THE LOW-POWER SPL

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Abstract

This paper describes the basic parameters and the machine layout of the Low-Power SPL (LP-SPL), a 4 GeV superconducting H^- linac. In the first stage this machine is only designed to replace the PS booster (PSB) and to inject into a new proton synchrotron (PS2) at CERN. At the same time the components are designed such that the machine can be upgraded to become a high-power proton driver (5 GeV, $>$ 4 MW) for future radioactive ion beam (RIB) facilities or for various neutrino production schemes at CERN. The consequences for the low-power design are explained together with the possible upgrade paths.

INTRODUCTION

The aim of the LP-SPL [1] (together with PS2) is i) to remove any reliability concerns of the ageing LHC injector chain, specifically to replace Linac2, PSB, PS and ii) to provide a proton beam that is suitable for all foreseen LHC upgrade scenarios (compare [2]). After a recent cost and performance comparison [3] between an RCS (Rapid Cycling Synchrotron) based PS2 injector and the LP-SPL, the CERN management endorsed the SPL despite the 30% higher cost of the installation. Since then the LP-SPL together with the PS2 are considered as the baseline scenario for an upgrade of the CERN proton injector chain.

PS2 requires the injection of 1.5×10^{14} particles per pulse with a 1 Hz repetition rate at an energy of 4 GeV. This beam will be provided by the LP-SPL as a 1.2 ms long pulse with an average pulse current of 20 mA. In case of the High-Power SPL (HP-SPL) the average pulse current in the linac will be doubled to 40 mA, reducing the PS2 injection period to 0.6 ms. At the same time the repetition rate will be increased to 50 Hz.

THE SPL PROJECT AT CERN

The HP-SPL has to deliver beams with different time structures to a variety of users. This necessary flexibility is achieved by augmenting the linac with a combination of an accumulator and compressor ring. These first compress the pulse length of the linac pulse from the ms to the μs range and then rotate the bunches to lengths in the ns range. Since the requirements for the time structure of a future neutrino driver are still evolving, we foresee the following construction stages (taken from [5]), which can be matched to a growing number of applications and to evolving time structure requirements for future users:

1. **Construction of Linac4** [6]: the 160 MeV normal conducting front-end of the SPL. This machine is approved and is expected to be operational in 2013. It will replace the present Linac2 (50 MeV) and will inject at 160 MeV into the PSB. It is also the first step towards reaching the full luminosity potential of the LHC. The location of Linac4 on the CERN site is such that a straight prolongation of Linac4 is tangential to the SPS, with enough space between the two machines to construct the SPL and a new proton synchrotron (PS2), which will replace the aging PS machine. This layout allows to use the Linac4 beam for the commissioning of SPL and PS2, while maintaining the operation of the present LHC proton injector chain (PSB - PS - SPS). This approach minimises any interruption to LHC operation until the new injector chain is fully operational. Figure 1 shows a block diagram of Linac4/SPL and Fig. 2 shows the layout of the new injector chain on the CERN site.

2. **Low-power SPL (LP-SPL)**: installation of a 4 GeV superconducting linac, producing 200 kW of beam power with a repetition rate of 2 Hz. Two families of superconducting cavities ($\beta = 0.65$ and $\beta = 1.0$) are used to accelerate the beam to its top energy. This machine will replace the PSB and will inject directly into PS2. The R&D for this machine is partly covered by the recently approved "white paper", an initiative by CERN director general, which also provides the funding for Linac4.

3. **High-power SPL (HP-SPL)**: extension of the LP-SPL to 5 GeV and increase of the repetition rate to 50 Hz, producing 4 MW (or more) of proton beam power. At this stage the beam can be used for the production of neutrinos via beta-beams [7] and to drive a pulsed RIB facility [8].

4. **Accumulator ring**: in this configuration the SPL can drive a beta-beam facility and produce a so-called Superbeam at the same time, which is considered to be a promising combination for neutrino physics [9]. The capability to drive a RIB facility and the LHC injector chain remains unchanged.

