SPS challenges

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BEAM'07, 5 October 2007

Acknowledgments: members of the SPS Upgrade Study Team and PAF working group, T. Bohl and T. Linnecar

Motivation (1/2)

The SPS is challenged by

- LHC upgrade scenarios (*W. Scandale, F. Zimmermann*):
  - 5×10^{11}/bunch spaced by 50 ns
  - 1.7×10^{11}/bunch spaced by 25 ns - ultimate LHC intensity (*talk of G. Arduini on 3.10.07*)
- Possibilities offered by completely new SPS injector chain Linac4-SPL-PS2 (*M. Benedikt et al.*):
  - LHC beam: 168 bunches with 4×10^{11}/bunch spaced by 25 ns injected at 50 GeV/c
  - FT/CNGS beam: total intensity of 10^{14} per injection (full SPS ring)

$\Rightarrow$ Beam with 5.5×10^{11}/bunch with 50 ns spacing will be analysed in the SPS assuming that it was produced in PS2 (*talk of R. Garoby on 2.10.2007*)

Motivation (2/2)

Maximum intensities in the SPS: achievements and future needs

		SPS record at 450 GeV	LHC request at 450 GeV	PS2 offer at 50 GeV/c
Bunch intensity	10^{11}	1.2	1.7/5.5^{*}	$3.6/7.2^{**}$
Total intensity	10^{13}	3.5(5.3^{***})	9.2	12.0
Beam current (RF)	A	1.5	3.5	4.6

* 10% beam loss assumed for PS-SPS and SPS-LHC beam transfer

** Intensity for 25/50 ns bunch spacing

*** CNGS beam at 400 GeV with 5 ns spacing and full ring

⇒ SPS upgrade is necessary

SPS Upgrade (1/2)

- Initial studies in PAF WG (chairman - R. Garoby)
- From March 2007 - SPS Upgrade Study Team

G. Arduini AB/ABP,
S. Calatroni TS/MME,
F. Caspers AB/RF,
P. Chiggiato TS/MME,
K. Cornelis AB/OP,
M. Jimenez AT/VAC,
T. Kroyer AB/RF,
G. Rumolo AB/ABP,
E. Shaposhnikova AB/RF,
M. Taborelli TS/MME,
F. Zimmermann AB/ABP

Web site: http://paf-spsu.web.cern.ch/paf-spsu/

SPS Upgrade (2/2)

- Ultimate goals
  - Reliably provide the LHC with the beam required for reaching ten times the nominal luminosity
  - Optimum use of possibilities offered by the new injectors both for the LHC and for other users (FT, CNGS...)
- Main tasks
  - Identify limitations in the existing SPS
  - Study and propose solutions
  - Design Report in 2010 with cost and planning for proposed actions

Status of the LHC beam in the SPS

- Nominal LHC beam parameters at 450 GeV:

$N_b = 1.15 \times 10^{11}$ ppb, $\varepsilon \leq 0.7$ eVs, $\varepsilon_n \leq 3.5$ μm

- LHC beam parameters at 450 GeV measured in 2004

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

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

- transverse normalised emittances (*G. Arduini et al.*):

$\varepsilon_H = 2.99 \pm 0.26$ μm - $\surd$

$\varepsilon_V = 3.61 \pm 0.26$ μm

Known intensity limitations in the SPS

Single bunch intensity

- space charge
- TMCI (transverse mode coupling instability)

Multi-bunch effects (total intensity)

- e-cloud
- coupled bunch instabilities at injection and high energy
- beam loss
- beam loading in the 200 MHz and 800 MHz RF systems
- heating of machine elements (e.g. MKE kickers)

Possible actions and cures

- Higher injection energy with PS2: 50 GeV/c instead of 26 GeV/c (discussed also at hhh06 workshop)
- Impedance reduction (after identification) - *talk of E. Metral*
- Active damping - upgrade of beam control (transverse and longitudinal feedbacks) - foreseen by White Paper
- Passive (Landau) damping due to increased nonlinearity (synchrotron frequency spread) with

