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PROGRESS IN THE DESIGN OF THE SPL, AN H$^-$ HIGH-INTENSITY LINAC AT CERN

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Abstract

The SPL (Superconducting Proton Linac) is a 4 MW 2.2 GeV H- linac, intended to re-use most of the 352 MHz RF equipment from the decommissioned LEP machine. Injecting into the CERN PS, this linac would improve the intensity and quality of the CERN proton beams, while as a stand-alone facility could provide intense beams of radioactive ions or neutrinos (Neutrino Superbeam). Together with accumulator and compressor rings, it would be a suitable driver for a Neutrino Factory.

Since the original proposal, many improvements to the design have been introduced, in order to simplify the layout and reduce costs. They include the reduction of the repetition frequency to 50 Hz, the design of a shorter superconducting (SC) linac section that goes up to the full energy with β=0.8 cavities, an improved DTL section including a new CCDTL design, a chopping line based on fast (2 ns rise time) low-voltage choppers and pulser, and a simplified front-end. Moreover, the problem of pulse mode operation of a superconducting linac with more than one cavity per klystron has been analysed in more detail, showing additional limitation but also proposing some possible compensation schemes.

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1 INTRODUCTION

The CERN physics programme depends crucially upon the characteristics of the proton beams delivered by the accelerator chain. For this reason, a major upgrade of the low energy accelerators has been proposed [1], profiting of the large inventory of RF equipment decommissioned from LEP. A superconducting 2.2 GeV H^- linac replacing the present 50 MeV proton linac (Linac2) and PS Booster (PSB) would benefit the approved physics programme (LHC, ISOLDE...) and could be built in a very cost-effective way, using klystrons, waveguides, cryostats and RF cavity components from LEP.

Recently, other applications have been suggested, and the design has evolved [2] to comply with the needs of a second generation ISOLDE-like facility (EURISOL) [3], a neutrino super-beam [4], and, ultimately, a neutrino factory [5]. Although the interest of such an upgrade of the CERN complex of accelerators is now clearly established, resources are limited because of the needs of the LHC project, and a staged realisation is necessary. The ongoing effort is concentrated on the low energy part of the machine (up to a few MeV) in the frame of the IPHI project [6], in collaboration with CEA and IN2P3 in France. In a second stage, the realisation of the 120 MeV room temperature front-end is envisaged as an improved injector for the PSB.

2 IMPROVED SPL DESIGN

A preliminary cost analysis carried out in 2001 led to some revisions of the SPL design, to reduce costs or to simplify the layout at no additional cost. In particular, the repetition rate has been reduced to 50 Hz, increasing at the same time the pulse length to 2.8 ms and the pulse current to 13 mA (Table 1). The reason was to reduce the power consumption in the linac, heavily influenced by the filling time of the SC cavities, as well as that of the following neutrino complex, simplifying at the same time the RF power distribution in the SC section with a regular pattern of 4 cavities per klystron. Additional complications are expected in the neutrino factory accumulator ring, due to the longer linac pulse, but instabilities should remain controllable.

Another improvement was the decision to base the design on new β=0.8 cavities up to the final energy, meaning that unmodified LEP cavities are no longer used. The additional cost of producing the new cavities is compensated by the 87 m reduction in the linac length, thanks to the higher transit time factor of the β=0.8 cavities. The cost is contained because the new 5-cell β=0.8 cavities are housed in unmodified LEP cryostats and re-use the expensive ancillaries of the LEP cavities. Additional arguments in favour of this move are the simplified RF power distribution, the option in new cavities to tune mechanical modes far from harmonics of the pulse frequency, and finally the chance to achieve higher gradients, through more modern coating and cleaning techniques.

Table 1: Main SPL parameters

Kinetic energy	2.2	GeV
Mean current during the pulse	13	mA
Beam duty cycle	14.0	%
Mean beam power	4	MW
Pulse frequency	50	Hz
Pulse duration	2.80	ms
Number of H^- per pulse	2.27	$\times 10^{14}$
Bunch frequency	352.2	MHz
Chopping duty cycle	61.6	%
Successive bunches/No. of buckets	5/8	
Maximum bunch current	22.7	mA
Norm. r.m.s. transverse emittance	0.4	π mm mrad
Longitudinal r.m.s. emittance	0.3	π deg MeV

