HIGH-INTENSITY PROTON BEAMS AT CERN AND THE SPL STUDY

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Abstract

The construction and operation of LHC is, and will remain, the first priority of CERN for many years. However, the proton injectors still deserve attention because of the beams they provide to users other than the LHC, and because of the need to prepare for future upgrades of the LHC luminosity. This is why a study has recently been performed to evaluate the benefits, for the various user communities, of the possible improvements to the accelerator complex. The outcome of this study is focused on the short and medium term (before 2010). In the longer term, choices depend on the physics experiments that will be included inside the CERN programme. In any case the flexibility and the broad range of applications of a Superconducting Proton Linac (SPL) already make it an attractive device whose development is worth pursuing. This analysis and the resulting recommendations are summarized in this paper.

1 INTRODUCTION

The availability and quality of the "low" energy accelerators has always been a strong asset of the CERN laboratory, and a convincing argument for the construction of a new accelerator at the energy frontier. LHC is not an exception, and its performance will strongly depend upon the characteristics of its injectors: it is crucial to optimize them for that role and to plan their improvement according to the foreseen needs of the collider. Moreover, other physics communities use the beams delivered by the injector complex, and their needs have also to be taken into account. For these reasons, the High Intensity Proton Working Group (HIPWG) [1] was created at the beginning of the year 2003, with the mandate to collect the needs of the various user communities, evaluate the benefits of the possible improvements to the accelerator complex and make recommendations to the management of the AB department. This working group will end in April 2004 with the publication of a report [2].

The analyses, results and recommendations of the HIPWG are discussed in Section 2, while the progresses towards the Superconducting Proton Linac are described in Section 3.

2 HIGH-INTENSITY PROTON WORKING GROUP

The present priorities of CERN have been used, and only the user communities already working on the site have been considered. Namely, the needs of LHC, neutrino and radio-active ion beam physics have been taken into account. For the other present users, i.e. AD, PS East area, nToF, and SPS Fixed Target (SFT), the assumption has been made that their requirements do not significantly influence the choice, and that every upgrade scenario envisaged would be compatible.

Table 1: Main users' requests.

User	CERN commitment*	Users' wishes	
	Short term	Medium term [~asap!]	Long term [> 2014]
LHC	Planned beams	Ultimate luminosity	Luminosity upgrade
SFT (COMPASS)	4.3×10^5 spills/year?	6×10^5 spills/year	
CNGS	4.5×10^{19} p/year	Upgrade ~ × 2	
ISOLDE	1.92 μA**	Upgrade ~ × 5	
Future ν beams			> 2 GeV, 4 MW
EURISOL			> 1-2 GeV, 5 MW

* Reference value for analysis.
** 1350 pulses/hour – 3.2×10^{13} protons per pulse (ppp).

Table 2: Main upgrades considered.

Description	Beneficiary
"Loss-less" PS multi-turn ejection	CNGS
Double PSB batch for CNGS	CNGS
Reduced basic period (0.9 & 0.6 s)	ISOLDE
Energy upgrade of linac 2	ISOLDE, CNGS
Linac 4 (160 MeV H^-) ⇒ single PSB batch for LHC	LHC, ISOLDE
Low energy RCS (PSB replacement)	LHC, ν
SPL	LHC, EURISOL, ν
30 GeV RCS	LHC, ν
New 30 GeV PS (~ "PS XXI")	LHC
1 TeV LHC injector ("Super-SPS")	LHC

In terms of schedule and resources, the users' requirements and the proposed upgrades fall into three main categories: (i) the short term, "low" (ideally zero) cost demands, which match the present commitments of

CERN and belong to the approved physics programme, (ii) the medium term, “medium” cost requests, which correspond to modest and progressive increases of performance for the present experiments, (iii) the long term, “high” cost wishes, which are linked to major equipment upgrades and to new experiments suggested for integration inside the future physics programme of CERN. The main users’ requests are summarized in Table 1, and the main upgrades considered in the analysis are given in Table 2.

Table 3: Proton flux with 1.2 s (actual) basic period of the PS complex in 2007. Double or single refer to the number of PSB batches sent to the PS, pot stands for protons on target, and SC for super-cycle.

