SIMULATION OF BEAM DYNAMICS INCLUDING SPACE CHARGE IN PROTON LINAC WITH ERRORS*

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Abstract

The LANA computer code (Linear Accelerators Numerical Analysis) has been modified in order to study the effect of random errors on beam dynamics in proton or heavy ion linacs. The standard well known set of different errors of the accelerating and focusing channel including geometry misalignments in all directions, magnetic and electric field imperfections and accelerating field instabilities are simulated. Partial as well as cooperative effects of the errors are analyzed. The LANA code includes space charge forces in the beam, using certain approximations. A comparison of the errors effect on the beam parameters with and without space charge in the 30 mA proton linac is presented. As was found the error effect on beam dynamics is a main contribution on halo formation as well as on beam losses.

1 INTRODUCTION

The present research has been done as part of the conceptual design of the 400 MeV proton linac for JHF at KEK, Tsukuba [1]. The linac includes an RFQ, MEBT, DTL and CCL. The errors study has been performed for the MEBT-DTL-CCL part of the whole linac – from 3 MeV up to 400 MeV. The CCL operates at the third harmonic of the fundamental frequency of 324 MHz, and a transition from the DTL to CCL occurs at 70 MeV. The structure of the linac has been designed for beam intensity of 30 mA.

This research has been done using LANA code [2], that has been developed in INR, Moscow since 1991. This code has been extensively used during the commissioning and operation of the Moscow Meson Factory linac [3]. LANA was also used during the commissioning of the Fermilab linac upgrade in 1993 [4]. Presently this code is being used at TRIUMF for the ISAC project [5] and at CERN for SPL design [6].

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2 MODEL

The errors which influence the beam dynamics in linacs can be divided into three groups [7]. Beam related errors, e.g. displacements of the beam with respect to the accelerator axis, mismatched beam in phase space, energy shift and spread, etc, compose the first group. Only errors of the displacements of the beam were considered in this study, taking into account the periodical steering of the beam position.

The second group of errors include time-independent (slow) errors - misalignments, e.g. tanks and drift tubes length and positioning, quads gradients, length and positioning, accelerating field flatness and setting of the amplitude and phase during the tune-up procedures, etc. A full set of this kind of errors is considered in this work.

The third group of errors consists of time-dependent (fast) errors – instabilities, e.g. amplitude and phase from the rf source, mechanical vibrational errors, field distortion due to transient beam loading, etc. This group of errors is responsible for the jitter in the beam. Only the accelerating field amplitude and phase instabilities were considered during this study as the major errors of this kind.

A simplified space charge model of the beam is used in LANA. This is a model based on the analytic relations between the charge density and the space charge electric fields for a distribution with 3-D ellipsoidal symmetry in real space [8]. Therefore this model can be applied to bunched beams only.

When doing error studies LANA provides the following values at the end of every accelerating cell in the cavity or every intertank element, e.g. drifts or quads: the transverse coordinates and derivatives of the beam center; the longitudinal average phase and energy of the bunched beam; the maximal radial extent of the beam; vertical and horizontal maximal and rms sizes of the beam; phase and energy maximal and rms spreads; the normalized rms emittances and the normalized emittances containing 99% particles in all 3 dimensions; and a number of other quantities of interest. A well known set of different errors in the linac were simulated during this study. Table 1 shows the tolerance limits for all simulated errors which are the maxima of the allowed deviations of the corresponding variables, uniformly distributed around its design value. The rms value of errors is 3 times less than the values listed in the table 1.

Table 1: Maximal tolerances limits

Error Type	Tolerance Limit
1. Transverse beam displacement	500 µm
2. tilt	1 mrad
3. CCL section length	100 µm
4. alignment	100 µm
5. Drift tube length	100 µm
6. alignment	100 µm
7. Quadrupole gradient	1.5 %
8. Length	100 µm
9. Alignment	100 µm
10. Displacement	50 µm
11. Tilt	0.5 mrad
12. Rotation	10 mrad
13. Field difference between CCL sections in amplitude	1 %
14. in phase	1 °
15. Non-flatness of the accelerated field in the cavity	3 %
Average accelerating field amplitude over DTL or CCL tank:	
16. tune-up	3 %
17. instability	1 %
Phase difference between neighbor cavities:	
18. tune-up	3 °
19. instability	1 °

The errors of the first group (1. and 2.) were applied at the entrance of each section where the steering of the beam is provided after the centering the actual position of the beam.

