The effects of a higher injection energy in the SPS

E. Shaposhnikova, AB/RF

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Acknowledgments: G. Arduini, R. Garoby, T. Linnecar, G. Rumolo, F. Zimmermann, J. Wenninger

Present 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, $\varepsilon_n \leq 3.5\ \mu$m

- 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., 2004*)

- transverse normalised emittances (*G. Arduini et al., APC 13.08.2004*):

$\varepsilon_H = 2.99 \pm 0.26\ \mu$m - $\surd$

$\varepsilon_V = 3.61 \pm 0.26\ \mu$m

Known intensity limitations in the SPS

Single bunch intensity

- space charge
- TMCI (transverse mode coupling instability)

Multi-bunch effects (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

Higher injection energy

How higher injection energy would affect these intensity limitations?

Main assumptions for analysis:

- Nominal (LHC) beam parameters at injection:

  - longitudinal emittance 0.35 eVs - unchanged

  - normalised transverse emittances: 2.8 μm - unchanged

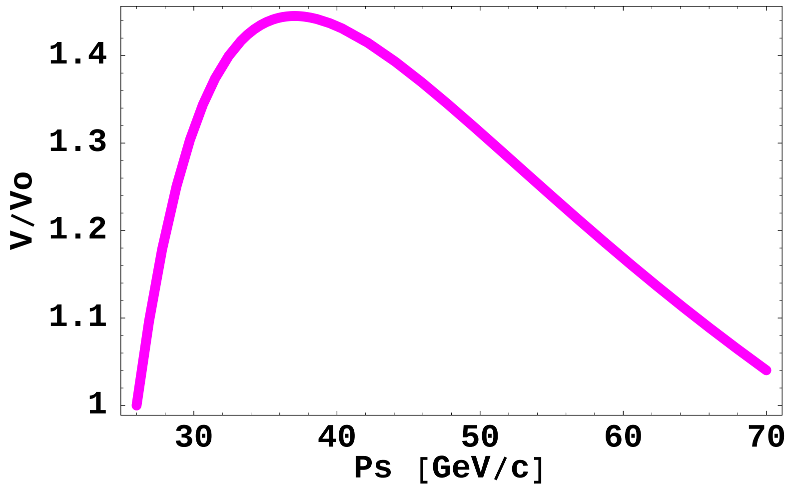
- Injection at 40 GeV/c and 60 GeV/c, magnetic cycle is similar to the present one (total time of acceleration, front porch)

- SPS is unchanged (impedance, RF systems)

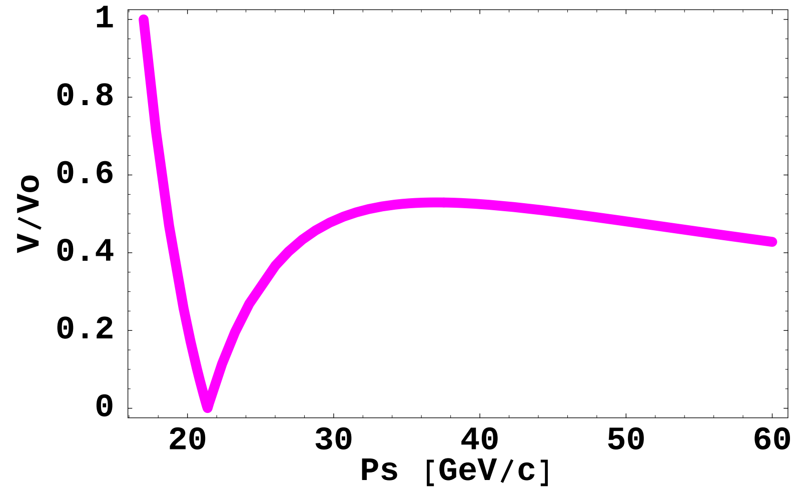
RF requirements (1/2)

