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Beam loss control in the LINAC4 design

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Summary

The Linac4 DTL reference design has been modified to reduce the power consumption in tank 1 by modifying the accelerating field and phase law. In addition we have adopted an FFDD focusing lattice throughout to minimize expected losses resulting from alignment errors. We have observed, however, that this design suffers from decreasing transverse acceptance and a sensitivity to misalignments that causes any expected beam loss to occur at the high energy end of the DTL. In this note we investigate two solutions to increase the acceptance, decrease its sensitivity to misalignments and eliminate the potential for a beam-loss “bottleneck” at 50 MeV.

1. Introduction.

The LINAC4 DTL reference design has been modified to reduce the power consumption in tank 1 by modifying the accelerating field and phase law. In addition we have adopted an FFDD focusing lattice throughout to minimize expected losses resulting from alignment errors. We have observed, however, that this design suffers from decreasing transverse acceptance and a sensitivity to misalignments that causes any expected beam loss to occur at the high energy end of the DTL. In this note we investigate two solutions to increase the acceptance, decrease its sensitivity to misalignments and eliminate the potential for a beam-loss “bottleneck” at 50 MeV.

The DTL has a constant drift-tube bore diameter of 20 mm throughout. Because the quadrupole strengths are monotonically decreasing throughout the linac, the beam size increases with β , effectively reducing the acceptance. One common design philosophy is to increase the drift-tube bore diameter in the higher energy tanks. A second common philosophy is to maintain constant quadrupole gradients throughout the linac to keep the beam size nominally constant. Increasing the bore, while otherwise retaining the rest of the cell geometry, has a small effect on the field integrals, but otherwise preserves the beam dynamics properties of the design. By ignoring the small decrease in the transit time-factor T the effect of an increased bore is easily tested using multiparticle beam dynamics simulations.

2. Beam dynamics with a large bore

The option of opening the drift-tube bore is attractive because it preserves the physics design of the DTL. In the analysis below we have used the spreadsheet DTLTool that calculates beam properties with linear space charge. As we have shown previously we expect a beam having a transverse emittance of $\varepsilon_{\text{rms},n} \approx 0.3\pi$ mm-mR with a Gaussian distribution extending to 9σ in emittance and 3σ in real space containing $\sim 99\%$ of the particles. Figure 1



shows the expected 3σ beam size, at both waist and bust, in the DTL with 64 mA, as a function of β .

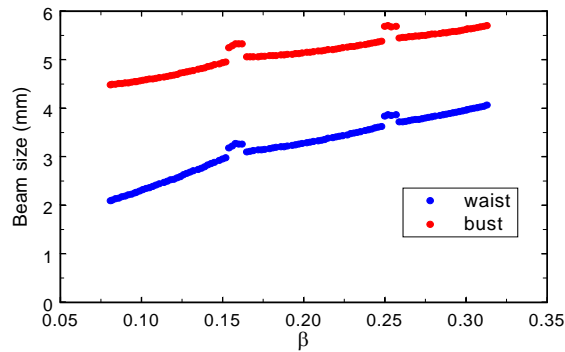


Figure 1. Beam size in the Linac4 DTL design.

Based on this simulation we would expect 99% of the beam to fill less than 60% of the drift tube bore at its largest point with no misalignments. If, however, we introduce the cumulative effects of random quadrupole misalignments we would expect the beam to fill $\sim 85\%$ of the bore in the last drift tube. Figure 2a shows the expected filling factor including the cumulative effect of random misaligned quadrupoles.

