Performance of the LHC (proton) Injectors and Intensity limitations

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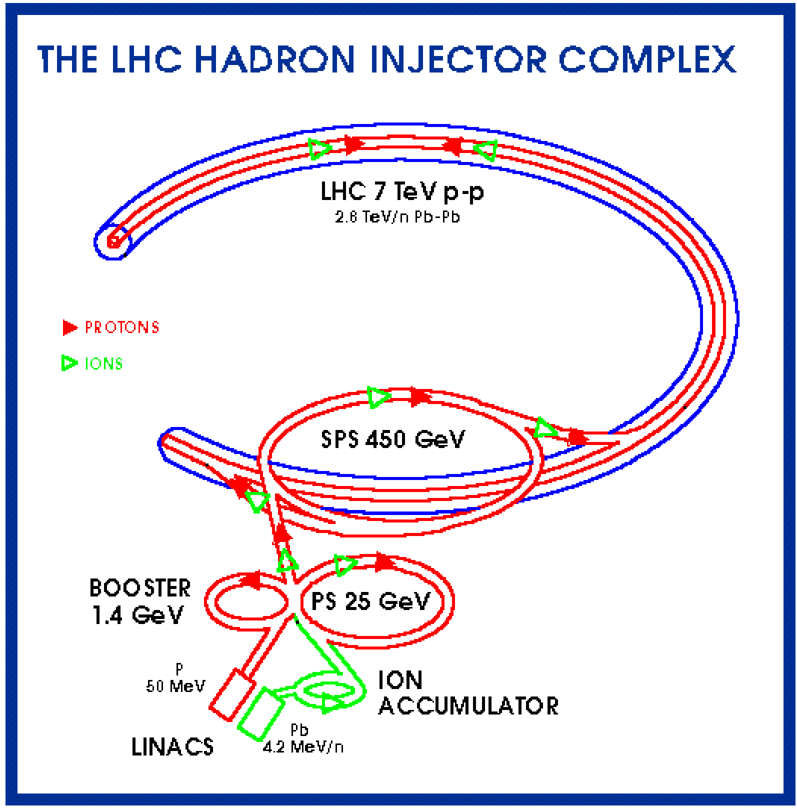
Outline

- The LHC Injector Complex
- The LHC beams
- Performance
- Present limitations
- Brief overview of the possible upgrade options
- Summary and Conclusions

The LHC Injector Complex

- **The LHC Proton Injectors:**
  - **Linac 2 (1979)**
  - **Proton Synchrotron Booster - PSB (1972)**
  - **Proton Synchrotron – PS (1959)**
  - **Super Proton Synchrotron – SPS (1976)**
- **Modifications to the PS-SPS Complex required to serve as LHC injector are almost complete.**
- **Main remaining item is the installation of TI2 (April-Aug 2007).**

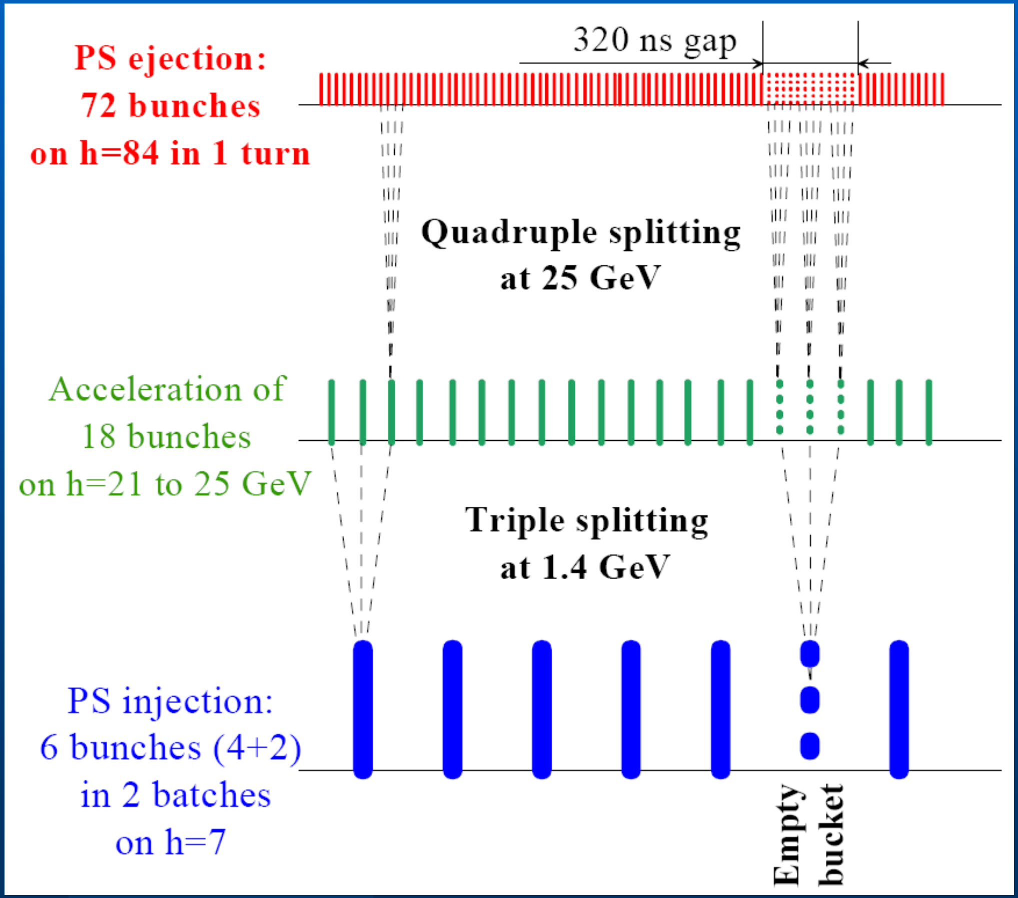


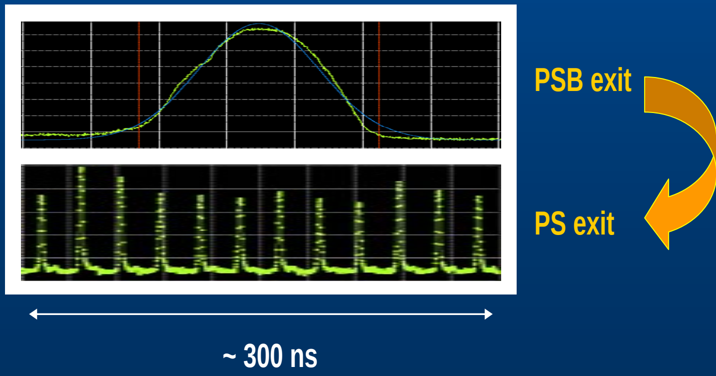
The LHC proton beam (25 and 75 ns)

	PSB@inj	PSB@extr	PS@inj	PS@extr	SPS@inj	SPS@extr
p [GeV/c]	0.31	2.14	2.14	26	26	450
K [GeV]	0.050	1.4	1.4	25.08	25.08	449.06
T_{rev} [μs]	1.67	0.572	2.29	2.1	23.07	23.05
Q (H/V)	4.3/5.45	4.2/5.2	6.22/6.25		26.13/26.18	
γ_{tr}	4.15		6.11		22.83	
bunches/ring	0-1	0-1	1-6	1-6x12 1-6x4	2-4×12-72 2-4×4-24	2-4×12-72 2-4×4-24
N_b [10^{11} p]	13.8 20.4	13.8 20.4	13.8 20.4	1.15 1.7	1.15 1.7	1.15 1.7
ΔT_{bunch} [ns]	-	-	326.88	24.97 74.91	24.97 74.91	24.95 74.85
τ_b [ns]	571	190	190	4	4	<2
$\varepsilon^*_{H,V}$ [μm]	-	<2.5	-	<3	-	<3.5
ε_L [eV.s]	~0.7	1.4 0.9	1.4 0.9	0.35	0.35	<0.8

75 ns LHC beam / Nominal 25 ns LHC beam / Ultimate 25 ns LHC beam

The LHC proton beam (25 and 75 ns)