Protons: matched voltage at injection V_{inj}/V_0

LHC beam



FT beam

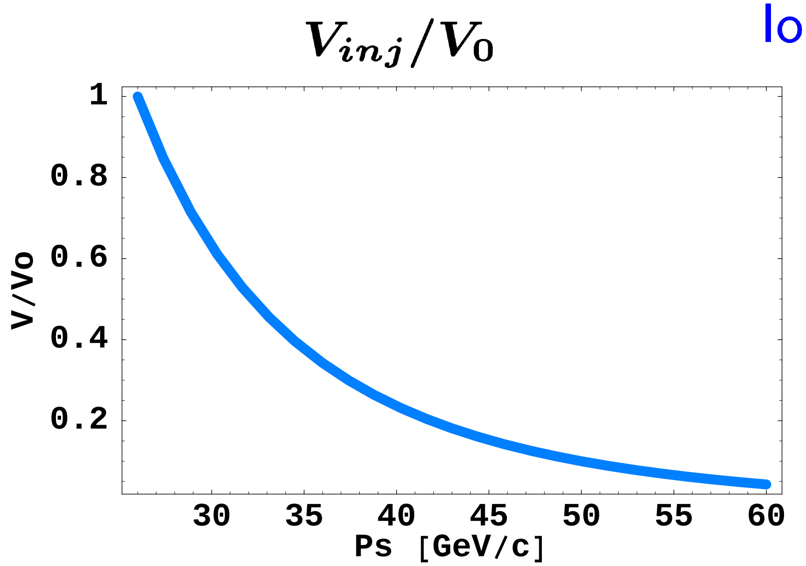


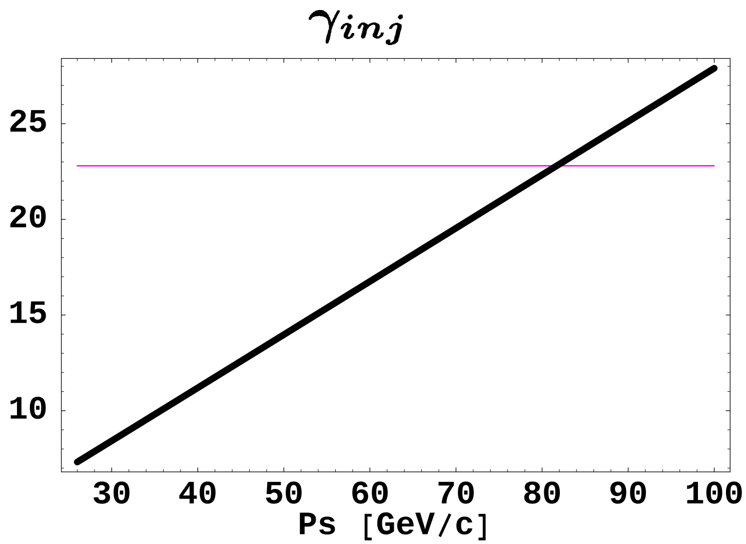
$\Rightarrow$ Matched voltage at injection goes in right direction in both cases (it is too low for LHC beam - 600 kV)

$\Rightarrow$ Hopefully no transition crossing for fixed target beam

RF requirements (2/2)

Ions





⇒ Voltage requirements at injection could be relaxed

⇒ Smaller frequency sweep: no fixed frequency acceleration $> \mathbf{40}$ GeV/c with present RF system and easier requirements for a new RF system with 12.5 ns bunch spacing for protons

- Injection into the SPS above transition only for $P_s > \mathbf{82}$ GeV/c (proton equivalent in the PS for Pb_{208}^{54+})

Single bunch limitations: space charge and IBS

- ppbar limit for space-charge tune spread: $\Delta Q_{sc} < 0.07$

- LHC beam:

  - nominal intensity - $\Delta Q_{sc} = 0.05$

  - ultimate intensity - $\Delta Q_{sc} = 0.07$

- LHC ions:

  - nominal intensity without bunchlets - $\Delta Q_{sc} = 0.08$

  - 25% beam loss, injection plateau 43 s, IBS growth time ~ 300 s

- 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*).

$\Rightarrow$ Significant improvement ($\propto 1/\gamma^2$), especially for ions

- no 100 MHz RF system, ...

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 in 2006 $N_{th} \sim 1.4 \times 10^{11}$ (*G. Rumolo et al*)

- Cure by high chromaticity and high voltage (slow beam loss?)

