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BUNCH STRETCHING IN THE TRANSFER LINE BETWEEN SPL[1] AND ACCUMULATOR & OPTIMIZATION AGAINST INITIAL ENERGY AND PHASE JITTER

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Abstract

The Superconducting Proton Linac (SPL) delivers bunches with a total length of 30 ps and a total energy spread of 5 MeV. Before injecting the beam into the Accumulator Compressor (PDAC)[2] ring the bunches have to be stretched to a total length in the range of 100-500 ps. The RF bucket in the ring has a height of ± 2 MeV and thus imposes a limit for the acceptable amount of energy and phase jitter at the end of the SPL. By carefully designing the transfer line, the acceptable jitter range from the linac can be maximized.
Several options have been studied to provide the necessary bunch stretching and have then been tested for their susceptibility to energy and phase errors. At the same time the actual layout of the line on the CERN site is taken into account. The results of this study are presented together with a proposal for a new, optimized version of the transfer line.

1) Superconducting Proton Linac
2) Proton Driver Accumulator Compressor

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1 Layout and principle

In the present SPL scenario the linac is located along the south-western fence of the CERN site and ends parallel to the ISR tunnel. The transfer line then starts with a curve (radius = 100 m) to bend the beam towards the injection into the ISR ring tunnel. Due to the width of the ring tunnel it will be possible to accommodate several parallel beam lines, meaning that the length of the transfer line is not restricted to the curve and the short straight section between the linac output and the ISR tunnel (Fig.1).

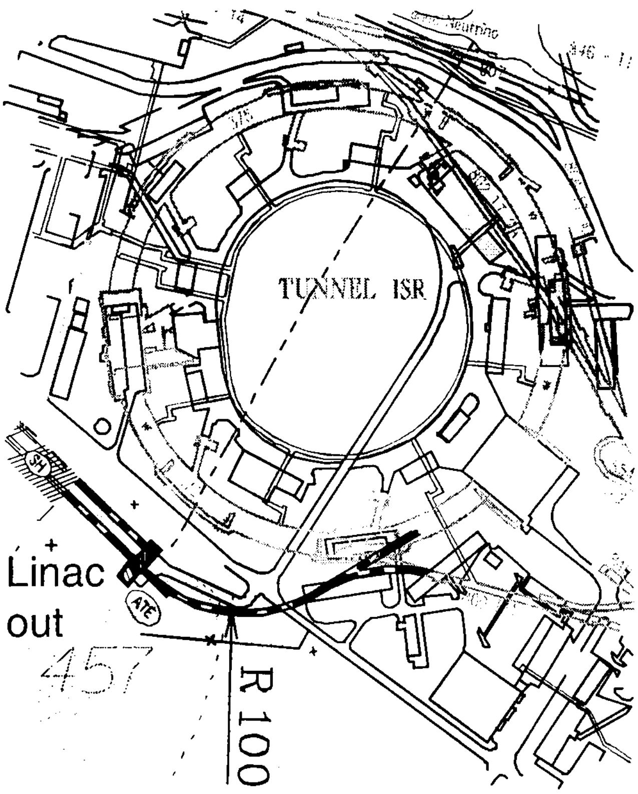

Figure 1: Layout of the transfer line on the CERN site

In order to stretch the bunches to a final length between 100 ps and 500 ps one has to use a certain length of drift, with only transverse focusing. Due to the lack of longitudinal forces the phase width increases, and the longitudinal phase space ellipse starts to rotate. Having reached the desired bunch length, several bunch rotation cavities ($\phi = -90^o$) "kick" the ellipse down to the phase axis and consequently decrease the energy spread (see Fig.2). An active debuncher at the beginning of the transfer line can be used to shorten the length of the drift, and as will be shown later, to stabilize the transfer line against phase and energy jitter from the linac. Such a debuncher consists of a number of cavities operating at $+90^o$.

In the following three different scenarios will be investigated:

1. drift + bunch rotation,
2. debuncher + drift + bunch rotation, and
3. drift + debuncher + drift + bunch rotation.

One case of the scenario no. 2 describes the version of the transfer line that is published in the SPL conceptual design report [1]. After explaining the transformation of initial errors through the transfer line, this scenario is optimized for higher error acceptance and proposed as the new reference layout.

