High brilliance and closer bunches from the LHC injectors

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LHC LUMI 2005, September 2, 2005

Outline:

- Existing LHC injectors
  - high brilliance
  - closer bunches
- New LHC injector (1 TeV) - first look

Acknowledgments: G. Arduini, T. Bohl, R. Garoby, T. Linnecar, G. Rumolo, F. Ruggiero, J. Tuckmantel, F. Zimmermann

Motivation

Main factors for the LHC luminosity upgrade expected from injectors:

(I) with existing injectors (*F. Ruggiero, F. Zimmermann*)

- **factor 2.2 from increase of bunch intensity from nominal to ultimate: $1.15 \times 10^{11} \rightarrow 1.7 \times 10^{11}$ with $\varepsilon_n = 3.5\ \mu$m**
- **factor 2.0 from reduced bunch spacing:**
  25 ns → 12.5 ns

⇒ 2.2 x 2.0 = 4.4

(II) with LHC injection energy of 1 TeV (*W. Scandale, HIF05*):

- **factor 2 from increase of bunch intensity by $\sqrt{2}$ ($\varepsilon_n = 7.5\ \mu$m)**
- **factor 1.4 from decreased LHC "turnaround time"**

⇒ 2 x 1.4 =2.8

- **the only possibility for increasing the LHC energy in future**

Part I:

Existing LHC injectors

Existing LHC injectors

Present situation

- **Nominal scheme:**

  Linac $\mathbf{H^+} \rightarrow$ **50 MeV**

  PSB: **3 rings with 1 bunch, h=2** → **1.4 GeV**

  PS: **2 injections** → **6 bunches, h=7, 14, 21** → **18 bunches** → **(25 GeV) 36 bunches, h=42** → **72 bunches, h=84, h=168** →

  SPS: **3-4 injections** → **216-288 bunches, h=4620** → **450 GeV**

- **LHC beam parameters at 450 GeV: experimental results (2004)**

  - 4 batches with 25 ns spaced bunches, $N_b = 1.15 \times 10^{11}$ **ppb -** ✓

  - longitudinal emittance of $\varepsilon = 0.6 \pm 0.1$ **eVs,** $\tau = 1.6 \pm 0.1$ **ns -** ✓ (*T. Bohl et al., 2004*)

  - transverse normalised emittances of $\varepsilon_H = 2.99 \pm 0.26$ **μm -** ✓ **and** $\varepsilon_V = 3.61 \pm 0.26$ **μm** (*G. Arduini et al., APC 13.08.2004*)

Existing LHC injectors

High brilliance and closer bunches

- **Brilliance** (Europe) ≡ brightness (USA) $= N_b/\varepsilon_n$
- Space-charge tune-spread:

$$\Delta Q_{sc} \propto \frac{\text{Brilliance}}{\beta\gamma^2}$$

$\Rightarrow$ Brilliance is limited by space charge in low-energy machines

- Now 12 LHC bunches are produced from 1 PSB bunch:
  - **Ultimate intensity** requires increase of brilliance in the PSB by **1.7** (for 85% beam transmission)
  - **Reduced bunch spacing** requires increase of brilliance in the PSB by similar factor

Existing LHC injectors

Brilliance - experimental results

PSB: 20×10^{11} ppb with nominal ε_n

PS: 1.4×10^{11} ppb with nominal ε_n and
1.7×10^{11} ppb with larger (?) emittances

SPS: 1.2×10^{11} ppb injected at 26 GeV/c with $2.8 \pm 0.2\mu$m (2004)

- **Transverse emittance evolution** in the LHC injector chain for one batch with 1.3×10^{11} at 26 GeV/c (*F. Roncarolo, wire scanners, 2003*)

emittance	PSB	PS		SPS	
1σ norm.	ext	inj	ext	inj	ext
ε_H (μm)	2.1	2.7	2.6	3.1	3.2
ε_V (μm)	2.8	3.0	3.0	3.3	3.5

- **SPS: emittance blow-up for 4 batches** in vertical plane $\sim 20\%$ (the end of the batch) due to e-cloud instability (*G. Arduini, Chamonix 2004*)

Existing LHC injectors

Higher brilliance

- **Present situation:**

  - 72 bunches with 1.4×10^{11} ppb @26 GeV/c in 3.6 s

- **Possible means to increase brilliance in PSB - PS:**
  (*M. Benedict, R. Garoby, Proc. of HHH04*)
  - **(1) Batch compression in PS:** **42 bunches with 2.65×10^{11} ppb → for the same total number of bunches LHC filling time increased by 33% with 7% less bunches**
  - **(2) Linac 4 (H^-, 160 MeV):** **72 bunches with 2×10^{11} ppb in 2.4 s → 17 % reduction of LHC filling time**
  - **(1)+(2):** **48 bunches with 3×10^{11} ppb in 2.4 s**

Existing LHC injectors

Closer bunches

- **All RF manipulations assumed to be done in the PS** (*O. Bruning, R. Cappi, R. Garoby et al., LHC Project Report 626, 2002*)
- **12.5 ns bunch spacing - one more bunch splitting in the PS, but**
  - **a new RF system in the SPS (and probably LHC):**

    (1) 160 MHz (easy for injection, but worst for extraction, needs a new capture system in the LHC - 200 MHz will not work)

    (2) 240 MHz (more capture loss in the SPS?)
- **10 ns bunch spacing - no changes in the SPS, but**
  - **a new RF system in the PS (95.4-100 MHz)**
- **15 ns bunch spacing - no changes in the SPS, but**
  - **a new RF system in the PS (63.5-66.7 MHz)**

Existing LHC injectors

Can SPS digest this beam? Known limitations:

Single bunch intensity/brilliance

- TMCI (transverse mode coupling instability)
- space charge

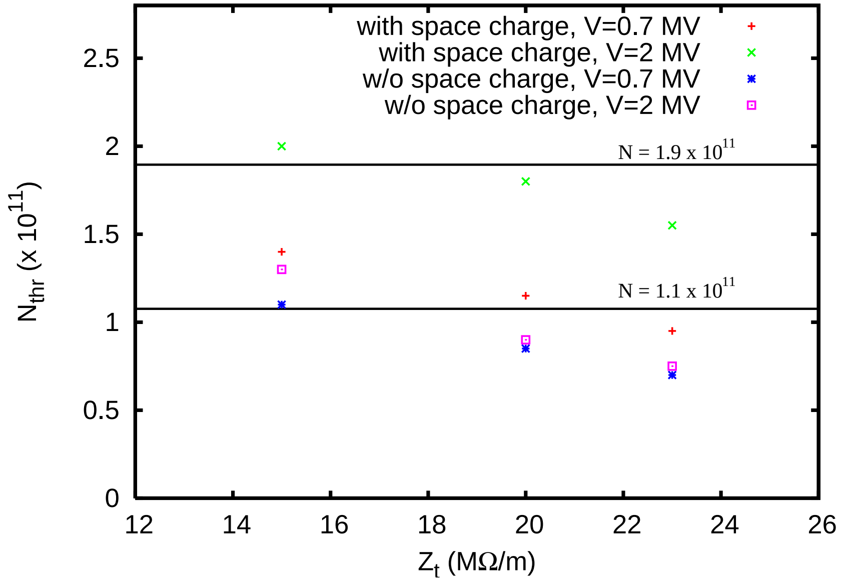
Multi-bunch effect (total intensity)

- e-cloud
- capture loss
- coupled bunch instabilities at injection and high energy
- beam loading in the 200 MHz and 800 MHz RF systems
- MKE kickers heating

Existing LHC injectors

Single bunch limitations in the SPS: TMCI

TMCI thresholds for LHC bunch at 25 GeV, $\xi = 0$

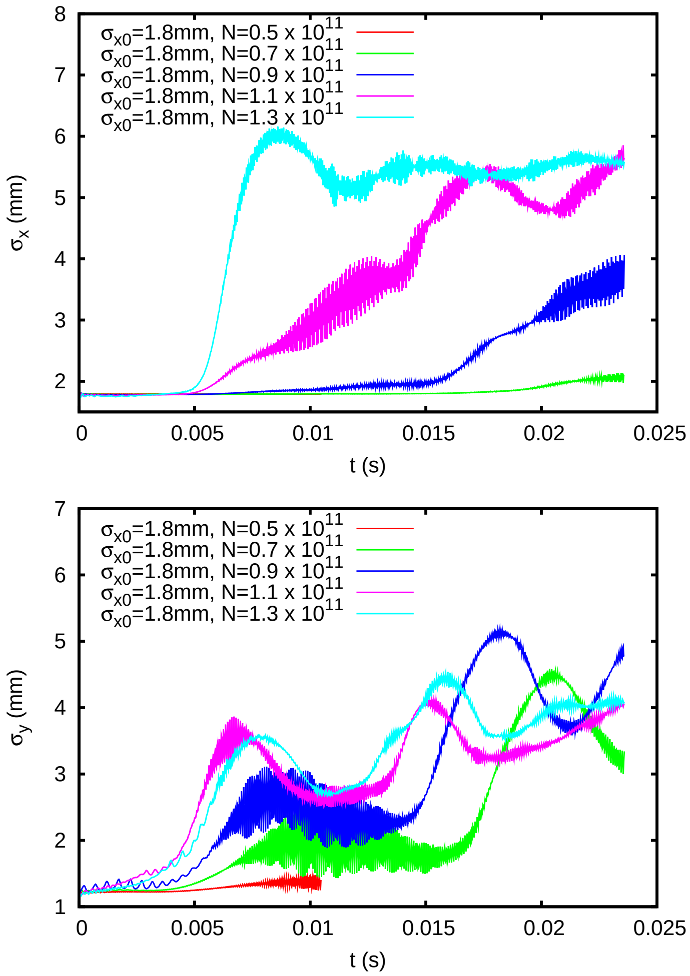


(*G. Rumolo et al., HEADTAIL, 2005*)

- **Fast transverse instability:** observed in 2002 at 25 GeV. $N_{th} = 1.2\times10^{11}$ for $\varepsilon = 0.3$ eVs, τ=3.6 ns, V=0.6 MV, $\varepsilon_{H,V} = 1\ \mu$m (*H. Burkhardt et al., 2003*)
- **Cure by high chromaticity and high voltage (slow beam loss?)**
- **Flat top:** $N_{th} = 1.9 \times 10^{11}$ **for** ε**=0.3 eVs.**
- **Low threshold for 4 more MKE kickers installed → screening** (*F. Caspers, E. Gaxiola et al.*)

Existing LHC injectors

Single bunch limitations in the SPS: space charge



- Increases the TMCI threshold, but causes emittance blow-up (*G. Rumolo et al., 2005*. Simulations at 25 GeV with $Z_t = 15$ MΩ/m, $\varepsilon = 2.5\ \mu$m).
- Tolerable space-charge tune spread:
  - PSB: $\Delta Q_{sc} < 0.5$
  - PS: $\Delta Q_{sc} < 0.3$
  - SPS: $\Delta Q_{sc} < 0.07$ (ppbar limit)
- SPS: $\Delta Q_{sc} = 0.05$ (0.07) for nominal (ultimate) LHC intensity
- Recent measurements in the SPS: beam loss $(1.2 \rightarrow 0.8) \times 10^{11}$ for $\Delta Q_V = 0.3$, lifetime 50 s for $\Delta Q_{H,V} = 0.14, 0.24$ (*H. Burkhardt et al., EPAC'04*).

