EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – AB DEPARTMENT

CERN-AB-2004-022 OP/RF

REPORT OF THE HIGH INTENSITY PROTONS WORKING GROUP

M. Benedikt, K. Cornelis, R. Garoby, E. Métral, F. Ruggiero, M. Vretenar

Editors: M. Benedikt, R. Garoby

Geneva, Switzerland
15 May 2004

ABSTRACT

The availability and the quality of the “low” energy accelerators have always been a strong asset of our laboratory, and a convincing argument for the construction at CERN 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 was created at the end of the year 2002, with the mandate to make recommendations to the management of the Accelerators and Beams department for the future of the CERN proton accelerator complex. The working group was specifically asked to collect the needs of the various users communities, evaluate the benefits of the possible improvements and elaborate a preferred long-term scenario of the CERN accelerator complex. Short-term first priority steps had to be proposed, in line and consistent with the long-term scenario. This document is the final report of the HIP working group.

CONTENTS

ABBREVIATIONS

AD	CERN Antiproton Decelerator
CNGS	CERN Neutrino beam to Gran Sasso
COMPASS	Common Muon Proton Apparatus for Structure and Spectroscopy
CT	Continuous Transfer
EURISOL	European Isotope Separation On-Line Radioactive Ion Beam Facility
FT	Fixed Target
HIP	High Intensity Protons
IP	Interaction Point
IR	Insertion Region
ISOL	Isotope Separation on Line
ISOLDE	CERN radioactive ion beam facility
LEIR	CERN Low Energy Ion Ring
LEP	CERN Large Electron Positron collider
LHC	CERN Large Hadron Collider
Linac2	CERN 50 MeV proton linear accelerator
Linac4	proposed 160 MeV H^- linear accelerator
MD	Machine Development
MKE	Magnet Kicker Extraction
nTOF	CERN neutron Time Of Flight facility
PFW	Pole-Face-Windings
P+M	Personnel plus Material
pot	protons on target
ppb	protons per bunch
ppp	protons per pulse
PS	CERN Proton Synchrotron
PSB	CERN Proton Synchrotron Booster
RCS	Rapid Cycling Synchrotron
R&D	Research and Development
REX-ISOLDE	CERN Radioactive beam linear accelerator at ISOLDE
RF	Radio Frequency
RIB	Radioactive Ion Beams
SPL	proposed 2.2 GeV Superconducting Proton Linac
SPS	CERN Super Proton Synchrotron
Super-SPS	proposed 1 TeV synchrotron injector for the LHC
TI8	Injection Tunnel to LHC point 8
TT41	Transfer Tunnel to CNGS target

CHAPTER 1

INTRODUCTION

The availability and the quality of the “low” energy accelerators have always been a strong asset of our laboratory, and a convincing argument for the construction at CERN 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 (HIP) working group was created at the end of the year 2002, with the mandate to make recommendations to the management of the Accelerators and Beams (AB) department for the future of the CERN proton accelerator complex. The working group was specifically asked to collect the needs of the various users communities, evaluate the benefits of the possible improvements and elaborate a preferred long-term scenario of the CERN accelerator complex. Short-term first priority steps had to be proposed, in line and consistent with the long-term scenario.

This document is the final report of the HIP working group. The physicists’ requests are summarized in Chapter 2. The present limitations of the accelerator complex are described in Chapter 3, and the improvements that have been considered are summarized in Chapter 4. Chapters 5, 6 and 7 deal with the benefits of these different upgrades for the main fields of user interests, LHC, neutrinos, Radioactive Ion Beams (RIB). The combined effects of some of the possible upgrades, including consequences for SPS Fixed Target (FT) physics are analysed in Chapter 8. The outcome of this study is naturally focused on the short and medium term (until 2010), but some guidelines for the long-term future are nevertheless expressed among the recommendations given in Chapter 9. The mandate of the working group is presented in Annex 1 and the various presentations that were given during working group meetings are listed in Annex 2.

CHAPTER 2

PHYSICS REQUESTS

2.1 STRUCTURING THE REQUESTS

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, RIB and SPS FT physics have been taken into account. For the other present users (AD, PS East Area, nTOF), the assumption has been that their requirements do not significantly influence the choice, and that every scenario envisaged would be compatible.

In terms of schedule and resources, the requested beams fall into three main categories:

- Short-term, “low”-cost (ideally zero) demands, which match the present commitments of CERN and belong to the approved physics programme.
- Medium-term, “medium”-cost requests, which correspond to modest and progressive increases of performance for the present experiments.
- 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.

2.2 LHC EXPERIMENTS

2.2.1 Nominal and ultimate performance (short and medium term)

The figure of merit for a collider such as the LHC is the luminosity

$$L = \frac{k_\mathrm{b} N_\mathrm{b}^2 f_\mathrm{rev} \gamma}{4\pi \varepsilon_\mathrm{n} \beta^*}$$

with k_b the number of bunches per ring, N_b the number of protons per bunch (ppb), f_rev the revolution frequency, ε_n the normalized rms transverse beam emittance (same in both planes), β^* the beta function at the interaction point and $\gamma = (1-\beta^2)^{-1/2}$ the relativistic Lorentz factor. L is proportional to the number of events per second and has thus to be maximized. But more conditions have to be satisfied: (i) the beam emittance has to fit into the small aperture of the superconducting LHC magnets; (ii) the total intensity $k_\mathrm{b} \cdot N_\mathrm{b}$ is limited by the thermal energy produced by synchrotron radiation that must be absorbed by the cryogenic system; (iii) the beam-beam effect, proportional to the transverse beam brightness $N_\mathrm{b}/\varepsilon_\mathrm{n}$, causing a spread in betatron tunes (“footprint”) when the beams are colliding, has to be kept below a certain limit; (iv) the space charge limit in the injectors, which also scales with $N_\mathrm{b}/\varepsilon_\mathrm{n}$. Conflicting requirements also determine the longitudinal emittance ε_L which has to be small at injection (small $\Delta p/p$ to ease beam transport from the SPS through the two ~2.5 km long lines), but large at collision to avoid transverse emittance blow-up by intra-beam scattering.

An elaborate optimisation procedure, taking into account these boundary conditions, has resulted in the LHC beam parameter set [1, 2] compiled in Table 2.1. The “ultimate” performance level corresponds to the LHC beam-beam limit, whereas the “nominal” performance combines high luminosity with operational margin. The LHC luminosity is expected to gradually reach the nominal value after a few years of operation (~ 2010), as a step towards the ultimate level.

The injector complex is a cascade of accelerators that were not originally designed and optimized for their future function for LHC. Taking into account their specificities, modifications have been defined [2], which will be completely implemented before the LHC starts, in 2007. The primary concern is to meet the LHC nominal parameters that correspond to the first years of operation of the collider (until ~ 2010).

At SPS extraction, the beam characteristics are summarized in Table 2.2.

Table 2.1: LHC nominal and ultimate proton beam parameters.

		Injection	**Collision**	
Proton momentum	[GeV/c]	450	7000	
Luminosity nominal ultimate	[$\mathrm{cm^{-2}s^{-1}}$]		1.0×10^{34} 2.3×10^{34}	
Number of bunches		2808		3564 bunch places
Bunch spacing	[ns]	25		
N_b (intensity per bunch) nominal ultimate	[ppb]	1.15×10^{11} 1.70×10^{11}		
Beam current nominal ultimate	[A]	0.58 0.86		
ε_n (transverse emittance, rms, normalized), nominal & ultimate	[μm]	3.6	3.75	Emittances equal in both planes; small blow-up allowed in LHC
ε_L (longitudinal emittance, total)	[eVs]	1.0	2.5	Controlled blow-up during acceleration
4σ (bunch length, total)	[ns]	1.7	1.0	Has to fit into 400 MHz buckets
$\Delta p/p$ (relative momentum spread, total)	[10^{-3}]	1.9	0.45	

Table 2.2: Beam characteristics at extraction from the SPS.

Proton momentum	[GeV/c]	450	
Number of SPS batches to fill LHC		2 × 12	1 SPS batch = 3 or 4 PS batches
SPS repetition time	[s]	21.6	
Number of bunches in SPS		3 or 4 × 72	
Bunch spacing in a PS batch	[ns]	25	
Time interval between PS batches	[ns]	225	SPS injection kicker rise-time: 220 ns
N_b (intensity per bunch) nominal ultimate	[ppb]	1.15×10^{11} 1.70×10^{11}	Assuming no loss between SPS and LHC
ε_n (transverse emittance, rms, normalized)	[μm]	3.5	
ε_L (longitudinal emittance, total)	[eVs]	0.6	
4σ (bunch length, total)	[ns]	1.7	Limited by LHC 400 MHz buckets

Experiments with beam have demonstrated that, indeed, the nominal beam can be obtained at the SPS extraction energy. However, the measured transmission efficiency from PS extraction to SPS at top momentum of 450 GeV/c is only of the order of 85%, so that the PS has to deliver more than 1.3×10^{11} ppb. In these conditions, the injector complex, as prepared for LHC, will not be able to provide the ultimate beam in the collider, essentially because of the excessive brightness now required from the PSB, which largely exceeds the expectations.

2.2.2 Beyond the ultimate luminosity (long term)

Reaching the nominal LHC performance ($1.0 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$) reliably and for long periods of time will be a challenging task. Attaining the ultimate performance ($2.3 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$) is going to be even more difficult. Nevertheless, it is already clear that any possibility to go above that level is worth exploring, as testified by physicists' interest [3]. The characteristics of the beam delivered by the LHC injector complex contribute to the limitation of the performance of the collider. Specifically, space charge effects limit the beam brightness N_b/ε_n, for a given longitudinal and transverse normalized emittance.

Possible upgrade paths to increase the luminosity up to 1.0×10^{35} $cm^{-2}s^{-1}$ and/or to double the beam energy have been identified in preliminary studies [4]. The resulting requirements at SPS extraction energy and in the PS are summarized in Table 2.3, in terms of beam brightness and bunch intensity.

Table 2.3: Requirements of LHC luminosity upgrades on the injectors.

LHC phase [β^*]	**LHC scheme description**	**Luminosity in IP1-IP5 [$\times 10^{34}$ $cm^{-2}s^{-1}$]**	**Bunch spacing in LHC**	**N_b (ppb) in SPS at 450 GeV/c within ε_n=3.5 μm; ε_L=0.7 eVs**	**PS brightness w.r.t. ultimate (assuming 100 % transmission)**
0 [0.5 m]	345 μrad cross. angle Long bunches {Table 3 – Reference 4}	3.6	25 ns	2.6×10^{11}	1.5
1a [0.25 m]	445 μrad cross. angle Short bunches {Table 4 – Reference 4}	4.6	25 ns	1.7×10^{11}	1
1b [0.25 m]	Scheme 1a with 15 ns bunch spacing	~ 7	15 ns	1.7×10^{11}	1.7
1c [0.25 m]	485 μrad cross. angle Nominal bunches {Table 6 – Reference 4}	7.2	25 ns	2.6×10^{11}	1.5
1d [0.25 m]	mrad cross. angle "Super-bunches" {Table 7 – Reference 4}	~ 9	88.9 μs	2.0×10^{11}	1.2
2 [0.25 m]	1 TeV injector Beam-beam compensation {Section 1.4 – Reference 4}	> 10	25 ns	$> 3.4 \times 10^{11}$ [ε_n = 7 μm]	> 2

An increased brightness is needed by all but one of the upgrades. Taking into account that the transfer efficiency between accelerators never reaches 100% (85% today), and tends to decrease at higher intensities, the effective brightness at the PS ejection has to be even larger than shown in the last column of Table 2.3.

Upgrade scenarios for the LHC and its injectors are further discussed in Chapter 5.

2.3 NEUTRINO EXPERIMENTS

2.3.1 CNGS (short term)

The "CERN Neutrino beam to Gran Sasso" (CNGS) programme [5] belongs to the CERN commitments. A proton beam is fast extracted in 2 halves from the SPS at 400 GeV/c and sent to a carbon target. The pions resulting from the interactions are focused by a set of 2 magnetic horns and decay inside a 1 km long evacuated pipe, generating neutrinos that will later travel through 732 km of earth before reaching the detectors in the Gran Sasso tunnel. The quality of the experiments depends directly on the total number of protons sent annually onto the target. The flux specified is of 4.5×10^{19} protons/year. Being at the upper limit of the present capability of the accelerators, it is a demanding use whose compatibility with the needs of LHC setting-up and exploitation is delicate and it will generate a substantial irradiation of the injector complex which is not compatible with a long-term operation.

Moreover, the interest is very high for a higher flux, especially since recent experiments have shown that the rate of valuable events will be smaller than originally estimated. Users are eager to benefit as soon as possible from an increase of flux. A preliminary analysis has estimated a potential gain of a factor 1.8 [6].

2.3.2 Neutrino super-beam, beta-beam and neutrino factory (long term)

To extend the experimental possibilities beyond the presently planned facilities in the world, the community of neutrino physicists is interested in three types of high flux neutrino sources [7].

The most powerful and costly solution is the neutrino factory (see typical layout in Figure 2.1). Based on a high power proton driver that sends beam onto a target, it collects the muons resulting from the decay of the pions, cools them and accelerates them quickly with respect to their lifetime (2 μs). The high energy muons (20-50 GeV) are then transferred into a storage ring where they stay until they decay. The storage ring has long straight sections beamed towards remote experiments, so that the neutrinos generated by muon decays are beamed towards remote experiments. However, a number of components in the neutrino factory still need intensive R&D (target, muon collection and cooling, muon accelerators). Therefore a staged construction is interesting.

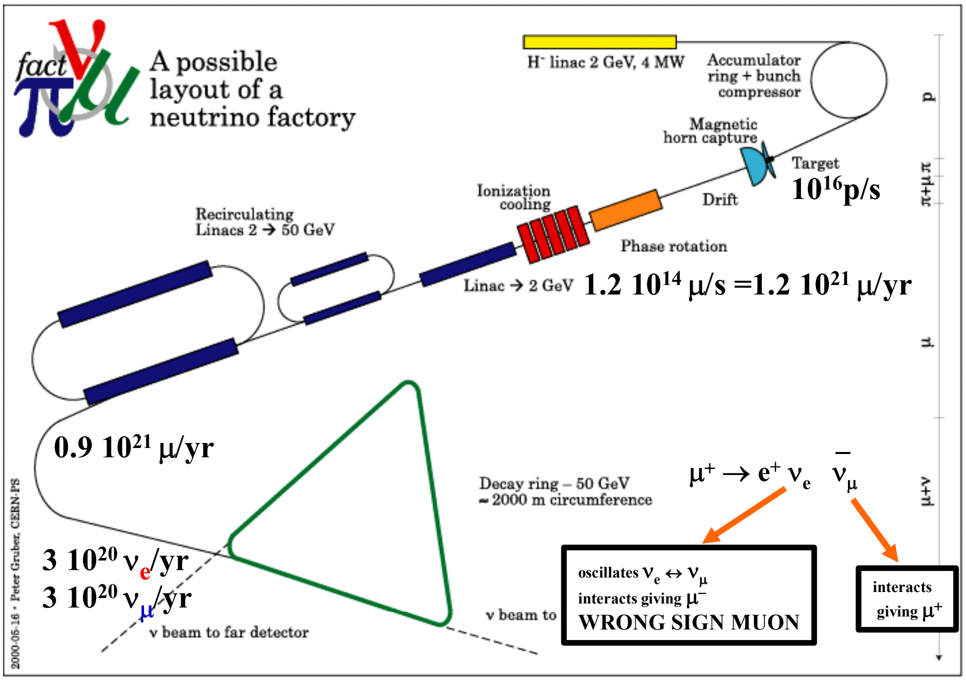

Figure 2.1: Possible layout of a neutrino factory.

The “super-beam” concept makes use of a similar proton driver, but the neutrinos sent to the experiments come from the pions decaying in an evacuated pipe following the target (see typical layout in Figure 2.2). Pion collection and focusing is more “conventional” than for a neutrino factory, and there is no accelerator network behind the target. The experimental reach is clearly inferior to a neutrino factory, and the power of the proton beam must largely exceed presently available values (~ 4 MW).

In the third and most recent scenario, the “beta-beam”, the neutrinos result from the beta decay of radioactive ions in a storage ring [8]. Like in a neutrino factory, long straight sections beam the neutrinos towards the remote experiments (see Figure 2.3). However, the accelerator complex is simpler and more conventional, because “cooling” is not necessary and acceleration of the unstable ions can take place in synchrotrons, their lifetime being of the order of seconds. The present layout even foresees to re-use the PS and SPS. The necessary radioactive ions like ^{6}He and ^{18}Ne can be produced by the Isotope Separation on Line (ISOL) method using a proton beam of ~200 kW power at a few GeV.

The combination of both super-beam and beta-beam is especially interesting, with neutrinos being send simultaneously towards a common detector. The physics reach approaches the potential of a neutrino factory, although at a more affordable cost. This solution is unique to CERN, due to the ISOLDE experience with radioactive ions and the availability of synchrotrons to accelerate these radioactive ions. It is likely that the time scale will be determined by the availability of the neutrino detectors. In the case of the Frejus laboratory which is ideally situated for a super-beam based on a 2.2 GeV Superconducting Proton Linac (SPL) and beta radioactive ions stored at a gamma of ~100, an earliest starting date of 2012 can be envisaged.

The characteristics of the proton driver needed for these three options are summarized in Table 2.4.

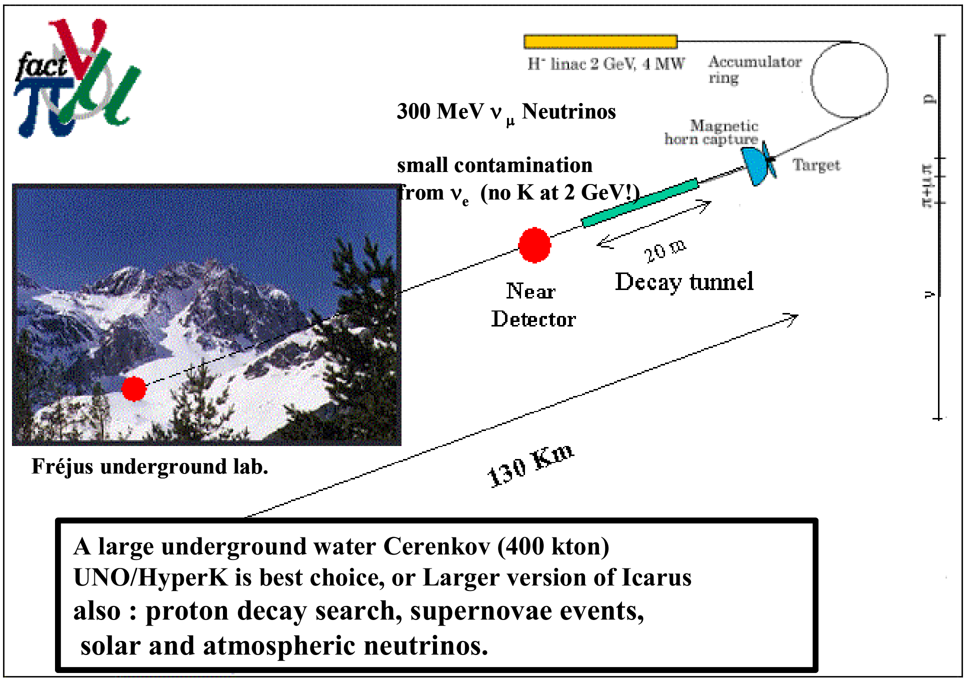

Figure 2.2: Possible layout of a neutrino super-beam facility.

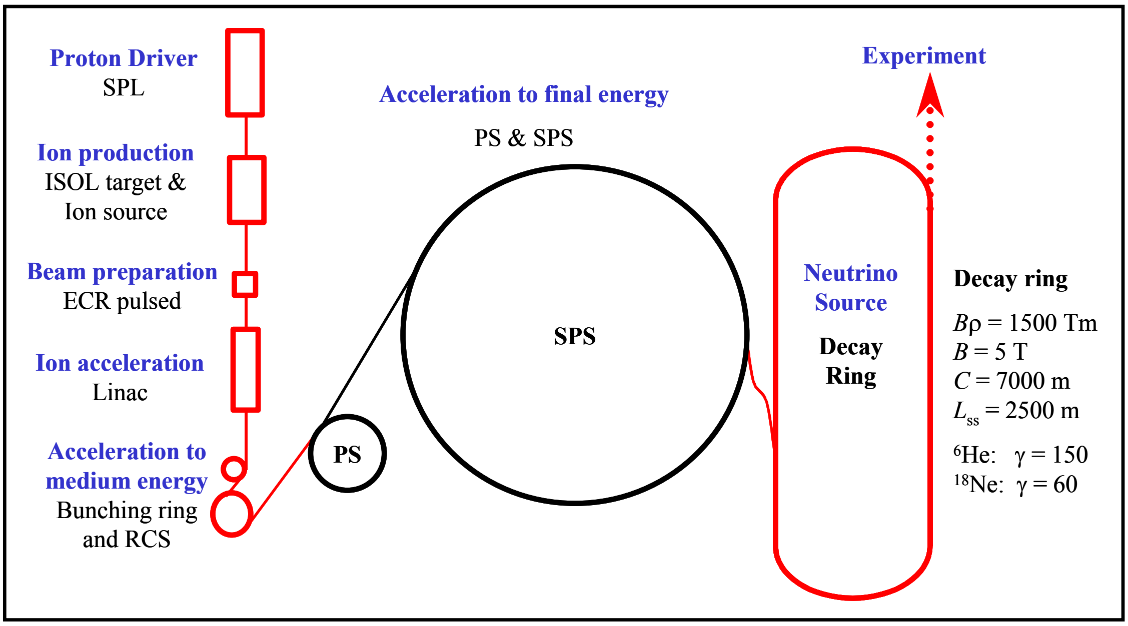

Figure 2.3: Possible layout of a neutrino beta-beam facility.

