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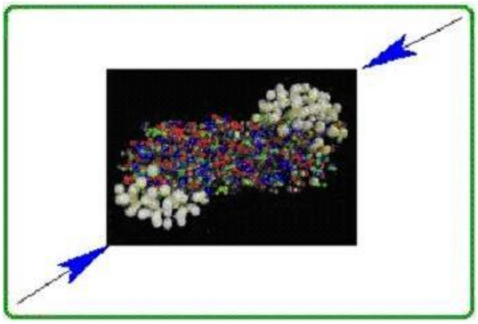

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R. Garoby, M. Benedikt, A. Fabich, F. Gerigk.

CERN – Geneva - Switzerland

Abstract

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Abstract

In its report, the SPC Review Panel has highlighted that the construction of a 4 MW SPL has to be motivated by the needs of a well-defined and approved physics programme, and that it should be compared with a Rapid Cycling Synchrotron (RCS) when considering only the needs of LHC. This report is meant to answer these remarks by describing the version of the SPL that would be built for the needs of LHC alone (the "Low Power" SPL or LP-SPL) and by making a preliminary comparison with an RCS.

Geneva, Switzerland
May, 2007

INTRODUCTION

In its report [1], the SPC Review Panel has highlighted that the construction of a 4 MW SPL has to be motivated by the needs of a well-defined and approved physics programme, and that it should be compared with a Rapid Cycling Synchrotron (RCS) when considering only the needs of LHC. This report is meant to answer these remarks by describing the version of the SPL that would be built for the needs of LHC alone (the “Low Power” SPL or LP-SPL) and by making a preliminary comparison with an RCS.

The technical part of this report is based on on-going work:

- the LP-SPL was already under study since the publication of the Conceptual Design Report of the SPL II in July 2006 [2].
- an RCS for ion operation is being studied in the frame of the beta-beam work package of the EURISOL Design Study [3] (6th European framework programme). The parameters of that machine were scaled to match the most recent requirements of PS2.

The proposed accelerator scenarios should be considered as a basis for comparison but should not be taken as definitive because their specifications could still evolve, especially because of PS2 whose study is only beginning.

The cost comparison has been started only very recently but it has benefited from the detailed analysis made at FNAL in 2005 between an RCS and a superconducting Linac as 8 GeV injector for the Main Ring [4]. Its validity is in the relative terms of comparison and not in the absolute ones.

EXECUTIVE SUMMARY

This report is addressing the remarks of the SPC Review Panel concerning the Superconducting Proton Linac (SPL) which is proposed as the future injector of the successor of the PS (PS2).

In case this new injector is only meant to supply beam to PS2, SPS and LHC, the proposal is to build a low power version of the SPL (LP-SPL), cycling at 2 Hz with half the instantaneous current of the full power version (20 mA instead of 40 mA) and with an energy of 4 GeV. These choices reduce the initial investment in infrastructure (electrical distribution, water cooling plant, cryoplant) and in the accelerator itself (almost 30 fewer klystrons and 1 GeV less of accelerating structures), but they preserve the possibility of upgrade whenever necessary.

In case this new injector is a Rapid Cycling Synchrotron (RCS), the only economically competitive solution is to make it fill PS2 with more pulses than the ratio of sizes PS2/RCS. This is only possible if the RCS deliver one bunch per pulse, which results in the needs for multiple bunch splittings in PS2, like in the PS today.

Therefore, even though both injectors should make PS2 able to deliver beam with the same characteristics for LHC, their complexity and operational margin are very different. With the SPL (or LP-SPL), PS2 is filled in 0.6 ms, while it takes 1.3 s with the RCS. Therefore the beam from the SPL can be quickly accelerated and suffers from high space charge only for a very limited amount of time. Moreover, the SPL can directly deliver beam with the time structure required by LHC, which avoids using beam gymnastics in PS2. This is not the case with the RCS beam which has to be submitted to three successive splittings to obtain the adequate time structure.

There is also a significant difference between the proton flux that can be delivered by the low energy accelerators (up to 50 GeV) to the other users, once the needs of the high energy machine are satisfied. In most cases, there are approximately 2.5 times more protons available at 50 and 4 GeV when using the SPL. In the extreme case where the SPS is operating at maximum rate for fixed target (CNGS-like operation), the RCS injector will not allow PS2 to cycle for any other user, while the SPL (or LP-SPL) will still make it possible.

For heavy ions, the RCS based option is a satisfactory solution that eases operation in PS2 and could re-use all the sophisticated beam gymnastics foreseen today in the PS. In the case of the SPL option, the heavy ion beam from LEIR would have to be injected directly in PS2 at a lower field (magnetic rigidity of 0.4 times the value at proton injection) and additional/different RF equipment will be needed. It is clear that solutions exist (e.g. by implementing the same RF system than when injecting from the RCS and renouncing to the advantage of no gymnastics for proton beams, although this is probably excessive), but no effort has been invested yet for an optimum scheme in that case.

The preliminary cost comparison presented in this report only considers the items that differ between both options. For these items, the 28 % difference in favor of the RCS solution is remarkably similar to the outcome of the analysis at FNAL in 2005.

The decision between the options has therefore to begin with the selection of the most important criteria. An RCS-based injector is the logical choice if cost is the only concern. However, if the ease of operation for LHC and the potential for other users (including future ones which could be served by an upgrade) are of more importance, then an SPL-based injector makes full sense.

In all cases, significant efforts must be invested in refining the design of the future PS2 and its injectors, and in building/testing prototypes of crucial components. This is especially true of the LP-SPL which involves more recent technological developments deserving demonstration of their performance in full scale prototypes. An early decision on the preferred option is necessary to efficiently use resources and to achieve the ambitious goals of the White Paper in 2011.

The relative merits of RCS and SPL options are summarized in the table below.

