ASSESSMENT OF FABRICATION AND ASSEMBLY TOLERANCES IN AN IH-DTL CAVITY THROUGH ELECTROMAGNETIC AND BEAM DYNAMICS SIMULATIONS

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Abstract

This work presents a comprehensive study of manufacturing and assembly errors in a 750 MHz Interdigital H-mode Drift Tube Linac (IH-DTL) cavity designed for a compact and efficient ion beam inyector. Operating at such a high RF frequency significantly reduces the cavity dimensions but it also increases the sensitivity to geometric imperfections, posing a substantial technological challenge for manufacturing and assembly. In this study, realistic machining deviations — including drift-tube misalignments, stem eccentricity, profile machining errors, and end-cell distortions — are introduced within typical fabrication tolerances. Three-dimensional electromagnetic simulations quantify the resulting perturbations in the resonant frequency, accelerating fields, and power efficiency. First, the most critical geometric perturbations were identified by means of a single cavity cell model. Then, those errors were implemented in a complete cavity, applied to all cells. The resulting field maps were subsequently imported into multi-particle beam dynamics simulations to evaluate their impact on beam quality, transmission, and emittance growth. The study provides experimental tolerance thresholds and offers guidance for cavity fabrication, quality control, and commissioning strategies for IH-DTL structures.

INTRODUCTION

H-mode interdigital radiofrequency (IH) cavities are a type of accelerating cavity well known for their high efficiency at low velocities, rendering them particularly suitable for the initial stages of linear accelerators. This type of structure is characterized by high shunt impedance and compact geometry, making it an attractive option for linear accelerators with space constraints and high-intensity requirements [1,2].

This technological framework is of particular importance in the context of hadron therapy, where compact and efficient accelerators are required to meet demanding clinical specifications. As part of the latest advances, CIEMAT, in collaboration with its industrial partner Added Value Solutions (AVS), is making progress on the design of a high-frequency linear injector intended for radiobiology studies [3], which will serve as a demonstrator for a future linac-based ion therapy facility. This injector is intended to accelerate $^{12}C^{6+}$ and $^{1}H^{+}$ ions up to 10 MeV/u in pulses of 5 µs. IH-DTL structures, designed to operate at 750 MHz, are currently actively being developed [4].

The application of structures operating at frequencies higher than usual entails certain additional constraints in RF design and cavity fabrication, as there is a high sensitivity to geometric deviations, whether in the positioning of the drift tubes, the eccentricity of the rods, machining tolerances, or overall alignment errors. Although these geometric aberrations may be of small magnitude, numerous studies [5,6] have shown that even small deviations can significantly alter the spatial distribution of the fields [7], causing shifts in the resonance frequency and undesirable variations in the impedance. Furthermore, these alterations not only affect the electromagnetic performance of the cavity, but also have direct consequences on the beam dynamics, including increased emittance, distortion of the longitudinal matching, and cumulative effects in acceleration schemes.

In this context, the study of tolerances in manufacturing is of crucial importance. Therefore, the objective of this report is to assess how geometric errors affect the performance of the first IH-DTL. By means of electromagnetic simulations, statistical analysis of geometric variations, and multiparametric beam tracking, we evaluate representative scenarios of machining errors, misalignments, and dimensional disturbances in order to quantify their impact on the field and beam dynamics, establishing verifiable manufacturing tolerances and acceptance criteria.

IH cavity

The IH cavity, which serves as the basis for the current analysis, is the first of a set of three [8]. It operates in TE110 mode, accelerating the beam from 5 MeV/u to 6.2 MeV/u over the course of 30 cells. The main RF and geometric parameters are specified in Table 1.

Table 1: Main Parameters of the IH-Cavity

Parameter	Value
Design average voltage (kV)	125
Energy gain (MeV/u)	1.23
Frequency (MHz)	749.48
Number of cells	30
Inner aperture (mm)	6
Length (m)	0.65
Power loss (kW)	69.9
ZTT (MΩ/m)	289.3

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The radiofrequency design of the cavity has been optimized through an iterative process in conjunction with beam dynamics. The drift tubes feature sloped end faces to mitigate the dipole push caused by rod-induced asymmetry [9]. In the inductive region, which accounts for most of the RF losses, the geometry has been optimized accordingly [10]. The resulting RF design achieves an average acceleration gradient of 5.57 MV/m with a power consumption of 70 kW.

