INJECTION AND EXTRACTION SYSTEMS FOR A HIGH-POWER PROTON SYNCHROTRON AT CERN

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Abstract

A new High-Power Proton Synchrotron (HP-PS) is being studied at CERN for the second phase of the Long Baseline Neutrino facility (LAGUNA-LBNO) where a 2 MW beam power shall impinge onto a target. A 4 GeV H^- injection based on foil stripping and extendable to laser-assisted magnet stripping is described. The proposed laser-assisted stripping is assessed with regard to the laser power requirements. The feasibility of a fast extraction system at 75 GeV is presented.

INTRODUCTION

The present CERN accelerator complex uses LINAC 2 with a proton source pulsing at about 1 Hz. With the upgrade to Linac4 in long shutdown two (LS2) in 2018, an H^- source pulsing at 2 Hz will be available which allows to use every second pulse for other experiments. For the LBNO facility it is envisaged to extend Linac4 with a 4 GeV superconducting linac (SPL) [1] which would serve as injector of the HP-PS. Its pulse length can be extended from the present 0.9 to 2 ms to reach the required injection intensity for the HP-PS, Table 1.

Table 1: Low Power SPL Parameters

Parameter	Unit	Value
Kinetic energy	[GeV]	4
Beam power	[MW]	0.144
Repetition rate	[Hz]	2
Beam pulse length	[ms]	0.9
Protons per pulse		$1.13 \cdot 10^{14}$

The 4 GeV H- ions from SPL have to be transferred via a large bending radius line to avoid Lorentz-stripping. The charge exchange injection system will be based on a foil stripping mechanism, with the upgrade possibility to a laser assisted magnet stripping system. Two extraction energy options, 50 and 75 GeV, are under study, Table 2. The choice is a trade-off between the instability limited beam intensity for the 50 GeV option and the magnet technology for the 75 GeV option. The beam sizes vary for the two options and so the required kicker deflection angle to reach the minimum clearance at the septum to extract the beam. However, the increased kicker deflection due to possible bigger beam sizes for the 50 GeV synchroton is overcompensated by the by 1/3 smaller magnetic rigidity compared to the 75 GeV option. The extraction system description below focusses on the more challenging 75 GeV option.

Table 2: HP-PS Parameters

Parameter	Unit	50 GeV	75 GeV
Inj/extr kin. energy	[GeV]	4 / 50	4 / 75
Inj/extr beam power	[MW]	0.19 / 2	0.13 / 2
Repetition rate	[Hz]	1	1
Total beam intensity		$2.5 \cdot 10^{14}$	$1.7 \cdot 10^{14}$
Main B field inj/extr	[T]	0.17 / 2.1	0.17 / 3.13

H^- INJECTION

Optics Requirements

The optics requirements for foil and laser stripping are contradictory and therefore two lattice versions are prepared, [2]. For the foil stripping scheme, the optics at injection was adapted to the following constraints. Assuming the minimum injected betatron function being fixed due to foil heating, the optimum betatron function at the injection point in the ring is given by matching the incoming and the ring phase space curvatures. The beam divergence α should be zero at the injection point. With an injected betatron function not smaller than 10 m due to foil heating, the ring betatron function should be around 35 m. A smaller ratio between injected and ring betraton function β_i/β_r decreases the number of foil hits and thus emittance blow up but increases the local foil heating.

For the laser stripping scheme it is primarily important to minimize the vertical beam size at the interaction point — if the interaction is in the horizontal plane — since it is proportional to the required laser peak power.

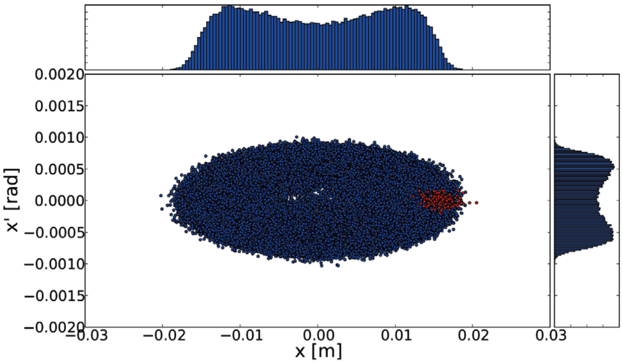

Figure 1: Phase space distribution after painting over 600 turns. The particles in red represent the last injected bunch.

Foil Stripping

The required intensity in the HP-PS is reached for about 600 injected turns or 2 ms. The number of foil hits during this process for a given betatron mismatch at injection can be minimized by adapting the painting function. Here the painting function was chosen to change the position of the injected beam proportional to $\#turn^{1/4}$ which moves very quickly the beam out of the phase space center and more slowly fills the outer phase space area. The resulting distribution is less dense in the center which will be compensated when taking into account space charge effects, Fig. 1.

