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Low energy proton driver for a neutrino factory

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LOW ENERGY PROTON DRIVER FOR A NEUTRINO FACTORY

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In contrast with other designs where the proton driver of a muon collider or of a neutrino factory is a synchrotron of energy up to 50 GeV, it is shown that a low-energy and high-power system inspired by neutron spallation sources can meet the requirements of a neutrino factory. Such a system consists of a 2 GeV linac, a fixed field accumulator that produces an adequate time structure and a compressor that reduces the bunch length to the final value of a few nanoseconds.

1 Introduction

The standard technique to produce intense muon beams relies on pion decay. The dominant parameter for pion production is the beam power on target. One is thus free to choose a beam of high energy with relatively low intensity or a more intense beam at a lower energy. The choice of a low energy imposes the use of a heavy target to produce positive and negative pions in approximately equal amounts. At CERN, two specific aspects triggered the study of a low energy machine. Most of the RF cavities and the klystrons of the Large Electron Positron (LEP) collider are not needed for LHC and can be recycled for a new project. In addition, the ISR tunnel could be re-used to house a new machine. The conversion of the 20 MW LEP RF system into a proton linac had already been studied within the LHC context¹ mainly to get a high beam brilliance. However, the investment in a superconducting linac is not justified for a machine such as LHC which needs to be filled only a few times a day. Totally different is the production of intense muon beams which needs the proton beam on the target² permanently, and then the investment makes full sense. The linac alone does not provide the beam time structure adapted to a neutrino factory. The correct sequence of intense proton bunches is performed in a large-size accumulator that neatly fits into the ISR tunnel. The final bunch length is obtained in a dedicated machine, the compressor, located in the same tunnel as the accumulator. The three machines are discussed in sequence.

2 Superconducting linear accelerator

Since the original proposal, the design of the linac has evolved. Its acronym, SPL for Super-conducting Proton Linac, is now somewhat misleading because it is actually an H^- linear accelerator. Its most recent status is being published³.

2.1 Layout

After a general survey of the various possible locations of the linac on the CERN site, it appeared that the most advantageous position would be just outside the west area of the Meyrin-St Genis site along an existing road (Fig. 1). The civil engineering consists of the tunnel for the machine, properly shielded, the klystron

Figure 1. The superconducting linac and the ISR tunnel on the CERN site.

gallery and the refrigeration hall. The components of the linac are shown in Fig. 2. The machine is classical up to 120 MeV and superconducting cavities are used at higher energy. The low- β cavities need a special development. Successful tests have been performed at $\beta = 0.8$ and at $\beta = 0.7$. The cavity operating at $\beta = 0.52$ represents a real technical challenge. The LEP cavities are kept unchanged for kinetic energies higher than 1 GeV.

Figure 2. Layout of the superconducting linac.

2.2 Parameters

The main concern for high-power machines is to keep the beam losses at a very low level ($\sim 1W/m$) so that the activation is weak enough to allow hands-on maintenance.

nance. This constraint applies to the linac and the downstream machines as well. The beam optics has to be very carefully matched in all the sections of the linac. Energy jitter would be a source of contamination for the accumulator. Its effect is substantially reduced by collimation in the achromatic bending section. The parameters are listed in Table 1.

Table 1. Parameters of the linac.

Ion	Kinetic Energy	Mean Pulse Current
H^-	2.2 GeV	11 mA
Duty Cycle	Mean Beam Power	Pulse Frequency
20 %	4 MW	75 Hz
Pulse Length	H^- per Pulse	Bunch Frequency
2.2 ms	$1.51 \cdot 10^{14}$	352.2 MHz
Filled (Empty) Buckets	H^- per Bunch	Longitudinal Emittance
5 (3)	$3.3 \cdot 10^8$	10^{-4} eVs
Horizontal / Vertical rms Emittance	ΔE jitter during Beam Pulse	ΔE jitter between Pulses
$0.6 \text{ } \mu\text{m}$	$\pm 0.2 \text{ MeV}$	$\pm 2 \text{ MeV}$

The time structure of the beam is a compromise between the requirements of the accumulator and the efficiency of a superconducting linac. Among the several schemes discussed, especially at a higher repetition frequency of 100 Hz, the present one has been chosen for its better efficiency. The chopper located between the two RF quadrupoles eliminates the three eighths of the beam; the intensity of the source and the bunch current are thus not too high. The repetition frequency (75 Hz) and the pulse length are not at the optimum values for an SC linac but the main-to-beam efficiency yet low ($\sim 12\%$) is acceptable. The bunch which is 24 ps long at the exit from the linac has to be elongated by a factor 20 before entering the accumulator; a bunch stretcher is still under study.

3 Accumulator

Various designs have been investigated for the accumulator. As for the linac, the ultra low loss criterion is mandatory and the scheme of the European Neutron Spallation Source⁴ has been adapted to the proton driver of a neutrino factory. It consists of an accumulation of protons⁵ over 660 turns by conversion of H^- ions into protons in a carbon foil at injection.

