BEAM DYNAMIC CALCULATIONS FOR THE SUPERCONDUCTING COSY INJECTOR LINAC

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Abstract

A superconducting injector linac for the Cooler-SYnchrotron COSY is under investigation to increase the intensity of polarized proton and deuteron beams [1]. In this report the layout and magnet requirements of the matching and linac section are discussed and sensitivity studies of the lattice performed to find the requirements for an orbit correction system. A 6-dimensional multi-particle tracking code [2] was used to simulate the beam in the transverse and longitudinal phase space.

INTRODUCTION

The Institut für Kernphysik of the Forschungszentrum Jülich is investigating a new injector (COSY-SCL) for the cooler-synchrotron COSY, which will replace the more than 30 years old cyclotron JULIC. Our aim is to increase the intensity of polarized proton and deuteron beams in COSY typically by a factor of 10 compared to what can be delivered to experiments at present. The conceptual design of COSY-SCL has been described previously [1]. It makes use of a superconducting linac, together with advanced ion sources and interchangeable 160 MHz RF-quadrupole (RFQ) pre-accelerators including booster cavities for H^- and D^- beams, respectively. The linac design is based on a 44 single-cell half-wave resonator (HWR) acceleration structure, of which the first 20 resonators operate at 160 MHz and the remaining 24 at 320 MHz, for delivering both polarized and unpolarized pulsed H^- and D^- beams at a kinetic energy between 50 and 60 MeV for charge exchange (stripping) injection into COSY. The beam current will be limited to 2 mA (peak) in pulses lasting up to 500 µs at a maximum repetition rate of 2 Hz.

Beam dynamic simulations have been carried out to investigate the transversal optics and orbit deviations in the matching and linac sections due to misalignments of optical and accelerating elements.

BEAM MATCHING SECTION

The layout of the matching section including the first two unit cells of the linac can be seen in Fig. 1 (upper part). The whole matching section has only a length of about 1 m, 78 cm for the focusing magnets including drift spaces and 21 cm for a 160 MHz rebuncher. Quadrupole doublets are used for transverse focusing. This simple type of focusing structure fits the requirements for the matching section, because it automatically creates a circular transverse beam profile between the two quadrupoles as well as in the middle of the rebuncher, where the beam size is of the order of 13 mm in diameter. The two quadrupole doublets located upstream and downstream of the rebuncher are also sufficient to match the orientation and size of the transverse phase space distribution from the exit of the RFQ section to the entrance of the first cryostat. The second quadrupole doublet is already part of the first linac unit cell. To reduce construction costs, the same quadrupole type like in the linac section can be utilized. Such quadrupoles have an effective length of 8.5 cm, an aperture of 38 mm and a maximum gradient of 45 T/m [3]. The following transverse beam properties at the end of the RFQ section are expected for D^-: $\varepsilon=5\pi$ mm.mrad (1σ, geometric), $\alpha_{x,y}=$ -1.5; 0.6, and $\beta_{x,y}=0.4$ m/radian; 0.2 m/radian [4]. In Figure 1 (lower part) the transverse beam envelopes are shown. The maximum focusing gradient for this layout is less than 20 T/m for D^- and less than 10 T/m for H^-. The diagnostic devices will be placed between the quadrupoles, following the same adjustment procedure like in the linac section itself [1].

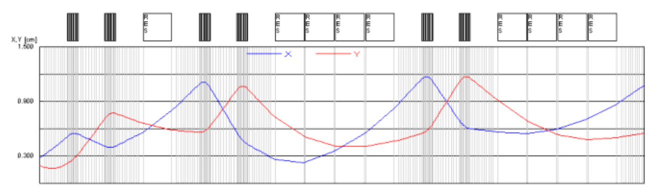

Figure 1: Matching section including the first two unit cells of the linac (upper part) and transverse 4σ beam envelopes in the matching section and at the entrance of the linac (lower part).

For longitudinal beam matching, a 2-gap-spiral resonator with approximately 100 kV maximum voltage and a length of 15 cm is proposed [4]. Since the RFQ sections for H^- and D^- are nearly the same, except for a few periods in the first part of the two RFQs, roughly the same particle distribution is expected for H^- and D^- at the exit of the RFQ section. The bunch length is about ±15° with a full energy spread of 75 keV/nucleon (Figure 2). In the drift between RFQ and rebuncher, the longitudinal phase space distribution diverges, leading to a bunch length of more than ±20°. The rebuncher inverts the energy deviation of the beam, leading to a converging beam in longitudinal phase space. This requires a peak voltage of 45 kV for D^- and 22.5 kV for H^- with the present rebuncher design. Thus the beam motion from the exit of the RFQ section to the entrance of the first cryostat corresponds to a 180° image of the beam in longitudinal phase space. The longitudinal phase space distribution continues to converge in the first cryostat to a very small

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bunch length of less than ±5° in the middle. Simulations show, that the presented layout is capable to accept 5 % variation of the initial beam parameters without beam losses. It also clarifies, that the rebuncher doesn't need any transverse beam focusing properties.

