FINAL BUNCH ROTATION AND MOMENTUM SPREAD LIMITATION FOR THE ESS FACILITY

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The key issue of the accelerator part of the European Spallation Source (ESS) is the loss free ring injection. In the transfer line between linac and compressor rings two rf cavities, phased independently, are installed followed by an achromatic collimator. This two-stage system allows an optimum energy spread limitation under varying beam current and energy ramping conditions. The system aims to have less than 10^{-4} particles outside an energy spread of ±2 MeV at ring injection. Longitudinal space charge forces are still present and cause an increase of the energy spread and the longitudinal emittance. Multiparticle calculations with varying beam currents are presented for the 130 m long straight transfer line after the linac end.

INTRODUCTION

The most critical part of the accelerator of the European Spallation Source [1] is the loss free injection into the compressor rings. Due to the 5.1 MW average beam power at 1.334 GeV, particle loss above 10^{-7}/m forbids unconstrained hands on maintenance of accelerator components. At the injection of the 1.2 msec long linac pulse into the two compressor rings the loss must be here at the 10^{-5} level. For achieving this with a 1000 turn H^- – injection scheme the linac beam has to be truncated in both transverse planes. The mean kinetic energy has to be varied by 4 MeV during injection, corresponding to 2×10^{-3} $\Delta p/p$ ramping. Less than 10^{-4} particles above an energy spread of ±2 MeV should be accepted by the stripping foil. The linac pulse has to be chopped at the 1.67 MHz revolution frequency with 60 % chopping efficiency [2].

The longitudinal halo collimation puts stringent conditions on the design of the high energy transfer line between linac end and compressor rings. The layout of this line consists of three parts:

- a straight transfer line of 75 m from the linac end up to a 700 MHz bunch rotation cavity
- a 42.5 π m circumference, 180 deg achromatic collimation system
- a 75 m final matching section up to the H^- – stripping foils

At the stripping foils the two 0.6 msec long linac pulses are separated vertically, with a final vertical separation of 1.5 m for the two accumulator rings. Longitudinal halo scraping is obtained by a two stage collimation system. First are two independently phased energy ramping and bunch rotating cavities which reduce considerably the particle number outside the wanted ±2 MeV value. The remaining particles are stripped and collected in an achromatic collimation system.

FINAL BUNCH ROTATION

The beam motion was studied for a 130 m straight transfer line including a bunching cavity. The rms values of the energy spread and the longitudinal emittance are shown in Fig. 1 and 2 for the ESS linac design parameters: 214 mA bunch current at 700 MHz and 1.334 GeV [3]. For the multiparticle calculation the linac output phase space distribution is used as the input distribution for the transfer line simulation [4]. The same focusing was adopted as at the coupled cavity linac end: a quadrupole doublet every 5.4 m resulting in an initial average transverse radius of 3.5 mm.

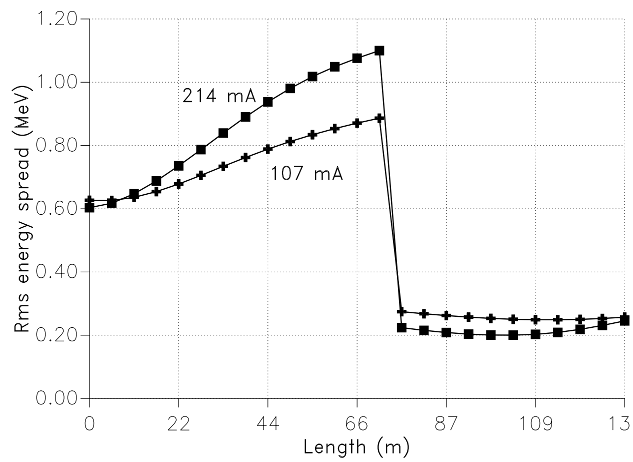

Fig. 1 Rms energy spread for full bunch current (214 mA) and half bunch current (107 mA) in the transfer line