Table 2.4: Proton driver characteristics for neutrino physics.

	Kinetic energy [GeV]	**Beam power [MW]**	**Burst length [μs]**	**Bunch length [ns rms]**	**Repetition rate [Hz]**
Super-beam	> 2	4	1-5	indifferent	≤ 50
Beta-beam	1-4	0.2	~ 1000	indifferent	≥ 50
Neutrino factory	> 2	4	1-5	1	≤ 50

2.4 FIXED TARGET PHYSICS

2.4.1 COMPASS (short and medium term)

For the time being, COMPASS is the only approved SPS FT physics programme. It cannot exploit an instantaneous proton rate exceeding 1.1×10^{13} protons per 4.8 s flat top. Therefore its performance depends on the total time over which protons are extracted, i.e. the product of the number of spills per year and the length of the extraction flat top. In its proposal [9], the experiment requested around 150 days of SPS operation dedicated to FT physics per year. At that time, the length of the FT supercycle was 14.4 s (with 4.8 s flat top) so that the initial COMPASS request corresponds to 7.2×10^5 spills per year for an overall machine efficiency of ~80%. This number is used as the nominal request for FT physics in the rest of this document and especially in Chapters 3 and 8.

However, it is important to underline that it will be impossible in the future to use a 14.4 s supercycle. For example, a supercycle length of 16.8 s has to be assumed in Chapters 3 and 8, which reduces the maximum available number of spills for 150 days of FT operation to 6.2×10^5. This number is the ultimate performance that FT physicists can expect, even in the absence of CNGS.

2.4.2 Long term

The long-term needs of FT physics could not be addressed by the HIP working group. These will be treated at the occasion of the review of the future possible non-LHC physics experiments organized by the SPS and PS Experiments Committee (SPSC) in September 2004 [10].

2.5 RADIOACTIVE ION BEAMS

2.5.1 ISOLDE (short term) [11]

The On-Line Isotope mass separator ISOLDE is a facility dedicated to the production of a large variety of radioactive ion beams for a great number of different experiments, e.g. in the field of nuclear and atomic physics, solid-state physics, life sciences and material science. The proton beam of the PSB is sent onto a target in one of the two available separators (General Purpose Separator or High Resolution Separator) from which radioactive ions are extracted. ISOLDE operation does not generally interfere with high energy physics, using PSB cycles that cannot be exploited by the PS (case of PS cycle longer than one basic period). The nominal request is for 50% of the PSB cycles, which corresponds to an average of 1350 cycles/hour. At the maximum intensity of 3.2×10^{13} protons per pulse (ppp), the average beam current delivered to ISOLDE is then 1.92 μA.

2.5.2 ISOLDE (medium term) [11]

Since October 2001, a charge breeding and post-acceleration facility has been added to the ISOLDE complex. Called REX-ISOLDE, it has already accelerated radioactive ions of mass number A between 7 and 153 and charge to mass ratio q/A higher than 1/4.5 at a kinetic energy per nucleon between 0.3 and 2.3 MeV/u. With an efficiency of a few percent, it is the only operational radioactive ion beam facility in the world which exploits a charge breeder. The plan is to preserve this leadership by improving the overall facility in the near future (extending the experimental hall, increasing the energy up to 4.3 and later 10 MeV/u, adding recoil mass separators). Therefore, the user community is expected to get larger and the proton flux has to grow and be brought as close as possible to the technical limit of 10 μA of the present experimental zone.

2.5.3 EURISOL (long term) [12]

To succeed to the first-generation RIB facilities such as ISOLDE, the European community of nuclear physicists is preparing the next-generation European ISOL RIB facility called “EURISOL”. The aim is to increase the variety of exotic ions produced, and to enhance the yields of such ions by orders of magnitude beyond those presently available. The ISOL method is considered to be complementary to the "in-flight" method which will be used in the proposed upgrade of the accelerator facility at GSI, Darmstadt.

Based on a powerful driver, radioactive ions are produced in EURISOL in one or two stages. For production in a single stage, the driver beam is directly used to irradiate the target, as in ISOLDE. The beam power needed is of the order of 200 kW at a few GeV of proton kinetic energy. For production in two stages, a driver beam of 5 MW is sent onto a target to produce spallation neutrons. Radioactive ions result from the bombardment by neutrons of the active target. This project has benefited from the support of the European Union in its 5th Framework programme. The outcome is a detailed proposal prepared by different groups focusing on the various parts. A sketch of the EURISOL facility is represented in Figure 2.4.

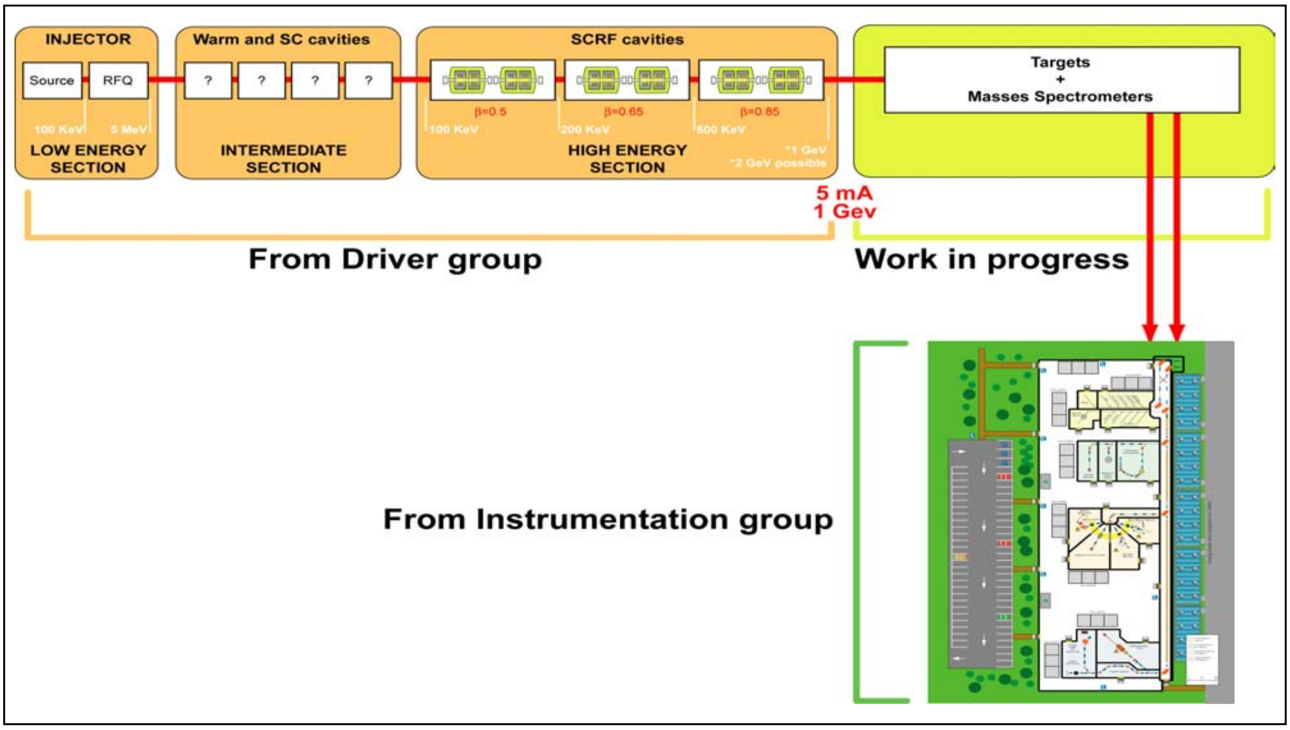

Figure 2.4: Sketch of the EURISOL facility.

In this present design, the assumption is made that a dedicated driver accelerator is being used. Therefore the beam is delivered continuously and options are considered with various types of ions. However, a proton driver shared with other users is perfectly acceptable [12], provided it meets the specifications summarized in Table 2.5.

Table 2.5: Proton driver characteristics for EURISOL.

	Kinetic energy [GeV]	**Beam power [MW]**	**Burst length [μs]**	**Bunch length [ns rms]**	**Repetition rate [Hz]**
One stage production	1-4	0.2	~ 1000	indifferent	≥ 50
Two stage production	1-4	5	~ 1000	indifferent	≥ 50

CHAPTER 3

PRESENT CAPABILITIES OF THE ACCELERATOR COMPLEX

In this chapter, the present capabilities of the CERN accelerator complex are analysed. The availability of proton beams for the period 2006 and 2010 is estimated and compared to the anticipated physics program. It is not the role of the HIP working group to define beam priorities or operational scenarios, so that the aim of this analysis is simply to detect an eventual shortfall in beam availability. However, in order to provide a transparent analysis with clear conclusions, a certain model for accelerator operation in terms of yearly running period, supercycle compositions and also beam priorities has to be assumed.

In the present analysis, the highest priority is given to the LHC beams. Then it is tried to fulfil the yearly nominal CNGS beam request by optimising the SPS supercycles accordingly. This procedure fixes automatically the beam (number of spills) available for SPS FT physics. For the PS complex, the highest priority is clearly to provide the beams for the SPS. Afterwards East Area physics and nTOF requests are fulfilled by choosing the PS supercycles accordingly. This fixes automatically the number of PSB cycles that are available for ISOLDE.

For the calculation of performance figures, the present operational beam characteristics of the accelerators in terms of maximum intensity per cycle and repetition rate are used.

3.1 OPERATION OF THE ACCELERATOR COMPLEX

3.1.1 Machine schedules from 2006 to 2010

For the period from 2007 to 2010 it is assumed that the PSB/PS complex will run for 6000 hours and the SPS complex for 5500 hours each year with beam. The time needed for setting up and dedicated machine development studies (MD) is estimated to be around 600 hours for the PSB/PS and around 800 hours for the SPS, thus reducing the time available for physics operation to 5400 hours for the PSB/PS and to 4700 hours for the SPS. This time is then further reduced by the availability of the different machines. Experience from previous years' operation suggests that the various physics beams can be delivered during ~90% of the scheduled time from the PSB/PS and during ~80% from the SPS (which may even be a little optimistic for the very high intensity CNGS beam). This gives around 4860 effective hours for physics operation for the PSB/PS complex and 3760 hours for the SPS complex [13].

The situation will be different in 2006, where more time will be needed for restarting PS and SPS after a long 18 months shutdown. Therefore, the time for physics will be reduced to 4500 hours at the PSB/PS and 4000 at the SPS, giving 4050 hours effective for physics on PSB/PS and 3200 hours on the SPS[1] [13].

Concerning LHC operation it is assumed that commissioning will start in April 2007 and that the operating time will be 5000 hours per year from 2007 onwards. Presently first estimates for LHC operation are being made [14] but no precise planning of setup, MD and physics periods for the LHC is yet available. Table 3.1 summarizes the different operation periods of the accelerator complex from 2006 to 2010.

Table 3.1: Assumed operation periods for the CERN accelerator complex from 2006 – 2010.

		2006		**2007 - 2010**			
		PSB/PS complex	**SPS complex**	**PSB/PS complex**	**SPS complex**		**LHC**
						2007 ions	
Total running time with beam	[h]	6000	5500	6000	5500	*5500*	5000
Setup and dedicated MD	[h]	1500	1500	600	800	*1300*	-
Physics operation	[h]	4500	4000	5400	4700	*4200*	-
Effective physics hours	[h]	4050	3200	4860	3760	*3360*	-

---

[1] Dedicated SPS MDs (e.g. LHC sector test) are not included in the physics period and will have to be scheduled separately.

Some time will be needed in 2006 to commission the LHC Pb-ion beam in the PS. It is assumed that most of this work can be done in parallel with normal operation and will not have a significant impact on the time available for physics. The commissioning of the LHC Pb-ion beam in the SPS is foreseen for 2007 and in contrast to the PS it is not desirable to do this commissioning in parallel with LHC operation. Assuming that the SPS will spend around 500 hours commissioning with ions, the time available for physics in 2007 will be reduced accordingly as indicated in Table 3.1. It is assumed that the LHC will run with Pb-ions for 20% of the time from 2008 onwards.

3.1.2 SPS operation modes and supercycles

During 2006, the SPS physics run will be dedicated to CNGS and FT operations. The assumed supercycle is 34.8 s long, composed out of three CNGS cycles (3 × 6 s), one FT cycle (12.0 s) and a 4.8 s long cycle for parallel SPS MD. This supercycle will be used during the complete physics run[2]. From 2007 onwards, SPS operation will be dominated by the LHC that will have the highest priority for beam (either protons or Pb-ions). CNGS and FT operations will also continue. Depending on the LHC status and request, three different operation modes are assumed for the SPS: LHC filling, LHC setup and CNGS – FT operation.

LHC filling mode (LHC single SPS user)

This operation mode will be mainly applied for preparing and during filling of the LHC. The SPS supercycle will contain exclusively the standard LHC cycle with an injection flat bottom for up to four PS batches. No other (parasitic) SPS cycles will be allowed to guarantee a fully identical machine situation from supercycle to supercycle. While keeping always the same magnetic cycle in the SPS, the beam types requested from the injectors may change depending on the LHC needs (pilot bunch, safety-, intermediate-, physics beams). Rapid switching between the different beam variants on a supercycle to supercycle basis is required. This will be achieved by fast switching between predefined supercycles where the SPS supercycle stays always the same and the injector supercycles change according to the requests. The supercycle in LHC filling mode will be always 21.6 s long, as the SPS magnetic cycle remains unchanged, independently of the specific beam request to the injectors.

LHC setup mode (multiple SPS users)

In LHC setup mode, the SPS supercycle will contain a short (single batch) LHC cycle with an injection plateau for only one PS batch. Most of the time a low intensity pilot bunch will be requested over long periods, for example to sort out an injection problem. In principle all beam variants compatible with a single PS batch could be requested on such a cycle. The SPS magnetic situation is considered less critical in this mode and a pilot bunch repetition time of around 20 to 25 s seems to be adequate. As the single batch LHC cycle is only 10.8 s long it is therefore possible to add two (parasitic) CNGS cycles resulting in an SPS supercycle for LHC setup mode that will be $10.8 + 2 \times 6.0 = 22.8$ s long[3].

It should be noted that this combined operation with beam destinations LHC and CNGS requires a fast electronic switch for rapid switching of the common power converter between the main bending magnets in the TI8 (LHC injection) and TT41 (CNGS) transfer lines. The installation of such a switch is foreseen and the system is expected to be available by 2007 as otherwise CNGS performance will be severely limited. This is because the existing manual hardware switch cannot be switched rapidly and not more than once or twice per day thus excluding CNGS operation when the LHC is in setup mode.

CNGS – FT mode (multiple SPS users):

The SPS will operate in this mode whenever there is no beam request from the LHC for longer periods (e.g. during physics or access). In this mode there will be no restrictions for SPS supercycle composition imposed by the LHC and it is assumed that the same supercycle as in 2006 will be executed (3 CNGS and 1 FT cycles) to deliver beam to both physics users[3].

---

[2] This supercycle composition is assumed for the analysis in this chapter. Depending on the definition of user priorities, the 2006 SPS physics supercycles may contain different combinations of CNGS and FT cycles. A possibility could be also to split the physics run into two dedicated parts.

[3] The two CNGS cycles foreseen in the LHC setup mode could also be replaced by a single FT cycle. Similar flexibility exists for the CNGS – FT mode where various supercycle compositions are possible. The final choice will depend on the priority given to the different users.

The time that the SPS will spend in the different operation modes from LHC start up onwards can presently only be estimated. Taking LEP experience into account it is assumed that in 2007 there will be an overall beam request from the LHC to the SPS during about 50% of the operation time from which 15% will be spent in LHC filling mode and the remaining 35% in LHC setup mode. This leaves 50% of the operation time for CNGS – FT mode in 2007. The overall LHC beam request should then fall to about 15% by 2010 with 5% spent in LHC filling mode and 10% in LHC setup mode leaving 85% for CNGS and FT operations. Table 3.2 summarizes the estimated distribution of SPS operation modes in 2006, 2007 and 2010.

It is assumed that Pb-ion commissioning in the SPS will require around 500 hours in 2007 and that the period available for CNGS – FT mode operation will be reduced accordingly, as indicated in Table 3.2. Once the LHC starts operating with ions, no difference between proton and ion operation is expected for CNGS – FT mode periods.

Table 3.2: Assumed distribution of SPS operation modes for 2006, 2007 and 2010.

SPS operation mode		**2006**	**2007**	***2007 ions***	**2010**
Physics operation	[h]	4000	4700	*4200*	4700
LHC filling mode	[%]	0	15	*15*	5
LHC setup mode	[%]	0	35	*35*	10
CNGS – FT mode	[%]	100	50	*50*	85

Switching between different SPS operation modes means changing the SPS supercycle and this will in general also imply a change of the SPS magnetic cycle. Presently an SPS supercycle change takes around ½ to 1 hour. For future operation (2006) it is foreseen to reduce this time to below 10 minutes. Even though there are no strict requirements, the switching should be as fast as possible as otherwise the overall efficiency might be severely lowered in the LHC era with several operation mode changes per day.

3.1.3 PSB/PS complex operation and supercycles

Both the PSB and the PS are capable of interleaving many users and supercycles can be modified on a cycle-by-cycle basis. Highest priority for the PSB/PS complex will be to supply the SPS with the beams required in the different operation modes (LHC beams, CNGS, FT). The remaining free slots in the supercycles will then be distributed to the different users: the PSB will supply beam to the PS, to ISOLDE and for PS parallel MD. The PS will supply beam for East Area with parasitic nTOF operation, nTOF, AD and SPS parallel MD. AD operation is essentially transparent and not analysed any further since it requires only a single cycle every two minutes only, which will replace a single East Area cycle.

3.2 PERFORMANCE OF THE ACCELERATOR COMPLEX

3.2.1 LHC proton operation

The supercycle length will be either 21.6 s (LHC filling mode) or 22.8 s (LHC setup mode). In filling mode, any combination of beams from a single, low intensity pilot bunch to the full 4 × 72 bunches nominal beam, will be available from the injectors on a cycle-by-cycle basis. In LHC setup mode any combination of beams from a single, low intensity pilot bunch to a single 72-bunch nominal beam can be provided. The feasibility of the different beam variants (single bunch, bunch trains, 25 or 75 ns spacing) with up to nominal LHC bunch intensity and emittances at 450 GeV/c in the SPS has been demonstrated.

The production of 25 ns beams with bunch intensities above nominal is severely restricted by the beam brightness that can be achieved from the PS Booster, the limiting factor being incoherent space charge tune shift at 50 MeV injection. The ultimate LHC beam (1.7×10^{11} protons per LHC bunch) is definitely out of reach, in contrast to what was estimated in 1993 [15]. This is due to two main reasons: Firstly, the LHC bunch train production scheme in the PS was changed in 1999 (12 LHC bunches produced from 1 PSB bunch instead of initially 21 out of 2) which required an intensity (brightness) increase in the PSB by a factor 8/7 [16]. Secondly, there are significant losses in the injector chain whereas the initial intensity requirements assumed 100% efficiency from capture in the PSB throughout the complete injector chain (and also the LHC). The major part of the beam losses (~10% for nominal and ~15% for ultimate beams) appears at start of acceleration in the SPS; efforts are presently invested to understand the mechanism leading to these losses and hopefully to reduce them. With the present performance an overall transmission of 85% is realistic for the nominal beam whereas the figure for the ultimate beam is only around 80%. In addition, the increase of the LHC crossing angle (1995) and the beta function at the interaction points, β* (2003), have to be compensated with a 10% higher LHC bunch intensity for the nominal beam[4].

To compensate for the observed beam losses and the various design changes, the injectors have to provide accordingly more intensity so as to keep the LHC luminosity unchanged. Table 3.3 compares PSB bunch intensities estimated in 1993 and required in 2003 to obtain the nominal and ultimate 25 ns beams in the LHC, taking into account presently observed losses (but assuming no losses in the LHC itself).

