

CORE AND HALO PARTICLE DYNAMICS OF HIGH INTENSITY PROTON BEAMS

M. Pabst and K. Bongardt, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
A. P. Letchford, Rutherford Appleton Laboratory, Chilton, Didcot, UK

Abstract

A very critical design issue for a high intensity proton linac is to keep particle losses below 1 W/m at the high energy end allowing unconstrained hands-on maintenance. For the ESS linac, with its 214 mA peak current, Monte Carlo simulations with up to one million particles are performed. Single particle trajectories are shown along the linac demonstrating the existence of a space charge potential with non-linear terms and transverse-longitudinal coupling.

Radial halo particles at the final energy of 1.334 GeV start at 70 MeV at the boundary of the longitudinal phase space and also transversely close to a boundary of a 4D waterbag distribution. The single particle motion of these halo particles is characterised, on the average, by conservation of the sum of all three emittances. Trajectories are presented for both horizontal-vertical coupling and also transverse-longitudinal coupling. Core particles have a very different behaviour. For core particles, located around the rms emittances at 70 MeV, the single particle emittances can be either increased or decreased.

1 INTRODUCTION

High intensity proton linacs can be either pulsed H^- – accelerators up to 5 MW average beam power or cw H^+ – accelerators up to 130 MW beam power. The major design problem is to reduce the particle loss along the linac down to 1 W/m which corresponds to a loss rate below $10^{-7}/m$. Losses above this limit prevent hands-on maintenance. Particle loss is caused by a small number of particles outside the dense beam core, called the beam halo. The origin and formation of the halo and its dynamics are important issues for understanding the particle loss.

For this investigation of halo properties the underlying realistic high current linac design is the linac of the European Spallation Source (ESS) [1][2]. The main part of the 5 MW ESS linac is a coupled cavity linac (CCL) at 700 MHz with an effective bunch current of 214 mA which accelerates the beam from 70 MeV up to 1.334 GeV. The CCL is designed to have a tune depression of about 0.8 in all three planes. This non space charge dominated design results in less than 10% RMS emittance increase, preserves the cylindrical bunch shape and reduces the sensitivity to mismatch and tolerances [3]. At the end of the linac at 1.334 GeV, a beam halo can be recognised which contains less than 10^{-3} of the particles. To understand the properties and dynamics of these halo particles, single particle trajectories have been examined.

2 PROPERTIES OF THE HALO

Results from Monte Carlo simulations with 200 000 particles are presented for the realistically designed ESS CCL. The output distribution of a preceding DTL was transferred into the CCL. No effect can be associated with the frequency jump and the change from a singlet to a doublet focussing system. Space charge calculations are fully three dimensional and no symmetries are assumed. At the input to the DTL at 5 MeV, the transverse and longitudinal phase spaces are filled independently with waterbag distributions. The space charge forces in such a distribution can be calculated analytically [4].

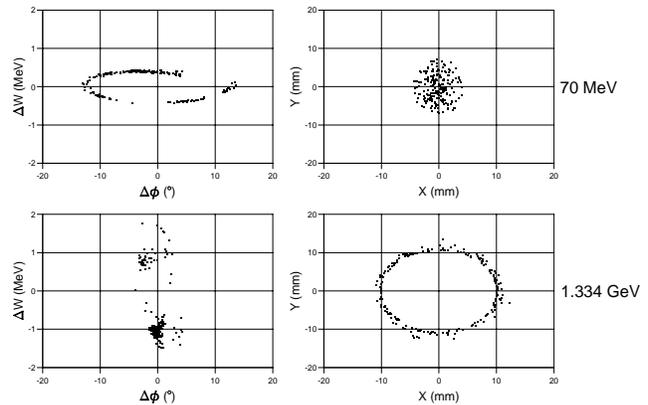


Figure 1: Longitudinal phase space ($\Delta W, \Delta \phi$) and real space (X, Y) projections at input (70 MeV) and at output (1.334 GeV) for the 200 outermost particles in (X, Y) space (halo particles) at the linac end.