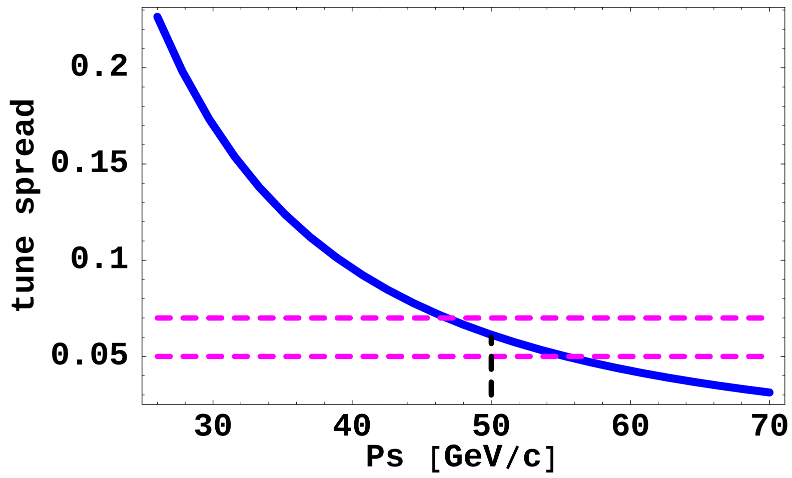
  - 800 MHz (4th harmonic) RF system

  - increased longitudinal emittance

Single bunch limitations: space charge

- Limit for space-charge tune spread: $\Delta Q_{sc} < 0.07$ (ppbar)
- ΔQ_{sc} at 26 GeV/c for the LHC beam in the SPS:
  - nominal intensity: 0.05
  - ultimate intensity: 0.07
  - upgrade scenario: 0.23

ΔQ_{sc} for 5.5×10^{11}/bunch



$\Rightarrow$ Sufficient improvement for bunch intensity of 5.5×10^{11} due to higher injection energy: $\Delta Q_{sc} = 0.06$

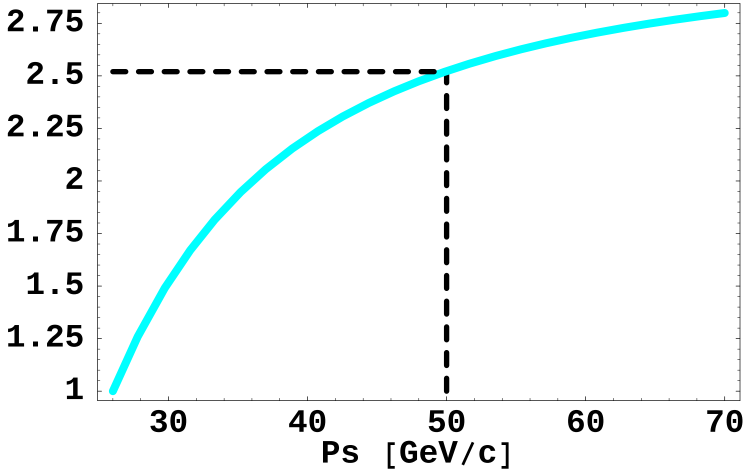
Single bunch limitations: TMCI

TMCI: Transverse Mode Coupling Instability

- With impedance model obtained as a best fit to measurements for the LHC bunch at 26 GeV/c (2006) $N_{th} \sim 1.4 \times 10^{11}$ (*G. Rumolo et al*)
- Threshold intensity scales as (matched voltage)

$$N_{th} \propto |\eta|\varepsilon_L$$

Normalised TMCI threshold N_{th}



$\Rightarrow$ At 50 GeV/c the TMCI threshold is increased by factor 2.5 ($\propto \eta$)

$\Rightarrow$ Increase of emittance to 0.6 eVs needed for 5.5×10^{11}/bunch

Electron cloud (1/3)

- Main intensity limitation in the SPS for nominal LHC beam.
- Leads to transverse emittance blow-up and instabilities:

- coupled bunch in H-plane (a few MHz)

- single bunch in V-plane in the batch tail (~ 700 MHz)

- Present cures:

- scrubbing run,

- high chromaticity in V-plane,

- transverse damper in H-plane

Electron cloud (2/3)

H-plane

• Coupled-bunch instability in H-plane at different energies.