	Filling time PS2	**Time structure for LHC**	**Relative proton rate**	**Fixed target physics**	**Ions**	**Upgrade potential**	**Relative Cost[1]**
SPL	0.6ms	inherent	2.5	Ideal	acceptable	high	1.28
RCS	1.3s	different	1	acceptable	Ideal	low	1
Advantage	**SPL**	**SPL**	**SPL**	**SPL**	**RCS**	**SPL**	**RCS**

[1] The relative cost considers only the items that differ between both options.

REQUIREMENT OF PS2 ON ITS INJECTOR

The PS2 synchrotron is proposed to replace the PS in the CERN complex of accelerators [5, 6]. In its present version, the size of PS2 is 15/7 the size of the PS and it accelerates protons to twice the energy of the PS. Its main characteristics are summarized in Table 1 below.

Table 1: PS2 parameters.

Reason	Physical parameter	Value
Space charge PS2	Injection energy (kinetic)	4 GeV
SPS improvement	Ejection energy (kinetic)	50 GeV
LHC	Transverse normalized 1 sigma emittances at ejection for LHC	3 mm.mrad
LHC	Longitudinal emittance/bunch with 25 ns bunch spacing at ejection	0.35 eVs
Twice the ultimate brightness + 10 % margin for beam loss	Nb of protons / bunch with 25 ns bunch spacing at ejection for LHC (total 168 bunches)	3.6×10^{11} (6.05×10^{13})
SPS / PS2 fixed target physics	Nb of protons / bunch with 25 ns bunch spacing (total)	7.5×10^{11} (1.25×10^{14})
Possible bunch spacings in LHC (25, 50 & 75 ns)	Size (ratio PS2/SPS)	15/77
	Circumference	1346.4 m
	h_{RF} for 25 ns (resp. 50 or 75 ns) bunch spacing	180 (resp. 90 or 60)
	Cycling period to 50 GeV without flat porch	2.4 s

The PS2 should be capable of providing (at ejection) twice the brightness of the so-called "ultimate" LHC beam with 10% intensity reserve for beam losses in the downstream accelerator chain. This translates into an intensity requirement of 4.0×10^{11} protons per LHC bunch at PS2 injection (assuming 25 ns bunch spacing and 10% loss in the PS2 itself) instead of presently 1.7×10^{11}. 25 ns bunch spacing corresponds to a harmonic number h_{RF}=180 in the PS2 and 168 buckets will be filled leaving a kicker gap of ~300 ns. Therefore a total intensity for LHC of 6.7×10^{13} protons per PS2 cycle must be provided by the injector.

The required normalized 1-sigma emittances in the PS2 are 3.0 μm as currently for the PS. Fixing the beam brightness determines the average line density in the machine and therefore the injection energy via incoherent space charge tune spread. To limit the tune shift at PS2 injection to $\Delta Q = -0.2$ an injection energy of 4 GeV is required.

For Fixed Target (FT) physics applications at SPS or PS2 the emittances can be increased and a total intensity 1.4×10^{14} protons per PS2 cycle should be provided by the injector. The main requirements on the injector of PS2 are summarized in Table 2.

Table 2: Requirements on the injector of PS2

Reason	Physical parameter	Value
Space charge	Injection energy to PS2 (kinetic)	4 GeV
Twice the ultimate brightness + 20 % margin for beam loss	Nb of protons per PS2 cycle for LHC	6.7×10^{13}
SPS / PS2 fixed target physics	Nb of protons per PS2 cycle for PS2 / SPS fixed target physics	1.4×10^{14}

1. OPTIONS FOR THE INJECTOR OF PS2

In the following Section 2.1 two options of an RCS-based injector chain are discussed. Section 2.2 describes the SPL option.

1.1. Rapid Cycling Synchrotron

The option of using an RCS as injector for the PS2 has not been studied at CERN so far and there is therefore also no conceptual or technical design study of an RCS available for the present comparison.

However an RCS for ion operation is presently being studied within the EURISOL Design Study in the 6th European framework programme [3]. This machine is designed to accelerate ions to a kinetic energy corresponding to 3.5 GeV protons. For the purpose of the present comparison, the EURISOL RCS design served as reference and was adapted to the PS2 requirements by simple scaling.

It should be noted that the present short-term investigations [7] can only give first indications on technical, operational and costs aspects.

The proposed RCS is a 10 Hz machine and its main parameters, scaled to fit the PS2 requirements, are quoted in Table 3. The RCS injection energy depends on the operation mode and is discussed below.

Table 3: Main RCS parameters

Reason	Physical parameter	Value
Space charge PS2	Ejection energy (kinetic)	4 GeV
LHC	Transverse normalized 1 sigma emittances at ejection for LHC	2.5 mm.mrad
	Size (wrt PS2)	1/5
	Circumference	269.279 m
	Cycling period	0.1 s

There are two fundamentally different operation modes for filling the PS2 with an RCS:

- Single bunch filling (h_{RF}=1 RCS operation), named RCS1
- Geometric filling (quasi free choice of harmonic in RCS), named RCS2

1.1.1. Option “Single bunch filling” (RCS1)

In the case of single bunch filling, the RCS is operated on harmonics 1 and sends a single bunch towards the PS2 on each cycle. A certain number of consecutive RCS pulses is accumulated at flat bottom in the PS2 and then accelerated. This scenario implies relatively long bunches at injection in the PS2 and longitudinal splitting will be needed to fabricate LHC type beams. To derive the relevant parameters a scenario similar to the present PS is assumed, where each bunch from the Booster is split in twelve to give the final LHC bunch spacing.

The PS2 harmonic number at ejection with a 40 MHz system is h=180. When assuming splitting by twelve, the corresponding harmonic number at injection is 180/12=15. Copying in more detail the PS scenario one would fill the PS2 (harmonics 15) with 14 consecutive shots from the RCS and leave one bucket empty as kicker gap. The bunches would then be triple-split and twice double split to give the final 25 ns spacing bunch train with 168 consecutive 40 MHz buckets filled. This could be realized in the PS2 with a tunable 10 MHz RF as main accelerating system and additional 20 MHz and 40 MHz fixed frequency systems.

