How far can we increase the Intensity per Pulse for CNGS?

PS&SPS Days, 14 January, 2004

E. Shaposhnikova for High Intensity CNGS team:

G. Arduini, T. Bohl, M. Chanel, R. Garoby, S. Hancock, K. Hanke,

T. Linnecar, E. Metral, R. Steerenberg, B. Vandorpe

plus help from OP shifts

Acknowledgments: A. Blas, E. Jensen, M. Paoluzzi, C. Rossi,

K. Cornelis, W. Hofle, E. Montesinos, E. Vogel, U. Wehrle

Outline

- Main results of high intensity CNGS test in 2004
- Intensity limitations and possible actions

How far can we increase the Intensity per Pulse?

How far can we increase the Intensity per Pulse?

- Not more than the CNGS target capability $\mathbf{7 \times 10^{13}}$.

How far can we increase the Intensity per Pulse?

- Not more than the CNGS target capability $\mathbf{7 \times 10^{13}}$.
- PSB can produce $\mathbf{4.1 \times 10^{13}}$ per one PS batch (1.2 s)

How far can we increase the Intensity per Pulse?

- Not more than the CNGS target capability $\mathbf{7 \times 10^{13}}$.
- PSB can produce $\mathbf{4.1 \times 10^{13}}$ per one PS batch (1.2 s)
- PS can produce $\mathbf{4 \times 10^{13}}$ in 2 batch operation (2.4 s)

How far can we increase the Intensity per Pulse?

- Not more than the CNGS target capability $\mathbf{7 \times 10^{13}}$.
- PSB can produce $\mathbf{4.1 \times 10^{13}}$ per one PS batch (1.2 s)
- PS can produce $\mathbf{4 \times 10^{13}}$ in 2 batch operation (2.4 s)

Then all depends on

- Hardware limitations
- Acceptable losses in the Accelerator Complex:

$\Rightarrow$ T. Otto: How many protons can we afford to lose annually in the PS complex? D. Forkel-Wirth: How many protons can we afford to lose annually in the SPS and its beam lines?

- Behaviour of relative losses with intensity

$\Rightarrow$ high intensity test in September 2004

High intensity CNGS test in 2004

Main goals

√ To obtain in given time maximum possible intensity at 400 GeV in the SPS with available intensity from PS.

√ To identify and study main intensity limitations in whole accelerator chain.

√ To study PS-SPS beam transfer optimization.

⊖ To make reference measurements to see the effect of upgrade for LHC.

Main results of high-intensity CNGS run (1/2)

- CNGS beam during period: 6.09-3.10.2004, high intensity from 15.09. CERN intensity record, but with non-negligible losses

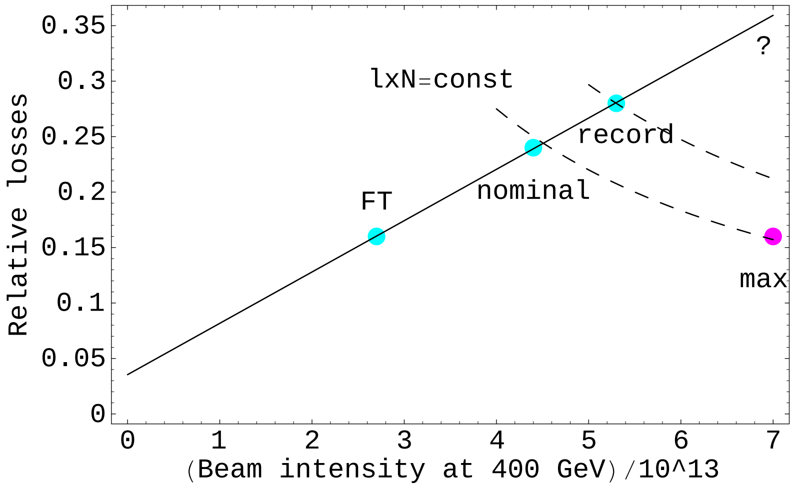
	Intensity/10^{13}		
Accelerator	injected	accelerated	extracted
PS Booster	4.3	3.84	3.4 ?
PS	3.57	3.42	3.2
SPS 27.10.04	3.0x2	5.7 after tr.	?
SPS 30.10.04	2.9x2	5.5 after tr.	5.3