Table 3.3: Bunch intensities for nominal and ultimate 25 ns LHC beams in 1993 and 2003.

		1993	**2003**
LHC nominal bunch	[ppb]	1.05×10^{11}	1.15×10^{11}
PSB nominal bunch	[ppb]	11.02×10^{11}	16.29×10^{11}
LHC ultimate bunch	[ppb]	1.70×10^{11}	1.70×10^{11}
PSB ultimate bunch	[ppb]	17.85×10^{11}	25.50×10^{11}

The nominal 25 ns LHC beam can be provided by the injector complex but the intensity and brightness required from the PSB are moving closer to what was defined as ultimate beam in 1993. There is no longer a comfortable margin left over from the emittance budget, which will make operation more critical. It is therefore of prime importance to continue the efforts to reduce the beam losses at SPS injection so as to regain some operational margin. This may even be essential if transmission from SPS (450 GeV/c) to the LHC (physics conditions at 7 TeV/c) is not 100% as assumed in the above analysis. The ultimate 25 ns LHC beam is presently not feasible in the PSB. Potential solutions are discussed in Chapter 5. The situation is different for 75 ns beams where both ultimate and nominal beams can be provided by the injector complex with some margin. This is because each PSB bunch is only split into four LHC bunches instead of twelve, thus the required brightness in the PSB is a factor three smaller.

Another potential limitation to LHC operation is beam induced heating of the SPS extraction kickers (MKE) and the tune kicker. The heating increases with bunch intensity and depends strongly on the bunch length and might therefore be critical for continuous operation with high intensity LHC type beams (e.g. during scrubbing runs), whereas no problems are anticipated for nominal beam operation [17]. Presently investigations are ongoing to search for short-term solutions reducing the MKE impedance and subsequently the heating [18].

3.2.2 CNGS operation

In 2006 all the SPS physics time will be dedicated to CNGS and FT operations and the SPS will be around 4000 hours running in CNGS – FT mode. The supercycle will be 34.8 s long and contain three CNGS cycles. Assuming a machine efficiency of 80% this gives a total of $\sim 1 \times 10^6$ CNGS cycles in 2006. From the start of LHC operation onwards CNGS will get beam either when the SPS is in CNGS – FT mode or during periods of LHC setup mode. In the latter case the supercycle will be 22.8 s long and contain two CNGS cycles. With the operation periods and distribution of SPS operation modes quoted in Tables 3.1 and 3.2 around $\sim 1 \times 10^6$ CNGS cycles will be available in 2007, increasing to $\sim 1.15 \times 10^6$ by 2010. It is interesting to note that the number of CNGS cycles per time unit (and of course also the average proton flux) is quasi identical in CNGS – FT and LHC setup modes. This means CNGS performance will only be a function of the time the SPS spends in LHC filling mode where no protons are delivered to CNGS.

To estimate the integrated yearly number of protons on target (pot) for CNGS it is assumed that the extracted intensity from the SPS will be 4.4×10^{13} per cycle[5]. Table 3.4 shows the beam available to CNGS

---

[4] This compensation is not required for the ultimate beam, where the bunch intensity is fixed by the LHC beam-beam limit.

[5] This corresponds to 90% of the intensity record, achieved during an MD with continuous specialist tuning and top performance of all machines.

under these conditions for 2006, 2007 and 2010. This should be compared to the "nominal" value of 4.5×10^{19} pot per year assumed for CNGS.

Table 3.4: Estimated yearly proton availability for CNGS in 2006, 2007 and 2010.

Year	**SPS physics operation [hours]**	**SPS in CNGS-FT or LHC setup mode [%]**	**Available [pot per year]**	**Requested [pot per year]**
2006	4000	100	4.4×10^{19}	4.5×10^{19}
2007	4700	85	4.4×10^{19}	4.5×10^{19}
2007[6]	*4200*	*85*	3.9×10^{19}	4.5×10^{19}
2010	4700	95	4.9×10^{19}	4.5×10^{19}

The number of available protons matches the CNGS request for the period 2006 to 2010. However, it must not be forgotten that the production of the CNGS beam is associated with large beam losses. The expected beam losses per year of nominal CNGS operation (4.5×10^{19} pot) are quoted in Table 3.5 [19].

Table 3.5: Expected beam losses during nominal CNGS operation.

Machine / process	**Intensity/cycle**	**Transmission**	**Loss/cycle**	**Loss/year**
CNGS target	4.40×10^{13}			
SPS 400 GeV to target (fast extraction)		~100%	negligible	negligible
400 GeV SPS	4.40×10^{13}			
TT10 to SPS 400 GeV (two injections)		92%	3.8×10^{12}	4.2×10^{18}
TT2/TT10 (two batches)	4.78×10^{13}			
Continuous transfer PS - TT2 (two batch)		90%	5.3×10^{12}	6.8×10^{18}
PS 13 GeV (two batches)	5.31×10^{13}			
PSB 1.4 GeV to PS 13 GeV (two batch)		92%	4.6×10^{12}	5.9×10^{18}
PSB 1.4 GeV (two batch)	5.78×10^{13}			

The figures were obtained by comparing CNGS operation to the high intensity FT beam that was delivered by the SPS until 1998. The yearly losses include also setup periods, controlled dumping of the beam, etc., where acceleration and transfer losses occur but the beam is finally not sent to the target.

Around 1.7×10^{19} protons will be lost along the accelerator chain (not including multi-turn injection losses in the PSB) during one year of nominal CNGS operation. This is nearly a factor two more than during the last year of high intensity FT operation for neutrino physics in 1998. A study has been launched to evaluate the effect of these losses on the irradiation of the PS components and their detrimental consequence not only on equipment lifetime (and machine availability) but also on the radiation dose taken by personnel in charge of maintenance and exploitation.

The Continuous Transfer (CT) from the PS is the most critical process, impressively underlined by the fact that it causes ~40% of the overall beam loss. A large part of this loss is concentrated on the thin electrostatic extraction septum. One consequence is that the high voltage septum cable will have to be changed several times a year, which will lead to significant machine down-time (cool down) and a considerable dose for the staff concerned. Moreover, a non-negligible part of the beam loss is distributed along the PS ring and irradiates all PS components but mainly the bending magnets. A novel method, to slice the beam without physical interception is presently being studied and could potentially reduce the losses at PS extraction by a significant factor (Chapter 6). The high beam losses are clearly the most critical issue for CNGS operation and a detailed analysis of all related effects and consequences (dose to personnel, equipment lifetime, machine down time, etc.) is required. Any reduction of beam losses is highly desirable and all efforts towards this goal should be fully supported.

---

[6] 2007 with Pb-ion commissioning in the SPS (see Section 3.1.1).

Another concern that should be mentioned is beam induced heating of the SPS MKE, like for LHC operation. However, recent simulations show that nominal CNGS operation will not be critical [17].

3.2.3 SPS Fixed Target operation

In the assumed operation scenario, the SPS will deliver spills for FT physics only when operating in CNGS – FT mode and there will be one spill every 34.8 seconds to the North Area. Production of the FT beam is considered a routine operation for the accelerator complex and no specific problems or limitations are anticipated. Table 3.6 gives the number of spills available to the North Area in 2006, 2007 and 2010. This should be compared with the COMPASS beam request of 7.2×10^5 spills per year (see Section 2.4).

Table 3.6: Spills available for SPS FT physics in 2006, 2007 and 2010.

Year	SPS physics operation [hours]	SPS in CNGS – FT mode [%]	Spills for FT physics	FT physics request
2006	4000	100	3.3×10^5	7.2×10^5
2007	4700	50	1.9×10^5	7.2×10^5
2007[7]	*4200*	*50*	1.7×10^5	7.2×10^5
2010	4700	85	3.3×10^5	7.2×10^5

As can be see from Table 3.6, the number of spills that will be available for physics is significantly below the assumed request (especially at the beginning of LHC operation). This means there is clearly a shortfall of beams for the SPS physics users (see also Chapter 8).

The fact that this shortfall appears only for FT and not for CNGS is just caused by the way the analysis was performed, i.e. choosing the supercycles such that first the CNGS beam request is fulfilled. A different strategy, fulfilling first the FT request, would simply highlight the same shortfall at the expense of CNGS. Both CNGS and FT are competing for SPS physics time and their performance will finally depend on the priority and the running time that is assigned to each of them. The effect of differently distributing the SPS operation time to both users is illustrated in Figure 3.1, where FT (numbers of spills) versus CNGS (pot) performance is plotted for 2006, 2007 and 2010[8].

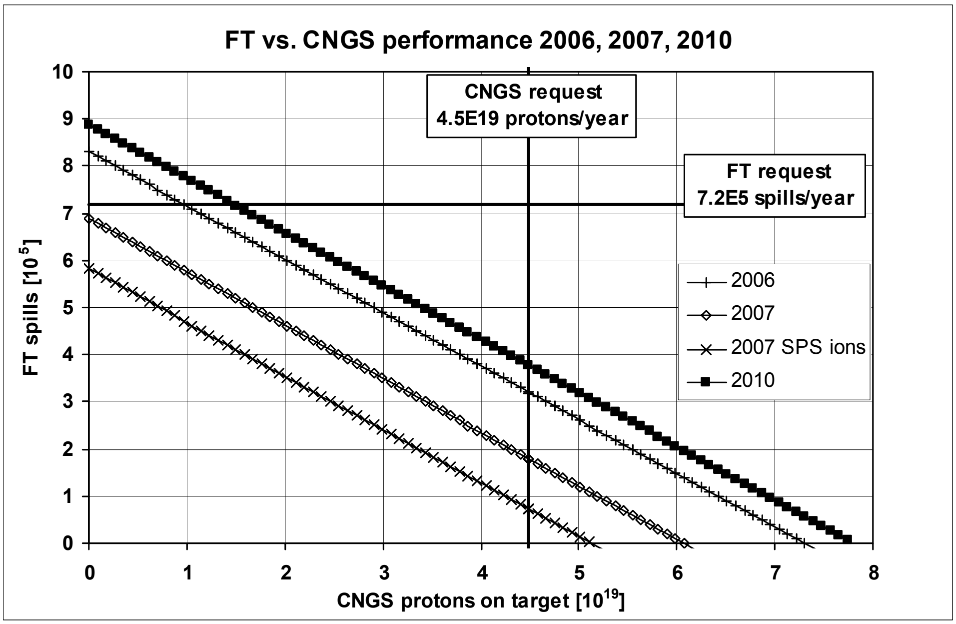

Figure 3.1: FT versus CNGS performance as a function of SPS physics time distribution.

---

[7] When assuming ion commissioning in the SPS (Section 3.1.1).

[8] This (first order) analysis is straightforward since the FT cycle (12s) is exactly twice the CNGS cycle (6s).

3.2.4 AD, nTOF and East Area operation

The PS will deliver physics beams for the AD, nTOF and the East Area. All beams are routinely provided by the PS complex. AD operation is essentially transparent for the beam availability because of the low request of only one cycle every 2 minutes. To estimate the number of protons that can be provided for nTOF, the present nominal performance of the PS is used (7.0×10^{12} protons per cycle for dedicated and 4.0×10^{12} protons for parasitic nTOF operation on East Area cycles). Table 3.7 compares the available protons for nTOF and the spills for the East Area with the physics request.

Table 3.7: Spills for East Area and protons for nTOF in 2006, 2007 and 2010.

Year	**PS physics operation [hours]**	**Spills to East Area**	**East Area request**	**Protons for nTOF**	**nTOF request**
2006	4500	1.3×10^6	1.3×10^6	1.4×10^{19}	$1 - 1.5 \times 10^{19}$
2007	5400	1.5×10^6	1.3×10^6	1.7×10^{19}	$1 - 1.5 \times 10^{19}$
2010	5400	1.5×10^6	1.3×10^6	1.7×10^{19}	$1 - 1.5 \times 10^{19}$

The PS complex can provide the physics beams requested for the period 2006 to 2010. The numbers quoted in Table 3.7 are consistent with the assumed SPS beam requests.

3.2.5 ISOLDE operation

The only direct physics client of the PSB is the ISOLDE facility. The figure of merit for ISOLDE operation is the average number of available PSB cycles and the official request amounts to a minimum of 50% of the yearly cycles. This corresponds to an average of 1350 PSB cycles/hour of PSB operation for ISOLDE. Table 3.8 compares requested and available cycles for ISOLDE for the period 2006 to 2010.

Table 3.8: PSB cycles for ISOLDE operation in 2006, 2007 and 2010.

Year	**PSB physics operation [hours]**	**PSB cycles to ISOLDE**		**PSB cycles requested**	
		[%]	**[cycles/h]**	**[%]**	**[cycles/h]**
2006	4500	48 %	1296	50%	1350
2007	5400	45 %	1215	50%	1350
2010	5400	47 %	1269	50%	1350

As can be seen from Table 3.8, the ISOLDE physics request can be nearly fulfilled in the period 2006 to 2010. However, this is not fully satisfying, especially since the ongoing ISOLDE upgrade programs will eventually lead to an increase of the request by a factor of five. Various possibilities to increase the beam availability are discussed in Chapter 7.

3.2.6 Effect of LHC ion filling on PSB/PS complex physics operation

Since PSB and PS can switch rapidly between different users at a few seconds notice, the LHC ion filling cycle will not make a big difference to the beams available for physics, unless the LHC requests of the full ion beam over long periods (several hours per fill). In this case, the beam availability for East Area, nTOF and AD users will fall, but more PSB cycles will be available for ISOLDE. At present it is assumed that LHC ion filling will be similar to LHC proton filling, with longer periods of single-bunch or single-batch requests to prepare for a short fill.

3.3 CONCLUSIONS

The overall conclusion is that the CERN accelerator complex, with the already ongoing improvements, cannot provide all the requested beams in the period 2006 to 2010 in the assumed operational scenario. There will be a significant shortfall of SPS cycles for CNGS and/or North Area FT operations. The performance of these two physics users will finally be determined by the fraction of SPS physics time that is assigned to each of them. All other physics requests (including LHC nominal beam) can be just satisfied.

The already ongoing improvements are:

- Installation of an electronic switch to enable CNGS (TT41) and LHC (TI8) operation within the same supercycle.
- Modification of the SPS control system to enable fast switching between different supercycles.

Without these modifications the amount of beam available for CNGS and FT operations will be even further reduced throughout the early years of LHC operation.

Other important issues that need to be considered in more detail are:

- The large beam losses associated with CNGS operation, especially the CT extraction from the PS.
- Losses on LHC type beams at SPS injection.
- Beam induced heating of the SPS extraction kickers (LHC and CNGS beams).

Finally it has to be clearly stated that with the present capabilities of the accelerator complex, any wishes for higher beam availability or upgrading of CNGS and ISOLDE performance cannot be fulfilled. The production of the ultimate LHC beam is also not feasible with the presently used scheme.

CHAPTER 4

LIST OF UPGRADES CONSIDERED

4.1 OVERVIEW

During the last years, different upgrade options with an impact on beam intensity have been proposed and/or developed at different levels of refinement. They have been considered by the High Intensity Proton working group, together with some others that were suggested in the course of the analysis. They are listed below, with reference to the chapters of this report, where their relative merits are analysed.

In the following tables, as in the rest of the chapter, the upgrade scenarios are grouped in the usual three categories of increasing complexity and cost. Table 4.1 lists short-term, low-cost options, Table 4.2 medium-term, medium-cost options and Table 4.3 long-term, high-cost options.

Table 4.1: Short-term, low-cost upgrade options.

	Description	**Benefiting users**	
A1	Pulsing the PSB at 0.9 s	ISOLDE	Chapter 7
A2	PS multi-turn extraction	CNGS	Chapter 6
A3	SPS solid-state switch and fast cycle change	CNGS	Chapter 6
A4	Higher intensity in the accelerator complex	CNGS, FT	Chapter 6
A5	Loss reduction in PS-SPS	CNGS	Chapter 6
A6	Double PSB batch for CNGS	CNGS, FT	Chapter 6
A7	Batch compression in the PS	LHC	Chapter 5

Table 4.2: Medium-term, medium-cost upgrade options.

	Description	**Benefiting users**	
B1	Pulsing the PSB at 0.6 s	ISOLDE	Chapter 7
B2	Energy upgrade of Linac2	ISOLDE	Chapter 7
B3	Construction of a new linac (Linac4)	LHC, ISOLDE	Chapters 5, 6 & 7
B4	H- charge exchange PSB injection	LHC, ISOLDE	Chapter 7

Table 4.3: Long-term, high-cost upgrade options.

	Description	**Benefiting users**	
C1	Construction of a >2 GeV 50 Hz linac (SPL)	LHC, RIB, neutrino	Chapters 5, 6 & 7
C2	Construction of a new PSB (2 GeV, RCS or multi-ring)	LHC, ISOLDE	Chapter 5
C3	Construction of a RCS-based driver (30 GeV, 8 Hz)	LHC, neutrino	Chapter 6
C4	Construction of a new 1 TeV LHC injector	LHC	Chapter 5
C5	Construction of a new 30 GeV PS (PS XXI)	LHC	Chapter 6

4.2 BRIEF DISCUSSION OF UPGRADE OPTIONS

A1. Pulsing the PSB at 0.9 s

The reduction of the basic period of the injector complex from the present 1.2 s to 0.9 s and its implications on the different machines and users has been the subject of several studies [20, 21].

A2. PS Multi-turn extraction

The new "loss-less" PS multi-turn extraction, initially proposed in 2002 [22], is since that time the subject of extensive beam experiments [23]. It is based on the use of nonlinear optics elements to create stable islands in horizontal phase-space. The islands are then adiabatically populated by varying the tune and are moved towards larger amplitudes and extracted – theoretically without beam loss.

A3. SPS solid-state switch and fast supercycle changes

The main hardware modification is the installation of a solid-state instead of the present mechanical switch to supply current to the main bending magnets in either the TI8 or the TT41 line. Modifications to the SPS timing and control system and to other accelerator equipment are required for fast and coordinated supercycle changes in the entire complex [13].

A4. Higher intensity in the accelerator complex

This topic includes all the factors that now limit the PS and SPS intensity [6, 24, 25, 26].

A5. Loss reduction in PS-SPS

This topic includes a general campaign for reducing the losses in the PS-SPS for the CNGS beam, based on the systematic realignment of the PS magnets, on the improvement of flexibility of and ease of control of machine parameters and on the training of staff with the high intensity beams.

A6. Double PSB batch for CNGS

A double-batch injection scheme between the PSB and PS machines is proposed [6] to increase the PS pulse intensity for the SPS from the present $\sim 3.0 \times 10^{13}$ to $\sim 5.0 \times 10^{13}$ protons. Several studies have already been performed [26], but many remain to be done.

A7. Batch compression in the PS

To circumvent the space charge limitation at low energy in the PS, a batch compression scheme is proposed for increasing the brightness of the proton beam for LHC [4, 27]. The number of bunches delivered at each PS cycle is reduced in proportion to the compression factor.

B1. Pulsing the PSB at 0.6 s

The reduction of the basic period of the injector complex from the present 1.2 s to 0.6 s and its implications on the different machines and users has been the subject of several studies [20, 21].

B2. Energy upgrade of Linac2

The energy upgrade of Linac2 was considered already in its design report. For the present study, some upgrade options have been considered, with a preliminary cost comparison [28].

B3. Construction of a new linac (Linac4)

The construction of a new 160 MeV H^- linac (Linac4) in the PS South Hall using modern technologies and RF equipment from LEP has been proposed in the frame of the SPL study [29, 30].

B4. H^- charge exchange PSB injection

The implementation of a modern charge-exchange H^- injection into the PSB is presently under study, as a natural complement to the construction of Linac4 [31].

C1. Construction of a >2 GeV 50 Hz linac (SPL)

The construction of a 2.2 GeV SPL of 4 MW beam power is envisaged for the needs of radioactive ion and neutrino physics [32], with benefits for the LHC upgrade.

C2. Construction of a new PSB (2 GeV, RCS or multi-ring)

An alternative solution to the SPL is to replace the PSB by another synchrotron cycling faster and possibly with multiple rings. The characteristics and cost of this machine depend whether its goal is limited to improve the accelerator complex for LHC or to provide multi-MW of beam power. The option of a new PSB having the size of the present one is briefly considered in Chapter 5.

C3. Construction of an RCS-based driver (30 GeV, 8 Hz)

The option of a new 30 GeV RCS at 8 Hz has been analysed in the frame of the neutrino factory studies [33]. The 30 GeV machine will have as injectors a booster ring and a 400 MeV linac.

C4. Construction of a new 1 TeV LHC injector

A new "ideal" LHC injector could be built either in the LHC tunnel or (superconducting) in the SPS tunnel. The different options have been recently envisaged [4].