Multi-bunch limitations in the SPS: electron cloud

(*G. Arduini et al., Chamonix 2004, EPAC'04, F. Zimmermann*)

- **Leads to transverse emittance blow-up and instabilities: coupled bunch in H-plane (a few MHz) and single bunch in V-plane in the batch tail (∼ 700 MHz)**
- **Multipacting for different bunch spacing (1 batch at 26 GeV):**

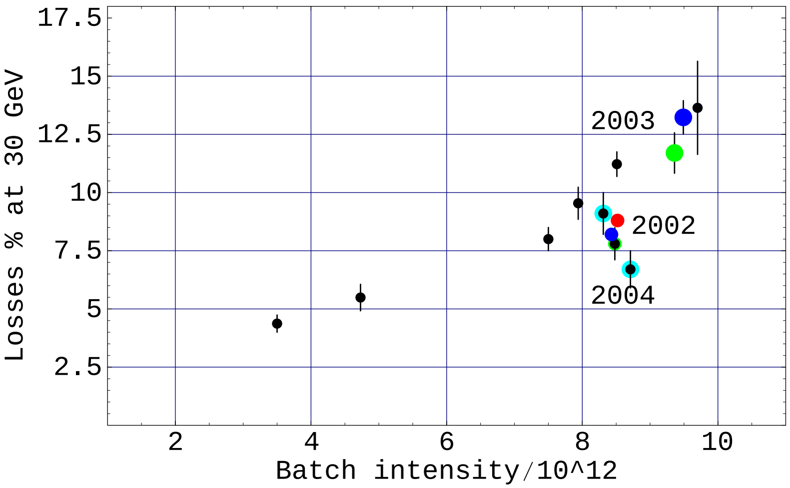
Bunch spacing (ns)	**75**	**50**	**25**	**15/10**	**5 (FT)**
$N_b/10^{11}$	**1.2**	**0.6**	**0.3**	**?**	**0.1**

- **Cures**
  - **For 25 ns spacing scrubbing run increases the threshold from 0.3×10^{11} to 1×10^{11}. More scrubbing?**
  - **Transverse feedback damps coupled-bunch modes in H-plane with growth rates ∼ 40 turns**
  - **High chromaticity (up to 1.5) in V-plane**

Existing LHC injectors

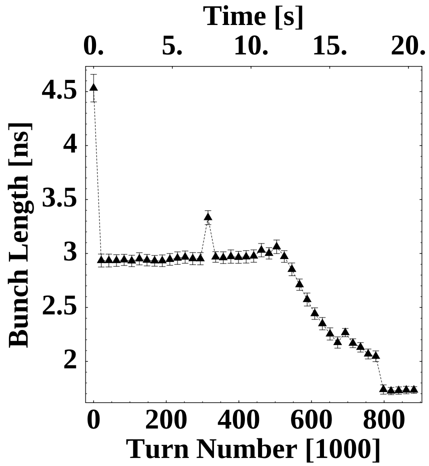
Multi-bunch limitations in the SPS: capture loss

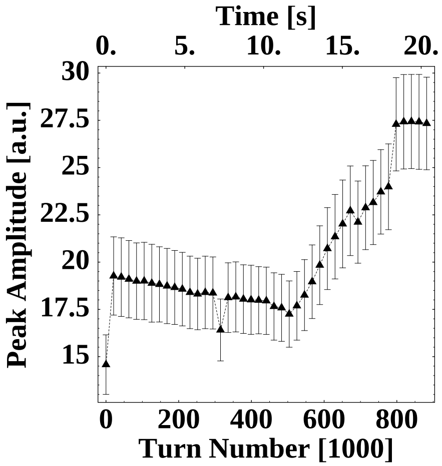
Relative capture loss
for different batch intensities



- **Strong dependence on batch intensity,** **much less on total (number of batches) or bunch intensity**
- **Reduction of relative loss for 75 ns bunch spacing**
- **Reduction of losses to 5.5±0.5% at the end of 2004 due to new working point (*G. Arduini*) and RF gymnastics (*T. Bohl et al.*)**
- **Loss mechanism is not clear (e-cloud?) → more studies**

Existing LHC injectors





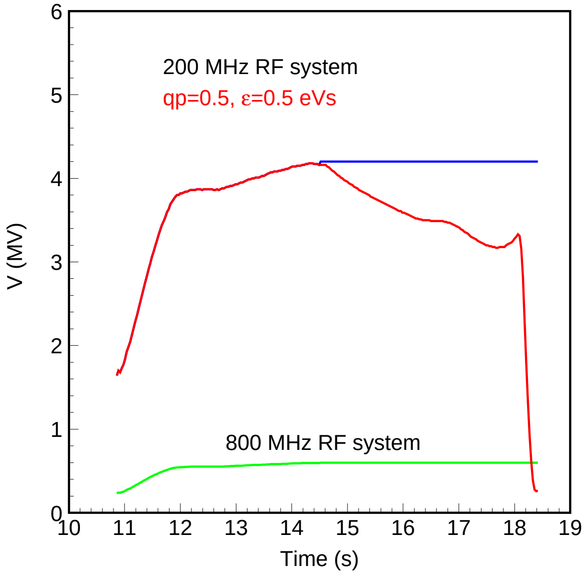
Multi-bunch limitations in the SPS: coupled bunch instabilities

- **Threshold:** single batch with 2×10^{10} ppb is unstable at $\sim$ 280 GeV
- **Source:** fundamental and HOMs of 200 MHz RF system (629, 912 MHz...)
- **Cures:**
  - the 800 MHz RF system in bunch-shortening mode through the cycle
  - controlled emittance blow-up by (1) mismatched voltage at injection: $\varepsilon_{2\sigma} = 0.35$ eVs → 0.45 eVs (2) beam excitation at 200 GeV with band-limited noise: → 0.6 eVs