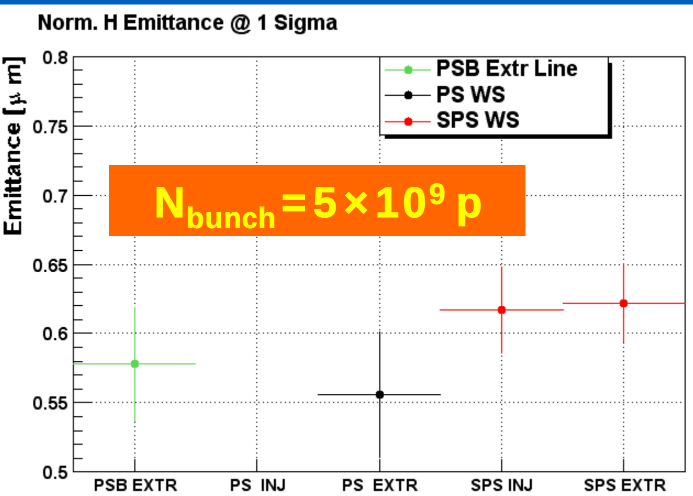


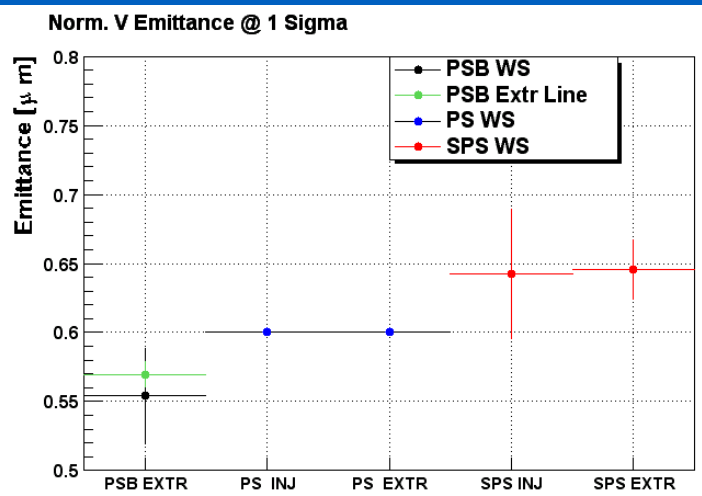


…but not only

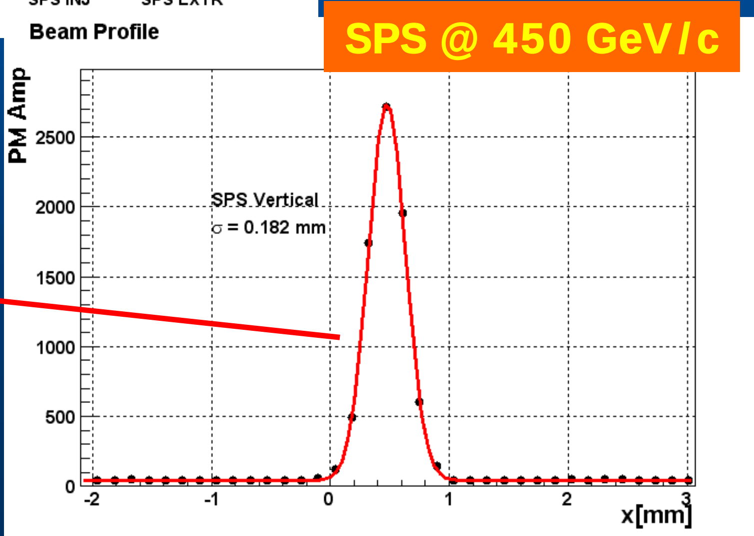
- **During commissioning and machine studies**,
  - **Probe Beam**, single bunch of $5x10^9$, with low emittance
  - **Single Bunch**, from $5x10^9$ up to $2x10^{11}$, at nominal emittance
  - **43 and 156 bunch scheme (TOTEM beam) consisting of small number of LHC bunches (max. 16 in the SPS)**
    - ➔**large bunch spacing**
    - ➔**no parasitic encounters**
    - ➔**no need of crossing angle**
- **During routine operation for physics**
  - **Pilot Beam** of $5\ 10^9$, preferably at the physics emittance
  - **Intermediate Beam** (1 PSB bunch out of 6) corresponding to:
    - 4 bunches in LHC at 75ns spacing
    - 12 bunches in LHC at 25ns spacing

Probe beam ”the smallest”





Injection oscillations and mismatch under control



Pilot and Commissioning beams

Controlled transverse emittance blow-up "pink noise" in the SPS TFB

Beam	N_{bunch} [10^{11}p]	$\varepsilon^*_{H/V}$ [μm]	ε_L [eV s]	$\#_{bunches}$	Δt_b [ns]
Probe beam	0.05-0.2 0.05	< 1 <0.7\<0.7	< 0.8 0.26	1 1	-
Pilot beam	0.05 0.05	< 1 <0.7-6\<0.7-14	<0.8 0.26	1 1	-
TOTEM/Commissioning beam	0.2-1.15 0.3 1.1	<3.5 0.95/0.85 <1.8\<1.3	<0.8 0.4 0.4	1-4-16 1-4-16	525 525

SPS @ 450 GeV/c

LHC beam - multibunch

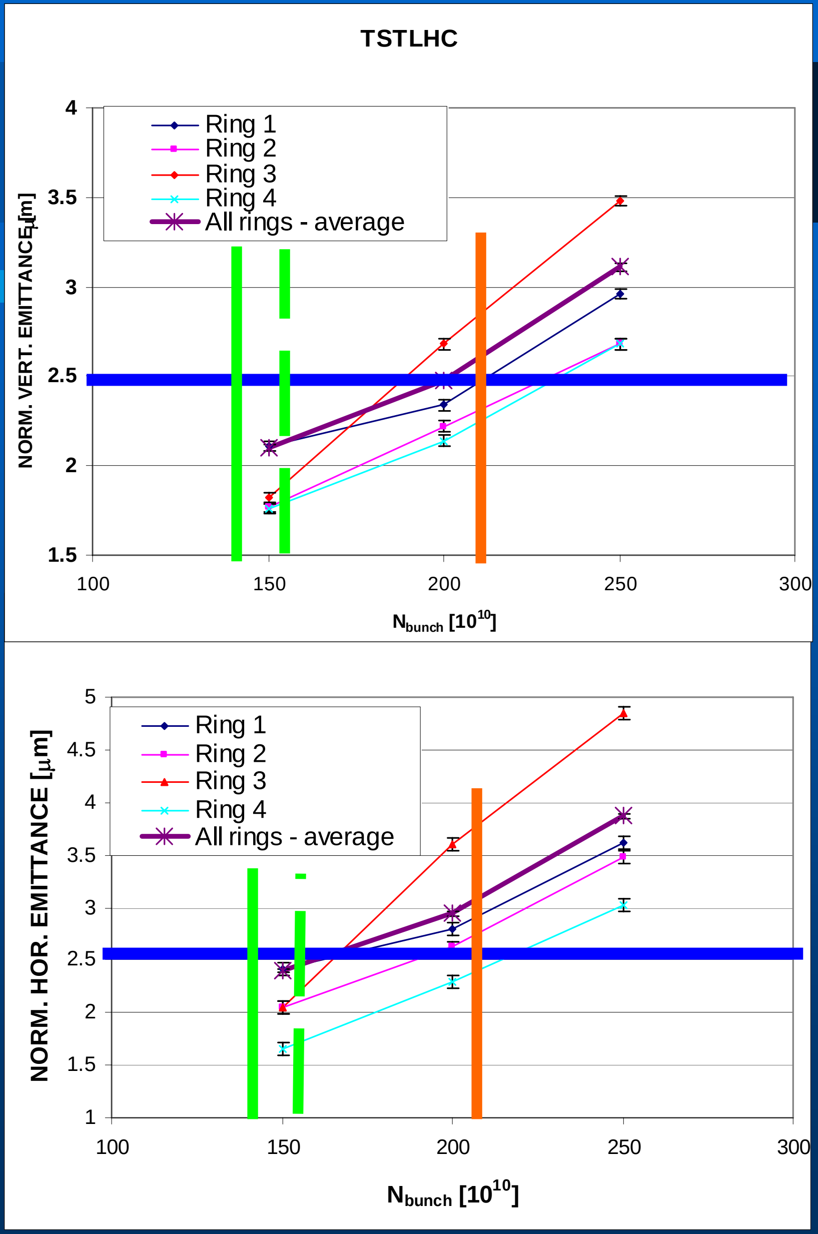
SPS @ 450 GeV/c

Beam	N_{bunch} [10^{11}p]	$\varepsilon^*_{H/V}$ [μm]	ε_L [eV s]	$\#_b$	Δt_b [ns]
Early ϕ-75ns	0.1-1.15 0.6 1.15	2.5\2.5 0.9±0.05\0.8±0.05 1.8±0.1\1.5±0.05	<0.8 0.6 0.6	1-6x4 1-4x24	75
Nominal	0.1-1.15 0.7 1.15	3.5\3.5 1.7\2 3.0±0.3\3.6±0.3	<0.8 0.6 0.6	1-6x12 1-4x72	25

