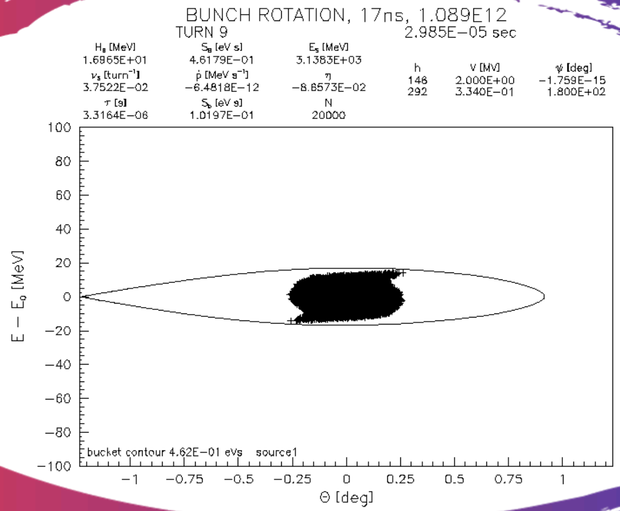
PDAC Challenges (2.2 GeV – 44 MHz)

Mean beam power: $P_{beam} = E_k \, N \, M \, f_{\mathrm{RepRate}} = \mathbf{4\ MW}$

2.2 GeV — **$\sim 1.1 \times 10^{12}$ p/b** — **140 bunches** — **75 Hz**



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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN–PS/2000–011 (AE)
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DESIGN OF A 2.2 GEV ACCUMULATOR AND COMPRESSOR FOR A NEUTRINO FACTORY

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Abstract

The proton driver for a neutrino factory must provide megawatts of beam power at a few GeV, with nanosecond long bunches each containing more than 1×10^{12} protons. Such beam powers are within reach of a high-energy linac, but the required time structure cannot be provided without accumulation and compression. The option of a linac-based 2.2 GeV proton driver has been studied at CERN, taking into account the space charge and stability problems which make beam accumulation and bunch compression difficult at such a low-energy. A solution featuring two rings of approximately 1 km circumference has been worked out and is described in this paper. The subjects deserving further investigation are outlined.

=> https://cds.cern.ch/record/442326/files/ps-2000-011.pdf

7th European Particle Accelerator Conference
26 th - 30 th June 2000
Vienna, AUSTRIA

Few-month (preliminary) study!

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PS DIVISION

CERN/PS 2000-069 (AE)

Collective Effects and Final Bunch Rotation in a 2.2 GeV – 44 MHz Proton Accumulator – Compressor for a Neutrino Factory

R. Cappi, J. Gareyte, E. Métral, D. Möhl

Abstract

This paper is a review of the collective effects and the final bunch rotation in the CERN scenario of a 4 MW proton driver for a neutrino factory.

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

=> https://cds.cern.ch/record/466922/files/ps-2000-069.pdf

Geneva, Switzerland
29 September 2000

2.2 GeV Accumulator and Compressor

- The geometry of the proton driver rings is determined by the preference that has been given to **install the 2 machines in the former ISR tunnel**. This tunnel has 150 m mean radius, with a width of about 15 m and height of 4 m
- **Choice of performing the bunch compression by means of a non-adiabatic process, imposes the use of 2 separate rings**: 1 for accumulation of the linac microbunches and 1 for compressing the resulting macrobunches. The RF cavities needed to perform the bunch rotation would be a potential source of problems if installed in the accumulator ring. Their high impedance and the unavoidably long filling time could drive beam instabilities during the accumulation period

2.2 GeV Accumulator and Compressor

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- Accumulator lattice has been designed at **RAL**. All the optics computations for the compressor have been carried out at CERN by using different codes including space charge effects
- **In the accumulator ring**, the beam is accumulated during **2.2 ms**
- The final bunch rotation is performed **in the compressor ring in ~ 30 µs**
- Since the bunch compression is much faster than the cavity filling time (~ 100 µs), the **phase shift due to the transient beam loading** increases almost linearly with time and **can be compensated by an appropriate frequency difference between generator and beam frequencies** (~ 20 kHz at 44 MHz)

2.2 GeV Accumulator and Compressor

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Table 1: Summary of linac output beam characteristics.