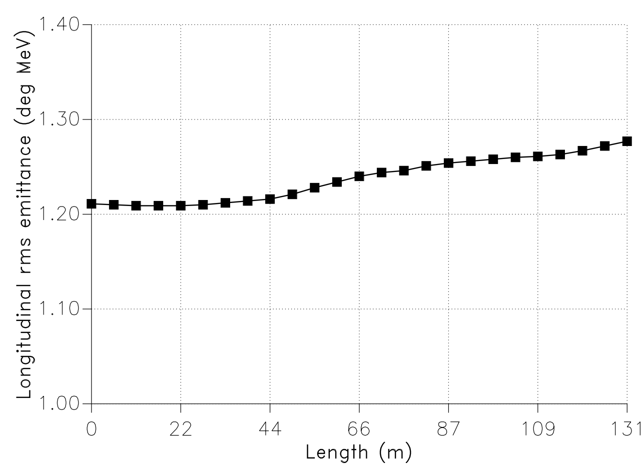

Fig. 2 Rms emittance for 214 mA in the transfer line

The rms energy spread and the longitudinal rms emittance are not constant along the transfer line as expected in a simple drift space. Due to small, but still not negligible, space charge forces the particles are not 'drifting' longitudinally but moving instead in a 'plasma channel' with decreasing strength. The envelope equation for the dense beam core with its mainly linear space charge forces is space charge dominated and not emittance dominated in spite of the high kinetic energy. The rms phase changes from 2 º to 6º (10º without bunching cavities), see Fig. 3. For constants quadrupole gradients, there is a reduction of the transverse beam size. The shielding of the conducting boundary is neglected, as the initial value of 0.5 cm for the bunch length is shorter than the pipe radius.

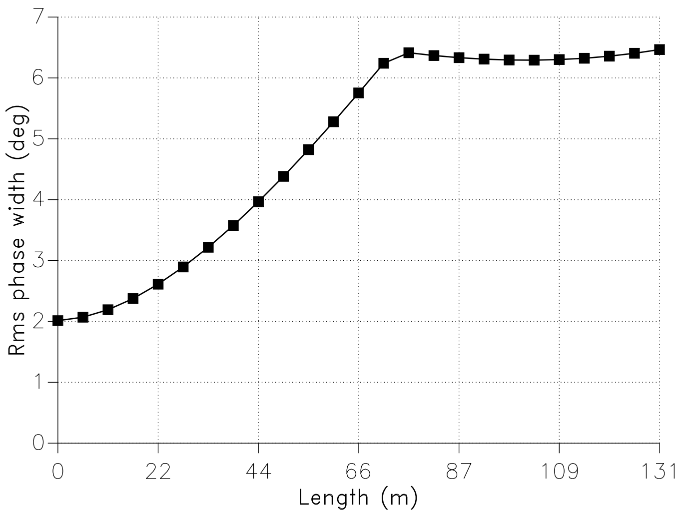

Fig. 3 Rms phase width for 214 mA in the transfer line

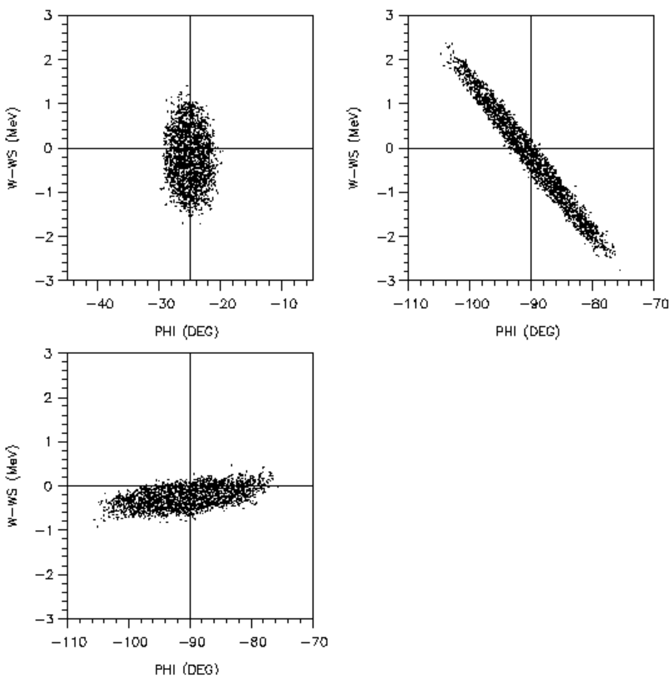

Fig. 4 Longitudinal rms emittances at end of CCL, before and after the buncher (upper left, upper right, lower left)

Along the 130 m long transfer line, the longitudinal rms emittance increases by the same amount as along the whole coupled cavity linac [4]. This increase is caused by the longitudinal mismatch along the line. The unexpected situation cannot avoided easily as the rms energy spread of 0.6 MeV at the linac exit is too large for loss free ring injection. With a bunch rotation cavity, placed after 75 m at 6º rms phase width, see Fig. 1, the rms energy spread is reduced to 0.2 MeV. About 11 MV rotation voltage is applied to a 4 m long 700 MHz coupled cavity. After the bunch rotation cavity the rms energy spread is not constant for a 50 m long transfer line. In Fig. 4 the longitudinal phase space is plotted at the linac end, before and after the bunch rotation cavity.

