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Abstract

A superconducting proton linac delivering a mean beam power of 4 MW is being considered at CERN as a potential front end for the proton driver of a neutrino factory. Built mostly with the rf equipment to be recuperated from LEP after its decommissioning, it would provide H- ions at a kinetic energy of 2 GeV, which is adequate for the production of pions and muons. The requirements specific to a neutrino factory are summarized, and the basic design of such a linac-based proton driver is given. Subjects of further studies are outlined.

Introduction

Superconducting proton linacs are efficient at providing a high beam intensity up to slightly more than 1 GeV kinetic energy and they are exploited in most projects aiming at high beam power [1, 2, 3, 4]. A previous study [5] has shown that a 2 GeV superconducting linac can be built at CERN using the large inventory of 352 MHz rf and superconducting cavities available after the decommissioning of LEP-2. The existing complex of high energy accelerators as well as the radio-active ion facility (ISOLDE) would benefit from the higher beam performance and repetition rate, while the renewal of the low energy part of the accelerator chain would positively improve the long term reliability. Moreover, the proposal was recently made [6] to design that linac for a higher mean beam power and use it as the front-end of a proton driver for a neutrino factory [6].

However the time structure of the beam required by the complex of muon accelerators behind the target is not directly feasible out of a linac, and special techniques must be implemented making use of an accumulator ring. These requirements were highlighted at a recent workshop [7] and possible solutions have since been envisaged.

Requirements of a neutrino factory

Existing studies for muon colliders and neutrino factories have concluded that 4 MW of proton beam power is adequate for achieving their physics goal [8]. During the first workshop on neutrino factories [7] the working group on targets quickly established that:
- this is the maximum power any conceivable target could reasonably handle,
- pion and consequently muon production in the low energy range depends mainly on beam power for $T \geq 2$ GeV.

Consequently the 4 MW figure has been used as a common specification for all proton driver scenarios.

The time structure of the pions/muons beam after the target must comply with the needs of the muon acceleration complex. Table 1 summarizes the requirements for the proton beam hitting the target, assuming that the muon beam is treated as foreseen in reference 7. This corresponds to a peak power during the beam pulse exceeding 10 GW (assuming the fastest tolerable repetition rate of 100 Hz, and a beam pulse of 4 μs) which is far outside the capability of an rf linac. An accumulator ring is therefore absolutely necessary.

Table 1: Requirements imposed on the proton beam time structure

Parameter	*Value*	*Source of constraint*
Bunch duration (rms)	~ 1 ns	Uncertainty in pion decay time
Time interval between bunches	> 100 ns	First bunch rotation after target
	> 300 ns	Second bunch rotation
Total duration of beam pulse	a few μs	Revolution time in the muon storage ring (single turn injection)
Beam pulse repetition rate	≤ 100 Hz	Background rejection in the distant experiments
		Power consumption in the muon accelerator complex

Since the longitudinal emittance of the bunches must be small, the accumulation process has to be able to provide the ultimate density tolerable in the ring. Charge exchange accumulation is the only possible solution and hence the linac must deliver H^- ions.

Moreover, gaps are necessary in the bunch train received by the accumulator to minimise loss and optimise longitudinal emittance of the accumulated beam. A fast beam chopper is therefore needed for precise control of the bunch train.

Proton driver based on a superconducting proton linac (SPL)

SPL design

Based on the design work published in 1998 [5], the proposed linac has the characteristics listed in Table 2. The beam power during the pulse is 20 MW (10 mA at 2 GeV) so that a 20 % duty factor is used to deliver the specified mean beam power of 4 MW (for example 2 ms pulses at 100 Hz repetition rate, or 4 ms at 50 Hz).

Table 2: Superconducting linac characteristics

Energy	2	GeV
Mean current	10	mA
Duty cycle	20	%
Beam power	4	MW
Maximum bunch current (maximum number of charges per bunch)	40 (7×10^8)	mA
Transverse emittance (rms, norm.)	0.6	μm
Longitudinal emittance (total)	80	μeVs
Rms bunch length at output	6	ps

The schematic layout of the Linac is shown in Figure 1. Superconducting rf structures are used in the range of kinetic energies between 100 MeV and 2 GeV, while the lowest energy part operates at room temperature.

