Synergies between the needs of LHC, neutrinos and Radio-active Ion Beams

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Abstract
An extensive upgrade of the LHC injectors is planned for reaching the ultimate potential of the collider during the second phase of its life, after 2020. As a result, the beam delivered by the SPS for fixed target physics will also be improved, in particular to the benefit of conventional neutrino beams. Moreover, the Superconducting Proton Linac (SPL) which is under design can be at the core of a multi-MW proton driver at 5 and/or 2.5 GeV, serving a neutrino facility, and/or a Radioactive Ion Beam facility of the next generation. The future accelerator complex is described and its potential for other applications than LHC is detailed.

1 Introduction

The LHC is designed for colliding proton beams at a centre of mass energy of 14 TeV with a nominal luminosity of 10^{34} $cm^{-2}s^{-1}$ in two interaction regions [1]. After modification, the existing complex of accelerators has been made capable to serve as injector and provide the beam required for that purpose [2]. Starting for these favorable conditions, the LHC should reach nominal performance within a few years. Without upgrade, the peak luminosity will then saturate and the halving time of the statistical experimental errors will become very large. An analysis has therefore been made of the possible scenarios for achieving a much higher rate of increase of the integrated luminosity (e.g., a factor of 10 would enlarge the discovery range for new particles by about 25 % in mass [3]). Beyond the need for improvements in the LHC itself, the characteristics of the injected beam have to be upgraded and the reliability of the whole complex has to be significantly increased [4, 5].

2 Plans for future LHC injectors

2.1 Motivation

The present LHC injectors have been built more than 30 years ago (the PS is the oldest, celebrating in November 2009 the 50^{th} anniversary of its first beam). Since their design, the state of knowledge in accelerator physics and technology has drastically progressed. Even though they have been regularly adapted and their operating mode has been sophisticated to cope with new needs and achieve unexpected levels of performance, they work nowadays at their absolute limit for the LHC. As the operation of the collider will become more regular, the (lack of) reliability of the injectors is likely to negatively impact on the integrated luminosity. Hence the plan to build new injectors operating simply and satisfying the future needs of the LHC with adequate performance margin.

Luminosity is directly related to beam brightness, the ratio N_b / ε_N of the number of protons in a bunch N_b to its normalized transverse emittance ε_N (in the approximation of same emittances in both transverse phase planes) which is then the main beam characteristic to improve. In the case of protons where synchrotron radiation is too weak to provide sufficient cooling, beam brightness is, at best, preserved during acceleration. The maximum achievable brightness is therefore limited by the tolerable space charge induced tune spread ΔQ_{sc} at low energy. In a given synchrotron, it is governed by the relation in Eq. (1):

$$\Delta Q_{sc} \propto -\frac{N_b}{\varepsilon_N} \frac{R}{\beta\gamma^2} \tag{1}$$

where R is the average radius and β, γ are the usual relativistic beam parameters.

2.2 Description

For the design of the future injector chain, the target brightness corresponds to bunches of 3.4 10^{11} protons within nominal emittances of 3.75 mm.mrad (25 ns time interval between bunches) circulating at 7 TeV in the LHC. The proposed complex [5] is sketched in Fig. 1, together with the present machines.