3 COMPARISON OF THE PARTIAL CONTRIBUTION OF DIFFERENT SETS OF ERRORS

Five different sets of errors were considered in this study:

1. All errors listed in Table 1.
2. All errors, except the 17th and 19th – the instability errors.
3. RF system errors only, i.e. from 13th to 19th.
4. RF system errors except instabilities errors.
5. Geometry misalignments, quad errors and beam mismatches, i.e. from 1st to 12th.

All these simulations were performed both with and without space charge effects taken into account.

Figs. 1, 2 and 3 presents the results of the 1st set of error simulations, listed above. It could be seen in Fig. 1 that the space charge effects have a smaller impact on the maximal beam radius growth compared to the error effect. The error effect for the beam without space charge gives approximately a factor of 4 in the maximal beam radius growth, but the space charge effect gives approximately a factor of 3 for the beam without errors and a factor of 2 – with errors for the simulated number of particles ~1200.

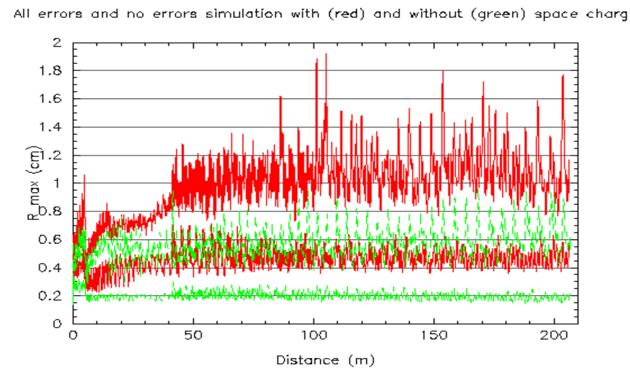

Figure 1. Evolution of the maximal beam radius along the linac with errors (upper lines) and without errors (i.e. design linac) with space charge (solid lines) and without space charge (dashed lines).

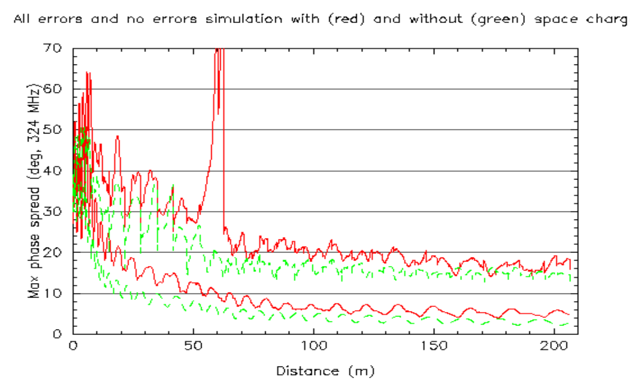

Figure 2. Evolution of the maximal phase spread along the linac with errors (upper lines) and without errors (i.e. design linac) with space charge (solid lines) and without space charge (dashed lines).

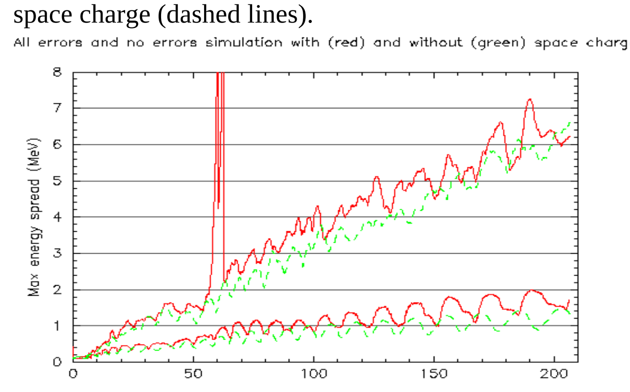

Figure 3. Evolution of the maximal energy spread along the linac with errors (upper lines) and without errors (i.e. design linac) with space charge (solid lines) and without space charge (dashed lines).

