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DESIGN OPTIONS OF A HIGH-POWER PROTON SYNCHROTRON FOR LAGUNA-LBNO

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Design studies have been initiated at CERN, exploring the prospects of future high-power proton beams for producing neutrinos, within the LAGUNA-LBNO project. These studies include the design of a 2 MW high-power proton synchrotron (HP-PS) using the LP-SPL as injector. This paper resumes the design options under study in order to reach this high power, and their implications regarding layout, magnet technology, beam loss control and RF considerations.

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Design studies have been initiated at CERN, exploring the prospects of future high-power proton beams for producing neutrinos, within the LAGUNA-LBNO project. These studies include the design of a 2 MW high-power proton synchrotron (HP-PS) using the LP-SPL as injector. This paper resumes the design options under study in order to reach this high power, and their implications regarding layout, magnet technology, beam loss control and RF considerations.

INTRODUCTION

In the framework of the LAGUNA-LBNO project under FP7 [1], design studies were launched for exploring the potential of high-power proton beams at CERN, for neutrino experiments. The present plan foresees at a first stage, the investigation of the future power capabilities in the existing injector complex, after its upgrade for the LHC (LIU project [2]). A High-Power Proton Synchrotron (HP-PS) with an H^- beam injected directly from the LP-SPL at around 4 GeV is considered for a second stage. The synchrotron should deliver beam with energies of around 50 GeV and average beam power of 2 MW on target. Several ring design options have been already explored [3], for meeting the high-power requirements. Adapting and extending previous studies undertaken for the PS2 ring [4], the design concepts for the HP-PS optics, layout, apertures and magnet technology are reported in this paper. Considerations regarding collimation design and the RF system are finally given.

PARAMETERS FOR REACHING 2MW

In order to reach high average beam power, the maximisation of both average current (number of particles and/or repetition rate) and kinetic energy would be ideal. The repetition rate is imposed by the source or linac, which, in the case of the LP-SPL, can be up to 2 Hz (see Table 1) [5]. The linac though is shared among different users, so this value should be taken as an upper limit. This is also true for any other machine of the complex. Thus, the average power should be scaled with the operating duty factor. At the same time, high repetition rate implies a fast ramping magnet system with challenging design requirements. It is also translated to a high electrical power consumption (operation cost), due to the high-voltage of the power supplies. Taking into account all the above and especially, the sharing constraint of the SPL pulse with the present CERN injector complex, a repetition rate of 1 Hz is chosen.

Table 1: Parameters of the LP-SPL relevant for HP-PS.

Kin. Energy [GeV]	4
Beam Power [MW]	0.14
Rep. rate [Hz]	2
Protons/pulse [10^{14}]	1.13
pulse length [ms]	0.9
Average/peak pulse current [mA]	20/32

Although the energy requirement can be driven by the specific physics needs, high energy is preferable for reaching the target power. For a given bending field and ring filling factor, the energy is proportional to the circumference. Conversely, for a fixed circumference, the maximum energy scales with the field at extraction, which is proportional to the ramp rate. A 50 GeV ring with circumference of 1174 m is the present HP-PS design baseline, which is compatible with super-ferric dipoles of 2.1 T peak field. 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 2. A normal conducting 30 GeV ring was found unrealistic with respect to the required intensity for reaching 2 MW.

Table 2: Design parameters of the baseline 50 GeV HP-PS ring and the alternative 75 GeV-ring.

Parameters [unit]	50 GeV	75 GeV
Circumference [m]	1174	
Beam Power [MW]	2	
Repet. Rate [Hz]	1	
RF Frequency [MHz]	40	
Symmetry	3-fold	
Lattice type	NMC arc, doublet LSS	
Kin. Energy @ inj./ext. [GeV]	4/50	4/75
Protons/pulse [10^{14}]	2.5	1.7
Dipole ramp rate [T/s]	4.2	5.9
Bending field @ ext. [T]	2.09	3.13
Max. quad. field [T]	1.19	1.53
Dipole gap height [mm]	93	73
Norm. emit. H/V [mm-mrad]	15/12.3	10.6/8.3

The high-energy option is quite interesting because, although it is based on a demanding magnet technology, it permits the reduction of the required pulse intensity from 2.5 to 1.7×10^{14} protons, as shown in Table 2. On the other hand, both intensities are quite larger than the present LP-

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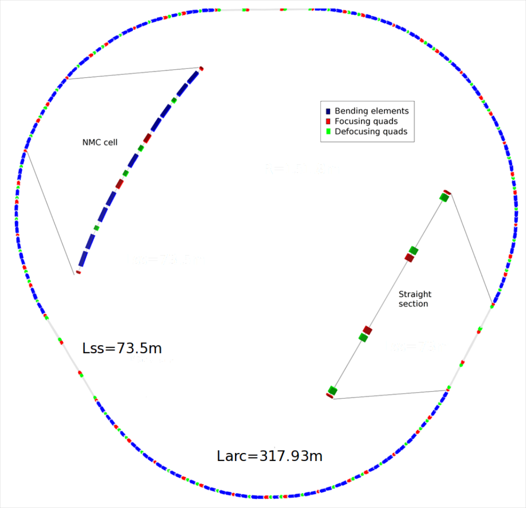

Figure 1: Layout of the HP-PS ring.

