EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – PS Division

CERN/PS 2000-065 (AE)
CERN/NUFACT/Note 030

Proton Drivers for Neutrino Factories: The CERN Approach

H. Schönauer, CERN, CH-1211 Geneva 23, Switzerland,
for the CERN Neutrino Factory Proton Driver Working Group:
B. Autin, R. Cappi, M. Chanel, G. Franchetti, J. Gareyte, R. Garoby,
M. Giovannozzi, H. Haseroth, M. Martini, E. Métral, D. Möhl, K. Schindl (CERN),
and other contributors:
W. Pirkl (CERN), G.H. Rees, C. Prior (RAL), I. Hofmann (GSI),
S. Koscielniak (TRIUMF), K. Bongardt, Yu. Senichev (FZJ).

Abstract

The paper describes the CERN approach for a proton driver for a Neutrino Factory. Two main layouts are presented: the so-called CERN Reference Scenario, based on a 2.2 GeV linac and an alternative one, based on a 30 GeV synchrotron. Both produce bunches of 1 ns (r.m.s.) and a beam power of 4 MW.

*FZJ, Jülich, Germany, ** GSI, Darmstadt, Germany, ***TRIUMF, Vancouver, Canada,
****Rutherford Appleton Laboratory, Chilton, Didcot, UK

NUFACT'00, Monterey, California, USA
22-26 May 2000-09-28

Geneva, Switzerland
28 September 2000-09-28

Proton Drivers for Neutrino Factories: The CERN Approach

H. Schönauer, CERN, CH-1211 Geneva 23, Switzerland,

for the CERN Neutrino Factory Proton Driver Working Group:
B. Autin, R. Cappi, M. Chanel, G. Franchetti, J. Gareyte, R. Garoby,
M. Giovannozzi, H. Haseroth, M. Martini, E. Métral, D. Möhl, K. Schindl (CERN),
and other contributors:
W. Pirkl (CERN), G.H. Rees, C. Prior (RAL), I. Hofmann (GSI),
S. Koscielniak (TRIUMF), K. Bongardt, Yu. Senichev (FZJ).

Abstract

The paper describes the CERN approach for a proton driver for a Neutrino Factory. Two main layouts are presented: the so-called CERN Reference Scenario, based on a 2.2 GeV linac and an alternative one, based on a 30 GeV synchrotron. Both produce bunches of 1 ns (r.m.s.) and a beam power of 4 MW.

1. Introduction and Philosophy

The basic facility parameters, like neutrino or muon flux, determine the proton beam power and other constraints through the estimated efficiencies and limits of the muon sections. At the NuFact'99 Workshop, a consensus was reached for a beam power of 4 MW on target, independent of beam energy, has been achieved. Another major constraint comes from pion/muon capture and first bunch rotation: The r.m.s. proton bunch length must not exceed 1 ns. Furthermore, a limit to the repetition rate due to the duty cycle (including the filling times) of the RF cavities, is estimated to be around 50 Hz. The length of the bunch train must not exceed the circumference of the muon decay ring. At present, this is assumed ~2 km. Looking further at muon collider scenarios, the number of bunches may be limited to four. For some muon bunch rotation schemes, in particular those using induction linacs, the distance between bunches should not be less than 200 ns.

In view of the uncertainty of some of these specifications, and to be prepared for possible their evolution, a "threefold way" has been chosen for the studies of 4 MW proton drivers :

1. A CERN-specific 2.2 GeV, 75 Hz scenario combining the 2.2 GeV Superconducting H^- Linac (SPL) based on recycled LEP cavities [1] (studied since 1996 as injector for the CERN PS), with an accumulator and a compressor ring in the ISR tunnel (Circumference = 948 m). Choosing a 44 MHz RF system matches it to the CERN muon rotation and cooling system [2].

2. For the case that, ultimately, slow repetition rates are needed, we opted for a 30 GeV, 8 Hz configuration (upgradable to 8 MW, 15 Hz by adding a second ring), using the ISR tunnel for the driver.
3. In the framework of a collaboration with RAL, a site-independent 5 GeV, 50 Hz and, recently, also a 15 GeV, 25 Hz scenario was investigated. They also designed a 180 MeV, 56 mA linac, derived from the ESS study [3], which is common to the three synchrotron scenarios.