LONGITUDINAL HALO COLLIMATION BY ENERGY RAMPING AND BUNCH ROTATION

As pointed out before the main task of the bunch rotation cavity is not to reduce the rms energy spread to its smallest allowed value, but to limit the total energy spread to ±2 MeV at the H^- – stripping foils. In addition the mean energy has to be ramped by 4 MeV during the pulse. The energy spread limitation must be fulfilled under varying beam current and ramping conditions.

In Fig. 1 the bunch rotation is shown also for a 'partly' filled bunch having 50% of its design current. Those bunches can be created by a chopping system at low energies [5].

As there is only a 20 % tune depression at full current for all three planes along the CCL, the output parameters for the 50 % current value will not differ very much to those for full current. However, due to less space charge, the phase width and energy spread, see Fig. 1, are increasing much slower. By keeping the rotation voltage unchanged this bunch cannot be rotated properly.

The required 4 MeV energy ramping can, in principle, be done with bunch rotation cavity by changing the synchronous phase by 21º. But as the 95 % phase width is around ±13º at the cavity position, see Fig. 4, this would result in a deformed phase space boundary which could lead to more particles outside the ±2 MeV limit at the stripping foil for the ramped beam

For a beam at the design intensity and emittance, with no ramping and field errors in the accelerating structures, only particles with emittances above 100 times the rms emittance are outside the ±2 MeV limit directly after the rotation cavity, see Fig. 4. However, 5% of the particles are outside the collimation limit before the bunch rotation cavity. For the partly filled bunch, see Fig. 1, the safety margin is 64 only. If random amplitude errors of 1% and phase errors of 1º are present in the CCL, the mean energy of the bunch center could be shifted by 0.6 MeV at the linac end [4]. This would drastically reduce the safety margin by 50%. As the phase width of the outermost particles is smaller than 60 º, 10 times the rms value, the cavity can operate with a sinussoidal field. Placing the cavity at larger phase values will increase the safety margin only, if higher harmonic field components are superimposed.

In order to keep this large safety margin also for half the beam current and for a energy ramped beam, a second independently phased 700 MHz cavity will be placed after the CCL. E.g., this allows to bring the 107 mA beam to the same orientation in phase space after the bunch rotation cavity as the 214 mA beam. At the new 100 MeV transfer line at Fermilab two bunching cavities are synchronized for routine operation. By varying amplitude and phase of both cavities, there are four independent knobs for achieving the longitudinal halo collimation under varying beam current and ramping conditions, including the influence of field errors and mismatch effects. As the design goal is the particle limitation outside the ±2 MeV limit and not the smallest possible rms energy spread, it could well be that the bunch has to be under- or overrotated. For allowing this operational flexibility the large safety margin (100 for a matched beam at full intensity) is of great importance.

ACHROMATIC COLLIMATION SYSTEM

After the bunch rotation cavity, the 75 m long line for vertical beam separation could, in principle, follow. Due to the enlarged rms phase width of about 6º the value for the bunchlength is increased to 1.5 cm, comparable to the pipe radius. Then, the space charge forces can neither be approximated by the short bunch limit for direct forces nor by the long bunch limit for image forces. In this transition region, the linear part of the forces is smaller than predicted by the direct Coulomb force assumption. However, the nonlinear part is larger than the Coulomb part [6]. The effect on the rms energy spread when using the short bunch approach is shown in Fig. 1. Here the rms energy spread is increased by 25%. The long bunch approach is calculated in [7]. Both calculations agree, that after the rotation cavity longitudinal forces are present. Therefore the large quoted safety margin at the position of the rotation cavity cannot be easily transformed to the H^- – stripping foils position, 75 m downstream.

To overcome this serious difficulty an achromatic collimation system has been designed [8], where the longitudinal halo limitation is made by stripping away the unwanted particles at a position of large normalized dispersion. This two stage longitudinal beam collimation is quite superior to all other discussed possibilities. With the ramping and rotation cavity the number of particles outside ±2 MeV is reduced considerably. The remaining particles are stripped and collected afterwards. For 5.1 MW average beam power scraping away 10^{-4} of the current results in 500 W average power, to be collected at a small spotsize. Even more important is the flexibility of the two stage system. Here it seems to be possible to find optimal solutions under various beam current and ramping conditions.

The transverse beam parameters have to be matched carefully to the achromatic conditions. The change from a doublet focusing system with small β–values to a triplet with large β–values has to be made in the transfer line between linac end and rotation cavity. A current dependent matching is mandatory. As the transverse particle distributions are not changing significantly along the transfer line, horizontal beam scraping is foreseen before the rotation cavity, vertical scraping is applied after the achromatic collimation section. Long low field gradient bending magnets are used in order to avoid unwanted Lorentz dissociation of the H^-– particles.

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