Measurements with 1.1×10^{11} ppb (*G. Arduini et al.*)

Momentum [GeV/c]	Growth time [turns]
26	300-400
55	800-900
450	6000

$\Rightarrow$ Instability growth rate $\sim 1/\gamma$

Electron cloud (3/3)

V-plane

• Simulations predict threshold reduction with energy (*G. Rumolo et al*) but increase for "50 ns" spacing (≥ 2?, *F. Zimmermann*)

• Intensive MD studies of e-cloud instability at different energies in 2007
- results in *talk of G. Rumolo*

⇒ Studies of the possible SPS chamber upgrade using

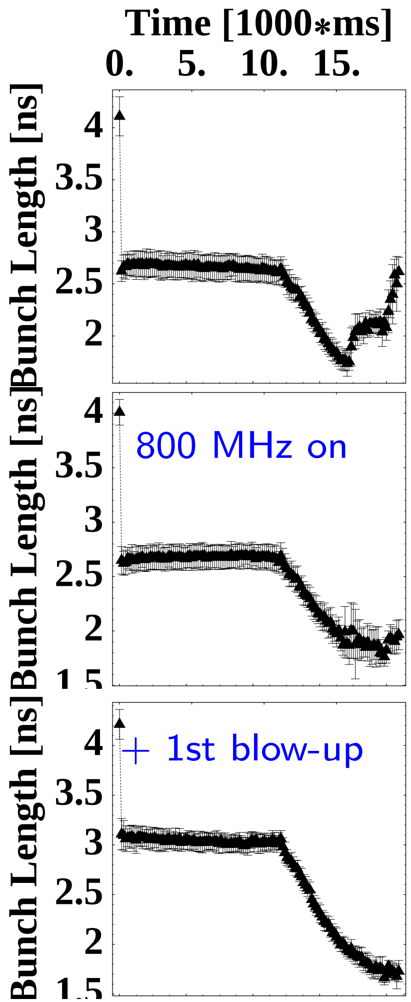
(1) TiN coating: *talk of S. Calatroni, P. Chiggiato and M. Taborelli*

(2) Cleaning electrodes: *talk of F Caspers and T. Kroyer*

(3) Grooves: in collaboration with SLAC - *M. Munro, M. Pivi, M. Venturini*

We plan to install 4 different samples in the SPS e-cloud measurement set-up (*M. Jimenez et al*) during 2007/2008 shutdown for beam tests in 2008

