EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN — AB DEPARTMENT

AB-Note-2007-033 ABP

Loss Control and Steering Strategy for the CERN LINAC4

A.M. Lombardi, J.B. Lallement, E. Sargsyan, S. Lanzone, G. Bellodi, M. Eshraqi, B. Hadorn

Abstract

A series of runs with the aim of defining alignment and gradient tolerances for the quadrupoles have been performed on the LINAC4 reference layout. The results, the implication on the machine layout and the correction schemes are reported in this paper.

Geneva, Switzerland

July, 2007

1. Introduction and motivation

One of the challenges in the design of modern high power LINACS is the prediction and –possibly- the control of the beam losses. The challenge raises from two sides: on one hand in order to map the losses with sufficient precision a number of particles at the limit of computing capability is necessary, on the other hand as the losses are mostly induced by machine errors (static errors and jitters) a large number of runs are necessary to have a good enough statistics for sensible predictions. The alternative is to design the machine with a generous ratio between the bore aperture and the beam size, to demand very tight machining and regulation tolerances and to design the shielding for heavy beam losses. This approach, i.e. to over-design, leads to very high cost and to heavy irradiation of the accelerator components which in turn excludes hands-on maintenance.

For LINAC4 **[1]**, we have decided to invest some effort in balancing aperture, loss control, machining and alignment tolerances and use of corrective elements. The duty cycle of LINAC4 is 0.1% when used as injector to the PS Booster but it grows to 3-4% if we consider its potential use as front-end of a high power proton driver like the Superconducting Proton Linac (SPL) **[2]** . The efforts of this study are in view of LINAC4 also as pre-accelerator of a Multi-Megawatt proton driver.

1.1. Reference layout

The layout of LINAC4 is sketched in Figure 1. It consists of a RF volume source (identical to the one in DESY) which provides an H- beam at 35 keV further post-accelerated to 95 keV. The first RF acceleration (from 95 keV to 3 MeV) is done by a Radio Frequency Quadrupole (the IPHI RFQ from CEA **[3]**). The RFQ resonates at 352 MHz, is 6 m long and it is powered by a 1 MW Klystron.

At 3 MeV the beam enters a 3.6 meter long chopper line, consisting of 11 quadrupoles, 3 bunchers and two sets of deflecting plates. This system has the capability of removing micro-bunches on the RF scale and rematching the beam to the subsequent system of accelerators. A rudimentary collimation is also performed in this line.

The beam is then further accelerated to 40 MeV in a conventional Drift Tube Linac at 352 MHz. The DTL, subdivided in 3 tanks, is 13.4 meters long and it is powered by 5 klystrons with a total power of 4 MW. Each of the 82 drift tubes is equipped with a Permanent Magnet Quadrupole.

At 40 MeV the velocity of the beam is such as to allow the transition to structures which do not follow cell-by-cell the beam velocity profile. In LINAC4 the acceleration from 40 to 90 MeV is provided by a Cell-Coupled Drift Tube Linac at 352 MHz. The CCDTL is made of 24 tanks of 3 cells each with a total length of 25.3 meters. Three tanks are powered by the same klystron, for a total of 8 klystrons delivering 6.5 MW. The focusing is provided by electromagnetic quadrupoles placed outside each tank.

The acceleration from 90 to 160 MeV is done in a Side Coupled Linac resonating at 704 MHz. The SCL is made of 20 tanks of 11 cells each with a total length of 28 m, powered by 4 klystrons delivering 12 MW. Focusing is provided by 20 electromagnetic quadrupoles.

This brings the total length of the Linac to 80 m, for a total of 18 klystrons, 55 electromagnetic quadrupoles and 82 permanent magnet quadrupoles.

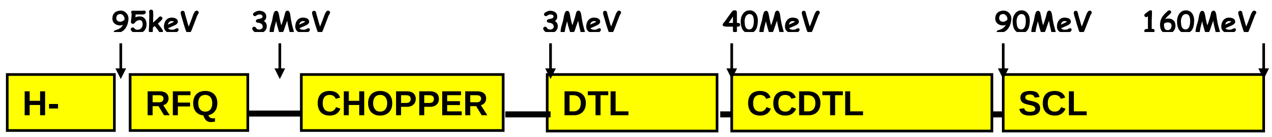


Figure 1 Schematic layout of LINAC4.

The end-to-end beam dynamics for the nominal beam and nominal LINAC, i.e. for a matched beam and no machine errors has been reported in reference **[4]** . The overall transverse emittance growth is 40% and the losses are 10%, mostly located in the 3 MeV chopper dump. On this reference layout a sensitivity study has been performed.

1.2. Calculations tools

The reference layout has been calculated both with the code Tracewin **[5]** and PATH **[6]** . The beam dynamics calculation results are the same with the two codes **[7]**, which can therefore be equivalently used. In the same conditions, the two codes give the same results for error studies, within statistical accuracy, the main difference between them lying in the steering procedure and the input/output information.
Therefore each case has been run with the code more appropriate for the task.

1.3. Definition of errors

The errors in this study are only applied to the magnetic elements (quadrupoles) and fall into 3 categories:

Gradient errors: expressed in percentage, they represent the deviation from the nominal field.
Transverse position errors : expressed in mm they represent the distance between the centre of the magnet and the ideal centre of the beam line in the two transverse planes.
Angle errors : expressed in degrees they represent the 3 angles between the ideal beam line reference and the system in which the magnet is a perfect quadrupole. A sketch in Figure 2 shows the convention adopted in the calculations.

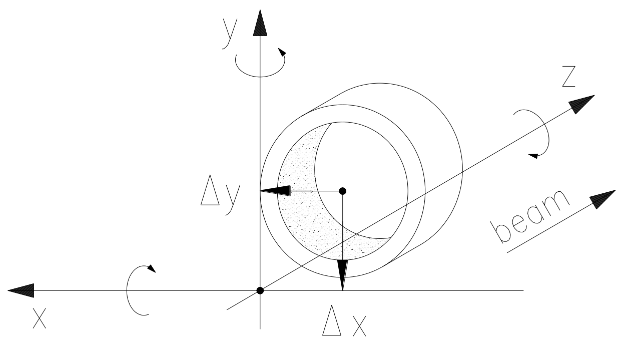


Figure 2 Definition of position and angle errors.

The error distribution can be either Gaussian (cut at 3 sigmas) or uniform. It is very difficult to predict the error distribution and from magnet experts and mechanical engineers we only have indications on the maximum value of the errors, with no information on their distribution. Unless otherwise indicated we have assumed a uniform distribution.

