SPS potential with upgraded injectors

E. Shaposhnikova (CERN/AB)

BENE, 14 November, 2006

Outline

- CNGS beam: production scheme and parameters
- Present capabilities of the complex
  (results of high intensity run in 2004)
- Future injector upgrade and consequences for CNGS beam

High intensity beams in CERN SPS Past and future

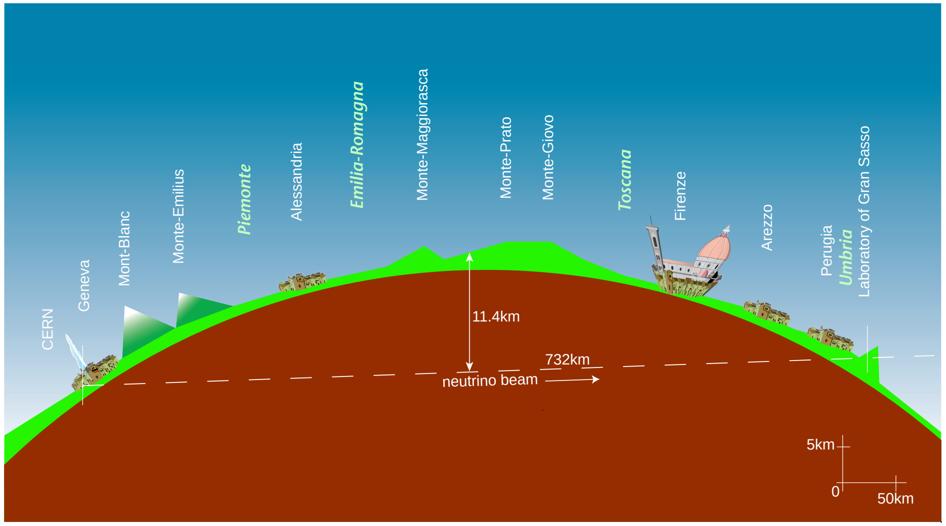
- 1997: Intensity record $\mathbf{4.8 \times 10^{13}}$ at 450 GeV/c (ν experiments) with normal operation around $\mathbf{4.2 \times 10^{13}}$ per cycle
- 1997 - now: SPS is delivering $\sim \mathbf{2.3 \times 10^{13}}$ for fixed target (FT) physics at 400 GeV/c
- 1997 - 2001: Accelerators upgrade in preparation for LHC beam. 2003: nominal LHC beam with $\mathbf{3.2 \times 10^{13}}$ at 450 GeV/c
- 2004: high intensity CNGS test with a new record of $\mathbf{5.3 \times 10^{13}}$ at 400 GeV/c
- 2006: nominal LHC intensity: $\mathbf{3.4 \times 10^{13}}$, CNGS commissioning and initial operation: $\mathbf{3.5 \times 10^{13}}$
- 2011 - ... Future accelerator upgrade

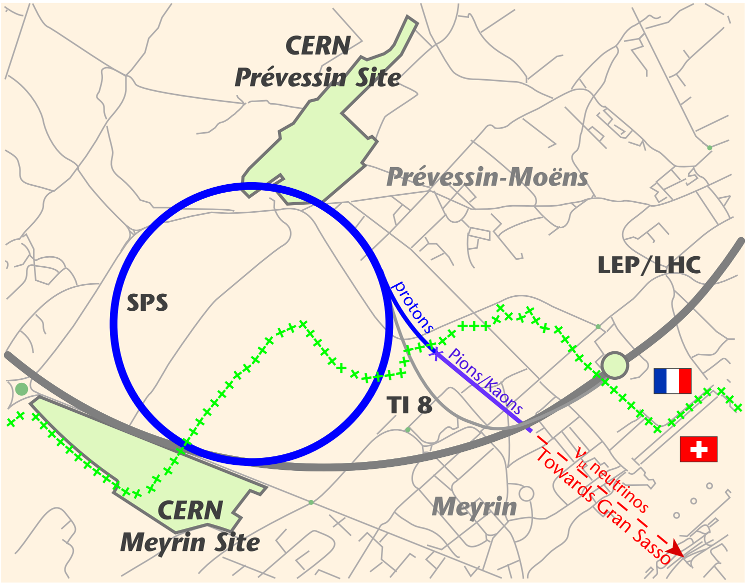
High intensity beams CNGS and LHC

Nominal beam parameters in the SPS

		CNGS	LHC
injection P_s	GeV/c	14	26
extraction P_s	GeV/c	400	450
transition crossing		yes	no
bunch spacing	ns	5	25
part of the ring filled		10/11	(3-4)/11
number of batches		2	3-4
number of bunches per batch		2100	72
bunch intensity	10^{10}	1.05	11.5
total intensity	10^{13}	4.8	3.3
cycle length	s	6.0	21.6
H/V normalised trans. emit.	μm	12/7	3.5