In this scenario the RCS will have to produce one bunch with an intensity corresponding to 12 LHC bunches per cycle i.e. 4.8×10^{12} protons per RCS cycle. To limit the incoherent tune spread ΔQ at injection to around -0.3, an injection energy of at least 400 MeV is required. For fixed target physics beams, the emittances can be increased and a total intensity of 1.0×10^{13} protons per RCS cycle should be provided. The main parameters for the RCS1 option “single bunch filling” are summarized in Table 4.

Table 4: RCS1 parameters for option “single bunch filling”

Reason	RCS parameter	Value
Space charge RCS	Injection energy (kinetic)	400 MeV
PS2 filling scheme	h_{RF}	1
PS2 filling scheme	Nb of pulses to fill PS2	14
LHC	Nb of protons per pulse for LHC	4.8×10^{12}
	Nb of protons per pulse for FT	1.0×10^{13}
	Filling time of PS2 (LHC and FT)	1.3 s
PS2	Longitudinal emittance for LHC	2.8 eVs
	RF Gymnastics in PS2 (LHC)	Splitting in12
	Cycling period of PS2 (LHC)	4 s
PS2/SPS kicker gap	Nb. of buckets filled in PS2 (h_{RF} in PS2)	168 (180)

It should be noted that the above described configuration, RCS1 “single bunch filling” and PS2 RF system configuration (10/20/40 MHz systems), is fully compatible with ion operation for LHC and ion fixed target physics.

1.1.2. RCS injector linac for option “single bunch filling”

The design of the 160 to 400 MeV injector linac which complements Linac4 is based on klystrons and accelerating structures that have already been studied and described in the Linac4 Technical Design Report [8]. While in principle it is possible to use both normal- or super-conducting cavities for this energy range, we have chosen the "traditional" normal conducting technology, since it is readily available and does not require a substantial R&D effort. The accelerating structure of choice is a Side Coupled Linac (SCL, often referred to as Coupled Cavity Linac, CCL) at 704 MHz. The structure is identical with the high-energy section of Linac4 (90 – 160 MeV, see Figure 1) and was recently constructed for the SNS project [9], where it operates at 800 MHz between 87 and 186 MeV.

An addition of a 160 to 400 MeV section, operating at 10 Hz, will require the exchange of all Linac4 klystron modulators, which are designed for a 2 Hz duty cycle and which cannot simply be upgraded to the new pulse structure.

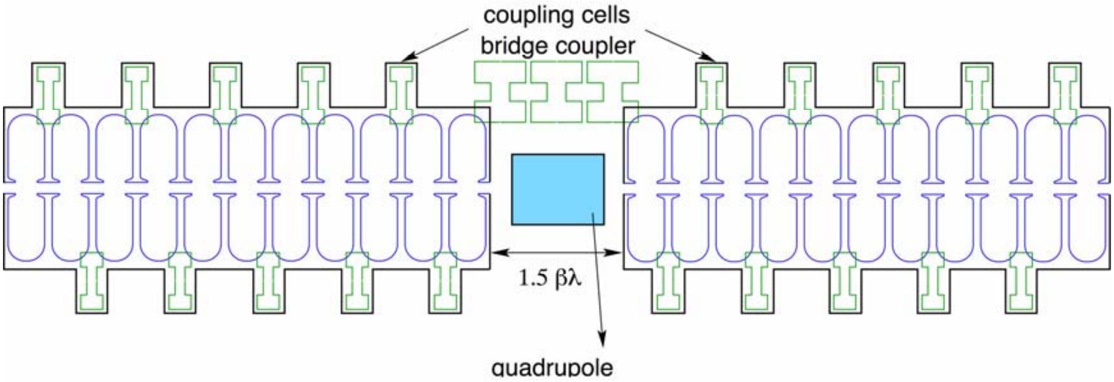

Figure 1: Two SCL modules from Linac4.

For this study we use cavity data, which was calculated for a normal conducting version of the ESS linac, where a CCL at 700 MHz covers the energy range from 70 to 1334 MeV [10]. The structure was optimized with the same criteria as used for Linac4 and has a shunt impedance between 39 and 49 MΩ/m (SUPERFISH - 20%) in the energy range of 160 to 400 MeV. In the ESS study a gradient of E_0 = 3.5 MV/m was chosen as the cost optimum. In the RCS injector linac, E_0 ranges from 3.2 to 3.5 MV/m, in order to keep the power consumption per module approximately constant at ~2 MW.

As klystrons, we assume 704 MHz, 4-5 MW devices which are proposed by two manufacturers for the high-energy section of Linac4. These devices are designed to cover the 2 Hz duty cycle of Linac4, as well as the 50 Hz duty cycle of the SPL [2]. One can imagine that klystrons, which are especially built for the needed time structure could reach higher power. However, given the small number of devices (7), the development cost for new klystrons is likely to outstrip any potential saving.

The beam dynamics for Linac4 (up to 160 MeV) and the SPL has been thoroughly tested (see [8, 2]). Since the RCS injector linac is a simple continuation of the Linac4 focusing structure we do not expect any show-stoppers, especially when considering the modest duty cycle of this machine.

The main parameters of the injector linac and its accelerating modules are given in the Tables 5 and 6 respectively.