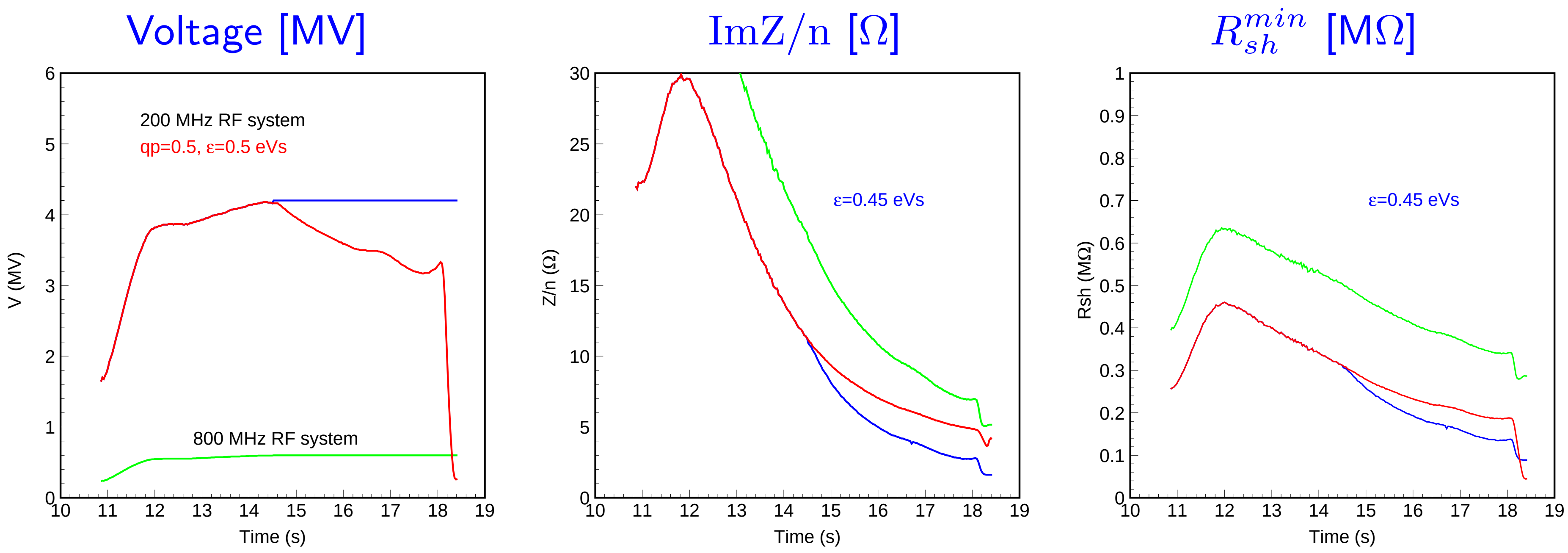
Longitudinal coupled-bunch instability (1/2)



- Threshold: single batch with 2×10^{10} per bunch is unstable at ~ 280 GeV
- Source: fundamental and HOMs of 200 MHz RF system (629, 912 MHz...)
- Cures:
  1. the 800 MHz RF system in bunch-shortening mode through the cycle
  2. plus controlled emittance blow-up by
     (a) mismatched voltage at injection: $\varepsilon_{2\sigma} = 0.35$ eVs $\longrightarrow$ 0.42 eVs
     (b) beam excitation at 200 GeV with band-limited noise: $\longrightarrow$ 0.6 eVs

Longitudinal coupled-bunch instability (2/2)

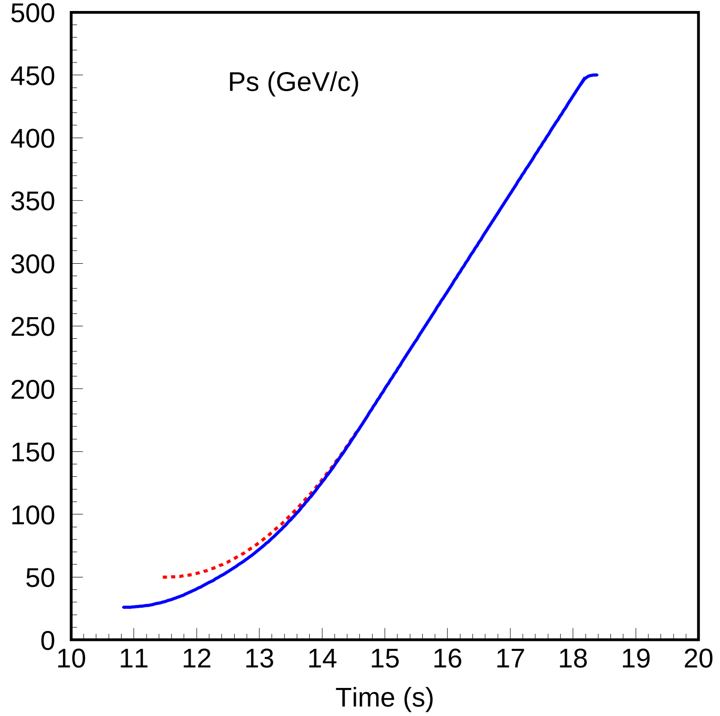
Threshold impedances for injection at 26 GeV/c and nominal LHC intensity