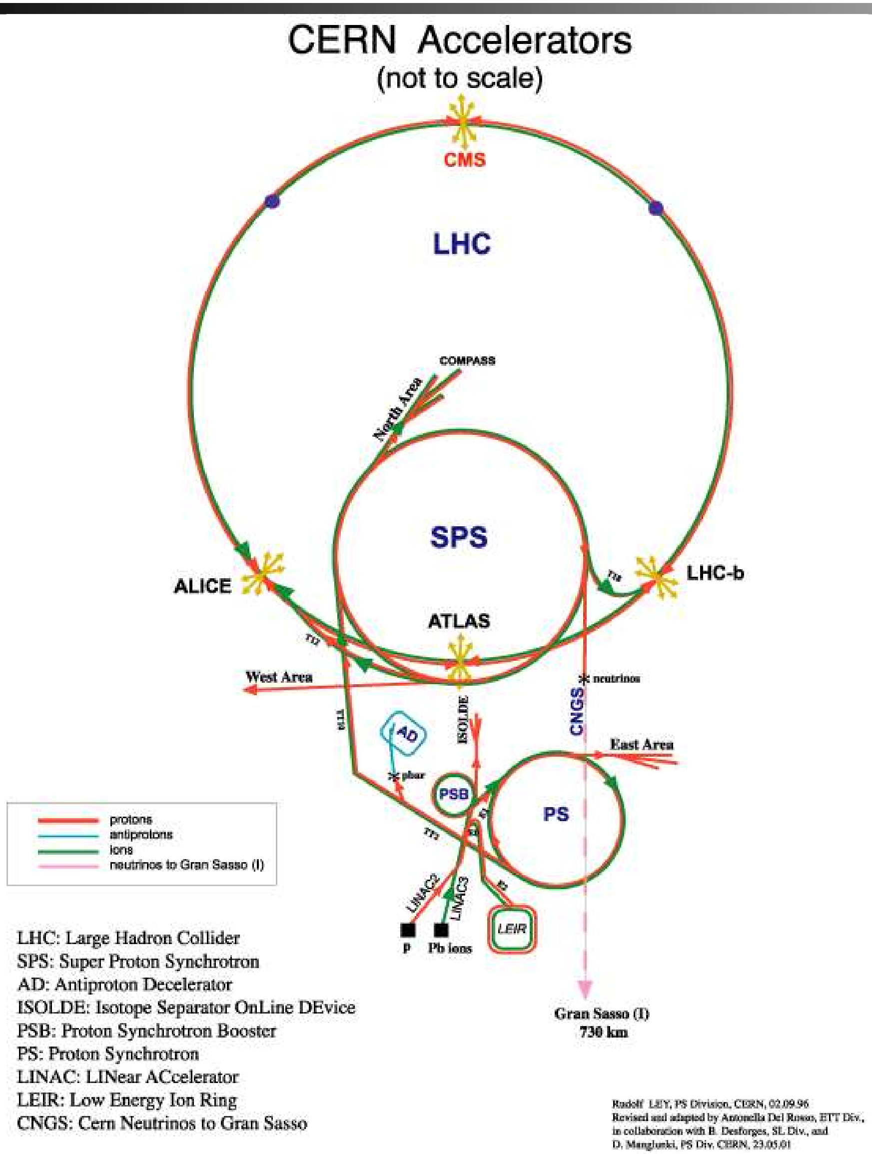
CNGS beam





http://proj-cngs.web.cern.ch/proj-cngs/Download/

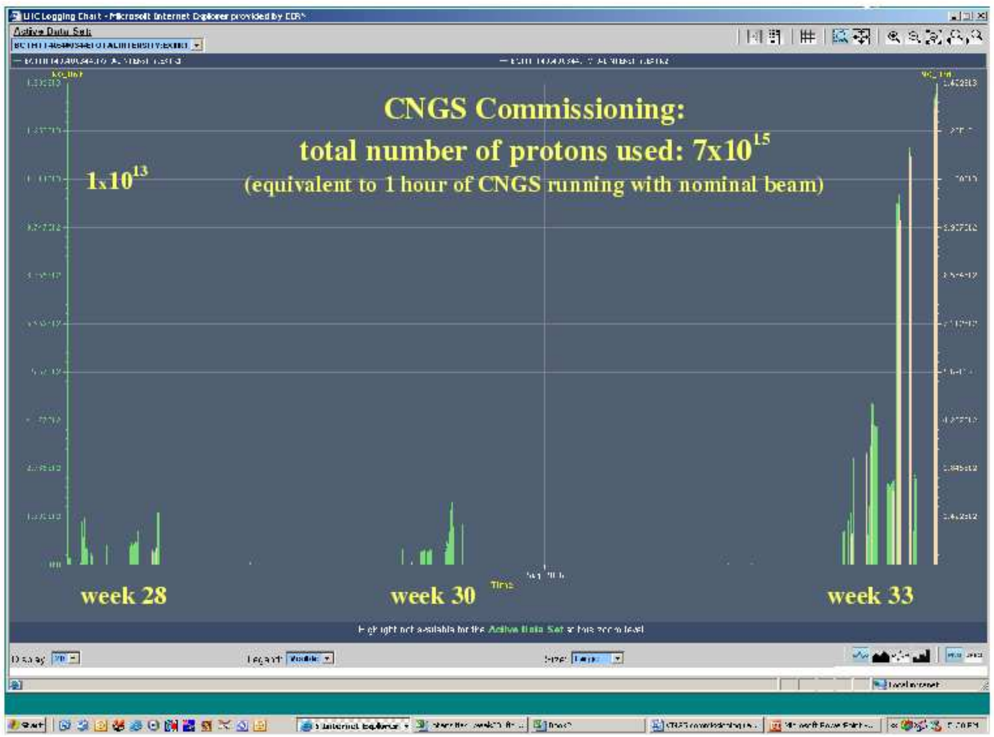
CNGS beam



Present production scheme

- Linac2: 0.75 MeV ⟶ 50 MeV
- Booster (4 rigs): 50 MeV ⟶ 1.4 GeV, 2 bunches/ring, 8 bunches each 1.2 s
- PS: 1.4 GeV ⟶ 13.1 GeV, acceleration at h=8, h=16 (10 MHz), transition crossing, flat top: debunching, rebunching at 200 MHz, 5-turn extraction
- SPS: 13.1 GeV ⟶ 399.1 GeV, 2 injections, acceleration at h=4620 (200 MHz), 2 fast extractions