In Figure 1, the 200 outermost radial halo particles are shown together with their position in the longitudinal phase space at 1.334 GeV. Also shown are the corresponding real space and longitudinal phase space positions at 70 MeV. There is obviously a strong transverse-longitudinal coupling because all the radial halo particles at 1.334 GeV start at the boundary of the longitudinal phase space at 70 MeV. Please note that the chosen 200 halo particles are not the outermost ones in real space at all energies. These particles are oscillating through the core. Also, they are not necessarily the outermost ones in either the horizontal or vertical phase space

In Figure 2, the same particles are shown in the transverse phase space at 70 MeV. All of the particles start from close to the boundary of the four dimensional transverse hyper-ellipsoid. The η 's and the ζ 's corresponds to the standard circle transformation of single particle coordinates and velocities. In Figure 2c the absolute value

of the transformed transverse velocity is plotted against the transformed transverse radius. Areas inside circles of Figure 2c are proportional to the sum of the transverse emittance. The inner line in Figure 2c is the boundary for a 4D waterbag distribution (total emittance = 6 x rms emittance) with the same rms emittances as the beam. The dashed line corresponds to the boundary for the actual distribution where the total emittance = 7.68 x rms emittance.

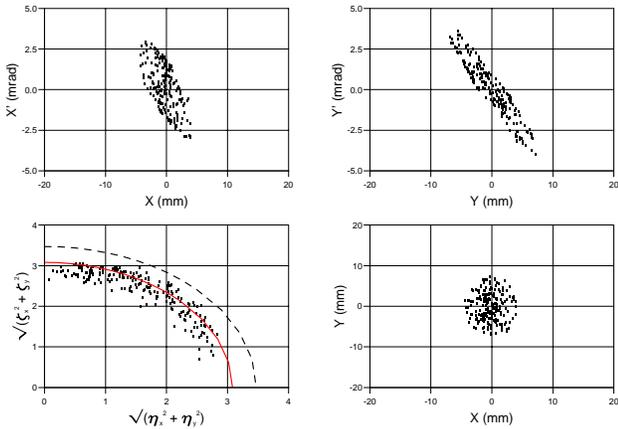


Figure 2: Transverse phase space projections of the halo particles at 70 MeV.

This strong horizontal-vertical correlation and the coupling to the longitudinal plane is also apparent at 1.334 GeV as shown in Figure 3a. Here the sum of the normalised single particle emittances $E_x + E_y + E_z$ is plotted against the sum of the normalised transverse emittances $E_x + E_y$, at 70 MeV and 1.334 GeV respectively, for the 200 radial halo particles. Evident is an increase in the sum of the transverse emittances, whereas the total sum stays constant on average, indicating a decrease in the longitudinal emittance on average. Figure 1 and Figure 3 are both a consequence of a transverse - longitudinal coupling term in the space charge potential. As a result radial core particles at 70 MeV become the outermost radial particles at the linac end. This process goes together with the exchange of emittances between the longitudinal and transverse directions.

For comparison, in Figure 3b the same parameters are plotted for particles in the beam core at 70 MeV. 200 particles are chosen which have single particle emittances in a range of 80% - 120% of the rms emittance in all three planes at 70 MeV. These core particles show completely different behaviour than the particles which become the radial halo at 1.334 GeV. Their total transverse emittance as well as their longitudinal emittance can either increase or decrease. Note that these core particles would be located in the lower left corner of Figure 3a.

Figures 4 and 5 show two typical halo particle single particle trajectories. Figure 4 depicts a particle with strong horizontal-vertical coupling. This leads to a rosette form

in the radial plane as the elliptical path precesses. The longitudinal emittance is large but conserved in this case.

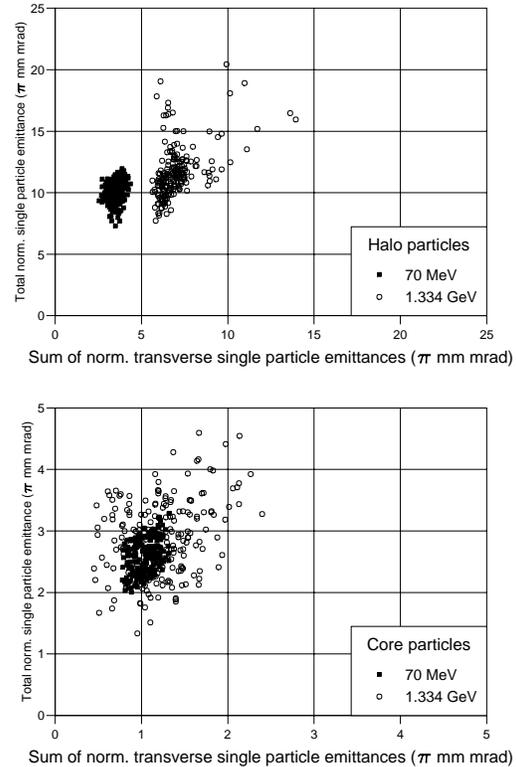


Figure 3: Plot of total normalized single particle emittance ($E_x + E_y + E_z$) as a function of the transverse single particle emittance ($E_x + E_y$) for the halo particles (upper graph) and some 200 selected core particles (lower graph)