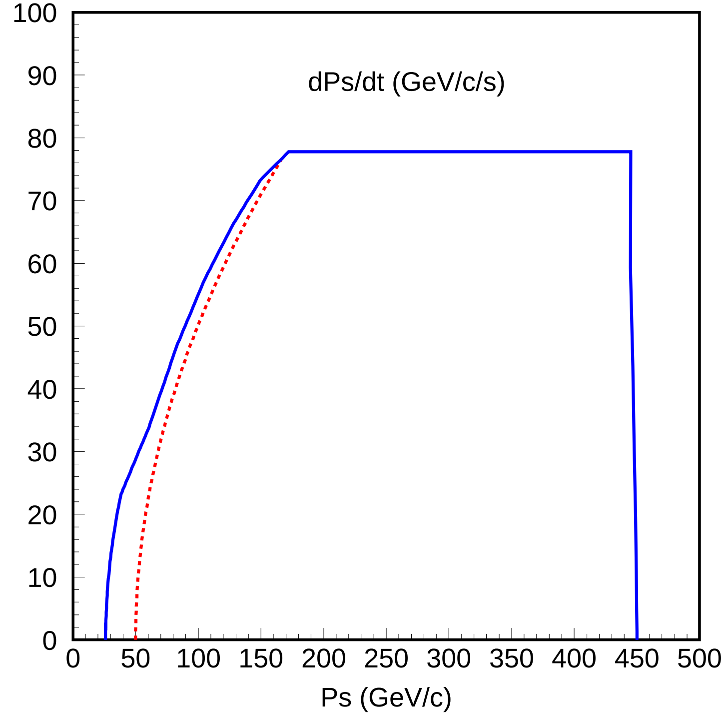
- Instability observed at $\sim 1.1 \times 10^{11}$/bunch (with 800 MHz off) at injection
- $\boldsymbol{N_{th} \propto \varepsilon^2} \Rightarrow \varepsilon \sim \mathbf{0.6}$ eVs at injection and controlled emittance blow-up to $\mathbf{0.9}$ eVs above 280 GeV for the LHC upgrade scenario with "50 ns beam"
- No significant change in thresholds due to injection at 50 GeV

