IMPLICATION OF MANUFACTURING ERRORS ON THE LAYOUT OF STABILIZATION SYSTEM AND ON THE FIELD QUALITY IN A DRIFT TUBE LINAC - RF DTL ERROR STUDY

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Abstract

The field flatness and the layout of the stabilization system in a drift tube linac are strongly dependent on the manufacturing errors that affect the local resonant frequency. In this paper a methodology is presented to study, firstly, the sensitivity of the resonant frequency and of the field flatness to each geometrical parameter of the drift tubes; then a set of tolerances for each parameter is found and a stabilization system layout is defined in order to keep the field flatness within an acceptable limit.

INTRODUCTION

The manufacturing errors of each part of a Drift Tube Linac, DTL, affect the Radio Frequency, RF, parameters. For this reason it is crucial to analyze the impact of these errors on the frequency and on the field flatness. According to the chosen tolerances it is possible, finally, to define the layout of the stabilization system.

In this paper the study is done for the ESS DTL [1] on which the first author has directly worked. The ESS DTL is an in-kind contribution from INFN/LNL [2]. It is composed of five RF cavities (or tanks) that are used to accelerate a proton beam of 62.5 mA from 3.62 MeV to 89.68 MeV at 352.21 MHz; the transverse focusing system is composed of permanent magnet quadrupoles arranged in a F0D0 lattice.

IMPACT OF THE FIELD FLATNESS ON THE BEAM DYNAMICS

Four error studies are performed to evaluate the impact of the accelerating field flatness on the beam dynamics of the ESS DTL. For each study a set of 1000 simulations are performed using the tolerances defined in [3] and gradually increasing only the tolerance of the field flatness from 1% to 4% (steps of 1%). It is important to underline that *the error studies are executed by using fieldmaps* [4] obtained applying errors on the geometric parameters of the DTL and solving the Maxwell equations in each tank for each simulation.

In addition the four studies are repeated considering the error on E_0 as a random variable uniformly distributed within its tolerance as done in [5].

The results of the studies are reported in Fig. 1: it is clear that modeling the error on E_0 as a random variable, uniformly distributed within its tolerance, underestimates of the emittance growth and the beam losses within the DTL. In addition the DTL output particle distribution is an inaccurate input for the downstream sections: this can lead to a dangerous underestimation of the emittance growth and of the beam losses in the rest of the ESS LINAC.

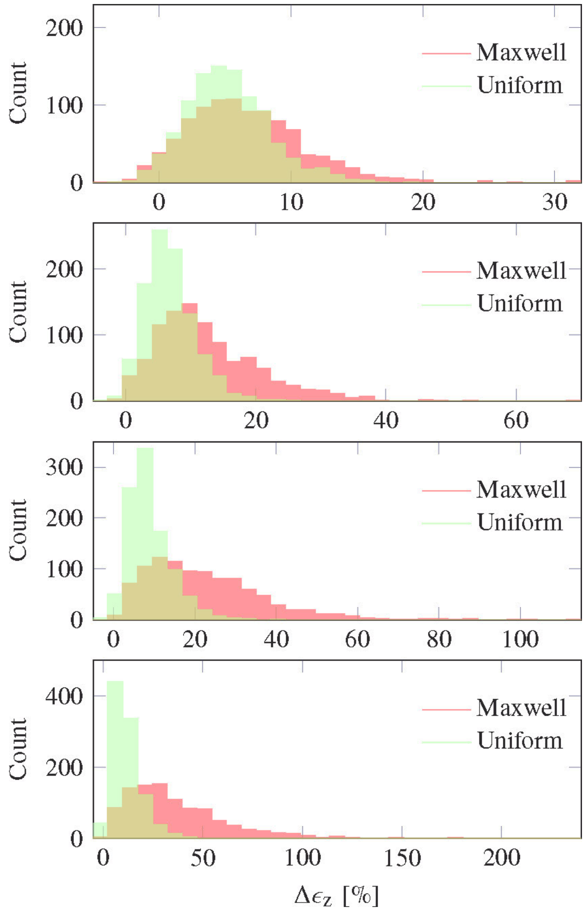

Figure 1: Additional longitudinal RMS emittance growth for the four error studies. The tolerance of the accelerating field flatness increases, from top to bottom, from 1% to 4%.

Keeping the DTL accelerating field flatness within 1% guarantees the ESS constraint on the losses (<1 W/m) is preserved for the entire ESS LINAC. The effect of a higher value of the flatness tolerance of the ESS DTL on the beam loss and on the emittance growth for all the sections following the DTL should be carefully investigated.

In the following sections a list of tolerances for all the drift tube geometrical parameters is found and a methodology to define the layout of the stabilization system is defined to keep the flatness within 1%.

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DTL CAVITY SHAPE

The ESS DTL design consists of 5 tanks, each composed of 4 modules or sub-tanks.