1.4. Quality factors and chosen limits

Errors in the focusing elements (gradient and position) cause beam losses, emittance growth and trajectory errors. The most important parameter to control is the beam losses, because of the potential irradiation of the machine and the correct dimensioning of the shielding. Second in priority is the emittance increase that should be limited in order not to compromise the quality of the beam delivered to the PS-Booster or to the SPL. Finally, the excursion of the beam centre should be limited in order to limit the number and strength of the steerers, and to avoid moving into the "bad field" area of the magnetic elements.
A compromise must be made between accepting losses and emittance degradation and requiring mechanical tolerances that are beyond the technological limit for machining and positioning within reasonable budget expenses. In our case we have established that errors are acceptable if their effect does not exceed the following limits:

1) Maximum average losses of 1 W/m at SPL duty cycle, 5%. This is dictated by shielding requirements.
2) Maximum localised losses (within 10 cm) of 0.1 W at SPL duty cycle, 5%. This allows hands-on maintenance.

3) Emittance growth of 15-20% (at 2 sigma) with respect to the nominal case. This value is well within the emittance budget of the PS-Booster.

1.5. Calculation procedure

The first goal of the error study is to define the alignment tolerances. We assume that alignment (position and rotation errors) and quadrupole gradient errors should be defined so that their effect on the beam is acceptable, i.e. within the limits defined above. Alignment and gradient errors having a larger effect than what defined in the previous paragraph are to be avoided during construction and installation. No corrective elements have been used during this evaluation phase.
The process to define the errors is in fact not so straightforward and a compromise between ideal tolerance and machining reality has to be made. This part entailed several iterations and discussions with the drawing office and engineers.
During the study we have assigned errors only in the x plane. We have previously checked that the x and y plane are fully independent and symmetric. By assigning errors in one plane only we can keep track of the particles that are lost in the other plane and have an idea of the halo particles that should be collimated out and that are generated by beam mismatch and not machine mis-match. All the loss values reported in this paper correspond to error in one transverse plane only. The losses are calculated at the LINAC4 duty cycle, unless otherwise indicated.

The second goal of this error study calculation is to define the number, power and location of the corrective elements (steerers) and the corresponding diagnostic elements (position pick-ups and profile monitors). In this set of runs a beam misalignment is introduced, in addition to the elements' misalignment, and corrective elements are switched on. The initial beam misalignment comes from an "educated guess", i.e. taking an error of 1mm and 1 mrad at the low energy end (3 MeV) and propagating it through the entire structure. This value, even though arbitrary, reflects typical accuracy of the beam profile monitors and steering at the source and first stage of acceleration. These error studies are carried out in two steps: first some 1000-2000 cases are run with machine and beam errors and the output beam characteristics are recorded for each run together with the errors generated. Then a set of the10 worst cases is selected, based on transmission or emittance growth. Steerers are applied on these selected cases and they are set to the values that would minimise the beam centre excursion at the locations of the given diagnostics. If the solution does not converge (i.e. it doesn't steer the beam back on axis to limit losses to the target values) the position of the steerers and/or diagnostics is changed and the process reiterated.

The third goal , which is work in progress and outside the scope of this paper, is to use the results of the above to define a collimation strategy, in order to remove from the beam at the lowest possible energy the particles that , under the influence of machine errors, would be bound to be lost.

2. Losses and emittance control in presence of machine errors: definition of the acceptable machine errors.

2.1. DTL

The reference DTL is composed of three RF tanks (3-10 MeV, 10-25MeV and 25-40 MeV) with a total of 86 quadrupoles, 82 housed in a drift tube and 4 placed in the inter-tank space. The required alignment of the quadrupoles has an effect not only on the accuracy of the magnetic centre of the magnet itself, but also on the drift tube machining tolerances, positioning and alignment technique. The effects of quadrupole misalignment are emittance increase and/or loss in transmission, due to reduced effective aperture in case of drift tube misalignment and to the orbit excursion induced by the dipole component of a misaligned quadrupole. Although 4 quadrupoles out of 86 are not placed in a drift tube, a distinction for the alignment procedure has not been made. The alignment precision for a quadrupole inside a drift tube was estimated to be between ±0.1 mm and ±0.2 mm **[8]**. It is not clear today which type of distribution the positioning errors would follow and therefore several runs have been done with a uniform and a Gaussian distribution. Together with these alignment errors, a 0.5% gradient error and an error on the angles of 0.2 degrees have been assigned (the latter ones do not have a significant effect).

Transverse error studies on the DTL have been performed both with TRACEWIN and with PATH, and the results from the PATH runs are summarised in Table 1. Runs are carried out with a beam of 50k particles coming from the RFQ, i.e. having already developed some halo. The full beam power at maximum energy is 1600 W (1 particle= 0.03W). 800 runs have been made for each case, except for the last one (±0.2mm 3σ Gaussian distribution) where 2000 cases have been run. The power losses have been calculated assuming a beam average current of 40 mA and a duty cycle of 10^{-3}. This value assumes the 70 mA nominal micro-bunch current of LINAC4, a chopping beam-on factor of 57% and the PS booster duty cycle. No safety margin is assumed in the values below. The maximum power loss quoted in the table is the absolute maximum over the 800 runs whereas the average is the mean over the lossy runs. The 5th column, i.e. the number of runs with losses below 0.25 watts, is significant since it shows the number of runs that would give losses below the 1 W/m level even at SPL duty cycle (50 times more than LINAC4). The 6th column shows the average of the output rms-emittance increase and the 7th column the average plus 2 sigma. The emittance increase is computed with respect to the rms normalised emittance at the DTL output in the unperturbed case (equal to 3.48 10^{-7} m rad).

Table 1
Effect of quadrupole misalignment on losses and emittance growth in the DTl, statistics over 800 runs and 50k particle/run. Power losses are calculated at the PS-Booster duty cycle.

Quad mis-alignment (mm)	% of lossy runs	Max power lost (watt)	Average power lost (watt)	Percentage of lossy runs with losses below 0.25watt	Average Rms-emitt increase	Δε_rms Average+2 sigma
±0.1 uniform	33%	0.25	0.04	100%	4.2 %	11%
±0.15 uniform	65%	25	0.15	92%	9.0%	21%
±0.2 uniform	85%	253	2.61	70%	14.3%	31 %
±0.2 3σ Gaussian	51%	1.6	0.06	97%	6.3%	16%

From the results above it is clear that an alignment tolerance of ±0.2 mm is not acceptable because of the high emittance increase and very high losses, which will be unsustainable at SPL duty cycle. An alignment of ±0.15 mm is at the limit of acceptance and considering that there is no safety margin in the data above, should be excluded as well. Therefore the alignment of the quadrupoles should be targeted at ±0.1mm with, at the limit, only a few drift tubes should be more than ±0.1 mm off. The results of the Gaussian distribution (3 σ=0.2 mm, i.e. 65% of quadrupoles are within ±0.07 mm) show that we should allow a maximum of 15 drift tubes with a misalignment bigger than ±0.14 mm.