All simulations were done with IMPACT [2] using 100000 particles and a 6D waterbag distribution (ratio between total bunch length and rms bunch length $\approx$ 2.83). The simulations start at the beginning of the superconducting part of the linac (120 MeV) with a longitudinal emittance of 0.6 π deg MeV, and a beam current of 40 mA. The emittance is likely to be reduced for future versions of the linac which will then entail changes in the longitudinal distribution. Up to now no bending magnets have been considered in the simulations.

2 Scenario no. 1: drift + bunch rotation

Without active debuncher the SPL linac tunnel becomes shorter and the the RF costs are reduced. On the other hand a longer drift is needed to sufficiently stretch the bunches. Furthermore there are less "knobs to turn" in order to stabilize the layout against phase and energy jitter.
Due to the relatively slow debunching process this set-up only makes sense for short bunches. In the present case a drift of 180 m stretches the bunches to a total length of $\approx$ 100 ps (Fig.2).

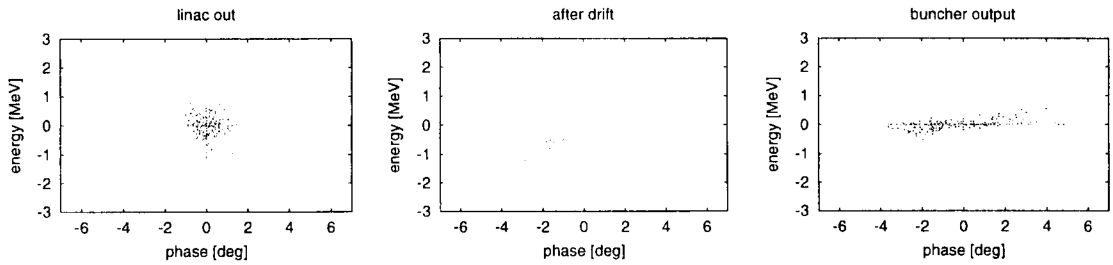

Figure 2: Beam evolution through the transfer line

After the drift, four bunch rotation cavities reduce the energy spread. The voltage that has to be imposed on these cavities is given by the slope of the longitudinal phase space ellipse after the drift (Fig.2). In this case the total bunch length of $\Delta\phi_b = \pm 6.25^o$ and the total energy width of $\Delta V_b = \pm 2.7$ MeV require a total voltage (to be seen by the beam) of:

$$V_{rotation} \approx \frac{\Delta V_b}{\sin(\Delta\phi_b)} \approx 25 \text{ MV} \tag{1}$$

Using one LEP kryostat with four LEP cavities as bunch rotator, this number translates into a cavity voltage of $E_0T = 3.7$ MV/m. In order to stabilize the system against initial phase offset a lower voltage of $E_0T = 3.2$ MV/m was chosen [Eq. (2)]. Therefore the beam ellipse remains slightly tilted after the bunch rotation.
The sensitivity against phase and energy offset at the linac output can be quickly estimated by the following formulae. For a cavity which operates either at -90^o or at $+90^o$ a phase offset $\Delta\phi$ yields an energy offset of:

$$\Delta W \approx qE_0Tl_{cav}\sin(\Delta\phi) \tag{2}$$

An additional phase error has to be taken into account, when a bunch with a certain energy offset passes the transfer line. The major part of this additional phase error accumulates during the drift, where an energy offset of ΔW yields a phase offset of:

$$\Delta\phi = \frac{l_{drift}\omega}{c_0} \cdot \left(\frac{1}{\beta(W_0)} - \frac{1}{\beta(W_0 + \Delta W)}\right) \tag{3}$$

First of all the acceptable phase error shall be estimated: To inject the beam lossfree into the PDAC RF bucket (± 2 MeV), the bunch center at the end of the transfer line must not be displaced by more than $\approx$ 1 MeV. Assuming a pure initial phase offset, the whole energy displacement of the bunch center occurs during the bunch rotation process. Eq. (2) relates the acceptable energy offset after bunch rotation to an acceptable phase jitter of $\pm 2.6^o$ at the linac output. This value would impose very tight constraints for the linac design. The only possibility to raise the acceptance for phase jitter would be to operate with longer bunches. In this case the bunch rotation voltage can be reduced and consequently the sensitivity to phase errors goes down. An example with numbers: aiming for an acceptance of $\pm 7.5^o$ (which will be achieved in a later scenario) and keeping the energy displacement during bunch rotation below ± 1 MeV requires $\approx$ 400 ps long bunches. To obtain this value the length of the drift has to be multiplied by a factor of four, resulting in a drift length of more than 700 m, which clearly exceeds feasable dimensions. The sensitivity of this design against energy offset is much less critical. One can easily work out from Eq. (2) and (3) that an energy offset of e.g. -7.5 MeV (100 ps long bunches) at the linac output yields an energy offset of -0.7 MeV after bunch rotation.