	LHC double CNGS single	LHC double CNGS double	LHC single (Linac 4) CNGS single	Basic user’s request
CNGS flux (pot/year)	4.4×10^{19}	6.4×10^{19}	7×10^{19}	4.5×10^{19}
PS East area spills	1.5×10^{6}	1.4×10^{6}	1.5×10^{6}	1.3×10^{6}
nToF flux (pot/year)	1.7×10^{19}	1.5×10^{19}	1.7×10^{19}	1.5×10^{19}
ISOLDE flux (μA) [pulses/hour]	1.75 1230	1.32 930	3.7 1310	1.9 1350
SFT spills	1.9×10^{5}	1.8×10^{5}	1.9×10^{5}	6×10^{5}
LHC SC length	22.8 s	25.2 s	22.8 s	Shortest
CNGS + SFT SC length	34.8 s	38.4 s	34.8 s	

Table 4: Proton flux with 0.9 s basic period of the PS complex in 2007. Double or single refer to the number of PSB batches sent to the PS, pot stands for protons on target, and SC for super-cycle.

	LHC double CNGS single	LHC double CNGS double	LHC single (Linac 4) CNGS single	Basic user’s request
CNGS flux (pot/year)	4.3×10^{19}	6.4×10^{19}	6.8×10^{19}	4.5×10^{19}
PS East area spills	1.5×10^{6}	1.4×10^{6}	1.5×10^{6}	1.3×10^{6}
nToF flux (pot/year)	1.6×10^{19}	1.5×10^{19}	1.6×10^{19}	1.5×10^{19}
ISOLDE flux (μA) [pulses/hour]	3.1 2150	2.6 1820	6.4 2240	1.9 1350
SFT spills	1.9×10^{5}	1.8×10^{5}	1.9×10^{5}	6×10^{5}
LHC SC length	23.4 s	25.2 s	23.4 s	Shortest
CNGS + SFT SC length	35.1 s	37.8 s	35.1 s	

In the analysis of the proton flux available to the users after 2006 (LHC starting only in 2007, there is no shortage before that year), the following assumptions have been made:

- **Accelerators operating time per year**
  - ○ PS: 5400 h (without setting-up)
  - ○ SPS/LHC: 4700 h (without setting-up)
  - ○ SPS in LHC filling mode: 15% (5%) of the time
  - ○ SPS in LHC pilot mode: 35% (10%) of the time
  - ○ SPS in CNGS&SFT mode: 50% (85%) of the time
- **Availability**
  - ○ PS & PSB: 90%
  - ○ SPS : 80%
- **Beam intensities**
  - ○ SPS for CNGS: 4.4×10^{13} and 7×10^{13} ppp
  - ○ PS for CNGS: 3×10^{13} and 4×10^{13} ppp.

Here, the LHC pilot beam is a “safety beam” to be used to establish circulating beam. The results of the analysis for beam availability in 2007 are summarized in Tables 3 and 4. The basic operational requirements taken into account (assuming the capability of quickly changing the SPS super-cycle and the presence of a solid-state switch for powering magnets in the TT41 SPS transfer line) are the following:

- **LHC filling super-cycle:**
  - ○ 1 LHC filling (flat porch for 4 PS injections), nominal length ≥ 21.6 s
- **LHC pilot super-cycle:**
  - ○ 1 LHC pilot + 2 CNGS, nominal length: 22.8 s
- **CNGS&SFT super-cycle:**
  - ○ 3 CNGS + 1 SFT + 1 MD (Machine Development), nominal length: 34.8 s.

The problem of the beam brightness for LHC with the present injectors’ scheme has also been looked at. Presently the PS can not provide the “ultimate” beam as can be seen in Table 5. Solutions to this problem are proposed in Table 6 using RF batch-compression and/or Linac 4 (see Section 3) [1]. Based on the above analyses and taking into account the major concern of irradiation caused by beam loss at high intensity, the HIPWG makes the following recommendations:

- At short term, define in 2004 and start in 2005 the three following studies:
  - ○ **New PS multi-turn ejection**
  - ○ **Increased intensity in the SPS for CNGS**
  - ○ **0.9 s basic period**
- At medium term, work on the design of Linac 4, to prepare for a decision of construction at the end of 2006 (covered with the resources already requested)
- At long term, prepare for a decision concerning the optimum future accelerator by pursuing the study of a Superconducting Proton Linac (covered with the resources already requested).

Table 5: Number of protons per bunch within the same transverse normalized rms emittances (~ 2.5 μm). The numbers in 2003 take into account the transmission losses in the SPS (~15%), but not those in the LHC.

	1993	2003
LHC nominal (p/b)	1.05×10^{11}	1.15×10^{11}
LHC ultimate	1.70×10^{11}	1.70×10^{11}
PS nominal (estimate)	1.05×10^{11}	1.30×10^{11}
PS ultimate (estimate)	1.70×10^{11}	2.00×10^{11}
PS max. (experimental)		1.40×10^{11}

Table 6: Means to improve the beam brightness for LHC.

