# FILAMENTATION EFFECTS AND IMAGE CHARGES IN HIGH $\beta$ PROTON TRANSFER LINES

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***Abstract***

The transfer line after a high intensity proton linac can be quite complicated due to either target illumination requirements or the matching conditions for loss free ring injection. In most cases, it is neither possible nor necessary to keep the beam bunched. Space charge forces are small but still effective in a long transfer line. As an example, the 1.334 GeV, 214 mA bunch current 130 m long transfer line between the linac and compressor ring of the European Spallation Source (ESS) is studied in detail. Monte Carlo simulations with 50000 fully interacting particles are presented.

Along the first 70 m, where the rms phase width is increased from 2$^o$ to 6$^o$, space charge forces effect the longitudinal and transverse rms parameters. In addition they cause filamentation in all three phase planes. If at 70 m a bunch rotator is placed, which keeps the bunch length constant, space charge effects are still present up to the end of the transfer line.

Without a bunch rotator, the bunch length increases fast enough that space charge effects can be neglected. However due to the increased bunch length, image forces are present in all three planes. A bunched beam with a cylindrical boundary in real space stays cylindrical along the transfer line. The axial fields are presented for parabolic radial and elliptical axial density distributions with and without a cylindrical conducting beam pipe. The results show that even for a bunch length equal to the pipe radius these effects cannot be neglected.

## 1 LONGITUDINAL SPACE CHARGE EFFECTS

For all proposed high intensity proton linacs [1], there is a high $\beta$ transfer line leading either to an accumulator ring or a fast cycling synchrotron or directly to a target station. Due to bunch currents up to 200 mA, space charges forces have to be considered. In most cases, it is neither possible nor necessary to keep the beam bunched. As an example, the effects on the longitudinal and transverse motion are discussed for the high $\beta$ transfer line [2] of the European Spallation Source ESS [3] with and without a bunch rotator.

In Fig.1, longitudinal phase space projections are shown at 4 positions along the ESS high $\beta$ transfer line with a bunch rotator.

The input distribution is obtained from Monte Carlo simulations with 50000 particles at the end of the 1.334 GeV, 700 MHz ESS coupled cavity linac. The bunch current is 214 mA, the normalised transverse and longitudinal rms emittances are 0.6 $\pi$ mm mrad and 1.3 $\pi$ $^o$MeV respectively [4].

For transporting the particle distribution along the 130 m long transfer line, a doublet focusing system is chosen with constant field strength and constant separation. The initial rms phase width is 2$^o$ . No accelerating fields are applied except a bunch rotation cavity after 70 m, where the rms phase width has grown to 6$^o$ . The bunch rotator decreases the energy spread by a factor of 3 compared to the initial value.

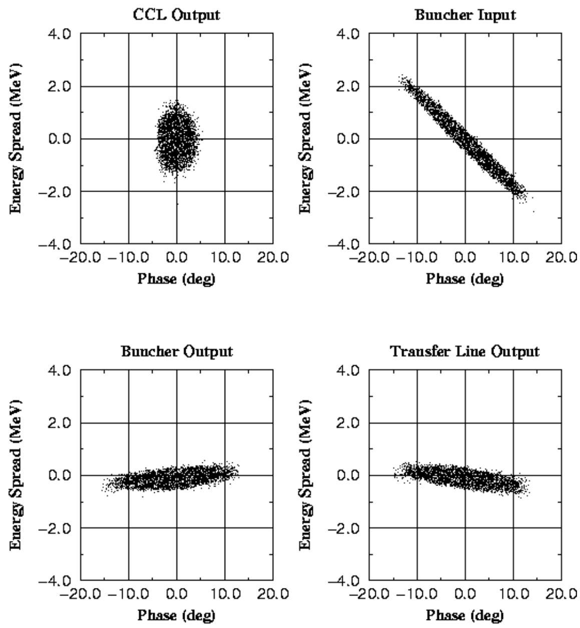


Fig. 1 Longitudinal phase space projections along the 130 m long ESS transfer line. A bunch rotator is located at 70 m.

It can be seen from Fig. 1, that space charge forces are present before and after the bunch rotation cavity. Before the buncher, the energy spread is increased by almost a factor of 2. After the buncher, despite the increased rms phase width of 6$^o$ , in only 70 m the longitudinal phase space ellipse changes its orientation from a focused to a defocused beam. A quite detailed explanation of both effects can be derived by looking at the linear space charge term only. At the bunch edges filamentation effects can be recognized.