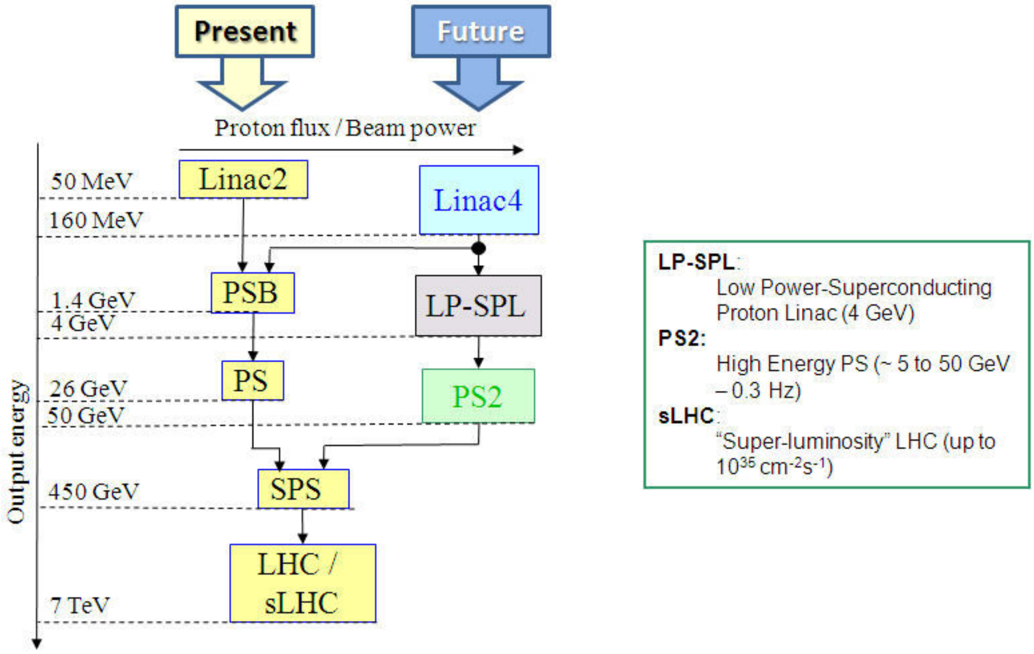

Fig. 1: Present and future accelerators

A new 50 GeV synchrotron (PS2) [6] will replace the existing 26 GeV PS and provide beam with the specified brightness (including ~20% margin) at injection in the SPS. Its main characteristics are given in Table 1. The increased injection energy in the SPS will reduce space charge and improve beam stability. Combined with other upgrades concerning mainly RF and the coating of the vacuum chamber to reduce secondary electron yield, this will allow the SPS to preserve beam characteristics and deliver the specified beam to the LHC.

Because of its superiority in terms of beam performance and potential for future applications, a superconducting linac (the Low Power SPL or LP-SPL) has been selected as the injector for the 50 GeV proton synchrotron PS2 [7]. Its low energy front-end (up to 160 MeV), called Linac4 [8], will first be used to replace Linac2 as injector of the PS Booster, providing beam with twice the $\beta\gamma^2$ of the present 50 MeV Linac2 and hence doubling the brightness of the PSB beam. The layout of these new accelerators on the CERN site [9] is shown in Fig. 2.

Table 1: PS2 characteristics

Physical quantity	**Value**	**Reason**
Injection energy	4 GeV	Space charge in PS2 (from Eq. (1))
Ejection energy	50 GeV	SPS improvement
Nb of protons/bunch with 25 ns bunch spacing for LHC (total in 168 bunches)	$4\ 10^{11}$ p/b ($6.7\ 10^{13}$ p)	Brightness goal for LHC upgrade (with 15 % margin)
Nb of protons/bunch with 25 ns bunch spacing for SPS fixed target (total in 168 bunches)	$6\ 10^{11}$ p/b ($1\ 10^{14}$ p)	SPS flux for fixed target physics
Cycling period to 50 GeV	2.4 s	LHC filling time & SPS flux
Transverse emittances at ejection of LHC-type beam (normalized – 1 sigma)	3 π mm.mrad	SPS requirement for LHC
Longitudinal emittance/bunch (25 ns bunch spacing)	0.35 eVs	SPS requirement for LHC
Circumference (ratio PS2/SPS)	1346.4 m (15/77)	LHC need for 25, 50 and 75 ns bunch spacing
RF harmonics for 25 ns bunch spacing (resp. 50 or 75 ns)	180 (90 or 60)	LHC need for 25, 50 and 75 ns bunch spacing

For the needs of the LHC, the LP-SPL will only deliver a moderate beam power (~140 kW) at 4 GeV. However, its superconducting accelerating structures are capable to operate at much higher duty cycle than required by the LHC. At the cost of some upgrade of RF and infrastructure, this capability could be later exploited to increase beam power up to 4 MW at 5 and/or 2.5 GeV for fulfilling the needs of a neutrino facility and/or a Radioactive Ion Beam facility of the next generation [10]. The initial and potential evolution of the linac specifications are summarized in Table 2.

