OPERATIONAL FLEXIBILITY OF THE SPL AS PROTON DRIVER FOR NEUTRINO AND OTHER APPLICATIONS

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Abstract

The pulse structure of proton linacs is determined by the linac energy, the RF system, and the maximum duty cycle of the source. Short bursts of protons in the microsecond range can be achieved by adding an accumulator ring and a reduction of the bunch length to the order of nanoseconds can be accomplished with an additional bunch compressor ring. The size of the rings along with their RF frequency determines the time structure of the proton driver output burst to hit the target. This pulse structure can be further modified using multiple fillings of the accumulator and compressor rings within one linac pulse. This paper illustrates the possible modes of operation of the SPL at CERN along with its limitations at various energies in combination with accumulator and compressor rings.

INTRODUCTION

The SPL [1] at CERN aims to supply high power beams at a repetition rate of 50 Hz to EURISOL [2] and/or a range of possible neutrino (ν) applications [3]. At the same time a 1 Hz beam can be injected into the PS for the regular CERN physics program (LHC, SPS fixed target physics, nTOF, etc.). While EURISOL prefers a CW beam, or at least a beam with high repetition rate (> 50 Hz) at energies of 1-2 GeV [4], ν schemes aim for energies between 5 and 10 GeV (at repetition rates between 10 and 100 Hz) to optimise the muon yield out of the target. This optimisation, however, still needs confirmation by the HARP [5] results, which are expected this year.

To meet the demands for higher energies the SPL output energy was increased from 2.2 GeV (in the 1$^{\text{st}}$ conceptual design report CDR1 [6]) to 3.5 GeV (2$^{\text{nd}}$ report CDR2 [1]) and is now considered for a further increase up to 5 GeV (CDR3 ?) to meet the specifications of the International Scoping Study (ISS) [7], which aims to define the optimum specifications for a ν-factory proton driver. The SPL reference design now consists of a normal conducting 180 MeV linac followed by two families of superconducting (SC) cavities, which accelerate the beam to its top energy of 3.5 GeV. Due to advances in the field of SC bulk niobium cavities, the linac length in CDR2 could be reduced by 35% despite the increase in energy. Since the demands for ν-factory proton drivers have changed considerably over the last years, the present SPL reference design has been developed with an emphasis on flexibility to allow changes in energy, beam current, and pulse length.

Three different ν production schemes are presently under study which need i) H$^-$ or proton beam on an ISOL-type target plus post accelerators ($\rightarrow$ β-beams), ii) H$^-$ linac plus accumulator ring and direct target ($\rightarrow$ Superbeam), and iii) H$^-$ linac plus accumulator and compressor ring ($\rightarrow$ ν-factory). The present SPL design can be the driver for all three schemes making it possible to envisage a staged approach for ν physics. At the same time it can provide beams for long-pulse EURISOL targets and supply the regular CERN physics program with protons.

The RF system is designed for a maximum duty cycle of 10% (nominal: $\approx 5\%$) to allow for longer beam pulses. Higher output energies can be achieved by adding SC cavities. The linac parameters for CDR1 and CDR2 are listed in Table 1 together with a possible energy upgrade to 5 GeV, which could be the subject of a 3$^{\text{d}}$ conceptual design report (CDR3).

The nominal SPL repetition rate of 50 Hz is a compromise between the needs of the various potential users. It is conceivable, however, to foresee different repetition rates for different modes of operation (e.g. 25 Hz for neutrinos and 50 Hz for EURISOL).