Without going into detailed simulations it is clear that this design has to be abandoned due its very small acceptance of phase errors.

Table 1: Layout parameters of the transfer line with: 180 m drift + bunch rotator (100 ps long bunches)

element	length [m]	no. of cavities	no. of focusing periods	cavity voltage [MV/m]	cavity phase [deg]
drift	179.1		14		
buncher	12.8	4	1	3.2	-90^o
total	191.9	4	15		

3 Scenario no. 2: debuncher + drift + bunch rotation

An active debuncher at the end of the linac serves two purposes: first of all it decreases the drift length of the transfer line and secondly it improves the acceptance for phase jitter from the linac.
Altogether three versions have been tested for this scenario: two with a 280 m long drift and 500 or 250 ps long bunches, respectively, and a third one with 230 m of drift and with a bunch length of 180 ps.
The first version was modelled in order to obtain a nominal output distribution with the smallest possible energy spread. It will also illustrate how an active debuncher raises the acceptance for phase jitter from the linac. After investigating the transformation of phase and energy jitter throughout the transfer line, the second version (with 250 ps long bunches) was modelled. It uses the same physical set-up of the transfer line as version no. 1 but with different voltages in the debunching- and the bunch rotation cavities. The voltages were optimized so that the transfer line can digest a higher amount of energy and phase jitter from the linac. Both versions use eight LEP type cavities as debunching unit, and two cavities as bunch rotator.
Eventually the third (and final) version was modelled, using not only the voltages but also the drift- and bunch length as free parameters. Apart from that this version has a symmetric cavity set-up with four cavites for debunching and the same number of cavities for the final bunch rotation.

Table 2: Layout parameters of the transfer line with: debuncher + 280 m drift + bunch rotator [500 ps (250 ps) long bunches]

element	length [m]	no. of cavities	no. of focusing periods	cavity voltage [MV/m]	cavity phase [deg]
debuncher	25.6	8	2	8.6 (4.3)	$+90^o$
drift	281.4		22		
buncher	12.8	2	1	4.4 (4.2)	-90^o
total	319.8	10	25		

Table 3: Layout parameters of the transfer line with: debuncher + 230 m drift + bunch rotator (180 ps long bunches)

element	length [m]	no. of cavities	no. of focusing periods	cavity voltage [MV/m]	cavity phase [deg]
debuncher	12.8	4	2	7.5	$+90^o$
drift	230.2		18		
buncher	12.8	4	1	2.5	-90^o
total	255.8	8	21		

Version 1: debuncher + 280 m drift + buncher, bunch length: 500 ps

This version represents the status of the transfer line which is published in the SPL conceptual design report [1].

Several energy and phase offsets have been imposed at the end of the linac to study their effect on the output distribution of the transfer line. Fig.3 shows an example for an initial energy offset of ±7.5 MeV and Table 4 lists the results for this error study.

