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$H_{11(0)}$ END CELLS FOR A 750 MHz IH STRUCTURE*

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Abstract

This article presents a study on the $H_{11(0)}$ end cell of an IH-DTL prototype for accelerating carbon ion beams from 5 to 5.5 MeV/u, which is designed for a hadron therapy linac injector. The voltage across the first and last gap in a drift tube linac tends to drop from a typical uniform voltage distribution along the inner cells. In the case of an IH cavity, the power cost to supply the necessary RF energy in this region is affected by the dimensions of the end cell and gap, as well as the girder undercut. The end cells were modeled in CST Microwave Studio for an appropriate power loss optimization of the most relevant dimensions. The same model also introduced dipole correction based on slanted faces, and transverse fields were analyzed.

INTRODUCTION

In the framework of the IKERTU-II project for the development of new and advanced components of future compact linear accelerators in hadrontherapy, CIEMAT is collaborating with the company Added Value Ind. Engineering Solutions (AVS) in the production of a 10-cell IH-DTL prototype for accelerating C^{6+} ion beams from 5 MeV/u while addressing the main challenges in its fabrication.

In pursuit of a full RF design of a 750 MHz IH-DTL, a study was previously made that looked into the RF characteristics based on simulations of one regular cell [1, 2]. Those single-cell simulations assumed a certain periodicity of the proposed geometry by setting proper $H_{11(0)}$ mode boundary conditions. The last index is written in brackets as it indicates the will of achieving uniform magnetic fields along the cavity, that is constant voltages across every gap. However, the magnetic field lines must turn back in a closed loop ($\nabla \cdot \mathbf{B} = 0$) by the two edges of the structure (see Fig. 1). This is usually obtained by cutting a certain amount of the girder that supports the stems (known as undercuts) and leaving space for the field lines to turn and connect both sides [3]. The end conducting wall of the cavity helps the transition from H-mode to E-mode, which has a negative impact on the RF power loss. In fact, the accumulation of magnetic field lines in this region is responsible for a greater density of power losses over the undercut walls. In addition, the voltage across the end gap is smaller than in the other gaps, therefore the overall shunt impedance of the structure is certainly degraded.

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This article will present the optimization study on the dimensions that define the end cell of a 750 MHz IH cavity in order to achieve the best power efficiency and voltage performance.

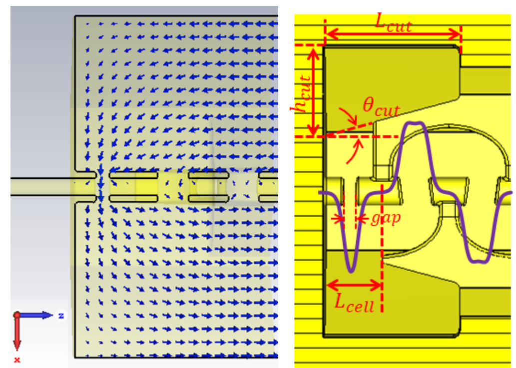

Figure 1: Left: cross-section top view with H-field lines at y=0. Right: cross-section lateral view, dimensional parameters of the end cell and undercut (in red), and graphic of E_z-field on z-axis (in purple).

MODELING THE END CELL

For this study, RF simulations have been performed in CST Microwave Studio [4] considering the union of three IH-type cell units, as shown in Fig. 1. These are modeled to be the first three gaps of a cavity that accelerates 5 MeV/u carbon ion beams at a rate of 120 kV per gap and a synchronous phase of -20°. Two of them present a regular geometry as described in [2], which connects successive stems of the same girder by an ellipse arc. The end cell consists of the conducting lid wall, with half a drift tube attached to it, and the opposing half stem. Perfect H boundary is set after the second regular cell, as we consider that three cells are enough for transitioning to the H-mode. Two trapezoidal undercuts are modeled with proper roundings, and parametrized by dimensions L_{cut}, h_{cut}, and θ_{cut}.