Table 1: SPL parameters for the 1$^{\text{st}}$ and 2$^{\text{nd}}$ design report and an energy upgrade to 5 GeV.

design		**CDR1**	**CDR2**	**CDR3**
year		2000	2006	?
energy	[GeV]	2.2	3.5	5
beam power	[MW]	4	4	4
repetition rate	[Hz]	75	50	50
protons per pulse	[10^{14}]	1.5	1.4	1.0
av. pulse current	[mA]	11	40	40
chopping ratio	[%]	62	62	62
pulse length	[ms]	2.2	0.57	0.40
bunch frequency	[MHz]	352.2	352.2	352.2
length	[m]	690	430	535
peak RF power	[MW]	32	162	220

OPTIMUM LINAC OPERATION

A major cost driver in SC linacs is the RF system and it is desirable to choose a mode of operation in which these costs can be kept at a minimum. The peak RF power consumption is given by the peak current and the top energy of the linac and determines the number of klystrons to be installed. The average RF power consumption or RF efficiency is governed by the duty cycle D of the RF system, which is related to the length of the beam pulses t_{b}, the cavity filling time τ_{f}, the repetition rate f_{rep} and the peak current I_{b}. It can be estimated [8] by

$$D \approx f_{\text{rep}}\left(\tau_{\text{f}} \ln(4) + t_{\text{b}}\right), \quad \tau_{\text{f}} \approx \frac{V_{\text{acc}}}{\omega_0 (R/Q) I_{\text{b}} \cos\phi_{\text{s}}}$$

with $V_{\rm acc}$ and $\phi_{\rm s}$ being the accelerating voltage and the synchronous phase. The cryogenic power of the SPL is dominated by dynamics losses, which are proportional to the number of installed cryo-modules and to the RF duty cycle. Additional RF power needed to compensate the effects of Lorentz-Force detuning in the SC cavities is also proportional to the RF duty cycle, which means that one can take the average RF power consumption as a measure of power efficiency for the complete installation.

Using the above formula for the 2 two SPL SC sections and adding the RF power of the normalconducting part one can plot the average SPL RF power consumption versus final linac energy for a 4 MW beam assuming different beam currents. In case of 50 Hz (nominal) and 25 Hz operation (optional) we obtain the curves plotted in Figs. 1 and 2.

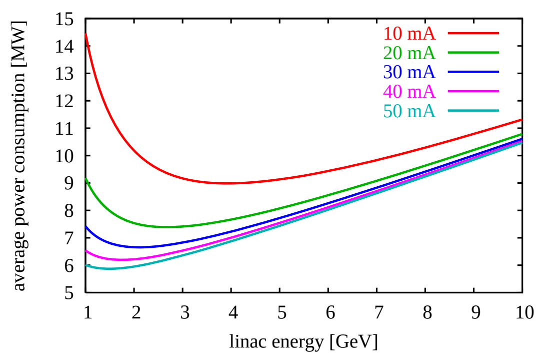

Figure 1: Av. SPL RF power at 50 Hz, 4 MW beam power for various pulse currents, top to bottom: 10 → 50 mA.

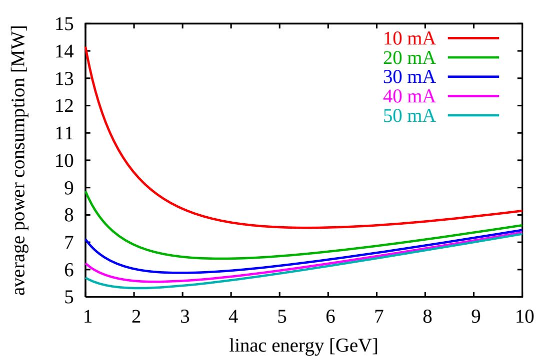

Figure 2: Av. SPL RF power at 25 Hz, 4 MW beam power for different pulse currents, top to bottom: 10 → 50 mA.

Higher currents result in a shorter filling time and reduce the ratio between filling time and beam pulse length at a given energy. From Fig. 1 one can see that at 50 Hz the power consumption for higher energy options is more and more dominated by the filling time because the beam pulse length is getting shorter. This results in an optimum working point between 4 and 1.5 GeV, for currents between 10 and 50 mA. For lower repetition rates (e.g. 25 Hz in Fig. 2) or higher beam power, the beam pulse length increases with respect to the filling time and the optimum working point becomes less dependent on the final beam energy.