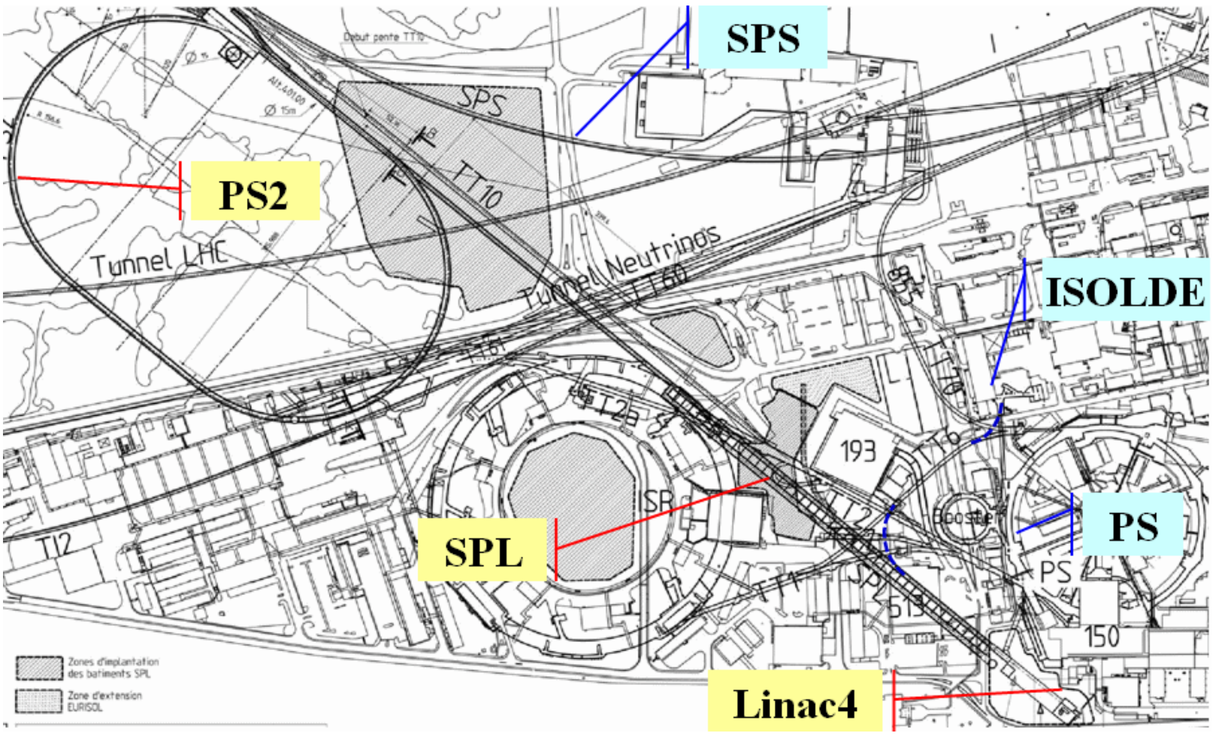

Fig. 2: Layout on the CERN site

Table 2: Low Power and High Power SPL beam characteristics

	LP-SPL	HP-SPL Option 1	HP-SPL Option 2
Maximum kinetic energy [GeV]	4	4 or 5 [a]	4 or 5 [a]
Average beam current during pulse [mA]	20	20	40 [b]
Pulsing rate [Hz]	2	50	50
Pulse duration [ms]	0.9	0.9	1.2 [b]
Beam power [MW]	0.14	2.25 @ 2.5 GeV **or** 4.5 MW at 5 GeV	5 @ 2.5 GeV **and** 4 MW at 5 GeV

[a] Required for a neutrino factory.
[b] Required for 2 simultaneous users of high beam power or for 5 MW at 2.5 GeV

2.3 Implementation plan

2.3.1 Linac4

The construction of the LP-SPL front-end, Linac4, has been approved at the end of 2007, as an efficient means to increase the performance of the PS complex and to prepare for the LP-SPL itself. As a result of this first step, the brightness per pulse of the PS Booster will be doubled, Linac4 providing beam at 160 MeV, with twice the $\beta\gamma^2$ of the present 50 MeV Linac2. The PS will be filled by a single pulse from the PSB, minimizing the time spent with a large space charge on the PS injection flat porch and hence suppressing the associated emittance blow-up and beam loss.