C5. Construction of a new 30 GeV PS (PS XXI)

The design of a new PS optimized for LHC injection has been studied with a certain detail in the years 1996/97 [34]. The PS XXI was a quasi-isochronous separate function machine going up to 30 GeV. It was mainly intended to improve performance for LHC by injecting at higher energy in the SPS.

CHAPTER 5

UPGRADES FOR THE LHC

5.1 INTRODUCTION

The time scale of an LHC luminosity upgrade is set by the statistical error “halving time” for the experiments and by the radiation damage limit for the Interaction Region (IR) quadrupoles, currently estimated to about 700 fb^{-1}. The error “halving time” is defined as the running time required to multiply the integrated luminosity by a factor four.

If the LHC reaches its nominal luminosity of 1.0×10^{34} cm^{-2}s^{-1} by 2011 (curve (a) in Figure 5.1), the radiation damage limit is attained by 2017 (curve (b)) and the error “halving time” exceeds 5 years in 2011 (curve (c)). If the luminosity continues to grow and reaches the ultimate value of 2.3×10^{34} cm^{-2}s^{-1} in 2016 (curve (a’)), the radiation damage limit is attained before 2015 (curve (b’)). Therefore it is reasonable to plan a machine luminosity upgrade based on new low-β IR magnets by 2014. The fact that the error “halving time” would exceed 5 years as soon as 2012 (curve (c’)) is another strong motivation for upgrading the luminosity.

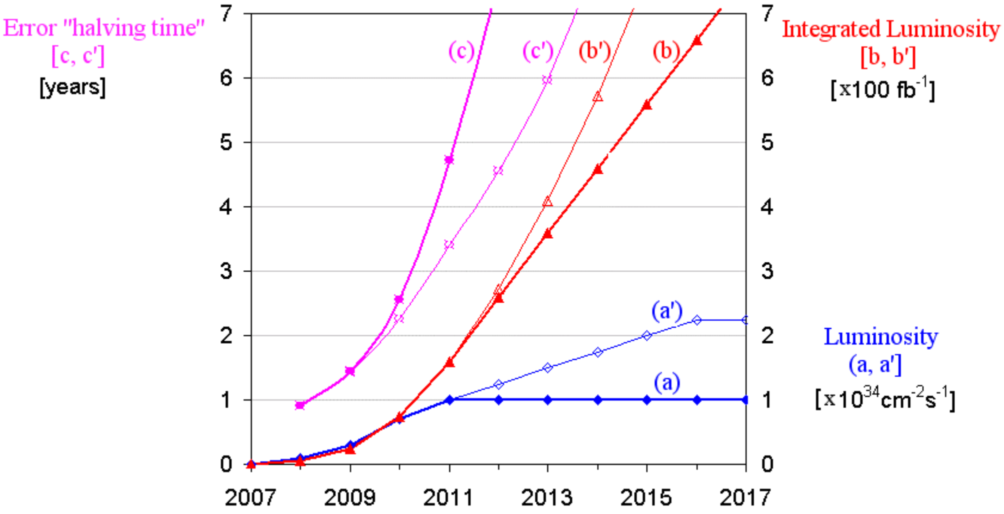

Figure 5.1: Foreseeable evolution of the LHC luminosity and of the experimental error halving time [35]. The IR magnets radiation damage limit corresponds to an integrated luminosity around 700 fb^{-1}.

A CERN task force has investigated the possibility of a staged upgrade of the LHC and its injectors, in view of increasing the luminosity from the nominal 10^{34} cm^{-2}s^{-1} to 10^{35} cm^{-2}s^{-1} in each of the two high-luminosity experiments. Possible scenarios for an upgrade of the centre-of-mass energy to 25 TeV have also been considered. The outcome of this feasibility study [4, 36] suggests options which are considered in the following part of this chapter and which have already been submitted to the CERN management [37].

5.2 LHC LUMINOSITY UPGRADE

Reaching and eventually exceeding nominal LHC performance will be challenging and requires learning how to overcome electron cloud effects, inject, accelerate, collide, and safely dump almost 6000 high intensity proton bunches, while protecting superconducting magnets and physics detectors by an adequate collimation system.

For beams colliding with a crossing angle θ, the luminosity is reduced by a geometric factor $F \approx [1 + (\theta\sigma_z/2\sigma^*)^2]^{-1/2}$, where σ_z is the bunch length and σ^* the transverse beam size. If the beam intensity is limited by effects other than the beam-beam interaction, the best strategy to maximize luminosity consists in operating the machine with short bunches and minimum crossing angle, compatible with adequate beam separation to reduce the effect of long range collisions. The "ultimate" luminosity of 2.3 × 10^{34} $cm^{-2}s^{-1}$ with $\beta^* = 0.5$ m in IP1 and IP5 corresponds to a beam-beam limited intensity of 0.86 A, i.e. about 50% higher than the nominal intensity of 0.58 A. This may already require some upgrade of SPS kickers, cryogenics (for electron cloud), LHC collimators, and possibly compensation of the long-range beam-beam collisions (currently limiting the Tevatron performance at Fermilab). Any further increase in luminosity relies on new IR magnets to reduce β^* by at least a factor 2 and increase the crossing angle by at least a factor $\sqrt{2}$, to keep the same relative beam separation at the parasitic collision points.

The baseline scheme to double luminosity without exceeding the ultimate beam intensity requires a new RF system to shorten the bunches by a factor 2 and avoid a significant luminosity loss associated with the increased crossing angle. New large-bore triplet magnets based on Nb_3Sn technology would enable to reach $\beta^* \leq 0.25$ m and a luminosity $L \geq 4.6 \times 10^{34}$ $cm^{-2}s^{-1}$ (see Table 5.1). These new IR magnets require a long and difficult period of 5-6 years for R&D, component development and prototyping, as well as about 3 years for final production. The baseline scheme is the safest option in terms of beam dynamics, machine protection, and radiation risks, but the IR magnets are challenging. To further increase the luminosity with this scheme requires an increased number of bunches and may not be compatible with electron cloud and long range beam-beam effects.

Alternative schemes of LHC luminosity upgrade are based on the possibility of colliding higher bunch intensities without exceeding the beam-beam limit, thanks to the reduction of the beam-beam tune shift for large crossing angles by the same geometric factor F. Since the luminosity depends quadratically on the bunch intensity, there is a net luminosity gain in colliding higher intensities with larger crossing angles, either nominal bunches with 25 ns spacing (with large Piwinski parameter $\theta\sigma_z/\sigma^*$, see the fourth column in Table 5.1) or long "super-bunches" (last column in Table 5.1). However operation in this new regime needs experimental tests.

Super-bunches require a new unconventional RF system and a complete redesign of the beam instrumentation, but minimize electron cloud effects and allow crossing angles of several mrad with no significant luminosity loss, provided their peak current density is scaled accordingly.

Table 5.1: LHC parameters at 7 TeV/c for various luminosity upgrade scenarios with reduced β*. The last column refers to one or several flat super-bunches with a total length of ~260 m, confined by barrier buckets.

Parameter	**Units**	**Baseline**	**Piwinski**	**Super-bunch**
Number of bunches		2808	2808	1
Bunch spacing	[ns]	25	25	
Protons per bunch	[10^{11}]	1.7	2.6	5600
Average beam current	[A]	0.86	1.32	1.0
Norm. transv. emittance	[μm]	3.75	3.75	3.75
Longitudinal emittance	[eVs]	1.78	2.5	15000
Peak RF voltage	[MV]	43	16	3.4
RF frequency	[MHz]	1202.4	400.8	10
R.m.s. bunch length	[cm]	3.78	7.55	7500
R.m.s. energy spread	[$10^{-4]}$	1.60	1.13	5.8
IBS growth time	[h]	42	46	63
Beta function at IP1-IP5	[m]	0.25	0.25	0.25
Full crossing angle	[μrad]	445	485	1000
Piwinski parameter	[$\theta\sigma_z/\sigma^*$]	1.50	3.27	
Luminosity at IP1-IP5	[$10^{34}/cm^2s$]	4.6	7.2	9.0

A beam current of 1 A distributed in 100 or more super-bunches yields a luminosity of 9×10^{34} $cm^{-2}s^{-1}$ for $\beta^* = 0.25$ m (see last column of Table 5.1), but handling of the event pile-up in the detectors would become challenging or even impossible [38]. Operation with bunched beams and large crossing angles of several mrad, to pass each beam through separate final quadrupoles of reduced aperture, would require crab cavities to avoid a severe luminosity loss.

In the case of conventional bunches the layout of the IR regions could be of the type sketched in Figure 5.2 [39], with separation dipoles first to reduce the number of long range beam-beam collisions (left), while super-bunches could be focused by independent quadrupole channels for each beam (right), possibly based on a cheaper superconducting technology such as Nb-Ti-Ta, with shorter R&D lead time [40].

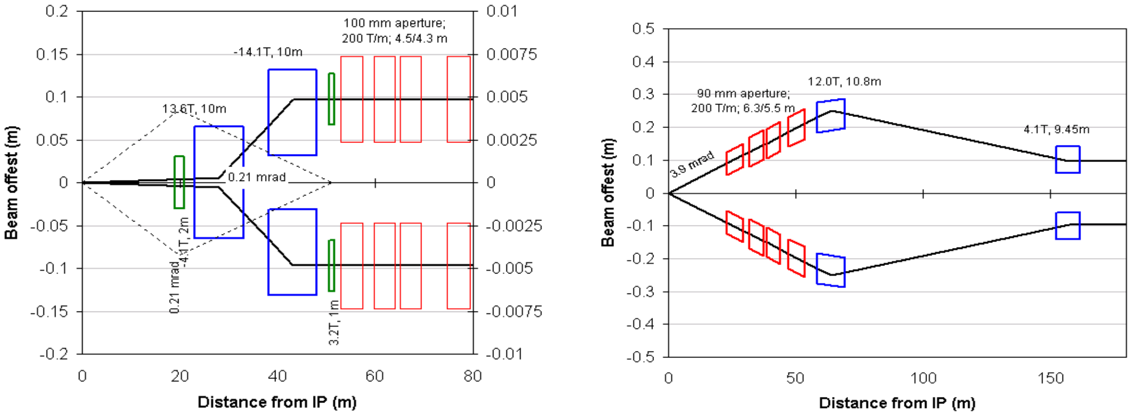

Figure 5.2: Possible IR layouts for conventional bunches (left) and super-bunches (right).

5.3 INTEREST OF LINAC4 AND SPL

Attaining and exceeding the ultimate LHC intensity while preserving the nominal transverse emittance requires higher brightness beams from the injectors, as indicated in Chapter 2, Table 2.3, in the ideal case of no beam loss through the SPS and LHC. In reality the brightness of the beam delivered by the PS complex will certainly need to be even larger[9]. For example, assuming 85% of transmission[10] through the SPS and LHC, the required bunch population at extraction from the PS ranges from about 2×10^{11} ppb for the baseline scheme to 3.1×10^{11} ppb for the scheme in the fourth column of Table 5.1. However, the PS can currently only deliver the LHC beam with a maximum population of about 1.5×10^{11} ppb, sufficient to slightly exceed nominal LHC performance (see also Section 2.2). The levels of brightness needed by any type of luminosity upgrade clearly necessitate major improvements of the injector complex.

The first possible solution is longitudinal batch compression in the PS using RF manipulations [41]. Since brightness is limited by space charge at injection in the PS, the idea is to compress the beam over a reduced fraction of the circumference at a higher energy. The resulting bunch train contains fewer bunches. As a consequence, more PS cycles are needed to fill the LHC so that the LHC filling time is increased by at least 35% and the beam availability for other users will be worse than described in Table 3.2 and Chapter 8. Moreover, the LHC filling factor is reduced by about 10%, to accommodate various kicker rise times. Furthermore, such RF manipulations are prone to imperfections and require significant development work.

A more reliable and flexible scheme to generate high brightness beams requires the replacement of Linac2 with a new Linac4 (cost about 70 MCHF), to overcome space charge limitations at injection in the PSB and avoid the long injection plateau in the PS. With Linac4 it is possible to reach a bunch population of 2×10^{11} ppb at extraction from the PS while simplifying operation (single PSB pulse per PS cycle) and reducing the LHC filling time. With a transmission efficiency of 85%, this allows to reach the ultimate luminosity. However, batch compression is again needed to upgrade the LHC luminosity beyond the ultimate value, still at the expense of shorter bunch trains.

---

[9] Experience at HERA and the Tevatron indicates transmission losses as high as 30%.

[10] The assumed transmission around 85% is currently achieved for LHC type beams in the SPS from injection to 450 GeV/c and does not include beam losses in the SPS-LHC transfer lines nor in the LHC from injection to collision energy.

The SPL (cost about 520 MCHF) would allow to inject directly into the PS at 2.2 GeV and to attain a bunch population of 4×10^{11} ppb at PS extraction with a ~20% shorter filling time, without relying on batch compression. LHC upgrade scenarios with a bunch population exceeding the ultimate intensity could then be seriously considered, although the transmission of such high density bunches through the SPS and LHC will certainly require a significant development effort. However, the LHC will only make use of a very small fraction of the SPL beam flux. The SPL is fully justified if a physics community is exploiting the high beam power and proton flux that it can deliver. If only the needs of LHC are taken into account, the alternative possibility of replacing the PSB by a higher performance synchrotron is a very valuable alternative that deserves further investigation.

5.4 INTEREST OF A NEW SYNCHROTRON REPLACING THE PS BOOSTER

The possibility of building a new, faster synchrotron to replace the PSB assuming Linac4 as injector deserves investigation as an alternative to the SPL.

5.4.1 Requirements

For the PS and the benefit of the following machines, including the LHC, improvements of interest are:

(a) Higher beam brightness at a correspondingly higher energy to keep the space charge tune shift constant in the PS. This point will be further discussed later on.

(b) Higher intensity within the physical aperture of the PS. This could be an additional argument for increasing the new PSB energy. However, the PS will be close to its maximum performance with the current PSB plus Linac4, when delivering around 5×10^{13} ppp. Beyond that, many difficulties appear, such as the need for more RF power. Similar limitations in the SPS require further investigation. Neither the SPL nor a new PSB can avoid these bottle-necks.

(c) Higher or more flexible repetition rate, to minimize flat-bottom time in the PS.

For direct users of the PSB beam (ISOLDE, EURISOL) the interesting improvements are:

(d) Higher repetition rate to increase the mean current (~ 10 μA for the ISOLDE upgrade).

(e) Combination of (d) with a higher intensity per pulse to reach a multi-MW beam power (EURISOL and neutrino super-beam).

5.4.2 Without need for high beam power at low energy

The main focus is on item (a), specifically in view of an LHC luminosity upgrade. With Linac4 injecting at 160 MeV into the four rings of the current PSB, the direct space charge tune shift is “matched” to the maximum value acceptable at injection into the PS at 1.4 GeV. Therefore, a further increase in beam brightness requires a higher injection energy into the PS, either by the SPL or by a new synchrotron replacing the PSB.

A new booster of the same size than the PSB and an ejection energy higher than 1.4 GeV would also require a higher injection energy, and thus an upgraded Linac4, to overcome the space charge limit at injection. For example, a kinetic energy of 2.2 GeV at the PS input has to be matched with an injection around 360 MeV in the new PSB. The corresponding swing of the magnetic field would be 3.3.

Since the space charge tune shift is proportional to the circumference of the synchrotron, a new booster with a shorter circumference could still use the Linac4 beam at 160 MeV and provide the required beam brightness at 2.2 GeV. To minimize the filling time of the PS, it has to have more than 4 rings and/or to cycle fast [Tentative parameters: 8 rings; average radius = 12.5 m, instead of the current 25 m; magnetic radius $\rho = 4.12$ m; vacuum chamber dimensions ~20 cm; injection energy = 160 MeV ($B\rho \sim 1.9$ Tm and $B \sim 0.46$ T); ejection energy = 2.2 GeV ($B\rho \sim 10$ Tm and $B \sim 2.42$ T); magnetic field swing ~5; frequency of magnetic cycle ~2 Hz; $dB/dt \sim 8$ T/s.]. For LHC, the PS performance would be comparable to that with the SPL (up to approximately 4×10^{11} ppb), although at a certainly significantly lower cost.

5.4.3 With need for high beam power at low energy

Items (c), (d) and possibly (e) could in principle be addressed by a new PSB. However the requirements of the direct users of the PSB, especially beam power and beam time structure, should be driving the design. In particular:

- 50 Hz operation (EURISOL request),
- about 4 MW beam power,
- "long" beam pulses for EURISOL,
- "short" and "few" bunches for the super-beam.

These specifications are difficult to meet with a rapid cycling synchrotron, especially the "long" beam pulse, whereas a 50 Hz SPL with an energy of 2.2 GeV would easily address them as well as items (a), (c) and (d). Item (e) would be naturally solved for EURISOL, but a compressor ring would be needed for the super-beam.

5.5 SUPER-SPS AND LHC ENERGY UPGRADE

The beam-beam limit for the so-called large Piwinski parameter regime is reached for a bunch population of 2.6 × 10^{11} ppb colliding in the LHC, corresponding to about 3.1 × 10^{11} ppb at extraction from the PS. This limit is assumed in the present approach to the LHC luminosity upgrade which relies mainly on replacing and improving the IR magnets, because long range beam-beam compensation schemes must be experimentally demonstrated before further upgrades of the injector chain, i.e. higher brightness injectors or an increased injection energy into the LHC by a pulsed Super-SPS, can be exploited for additional LHC luminosity gains.

However, once/if a satisfying scheme for long-range beam-beam compensation is available, the intensity per bunch could be further increased at constant beam-beam limited brightness, with an approximately proportional gain in luminosity. This could be obtained with an increased bunch intensity and brightness at the nominal LHC injection energy followed by a controlled emittance blow-up at high energy, i.e. after passing the bottle-neck of the limited physical aperture at injection in the LHC. Raising instead the injection energy in the LHC, the bunch intensity and normalized emittance could be increased in the same proportion, and a similar result would be obtained more easily in the LHC. A pulsed Super-SPS would have to be added to the injector complex (cost about 150-200 MCHF) as well as new superconducting transfer lines (cost about 60-70 MCHF or possibly less for super-ferric magnets excited by a single high temperature superconducting line, bringing the total cost of an SPS upgrade including personnel and materials to about 300 MCHF), which could also be the first step for an LHC energy upgrade. This programme may profit decisively from the development pursued at present by GSI, Darmstadt and associated labs (in particular IHEP, Protvino and BNL, Brookhaven) for the FAIR facility proposed at GSI [42]. It is worth mentioning that such a Super-SPS may also be potentially interesting for FT experiments on rare kaon decays.

For upgrading the energy of the LHC, higher field dipole magnets have to be used. Dipole magnets with a nominal field of 15 T and a safety margin of about 2 T are considered as a reasonable target for 2015 and could be operated by 2020. This would allow to reach a proton beam energy around 12.5 TeV in the LHC tunnel (approximate cost 2000 MCHF), but requires a vigorous R&D programme on new superconducting materials.

5.6 SUMMARY AND CONCLUSIONS

It is reasonable to plan an LHC luminosity upgrade based on new large-bore IR magnets by 2014. This would enable CERN and the international high energy physics community to exploit fully the potential of the machine, of the injectors, and of the detectors. Further beam dynamics studies are needed to define an optimum upgrade scheme, in particular to finalize the IR design and to orient future magnet developments.

With Linac4 injecting at 160 MeV into the four rings of the current PSB, the brightness of the beam from the PS will increase and ultimate luminosity should be attainable in the LHC provided the transmission through the SPS and LHC reaches ~85%. Investigation with a higher brightness will also be possible during study sessions to prepare for further luminosity upgrades.

An additional increase in beam brightness and thus, potentially, in LHC luminosity requires a higher injection energy into the PS, either by a superconducting proton linac or by a new synchrotron replacing the PSB. This latter option deserves more investigations. An alternative possibility to increase the LHC luminosity, which could also be the first step for an LHC energy upgrade, is a pulsed Super-SPS associated with new superconducting transfer lines. It should also be kept in mind that magnets and infrastructure of the PSB, PS, and SPS may deteriorate after several years of operation with LHC and especially with CNGS beams. In any case, the nature of the future physics programme at CERN will determine the specifications and influence the choice of the optimum solution.

The LHC luminosity increase associated with higher brightness injectors or Super-SPS relies on long-range beam-beam compensation schemes, yet to be experimentally validated.

