PLANAR STRUCTURES FOR ELECTRON ACCELERATION

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Recently planar RF structures have gained appreciable interest due to their unique features. They have been proposed for very high frequency applications, where they are ideally suited for fabrication by deep X-ray lithography, for linear colliders and for sheet-beam klystrons. The paper presents structures for the different possible applications: Travelling and standing wave structures, side-coupled structures, structures with a position independent accelerating field and cavities for accelerating wide sheet-beams.

I. INTRODUCTION

Planar RF-structures consist of two or more metallic or dielectric slab materials supporting "match-box" like cavity resonators. The slabs can be in direct contact, thus forming closed rectangular structures (Fig. 1 a), or electrically separated forming an open structure where the fields, however, decay exponentially in the gap (Fig. 1 b).

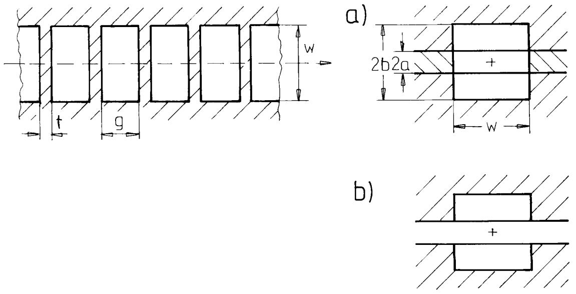

Figure 1. Examples for planar structures; a) closed structure; b) open Muffin-Tin structure.

Recently, these planar structures have gained more and more interest due to some unique features which may be important for special applications. The most important reason is for high frequency applications. It is obvious that above frequencies of 30 - 50 GHz it will be very hard to realize axis-symmetric structures. On the other hand, modern microfabrication techniques like stamping, microvibration or deep X-ray lithography with subsequent electrodeposition (LIGA [1]) offer the possibility to produce planar structures with sufficient precision. Especially LIGA seems to be perfectly suited for very high frequencies, let us say around 100 GHz. It has fabricational tolerances in the micrometer regime and allows for adding complexity to the geometry nearly free of costs. Thus, side-coupled structures, multi-periodic structures, low energy structures with inherent alternating-phase (AP) focusing and many others are possible. This technology is currently explored in a study of a 50 MeV electron linac powering a micro wiggler [2].

Other applications may be for future linear colliders because of several unique system requirements [3]. First, in order to keep the power consumption within reasonable limits, the linacs must operate at high frequencies, higher than 30 GHz. Secondly, a multibunch operation is necessary and therefore it is vital to reduce the wakefield effects. Planar structures have more geometric degrees of freedom than axis-symmetric structures and this can be used to reduce wakefields. Thirdly, flat beams with a large aspect ratio and an extremely low emittance in one plane are required. Wide rectangular apertures, or even better, open muffin-tins, are ideally suited for such beams because wakefields can be dramatically reduced in the direction of the slit.

Finally, another important application may be for high frequency and/or high power klystrons. The current transport capability of klystrons decays with the square of the RF wavelength because the RF cavities and therefore the beam-pipe scale correspondingly. The only way out of the unfavourable frequency scaling is to use multi-beam or sheet-beam devices. Sheet-beams [8] together with planar RF structures allow for a more favourable frequency scaling because one dimension is independent of the frequency and can thus be increased.

Due to the rectangular geometry with plane interfaces between different subregions, planar structures are well suited for ananalysis with the mode matching technique. In case of closed subregions the fields are expanded in series of eigenmodes, whereas in open subregions Fourier integral representations are used [5]. For numerical analysis a finite difference calculus in frequency as well as time domain is the obvious choice. In fact, many geometries were calculated with MAFIA [6]. Recently, we have developed a finite difference code GdfidL [7] which takes advantage of the special geometry in order to increase the speed and to allow for different mesh sizes in subregions.

II. TRAVELLING WAVE STRUCTURES WITH NON-FLAT FIELDS

The simplest planar structure is a chain of rectangular cavities, Fig. 1 a. It might be suited for special applications in the lower part of the frequency range we are considering here, i.e. somewhere between 30 and 60 GHz. The main RF parameters are close to the ones for an open muffin-tin structure, Fig. 1 b.