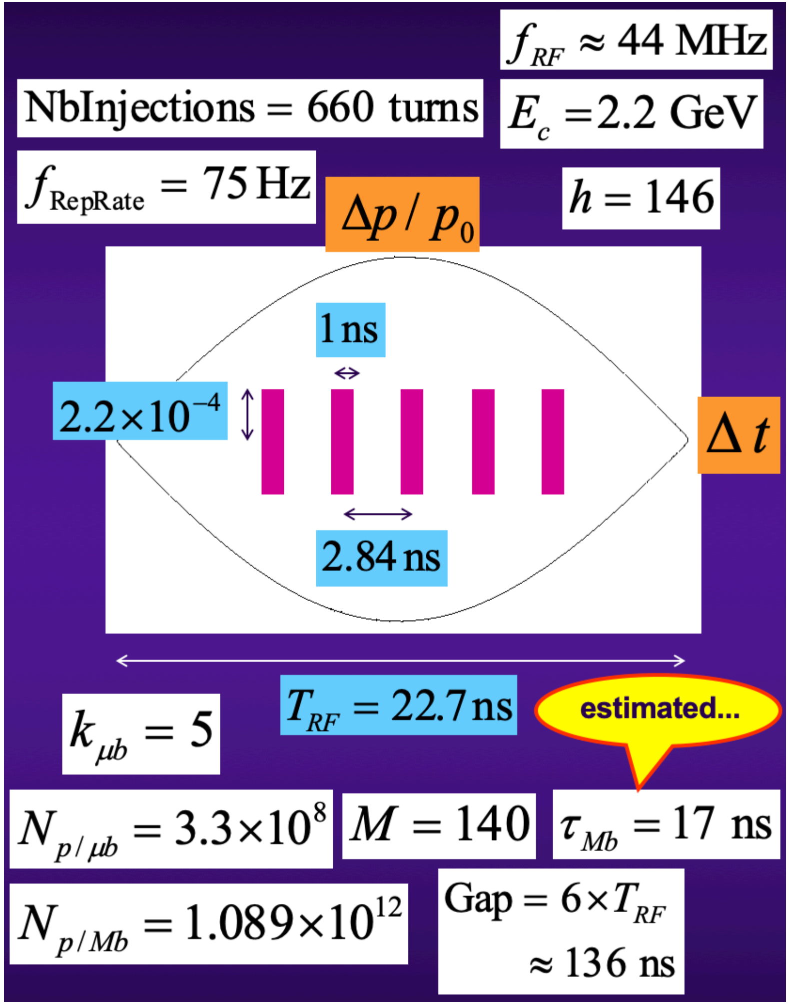
Parameter	Unit	Value
Mean beam power	MW	4
Kinetic energy	GeV	2.2
Rep. rate	Hz	75
Pulse duration	ms	2.2
# of micro-bunch trains × turns		140×660
Pulse intensity		1.5×10^{14}
Train spacing	ns	22.7
# of micro-bunches/train		5
Micro-bunch spacing	ns	2.84
Micro-bunch intensity		3.3×10^{8}
Micro-bunch length	ns	0.5
Energy spread (2σ)	MeV	0.2
Energy jitter within pulse	MeV	± 0.2
Energy jitter between pulses	MeV	± 2
$\Delta p/p$ (2σ)		0.08×10^{-3}
ϵ_l	eVs	0.2×10^{-3}
$\epsilon^*_{h/v} = \beta\gamma\sigma^2_{h,v}/\beta_{h,v}$	μm	0.6

Table 2: Summary of output beam characteristics common to accumulator and compressor rings.