The characteristic features of the proton driver scenarios are summarised in Table 1, which also outlines the methods of bunch compression typical for the scenarios and their specific problems.

Table 1: 4 MW Proton Drivers and their Bunch Compression Technique studied at CERN and RAL

Philosophy	High Energy Linac (2.2 GeV) + Accumulator / Compressor	DTL (180 MeV) + Stages of RCS's (Rapid Cycling Synchrotrons)		
Scenario	CERN SPL + PDAC	RAL		CERN Slow 'RCS'
	2.2 GeV / 75 Hz	5 GeV / 50 Hz	15 GeV /25 Hz	30 GeV / 8 Hz
	CERN-specific	Site-independent	CERN-specific (ISR Tunnel)	
Rings	Accumulator + Compressor	2 RCS 1.2 GeV /50Hz 2 RCS 5 GeV/25 Hz	2 RCS 3 GeV/25Hz 2 RCS 15GeV/12.5Hz	1 RCS 2.2GeV/50Hz 1 RCS 30GeV/8.3Hz
Bunches	140	4	6	8
ε_L [eVs]	0.1	1	2	2
RF Compression	h=146 / 44 MHz 2 MV	h=4 / 3 MHz / 2 MV in 3 harmonics	h=36 / 11 MHz 1.7 MV	h=32 / 10 MHz 3.5 MV
Compression Method	η~-0.1 Bunch Rotation in 7-8 turns	η ~ -0.0013 at end of Cycle, Bunch Rotation	η ~ -0.00006 Adiabatic Compression	η~-0.0002 Adiabatic Compr. for Z/jn < 3 Ω !
Critical Features	Laslett ΔQ: ~ - 0.2, but <-1 for small number of bunches	Space Ch. > Chamber Impedance Rotation delicate	Space Ch. ≈ Chamber Impedance ΔQ dependence of α_1.	Limits to α_1 in conflict with high-γ_t lattice

The CERN study concentrated from the beginning on the first scenario, named *PDAC*: Proton Driver Accumulator-Compressor. This *CERN Reference Scenario* would upgrade the performance of the CERN PS, thereby increasing the luminosity of LHC, and also upgrade the ISOLDE facility. It is still possible that errors in the calculated pion production at 2.2 GeV may be revealed by the forthcoming HARP experiment [4] at the CERN PS, which would force the choice of a higher beam energy of 5 - 30 GeV. Actually, the approach of having a chain of "Rapid Cycling Synchrotrons" (RCS) is generally considered to be more economic than the combination of high-energy linac plus accumulator ring. Linac energies not exceeding 150–180 MeV facilitate the handling of the RF capture loss, which is very difficult to suppress completely. A driver synchrotron of 25-30 GeV could inject into the CERN SPS above transition energy, substantially upgrading its performance for LHC and fixed target physics [5]. ISOLDE would equally profit from the 440 kW beam power of the 2.2 GeV booster synchrotron.

This article concentrates on the accumulator and compressor rings of the CERN Reference Scenario; the SPL was presented at this Workshop by R. Garoby and is well-documented [1]. Only a section is devoted to the alternative 30 GeV, 8.3 Hz Slow Cycling RCS scenario. The two intermediate-energy RCS's are described in the contribution of C.R.Prior and G.H.Rees [6]

2. The CERN Reference Scenario: PDAC - Proton Driver Accumulator /Compressor

In order to serve a neutrino facility, the 2 ms long pulse of low average current (11 mA) from the SPL linac needs to be converted into a train of short (1ns rms) bunches. The length of the train must be under the 2 km circumference of the muon storage ring. A ring fitting into the existing ISR tunnel (C=942 m, 15 m wide) seems to be the natural choice for accumulating 1.5×10^{14} protons at 75 Hz. Initially, an attempt was made to design one ring with a nearly isochronous lattice at 2 GeV ($\gamma = 3.1$), in order to perform the bunch rotation with modest RF voltage. It soon became clear that this was not the ideal approach: Space charge causes blow-up of the 0.5 ns long linac micro-bunches, and requires high RF voltage for macro-bunch compression. Moreover, there is a strong non-linear effect of space charge on momentum compaction such that transition energy varies over the bunch.