Transverse emittance still marginal in the vertical plane

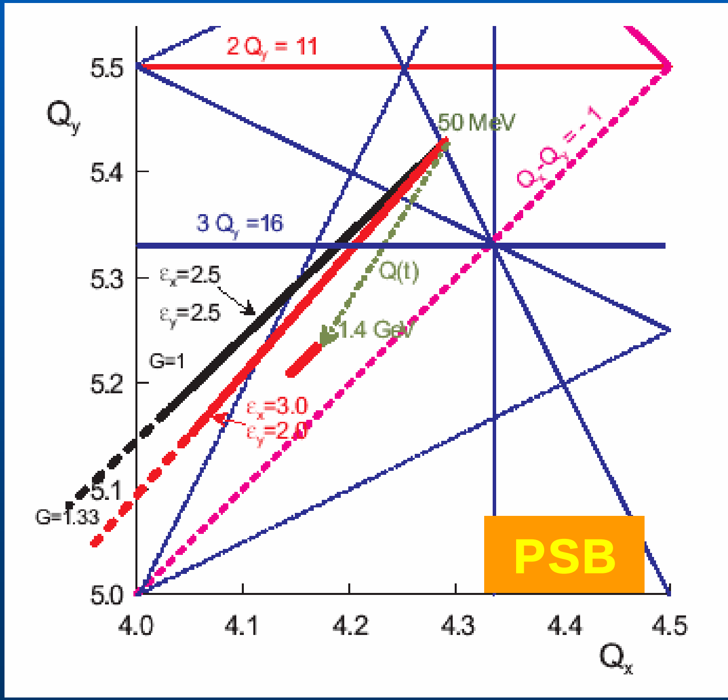
PSB limitations

- Space Charge limits:
  - LHC beam brightness. Feasible for the NOMINAL beam in spite of the margin required to account for losses in PS and SPS (dashed line). Difficult to meet for the ULTIMATE beam, in particular for ring 3
- Minimizing the losses in the downstream machines is mandatory as well as understanding the behaviour of PSB ring 3.



PSB limitations (space charge)

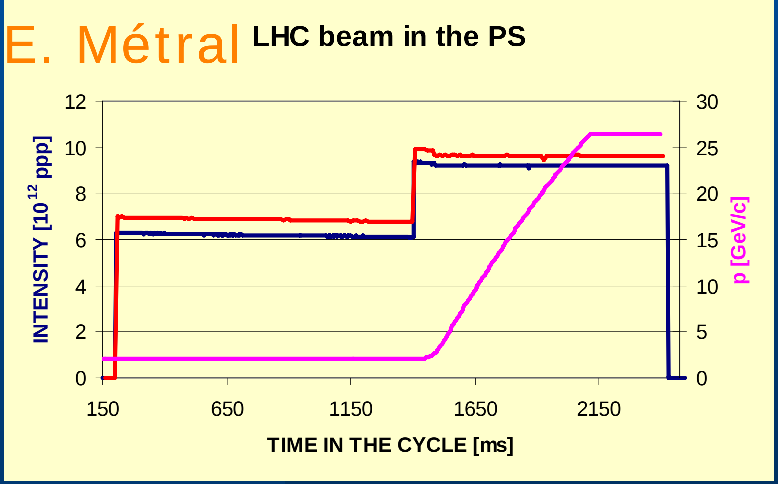
- **Transverse plane:**
  - **ΔQ_V=-0.5 for the ultimate beam for injection at 50 MeV**
  - **Beam captured in double harmonic system to provide flat longitudinal distribution**
  - **New working point (4.28/4.60 instead of 4.28/5.60) implemented in 2005 ➔ no crossing systematic resonances like $3Q_V$=16 (PSB is composed by 16 identical cells).**

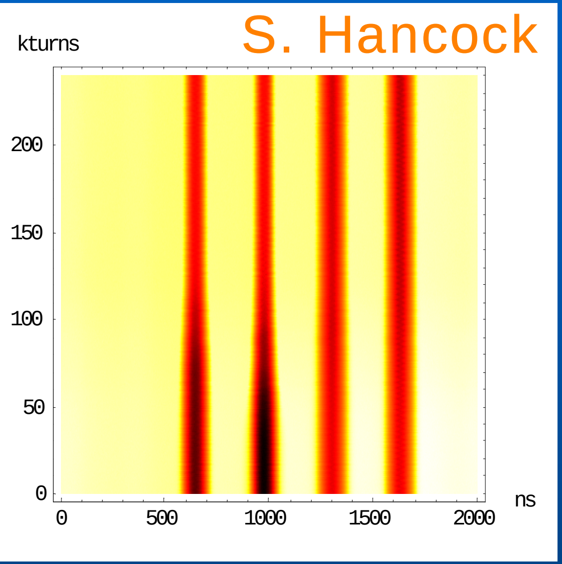


K. Schindl

PS limitations (space charge)

- **Double-batch injection in the PS for the LHC beam in order to keep ΔQ_{SC} at injection in the PSB below 0.5 → 1.2 s PS injection plateau → limit on ΔQ_{SC} in the PS ~0.25**