The situation is less critical for the tank-to tank alignment. Following a request of the mechanical engineer/survey team we have allowed ±0.2 mm between tanks, assuming the quadrupoles inside the tanks are aligned to better than ±0.1 mm. The results over 800 runs and 50k particles are summarised in Table2.

Table 2
Effect of tank misalignment on losses and emittance growth, statistics over 800 runs, 50k particles/run. The quadrupoles inside the tank are aligned to ±0.1mm.

Tank alignment (mm)	% of lossy runs	Max power lost (watt)	Average power lost (watt)	Percentage of lossy runs with losses below 0.25watt	Average Rms-emitt increase	Δε_rms Average+2 sigma
±0.1 uniform	36%	0.9	0.04	99.6%	4.2%	11%
±0.2 uniform	40%	0.4	0.04	99%	4.6%	12%

In conclusion, the alignment of the quadrupoles with respect to the beam axis should be better than ±0.1mm but each DTL tank as a whole can be aligned to better than ±0.2mm.

2.2. CCDTL

In the CCDTL the alignment of the quadrupoles is independent of the alignment and machining tolerances of the RF structures and therefore precise alignment is relatively easier. The bore aperture of the CCDTL is also 1.4 times the DTL one, once again easing the transverse tolerances. The errors are applied to the gradient (±0.5% of the nominal value) and to the quadrupole's transverse position (±0.1 mm and ±0.2 mm). The full beam power at maximum energy is 3600 Watts.
The effects on losses and emittance growth in the CCDTL are reported in Table 3. The results are calculated over 1200 runs with 50k particles/run and the emittance increase is calculated with respect to the rms normalised emittance at the CCDTL output in the unperturbed case (equal to $3.55\ 10^{-7}$ m rad).

Table 3
Effect of quadrupole misalignment and gradient errors on losses and emittance growth in the CCDTL, statistics over 1200 runs, 50k particles/run.

quadrupole alignment (mm)	% of lossy runs	Max power lost (watt)	Average power lost (watt)	Percentage of lossy runs with losses below 0.25watt	Average Rms-emitt increase	Δε_rms Average+2 sigma
±0.1 uniform	58%	0.35	0.08	99%	0.5%	1.4%
±0.2 uniform	81%	1.9	0.21	75%	1.5%	3.5%

The effect on the CCDTL emittance seems to be under control, also with alignment tolerances twice as much what has been estimated by the mechanical engineers **[8]**. It is remarkable that the losses are mostly localised in the last quadrupole of the CCDTL, where the phase advance is changed in order to match to the next structure. Figure 3 shows the loss map for both sets of errors (±0.1 mm and ±0.2 mm).

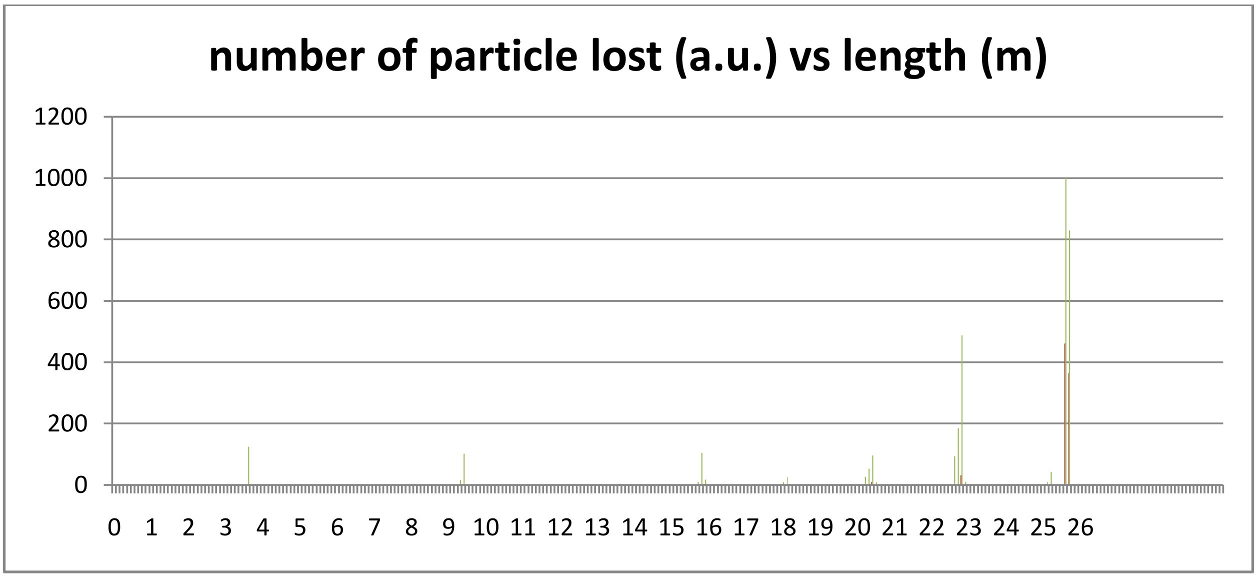


Figure 3 Localisation of losses in the CCDTL, in red the ±0.1 mm case, in green the ±0.2 mm.

A tolerance on the alignment of the quadrupoles in the CCDTL at ±0.1 mm has virtually no impact on the emittance increase and generates losses that are acceptable also at SPL duty cycle. An alignment at ±0.2 mm is still acceptable from the point of view of emittance increase although it would generate losses at the limit of what is acceptable at a SPL duty cycle. The highest losses in both cases are mostly localised in the last quadrupole of the machine.

2.3. SCL

Alignment issues in the SCL are very similar to the CCDTL's. The errors are applied to the gradient (±0.5% of the nominal value) and to the quadrupoles transverse position (±0.1 mm and ±0.2 mm). The study was performed with 500k particles in order to have a more precise mapping of the losses. The full SCL beam at the highest energy (40 mA, 160 MeV) carries 6400 W beam power at the LINAC4 duty cycle (0.1%) and 320 kW at the SPL duty cycle (5%) and therefore a high number of particles is necessary to avoid overestimating the localised losses.

