A METHOD TO DESIGN MULTI-CELL ACCELERATOR CAVITIES

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Abstract

An efficient method for designing multi-cell accelerator cavities has been developed. It is similar to the approach used by Superfish codes for drift-tube linacs (DTL), where a few single cells at representative beam velocities are tuned in 2D and their geometrical parameters are interpolated to cover the required beam-velocity range. The method is implemented using 3D electromagnetic (EM) modeling with CST MicroWave Studio, which allows its application for various types of resonators, e.g., for H-mode cavities. Interpolating results of 3D EM design of tuned representative single-cell cavities leads to a 3D multi-cell cavity model that can be finalized with just a few small adjustments. As a challenging application example, we design multi-cell resonators of three types – cross-bar (CH) and inter-digital (IH) H-mode, as well as DTL – for accelerating muons in the velocity range of v/c = 0.08-0.3, and compare their performance.

INTRODUCTION

Many accelerating structures in RF linacs are multi-cell cavities. One of the best known and historically first is the example of long cylindrical resonators (tanks) in ion drift-tube linacs (DTL), e.g., [1]. The DTL tank operates in the TM_{010} mode and can be designed essentially analytically because of its simple axisymmetric field pattern. 2D design codes like Superfish, first introduced in the 1960s and further developed in the 1980s [2], simplified and practically automated the DTL design process.

The design procedure consists of tuning single-cell TM_{010}-mode cavities (DTL tank "slices") at a few values of the beam velocity $\beta = v/c$ that cover the beam-energy range of the tank. The DTL cell length is $L_c = \beta\lambda$, where λ is the RF wavelength. The tuning for the first selected DTL cell is usually done by adjusting its outer radius to obtain the design frequency. The other cells are tuned with this radius fixed to the same frequency by adjusting other geometrical parameters, e.g., the gap length. The number of cells n in the tank depends on its energy range and the average cell electric field E_0 or accelerating gradient E_0T, where T is the cell transit-time factor. The cell parameters are interpolated, and the tank layout can be finalized by iterations. This process was automated by the LANL Accelerator Code group [2]. DTLfish, a specialized version of Superfish, produces a table of the DTL cell geometric parameters and transit-time factors at the β values of reference cells. This data is then used, together with the initial beam parameters, by Parmila to design a DTL tank, both its layout and the strengths of focusing quadrupoles, and to simulate its beam dynamics. All the above codes are 2D and work for axisymmetric structures. 3D effects in DTLs are not very important: elements like stems or post-couplers introduce just small field perturbations.

GENERAL MULTI-CELL CAVITIES

Here we extend this approach to a wider class of multi-cell accelerating cavities, including those where 3D effects are essential. One of these types are H-mode resonators operating in $TE_{m1(0)}$ mode. The most important of them are inter-digital (IH, m=1) and cross-bar (CH, m=2) cavities, which are very efficient at low beam velocities, e.g., see [3]. The reference cells (slices) in this case have different boundary conditions (BC) on their end walls: magnetic (H_t=0) instead of electric (E_t=0) for DTL. The H-mode cells do not have axial symmetry, so a 3D solver is needed to find their modes. We employ the CST MicroWave Studio (MWS) eigensolver [4] but other solvers can work as well. The idea remains the same as for DTL: reference cells are tuned (now with MWS) and their parameters are interpolated over the β-range of interest. After that a 3D multi-cell cavity model can be built and finally tuned with only small adjustments.

One should expect an essential difference between DTL and H-mode cavities: DTL end cells have the same BC as middle ones, but in H-mode resonators the BC on the cavity metal end walls differ from those in middle cells. This is reflected in the longitudinal mode index (0): the parenthesis means that the mode field is not really homogeneous along the cavity length; it tends to vanish near the cavity ends, unlike that in DTL.

A similar approach can be used for other multi-cell cavities. Though usual traveling-wave (TW) structures are axisymmetric, one could consider TW cavities with essentially 3D elements. Their cells can be tuned with MWS eigensolver using periodic BC with a required phase advance.

We proceed by demonstrating the method application in designing three types of multi-cell cavities – DTL, IH, and CH – for a muon accelerator section at 324 MHz in the low beam velocity range β = 0.08-0.3, corresponding to muon energies from 340 keV to about 5 MeV. Such a section is considered in the muon linac for the planned experiment E34 to measure muon (g-2) with a record-high precision at J-PARC. The case is challenging because the beam velocity and the cell length increase almost four times along the cavity.

LOW-VELOCITY MUON LINAC

DTL

The DTL was designed using the Superfish/Parmila approach described above. The cavity is 113 cm long for E_0 = 4.5 MV/m, and has 7 cells (7 gaps, 6 full drift tubes (DTs) and two half-DTs), see [5] for details. No post-couplers are needed in such a short tank. Its CST 3D model only required a small radius adjustment to get the exact frequency. The maximal electric fields are low so

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the gradient can be safely increased. The DTL parameters are compared to other structures in Table 1.