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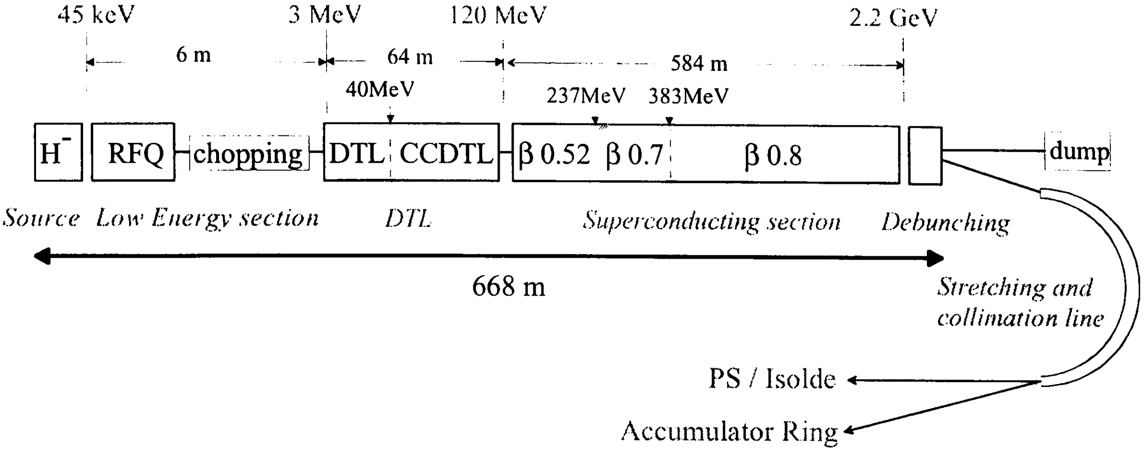

Figure 1: SPL Schematic Layout

Some additional improvements were applied to the chopper and to the Drift Tube Linac (DTL) sections, to obtain the overall layout presented in Fig. 1 and Table 2.

Table 2: SPL sections

Section	Final energy	No. of cavities	Peak RF power	Kly-strons	Tetr-odes	Length
	(MeV)		(MW)			(m)
Source	0.045	-	-	-	-	1
RFQ	3	1	0.5	1	-	2.4
Chopper	3	3	0.06	-	3	3.6
DTL	120	13	11.8	15	-	64
β=0.52	236	42	1.5	-	42	101
β=0.7	383	32	1.9	-	32	80
β=0.8 I	1111	52	9.5	13	-	166
β=0.8 II	2235	76	14.6	19	-	237
Debunch.	2235	4	-	1	-	13
Total		223	39.9	49	77	668

3 RFQ AND CHOPPING

The proposed SPL chopper structure consists of a pair of deflecting plates with a meander type delay printed on alumina, without separating ridges [7]. Tests carried out on prototypes (double 100 Ω meander on 3 mm alumina, Fig. 2) show good agreement with numerical simulations in terms of attenuation and dispersion. The printed meander on alumina has very good vacuum properties, easy implementation and good radiation resistance and heat transfer (water cooled metal ground plane). The 100 Ω characteristic impedance permits a meander width below 25 mm for β=0.08 and thus economy on driver power, and the possibility to install the deflectors inside quadrupoles. A prototype of the 500 V chopper pulse amplifier has been realised, and tests are in progress [8].

The chopper line is composed of two 1 m long double FODO sections for transverse matching between a fast phase advance in the accelerators and a slow one in the chopper, plus a 1.6 m long FODO period in between. The latter houses the chopper inside the quadrupoles and provides the 90° phase advance at the dump placed at its end, needed for the separation of chopped and unchopped beam.

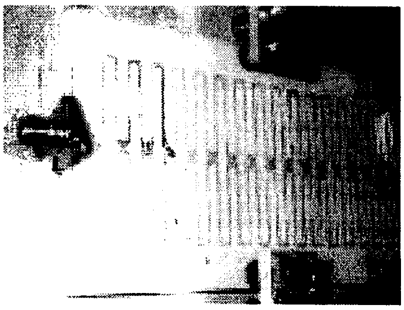

Fig.2: Chopper prototype, double 100 Ω layout (Z_0=50 Ω)

A test of the chopping line using a 3 MeV segment of the 352 MHz IPHI RFQ, presently being assembled, is in preparation with CEA and CNRS-IN2P3 (France). By subsequently adding the second RFQ segment up to 5 MeV, beam tests up to 100 mA and in CW are anticipated with a proton beam chopped at 3 MeV and then accelerated to 5 MeV. Beam measurements will include chopping efficiency and halo development. The test stand will be located at CEA-Saclay.

4 DRIFT TUBE LINAC

The DTL section relies on a conventional Alvarez design up to 40 MeV. From this energy, the focusing period can be increased, keeping the longitudinal phase advance below 65° to avoid emittance exchange, and a Cell-Coupled DTL design (CCDTL [9]) at 352 MHz has been adopted, characterised by identical coupling cells. A 12-cell cold model (Fig. 3) has been realised and tested.