Linac4 is equipped with normal conducting accelerating structures. The frequency of 352.2 MHz has been chosen for its convenience for accelerating protons in this energy range, and because of the availability of a large inventory of LEP RF equipment. The block diagram of the accelerator is shown in Fig. 3. Thirteen former-LEP klystrons and six new pulsed devices are used to excite the four different types of accelerating structures. A four vane RFQ bunches and accelerates the beam up to 3 MeV where a wideband / high speed chopper (rise and fall time <2 ns) tailors the bunch train to the needs of the following synchrotron. An Alvarez-DTL equipped with permanent quadrupole magnets brings the energy up to 50 MeV. Cavity-Coupled DTL (CCDTL) structures are used in the energy range from 50 to 102 MeV followed by Pi Mode Structures (PIMS) for acceleration up to 160 MeV.

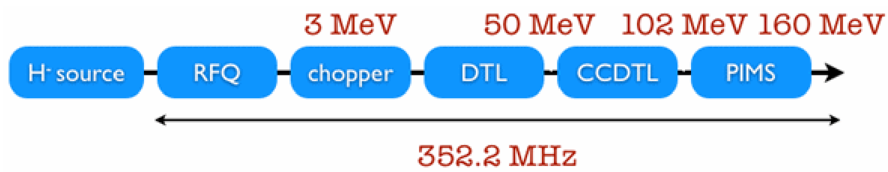

Fig. 3: Block diagram of Linac4

Civil Engineering work will finish at the end of 2010. Installation of the infrastructure will then take place in 2011, followed by the installation of the accelerator itself. Linac beam commissioning will start in the middle of 2012 and last until the third quarter of 2013, when all accelerators will be stopped and the PSB will be modified. After 3 months of beam commissioning, operation will resume in April 2014 and Linac4 will become the source of all protons for high energy physics at CERN.

2.3.2 New LHC injectors

The study of the LP-SPL, PS2 and SPS upgrade has also been approved at the end of 2007, with the goal of preparing a project proposal for mid-2012.

The LP-SPL will deliver beam at 2Hz with the characteristics shown in Table 2. It is made up of 2 sections of superconducting cavities accelerating the H^- beam from 160 MeV to 4 GeV [9]. Both sections operate at 704 MHz and use 5-cell elliptical cavities differing by the use of different geometric β (respectively 0.65 and 1.0). Challenging peak surface fields of 50 MV/m and 100 mT are assumed, corresponding to accelerating gradients of 19.3 and 25 MV/m. Medium β cavities are grouped in 10 cryomodules of 11.5 m length containing 6 cavities and 2 quadrupole doublets. High β cavities are grouped in 18 cryomodules of 14.3 m length containing 8 cavities and 1 quadrupole doublet. As shown in the block diagram of Fig. 4, beam extraction is foreseen at ~1.4 GeV for supplying particles to the ISOLDE experimental area (Fig. 2).