- Intensity records in the PS (with one PSB batch) and the SPS at different moments $\longrightarrow$ potentially more intensity at 400 GeV
- Total losses for record intensity: 28%. Expected (*Report of HIPWG, AB-2004-022*) for nominal (4.4×10^{13}) CNGS operation: 24%. Present FT operation: 16%

Main results of high-intensity CNGS run (2/2)

Relative total losses

in the CERN accelerator chain



- Total losses: $\mathbf{N_{ext}^{SPS}/(2 \times N_{inj}^{PSB})}$
- $\mathbf{0.85 \times 8.2 \times 10^{13} = 7.0 \times 10^{13}}$

- Relative losses are increasing with intensity (space charge effects, instabilities, ...)

$\Rightarrow$ improved performance

- Impact of losses increases with beam energy $\longrightarrow$ losses in the PS and especially in the SPS are more critical

$\Rightarrow$ Double-batch injection from the PSB has more potential

Intensity limitations: PS Booster

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 efficiency $\sim 60\%$
- Ring 3 systematically has a smaller emittance and intensity due to losses at injection $\longrightarrow$ potential gain $(10 - 15) \times 10^{11}$ - studies
- 10% losses during first 80 ms (fine adjustments)

  $\Rightarrow$ test (< 2007) and implementation of all-digital beam control
- Realignment of all 4 rings
- New working point (4.17,4.23). The PSB record with old WP.

Intensity limitations: PS

- Injection losses $\sim (6-8)\%$ due to PS acceptance limitations
  $\Rightarrow$ better instrumentation in transfer line (intensity calibration...)
  $\Rightarrow$ alignment and smaller vertical emittance from PS Booster
  $\Rightarrow$ transverse damper for injection oscillations
- Extraction losses $\sim 8\%$ $\Rightarrow$ new CT (M. Giovannozzi)
- Problems with the 10 MHz system - required performance close to the system limit (1 gap-relay control-board broken, 3 gap-relays, 1 final amplifier and 1 power supply changed...)
  $\Rightarrow$ preventive maintenance (new RF tubes, spare gap relays)
  $\Rightarrow$ study ($<$2007) and implement solid-state gap short-circuits

PS - SPS transfer. Motivation for studies (1/2)

Nominal scheme:

PS: acceleration at h=16, reduction of voltage to 4 kV, debunching, recapture/modulation at 200 MHz with 7 cavities, ~ 24 kV each

SPS: capture into 200 MHz RF system

- How many 200 MHz cavities are really necessary in the PS for beam recapture/modulation before extraction?
- Up to three used for controlled emittance blow-up.

$\Rightarrow$ Possible actions for 200 MHz RF system:

• useless cavities could be suppressed $\longrightarrow$ less impedance and maintenance (2005?)

• new electronics for voltage control loops

• or new 200 MHz system with RF feedback and fast tuning

PS - SPS transfer. Motivation for studies (2/2)

- Debunched beam in the PS: microwave instability leading to momentum blow-up and absence of kicker gap

Is debunching really necessary?

- \- If not, can one use harmonic h=8 instead of h=16?

  $\Rightarrow$ Beam bunched at h=8 would provide sufficient kicker gap for new CT extraction.

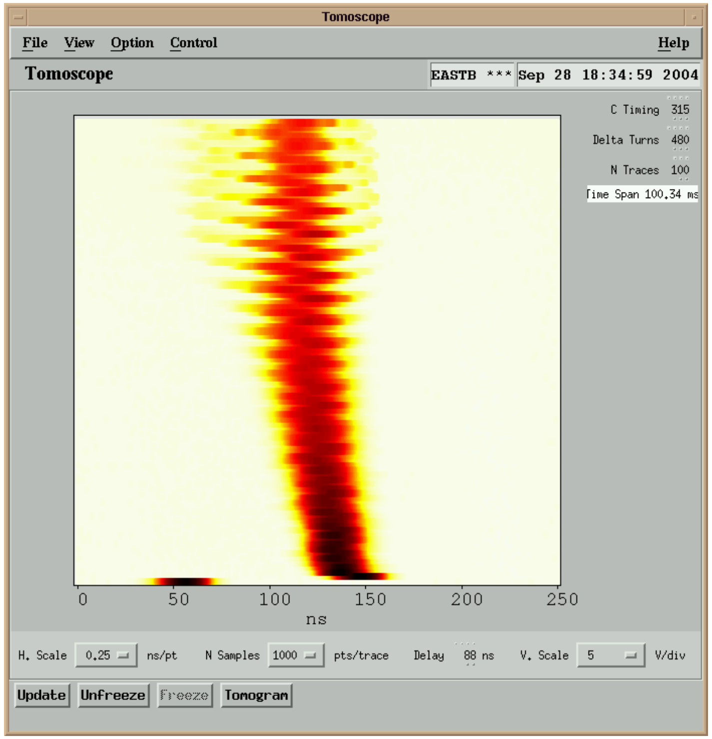
  $\Rightarrow$ Splitting from h=8 to h=16 requires additional time and flat portion in the cycle (1.2 s $\Leftrightarrow$ 0.9 s cycles).