The reference dimensions of the end cell (#0) and the inner cells (#1 and #2) are collected in Table 1. The profile of the

Table 1: End Cell and Regular Cell Dimensions

Cell #	L_{cell} [mm]	gap [mm]	slant [°]	$R_{ellipse}$ [mm]
0	20.56	9.02	5.0	-
1	20.62	9.00	7.4	20.0
2	20.73	8.96	7.7	20.0

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auto-inductive region is designed with flat walls, with sizes of 100.3 mm horizontal and 91.0 mm vertical (named as D_h and D_v). A transverse electric field correction is applied by a slant on the opposing faces of consecutive drift tubes, as proposed in [1], in order to avoid undesired kicks on the beam. Since undercuts yield loose connection to the last stem, the ellipse arc heights ($R_{ellipse}$) need to be reduced to 20 mm, as opposed to recommendations given in [2] for maximizing the efficiency of regular cells.

DIPOLE KICK CORRECTION

The asymmetry between the first two drift tubes is different than in regular cells. Only one of them is supported by a stem, while the other one is attached to the end cavity wall. This produces a slightly different transverse field profile that can be corrected by the same slanted-faces strategy as in inner cells [1].

Figure 2 shows the resulting transverse fields along the beam trajectory for two different gap sizes. The slant correction aims at suppressing the transverse effective voltage, which takes into account the oscillating fields seen by the beam. As it happens for regular cells, a greater slant correction is required for wider gaps, and they show stronger peaks of transverse fields than for shorter gaps.

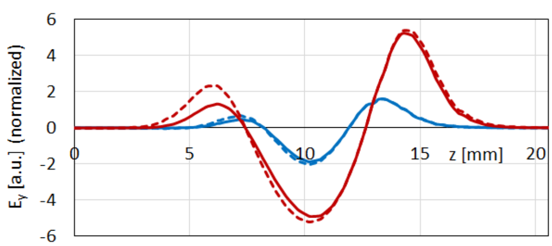


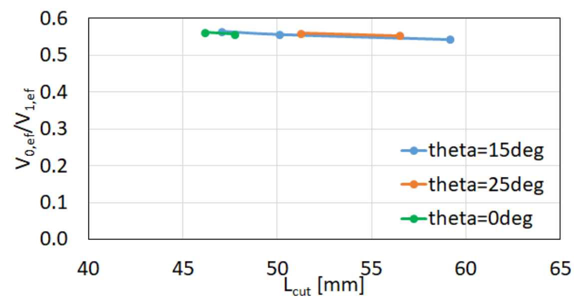
Figure 2: Transverse E_y field on the z-axis of the end cell, for a gap of 6 mm (blue) and 9 mm (red), optimized for slants of 1.8° and 5.4°. Dashed lines indicate complex-magnitude field and solid line transit-time effective field (ϕ_s=-20°).

OPTIMIZATION

Two approaches have been adopted for this study. First, we have analyzed the effect of varying the undercut dimensions L_{cut}, h_{cut} and θ_{cut}, but keeping the rest of cell dimensions fixed as stated in Table 1. Secondly, we have investigated the effect of the end cell length L_{cell} (which can be considered as a free parameter as long as the distance between consecutive gap centers remains unchanged) and also the gap size of the end cell. In order to evaluate the performance of every geometry we have evaluated two figures of merit. One is the ratio between the effective voltage across gap #0 and gap #1, being in the latter fairly equal to the effective voltage across gap #2. The other one is the RF power loss over the copper walls of the three cells, considering the effective gap voltages of cells #1 and #2 at a nominal 120 kV. This quantity is the equivalent of the shunt impedance.