ANALYSIS OF DEVIATIONS

EM Fields Impact

The mechanical design process has revealed a number of potential manufacturing defects, which have led to the definition of a set of tolerances relevant to this study. Geometric shape tolerances, which account for the flatness of the surface where the stems are attached to the frame, affect both the displacement along the Y-axis of the cavity and the alignment of the drift tubes with the axis of the cavity. The positional tolerances specify that the stems, which are positioned in the frame along the X and Z axes of the cavity reference system using a pair of pins, have a tolerance of 0.02 mm in the Z direction and 0.01 mm in the X direction.

In order to determine which errors have the greatest impact on the electromagnetic field of the cavity, firstly we evaluate a single-cell model. The longitudinal and rotational displacements of 0.2 mm and 0.2° respectively for each of the stems were taken into account (see Fig. 1). The effect on the voltage was analyzed by considering each of the cartesian components of the electric field individually, thereby separating the repercussions of each component in the integration. The results show that the most significant shift come from displacements along the Y and Z axis and rotations around the X-axis. These errors cause up to 0.4% variation in longitudinal effective voltage and up to 20% in transverse voltage. In the case of rotations around the X-axis, these cause a variation in the cell's air gap and, therefore, have an additional impact on the field distribution.

Taking into account the manufacturing tolerances and the geometric deviations considered, the IH structure is parameterized with a complete cavity model that the following possible defects are implemented: transverse and longitudinal displacements of the stems, variation in the length of the gaps, and rotation of the drift tubes about the X-axis. As the number of combinations of the defects is very high, a series of assumptions are considered to allow for quantitative analysis without compromising validity: each type of defect is evaluated independently; deviations are applied only to the lower stems, causing a relative variation of the stems in each cell; the defects are applied to all cells with the same magnitude. In summary, the cavity is evaluated under 11 different scenarios (see Table 2): displacements of the lower stems in the longitudinal direction and in the transverse direction; rotations of the lower stems around the cavity's x-axis to simulate a lack of parallelism between the mounting surfaces; uniform variations in the gaps; as well as rotations of the drift tubes around their local x-axis to simulate misalignments with respect to the cavity axis.

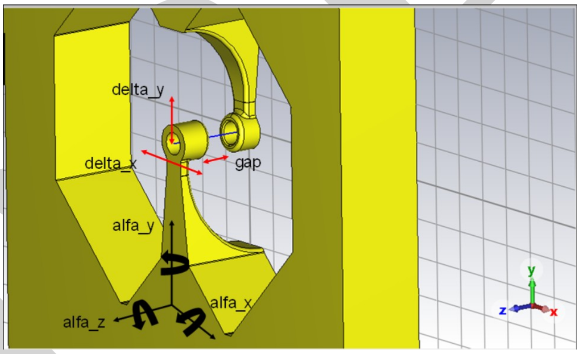


Figure 1: Stem degrees of freedom in the single-cell model.

Table 2: Cavity Error Cases

Case	Implication	Value
#1	Drift tubes rotation	$\alpha_{dt} = -0.2°$
#2	Drift tubes rotation	$\alpha_{dt} = +0.2°$
#3	Lower stems rotation	$\alpha = -0.02°$
#4	Lower stems rotation	$\alpha = +0.02°$
#5	Transverse shift	$\Delta x = +0.2$ mm
#6	Transverse shift	$\Delta y = -0.2$ mm
#7	Transverse shift	$\Delta y = +0.2$ mm
#8	Longitudinal shift	$\Delta z = -0.2$ mm
#9	Longitudinal shift	$\Delta z = +0.2$ mm
#10	Gaps reduced	−0.2 mm
#11	Gaps increased	+0.1 mm

The electromagnetic field maps of the resonant mode are calculated for each geometric deviation using finite element simulations. When the same type of shift is applied to all cells simultaneously, the capacitance and inductance of the cavity are modified, and consequently the resonance frequency changes. To isolate this effect in the field maps, the cavity is re-tuned to its nominal resonance frequency.

