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de Prisco, Renato

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LUND UNIVERSITY

PO Box 117  
221 00 Lund  
+46 46-222 00 00

# BEAM DYNAMICS STUDIES OF THE ESS LINAC USING A NEW MULTICELL CAVITY MODEL

R. De Prisco\*, Lund University, Lund, Sweden  
 C. Plostinar, ESS, Lund, Sweden

## Abstract

The European Spallation Source is designed to deliver 5 MW proton beam power on the target while keeping the beam induced losses below 1 W/m throughout the LINAC. This implies the need of accurate models to correctly describe the longitudinal beam dynamics within the multi-cell cavities. In all the previous error studies the cells of a multi-cell cavity were modelled as a sequence of independent gaps and the errors were applied directly on the amplitude of each cell accelerating field, considered as random variable. In this paper, instead, we present a new detailed analysis of the effect of the error tolerances on the beam dynamics including a new model to calculate the amplitude errors of the accelerating field in the multi-cell cavities: errors are applied on the geometrical parameters of each cavity; then the accelerating field is calculated solving the Maxwell equations over all the cavity.

## INTRODUCTION

The following multi-cell cavities are present in the ESS LINAC: RFQ, DTL, spoke, medium- $\beta$ , high- $\beta$ .

Generally speaking the cells in a cavity are just a virtual abstraction useful to describe the solutions (modes) of the Maxwell equations in the cavity.

Many particle tracking codes describe all the cells in the same cavity as a sequence of independent one-cell cavities (or gaps). It is up to the user to make sure that the accelerating field of a sequence of independent gaps is a solution of the Maxwell equations.

## THE ACCELERATING FIELD IN A MULTI-CELL CAVITY

In the previous error studies [1] [2] the multi-cell cavities were modeled as a sequence of independent gaps as shown in the Fig. 1 for a cavity of 3 cells.

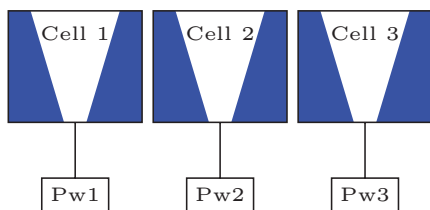


Figure 1: Multi-cell cavity as sequence of independent gaps.

The error of the accelerating field  $E_0$  was modeled, cell by cell, as a random variable uniformly distributed within its tolerance.

\* renato.deprisco@ess.se

In this paper, instead, an iterative procedure is defined to calculate  $E_0$  for each cavity: a set of tolerances is specified for all the geometrical parameters of the cavity, then the electromagnetic field is calculated solving the Maxwell equations. The algorithm is shown in the Fig. 2 where  $E_d$  is the desired flatness of the accelerating field.

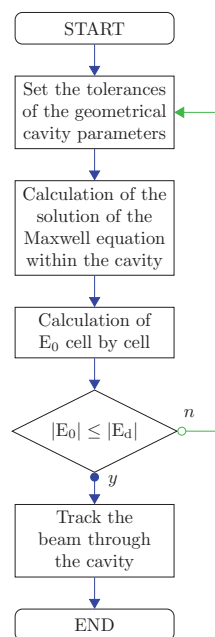


Figure 2: Algorithm to calculate the accelerating field  $E_0$ .

It is important to emphasize that a mechanical error in a cell influences the accelerating field in all the cavity and not only in that cell [3] as schematically shown in the Fig. 3.

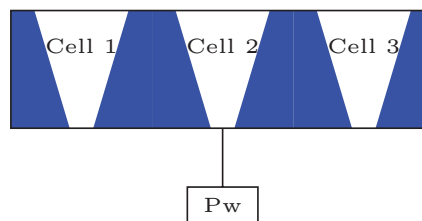


Figure 3: Multi-cell cavity model.

For this reason considering the cells of the same cavity as independent gaps and, consequently, modeling the error of the accelerating field  $E_0$ , cell by cell, as a random variable uniformly distributed within its tolerance is an unrealistic approach.

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Since the ESS will send the beam to a fixed tungsten target the emittance is not as important a factor as for the injectors. On the other hand the beam halo should be carefully investigated because it can cause particle loss which can damage the accelerator components and lead to an unwanted radioactivity.

To analyze the difference of the beam dynamics due to the two cavity models we will use the Drift Tube Linac, DTL. The DTL accelerates the proton beam with a 62.5 mA pulse peak current from 3 to 89 MeV. It is designed to operate at 352.21 MHz with a duty cycle of 4 % and it is composed by 5 cavities (or tanks) of 61, 34, 29, 26, 23 cells each [4] [5].

The geometrical details near the Drift Tube, DT, nose of a DTL right half cell are shown in the Fig. 4. 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,  $\alpha$ , 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,  $R_o$ .