$\ominus$ No debunching in the PS - potential degradation of spill for FT beam (M. Hauschild) - to be studied

PS - SPS transfer. Results in the PS

Coupled bunch instability

of the beam at h=8



Instability on h=8 above transition

Stability limitations when usual scenario was changed (operation at h=8 without splitting):

- violent coupled bunch instabilities on the 3.5 GeV/c plateau
- single bunch longitudinal instability above transition

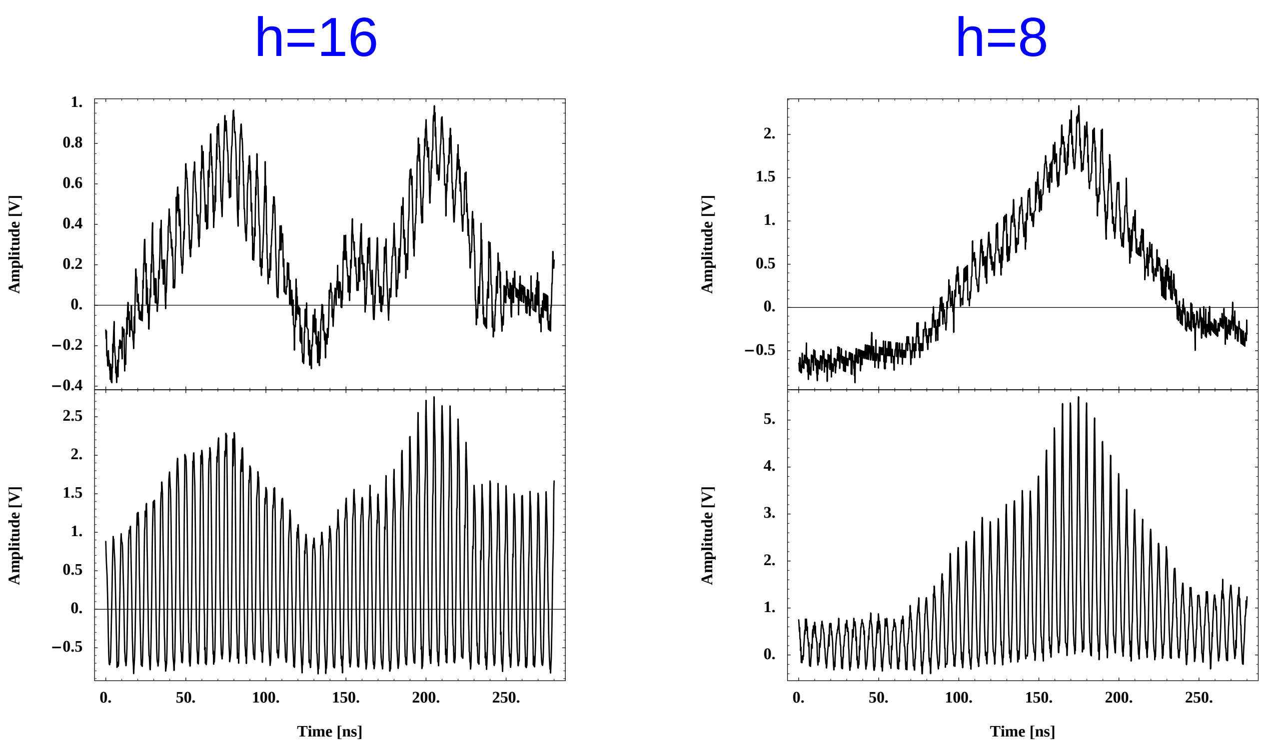
$\Rightarrow$ one-turn-delay feedback (AD) helped in both cases - upgrade