	PS batch compression	Linac 4	PS batch compression + Linac 4
Bunch intensity (PS max.)	2.65×10^{11}	2.00×10^{11}	3.00×10^{11}
Nb. of bunches / PS pulse	42 (48)	72	48
PS repetition (1 BP = 1.2 s)	3 BP	2 BP	2 BP

3 LINAC DEVELOPMENTS

The study made by the HIPWG confirms the strong interest of linacs for improving the performance of the proton beams at CERN. Three phases are distinguished, in increasing order of beam energy, cost and benefits.

In the first phase the performance of the pre-injector, up to 3 MeV of kinetic energy, will be investigated. A test stand equipped with an RFQ accelerator has been funded and is presently under preparation, with the goal of operating with beam during the year 2007.

In the second phase, it is planned to build a new linac to replace linac 2, the present injector of the PSB, and increase by a factor of two the intensity and brightness of the PSB beam. This accelerator being the fourth hadron linac to be built at CERN, it is called Linac 4. Based on the 3 MeV pre-injector, it will accelerate H^- ions to a kinetic energy of 160 MeV. The management is planning to decide upon its construction during the year 2006. In case of approval at that time, the setting-up with beam could take place in 2010 and operation for physics could begin in 2011 with immediate benefits for LHC and ISOLDE.

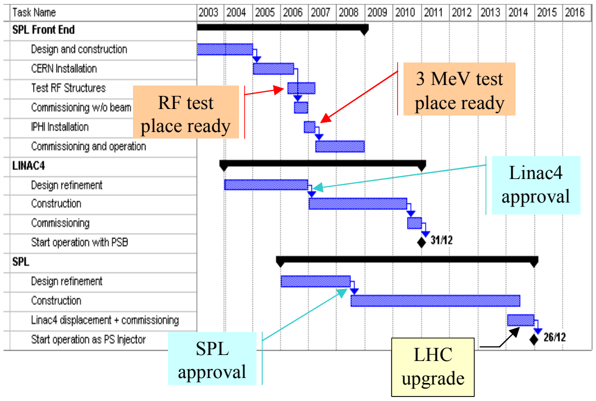

Figure 1: Indicative multi-year planning for the full SPL project.

In the third phase, the full SPL would be built. The decision on its construction will depend upon the future physics programmes at CERN and upon the needs of the LHC upgrade. Considering that the finalization and setting-up of the SPL imply an interruption of the proton beams of one year, it is logical to plan it during the shutdown for LHC upgrade which is estimated to be in 2014. Therefore the decision of construction has to be taken during the year 2008. An indicative planning highlighting these key dates is given in Fig. 1.

3.1 3 MeV Test Stand

The low-energy front-end, up to the energy of a few MeV, is considered as the most difficult part of a linac, where the beam emittance and the particle distribution are generated. Its performance determines the beam loss and characteristics of the whole accelerator. To gain experience on this section and to test critical linac equipment, a 3 MeV test stand is being prepared, to be housed in the South Hall of the CERN PS. The cornerstone of the test stand will be the IPHI RFQ [3], which started as a French development by the CEA and CNRS-IN2P3, and has lately become the subject of a collaboration with CERN. Initially foreseen for continuous operation at a beam current of 100 mA, as demonstrator for a new generation of high beam power machines, this RFQ (90 keV – 3 MeV, 352 MHz) will first be tested at the CEA-Saclay in 2006. Afterwards it will be transferred to CERN where it will be used at low duty cycle (0.1%) to accelerate a beam current of 40 mA. Tests will begin with an existing proton source. An H^- source, in principle of the ECR-type presently under development at CERN and at CEA-Saclay, will be substituted as soon as possible.

Following the RFQ in the test stand, a 3.6 m long chopper line, presently under construction at CERN, will give to the beam the time structure needed in the Linac 4 and SPL. It includes two choppers, travelling-wave deflecting structures with very fast rise and fall times (< 2 ns), housed inside two standard CERN linac quadrupoles. The main functions of the line are (i) to make beam chopping possible and dump “cleanly” the eliminated part of the beam, (ii) to match the beam out of the RFQ into the following accelerator, and (iii) to provide space for beam diagnostics. A specially-developed detector named “Beam Shape and Halo Monitor” will allow time-resolved measurements of beam shape with a large dynamic range, covering at the same time the beam core and the tails of the distribution.