SPL design goal of 1.13×10^{14} protons/pulse [5]. The easiest and cheapest solution for LP-SPL to meet the HP-PS intensity needs would be the lengthening of the pulse by a factor of up to 2.5. This option may have some impact on the modulator energy, the cryogenic load increases, but there is little difference for the klystrons. Higher pulse current or energy would be much more expensive solutions. A longer linac pulse, though, increases the injection turns into the ring and the charge exchange injection process, through a stripping foil, should be optimised with respect to temperature rise and hitting rate.

OPTICS AND LAYOUT

For simplification, the two rings are based on the same optics and layout. The HP-PS does not have strict layout requirements, apart from positioning the injection point compatible to the SPL. Considering the target position towards the SPS north area, the same long-straight section (LSS) can be used for housing the injection and extraction. The ring is 3-fold symmetric, in order to accommodate in the other two LSSs the collimation and RF systems. A schematic layout of the ring is displayed in Fig. 1.

Negative Momentum Compaction (NMC) arc cells are necessary for avoiding transition and to reduce losses. As the dispersion is quite high, the chromaticity sextupoles' reduced strengths improve the ring's non-linear dynamics performance. The HP-PS arcs are built out of 5 NMC cells. For increasing the filling factor, the dispersion suppression is assured by locking the arc phase advance to a multiple of 2π (8π in that case). The optics of the LSS is based on quadrupole doublets which allow more space for installing the corresponding equipment. The four families are used for achieving optics constraints especially for beam transfer equipment and general tuning. The design of beam transfer element is based on PS2, with only one (fast) extraction system. The horizontal tuning ability of the ring is provided principally by the LSS, whereas the vertical tune is quite flexible. The optics of on sixth of the ring is shown in Fig. 2 for the working point $(Q_x, Q_y) = (13.24, 7.21)$, with the horizontal and vertical beta functions (black and red lines) limited to below 55 m around the ring, and the horizontal dispersion (green curve) oscillating between ±4 m.

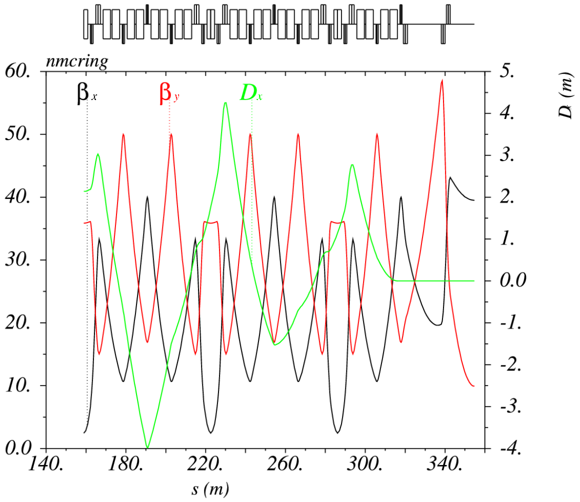

Figure 2: Horizontal (black) and vertical (red) beta functions and horizontal dispersion (green) of one sixth of the HP-PS ring (half arc and half LSS).

SPACE-CHARGE AND APERTURE

The incoherent space-charge tune shift

$$\Delta Q_{x,y} = -\frac{r_0 N_b}{(2\pi)^{3/2}\sigma_z \beta^2 \gamma^3} \oint \frac{\beta_{x,y}}{\sigma_{x,y}(\sigma_x + \sigma_y)} ds$$

can be used for determining the transverse emittances. This expression assumes Gaussian bunches which produce larger tune-shifts. This is a pessimistic consideration, as the beam will be painted to a quasi-uniform distribution. A

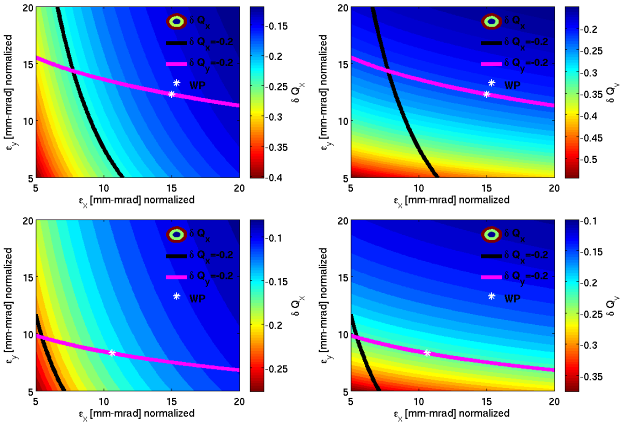

Figure 3: Horizontal versus vertical normalised emittance colour-coded with the horizontal (left) and vertical (right) space charge tune-shift for a Gaussian bunch, for the HP-PS option of 50 (top) and 75 GeV (bottom). The black and purple curves correspond to the horizontal and vertical space charge limit of -0.2.