The interesting result is that the relative effect of the errors is smaller in the case of a charged beam (~3 times growth of the maximal beam radius) compared to the case of a non-charged beam (~4 times growth of the same parameter).

The halo formation process could not be studied in detail because of the limited number of particles used for the statistical simulations. But in some cases of charged beam simulation where the field instabilities were included a few particles were lost. These losses indicate intensive halo formation induced by instabilities of the accelerating field.

4 PROBABILITY ANALYSIS

The probability distributions of the maximal beam radius and the longitudinal effective emittance, containing 99% of particles, are presented in Figures 4 and 5 respectively. These figures show the probabilities for simulations without space charge for 400 and 100 random errors samples. Also the probability distributions of the simulations with space charge for 100 errors samples are shown on the same figure in a different scale.

The detailed consideration of the probability distributions, which could not be discussed here because of the limited space, show that the statistics of 400 errors samples is good enough for the transverse beam parameter study and reasonable for the longitudinal ones. The 100 errors samples analysis shows good qualitative results, but insufficiently reliable quantitative ones.

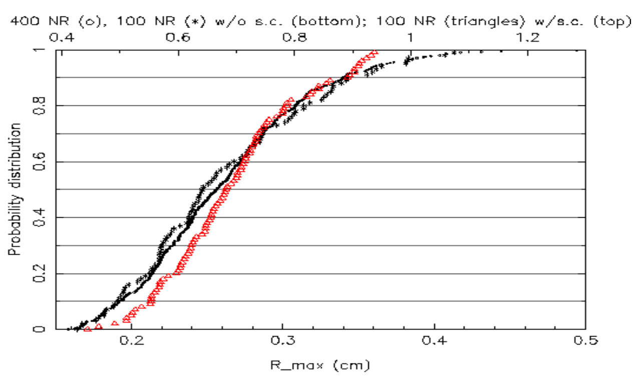

Figure 4. Probability distribution of the maximum beam radius from 400 NR (dots), 100 NR (asterisks) without space charge; and from 100 NR (triangles, upper scale) with space charge.

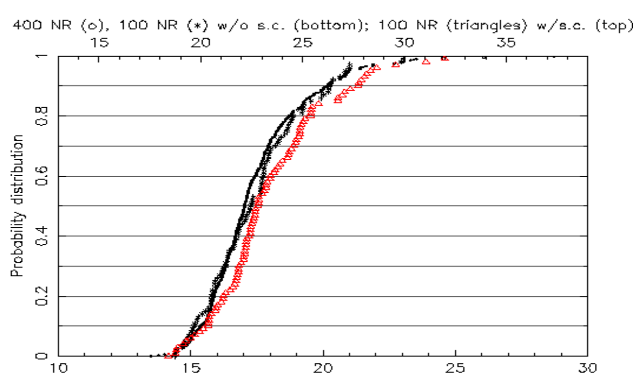

Figure 5. Same as in Figure 4, but for the longitudinal effective emittance, containing 99% of particles.

5 CONCLUSIONS

The time-consumptive calculations that were done for the statistical analysis of the errors influence on the charged beam dynamics provide interesting results and emphasizes the problem of halo formation which is not the subject of the present article. Though in the conclusion of this study we would like to state that the halo formation takes place in the regions of the non-adiabatic changes of the linac main parameters and is induced by the instabilities of the accelerating field.

The probability distributions study confirms that the number of samples for such a study could be chosen to be about 200-300 for the transverse beam dynamics and about 400-500 for the longitudinal ones.

These studies show that the given values of the tolerance limits (table 1) could be recommended in order to meet the requirements of low losses in the linac.

While the most sensitive error for the transverse emittance growth is quad rotations, the one for the longitudinal dynamics is the accelerating field instability.

The relative increase of the maximum beam radius is smaller in the case of the charged beam simulation compared to the relative growth of this quantity in the non-charged beam simulation. Nevertheless the cooperative effect of space charge and the errors could lead to halo formation if no special care is provided to control this process.

6 REFERENCES

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