The beam from the chopper line will be transported through a diagnostics line before being dumped.

The test stand will be equipped with 2 klystrons recuperated from the LEP machine. One will provide RF power to the RFQ, while the other will be used for testing prototype RF structures for higher energies. A 3D representation of the RFQ with its waveguide inputs and of the CERN chopper line is presented in Fig. 2.

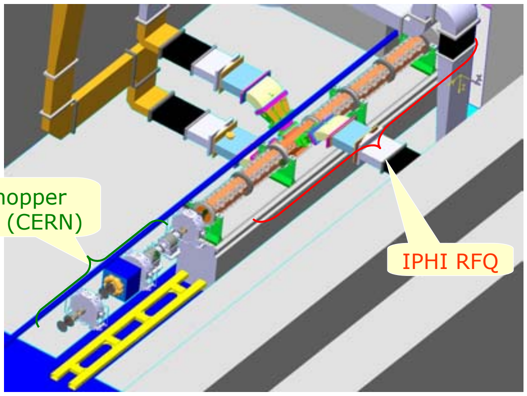

Figure 2: The beam line of the 3 MeV test stand.

3.2 Linac 4

The 160 MeV Linac 4 will be built as an extension along the same axis of the 3 MeV pre-injector. In its first use as injector for the PSB, it will operate at low duty cycle (~ 0.1 %). However the RF structures will be dimensioned for the higher duty cycle, ~ 15%, required by the SPL. The parameters of the two operating modes are presented in Table 7.

Table 7: Linac 4 specifications.

	Phase 1 (PSB)	Phase 2 (SPL)	
Maximum repetition rate	2	50	Hz
Source current	50	30	mA
RFQ current	40	21	mA
Chopper beam-on factor	75	62	%
Current after chopper	30	13	mA
Pulse length (max.)	0.5	2.8	ms
Average current	15	1820	µA
Max. beam duty cycle	0.1	14	%
Number of particles per pulse	0.9	2.3	$\cdot 10^{14}$
Transv. emittance (rms, norm.)	0.28	0.28	π mm mrad
Longitudinal emittance (rms)	0.15	0.15	π deg MeV

Three types of accelerating structures will be used: (i) Alvarez Drift Tube Linac between 3 and 40 MeV, (ii) Cell Coupled Drift Tube Linac between 40 and 90 MeV, and (iii) Side Coupled Linac above 90 MeV. The RF frequency is of 352 MHz up to the end of the CCDTL structures, and 704 MHz in the remaining part of the accelerator. Table 8 shows the main characteristics of these structures. Out of the 17 klystrons needed, 12 will come from the stock of 352 MHz klystrons recuperated from the LEP machine.

To transport the beam from Linac 4 to the PSB, a 200 m long transfer line will be built, equipped with 2 RF cavities and 27 quadrupoles.

The R&D programme for Linac 4 has been recently integrated in a Joint Research Activity (JRA) partially funded by the European Union. The JRA, called HIPPI (High Intensity Proton Pulsed Injectors) [4], coordinates the efforts of 9 European Laboratories in the development of the technologies for the next generation of European high-intensity linac facilities and covers the period 2004-2008. In this context, different types of normal conducting linac structures will be studied and compared, superconducting alternatives for the high-energy sections will be developed, the chopper design and chopping measurements will be analysed and finally there will be a strong effort in the development and coordination of tools for beam dynamics simulations.

In addition to the European programme, CERN benefits from projects in Russian laboratories which are funded or in the process of being funded by the International Science and Technology Centre (ISTC-Moscow). The first one, already approved, is aimed at the construction of a high-power CCDTL prototype, while the other two, still in the approval process, are focused on the development of a DTL structure and of a low-cost alternative to DTL.

Table 8: SPL room-temperature sections (Linac4).

	Output energy (MeV)	No. of cavities (tanks)	Peak RF power (MW)	No. of klystr.	Length (m)
LEBT	0.095	-	-	-	2
RFQ	3	1	0.9	1	6
Chopper line	3	3	0.1	-	3.7
DTL	40.2	3	4.8	5	16.7
CCDTL	90	27	5.6	6	30.1
SCL	160	20	13.8	5	27.8
Total		54	25.2	17	86.3

3.3 SPL

The Superconducting Proton Linac (SPL) [5,6] is the ultimate multi-GeV, multi-MW linear proton machine considered at CERN. Operating at 50 Hz, it will be used both as a high-performance injector for the PS, replacing the PSB, and as a high-power proton driver for other physics applications, possibly complemented with an accumulator ring.