$\Rightarrow$ dedicated broad-band longitudinal damper

PS - SPS transfer. Results in the SPS (1/2)

- No significant difference for maximum and minimum 200 MHz modulation. However a minimum 200 MHz modulation (1 cavity ~ 24 kV) is absolutely necessary “to see” the beam in the SPS.
- For debunched beam (for the same voltage before extraction to the SPS) the total transmission in the SPS is better by approximately 1%.
- h=16: Losses in the SPS increase with increasing 10 MHz voltage in the PS. The best transmission in the SPS is for the lowest voltage (2.5 kV).
- h=8: losses were increased by 50% (compared with h=16)

PS - SPS transfer. Results in the SPS (2/2)



Beam on the flat bottom at $t = 0$ ms (top) and $t = 220$ ms (bottom).

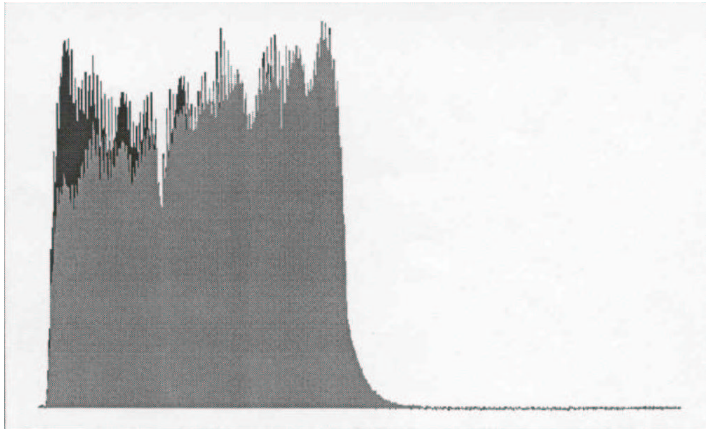
- Peak line density is important for transmission in the SPS

$\Rightarrow$ Low voltage in the PS (difficult to control)

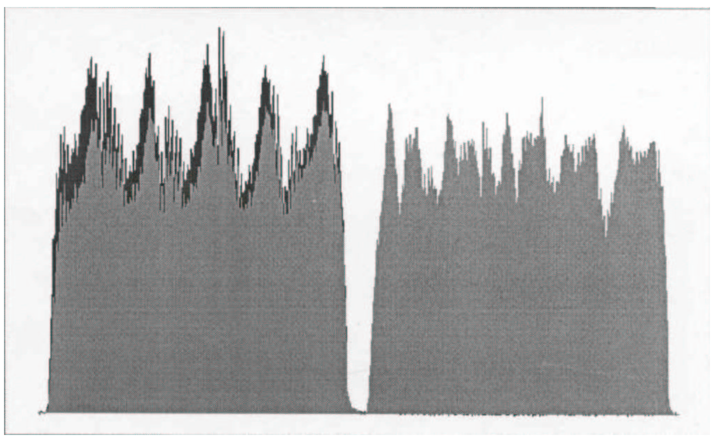
$\Rightarrow$ Bunch lengthening mode at h=8 plus h=16 in the PS

Intensity limitations: SPS. Injection

0.8 MV constant



0.8 MV increased to 2.5 MV



⟵ one turn ⟶

- 5% injection losses $+2\%$ losses on the flat bottom from 1 batch

$\Rightarrow$ vertical aperture limitations: TIDVG (2006), other bottle-necks?

- Nominal scheme (0.8 MV): triangular shape of the 1st batch and ghost bunches in the kicker gap
- "Quasi-adiabatic capture" (0.8 MV increased to 2.5 MV): (3-4)% loss in front porch.

$\Rightarrow$ new beam control for separate RF gymnastics for each batch

Intensity limitations: SPS.

