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CELL GEOMETRY OPTIMIZATION FOR DIPOLE KICK CORRECTION IN A HIGH FREQUENCY IH STRUCTURE*

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Abstract

Given the asymmetry in the stem configuration of an IH-DTL structure, an electric dipole component is always present between drift tubes, and it is especially significant for reduced dimensions in high-frequency regimes. Here we study the effect of different modifications of the drift tubes geometry of a 750 MHz IH-DTL to eliminate the impact of the dipole component in the transverse beam dynamics. Tracking simulations through a single cell are also performed to assess the outcomes in particle's trajectory offset and angle.

INTRODUCTION

Interdigital H-mode structures are common components in linac injectors due to their high power efficiency performance in the acceleration of beams below 25% of the speed of light [1]. Following the recent progress at CERN on a "bent-linac" design for carbon ion beams [2] that comprises a highly compact RFQ [3] operating at 750 MHz, here we present a conceptual study of a high frequency IH-DTL structure for the injector, downstream the mentioned RFQ, accelerating in the energy range of 5 to 10 MeV/u. The baseline design tries to continue the work in [4] on the optimized cell geometry of a 750 MHz IH-type structure.

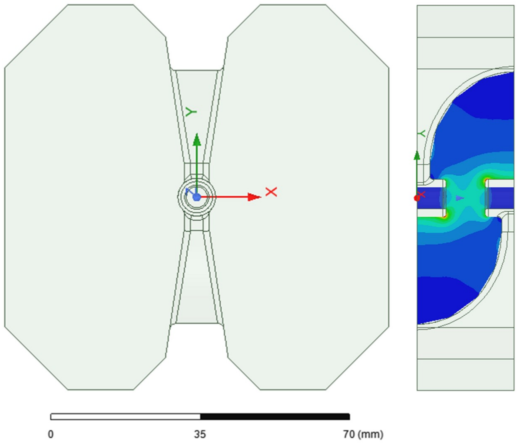

Figure 1: Front view (left) and lateral cross-section (right) of one standard IH cell. Electric field map is represented in the YZ plane.

Structures with very small apertures, and high frequency regimes, require special attention to the beam dynamics which is strongly affected by small errors in geometry dimensions. In addition, the asymmetry with opposing stems introduces a very significant transverse component of the electric field. Benedetti et al [4] proposed the mitigation of such dipole kick by adjusting the length of the first and last cells of the rf tank. In this study, we consider several proposals of geometrical modifications of the drift tubes that aims at either reducing or compensating the transverse electric fields. Simulations of the electromagnetic fields were performed in ANSYS HFSS [5], and calculations of different figures of merit were compared for each model.

Figure 1 shows the conformed geometry in vacuum of one regular cell of an IH structure, which respects the idea in [4] of using flat copper walls for the outer cavity profile, but has been revised with a round profile in seek of smaller power losses [6]. The model in Fig. 1 is used as baseline for this study. The cell length is 23.085 mm, corresponding to an ion speed of $\beta = 0.12$. The internal bore diameter of the drift tube is 5 mm, its thickness is 2 mm, and the gap length is 9.315 mm. The horizontal and vertical sizes of the outer profile of the cavity are 91.35×91.35 mm.

For such a model, the electric field along the ideal particle path is represented in Fig. 2 by the axial (z) and transverse (y) components. The transverse voltage, responsible of deflecting the beam, entails 8.4% of the total axial voltage in a single cell. The goal of this study is to reduce the deflecting effect by modifying the standard drift tube geometry close to the gap.

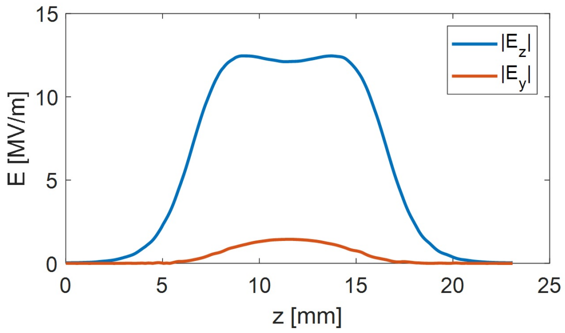

Figure 2: Axial (blue) and transverse (red) field profile along the centre of the rf cell. Fields are scaled to an axial effective voltage of 120 kV.