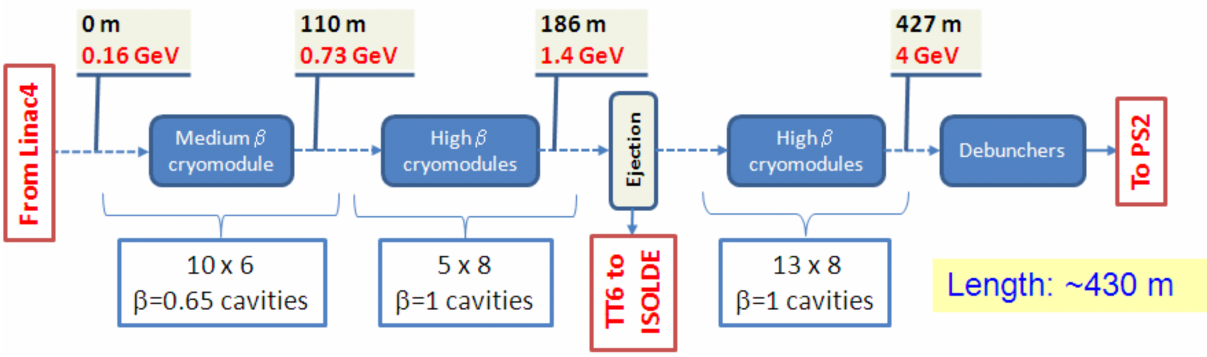

Fig. 4: Block diagram of the LP-SPL

The main characteristics of PS2 and its beam are summarized in Table 1. The basic design choices for the accelerator have recently been made [6]. To satisfy the integration requirements, a race track shaped is preferred. Charge exchange injection is implemented to accumulate the H^- beam from the LP-SPL. Fast injection is foreseen for heavy ions from LEIR. Beam can be extracted at the highest energy (50 GeV) either in a single turn (for LHC), in five turns (for SPL fixed target physics) or by slow resonant ejection (for a potential experimental area). The lattice is of the Negative Momentum Compaction (NMC) type, to avoid the crossing of transition during acceleration (γ_t=37i). The RF system operates over the frequency range from 18 to 40 MHz. The spacing between bunches and the overall time structure of the circulating beam is obtained directly at injection, through an adequate chopping in the LP-SPL front end. Compared to the complexity of the scheme presently used in the PSB and PS, this simple mode of operation is expected to be very robust and reliable.

If the decision to build the new injectors is taken at the end of 2012, their construction will start at the beginning of 2013. Once the tunnels are available, the LP-SPL will be progressively installed and beam commissioned at increasingly higher energies. PS2 will first be tested with a fast injected proton beam from the PS and afterwards with the H^- beam from the LP-SPL using charge exchange injection. Both accelerators will be fully beam commissioned without interfering with the LHC physics program. Once the foreseen beam characteristics are obtained at the exit of PS2, the connection will be made with the SPS in 2019-2020.

2.3.3 High Power SPL options

The beam power of the LP-SPL can later be upgraded to multi-MW by increasing the cycling rate to 50 Hz (Table 2), which implies the replacement/upgrade of power supplies and a major upgrade of the infrastructure (electricity, water cooling and cryogenics).

If a beam power larger than 2 MW is needed at 2.5 GeV, or if two high power users require ~4 MW simultaneously, the beam current during the pulse will have to be doubled to 40 mA, doubling the number of high power RF amplifiers. Enough space will be reserved in the linac tunnel to eventually add accelerating structures and bring the beam energy to 5 GeV, as required for a neutrino factory.

3 Potential for neutrino experiments

3.1 PS2

As a result of the requirements of the LHC upgrade, PS2 will be capable to deliver up to 10^{14} protons/pulse at 50 GeV every 2.4 s to the SPS for fixed target physics. This corresponds to an average beam power of 330 kW or to ~4 $\times 10^{20}$ pot/year (~6 times the capability of today's PS).

To meet the needs of neutrino physicists who are expecting 3×10^{21} pot/year [11], a new design is therefore needed. Beam loss analysis and management should be studied in great detail to make sure that hands-on maintenance will remain possible. The only means to increase beam power being linked to the intensity per pulse and the repetition rate, it can be predicted that a MW-class PS2 will require larger magnet apertures, more RF voltage and RF power, more powerful magnets power supplies and much more involved collimation and beam abort systems.

3.2 SPS with the new injectors

With respect to the PS, PS2 will deliver to the SPS for fixed target physics a beam of much better characteristics (Table 3).

Table 3: Comparison between PS and PS2 for fixed target physics with the SPS

	PS	**PS2**	**Advantage of PS2**	**Benefit for SPS**
Injection energy in the SPS [GeV]	14	26-50	Injection above transition Smaller beam size	No transition crossing Less loss at injection
Number of pulses for filling the SPS	2	1	No SPS injection flat porch	Less loss on flat porch Gain of 1.2s in SPS cycle
Longitudinal beam characteristics	Partly bunched	Fully bunched	Matched bunch to bucket transfer	Less capture loss
Number of protons/pulse	$2\times3\times10^{13}$	10^{14}	Higher intensity	Potential for higher intesnity

Assuming that the SPS is upgraded and made capable to accelerate and transfer the beams specified for the LHC upgrade, the beam for fixed target physics will be limited in the SPS mostly by RF (voltage and power) and activation due to beam loss. If beam is sent onto the CNGS target [12], the design parameters of the CNGS facility will be the actual limits (maximum intensity per pulse for target and horn, maximum flux to target/horn and hadron stop). Moreover, all radiation protection calculation shall be redone with the new parameters, more shielding is likely to be needed and a new INB approval by the French IRSN has to be obtained. This has been studied in 2006, and the results published in Ref. [12] show that the potential proton flux on target at 400 GeV can be brought up to 2 or 3 times the nominal value for CNGS (Table 4).

