SYNCHROTRON-BASED PROTON DRIVERS FOR A NEUTRINO FACTORY

C.R. Prior & G.H. Rees, CLRC, Rutherford Appleton Laboratory, Chilton, Didcot, U.K.
H.O. Schönauer, CERN, Geneva, Switzerland

Abstract

Synchrotron-based proton drivers for a neutrino factory are under study at the Rutherford Appleton Laboratory (RAL), complementing a similar investigation using a high energy linac plus storage rings at CERN. Of the two sets of design parameters being considered, one is based on four synchrotron bunches per pulse at a final energy of 5 GeV and 50 Hz; the other is at 25 Hz with six bunches per pulse at 15 GeV. Both scenarios provide 4 MW of beam power. Bunch compression to 1 ns rms at the pion target is the most challenging aspect, and the driver parameters are dictated by this requirement. The paper includes brief details of the two scenarios, covering the choice of low energy linac and the rationale for the synchrotron lattices; injection, trapping and acceleration are described; and possible ways of achieving the final bunch compression are discussed. Simulation results are outlined, showing the feasibility of the proposals.

1 INTRODUCTION

Two rapid cycling synchrotron options are under study at RAL as a possible proton driver for a neutrino factory. The first option (Driver 1, Figure 1) has an output energy of 5 GeV at 50 Hz, and the other (Driver 2, Figure 2), 15 GeV at 25 Hz. Both must provide 4 MW of beam power with final output bunch durations of 1 ns rms. The 5 and 15 GeV options provide four and six bunches per cycle, respectively, and there is the potential for an upgrade to 6 MW for the 15 GeV case.

The energy of 5 GeV has been selected for study as this is the lowest energy at which it appears practical to achieve the specified final synchrotron bunch durations. A lower energy of 2.2 GeV is under consideration at CERN, however, in a scheme involving a full energy linac, a large circumference accumulator ring and a separate compressor [1]. RAL collaborates with CERN on the design of these 2.2 GeV, 75 Hz rings.

For the synchrotron options, a low linac injection energy has been chosen to assist in achieving the bunch duration specifications. The scheme proposed for Driver 1 uses a 180 MeV H^- linac to feed two 50 Hz, 1.2 GeV synchrotrons, operating almost in phase; together these feed two 25 Hz, 5 GeV rings in alternate cycles; the combined output, after bunch compression, is at 5 GeV and 50 Hz. For Driver 2, the basic scheme remains the same but the 50 Hz, 1.2 GeV rings are replaced by a pair at 25 Hz and 3 GeV, and the 25 Hz, 5 GeV rings by a pair at 12.5 Hz and 15 GeV, with a combined output at 25 Hz. All rings use biased sine wave guide fields.

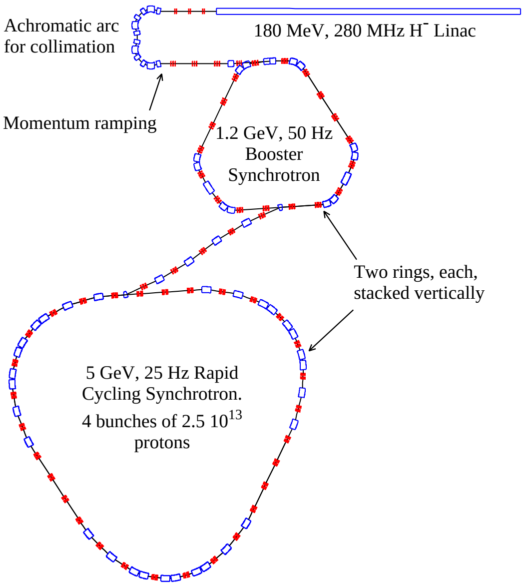

Figure 1: Layout of the 5 GeV, 50 Hz, 4 MW proton driver.