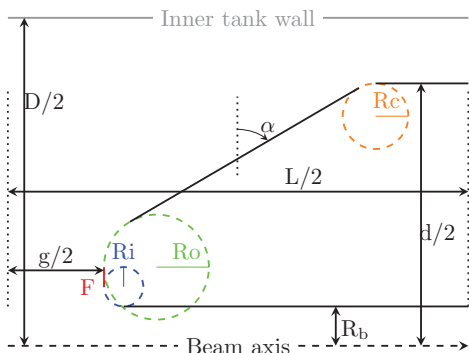


Figure 4: Details of right half cell drift tube.

At first the errors of each parameter are applied individually in order to evaluate their individual effect on the flatness of the accelerating field 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* [3]. The PCs are supposed inserted with their *optimum length* [6] [7]. We suppose that *all the interfaces are properly integrated* [8] [9].

### Comparison of the Two Models of the Multi-cell Cavities

The following *static* [10] errors are included, modeled as random variables uniformly distributed within their tolerances and changed in the same way, linac by linac, for all the 4 studies: the quadrupole transverse position,  $dx$ ,  $dy$ , rotation,  $d\phi_x$ ,  $d\phi_y$ ,  $d\phi_z$ , gradient,  $dG$ , and multipoles,  $dG_n$

( $n=3,4,5$ ), errors; cell field phase,  $d\phi_s$ , error; cavity field,  $dE_k$ , and phase,  $d\phi_k$ , error.

The tolerance of the field flatness,  $dE_0$ , is gradually increased from 1% to 4% for all the five tanks. Then the error studies are repeated with the *only* difference that  $E_0$  is modeled as a random variable uniformly distributed within its tolerance.

For the beam dynamics studies reported in this paper the beam is generated at the RFQ input with a gaussian distribution truncated at  $4\sigma$ . The nominal RFQ output distribution is saved and used as input distribution for the rest of the ESS LINAC. The beam parameters at the RFQ output and their tolerances are reported in Table 1. The number of particles used is 1 M and the statistic of each study is based on 1000 linacs.

The space charge routine used is PICNIC [10] and we underline again that only the *static* errors [10] are considered.

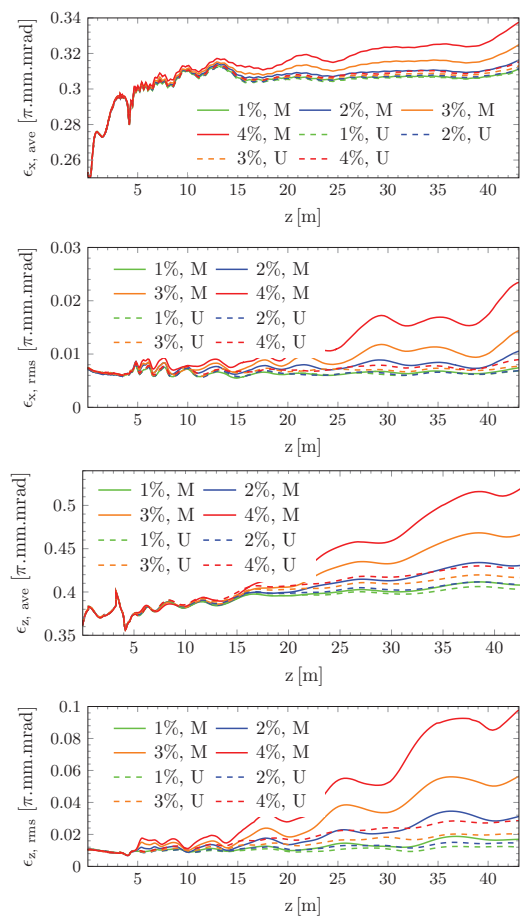


Figure 5: From top to bottom: average and RMS of the horizontal emittance,  $\epsilon_{x, \text{ave}}$ , average and RMS of the longitudinal emittance,  $\epsilon_{z, \text{ave}}$ . The letter M indicates that the accelerating field is calculated solving the Maxwell equations while the letter U indicates that  $E_0$  is modeled as a random variable uniformly distributed within its tolerance. The percentage indicates the tolerance of  $E_0$ .

From the Fig. 5 is clear that modeling a long cavity as a sequence of independent gaps underestimates the emittance

growth. In this case the difference of the beam dynamics parameters between the cases of 1% and 4% is not relevant and this could induce, easily, to a wrong decision on the acceptable tolerances. We underline that calculating the accelerating field using the new algorithm gives an emittance growth in the case of flatness within 2% that is larger than the emittance growth of all the cases in which the DTL is modeled as a sequence of independent gaps.

