THE 4 GEV H⁻ BEAM TRANSFER LINE FROM THE SPL TO THE PS2

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Abstract

The proposed new CERN injector chain LINAC4, SPL, PS2 will require the construction of new beam transfer lines. A preliminary design has been performed for the 4 GeV SPL to PS2 H^- transfer line. The constraints, beam parameters and geometry requirements are summarised and a possible layout proposed, together with the magnet specifications. First considerations on longitudinal beam dynamics and on beam loss limitations from H^- lifetime are presented.

INTRODUCTION

In order to provide the reliable high-intensity beams required for the planned LHC luminosity upgrade [1] an upgrade of the present LHC injector chain has been proposed by the study group on Proton Accelerators for the Future (PAF). Within the scope of this upgrade it is foreseen to stage the replacement of the present injectors LINAC2, PS Booster and PS by a new superconducting H^- linac (SPL) [2], its low energy front end LINAC4 [3] and a new proton synchrotron (PS2) [4]. The SPS accelerator will also require important system upgrades. This new injector chain will also improve the beam availability which is limited in the present chain by the age of the accelerators dating from 1959 to 1978. These new machines require also new transfer lines, the preliminary design of one of which – from SPL to PS2 – is presented in this paper.

BEAM LINE PROPERTIES

General Beam Parameters

The new LHC injector chain could also serve as driver for future physics experiments like a possible neutrino facility and should therefore have flexible beam properties. Hence, there exists a low power and a high power design version of the SPL delivering beams with kinetic energies of 4 and 5 GeV and beam powers of 0.2 and 4 MW respectively (LP-SPL and HP-SPL). An interesting further option for the future might be to operate the SPL at 5 GeV but with low power beams (LP-SPL-5G). The first part of the SPL-to-PS2 transfer line up to the point where a beam line to a future facility can branch off must therefore be compatible with all options whereas the second part needs to be compatible only with the 4 and 5 GeV versions of the LP-SPL. The most important beam parameters concerning the transfer line are summarized in Table 1.

Beam Loss Limitations

A characteristic of the H^- beam in contrast to proton beams is that the outer-shell electron can be easily removed in strong magnetic fields, due to the so-called Lorentz stripping. To limit the resulting beam loss and to prevent radiation protection problems, the magnetic fields of the beam line elements must not exceed a certain value. This maximum B field has been calculated from the maximum fractional loss rate df/ds using the following equation (from [5])

$$\frac{df}{ds} = \frac{B}{A_1}\exp\left(-\frac{A_2}{\beta\gamma c B}\right),$$

where β and γ are the relativistic β and γ factors and c the light velocity. A_1=2.47·10^{-6} Vs/m and A_2=4.49·10^{9} V/m are constants [5]. The maximum fractional loss values were calculated from a maximum power loss of 0.1 W/m. The resulting limits for the magnetic field and the bending radii are listed in Table 1.

Table 1: Beam Parameters of the Different Modes of Operation of the SPL

Parameter	LP-SPL	LP-SPL-5G	HP-SPL
Kin. energy [GeV]	4	5	5
Beam power [MW]	0.192	0.24	4
Repetition rate [Hz]	2	2	50
Particles per pulse	$1.5\cdot10^{14}$	$1.5\cdot10^{14}$	$1.0\cdot10^{14}$
Pulse length [ms]	1.2	1.2	0.4
Average/peak pulse current [mA]	20/32	20/32	40/64
Max. fract. loss [m^{-1}]	$5.2\cdot10^{-7}$	$4.17\cdot10^{-7}$	$2.5\cdot10^{-8}$
Max. B field [T]	0.115	0.0950	0.0858
Min. bend. radius [m]	141	206	228

Geometrical Constraints

The beam line has to overcome an altitude difference of 21 m between the SPL and the PS2 over a distance of only 421 m. Due to the limited magnetic field the beam line must be bent smoothly. Furthermore, several tunnels (e.g. of the TI 2 transfer line) have to be crossed by the beam line which means that the line has to pass by a fixed point (point C in Fig. 1) to ensure a sufficient distance from the existing tunnels. The first beam line design results in a large tunnel slope of maximum 7.7%.

BEAM LINE LAYOUT

On the basis of these limits the beam line layout shown in Fig. 2 has been proposed. It is based on a FODO lattice with 90° phase advance per cell and a cell length of 25 m. It consists of two combined horizontal and vertical bending sections which bend the beam downwards and to

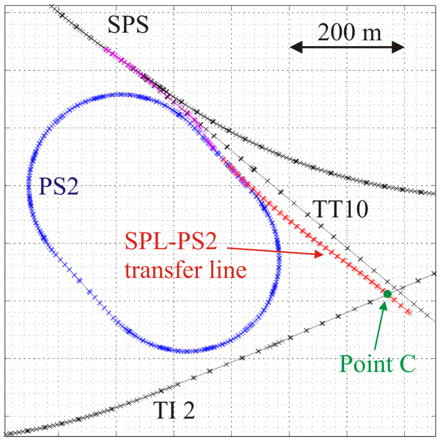

Figure 1: Plan of the foreseen location of the PS2 and the SPL-PS2 transfer line.