CHAPTER 6

UPGRADES FOR NEUTRINOS

In the framework of the activities to prepare the future high intensity proton beam for the CNGS project [5], a critical review of the key processes used to generate such a beam was carried out [6], in view, possibly, of an upgrade beyond the nominal flux of ~4.5 × 10^{19} pot per year. The analysis made by the HIP working group is given in Section 6.1. The main limitations and the possible improvements to the PS machine are reviewed in Section 6.1.1. The imperfections of the present CT extraction from PS to SPS are described together with a potentially "loss-less" alternative process. The possibility to increase the beam intensity to ~5 × 10^{13} protons per PS cycle by injecting two PSB batches in the PS is commented. The main limitations of the SPS machine are reviewed in Section 6.1.2. The issues concern essentially the RF equipment, the transverse and longitudinal instabilities, and the heating of the MKE. Conclusions for the CNGS beam are drawn in Section 6.1.3. Finally, the future beams for neutrino physics (after Gran Sasso) are treated in Section 6.2.

6.1 PROTON BEAM FOR CNGS

6.1.1 High intensity proton beams in the PS

Multi-turn ejection from the PS: the present "Continuous Transfer" scheme

Developed in the mid-seventies [43], the CT scheme is used to extract the PS beam in 5 turns, filling 5/11 of the SPS circumference with a single PS pulse (the ratio of the circumferences of SPS and PS being 11). In Figure 6.1 the layout of the extraction elements is shown, together with the horizontal normalized phase space. Just before extraction, the horizontal tune is set to 6.25 and the closed orbit is modified so that the blade of an electrostatic septum intercepts the beam. Four slices are shaved off the main core and extracted as a continuous ribbon over four turns. The central part is extracted last, during the fifth turn, by changing the beam trajectory so as to jump over the septum blade. The net result is that the horizontal emittance of the extracted beam is decreased with respect to that of the circulating one.

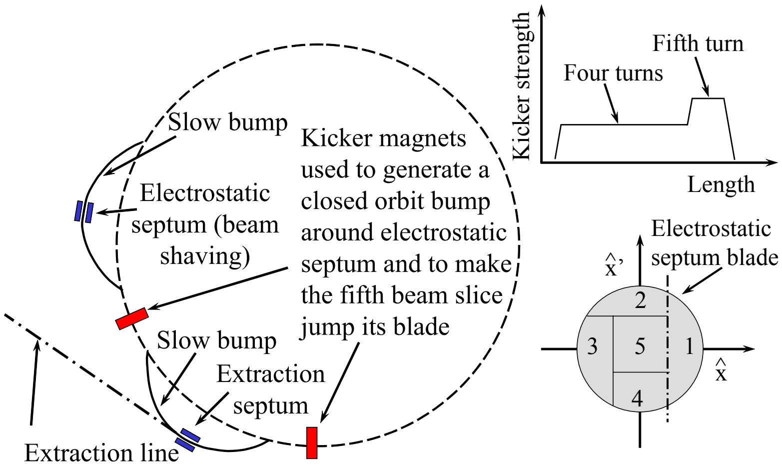

Figure 6.1: Principle of the CT extraction from the PS machine: the extraction scheme (left), the kicker strength as a function of time (upper right), and the normalized phase space (lower right).

To overcome the SPS aperture limitation in the vertical plane, a special optics in the transfer line joining the PS and the SPS allows exchanging the two transverse emittances [44]. However, a number of drawbacks are present, namely: i) beam losses, especially at the electrostatic septum, are unavoidable. They amount up to 15%[11] of the total beam intensity [45]; ii) the extracted slices do not match the natural structure (elliptical) of phase space, thus generating a betatron mismatch. This, in turn, induces emittance blow-up in the receiving machine; iii) the extracted slices have different transverse emittance.

In the framework of the HIP working group, a detailed analysis of the losses for the beam for CNGS was performed [19]. The outcome is rather striking: for 4.5 × 10^{19} pot per year, approximately 1.7 × 10^{19} are lost in the accelerator chain, corresponding to about 40% of the total flux. A large fraction of these losses, i.e. 0.7 × 10^{19}, or 40% of the total intensity, is lost because of the CT extraction process from the PS.

Multi-turn ejection from the PS: the alternative "loss-less" extraction scheme

In the quest for an improved extraction mode, a novel approach has been proposed [22, 46, 47]. Nonlinear elements such as sextupoles and octupoles are used to generate stable islands in the horizontal phase space. Then, by varying the horizontal tune, particles can be selectively trapped in the islands by adiabatic capture: some will remain in the phase space area around the origin, while others will migrate to the stable islands. As a result, the beam is split into a number of parts in transverse phase space, determined by the order of the resonance used, without any mechanical action. Finally, it is possible to move the particles trapped inside the islands towards higher amplitudes. This increases the separation between the different beamlets so that enough room is available for the beam to jump over a septum blade with almost no particles lost. The final result of a typical capture process inside stable islands is shown in Figure 6.2, where the beam distribution as well as its projection are depicted.

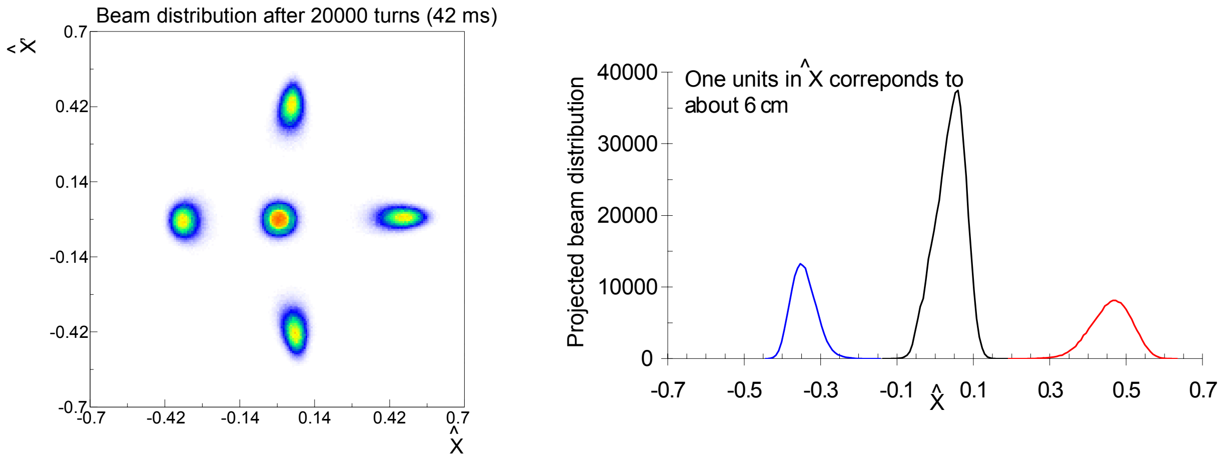

Figure 6.2: Results of the numerical simulations for the adiabatic capture inside stable islands (left: final horizontal phase space distribution, right: projected beam distribution onto horizontal axis).

No intercepting device is used to split the beam; hence particle losses are limited to the fraction of the beam improperly deflected during the kicker rise time. Furthermore, the beam from the first four beamlets has constant transverse characteristics that match well the natural phase space structure (elliptical), thus inducing a limited emittance blow-up after filamentation [48].

Following the encouraging results of the numerical simulations, a measurement campaign on the PS machine was launched in the year 2002 and continued throughout the whole of 2003. To coordinate these activities, a study group was formed [49] and its present conclusions [23] are summarized below.

Experimental Results

Efforts were devoted to the experimental test of the key processes required for the novel multi-turn extraction, namely adiabatic capture, and extraction proper. Additional sextupoles and octupoles had to be installed in the PS ring. The main results can be summarized as follows:

---

[11] Losses can be reduced down to 10% or even less, but such performance requires careful and continuous tuning, hence it can be hardly maintained over reasonably long periods.

Adiabatic capture was successfully tested at low intensity, without any beam loss (see Figure 6.3 (left)). At high intensity, beam trapping and beamlets separation were achieved (see Figure 6.3 (right)). Tests for studying how to increase the fraction of beam trapped in the islands were successfully performed and the data analysis is in progress. However, under these conditions, losses were observed and they could not be removed so far.

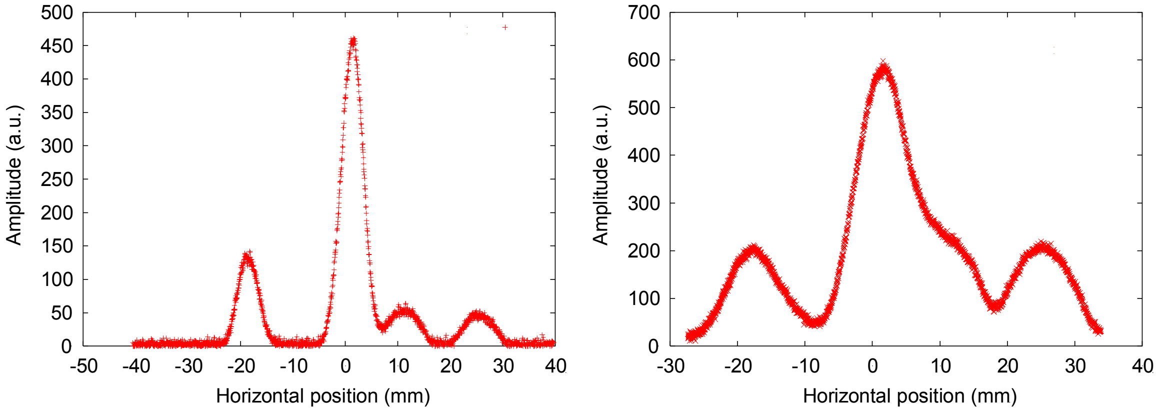

Figure 6.3: Horizontal beam profile measured with the wire scanner located in section 54 at the end of the capture process with a low intensity beam (5×10^{11} ppb) (left), and nominal intensity (6×10^{12} ppb) (right).

Extraction of the five beamlets was tested with a low intensity bunch: beam extracted over five turns was observed in the TT2 transfer line, although with a rather low efficiency, and difference in trajectory between the five beamlets was observed. Note that hardware constraints made capture of a high intensity bunch and extraction mutually exclusive.

Future work

Although most of the fundamental questions have been addressed and encouraging results have been obtained, detailed investigations are still needed for a number of points concerning beam physics and hardware issues.

Most of the numerical simulations performed until now refer to simple models of horizontal betatron motion, including nonlinear effects due to sextupoles and octupoles. The results will have to be cross-checked against simulations for realistic models of the PS machine.

For the capture process, the most critical point is the presence of beam losses at high bunch intensity. A new octupole (from the SPS stock) was installed in section 21 during the shutdown 2003/2004 to improve the lattice and provide the correct phase of the islands at the location of the electrostatic septum, hopefully removing the incompatibility between capture and extraction. New sextupoles and octupoles, together with their power converters, will be needed to make this process operational.

One of the peculiarities of the PS machine is that the four working point parameters (Q_H, Q_V, Q'_H and Q'_V) are set by means of three coils installed in the gap of the main magnet, the so-called Pole-Face-Windings (PFW) and the "figure-of-eight" loop. Therefore, only three degrees of freedom are available to control the four physical parameters. The possibility of precisely controlling the working point is of paramount importance to setup the proposed multi-turn extraction, and this would also be extremely useful for routine operation. For these reasons, the analysis of possible solutions to remove present limitations has been undertaken in the framework of the activities of the study group for the new multi-turn extraction in the PS machine.

For the sake of completeness, it is worth mentioning that two issues have not been addressed yet, namely the implications of delivering a bunched beam, on harmonic 8 or 16, to the SPS, and of increasing the extraction energy to 26 GeV/c. These two issues have to be clarified during experimental tests in the SPS. It is very important that they are studied in 2004 to prepare a consistent proposal for the upgrade of the beams for CNGS.

Resources and possible implementation

A preliminary estimate has been made of the resources needed to implement the new ejection scheme giving a total budget (P+M) of ~ 7.5 MCHF dominated by the cost of new fast bumpers (~ 4 MCHF) [23]. Alternative solutions are under investigation to reduce cost and delay by re-using the largest possible amount of existing equipment [50]. The most favourable schedule of implementation of the new ejection scheme is the following:

- 2004: Experimental tests with beam will demonstrate whether the source of beam losses and the reason for incompatibility between capture and extraction of high intensity bunches have correctly been understood. In parallel, numerical simulations will be pursued to analyse the collected data, and refine the understanding of the various processes.
- At the end of the year, a project proposal will be published, including the resources needed, and submitted for approval to the management.
- 2005: Assuming an immediate authorization and funding, hardware design and construction should begin early in 2005. Simulations will be continued.
- 2006: The commissioning of the CNGS beam will be made with the nominal scheme, i.e. a single batch beam delivered to the SPS after slicing by means of the standard CT at nominal intensity, i.e. ~3×10^{13} protons per PS batch. In parallel, experimental tests will continue with the available hardware, possibly improved at the level of the magnets, power converters and working point control. Tests to deliver the beam with the new scheme to the SPS could be attempted.
- 2008: If started in 2005, the complete hardware might be available for the commissioning of the new multi-turn extraction to take place during setting-up. The full benefit of the new ejection scheme would then be available. This would possibly allow envisaging an increase of the nominal intensity to CNGS.

Increasing the proton intensity

The status of the PS has improved since 1997, when the last high intensity operation period with the CT took place. The machine impedance has decreased with the removal of the 114 MHz RF cavities used for lepton acceleration: that should improve the longitudinal stability, especially during debunching/rebunching at 14 GeV/c. The injection energy has been brought up to 1.4 GeV to reduce space charge induced tune spread ΔQ, and that should be beneficial to the transverse emittances of the PS beam.

Double-batch injection from the PSB

The PS is presently able to deliver ~3×10^{13} ppp every 1.2 s to the SPS. It has been proposed in Reference 6, to reach ~5×10^{13} ppp every 2.4 s, by filling the PS with two batches from the PSB. Tests have already begun, mainly on space charge phenomena and coherent instabilities, leading to a record intensity of 4×10^{13} ppp at 14 GeV/c [26, 51]. More studies remain to be done concerning both transverse and longitudinal multi-bunch instabilities.

Linac4 and single batch injection from the PSB

Replacing the present Linac2 with Linac4 (160 MeV, H^-), space charge effects at injection in the PSB can be reduced by a factor of 2 [52]. For given normalized transverse emittances, the intensity can be doubled, so that the PS can receive enough protons from a single PSB cycle to make ~5×10^{13} protons available every cycle to the SPS. Unfortunately, since the availability of Linac4 cannot be expected before the year 2010 at the earliest, such an improvement will probably arrive too late for the CNGS experiment.

6.1.2 High intensity proton beams in the SPS

The key parameter to measure the performance of the neutrino experiments at the Gran Sasso, is the integrated number of protons delivered on target per year.

One possible means to improve it is to maximize the number of protons accelerated per elementary SPS cycle. The record intensity of 4.8×10^{13} protons per cycle was obtained in 1997, and the limitations were identified as being (i) the PS transverse emittances, (ii) the contacts in the 200 MHz standing wave cavity's damping loops that became too hot, and (iii) the performance of the feedback of the 350 MHz superconducting cavities. These limitations should have disappeared, since the 200 MHz and 350 MHz cavities that were used for lepton acceleration have been removed, and the PS emittances are expected to be reduced after the upgrades for LHC. The dominant intensity limitations known today are analysed below.

The other possible means to increase the proton flux is to optimize the operation efficiency, i.e. using fast switching between different modes (e.g. LHC filling to CNGS cycle etc.) which is addressed at the end of this section.

CNGS target limitations

The SPS beam will be ejected in two halves at 50 ms interval to the CNGS target, each half corresponding to a PS pulse of 10.5 μs. The mechanical and thermal capability of the target limit the intensity per ejection to 3.5×10^{13} protons, leading to the ultimate intensity goal of 7×10^{13} protons per SPS pulse [53].

RF hardware limitations

The maximum RF power that can be delivered to the travelling wave cavities limits the maximum intensity. Part of the LHC project was the upgrade of the SPS cavity windows and couplers to cope with a power of 1 MW per cavity. The thermal limit on the coaxial lines stays at 750 kW, but the power can be pushed to 1 MW for a few seconds. As beam intensity increases, the power needed for acceleration can become very large for two reasons: (i) the power delivered to the beam is proportional to the beam current, and (ii) the longitudinal emittance increases with the intensity, so that the RF acceleration voltage has to increase too. The typical emittance for a beam of 4×10^{13} protons at injection is 0.2 eVs, and it is difficult to predict what it will be at higher intensity. In any case, it will be larger, for example because of the known instabilities encountered during debunching – recapture in the PS before extraction.

For illustration, the RF power per cavity needed to accelerate 7×10^{13} protons per cycle for two different bucket areas is shown in Figure 6.4 [24]. It exceeds 1 MW, at the start of acceleration, for a beam of 0.6 eVs. Due to the particular transfer properties of the travelling wave cavities, the critical point is below transition. Slowing down the start of the acceleration is not helping very much and would be detrimental for transition crossing that would become too slow. Above transition only 60% of the power is needed. This is one of the arguments to favour an injection energy in the SPS above transition.

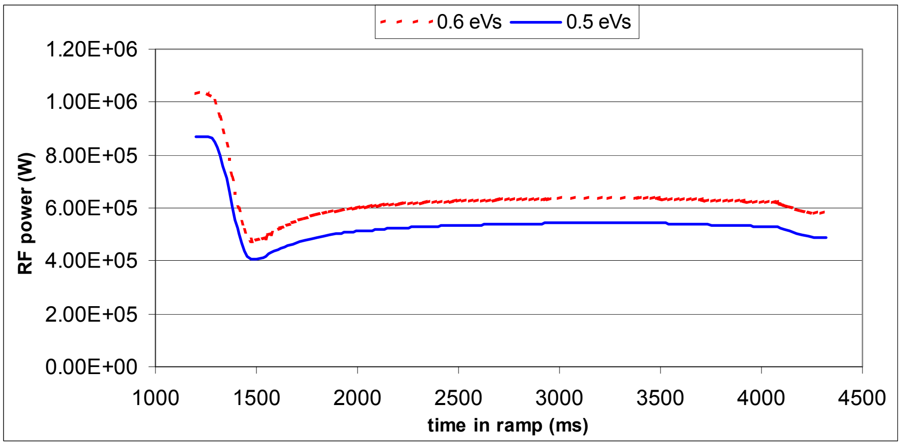

Figure 6.4: RF power needed to accelerate a beam of 7×10^{13} protons from 14 GeV/c to 400 GeV/c with a longitudinal emittance of 0.5 eVs (blue, full line) and 0.6 eVs (red, dotted line).

Moreover, because of their short filling time of a few hundreds of nanoseconds, transient periodic beam loading will take place in the travelling wave cavities of the SPS, at twice the beam revolution frequency because of the two gaps without particles. With 7×10^{13} protons circulating in the SPS for CNGS, the local beam current (~1.1 A (RF)) will be similar to the one encountered for the nominal beam for LHC (~1.5 A (RF)). However, the feedback and feedforward loops implemented to address this issue for the needs of the proton beam for LHC can only operate between 26 and 450 GeV/c. Their frequency range would then have to be extended to benefit from their action for the CNGS beam.

Longitudinal instabilities

Before the 2000-2001 shutdown, a typical high intensity beam (4×10^{13} protons) injected in the SPS with a longitudinal emittance of 0.18 eVs/bunch was blowing-up to 1.8 eVs around 300 GeV because of a longitudinal instability. Since then, no such high intensity beams have been tried in the SPS, although it is still clear that stability remains more problematic at high energy. The instability thresholds for narrow- and broad-band impedances shown in Figure 6.5 in the case of an LHC cycle are representative of the behaviour expected in the case of an FT cycle. Stability being higher for bunches of larger longitudinal emittance, the situation can be improved by increasing it within the limits allowed by the available RF power and the momentum acceptance of the CNGS transfer line. For example, blowing-up the emittance as $\sim\sqrt{E}$ to 1 eVs, the dotted threshold curves apply in Figure 6.5. Ways of producing a controlled emittance increase with the 800 MHz cavities were successfully tried on the LHC beam.

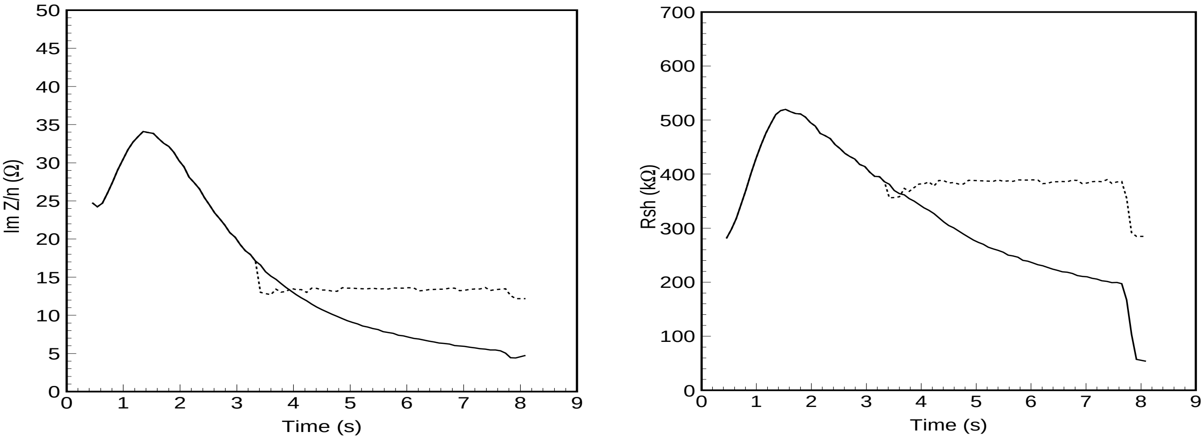

Figure 6.5: Instability thresholds for broad-band impedance (left) and narrow band impedance (right) for a longitudinal emittance of 0.5 eVs. If the emittance increases as $\sim\sqrt{E}$ to 1 eVs, the dotted threshold curves are obtained. The bunch current is 0.7 A.

