A HIGH-POWER SUPERCONDUCTING H^- LINAC (SPL) AT CERN

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Abstract

The conceptual design of a superconducting H^- linear accelerator at CERN for a beam energy of 2.2 GeV and a power of 4 MW is presented. Using most of the superconducting RF cavities available after the decommissioning of LEP, it operates at 352 MHz and delivers 10^{16} protons per second. At an early stage it will upgrade the performance of the PS complex by replacing Linac2 and the PS booster, by injecting protons directly into the PS. The brilliance of the LHC beam will thus be tripled. The present ISOLDE facility can be supplied with five times more beam current than to-day. In conjunction with an accumulator and a compressor, the purpose of its design is to be the proton driver of a neutrino factory at CERN.

1 INTRODUCTION

The ever-increasing flux of secondary particles requested by physics experiments can only be met using higher power proton beams. These requests have re-activated the study of a Superconducting Proton Linac (SPL) already proposed as an upgraded injector for the CERN PS. Triggered by a previous proposal to re-use the LEP-RF hardware for the proton driver of an energy amplifier [1][2], this machine was originally intended for accelerating mainly protons.

The following studies show the advantages of a common H^- operation for all users. The linac parameters must be defined to suit the following possible uses:

- PS ring for the LHC and other high-intensity fixed-target applications
- Increased flux (~ × 2) for CERN Neutrinos to Gran Sasso (CNGS)
- Increased flux for Anti-proton Decelerator
- Increased flux for Neutron Time of Flight (TOF) experiments
- ISOLDE: increased flux, higher duty cycle, multiple energies
- Driver for a future neutrino factory
- Generation of a conventional neutrino beam for medium-distance experiments (~ 100 km)

2 CHOICE OF PARAMETERS FOR THE LINAC

The definition of the final linac energy, as for the pulsing parameters (pulse repetition rate and length) is the result of a compromise between many requirements [3]. Although by adding up all the available LEP cavities an energy of about 3 GeV could be reached, a final linac energy of 2.2 GeV has been selected slightly above the pion production threshold, in order to release to some extent the space-charge problems in the accumulator without an excessive increase in the length and cost of the machine (Table 1).

Table 1 Main linac design parameters

Particles	H^-
Kinetic energy	2.2 GeV
Mean current during pulse	13 mA
Repetition frequency	50 Hz
Beam pulse duration	2.8 ms
Number of particles per pulse	2.27×10^{14}
Duty cycle	14%
Mean beam power	4 MW
RF frequency	352.2 MHz
Chopping factor	40%
Transverse r.m.s. emittance (norm.)	0.6 μm

In the same way, a linac mean current during the pulse of 13 mA has been selected as a compromise between many factors. A lower current reduces the number of klystrons needed by the superconducting section, at the cost of an increase in the complexity of the power distribution network and in the sensitivity of the linac to vibration errors in the superconducting cavities. It would also lead to a longer linac pulse, increasing the number of turns required at injection in the accumulator and the time for dangerous instabilities to develop. In contrast, a higher current improves the power efficiency of the room temperature section and reduces the number of injected turns, but also introduces space-charge problems at the low-energy linac end and increases the RF power to the superconducting section, requiring a higher number of klystrons. A current of 13 mA is a good compromise between these factors and has the additional advantage that no modifications are needed to the input couplers of the LEP cavities.

The selection of beam power, energy and pulse current determines the linac duty cycle, 16.5% in this case. The choice of the repetition rate is determined by the superconducting cavities. In a superconducting linac the cavities are largely overcoupled, and the rise time of the fields in the structures is of the order of a few milliseconds. In order to establish the field in the cavities, a large amount of RF power is reflected from the couplers and has to be absorbed into the loads. A pulsed superconducting linac is therefore more effective in terms of the conversion of mains power into beam power at low repetition rates. On the other hand, a lower repetition rate means a longer beam pulse, which could dangerously increase the number of turns for accumulation in the following ring. A repetition rate of 50 Hz and a pulse length of 2.2 ms have therefore been selected, corresponding to 660 injection turns into the accumulator. Simulations of injection into the accumulator indicate that this number of turns is still acceptable, whilst the repetition rate, 3/2 of the mains frequency, remains below the 100 Hz mechanical oscillation frequency of the LEP cavities.