CNGS commissioning



E. Gschwendtner

- CNGS construction: 2000-2006
- Hardware commissioning: February - April 2006
- Dry runs: April - May 2006
- Commissioning with beam: 3 weeks in July-August 2006
- Maximum proton intensity in 2006: $\mathbf{3.5 \times 10^{13}}$/cycle at 400 GeV/c
- From 2007: $\mathbf{4.5 \times 10^{19}}$/year $\times \mathbf{5}$ years

CNGS commissioning team: K. Elsner, M. Meddahi, E. Gschwendtner et al.

CNGS beam

Nominal CNGS beam:

- Intensity: $\mathbf{4.8 \times 10^{13}}$ (two 10.5 μs pulses with 50 ms interval)
- Beam power: 500 kW. Flux: $\mathbf{4.5 \times 10^{19}}$ p/year

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$\Rightarrow$ High intensity CNGS test in September 2004

- to see the effect of accelerator upgrade for nominal LHC intensity
- to identify and study main intensity limitations in whole chain

Upgrade of accelerators PSB and PS

Booster:

- new working point
- acceleration at h=5 ⟶ h=1 (no coupled-bunch instabilities) + h=2 – to decrease space-charge effects + h=9 – for controlled long. emittance blow-up at high energies

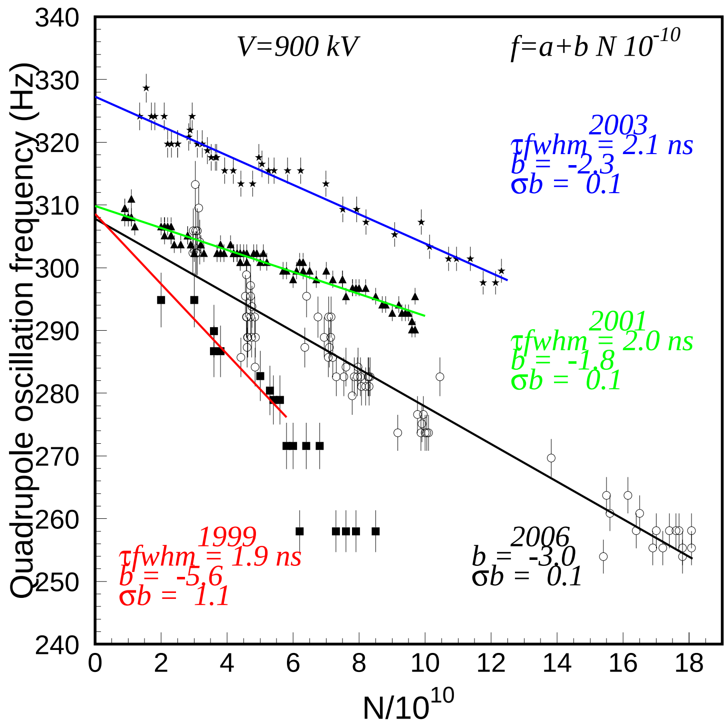
PS:

- 1.0 GeV ⟶ 1.4 GeV to reduce space charge tune spread
- acceleration at h=20 ⟶ h=8
- equipment alignment – to increase machine acceptance
- lepton equipment removed (114 MHz RF system, ...)

⊖ installation of 13/20, 40, 80 MHz RF systems for LHC

Upgrade of accelerators
SPS

Beam measurements at 26 GeV/c:
slope (b) $\propto$ impedance $\mathrm{Im}Z/n$



- Impedance reduction (1999/2001)
  - shielding of different elements, including kickers, septa and 800 pumping ports
  - removal of lepton equipment (100 MHz, 200 MHz SW and 352 MHz RF systems)
- Upgrade of the main 200 MHz RF system
  - new power couplers
  - RF feedback system per cavity

$\ominus$ But... installation of extraction kickers for LHC: 5 in 2003 and 4 in 2006

High-intensity CNGS run
Beam intensities

- CNGS beam during period: 6.09-3.10.2004, high intensity from 15.09.2004 (*G. Arduini, T. Bohl, M. Chanel, R. Garoby, S. Hancock, K. Hanke, T. Linnecar, E. Metral, E. Shaposhnikova, R. Steerenberg, B. Vandorpe, Proc. PAC 2005, Knoxville*)

	Intensity/10^{13}		
Accelerator	injected	accelerated	extracted
Booster	4.3	3.84	3.65
PS	3.57	3.42	3.15
SPS (27.09.04)	3.0x2	5.7 after trans.	-
SPS (03.10.04)	2.9x2	5.5 after trans.	5.3