Transition crossing in the SPS is also a lossy process. Before the SPS impedance was reduced, the losses increased rapidly with intensity, reaching ~5% at 4.5×10^{13} protons. However, in 2002, a single bunch of 8×10^{10} protons has successfully been accelerated to high energy with only 6.5% loss at transition [24] while the previous record was of 2×10^{10} protons in a single bunch [54].

More experiments with beam are needed to investigate the present performance and to estimate the level of losses for the ultimate CNGS intensity of 7×10^{13} protons (corresponding to 1.7×10^{10} ppb). In case this appears to be a limiting factor, injection above transition would eliminate the problem.

Transverse instabilities

Once the beam intensity in the SPS is higher than 5×10^{12} protons, the beam is suffering from the resistive wall instability created by a low frequency, long range wake field that builds up over several turns. The beam starts to oscillate with the lowest order coupled bunch modes. A transverse feedback, the so-called “damper”, has been installed in the SPS, in order to damp it in both planes. For high intensities, a fast damping rate and a high gain are needed, that will limit the dynamic range. Therefore injection oscillations will have to be kept within a smaller range.

In 2002, a high frequency vertical instability was observed on the SPS fixed target beam that was due to electron cloud. It appeared already at a moderate intensity of 2.5×10^{13} protons, but only in the presence of electron activity in the parasitic MD cycle. It occurs in the middle of the ramp where the bunch density is the highest and hence, more favourable for multi-pacting. It shows up as a vertical coupled bunch instability with a frequency of 15 to 30 MHz. It cannot be excluded that, for higher intensities the multi-pacting will be strong enough to set on without MD cycle.

The electron cloud activity is one of the main problems for the LHC beam in the SPS. Dedicated scrubbing campaigns (~10 days) are organized every year in order to clean the surface of the vacuum chamber and reduce secondary emission. The CNGS beam will certainly profit from this, but the question remains whether this vertical instability will stay under the limits that can be handled by the combined action of the damper and the octupoles.

Other hardware limitations

During the scrubbing run in 2003, excessive heating was observed on the MKE installed in the long straight section 4 (LSS4) during the shutdown 2002/2003. This heating is due to the current induced by the LHC bunch trains in the ferrite-loaded kicker, leading to undesirable effects:

- Out-gassing of the ferrite triggering vacuum interlocks. It should, in principle, disappear after conditioning. However, for the moment, conditioning has not been observed and out-gassing is indeed a practical problem.
- Reduced kick strength, once the Curie temperature is exceeded in the ferrite. According to measurements in the SPS and in the laboratory, that should not be the case for a nominal CNGS beam (4.4×10^{13} protons). Because of the short bunch length, the LHC beam results in a much stronger heating. However, for an intensity of 7.0×10^{13} protons, the Curie temperature could also be reached during the cycle for CNGS. In any case, continuous operation for CNGS, interleaved with several hours of LHC filling, might cause problems. Attempts are presently being made for improving the cooling efficiency.
- Mechanical damage could result from excessive thermal stress.

More machine studies are needed in order to fully understand the impact of the non-negligible impedance of the MKE on longitudinal and transverse instabilities for both CNGS and LHC beams [55]. There are already signs that it is also causing problems to the LHC beam by reducing the bucket size and generating beam losses at 26 GeV/c. A possibility to reduce the ferrite impedance is under study, which would cure both the heating of the magnet and the effects on the beam [18].

Multi cycling

To increase the proton flux for CNGS, a first possibility is to increase the repetition rate of the accelerator cycle. The working group did not consider the option to increase the ramping rate of the SPS because of its excessive cost (main power supply and RF). However, the benefits of reducing the basic repetition period of the injector complex from 1.2 s to 0.9 s and to 0.6 s have been analysed [20], with the result that the gain for CNGS and SPS FT physics is marginal because the repetition rate is dominated by the SPS up/down ramping rate and not by the length of the injection flat bottom; it is mainly ISOLDE that would profit from such a modification (see Chapter 8).

Another possibility to increase the proton flux is to optimize the machine supercycles and to minimize the time required for supercycle changes. Therefore:

- There is a need to switch between LHC pilot and CNGS on a cycle-to-cycle basis. Hence, a fast electronic switch is needed for rapid switching of the common dipole power converter between the transfer line bending magnets for TI8 and TT41 [13].
- The control system should allow for the SPS supercycle to be changed quickly.

A new timing system, which will allow fast changes of the supercycle, will be commissioned in 2004, and the necessary solid state switch will be ready at the beginning of the first run for CNGS in 2006. These measures are mandatory to provide the nominal proton flux.

6.1.3 Conclusions for CNGS

Without important modifications to the existing accelerators, the nominal flux of protons (4.5×10^{19} pot per year) can only be delivered to CNGS at the detriment of SPS FT physics. A detailed analysis is given in Chapters 3 and 8. However, beam losses are a major concern such that no increase of the proton flux to CNGS can reasonably be envisaged. In order to limit the level of irradiation of the PS machine and the radiation dose to personnel in charge of maintenance and exploitation, the replacement of the continuous transfer ejection is strongly recommended as a first measure.

To obtain a higher flux for CNGS, the SPS intensity per pulse has to be increased. At 7×10^{13} ppp, the flux could reach 6.3×10^{19} pot per year, with the present assumptions about the LHC filling time and with 1.8×10^{5} spills per year for the other FT physics experiments (see Chapter 8, Tables 8.2 and 8.5 for 2007). That would also bring in the possibility to arbitrate between users of the SPS beam, for example by increasing the number of FT spills while preserving the nominal flux for CNGS.

This higher intensity can be obtained with double batch operation from PSB to PS which will seriously reduce the number of cycles available to ISOLDE. The reduction of the basic period and PSB repetition time to 0.9 s would release the constraints on the users of the PS complex, and especially of ISOLDE.

6.2 FUTURE NEUTRINO BEAMS (AFTER GRAN SASSO)

In the framework of the HIP working group, the various ideas for future neutrino beams beyond the Gran Sasso experiments have been reviewed [7]. The accelerator R&D is coordinated by the European Muon Coordination and Oversight Group (EMCOG), with the goals to (i) have a conceptual design report of a future neutrino facility before LHC start-up; (ii) give high priority to the R&D for the SPL [56], target and horn, and (iii) perform a Muon Ionization Cooling Experiment (MICE) for a neutrino factory. Three different scenarios for future neutrino facilities are being contemplated: super-beam, neutrino factory, and beta-beam. The corresponding requirements on the accelerator chain are discussed in the following sections.

6.2.1 Super-beam

In the super-beam scheme, neutrinos result from the decay of pions produced when the multi-MW proton beam hits the target [7]. The only necessary accelerator is the proton driver which has to deliver megawatts of beam power at a few GeV. A duty cycle of $\sim 10^{-4}$ (beam burst duration/repetition period) is required for the suppression of the atmospheric background in the remote experiment. Such a duty cycle is naturally obtained with an RCS, while a linac like the SPL has to be complemented with an accumulator ring.

6.2.2 Neutrino Factory

In a neutrino factory, neutrinos come from the decay of high energy muons circulating in a storage ring. Long straight sections are oriented towards the remote experiments. A complex set of devices is needed to generate the short proton bunches (proton driver), the pions (target), to collect the muons from the decaying pions, to cool and accelerate them before they decay.

It is possible to use the same proton driver as for the super-beam, although a slower repetition rate would be preferable for the pulsed muon complex. Two approaches for the proton driver have been studied at CERN [57]. The two possibilities are either a 2.2 GeV SPL operating at 50 Hz and combined with an accumulator plus a compressor ring [58, 59], or a 30 GeV RCS [33]. Both produce bunches of 1 ns rms bunch length and a beam power of 4 MW at a comparable cost.

While the time structure provided by the RCS solution seems better adapted to the requirements of a neutrino factory, the SPL solution has more potential for a multi-purpose facility, serving multiple communities of users. The optimum proton energy for a super-beam is being investigated by the Hadron Production experiment (HARP) at the PS [60].

6.2.3 Beta-beam

In a beta-beam facility [8], the neutrinos are generated by beta decay of radioactive ions circulating in a storage ring. Like in a neutrino factory, long straight sections beam the neutrinos towards the remote experiments. The accelerator complex is simpler than in a neutrino factory, because “cooling” is not necessary and acceleration of the neutrinos’ parents can take place in conventional accelerators, the lifetime of the radioactive ions being of the order of seconds. The present layout foresees to use the PS and SPS. The latter seems to be the bottleneck in the chain, due to space charge effects.

The necessary radioactive ions like ^{6}He and ^{18}Ne can be produced by the ISOL method using a continuous or pulsed proton beam at a few GeV. In the case of the SPL driver, only a few percent of the available proton intensity is needed for ion production. The activation of all the accelerators in the chain is a major issue because of the short lifetime of the ions.

The combination of both super-beam and beta-beam is especially interesting, with neutrinos being sent simultaneously towards a common detector. The physics reach would approach the potential of a neutrino factory, although at a more affordable cost. This solution is unique to CERN, due to the ISOLDE experience with radioactive ions and the availability of synchrotrons to accelerate these radioactive ions. It is likely that the time scale will be determined by the availability of the neutrino detectors. In the case of the Frejus laboratory which is ideally situated for a 2.2 GeV SPL based super-beam and beta radioactive ions stored at a gamma of ~100, an earliest starting date of 2012 can be envisaged.

CHAPTER 7

UPGRADES FOR RADIOACTIVE ION BEAMS

7.1 PRESENT STATUS AND UPGRADE PLANNING OF THE ISOLDE FACILITY

At present, ISOLDE is a worldwide unique facility for production and acceleration of radioactive ion beams [11]. The ISOLDE physics programme has evolved from the traditional fields of nuclear and atomic physics to cover more applications, like nuclear astrophysics, solid state physics and medicine/biology, altogether using now about 39% of ISOLDE beam time. Moreover, the commissioning of the REX post-accelerator in 2001 has considerably increased the physics reach of the facility and extended the user base of ISOLDE. Upgrades of the REX accelerator from the present 2.2 MeV/u to higher energies are already planned for the years 2004 (3.1 MeV/u) and 2005-06 (4.3 MeV/u). They will bring beams of higher atomic mass above the Coulomb barrier, increasing the physics interest and the beam demands. The construction of a new experimental hall is already under way.

In order to meet the increasing user demand, the ISOLDE group has started a reflection on a High Intensity and Energy - ISOLDE. The main assumption is that the increase in REX energy should go in parallel with an intensity increase of the primary proton beam. The arguments for an intensity increase are: i) the higher statistics (with a better signal to noise ratio) would reduce the time for data taking and allow to accommodate more users; ii) the increased rate of RIB per target, the target lifetime which does not scale with intensity remaining the same; and iii) more exotic ions will be visible above the experimental threshold. The intensity limit for the present ISOLDE facility is determined by the radioprotection for target stations, and estimated at 10 μA [11, 61].

The production of the 1.4 GeV proton beam for ISOLDE involves only the Linac2 and the PSB machines. The present CERN commitment towards ISOLDE is based on a number of "shifts" per year, corresponding to about 50% of the total number of PSB cycles and was usually fulfilled during the last years. With the PSB repetition time of 1.2 s and considering 90% beam availability this translates to 1350 pulses/hour. Multiplying this figure by the nominal PSB ISOLDE intensity of 3.2×10^{13} ppp gives an average current of 1.92 μA usually available for ISOLDE [62].

The demand coming from the ISOLDE community for the period 2006-10 is for an increase of this figure up to the target limit of 10 μA, i.e. a factor of ~5. The present limitation in average current comes from both the maximum proton intensity that can be produced and the number of PSB pulses that are available for ISOLDE. These two points are therefore the key issues for an upgrade analysis.

7.2 BEAM INTENSITY LIMITATIONS AND IMPROVEMENT SCENARIOS

The main limiting factor for the proton beam intensity that can be provided by Linac2 and PSB is the excessive incoherent space charge tune shift that occurs at 50 MeV injection into the PSB. With an intensity of around 1×10^{13} protons per PSB ring, the vertical space charge tune spread during RF capture exceeds 0.5 and the combination of several techniques is required to avoid large beam losses and to make high intensity operation possible.

A horizontal multi-turn scheme (10-13 turns) is used to inject the Linac2 beam into the PSB. To make full use of the available aperture, coupling of the transverse planes is applied during injection in order to transfer some of the horizontal oscillation into the vertical plane. Already during the injection process, the main magnetic field is ramped to accelerate the beam out of the space charge regime as quickly as possible. A dual harmonic (h=1 and h=2 in anti-phase) RF system is employed to flatten the bunches during the capture process and the early acceleration phase to improve the bunching factor hereby reducing the incoherent space charge tune spread of the beam. Nevertheless a sophisticated resonance compensation scheme is needed to avoid the destructive effect of transverse betatron resonances up to third order. All these techniques have been studied and optimized over the last years. Very little margin is left for further improvements and no significant increase in beam intensity can be expected with the present operation conditions.

The only straightforward way to significantly improve the PSB beam intensity is to attack the problem directly at its roots, i.e. to reduce the space charge tune spread at injection by increasing the injection energy. The space charge tune shift is inversely proportional to $\beta\gamma^2$, and the experience of other laboratories having increased their linac energy confirms that the final accumulated intensity is roughly proportional to $\beta\gamma^2$ at injection. The Fermilab linac upgrade (1993, 200 to 400 MeV corresponding to a factor 1.7 in $\beta\gamma^2$) opened the way for an increase of the booster intensity from 3×10^{12} to 5.5×10^{12} protons per pulse [63].

Taking the requirement to make the LHC beam in a single batch as the final goal, the PSB intensity has to be increased by a factor two. This improvement should be obtained by increasing $\beta\gamma^2$ at injection by a factor two, i.e. by increasing the linac energy from the present 50 MeV up to 160 MeV. If the linac is upgraded, then it is almost mandatory to change at the same time the particle type from protons to H^-. This means to strongly modify the PSB injection area, but the advantages of a modern charge-exchange injection in terms of beam loss reduction, phase space painting options and emittance control clearly justify the investment. Simulations of 160 MeV H^- injection and accumulation in the PSB are in progress, and present results confirm the expected gain in intensity [31, 52].

The option of increasing the energy of Linac2 has been considered but finally discarded due to the limited energy achievable in the available space at the end of the linac, about 20 m. Using standard tanks at 202 MHz, only 80 MeV could be reached, at a cost of about 30 MCHF (P+M). The limited increase in PSB intensity would present only a minor interest for ISOLDE, and no significant advantages for the other users [28]. Higher gradients could be achieved by linac tanks at double frequency (405 MHz), allowing to reach about 100 MeV. However, the cost would be higher, due to the completely new RF system to be designed and built, and the gain still marginal. Structures at higher frequency and gradient can not be used due to the low transfer energy.

The preferable solution is to build a new linac injector. Being the fourth linac to be built at CERN, the latter would be naturally called Linac4. This option has been recently studied with a certain detail as an outcome of the SPL study. The energy of the original SPL room-temperature injector has been increased from 120 to 160 MeV, and its design can be directly used for the Linac4 [30]. The new linac would be housed in the PS South Hall, where the required 100 m space and the infrastructure (water, electricity, etc.) are largely available, and its beam would go to the PSB in a line parallel to the existing LEIR transfer line. Another factor contributing to lowering the construction cost is that most of the Linac4 makes use of 352 MHz RF equipment recuperated from the LEP machine. Moreover, an RFQ injector that can be used for Linac4 will be given to CERN by the "Injecteur de Protons de Haute Intensité" (IPHI) collaboration (CEA and IN2P3), at the end of their testing period in 2006. It must also be taken into consideration the fact that a modern linac would profit of technologies, like low energy chopping and collimation, intended to minimize beam losses and reduce the environmental impact of high intensity operation. The target value of 6.4×10^{13} ppp in the PSB (factor two with respect to present peak intensity) could be reached with a linac delivering 30 mA H^- current during pulses of up to 500 μs length. The overall cost of a 160 MeV Linac4 in the PS South Hall, including the modification to PSB and the transfer line, has been estimated at 70 MCHF (P+M). Figure 7.1 shows a schematic layout of Linac4 in the South Hall.

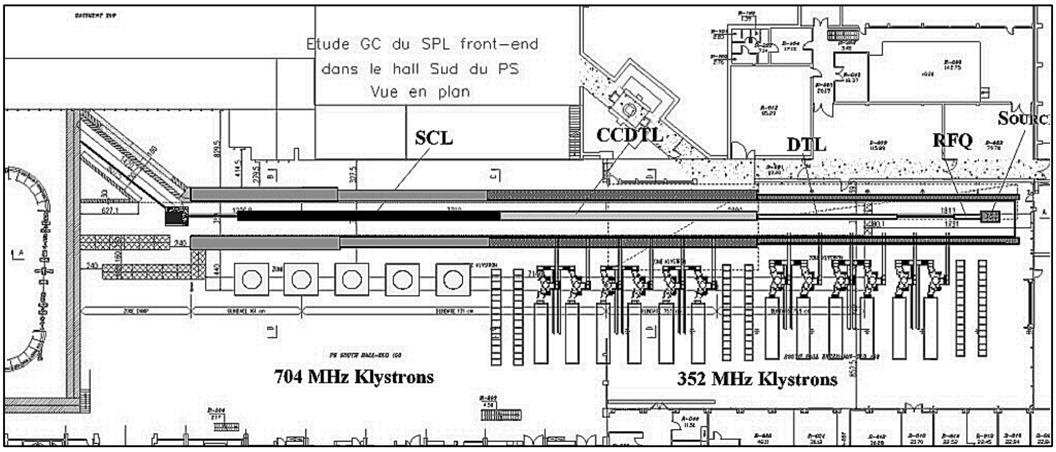

Figure 7.1: Layout of Linac4 in the PS South Hall.

7.3 INCREASING THE NUMBER OF PSB CYCLES AVAILABLE FOR ISOLDE

Presently, on average, around 50% of the PSB cycles are made available for ISOLDE and the remaining 50% correspond to beams that are sent to the PS for the various other physics programmes on PS and SPS. Since this ratio will not significantly change in the short and medium-term future, no changes for ISOLDE can be expected with the present operating conditions (see Chapter 8).

To increase the number of available PSB cycles for ISOLDE, in a transparent way for the other physics users, the total (yearly) number of cycles has to be increased. There are two approaches: either prolonging the PSB operation period or increasing the PSB repetition frequency. With the latter option in mind several machine developments and studies were performed in 2001 and 2002 to investigate the feasibility of decreasing the PSB repetition time (and also the Linac2 repetition time) from the standard 1.2 s to 0.6 s [21]. The choice of 0.6 s was motivated by the fact that the PSB main power supply, after major upgrading in the framework of the "PS for LHC project", just allows to perform a 1.4 GeV magnetic cycle within 0.6 s.

The outcome of the investigations was that a repetition time of 0.6 s is feasible for Linac2 with only minor modifications (the machine was initially designed for 2 Hz operation) but too demanding for the PSB, pushing several essential machine systems towards or beyond their limits. Even though all physics beams could be produced on short 0.6 s cycles with nominal performance, several systems of the PSB would not support 24 h operation with 0.6 s cycling. Especially the main power supply transformers (rms current limited), the first and second harmonics RF systems (rms power and cooling limited) and the main magnets cooling circuit would require major upgrade or replacement. In addition, several power converters in the transfer lines PSB - PS and PSB - ISOLDE would also need replacement so that the total cost for reducing the PSB repetition time to 0.6 s would be in the order of 10 MCHF and require significant manpower investment.

The situation is fundamentally different when analysing a reduction of the repetition time to 0.9 s. In this case, all PSB systems can operate within specifications, only a single transfer line power converter needs replacement and a few others some upgrade work. The overall cost can be roughly estimated to around 1-2 MCHF and accordingly less manpower is required so that a reduction of the PSB repetition time can be considered a valid short-term upgrade possibility.