The choice of the number of bunches per ring and the rf harmonic numbers is discussed in §2.2, together with the injection and acceleration systems. Similar magnet lattices are chosen for the 1.2 GeV and 3 GeV booster synchrotrons to accommodate the H^- injection scheme. The triplet lattice has been developed for the ESS [2] accumulator, and a similar type is also considered for the CERN 2.2 GeV accumulator. Simpler doublet lattices are proposed for the 5 and 15 GeV rings, and for the CERN 2.2 GeV compressor, where a triplet is also a possibility. Final bunch compression is addressed in §2.3.

2 THE RAPID-CYCLING SYNCHROTRON OPTIONS

2.1 Injector Linac

An energy of 180.2 MeV has been chosen for the 57 mA, H^- injector linac, allowing small longitudinal bunch areas in the rings at reasonable transverse space charge levels. The injector has an overall length of 129 m and consists of a 2.493 MeV, 280 MHz RFQ, a chopper section and an eight tank, 280 MHz Alvarez linac. Each of the eight tanks requires a 3 MW peak power rf (radio frequency) generator, including 25% additional power for field control. The chopping section provides a 70% beam duty cycle at a sub-

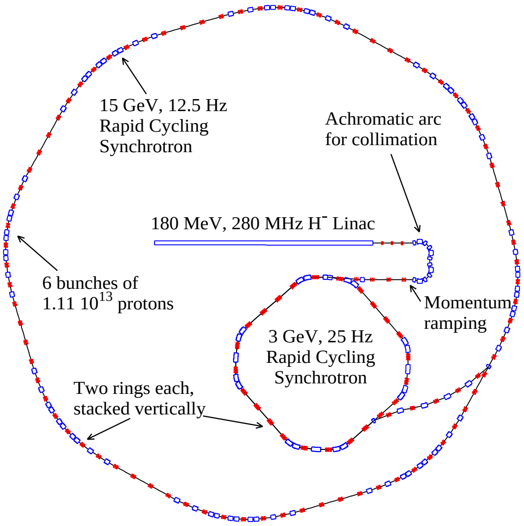

Figure 2: Layout of the 15 GeV, 25 Hz, 4 MW proton driver.

harmonic of 280 MHz which is close to the rf frequency of the booster rings (RCS1) at injection.

Between the linac and rings is a beam line that provides some debunching of the linac microbunches, subsequent momentum reduction, collimation and ramping, and vertical beam separation for each RCS1. Separate 280 MHz cavities are required for each stage. The four period, 41.6 m, achromatic collimator bends the H^- beam through $180°$ and includes some reverse bends and two buncher cavities. A range of fractional momentum ramping up to $4\,10^{-3}$ is provided, with normalised transverse rms emittances of approximately $0.26\,(\pi)\,\mu$rad.m.

2.2 *Injection, Trapping and Acceleration*

The use of booster and main rings allows the different requirements of injection and bunch compression to be treated separately. A triplet lattice has been adopted for the boosters, providing regions of high dispersion for injection and momentum collimation, and long dispersion-free straights for the rf systems, betatron collimation and fast extraction. Typical lattice functions are shown in Figure 3. Driver 1 has three superperiods and mean radius 32.5 m, and Driver 2 has four superperiods and radius 50 m. Injection is via an $\mathrm{Al_2O_3}$ stripping foil in a low field dipole (~ 0.05 T) where the normalised dispersion $D_h/\sqrt{\beta_h}$ is in the range 1.6-1.8. 160 turns are injected into Driver 1 over 200 μs and 70 turns into Driver 2 over 134 μs. The intervals are timed symmetrically about the minimum of the accelerating wave-form, injecting into a decelerating bucket at the start of injection and an accelerating bucket at the end. Momentum painting of longitudinal phase space improves the accumulated beam distribution and enhances the bunching factor. Vertical orbit bump magnets and dispersion coupling into the transverse horizontal plane control the transverse distribution and the parameters are chosen to reduce subsequent traversals of the stripping foil by recirculating protons. Excessive foil temperatures are thereby avoided.