Parameter	Unit	Value
Pulse duration	μs	3.3
RF freq. f_{RF}	MHz	44.02
# of bunches/h		140/146
Bunch intensity	protons	1.1×10^{12}
ϵ_l	eVs	0.1
$\epsilon^*_{h/v} = \beta\gamma\sigma^2_{h,v}/\beta_{h,v}$	μm	50

Table 3: Summary of geometrical and optical parameters of the accumulator and compressor ring.

Parameter	Accumulator	Compressor
Radius (m)	151	151
Main dip. field (T)	0.69	0.49
γ_{tr}	14.837	15.089
η	−0.0848	−0.0849
$\beta_h{}^{max}/\beta_v{}^{max}$ (m)	26.4/26.2	24.5/25.5
D_h^{min}/D_h^{max} (m)	0.0/4.6	0.0/1.8
Q_h/Q_v	11.23/13.30	17.18/16.40
Super-symmetry	8	8
Vac. pipe half width (m)	0.09	0.09
Vac. pipe half height (m)	0.09	0.09
# of dip.-quad./super-per.	3 − 22	5 − 17
Length of s.s./super-per. (m)	73.4	86.2


$f_{RF} \approx 44$ MHz
NbInjections = 660 turns
$E_c = 2.2$ GeV
$f_{\text{RepRate}} = 75$ Hz
$\Delta p / p_0$
$h = 146$
1 ns
2.2×10^{-4}
Δt
2.84 ns
$k_{\mu b} = 5$
$T_{RF} = 22.7$ ns
estimated...
$N_{p/\mu b} = 3.3 \times 10^{8}$
$M = 140$
$\tau_{Mb} = 17$ ns
$N_{p/Mb} = 1.089 \times 10^{12}$
Gap $= 6 \times T_{RF}$
≈ 136 ns

Collective effects

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- Mechanisms looked at in the accumulator ring
  - Transverse space charge
  - RF matching w/o and w/ space charge
  - Longitudinal microwave instability from a broad-band impedance
  - Longitudinal coupled-bunch instability from RF HOMs
  - Transverse head-tail instability (single-bunch and coupled-bunch) from RW
  - TMCI from a broad-band impedance
  - BBU (single-bunch and multi-bunch) from a broad-band impedance
- Mechanisms looked at in the compressor ring
  - Bunch rotation with longitudinal space charge (analytically and using the ESME program)

Collective effects: preliminary conclusions (at that time)

- The CERN 2.2 GeV – 44 MHz scenario for the proton driver of a neutrino factory looks promising

- **No major obstacles** have been found with the current parameters

- **More detailed investigations have to be performed to investigate**
  - **Electron-cloud effects**
  - **Halo formation and beam losses in both rings**

Collective effects: preliminary conclusions (at that time)

- Some other scenarios were also briefly looked at
  - **Other RepRates: 50 Hz and 25 Hz**
  - **RCS (2-30 GeV) as an alternative to PDAC**

- Several meetings with RAL
  - At CERN (20-21/01/2000)
  - At Oxford (04-05/05/2000)
  - At London (22/02/2001)

Next

- All this should be carefully checked (with detailed simulations) and updated

…E.g.:

> correct description of the phenomenon. On the other hand, as concerns the transverse mode coupling instability, the threshold number of protons per bunch given by Eq. (19) can be considered to be a conservative estimate, since in this case space charge seems to have a strong stabilizing effect [11].