There are losses in the SCL also in the nominal unperturbed case due to halo particles developed during the acceleration between 95 keV and 90 MeV. The losses in the unperturbed case are at the level of $4\ 10^{-6}$ and they account for 0.014 W of power lost. Results of the error studies are reported in Table 4. The results are calculated over 1000 runs with 500k particles each and the emittance increase is calculated with respect to the rms normalised emittance at the SCL output in the unperturbed case (equal to $3.8\ 10^{-7}$ m rad).

Table 4
Effect of quadrupole misalignment and gradient errors on losses and emittance growth in the SCL, statistics over 1000 runs, 500k particles/run.

quadrupole alignment (mm)	% of lossy runs	Max power lost (watt)	Average power lost (watt)	Percentage of lossy runs with losses below 0.25watt	Average Rms-emitt increase	Δε_rms Average+2 sigma
±0.1 uniform	100%	0.1	0.02	100%	0.5%	1.3%
±0.2 uniform	100%	0.8	0.05	99.7%	1.7%	4.5%

Losses in the SCL are localised in the quadrupoles, and the transverse coordinates of the lost particles as a function of their location along the SCL are shown in Figure 4. One can identify the particles that would be lost also in a perfect machine; they are the one that are lost because they exceed the bore aperture in the transverse plane where there are no errors (y-plane). These particles, which contribute to more than 50 % of the average power lost, could possibly be collimated out at lower energy.

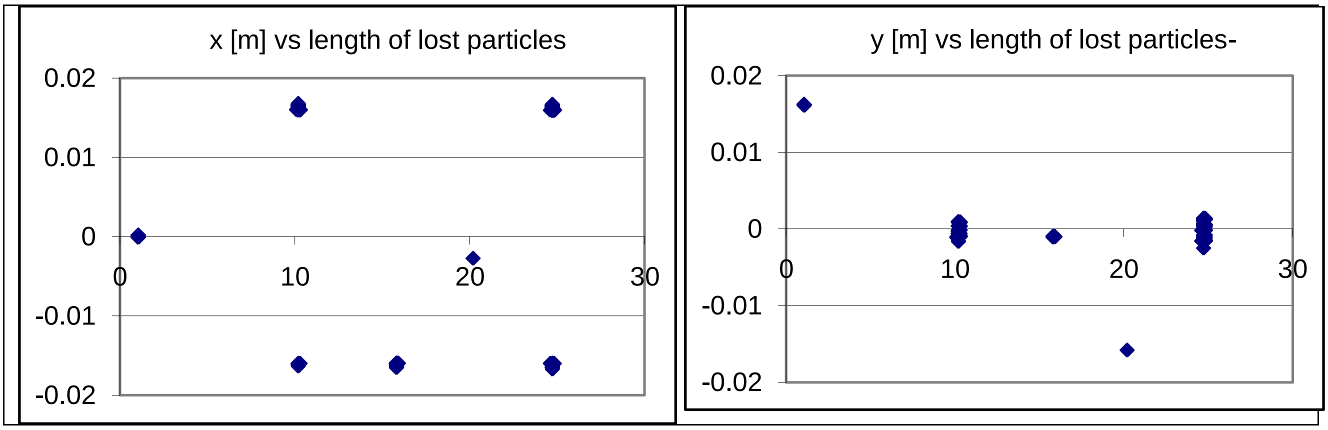


Figure 4 Transverse coordinates of lost particles in the SCL. Total of 1000 runs.

For the SCL an alignment of 0.1 mm is preferred although 0.2 mm is acceptable at PS-Booster duty cycle.

3. Losses and emittance control in presence of beam errors: definition of correcting elements.

Unexpected beam alignment errors are another source of losses and emittance growth in a LINAC. Ideally these beam errors are small and can be controlled but in all existing machines remnant beam alignment errors at the level of 0.5 mm and 1 mrad are typical at the low energy end and they are usually one order of magnitude higher than the achievable alignment tolerances. In order to cope with any unexpected beam alignment error a set of correcting elements to change the beam centre divergence (steerers dipoles) and diagnostic elements to record the beam centre position (called from now-on "screen") are installed in the machine. In the low energy end of LINAC4 (Chopper and DTL) the combination of space charge, low energy and a frequency of 352MHz calls for a design as compact as possible and therefore availability of space for placing steerers and screens is an issue. The purpose of the work reported in this chapter is to determine the number and strength of steerers and the number of screens necessary to match or exceed the performance of LINAC4 in presence of machine errors (but with no beam errors), basically following the guidelines of paragraph 1.4 .
The nominal steerers can provide an integrated field of 3.9 mT m, corresponding to a kick from 10 to 2 mrad in the energy range from 3 to 160 MeV.
The remnant centre position errors assumed in this study are reported in Table 5. These values are an educated guess based on the remnant beam centre position of the study reported in the previous chapter.

Table 5
Remnant beam centre position assumed.

	Sigma-x (mm)	Sigma-xp (mrad)
DTL	0.3	0.3
CCDTL	0.9	0.9
SCL	0.5	0.4

3.1. DTL

We have run the DTL with machine errors (±0.1mm alignment, ±0.5% gradient error) and with beam errors on a Gaussian distributions cut at 3 sigma, with 1 sigma equal to 0.3 mm and 0.3 mrad respectively. The effect on the beam is an average emittance increase of 9% and a emittance increase at 2 sigma of 23%. These values are about twice as much what is observed in presence of machine errors and they exceed the limits. 45% of the runs show losses, with a maximum power lost of 1.2 Watts. Although this value is within the 1 watt/m limit, it is nevertheless important to have steerers to control and limit the losses. In the present design there is not enough space in the intertank region to place steerers. The DTL, together with the other structures, is being redesigned and a longer drift between the tanks (2βλ instead of 1 βλ) will be left to install steerers **[10]**. The losses occur mostly at the transition between tank1 and tank2 and in tank3 (Figure 5). Tank2 turns out to be remarkably stable with respect to misalignment.