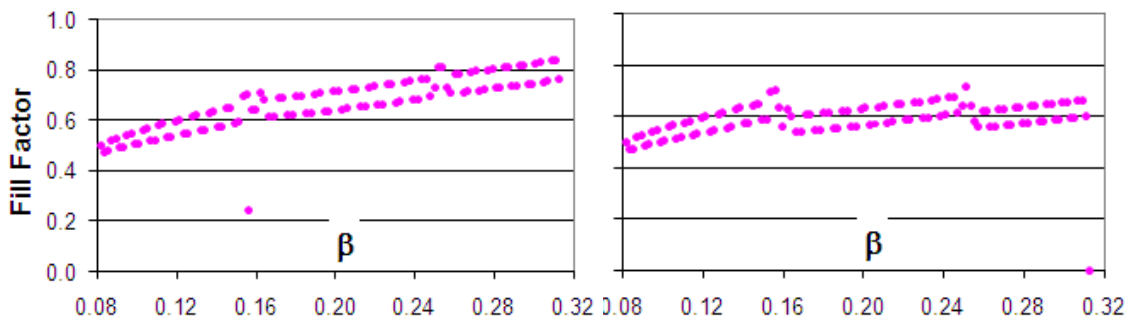


Figure 2. Filling factor for a. constant bore and b. increasing bore.

If we increase the drift-tube bore diameter in tanks 2 and 3 from 20 mm to 22.5 mm and 25 mm, respectively, we can reduce the expected filling factor to no more than the value at the exit of tank 1, or $\sim 70\%$. The expected filling factor for a design with an increasing bore diameter is shown in figure 2b.

Another useful parameter for assessing the potential for beam loss is the transverse acceptance. Figure 3a shows that the linac acceptance, based on the real-estate phase advance derived from envelope equations, monotonically decreases with β . By increasing the bore we can restore the acceptance in tanks 2 and 3 as shown in figure in figure 3b.

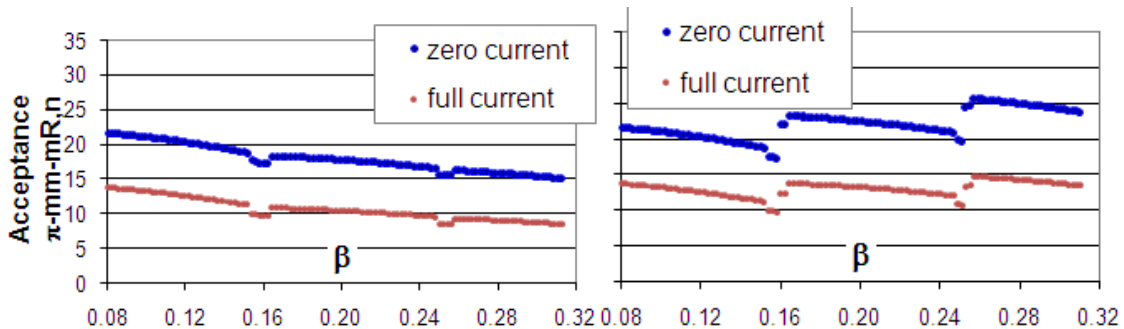


Figure 3. Analytical acceptance for a. a constant bore and b. an increasing bore.

We can see this effect more graphically in figures 4a and 4b. They show that the acceptance in the constant-bore design is nominally determined by tank 3 (magenta points), while the acceptance of the DTL with an increasing bore, red circles, is determined by tank 1 only and is $\sim 20\%$ larger. These acceptance plots were generated by transporting an array of zero-current “pencil beams” through the linac using the LTrace code and plotting the initial coordinates of those that did not intercept the bore. The acceptance values listed in figure 4 are derived from the area of an ellipse fit to the initial coordinates of surviving pencil beams and agree with the analytically derived values shown in figure 3.