The RF frequency for the high-energy part of the linac is determined by the existing LEP cavities and klystrons at 352 MHz. For the new superconducting cavities that have to be constructed for a beta lower than unity, the choice of the same frequency allows us to take advantage of the CERN niobium sputtering fabrication technique and to re-use couplers and cut-off tubes recuperated from LEP units. For the structures at room temperature, this frequency offers a good compromise between the large dimensions and easier fabrication tolerances of lower frequencies and the better shunt impedance of higher frequency structures. The RF cavities can thus have the same frequency all along the linac, simplifying the RF system and avoiding frequency jumps which are dangerous for the beam dynamics. The frequency of 352.2 MHz also lies at the boundary between klystron and tetrode amplifier technology, providing additional flexibility in the design of the RF system and the possible use of both types of power source. For the sections with high-power cavities (the room temperature structures and the high-energy part of the superconducting linac) the 1 MW klystrons of LEP are well suited, with simple (from one to six cavities per klystron) RF distribution networks. For the cavities of the low-beta superconducting sections, where the power per cavity is lower and the beam is very sensitive to errors in cavity field, it is more convenient to use 100 kW conventional tetrode RF amplifiers, each one feeding a single cavity.

The transverse emittance of the linac must be carefully controlled for two reasons, to minimize losses and to achieve the high beam brightness required by the LHC. An r.m.s. normalized emittance of 0.2 π mm mrad is considered to be a reasonable goal for the H^- source, whilst in order to keep a large safety margin, a design emittance of 0.6 π mm mrad has been adopted at the input of the accumulator ring. An intermediate design emittance of 0.4 π mm mrad has been assumed for the different linac sections.

A major concern in the design of the linac is the reduction of beam losses, in order to avoid activation of the machine and irradiation of the environment. The main constraint is to maintain losses below the commonly agreed limit for hands-on maintenance of 1 W/m, corresponding for this design to a relative loss per metre of 2.5×10^{-7} at the high-energy end, or 0.5 nA/m. The shielding is dimensioned to keep radiation at the surface below the limit for public areas, assuming a 1 W/m loss in the machine.

3 REFERENCE DESIGN OF THE LINAC

The present design makes extensive use of the large inventory of RF equipment dismantled from LEP. The 800 m long superconducting linac that accelerates the H^- ions to 2.2 GeV re-uses all klystrons and 60% of the LEP modules in its high-energy part (see Fig 1). New $\beta = 0.52$ and $\beta = 0.7$ acceleration modules are assumed between 120 and 390 MeV. Between 390 MeV and 1 GeV, LEP cryostats are re-used, equipped with new five-cell, $\beta = 0.8$ cavities.

Below 120 MeV, room-temperature accelerating structures are employed. Leaving the ion source at 45 keV, the H^- beam is bunched at 352 MHz and accelerated to 3 MeV in an RFQ. It then passes through a transfer line equipped with fast deflecting electrostatic kickers ("choppers") which eliminate the unwanted bunches onto a collector and provides the proper time structure for an optimum longitudinal capture in the accumulator. Further acceleration to 120 MeV is made cascading an RFQ, a Drift Tube Linac (DTL) and a Cavity Coupled Drift Tube Linac (CCDTL).

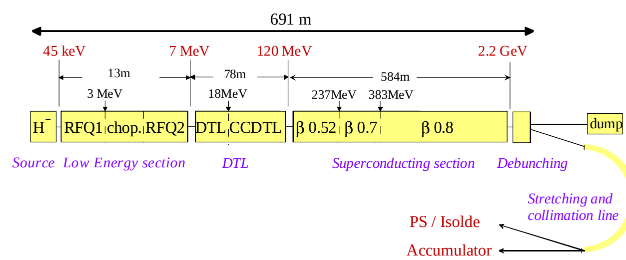

Figure 1: SPL block diagram

Protons are accumulated at 2.2 GeV over 660 turns in the accumulator ring, using charge exchange injection [4]. Of the 146 buckets generated by the 44 MHz RF system 140 are progressively populated by up to 1.08×10^{12} p/b. At the end of accumulation, the bunches are fast ejected and transferred into the compressor ring, where bunch compression takes place in seven turns, with 2 MV at 44 MHz and 350 kV at 88 MHz. The 1 ns rms long bunches are then ejected on to the target.

On the CERN site (see Fig. 2), the accumulator and the compressor rings are situated at the location of the ex-ISR, and existing tunnels are re-used for the transfer of the SPL beam to the PS and to the ISOLDE experimental facility.

