Error study on the normal conducting ESS linac

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ERROR STUDY ON THE NORMAL CONDUCTING ESS LINAC

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Abstract

One of the preliminary, but important test to evaluate the robustness of the accelerator design is performing the statistical error study by introducing realistic tolerances on the machine components.

In this paper the guidelines to define the tolerances and the correction system are summarized in order to validate the design. Firstly statistical studies have been performed in order to define the sensitivity to single errors and to fix the tolerances. Then all errors, within the previous defined tolerances, are applied with the correction system to evaluate the beam quality and to check if the system guarantees a radiologically safe operation.

INTRODUCTION

The European Spallation Source (ESS) uses a LINear ACcelerator (LINAC) to deliver the high intensity proton beam to the target station. The normal conducting ESS LINAC accelerates a proton beam of 62.5 mA from 0.075 MeV to 89.68 MeV at 352.21 MHz. The pulses are 2.86 ms long with a duty cycles of 4%. Permanent Magnet Quadrupoles (PMQs) in the DTL are used as focusing elements in a FODO lattice. The average beam power is 5 MW with a peak beam power at target of 125 MW.

SPACE CHARGE ROUTINE

The first crucial point to accurately describe the space charge effect of the high current LINAC is to choose a proper space charge routine. For these studies the PICNIC routine is chosen because, by applying the errors, the assumption of cylindrical symmetry on the bunch shape can not be guaranteed [1].

The second crucial point is the choice of the mesh size in the beam and the particle number. There is an optimum mesh size respect to which a larger mesh size deteriorates the resolution whereas a smaller mesh size induces a small number of particle per cell and, consequently, statistical noise. For these studies the mesh size is 15 both in transverse and in longitudinal planes. The number of particles is 1 million.

ERROR STUDY STRATEGY

The normal conducting ESS LINAC is composed of three structures: Radio Frequency Quadrupole (RFQ), Medium Energy Beam Transport (MEBT), Drift Tube Linac (DTL).

For each section, at first, each error is applied individually to evaluate the emittance growth sensitivity. At this stage the errors are analyzed without the correction steerers. *In a very preliminary approach* the additional emittance growths, due to the individual errors, in the $k-$plane, $\Delta\epsilon_k$ (with respect to the emittance growths in the case without error in the same plane, $\epsilon_{\text{out, NO ERR, }k}$) can be considered as independent variables. With this hypothesis a rough value of the total squared additional emittance growth, for the case in which all errors are applied simultaneously, can be approximated by the sum of the squared individual additional growths. This calculation is useful to fix a preliminary acceptable limit for each error.

The additional emittance growth is defined as:

$$\Delta\epsilon_k = \frac{\epsilon_{\text{out, ERR, }k} - \epsilon_{\text{out, NO ERR, }k}}{\epsilon_{\text{out, NO ERR, }k}}, \tag{1}$$

where $\epsilon_{\text{out, ERR, }k}$ is the output emittance in presence of errors in the $k-$plane.

In the second step all the errors are applied simultaneously with the corrector steerers. A fine tuning on the tolerances is done in order to have the total additional emittance growth limited to 10 % per structure and the losses less than 1 W/m everywhere. Finally a steerer study is done for the DTL by varying their number, position and strength in order to reduce further the losses.

Each case is simulated using 1000 linacs.

ERROR DEFINITIONS

It is possible to separate the errors in two categories: *static* and *dynamic* in time. To the static category belong: quadrupole transverse position, dx, dy, rotation, $d\phi_x$, $d\phi_y$, $d\phi_z$, and gradient, dG, errors; structure to structure alignment, dx_T, dy_T, errors; field amplitude, dE_0, and phase, $d\phi_s$, error; klystron field, dE_k, and phase, $d\phi_k$, error. The klystron field, $dE_{k,d}$, and the phase, $d\phi_{k,d}$, jitter error belong to the dynamic category.

RFQ AND MEBT

The beam is generated at the RFQ input with a gaussian distribution truncated at 4σ. The nominal RFQ output distribution is saved and used in the MEBT and global error studies. The main beam parameters at the RFQ output and the tolerances for the RFQ and MEBT are reported in [2]. The effective gap voltage of the three bunchers in the MEBT are tuned to match the Twiss input DTL parameters. The MEBT output Twiss parameters and, in parentheses, their difference, in percentage, from the input ideal Twiss Parameters of the DTL are reported in Table 1.

By introducing in the MEBT the tolerances defined in [2] it is possible to define the variation interval for each output beam parameter. The intervals are reported in the Table 2.