The H^- beam from the source is bunched and accelerated up to 2 MeV by a first Radio Frequency Quadrupole (RFQ) at 352 MHz. At that energy, a fast travelling wave electrostatic chopper (rise and fall times < 2 ns) eliminates the unwanted bunches and provides the optimum bunch train for filling the accumulator with a minimum of uncontrolled beam loss and induced activation. A promising design with the required rise time is being developed at Los Alamos for the SNS project [9]. For a given mean current of 10 mA during the pulse, the required source current as well as the bunch current depend upon the chopping factor. The value of 40 mA assumed in Table 2 is possible with existing H$^-$ sources and space charge effects are tolerable. A second RFQ brings the energy up to 7 MeV. Dedicated sections inside both RFQs provide matching to the chopper and to the second RFQ.

Between 7 MeV and 20 MeV, the beam is accelerated in a standard room temperature Drift Tube Linac (DTL) section. Above 20 MeV less conventional DTL sections are used with the focusing quadrupoles either in only a fraction of the drift tubes (Quasi-DTL) or outside of the DTL tanks (Separated-DTL).

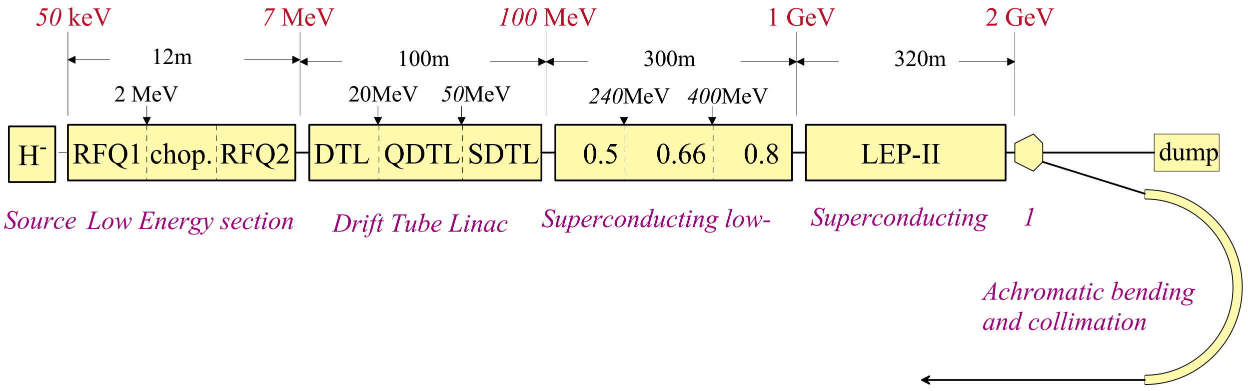

Figure 1: Schematic layout of the SPL

The superconducting (SC) structure starts at 100 MeV. It is sub-divided into 4 sections made of cavities optimised for beta 0.48, 0.66, 0.8 and 1 respectively. The 4-cell cavities at beta 0.48 will be fabricated in bulk niobium, while the others use the standard CERN technology of niobium sputtering on copper. The 4-cell cavities at beta 0.66 exploit some components recuperated from the LEP-2 cavities like the input coupler, while the 5-cell beta 0.8 cavities are housed in LEP-2 cryostats. Existing LEP-2 cavities are directly employed along the 320 m long beta 1 section. The existing input rf coupler is perfectly compatible with the SPL current of 10 mA.

The effective accelerating gradients in the four sections are shown in Figure 2. In spite of the fact that the present LEP run has demonstrated that LEP-II cavities can operate above their design value of 6 MV/m and that a further improvement could be expected in pulsed mode, the SPL design is based on a conservative value of 7 MV/m for the beta 1 section. The reason is that the existing LEP waveguide distribution system, based on 8 cavities per klystron, can be re-used without modification. In case gradients higher than 10 MV/m could be reached in pulsed mode by at least part of the LEP cavities, a layout with 4 cavities per klystron and a much shorter linac would become the natural choice. For the 5-cell beta 0.8 cavities, instead, a gradient of 9 MV/m can be reasonably assumed, extrapolating from the CW measurements done on a test cavity. This gradient would need 4 cavities per klystron. The section made of beta 0.66 cavities has a much lower gradient, based on the tests done on a niobium-sputtered cavity, and again 8 cavities per klystron would be appropriate. To overcome the problem related to sputtering at low angles, a new beta 0.7 test cavity is in production, with a geometry optimised for the sputtering process. This type of cavity is expected to be able to run at higher gradients, and finally to replace the entire beta 0.66 section in the SPL design.