SPS acceleration cycle with PS2

Synchronous momentum

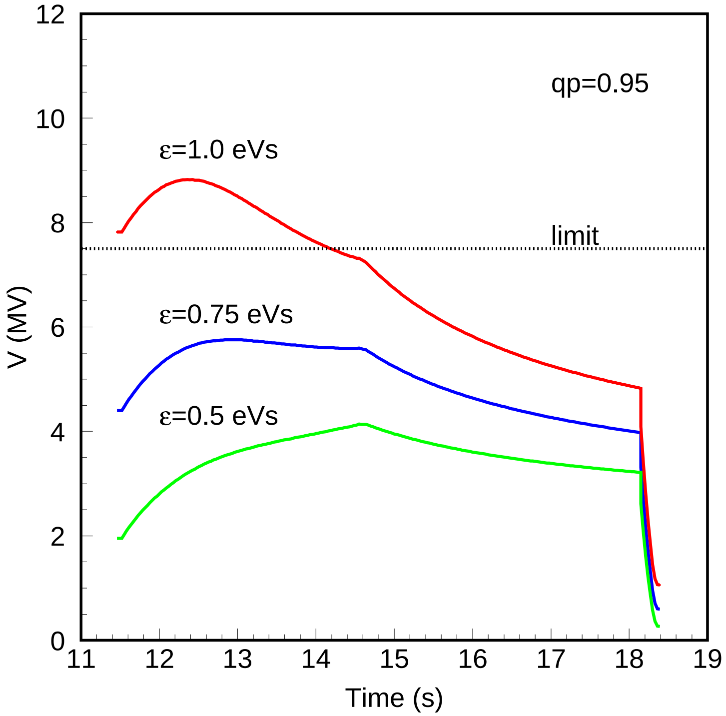


dP_s/dt

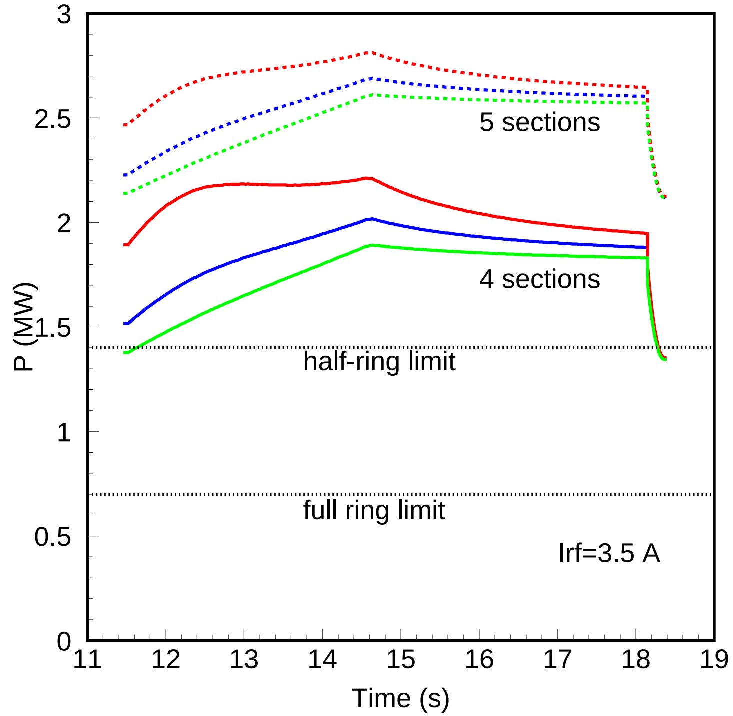


RF requirements (1/3)

Total voltage @200 MHz



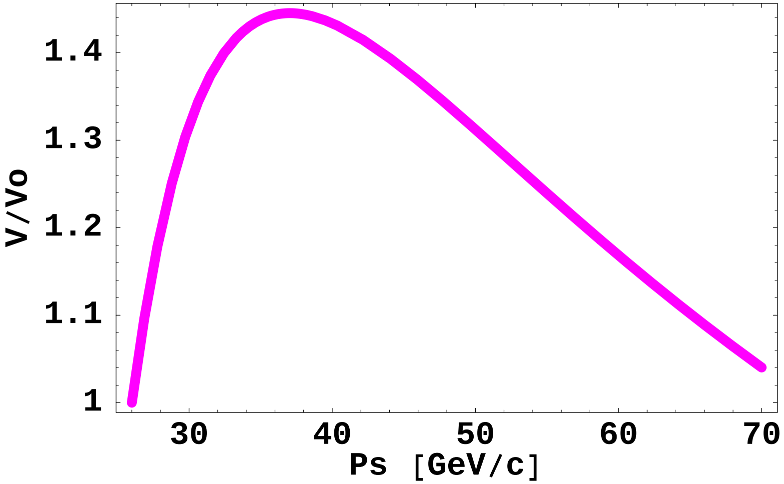
Power per 200 MHz TW cavity



- To avoid beam loss in operation: $A \simeq 1.4\,\varepsilon \rightarrow$ for $\varepsilon_{inj} = 0.6$ eVs at the beginning of ramp we need $A = 0.85$ eVs (or 0.75 eVs with 0.9 filling factor)
- The required voltage can be reduced by slow ramp

RF requirements (2/3)