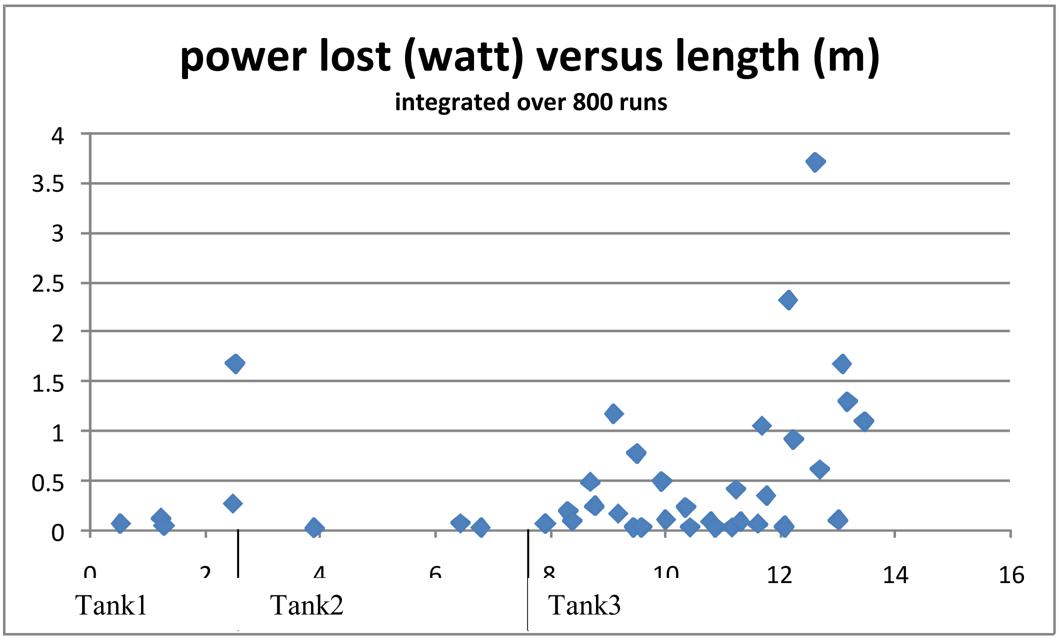


Figure 5 Location of the losses in the DTL in presence of machine and beam errors. Integral over 800 runs, 50kparticle/run

3.2. CCDTL

We have run the CCDTL with machine errors (±0.1mm alignment, ±0.5% gradient error) and with beam errors as expected in Table 5 (Gaussian distributions cut at 3 sigma, with 1 sigma equal to 0.9 mm and 0.9 mrad respectively). The effects on the transmission and on the emittance growth are catastrophic, with losses in every run, and losses as high as 60% of the beam. In only 11% of the runs the losses would be less than 1 W /m also at LINAC4 duty cycle. The losses as a function of run number are shown in Figure 6 for a statistics of 1500 runs and 50k particles/run. The rms emittance growth (at 2 sigma) is 24%.

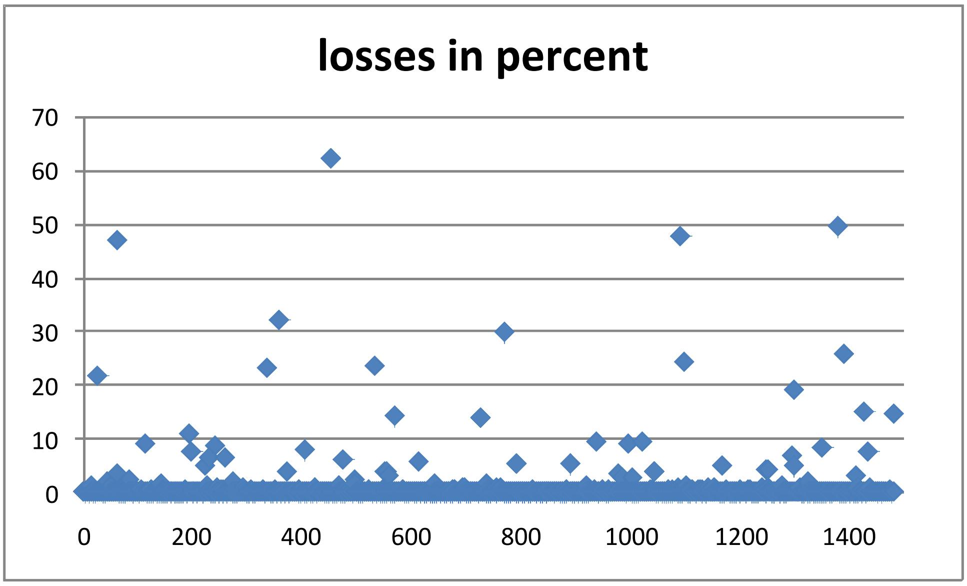


Figure 6 Losses in the CCDTL in presence of machine and beam errors

A set of 8 steerers with a maximum integrated field of 3.9 mTesla m and 8 screens, placed after each module, turned out to be necessary to recover transmission. Their effect on the case with the highest losses is shown in Figure 7. An automated procedure sets the values of the steerers in order to minimise the beam misalignment at the screen. This same procedure can be used on a real accelerator. Figure 8 shows the trajectories after steering and in presence of machine errors for the eight worst cases. It is demonstrated that the steering corrects not only for beam errors but also for machine errors. Localised losses are reduced to below 0.08 W (Figure 9). This value should be further reduced for SPL operation. A study of a new optics to remove this hot spot is necessary.