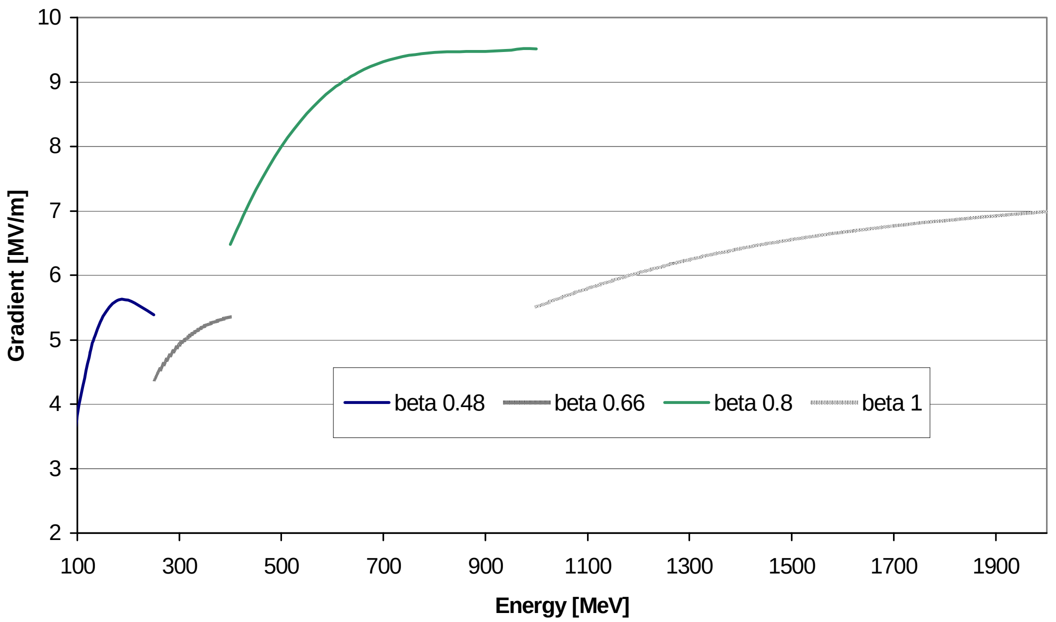

Figure 2: Effective gradients in the 4 sections of the superconducting linac

Pulsing superconducting rf structures presents some difficulties due to microphonic vibrations which randomly detune the resonators and perturb the phase and amplitude of the accelerating field. However simulations show that adequate servo-systems can in principle reduce these effects to acceptable levels, especially in the case of the stiff Nb-sputtered copper cavities [5]. On the other hand, pulsed operation should allow for higher gradients than in CW (tests are foreseen in the near future), and it should also help operate at lower *Q*-values, the static cryogenic losses being dominant.

The hardware components of the linac and some of their characteristics are listed in Table 3. Each of the 33 klystrons used in the superconducting part operates at a maximum power of 800 kW, with a comfortable safety margin for phase and amplitude control with respect to their maximum power of 1.3 MW.

Table 3: SPL hardware

Section	Output energy [MeV]	Frequency [MHz]	No. Cavities	RF Power [MW]	No. Klystrons	Length [m]
RFQ1	2	*352.2*	1	0.5	1	2.5
RFQ2	*7*	352.2	1	0.5	1	4
DTL	*100*	352.2	29	5.8	6	99
SC β=0.48	*235*	352.2	40	1.4	5	89
SC β=0.66	*360*	352.2	24	1.2	3	60
SC β=0.8	1010	352.2	48	6.5	12	148
SC LEP-2	2000	352.2	104	9.9	13	320
TOTAL			303	25.8	41	~723

Each klystron feeds 8 cavities in the beta 0.48, 0.66 and 1 sections, and 4 cavities in the beta 0.8 section which works at a higher gradient. The power per klystron in the two lower beta sections is deliberately kept low (200-400 kW) to limit to 8 the number of cavities each one of them feeds and ease the regulation problem and the complexity of the distribution network. A total of 26 LEP-2 4-cavity modules with their cryostats are re-used, i.e. only 36% of the 72 presently installed in LEP. Moreover, 12 cryostats are recuperated for the beta 0.8 modules, giving a total of 38 cryostats that can be re-used (53%). Most of the LEP-2 klystrons (36 plus some spares), the high voltage distribution boxes, the high voltage high power converters and a large fraction of the waveguide distribution system are recuperated, making up about 90% of the linac rf system.