We report the histograms of the occurrences of the additional longitudinal RMS emittance growth,  $\Delta\epsilon_z$  and at the longitudinal halo parameter,  $h_z$ , shown in the Fig. 6, to emphasize the difference between the beam dynamics results of the two models when the flatness is kept within 1%.

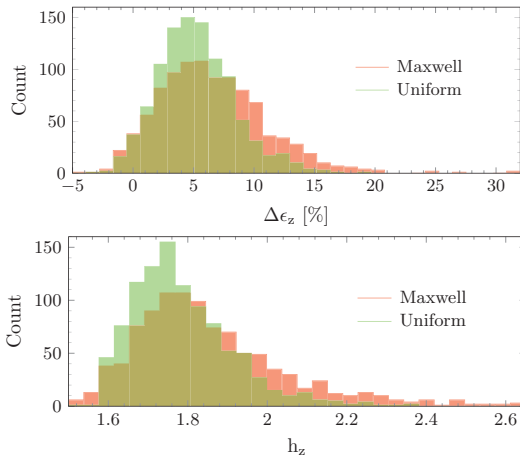


Figure 6: Additional longitudinal RMS emittance growth,  $\Delta\epsilon_z$ , (top) and Halo Parameter,  $h_z$ , (bottom) when the flatness of  $E_0$  is within 1%.

## ERROR STUDY OF THE ESS LINAC

Using the tolerances defined in the Table 1 and 2 we perform a global error study. The subscript B refers to the MEBT, S to the Super Conducting, SC, cavities.

Table 1: Tolerances of the Beam at the MEBT Input

dx, dy [mm]	dx', dy' [mrad]	dE [keV]	$\Delta\epsilon_{x,y,z}$ [%]	$M_{x,y,z}$ -	dI [mA]
0.3	1	36.2	5	5	0.625

Table 2: Static Errors Tolerances

Parameter	CAV <sub>B</sub>	DTL	QUAD <sub>B,S</sub>	CAV <sub>S</sub>
dx, dy [mm]	0.5	0.1	0.2	1.5
$d\phi_x, d\phi_y$ [deg]	0.115	0.5	-	0.129
$d\phi_z$ [deg]	-	0.2	0.06	-
$\Delta G$ [%]	-	0.5	0.5	-
$\Delta E_0, \Delta E_k$ [%]	-1	1,1	-, -	5,1
$\Delta\phi_s, \Delta\phi_k$ [deg]	-1	0.5,1	-, -	-,1

The averages of the normalized RMS emittances and the power losses are shown in the Fig. 7. The losses are due to the particles that were in the tail of the beam at the RFQ out or that have not been captured inside the RF bucket after the frequency transition (352,21MHz/704,42MHz) at the interface SPOKE/MEDIUM- $\beta$  cavities.

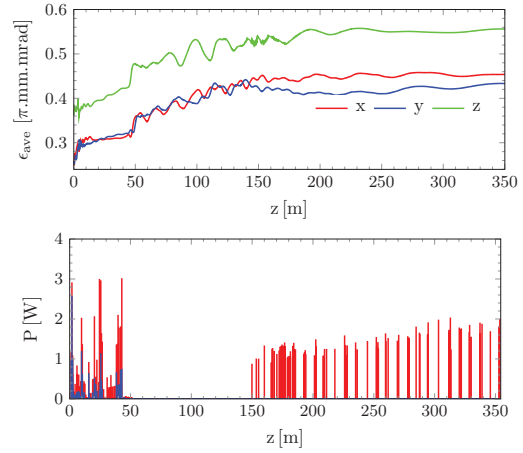


Figure 7: Averages of the normalized RMS emittances and power loss at 100% (red) and 99% (blue) confidence levels along the accelerating sections of the ESS LINAC.

## CONCLUSION

The cavity model is important for the reliability of the beam dynamics parameters and of the power loss map: losses in the normal conducting section due to a simplified model can mask dangerous losses in the high energy part of the LINAC. Vice versa losses in the SC section due to a simplified model can lead to an unjustified reductions of the tolerances and, so, to a higher cost.

The studies show that modeling the error of the accelerating field, cell by cell in a multi-cell cavity, as a random variable, uniformly distributed within its tolerance, causes an underestimation of the emittance growth and of the halo parameters. The larger the number of cells is in a multi-cell cavity, the higher the underestimation of the beam dynamics parameters is. This means that the new cavity model is very important for the RFQ and for the DTL.

In the case of the ESS LINAC the error studies with the new model of the multi-cell cavities show that the considered tolerances assure a particle loss level, along the accelerating sections, below the acceptable limit of 1 W/m at 99% confidence level when only the static errors are applied.

## ACKNOWLEDGEMENT

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