Voltage at injection for $\varepsilon = const$



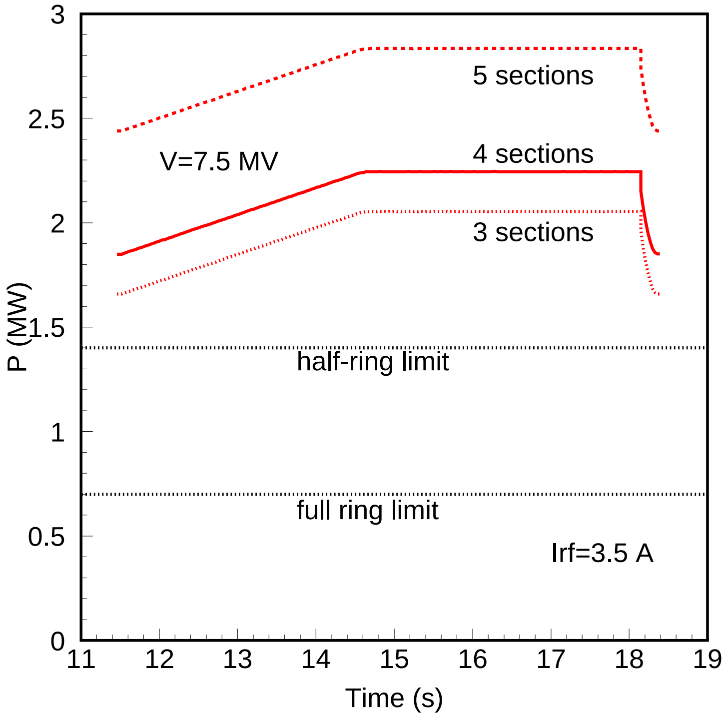
- For injection at 50 GeV/c with $V_{max} = 7.5$ MV: $\varepsilon_{inj} \leq 0.8$ eVs ($V \propto \varepsilon^2$)
- For the same ε_{inj} higher voltage would be needed for injection in the range (30-50) GeV/c

$\Rightarrow$ The PS2 energy ≥ 50 GeV

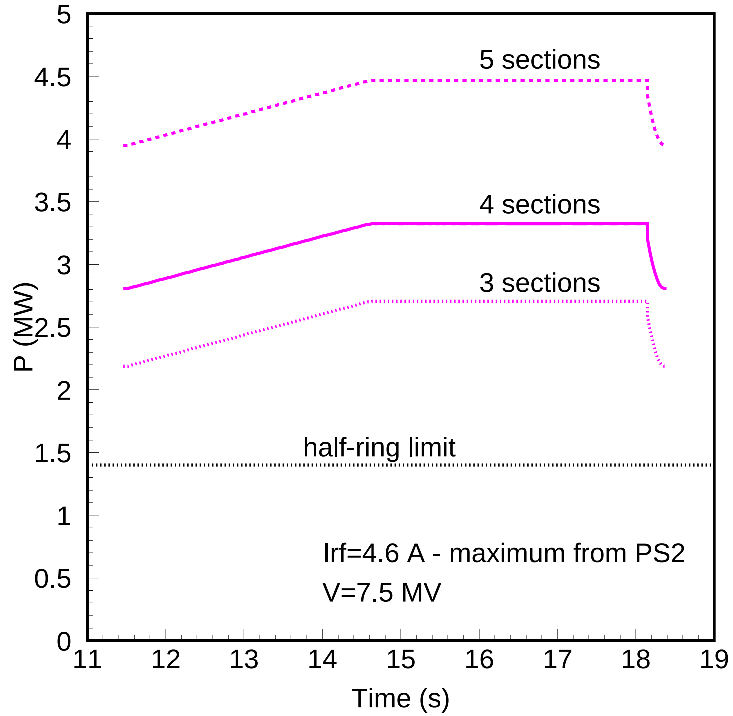
RF requirements (3/3)