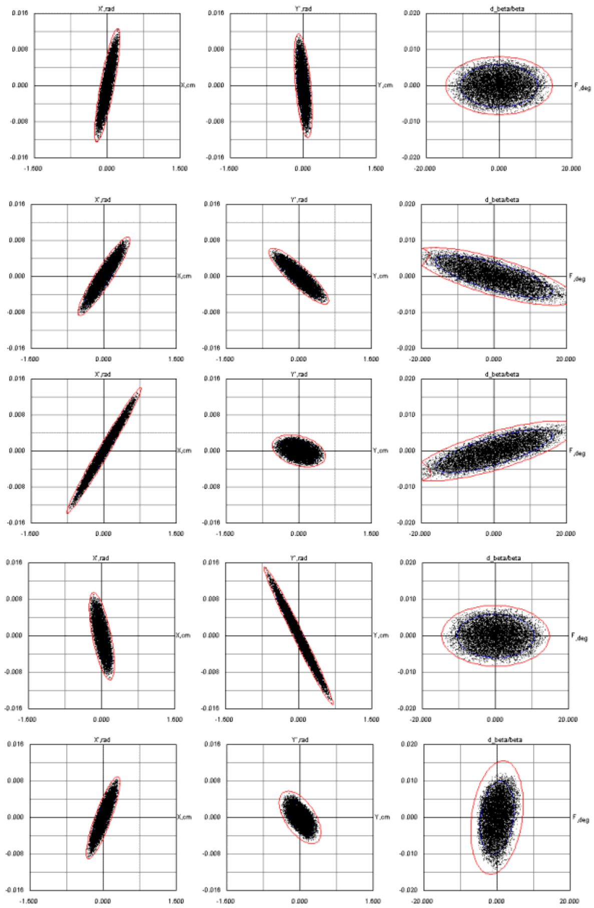

Figure 2: Transverse and longitudinal phase space distribution of the beam (from the top) at the exit of the RFQ section, the entrance of the rebuncher, the exit of the rebuncher, the entrance of the first cryostat, and in the middle of the first cryostat.

LINAC SECTION

Four resonators will be mounted in each cryostat. Quadrupole magnets and also diagnostic devices will be placed between the cryostats. Transverse beam focusing in the linac is based on a doublet like structure outside the cryostats, utilizing two conventional quadrupole magnets in each unit cell with a diagnostic box in between. Since we are limited in length of the unit cells due to beam dynamical requirements for the longitudinal phase space [1], the design of the quadrupoles is critical in terms of physical length and maximum gradient. We tried to optimize the drift space between the quadrupoles and the length of the magnets by two criteria, moderate quadrupole gradients with acceptable beam envelopes. After several iterations, we came to the conclusion that the best compromise is to use a unit-cell length of 1.7 m and an effective quadrupole length of 8.5 cm with theoretical gradients of less than 40 T/m. This corresponds to a physical magnet length of 12.5 cm and a drift space of 13 cm in between the two quadrupoles of a doublet. Identical arrangements can be used for all unit cells.

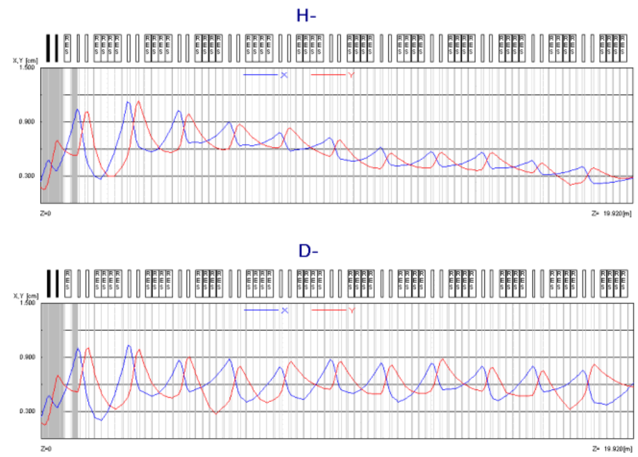

Figure 3: Lattice of the linac including the matching section. 4σ beam envelopes computed for accelerating H^- (upper plot) and D^- periodically constant throughout the linac and can be optimized further.

Figure 3 shows the beam envelopes computed for H^- and D^- using 10000 particles. The quadrupole settings are chosen for keeping the beam envelopes periodically constant throughout the linac and can be optimized further. The betatron amplitudes and thus also the beam envelopes have a periodic structure. The minimum of the betatron amplitude in each unit cell is slightly increasing with the rigidity of the beam, depending on the focusing strength applied. The 4σ beam envelope is expected to be less than 12 mm. The maximum gradient needed for this lattice is about 25 T/m for 50 MeV H^- and 38 T/m for 56 MeV D^-. Figure 4 shows the results obtained for the 6-dimensional phase space of the H^- and D^- beams at the linac exit.

