LATEST NEWS ON THE BEAM DYNAMICS DESIGN OF SPL

P. A. Posocco, M. Eshraqi[#], A. M. Lombardi, CERN, Geneva, Switzerland
and [#]ESS Lund, Sweden

Abstract

SPL is a superconducting H⁻ LINAC under study at CERN. The SPL is designed to accelerate the 160 MeV beam of LINAC4 to 5 GeV, and is composed of two families of 704.4 MHz elliptical cavities with geometrical betas of 0.65 and 1.0. Two families of cryo-modules are considered: the low-beta cryo-module houses 3 low-beta cavities, whereas the high-beta one houses 8 cavities. The transverse focusing is performed with normal-conducting quadrupoles arranged in 2 different lattices: FD0 at lower and F0D0 at higher energies. The regular lattices are interrupted at the transition between low beta and high beta cryo-modules and for extracting medium energy beams at 1.4 and 2.5 GeV, where the change of the transverse lattice is performed. In this paper the latest beam dynamics studies will be presented together with the sensitivity of the SPL performance to RF errors, alignment tolerances and quadrupole high order components.

INTRODUCTION

The SPL [1] is the CERN study of a superconducting linac providing a 5 GeV/4 MW H⁻ beam suitable for neutrino facilities and potentially also for other users (see Table 1). Fixed target experiments are foreseen at lower energies, like ISOLDE at about 1.4 GeV or Eurisol at 2.5 GeV. LINAC4 [2] accelerates H⁻ ions from 45 keV to 160 MeV in a sequence of normal conducting structures at 352.2 MHz and injects the beam into SPL: the H⁻ are then accelerated from 160 MeV to 5 GeV by 244 5 cells elliptical cavities (704.4 MHz) whose geometric β in the low energy part is equal to 0.65 and 1.0 above (see Figure 1). The nominal accelerating gradients are 19 and 25 MV/m respectively. The transition energy between the two families is set to 750 MeV, optimized in order to have the best beam dynamics and the most efficient acceleration [3]. Presently two scenarios are under study using a peak current of either 32 mA or 64 mA, both with a beam power of 4 MW.

LINAC DESCRIPTION

SPL layout options were described extensively in [4]. The present layout (called "mixed") involves FD0 periods at low energy and F0D0 at high energy, combining the advantages of both lattices, respectively high segmentation and low field quadrupoles. This allows the magnets to be normal conducting and their length, 300 mm, is such that for a chosen transverse focusing the maximum gradient is below the threshold to keep H⁻ stripping losses below 0.1 W/m.

Table 1: SPL Main Parameters

Parameter	Unit	SPL LC	SPL HC
ion		H-	H-
Energy	[GeV]	5	5
Beam power	[MW]	4	4
Repetition rate	[Hz]	50	50
Average pulse current	[mA]	20	40
Peak pulse current	[mA]	32	64
Source current	[mA]	40	80
Chopping ratio	[%]	62	62
Beam pulse	[ms]	0.8	0.4
Duty cycle	[%]	4	2

The acceleration begins with 3 low-β cavities per period being housed in a "short" (4.68 m) cryo-module preceded by a pair of quadrupoles. In the high-β region, starting from 750 MeV to 2.5 GeV a pair of quads is followed by 8 cavities housed in one "long" (13.26 m) cryo-module, while after the 2.5 GeV branching each single quad will be followed by one cryo-module, making a long F0D0 focusing (see Figure 2). Each period is equipped with a steerer for each plane and a Beam Position Monitor.

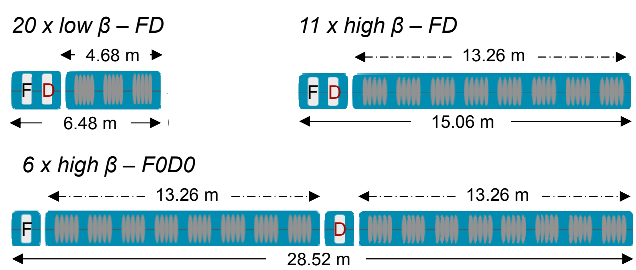

Figure 2: SPL lattice periods.