IH Structure

The cell length in H-mode cavities is $L_c = \beta\lambda/2$, and the structure "period" contains two cells. For comparable gradients, IH should then have about twice as many cells at DTL. We have chosen to keep ratio g/L_c, DT radii, and the stem length to the vane (girder) fixed. The frequency is tuned by adjusting the cell radius with CST optimizer. One reference cell used for designing the IH structure is shown in Figure 1 (outer cavity walls are not shown, vacuum volume is in transparent blue).

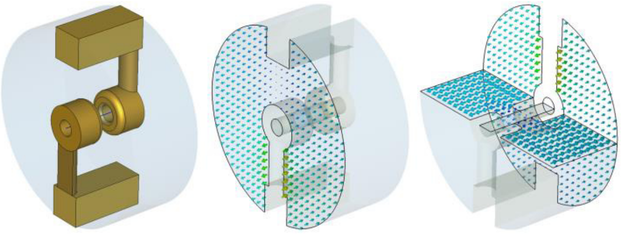

Figure 1: IH-structure cell for $\beta = 0.15$ and magnetic field of its TE_{110} mode at cell boundaries and in mid-plane.

The IH cell parameters are interpolated using a simple Matlab script. The resulting 18-cell IH cavity model is shown in Fig. 2 (top – 3D view, bottom – side view). Note that the vacuum region radius is larger downstream than upstream, cf. Table 1. The outer walls overlap the vanes near the cavity entrance (left). Such a cavity can be made out of two half-shells, with one vane and connected DT set on each, clamped together.

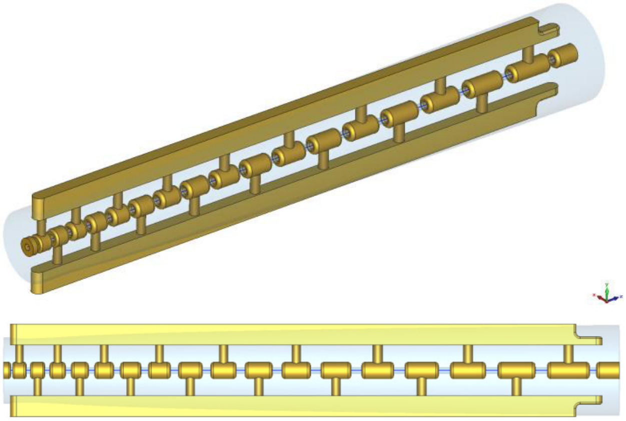

Figure 2: 18-cell IH structure (outer walls not shown).

As expected, the on-axis electric field of the initial 3D model was not flat: the gap field decreased near the cavity ends. There are known methods for improving the field flatness in H-mode cavities, e.g., see in [3]. Here the vanes are rounded at both ends and also undercut at the high-energy end, which makes it easier for magnetic fields to turn around in the end cells. The IH cavity parameters are listed in Table 1.

CH Structure

A similar CST tuning procedure is applied to the CH cavity. The ratio g/L_c here is decreased compared to IH but the overall cavity length is the same, cf. Table 1. The surface fields in the 18-cell CH cavity are shown in Fig. 3. Here the vanes are undercut at both ends to improve the field flatness along the cavity.

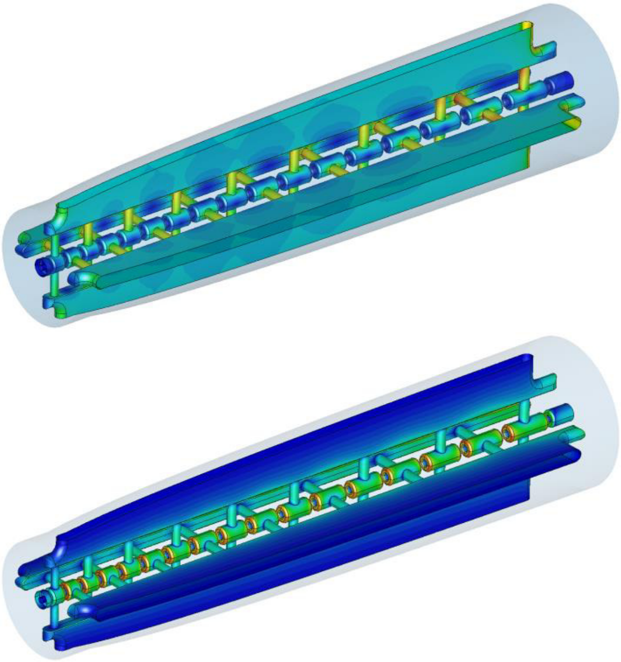

Figure 3: Surface field magnitude in 18-cell CH structure: top – surface current; bottom – electric field, log scale. Red indicates high values, blue low ones.

Summary

Our results for three structures are summarized in Table 1. The Kilpatrick field at 324 MHz is E_K = 17.84 MV/m. The power loss values assume ideal copper surface.