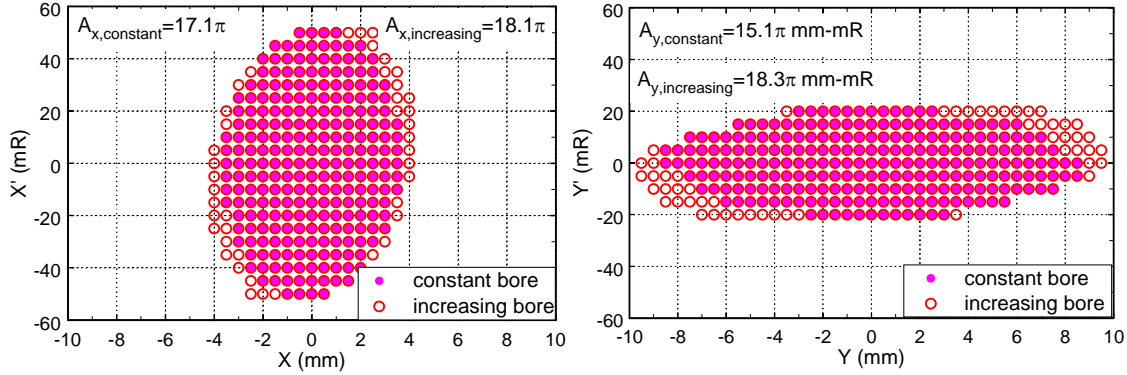


Figure 4. a. Horizontal and b. vertical acceptance of constant- and increasing-bore DTL designs.

3. Misalignments

When we introduce a sample set of random misalignments that increase the filling factor to 0.96, the acceptance is reduced by 30% of the aligned value horizontally and by 25% vertically as shown in figure 5. By increasing the bore the acceptance is only reduced by $\sim 15\%$ and $\sim 20\%$ of the aligned case.

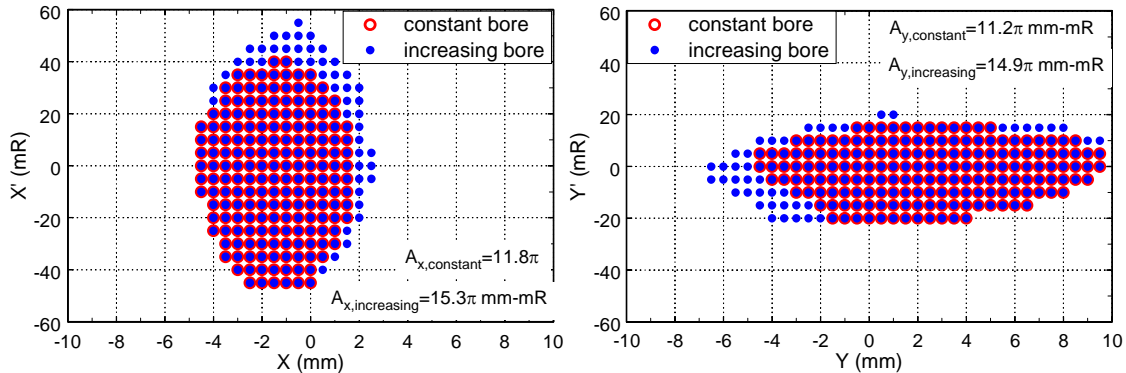


Figure 5. a. Horizontal and b. vertical acceptance of constant and increasing-bore DTL designs with errors

Figure 5 shows graphically the benefits of opening the bore in tanks 2 and 3 for a single set of misalignments. Since we will never know the actual positions of the drift tubes, it is important to look at the benefits statistically. Figure 6a shows the probability distribution of the filling factor, calculated by LTrace, for both designs. We can see that that the probability that the beam will not touch the drift-tube bore at a radius of 3σ (containing $\sim 99\%$ of the beam) in the constant-bore design is $\sim 87\%$. By opening the bore in tanks 2 and 3 we increase the probability to $>99.5\%$.

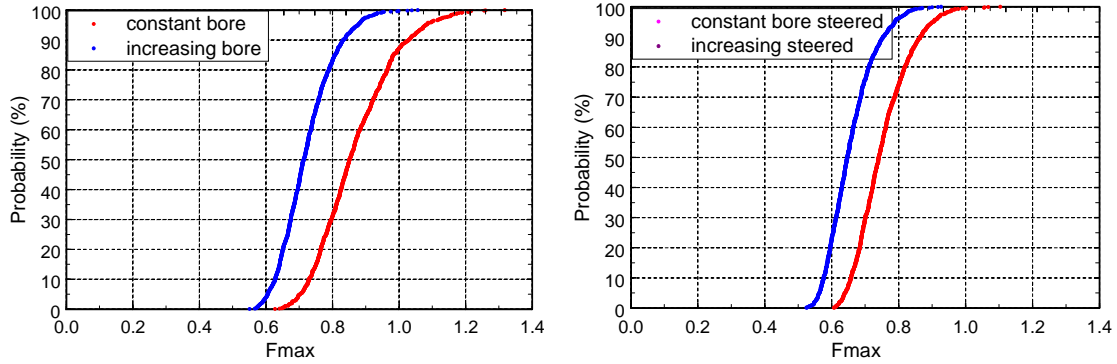


Figure 6. Filling factor in the constant and increasing-bore designs, a, without steering and b, with intuitive steering.