- Intensity records in the PS (with one PSB batch) and the SPS, but at different moments $\longrightarrow$ potentially more intensity at 400 GeV/c
- Total losses (in all rings) for record intensity: 38%

High-intensity CNGS run Booster

Typical example from 2004 run

	Intensity/10^{10}				
Ring	1	2	3	4	Total
Normal operation (12 turns)	940	1010	835	914	3700
Max. intensity (13 turns)	993	1020	889	935	3840

- Linac2: 175 mA. Injection over 12 or 13 turns with efficiency $\sim 60\%$
- All 4 rings are the same but behave differently $\longrightarrow$ difficult for tuning
- 10% losses during first 80 ms when beam is space charge dominated

$\Rightarrow$ Increased injection energy to overcome space charge limitation ($\propto \gamma^{-2}$)

High-intensity CNGS run PS

- Injection losses $\sim \mathbf{6\%}$ due to PS acceptance limitations
  $\longrightarrow$ smaller transverse emittance, allignment
- Intensity limitation due to space charge at injection
  $\longrightarrow$ higher injection energy
- Continuous losses through the cycle $\sim \mathbf{3\%}$
  $\longrightarrow$ studies
- Extraction losses $\sim \mathbf{10\%}$ with present 5-turn continuous extraction
  $\longrightarrow$ new resonant islands extraction (*M. Giovannozzi et al.*)
- Required performance of the 10 MHz RF system close to the limit (1 gap-relay control-board broken, 3 gap-relays, 1 final amplifier and 1 power supply changed...)
- Significantly increased radiation level

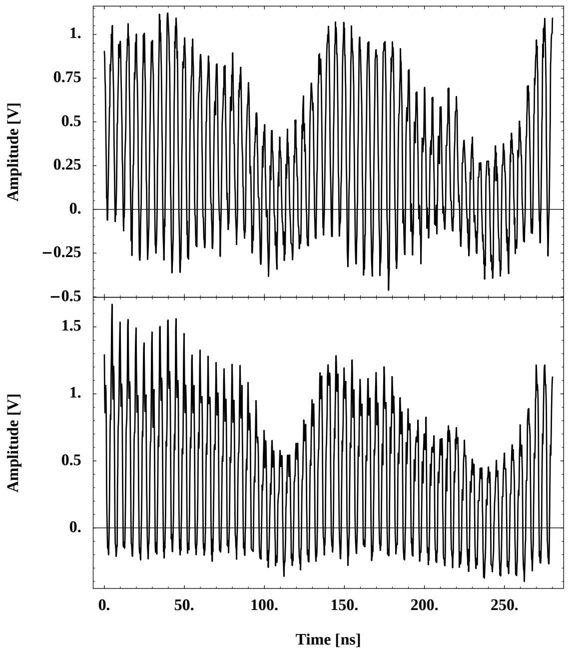
$\ominus$ The oldest CERN ring - constructed in 1959, almost on the surface

High-intensity CNGS run
PS - SPS transfer

Beam on the SPS flat bottom: first turn (top) and after capture at 220 ms (bottom)