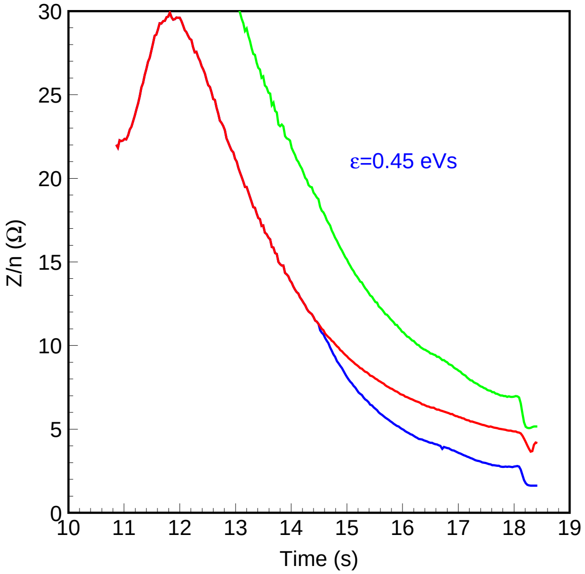
Existing LHC injectors

Threshold impedances for nominal intensity in the SPS

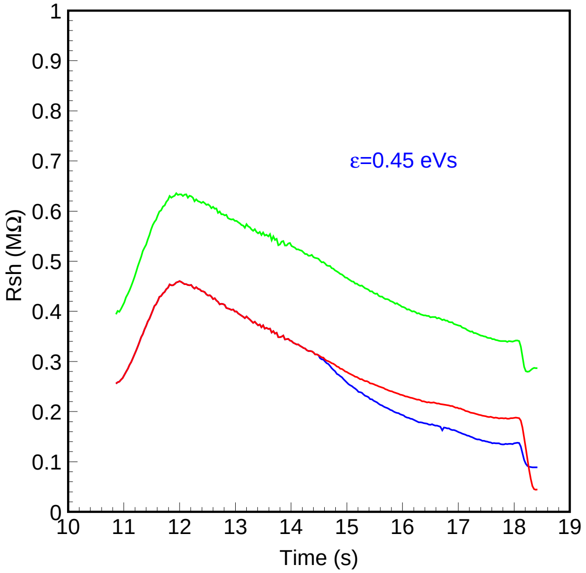
Voltage (MV)



ImZ/n (Ω)



R_{sh}^{min} (MΩ)



$\Rightarrow$ **Controlled emittance blow-up for higher current:** $\varepsilon \propto \sqrt{I_A}$

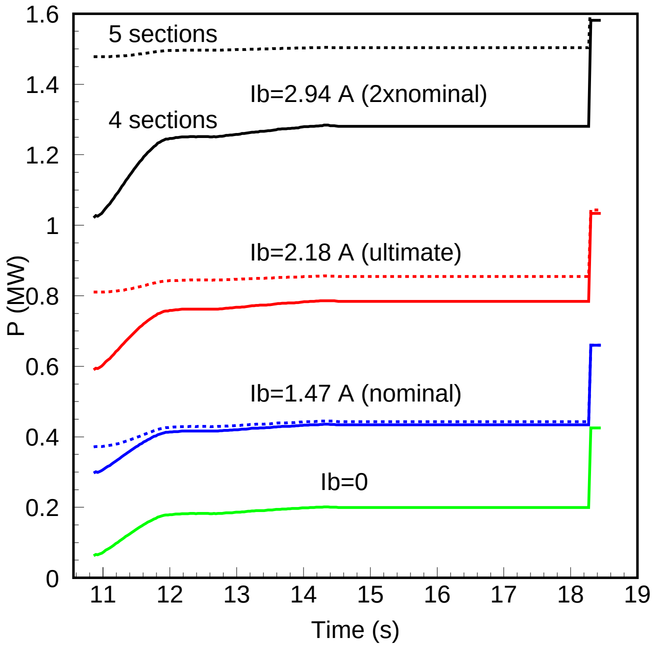
- **SPS:** **8 MV @200 MHz → acceleration of 0.8 eVs (instability at injection for 1.5×10^{11})**

- **LHC:** **3 MV @200 MHz → capture of $\varepsilon <$1.0 eVs (*J.Tuckmantel, Chamonix 99*). Ultimate intensity: $\varepsilon = 0.73$ eVs at 450 GeV.**

Existing LHC injectors

Beam loading

RF power needed for different beam currents



- **Voltage for 0.6 eVs bucket - optimistic for high intensities**

Maximum available RF power in one TW cavity (in the pulsed mode)

- **200 MHz (limited by coaxial line and coupler-cavity connection):**

- 700 kW for full SPS ring

- 1.4 MW for 1/2 ring - not tested, planned for the end of 2006

$$P_n = \frac{V_n^2}{Rl_n^2} + \frac{Rl_n^2 I_b^2}{64} + \frac{V_n I_b}{4} \sin\phi_s$$

n=4, 5, V=2(V_4+V_5), R=27.1 $k\Omega/m^2$, l_n=(11n-1)0.374 m

- **800 MHz: 210 kW in one cavity, after upgrade - 150 kW in the second**

Summary for existing injectors (1/2)

Main limitations

- **Higher brilliance:** nominal emittance is not yet reached in the SPS in the vertical plane due to e-cloud.
- **Closer bunches:** new RF system needed either in the PS (10, 15 ns) or SPS and LHC (12.5 ns). In the SPS more problems with e-cloud (V-emittance blow-up) and coupled bunch instabilities.
- Intensity dependent **capture losses in the SPS**. Were reduced in 2004, but their exact cause and therefore scaling is not clear.
- **Coupled bunch instabilities in the SPS** can be cured by controlled emittance blow-up → 200 MHz capture system in the LHC.
- **Beam loading** in 200 MHz and 800 MHz RF systems - limit at ultimate intensity for known performance.
- **Fast transverse instability** for more MKE kickers or higher bunch intensities. Below the threshold - emittance blow-up. Cure by chromaticity at high voltage could increase losses.

