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Linac-based Proton Driver for a Neutrino Factory

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Abstract

A Neutrino Factory Proton Driver based on a superconducting proton linac has been designed in the CERN context. The 5 GeV/4 MW H^- beam from the linac is accumulated using charge exchange injection in a fixed-energy synchrotron and afterwards transferred to a compressor ring, where bunch rotation takes place. The lattices of the accumulator and compressor are described, as well as magnet technology and RF manipulations. Critical issues related to charge-exchange injection, space-charge effects in the compressor and beam stability in the accumulator, are addressed. The analysis is focused on the baseline scenario, which provides 6 bunches on the target. Results of preliminary analysis of options with less bunches (three and one) are also presented.

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1. Introduction

According to the specification assembled in the context of the International Scoping Study [1], the Proton Driver for a Neutrino Factory must deliver 4 MW of beam power at 5-15 GeV, in a small number of short bunches (~2 ns rms) onto a production target. The CERN–proposed scenario [2] is based on the 5 GeV High Power version of the Superconducting Proton Linac (HP-SPL) which can deliver 10^{14} protons at a repetition rate of 50 Hz [3]. Two additional fixed-energy rings are needed to transform the long linac pulse into the required bunches on the target [2, 4, 5].

2. Principle

In the first ring (the accumulator), the chopped linac beam is accumulated in a few long bunches, using charge-exchange injection. The accumulator is isochronous to preserve the time structure of the linac beam, and it has no RF system to minimize impedance. Once accumulation is finished, bunches are transferred one by one to the compressor ring where bunch rotation takes place with the energy stored in the RF cavities. The ratio between the two rings is such as to guarantee the arrival of the successive bunches at the correct location in the compressor. This principle is described in Ref. [4] and sketched in Fig. 1 in the case of 6 bunches.

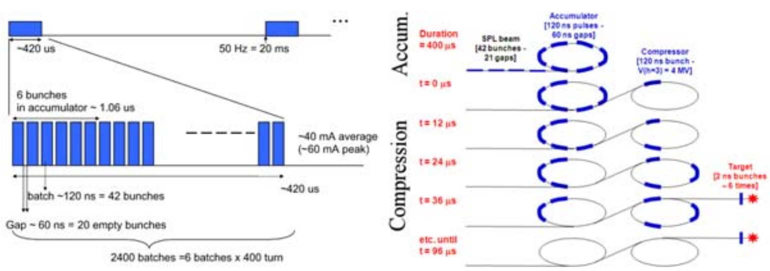

Figure 1. Principle of bunch generation with a Linac-based Proton Driver.

3. Accumulator and compressor design

Figure 2 shows the lattices of both rings in the 6 bunches case. In contrast with the accumulator which is isochronous and without RF, the compressor has large slippage factor and RF voltage for a fast phase rotation. Table 1 summarizes the main parameters of both rings. The transverse emittance of 3π mm.mrad results from the competing requirements of injection foil heating, aperture, space charge and beam size on target, while the longitudinal parameters are set by phase rotation and required bunch length on target, leading to a momentum spread of 0.863×10^{-3} rms and a total bunch length of 120 ns before rotation. Variable chopping of the linac beam is used to obtain a flat profile, with smooth edges to minimize longitudinal space-charge effects.

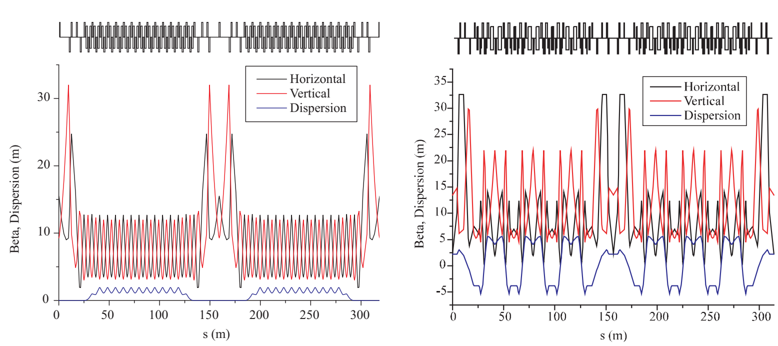

Figure 2. Accumulator and compressor lattices for the 6-bunches scenario.