As we have shown previously, intuitive steering can further reduce the filling factor. Figure 6b shows the probability distribution of the filling factor for both designs with intuitive steering. In the constant-bore design with steering we can expect, with a >99% confidence level, that the beam will not touch the bore anywhere at 3σ . If we apply intuitive steering to the increasing-bore design, we would expect that the beam would never exceed 90% of the bore radius. This would give us a very good chance of meeting the 1-W/m beam-loss criteria.

Increasing the bore diameter has one further important advantage. Figure 7 shows the probability distribution of the energy at which we would expect the beam to be scraped at its largest excursion in the DTL. Figure 7a shows that with a constant bore we can expect, with ~80% probability, that any beam loss would occur at energies above 40 MeV. Opening the bore essentially linearizes the expected beam loss with energy as we see in figure 7b. Including steering in the in the constant-bore case has the same effect of linearizing beam loss with energy. Combining steering with the opened bore significantly improves the situation reducing the probability of beam loss at energies above 30 MeV to only 10%. In this case we would expect only a very small fraction of the halo to be lost.

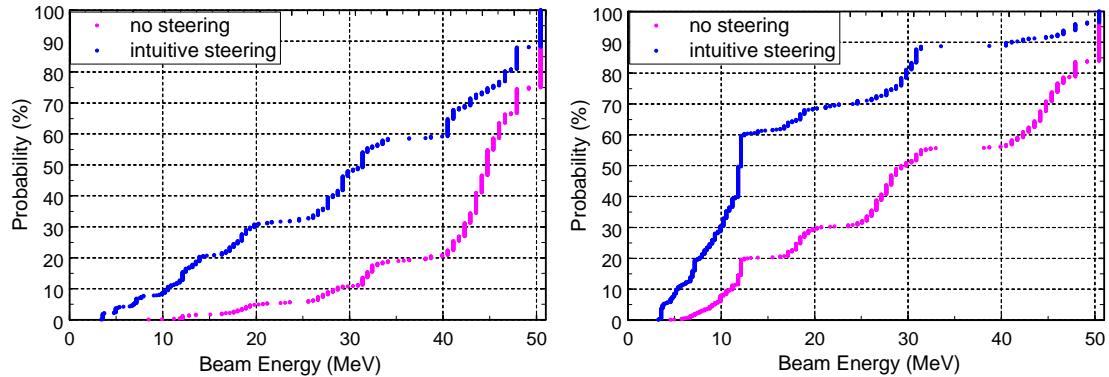


Figure 7. Probability of beam loss as a function of energy with errors, with and without steering, a. constant bore and b. increasing bore.

4. Power Considerations

Opening the bore diameter in a drift tube allows the electric fields to penetrate further into the bore. This reduces the transit-time factor T , which, in turn, reduces the acceleration efficiency of the structure. Furthermore, we would expect any reduction in T to also reduce the real-estate shunt impedance ZT^2 , making the structure less power efficient.

Using the code GenDTL which calls Superfish we have redesigned the cells in tanks 2 and 3 to have larger bore diameters. In this procedure the gap length and face angle were used as free parameters to tune the cell frequency while maintaining all of the rest of the drift-tube dimensions. The new drift tubes, having a larger bore, also have larger gaps and face angles.

The transit time factors and shunt impedance for the constant bore and increasing bore designs are shown in figures 8a and b.

