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Keywords : High-Power Proton Synchrotron (HP-PS) ; LAGUNA-LBNO

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The prospects for future high-power proton beams for producing neutrinos at CERN within the LAGUNA-LBNO study, include the design of a 2 MW High-Power Proton Synchrotron (HP-PS). In this paper, the optics design of the ring is reviewed, comprising Negative Momentum Compaction (NMC) arc cells and quadrupole triplet long straight sections, flexible enough to achieve the constraints imposed mainly by different beam transfer equipment and processes. A global tunability study is undertaken including aperture and magnet parameter considerations. Basic correction systems are specified and their impact to beam dynamics including dynamic aperture is finally evaluated.

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OPTICS DESIGN OF THE HIGH-POWER PROTON SYNCHROTRON FOR LAGUNA-LBNO *

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Abstract

The prospects for future high-power proton beams for producing neutrinos at CERN within the LAGUNA-LBNO study, include the design of a 2 MW High-Power Proton Synchrotron (HP-PS). In this paper, the optics design of the ring is reviewed, comprising Negative Momentum Compaction (NMC) arc cells and quadrupole triplet long straight sections, flexible enough to achieve the constraints imposed mainly by different beam transfer equipment and processes. A global tunability study is undertaken including aperture and magnet parameter considerations. Basic correction systems are specified and their impact to beam dynamics including dynamic aperture is finally evaluated.

INTRODUCTION

Design studies for a High-Power Proton Synchrotron (HP-PS) have been initiated in the framework of the LAGUNA-LBNO project under FP7 [1], in order to enhance the potential of high-power proton beams at CERN, for neutrino experiments. The HP-PS is designed to receive an H^- beam from the Low Power Super-conducting Proton Linac (LP-SPL) [2] at around 4 GeV, through a charge exchange injection system (foil or laser stripper) [3]. The high-intensity proton beam is formed by a multi-turn phase space painting process and accelerated to 50 GeV for delivering an average beam power of 2 MW on target. Several ring design concepts have been already explored regarding the HP-PS beam dynamics and technology [4]. In this paper, the ring optics choices and performance are being detailed, including tunability studies, linear correction systems and single particle non-linear dynamics.

RING PARAMETERS

In order to reach high average beam power, the HP-PS needs to maximise the product of average current (number of particles times repetition rate) and kinetic energy. Considering a maximum rate of 2 Hz imposed by the LP-SPL, and an operating duty factor of 50%, the repetition rate of the HP-PS is chosen to be 1 Hz. Higher extraction energy is preferable for reaching the target power but this requires larger circumference or bending field at flat top, for a certain ring filling factor. A 50 GeV ring with circumference of 1256.7 m is the present design baseline. It is filled with super-ferric dipoles of 2.1 T peak field. The circumference was increased with respect to a previous version of the design [4], allowing the optimal filling of the SPS, if this is required in the future. An alternative parameter set is also considered, for a ring with the same circumference, but a higher energy (75 GeV), where the dipoles need to reach a peak field of 3.1 T. The design parameters for the two energy options of the HP-PS can be found in Table 1.

Table 1: Design parameters of the baseline 50 GeV HP-PS ring and the alternative 75 GeV-ring.

Parameters [unit]	50 GeV	75 GeV
Circumference [m]	1256.7	
Beam Power [MW]	2	
Repet. Rate [Hz]	1	
RF Frequency [MHz]	40	
RF harmonic	168	
Number of bunches	157	
Symmetry	3-fold	
Lattice type	NMC arc, triplet LSS	
Kin. Energy @ inj./ext. [GeV]	4/50	4/75
Protons/pulse [10^{14}]	2.5	1.7
Dipole ramp rate [T/s]	3.5	5.5
Bending field @ ext. [T]	2.1	3.1
Max. quad. field [T]	1.23	1.85
Dipole gap height [mm]	118	86
Norm. emit. H/V [mm-mrad]	10/17	10.6/8.3
Energy spread @ injection [10^{-3}]	5.4	5.4

The high-energy option is quite interesting because, although it is based on a demanding magnet technology (peak field and ramp rate), it permits the reduction of the required pulse intensity from 2.5 to 1.7×10^{14} protons, as shown in Table 1. Both intensities require longer linac pulses than the present baseline of the LP-SPL [2], which thereby impacts the temperature rise and hitting rate of the stripping foil. On the other hand, if the magnetic parameters appear beyond reach, a reduction of the repetition rate by 20% with a corresponding increase of the intensity should be considered, for reducing the ramp rate to around 4.7 T/s. At present, a 40 MHz RF system is considered (as in PS2 [5]), which allows some tuning flexibility but also lower peak currents, as compared to the 10MHz RF system of the actual PS.

LAYOUT AND OPTICS

The two rings are based on the same optics and layout, although magnet parameters have to be adapted for reaching the higher energy. The HP-PS does not have strict layout requirements, apart from positioning the injection point such that it is compatible to the SPL. Considering the

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high-power target position towards the SPS north area and a possible future connection with the SPS ring, the same long-straight section (LSS) can be used for housing injection and extraction. The ring is three-fold symmetric and accommodates in the other two LSSs, the collimation and RF systems.