5. **Compressor ring**: this enables the SPL to produce bunches in the nanosecond range, which are nowadays recommended for a neutrino factory target. In case further target studies prove the need for higher proton energies it seems realistic to extend the SPL to

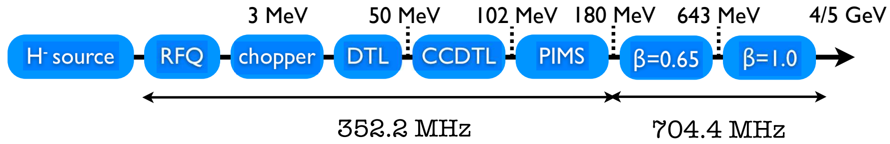

Figure 1: Block diagram of Linac4 and SPL.

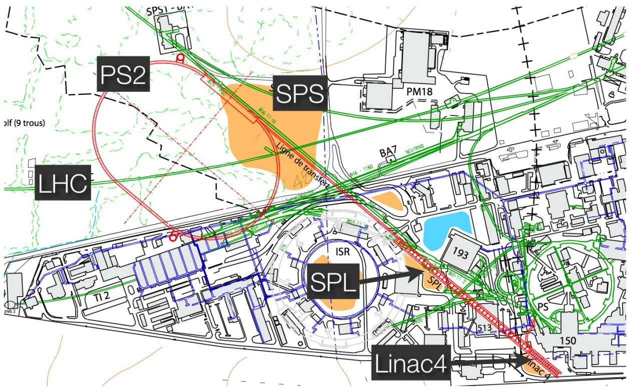

Figure 2: Layout of the SPL on the CERN site.

the 10 GeV range. A similar approach is proposed at FNAL in the 8 GeV proton driver project [10]. Energies beyond 10 GeV do not seem practical, since H$^-$ stripping due to magnetic fields and black-body radiation becomes a serious problem [11, 12, 13].

It should be noted that the optimum energy and time structure for neutrino factory targets has not yet been experimentally determined. In this context the flexibility of the linac-based solution may ease the task of adapting the proton driver time structure to an evolving set of input parameters for a neutrino factory. The main parameters of Linac4, LP-SPL, and HP-SPL are summarised in Table 1.

Table 1: Parameter list for the machine evolution from LP-SPL to HP-SPL.

	LP-SPL	*HP-SPL*
Energy [GeV]	4	5
Beam power [MW]	0.192	> 4
Repetition rate [Hz]	2	50
Av. pulse current [mA]	20	40
Chopping ratio [%]	62	62
Beam pulse [ms]	1.2	0.4 - 0.6
Protons p. pulse [10^{14}]	1.5	1.0-1.5
Filling time PS2 [ms]	1.2	0.6
Beam duty cycle [%]	0.24	2.0
No. SC cavities	194	234
No. klystrons (352 + 704 MHz)	19+28†	19+57
RF peak power [MW]	100	219
Av. power consumption [MW]	4.5	38.5
Length [m]	459	534

SUPERCONDUCTING LINAC DESIGN

The superconducting section of the SPL is based on only two families of cavities with a geometrical beta of 0.65 and 1.0, respectively (see Table 2). The accelerating gradients of 19 and 25 MV/m have been chosen after considering the peak surface fields already achieved in tests with various cavities, which are summarised in Fig. 3. The chosen gradients correspond to a peak surface field of 50 MV/m, which is challenging but which seems realistic assuming that one can invest several years of R&D in the engineering of cavities and cryo-modules. Another conclusion to be drawn from Fig. 3 is that the maximum gradient does not seem to have a strong frequency dependance. Figure 4 shows a similar graph for the maximum surface magnetic field, which was limited to 100 mT in the case of the SPL.

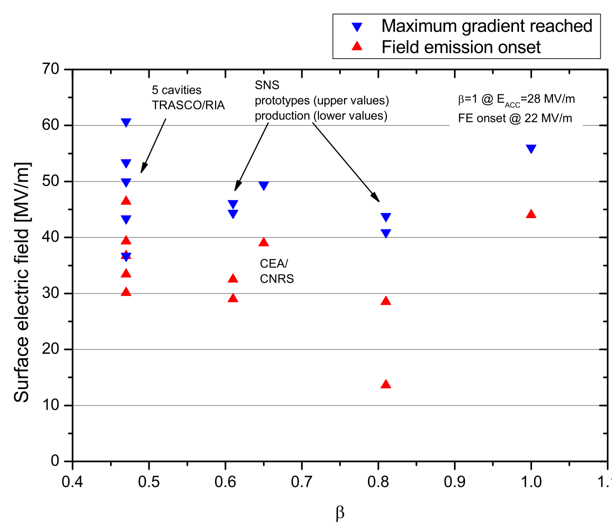

Figure 3: Peak surface electric fields corresponding to the maximum gradients reached in cavity tests (down triangle) and to the onset field emission (up triangle). From left to right: TRASCO/RIA (704/805 MHz), SNS (805 MHz), CEA/CNRS (704 MHz), SNS, TTF (1.3 GHz).

