

Figure 3: Flux and average momentum of positive and negative particles at the end of the phase rotation channel.

This choice of how to run the phase rotation system is actually another of the many branch points in the design of a front-end system. The choice made here has two main advantages. (1) Subsequent systems down to the collider should have approximately equal numbers of particles per bunch. As a result, hardware design, beam loading and instabilities should be similar for the two beams. (2) This mode of operation gives both charges of particle beam for every proton driver pulse on target. However, this mode of operation also has two disadvantages. (1) The phase spaces of the two beams in the charge separation system are different. The positive beam has higher momentum, while the negative beam is spread out more in time. This makes it more difficult to simultaneously optimize the charge separation system for both signs. (2) The phase chosen does not give the maximum number of particles available from the phase rotation system.

There is an alternative mode of operation, which was adopted in a previous feasibility study [1], where one proton driver pulse is dedicated to the positive charge beam and the following pulse is dedicated to the negative charges. However, the pulse repetition frequency for a given sign in this mode is only 50%. At this point it is not clear which scheme is better.

## CHARGE SEPARATION

We assume that the charge separation system must deliver the two beams to separate linear 6D precooling channels. We require that the two channels be parallel to each other, and be in a plane roughly parallel to the surface of the earth. Since the precooler will almost certainly contain low-frequency rf cavities, we also demand that the two channels be a reasonable distance, say ~5 m, apart. We want the final charge-separated beams to be as identical as possible. Thus the system should also include some provision for reducing the momentum of the positive beam. We would also like to present the precooler with “clean” beams. Thus some provision must be included to remove the dispersion that has to be introduced to do the charge separation.

The conventional method of charge separation uses a sequence of dipoles. However, since the phase rotator and most cooling designs use solenoidal focusing, it is more natural to use a bent solenoid to separate the charges [7]. Dispersion in a bent solenoid occurs in the direction perpendicular to the bending plane. The amount of dispersion is proportional to the total bend angle.

In the simulations [8] we use a constant radial cut-off of 30 cm everywhere, except in the bent solenoid that does the actual charge separation. The charge separation bent solenoid needs a very large aperture to contain both the incoming and outgoing beams. The charge separation bent solenoid does not use a superimposed dipole field, whereas all other bent solenoids used in the charge-separated transport lines do have a dipole field to keep the reference momentum on the system axis. All the bent solenoids have a curvature factor  $h \sim 0.3$ . The charge separation bent solenoid has two circular holes of radius 30 cm in the exit plane. The centers of the holes are adjusted to match the mean transverse deflection of the two charges. The tails of the beams are lost getting into the holes and, in addition, there are significant losses of particles with large divergences over the following few meters of the transport.

As a figure of merit we look at the number of particles at the end of the system that are enclosed in a rectangular box in longitudinal phase space. The box has a length of 6 m and a height of 200 MeV/c. These values were chosen to roughly take into account the maximum likely momentum acceptance and rf frequency (~40 MHz) of the precooler. The position of the box in phase space is varied to find the location with the maximum particle density.

The optimal charge separation configuration is shown in Fig. 4. We found that the transmission through the system was maximized by introducing a 1 m long transition region (T) where the solenoidal field was increased from 1.75 to 3 T. Increasing the solenoid above 3 T does not help because it causes the separation of the centers of the charge distributions at the exit plane to come too close together. We also include a transition region (-T) in the output beamline that returns the solenoid field to 1.75 T. The total length of the positive channel is 16.7 m, while that of the negative channel is 11.4 m.

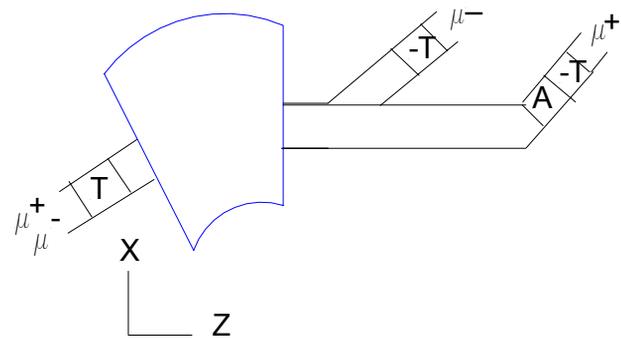


Figure 4: Schematic diagram of the optimal charge separation configuration.

The simulations include particle decay, an absorber in the high momentum line (A), and a realistic field model. The length of the absorber was chosen so that the positive and negative beams had the same momentum ( $\sim 200$  MeV/c) at the end of the system. The absorber was a 75 cm long cylindrical block of LiH.

The bent solenoids were modeled by specifying a smoothly varying solenoid field  $B_s(s)$ , dipole field  $B_y(s)$  and curvature  $h(s)$  along the axis. ICOOL fits nearby grid points to a polynomial in order to interpolate values off the grid points and to obtain required s-derivatives analytically. The code uses a 3rd order solution of Maxwell's equations to obtain field values at off-axis points. We required the same geometrical curvature function for positive and negative particles in order to ensure the final beam channels were parallel.

The design does a good job in equalizing the two beam momenta and in removing the dispersion. There is a significant drop in transmission compared with a hard-edge model of the fields. Although the magnitudes of the curvature and dipole field were optimized, no attempt was made to optimize the shape of the on-axis fields. Most of the positive particles fit in the standard phase space box, while a significant fraction of the negative particles do not. The negative particles have a much wider time spread. Almost all of the dispersion is removed at the end of both channels. The distribution of particles at the bent solenoid exit plane is shown in Fig. 5.

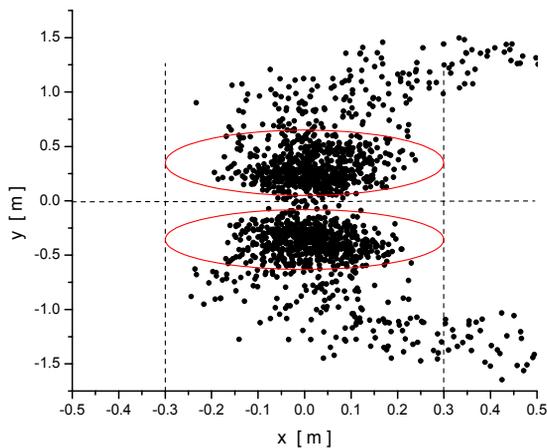


Figure 5: x-y distribution of particles at the exit plane of the charge separation bent solenoid.

Approximately 60% of the beam at the end of the phase rotation channel is in a halo outside the desired phase space box.

## BEAM PROPERTIES

So far self-consistent simulations have been completed through the 39 m long phase rotator and the 11-17 m long charge separation system. The beam properties at the end of the channel are summarized in Table 1.

Table 1: Beam properties at end of charge separation channel

Charge	$\epsilon_{TN}$ [mm]	$\epsilon_{LN}$ [mm]	$p$ [MeV/c]	$\mu / p$
+	21	420	204	0.27
-	23	380	205	0.28

Both sign beams have large normalized transverse emittances  $\sim 22$  mm and large longitudinal normalized emittances  $\sim 400$  mm. Sending the positive beam through the LiH absorber results in both beams having mean momentum  $\sim 204$  MeV/c. The last column gives the final number of muons in the standard longitudinal phase space box per incident proton on the production target. At the end we still have a significant useful muon yield  $\sim 0.28$   $\mu/p$ . Now that the charges have been separated, the next step will involve precooling the beam emittance to a level where injection into a ring cooler is possible.

## REFERENCES

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