A layout with two rings of high transition energy, separating the functions of accumulation and bunch rotation, is much more robust. Its parameters are listed in Table 2. Microbunches debunch quickly, space charge has little influence on the linearity of the lattice, and the high synchrotron tune in the accumulator produces a smooth distribution in longitudinal phase space, which is a good start for the rotation. The latter requires more RF voltage, but the critical issue of fast cavity filling is circumvented. The pre-detuned, filled, compressor cavities minimise transient beam loading.

Table 2: Parameter List for the 2.2 GeV **P**roton **D**river **A**ccumulator-**C**ompressor

Parameter	**Unit**	**Accumulator**	**Compressor**
Beam			
kinetic energy, T	GeV	2.2	
pulse frequency	Hz	75	
pulse duration	μs	3.3	
number of bunches		140	
pulse intensity	p/pulse	1.51×10^{14}	
bunch spacing	ns	22.7	
bunch intensity	p/bunch	1.1×10^{12}	
bunch length (4σ)	ns	14 - 17	6
rel. momentum spread (2σ)		1.5×10^{-3}	5×10^{-3}
norm. hor. emittance (1σ)	μm	50	

Machine			
radius, R	m	151	151
main dipole magn. field, B	Tesla	0.69	0.49
number of injected turns		660	1
η		-0.085	-0.086
γ-transition		14.84	15.09
Q_x, Q_y		11.23, 13.30	17.18, 16.40
RF			
RF voltage, V_{RF}	MV	0.3	2
harmonic number, h		146	
RF frequency, f_{RF}	MHz	44.02	
synchrotron frequency, f_s	kHz	3.3	~11.3

For the proposed implantation of the SPL on the CERN site [1], the debunching section and the 90° collimator achromat will also be installed in the ISR tunnel. The accumulator ring is filled by H^- injection over 660 turns. Figs. 1a, 1b shows a superperiod of the accumulator with a long dipole at the centre of a dispersion bump, which is absent in the compressor lattice (Figs. 2a, 2b). This low-field dipole bends the trajectory of the injected beam towards the foil with a minimum of excited H^0 states. The technique of ramping of the linac energy for horizontal ’painting’ by placing the foil at a point of large dispersion (anti-correlated with a vertical orbit bump to produce a K-V-like transverse distribution) has been proposed for a number of high-intensity machines, notably ESS. With an average of 4-5 foil traversals of the circulating beam, the carbon foil temperature will not exceed 1800 K, a rather conservative value.

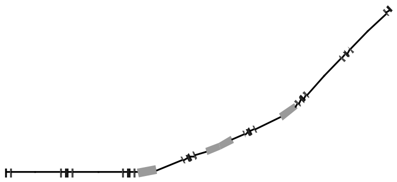

Fig. 1a: Structure of a Superperiod of the Accumulator

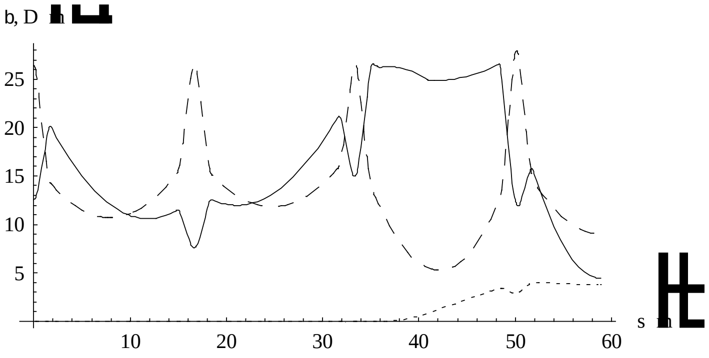

Fig. 1b: Lattice Functions β_H (solid) , β_V (dashed) and D_H (dotted) for one Half of the Accumulator Superperiod