Summary for existing injectors (2/2)

Possible improvements and machine studies in the SPS:

- **Further SPS impedance reduction (MKE screens, improved passive damping of HOMs, search for transverse impedances...)**
- **Capture loss studies with shorter bunches from PS, the same or larger emittance (extra RF voltage in the PS)**
- **Increased voltage of 800 MHz RF system (1 more cavity in operation in 2006)**
- **Emittance blow-up up to 0.75 eVs for ultimate intensity - study effect of the synchrotron frequency shift along the batch**
- **Capture loss and beam lifetime studies (e-cloud, machine resonances, noise...) - analysis of 2004 data!**
- **High power RF tests in 2006 (pulsing mode)**
- **Ultimate intensity bunches injected into the SPS**
- **Scrubbing runs at higher intensities**

Part II:

New LHC injector

New LHC injector

Linac → PSB → PS → SPS → Super-SPS → LHC

Super-SPS: Super - Super Proton Synchrotron (Super-Duper?) →

Hyper Proton Synchrotron → HPS (High energy)

Assumptions

- **SPS: 25 GeV → 150 GeV**
- **HPS: 150 GeV → 1 TeV**
  - **SPS tunnel: R=1100 m, $\gamma_t = 23$ for both rings**
  - **No major changes in the PSB, PS and SPS**
  - **The HPS: the 400 MHz (SC) or 200 MHz (NC) RF system (more in talk by Joachim T.)**
  - **Fast acceleration ramps in the SPS and HPS**

Acceleration in the SPS: 25 GeV → 150 GeV (1/5)

Present situation

- **Magnets:**
  - maximum rate 165 GeV/s,
  - saturation above 300 GeV,
- **The 200 MHz TW RF system:**
  - $V_{max} = 8$ MV,
  - peak power 700 kW/cavity
- **Longitudinal impedance:**
  - Im$Z/n = 7\ \Omega$
  - HOMs: $R_{sh} = 400$ kΩ at $f_r = 600$ MHz, ...

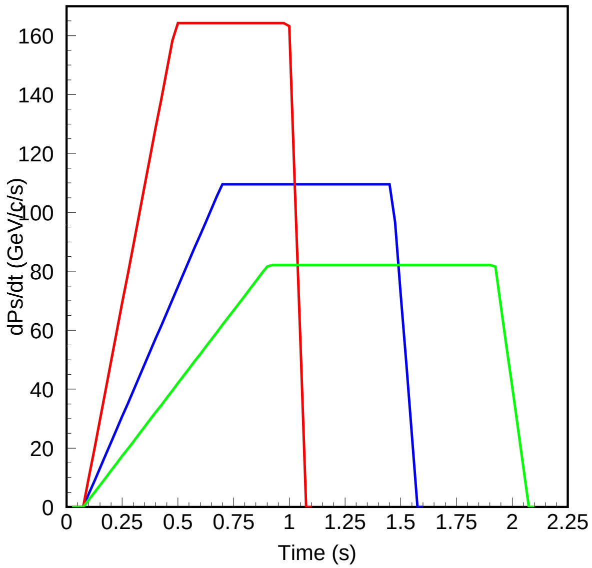
- RF voltage needed for different magnetic ramps and emittances

ramp s	ε eVs	V_{max} MV
1.0	0.5	9.2
1.0	0.4	8.0
1.5	0.5	7.0
2.0	0.5	6.0

- Controlled emittance blow-up?

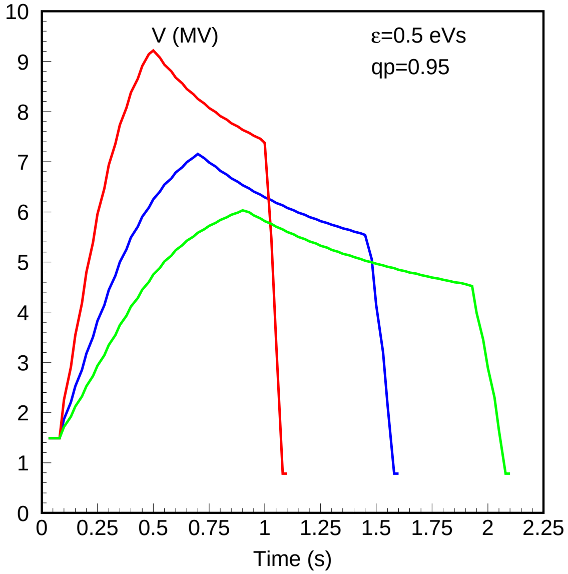
Acceleration in the SPS: 25 GeV → 150 GeV (2/5)