The geometrical details near the Drift Tube, DT, nose of a DTL right half cell are shown in the Fig. 2. The full gap is g and the full cell length is L. The bore radius is R_b. The full cavity diameter is D and the DT diameter is d. The flat length is F. The face angle, α, is the angle that the DT face makes with the vertical. There are three circular arcs on the DT profile: the corner radius, R_c, the inner nose radius, R_i, and the outer nose radius, R_o.

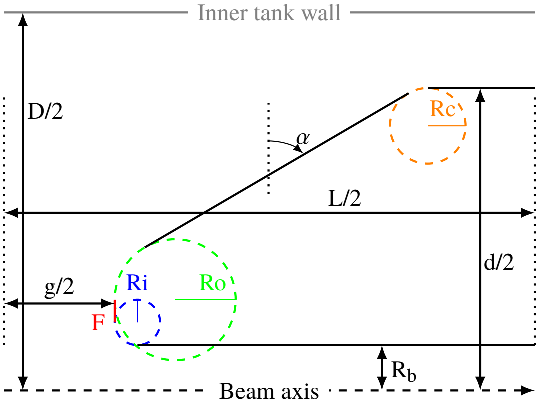

Figure 2: Details of right half cell drift tube nose.

The nominal values of the constant geometrical parameters of Fig. 2 are summarized in the Table 1 for each tank of the ESS DTL.

Table 1: Geometrical Tank Parameters of the ESS DTL

Tank	1	2	3	4	5
Modules [#]	4	4	4	4	4
Cells [#]	61	34	29	26	23
L_T [mm]	7618	7101	7583	7847	7687
R_b [mm]	10	11	11	12	12
R_o [mm]	8	8	8	8	8
R_c [mm]	5	5	5	5	5
R_i [mm]	3	3	3	3	3
F [mm]	3	3	3	3	3
d [mm]	90	90	90	90	90
D [mm]	520	520	520	520	520
D_s [mm]	28	28	28	28	28

RF DTL ERROR STUDY

The geometrical parameters considered in this analysis are: g, L, R_c, R_i, R_o, F, α, R_b, d, D and D_s, where D_s is the diameter of the stems.

In order to evaluate the individual effect of manufacturing errors of each parameter on the frequency and on the flatness of the accelerating field, at first each error is applied individually, without the post coupler stabilization system. This step is useful to set the *preliminary* individual tolerances.

In a second step all the errors are applied simultaneously in order to set the *final* tolerances and to define the *associated* layout of the stabilization system that keeps the flatness of the accelerating field within the desired limit. We define the *optimum lengths* of the PCs as the lengths for which there is the *confluence* [6]. The PCs are supposed inserted with their *optimum length* [4].

It is important to underline that, from this moment, we suppose that the interfaces of the DTL and the stabilization system, if present, are *fully integrated* [7] in the design to avoid the *self perturbation phenomena* [4] of these components.

Individual Errors

The impact of each manufacturing error on the frequency and on the field flatness is analyzed.

Called p one of the parameters g, L, R_c, R_i, R_o, F, α, R_b, d, D, D_s, the error, on the same parameter, is modeled, cell by cell, as a random independent variable, uniformly distributed within a range Δp. For each cell: $p_i = p_{nom} + \Delta p_i$ with $i \in [1, N_{cells}]$, $\Delta p_i \in [-\Delta p; \Delta p]$ and p_{nom} defined in the Table 1. N_{cells} is the total number of cells in each tank.

Fixed Δp, a set of 1000 RF simulations, solving the Maxwell equations within the cavity, are performed for each tank to record the global frequency and the accelerating field flatness. The study is repeated by gradually increasing the range Δp.

For brevity it will be reported in the Fig. 3 the average error, the maximum error and the standard deviation, over 1000 simulations, for each cell, only in case of errors applied to the gaps in the first tank of the ESS DTL.

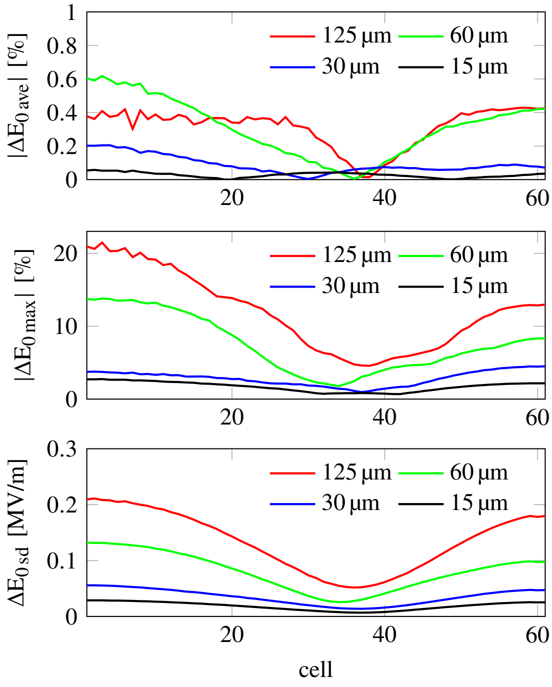

Figure 3: Average error, maximum error and the standard deviation, over 1000 simulations, due to the gap error in the first tank of the ESS DTL.

