DESIGN PARAMETERS OF A HIGH-POWER PROTON SYNCHROTRON FOR NEUTRINO BEAMS AT CERN

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Abstract

Design studies have been initiated at CERN for exploring the prospects of future high-power proton beams for producing neutrinos within the LAGUNA-LBNO project. These studies include a possible increase of the SPS beam power from 500kW to 700kW for a new conventional neutrino beam line based on the CNGS technology, and at a second stage a 2 MW High-Power Proton Synchrotron (HP-PS) using the Low Power Superconducting Proton Linac (LP-SPL) as injector. A low energy 5GeV-4MW neutrino super-beam alternative based on a high-power version of SPL is also considered. This paper concentrates on the HP-PS by exploring the parameter space and constraints regarding beam characteristics, machine hardware and layout, for reaching the 2 MW average beam power.

INTRODUCTION

In the framework of the LAGUNA-LBNO project under FP7 [1], present design studies investigate the potential of high-power proton beams at CERN, for producing neutrinos. The present plan foresees the upgrade of existing or building new accelerators, in a staged approach. One of the stages focuses in the construction of a High-Power Proton Synchrotron (HP-PS) with an H^- beam injected directly from the LP-SPL at around 4 GeV. The synchrotron should deliver beam with energies of above 30 GeV and average beam power of 2 MW on target. This paper focuses on examining the parameter space of different ring options for the HP-PS, based on simple scaling arguments. The parameters of the PS2 ring [2], which was considered a few years ago as a possible replacement of the actual PS, in view of the LHC injector upgrade, are used as a baseline for comparison.

BEAM POWER

The average beam power $P = qf_rN_pE_k$ is the product of the charge q, the repetition rate f_r, the number of charged particles N_p and the kinetic energy of the beam E_k. The first three parameters define the average current per machine pulse $\bar{I} = qf_rN_p$. High average beam power, implies both large average current (number of particles and/or repetition rate) and kinetic energy.

In Fig. 1, the average current is plotted versus the kinetic energy in logarithmic scale for a number of high power accelerators under operation or in the design phase. The average power is represented by straight lines starting from the bottom left part and moving to upper right. It is interesting to observe that most existing high-power accelerators operate at energies of less than 5 GeV, with the exception of the J-PARC main ring (50 GeV). The HP-PS should be also in that area, i.e. high energy with average current of a few tens of μA. Note that the actual CNGS beam coming from the SPS at 400 GeV is found out of the figure scale in the bottom right corner, i.e. very high energy but with very low average current, due to the very low repetition rate.

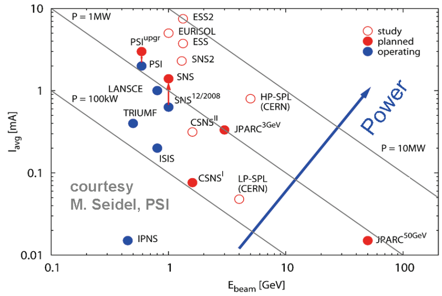

Figure 1: Average current versus kinetic energy for a number of existing (blue) and future (red) high power machines [3].

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

Parameters	LP-SPL
Rep. rate [Hz]	2
No of protons [10^{14}]	1.1
pulse length [ms]	0.9
Kin. Energy [GeV]	4
Beam Power [MW]	0.14

For reaching this high power, the starting point are the nominal parameters of the LP-SPL relevant to the beam power, presented in Table 1 [4]. A beam power of 1.8 MW can be obtained by using the full potential of LP-SPL extrapolated to 50GeV, assuming a dedicated operation with the maximum repetition of 2Hz. Using simple scaling laws, five flavours of parameters for the HP-PS were obtained and presented in Table 2. As a comparison, the PS2 parameters are included in the first column. The average power from PS2 was 0.4 MW, i.e. a 5-fold increase is needed in order to reach the target power for the HP-PS. The straightforward way to reach 2 MW is by slightly lengthening the linac pulse, from 0.9 to 1 ms and this corresponds to 10 % higher intensity, i.e. 1.25×10^{14} protons per pulse (HP-PS-I). For reducing the energy, the average current has to be increased to reach the same power. In option II, corre-

Table 2: Design Parameters of Five Ring Options for the HP-PS, as compared to the PS2