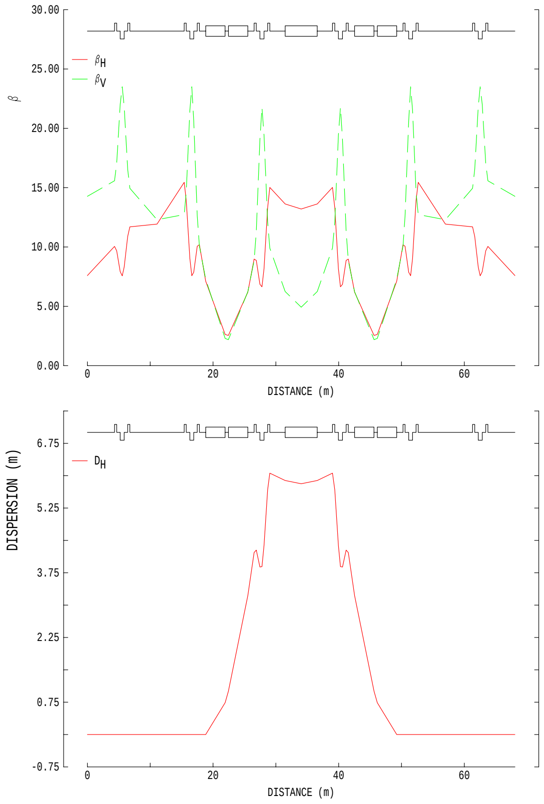

Figure 3: Lattice functions for the booster synchrotrons.

Low loss levels are required to permit hands-on maintenance in the rings. H^- and proton interactions with the foil account for about 0.01%; otherwise the main source of loss stems from the mechanism for trapping the beam in the first stages of acceleration. The latter can be eliminated using a suitably programmed system of rf voltages, with an rf frequency range allowing limited radial steering after injection. A single harmonic $h = 2$ system with maximum peak voltage $\hat{V} = 0.28$ MV is used in Driver 1, while Driver 2 has $h = 3$ and $\hat{V} = 0.4$ MV. Two bunches each of $2.5\,10^{13}$ protons and three of $1.11\,10^{13}$ protons are accumulated in the drivers respectively. At ejection, the respective bunch durations are 100 ns and 50 ns.

2.3 *Final Bunch Compression*

For each driver, the bunches in the two vertically-stacked booster rings are extracted and transferred together to either the upper or the lower of the two main synchrotrons in alternate cycles. Each transfer line contains a pulsed dipole magnet to provide vertical beam splitting.

The design of the main synchrotrons is dictated by the requirements of the final 1 ns rms bunch compression. Extensive simulation studies have suggested that this can be achieved by working close to transition energy. The lattice requirement that $\gamma_t \gtrsim \gamma$ at top energy has been adopted to meet this condition, avoiding crossing transition and any subsequent instabilities. Simple doublet lattices are proposed with small transverse space charge tune shifts, and the dispersion functions are designed to resist depression of γ_t as the bunches compress (Figure 4). Inductive impedances $Z_{\|}/n$ ~5-10 Ω are envisaged for the metallic and ceramic vacuum chambers to reduce longitudinal space charge effects.

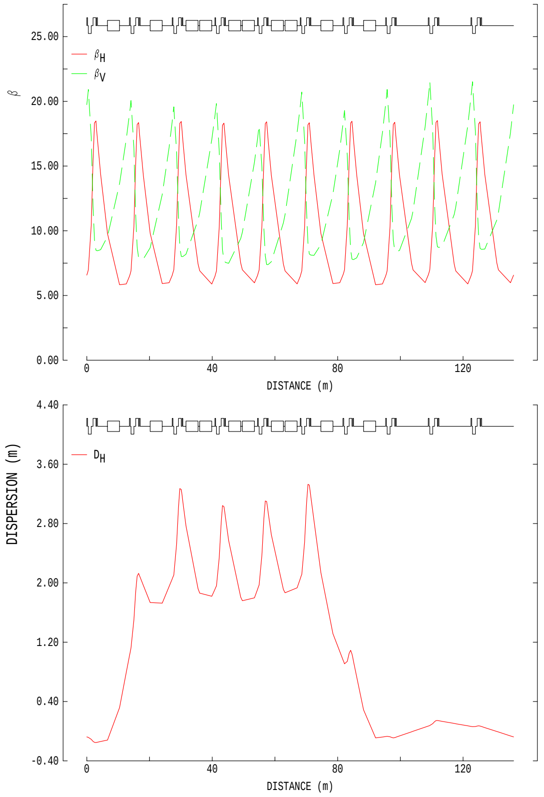

Figure 4: Lattice functions for the main synchrotrons.