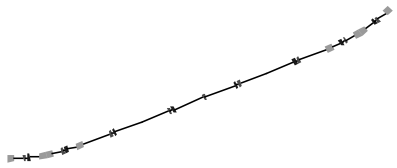

Fig. 2a: Structure of a Superperiod of the Compressor

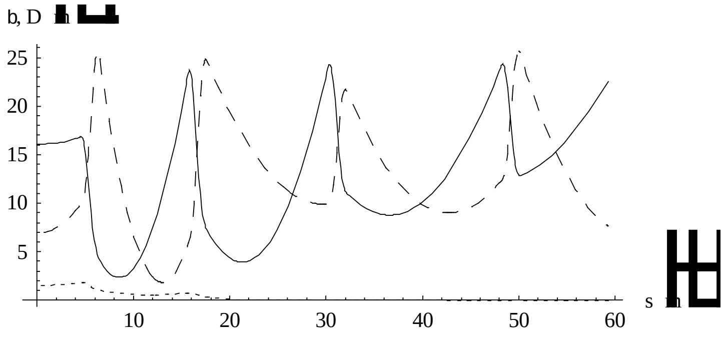

Fig. 2b: Lattice Functions β_H (solid) , β_V (dashed) and D_H (dotted) for one Half of the Compressor Superperiod

In order to keep particles away from the separatrix, five out of eight 352 MHz microbunches are injected into the 44 MHz bucket, the others are chopped off. The RF voltage is raised linearly from 30 to 300 kV to maintain the bunch approximately matched in the presence of the increasing space charge. Owing to the high γ_t, about six full synchrotron periods are completed during accumulation, yielding a smooth ellipse-like phase space distribution (Fig. 3a), which ensures a well-confined bunch after rotation in the compressor (Fig. 3b).

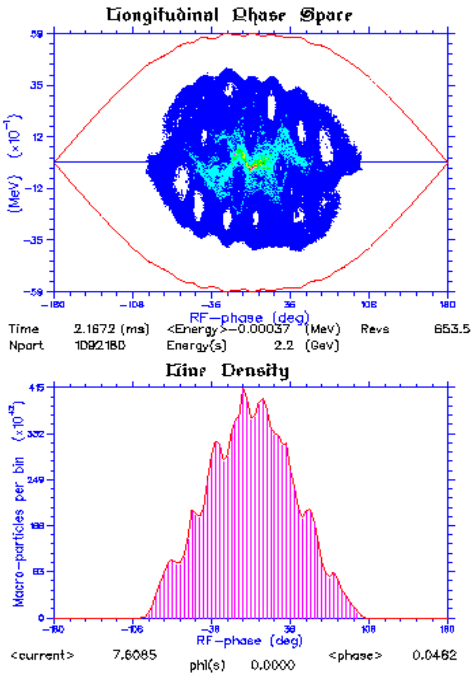

Figure 3a: Bunch after 660 Turns (End of Accumulation / Begin of Rotation)

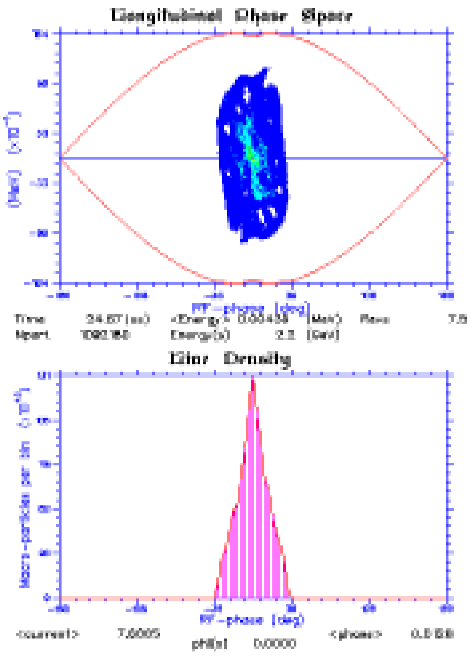

Figure 3b: Bunch after 7.5 Turns (End of Rotation) in the Compressor

Space charge and thresholds of collective effects have been checked for the accumulator. Only the microwave instability raises concern, as the calculated growth time of 0.6 ms for a broadband impedance of (Z/jn) = 1 Ω is of the order of the accumulation time (2.2 ms). A more detailed simulation [7] predicts stability by Landau damping due to the tails of the distribution. Space charge effects are expected in the compressor at the end of bunch rotation, but the Laslett tune shift is not more than $\Delta Q \sim -0.2$. In an earlier PDAC version, featuring only 12 bunches to match the constraints of a muon induction linac, an impressive $\Delta Q \sim -2$ had been calculated for maximum compression. This was considered acceptable in view of the short time for which this shift is active, but a weak horizontal halo appeared in tracking studies [8].