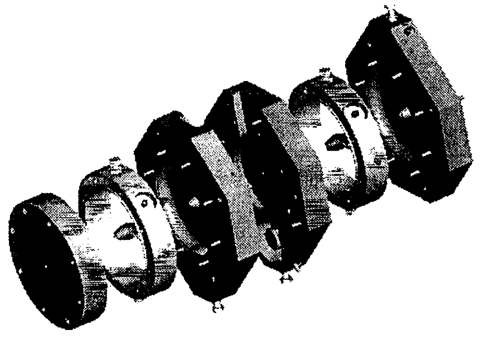

Figure 3: Exploded view of the CCDTL cold model

The advantages of this structure are easy access and alignment for the quadrupoles, low construction cost, stable $\pi/2$ mode operation, continuous focusing lattice, and simple RF distribution with one klystron per tank. However, at this relatively low frequency the real-estate shunt impedance of the CCDTL remains similar to that of a conventional DTL.

5 SUPERCONDUCTING SECTION

The beam dynamics design of the SC section has been re-optimised for minimum emittance exchange, maximum stability against mismatch and simplified layout for minimum cost [10]. The length of the focusing periods, each containing a quadrupole doublet of 120 mm aperture diameter, is increased along the linac to a maximum of eight cavities (two cryostats) per period above 1.1 GeV. This corresponds to 13 to 21 $\beta\lambda$ per period and keeps the maximum longitudinal phase advance below 65°. The relatively low longitudinal phase advance allows the full current tune ratio (σ_l/σ_t) to be kept below 0.8 thus avoiding emittance exchange between the longitudinal and the transverse plane [11]. At the same time the maximum transverse phase advance can be held below 85° to avoid particle lattice instabilities. A smooth phase advance per metre in both planes ensures a minimum mismatch in the transition areas between sections, which are matched with existing beam line elements (Fig. 4). Mismatch simulations with 50 M particles show only moderate emittance growth even for strong initial mismatch (30% radial) [10].

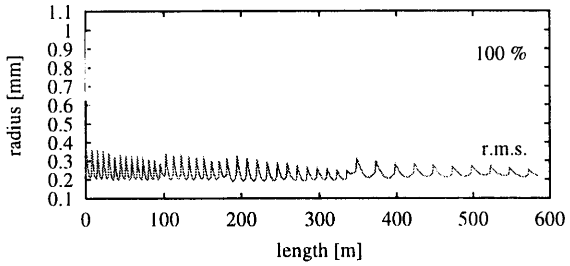

Figure 4: r.m.s. and 100% beam radii in the SC section

6 PULSED OPERATION

A test was performed to demonstrate that the CW LEP klystrons could be operated in pulsed mode for the SPL. The required SPL pulse sequence (Fig. 5) was obtained by pulsing the modulating anode, adding 8 μF storage capacitors in parallel to the klystron and making some minor modifications to the tetrode modulator in order to decrease the rise time. Simulations show that up to 12 klystrons can be connected in this way to one 100 kV LEP power supply. The power required is between 500 and 810 kW per klystron, leaving some margin from the 1 MW maximum power for regulation and for losses in the waveguides.

A major concern for pulsed operation is the effect of cavity detuning by mechanical vibrations excited by Lorentz forces. A compensation based on the vector sum feedback (4 cavities per klystron) can alleviate the problem but nevertheless can only compensate for vibration amplitudes below 40 Hz [2]. Moreover, recent simulations [12] show that a control instability by spontaneous symmetry breaking can rapidly grow in a vector-sum stabilised multi-cavity system leading to chaotic motion of the cavities. A mathematical analysis shows that in such a control loop any microscopic random scatter during one pulse is fed back over mechanical cavity oscillation, RF detuning, forced voltage vector sum and Lorentz force to a new scatter during the following pulse and a growing series cannot be excluded [13].

Possible remedies are mechanical actuators (piezos) counteracting the Lorentz detuning or fast high-power phase and amplitude modulators with sufficient range. A prototype modulator based on magic-T's and ferrite-loaded waveguide sections is on order.

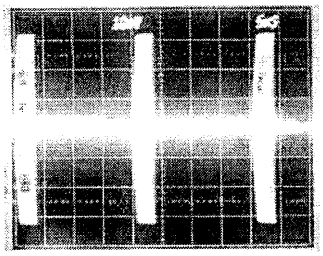

Figure 5: RF output power for a pulsed LEP klystron (800 kW, 5 ms/div)

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