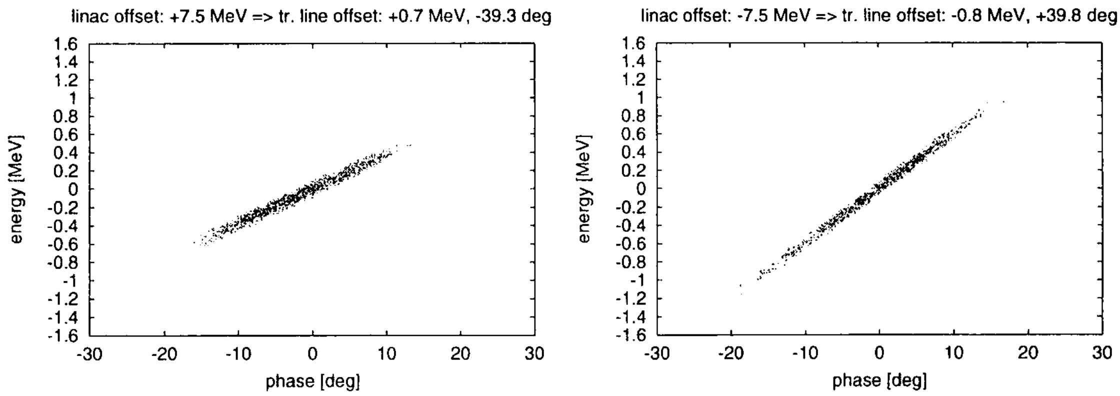

Figure 3: Transfer line output for an initial offset of ± 7.5 MeV (debuncher + 280 m drift + bunch rotator, bunch length: 500 ps)

Table 4: Transfer line output for several inital phase and energy offsets (debuncher + 280 m drift + bunch rotator, bunch length: 500 ps)

Initial offset	**nominal**	**±5MeV**	**±7.5MeV**	**±10MeV**	**±2.5°**	**±5°**
Output offset	±0.0MeV ±0.0°	±0.3MeV ±26.5°	±0.8MeV ±40°	±2.6MeV ±53°	±0.3MeV ±25°	±0.5MeV ±47°
ΔW [MeV]	±0.2	±0.7	±1.5	±2.7	±0.6	±2
$\Delta\phi$ [deg]	±28	±28	±28	±28	±28	±28

The assymetric output offset and the unequal bunch rotation for ±7.5MeV (Fig.3) is induced by the phase slippage in the 4 cell cavities. In case of energy or phase offset the tasks of focusing and acceleration inside a cavity become slightly seperated. Depending on the sign of the offset, the particles experience either more acceleration or more focusing force in the first two cells than in the last two cells of one cavity. Hence the deviation from the reference energy level becomes different. In the actual case the assymetry is enhanced by the fact that eight cavities are used for debunching the beam and only two cavities are used for bunch rotation. In a later example were four cavities are used for both tasks, the resulting assymetry is barely visible.

However, comparing these results with the previous scenario without active debuncher, one can see that the effect of initial phase jitter is reduced, while the effect of initial energy jitter (±7.5MeV) is about the same (Table 4). The acceptable phase and energy jitter for this version is in the range of ±6.5 MeV **or**[1] ±4°.

3.1 Optimization against initial phase and energy jitter

The evolution of initial phase and energy offset throughout the elements: debuncher, drift, bunch rotator can be shown with two simple pictures [bearing in mind Eqs.(2) and (3)].

An initial positive phase or energy offset (Fig.4) corresponds to bunches that arrive too early with respect to the RF cavity voltage. Faster bunches see on average a positive RF voltage (instead of 0) in the debuncher and are therefore accelerated. During the passage of the drift these bunches gain even more in

[1] Combined errors were not investigated for this version.

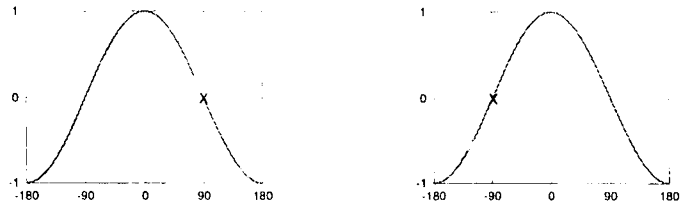

Figure 4: Arrival of bunches with positive phase or energy offset in the debunching (left) and bunch rotation (right) cavities

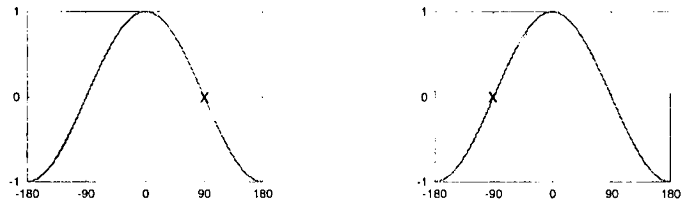

Figure 5: Arrival of bunches with negative phase or energy offset in the debunching (left) and the bunch rotation (right) cavities

phase and therefore arrive even earlier in the bunch rotation cavities. Here they see on average a negative RF voltage and are thus decelerated. For particles with an initial negative phase or energy offset (Fig.5) the inverse rules apply. The evolution of the average bunch energy (Fig.6) illustrates how the system can be tuned by varying the voltages of the debuncher- and the bunch rotation cavities.