Table 4: Protons on target per year [$\times10^{19}$] for 200 days of SPS operation with 80 % machine availability

SPS cycle length	**6 s**		**4.8 s**	
Injection momentum	**14 GeV/c**		**26 GeV/c**	
Beam sharing	**0.45**	**0.85**	**0.45**	**0.85**
Present injectors (4.8×10^{13} p/p)	5	9.4		
Future injectors + SPS RF upgrade for LHC (7×10^{13} p/p)			9	17.1
Future injectors + new SPS RF system (10^{14} p/p)			12.9	24.5

3.3 High power SPL

A superconducting proton linac is a safe and reliable solution for the supply of a high power proton beam at a few GeV. As such, the LP-SPL has the potential to be upgraded to multi-MW of beam power at up to 5 GeV. For neutrino applications, however, the proton beam on target must also have a time structure which a linac cannot deliver: for a superbeam, a pulse of a few µs is required, while for a neutrino factory a few bunches of ~2ns rms bunch length are mandatory. The linac beam has therefore to be complemented with one or two rings.

3.3.1 Application to a Neutrino Factory

A neutrino factory has very demanding needs (Table 5), as defined by the ISS working group [13].

Table 5: Proton driver requirements of a neutrino factory [13]

Parameter	Value
Average beam power [MW]	4
Pulse repetition frequency [Hz]	50
Beam kinetic energy [GeV]	10 ± 5
Bunch length (rms) [ns]	2 ± 1
Number of proton bunches	3 or 5
Sequential extraction delay [µs]	≥ 17
Pulse duration (liquid Hg target) [µs]	≤ 40
Pulse duration (solid target) [µs]	≥ 20

A scheme has been designed which can potentially meet these specifications [14], using the 5 GeV high power SPL and two fixed energy rings of approximately 300 m. In the first ring (the accumulator), the chopped linac beam is accumulated in a few long bunches, using charge-exchange injection. The accumulator is isochronous to preserve the time structure of the linac beam, and it has no RF system to minimize the impedance. Once accumulation is finished, bunches are transferred one by one to the second ring (the compressor) where they are rotated in the longitudinal phase plane and ejected to the target when their length is minimum. This principle is sketched in Fig. 5 in the case of 6 bunches. Bunch rotation takes place with the energy stored in the cavities of the low frequency RF system.

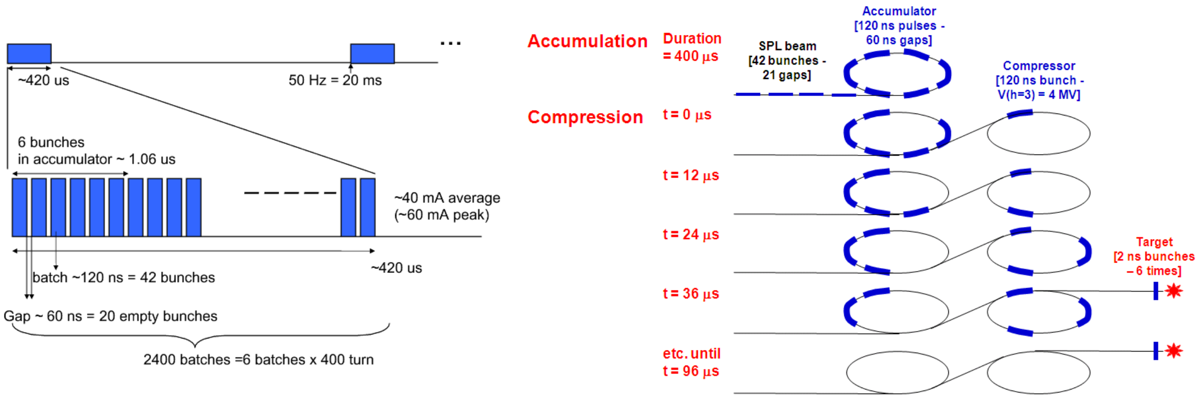

Fig. 5: Principle of bunch generation for a neutrino factory

The accumulator and compressor rings have been designed and particle tacking simulations have shown that bunches of 2 ns rms length can indeed be generated (Fig.6). The study of collective effects in the accumulator has revealed that the impedances required for stability are within reach. More difficult scenarios have been developed for generating less than 6 bunches. The main parameters of the rings in these different cases are shown in Table 6.