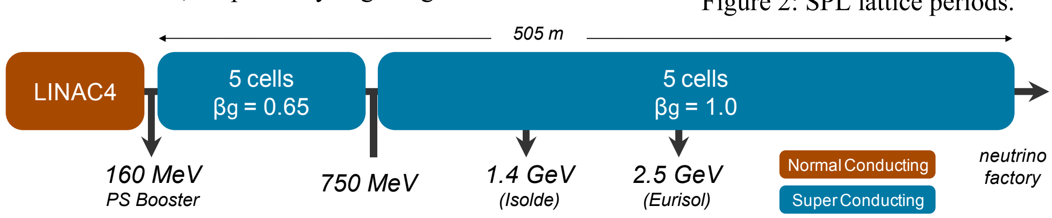

Figure 1: SPL conceptual layout (longitudinally to scale).

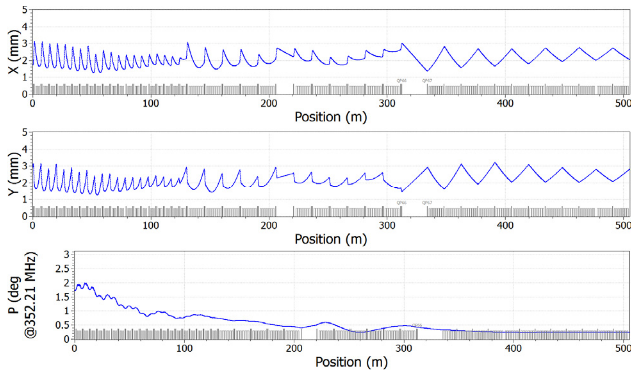

Figure 3: RMS envelopes along the SPL.

The beam dynamics simulations (see Figure 3) are performed for a 60 mA beam from LINAC4. In absence of any manufacturing and assembly errors and any RF amplitude and phase errors, the SPL transports and accelerates the H^- beam from LINAC4 preserving the beam quality, i.e. with full transmission and minimum emittance growth (see Table 2). Beam dynamics design, simulation, and calculations are done using the multi-particle code TraceWin [5] using 50k macro particles. Matching was done very carefully at the transition from low to high β and also across the extraction branches since long extraction drift spaces can have a significant impact on beam halo development. The transverse RMS radius stays below 3 mm and the outermost particles stay confined within 10 mm all along the LINAC. With a bore radius of 50 mm there is a high safety margin for losses.

Table 2: Nominal SPL Beam Dynamics Results

emittance		X	Y	Z
		(normalized π mm mrad)		(MeV deg)
IN	RMS	0.338	0.339	0.196
IN	99%	2.27	2.16	1.40
OUT	RMS	0.353 (+4.4%)	0.366 (+7.9%)	0.201 (+2.5%)
OUT	99%	2.39 (+5.3%)	2.51(+16%)	1.62 (+16%)

LONGITUDINAL SENSITIVITY

In order to test the effect of phase and amplitude jitter on the SPL longitudinal beam dynamics, sets of 10k LINACS with increasing jitter values were generated. The input beam from LINAC4 is affected by jitter as well (0.1% on the average energy, 1 deg on the average phase and 5% on the longitudinal emittance). In Figure 4 the output longitudinal effective distribution (sum of the output distributions of all the LINACS in a set) is shown for the different cases: if we have only the input jitter, the effective 99% emittance is 50% bigger than the nominal one, whereas for 0.5% for the amplitude 0.5 deg for the phase is 2 times bigger and for 1% 1 deg we have a factor of 5. If the output energy jitter must be limited to 0.1%, 0.5%-0.5 deg is the specification needed for the RF controls.