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Table 1: Nominal Twiss Parameters at the MEBT Output

	α	β [mm/π.mrad]	ϵ [mm.π.mrad]
X	1.34 (-6.4%)	0.21 (-3.3%)	0.28
Y	-4.18 (-2.2%)	0.76 (-3.7%)	0.29
Z	0.13 (-0.8%)	0.41 (-0.5%)	0.37

Table 2: Beam Parameter Intervals at the MEBT Output

Parameter	Unit	Interval
x	[mm]	-0.002 ± 0.204
y	[mm]	0.003 ± 0.421
x'	[mrad]	-0.012 ± 1.168
y'	[mrad]	0.025 ± 2.065
dE	[keV]	-0.759 ± 7.613
α_x		1.338 ± 0.118
β_x	[mm/mrad]	0.215 ± 0.016
α_y		-4.189 ± 0.308
β_y	[mm/mrad]	0.764 ± 0.040
α_z		-0.120 ± 0.062
β_z	[deg/MeV]	273.7 ± 20.5

The histogram of the occurrences of each parameter at the MEBT output has a gaussian shape. The width of each interval in the Table 2 is equal to $0.5 \times \sqrt{2\pi} \times \sigma$ and it is also half base length of a rectangle with height equal to the maximum of the gaussian (σ is the standard deviation of the approximant gaussian function).

DTL

The actual DTL design [3] consists of 5 tanks with an ideal constant accelerating field integral in each tank. Even if the cells, different in length, have the same frequency, the accelerating field integral is not the same for all the cells of each tank. This is due to the fact that there is not a perfect mode matching between the adjacent cells built individually. The mismatch produces a natural tilt of the accelerating field integral along the cells that must be compensated.

The Accelerating Field Tuning Error

We define *nominal* accelerating field integral, E_0, the field after the compensation [4] and *accelerating field tuning error* its difference with respect to the ideal constant one. The nominal E_0 is, on average, within 0.18% of its ideal value [3]. In all of the following error studies we consider that the accelerating field in the DTL is the nominal one that can be affected by other errors (dE_0, dE_k, $dE_{k,d}$).

The Natural Emittance Growth

We investigate the sensitivity to each individual in two cases: by using a gaussian distribution, cut at 3σ, matched at the DTL input and by using the MEBT output distribution. We define *natural emittance growth* as the emittance growth in the DTL when this structure is affected only by the accelerating field tuning error. The natural emittance due to a gaussian matched (at the DTL input) distribution, $\Delta\epsilon_{\mathrm{nat},\,G}$, and due to a MEBT output distribution, $\Delta\epsilon_{\mathrm{nat},\,M}$, are reported in Table 3. For the Gaussian case we use as input emittance, both in X and Y, an average between the two homologous values at the MEBT output.

Table 3: Natural Emittance Growth

	$\epsilon_{\mathrm{in},\,G}$, $\epsilon_{\mathrm{in},\,M}$ [mm.π.mrad]	$\epsilon_{\mathrm{out},\,G}$, $\epsilon_{\mathrm{out},\,M}$ [mm.π.mrad]	$\Delta\epsilon_{\mathrm{nat},\,G,\,M}$ [%]
X	0.2857, 0.2832	0.3034, 0.2947	6.2, 4.1
Y	0.2857, 0.2882	0.3020, 0.2976	5.7, 3.3
Z	0.3728, 0.3728	0.3872, 0.3840	3.9, 3.0

Table 3 shows that the natural emittance growth is higher when a gaussian distribution, matched to the DTL input, is used.

Individual Errors

The more relevant additional emittance growths, due to the individual errors, are shown in the Fig. 2, but the same study is done for all the errors mentioned before. It is important to underline that the error on the accelerating field is not studied by varying randomly the field cell by cell in each tank: such an approach does not agree with the Maxwell equations. For each run, random, but limited, volume perturbations are applied, cell by cell, so that the accelerating field, calculated tank by tank, is within a desired percentage from its nominal value. From these studies it is evident that the MEBT distribution induces higher additional emittance growth.

Multipole Studies

In Fig. 1 we report only the additional transverse emittance growth due to the individual higher-order (n=3, 4, 5) multipole components since the longitudinal one is not relevant. Their magnitudes are expressed in percentage of the quadrupole strength at 3/4 of bore radius from the beam axis. $\Delta\epsilon$ is negligible for quadrupole and dodecapole. For all the runs there are no losses.

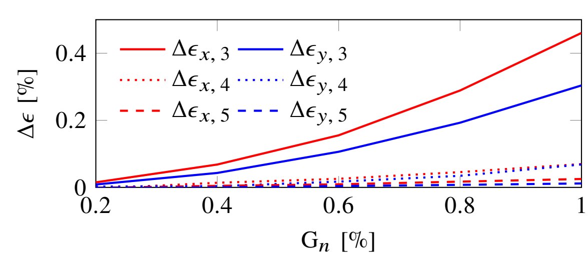

Figure 1: Additional emittance growth due to the multipoles.

An error study is done by introducing all the higher-order multipole with a maximum gradient of 1%. The transverse additional emittance growth is 0.5%. The effect can be amplified in presence of other errors because the centroid oscillation and the growth of the beam dimension induce

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more particles where the multipole field is more strong. An error study is running to evaluate this effect.