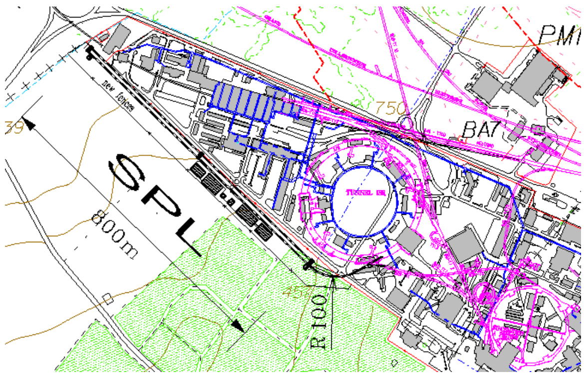

Figure 2: Proton driver complex on the CERN site.

4 SUPERCONDUCTING LAYOUT OF THE LINAC

The superconducting part of the linac covers the energy range between 120 MeV and 2.2 GeV. It is composed of four sections made of cavities designed for $\beta = 0.52$, 0.7, 0.8 and 1 [5]. The cavities at $\beta = 0.52$ and 0.7 contain four cells, whilst the $\beta = 0.8$ cavities are made of five cells, to allow the existing LEP cryostats to be re-used. For the two lower β sections, new cryostats have to be made, which will contain four cavities in the $\beta = 0.7$ section and three cavities in the $\beta = 0.52$, to shorten the focusing period at low energy.

The cavities at $\beta = 0.8$ and $\beta = 0.7$ can be produced with the standard CERN technique of niobium sputtering on copper. A β of 0.7 is considered as the minimum that can be achieved with this technique. The cavities at $\beta = 0.52$ could be made instead in bulk niobium or with a modified sputtering technique, with technologies still to be developed.

The layout of the superconducting linac is given in Table 2. It has been assumed that in the linac the LEP cavities will operate at 7.5 MV/m, the mean gradient achieved during the 1999 run. For the $\beta = 0.8$ cavities that have to be specifically built for the linac, special cleaning procedures to achieve high gradients can be applied, and a design gradient of 9 MV/m can be foreseen. During tests, a $\beta = 0.8$ cavity has already reached gradients of 10 MV/m. The Q_{ext} assumed for the different sections includes a 20% overcoupling with respect to the theoretical value to increase the bandwidth and to reduce cryogenic losses at the end of the pulse.

The cavities in the $\beta = 0.52$ and 0.7 sections are fed by individual 100 kW tetrode amplifiers, in order to minimize the amplitude and phase errors due to mechanical vibrations in the low beta range where the still large β variation per cavity make the beam very sensitive to errors. From the $\beta = 0.8$ section the LEP 1 MW klystrons can be used. One klystron feeds four cavities in the $\beta = 0.8$ section and six cavities in the $\beta = 1$ section, via 2/3 – 1/3 power splitters. The RF power required from each klystron in these sections goes from 470 to 750 kW, leaving enough margin for the vector-sum compensation of cavity errors. Correct phasing between cavities is achieved by changing the waveguide length.

This scheme re-uses 108 cavities out of the 288 installed in LEP. Considering that eight more LEP cavities are needed for the bunch rotation before injection into the accumulator, only 40% of the existing LEP cavities are needed in the present linac design.

5 ONGOING ACTIVITIES

Theoretical work is concentrated on the refinement of the SPL design and the solution of the remaining problems, in close relation with the development of critical hardware (Table 3). In particular, a recent study has underlined that more work is required for a proper control of the field in the cavities when multiple superconducting resonators are driven by a single klystron [6].

Improvements to the reference design [3] are being studied, based on reducing the repetition rate to 50 Hz, generalizing the use of $\beta = 0.8$ cavities up to 2.2 GeV and increasing the beam current during the pulse. Preliminary investigations of the consequences for the accumulator and compressor rings have not revealed any dramatic problem, apart from more stringent impedance requirements, because of the microwave instability and the need for more efficient countermeasures against electron clouds and their effect.

Alternatively, if the production of pions from a 2.2 GeV proton beam proves to be unfavourable, or if difficulties arise in the neutrino complex, due to the choice of 23 ns spaced bunches, the design of the proton driver could change and make use of Rapid Cycling Synchrotron(s) (RCS) [7].