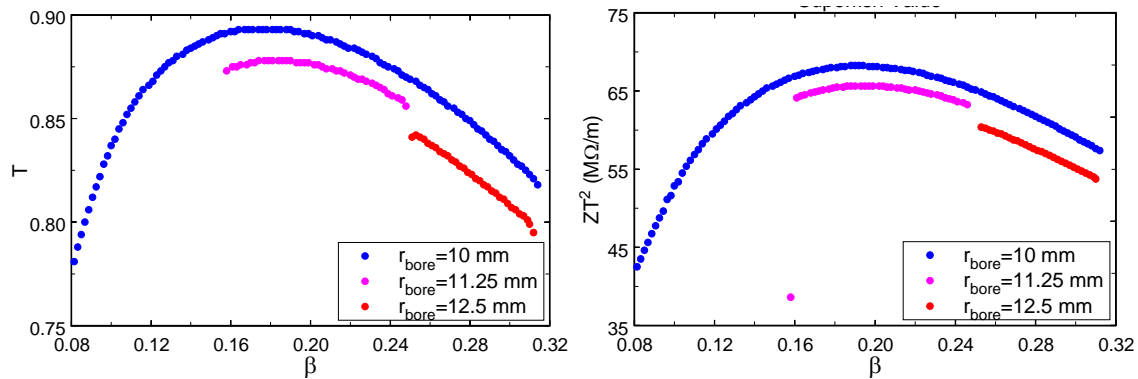


Figure 8. a, transit time factor and b, shunt impedance with constant and increasing bore.

5. Beam dynamics with constant strength quadrupoles

We have investigated a second option for increasing the transverse acceptance by increasing the quadrupole gradients in tanks 2 and 3. This option is attractive because it preserves the cavity design. As a trial design we set all quadrupole strengths (GL) equal to 1.55 T in tanks 2 and 3. This causes the beam size to decrease slightly with β . Figure 9 shows that the resulting acceptance increases with β . Figure 10 shows that this results in a constant filling factor with expected misalignments through tanks 2 and 3 which is exactly what we want.

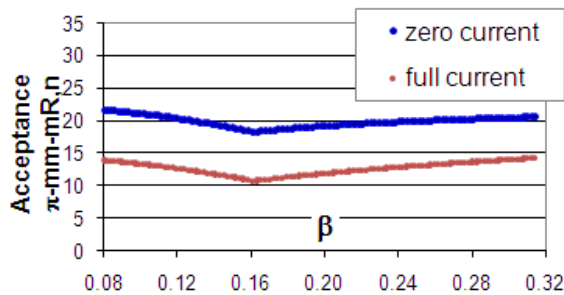


Figure 9. Transverse acceptance with constant-gradient quads in tanks 2 and 3.

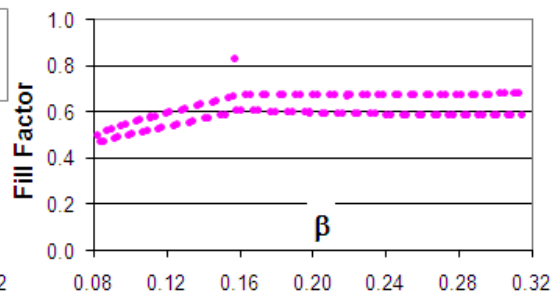


Figure 10. Filling factor with constant-gradient quads in tanks 2 and 3.

We typically design modern linacs to have an equipartitioning ratio close to unity to assure that there is no free energy available for energy and emittance transfer. The Hofmann stability diagram in figure 11 shows the instability stop bands that can lead to emittance transfer for emittance ratios $\epsilon_z/\epsilon_x \approx 1.2$. These stop bands correspond to integer values of tune ratios ($k_z/k_x = 1, 1/2, 1/3$). “Simulations show that the integer stop band, $k_z/k_x = 1$, is usually the only significant mode of concern for emittance transfer. Consequently, nonequipartitioned beams for rf linac designs are safe from emittance transfer, provided that the $k_z/k_x = 1$ stop band is avoided, or if the equipartitioning ratio is not far from unity to limit the available free energy.”¹

¹ Wangler, T. *RF Linear Accelerators*, 2nd edition. Wiley-VCH Verlag GmbH & Co. 2008. P321