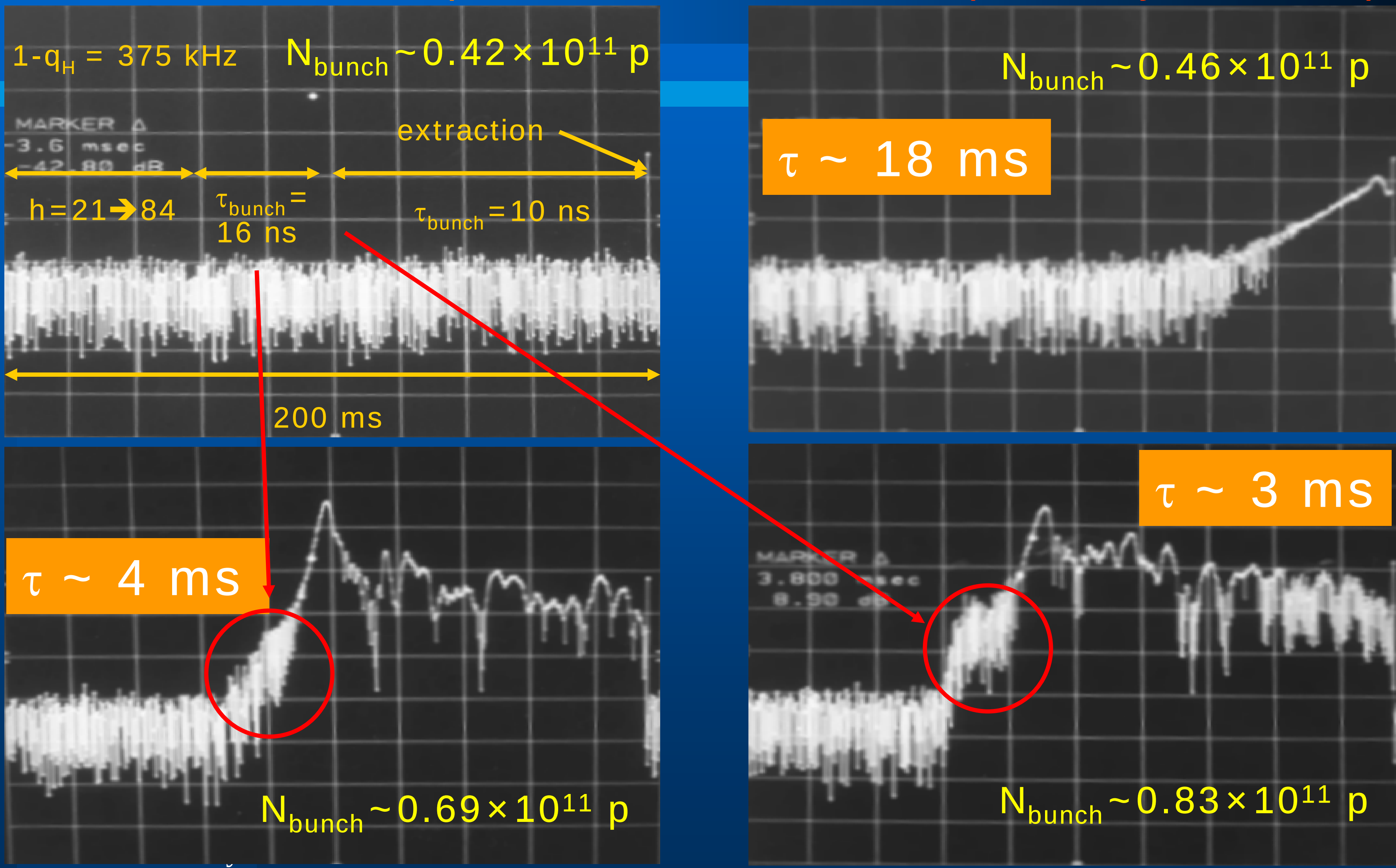




- **Losses mainly affecting more intense and/or shorter bunches (longitudinal scraping) probably related to space charge driven resonance trapping phenomena (G. Franchetti, E. Métral et al.).**

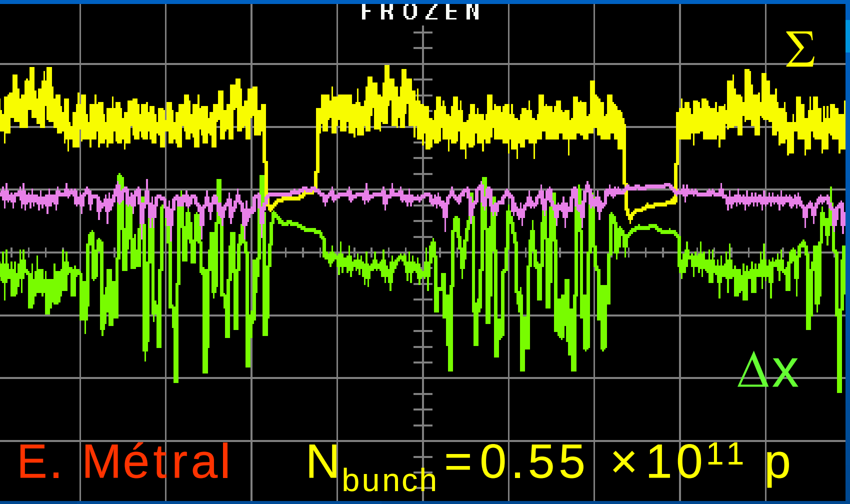
PS limitations (e-cloud)

Adiabatic bunch compression 16 ns → 10 ns (normally not done)



E. Métral-2001

PS limitations (e-cloud)



R. Cappi et al.

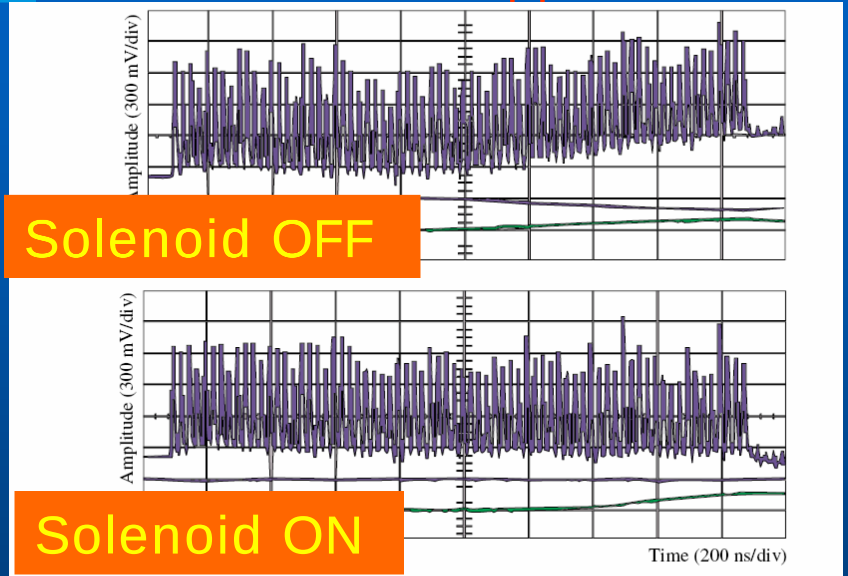


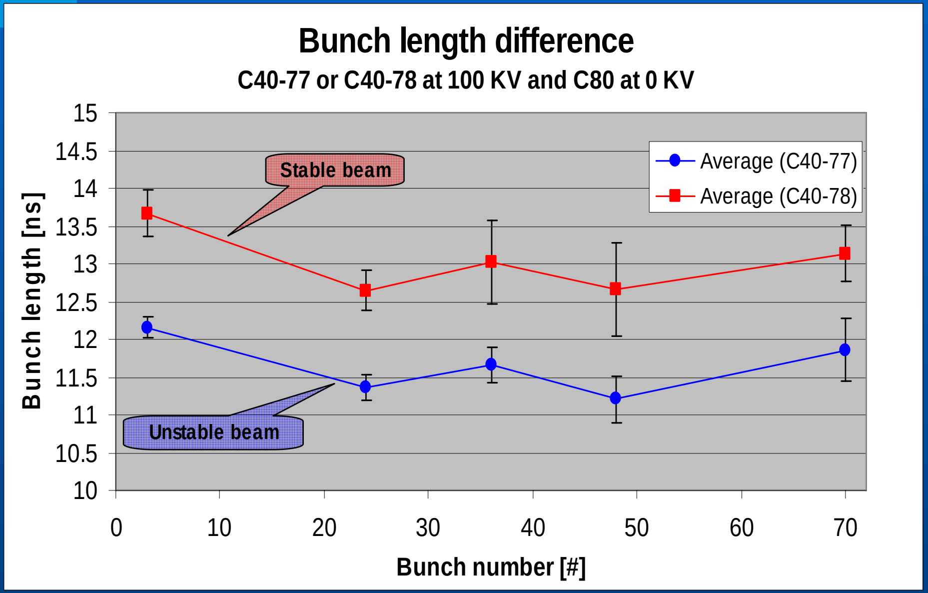
FIG. 2. (Color) Measured baseline drift in a TT2 electrostatic pickup: $I_{solenoid} = 0$ (upper panel) and $I_{solenoid} = 10$ A (lower panel). The details of the solenoid will be discussed in Sec. III C. From top to bottom: Σ, Δx, and Δy (Δx, Δy signals almost coincide with the grid lines). This pickup has a bandwidth wide enough to allow discriminating the short bunches. Such a structure is not observable on Δx and Δy signals as the beam is centered in the pickup.

- **N_{th}~0.5 ×10^{11} p/bunch close to the threshold for the onset of the electron cloud build-up**
- **Mainly horizontal instability**
- **Beam size blow-up: ×10-20 (H) and ×2 (V)**

- **Signs of electron cloud build-up and suppression with solenoidal field**

PS limitations (e-cloud)

- In 2006 observed intermittently single bunch and coupled bunch (mainly horizontal) instability
  - N_{th} ~ 0.6x10^{11} p/bunch
  - Growth times: few tens of turns
  - Creating “holes” of at least 12 bunches along the batch increases the threshold. No instability observed for <60 bunches
  - Dependence on bunch length (stronger instability for shorter bunches)
- Found a bad voltage calibration for one of the 40 MHz RF cavities (spare) used for high energy splitting and bunch rotation resulting in shorter bunch length



Hardware problem was understood and solved but it showed how little is the margin for operation with nominal beam.