For loss free injection into the ESS compressor rings, there should be less than $10^{-4}$ particles outside an energy spread of ±2 MeV. Uncorrelated amplitude and phase errors of ±1 % and ±1° respectively will cause an oscillation of the beam center of 0.6 MeV [1]. During a start-up period with approximately half of the design current, optimal bunch rotation can only be obtained by using a debunching cavity just behind the ESS coupled cavity linac. This keeps the rms phase width to 6 ° at the bunch rotation cavity, independent of the bunch current, but increases the operational complexity. As the energy spread collimation has to be guaranteed for all bunch currents including much larger rf tolerances during the start-up period, an achromatic bending system is installed after the bunch rotation cavity [2,3].

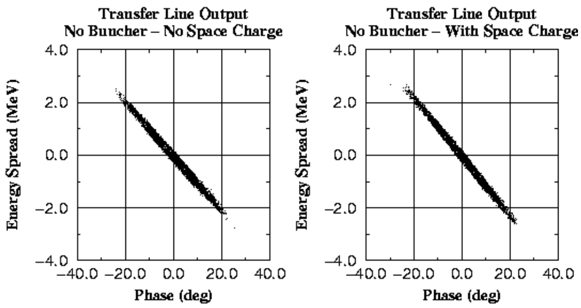


Fig. 2 Longitudinal phase space projections at the end of the ESS transfer line without a bunch rotator

For other accelerator scenarios than for spallation sources, the linac beam is allowed to debunch. In Fig.2 the longitudinal phase space is shown at the end of the ESS transfer line without a bunch rotation cavity. Clearly seen is the increase of the phase width by more than a factor of 2 compared to the ESS reference design. The rms energy spread changes by 10 % for the 60 m long line, where the space charge density is 3 times less than at the beginning. Some filamentation at the head and tail of the bunch can be seen. In addition in Fig.2 the phase space distributions are shown at the end of the transfer line assuming no space charge after the bunch rotator. Both distributions look very similar indicating that for a partly debunched beam the influence of space charge can be neglected. The starting distributions are effected by space charge along the first 70 m.

## 2 TRANSVERSE SPACE CHARGE EFFECTS

In Fig.3, the radial distributions are shown at the beginning and the end of the ESS high $\beta$ transfer line with a bunch rotator. The quadrupole gradient is kept constant. Clearly seen is a decrease of the transverse beam size resulting from the increase of the longitudinal phase width. But much more important than the size of the dense core, which can be adjusted by choosing the appropriate quadrupole strength, are the more than $10^{-3}$ particles outside the core. This is about a factor of 3 larger than the number at the beginning.

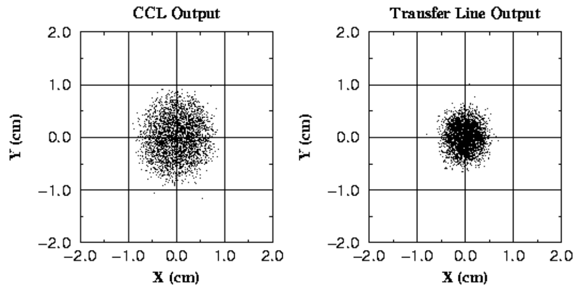


Fig. 3 Radial phase space projections at the beginning and the end of ESS transfer line. A bunch rotator is included.

For achieving loss free ring injection into the ESS compressor rings, the linac beam has to be truncated transversely. This is achieved by placing stripping foils along the achromatic bending section of the ESS high $\beta$ line.

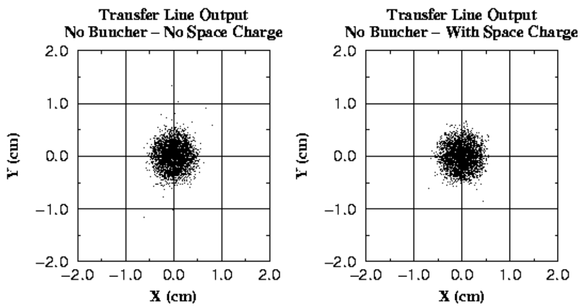


Fig. 4 Radial phase space projections at the end of the ESS transfer line. No bunch rotator is included.