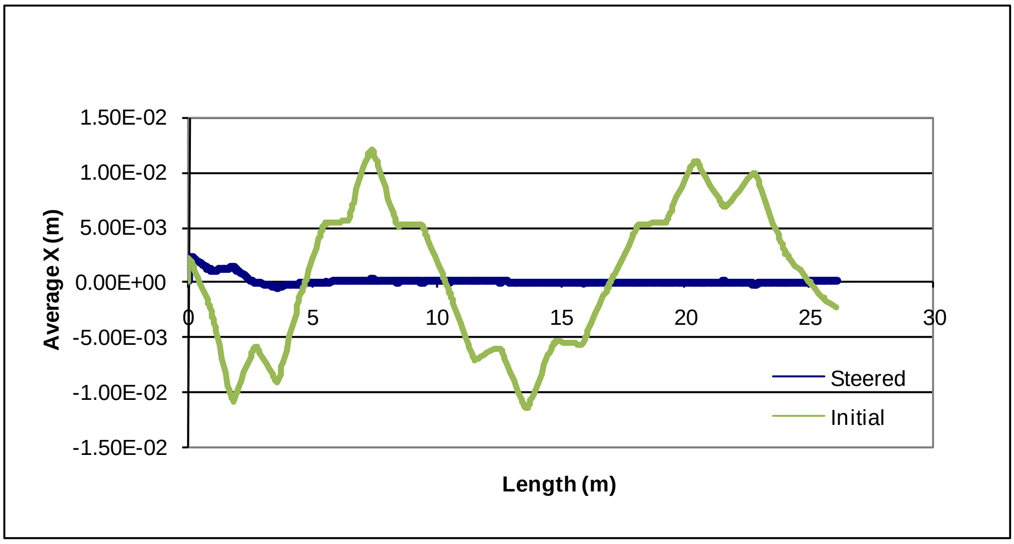


Figure 7 Beam trajectories in the CCDTL before and after steering

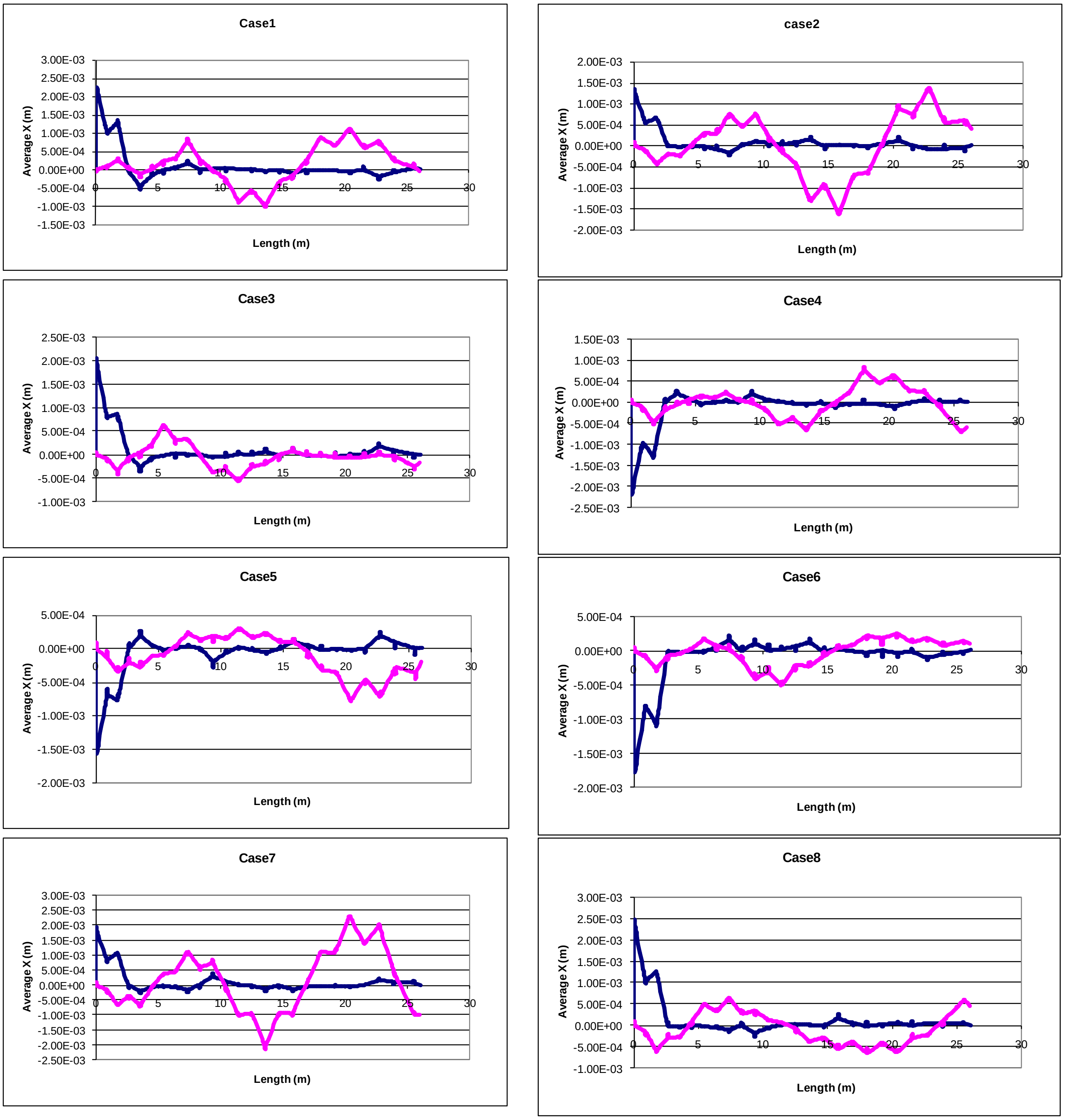


Figure 8 Beam centre position along the CCDTL for the 8 highest loss cases before and after steering (Light/pink : no steerers no beam jitter, Dark/blue : Steering + initial beam jitter)

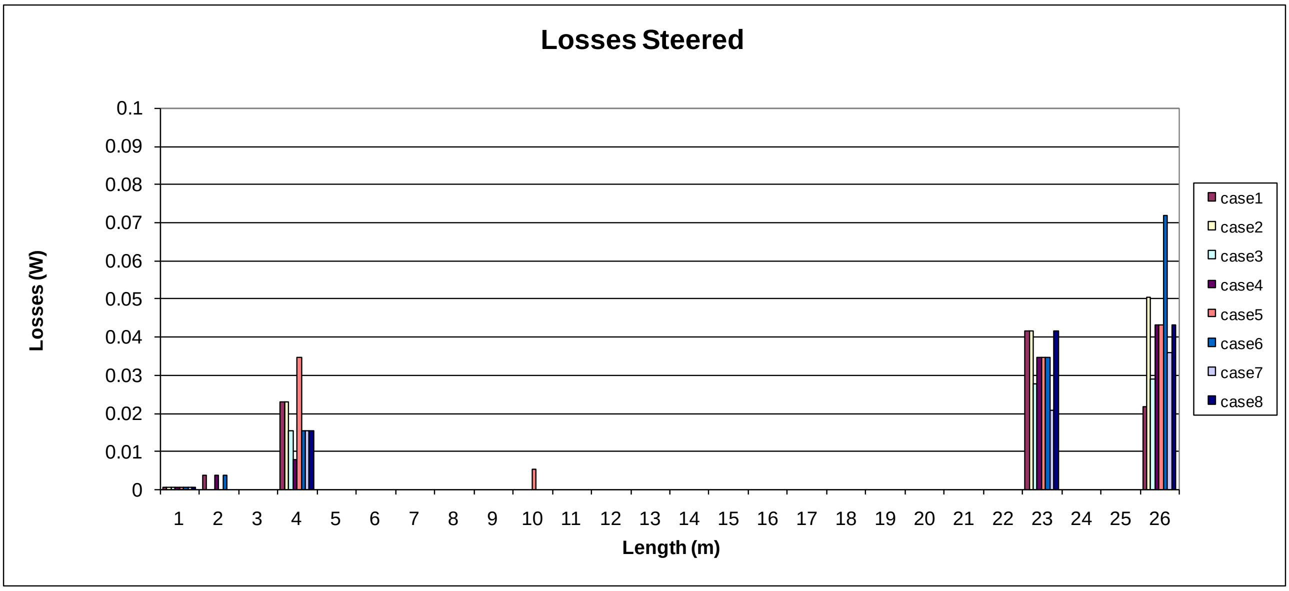


Figure 9 Location of the remnant losses after steering in the CCDTL.