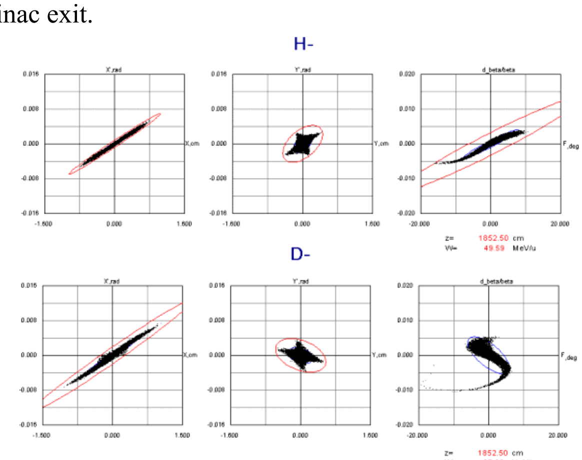

Figure 4: The 6-dimensional phase space computed by tracking simulations for 50 MeV H^- (upper plots) and 56 MeV D^- (lower plots) beams at the linac exit.

These results indicate that in such a lattice we would have to expect a transverse geometric beam emittance (4*rms) of less than 4π mm.mrad for H^- and about 5π mm.mrad for D^- at the linac exit (see table 1).

Table 1: Geometric beam emittance (4*rms and max.) at the exit of the linac section.

	Horizontal (geom.)	Vertikal (geom.)
H^-		
4*rms	2.6π mm.mrad	3.6π mm.mrad
Max.	8.9π mm.mrad	16.7π mm.mrad
D^-		
4*rms	4.6π mm.mrad	4.7π mm.mrad
Max.	36.2π mm.mrad	20.5π mm.mrad

For the longitudinal phase space at extraction one finds minimum Δp/p values of $\pm 2\times 10^{-3}$ and $\pm 8\times 10^{-3}$, respectively, depending on the orientation of the longitudinal phase space distribution of the beam.

SENSITIVITY OF THE LATTICE

Orbit deviations in the linac are mainly caused by misalignments of magnets and resonators. To determine such effects, magnets and resonators are randomly shifted in all three dimensions by maximum values of ±0.1 mm and ±0.75 mm, respectively [5]. In addition the phase and amplitudes of the resonators are also randomly changed by up to ±0.5° and ±0.5 %. For each case ten samples of 1000 particles were tracked through the matching and linac section. Figure 5 shows the resulting orbit deviations and associated divergences of the beam center for H^- in the horizontal and vertical plane.

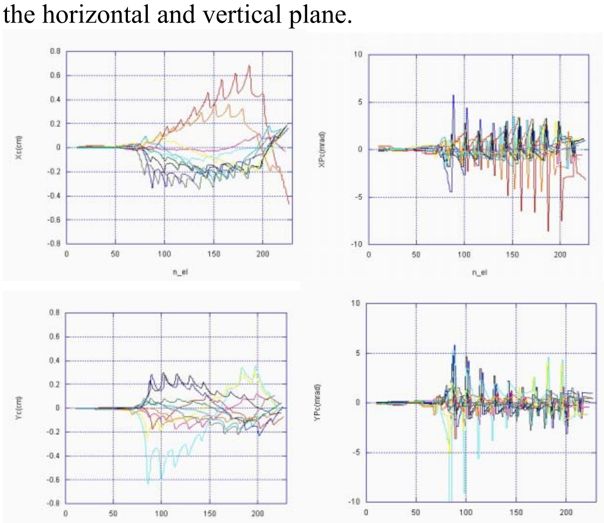

Figure 5: Orbit deviations (left) and divergences (right) of the beam center in the horizontal (upper plots) and vertical (lower plots) planes for H^- versus element number for ten different cases of randomly distributed errors.

The orbit deviation of the beam center for H^- is less than 8 mm with a orbit divergence up to 10 mrad. For D^- this effect is smaller. The maximum orbit deviation of the beam center in both planes is only about 4 mm and the maximum orbit divergence about 8 mrad. Taking maximum beam envelopes of about 11 mm and maximum orbit deviations of about 8 mm into account, the acceptance of the machine is too small without orbit corrections, leading to significant beam losses.

CONCLUSION

For 50 MeV H^- and 56 MeV D^-, quadrupoles with an effective length of 8.5 cm and a maximum gradient of 45 T/m are sufficient to focus the beam in the given lattice with a unit cell length of 1.7 m. Without correction, significant beam losses are expected. To reduce beam losses, typical correcting angles of up to a few milliradian for H^- and D^- are required, if one would place correcting dipoles between the quadrupoles of the doublets or use extra dipole windings on the quadrupoles. A correction system or beam based alignment is certainly needed under these circumstances, and a steering concept will have to be developed.

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