dP_s/dt



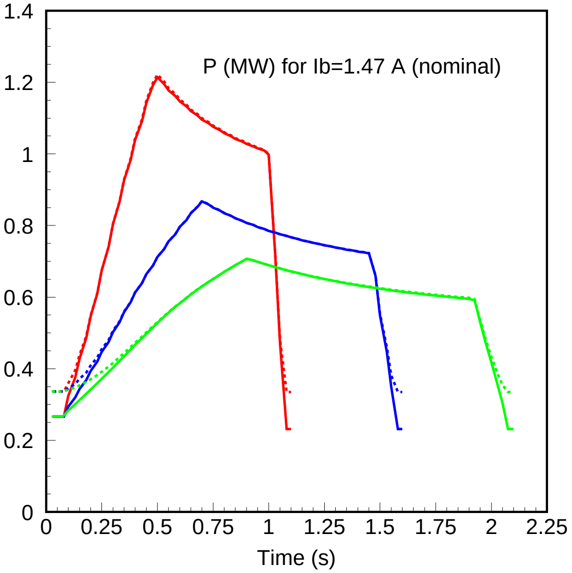
$\Rightarrow$ **ramp $\geq$ 1 s**

Voltage



$\Rightarrow$ **ramp $\geq$ 1.5 s**

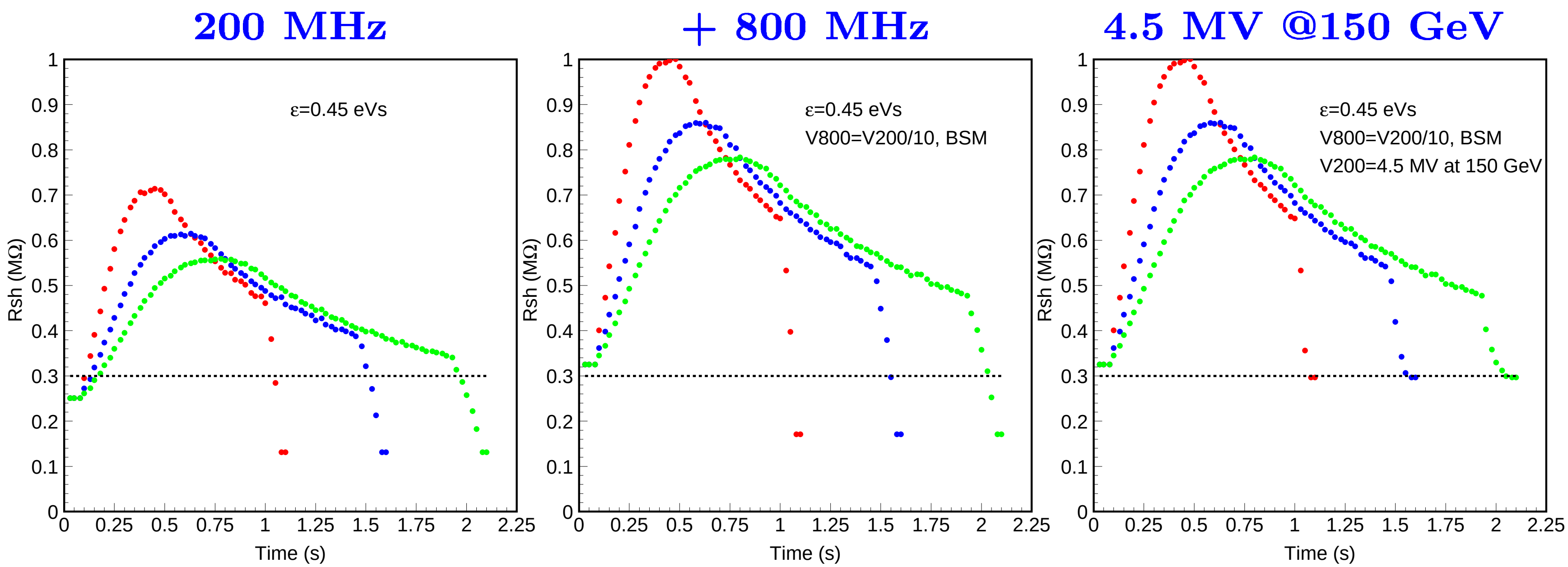
Power



$\Rightarrow$ **ramp $\geq$ 2.0 s**

Acceleration in the SPS: 25 GeV → 150 GeV (3/5)

Threshold of coupled bunch instabilities at nominal intensity



200 MHz

+ 800 MHz

4.5 MV @150 GeV

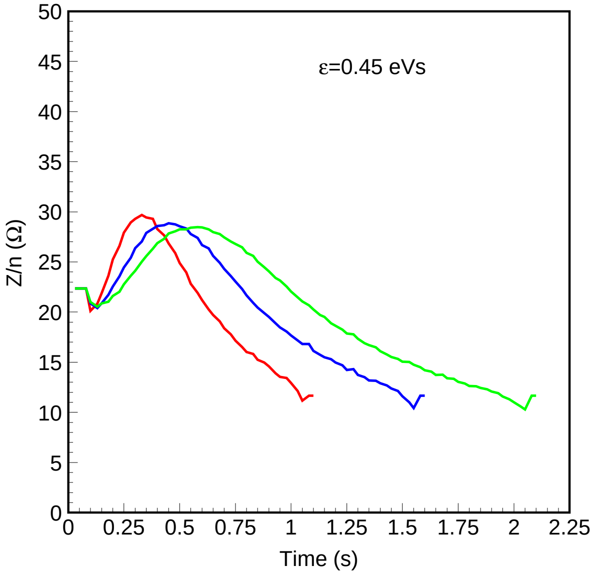
⇒ **The stabilising effect of 800 MHz RF system on the 150 GeV flat top is smaller than at 450 GeV**

⇒ **Emittance blow-up to (0.5-0.6) eVs for nominal intensity**

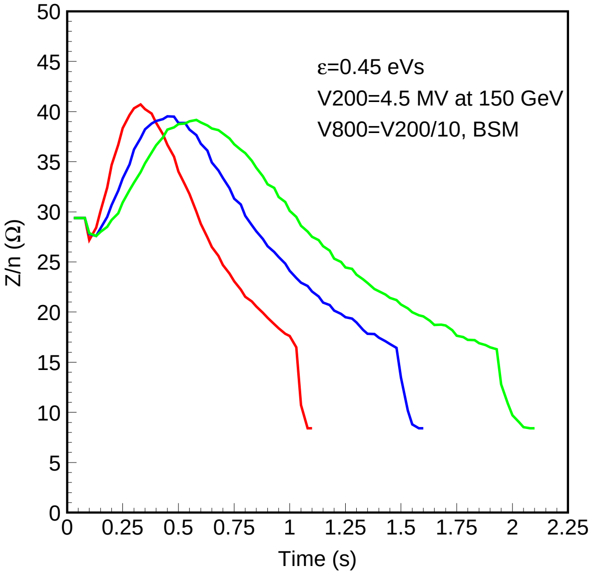
Acceleration in the SPS: 25 GeV → 150 GeV (4/5)

Threshold broad-band impedance ImZ/n leading to the loss of Landau damping at nominal intensity

200 MHz



+ 800 MHz+4.5 MV @150 GeV



⇒ Some improvement in comparison with acceleration up to 450 GeV

- **With present $Z/n \simeq 7\ \Omega \Rightarrow$ just OK for nominal intensity**

Acceleration in the SPS: 25 GeV → 150 GeV (5/5)

The SPS cycle length with present pre-injector chain

PS	SPS			
basic period s	flat bottom length s	extra V @200 MHz MV	length of ramp up + down s	cycle length s
1.2	3.6x3=10.8	0	3.6	14.4
1.2	3.6x3=10.8	3	2.4	12.6
0.9	2.7x3=8.1	0	1.5+1.2=2.7	10.8
0.9	2.7x3=8.1	3	1.0+0.8=1.8	9.9

⇒ With present pre-injectors the SPS cycle length $T_{SPS}^{cycle} \geq 10$ s

- **For $T_{SPS}^{cycle} = T_{HPS}^{cycle}$ the HPS ramp $\sim T_{HPS}^{cycle}/2 \simeq$ (5-6) s.**
- **The same total time for (2x4 batches) injections from the SPS, then the HPS is cycling each (20-24) s.**