Table 5: Parameters of the injector linac, option “single bunch filling”

Parameter	**Value**	**Unit**	**Comment**
Energy range	160 - 400	MeV	
Repetition rate	10	Hz	
Beam pulse length	0.15	ms	0.1 needed for PS2
Average pulse current	40	mA	Linac output
RF frequency	704	MHz	
Synchronous phase	-18	deg	
Bunch frequency	352	MHz	
Average beam power	24	kW	
Linac length	111	m	
Peak RF power	28.2	MW	
Average power RF system	232	kW	Incl. power supplies
Number of klystrons	7		
Number of accel. modules	14		
Cavities per modules	4		
Cells per cavity	12		
Number of quadrupoles	56		FODO lattice
Transverse emittance	0.4	π mm mrad	r.m.s. normalised
Longitudinal emittance	0.2	π deg MeV	r.m.s. at 352.2 MHz

Table 6: SCL module parameters, option “single bunch filling”

Module	**Energy**	**Gradient**	**Beam power**	**Total power**	**Length**
	[MeV]	[MV/m]	[MW]	[MW]	[m]
1,2	190.9	3.5	1.24	3.9	13.4
3,4	223.8	3.5	1.32	4.1	14.3
5,6	257.6	3.4	1.35	4.0	15.1
7,8	292.9	3.4	1.41	4.1	15.8
9,10	328.6	3.3	1.43	4.0	16.4
11,12	365.6	3.3	1.48	4.1	17.0
13,14	402.5	3.2	1.48	4.0	17.5
Total	**402.5**		**9.7**	**28.2**	**109.5**

1.1.3. Option “Geometric filling” (RCS2)

In this scenario the filling of the PS2 is achieved by five consecutive pulses from the five times shorter RCS, similarly to filling the PS with the four PSB rings today when there is more than one bunch per ring.

The specific interest in this scenario is clearly to produce the LHC bunch pattern (40 MHz structure) already at injection in the RCS by using the corresponding harmonic number h_{RF}=36. This avoids any longitudinal bunch splitting in the PS2 that could be equipped with a 40 MHz RF system only. Sufficient gaps in the bunch train will have to be provided to pulse RCS ejection and PS2 injection kickers meaning that at least 4 buckets out of 36 have to be left empty.

In the option “geometric filling” the PS2 machine will be completely filled by 5 RCS cycles whereas in the option “single bunch filling” 14 RCS cycles will provide the same total number of protons for PS2. Therefore the RCS intensity per cycle is a factor 3 higher in “geometric filling” option. This higher intensity requires an increase in injection energy to at least 1150 MeV to keep the same space charge tune spreads at injection as for the “single bunch filling” option. The main parameters for the RCS option “geometric filling” are summarized in Table 7.

Table 7: RCS2 parameters for option “geometric filling”

Reason	RCS parameter	Value
Space charge RCS	Injection energy (kinetic)	1150 MeV
PS2 filling scheme	h_{RF}	36
PS2 filling scheme	Nb of pulses to fill PS2	5
LHC	Nb of protons per pulse for LHC	1.3×10^{13}
	Nb of protons per pulse for FT	2.5×10^{13}
	Filling time of PS2	0.4 s
PS2	Longitudinal emittance per bunch for LHC	0.3 eVs
	RF Gymnastics in PS2	none
	Cycling period of PS2	2.8 s
PS2/SPS kicker gap	Nb. of buckets filled in PS2 (h_{RF} in PS2)	152 (180)

The increase in injection energy by a factor 3 is clearly an economic disadvantage of the “geometric filling” option. Moreover, that solution is not directly compatible with ion operation which would require an additional RF system in the RCS. Alternatively, PS2 could be equipped with the necessary RF to deal directly with the beam from LEIR as in the case of the SPL (see section 3.1).

1.1.4. RCS injector linac for option “geometric filling”

In this version the linac has to inject at 1.15 GeV into the RCS. At this energy we recommend a superconducting linac, consisting of two families of cavities for a geometrical beta of 0.65 and 1.0. Using the same cryo-modules and cavities as used for the SPL up to an energy of 1.15 GeV, one can derive the parameter quoted in Table 8. It should be pointed out that this machine resembles a low-duty cycle version of the SNS linac in Oakridge, requiring a comparable R&D effort. Similarly as for the SNS project a superconducting linac is considered cheaper than a normal conducting version due to the savings in installed RF power and a reduced number of cavities. Compared to the LP-SPL, the same amount of R&D on superconducting cavities is necessary.

Table 8: Parameters of the injector linac, option “geometric filling”

Parameter	**Value**	**Unit**	**Comment**
Energy range	160 - 1210	MeV	1150 needed for PS2
Repetition rate	10	Hz	
Beam pulse length	0.3	ms	0.2 needed for PS2
Average pulse current	20	mA	Linac output
RF frequency	704	MHz	
Synchronous phase	-15	deg	
Bunch frequency	352	MHz	
Average beam power	69	kW	
Linac length	161	m	
Peak RF power	22.4	MW	
Average power for RF + cryogenics	0.6+0.7	MW	Incl. power supplies
Number of klystrons	12		
Number of NC SCL cav.	4		160 – 180 MeV
Number of SC cavities	82		
Cavities per cryo-module	6/8		
Cells per cavity	5		
Number of SC quadrupoles	38		FODO lattice
Transverse emittance	0.4	π mm mrad	r.m.s. normalised
Longitudinal emittance	0.2	π deg MeV	r.m.s. at 352.2 MHz

1.2. Superconducting Proton Linac

The SPL was initially conceived for high-power proton applications such as neutrino physics and the production of radioactive ion beams by the “Isotope On Line separation” technique (e.g. EURISOL). A block diagram is shown in Figure 2.

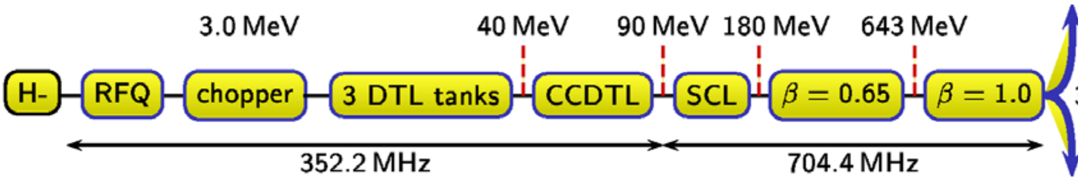

Figure 2: Block diagram of the SPL

As such, the nominal machine design [2] foresees a 50 Hz repetition rate and a beam power in the megawatt range. A detailed technical design of this linac is given in [2]. Using these design elements one can establish the different accelerating sections of a 4 (LP-SPL) or 5 GeV (SPL for neutrinos) machine as given in Table 9.

