SPL Transfer Line


Keywords: SPL, PS2, Transfer Lines, Space Charge

Summary
The study of the longitudinal properties of the beam accelerated by SPL at the injection of the following accelerator is very important to optimize its performance. Therefore we connected the latest version of SPL (5 GeV) to the PS2 with a transfer line previously designed by the TE/ABT-BTP Section making it an example of how to transport the SPL beam out of the very densely built Meyrin site to a place where a following accelerator can be realized.

1. The SPL, the PS2 and the Transfer Line

A study has been conducted [1] on the possibility to overcome the present injector chain limitations by replacing the present injectors Linac2, PS Booster and PS by a new linear H-accelerators, Linac4 and a Superconducting Proton Linac (SPL) [2], and a 50 GeV proton synchrotron (PS2) [3] (see Figure 1).

Figure 1: Sketch of the Meyrin site present accelerators and transfer lines (in green), Linac4, the SPL and the PS2 (in red).

The design of the transfer line between the SPL [4] and the PS2 is a challenging example of how to transport the SPL beam to a user facility (fixed target or further acceleration) outside the Meyrin site, overcoming the difficulty of different altitudes and orientations. In particular this transfer line [5, 6] has to match an altitude difference of 21 m over its length of ~400 m.

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Furthermore, the bending strength has to be limited to prevent Lorentz stripping of the H-beam. This results in a large slope of 8.1% of the beam line. The beam line layout (see Figure 2) consists of a FODO lattice combining horizontal / vertical achromats with 90° phase advance per cell with a cell length of 25 m. The bending is performed with two combined horizontal and vertical achromats which provide a dispersion-free region in between and easy matching to the required beta function and dispersion value at the end of the beam line. The drift between the quadrupoles is long enough to install SPL cryostat with 3 cavities to perform the requested longitudinal manipulation.

Figure 2: Sketch of the transfer line. A F0D0 lattice (25 m) provides transverse focalization with room for the horizontal and vertical bending magnets and the cryostat of the rebuncher.

2. Longitudinal debunching

The bunch at the end of the SPL (5 GeV) has an energy spread of ±2 MeV (0.04%). If space charge forces weren’t present, the bunch would keep the same energy spread and its length would slowly increase by (see Figure 3(a)):

\[ \Delta \varphi_{\text{max}} = \frac{1}{(\beta \gamma)^2} \cdot \frac{360}{\lambda} \cdot \frac{\Delta E}{E} \approx \pm 8.5 \times 10^{-3} \text{ deg/m} \]

Due to the space charge forces at 30 mA the energy spread will increase and a faster debunching will occur: for example at the end of the transfer line the bunch will be ±20 deg ±10 MeV (2%), as shown in Figure 3(b). Moreover one has to consider the energy jitter produced by the voltage and phase jitter of the 244 cavities of the SPL too which will be added to the bunch energy spread [7], making the injection into the following structure very difficult (maximum acceptable energy spread of about ±0.1%).

Figure 3: Maximum phase (at 352 MHz) and energy spread of the bunch along the transfer line, w/o (a) and with (b) space charge (30 mA).
For this reason installing a rebunching section in the transfer line is foreseen [4]: both the bunch and the jitter generated energy spread will be reduced with a rotation of the phase space (sketched in Figure 4), freezing at the same time the longitudinal debunching.

Figure 4: The beam gets debunched due to the long drift and the energy spread increases due to the Space Charge. Applying a calibrated voltage rotates longitudinally the bunch reducing the energy spread and the debunching in the line downstream.

3. Rebuncher set-up

The required voltage of the rebuncher depends on the bunch phase and energy spread. Using the expression found before, taking into account a correction for the space charge and the energy spread at the end of the 400 m transfer line we find:

\[ V_{eq} = \frac{\Delta E_{\text{max}}}{e \sin(\Delta \phi_{\text{max}})} = \frac{10 \text{ MV}}{0.02 \text{ deg/m} \cdot \frac{180}{\pi}} \approx 28,600 \text{ MV} \cdot \text{m} \]

As every SPL cavity is able to deliver 25 MV, placing the rebuncher in the second half of the line would limit the number of installed cavities to 4.

In Figure 5 the dispersion along the line is shown. As the rebuncher must be installed in a dispersion free region, it can be installed in the half period just before the last dispersive region at 290 m from the beginning.

Figure 5: Vertical and horizontal dispersions along the transfer line.
At this position the longitudinal phase space is shown in Figure 6:

![Figure 6: Longitudinal (phase at 352 MHz) bunch distribution after 290 m from the SPL output.](image)

The required voltage is:

\[
V_{\text{eq}} = \frac{\Delta E_{\text{max}}}{\sin(\Delta \phi_{\text{max}})} = \frac{7 \text{ MeV}}{\sin(6^\circ)} \approx 67 \text{MV}
\]

which means 3 cavities operated at \( \sim 22 \text{ MV/m} \).

3. **Beam dynamics simulations**

The beam can be easily transported along the transfer line and, as expected, the rebuncher reduces by a factor 10 the energy spread and stops the debunching (see Figure 7). The transverse emittance remains constant along the line, whereas, due to the space charge, both the longitudinal emittance and halo increase (see Figure 8).

![Figure 7: RMS envelopes (phase at 352 MHz) along the transfer line.](image)
Figure 8: Normalized RMS emittances (top) and beam halo (bottom) along the transfer line.

4. **Effect of the rebuncher on the beam jitter**

The SPL is made of 244 independently powered cavities. Phase and amplitude stability of the cavities' voltage affect the longitudinal properties of the single bunch, creating statistically an increase of the energy spread of the beam at the end of the linac, as shown in the first column of Figure 9. As the rebuncher is set up to reduce the energy spread of the single bunch, it will
reduce the jitter induced energy spread as well, as shown in the second column of Figure 9. Only a small retuning of the cavity voltage is required. Even with 1% - 1 deg of SPL jitter we would be able to provide a less than $5 \times 10^{-4}$ energy spread beam to the following accelerator.
5. Conclusions

The SPL beam can be transported hundreds of meters from the accelerator without quality degradation. The beam dynamics details of a 400 m long line composed of 32 quadrupoles and a debuncher has been studied. This line would allow injecting the SPL beam in the PS2, respecting the accelerator’s layout of the CERN site and matching the necessary beam quality at injection.

6. References