4. Critical issues

Two–dimensional painting is used in the charge exchange injection to keep the stripping-foil temperature below 2000 K. A moving vertical bump of the H^- beam is also necessary in the case of a single bunch [5]. The minimum emittance achieved in this case is 67% larger (5 instead of 3 π mm.mrad).

Table 1. Main parameters of the accumulator and compressor rings.

Ring	Parameter	6 bunches case	3 & 1 bunch cases
Accumulator	Circumference (m)	318.5	185.8
	Nb. of turns of accumulation	400	640 / 1920
	Working point (H/V)	7.77 / 7.67	7.37 / 5.77
	Type of magnets	NC	SC
Compressor	Circumference (m)	314.2	200
	Nb. of turns for compression	36	86
	RF voltage (MV)	4	1.7
	Transition gamma	2.3	2.83
	Working point (H/V)	10.79 / 5.77	4.21 / 2.74
	Type of magnets	SC (bendings)	NC
	Time interval between bunches (μs)	12	30

Results of ORBIT [7] simulations of bunch rotation (Fig. 3) show that transverse space-charge is tolerable, partly because of the rapidity of the rotation and partly because of the large horizontal beam size due to dispersion which keeps the Laslett tune shift small enough to avoid integer resonance crossing.

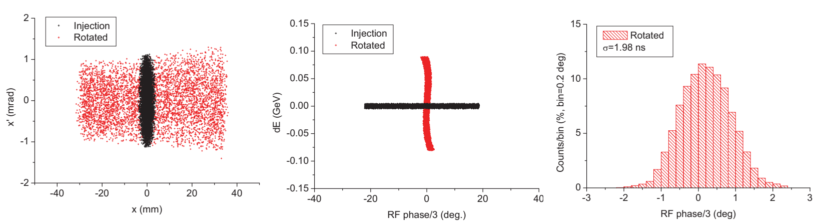

Figure 3. Phase space plots before and after bunch rotation.

Because of the absence of synchrotron motion in the isochronous accumulator, beam stability in the longitudinal and transverse planes deserved study. Analytical and computer tracking results (using HEADTAIL [8]) show that the beam can remain stable in all planes applying acceptable practical constraints [6]. The narrow-band component of machine impedance can be neglected due to the absence of RF cavities and the resistive-wall is not an issue because the rise-time $\tau \sim 8.2$ ms is long compared to the accumulation time. The effect of the broad-band impedance (BB) was analyzed with simulations, assuming the full intensity during all of the accumulation. Figure 4 (left) shows the transverse beam size evolution for different values of chromaticity, considering a BB impedance of 1 MΩ/m, 1 GHz and $Q_R = 1$. The instability can be cured with a tune spread of $\Delta Q \sim 0.02$ either from chromaticity or from octupoles detuning with amplitude. Threshold scales linearly with impedance.

As shown in Fig. 4 (right), a longitudinal broad-band impedance of a few Ω is tolerable. Electron-clouds should not be an issue, because the long and flat bunch profiles are not favorable to their build-up. Similar numbers are obtained for the 3-bunches accumulator. The single bunch scenario is expected to lead to three times more stringent values, since the bunch intensity is triple.

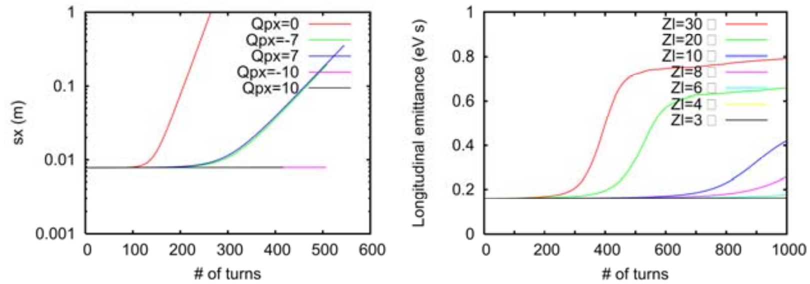

Figure 4. Left: Horizontal beam size evolution, as a function of chromaticity for $Z_{\perp}$=1MΩ/m, Q_R=1, f_R=1 GHz. Right: Longitudinal emittance evolution for different values of $Z_{//}$.

5. Conclusion

A 4 MW beam with the time structure required by a neutrino factory can be obtained with a linac-based proton driver. More work is now required for minimizing beam-loss and cost, in close connection with the design of equipment like RF, collimators and injection and extraction systems.

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