In a first stage, this machine can also be built as a low duty cycle PS2 injector, ideally suited for the LHC luminosity upgrade plans. It could later be upgraded towards higher beam power if required by new physics experiments. Therefore the tunnels are dimensioned for the needs of the full performance SPL. This makes it possible to locate all klystrons and associated power modulators for the LP-SPL in the klystron tunnel. When the machine will be upgraded, the number of klystrons feeding the superconducting cavities will have to be doubled, so that the beam current can be doubled as well. All power modulators will have to be replaced and half of the equipment will be installed in a surface building, while the other half will be installed underground, next to the klystrons.

Table 9: Accelerating sections of the full performance SPL and low power LP-SPL*

Section	**Energy**	**cavities**	**SPL: $P_{peak,RF}$**	**LP-SPL: $P_{peak,RF}$**	**Length**
	[MeV]		[MW]	[MW]	[m]
Source	0.095	-	-	-	3
RFQ	3	1	1.0	1.0	6
Chopper	3	3	0.1	0.1	3.7
DTL	40	3	3.8	3.1	13.6
CCDTL	90	24	6.4	5.4	25.5
SCL	180	24	15.1	13.7	34.9
$\beta = 0.65$	643	42	18.5	9.3	86
$\beta = 1.0$	4000	152	134	67.1	286
$\beta = 1.0$	5000	40	40	-	75
Total		**289/249***	**219**	**100**	**534/459***

* SPL/LP-SPL

The number of connecting ducts necessary for the additional waveguide connections between the two tunnels will be realized from the start. The connection infrastructure for cooling water, Helium, and electricity will be built to support both linac versions. The klystrons will be able to operate at both duty cycles. These provisions yield only a modest impact on cost for the initial LP-SPL but they simplify substantially any potential upgrade. The major changes, which are necessary for a future upgrade and which contribute to reducing the cost of the LP-SPL, include:

1. exchanging all klystron power modulators, and constructing a new surface building to house one half of this equipment,
2. replacing the cryo-plant, increasing the capacity for Helium storage and the the size of the surface building housing the cryo-plant and cold boxes,
3. installing 27 new klystrons and 27 new waveguide connections between the klystron gallery and the accelerating tunnel,
4. installing 5 additional cryo-modules containing 40 cavities and 10 superconducting quadrupoles,
5. replacing the water cooling towers and upgrading the air conditioning units,
6. installing a new H^- ion source, capable of providing a high duty cycle beam,
7. upgrading the electrical infrastructure.

An increased cryogenic temperature (4.5 K) for the LP-SPL was not considered, since it only yields noticeable savings if the cryo-modules and the cryogenic infrastructure are designed to always operate at that temperature, even for the full SPL. At present it is not clear if the foreseen gradients in the SPL cavities can be reached at 4.5 K. Furthermore, 2 K operation promises savings in operational costs if the linac has to provide high average beam power.

The main parameters of the low- and high-power SPL are listed in Table 10. We note that the LP-SPL already supplies twice as many particles as needed for the PS2/SPS/LHC chain. Reducing the number of particles would not result in any significant saving.

Table 10: Comparison of linac parameters for LP-SPL and SPL

Parameter	SPL	LP-SPL	Unit	Comment
Ejection energy	5.0	4.0	GeV	
Beam power	4.0	0.192	MW	
Repetition rate	50	2	Hz	1 Hz needed for PS2
Av. pulse current	40	20	mA	After chopping
Peak pulse current	64	32	mA	
Protons per pulse	>1.0	1.5	10^{14}	1.4 needed for PS2
Chopping ratio	62	62	%	
Beam Pulse length	0.4-0.7	1.2	ms	1.12 needed for PS2
Maximum filling time of PS2	0.6	1.2	ms	
Protons per pulse	1.0	1.5	10^{14}	1.4 needed for PS2
Beam duty cycle	2.0	0.24	%	
No. klystrons (704 MHz)*	53	24		Max. 8 cav./klystr.
Peak RF power*	196	79	MW	
Average power consumption*	38	3.9	MW	
Cryogenics av. power consumption	4.5	1.5	MW	
Cryogenic temperature	2.0	2.0	K	
Length*	447	372	m	

* excluding Linac4

2. TECHNICAL COMPARISON

2.1. Modes of operation

The generation of the proton beams in all the variants considered is well defined. A comparative assessment of the differences between today's situation and the RCS- and SPL- based options is given in Table 11.

Table 11: Comparison of the modes of operation for protons

Characteristics	**Today**	**RCS "single bunch filling"**	**RCS 2 "geometric filling"**	**"LP-SPL"**
for LHC				
Complexity of operation	**Large** (4 transfers between accelerators + 3 long injection porches + PS gymnastics)	**Large** (4 transfers between accelerators + 3 long injection porches + PS gymnastics)	**Medium** (4 transfers between accelerators + 3 long injection porches)	**Small** (3 transfers between accelerators + 2 long injection porches)
Risk with operation	**Large** (complexity + lack of margin + low reliability)	**Medium** (complexity)	**Small**	**Small**
Beam loss	**Medium** (complexity + lack of margin + low reliability)	**Medium** (complexity)	**Small**	**Small** (minimum complexity)
for SPS FT				
Complexity of operation	**Medium**	**Large**	**Medium**	**Small**
Risk	**Medium**	**Medium**	**Small**	**Small**
Beam loss	**Medium**	**Medium**	**Small**	**Small**
for PS2 FT				
Cycling period (beam power)	**2.4 s** (24 GeV low intensity)	**4 s** (250 kW)	**2.8 s** (320 kW)	**2.4 s** (420 kW)
Complexity of operation	**Small**	**Medium**	**Small**	**Small**
Risk	**Small**	**Small**	**Small**	**Small**
Beam loss	**Small**	**Small**	**Small**	**Small**

The generation of beams of heavy ions is very different. In all cases, heavy ions are first accelerated in Linac3. Multiple pulses from Linac3 are accumulated, cooled and accelerated in LEIR which finally transfers between 1 and 4 bunch to the next synchrotron (the PS today).