Laser Stripping

Reduction of beam loss and activation motivate to design the injection system with the possibility to upgrade to a laser assisted magnet stripping scheme. Such a scheme is described in detail for the 4 GeV injection into PS2, which was foreseen to replace the PS in the LHC injector chain [3]. Several parameters differ between the PS2 and HP-PS injection systems. The number of injected turns has to be increased from 200 to 600 in the HP-PS which leads to an increased number of foil hits and emittance blow up. The latter is less critical for the HP-PS since its purpose is not to produce beams for luminosity production, as the aim was for PS2, but for a fixed target beam. However, the target emittance should be reached via controlled painting and not be significantly affected by foil scattering. The 2.6-3.8 times higher injected beam power of the HP-PS with respect to the PS2 is the main motivation for a laser stripping system. A sketch of the injection setup with a combined foil and laser system is shown in Fig. 2. Lorentz-stripping in a wiggler magnet or photodissociation by laser light can be used to neutralise the H^- ions. The advantage of using laser photodissociation for 4 GeV ions is not only to avoid emittance growth originating from the finite stripping length in the magnet, but the possibility to use resonances which leave the H^0 in an already excited state. In a second step, these excited atoms can be pumped onto a higher energy level which has the dual advantage of a longer lifetime for spontaneous decay and shorter lifetime for stripping off the second electron. The required laser parameters to pump the H^0 ions to the excited states n=2 and n=3 are shown in Table 3.

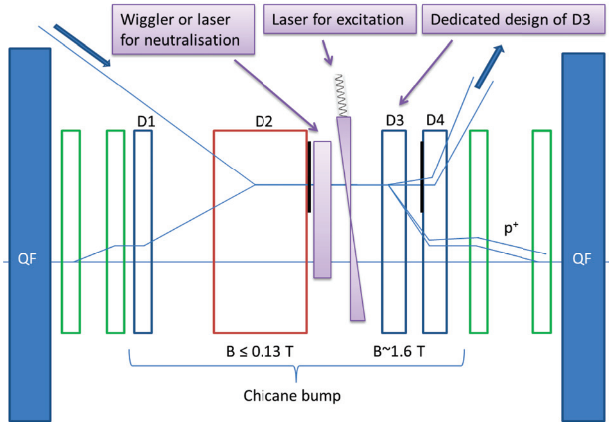

Figure 2: Combined foil and laser H^- injection system. The chicane bumpers are indicated in blue and red, the painting bumpers in green. Two foils are shown, one for the stripping of the injected ions and one for the waste beam. The laser equipment consists of a wiggler, an excitation laser and a specifically designed third chicane magnet.

Table 3: Laser Characteristics for H^0 to Proton Stripping

Parameter	**Unit**	**n=2**	**n=3**
Wavelength	nm	1064	1064
Laser/H^- angle	deg	47.50	8.39
Angular spread	deg	±0.10	±0.42
Micropulse energy	μJ	360	92
Macropulse length	ms	2	2
Macropulse energy	J	253	65
Peak power (single pass) * 3 (margin)	MW	21.6	5.5
Average power	kW	127	33
Vertical laser beam height (1 σ rms)	mm	1.5	1.5
Linac pulse, 1 σ rms separated by 2.84 ns	ps	15	15
Microbunch frequency	MHz	352	352
Laser repetition rate (max)	Hz	1	1

One of the lasers for the CLIC test facility CTF3 at CERN is the photoinjector PHIN. After the second amplifier, PHIN delivers a 9 kW average power with 1.5 GHz intra burst repetition rate [4]. Its bunch duration is measured between 8-10 ps. First experiments of a power build up cavity for the SNS stripping scheme at 355 nm resulted in a factor 25 power build up, with further improvements a build up factor of 100 should be achievable [5]. Assuming the n=3 excitation with a required average power of 33 kW, the PHIN output power needs to be enhanced by a factor 4 which can be easily obtained by a cavity. The oscillator for an appropriate pulse rate and pulse duration seems feasible.