Parameters	PS2	HP-PS-I	HP-PS-II	HP-PS-III	HP-PS-IV	HP-PS-V
Circumference [m]	1346.4	1256	1009	763	1256	1256
Symmetry	2-fold	3 / 4-fold				
Beam Power [MW]	0.37	2.0				
Repetition rate [Hz]	0.42	2	2	2.6	1.3	1
Kinetic Energy @ inj./ext. [GeV]	4/50	4/50	4/40	4/30	4/50	4/50
Protons/pulse [10^{14}]	1.1	1.25	1.6	1.6	1.9	2.5
pulse length [ms]	0.9	1.0	1.3	1.3	1.6	2.0
Dipole ramp rate [T/s]	1.4	6.1	6.0	7.5	4.0	3.1
Bending field @ inj/ext. [T]	0.17/1.7	0.17/1.7	0.21/1.7	0.27/1.7	0.17/1.7	0.17/1.7
Fractional beam loss [10^{-4}]	35.1	6.5	5.0	4.0	6.5	6.5
Space-charge tune-shift H/V	-0.13/-0.2	-0.2/-0.2				
Lattice type	NMC arc, doublet LSS and DS	Resonant NMC arc, doublet LSS				
Norm. emit. H/V [μm]	9/6	6.8/6.7	8.6/8.5	11/11	10.5/10.3	13.7/13.4
Max. beta H/V [m]	60/60					
Max. dispersion [m]	3.2	5				
Dipole gap height [mm]	80	85	95	108	105	120
RMS electrical Power [MW]	5.2	23.8	21.2	22.7	19.3	17.0

sponding to a 40GeV ring, this is achieved by further increasing the linac pulse and total intensity, while option III targets an even lower energy of 30GeV. In that case, the repetition rate is further increased to 2.6Hz. The two remaining ring options correspond to 50 GeV rings, with reduced repetition rates and proportionally increased intensity, which necessitate a further increase of the linac pulse. This translates to longer injection plateau in the ring where the beam is more sensitive to collective effects, instabilities and thereby beam loss.

CIRCUMFERENCE

The PS2 circumference was fixed to 15/77 of the SPS for increasing the flexibility in the choice of the injected bunch patterns [5]. Neglecting RF beam transfer arguments, the circumference C can be determined by $C \approx 3.335 \frac{2\pi\beta E}{Bk}$, i.e. the kinetic energy E, the bending field at extraction B, and the filling (or packing) factor k, representing the ratio between the total bending length over the ring circumference. For pure FODO rings like the PS or SPS, this parameter is approximately equal to 2/3, but for the PS2 which employes Negative Momentum Compaction (NMC) arc cells, the filling factor is smaller and equal to around 1/2. This may be considered as an upper limit for the filling factor for this type of cells, due to the nature of the optics, which impose variable bending strength (cells with no or reduced number of dipoles) for modulating dispersion. Considering iron dominated magnets, the bending field should not exceed 1.7 T. In this respect, the circumference depends solely on the energy. The 50 GeV rings (options I, IV and V) are thus the longest (1252 m). The only ring below 1km is only achieved by the 30GeV ring (option III), approaching the circumference of the actual PS.

REPETITION RATE

The repetition rate is imposed by the source or linac. On the other hand, the linac may be shared with other users, so this value should be considered as an upper limit. In order to estimate the magnet ramp rate, it is assumed a linear ramp and fall of the field and equal length among the injection and extraction plateaux. This length is slightly different for each ring due to the different linac pulse. As the extraction bending field is the same for all rings (1.7 T), the injection field is scaled with the ratio between injection and extraction energy. The ramp rates are indeed much higher than for the PS2, ranging from 3.1 (ring V) to 7.5 T/s (ring III). These high magnet ramp rates are translated to high voltage ratings for the main power supply, which themselves lead to high electrical power consumption. Note that the SIS synchrotron design for FAIR project consider super-ferric magnets with 4 T/s ramp rate [6], which is a good option for reducing electrical power with an extra cost and power for cryogenics. Finally, the rapidly varying field generates Eddy currents in the vacuum chambers which themselves attenuate and distort the accelerator magnets fields, alter the field or gradient uniformity and affect beam stability.