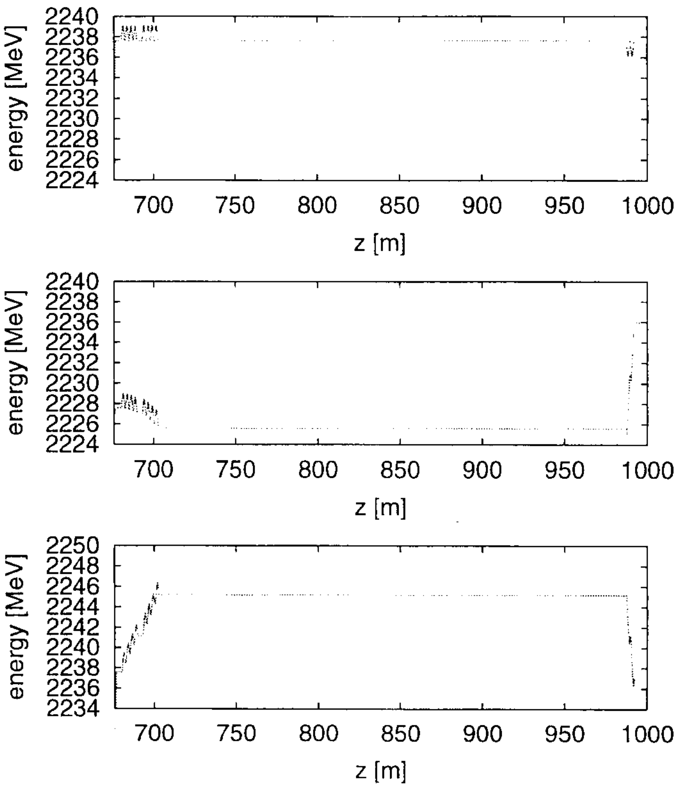

Figure 6: Evolution of average bunch energy in the nominal case (upper), with -10 MeV initial offset (middle), and with $+7.5^o$ initial offset (lower).

Version 2: debuncher + 280 m drift + buncher, bunch length: 250 ps
Using the optimization measures mentioned above and a shorter bunch length of 250 ps the same set-up was tuned for higher jitter acceptance.

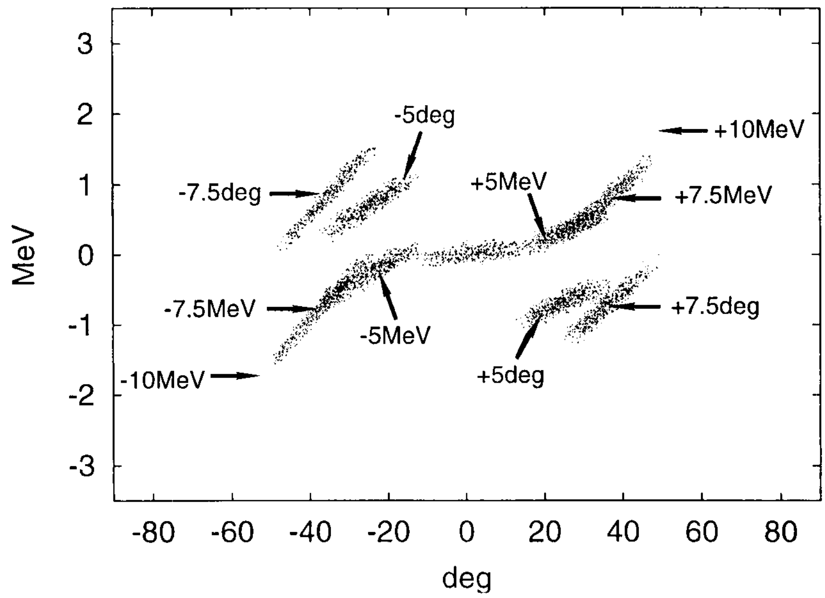

Figure 7: Transfer line output for several initial phase and energy offsets (debuncher + 280 m drift + bunch rotator, bunch length: 250 ps)

From Fig.7 one can see that the maximum acceptable jitter at the the linac output is now raised to approximately ±8 MeV **or** $\pm8^o$. Combining the initial offsets decreases the acceptance to a range of ±5 MeV **and** $\pm5^o$.