The SPL re-uses the equipment of Linac 4 in its front-end, although in a different location. In its original design, based on the quasi-exclusive use of LEP RF hardware, acceleration beyond 160 MeV takes place in a 550 m long superconducting linac section which brings the beam kinetic energy up to 2.2 GeV. The schematic layout of this version of the SPL is presented in Fig. 3. Table 9 presents the main parameters of the superconducting section, which is made of 352 MHz elliptical cavities at three different beta values.

An improved design is in preparation (to be ready by the end of 2004), based on state-of-the-art bulk Niobium superconducting cavities operating at 704 MHz. For the same output energy, the SPL will be shorter, or, for a similar length, the energy will be higher.

The instabilities induced by cavity vibrations due to the pulsed mode of operation have been studied in different laboratories. Stiffening techniques have been proposed and compensation schemes are under investigation. In particular, CERN is testing a prototype high power phase and amplitude modulator intended to facilitate the stabilisation of a string of superconducting cavities fed by a single klystron [7].

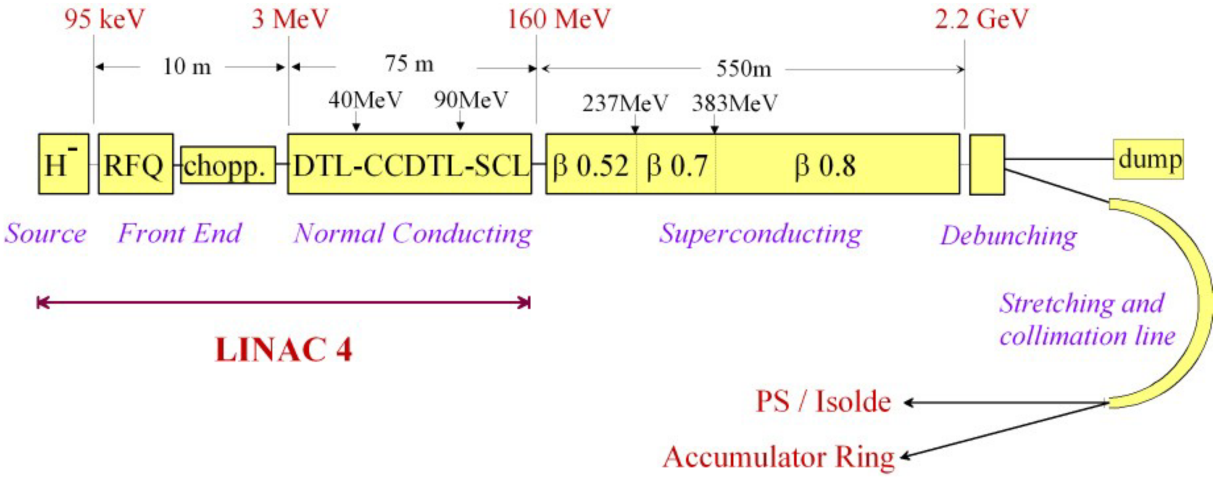

Figure 3: SPL schematic layout (original design).

Table 9: SPL superconducting section parameters.

Section beta	0.52	0.7	0.8	0.8	
E0T	3.5	5	9	9	MV/m
Cavities	27	32	52	76	
Cryostats	9	8	13	19	
Type of ampl.	tetrodes	tetrodes	klystrons	klystrons	
# Amplifiers	42	32	13	19	
Synchr. phase	-25	-20	-18 / -15	-15	deg
Length	67	80	166	237	m
Input Energy	120	236	383	1111	MeV
Output Energy	236	383	1111	2235	MeV
Focusing	FDO	FDO	FDO	FDOO	

4 CONCLUSION

A path for improving the CERN complex of proton accelerators has been established. Short and medium term/cost measures have been recommended, about which management decisions are expected soon. More expensive and longer term measures are based on linacs. Linac 4 is strongly recommended, and the SPL is a highly competitive contender if news physics experiments requiring MW of beam power are included in the CERN programme.

Developments for proton linacs have significantly progressed. The number of collaborations has greatly increased with the support of the EU and the ISTC. More collaborations are not only welcome, they are necessary.

The preparation of the 3 MeV test place is advancing according to schedule. A draft planning now exists. Continuous and increasing support is needed from the CERN management to make it real.

ACKNOWLEDGEMENTS

The help and support of the many particle and accelerator physicists who were interviewed by the HIPWG is gratefully acknowledged [1]. The remarkable progress in linac developments is the outcome of the work of the SPL study team [6].

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