Power per 200 MHz TW cavity with $V = 7.5$ MV for

LHC upgrade intensity



maximum PS2 intensity



⇒ Cavity length could be optimised ($5 \rightarrow 3$ sections)

⇒ The 200 MHz and 800 MHz power plant should be doubled

⇒ R&D for re-design of couplers and coaxial lines

Future FT/CNGS beam in the SPS

RF voltage [MV] for different acceleration time

	SPS= 11 PS	SPS $\simeq$ 5 PS2	
	3.0 s	3.0 s	4.2 s
$\geq$ 250 GeV/c	7.5	7.5	6.0
maximum	7.6	10.5	7.0

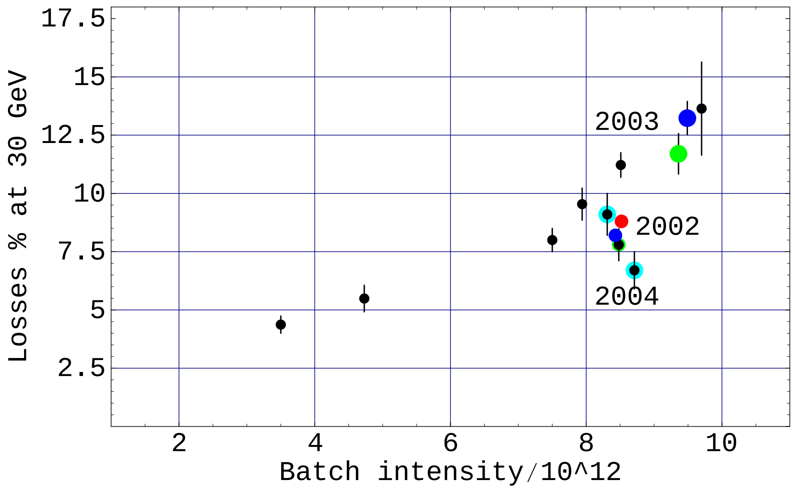
RF power per cavity [MW] for different acceleration time

N	SPS= 11 PS	SPS $\simeq$ 5 PS2	
$[10^{13}]$	3.0 s	3.0 s	4.2 s
4.8	0.65	0.75	0.5
7.0	0.85	1.0	0.7
10.0		1.4	1.1

- Double RF power and 40% more voltage for short ($t_{acc} = 3.0$ s) cycle
- For the same number of pot/year - 25% more intensity in the SPS for long cycle (*M. Meddahi, E. S., CERN-AB-2007-013 PAF*)

Beam loss

Relative capture loss
for different batch intensities



- Strong dependence on intensity
- Relative beam losses increase with intensity (instabilities, beam size ...)
- To keep the same absolute loss (radiological impact) relative loss should be reduced for higher intensity
- Main limitation for intensity increase during "record" CNGS run in 2004

⇒ Improved machine performance and radioprotection. Beam collimation?

Summary (1/2)

The LHC upgrade scenario with 50 ns bunch spacing is very challenging for the SPS. Nevertheless

- The increased injection energy with PS2 (≥ 50 GeV) should help to overcome single bunch limitations (space charge and TMCI)
- Increased longitudinal emittance at injection (≥ 0.6 eVs) should cure multi-bunch effects and TMCI (completely)
- To accelerate "50 ns" beam with large longitudinal emittance the RF system of the SPS should be seriously upgraded: doubling of power plant with R&D for its most critical elements.
- Vertical e-cloud instability is a "bottle-neck" $\rightarrow$ the SPS vacuum chamber upgrade should be studied
- SPS impedance control is essential for any future intensity increase

Summary (2/2)

What was not discussed but not forgotten:

- Injection kicker at 50 GeV/c
- Beam control:
  - longitudinal feedback, feedforward and damper
  - transverse feedback/damper
- Beam dump
- Beam instrumentation
- The 200 MHz capture RF system in the LHC

$\Longrightarrow$ The SPS must be significantly improved to match all other upgrades in the accelerator chain! - Any good ideas?