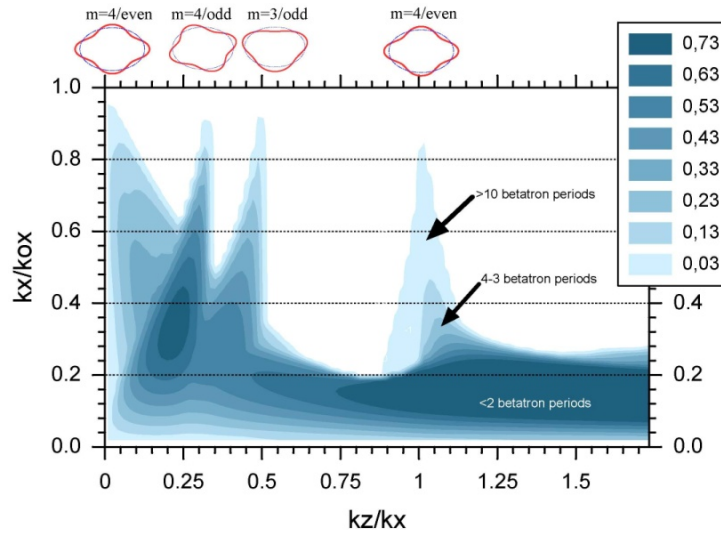


Figure 11. Hofmann stability plot for $\epsilon_z/\epsilon_x = 1.2$.

By fixing the transverse focusing we have violated the unity equipartitioning ratio of the baseline design. Figure 12 shows the equipartitioning ratio for both the baseline design, in dark blue, and the constant gradient design in magenta. Figure 13 shows schematically the Hoffmann diagram where we see that the baseline design, in dark blue, lies safely between the 1st and 2nd resonance throughout the DTL. With constant gradient quadrupoles the beam dynamics remains clear of the first resonance but crosses the 2nd resonance. Because we expect the ratio of beam emittances to be close to unity, $\epsilon_z/\epsilon_x \approx 1.2$, there should be very little free energy available for emittance transfer and because simulations show the second Hoffmann resonance to be very weak, we can expect this design to be stable.

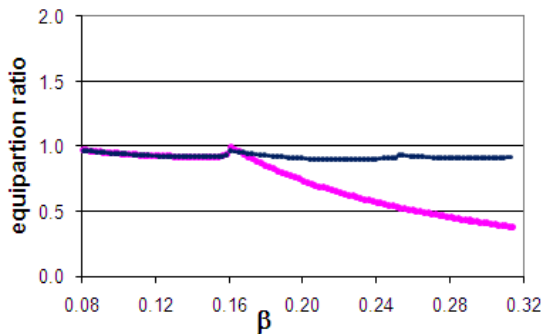


Figure 12. Equipartitioning ratio with decreasing and constant-gradient quadrupoles.

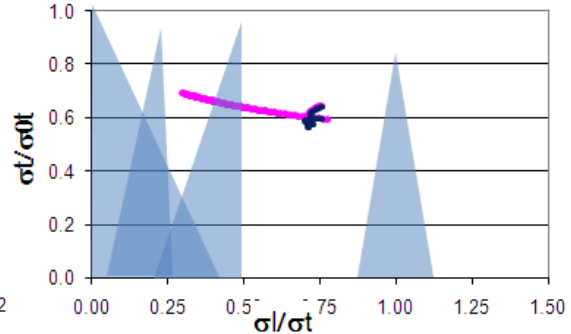


Figure 13. Hoffmann resonance diagram decreasing and constant-gradient quadrupoles.

4. Discussion

Opening the bore in tanks 2 and 3 is a very effective way to increase the acceptance of the DTL and reduce the probability of beam loss in the presence of misalignments. In addition it effectively reduces the energy at which we would expect to lose beam thereby reducing the potential activation. As we see from the error studies we would expect to accelerate the full beam without measurable loss using intuitive steering. If the alignment is better than expected the situation is further improved.

The consequence of increasing the bore is a degradation in T and ZT^2 resulting in a significant increase in the power requirement. The potential risk of running out of power outweighs any benefits of this scheme.

Increasing the quadrupole gradients increases the transverse acceptance and significantly reduces the risk of beam loss at high energies. The risk of emittance increase due to energy transfer between longitudinal and transverse planes is negligible. If this lattice is compatible with the lattice in the following CCDTL structure, we should consider it as an upgrade to the baseline DTL design.