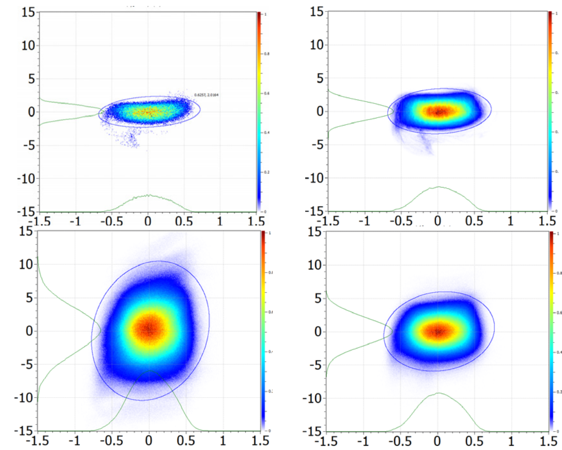

Figure 4: Output Long. effective distributions [MeV-deg 352 MHz] clockwise from up/left: nominal, input jitter, input jitter and 0.5%-0.5 deg, input jitter and 1%-1 deg.

In case the SPL operates with 20 mA average current, it is possible to drive two high-β cavities with a single high power klystron. In case of one klystron per cavity (1:1) the cavity is stabilized against the effects of beam loading along the pulse with a feedback on amplitude and phase. In the 1:2 case the feedback can act only on the vector sum of the 2 cavity amplitudes. This means that if two paired cavities have different loaded Q values (Q_L), the two cavity amplitudes will drift apart along the pulse. If they have different Lorentz detuning coefficients the operating phases will drift apart [6]. These phenomena will cause a degradation of the longitudinal beam quality along the pulse as well as a final energy different from nominal. For these reasons we generated sets of 10k LINACS applying these specific coupled errors in the high-β section. The results were studied plotting the longitudinal emittance and energy error as a function of the difference to the nominal values, compared with the errors given by the input beam/RF jitters and referring to the 0.10% limit for the comments.

For the Q_L case, having errors at the end of the pulse bigger than 5% in cavities amplitude may cause a longitudinal loss of particles. If we want that the effect on the final emittance is lower than the RF jitter smearing process shown before, the final error must be lower than 3% (see Figure 5). The corresponding error on the output energy is therefore limited to 0.3% (see Figure 6).

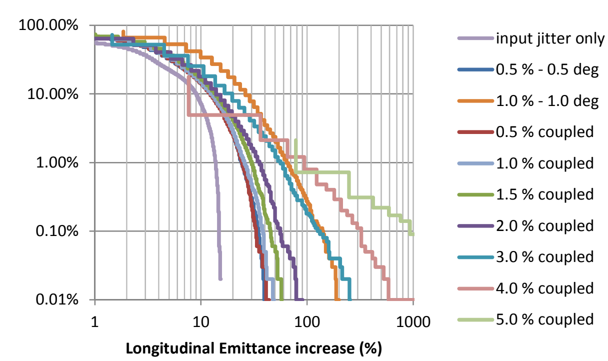

Figure 5: Longitudinal emittance increase in case of different Q_L values.

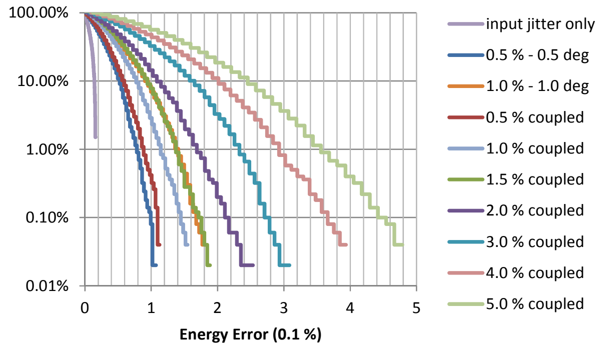

Figure 6: Output energy error in case of different Q_L values.

Concerning the Lorentz detuning case, the effect of this error is lower and the specification can be set at 5 deg with a maximum energy offset of 0.15%.