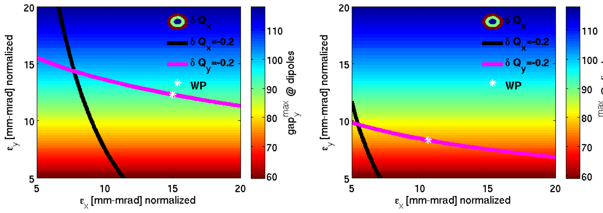

Figure 4: Horizontal versus vertical normalised emittance area colour-coded with the dipole gap for the HP-PS option of 50 (left) and 75 GeV (right). The black and purple curves correspond to the horizontal and vertical space charge limit of -0.2.

reasonable space-charge limit is set to -0.2 in both planes. In order to get the single bunch beam characteristics, a 25 ns bunch structure is considered, as for PS2, with the corresponding full bunch length of 17.8 ns and total energy spread of 6.43×10^{-3}. The ring is assumed to be fully filled, leaving a 250 ns gap for kicker rise/fall time.

In Fig. 3, the horizontal and vertical normalised emittance area is parameterised with the horizontal (left) and vertical (right) space charge tune-shift, for the 50 (top) and 75 GeV (bottom) case. The blue colours represent the lower absolute tune-shift whereas the higher values correspond to red colours. The two solid curves trace the -0.2 space charge limit. The minimum normalised emittances which fulfil the space charge constraint are thus towards the right upper corner of the plot. As the vertical acceptance is more critical, the emittances are chosen such that the vertical beam size is larger, i.e. $(\epsilon_x, \epsilon_y) = (15, 12)$ mm-mrad for the 50 GeV ring and $(\epsilon_x, \epsilon_y) = (11, 8)$ mm-mrad, for the 75 GeV one. Having smaller beam sizes for the 75 GeV option is advantageous with respect to the acceptance and thereby the required dipole gaps. In Fig. 4, the normalised emittance area is colour-coded with the gap height for the two ring options. These gaps are designed to fit a 4.5 σ beam in both planes including vacuum pipe thickness, mechanical and orbit tolerances. The required gap of 93 mm for the 50 GeV ring drops to 73 mm for the 75 GeV case.

DIPOLE MAGNET DESIGN

Due to space constraints imposed in order to reduce the circumference, the ring could only achieve 41 GeV for iron dominated dipoles of 1.7 T. It is thus necessary to employ super-ferric magnets of 2.1 T to reach 50 GeV. Note that the SIS synchrotron design for the FAIR project considers super-ferric magnets with similar field and ramp rate [6]. A super-ferric dipole magnet was also studied as option for PS2 and a prototype was built and tested successfully [7]. This design, could be extrapolated to the HP-PS parameters. The magnet system for the 75 GeV ring is very challenging, due to the combination of high field and ramp rate. If these 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.

LOSSES CONTROL AND COLLIMATION

The aim of the collimation system would be to localise slow losses in a controlled way in properly equipped locations, i.e a dedicated LSS for the transverse system and a dispersive location in the upstream arc for momentum collimation. Considering the average uncontrolled losses' canonical limit of 1 W/m and assuming the pessimistic scenario that all losses occur at extraction, the fractional beam loss limit is set to a few 10^{-4}. On the other hand, most losses would probably occur at injection and start of the ramp were beam sizes are large. A similar value though is being set by the cryogenic load and super-ferric magnet quench limit. At present, design approaches and simulations similar to the PS2 have been initiated.

RF SYSTEM CONSIDERATIONS

Based on experience with the existing CERN injectors, two RF frequency options could be considered for the HP-PS. A high frequency RF system similar to the one of the SPS (200 MHz) and a low frequency one as in the PS (10 MHz). The first one allows a much lower bunch peak current due to the large number of bunches. The tuning range though is much more flexible in a 10 MHz system. An additional advantage is the possibility to have higher harmonic RF systems to flatten the bunches, lower the peak current and mitigate instabilities. At present, an intermediate frequency RF system of 40 MHz system is considered (as in PS2), which can be made tuneable in limited range.

SUMMARY

Two ring options for the HP-PS were elaborated following the same layout and optics but different energy and intensities, for reaching 2 MW. Space charge tune-shift considerations were employed to define the target emittances and thereby magnet aperture and gradients. The use of super-ferric dipoles is appealing, for reaching a given energy with a shorter ring. The collimation system under design should be able to protect the magnets from quenching. A 40 MHz RF system is being considered as a compromise for tuning ability and low peak current.

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