Acceleration is achieved by cavities with programmed rf fields. For Driver 1, where the rings contain four bunches, these are at $h = 8$ with maximum $\hat{V} = 0.575$ MV. Additional $h = 24$ cavities are brought into play over the last 1 ms of the cycle, with peak total voltage rising linearly to 0.5 MV. Simulations show a final rms bunch duration of 1 ns, with peak momentum spread $\Delta p/p$ ~1.6% and longitudinal emittance ϵ_L ~1.0 eV.s. In the case of Driver 2, $h = 36$ cavities with $\hat{V}$ rising to 1.7 MV in mid-cycle, then falling to 0.6 MV, give similar results with the final conditions achieved from adiabatic bunch compression.

A consequence of working close to transition is that second order momentum effects need to be taken into account. With a particle's increased path length defined by $L = L_0(1 + \alpha_0\delta + \alpha_1\delta^2 + O(\delta^3))$, where $\delta = \Delta p/p$, the change in revolution period is

$$\frac{\Delta t}{t} = \left(\alpha_0 - \frac{1}{\gamma^2}\right)\delta + \left(\alpha_1 - \frac{\alpha_0}{\gamma^2} + \frac{\beta^2 + 2}{2\gamma^2}\right)\delta^2 + O(\delta^3).$$

In the CERN 2.2 GeV compressor ring, the first term dominates. However, for the two synchrotron-based proton drivers, both terms are comparable. An arrangement of sextupole magnets has been devised to correct the chromaticities and simultaneously over-compensate α_1, thereby eliminating both second order path-length and kinematic effects.

3 SUMMARY

A summary of the main parameters of the two drivers is given in Table 1.

In a proton driver of fixed power, the product of the output energy and the repetition rate offers a crude figure of merit for the pion target. This suggests some bias towards the 15 GeV option. A further advantage of Driver 2 is that the main ring would fit into the CERN ISR tunnel.

Table 1: Main parameters of the two synchrotron drivers.

Parameter	**Driver I**	**Driver II**
Booster Synchrotrons:		
Kinetic energy (MeV)	180 → 1200	180 → 3000
Number of bunches	2	3
Bunch intensity	2.5×10^{13}	1.1×10^{13}
No. of injected turns	160	70
Injection period (μs)	200	134
Mean radius (m)	32.5	50.0
γ-transition	4.73	5.97
Normalised dispersion $D_h/\sqrt{\beta_h}$ at foil ($\mathrm{m}^{1/2}$)	1.6	1.8
Q_h, Q_v	4.24, 4.35	5.70, 4.32
Harmonic number	2	3
Peak rf voltages (MV)	0.28	0.40
Main Synchrotrons:		
Kinetic energy (GeV)	1.2→5.0	3.0→15.0
Number of bunches	4	6
Mean radius (m)	65.0	150.0
γ-transition	6.50	17.14
γ	2.28→6.33	4.20→16.99
Q_h, Q_v	7.78, 5.80	20.41, 15.24
ΔQ_h, ΔQ_v	-0.07, -0.13	-0.02, -0.02
Chromaticities	-1.15, -1.21	-1.15, -1.31
Harmonic numbers	8 and 24	36
Peak rf voltages (MV)	0.58/0.5	1.7

REFERENCES

[1] R. Cappi et al: "Design of a 2.2 GeV Accumulator and Compressor for a Neutrino Factory". Proceedings of this conference.

[2] G. Bauer, T. Broome, D. Filges, H. Jones, H. Lengeler, A. Letchford, G. Rees, H. Stechemesser, G. Thomas (eds): "ESS: A Next Generation Neutron Source for Europe. Vol III: The ESS Technical Study". November 1996.