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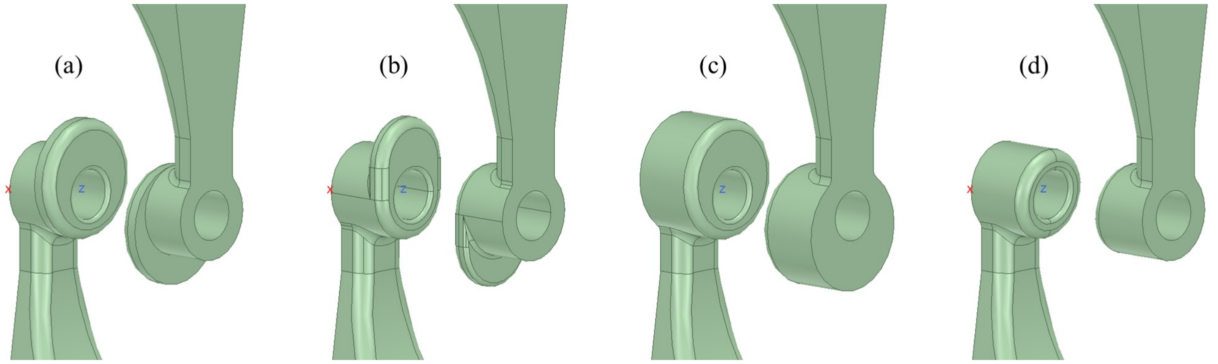

Figure 3: Four proposals of drift tube modifications for electric dipole compensation.

DRIFT TUBES SHAPE VARIATIONS

Four variations of the drift tubes are analysed in this study, shown in Fig. 3. For the sake of a fair comparison, the gap between drift tubes and the stem dimensions are the same than in the standard cell. One dimension of the new feature is used as an optimisation parameter to minimize the transverse deflection. To do so, we consider the minimisation of the integral of the transverse field component:

$$V_y = \int_0^{L_{\mathrm{cell}}} E_y(z)\,\mathrm{d}z. \tag{1}$$

The results of V_y as a function of the optimisation parameter are represented for all drift tubes variations in Fig. 4.

Since the new shape changes the capacitance between tubes, the resonant frequency is shifted by few MHz. This is tuned back to nominal value (750 MHz) by adjusting the size of the outer profile of the cavity, which only affects the auto-inductive region.

Circular Disk Feature

A common choice of dipole correction is adding small bulges at the edges of the drift tube [1, 7] that compensate the electric field orientation from the accumulated charge in the stems. This bulge, shown in Fig. 3(a), is modelled as a 2 mm thick circular disk, with a larger diameter than the drift tube, but off-centred, so that it makes a tangent point on the side of connection with the stem bar. This offset is used as optimisation parameter for minimising V_y, with the clear trend shown in Fig. 4.

Racetrack Disk Feature

Based on the same principle of the circular disk, a racetrack shape is adopted to reduce the bulge material on the laterals of the drift tube. As it can be seen in Fig. 3(b), one arc of the racetrack is matched to the drift tube contour, and the centre of the second arc is displaced by an offset, which is again used as the optimisation parameter.

Aperture Off-Centre

In this case, instead of machining bulges, the whole drift tube is designed so that the aperture where the beam travels is off-centre. In our model, shown in Fig. 3(c), we keep the aperture and the stem connection in the same position as the standard cell, but we introduce an offset for the cylinder axis that defines the copper-made drift tube. The offset is the only optimisation parameter for minimising V_y.

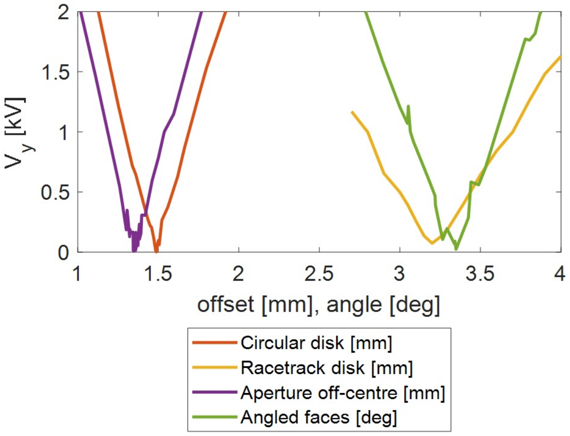

Figure 4: Optimisation curves of four variations for V_y minimisation.

Angled Faces

A slant is introduced in machining opposing faces at the edges of the drift tubes. In this way, we intend to compensate the asymmetry of the inverted stems and reorient the electric field lines across the gap. The resulting model is shown in Fig. 3(d). Here, the optimisation parameter is the angle of the slanted faces with respect to the original. Only 3.4 degrees of slant between faces is enough to minimise deflecting voltage, which is strongly sensitive to slant angle: a deviation of 1 degree results in a transverse voltage of 2.4% with respect to axial voltage.