The sensitivity of each geometrical parameter, σ, a list of preliminary tolerances, selected at the end of the individual error studies, and their maximum detuning are reported in Table 2 for to first cell of the ESS DTL first tank.

Table 2: Static Frequency Error and Geometrical Tolerances

p	$\sigma_{1,1}$ [kHz/mm]	Δp [mm]	Δf_{MAX} [kHz]
α	9468	±0.025	±236
g	5144	±0.025	±129
L	-1387	±0.030	∓42
$\mathbf{R_c}$	-729	±0.025	∓18
$\mathbf{R_i}$	677	±0.025	±17
$\mathbf{R_o}$	44	±0.025	±1
F	887	±0.025	±22
$\mathbf{R_b}$	-508	±0.025	∓13
d	-830	±0.025	∓21
D	-448	±0.100	∓45
$\mathbf{D_s}$	127	±0.025	±3
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Global Errors

Once the individual effects are analyzed and a preliminary list of tolerances selected, a final error study, of 1000 simulations, is performed to analyze the simultaneous effect of all the geometrical errors on the frequency and on the flatness of the accelerating field. The results for the first tank of the ESS DTL are reported in Fig. 4.

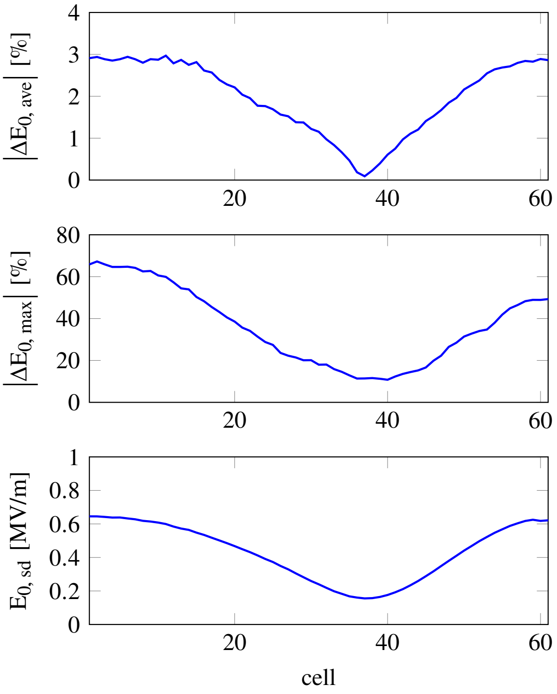

Figure 4: Average error, maximum error and the standard deviation due to a simultaneous geometrical errors in the first tank of the ESS DTL.

It is important to look at the statistical properties of the tank frequency detuning: the average is -0.02 MHz, the maximum, in absolute value, is 0.21 MHz and the standard deviation is 0.09 MHz.

TUNING RANGE

Fixed the tolerances of Table 2 and calculated the statistical properties of tank 1 (which contains shorter cells), a tuning range of 0.55 MHz (*using a safety factor 6 over the standard deviation*) is sufficient to garantee the tunability of the target *global frequency* [7] for the ESS DTL.

STABILIZATION SYSTEM

The accelerating field is firstly adjusted by retuning the two end cells for each of the 1000 simulations for which the flatness is bigger than 1%. Then the DTL equivalent trasmission line model [6] is built and the post couplers are inserted for each of these cases in order to keep the flatness within 1%. Using the tolerances of Table 2, the maximum distance between two consecutive PCs that keeps the flatness within 1% is 33 cm.

It is important to underline that:

- the layout of post couplers is strictly linked to the set of chosen tolerances;
- an important premise is that the post couplers are inserted with their optimum lengths;
- a crucial assumption is that the *preliminary design is finalized with the integration of interfaces and stabilization system* [7].

The presence of the stems, post couplers, vacuum grids and power couplers *not locally compensated* induces a global and local detuning [7]. The last one, in particular, could cause strong *additional tilts* on the accelerating field for which the stabilization system is not designed and, therefore, inefficient.

CONCLUSION

The tuning range can be properly estimated only defining the tolerances for *all* the DTL geometrical parameters.

The layout of the stabilization system has to be fixed by basing it on the maximum slope of the accelerating field induced by the simultaneous geometrical DT errors.

The stems, post couplers, vacuum grids and power couplers have to be integrated in the design. Uncompensated interfaces induce a global detuning, but most of all, a dangerous local detuning, comparable with the one induced by the selected tolerances. This could cause additional accelerating field tilts for which the stabilization system is not designed making the requirement on the flatness unreachable.

The beam dynamics studies to evaluate the emittance growth and the beam loss have to be performed using the real field maps. Modeling the accelerating field, cell by cell, within each tank, as a random variable uniformly distributed within its tolerance, which does not respect the Maxwell equations, leads to wrong beam dynamics results especially when the tolerance is large.

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