The management of beam losses is a major concern for the design of such a high intensity linac. The general agreement among accelerators experts is that in order to allow hands-on maintenance of the machine, distributed losses have to be kept below 1 W/m. For the SPL, this means a relative loss of only 2.5×10^{-7} per meter at 2 GeV. Particular care has therefore to be put into the design in order to avoid the migration of particles into diffused halos that would lead to uncontrolled losses along the machine. This can be achieved by preventing mismatches between sections, making use of proper matching units and by avoiding abrupt changes in the focusing parameters. The important role played by space charge in halo formation favors in this respect the lower bunch currents. For example, in the SC section the beam dynamics is space charge dominated for bunch currents exceeding 40 mA. An important feature of the superconducting cavities used in the SPL is the large aperture (between 200 and 240 mm), that allows most of the halo particles to be transported up to the end of the linac in the transport line, where they can be properly removed by special collimators.

Accumulation / compression scheme

The capabilities of the accumulation and compression set-up will probably dictate a number of characteristics of the proton driver, like the minimum number of bunches, the maximum number of protons per pulse and consequently the minimum repetition rate. Work is progressing in that direction but no conclusion can be drawn yet concerning feasibility. Although different designs are under investigation, they share the basic principles illustrated in Figure 3.

In the case represented, the linac is pulsed every 10 ms (100 Hz) and provides a beam pulse of 2 ms duration. This beam pulse is accumulated in a first ring, using charge exchange injection. Assuming a ring which fits inside the existing ISR tunnel at CERN, the revolution time is 3.4 μs so that 590 turns are injected in 2 ms. The pulse is made up of bursts of 30 consecutive 1 ns long bunches of 6×10^8 protons, spaced by one wavelength at 352.2 MHz (2.84 ns) with a periodicity of 284 ns (100 wavelength at 352.2 MHz). These bursts build up the intensity in 12 macro-bunches (~ 85 ns long) circulating in the accumulator. After the linac pulse each bunch is made up of 1.04×10^{13} protons, and the accumulator contains a total of 1.25×10^{14} protons.

A promising idea for achieving a high enough longitudinal density of protons is for the accumulator to be isochronous. Bunches can be progressively populated without spreading in azimuth and in principle without the need for an rf system.

Sketches of a macro-bunch in the longitudinal phase plane during accumulation (a) and after bunch compression (b) are shown in Figure 4. At the end of the 2ms injection process, macro-bunches are long and have a small energy spread (estimated parameters: T_B=85 ns, $\Delta p/p_{ACC}$=2.8×10^{-3}). Conservation of longitudinal emittance imposes that:

$$T_B \times \Delta p / p_{ACC} = T_{BCOMP} \times \Delta p / p_{COMP}$$

so that, for given bunch lengths during accumulation and on the target, the final momentum spread is directly proportional to the momentum spread at the end of accumulation.