EXTRACTION SYSTEMS

For the HP-PS a fast extraction system is foreseen. The kicker and septum magnets are placed in two 18 m long drifts on either side of the 24 m long H^- injection. In order to estimate the required clearance between the circulating and extracted beam at the septum entrance, the following calculation of half beam sizes is used:

$$A_{x,y} = n_\sigma \sqrt{k_\beta \beta_{x,y} \frac{\epsilon_{N;x,y}}{\gamma_r \beta_r}} + \left| k_\beta D_{x,y} \sigma_\delta \right| + c.o. + align \quad (1)$$

where β and D denote the betatron and dispersion functions with their uncertainty factor k_β, ϵ and σ_δ the distributions of emittance and momentum spread, $c.o.$ the trajectory variation and γ_r and β_r the relativistic parameters. The beam sizes are calculated for $n_\sigma = 4$, $k_\beta = 1.2$, $c.o. = 2$ mm and align=4 mm. A full momentum spread of $5.4 \cdot 10^{-3}$ is assumed. The deflection required to reach a 5 mm clearance for the septum blade assuming a normalised emittance of 8 μm is 2.1 mrad for the kicker system, Fig. 3. In or-

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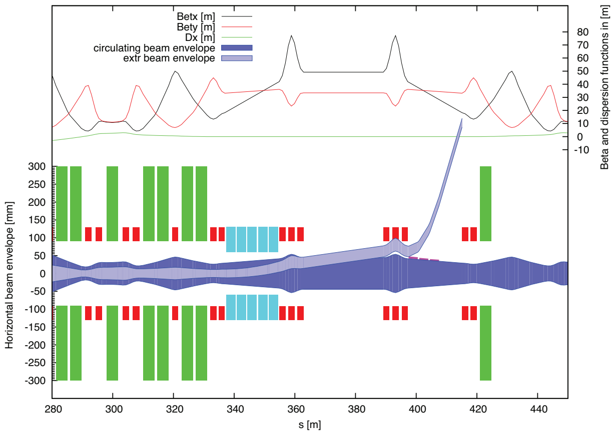

Figure 3: Betatron and disperson functions of the long straight section in the top plot and beam envelopes at extraction on the bottom. The elements in green denote dipoles, in red quadrupoles and in turquoise the kicker magnets. The septum blades are indicated in magenta.

der to reach this deflection with a maximum rise time of 250 ns, a transmission line magnet concept in short-circuit mode is chosen. This results in a higher current than for a terminated system and thus, a moderate voltage to allow for conventional cables. The drawback of the short-circuit system is its limit with respect to the rise time. The total system length of 16.7 m does not provide enough margin for upgrades. A more demanding rise time would require a higher number of shorter magnets and in total increase the system length. Since the HP-PS assumes a total intensity of up to $2.5 \cdot 10^{14}$, the need of an impedance screen needs to be clarified. Presently the vertical beam size does not leave space for a screen in the magnet gap. A screen would also delay the rise time of the system. In this case a terminated system with higher voltages which require SF6 filled cables might be the only possiblity to meet the rise time specification.

For the septa magnets a total deflection of 52 mrad is required to clear the downstream quadrupoles. A first thin septum is with 5 mm thickness is assumed. The triplet quadrupoles in the long straight section require an increased aperture of 100 mm due to the extracted beam passage.

CONCLUSIONS

A 4 GeV H^- injection system was studied earlier for PS2 and is in this paper adapted to the requirements of the HP-PS. The main changes are given by the longer injection pulses and higher injected beam power. The optics constraints are given for the foil and laser stripping scheme which lead to two dedicated injection optics settings. The injection painting was studied for the foil case in order to paint a rather uniform distribution in phase space and minimize the number of foil hits due to the circulating beam. The injection scheme is complemented by the equipment foreseen to upgrade to laser stripping, motivated by reduction of beam loss and activation. In case the hydrogen atoms are left already in an excited state after the neutralisaton step, the laser parameters to further excite the atoms to the n=3 state and - from there do the final stripping in the third chicane magnet - seem feasible. The parameters of the at CERN available photoinjector laser match well the requirements if assuming that a power build up by a factor 4 can be reached via a cavity.

Table 4: Kicker and Septum Parameters for a 75 GeV Fast Extraction

Parameter	Unit	Kicker	Septum
Deflection angle	[mrad]	2.1	52
Integrated field	[Tm]	0.532	13.16
Rise time	[ns]	250	-
Impedance	[Ohm]	12.5	-
Voltage	[kV]	40	-
Current	[kA]	3.2	27
Magnet gap/width	[mm]	90/120	34/120
Septum thickness	[mm]	-	5
Magnet length	[m]	0.675	
Number of magnets		18	
Magn./total length	[m]	12.15/16.7	13.2/16.7
Magnetic field	[T]	0.045	1.0

A fast extraction system at 75 GeV is presented. The maximum kicker deflection of 2.1 mrad in 18 m length allows to extract a beam with an 8 μm emittance for the present optics. The need of a beam screen has to be clarified and its effect on the kicker system rise time and the magnet gap to be revised. The septum magnet parameters seem feasible. The extraction system for a 50 GeV HP-PS will require to extract larger normalised emittance beams which is, however, overcompensated by the reduced magnetic rigidity. Therefore a 50 GeV extraction system will have less stringent hardware requirements.

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