Table 6: Main parameters of the accumulator and compressor for a neutrino factory

Ring	Parameter	6 bunches case	3 & 1 bunch cases
Accumulator	Circumference [m]	318.5	185.8
	Nb. of accumulation turns	400	640 / 1920
	Type of magnets	NC	SC
Compressor	Circumference [m]	314.2	200
	Nb. of compression turns	36	86
	RF voltage on h=3 (MV)	4	1.7
	Transition gamma	2.3	2.83
	Type of magnets	SC	NC
	Interval between bunches [μs]	12	30

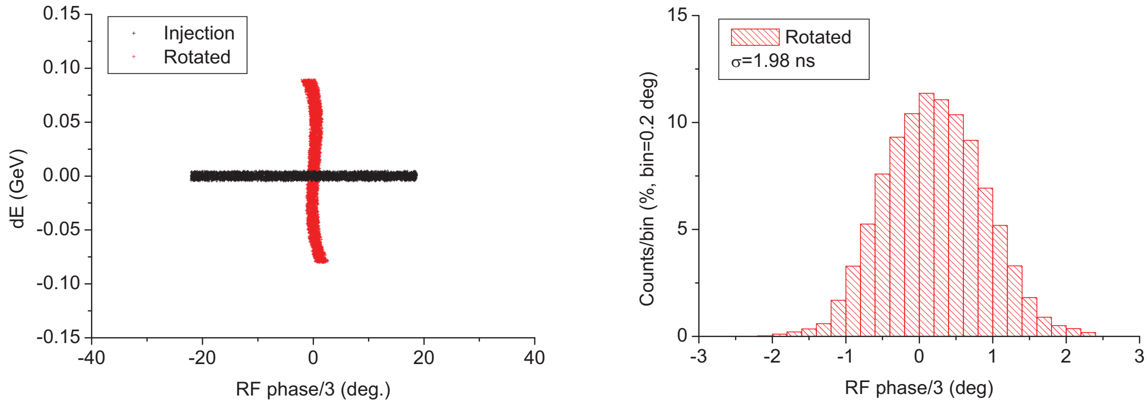

Fig. 6: Bunch rotation in the longitudinal phase plane (left) and longitudinal density at ejection (right)

3.3.2 Application to a low energy neutrino "super-beam"

To generate a low energy neutrino superbeam from π decay, the time structure of the beam provided by the accumulator is perfectly adequate and the compressor is not necessary.

3.3.3 Application to a "beta-beam" facility

In the context of the EURISOL Design Study supported within the 6^{th} Framework Program of the European Union [15], the possibility has been studied to generate electron neutrinos and antineutrinos from the beta decay of ^{6}He or ^{18}Ne radioactive ions. It has been shown that the necessary flux of 3×10^{13} ^{6}He per second can be obtained irradiating a Beryllium Oxide target with the spallation neutrons resulting from a proton beam of ~200 kW at 1-2 GeV on a converter target. The SPL would be perfectly able to satisfy this need. However, no satisfying solution has yet been found for getting the necessary flux of 2×10^{13} ^{18}Ne ions/s, although a promising technique based on 70 MeV proton irradiating an Aluminium Oxide target has recently been proposed.

4 Synergy with a Radioactive Ion Beam Facility

With its 50 Hz rate, the high power SPL is a competitive proton driver for a radioactive ion beam facility of the next generation (EURISOL-like) [15]. The beam from the SPL can directly be used, and even preferably the H^- ions, without the need for an intermediate ring. Figure 7 shows a possible layout on the CERN site.