- Threshold intensity scales as

$$N_{th} \propto \gamma \omega_{s0} \tau^2$$

where for matched voltage the synchrotron frequency ω_{s0}

$$\omega_{s0} \propto \sqrt{\frac{\eta V_{inj}}{\gamma}} \propto V_{inj}$$

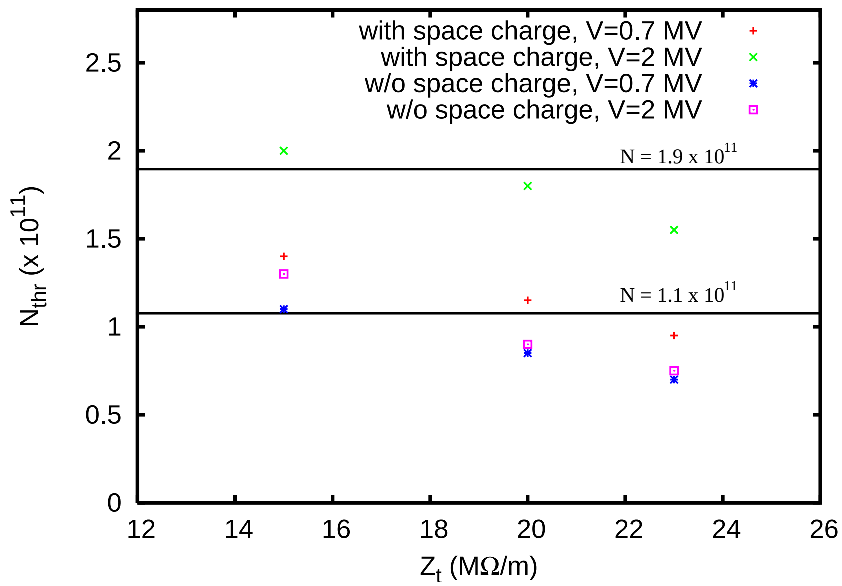
$\Rightarrow$ Threshold increase by factor 3-4 for matched voltage.

Single bunch limitations: TMCI + space charge

TMCI thresholds

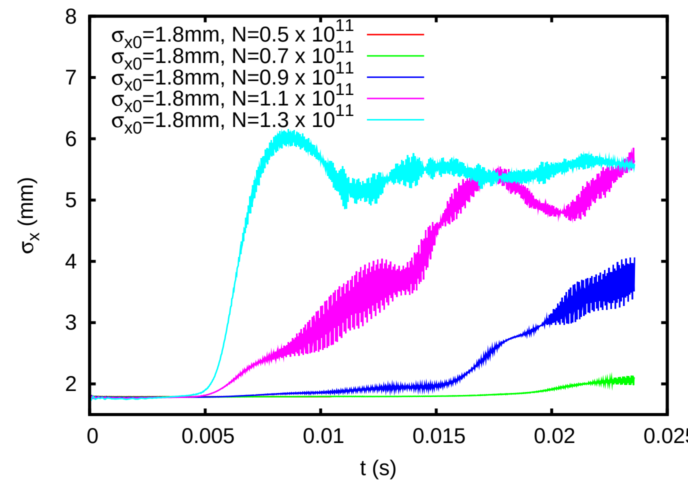
for LHC bunch at 26 GeV/c, $\xi = 0$

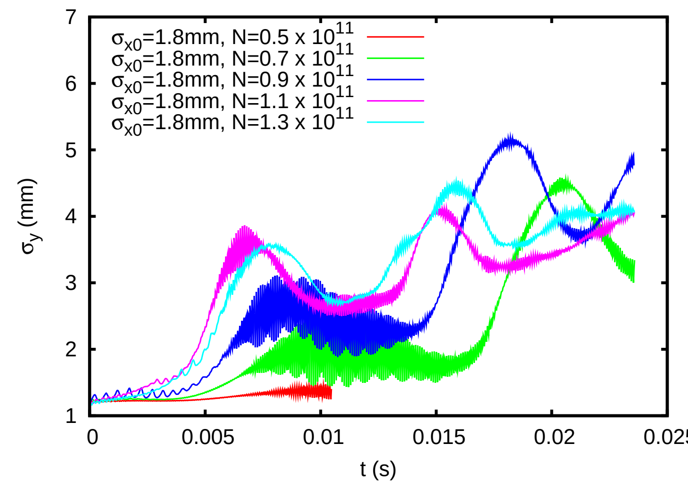
(*G. Rumolo et al., HEADTAIL, 2005*)



TMCI threshold at 60 GeV/c without space charge? $\longrightarrow$ simulations

Emittance blow-up for $N < N_{th}$





Electron cloud (1/2)

- 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 ($\sim \mathbf{700}$ MHz)

- Cures:

- scrubbing run,

- high chromaticity in V-plane,

- transverse damper in H-plane

- Emittance blow-up for 4 LHC batches in V-plane $\sim$ 20% at the end of the batch (*G. Arduini, Chamonix 2004*)

Electron cloud (2/2)

• Coupled-bunch instability in H-plane at different energies.
Measurements with $\mathbf{1.1 \times 10^{11}}$ ppb (*G. Arduini et al.*)

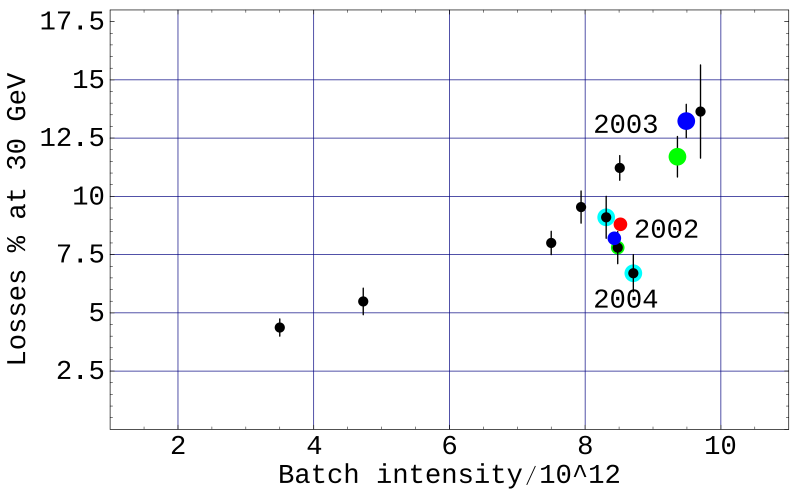
Momentum [GeV/c]	Growth time [turns]
26	300-400
55	800-900
450	6000

$\Rightarrow$ Instability growth rate $\sim \mathbf{1}/\gamma$

• Probably no significant changes for instability in V-plane (*F. Zimmermann*) - to be checked in simulations

Capture loss

Relative capture loss
for different batch intensities

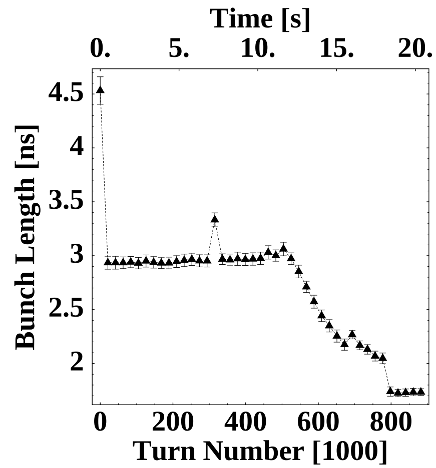


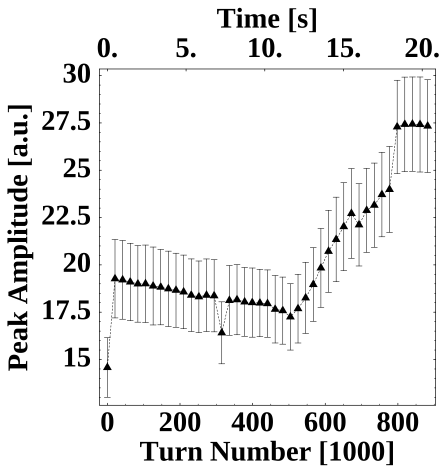
- Strong dependence on batch intensity, much less on total (number of batches) or bunch intensity
- Reduction of relative loss for 75 ns bunch spacing
- Reduction of losses to $5.5 \pm 0.5\%$ at the end of 2004 due to new working point (26.19,26.13) $\rightarrow$ (26.13,26.19) and RF gymnastics

$\Rightarrow$ Loss mechanism is not clear (should be better if space charge or e-cloud are involved)

$\Rightarrow$ Smaller beam size ($\propto 1/\gamma_{inj}$) should help for injection loss

Longitudinal coupled-bunch instabilities (1/3)