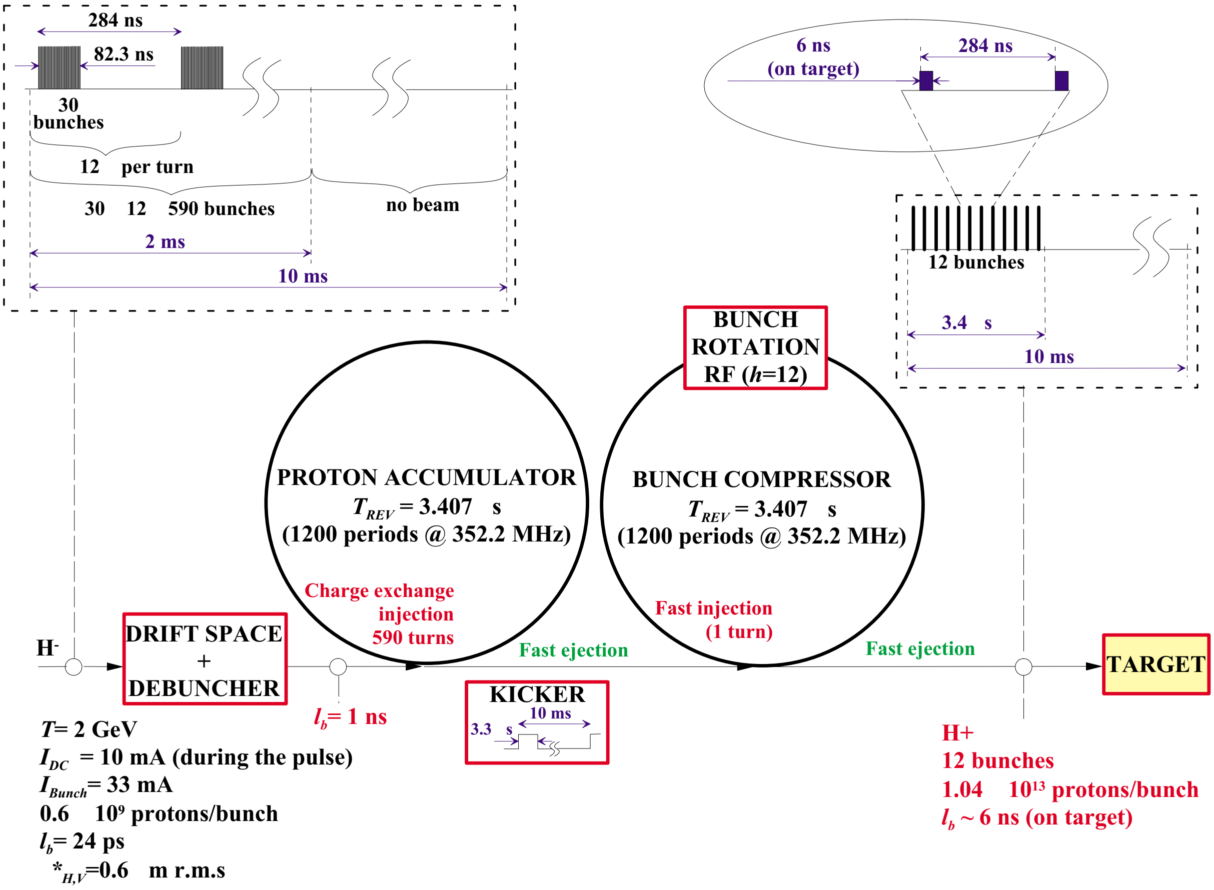

Figure 3: Beam accumulation and bunch compression scheme

Since the bunch sent to the target must be short it has to have a large $\Delta p/p$ (estimated parameters: T_{BCOMP}=6 ns, $\Delta p/p_{COMP}=4\times10^{-2}$). Such a large $\Delta p/p$ is difficult to handle in the accumulator ring which would need a very large physical aperture because of its large momentum compaction factor and large size. The proposal is therefore to transfer the 12 bunches immediately after the end of accumulation into a compression ring, with a much smaller momentum compaction factor and adequate rf for bunch rotation.

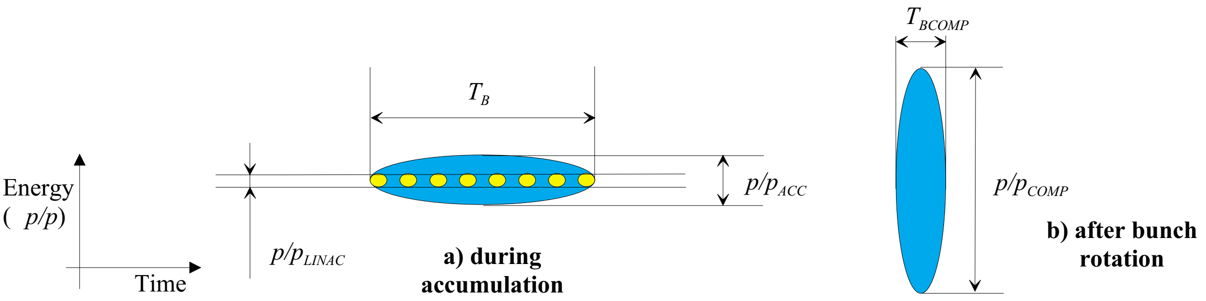

Figure 4: Macro-bunch in the longitudinal phase plane

Acceptances of such an isochronous ring, beam stability in all planes, design of a realisable charge exchange injection scheme are among the numerous issues being addressed to evaluate the feasibility of such an accumulation/compression set-up.

Conclusion

A superconducting 2 GeV linac is capable of efficiently delivering the 4 MW of beam power required on the target of a neutrino factory. But adequate beam characteristics also depend upon the design of the accumulator and compressor rings which is still in progress.

Moreover, experimental results are necessary to precisely quantify the relative efficiency of pion collection from protons of various energies and help decide upon the optimum proton beam energy.

Finally, since research and development concerning devices and concepts used for the muon accelerator complex have only recently begun, new ideas are likely to appear and modify the requirements on the proton beam characteristics. In this respect, the flexibility of a linac-based facility makes it superior to a facility built with rapid cycling synchrotrons.

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