Table 2 Layout of the superconducting sections

Section	Design beta	Gradient [MeV/m]	No. of cells/cavity	Cryostat length [m]	Input Energy [MeV]	Output Energy [MeV]	No. of cavities	No. of cryostats	No. of tubes	RF Power [MW]	Length [m]
1	0.52	3.5	4	5.76	120	236	42	14	42 T	1.5	101
2	0.70	5	4	8.46	236	383	32	8	32 T	1.9	80
3	0.80	9	5	11.29	383	1111	52	13	13 K	9.5	166
4	0.80	9	5	11.29	1111	2235	76	19	19 K	14.6	237
TOTAL							202	54	32K+74T	27.9	584

Table 3: Studies for the proton driver

Item	Main issue
H^- source	Design
Chopper	System design
RT linac	Structures development
SC cavities	Pulsed test of cavities Dev. of low β structures
Klystrons and supplies	Pulsed operation
Servo-systems	Field stab. in pulsed mode
Beam dynamics	Optimization

An R&D programme has also been established to investigate [8]

- The behaviour of the cavities with respect to Lorentz forces under pulsed regime
- The frequencies of the main mechanical resonances
- The requirements for stability of the cryogenics system
- The utility of active compensating devices such as piezo actuators

6 NEUTRINO FACTORY SCHEME AT CERN

The neutrinos delivered by a neutrino Factory result from the decay of high-energy muons circulating in a storage ring. These muons are themselves decay products of the pions produced by the interaction of a proton beam with the atoms of a target.

In the CERN scheme (see Fig. 3), the H^- beam supplied, at 50 Hz, by a 2.2 GeV Superconducting Linac (SPL), is injected for 2.2 ms in an accumulator ring whose proton bunches are afterwards shortened in a compressor ring. A mean flux of 1.1×10^{16} protons/s (or ~ 10^{23} protons/year, taking 10^7 s/year) is delivered to the target.

A liquid metal jet is used for the target, inserted inside a magnetic horn for collecting pions over a broad kinetic energy range (100 to 300 MeV) and a large solid angle. These pions, as well as the muons resulting from their decay, are transported in a 30 m long decay channel with transverse focusing by a 1.8 T solenoidal field. After passing through this channel, the muon bunches traverse a series of 44 MHz cavities which (by “rotation” in the longitudinal phase plane) reduce their energy by a factor of 2. the beam then passes through liquid hydrogen cells for ionization cooling, and 44 and 88 MHz RF structures for recovery of longitudinal energy. After this treatment, 250 m behind the target, each transverse phase plane is multiplied by 4). Solenoidal focusing is still used in the following linear accelerator which operates at harmonics of 44 MHz to increase the energy up to 2 GeV.

A cascade of two Recirculating Linear Accelerators (RLA), equipped with LEP-type 352 MHz superconducting RF cavities providing a total of 12 GeV of single-pass energy gain, accelerate this beam in four turns up to 50 GeV.

The 3.3 μs burst of 50 GeV muons is injected into the 2 km circumference muon storage ring, where it is left to decay until the next burst is available, 13.3 ms later. More than 10^{14} μ/s enter this ring, and approximately 3×10^{20} neutrinos are then generated every year in each of the long straight sections oriented towards remote experiments, thousands of kilometres away.

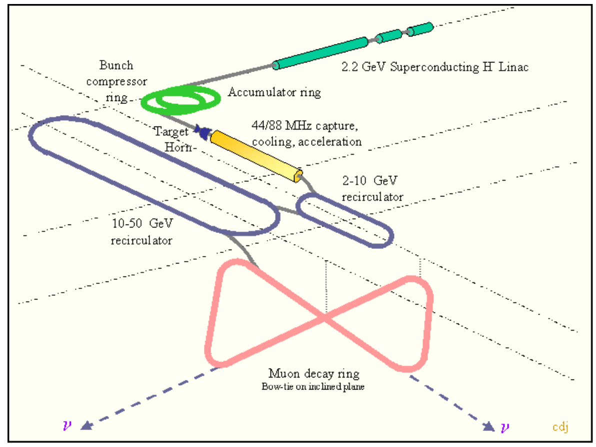

Figure 3: Layout of the CERN reference scheme for a Neutrino Factory

7 CONCLUSION

It is quite encouraging to report on the amount of work carried out in the last three years for this project, in the CERN context, where the LHC project has top priority and the resources are diminishing drastically. This paper shows the great potential of a high-energy, high-power proton linac at CERN, as well as the great value of the LEP RF knowledge and equipment for the Organization.

The R&D programme is going to continue in order to improve the quality of the present design and test set-ups are already available in order to verify the viability of hardware components.

8 REFERENCES

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