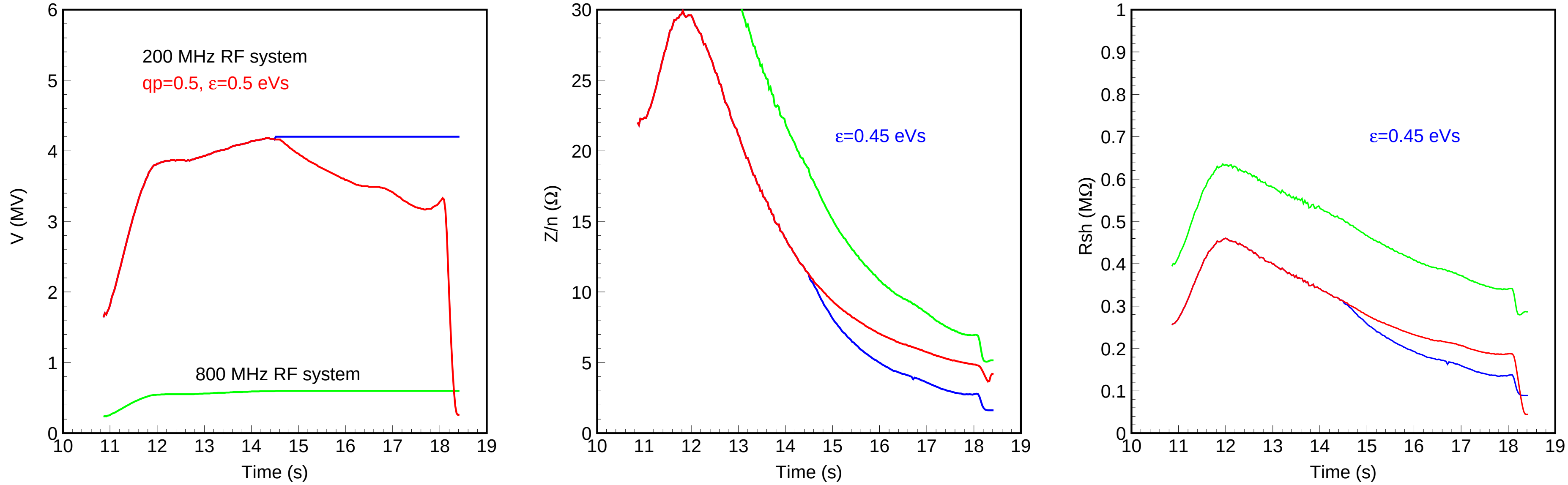


- Threshold: single batch with $\mathbf{2 \times 10^{10}}$ ppb is unstable at $\sim \mathbf{280}$ GeV
- Source: fundamental and HOMs of 200 MHz RF system (629, 912 MHz...)
- Cures:
  - the 800 MHz RF system in bunch-shortening mode through the cycle
  - controlled emittance blow-up by
    (1) mismatched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

Longitudinal coupled-bunch instabilities (2/3)

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

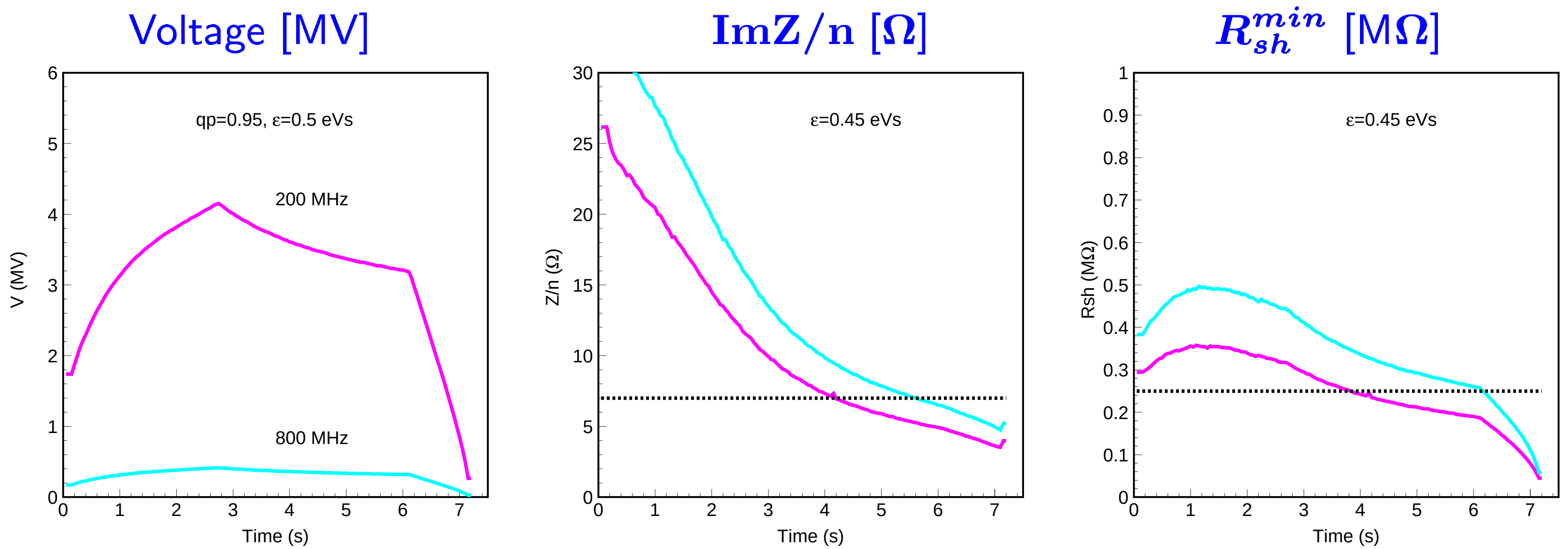
Voltage [MV] $\quad$ $\mathbf{ImZ/n}$ [Ω] $\quad$ R_{sh}^{min} [MΩ]