The potential gain for ISOLDE is still important. With 0.9 s repetition time instead of 1.2 s, the number of PSB cycles in a given period increases by 33%. Assuming (to first order) that the 33% additional cycles are made available for ISOLDE (i.e. the number of cycles for other users remains unchanged) the gain factor is $(50 + 33)/50 = 1.66$ so that instead of 1350 cycles, as presently, around 2240 cycles would be available per hour for ISOLDE.

Obviously 0.6 s repetition time would be significantly more beneficial for ISOLDE (with assumptions as above the gain factor is $(50 + 100)/50 = 3.0$) but it requires ten times more investment than the 0.9 s option and does not benefit other CERN users in a way comparable to e.g. the Linac4 option.

Results of detailed calculations are given in Chapter 8.

7.4 ESTIMATE OF SHORT AND MEDIUM-TERM ISOLDE PERFORMANCE

The effect of the two potential upgrades on the performance of the ISOLDE facility is analysed below. The decrease of the PSB repetition time from 1.2 s to 0.9 s is considered a short-term option that could already be effective in 2006. The intensity increase by a factor two, expected from a new Linac4 is a medium-term option and could be achieved at the earliest by 2010. Combining the two options, the overall gain for ISOLDE would be $2 \times 1.66 = 3.32$, i.e. the average current to ISOLDE can be estimated to reach ~6.4 μA.

The different scenarios are summarized in Table 7.1. The number of cycles available for ISOLDE is compatible with all other physics requirements and especially the assumed LHC and SPS operation modes (see Chapter 3). The assumed intensities per PSB pulse are 3.2×10^{13} ppp with Linac2, and twice more, 6.4×10^{13} ppp with Linac4. The "gain factor" is the ratio of the expected average current and the present average current of 1.92 μA (Section 7.1). In the case of Linac4 upgrade, it is assumed that the LHC beam will be produced with single batch filling of the PS instead of the presently used double batch operation, hereby freeing some more cycles for ISOLDE during periods with LHC beam requests.

Table 7.1: Expected ISOLDE performance under various upgrade scenarios.

Scenario	**2006**		**2007**[12]		**2010**			
	1.2 s Linac2	**0.9 s** Linac2	1.2 s Linac2	**0.9 s** Linac2	1.2 s Linac2	**0.9 s** Linac2	1.2 s **Linac4**	**0.9 s Linac4**
PSB cycles/hour	1300	2250	1210	2110	1270	2200	1290	2240
% of PSB cycles	48	63	45	59	47	61	48	62
Protons/pulse [$\times 10^{13}$]	3.2	3.2	3.2	3.2	3.2	3.2	6.4	6.4
Protons/hour [$\times 10^{16}$]	4.2	7.1	3.9	6.7	4.1	7.0	8.3	14.1
Av. current [μA]	1.9	3.2	1.7	3.0	1.8	3.1	3.7	6.4
Gain factor	0.97	1.64	0.90	1.55	0.94	1.61	1.91	3.28

The final conclusion is that reducing the PSB repetition time from 1.2 to 0.9 s is an important, cost-effective short-term option that provides a significant gain of ~60% increase in average current (via the number of available cycles) for ISOLDE. In the medium term, another important gain of ~100% increase in average current (via peak current per pulse) can then be achieved with Linac4. Combining the two options will result in an increase of the average current by a factor ~3.3 as compared to the present situation.

7.5 LONG-TERM FUTURE FOR ISOLDE AND RIB FACILITIES AT CERN

The long-term future and needs of ISOLDE have to be seen in the context of the EURISOL study [12, 64]. The Nuclear Physics European Collaboration Committee (NuPECC) working group on the next generation RIB facilities in Europe came to the conclusion that these future facilities should aim at ions intensities 1000 times higher than in the present ones [65]. The resources for designing and finally building such facilities can only be found by a joint effort of the European countries, and a study called EURISOL is being carried on since the year 2000 by ten major European laboratories. The study has been supported by the European Union within the 5th Framework Programme, and the community is presently applying for funding of a Design Study in the 6th Framework Programme. The goal of the design group is to build the EURISOL facility soon after 2010. Once available, the focus on RIB experiments will move away from the present facilities, including ISOLDE.

The proton driver in the present EURISOL design consists in a superconducting 1 GeV linear accelerator, delivering either a DC beam of 5 mA to a spallation target (5 MW beam power) or a lower intensity of 100 μA to one of several conventional ISOL targets. The design has many points in common with other high-power facilities proposed for neutrino physics or other applications, like the SPL at CERN. The EURISOL proton driver is designed to deliver the beam continuously, but from the experimenters' point of view, the 50 Hz pulsed beam from the SPL is perfectly acceptable [12]. For the spallation target, beam power is the important parameter and the SPL energy of 2.2 GeV is consistent with the needs of EURISOL. Using H^- as projectile makes no difference for the target.

In conclusion, for physics with radioactive ion beams, the SPL would be an adequate device making the CERN-site highly attractive for a future EURISOL facility.

---

[12] The figures for 2007 assume only proton operation in the SPS. In the case of ion commissioning (see Section 3.1.1), ISOLDE would benefit from periods when the SPS request (only) ions.

CHAPTER 8

EFFECT OF UPGRADES ON PROTON BEAM AVAILABILITY

The effects of some of the proposed accelerator complex upgrades on the proton beam availability for the period 2006 to 2010 are analysed in this chapter. The upgrades considered in detail are:

(i) Reduction of the basic period (and the Linac2 and PS Booster repetition time) from the present 1.2 s to 0.9 s or 0.6 s. Consequently the number of available PSB cycles is increased by either 33% (0.9 s) or 100% (0.6 s). A change of the basic period length also implies modifications of most of the PS and SPS cycles. The effect is however rather small on the SPS since the length of the SPS cycles is usually determined by the time required for the cycling and not by the injection flat bottom. More details on the effect of reduced basic period on PS and SPS cycles can be found in Reference 20. The beam characteristic (intensity, emittance, etc.) for all users is assumed to be independent of the basic period length.

(ii) Increase of the CNGS intensity from 4.4×10^{13} to 7.0×10^{13} protons per SPS cycle. For this option it is assumed that PS and SPS high intensity performance can be pushed by around 60% as compared to the nominal CNGS scenario. The higher intensity in the PS is achieved by using two consecutive injections from the PSB (double batch filling), similar to LHC operation [6]. Production and characteristic of the beams for all other physics users are to first order identical to the nominal scenario. The main impact of this option is therefore the increased number (factor 2) of PSB cycles required for CNGS operation.

(iii) A new Linac4 (160 MeV, H^-) as injector for the PSB [30]. In this scenario it is assumed that the increased injection energy allows doubling the beam brightness in the PSB. Therefore the nominal (and also the ultimate) LHC beam can be produced with a single PSB pulse in contrast to the presently used double batch scheme, thus reducing the number of required PSB cycles by a factor of two. A similar argument applies to CNGS operation, where the higher intensity (7.0×10^{13}) can be achieved with a single PSB batch for the PS, avoiding the disadvantageous double batch filling required for option (ii). As discussed above, it is assumed that PS and SPS can handle the 60% increase in intensity. Finally it is expected that the PSB intensity for ISOLDE can be doubled from the nominal 3.2×10^{13} to 6.4×10^{13} ppp. All other physics beams will be produced like in the nominal scenario.

The comparison of the various upgrades is based on the operation conditions and guidelines that were defined for the performance analysis of Chapter 3. The same supercycle compositions, user priorities and beam requests were assumed. Tables 8.1 to 8.9 summarize the beam availability for all physics users for 2006, 2007 and 2010 for the following three scenarios:

- Present operational beam characteristics (“standard operation”).
- Increased CNGS intensity of 7.0×10^{13} per SPS cycle (“CNGS double batch”).
- 160 MeV H^- injection into the PSB (“Linac4”).

Tables 8.1 to 8.3 are for the present Linac2 and PSB repetition time of 1.2 s, Tables 8.4 to 8.6 assume 0.9 s and Tables 8.7 to 8.9 are for 0.6 s.

As already discussed in Chapter 3, the SPS supercycles were optimized such as to fulfil the nominal CNGS beam request of 4.5×10^{19} pot per year with standard operation. With the proposed upgrades (high intensity for CNGS, Linac4) this request is exceeded for all of the cases. The corresponding overflow however serves not necessarily (only) for improving CNGS performance but could also be used to increase the number of SPS spills for FT physics by simply reducing the number of CNGS cycles. The effect of limiting CNGS to nominal performance and of redirecting the hereby freed SPS time to FT operations is indicated by the values in brackets for CNGS and FT in Tables 8.1 to 8.9.

ISOLDE performance is quoted in three different ways: pulses per hour, average percentage of PSB cycles and average current. This is because the present way of quantifying ISOLDE performance by quoting either PSB pulses or percentage of cycles makes little sense when changing the PSB repetition time.

It should be noted that Linac4 is considered a medium-term option that will be available by 2010 at the earliest. Nevertheless performance figures for this option are quoted for 2006 and 2007 for comparison.

The case of ion commissioning in the SPS in 2007 (see Section 3.1.1) is not considered. The corresponding figures can be simply obtained by scaling the 2007 values with the ratio of the SPS physics operation time with (4200 hours) and without (4700 hours) ion commissioning. SPS ion commissioning has nearly no effect on the PS users whereas ISOLDE performance will be improved on the percent level.

8.1 BEAM AVAILABILITY FOR 1.2 s PSB REPETITION TIME

Table 8.1: Beam availability in 2006 with 1.2 s PSB repetition time.
Comparison of standard operation with CNGS high intensity and Linac4 options.

2006 Accelerator complex performance for 1.2 s PSB repetition time				
	Request	**Standard operation**	**CNGS high intensity**	***Linac4***
CNGS [$\times 10^{19}$ pot/year]	4.5	4.4	6.3 (4.5)	*7.0 (4.5)*
FT [$\times 10^{5}$ spills/year]	7.2	3.3	3.0 (4.5)	*3.3 (5.1)*
East Area [$\times 10^{6}$ spills/year]	1.3	1.3	1.2	*1.3*
nTOF [$\times 10^{19}$ pot/year]	1.0-1.5	1.4	1.3	*1.4*
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	1300 (48%) 1.9	930 (34%) 1.3	*1300 (48%)* *3.7*

Table 8.2: Beam availability in 2007 with 1.2 s PSB repetition time.
Comparison of standard operation with CNGS high intensity and Linac4 options.

2007 Accelerator complex performance for 1.2 s PSB repetition time				
	Request	**Standard operation**	**CNGS double batch**	***Linac4***
CNGS [$\times 10^{19}$ pot/year]	4.5	4.4	6.3 (4.5)	*7.0 (4.5)*
FT [$\times 10^{5}$ spills/year]	7.2	1.9	1.8 (3.3)	*1.9 (3.7)*
East Area [$\times 10^{6}$ spills/year]	1.3	1.5	1.4	*1.6*
nTOF [$\times 10^{19}$ pot/year]	1.0-1.5	1.7	1.5	*1.7*
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	1210 (45%) 1.7	890 (33%) 1.3	*1260 (47%)* *1.8*
SPS LHC filling cycle [s]	-	21.6	21.6	*18.0*
SPS LHC pilot cycle [s]	-	22.8	25.2	*22.8*

Table 8.3: Beam availability in 2010 with 1.2 s PSB repetition time.
Comparison of standard operation with CNGS high intensity and Linac4 options.

2010 Accelerator complex performance for 1.2 s PSB repetition time				
	Request	**Standard operation**	**CNGS double batch**	**Linac4**
CNGS [$\times 10^{19}$ pot/year]	4.5	4.9 (4.5)	7.0 (4.5)	7.8 (4.5)
FT [$\times 10^{5}$ spills/year]	7.2	3.3 (3.8)	3.0 (5.1)	3.3 (5.7)
East Area [$\times 10^{6}$ spills/year]	1.3	1.5	1.4	1.5
nTOF [$\times 10^{19}$ pot/year]	1.0-1.5	1.7	1.5	1.7
ISOLDE [pulses/hour] Average current [μA]	1350 (50%) 1.9	1270 (47%) 1.8	920 (34%) 1.3	1290 (48%) 3.7
SPS LHC filling cycle [s]	-	21.6	21.6	18.0
SPS LHC pilot cycle [s]	-	22.8	25.2	22.8

8.2 BEAM AVAILABILITY FOR 0.9 s PSB REPETITION TIME

Table 8.4: Beam availability in 2006 with 0.9 s PSB repetition time. Comparison of standard operation with CNGS high intensity and Linac4 options.

2006 Accelerator complex performance for 0.9 s PSB repetition time				
	Request	**Standard operation**	**CNGS double batch**	***Linac4***
CNGS [$\times 10^{19}$ pot/year]	4.5	4.2	6.3 (4.5)	*6.7 (4.5)*
FT [$\times 10^{5}$ spills/year]	7.2	3.2	3.0 (4.5)	*3.2 (4.8)*
East Area [$\times 10^{6}$ spills/year]	1.3	1.2	1.1	*1.2*
nTOF [$\times 10^{19}$ pot/year]	1.0-1.5	1.3	1.3	*1.3*
ISOLDE [pulses/hour] Average current [µA]	1350 (50%) 1.9	2250 (63%) 3.2	1850 (51%) 2.6	*2250 (63%)* *6.4*

Table 8.5: Beam availability in 2007 with 0.9 s PSB repetition time. Comparison of standard operation with CNGS high intensity and Linac4 options.

2007 Accelerator complex performance for 0.9 s PSB repetition time				
	Request	**Standard operation**	**CNGS double batch**	***Linac4***
CNGS [$\times 10^{19}$ pot/year]	4.5	4.3	6.3 (4.5)	*6.8 (4.5)*
FT [$\times 10^{5}$ spills/year]	7.2	1.9	1.8 (3.3)	*1.9 (3.6)*
East Area [$\times 10^{6}$ spills/year]	1.3	1.5	1.4	*1.5*
nTOF [$\times 10^{19}$ pot/year]	1.0-1.5	1.7	1.6	*1.7*
ISOLDE [pulses/hour] Average current [µA]	1350 (50%) 1.9	2110 (59%) 3.0	1760 (49%) 2.5	*2210 (61%)* *3.2*
SPS LHC filling cycle [s]	-	18.9	18.9	*18.9*
SPS LHC pilot cycle [s]	-	23.4	25.2	*23.4*

Table 8.6: Beam availability in 2010 with 0.9 s PSB repetition time. Comparison of standard operation with CNGS high intensity and Linac4 options.

2010 Accelerator complex performance for 0.9 s PSB repetition time				
	Request	**Standard operation**	**CNGS double batch**	**Linac4**
CNGS [$\times 10^{19}$ pot/year]	4.5	4.7 (4.5)	7.0 (4.5)	7.5 (4.5)
FT [$\times 10^{5}$ spills/year]	7.2	3.2 (3.4)	3.0 (5.1)	3.3 (5.6)
East Area [$\times 10^{6}$ spills/year]	1.3	1.5	1.4	1.5
nTOF [$\times 10^{19}$ pot/year]	1.0-1.5	1.6	1.5	1.6
ISOLDE [pulses/hour] Average current [µA]	1350 (50%) 1.9	2200 (61%) 3.1	1810 (50%) 2.6	2240 (62%) 6.4
SPS LHC filling cycle [s]	-	18.9	18.9	18.9
SPS LHC pilot cycle [s]	-	23.4	25.2	23.4

8.3 BEAM AVAILABILITY FOR 0.6 s PSB REPETITION TIME

Table 8.7: Beam availability in 2006 with 0.6 s PSB repetition time.
Comparison of standard operation with CNGS high intensity and Linac4 options.

2006 Accelerator complex performance for 0.6 s PSB repetition time				
	Request	**Standard operation**	**CNGS double batch**	***Linac4***
CNGS [× 10^{19} pot/year]	4.5	4.4	6.6 (4.5)	*6.9 (4.5)*
FT [× 10^{5} spills/year]	7.2	3.3	3.1 (4.7)	*3.3 (5.0)*
East Area [× 10^{6} spills/year]	1.3	1.3	1.2	*1.3*
nTOF [× 10^{19} pot/year]	1.0-1.5	1.4	1.3	*1.4*
ISOLDE [pulses/hour] Average current [µA]	1350 (50%) 1.9	4000 (74%) 5.7	3540 (66%) 5.0	*4000 (74%)* *11.4*

Table 8.8: Beam availability in 2007 with 0.6 s PSB repetition time.
Comparison of standard operation with CNGS high intensity and Linac4 options.

2007 Accelerator complex performance for 0.6 s PSB repetition time				
	Request	**Standard operation**	**CNGS double batch**	***Linac4***
CNGS [× 10^{19} pot/year]	4.5	4.4	6.6 (4.5)	*7.0 (4.5)*
FT [× 10^{5} spills/year]	7.2	1.9	1.9 (3.5)	*1.9 (3.7)*
East Area [× 10^{6} spills/year]	1.3	1.6	1.5	*1.6*
nTOF [× 10^{19} pot/year]	1.0-1.5	1.7	1.6	*1.7*
ISOLDE [pulses/hour] Average current [µA]	1350 (50%) 1.9	3880 (72%) 5.5	3490 (65%) 5.0	*3960 (73%)* *11.3*
SPS LHC filling cycle [s]	-	19.8	19.8	*18.0*
SPS LHC pilot cycle [s]	-	22.8	24.0	*22.8*

Table 8.9: Beam availability in 2010 with 0.6 s PSB repetition time.
Comparison of standard operation with CNGS high intensity and Linac4 options.

2010 Accelerator complex performance for 0.6 s PSB repetition time				
	Request	**Standard operation**	**CNGS double batch**	**Linac4**
CNGS [× 10^{19} pot/year]	4.5	4.9 (4.5)	7.4 (4.5)	7.8 (4.5)
FT [× 10^{5} spills/year]	7.2	3.3 (3.8)	3.1 (5.4)	3.3 (5.7)
East Area [× 10^{6} spills/year]	1.3	1.5	1.5	1.5
nTOF [× 10^{19} pot/year]	1.0-1.5	1.7	1.6	1.7
ISOLDE [pulses/hour] Average current [µA]	1350 (50%) 1.9	3960 (73%) 5.6	3520 (65%) 5.0	3990 (74%) 11.4
SPS LHC filling cycle [s]	-	19.8	19.8	18.0
SPS LHC pilot cycle [s]	-	22.8	24.0	22.8

8.4 CONCLUSIONS

Performance figures in Tables 8.1, 8.2 and 8.3 clearly show that, if no improvement is made, the accelerator complex will not be able to fulfil the basic user requests. This is especially the case during the early years of LHC operation (2007-2009). Because of the priority assumed for CNGS in the analysis, it is the FT physics programme (COMPASS) that suffers the most, with receiving less than 50% of the requested number of protons (see also Figure 3.1).

The nominal flux of particles to which CERN is committed in the next few years induces a large amount of beam losses and radioactivity with possibly adverse effects on the availability of the accelerators and the radiation dose taken by personnel in charge of maintenance and exploitation. An increase of the proton flux can therefore be only envisaged together with a corresponding reduction of the beam losses.

The comparison between upgrades highlights that a significant increase of the SPS intensity per pulse for CNGS is a very effective way of improving the performance for CNGS and/or FT, whereas the choice of the basic period length and the PSB repetition time has no important influence on these physics users. A potential way of achieving this is to fill the PS with two consecutive PSB cycles (double batch operation) and to improve on high intensity operation of PS and SPS. This has unfortunately the detrimental effect of reducing the number of PSB cycles available to other users. With the present PSB repetition time of 1.2 s, ISOLDE operation would seriously suffer, as can be seen in Tables 8.1 to 8.3, whereas for the PS (East Area, nTOF, AD) no shortage of cycles or beam availability is anticipated. The straightforward way of improving ISOLDE performance is to decrease the PSB repetition time. For a repetition time of 0.9 s (Tables 8.4 to 8.6), ISOLDE performance will still be ~30% above request when double batch operation is used for CNGS. A further decrease of the repetition time to 0.6 s profits again mainly ISOLDE that will then reach 2 or even 2.5 times the requested performance.

The installation of Linac4, as injector for the PSB, will significantly increase the proton flux for ISOLDE (~×2), and to a lesser extent, for CNGS and FT (~×1.1). For LHC, Linac4 is also very valuable for the twice higher brightness that can be achieved in the PSB. Moreover, PSB cycles are freed for other users because LHC nominal and ultimate beams and also very high intensity CNGS type beams can be produced with single PSB batches. When combined with a shorter basic period of 0.9 or 0.6 s, Linac4 will bring the flux to ISOLDE to 3.4 or even 6 times the nominal request.

Starting to implement in 2005 the analysed improvements (reduced PSB repetition time, increased intensity in SPS for CNGS, Linac4), the basic and also some of the upgrade requests of most of the physics users can be progressively satisfied. However, it should be noted that the remaining major bottleneck is the performance of the SPS users CNGS and FT physics that is simply limited by the available SPS operation time.