Table 1: Structure Parameter Comparison

Parameter, units	**DTL7**	**IH18**	**CH18**
Cavity length, cm	112.6	145.7	145.7
Cavity radius, cm	26.5	7.83-10.9	13.1-17.3
Aperture radius, cm	1	0.75	0.75
DT outer radius, cm	5	2	2
g/L_c	0.16-0.28	0.25	0.2
Quality factor Q	44769	10286	13266
$Z_{sh}T^2$, MΩ/m	39.2	49.6	40.7
Average T	0.82	0.94	0.95
Average E_0, MV/m	E_0=4.5	E_0T=3	E_0T=3
E_{max}/E_K	1.64	1.7	1.9
P_{wall}, kW, 100% duty	392	264	322

The maximal fields are relatively low, so the gradients can be safely increased in DTL and IH. This is important for the muon linac: higher acceleration pace reduces the muon losses to decays. The maximal fields in CH can be reduced by increasing the relative gap width g/L_c from 0.2 to 0.25, the value used in IH.

The DT outer size in DTL is quite large, so permanent-magnet quadrupoles (PMQ) can be easily inserted into DTs, especially because the required quad gradients here are rather low, 25-35 T/m. The beam dynamics in this case was checked [5] with CST Particle Studio. We expect that for IH and CH cases the required PMQ strengths are even lower, which will make possible inserting PMQ in their smaller DTs. Alternatively, the structures can be designed with alternating larger DTs containing PMQ and smaller ones without magnets [3].

The cavity on-axis longitudinal electric fields are plotted in Fig. 4. The vertical electric field in IH is < 5% of the longitudinal one in the downstream wider gaps and much lower than that in the upstream gaps. Note that the field in the first cell of both CH and IH structures is low. Probably, the easiest fix would be redesigning these structures in such a way that the first two cells work at the same velocity, $\beta_1 = \beta_2 = \beta_{in}$. The field in the last gap can be increased by making the gap shorter.

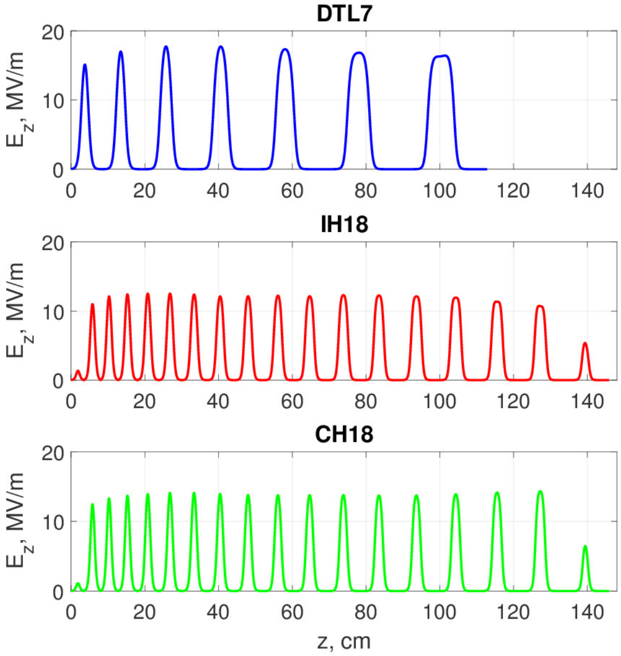

Figure 4: Magnitude of the on-axis longitudinal electric field in three cavities. The field scaling is in Table 1.

The effective shunt impedance is reasonably high, even for the IH structure that is typically used and efficient at lower beam velocities. Though both IH and CH structures presented here are much better than more traditionally designed preliminary versions in [5], the DTL option is the simplest and appears to be the best. One should also mention another possible viable solution based on H-mode structures with alternative-phase focusing [6].

CONCLUSION

We presented a convenient method for designing multi-cell accelerator cavities with essentially 3D features. It is a generalization of the approach used by Superfish codes for drift-tube linacs (DTL). A few single-cell cavities at representative beam velocities are tuned in 3D with CST MWS, and their geometrical parameters are interpolated in the required beam-velocity range. The method can be applied for various types of resonators. Interpolating results of 3D EM design of tuned representative single-cell cavities leads to a 3D multi-cell cavity model that can be easily finalized with CST. We demonstrated the method by designing multi-cell resonators of three types – DTL, inter-digital (IH) and cross-bar (CH) H-mode – for muons in the velocity range of $v/c = 0.08\text{-}0.3$. The structure performances are compared in Table 1.

We believe that the method can be useful for other applications. It simplifies the way to build a good first approximation for a multi-cell accelerating cavity, which then can be more easily tuned with a 3D code, e.g., CST or HFSS. Our experience of working with large 3D full-tank CST models of the 100-MeV LANSCE DTL was successful: the RF fields of the operating mode in the tanks were calculated [7] with MWS and used for Particle Studio PIC simulations of beam dynamics in the DTL. The PIC results elucidated interesting details of the longitudinal halo and particle loss in the DTL [8].

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