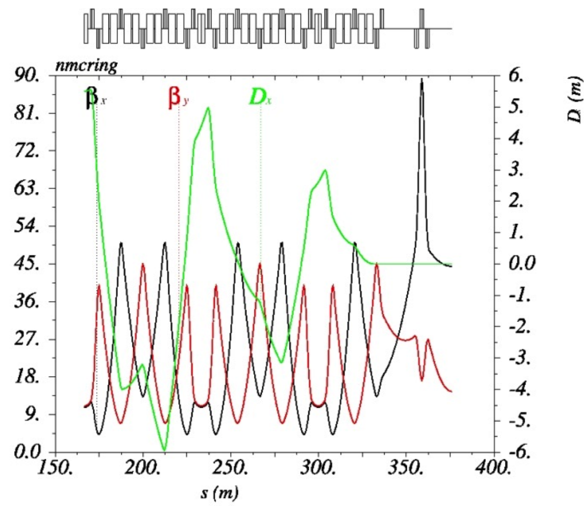

Figure 1: Horizontal (black) and vertical (red) beta functions and horizontal dispersion (green) of one sixth of the HP-PS ring (half arc and half LSS), for the injection optics corresponding to stripping with a foil.

The HP-PS arcs are made out of five Negative Momentum Compaction (NMC) arc cells for avoiding transition and reducing losses. The full arc becomes achromatic by imposing the horizontal tune to be a multiple of $4 \times 2\pi = 8\pi$. As compared to the previous design, a particular effort was made to reduce the transition gamma to a value of $15i$, thereby maximising the momentum compaction factor and increasing instability thresholds. The LSS lattice is based on quadrupole triplets which allow more space for installing the corresponding equipment. The five families are used for achieving optics constraints especially for beam transfer equipment and general tuning. In particular, two different injection optics were produced for the requirements of foil or laser stripping. The LSSs are asymmetrically detuned at extraction in order to produce the optics functions and phase advances required by the fast extraction elements. The horizontal tuning ability of the ring is provided principally by the LSS, whereas the vertical tune is quite flexible.

The optics of one sixth of the ring is shown in Fig. 1 with the optics in the LSS corresponding to the foil stripping constraints. In that case, the working point is $(Q_x, Q_y) = (13.24, 12.22)$, with the horizontal and vertical beta functions (black and red lines) limited to below 50 m in the arc, but reaching a peak value of 90 m in the LSS. The horizontal dispersion (green curve) oscillates between ± 6 m. The LSS optics for the laser stripping options looks quite similar, apart from the center of the section, where the vertical beta function is reduced to values below 10 m. For achieving this, the vertical phase advance has to be increased and the vertical working point is moved higher by an integer to 13.22, while the horizontal is kept the same.

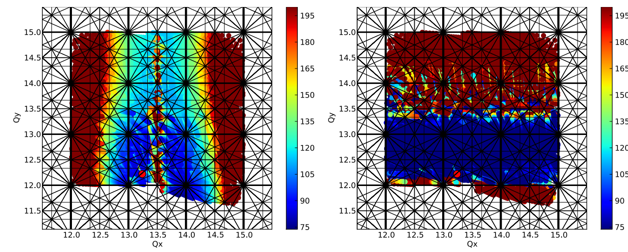

Figure 2: Horizontal versus vertical working points for a large number of matched HP-PS rings with the foil injection option, colour-coded with maximum horizontal (left) and vertical beta function (right).

The ability to tune the ring to different working points is displayed in Fig. 2. The HP-PS lattice is tuned for several horizontal and vertical working points (from 12 to 15 integer units). These working points are represented in the plots with a colour-coding corresponding to the maximum horizontal (left) and vertical beta function (right). Although these lattices are tuned for the foil injection constraints, the ones corresponding to laser stripping injection look very similar. The beta functions get smaller values for working points between 12 and 13.5 in the vertical plane. The maximum vertical beta depends less in the horizontal working point position. With respect to the horizontal plane, though, the best working points are found between 12.5 and 14.5, with the exception of 13.5, the location of the systematic half integer resonance.

SPACE-CHARGE AND APERTURE

In Fig. 3, the horizontal and vertical normalised emittance area is parameterised with the dipole half-gap (left) and maximum quadrupole radius (right) for the 50 GeV ring with the foil injection optics. These gaps are designed to fit a 4 σ beam in both planes including vacuum pipe thickness, mechanical and orbit tolerances. For estimating the minimum acceptable transverse emittance, a pessimistic limit of the incoherent space-charge tune shift of -0.25 (Gaussian approximation), in both planes, is considered, for a full bunch length of 13 ns and total energy spread of 5.43×10^{-3}. Only the emittance areas that satisfy the space-charge limit are shown. The vertical emittance mainly affects the dipole acceptance, whereas the quadrupole radius is largely determined by the horizontal beam size. The emittances are chosen to be $(\epsilon_x, \epsilon_y) = (10, 17)$ mm-mrad, requiring a 60 mm vertical half-gap and an 83 mm radius. A rounder beam which can reduce the dipole gap could be also envisaged, but the quadrupole radius increases, as well as the maximum pole tip field, which is limited to around 1.2T.