PS limitations (e-cloud)

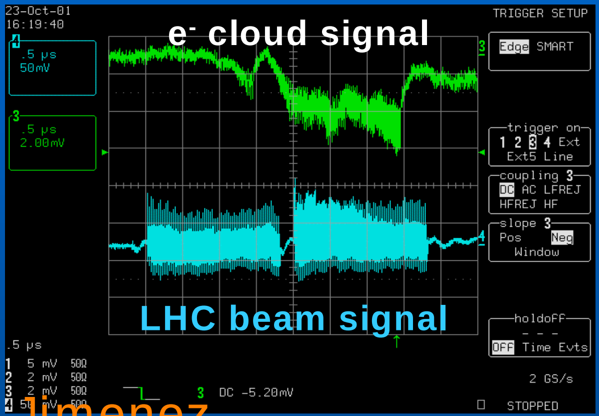
- **Observations are consistent with e-cloud instability observed in 2001 but only in a special mode of operation when the bunches where kept short (less than 10 ns) for several tens of ms**
- **We need to build some margin (taking into account that we will have to open the machine vacuum in the future to continue the magnet renovation campaign – at least its first phase):**
  - **Review the RF gymnastics at high energy**
  - **Complete the commissioning of the transverse feedback**
  - **Envisage new filling schemes**

SPS limitations (e-cloud)

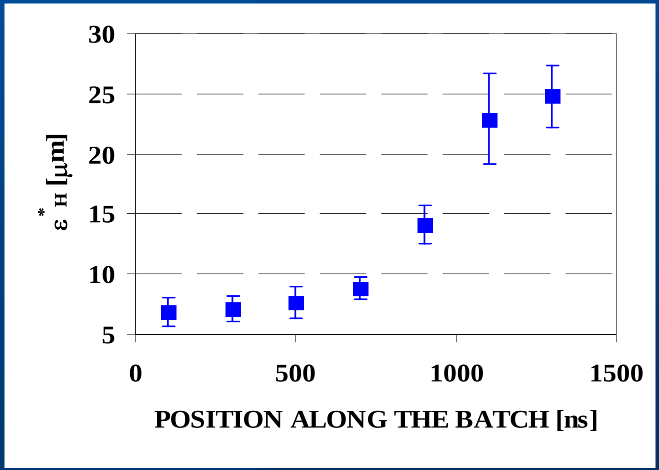
- Above a given threshold (~ 0.2×10^{11} p) an electron cloud builds-up along the LHC bunch train and couples subsequent bunches or the head and the tail of each bunch in the trailing edge of the batch

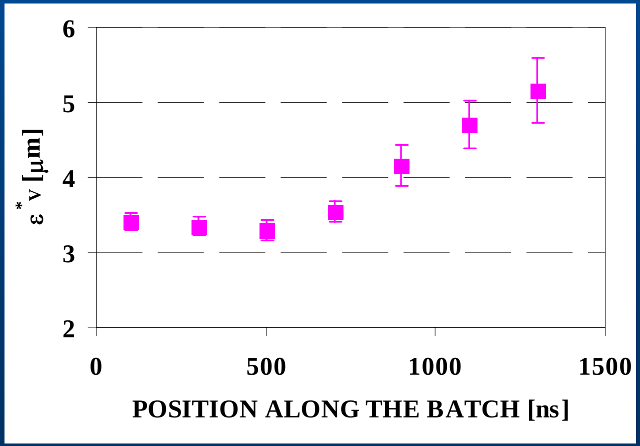
→ instabilities

→ blow-up of the tail of the batch.



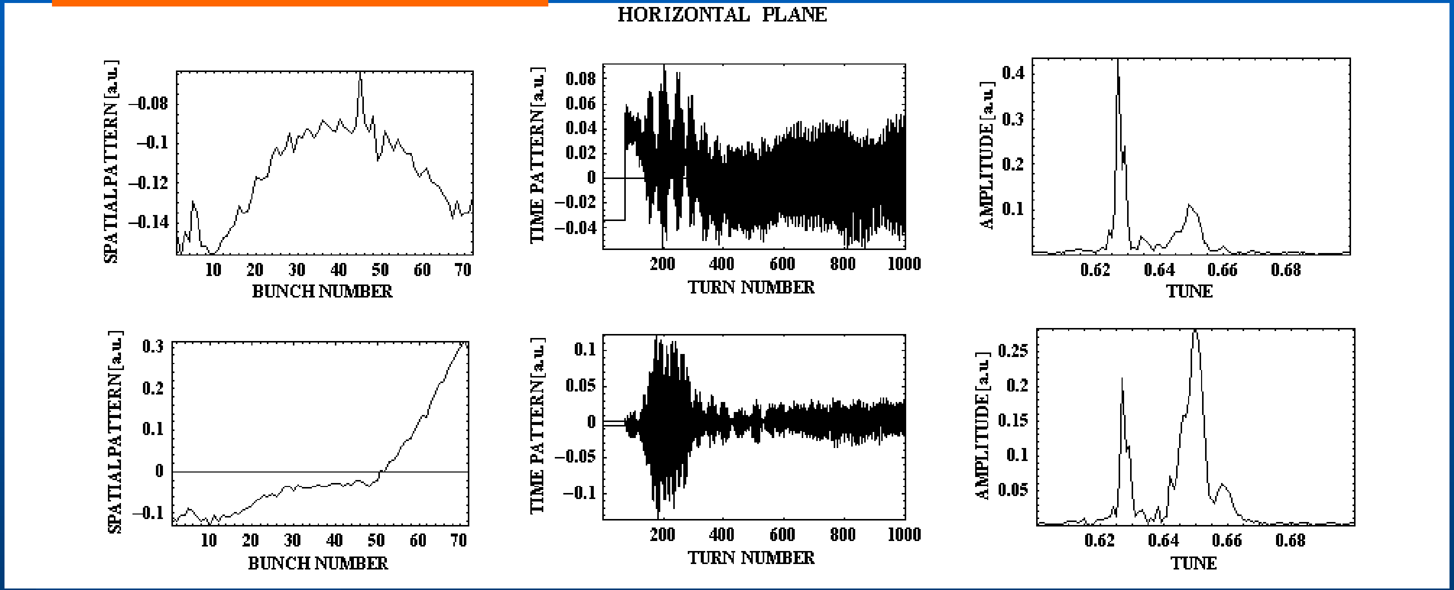
J.-M. Jimenez





SPS limitations (e-cloud)

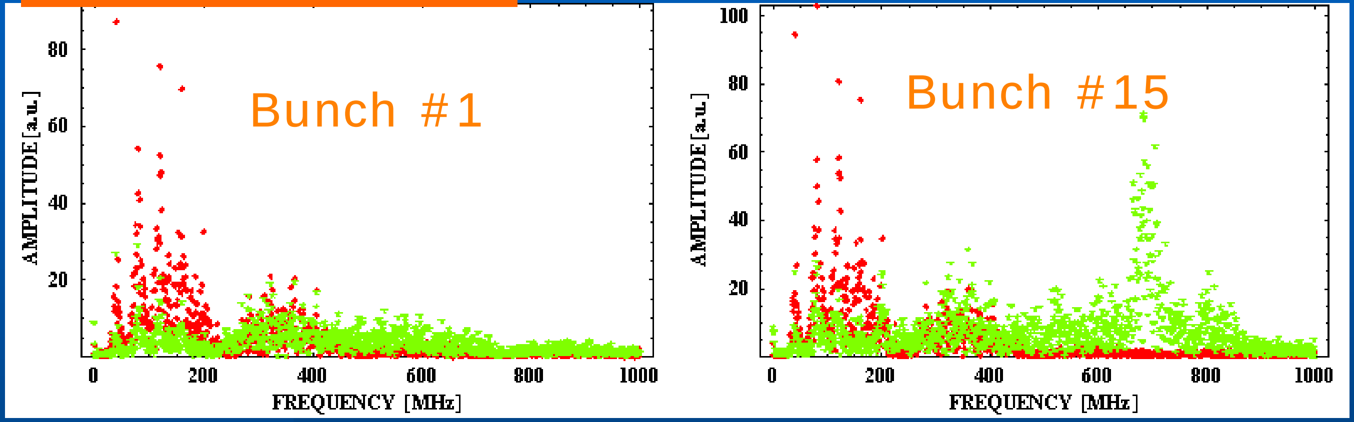
Horizontal plane



- **Low order (~1-2 MHz) CB-mode**
- **Cures: Transverse feedback (bandwidth 0–20 MHz). A further increase of the intensity above nominal might need an upgrade**