The RCS1 for "single bunch filling" is capable to capture and accelerate the LEIR beam by a factor of approximately 2.5 in momentum, which should ease capture and processing in PS2. The RF system required for protons in PS2 could easily be made compatible with the specific needs of heavy ions.

In the case of the SPL, the beam from LEIR has to be injected directly in PS2. This requires an upgrade of the LEIR main power converter and extraction elements to reach a magnetic rigidity of 6.7 Tm. The corresponding field in the PS2 magnets will then be at 0.4 of the value for proton injection. Moreover additional/different RF equipment is needed because the 40 MHz RF system proposed for protons is not able to capture and accelerate the LEIR bunches. It is clear that solutions exist (e.g. by implementing the same RF system than when injecting from the RCS and renouncing to the advantage of no gymnastics for proton beams, although this is probably excessive), but no effort has been invested yet for an optimum scheme in that case.

A tentative comparison of the modes of operation for heavy ions is given in Table 12.

Table 12: Comparison of the modes of operation for heavy ions.

Characteristics	**Today**	**RCS 1**	**RCS 2**	**“LP-SPL”**
for LHC				
Complexity of operation	**Medium** (multiple gymnastics in the PS)	**Medium** (multiple gymnastics in PS2)	**Large** (probably preferable to inject directly in PS2 => low injection energy + multiple gymnastics in PS2)	**Large** (inject directly in PS2 at low injection energy + multiple gymnastics in PS2)
Risk with operation	**Large** (complexity + low reliability)	**Medium** (higher injection energy in PS2)	**Large** (Low injection energy in PS2)	**Large** (Low injection energy in PS2)

3.2 Performance comparison

Both the RCS and SPL options were designed to meet the requirements of the LHC upgrade. Consequently they do not differ in terms of beam intensity or beam quality (e.g. transverse emittances, etc.). They differ however in the overall time needed to fill the LHC because of the different filling schemes and cycle lengths of PS2 and also because of the shortened time needed to fill the SPS. Table 13 compares all proposed injector options including the present situation using the PS as far as the LHC filling is concerned. The differences in filling time between the three upgrade options are quasi-negligible.

Table 13: Performance comparison for LHC filling

Characteristics	**Today**	**RCS 1**	**RCS 2**	**“LP-SPL”**
for LHC				
Cycling period for LHC	**3.6 s**	**4 s**	**2.8 s**	**2.4 s**
SPS filling time (cycling period)	**10.8 s** (21.6 s)	**4 s** (14.8 s)	**2.8 s** (13.6 s)	**2.4 s** (13.2 s)
LHC filling time (per ring)	**~ 260 s**	**~ 178 s**	**~ 163 s**	**~ 158 s**

Comparing the overall performance for non-LHC physics with the different injector options is difficult because it depends strongly on the physics programs (e.g. beam energy, beam intensity, extraction type, etc.).

An indicative picture can be obtained by giving priority for beam usage to the SPS first and next to PS2, and to distribute all the beam left to low energy applications. With this approach maximum use is made of the highest energy machines and beam for lower energy machines is only available in the shadow of the high energy cycles.

The analysis uses the 400 GeV SPS cycle length as the free parameter that can vary from a minimum of 4.8 s (fast ejection like for CNGS) to a maximum of 16.8 s (maximum length slow ejection) with a single PS2 injection per cycle.

The length of the PS2 50 GeV cycle depends upon the injector option. For RCS1 it will be of 4.0 s for SPS filling and of 3.6 s for PS2 physics with 14 RCS injections per cycle. With RCS2 the PS2 50 GeV cycle will be of 2.8 s both for SPS filling and PS2 physics. For the LP-SPL option, the PS2 50 GeV cycle will be 2.4 s long both for SPS filling and PS2 physics. Alternatively all PS2 physics cycles can be ~1 s longer with a flat top for slow extraction.

All cycles of the RCS or all pulses of the LP-SPL that are not used by the PS2 machine are available for low energy beam users up to 4 GeV.

Figure 3 shows the result for the three injector options. The horizontal axis is SPS cycle length, the vertical axis is the proton rate or the percentage of protons available at each energy level relative to the total number of protons produced. RCS1 produces 1×10^{14} protons per second. The total rate produced by RCS2 and also LP-SPL is 2.8×10^{14} protons per second which is beyond the visible plot scale.

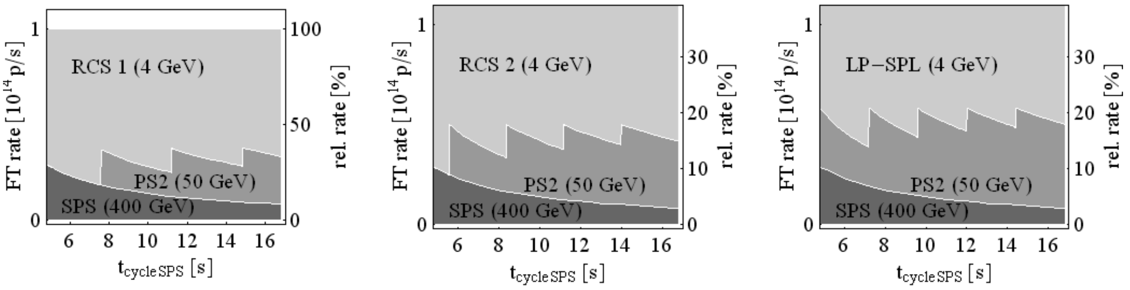

Figure 3: Proton availability for FT operation for RCS1, RCS2 and LP-SPL options.

It can be seen that the proton rate for SPS physics is independent of the injector option since even the shortest SPS 400 GeV cycle is longer than the injector cycles.

For PS2 physics the proton rate depends strongly on the injector option because the PS2 cycle length itself depends strongly on its injector. In the RCS1 case the PS2 cycle is longest and the SPS cycle has to be longer than 7.6 s for an additional PS2 50 GeV physics cycle to be available. The situation is improved with the RCS2 option, but only with the LP-SPL injector the PS2 can supply a 50 GeV cycle for physics even when the SPS is cycling at its highest rate.