Figure 5 represents a longitudinal-vertical coupling. The horizontal emittance is much smaller than the vertical one here. The longitudinal emittance decreases as the vertical emittance increases, the sum remaining more or less constant. The rosette form in the $(Y, \Delta\phi)$ plane is not as evident as in Figure 4. One reason may be the presence of non-linear external forces at the bunch head and tail. Also the difference in the transverse and longitudinal phase advance prevents a regular form, as in Figure 4, from appearing.

This analysis of halo particle properties is somewhat different to results obtained by the particle-core model [6]. Normally, an unbunched space charge dominated beam with tune depressions below 0.5 is considered. The space charge forces are assumed to be linear inside the core. Test particles are positioned outside the core. Their motion, caused by strong mismatch, is studied. Chaotic behaviour can be seen. This model cannot describe how core particles can become halo particles. However, phase space boundaries can be obtained.

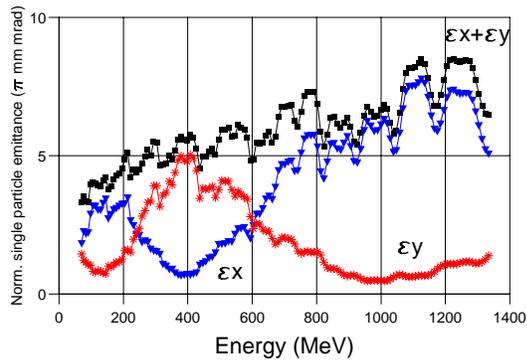


Figure 4: Single particle emittances and trajectories along the ESS CCL of a selected halo particle.

3 HALO PRODUCTION RATE

As has been recognised before from investigations of dc beams [5], halo production in a bunched beam is increased due to mismatch [3]. In the results presented above, there is about 60% change in the matched transverse beam radii, due mainly to the change in the number of accelerating cells per focusing period. In addition, the 20% longitudinal dc emittance growth which occurs in the preceding DTL has not been corrected for at the CCL input. By injecting a longitudinally matched beam, the longitudinal halo, which is not shown here, is substantially decreased. The driving force for the halo production is the non-linear space charge potential, associated with the non-self consistent distribution of a cylindrical bunch. Even for a perfectly rms matched beam there will be halo production. Mismatch, tolerances and errors then enhance the halo production rate.

This is somewhat different from the situation for a dc beam. Here, self consistent particle distributions are known which result in a zero halo production rate for a matched beam. Mismatch is then the driving term for halo production, not only an enhancement factor. More realistic unbunched distributions are associated with non-linear space charge forces with an elliptical boundary in real space. It appears to be difficult to scale the halo production rate from a dc beam to a bunched beam as in the latter case the transverse-longitudinal coupling cannot be ignored.

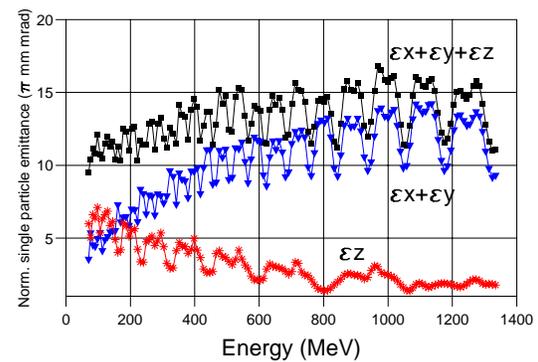


Figure 5: Single particle emittances and trajectories along the ESS CCL of another selected halo particle.

In order to estimate a particle loss rate at the beam pipe, Monte Carlo simulations with one million particles have been carried out for the first third of the CCL. From these on-going studies it is hoped to extrapolate, using data for 200 000 and 1 000 000 particles, the particle distribution at the pipe radius. Quadrupole displacement errors have also been included in some simulations. As expected, even for beam displacements of up to 4 mm, the particle distribution is only weakly effected. More dramatic changes are expected when sextupole errors are included.

4 REFERENCES

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