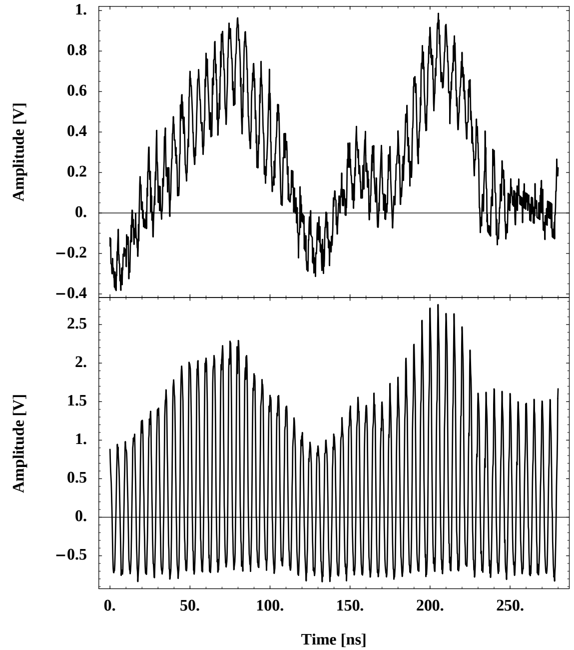
PS: h=16, debunching

240 kV @200 MHz



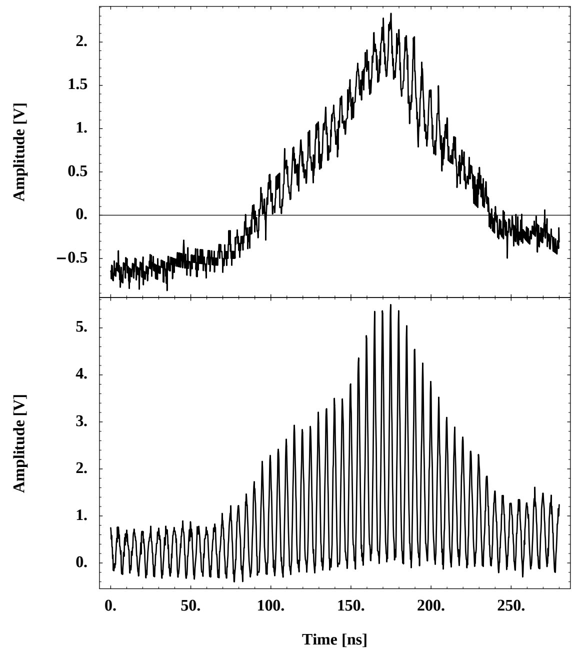
PS: h=16, no debunching

30 kV @200 MHz



PS: h=8, no debunching

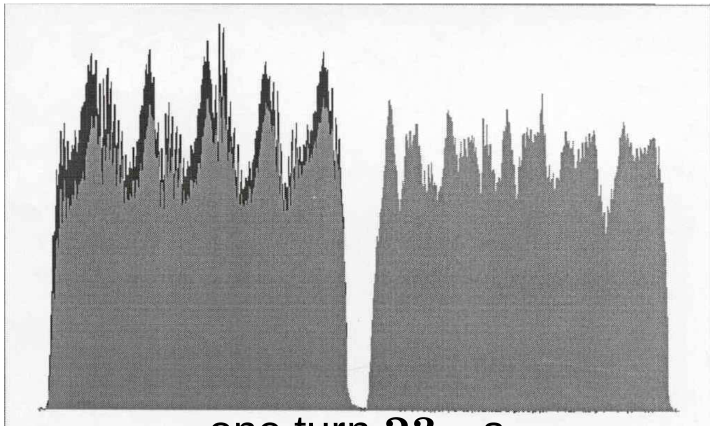
30 kV @200 MHz



- No bunch-to-bucket transfer, absence of kicker gap ⟶ losses

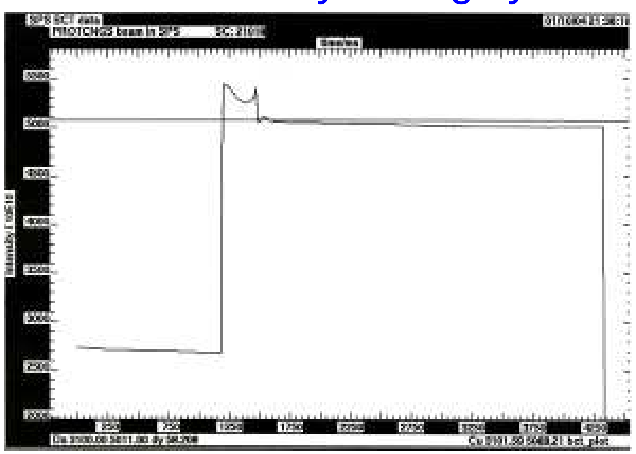
High-intensity CNGS run SPS

2 batches at injection



⟵ one turn $\mathbf{23}\ \mu$s ⟶

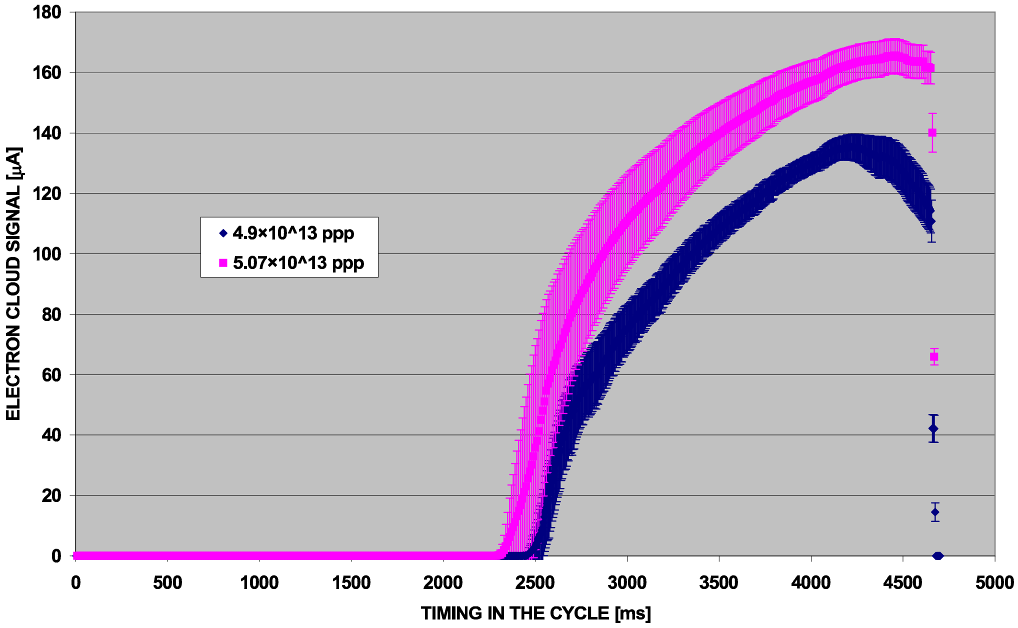
Beam intensity during cycle



- Injection losses - 5%
- Losses on the flat bottom $\sim \mathbf{2\%}$
- Some particles in the gap - losses at extraction ($\sim \mathbf{2\%}$)
  $\Rightarrow$ cleaning by transverse damper
- Capture loss 3-4%
- Beam losses at transition: 4%
- Continuous losses after transition: $\mathbf{5\%} \longrightarrow \mathbf{2\%}$
  $\Rightarrow$ early beam dump
- Heating of extraction kickers, wire scanners, more RF trips ...