The cryo-module design will be based on the ILC/XFEL approach, using long interconnected cryo-modules with superconducting quadrupoles to minimise the number of cold-warm transitions. An appropriate R&D effort to redesign the ILC/XFEL cryo-modules for the SPL is planned until 2012, when a decision regarding the construction of the LP-SPL is expected. Until this date the SPL study group is preparing a technical design report, which will be the basis for a decision of the CERN management on construction.

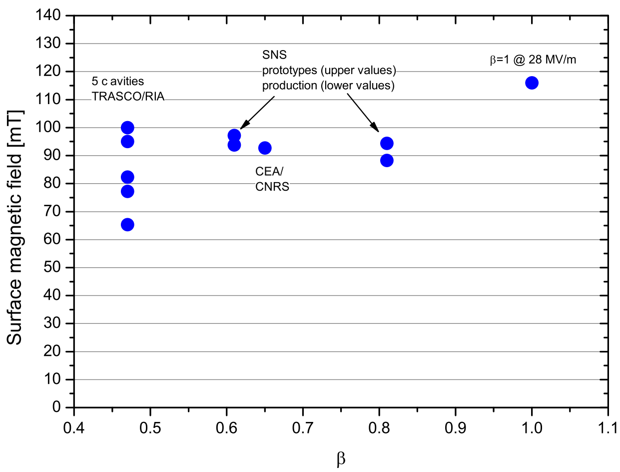

Figure 4: Peak surface magnetic fields corresponding to the maximum gradients reached in cavity tests. From left to right: TRASCO/RIA (704/805 MHz), SNS (805 MHz), CEA/CNRS (704 MHz), SNS, TTF (1.3 GHz).

Table 2: Characteristics of the two families of superconducting cavities.

section	$\beta = 0.65$	$\beta = 1.0$
accelerating gradient [MV/m]	19	25
el. peak surface field [MV/m]	50	
mag. peak surface field [mT]	100	
R/Q [Ω]	290	570
quality factor at 2 K	$\geq 10^{10}$	
cells per cavity	5	
cavities per module	6	8
focusing periods per module	2	1
module length [m]	11.45	14.26
focusing period length [m]	6.13	15.06
aperture radius [mm]	42.5	45

CIVIL ENGINEERING

While Linac4 is installed horizontally, the SPL tunnels will have a slope of $\approx 1.6\%$, to avoid crossings with existing tunnels and to ensure sufficient distance to tunnel areas which need to be accessed during operation. Furthermore the slope is necessary to reach the depth for the injection into the PS2, which is approximately 50 m under ground. The civil engineering effort for the LP-SPL is made in view of the full power operation of the machine. In particular this means:

i) keeping a distance of $\geq$ 8 m of earth between the SPL accelerating tunnel and areas that must be accessible during the operation of the machine. This distance ensures a radiation dose suitable for public access for instance for overground parking areas or basements of buildings.

ii) providing enough tunnel space for the HP-SPL infrastructure, comprising klystron, klystron modulators, cooling water pipes, air conditioning, etc.

Based on the above points a first layout of the tunnel cross sections is shown in Fig. 5. The klystron gallery and the accelerating tunnel have diameters of 6 m and 4.5 m, respectively. The distance between the tunnels is 9 m to ensure safe access to the klystron gallery during the SPL operation. The size of the klystrons is based on estimates using existing devices with similar specifications. The dimensions of klystron modulators was estimated by the CERN Power Group, which is now developing the modulators for Linac4, and the requirements of the services have been taken from [1].