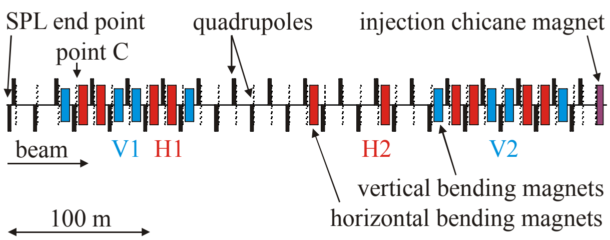

Figure 2: Beam line layout of the SPL-PS2 transfer line. A FODO lattice with 90° phase advance per cell and four families of bending magnets is being used.

the left and thereafter to the right and upwards into the PS2 plane. It may be possible to reuse former LEP dipole magnet cores equipped with new coils as bending magnets, since these are ideally suited for the SPL-PS2 transfer line due to their low magnetic field. With this magnet type the beam loss requirements are fulfilled for HP-SPL and 5 GeV LP-SPL beams in the first and second bending section respectively (Table 2).

Table 2: Magnet Specifications

Dipole family	**Quantity**	**Length [m]**	**B [T] @ 4GeV**	**B [T] @ 5 GeV**
V1	4	5.75	0.043	0.052
H1	4	5.75	0.045	0.055
H2	6	5.75	0.073	0.089
V2	4	5.75	0.053	0.065
Quadrupole family	**Quantity**	**Length [m]**	**G [T/m] @ 4GeV**	**G [T/m] @ 5 GeV**
Matching 1	4	2	1.05	1.27
Arc QF	11	2	0.97	1.17
Arc QD	11	2	0.97	1.17
Matching 2	8	2	1.13	1.37

OPTICS SIMULATIONS

For the proposed design, detailed optics simulations at zero current have been carried out initially with MAD-X [6]. The simulated beta and dispersion functions are shown in Fig. 3. The beam line has been matched to the SPL and the PS2 using four and eight quadrupoles respectively (Table 2). The lattice has been optimized to suppress the dispersion by arranging the dipole magnets in equally powered pairs with 180° phase advance so that their dispersion effects cancel. Subsequently the required dispersion value of -0.4 m in the horizontal plane at the injection point into the PS2 was created by varying the matching quadrupoles.

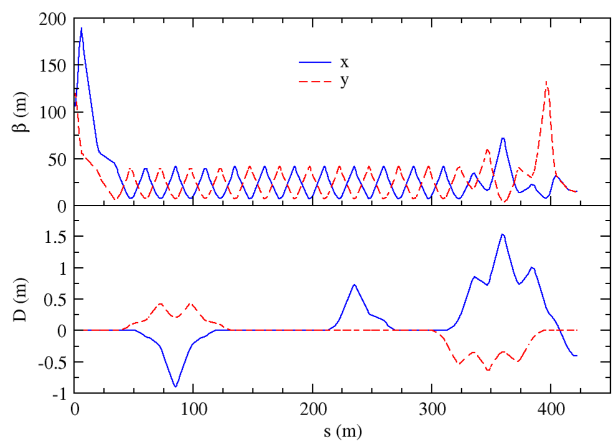

Figure 3: Simulated beta and dispersion functions along the SPL-PS2 transfer line for a 4 GeV H$^-$ beam using MAD-X.

In a second step multi-particle simulations were performed using the code TraceWin [7], which takes longitudinal beam dynamics and space charge effects into account.

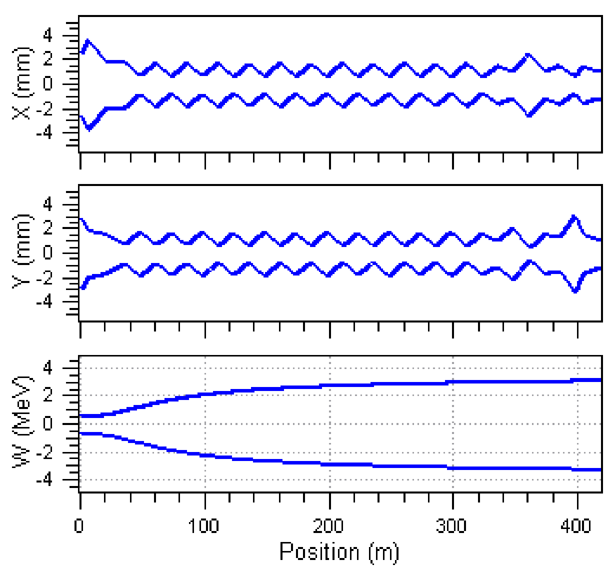

Figure 4: Envelopes in the horizontal (top) and vertical (middle) planes plus the beam energy spread (bottom) evolution along the beam line with a current of 62 mA.