Open muffin-tin structures are the ideal candidate for very high frequency application, around 100 GHz, and for fabrication with LIGA. They are double-sided and do not need brazing in the region of RF-fields, they are easy to cool from top and bottom and the side openings provide vacuum pumping slots. At $2\pi/3$ travelling wave mode structure at 120 GHz was first studied in ref. [4]. The main parameters are repeated in table 1.

Table 1. Geometrical and RF parameters for a $2\pi/3$ travelling wave mode in an open muffin-tin.

<table>
<tr><td colspan="2">$a = 0.3$ mm</td><td colspan="2">$b = 0.9$ mm</td><td colspan="2">$w = 1.8$ mm</td></tr>
<tr><td colspan="2">$g = 0.633$ mm</td><td colspan="2">$t = 0.2$ mm</td><td colspan="2">$d = 0.8$ mm</td></tr>
<tr><td colspan="3">$Q_0 = 2160$ for Cu</td><td colspan="3">$r_0/Q = 144.6$ kΩ/m</td></tr>
<tr><td colspan="3">$r_0 = 312$ MΩ/m</td><td colspan="3">$k = 0.0475$</td></tr>
<tr><td colspan="3">$v_g = 0.043\ c_0$</td><td colspan="3">$\alpha = 13.5\ \mathrm{m}^{-1}$</td></tr>
</table>

The optimum structure lenght l_{opt} for the highest energy gain ($\alpha l_{opt} = 1.26$) is $l_{opt} = 9.3$ cm. However, there are many reasons to make l shorter and it was chosen to 7 cm corresponding to 84 cells. Then, the required input power per structure is 29 kW in order to get 10 MV/m average gradient. The ratio of power dissipation at structure input to structure output is 6.6 to 1. This large ratio leads to an appreciable temperature rise in the irises at the input end and will require a powerful cooling system in order to control the heat gradient.

Certainly, the better solution would be a constant gradient (CG) structure which has a constant power dissipation and is less sensitive to frequency errors and to beam break-up. At high frequencies, however, where we would like to use lithography for fabrication, a varying aperture and therefore a varying structure depth would complicate the process enormously. Then, it might be preferable to use standing wave (SW) structures (chapter IV).

Contrary to axis-symmetric structures, the accelerating fields in planar structures depend normally on the transverse position. The synchronous space harmonic of the accelerating field component can be written as

$$E_z = E_0 \cos k_x x \cdot \cos k_y y \cdot e^{j\varphi}, \quad \varphi = \omega t - k_z z \qquad (1)$$

where

$$k_z = k/\beta, \quad k_y^2 = -k_x^2 - (k/\beta\gamma)^2, \quad k_x \approx \pi/w.$$

For relativistic particles we have $k_y^2 = -k_x^2$ and the field varies with cos $k_x x$ in x-direction and with cosh $k_x y$ in y-direction, that means the acceleration depends on the position which may be tolerable only for very small excursions x and y. By the way, the transverse forces have quadrupole character.

$$F_x = -eE_0 \frac{k_x^2}{k} \sin\varphi \cdot x, \quad F_y = eE_0 \frac{k_x^2}{k} \sin\varphi \cdot y \qquad (2)$$

and could be used for focusing.

III. TRAVELLING WAVE STRUCTURES WITH FLAT FIELDS

Some applications require an accelerating field which is independent of the transverse positions, at least over a certain fraction of the aperture area. Planar structures can be modified to meet this requirement. For that purpose we increase either the capacitive load, Fig. 2a, or the inductive load, Fig. 2b, at the cavity sides. As a result, the space harmonic with $k_x = 0$ becomes the dominant space harmonic and the field is independent of x and y over a large fraction of the aperture.