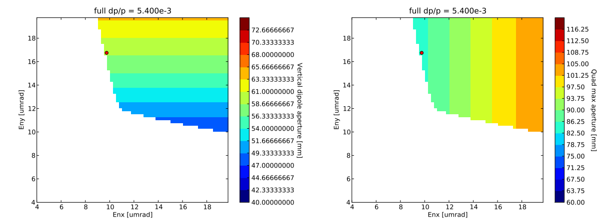

Figure 3: Horizontal versus vertical normalised emittance area colour-coded with the dipole half-gap (left) and the quadrupole radius (right) for the HP-PS option of 50 GeV with the foil injection optics. Only emittances satisfying the space charge limit of -0.25 are shown.

ORBIT CORRECTION AND DYNAMIC APERTURE

Random dipole field errors (rms of 5×10^{-4} of the main field), quadrupole transverse misalignments (rms of 0.2 mm) and dipole rolls (rms of 0.2 mrad) were introduced in both versions of the HP-PS ring optics for evaluating their impact on orbit distortion. A correction was applied using dipole steerers positioned close to all quadrupoles. The resulting distribution of the orbit distortion for both planes and the two different optics is presented in Fig. 4. In all cases, the uncorrected orbit distortion is quite large with a mean value of around 9 mm. After correction, this drops to below 0.5 mm on average. The maximum required strength of the corrector magnets is below 0.16 mrad, well within the magnets' capability.

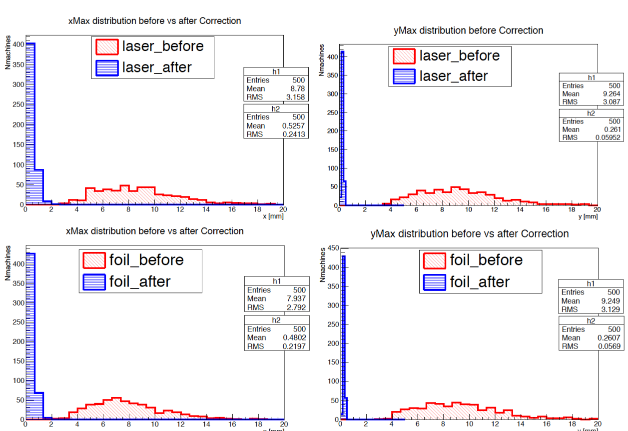

Figure 4: Distribution of maximum horizontal (left) and vertical orbit distortion (right) for the foil (bottom) and laser injection optics (top), before (red) and after orbit correction (blue).

Dynamic aperture (DA) simulations were performed in order to evaluate the robustness of the design with respect to single particle non-linear dynamics. As the dispersion is quite high, the two families of chromaticity sextupoles' have quite reduced strengths and the ring's non-linear dynamics performance is not at all limited by them. The introduction of the previously mentioned linear errors and misalignments that distort the orbit have also a minor impact in the DA. The single-particle non-linear dynamics is actually dominated by multi-pole field errors. This is clearly presented in Fig. 5, where the DA is computed for 1000-turn tracking with MADX-PTC, with a magnet error table used for the PS2 study [5]. The results for one hundred random error distributions (grey curves) correspond to on and off-momentum particles with the maximum energy spread of 0.5%. The average values are represented by the solid red (on-momentum), blue (+0.5%) and green (-0.5%) curves. The DA is tight but above 6 σ in both planes, 30% higher than the physical aperture.

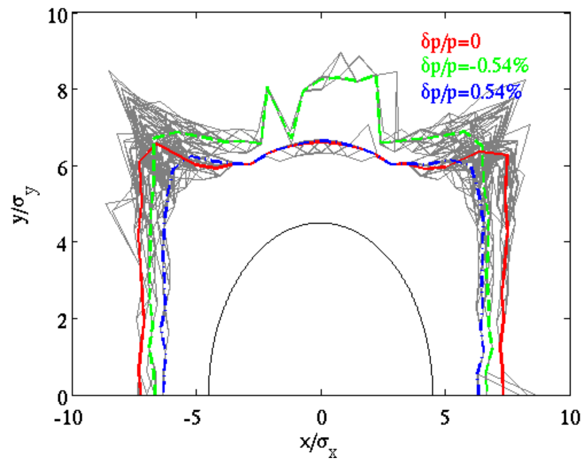

Figure 5: Transverse dynamic aperture measured in beam sizes for the HP-PS ring for 1000-turns tracking, using 100 random seeds of multipole magnet errors (grey), its average for on-momentum (red) and for energy spread of +0.5% (blue) and -0.5% (green).

SUMMARY

The optics of the HP-PS ring was designed to achieve a low imaginary transition energy and assure flexibility for different injection options and extraction constraints, for a wide tuning range. Using a space charge tune-shift limit, the target emittances and thereby magnet aperture and gradients were determined. The linear correction systems is straightforward and the non-linear single particle dynamics is dominated by multi-pole magnet errors. The completion of the study will be performed with the finalisation of the collimation system design [6] and tracking studies including space-charge.

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