Varying Undercut Dimensions

Figure 3 shows the results of the voltage ratio and power loss with different undercut dimensions. At a given θ_{cut} and L_{cut}, the third parameter h_{cut} is chosen to tune the eigenmode frequency at 750 MHz. There is no meaningful effect of the undercut shape on the produced voltage across the gap of the end cell. However, one can see that shorter cuts with larger angles are preferred to reduce losses.



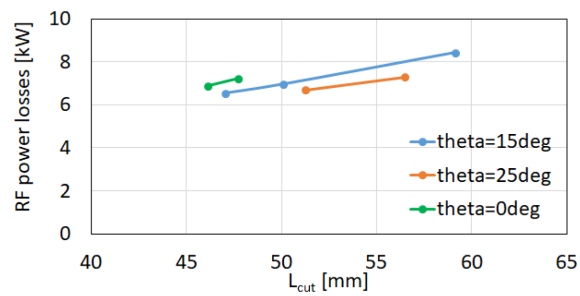


Figure 3: Ratio of effective voltages across gaps #0 and #1 (top) and RF power losses over the simulated cells at a nominal voltage (bottom) for different undercut dimensions.

Varying End Cell Length and Gap

As we see in Fig. 4, the effective voltage produced across gap #0 is strongly dominated by such gap size, no matter what the end cell length is. Reducing the gap size from 9 mm to only 4 mm helps increase the voltage ratio from 56 to 65%, which is an extra 11 kV. Despite this gain in voltage, the shunt impedance remains unaffected, around 235-240 MΩ/m, due to the resultant increment of power losses. A slight improvement can be seen for shorter cell lengths as it defines less surface for RF currents.

Figure 5 shows the resulting electric field profiles on the z-axis along the first two cells at different cell #0 dimensions. Shorter gaps imply greater peaks of gradient, thus greater surface fields, although smaller than in regular cells where fields are more critical (Kilpatrick's limit). It is also worth mentioning that a shorter gap produces a smaller dipole kick and requires a smaller angle of correction between opposite drift tube faces.

EFFICIENCY IMPROVEMENTS

Conventional IH-DTL structures assemble the stems over equally-long girders on the top and bottom of the cavity, and undercuts are machined on them. In our model of Fig. 1, the

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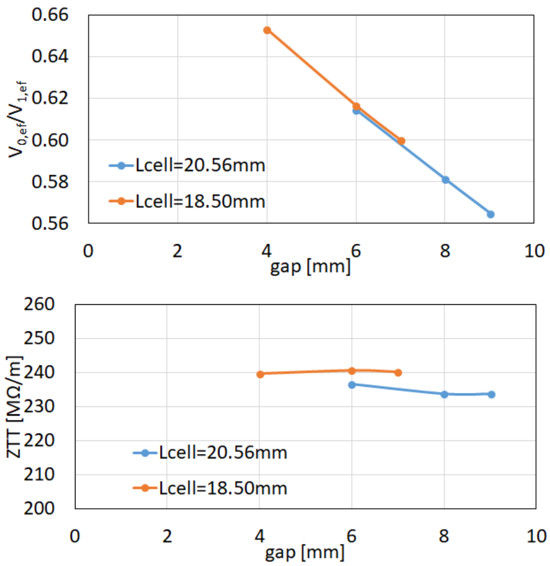

Figure 4: Ratio of effective voltages across gaps #0 and #1 (top) and overall effective shunt impedance (bottom) for different end cell #0 dimensions.

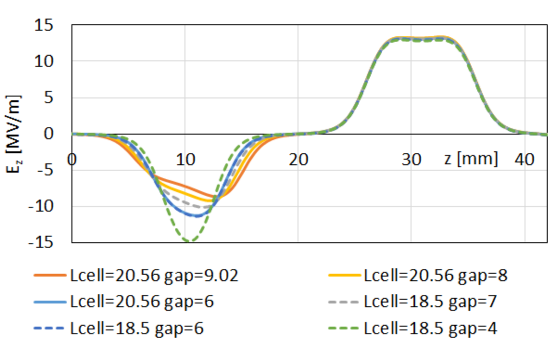

Figure 5: Longitudinal electric field along the first two cells on the z-axis. Fields are scaled to nominal effective voltage of 120 kV at gaps #1 and #2.