Simulations showed that the horizontal and vertical emittances of the beam increase by 23% and 2% respectively. Higher emittance growth in the horizontal plane is due to the chromaticity of the line which is needed for dispersion matching at the injection point into PS2. The energy spread of the beam, as an effect of space charge, increases from ±1.5 MeV to ±7 MeV. If further studies confirm the need for a lower energy spread a debuncher cavity has to be added into the transfer line. The evolution of the beam envelopes and the energy spread along the beam line is shown in Fig. 4.

TRAJECTORY CORRECTION

An investigation of possible trajectory correction systems, based on the following assumed errors, has been carried out using MAD-X:

- Quadrupole displacement errors: Gaussian distribution in x/y-plane with σ = 0.2 mm;
- Dipole field errors: Gaussian distribution of deflection angle with σ = 10 μrad (corresponds to a relative field error of $5 \cdot 10^{-4}$);
- Dipole tilt errors: Gaussian distribution with σ = 0.2 mrad;
- Monitor errors: Flat random distribution of ±0.5 mm in both planes;
- Injection error: Gaussian distribution of position and angle with σ = 0.5 mm and 0.05 mrad respectively;
- Monitor failure probability of 5%.

Based on these errors the following correction schemes have been studied:

- each quadrupole equipped with one monitor and one corrector (referred to as 1-in-1 scheme);
- every third corrector and monitor has been dropped from the 1-in-1 scheme (2-in-3 scheme);
- each quadrupole equipped with one monitor, two consecutive quadrupoles out of three equipped with correctors (combined 1-in-1 / 2-in-3 scheme).

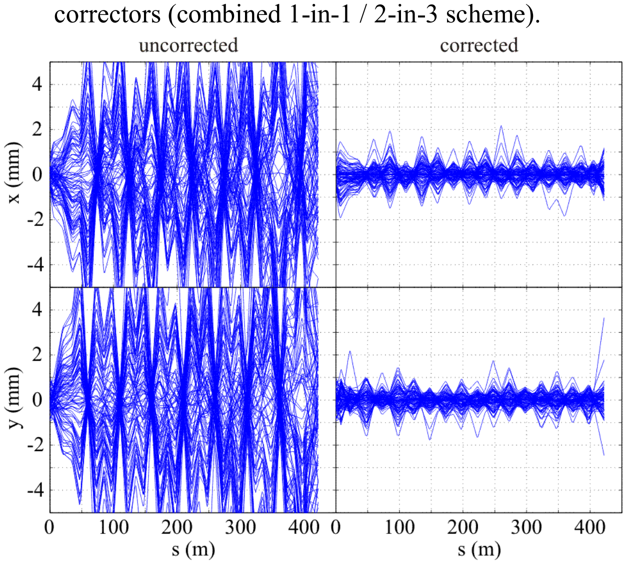

Figure 5: Plot of 100 uncorrected and corrected trajectories for the combined 1-in-1 / 2-in-3 scheme.

The combined scheme was identified to be the optimum solution. Whereas the stability is comparable to the 1-in-1 scheme the costs are lower. In the 2-in-3 scheme, however, the trajectory excursions are higher, especially in the case of monitor failures. Figure 5 shows 100 simulated uncorrected and corrected trajectories for the combined scheme. The resulting corrector strength is below 0.04 T and the trajectory excursion is in most cases less than 1 mm, which is within the specification. However, there exist a few rare cases where the correcting system fails. This might happen if one of the two last monitors or two consecutive monitors fail.

CONCLUSION

The feasibility of the H^- beam line from the SPL to the PS2 has been demonstrated. The proposed design fulfils the geometrical constraints as well as the beam loss requirements and is optimized in view of the costs.

Multi-particle simulations showed that the emittance increase in the line for a current of 62 mA is within the acceptance of PS2. A debuncher should be added into the beam line if further studies on PS2 confirm the need for a lower energy spread at the injection point.

In addition to the FODO version of the beam line an alternative lattice based on doublets with 90° phase advance per cell and three times the SPL cell length of 14.4 m is also under study. First results show that the constraints can also be fulfilled with this lattice, however, with a slightly larger slope of 8% and larger beta function values. More detailed work on both designs will be carried out.

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