3. The CERN Alternative Scenario: The 30 GeV / 8 Hz Proton Driver

This scenario is *not* matched to the 44 MHz muon collection system (but a 40.27 MHz collection system could handle the bunch structure from this proton driver). The driver synchrotron, also using the ISR tunnel, is filled on a 2.2 GeV, 60 ms, flat bottom by four batches of two bunches each from a 1/4-size 50 Hz booster (similar to the AUSTRON RCS design [9]). At the end of the booster cycle these bunches are pre-compressed to fit into the buckets of a h=32 RF system of the driver, which accelerates the eight bunches in 45 ms to top energy. The necessary peak voltage of 3.8 MV is delivered by 22 cavities of a novel design [10]: An external mechanical tuner, coupled to the cavity by 31/8" cables produces the required frequency variation of ~ 4%. Each cavity (L = 1.8 m, r/Q = 42 Ω, Q = 5000-10000) should contribute 175 kV. The high peak RF voltage can provide naturally short bunches without compression at top energy, if the transition energy is chosen to be not too far above it, and if the vacuum chamber impedance can be limited to (Z/jn) ≤ 2 Ω. The feasibility of the approach has been demonstrated by tracking studies, including a broadband resonator or a set of equivalent high-Q resonant longitudinal impedances. For a top energy of 30 GeV, the optimum γ_t is ~40. A "resonant" lattice, similar to that proposed earlier for high γ_t-values [11], was designed, which has excellent dynamic apertures. It is by no means trivial to fulfil the needs for long dispersion-free straight sections, chromaticity correction, limited dispersion, and linearity of momentum compaction, when more than half of the circumference is taken up with bending magnets. In fact, a limit to the quadratic term $|\alpha_1| \leq 0.01$ of the momentum compaction was found by simulation. This condition is in general not met by the resonant lattice, except for a region of partially-compensated chromaticity around $\xi_{x,z} \sim -6$, a value which is just acceptable. Nevertheless, an alternative, more conventional, lattice of γ_t ~30, limiting the top energy to 25 GeV (still above transition of the SPS), is being studied. Tables 3 and 4 summarise the main parameters of the booster and the driver synchrotrons. A possible topology, where the complete injector is inside the ISR tunnel, is shown in Figure 4.

Table 3: Booster Beam and Machine
Parameters for the Alternative Scenario

Parameter	**Unit**	**Value**
Kinetic energy	GeV	2.2
Pulse frequency	Hz	50
Pulse intensity	protons	2.5×10^{13}
Number of bunches		2
Circumference	m	238
Nr. of injected turns (56 mA)		100
RF harmonic number		2
RF frequency	MHz	1.38-2.42
RF peak voltage	MV	0.35
Space charge tune shift at inj.		-0.18

Table 4: Driver Output and Machine parameters for the Alternative Scenario

Parameter	**Unit**	**Value**
Mean beam power	MW	4
Kinetic energy	GeV	30
Pulse frequency	Hz	8.33
Pulse intensity	protons	10^{14}
Number of bunches		8
Bunch length (1σ)	ns	1
Momentum spread (2σ)		0.008
Transv. emittances, norm. (2σ)	μm	150 π
Longitudinal emittance / bunch	eVs	2
Circumference	m	952
RF harmonic number		32
RF frequency	MHz	9.7-10.2
RF peak voltage	MV	3.8
Transition energy γ_t		39
Tune shift on flat bottom		-0.22