SPS-HPS transfer @150 GeV (1/2)

- Nominal longitudinal emittance at injection into the SPS is 0.35 eVs, after capture into mismatched voltage - 0.42 eVs
- Extraction at 150 GeV: $4\sigma_t$ =2.2 ns for 0.6 eVs with 7 MV at 200 MHz (at 450 GeV: $4\sigma_t$ =1.6 ns for 0.6 eVs - achieved)

$$\text{bunch length} \qquad \tau \propto \frac{\varepsilon^{1/2}}{(V\gamma)^{1/4}}$$

- For transfer into 400 MHz RF system in the HPS ($T_{rf} =$ 2.5 ns):
  - No emittance blow-up: $4\sigma_t$ =1.65 ns for 0.35 eVs
  - The 200 MHz voltage V in the SPS increased $\propto 1/\gamma_{ext}$ (factor 1.5 for 0.42 eVs emittance) - new RF system
  - A 400 MHz RF system installed in the SPS
  - Bunch rotation - needs linear part of the bucket (distorted bunches) + beam loading problem for low voltages
  - A 200 MHz (“capture”) RF system in the HPS

SPS-HPS transfer @150 GeV (2/2)

SPS		HPS	
V_{200} MV	V_{400} MV	V_{200} MV	V_{400} MV
7+9	0	0	10
7	10	0	10
7	0	8	4
4.5	0	4.5	0

(200 → 400) MHz transfer:

- $\gamma_t = 22.8$, $\varepsilon = 0.5$ eVs
- $4\sigma_t = 1.7$ ns → $6\sigma_t = 2.5$ ns ($\varepsilon_{2\sigma}$ - 85% of particles)

- SPS-LHC transfer at 450 GeV: 3 MV @200 MHz in LHC → $4\sigma_t = 1.7$ ns for 0.5 eVs

$$A_{bucket} \propto \sqrt{\frac{V\gamma^3}{f_{rf}^2 h}}$$

- Factor $\sqrt{3^3/3.86} = \sqrt{7} \simeq 2.65$ → 3 MV × 2.65 = 8 MV in HPS

⇒ (8-10) MV extra needed for (200→400) MHz transfer @150 GeV

Acceleration in the HPS: 150 GeV → 1 TeV (1/3)

γ_t	ε eVs	ramp length s	V_{400} MV	V_{200} MV
23	0.6	3.0	23	13
30	0.6	3.0	19	12
23	0.5	3.0	20	12
23	0.6	6.0	16	7

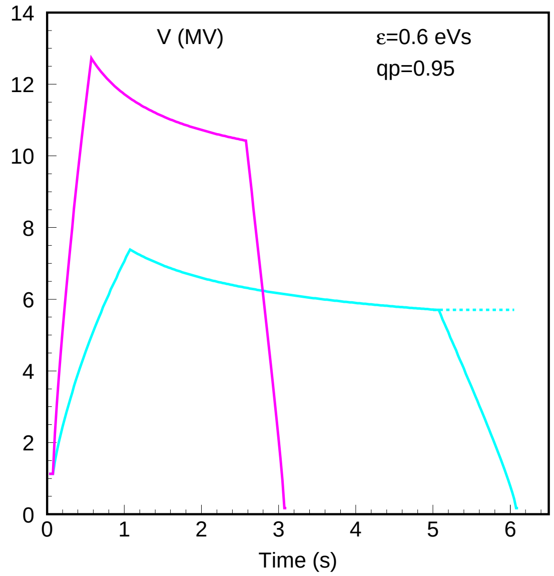
- 400 MHz RF system (SC)
  - easy transfer to 400 MHz RF system in the LHC, but...
  - needs 200 MHz cavities in the SPS or HPS with voltage sufficient for acceleration in 6 s!
- 200 MHz RF system (NC)
  - cavities exist (8 MV) - “capture system” of LHC
  - for transfer to LHC @1 TeV for the same ε and V - 20% shorter bunches or $\sqrt{2}$ larger emittances (0.85 eVs)

New LHC injector

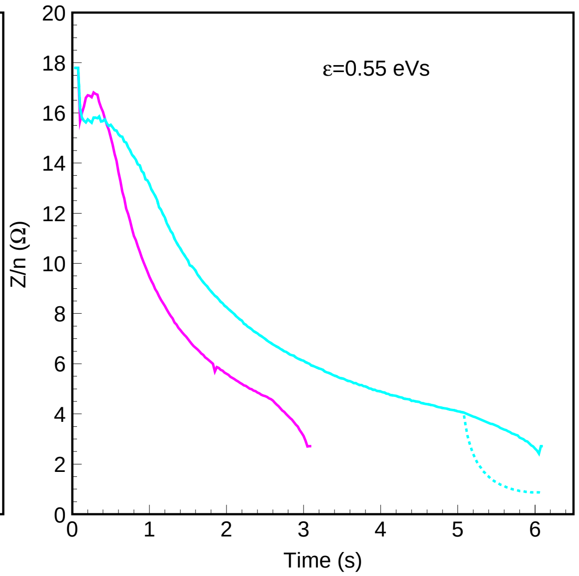
Acceleration in the HPS: 150 GeV → 1 TeV (2/3)