Acceleration - transition crossing (1/3)

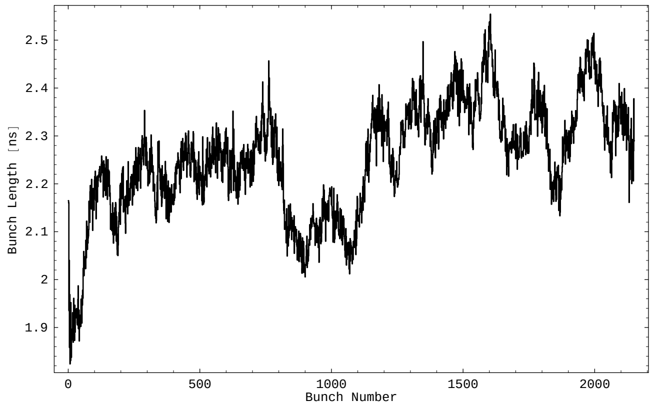
- Higher voltages than in the past (1998). Cannot be reduced by more than (0.5-1) MV without losses. $\longrightarrow$ More MKE heating (210 W/m - $\mathbf{107^o}$) than hoped (J. Uythoven). Probably OK $\leq \mathbf{6 \times 10^{13}}$.
  $\Rightarrow$ MKE shielding - studies (F. Caspers, E. Gaxiola *et al.*), new design (after 2009?)
- Continuous beam losses after transition even for modest intensities $\longrightarrow$ feedback in operation during ramp.
- Increased feedback gain improved transition crossing, but created problems in the front porch
  $\Rightarrow$ variable gain is necessary (upgrade)

Intensity limitations: SPS.

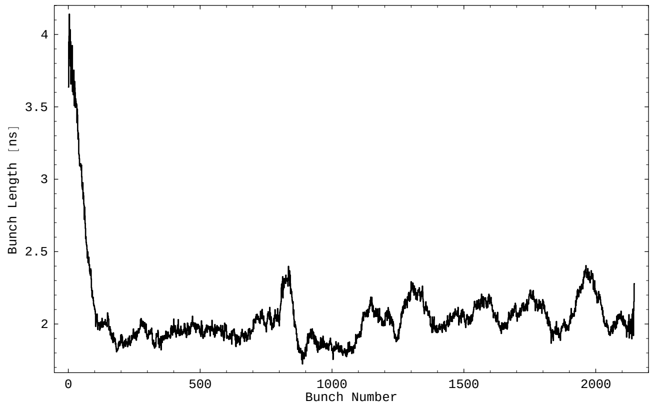
Acceleration - transition crossing (2/3)

Bunch length in the batch

before transition



after transition



- Significant emittance blow-up for first 100 bunches in the batch (factor 2 in bunch length)
- Continuous losses ($\sim 5\%$) after transition crossing led to interlock and early beam dump
  $\longrightarrow$ improved at the last day by phase loop adjustment

Intensity limitations: SPS.
Acceleration - transition crossing (3/3)

- Feedforward could be used only after transition
  $\Rightarrow$ upgrade of frequency range
- Power limitations (550 kW in pulsing mode) were not reached so far, however more problems with RF trips
- Coupled bunch instability at high energies (no losses).
  $\Rightarrow$ the 800 MHz RF system in bunch shortening mode (will be operational for LHC beam)
- e-cloud during acceleration (100 GeV/c) and ZS sparking
  $\Rightarrow$ J. Borburgh: Operating the septa beyond their design specs

Summary (1/2)

- No fundamental intensity limitations were reached ($\mathbf{5.3 \times 10^{13}}$) so far, however suggested hardware modifications should improve performance of the PS and SPS in particular to reduce losses and radiation
- Double-batch injection from PSB, new CT plus further improved PS and SPS performances needed to obtain maximum intensity at 400 GeV
- Relatively fast increase in intensity during the 2004 test as a result of recent upgrade. Further progress will be more slow $\longrightarrow$ more studies and fine tuning in future

Summary (2/2)

- PS-SPS transfer. PS: only one 200 MHz cavity is needed. SPS: transmission weakly depends on debunching and improves for lower voltage before extraction in the PS
- Aperture limitations were seen in all accelerators - continue search and realignment
- Less reliable operation at high intensity - preventive maintenance
- Better instrumentation can help (losses, ε_t)
- Due to limited time of the run not all possibilities to improve performance were explored