High-intensity CNGS run SPS

Electron cloud



- e-cloud signal during acceleration (100 GeV/c) even for conditioned machine
- strong dependence on intensity and bunch length
- caused sparking of electrostatic septa at the end of the cycle

$\Rightarrow$ Can be improved by replacing the SPS vacuum chamber (6000 m)

High-intensity CNGS run
Beam losses

- Beam loss is at the moment the most critical issue for CNGS beam due to
  - induced radiation (even for nominal intensity)
  - eventual lack of protons (ultimate intensity)
- To provide nominal CNGS beam intensity $\sim \mathbf{3}$ times more particles needed from Linac.
- Radiological impact increases with number of particle lost and their energy
  $\Rightarrow$ losses in the PS and especially in the SPS are more critical
  $\Rightarrow$ to keep absolute losses constant, relative losses should decrease with intensity
  $\ominus$ But... relative losses are increasing with intensity (collective effects, beam size ...)!

Beam		FT	CNGS		
		2004	nomin.	record	upgrade
Intensity at SPS ext.	10^{13}	2.6	4.4	5.3	7.0
Relative loss	%	16	24	38	$<$ 20

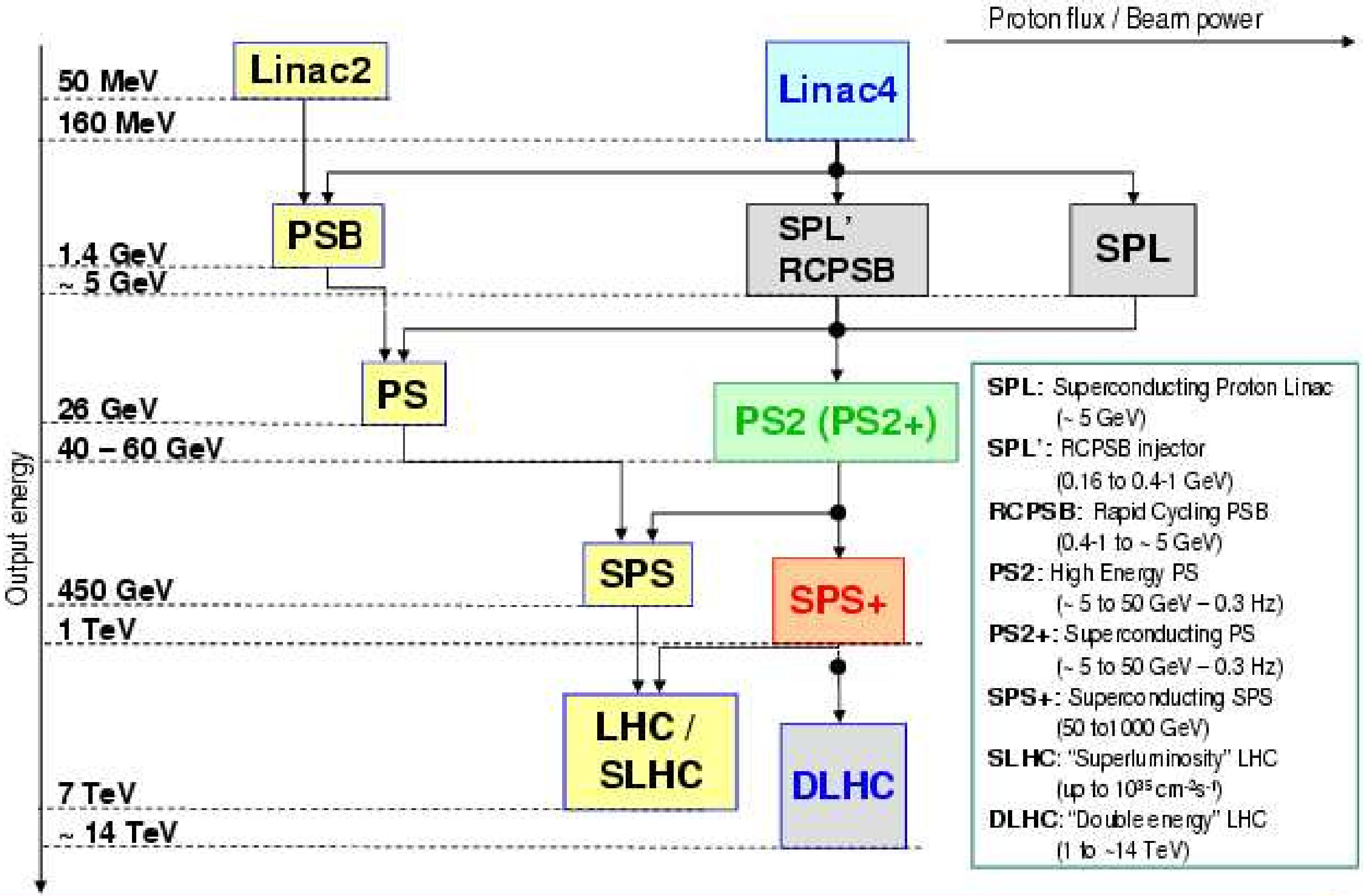
$\Rightarrow$ Significantly improved accelerator performance needed for higher intensities!