Beam stability at nominal intensity

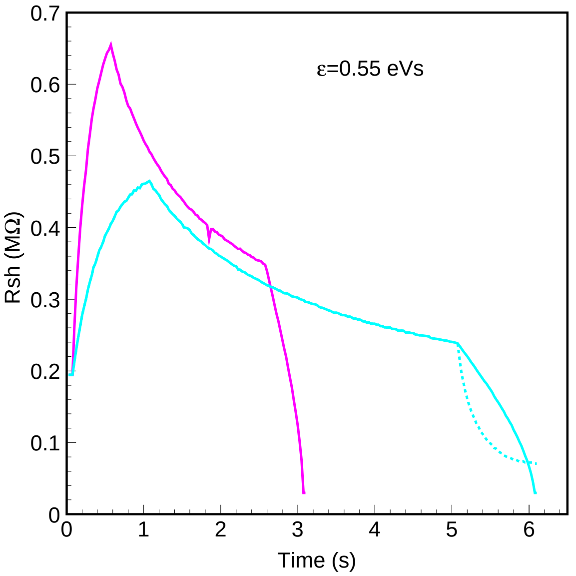
The 200 MHz voltage programme



Broad-band impedance



Narrow-band impedance



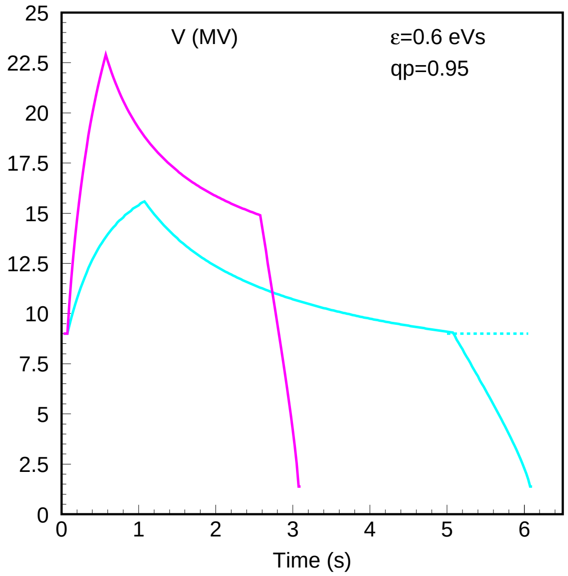
$\Rightarrow \mathrm{Im}Z/n < 0.5\Omega$ $\Rightarrow R_{sh} < 70\ \mathrm{k}\Omega$

- **No 800 MHz RF system... but for $\varepsilon < 0.85$ eVs - still no 200 MHz RF system needed in LHC → emittance blow-up at high energy**

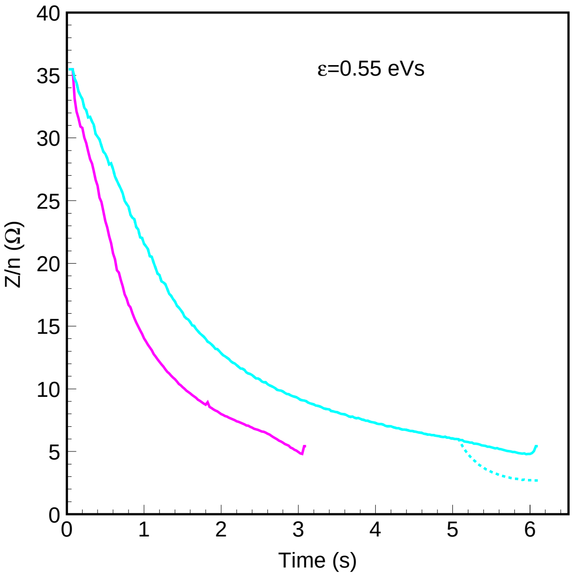
Acceleration in the HPS: 150 GeV → 1 TeV (3/3)

Beam stability at nominal intensity

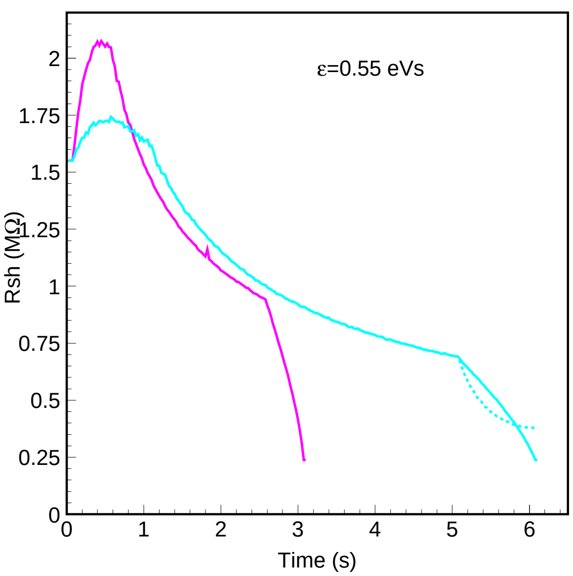
The 400 MHz voltage programme



Broad-band impedance



Narrow-band impedance



$\Rightarrow$ **Im**$Z/n < 2.5\ \Omega$ $\Rightarrow$ $R_{sh} < 400\ \mathrm{k}\Omega$

- **Significantly less tight impedance budget than for the 200 MHz RF system, but with more impedance in the ring.**

Summary for new injector

- Reducing the top energy in the SPS to 150 GeV
  - allows the ramp length to be reduced to 2 s
  - does not improve longitudinal beam stability (coupled-bunch) on the flat top and controlled emittance blow-up may still be necessary
  - makes more difficult bunch-to-bucket transfer into 400 MHz RF system of the next ring
- HPS (Super-SPS):
  - with present SPS minimum ramp length can be 6 s
  - using a 400 MHz (SC) RF system requires extra capture RF system and twice more volts than for 200 MHz
  - using a 200 MHz (NC) RF system seems to be optimum, but requires tight impedance budget (probably achievable for a new machine)

Appendix

Threshold for coupled-bunch instability

(equally spaced bunches) due to resonant impedance with frequency $f_r = f_0 n_r = pMf_0 + nf_0 + mf_s$

$$R_{sh} < \frac{|\eta| E}{e I_0} \left(\frac{\Delta p}{p}\right)^2 \frac{\Delta\omega_s}{\omega_s} \frac{F}{f_0 \tau} xG(x),$$

f_0 is the revolution frequency, $\eta = 1/\gamma^2 - 1/\gamma_t^2$, I_0 is the average beam current, $\frac{\Delta p}{p}$ is the relative momentum spread, $\frac{\Delta\omega_s}{\omega_s}$ is the relative synchrotron frequency spread, $F \sim 0.3$ is defined by the particle distribution.

(*V. Balbekov, S. Ivanov, 1984*)

Function

$$xG(x) = x \min\{J_m^{-2}(\pi x)\},$$
$$x = f_r \tau$$