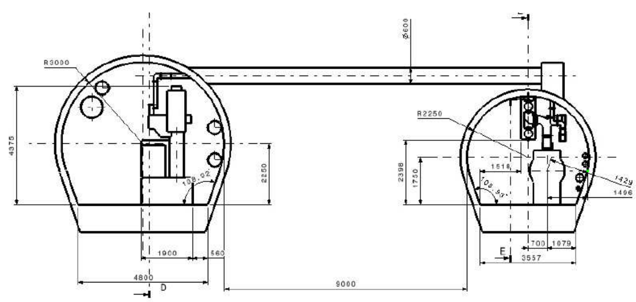

Figure 5: Cross-section of the accelerator tunnel (right) and klystron gallery (left).

As one can see from Fig. 6 most of the klystron tunnel volume is taken by the klystron modulators, despite the fact that approximately half of the modulator equipment is already housed on the surface. In the accelerating tunnel considerable space is taken by the RF distribution network, which splits the power from the klystrons to the single cavities.

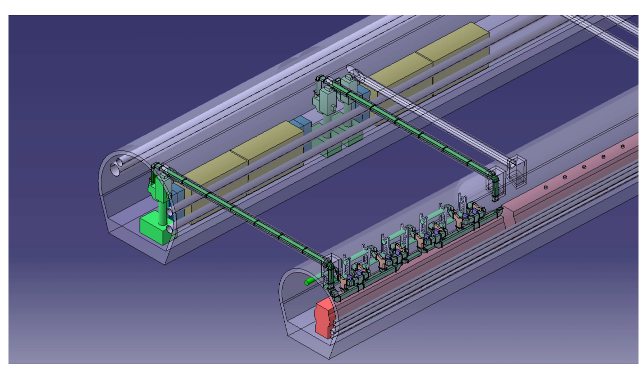

Figure 6: 3D layout of accelerator tunnel (right) and klystron gallery (left).

RCS VERSUS LINAC

Following a request of the CERN Scientific Program Committee (SPC) a comparison was made between a synchrotron-based and linac-based proton driver for PS2 (see also [5]). The goal was to outline the pros and cons of each solution and to compare with the findings of the FNAL proton driver study II [10] which compared a 8 GeV full-energy superconducting linac with a 600 MeV linac plus an 8 GeV synchrotron. The FNAL aim was to achieve initially 0.5 MW beam power and to have the possibility to upgrade the power to 2 MW. It was found that the linac-based solution is approximately 30% more expensive than the synchrotron-based solution. Nevertheless the linac solution was preferred due to: i) its upgrade potential and its adaptability to future proton needs at FNAL, and ii) the possibility to construct a test bench for the International Linear Collider (ILC), making use of TESLA-style SC cavities and cryo-modules.

The CERN study compared the low-power SPL (4 GeV, 0.2 MW) with a rapid cycling synchrotron [3]. Both machines have to provide $1.5 \cdot 10^{14}$ particles per pulse with a 1 Hz repetition rate for injection into PS2 with 4 GeV injection energy. In accordance with the FNAL study it was found that the linac solution demands a 28% higher initial investment. However, due to its upgrade potential and its expected performance advantages, the linac solution was endorsed by the management and represents now the base line for the planned upgrade of the CERN proton injector chain. The relative merits of each solution are summarised in Table 3.

Table 3: Relative merits of RCS and SPL options for the injection into the proposed CERN PS2, see [3].

	SPL	*RCS*	*Advantage*
Filling time PS2	0.6 ms	1.3 s	SPL
Time struct. LHC	inherent	different	SPL
Rel. proton rate	2.5	1	SPL
Fixed target phys.	ideal	acceptable	SPL
Ions	acceptable	ideal	RCS
Upgrade potential	high	low	SPL
Relative cost†	1.28	1	RCS

† the relative cost considers only the items that differ between both solutions

SUMMARY

The normal conducting part of the SPL (Linac4) is approved and is planned to deliver protons in 2013. The LP-SPL together with PS2 is now the baseline scenario for upgrading the LHC proton injector chain. A new layout for whole proton injector complex has been found which allows the staged construction of Linac4 and SPL with minimum interruption of LHC operation. The first stage of the SPL, the LP-SPL is designed such that it can be upgraded to a multi MW proton linac for a reasonable cost. A civil engineering feasibility study including a cost estimate for the construction of the SPL is in preparation.

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