It should be noted that H^- operation may be limited by the achievable H^- ion source duty cycle, which provides a strong incentive to operate high-power H^- linacs at higher energies. While for injection into subsequent rings (accumulator, CERN PS) H^- injection is mandatory to achieve small-emittance beams, applications like EURISOL which use the linac beam directly could operate with protons. In this case a lower linac energy would reduce the average RF power needs. In order to facilitate the acceleration of both particle species, two separate front-ends (up to the DTL) need to be installed along with a switching device to combine the beam lines. With this set-up one can imagine even a pulse to pulse switch from proton to H^- acceleration.

TRANSFER LINES

While it is technically simple to increase the energy of the SPL, high-energy operation becomes increasingly difficult due to the consequences of H^- stripping caused by i) the magnetic field in the bending dipoles and ii) blackbody radiation of the beam pipe. The average beam loss per metre due to magnetic field stripping can be estimated [9] with

$$\frac{P_{\rm loss}}{1\,m} = P_{\rm beam}\frac{B}{A_1}e^{-\frac{A_2}{\beta\gamma c B}}$$

where B is the magnetic field, c the speed of light, and A_1, A_2 are constants which are fitted to experimental data (here we use: $A_1 = 8\times10^{-6}$ Vs/m, $A_2 = 4.3\times10^9$ V/m). The losses can be kept below 0.1 W per metre by keeping the radius of all bends in the H^- transfer line above a minimum radius which is plotted in Fig. 3.

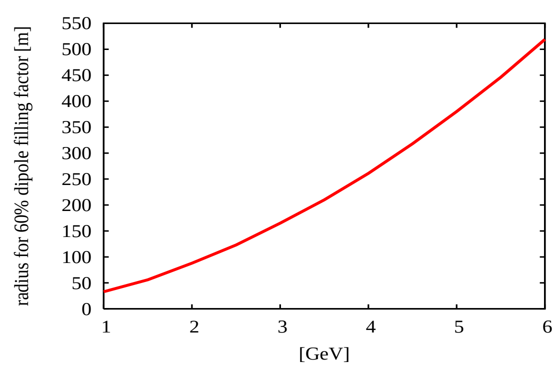

Figure 3: Minimum arc radius for a 4 MW beam, assuming 0.1 W/m stripping losses and a 60% dipole filling factor.

H^- stripping due to blackbody radiation was recently studied in the context of the Fermilab 8 GeV proton driver [10, 11]. The process saturates for energies above 10 GeV at a loss rate of $\approx 1\times10^{-6}$/m. At 3.5 GeV this effect yields a loss rate of $\approx 0.2\times10^{-6}$/m, which is already close to the maximum allowed loss budget of 1 W/m for hands-on maintenance, meaning that the beam pipe needs to be cooled in order to reduce the radiation of the beam pipe.

Reducing the length of any potential transfer line in order to minimise stripping losses limits the capabilities to reduce the linac energy jitter via bunch rotation and has to be compensated by increased RF gradients for the bunch rotation. Using straight transfer lines to avoid H^- stripping in the dipoles removes any possibility for longitudinal momentum collimation and may therefore be impractical.

ACCUMULATOR & COMPRESSOR

All bunches of a single linac pulse are injected into the accumulator ring via charge-exchange H^- injection. The circumference of the accumulator thus determines the length of the beam burst while its RF harmonic number defines the number of accumulated bunches. Since the publication of CDR1 [6] the beam burst requirements for a ν-factory proton driver have changed from 140 (1 ns r.m.s.) bunches at 2.2 GeV and 75 Hz to the presently favoured ≈ 5 (≈ 2 ns r.m.s.) bunches at energies above 5 GeV and 50 Hz repetition rate. One can assume that the time structure will be subject to further revisions and it is important to be able to tailor the proton driver beam to new demands without fundamentally changing its design for each revised set of parameters. For a linac based proton driver this can be done by adapting the accumulator/compressor ring design and one can thus use the same linac design for an evolving group of users, as for instance: EURISOL and β-beams in stage I (no rings), EURISOL and superbeam in stage II (with accumulator ring), and a full ν-factory in stage III (with accumulator and compressor ring). This approach also allows a stepwise development of high-power targets, which becomes more challenging for decreasing burst and bunch lengths from the proton driver.