3.3. SCL

We have run the SCL with machine errors (±0.1mm alignment, ±0.5% gradient error) and with beam errors as expected in Table 5 (Gaussian distributions cut at 3 sigma, with 1 sigma equal to 0.5 mm and 0.4 mrad respectively). The effects on transmission are not dramatic, losses are evenly distributed, there are no localised hot spots and the maximum total loss is 0.7 W at the LINAC4 Duty Cycle. The dominant effect of the errors in the SCL is the emittance growth which can be as high as 17% at 2 sigma. A set of 4 steerers and four screens are necessary to avoid the losses and to control emittance growth.

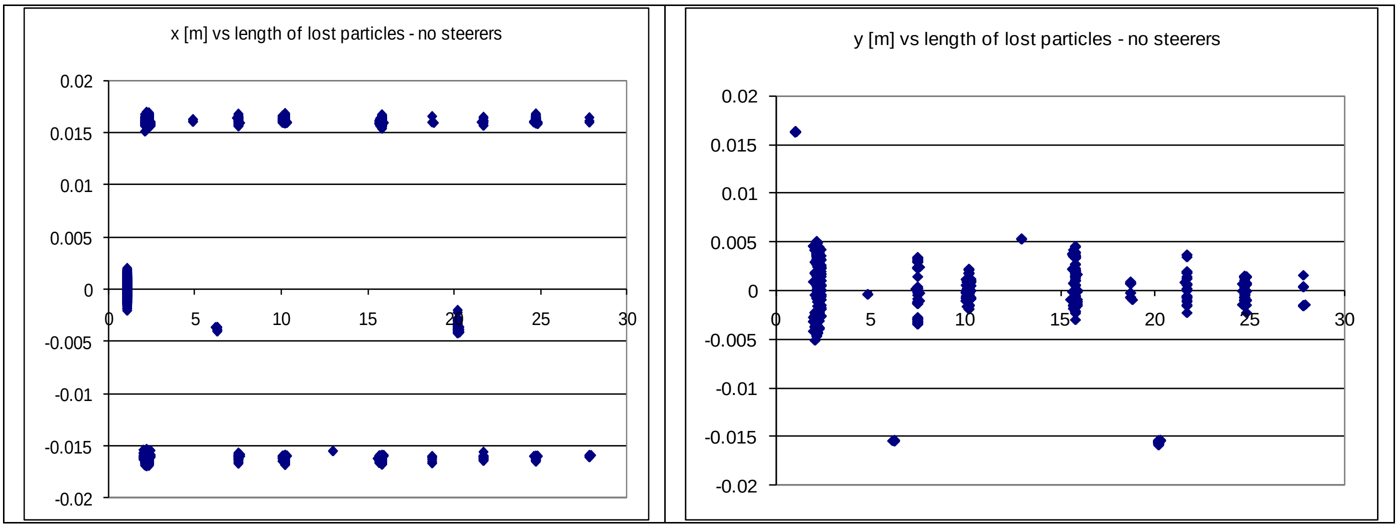


Figure 10 Horozonthal (x) and vertical (y) coordinates of the lost particle in the SCL. Total of 650 runs.

When the four steerers are set at the appropriate value to minimise the centre excursion on the 4 screens the performance is recovered and the remaining losses are 0.015 W. The emittance growth is recovered, as can be seen on Figure 11.

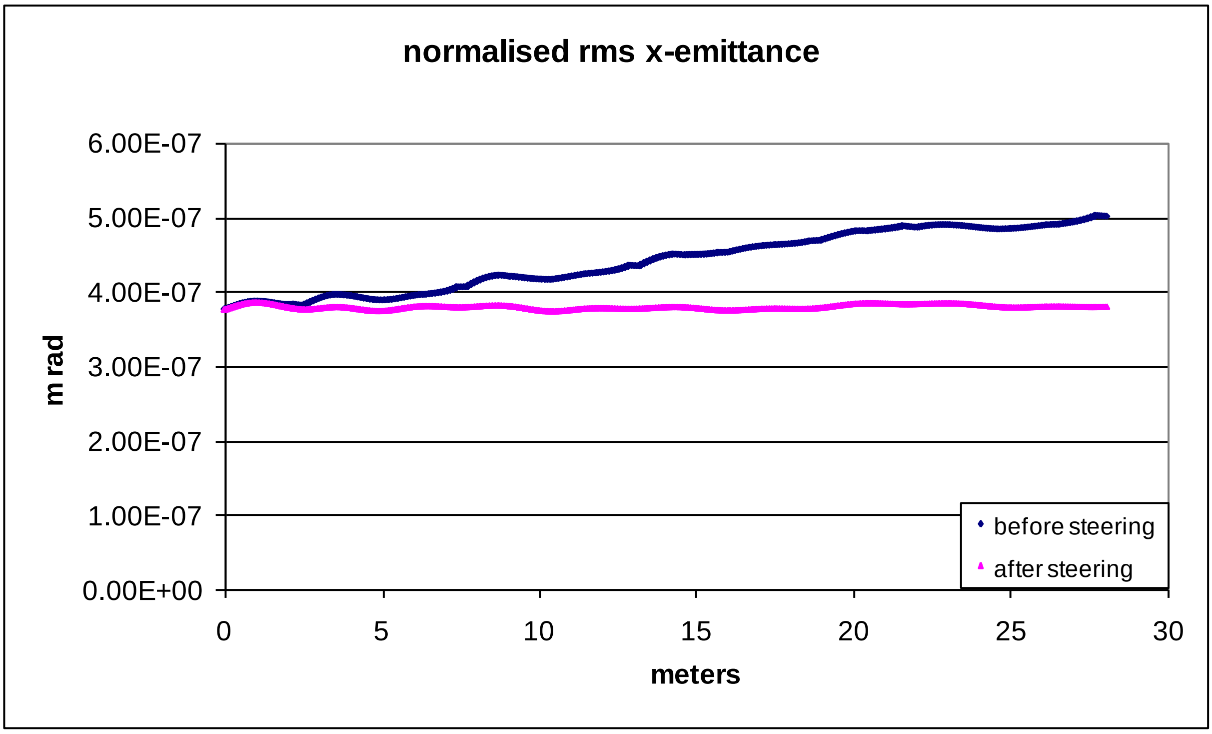


Figure 11 RMS normalised emittance along the SCL in presence of machine and beam errors before and after steering.