SPS limitations (e-cloud)

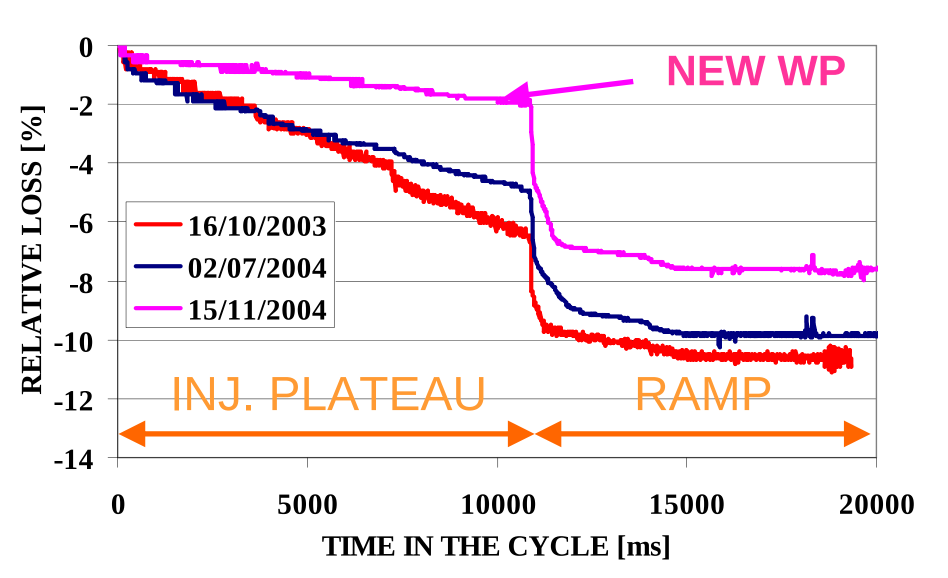
Vertical plane



- **TMCI like instability (~700 MHz) affecting trailing bunches.**
- **Cures: (ξ_V > 0.4-0.5) ➔ large tune spread. How far can we go above the nominal intensity**

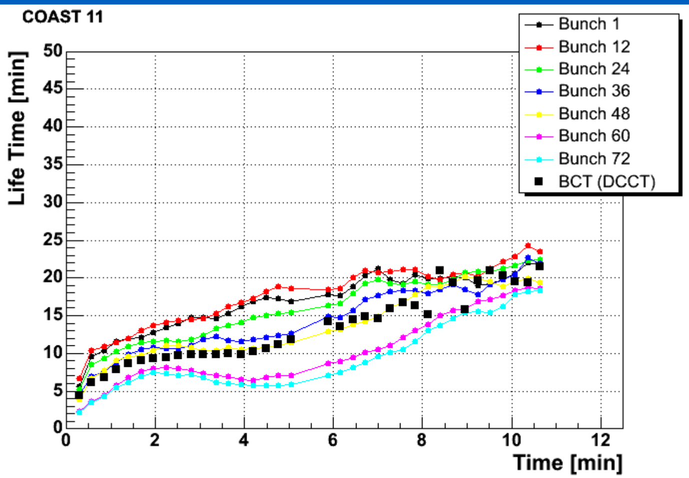
SPS limitations (low energy losses)

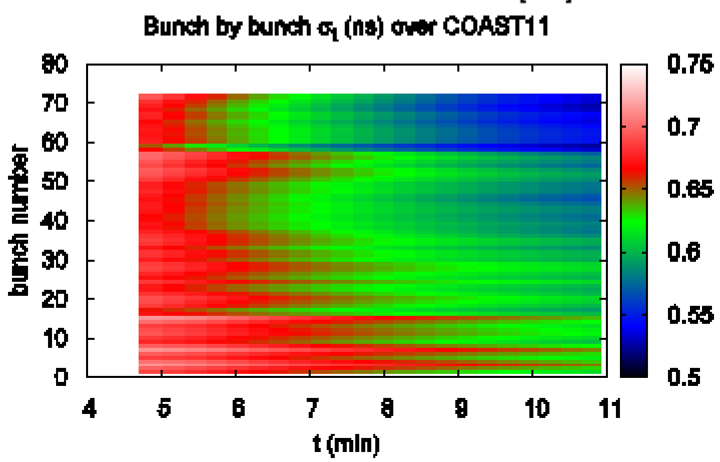
- **Low energy losses:**
  - ➔ **reduction from >10 to 7-8 %**
  - – **New RF voltage programme (end of 2003)**
  - – **New working point compatible with larger momentum spread (end of 2004) and large vertical chromaticity required to fight the ECI. Results confirmed in 2006.**



Need to understand better the blow-up and loss mechanisms at the beginning of the ramp.

SPS limitations (low energy losses)

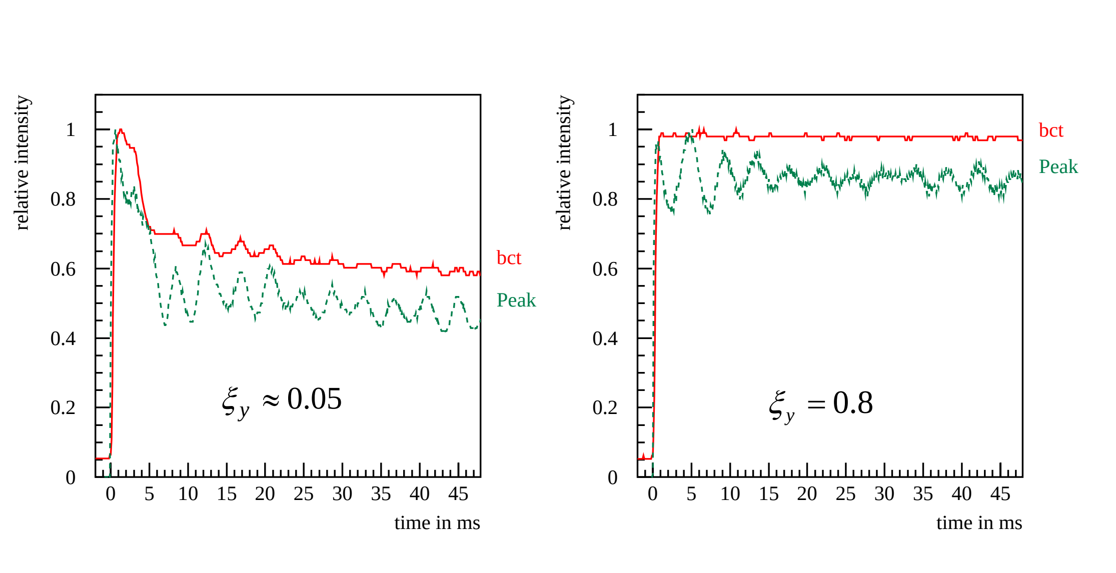




- **Short lifetime even after optimization of the working point**
- **"longitudinal" lifetime dominate (capture losses due to Re Z_L and bunch shape) in the first few s ➔ Impedance reduction and optimization of the bunch shape from PS**
- **Difference in lifetime between the head and the tail of the batch**
  - **recovers as the intensity decreases**
  - **Bunches are getting shorter particularly at the tail of the batch …..while electron cloud signal disappears**
- **E-cloud density variation during the bunch passage and synchrotron motion lead to periodic tune modulation and trapping-de-trapping on resonance islands ➔ halo and losses ➔ only cure so far: "scrubbing"**

SPS limitations (TMCI)