Beam Dynamics Effects

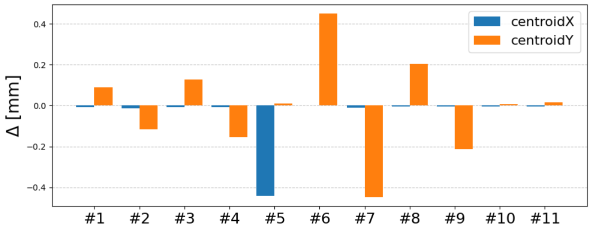
The field maps are imported into the Tracewin simulation code to analyze the effects of deviations. The input distribution is based on the RFQ-MEBT output beam obtained from a maximum-acceptance beam containing 100, 000 macroparticles and a current of 1 µA. The results of the beam path through the cavity for the modified fields are compared with the nominal case, analyzing the main beam parameters in the longitudinal and transverse directions.

In the transverse plane, the lateral displacement of the stems has a significant influence on the centering and the beam size at the end of the cavity (see Fig. 2). Furthermore, other sources of error also affect the displacement of the centroid, which can lead to appreciable losses before the beam enters the next cavity, especially in sections where the mechanical apertures are small or where there are sensitive elements near the axis. Although the observed increase in transverse emittance is moderate (see Fig. 2c), its presence indicates that the disturbance not only displaces the beam, but also introduces additional mismatch components that could amplify along the line. This underscores the importance of ensuring proper transverse alignment of the stems, as well as having early correction elements available when mechanical tolerances cannot be fully guaranteed.

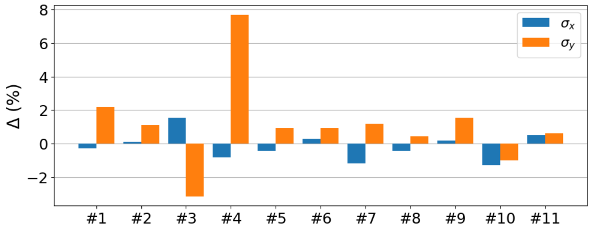
In the longitudinal direction (see Fig. 3), the error with the greatest impact is the collective rotation of all the stems around the x-axis, simulating a lack of parallelism between the upper and lower mounting surfaces. This type of misalignment induces a noticeable change in the accelerator field profile, resulting in a cumulative variation in energy gain of up to 0.6%. This figure is significant in terms of longitudinal acceptance and synchronism in the subsequent cavities, especially in chains where beam phase plays a critical role in preventing bunching degradation. This effect cannot be compensated for by the magnetic elements located at the cavity exit, since these act only on the transverse motion and do not affect the longitudinal dynamics. As an additional consequence, this rotation also generates a slight asymmetry in the field that manifests itself as an increase in the transverse beam size, reinforcing the need to strictly control the flatness and parallelism of the mounting surfaces during manufacturing and assembly.

CONCLUSION

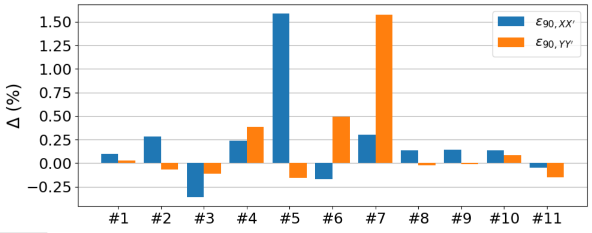
A tolerance analysis of a 750 MHz IH-DTL cavity has been performed through electromagnetic and beam dynamics simulations. Due to the high operating frequency and compact geometry, the structure shows prominent sensitivity to geometric shifts. The single-cell study identifies transverse and longitudinal stem displacements, together with rotations around the x-axis, as the most critical perturbations. When applied to the full cavity, these errors significantly modify the field distribution, even after frequency re-tuning.