4. Conclusions and outlook

By running a series of error studies and evaluating the effect on the beam quality of machine alignment and beam alignment errors, the tolerances for the magnetic element's position and gradient; and the tolerances for the tank's alignment have been defined. Moreover the correction system (steering elements and position monitors) has been defined. The remnant losses are within tolerances at the SPL duty cyle everywhere in the machine except at one spot (transition CCDTL to SCL). Work is in progress to modify the optics and reduce the losses at this point. Moreover this work has highlighted the need for steering in the DTL, and considerations to leave enough space between the tanks are the subject of note in preparation **[10]**. The continuation of this works entails the study of a collimation system, to confine the losses in dedicated places and ideally stop at the lowest possible energies the particles bound to be lost downstream.

5. References

[1] F. Gerigk, M. Vretenar editors, LINAC4 Technical Design Report, CERN-AB-2006-084 ABP/RF
[2] F. Gerigk editor, Conceptual design of the SPL II, a high-power superconducting H- linac at CERN, CERN Report (CERN-2006-006)
[3] P.-Y. Beauvais, Recent evolutions in the design of the french high intensity proton injector (IPHI),Proc. European Particle Accelerator Conf., Lucerne, Switzerland, 2004.
[4] A. Lombardi, E. Sargsyan, S. Lanzone, J-B Lallement, G Bellodi, M. Baylac, R. Duperrier, D.Uriot, End-To-End Beam Dynamics For Cern LINAC4 , Proceedings of the 39th ICFA Advanced

Beam Dynamics Workshop on High Intensity High Brightness Hadron Beams (HB2006), Tsukuba, Japan, May 29 – June 2, 2006
[5] R.Duperrier, N. Pichoff, D. Uriot, "CEA Saclay codes review", ICCS Conference 2002, Amsterdam
[6] A. Perrin, J.-F. Amand, T. Muetze, "Travel User Manual"
[7] S. Lanzone, J.B. Lallement, A. Lombardi, E. Sargsyan, "END-TO-END SIMULATIONS OF LINAC4", AB-Note-2006-033 ABP.
[8] P. Bourquin, Y. Cuvet private communication
[9] M. Baylac, JM de Conto, E. Froidefond, E. Sargsyan, "Statistical Simulations Of Machine Errors For LINAC4", Proceedings of the 39th ICFA Advanced Beam Dynamics Workshop on High Intensity High Brightness Hadron Beams (HB2006), Tsukuba, Japan, May 29 – June 2, 2006
[10] note in preparation.

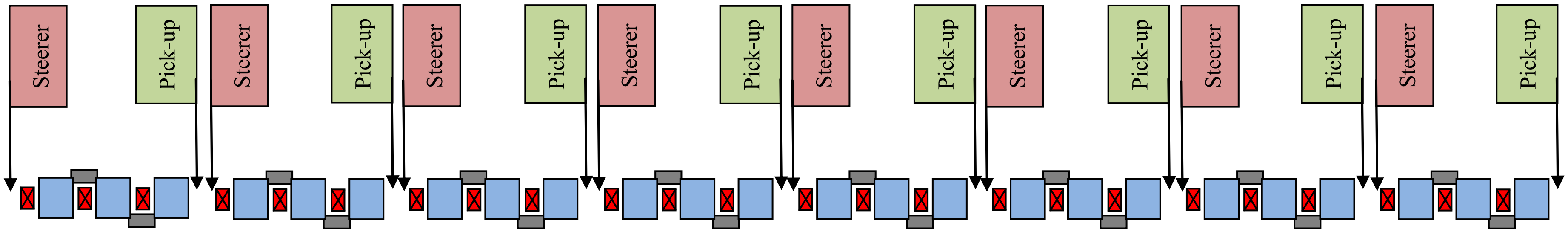
6. APPENDIX 1 – Summary of alignment and gradient tolerances.

DTL	Quad alignment	±0.1 mm	Critical
	Quad rotation (3 planes)	±0.2 deg	Could be relaxed to ±0.5 deg around the x and y axis.
	Gradient	±0.5%	
	Tank-to-tank alignment	±0.2 mm	
CCDTL	Quad alignment	±0.1 mm	Non critical for PS-Booster operation
	Quad rotation (3 planes)	±0.2 deg	Could be relaxed
	Gradient	±0.5%	
SCL	Quad alignment	±0.1 mm	Non critical
	Quad rotation (3 planes)	±0.2 deg	Could be relaxed to ±0.5 deg around the x and y axis.
	Gradient	±0.5%	

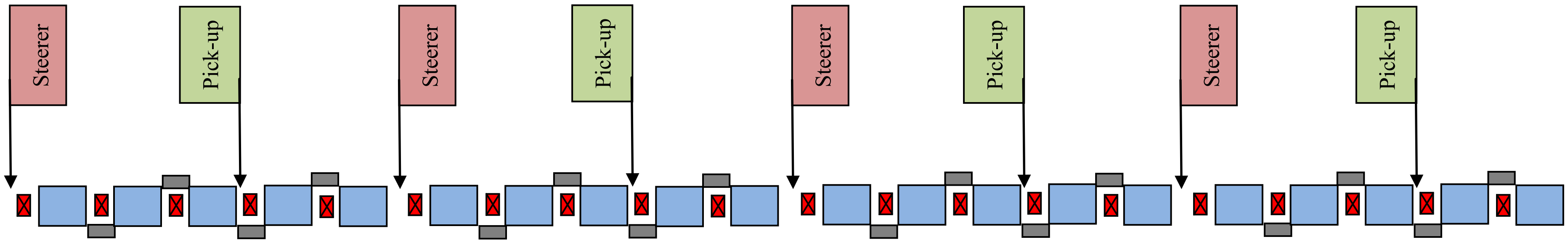
N.B.

We have not investigated whether higher tolerances on the gradient could be acceptable.

7. APPENDIX 2 – Location of steerers and screens in the CCDTL and SCL.



Location of steerers and screens (pick-ups) in the CCDTL



Location of steerers and screens (pick-ups) in the SCL