The increase in beam energy and beam current from CDR1 to CDR2 shortens the linac beam pulse length (compare Table 1), reduces the number of injection turns for a given ring size, and reduces the space charge tune shift in the rings. This means one can reduce the size of the accumulator ring, while keeping the same space charge tune shift ($\Delta Q_{\rm sc}$). Table 2 lists various scenarios for different energies which result in a more or less equal $\Delta Q_{\rm sc}$ at the end of the bunch compression. In all cases a normalised transverse r.m.s. emittance of $120\,\pi$ mm mrad was assumed. Keeping instead only the transverse acceptance constant would even reduce the space charge tune shifts for CDR2/3.

Filling the accumulator and compressor rings twice per linac pulse (see 2$^{\rm nd}$ column for CDR2/3 in Table 2) further reduces the tune shift and enables comfortable operation of two different targets (if needed). Another option is to transfer the bunches one by one from the accumulator to the compressor, spacing them twice more in the accumulator. With both rings of almost the same size, the RF frequency in the compressor will be ≈half the bunch frequency in the accumulator and bunch rotation will proceed cleanly thanks to an initial bunch length significantly smaller than the RF period. Obviously, once half the accumulated bunches have been transferred to the compressor, another bunch can only be injected after the first one is compressed and ejected. Choosing properly the $\gamma_{\rm t}$ of the accumulator this time interval can be minimized. In this scenario it may also be possible to accumulate the beam without any RF system and to create for instance a 6 MHz structure in the accumulator ring only with the low-energy beam chopper. Since the velocity difference of the accumulated particles is small at high energy, the 6 MHz structure would be maintained during accumulation and one could then use a 3 MHz RF system (plus higher harmonics) to do the bunch compression.

Table 2: Output parameters for different operating modes, assuming equal accumulator and compressor ring size, 4 MW of beam power, and $\varepsilon_{\rm t,rms,norm} = 120\,\pi$ mm mrad.

design	CDR1	CDR2		CDR3	
energy [GeV]	2.2	3.5		5.0	
p.p.pulse [10^{14}]	1.5	1.42		1.0	
$\mathbf{f_{repetition}}$ [Hz]	75	50		50	
$\beta\gamma^2$	10.7	21.8		39.5	
$\mathbf{R_{compr}}$ [m]	151	76		47	
inj. turns	660	348		400	
$\mathbf{f_{RF}}$ [MHz]	44.0	11.0		5	
b. spacing [ns]	22.7	90.0		200	
r.m.s. bunch length [ns]	1	2		2	
$\mathbf{N_{bunches}}$	140	17	2×17	5	2×5
$\mathbf{N_{bursts}}$	1	1	2	1	2
$\mathbf{\Delta Q_{sc}}$	0.13	0.13	0.06	0.1	0.05

SUMMARY

We outlined the potential and the limitations of the SPL and showed that with various combinations of accumulator/compressor rings a SPL based proton driver can be adapted to the needs of a large user community (various ν schemes, EURISOL, CERN physics program). Without fundamentally changing the basic linac design the SPL can offer a staged approach to ν physics and cover a wide range of future parameter changes.

REFERENCES

[1] The SPL study group, to be published, Ed. F. Gerigk.

[2] http://www.ganil.fr/eurisol/Final_Report/Appendix-B.pdf

[3] BENE steering group, CARE-Report-06-009-BENE.

[4] E. Noah *et al.*, EPAC 2006.

[5] http://harp.web.cern.ch/harp/

[6] The SPL study group, CERN 2000-012, Ed. M. Vretenar.

[7] http://www.hep.ph.ic.ac.uk/iss/

[8] F. Gerigk, CERN AB-Note-2006-011 RF (2006).

[9] L.R. Scherk, *Can. J. Phys.* **57** (1979) 558.

[10] W. Chou *et al.*, PAC 2005.

[11] H.C. Bryant and G.H. Herling, *J. Modern Optics* **53** 1-12 (2006) 45.