=> We know, since, that (strong) space charge has a destabilizing effect…

Thank you for your attention

Appendix

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APPENDIX: List of the Accumulator (A), Compressor (C) and beam parameters

$a = \left(a_x + a_y \right) / 2$	Average beam radius. $a^{\mu b} = 2.16$ mm. $a^{MbA} = a^{MbC} = 1.98$ cm
$a_{x,y} = \sqrt{2} \left[\varepsilon_{x,y}^{\mathrm{rms}} \beta_{x,y} + \left(D_{x,y} \sigma_p / p_0 \right)^2 \right]^{1/2}$	$\sqrt{2} \times$ the rms horizontal and vertical beam dimensions. $a_x^{\mu b} = 2.25$ mm, $a_y^{\mu b} = 2.07$ mm, $a_x^{MbA} = a_x^{MbC} = 2.06$ cm, $a_y^{MbA} = a_y^{MbC} = 1.89$ cm
$b = b_x = b_y = 9$ cm	Radius of the circular vacuum chamber of A and C
$B = f_0 \tau_b$	Bunching factor

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$c = 2.997925\times10^{8}$ ms^{-1}	Velocity of light
$D_{x,y}$	Average transverse dispersion functions. $D_x^A = R/(Q_x^A)^2 = 1.20$ m, $D_x^C = R/(Q_x^C)^2 = 0.51$ m, $D_y^A = 0$ m, $D_y^C = 0$ m
$e = 1.6\times10^{-19}$ C	Elementary charge
$E = E_0 + E_c = 3.138$ GeV	Proton total energy
$E_0 = 0.938$ GeV	Proton rest energy
$E_c = 2.2$ GeV	Proton kinetic energy
$f_0 = 301.536$ kHz	Average revolution frequency in A and C
$f_r^{BB} \approx c/(2\pi b) = 0.53$ GHz	Resonance frequency of the broadband impedances (cut-off frequency of the vacuum chamber)
$f_{\mathrm{RepRate}} = 75$ Hz	Repetition rate of the proton driver
$f_{RF} = h\, f_0 = 44.0243$ MHz	Average RF frequency in A and C
$f_{\xi_{x,y}} = (\xi_{x,y}/\eta)\, Q_{x,y}\, f_0$	Transverse chromatic frequencies. $f_{\xi_x}^A = 39.93$ MHz, $f_{\xi_y}^A = 47.29$ MHz
$h = 146$	Harmonic number in A and C
$I_p = 3\,e\,N_b/2\tau_b$	Bunch peak current considering a parabolic line density. $I_p^{\mu b} = 0.16$ A, $I_p^{MbA} = 15.37$ A, $I_p^{MbC} = 65.34$ A
$I_0 = N_b\, e\, f_0$	Bunch average current. $I_0^{\mu b} = 0.000016$ A, $I_0^{MbA} = I_0^{MbC} = 0.053$ A
$j = \sqrt{-1}$	Imaginary unit
L	Total (4σ) bunch length (in meters). $L_{\mu b} = 0.143$ m, $L_{MbA} = 4.863$ m ("estimated" length of a macro-bunch at the end of accumulation), $L_{MbC} = 1.144$ m
$L_t \approx (M_{\mu b} - 1)\times t_{sep}^{\mu b} = 11.36$ ns	Length (in meters) of the Linac train
$m_0 = 1.67\times10^{-27}$ kg	Proton rest mass
M	Number of bunches. $M_{\mu b} = 5$ (per Linac injection train), $M_{MbA} = M_{MbC} = 140$
$N_{injections} = 660$	Number of injection turns in A
N_b	Number of protons per bunch. $N_{\mu b} = 3.3\times10^{8}$, $N_{MbA} = N_{MbC} = 1.089\times10^{12}$
$P_{beam} = E_c\, N_{MbC}\, M_{MbC}\, f_{\mathrm{RepRate}} = 4$ MW	Mean beam power
$Q_r^{BB} \approx 1$	Quality factor of the broad-band impedances
$Q_s = f_s/f_0$	Synchrotron tune
$Q_{x,y}$	Transverse coherent tunes (in the absence of wake fields). $Q_x^A = 11.23$, $Q_y^A = 13.30$, $Q_x^C = 17.18$, $Q_y^C = 16.40$
$r_p = 1.54\times10^{-18}$ m	Classical proton radius
$R = 151$ m	Average machine radius of A and C
$R_{r,l}^{BB} = (f_r^{BB}/f_0)\times\lvert Z_l^{BB}(p)/p\rvert$	Longitudinal shunt impedance of the broadband resonator
$R_{r,t}^{BB} = 2\,c\,R_{r,l}^{BB}/(2\pi\, f_r^{BB}\, b^2)$	Transverse shunt impedance of the broadband resonator