Version 3: debuncher + 230 m drift + bunch rotator, bunch length: 180 ps
For this scenario the debunching unit is reduced from eight to four LEP type cavities and the bunching unit now uses four instead of two cavities. This has the beneficial effect of reducing the length of the linac, and of producing a more symmetric deviation of bunches that only differ by the sign of their initial offset (see section 3.1). Apart from that the drift length is reduced due to the shorter final bunch length.
The length of the drift as well as the voltages in the cavities have been optimized in order to digest the highest possible amount of phase and energy jitter from the linac. As a result a maximum jitter of ±10 MeV **or** $\pm10^o$ can be accepted by the transfer line (only the case with -10^o slightly exceeds the limit of +2 MeV). The results of the error study are shown in Fig.8.
Combining energy and phase offset yields a jitter acceptance of ±6 MeV **and** $\pm6^o$. This scenario is proposed to be the new reference layout for the SPL transfer line.

4 Scenario no. 3: drift + active debuncher + drift + bunch rotation

In the previous scenario the debunching unit is placed right after the linac. The advantage of that set-up is that the power supply and the necessary cooling facilities are already available. The disadvantage is that the bunches go through the curve with an increased energy spread, which enforces large apertures for the bending magnets. Therefore it is of interest to investigate the possibility of placing the debuncher after the curve instead of before. The parameters for this layout are listed in Table 5.
Due to the 64m of drift before the debuncher, this scenario is more sensitive to initial energy jitter than the previous one. Bunches that initially only have a certain energy displacement, experience an additional phase displacement during the drift. This yields a maximum acceptance for the initial offset in the range of ±7.5 MeV **or** $\pm7^o$. Fig.9 shows the resulting longitudinal phase space distributions from the error study.

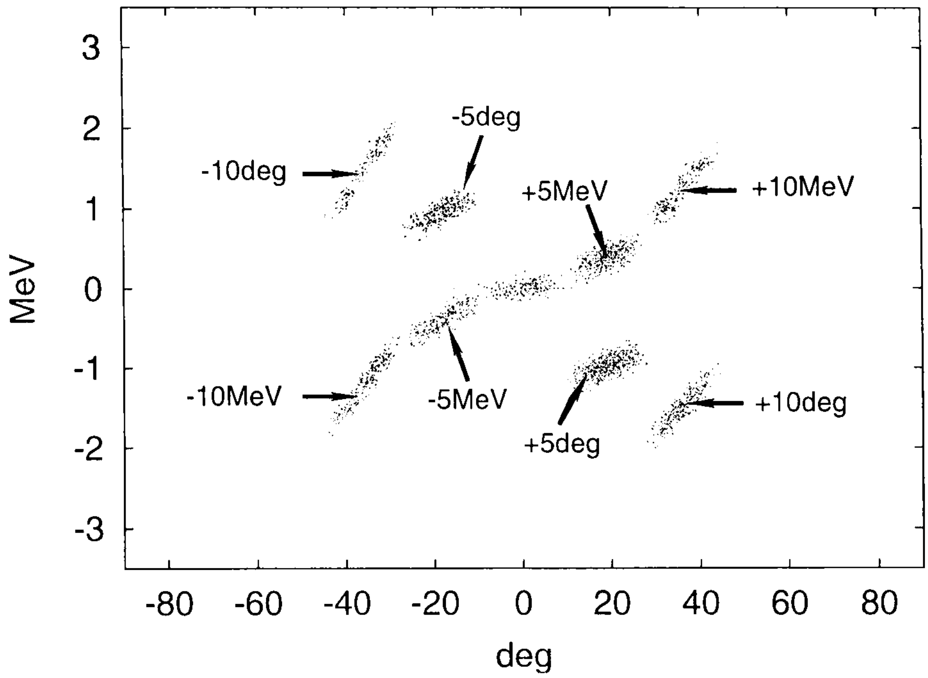

Figure 8: Transfer line output for several initial phase and energy offsets (debuncher + 230 m drift + buncher, bunch length:180 ps, **new reference scenario**)