3.1 Collimation and lattice

Due to the large size of the ring, the particles traverse the carbon foil only five times and it is not necessary to resort to laser stripping. The elimination of the weakly-bound electron is relatively easy but a certain amount of excited ions remain. Ionizing the hydrogen atoms is harder, and about 1 % of them are left un-stripped. Both types of particle have to be dumped right after the foil. The proton beam halo is scraped in a system of collimator and collector located roughly 160 degree betatron phase advance apart. Momentum scraping is planned in high dispersion regions. As a consequence of the collimation requirements, the lattice contains long

Figure 3. Superperiod (left) and characteristic functions (right) of the accumulator lattice.

straight sections and a triplet cell has been chosen. The horizontal and vertical β functions and the orbit dispersion (Fig. 3) have a maximum value of 23, 27 and 3.5 m respectively. The general shape of the ring is an octagon. The machine is also equipped with systems of bumpers to paint the transverse phase space and thus reduce the space charge potential.

3.2 Time structure

The time structure of the proton beam is determined by the muon collection, the cooling system and the filling of the decay ring. For a final muon energy of 50 GeV, the muon decay e-folding time is roughly 1 ms. For two e-folding times, the repetition frequency could be about 500 Hz. It is presently limited to 75 Hz for reasons of power consumption. The monochromatization and the first stage of cooling in the present scheme⁶ operate at 44 MHz, a frequency already used in the CERN PS. The same cavities are foreseen for the accumulator and they will work at the harmonic number 146. A large number of bunches (140) alleviates the space charge problems and is quite acceptable for a neutrino factory. This concept however could not be applied to a muon collider. The accumulation relies on the injection of five bunches in the same RF bucket at different synchrotron phases for each turn. The RF voltage is progressively increased from 30 to 300 kV to compensate for the repulsive Coulomb force and provide longitudinal focussing.

The final longitudinal emittance has been determined by simulation. The list of parameters is given in Table 2.

Table 2. Parameters of the Accumulator.

Circumference	Superperiods	Dipole Field
942.478 <i>m</i>	8	0.69 <i>T</i>
γ_t	η	rms Bunch Length
14.837	-0.0848	3.5 <i>ns</i>
Number of Turns	Number of Bunches	Linac Bunches per Accumulator Bunch
660	140	5
H^- per Bunch	Bunch Frequency	Longitudinal Emittance
1.110^{12}	44.02 <i>MHz</i>	0.1 <i>eV s</i>
rms Normalized Transverse Emittance	ΔQ of Linac Bunch (H, V)	ΔQ of Accumulator Bunch (H, V)
50 μm	-0.065, -0.060	-0.076, -0.07

3.3 Space-charge effects

The various possible collective instabilities have been analyzed in detail for the injected microbunch and for the macrobunch resulting from the accumulation process. It turns out that the microwave instability is the most dangerous process (Fig. 4). It was studied using a model of broad-band impedance bounded by the cut-off frequency of the vacuum chamber (~ 530 MHz) with the macro bunch in its final state of charge. The rise time of the instability is considered tolerable if it is of the order of magnitude of the accumulation time (2.2 ms). For a broad-band impedance Z/p smaller than 1Ω , the rise time exceeds 0.6 ms and simulation results confirm that no detrimental effects occur at the end of the accumulation.

4 Compressor

4.1 Bunch compression

Reducing the bunch length to its final value of 1 ns rms is performed by letting the bunch rotate in longitudinal phase space by a quarter of a synchrotron period. This operation could be thought of in the accumulator but would present a number of disadvantages. The cavities would have to be filled in a time short with respect to the synchrotron period, and of the order of 3 μs . Moreover, the high-gain RF feedback needed to compensate for the beam loading would lower the gradient

Figure 4. Variation of the microwave instability rise-time with the broad-band impedance.

achievable in the cavities. More cavities would thus be required for beam compression, which would add to the impedance budget and make the accumulator prone to microwave instabilities. For these reasons, one prefers to separate the functions of accumulation and compression at the cost of an extra ring. The parameters of the compressor are given in Table 3 and the longitudinal phase portraits of a bunch before and after rotation in Fig. 5.

Table 3. Parameters of the Compressor.

Circumference	Superperiods	Dipole Field
942.478 <i>m</i>	8	0.49 <i>T</i>
γ_t	η	Pulse Length
15.089	-0.0849	3.3 μs
Number of Turns	Number of Bunches	Bunch Frequency
8	140	44.02 <i>MHz</i>
rms Bunch Length	$\Delta p/p$ at 2σ after Compression	ΔQ after Compression
1 <i>ns</i>	$5 \cdot 10^{-3}$	-0.210, -0.197

4.2 Lattice

The compressor has the same super-periodicity and length as the accumulator . It can be located either above the accumulator or in the same plane; in the latter case, the two rings are rotated by $\pi/8$ with respect to one another. Since, the beam stays for only eight turns in the machine, it does not have time to blow up and no sophisticated collimation system is foreseen. As a result, the lattice is

Figure 5. Phase portraits as a bunch before (left) and after (right) compression.

”lighter” than the accumulator lattice and is based on doublet cells and dispersion suppressors (Fig. 6). The maximum values of the β -functions are roughly the same as for the accumulator, and the orbit dispersion is smaller. Its geometry is chosen so that the accumulator and the compressor can lie in the same plane.

Figure 6. Superperiod (left) and characteristic functions (right) of the compressor lattice.

5 Conclusion

The feasibility of a low-energy and high-power proton driver for a neutrino factory has been established. Such a system would increase the present CERN proton production by more than two orders of magnitude in an economical way. The validity of the choice of a low energy for pion production will soon be checked by the HARP experiment⁷.

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