- Controlled emittance blow-up to 0.73 eVs for ultimate beam stability on the flat top $\longrightarrow$ capture RF system in the LHC
- Instability at injection observed at $\sim \mathbf{1.3} \times \mathbf{10^{11}}$ (with 800 MHz off)

Longitudinal coupled-bunch instabilities (3/3)

Threshold impedances for injection at 60 GeV/c for nominal intensity

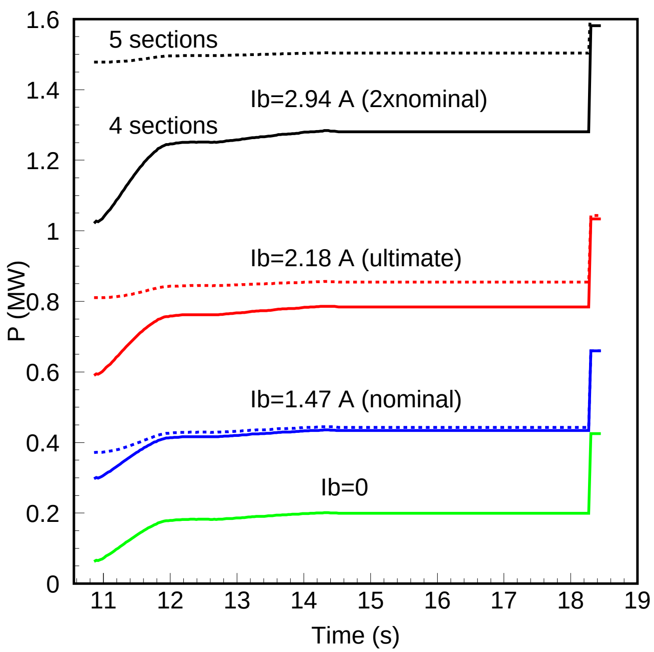


⇒ Thresholds are practically indifferent to injection energy changes ($\sim$ **20%**)

→ larger emittance at injection needed (PS)

Beam loading

RF power for different beam currents (from 26 GeV/c)



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
- 800 MHz:
  210 kW in one cavity and 150 kW in the second (after upgrade)

⇒ RF power requirement is mainly determined by the cycle

Summary (1/2)

Advantages of the increased injection energy in the SPS:

- No transition crossing for proton beams and probably light ions
- Easier acceleration of lead ions
- Smaller space change tune spread and IBS growth time (critical for nominal ions and ultimate protons, probably also for capture loss)
- Threshold increase in H-plane of coupled-bunch instabilities due to e-cloud
- TMCI threshold increase without effect of space charge
- Smaller physical transverse emittance - less injection losses
- Shorter acceleration time (10%)
- ...

Summary (2/2)

No obvious effect on the known "bottle-necks":

- Vertical e-cloud instability
- Longitudinal coupled-bunch instabilities
- Beam loading

Points to check

- Vertical e-cloud instability (measurements and simulations)
- TMCI threshold with effect of space charge included (simulations)

In general it should be a much easier machine to operate!