$t_{sep}^{\mu b} = 2.84$ ns	Separation in time between (the centres of) 2 consecutive micro-bunches
$T_{accumulation} = T_0\, N_{injections} = 2.2$ ms	Accumulation time
$T_0 = 1/f_0 = 3.32\ \mu$s	Average revolution period in A and C
$T_{RF} = 1/f_{RF} = 22.715$ ns	Average RF period in A and C
$Z_0 = 377\,\Omega$	Free space impedance
$\beta = \sqrt{1-\gamma^{-2}} = 0.9543$	Relativistic velocity factor
$\beta_{x,y} = R/Q_{x,y}$	Average transverse betatron functions. $\beta_x^A = 13.45$ m, $\beta_y^A = 11.35$ m, $\beta_x^C = 8.79$ m, $\beta_y^C = 9.21$ m
$\gamma = E/E_0 = 3.345$	Relativistic mass factor
γ_{tr}	Relativistic mass factor at transition energy. $\gamma_{tr}^A = 14.837$, $\gamma_{tr}^C = 15.089$
$\varepsilon_0 = 8.84\times10^{-12}$ Fm^{-1}	Permittivity of free space
ε_l	Longitudinal bunch emittance. $\varepsilon_l^{MbA} = 0.1$ eVs
$\varepsilon_{x,y}^{\mathrm{norm},1\sigma} = \beta\,\gamma\,\varepsilon_{x,y}^{\mathrm{rms}}$	Normalized rms transverse emittances. $(\varepsilon_{x,y}^{\mathrm{norm},1\sigma})_{\mu b} = 0.6\ \mu$m, $(\varepsilon_{x,y}^{\mathrm{norm},1\sigma})_{MbA} = (\varepsilon_{x,y}^{\mathrm{norm},1\sigma})_{MbC} = 50\ \mu$m
$\eta = \gamma_{tr}^{-2} - \gamma^{-2}$	Slippage (or off-momentum) factor. $\eta^A = -0.08481$, $\eta^C = -0.08496$
$\xi_{x,y} \approx -1$	Transverse (relative) chromaticities in A and C
$\rho_w = 10^{-6}\ \Omega$m	Vacuum chamber resistivity (stainless steel)
τ_b	Total (4σ) bunch length (in seconds). $\tau_{\mu b} = 0.5$ ns, $\tau_{MbA} = 17$ ns ("estimated" length of a macro-bunch at the end of accumulation), $\tau_{MbC} = 4$ ns
$\phi_2 = -\phi_1$	Bunch half length (in RF phase). $\phi_2^{MbA} = -\phi_1^{MbA} = 134.7$ deg
$\omega_0 = 2\pi\, f_0$	
$\omega_r^{BB} = 2\pi\, f_r^{BB}$	
$\omega_{RF} = 2\pi\, f_{RF}$	
$\omega_{x,y} = Q_{x,y}\,\omega_0$	Transverse betraton angular frequencies
$\omega_{\xi_{x,y}} = 2\pi\, f_{\xi_{x,y}}$	
$\Delta p/p_0 = \pm\, 2\,\sigma_p/p_0$	Maximum relative bunch momentum spread
$(\Delta p/p_0)_{\mathrm{FWHH}} = 2\sqrt{2}\,(\sigma_p/p_0)$	Full width at half height of the bunch momentum distribution (considering a parabolic distribution)
σ_p/p_0	Rms relative bunch momentum spread. $(\sigma_p/p_0)_{\mu b} = 4\times10^{-5}$, $(\sigma_p/p_0)_{MbA} = 7.25\times10^{-4}$, $(\sigma_p/p_0)_{MbC} = 2.25\times10^{-3}$