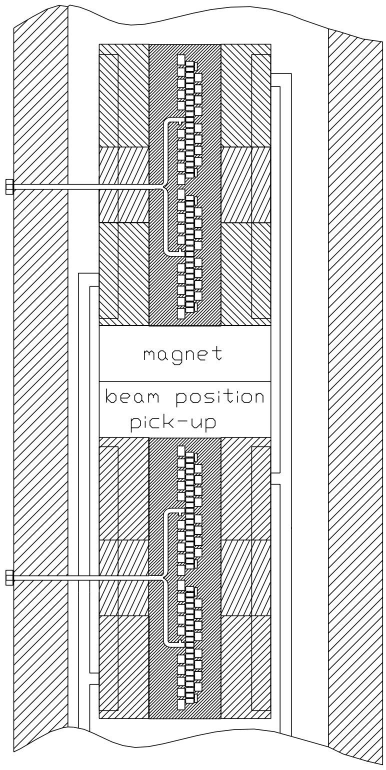

Figure 6: Top-view of the RF structure housed in a vacuum vessel.

6 REFERENCES

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