ALIGNMENT SENSITIVITY

In order to test the transverse beam correction provided by the 2 steerers – 1 BPM system, a beam with 0.1 mm 0.1 mrad RMS beam input jitter and 0.3 mm 0.3 mrad RMS random residual misalignment was accelerated through the SPL with and w/o the correction system for different quad misalignments (5k LINACS each). It turned out that once the correction is activated, the transverse emittance increase does not depend on the misalignment amplitude and is always limited to 10% (see Figure 7). Small losses were found 0.3 mm RMS errors without corrections, which is why the error limit was set to 0.2 mm RMS.

Once the misalignment of the cavities is taken into account, the emittance increase becomes 15% for 2 mm RMS. The corresponding max steerer strength is 3 mT m.

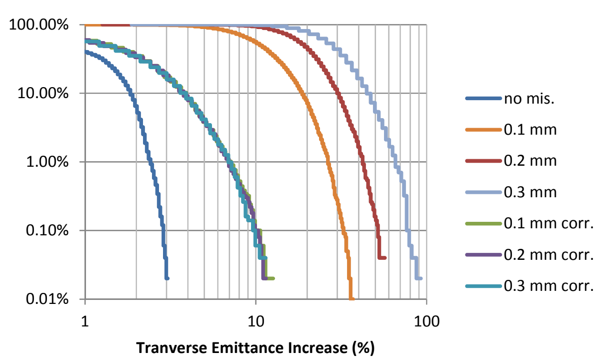

Figure 7: Transverse emittance increase due to the quadrupole misalignment (RMS).

HIGHER ORDERS SENSITIVITY

In order to test the effect of the quadrupole higher order components we run the LINAC in the extreme condition of input errors as before and random misalignment of 0.2 mm RMS for the quads and 3 mm RMS for the cavities. The components are evaluated at the reference radius of 30 mm and expressed in terms of units (10^{-4} of the quadrupole field). In Figure 8 the longitudinal emittance increase compared to the nominal case is plotted as a function of the components strength. The beam quality does not change for a dodecapole component of 30 units, with 5 units being easy to achieve. For the nested coils induced sextupole component, the very high 300 units value is still fine ([7] for comparison with SNS). It has to be noticed that increasing the component to 1000 units will excite the 60 deg resonance at the beginning of the high-β section.

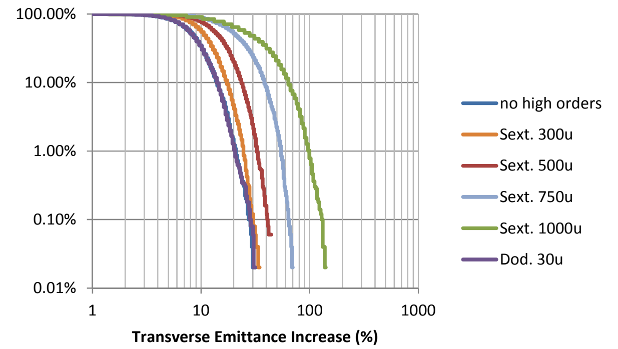

Figure 8: Quadrupoles higher order effects on the transverse emittance.

CONCLUSIONS

The nominal SPL beam dynamics design has been proven to be very solid. The RF jitter specifications are set to 0.5% in amplitude 0.5 deg in phase, quite standard values for LINACS of this kind. It seems that operating the SPL in the low current mode with 2 high-β cavities per klystron works if the feedback residual errors are lower than 3% in amplitude and 5 deg in phase.

The transverse correction system with a couple of single plane steerers and one BPM per period works flawlessly up to 0.2 mm quad and 2 mm cavities RMS misalignment. The maximum required steerer strength for this extreme case is 3 mT m and the beam can still be accelerated without losses even if the correction system is off.

Concerning the quadrupole higher order components, having a dodecapole less than 30 units (× 10^{-4} at 30 mm radius) will not cause any sensible change in the beam characteristics whereas for the sextupole induced by the steerers 300 units will be fine.

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