In all cases the largest amount of protons is available for low-energy physics. Here the options LP-SPL and RCS2 provide roughly three times more protons than RCS1.

The specific case of SPS operation dedicated to CNGS-type highest intensity operation is summarized in Table 14. Here the SPS is continuously cycling in 4.8 s.

Table 14: Performance comparison with SPS dedicated to CNGS-type physics [11]

Beam characteristics with SPS dedicated to CNGS physics	**Today**	**RCS1**	**RCS2**	**“LP-SPL”**
for SPS FT				
SPS minimum cycling period	**6 s**	**4.8 s**	**4.8 s**	**4.8 s**
for PS2 FT				
Number of PS2 cycles available/supercycle	**1-3**	**~ 0**	**~ 1 (~ 30 GeV)**	**1 (50 GeV)**
Number of pulses/hour	**up to 1800**	**~ 0**	**~ 2000**	**2000**
Number of protons/hour		**~ 0**	**~ 2.5x10^{16}**	**2.5x10^{16}**
Average beam power		**~ 0 kW**	**< 55 kW**	**55 kW**
for low energy beam users				
Number of cycles of PSB/RCS/LP-SPL available/supercycle	**2-0**	**33**	**~ 38**	**7.6**
Number of pulses/hour	**up to 1200**	**~ 24750**	**~ 28500**	**~ 5700**
Number of protons/hour	**up to 4x10^{16}**	**~ 25x10^{16}**	**~ 71x10^{16}**	**~ 80x10^{16}**
Average beam power	**up to 2.4 kW**	**~ 44 kW**	**~ 126 kW**	**~ 142 kW**

The performance of PS Booster, RCS1, RCS2 and LP-SPL options in dedicated operation for low-energy beam users is compared in Table 15.

Table 15: Performance of PSB/RCS1/RCS2/LP-SPL in dedicated low-energy operation

Characteristics	**PSB**	**RCS1**	**RCS2**	**LP-SPL**
Beam energy	**1.4 GeV**	**4 GeV**	**4 GeV**	**4 GeV**
Cycling period	**1.2 s**	**0.1 s**	**0.1 s**	**0.5 s**
Number of protons/hour	**9.6x10^{16}**	**36x10^{16}**	**90x10^{16}**	**100x10^{16}**
Average beam power	**7.2 kW**	**64 kW**	**160 kW**	**180 kW**
Beam time structure	**4 bunches in 2 μs**	**1 bunch in < 1 μs**	**30 bunches in < 1 μs**	**1.2 ms pulse**

3.3 Upgrade potential

In the RCS case, the accelerator is designed to achieve well specified beam characteristics which can later only marginally be increased.

In the LP-SPL case, the potential is built-in to upgrade beam energy up to 5 GeV and beam power to the multi-MW level. That could meet the needs of a neutrino facility (4 MW @ 5 GeV are within the specifications of the Internal Scoping Study for a neutrino factory) or of an ISOL-type radioactive ion facility like EURISOL (5 MW @ 1-2 GeV are needed for indirect production of isotopes using spallation neutrons).

3. RELATIVE COST

The option RCS2 (geometric filling) will clearly be more costly than RCS1 because of the significantly higher injection energy and because it still contains some unsettled technical issues. It has therefore been discarded from this cost analysis.

Since a cost comparison with absolute numbers cannot be done reliably at this point we have used the following approach to compare the RCS “single bunch filling” option with a low-power SPL:

- only the main cost drivers have been estimated, since we assume that the cost of most of the smaller infrastructure like electric cabling, security systems, etc will be of the same order for both machines,
- as far as possible the cost numbers are based on the same estimates, provided by the various CERN departments for civil engineering (estimate of buildings, tunnels, shafts, etc), cooling & ventilation and electricity,
- no upgrade of the electrical infrastructure was included (new HV feeder from Prevessin, new 66 kV/18 kV station in Meyrin, Static Var Compensators (SVC) needed to compensate for the pulsed load),
- no separate control room was included,
- when calculating the cost of different items (e.g. cryogenics for the SPL or dipoles for the RCS) an attempt was made to use the same level of detail and to use numbers that are based on the experience at CERN,
- cryo-modules and SC cavities for the SPL have been valued using the 8 GeV proton driver study from FNAL, since the length and complexity of these devices are very similar in both projects. For the testing of the SC cavities, four fully equipped test stands (high power RF, cryogenics etc.) are foreseen in the RF budget to check and condition all cavities before installation in the tunnel, within 2 years (approximate cost: 15 MCHF for building and operating the four of them during 2 years and keeping 2 fully furbished test places afterwards for the needs of long term maintenance and development).
- manpower has not been estimated (lack of time).
- the R&D is not included in the costing. It is expected that most of the work and of the resources will be provided by collaborating institutes, supplemented by the support of the European Commission in its 7th Framework Programme.

This approach should result in a realistic cost difference between the two options but it does not necessarily provide a reliable estimate of the full project cost for either option.

It is assumed that the location of Linac4 is the same in both scenarios. This is motivated by the requirement to minimize any interruption of LHC operation during the construction and commissioning phase of both machines. With Linac4 under the “Mont Citron” pointing to the direction of PS2 and SPS injection as shown in Figure 4, the new injectors can be commissioned while the old PSB/PS proton chain can be supplied with protons simultaneously. This means that for both scenarios an underground tunnel of equal length connects Linac4 with PS2 and the SPS. In case of the SPL almost 500 m of large diameter accelerating tunnel (4.5 m) plus a parallel klystron tunnel (diameter: 5.5 m) are needed, while in the RCS version only 110 m of parallel tunnels with the same large diameters are assumed. For the RCS a circular

tunnel with a circumference of 267 m (diameter 5.5 m) is needed for the synchrotron together with a new large (diameter x depth: 12 x 35 m) access shaft to lower equipment. Connecting transfer lines are assumed to be 3 m in diameter. A possible location of the RCS is adjacent to the transfer tunnel from linac4 to PS2 as shown in Figure 4.
The number of surface buildings has been scaled from the SPL conceptual design report and reduced to house the installations of the LP-SPL. For the RCS solution the buildings were scaled from the existing installations of the PSB, taking into account the footprint of the power converters for the dipoles.