In Fig.4, the radial distributions are plotted at the end of the transfer line without a bunch rotator. Like in the longitudinal case, for comparison results with and without space charge are given. Both distributions look very similar. Again, there are more than $10^{-3}$ particles outside the dense core.

## 3 IMAGE CHARGES IN HIGH $\beta$ TRANSFER LINES

Until now, the space charge forces have been calculated by ignoring the effect of the cylindrical conducting beam pipe. This approach is valid in the 'short' bunch limit, where the bunch length in the rest frame is much shorter than the beam pipe radius. In the 'long' bunch limit, where the bunch length is much larger than the beam pipe radius, especially for the longitudinal space charge force, the influence of the conducting pipe can no longer be neglected.

In contrast to the approach of circular machines, at the linac end the bunch has a cylindrical boundary in real space inside a cylindrical beam pipe. This cylindrical bunch shape is conserved along the transfer line, see Fig.5. No thermalization is to be seen.

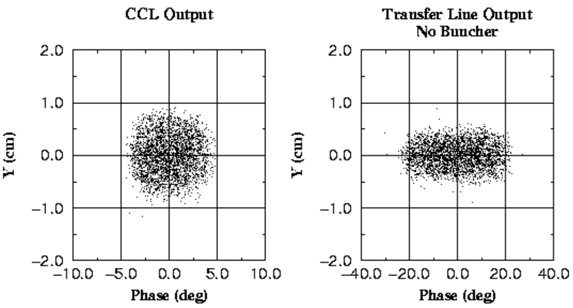


Fig. 5 Real space projections for full current at the beginning and the end of the ESS transfer line without a bunch rotator.

For analysing the influence of the conducting beam pipe, a cylindrical beam with a parabolic radial and an elliptical axial density is assumed. The radius of cylindrical conducting pipe is kept at 4 cm, the transverse beam radius at 1.3 cm. The half bunch length $z_m$ in the rest system is chosen to be either 4 cm or 10 cm. These values correspond for the ESS case to a rms phase width of $6^o$ and $15^o$ respectively.

Fig.6 shows the axial fields in the rest system in free space for both cases and the ratio between the axial fields with and without the cylindrical conducting beam pipe. All electric fields are proportional to the total charge divided by square of the transverse beam radius [5]. It can be seen from Fig.6 that the axial field has strong non-linear components and coupling to the radial plane. For bunch lengths larger than the beam radius, the non-linear components are increasing. This explains the filamentation seen in Fig.2.

Image charges cannot be neglected longitudinally for bunch lengths equal to or greater than the pipe radius. They will enhance the longitudinal filamentation for the head and tail particles of the bunch. The linear axial field components decrease causing a slowing down of the debunching process [6]. Radially, image charges are unimportant, if only one third of the beam pipe is filled by the beam and if the radial and axial distributions are the quoted ones. For 'long' cylindrical bunches in a cylindrical beam pipe, the total space charge potential is proportional to the line density [7]. Any change of the line density due to axial space charge forces will have an effect on the radial field.

To study image forces accurately in the intermediate regime between short and long bunches, the total force on each particle has to be calculated by double series over Bessel functions. Based on the method given in [8], a fast converging formula will be implemented.

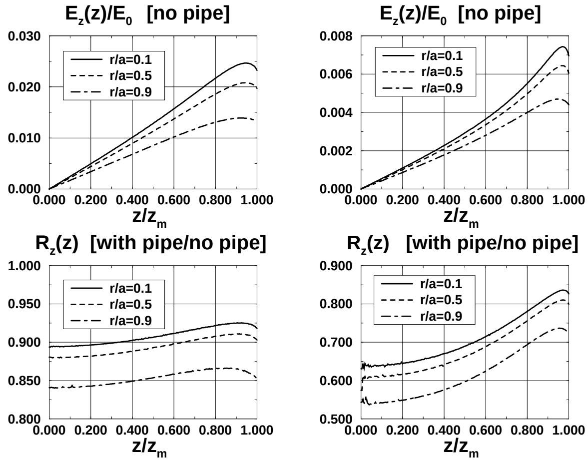


Fig. 6 The axial fields in free space (top) and the field ratios (bottom). Left column corresponds to 4 cm half bunch length and the right one to 10 cm half bunch length

## 4 REFERENCES


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