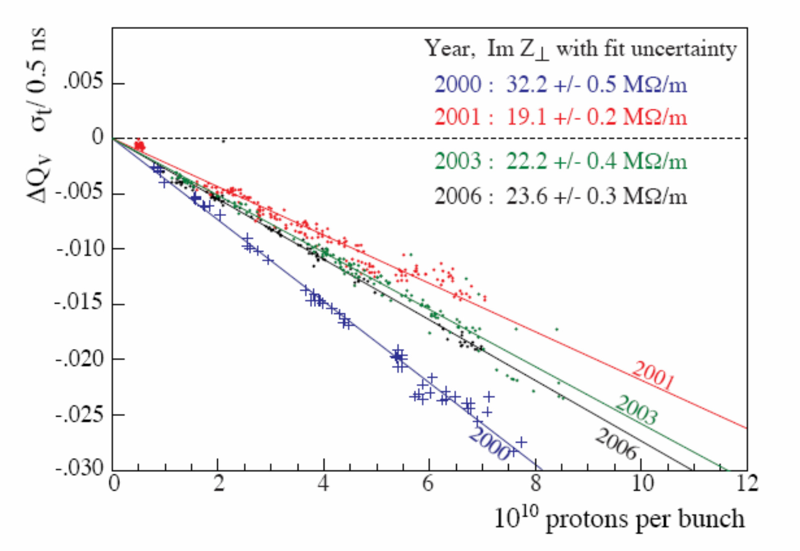
- **Fast vertical instability observed since 2002 and studied in 2003-2004 for single LHC bunches with low longitudinal emittance (ε_L~0.2 eV.s < $\varepsilon_{L\ LHC}$ =0.35 eV.s) for N_b>0.6×10^{11} p ➔ Driven by the machine $Z_{tr.}$ Expect instability threshold close to the ultimate intensity for $\varepsilon_{L\ LHC}$**

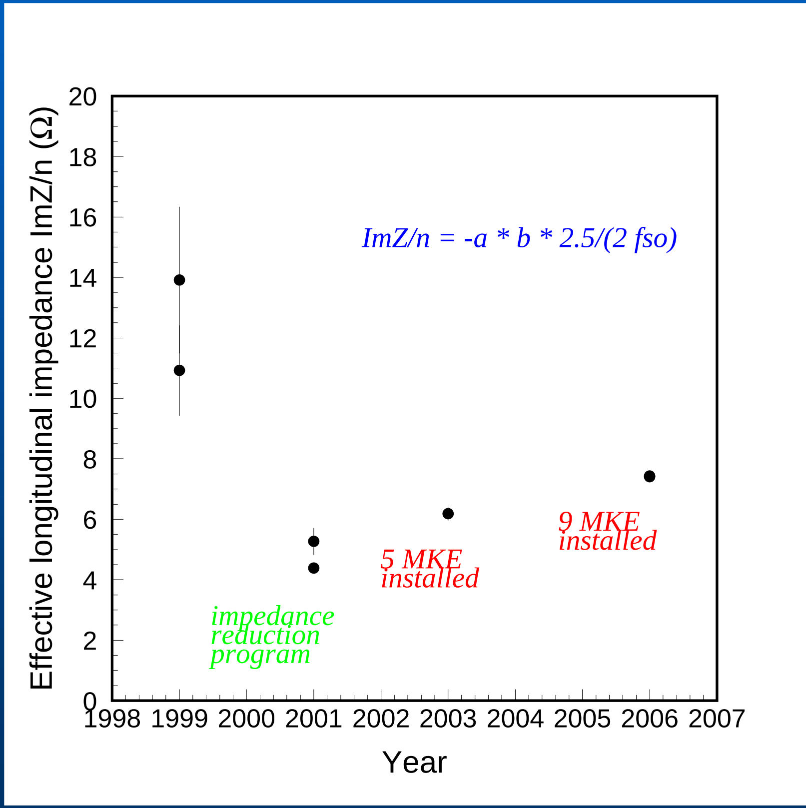


- **Since 2002 a constant increase on the 800 MHz RF voltage required to stabilize the beam has been also observed ➔ due to increased Im Z_L**

SPS limitations (TMCI)

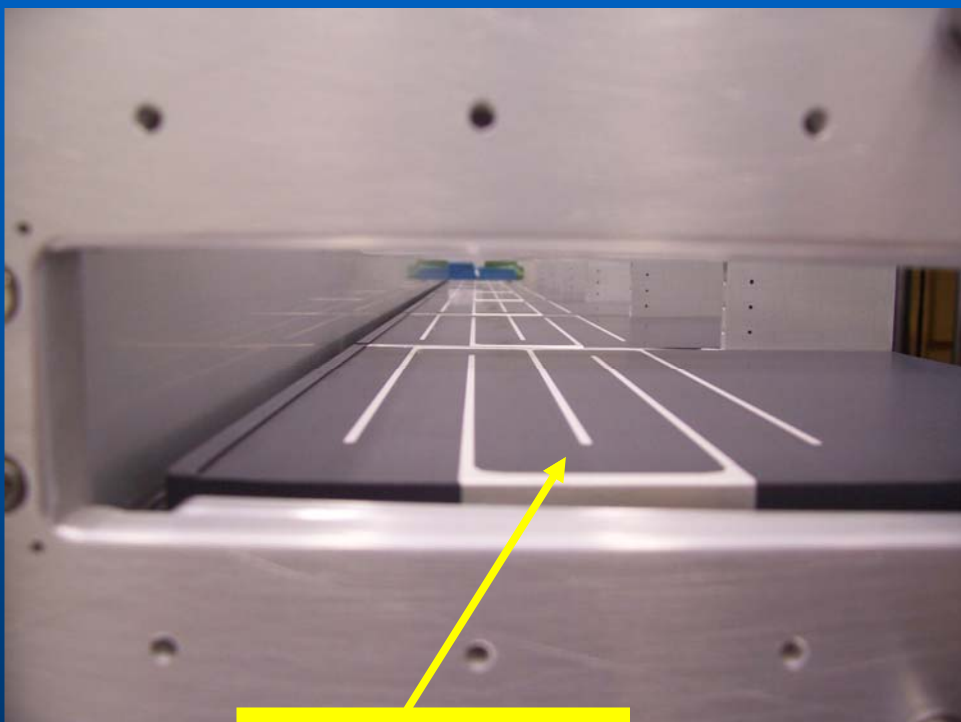
2006 results are preliminary





Significant contribution from the kickers (in particular extraction kickers).

SPS limitations (TMCI)



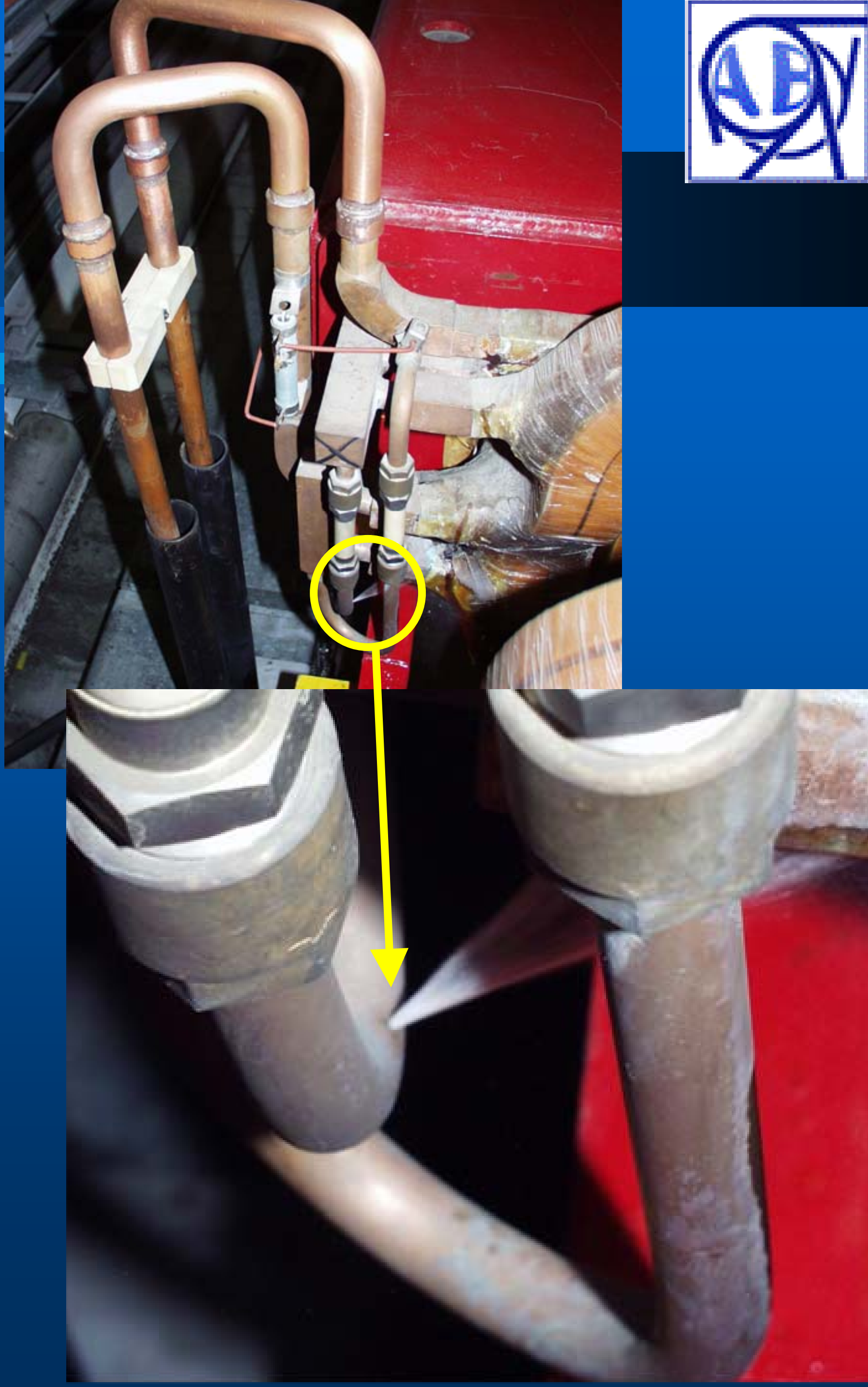
- **Impedance reduction campaign for the extraction kickers started with a prototype module installed in the machine**
- **Impedance measurements performed in the laboratory ➔ effect on beam stability being estimated before continuing with the programme**
- **Plan to build an impedance DB for the SPS (....and ultimately for all the injectors)**