Short-term improvements

- Identified lack of protons (*HIPWG, M. Benedict et al., 2004*)
- Reduction of the PSB basic period (1.2 s $\longrightarrow$ 0.9 s) - test in 2005
- Longer SPS flat top for FT/COMPASS - 2006
- Shorter pilot LHC cycle (LHC setting-up) - 2006
- Studies for reduction of losses (*BLRWG, G.Arduini et al., 2004 -*)
- Machine realignment, search and removal of aperture limitations
- New multi-turn extraction in PS (loss: 10% $\longrightarrow$ 2%) from 2008
- Refurbishing of the PS magnets (2004 - ...), new power supply (2007)
- Beam control upgrade
- Shielding of the SPS extraction kickers plus new design

Future upgrade of accelerators

Scenarios for the CERN accelerator complex (*R. Garoby et al., CERN PAF, 2006*)



Future upgrade of accelerators Linac4, SPL, PS+

- PSB with Linac4 (160 MeV - 1.4 GeV) - 2011
  (*M. Vretenar - linac developments, this CARE meeting*)
  - increased space charge limit (losses, beam size)
- PS+ (50 GeV) - 2016 (*WG - M. Benedikt et al., CERN*)
  - full performance with SPL - Superconducting Proton Linac (3.5 GeV)
  - limited performance with existing PS (staged approach)
  - underground ring appropriate for high intensity operation
  - twice higher line density in twice circumference $\longrightarrow \mathbf{1.2 \times 10^{14}}$
  - repetition time 2.5 s
  - maximum effective beam power - 400 kW

$\ominus$ Not optimised for heavy ions...

Future upgrade of accelerators
SPS

CNGS/FT beam

- total maximum intensity from PS2: 1.2×10^{14}
  4200 bunches with 3×10^{10}/bunch
  (ultimate LHC: 288 bunches with 1.7×10^{11}/bunch)
- 1 batch injection $\longrightarrow$ shorter acceleration cycle (by 1.2 s)
- no transition crossing (transition energy 21.4 GeV) $\longrightarrow$ less losses

$\ominus$ But... old ring (impedance, e-cloud, RF systems, power...)

“Upgrade" CNGS intensity needs RF upgrade and impedance reduction

Significantly more? $\Rightarrow$ SPS+ (SC, 50 $\longrightarrow$ 1000 GeV)

Future upgrade of accelerators
Beam availability

- Higher reliability of injector chain - present machines are more than 30 years old (including SPS)
- Shorter FT/CNGS cycles (by 20%)
- Shorter LHC filling time (by 45%) $\longrightarrow$ more cycles available for other physics (50% of beam time for LHC first year(s) assumed to go down to 15% later)

But

- other SPS users: COMPASS, kaon physics, ions and machine development sessions to improve performance!
- reduced LHC run in future with high luminosity (filling more often)

Beam availability Example: 2006

CERN - AB & OP eLogbook - Statistics http://elogbook.cern.ch/eLogbook/statistics.jsp?lgbk=50&fromDate=2

Statistics for the eLogbook: SPS From: 20060807 Period: Morning To: 20061106 Period: Morning

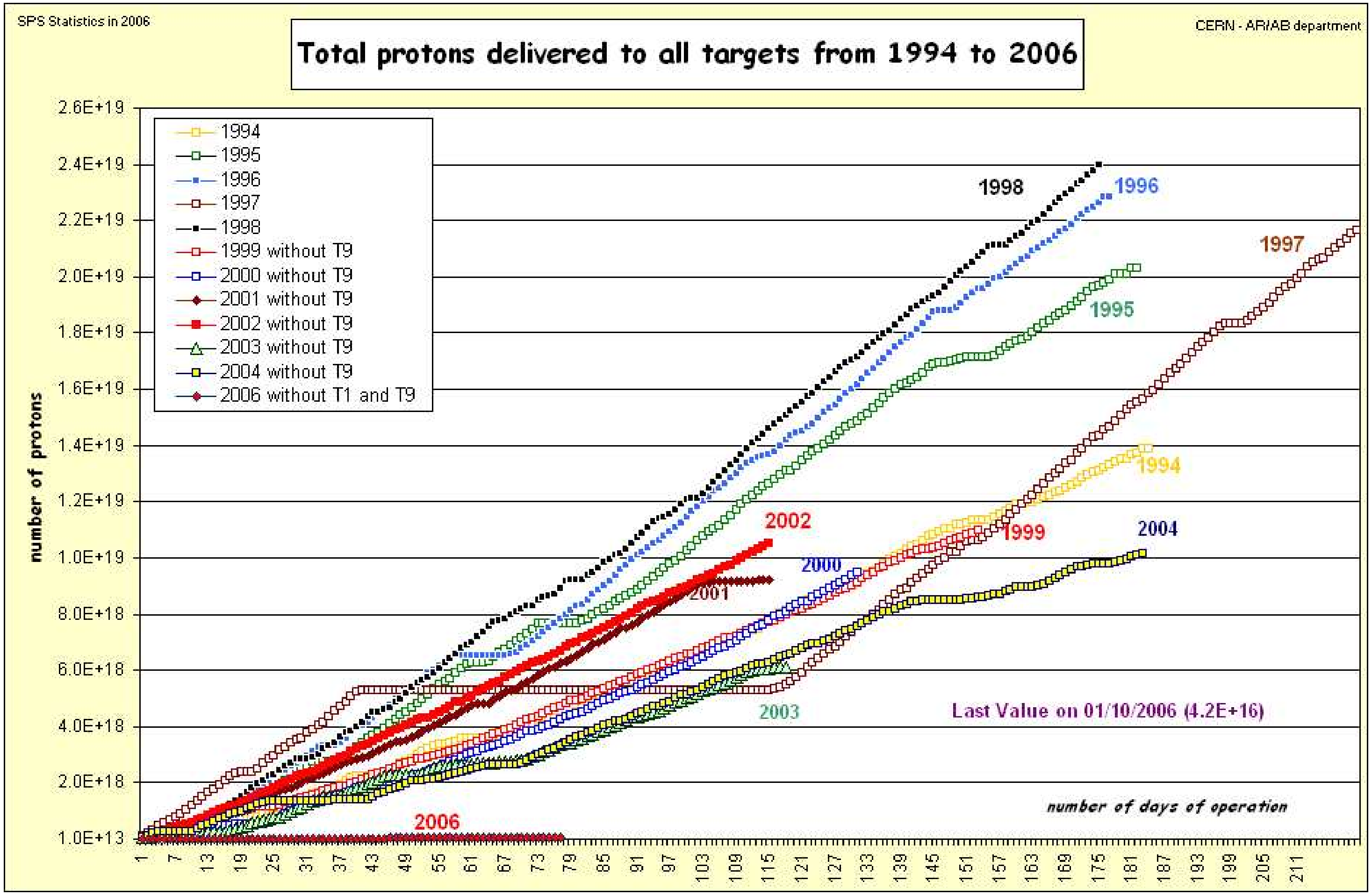
Start Statistics ...