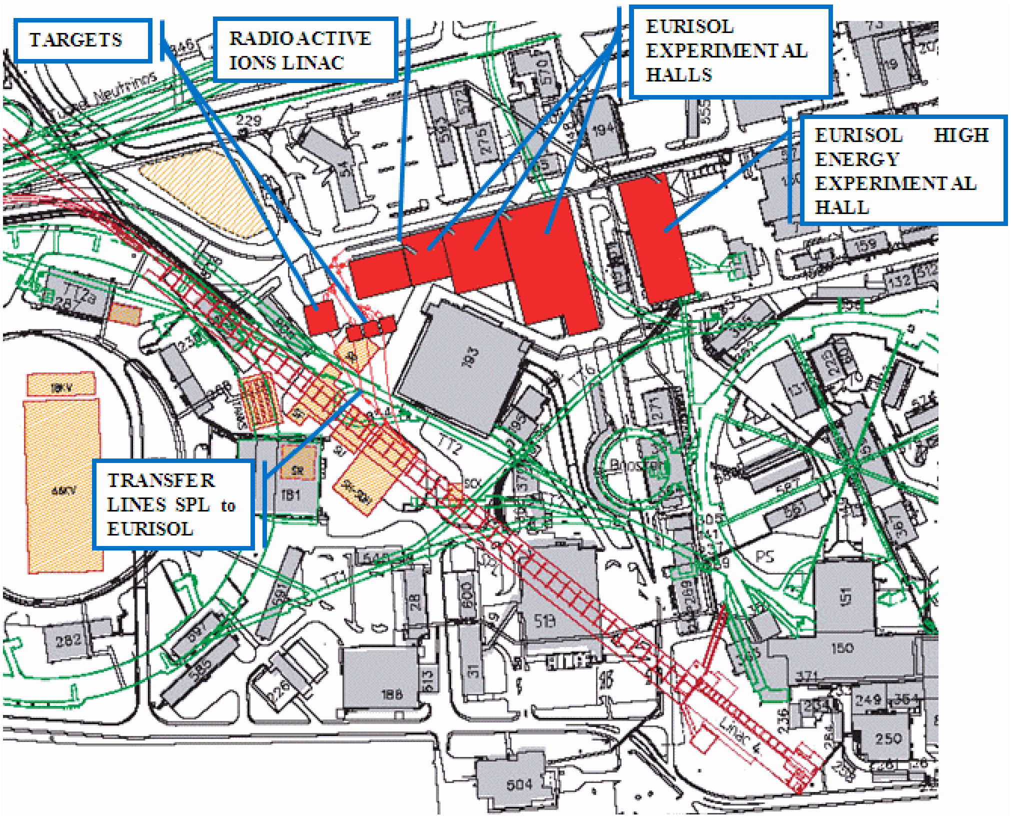

Fig. 7: ISOLDE and EURISOL layouts on the CERN site

In a first stage, the present ISOLDE area will receive ~1.4 GeV protons from the LP-SPL in proton pulses of 20 mA / 0.9 ms length at an average rate of 1.25 Hz (3 pulses out of 4, every 0.6 s), which corresponds to a beam power of 31 kW. If ISOLDE users are interested in a lower beam energy of 1 GeV and a reduced pulse length of 0.38 ms, the rate could be increased to ~3 Hz for the same beam power, by reducing the field in the cavities and accelerating a slightly higher current in the LP-SPL (28 mA instead of 20 mA).

In a second stage, the LP-SPL could be upgraded to high beam power by increasing its repetition rate to 50 Hz (HP-SPL Option 1 in Table 2). The EURISOL experimental area could then receive up to 2.25 MW of beam power at 2.5 GeV, if there is no other user of the SPL high power beam. To get 5 MW, or to be able to operate simultaneously with another user of high beam power, the beam current should be increased by a factor of two to 40 mA, by doubling the number of klystrons in the SPL (HP-SPL Option 2 in Table 2).

5 Summary

The chain of accelerators made up of the LP-SPL, PS2 and the upgraded SPS will provide a lot of flexibility for tailoring the beam injected inside the LHC to whatever solution will finally be implemented for upgrading the integrated luminosity. Users of ISOLDE and SPS fixed target beams will immediately benefit from these new accelerators. The LP-SPL and the SPS have the potential to be upgraded for supplying a higher beam power. If this capability is needed for PS2, its design should be revisited accordingly. A superconducting proton linac is especially worthwhile in the CERN context because of its capability to be upgraded into the proton driver for a neutrino facility and/or a EURISOL-like radioactive ion beam facility.

Acknowledgement

This document summarizes the work of multiple teams (HIP and PAF working groups; PS2, SPL and SPS upgrade study teams; neutrino study team) and of numerous workshops (especially the HHH and NuFact series). The references are an attempt at pointing to the main sources of information.

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