CHAPTER 9

RECOMMENDATIONS

9.1 SHORT-TERM, HIGH-PRIORITY MEASURES

Without any improvement, the proton accelerator complex will not be able to satisfy all the commitments for physics during the period 2006-2010 (Chapter 3). Moreover, the foreseeable high beam loss during CNGS operation will irradiate equipment, render maintenance and repair problematic, and endanger the operation for LHC.

This is why we strongly support:

- the on-going efforts to modify the control system for increasing the flexibility in the change of operating modes. We underline that, to achieve that goal in 2006, the accelerator equipment must imperatively be adapted before that date,
- the decision to install immediately a solid state switch to supply current to the bending magnets in either TI8 (for LHC) or TT41 (for CNGS) within the same supercycle and to have it available for the start-up in 2007.

Moreover, we consider of the utmost importance to give a high priority to the minimization of beam loss and irradiation:

- by developing rapidly the proposed new multi-turn ejection scheme from the PS and implementing it as soon as possible,
- by systematically realigning the PS during the shutdowns,
- by improving the flexibility and ease of control of the machine parameters (independent control of the current in the 5 PFW circuits in the PS, beam instrumentation and feedbacks,…)
- by practicing with high intensity beams before the shutdown in 2005, to train staff and to precisely determine the actual capabilities and weaknesses in the accelerator complex.

The resources needed and a possible planning are given in Table 9.1.

Table 9.1: Short-term measures.

SUBJECT	RESOURCES[13]				PLANNING	
	CERN staff	**Visitors & Students**	**Material**	**Beam time**	**Start**	**End**
New PS ejection scheme: studies (beam & simulations)	~4 man-years	~4 man-years	-	parasite cycles + 3 × 8 h in 2004 + continuation after 2005	already started	2007
New PS ejection scheme: implementation[14]	17 man-years	-	4.25 MCHF	setting up in 2008	January 2005	March 2008
Machine studies at high beam intensity [15]	~2 FTE/year	1 FTE/year	-	parasite cycles + 2 × 8 h in 2004 + continuation after 2005	-	-
Independent control of 5 PFW in the PS[16]	1 man-year		-	setting up in 2006		April 2006

---

[13] Needed resources, independently of availability.

[14] First estimate, assuming no modification to the PS RF systems (transferred beam is bunched on h=8).

[15] Concerns all accelerators up to the SPS; covers also the needs stated in Section 9.2.

[16] Application software development.

9.2 SHORT-TERM, MEDIUM-PRIORITY MEASURES

9.2.1 Increase of the SPS intensity per pulse for CNGS

Even with the full benefit of the measures listed in Section 9.1, a significant shortfall of SPS cycles will remain for CNGS and/or FT operation (Section 3.2.3). Furthermore, to stay competitive with similar experiments elsewhere in the world, CNGS users are eagerly expecting more particles than presently foreseen (Section 2.3.1).

Therefore, we recommend to increase the intensity of the CNGS type of beam in the SPS. This entails:

- to analyse the needs (RF, beam feedbacks, impedance reduction, …) and to define a precise improvement programme, preferably by the end of 2004. In particular the longitudinal impedance of the SPS ejection kickers is an identified limitation that we urge to improve as soon as possible,
- to start implementing it as soon as possible, profiting from the 2005 shutdown.

9.2.2 Reduction of the PSB repetition time

Since the increase of intensity per pulse in the SPS will be obtained with two PSB batches filling the PS (Section 6.1.1), less PSB cycles will be available for ISOLDE (33 % of the cycles and 1.3 μA – from Tables 8.1, 8.2 and 8.3). This is less than today's commitment and it contradicts the efforts of the ISOLDE community to improve and extend the physics reach and user base of their facility.

For this reason, we consider as essential to implement a reduction of the PSB repetition time down to 0.9 s. The resources needed being relatively small, this improvement should be applied as quickly as possible, to be effective already during the year 2006.

9.3 MEDIUM-TERM MEASURES

After the year 2010, when the measures described in Sections 9.1 and 9.2 will be fully implemented, the need will be strong for maximizing the integrated luminosity in the LHC, reaching and investigating the possibility to exceed the ultimate luminosity, and for increasing further the proton flux to ISOLDE (Chapter 2). The best means to address both of these requests is to improve the performance of the beam from the PSB, in terms of brightness for the LHC (Chapter 5) and in terms of intensity per pulse for ISOLDE (Chapter 7). The present 50 MeV proton linac actually limits performance in that respect.

Therefore we recommend to replace the 50 MeV proton Linac2 by a 160 MeV H^- linac (Linac4). This requires:

- to actively pursue R&D on components and beam dynamics, to prepare a technical design report for the year 2006,
- to start its construction as soon as the necessary resources can be made available, if possible by the end of 2006 so that Linac2 could be replaced by the end of 2010.

It is worthwhile underlining that this new linac will be an essential component of the upgraded accelerator complex for many years, whatever option is preferred for the long-term future. The precise benefits for all the other proton beams from the PS will deserve case-by-case investigations.

9.4 LONG-TERM MEASURES

The selection of the optimum accelerator to build after Linac4 depends upon decisions which are not yet taken, about the future favoured physics programmes at CERN. It is therefore impossible to specify it today. It is however possible to summarize the arguments concerning the various possible choices, as shown in Table 9.2 (details are given in Chapters 5, 6, 7 and 8).

Table 9.2: Potential of future proton accelerators.

	INTEREST FOR			
	LHC upgrade	**Neutrino physics beyond CNGS**	**Radioactive ion beams (EURISOL)**	**Others**
SPL[17] (>2 GeV – 50 Hz)	Valuable	Very interesting for super-beam + beta-beam	Ideal	Spare flux ⇒ possibility to serve more users
RCS (30 GeV – 8 Hz)	Valuable	Very interesting for neutrino factory	No	Valuable
New PS (30 GeV)	Valuable	No	No	Valuable
New LHC injector (1 TeV)	Very interesting for doubling the LHC energy	No	No	Potential interest for kaon physics

It is clear from this table that, for the time-being, the SPL has the potential to satisfy the largest number of physics communities, which justifies pursuing the on-going study.

However, if the decision is made not to support the non-LHC physics communities at CERN, the conclusion can be quite different. In such a case, a specific study will be needed to determine the most cost effective upgrades.

9.5 SUMMARY

SUMMARY OF THE RECOMMENDATIONS

1. In the short term, to define in 2004 and start in 2005 the 3 following projects:
    a. New multi-turn ejection for the PS.
    b. Increased intensity in the SPS for CNGS (implications in all machines).
    c. 0.9 s PSB repetition time.

2. In the medium term, to work on the design of Linac4, to prepare for a decision of construction at the end of 2006.

3. In the long term, to prepare for a decision concerning the optimum future accelerator by pursuing the study of a Superconducting Proton Linac and by exploring alternative scenarios for the LHC upgrade.

---

[17] Comparison should be made with an RCS of similar characteristics.

ACKNOWLEDGEMENTS

This study has been triggered by, and has extensively used, the work done previously by numerous accelerator physicists that made proposals for improving the CERN complex of accelerators. It is hoped that the list of references does justice to their respective contributions.

The sympathy and support of all the physicists contacted is worth underlining, and especially their effort to formulate their needs in understandable terms. They deserve grateful thanks, and among them especially M. Hauschild and L. Gatignon which were instrumental in helping understand the case of the COMPASS experiment.

The authors also want to formulate a special thank to the management of the Accelerators and Beams department, and especially to J.P. Delahaye, who supported the working group investigations, despite the pressure of the short-term priorities.

ANNEX 1

MANDATE OF THE HIP WORKING GROUP

JPD/lmg

PS/DR/Memo 2002-019
4.12.2002

M E M O R A N D U M

To : M. Benedikt, K. Cornelis, E. Métral, F. Ruggiero, M. Vretenar

From : J.P. Delahaye, S. Myers

Subject : Working Group of the High Intensity Proton project (HIP)

Following the recommendation of the "High Intensity Proton" (HIP) project leader and in agreement with your group leader, we invite you to be member of the corresponding working group under the leadership of R. Garoby and with the following mandate as defined in the HIP mandate:

- Define a list of specifications for beam performance based on perceived future physics needs.
- Investigate possible upgrades of the CERN complex of proton accelerators.
- Publish a summary of various alternatives and compare them in terms of performance, flexibility and approximate cost. The associated requirements in technical competence should be underlined. A preferred scheme should be indicated with the possible option of a staged realisation.
- Present the recommendations for approval by the A&B management by the end of 2003.

We hope that you will be able to accept this challenging task which is very important for the future of the CERN accelerator complex.

cc: A&B Management Board
R. Garoby
C. Wyss

ANNEX 2

PRESENTATIONS AT HIP MEETINGS

Estimation of proton beam availability from 2006 to 2010
S. Baird, 29.01.2003.

ISOLDE Upgrade and Future Plans,
T. Nilsson, 12.02.2003.

Cycling of the PS Complex and the SPS: Analysis and Possibilities for Optimisation,
M. Benedikt, G. Métral, 12.02.2003.

CNGS - Status and Proton Beam Performance,
K. Elsener, 26.02.2003.

PS Multi-Turn Extraction,
M. Giovannozzi, 26.02.2003.

SPS “ppm” and fast supercycle changes,
M. Lamont, 12.03.2003.

Upgrade of the CERN Linacs,
M. Vretenar, 12.03.2003.

Some EURISOL Issues,
A. Mueller, 26.03.2003.

Future Neutrino Beams,
A. Blondel, 09.04.2003.

The RCS Driver Option,
H. Schönauer, 09.04.2003.

LHC and beyond,
F. Ruggiero, 23.04.2003.

Various aspects of Continuous Transfer PS - SPS,
D. Manglunki, 07.05.2003.

SPS high intensity operation - longitudinal aspects,
E. Chapochnikova, 21.05.2003.

SPS high intensity operation - transverse aspects,
K. Cornelis, 21.05.2003.

Physics potential of LHC luminosity upgrade,
T. Virdee, 27.08.2003.

Proton availability and supercycles 2006 to 2010 "all flavours",
M. Benedikt, 08.10.2003.

PS machine improvements for high intensity beams,
E. Métral, 08.10.2003.

Beam losses during nominal CNGS operation,
M. Benedikt, 20.10.2003.

Generation of high brightness beams for LHC,
R. Garoby, 05.11.2003.

Recent results on 160 MeV H- injection into the PSB,
M. Martini, 10.12.2003.

SPS limitations for high density beams,
K. Cornelis, 10.12.2003.

Analysis of Batch Compression in the PS for highest brightness,
R. Garoby, 10.12.2003

REFERENCES

[1] P. Lefèvre, T. Petterson (editors), *The Large Hadron Collider, Conceptual Design*, CERN/AC/95-05 (LHC), Geneva, 1995.

[2] *LHC Design report*, to be published, CERN, Geneva, 2004.

[3] F. Gianotti, M.L. Mangano, T.S. Virdee, *Physics Potential and Experimental Challenges of the LHC Luminosity Upgrade*, CERN-TH-202-078 (2002), Geneva, 2002.

[4] F. Ruggiero (editor), *LHC Luminosity and Energy Upgrade*, CERN LHC Project Report 626, Geneva, 2002.

[5] K. Elsener (editor), *The CERN Neutrino Beam to Gran Sasso (NGS)*, CERN 98-02 and CERN-SL/99-034(DI), Geneva, 1998 and 1999.

[6] R. Cappi (editor), K. Cornelis, J.-P. Delahaye, R. Garoby, H. Haseroth, K. Hübner, T. Linnecar, S. Myers, K. Schindl, C. Wyss, *Increasing Proton Intensity of PS and SPS*, CERN-PS (AE) 2001-041, Geneva, 2001.

[7] A. Blondel, *Future Neutrino Beams*, HIP meeting,
http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-09Apr03-ABlondel.ppt

[8] P. Zucchelli, *A novel concept for a* $\bar{\nu}_e/\nu_e$ *neutrino factory: the beta-beam*, Phys. Lett., B532, 2002.

[9] G. Baum et al., *The COMPASS proposal*, 1996,
http://wwwcompass.cern.ch/compass/proposal/welcome.html

[10] http://committees.web.cern.ch/Committees/SPSC/Villars-Aim.html

[11] T. Nilsson, *ISOLDE Upgrade and Future Plans*, HIP meeting,
http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-12Feb03-TNilsson.ppt

[12] A. Mueller, *Some EURISOL Issues*, HIP meeting,
http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-26Mar03-AMueller.ppt

[13] S. Baird, *Estimation of Proton Beam Availability from 2006 to 2010*, HIP meeting,
http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-29Jan03-SBaird.doc

[14] R. Bailey, *What LHC Operation will look like*, Proc. of the LHC Project Workshop, Chamonix XIII, CERN-AB-2004-014 ADM, 2004.

[15] K. Schindl, *Conversion of the PS complex as LHC proton pre-injector: Project proposal*, PS/DI/Note 94-17, Geneva, 1994.

[16] R. Garoby, *Status of the nominal proton beam for LHC in the PS*, Proc. of the Chamonix Workshop on LEP-SPS Performance, Chamonix, 1999.

[17] J. Uythoven, *MKE Beam induced Heating – Follow-up*, APC meeting,
http://ab-div.web.cern.ch/ab-div/Meetings/APC/2003/apc031003/uythoven.pdf

[18] F. Caspers, *MKE Kicker Impedance Reduction Aspects*, APC meeting,
http://ab-div.web.cern.ch/ab-div/Meetings/APC/2004/apc040109/caspers.pdf

[19] M. Benedikt, *Estimation of Beam Loss for Nominal CNGS Operation*, HIP meeting,
http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-20Oct03-MBenedikt.pdf

[20] M. Benedikt, G. Métral, *Cycling of the PS Complex and the SPS: Analysis and Possibilities for Optimisation*, HIP meeting,
http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-12Feb03-MB.doc

[21] M. Benedikt, *Results of Tests for Linac2 and PSB at 600 ms*, PPC meeting,
http://psdoc.web.cern.ch/PSdoc/ppc/ppc021122/ppc021122.html

[22] R. Cappi and M. Giovannozzi, *Novel Method for Multi-Turn Extraction: Trapping Charged Particles in Islands of Phase Space*, Phys. Rev. Lett. 88, 2002.

[23] M. Giovannozzi (editor), *Report of the Study Group on the New Multi-Turn Extraction in the PS Machine*, CERN-AB-2004-003 (ABP), Geneva, 2004.

[24] E. Chapochnikova, *SPS high Intensity Operation – Longitudinal Aspects*, HIP meeting, http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-21May03-EChapochnikova.pdf

[25] K. Cornelis, *SPS high Intensity Operation – Transverse Aspects*, HIP meeting, http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-21May03-KCornelis.ppt

[26] E. Métral, *High Intensity Studies at PS*, PPC meeting, http://psdoc.web.cern.ch/PSdoc/ppc/ppc021213/ppc021213.html

[27] R. Garoby, *Analysis of Batch Compression in the PS for highest brightness*, HIP meeting, http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-10Dec03-RGaroby.ppt

[28] M. Vretenar, *Upgrade of the CERN Linacs*, HIP meeting, http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-12Mar03-MVretenar.ppt

[29] F. Gerigk, M. Vretenar, *Design of a 120 MeV H- Linac for CERN High-Intensity Applications*, Linac2002 Conference, Gwangju and CERN/PS 2002-056(RF), 2002.

[30] R. Garoby, K. Hanke, A. Lombardi, C. Rossi, M. Vretenar, F. Gerigk, *Design of the Linac4, a new Injector for the CERN Booster*, to be published at Linac2004, Lubeck (Germany), 2004.

[31] M. Martini, C. Prior, *High-intensity and High-density Charge-exchange Injection Studies into the CERN PS Booster at Intermediate Energies*, to be published at EPAC 2004, Lucerne, 2004.

[32] The SPL Study Group, *Conceptual Design of the SPL*, CERN 2000-012, Geneva, 2000.

[33] B. Autin et al., *A Slow-Cycling Proton Driver for a Neutrino Factory*, Proc. of EPAC 2000, Vienna, 2000.

[34] B. Autin R. Cappi, R. Garoby, J. Gruber, J.P. Riunaud, K. Schindl, *PS-XXI, a new synchrotron for the LHC injector*, CERN-PS-97-012-DI, Geneva, 1997.

[35] J. Strait, private communication, 2003.

[36] F. Ruggiero, *LHC Accelerator R&D and Upgrade Scenarios,* CERN LHC Project Report 666, Geneva, 2003.

[37] F. Gianotti, L. Rossi, F. Ruggiero, and T. Virdee (editors), Appendix B, *LHC Upgrade*, in *Future Projects and associated R&D*, CERN/SPC/834 and CERN/CC/2531, Geneva, 2003.

[38] T. Virdee, private communication, 2003.

[39] J. Strait et al., *Towards a new LHC Interaction Region design for a luminosity upgrade,* CERN LHC Project Report 643, Geneva, 2003.

[40] F. Ruggiero et al., *Performance limits and IR design challenges of a possible LHC luminosity upgrade based on Nb-Ti SC magnet technology*, to be presented at EPAC 2004, Lucerne, 2004.

[41] R. Garoby, *Generation of high brightness beams for LHC*, HIP meeting, 2003, http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-05Nov03-RGaroby.ppt

[42] See web page on GSI Rapid Cycling Magnets, 2004.

[43] C. Bovet, D. Fiander, L. Henny, A. Krusche, G. Plass, *The Fast Shaving Ejection for Beam Transfer from the CPS to the CERN 300 GeV Machine*, Proc. of PAC 1973, New York, 1973.

[44] L.R. Evans, *A Phase Plane Exchange Section for the SPS Antiproton Injection Beam Line*, CERN SPS (DI) 80-2 (1980).

[45] D. Manglunki, *Various aspects of Continuous Transfer PS-SPS*, HIP meeting, http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-07May03-DManglunki.ppt,

[46] R. Cappi and M. Giovannozzi, *Adiabatic Capture of Charged Particles in Islands of Phase Space: a new Method for Multi-Turn Extraction*, EPAC 2002, London, 2002.

[47] R. Cappi, M. Giovannozzi, *Adiabatic Capture of Charged Particles in Stable Islands: a Novel Approach to Multi-Turn Extraction*, PAC 2003, Portland, 2003.

[48] R. Cappi and M. Giovannozzi, *Computation of Betatron Mismatch and Emittance Blow-up for Multi-turn Extraction*, CERN-PS (AE) 2002-083, 2002.

[49] http://ab-div.web.cern.ch/ab-div/Meetings/ABMB/2003/20030630.html

[50] M. Giovannozzi, private communication, 2004.

[51] E. Métral, *High Intensity and High Density Beams in the PS*, PPC meeting, http://psdoc.web.cern.ch/PSdoc/ppc/ppc011207/ppc011207.html.

[52] M. Martini, *Latest Results on 160 MeV H- Injection in the PSB*, HIP meeting, http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-10Dec03-MMartini.pdf

[53] K. Elsener, *CNGS Status and Proton Beam Performance*, HIP meeting, http://ab-div.web.cern.ch/ab-div/Projects/hip/Presentations/HIP-26Feb03-KElsener.ppt

[54] J. Gareyte, private communication.

[55] E. Chapochnikova, *Impedance Effects in the SPS*, Proc. of Chamonix XIII, CERN-AB-2004-014 ADM, Geneva, 2004.

[56] R. Garoby, *A New Proton Injector at CERN*, AB-Note-2003-048 (SPL), Geneva, 2003.

[57] H. Schönauer et al., *Proton Drivers for Neutrino Factories: The CERN Approach*, Proc. NUFACT'00, Monterey, 2000.

[58] B. Autin et al., *Design of a 2.2 GeV Accumulator and Compressor for a Neutrino Factory*, Proc. of EPAC 2000, Vienna, 2000.

[59] R. Cappi, J. Gareyte, E. Métral, D. Möhl, *Collective Effects and Final Bunch Rotation in a 2.2 GeV - 44 MHz Proton Accumulator - Compressor for a Neutrino Factory*, Proc. of NUFACT'00, Monterey, 2000.

[60] E. Radicioni, *HARP: a hadron production experiment*, hep-ex/0206028, CERN, Geneva, 2002.

[61] D. Forkel-Wirth et al., *Reflections on Super-ISOLDE*, CERN/TIS-RP/TM/2000-18, Geneva, 2000.

[62] Addendum to the Memorandum of Understanding for the Execution of the ISOLDE Experiments at the PS-Booster, CERN, Geneva, 2004.

[63] E. Prebys, FNAL, private communication and M. Popovic, L. Allen, A. Moretti, E. McCrory, C.W. Schmidt, T. Sullivan, *High Current Proton Tests of the Fermilab Linac*, Linac2000 Conference, Monterey, 2000.

[64] http://www.ganil.fr/eurisol/

[65] http://www.nupecc.org