Availabilities			
Lines	**In Super Cycle**	**In Fault**	**Availabilities (%)**
SFTPRO1	1160 [h] 00 [min] 15[s]	232 [h] 27 [min] 16[s]	**79%**
SFTPRO2	680 [h] 22 [min] 16[s]	92 [h] 02 [min] 01[s]	**86%**
CNGS1	463 [h] 13 [min] 13[s]	105 [h] 38 [min] 24[s]	**77%**
CNGS2	35 [h] 19 [min] 53[s]	3 [h] 21 [min] 27[s]	**90%**
CNGS3	35 [h] 19 [min] 53[s]	3 [h] 21 [min] 27[s]	**90%**
LHC1	161 [h] 20 [min] 44[s]	25 [h] 37 [min] 30[s]	**84%**
LHC2	74 [h] 58 [min] 53[s]	9 [h] 49 [min] 19[s]	**86%**
MD	165 [h] 17 [min] 24[s]	61 [h] 53 [min] 25[s]	**62%**
TOTAL	**2775 [h] 52 [min] 31[s]**	**534 [h] 10 [min] 49[s]**	**80%**

Beam availability Example: 2006

Systems for SFTPRO1		
GROUP NAME	FAULT NAME	DURATION
AT	MISC	44 [min] 29[s]
AT	Main Magnets	14 [h] 08 [min] 42[s]
AT	Vacuum	18 [h] 46 [min] 28[s]
ATB	MISC	39 [min] 26[s]
ATB	Targets & Dumps	41 [min] 59[s]
BT	Kickers	22 [h] 54 [min] 32[s]
BT	MST, MSE	4 [h] 16 [min] 24[s]
BT	ZS	8 [h] 55 [min] 11[s]
CO	Computer	08 [min]
CO	Interlock	3 [h] 33 [min] 52[s]
CO	MISC	18 [min]
CO	Software	1 [h] 04 [min] 47[s]
CO	Timing	02 [min] 24[s]
CPS	LINAC2	4 [h] 25 [min] 53[s]
CPS	MISC	2 [h] 49 [min] 41[s]
CPS	PS	66 [h] 31 [min] 04[s]
CPS	PSB	6 [h] 41 [min] 18[s]
Miscellaneous	Random Fault	3 [h] 44 [min] 25[s]
Miscellaneous	Storms	1 [h] 02 [min] 32[s]
OP	Access	2 [h] 57 [min] 46[s]
OP	Beam Losses	31 [min] 51[s]
OP	Setting Up	8 [h] 23 [min] 59[s]

Beam availability
Number of days of operation



Summary

- Successful CNGS commissioning in 2006. Operation with a nominal CNGS intensity of $\mathbf{4.8 \times 10^{13}}$ from 2007. Radiation is a main issue
- A new intensity record was obtained in the CERN accelerator chain ($\mathbf{5.3 \times 10^{13}}$) as a result of recent upgrades (for LHC beam). Can be operational only after beam loss reduction
- Significant intensity increase can be achieved in PS2 at 50 GeV after future injector upgrade
- Some intensity limitations (but not all) will be removed in the SPS at increased injection energy (with PS2).
- Average beam availability in the past - 80%
- Total number of protons delivered can be increased in future with shorter cycles and more reliable operation

Near future plans

The CERN White Paper “Scientific Activities and Estimates for 2007 and Provisional Projections for the Years 2008-2010 and Perspectives for Long-Term" was presented by CERN DG R. Aymar in October 2006 to CERN Council with request for resources for the next 4 years which includes “as a high priority"

- Linac 4 construction (55 MCHF + 115 FTE)
- Design SPL (40 FTE)
- Design PS2 (30 FTE)