INTENSITY

The intensity is limited by space-charge and other collective effects and instabilities, especially at injection. In particular, the incoherent space-charge tune shift

$$\Delta Q_{x,y} = \frac{r_0 N p C}{2(2\pi)^{3/2}\sigma_z \beta\gamma^2\epsilon_{x,y}}$$

can be used as the parameter through which the transverse beam emittances can be determined. Note that this expression assumes Gaussian bunches which correspond to the higher tune-shift. A reasonable limit is set to -0.2 in both planes, as for the PS2. In order to get the single bunch beam characteristics and for the sake of comparison with PS2, a 25ns bunch structure is considered. The rings are assumed to be fully filled filled with bunches leaving only a 150 ns gap for kicker rise/fall time (300ns for PS2). The same full bunch length of 17.8 ns is also considered for all ring options by tuning the injection voltage while changing circumference and harmonic number. Although this may seem arbitrary, especially in the case of high intensity beams, for which the bunches are much longer and the harmonic number reduced, the ratio between single bunch intensity and bunch length remains almost constant. For keeping space-charge tune-shift below the target value, the transverse emittances have to be increased in all cases, apart from ring I, whose higher intensity is offset by the reduced circumference, as compared with PS2. Indeed, a reduced circumference may be interesting especially if it is followed by an increased bunch length, pointing to the use of cryogenic magnets.

ELECTRICAL POWER

The electrical power consumption for ramped magnets depends on the power supply voltage, which itself depends on the maximum magnetic field, the magnet physical characteristics (length, aperture gap and height) and the ramp rate. Considering the same optics for all rings, with maximum betas of 60m and dispersion of 6m and an energy spread of 0.6% (as for PS2), the gap height for each ring can be computed. The total dipole length is simply given by the imposed filling factor of 0.5. The electrical power estimated is more than a factor of three higher than the one of PS2 [7], reaching tens of MW. Indeed, ring option V presenting the lower ramp rate, cannot take full advantage of this reduction, due to the increased intensity. The larger emittances, needed for keeping space charge tune-shift low, impose larger gaps. The high electrical power consumption of iron dominated magnets makes the choice of super-ferric magnets very attractive.

LOSSES CONTROL

Considering the average uncontrolled losses' canonical limit of 1 W/m around the ring, and assuming the pessimistic scenario that all losses occur at extraction, the fractional beam loss limit is set to a few 10^{-4} for all ring options, i.e. almost an order of magnitude lower than PS2. This is consistent with requirements of other high-power synchrotrons (e.g. the SNS accumulator ring [8]) and becomes more stringent for shorter rings, as there is less space for distributing the losses. These strict loss limits require an efficient collimation system in a dedicated straight section, in combination with momentum collimation in the arcs.

OPTICS AND LAYOUT

In contrast to PS2, the HP-PS does not have strict layout requirements, apart from positioning the injection area parallel to the SPL. A three or four-fold symmetric ring would be desirable in order to accommodate in separate straight sections beam transfer equipment, RF and collimation. NMC cells are necessary in order to avoid transition and associated losses. In Fig. 2, the optics of a quarter of a resonant PS2 ring is presented. The ring consists of five NMC arc cells with horizontal phase advance tuned to 8π. A resonant arc cell can further increase the filling factor and presents very good non-linear dynamics performance [9].

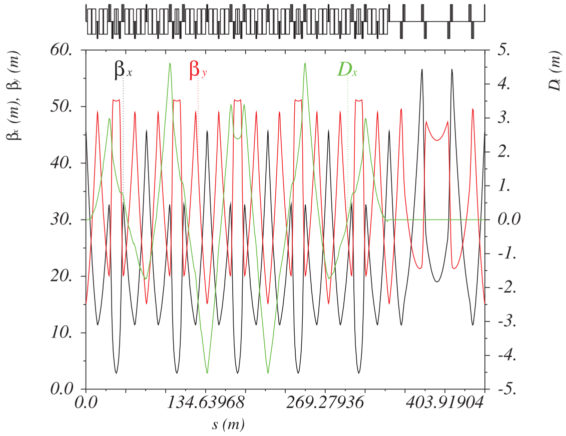

Figure 2: Horizontal (black) vertical (red) beta functions and horizontal dispersion (green) of a quarter of the resonant PS2 ring [9].

SUMMARY

Five ring options for the HP-PS were elaborated following different paths for reaching beam power of 2 MW. There are various challenges for producing this high power due to the magnet ramp-rate, space-charge, losses, limited acceptance and increased space. The preferred rings are the ones associated with the highest energy, i.e. longer circumference, and lower repetition rate (ring V). These considerations lead to parameters that are close to the ones of PS2. The use of high-field super-ferric magnets is very appealing, for reaching a given energy with a shorter ring and reduced construction cost. The additional advantage would be the lower space-charge tune shift thereby enabling smaller emittances and lower magnetic gaps, easing the magnetic design and reducing the cost of the magnets themselves. Finally, an option which is presently considered but not described is the accumulation of a higher intensity to a short ring at low energy.

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