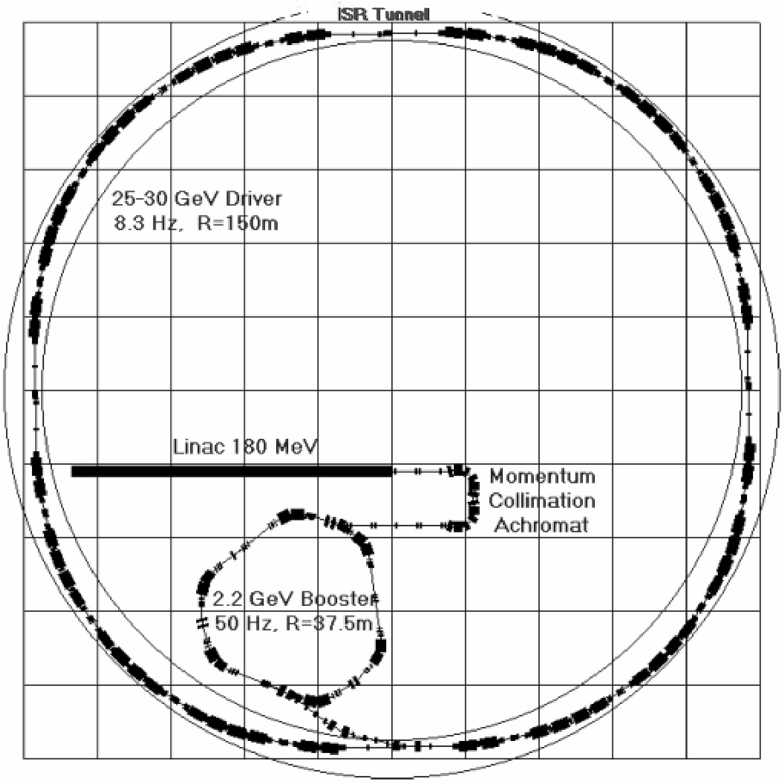

Figure 4: The CERN 30 GeV, 8 Hz Proton Driver in the ISR Tunnel with its Injector. Grid Size 30m.

4. Conclusions

The study of the CERN Reference proton driver PDAC has shown that this scenario, which adapts the 2.2 GeV superconducting linac SPL to the original 44 MHz Muon Rotation and Cooling scheme, looks very promising. No major problems have emerged and in some respects its parameters are rather conservative. The study will continue focusing on the aspects that have not been studied yet or need refinement.

The study of the alternative 8 Hz synchrotron scenario will be completed by the evaluation of a 25 GeV driver with a more conservative lattice, a more detailed assessment of the coherent effects, and a study of halo development during the up to 60 ms long stacking. The study will then be suspended. It will resume if a future evolutions of scenarios for a neutrino factory enters into conflict with the Reference Scenario.

5. References

[1] R. Garoby, "CERN Linac Driver Proposal", http//:www.lbl.gov/Conferences/nufact00/docs/WG4_0524_Garoby_sF.pdf ;

A. Lombardi, M. Vretenar, eds. "Conceptual Design of a 2.2 GeV – 4 MW Superconducting H^- Linac at CERN", CERN Yellow Report (2000) in preparation ;

M. Vretenar., "A High-Intensity H^- Linac at CERN Based on LEP-2 Cavities", Proc. Linac2000, Monterey, August 2000, to be published

[2] A. Lombardi : "A 40/80 MHz System for Phase Rotation and Cooling", this Workshop

[3] ESS-96-53-M: The ESS Technical Study, November 1996

[4] M. Catanesi et al., "The Harp Pion Production Experiment", this Workshop, 1997, p. 103

[5] B. Autin et al., "PS XXI, A New Synchrotron for the LHC Injector", Particle Acc. 58

[6] C.R. Prior, G.H. Rees, "Proton Drivers: The RAL Approach", this Workshop

[7] I. Hofmann, Personal communication

[8] G. Franchetti, "Transverse Space Charge Effect During Bunch Compression", Neutrino Factory Note 36, http://molat.home.cern.ch/molat/neutrino/nfnotes.html, August 2000

[9] P. Bryant et al., "The Accelerators for the AUSTRON Spallation Source", Proc. 4th EPAC, London, June 1995, p. 2667.

[10] W. Pirkl, Personal communication

[11] A. Iliev, Yu. Senichev, "Racetrack Lattices for Low-Medium-Energy Synchrotrons ", Proc. 14th PAC, San Francisco, May 1991, p.1904.