RESULTS

Transverse Field Profile and Deflections

The electric fields on the beam axis have been evaluated for the optimised variations (Fig. 5). The geometries with bulges and with aperture off-centre achieve very low levels of transverse field across the gap, offering a fairly uniform profile with ripples of about 100 kV/m. Contrastingly, the

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field profile produced by the angled faces variation show three peaks of alternating field direction in y axis, although the net voltage due to transverse field is still zero. It is noted that the maximum peak results in half of the standard one.

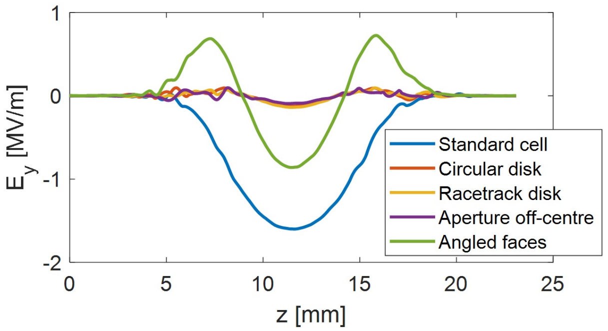

Figure 5: Transverse electric field profile for the standard cell and presented four variations. Fields are scaled to an axial effective voltage of 120 kV.

The effect of the field shape caused by the angled faces variation is simulated for a single C^{6+} ion entering to the cell on centred axis with no angle, and a velocity of $\beta = 0.12$, by solving $\mathrm{d}\vec{p}/\mathrm{d}t = q\vec{E}$. The ion trajectory, depicted in Fig. 6, describes a very small deflection at its halfway point and gets corrected at the exit back to zero offset position and angle, which is the optimum for entering the following cell.

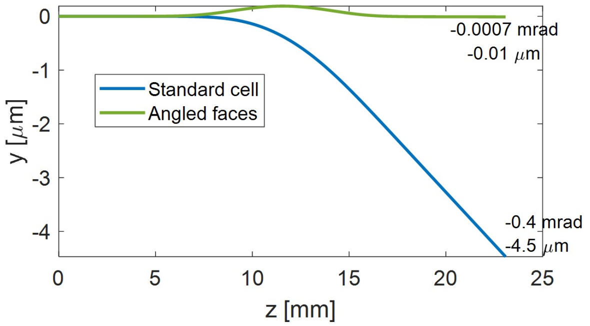

Figure 6: Particle trajectory comparison between the standard cell and the angled faces variation, for an effective axial volt age of 120 kV.

Figures of Merit

To compare the performance and suitability of each variation that suppresses the electric dipole component, we analyse in Table 1 a series of figures of merit.

The size of the cavity (D) is adjusted to tune the resonant frequency to 750 MHz. Adding more material on the drift tubes, as it is the case for the first three variants, increases electric capacitance and decreases frequency. For this reason, the size of the cavity needs to be from 6 to 11 mm smaller. For the shape with angled faces, electric capacitance is barely altered. Transit time factor (T), which is mainly dominant by gap size, does not show remarkable differences among all variations.

Table 1: Figures of merit on standard cell and variations

Model	D **[mm]**	T	ZTT **[MΩ/m]**	η
Standard	91.35	0.902	360	7.7
Circular disk	82.41	0.903	267	7.2
Racetrack disk	85.60	0.905	291	8.6
Aperture offset	80.65	0.907	250	8.6
Angled faces	91.00	0.903	356	8.2

We do find a large diversity in the results of the effective shunt impedance (ZTT), a relevant indicator of the power efficiency performance of the rf cavity. The circular and racetrack disk features added on the drift tubes degrades the efficiency in 26% and 19%, respectively. This is even worse for the case of the aperture offset, that loses 30% of shunt impedance. The angled faces variation represents the least modification of the geometry, thus the smallest degradation of ZTT is accomplished (1%). This performance makes the latter a promising candidate to be applied on a full IH structure.

The field enhancement factor (η) is defined here as the ratio between the peak electric field on copper surface and the average gradient on axis. Most of the models show an increase in the surface field with respect to the applied voltage between gaps. Aiming at a maximum surface field of 50.6 MV/m, 2 times Kilpatrick's limit, the proposed variations allow for a maximum average gradient from 5.8 to 7.0 MV/m, corresponding to effective axial voltages ($V_z T$) of 122 to 145 kV. Nominal voltage in design for the 23.085 mm long cell presented here is 120 kV, still below the potential breakdown limits on dipole-corrected models.

CONCLUSIONS

Different alternatives are shown to be valid for correcting electric deflection in an IH-DTL. Although no mechanical assessment has been made here, the angled faces variation seems to be the simplest geometry feature to compensate field orientation across the gap. At the same time, its larger shunt impedance makes it the most favourable option regarding its efficiency. Dimension sensitivity studies should be examined in the future for tolerance specifications, so that this feature is considered to be integrated in the design and construction of a complete IH-type structure.

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