As an example we give a muffin-tin cavity with increased inductive load at the sides which could be used for a high power sheet-beam klystron at 11.4 GHz similar to the cavity proposed in ref. [8]. Fig. 3a shows the lower half of the cavity with the electric field of the fundamental mode. The beautifully flat distribution of the field over three quarters of the cavity is depicted in Fig. 3b. Clearly, the cavity is well suited for acceleration of a 10 cm wide beam. By the proper choice of the dimensions it was possible to shift the closest higher mode (in horizontal direction) more than 1 GHz up in frequency and it is therefore conceivable to couple it out by means of a high-pass filter structure at the cavity sides.

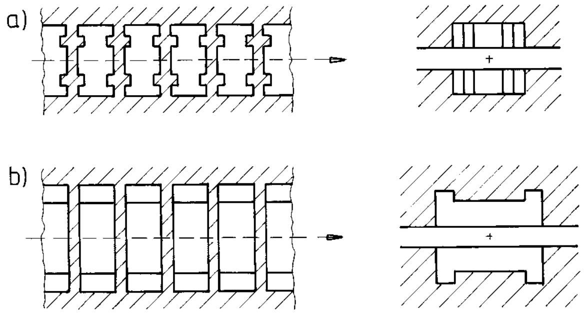

Figure 2. Muffin-tin structures with flat accelerating fields near the beam axis; a) increased capacitive and b) increased inductive load at the sides.

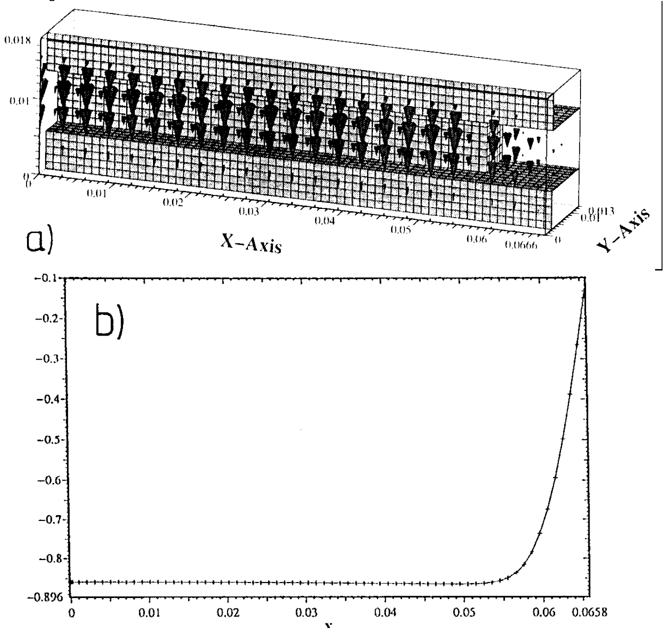

Figure 3. Flat-field muffin-tin structure; a) field plot and b) field distribution along the x-axis.

IV. STANDING WAVE SIDE-COUPLED STRUCTURES

As mentioned above, the TW-CG structure is in many respects the ideal structure for electron acceleration. However, the fabrication by lithography of a structure with varying aperture will be very difficult although in principle possible. Therefore, SW-structures were considered in ref. [9]. They have a constant power dissipation but a shunt impedance which is only half that of a TW-structure, except for the π-mode. On the other hand, the group velocity and the mode spacing is very small around the π-mode. As a consequence, the structure is sensitive against fabricational and frequency errors, it has a cell-to-cell phase error and only a small number of cells can be coupled.

A way out of these problems is often used in proton machines. The accelerating cells are not coupled directly but via off-axis coupling cells, in such a way that the structure is operated in the π/2-mode but the effective phase advance from main-to-main cell is π. Although in our case the direct coupling cannot be lowered we still can get the same behaviour. By making the passbands of two structures, the chain of accelerating cells and the chain of coupling cells, coalesce at the 2π phase shift per period we obtain an effective π-phase advance for the accelerating cells with a high group velocity while the coupling cells remain unexcited. The additional complication due to the coupling cells is only a complication in the design process but is more or less free of extra fabricational costs.