end of the second stem makes a last elliptical arc to imitate the geometry of conventional girders. However, such arc does not play any role neither in the capacitance between drift tubes nor the auto-inductance of the cavity. For this reason, we have proposed to remove the last arc and finish the stem in a vertical wall as depicted in Fig. 6. This modification requires a slight increment of 2 mm on the undercut length L_{cut} to retune the eigenmode frequency to 750 MHz. Additional refinement on the dipole electric field correction must be made due to the new alteration of the opposing stems asymmetry. The overall efficiency performance, in this case, is improved from a shunt impedance of 236 to 248 MΩ/m. Such modification in the geometry of both ends of the cavity entails savings of 480 W peak power.

An alternative approach to reduce RF losses goes through shortening L_{cut}. In compensation for the rise of the resonant frequency, the transverse size of the cavity is required to be bigger, thus allowing more space for higher

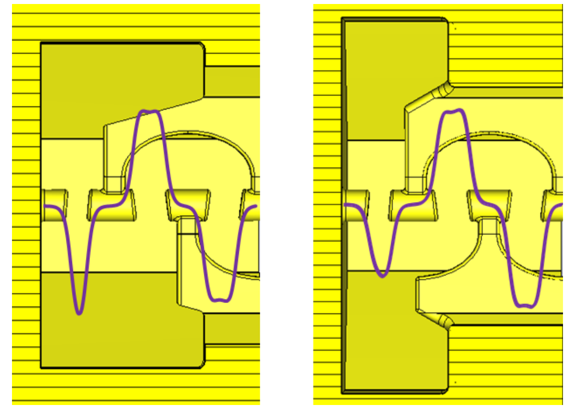

Figure 6: Cross-section lateral view of the adapted-stem model (left) and the shorter undercut approach (right). On top, we represent the E_z field along the z-axis.

(but shorter) undercuts. The three ending cells of a much wider cavity, D_v=105.6 and D_h=131.4 mm in vertical and horizontal directions, have been modeled and simulated in CST (see Fig. 6). The undercut length has been reduced to L_{cut}=30.5 mm, with an angle of θ_{cut}=30°. Results show an enhancement of the shunt impedance to 263 MΩ/m despite having about a 20% larger cavity. Suppressing the arc of the second stem as we previously described enhances the shunt impedance even more to 285 MΩ/m.

The latter strategy entails some drawbacks to the design of the whole cavity. If the inner regular cells preserve the same cavity size, they do not respond to the same resonant frequency. Therefore, the field profile is not uniform but a hill shape. This approach is well recommended for IH-DTL structures with a small number of cells, where the length of the end cells is an important fraction of the whole cavity and RF power savings become considerable (up to 2 kW for the mentioned example). For longer cavities, it is preferred to obtain a rather uniform voltage distribution across most of the gaps. This could be achieved by applying the large cavity dimensions only to the last cell and leaving a physical step to shrink D_v and D_h to optimal sizes for the inner cells. This could be seen as equivalent to the proposed end cell design by Amaldi et al [5], which was also explored as an alternative in Ref. [6].

CONCLUSIONS

The presented study, based on RF simulations specific to the end cells of an H_{110}-mode cavity, shows practical ideas such as shortening the undercut to minimize losses and shrinking the gap size of the end cell to gain voltage. They will be taken into consideration in the current design of a high-efficiency IH-DTL structure by CIEMAT and AVS. The collaboration is already designing a cavity prototype at 750 MHz for 5 MeV/u C^{6+} beams, in a short version of 10 gaps, to encounter the main challenges from both mechanical, assembly and RF engineering perspective of operating this type of cavities at such a high RF frequency for the first time [7].

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