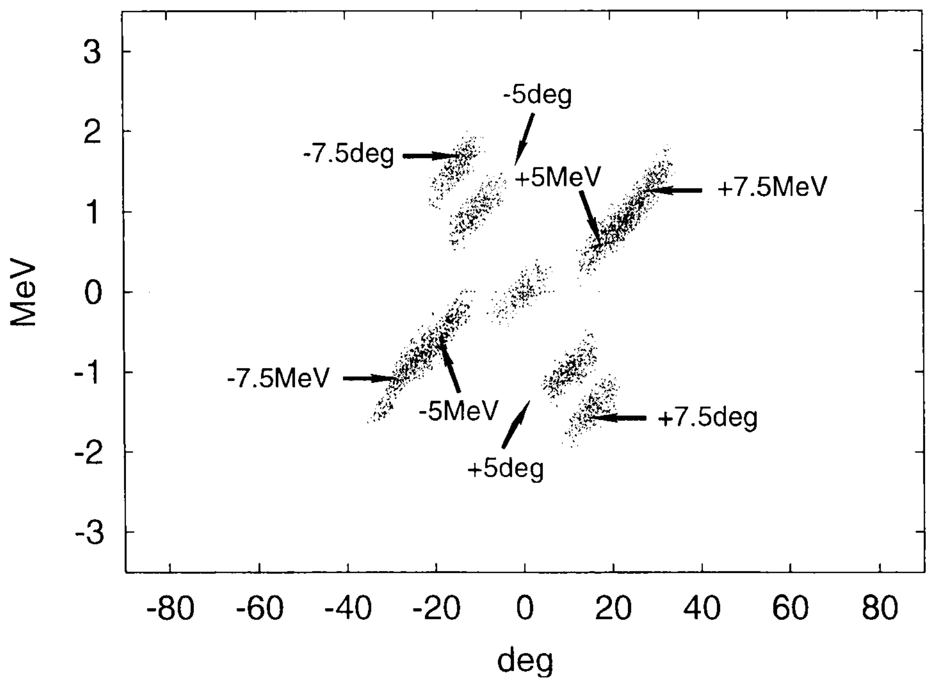

Figure 9: Transfer line output for several initial phase and energy offsets (64 m drift + debuncher + 130 m drift + bunch rotator, bunch length: 150 ps)

Table 5: Layout parameters of the transfer line with: 64 m drift + debuncher + 130 m drift + bunch rotator (180 ps long bunches)

element	length [m]	no. of cavities	no. of focusing periods	cavity voltage [MV/m]	cavity phase [deg]
drift	63.9		5		
debuncher	12.8	4	1	4.3	$+90^o$
drift	127.9		10		
buncher	12.8	4	1	3.2	-90^o
total	217.4	8	17		

5 Conclusions

Several options have been studied and optimized in order to stretch the linac bunches and fit them into the PDAC bucket of ± 2 MeV. Assuming that there is no energy or phase jitter at the end of the linac, this task can be perfectly fulfilled by a simple drift followed by a bunch rotation cavity (scenario no. 1).
A more flexible system is needed if one takes into account the actual energy and phase offset at the linac output. This flexibility can be achieved by an active debuncher at the beginning of the transfer line (scenario no. 2). Now there are three adjustment "knobs" for three bunch characterics: debuncher voltage, drift length, and bunch rotation voltage are used to tune the final energy spread, and the final energy offset of the bunches in case of initial phase or energy offset. Taking the bunch length as a variable (within certain limits) one can find an "optimum" were the acceptance for phase and energy errors becomes maximal. This optimum was found for the set-up with four debunching cavities, 230 m of drift, four bunch rotation cavities, and a bunch length of 180 ps (scenario no. 2, version 3). In this case the transfer line can accept $\pm 6^o$ **and** ± 6 MeV (with both offsets occuring simultaneously). I propose this scenario as the new reference layout for the SPL transfer line, keeping in mind that some of the parameters might change in order to adapt the system to a future change of the longitudinal emittance.
An additional drift *before* the debunching cavities might be desirable in order to have less energy spread when the bunches pass the curve that follows the SPL (scenario no. 3). However, this measure reduces the error acceptance of the system.
In all three scenarios it is possible to "trade" a bigger phase offset against a smaller energy offset and vice versa. The error acceptance will be reduced, when considering a mismatched linac beam.

6 Acknowledgements

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