In Fig. 4, geometry (1) the standard arrangement of a side-coupled muffin-tin structure is shown. Because of the large off-axis cells, the accelerating field wiggles slightly around the beam axis. Therefore, we analysed geometry (2) next. This geometry has the largest bandwidth and is expected to be the less sensitive against errors due to the multiple coupling. Unfortunately, it carries a horizontally polarized dipole mode which is synchronous with the beam. Nevertheless, for many applications this may be tolerable because the shunt impedance of the dipole mode is very small. In the third geometry of Fig. 4, the symmetry with respect to the z-axis is broken. In that way the dipole mode is shifted to lower frequencies while the accelerating field remains parallel to the z-axis. All three geometries have a high group velocity, around 5 % of the velocity of light and a π phase shift from main-to-main cell. The shunt impedance is only reduced by typically 15 % as compared to a single-periodic 2π/3 mode TW-structure.

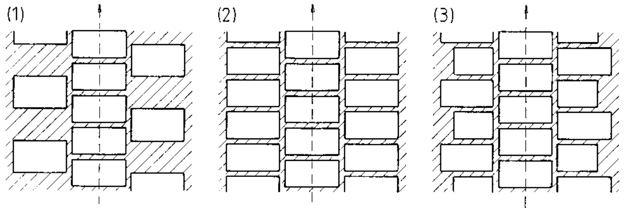

Figure 4. Side-coupled muffin-tin structures with (1) alternating, (2) symmetrically arranged coupling cells and (3) with broken symmetry.

V. CONCLUSIONS

Planar structures have one geometric degree of freedom more than axis-symmetric structures. This freedom in choice can be used in different ways: To adjust the structure geometry to the beam geometry, to modify the transverse dependence of the accelerating field or to reduce wakefields. Every choice has its particular application like for sheet-beam klystrons, linear colliders or for very high frequency structures around 100 GHz.

Although planar structures may stay an exception for applications with frequencies below 30 to 50 GHz, they certainly will be the top choice for higher frequencies. Especially if they can be made with modern microfabrication techniques, such as high-precision stamping or LIGA, they offer unprecedented advantages. Nearly any complex structure, as long as it is planar, can be fabricated with no extra costs. Only the designer's skill limits the possibilities. Thus, input couplers, extraction circuits, filter devices, single- and multiperiodic structures, alternating phase focusing structures and others, they all can be integrated on a slab support.

VI. ACKNOWLEDGEMENT

The author would like to thank the APS project at Argonne National Laboratory for supporting these studies.

VII. REFERENCES

[1] E.W. Becker, W. Ehrfeld, P. Hagmann, A. Maurer and D. Münchmeyer: Microelectronic Engineering, No. 4, 1086, pp. 35-56.

[2] A. Nassiri et al., "A 50-MeV mm-wave electron linear accelerator system for production of tunable short wavelength synchrotron radiation", IEEE, International Electron Device Conference, Washington D.C., December 1993, pp. 169-172.

[3] D. Yu et al., "High frequency planar accelerating structures for future linear colliders", AIP Proceedings of the 6th Workshop on Advanced Accelerator Concepts, Lake Geneva, June 1994.

[4] H. Henke, Y.W. Kang and R.L. Kustom, "A mm-wave RF structure for relativistic electron acceleration", Argonne National Laboratory, internal report ANL/APS/MMW-1, 1993.

[5] M. Filtz, "Analytical calculation of waves in a muffin-tin structure", Proceedings of the 4th European Particle Accelerator Conference, London 1994, pp. 1271 - 1273 and "Coupling impedances of muffin-tin structures with closed and open sides", these proceedings.

[6] R. Klatt et al., Proceedings of the 1986 Linear Accelerator Conference, Stanford internal report SLAC-Report 303, Sept. 1986.

[7] W. Bruns, "Error sensitivity for side-coupled muffin-tin structures using a finite difference program", these proceedings.

[8] D. Yu and P. Wilson, "Sheet-beam klystron RF cavities", IEEE Proceedings of the 1993 Particle Accelerator Conference, Washington, pp. 2681-2683.

[9] H. Henke and W. Bruns, "A broad-band side-coupled mm-wave accelerating structure for electrons", Proceedings of the 1993 IEEE Particle Accelerator Conference, Washington D.C., May 1993, vol. 2, pp. 94-906.