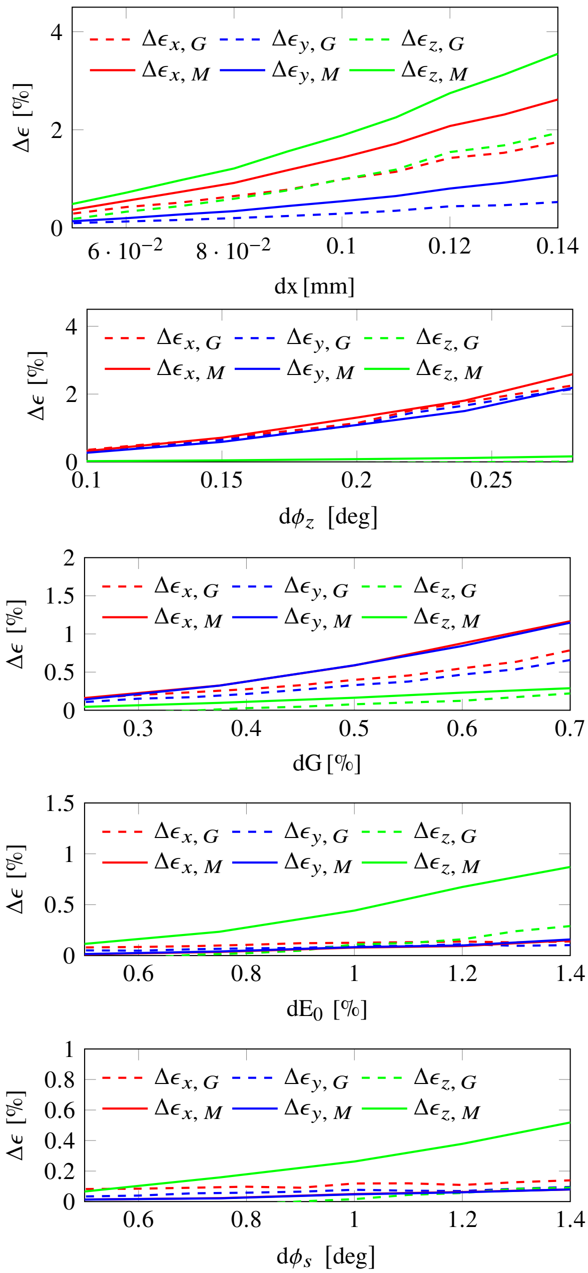

Figure 2: $\Delta\epsilon$ due to the individual errors.

Tolerances

One possible set of tolerances that keeps the losses below 1 W/m, when the beam is transported through all the previous sections with their tolerances, is reported in Table 4.

Steerer Studies

To reduce the losses, two additional steerers, X and Y, are placed in the MEBT with an additional beam position monitor in the first DTL drift tube. Table 5 shows the total power loss as function of the maximum steerer strength, S_M and the percentage of the cases that has a power loss less than

Table 4: DTL Tolerances.

Parameter	Tolerance
dx, dy [mm]	0.1
$d\phi_x, d\phi_y, d\phi_z$ [deg]	0.5, 0.5, 0.2
ΔG [%]	0.5
$\Delta E_0, \Delta E_k, \Delta E_{k,d}$ [%]	1, 1, 0.2
$\Delta\phi_s, \Delta\phi_k, \Delta\phi_{k,d}$ [deg]	0.5, 1, 0.2
dx_T, dy_T [mm]	0.1

the reported value. It is clear that, having fixed the steerer position, there is an optimum S_M for which the losses are minimized. An increase of S_M can cause of higher losses.

Table 5: Total Loss as Function of Steerer Strength

S_M	**Total Loss**		
	90%	99%	100%
[G.m]	[W]	[W]	[W]
4	0.52	1.95	9.94
8	0.47	1.95	6.75
12	0.59	2.92	14.26
16	0.87	4.55	21.32

CONCLUSION

The error study shows that the normal conducting section of the ESS LINAC is robust: the total $\Delta\epsilon$ is around 6% for both MEBT and DTL and, as shown in the Fig. 3, the losses of 99% of the cases are less than 1 W/m if S_M=8 G.m.

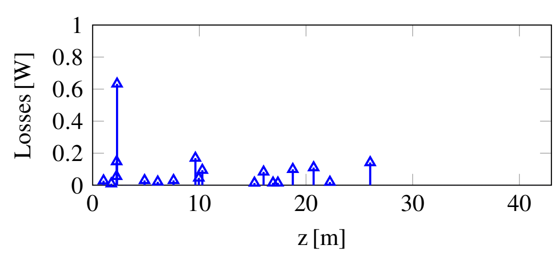

Figure 3: Losses in MEBT and DTL.

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