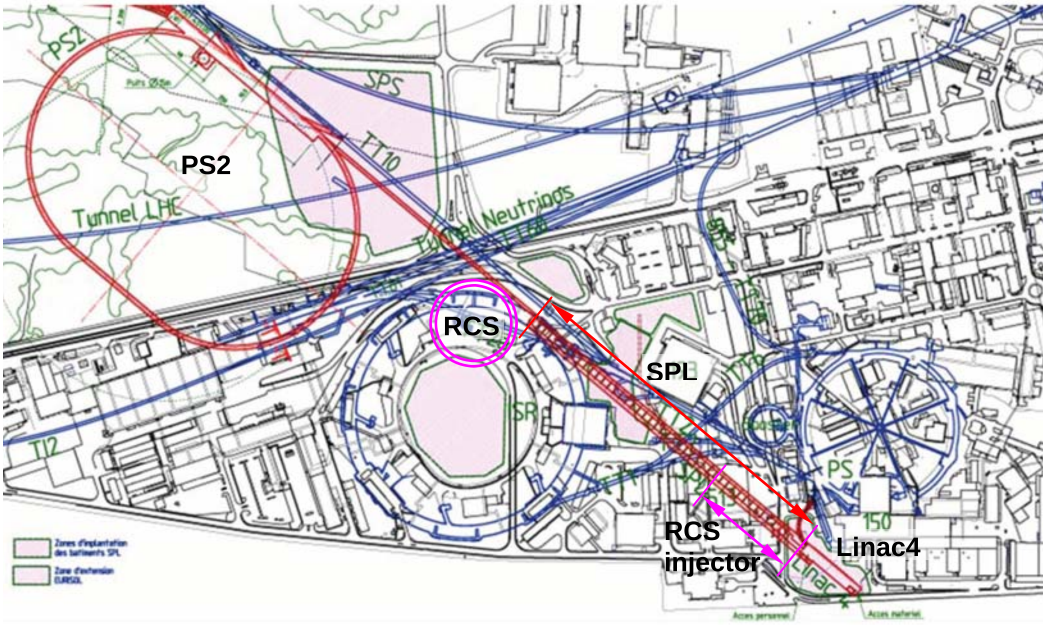

Figure 4: Layout of the new injectors

The installations and buildings for cooling & ventilation, cryogenics, and electricity are estimated according to CERN experience with such facilities. The same approach was taken for normal and superconducting magnets in both scenarios. Klystron and modulator costs are based on commercial cost estimates. Vacuum systems are extrapolated from the recent Linac4 costing exercise.

All items in the cost comparison (Table 16) include a 30% contingency.

For the items taken into account in this preliminary analysis, there is a cost difference of 28 % in favor of the RCS solution. This is consistent with the FNAL estimate, which calculated a 30% difference. It should however be noted that, in the CERN case, the cost of the items that are considered to be similar in both options is not included (labeled “U” in Table 16), which should reduce noticeably the effective difference in percentage.

Moreover, the LP-SPL construction cost contains some added value, because the upgrade to the full performance SPL is already foreseen.

Table 16: Construction costs of major components

Item	**RCS1**	**LP-SPL**	**ΔCost (SPL-RCS)**
	[MCHF]	**[MCHF]**	**[MCHF]**
Civil engineering (underground)	25.2	34.1	8.9
Civil engineering (surface)	13.9	9.2	-4.7
Electricity (construction)	3.3	2.0	-1.3
Cooling & ventilation	7.9	5.2	-2.7
Cryogenics	-	16.9	16.9
Magnets	15.6	1.3	-14.3
Magnet power supplies	33.2	0.5	-32.7
Injection and extraction	24	20.8	-3.2
RF power	72.8	41.2	83.1
NC/SC RF cavities (incl. Cryomodules & test places)		114.7	
Control system	3.9	12.3	7.5
Instrumentation	9.1	10.6	0.6
Vacuum	7.7	9.4	1.7
Other items, similar for both options (not costed)	U	U	0
Total	217 + U	278 + U	61

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REFERENCES

[1] SPC Review Panel’s Report of the White Papers on extra-resources for the years 2008-2010.

[2] Conceptual Design of the SPL II, F. Gerigk (editor), CERN-2006-006.

[3] EURISOL, http://www.eurisol.org

[4] FNAL Proton Driver Study II, TM-2169 Part I, http://www-bd.fnal.gov/pdriver/

[5] Preliminary accelerator plans for maximizing the integrated LHC luminosity, M. Benedikt, R. Garoby, F. Ruggiero, R. Ostojic, W. Scandale, E. Shaposhnikova, J. Wenninger, CERN-AB-2006-018-PAF, http://doc.cern.ch/archive/electronic/cern/preprints/ab/ab-2006-018.pdf

[6] Potential for neutrino and radioactive beam physics of the foreseen upgrades of the CERN accelerators, M. Benedikt, R. Garoby, F. Ruggiero, R. Ostojic, W. Scandale, E. Shaposhnikova, J. Wenninger, CERN-AB-2006-019-PAF,

http://doc.cern.ch/archive/electronic/cern/preprints/ab/ab-2006-019.pdf

[7] A Rapid Cycling Synchrotron option for the CERN proton accelerator complex upgrade, M. Benedikt, C. Carli, A. Fabich, S. Hancock, A. Lachaize, A. Tkatchenko, to be published.

[8] Linac4 Technical Design Report, F. Gerigk (Ed.) and M. Vretenar (Ed.), CERN AB-2006-084.

[9] Spallation Neutron Source, Oakridge National Laboratory, Tennessee, USA, http://www.sns.gov

[10] European Spallation Source, Reference Volume III: The ESS Technical Study, ISBN 090 237 6 500.

[11] Analysis of the maximum potential proton flux to CNGS, M. Meddahi, E. Shaposhnikova, CERN-AB-2007-013.