(a) Centroid evolution

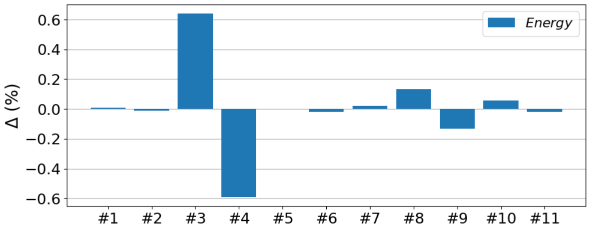


(b) RMS beam size

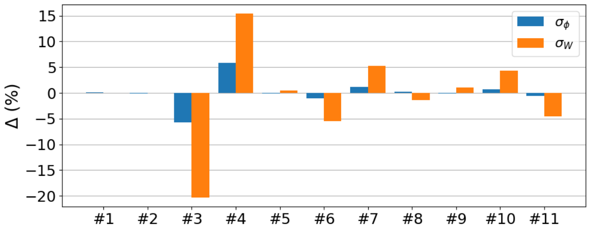


(c) 90% transverse emittance

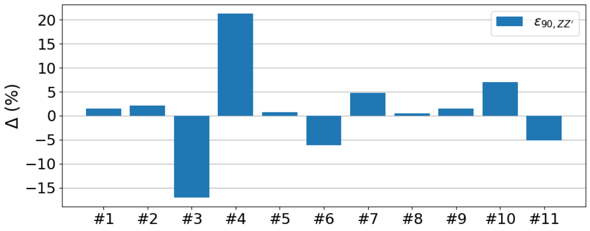
Figure 2: Impact of deviations on transverse beam dynamics.



(a) Energy mean



(b) RMS longitudinal phase space



(c) 90% longitudinal emittance

Figure 3: Effect of discrepancies on longitudinal dynamics.

In beam dynamics, transverse misalignment mainly induces beam centroid shifts and moderate emittance growth. In contrast, longitudinal effects are dominated by collective stem rotations, leading to distortions in the accelerating field and energy deviations. These results highlight the importance of strict control of alignment and parallelism during fabrication and assembly, providing guidance for defining mechanical tolerances in high-frequency IH-DTL cavities.

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REFERENCES

[1] H. P. Li *et al.*, “Study and design of the coupled cavity with ladder RFQ and IH-DTL structure for transportable neutron source”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 1056, p. 168645, 2023. `doi:10.1016/j.nima.2023.168645`

[2] K. Isokawa *et al.*, “Development of high gradient IH linac”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 415, p. 287, 1998. `doi:10.1016/S0168-9002(98)00604-4`

[3] C. Oliver *et al.*, “A 750 MHz compact and versatile $^{12}C^{6+}$ accelerator for advanced radiobiology and therapy research”, presented at IPAC’26, Deauville, France, May. 2026, paper THP4028, this conference,

[4] J. Giner Navarro *et al.*, “Conceptual RF design of 750 MHz IH cavities for $\beta = 0.10$–0.15 ion beams in medical accelerators”, *Nucl. Eng. Technol.*, vol. 56, p. 3536, 2024. `doi:10.1016/j.net.2024.04.001`

[5] M. Otani *et al.*, “Interdigital H-mode drift-tube linac design with alternative phase focusing for muon linac”, *Phys. Rev. Accel. Beams*, vol. 19, p. 040101, 2016. `doi:10.1103/PhysRevAccelBeams.19.040101`

[6] P. F. Ma *et al.*, “Development of a compact 325 MHz proton interdigital H-mode drift tube linac with high shunt impedance”, *Phys. Rev. Accel. Beams*, vol. 24, p. 020101, 2021. `doi:10.1103/PhysRevAccelBeams.24.020101`

[7] R. Tang *et al.*, “Mechanical design and error analysis of a 325 MHz IH-DTL test cavity”, in *Proc. 9th Int. Particle Accel. Conf. (IPAC’18)*, Vancouver, BC, Canada, pp. 1189–1189, Apr.–May 2018. `doi:10.18429/JACoW-IPAC2018-TUPAL075`

[8] G. Moreno *et al.*, “Design and em simulations of 750 MHz IH-DTL tank for carbon ion in medical applications”, in *Proc. 16th Int. Part. Accel. Conf. (IPAC’25)*, Taipei, Taiwan, pp. 1502–1505, Jun. 2025. `doi:10.18429/JACoW-IPAC2025-TUPS036`

[9] R. López *et al.*, “Cell geometry optimization for dipole kick correction in a high-frequency IH structure”, in *Proc. 31st Int. Linear Accel. Conf. (LINAC’22)*, Liverpool, UK, pp. 146–149, Aug.–Sep. 2022. `doi:10.18429/JACoW-LINAC2022-MOPOGE04`

[10] G. Moreno *et al.*, “Effect of high-magnetic field region geometry on the efficiency of a 750 MHz IH structure”, in *Proc. 31st Int. Linear Accel. Conf. (LINAC’22)*, Liverpool, UK, Aug.–Sep. 2022. `doi:10.18429/JACoW-LINAC2022-MOPOGE05`