Not only beam physics limitations…

- **Aging of the PS main magnets coils**
- **Important refurbishment program ongoing for the coils of the PS Main Magnets.**
  - **26 during the 2004-2006 SD**
  - **8 during the 2006-2007 SD**
  - **money available for refurbishing ~50 magnets out of 100**

Not only beam physics limitations…

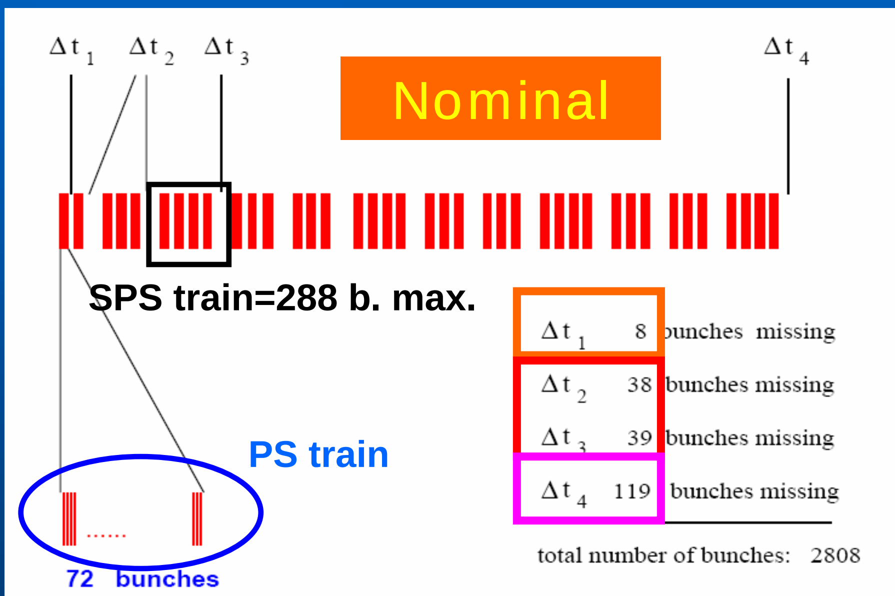
- **Weaknesses in the design of the water manifolds of the SPS main dipoles produced by one of the manufacturers**
- **Renovation started:**
  - **75 dipoles during the SD 2006-2007**
  - **The rest (180) in ~3 slots in future machine shut-downs**

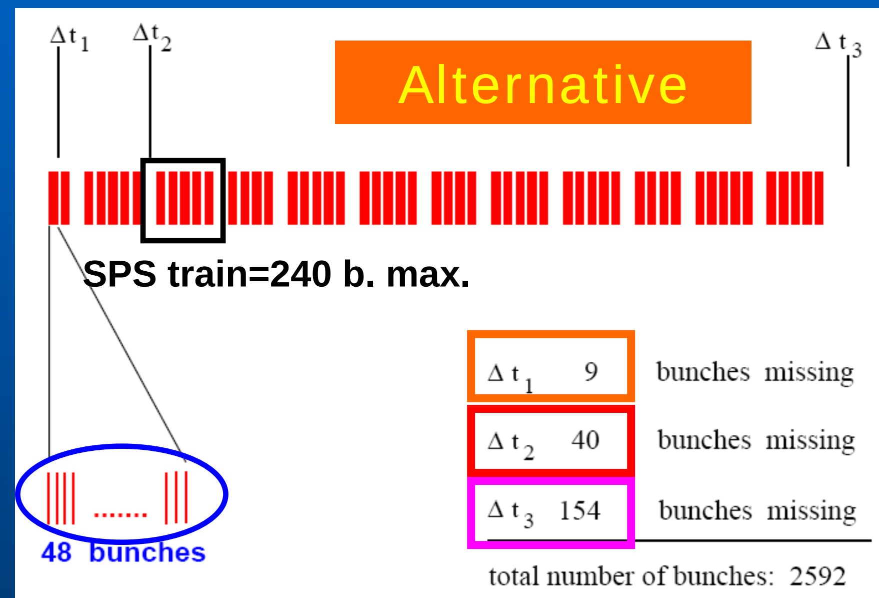


Not only beam physics limitations…

- **Large vacuum leak discovered on Tank 3 of LINAC2.**
- **Vacuum tightness of the RF tanks and drift tubes is a weakness from the very beginning. Secondary vacuum systems can be employed to mitigate problems.**
- **A re-design of the tanks would be required to solve the problem.**

Alternative filling schemes





SPS Inj. Kicker rise-time

LHC Injection Kicker rise-time

LHC Beam Dump Kicker rise-time

E. Métral

Alternative filling schemes

PS

- **Single batch injection in the PS → less losses at low energy during the 1.2 s long flat-bottom (space charge)**
- **No signs of instabilities observed the 48-bunch beam in 2006**
- **No constant tuning required for the second batch injection.**

SPS

- **Lower total int. → better for the coupled-bunch instability induced by the resistive-wall impedance.**
- **Larger spacing among PS trains in the SPS → better because the nominal rise-time for the injection kicker has not yet been achieved**
- **Shorter injection plateau**

Limited "cost" in terms of peak luminosity ~8 % (could be almost totally recovered by lower losses in the PS at low energy) but large potential for reliability and simplicity of operation

Possible upgrades under study

- New 160 MeV H^- LINAC
- Super-conducting Linac up to 3.5-5 GeV
- New proton synchrotron replacing the PS: 3.5-5 GeV to 50-70 GeV
- SPS upgrade?

Possible upgrades under study

- **New H^- Linac Injector (LINAC4) – Most advanced**
  - **Injection Energy: 50 → 160 MeV**
  - **ΔQ_{sc} reduced by a factor 2**
  - **H^- charge exchange injection → longer pulses with reduced peak current**
  - **Presently studying:**
    - **Painting schemes (transverse and longitudinal)**
    - **Expected gain in brightness in the PS Booster and the required modifications in the PSB: do we have to care only about space charge?**
    - **Try to predict the emittance of the beam at top energy: used ACCSIM so far, plan to start comparison with ORBIT and envisaging experiments to benchmark the codes**

Linac 4

Ion species	H^-
Output energy	160 MeV
Bunch frequency	352.2 MHz
Max. rep.-rate	2 Hz
Beam pulse length	400 μs
Max. beam duty cycle	0.08%
Chopper beam-on factor	62%
Chopping scheme	222/133 full/empty buckets
Source current	80 mA
RFQ output current	70 mA
Linac current	40 mA
Average current	0.032 mA
Beam power	5.1 kW
No. particles per pulse	1.00×10^{14}
No. particles per bunch	1.14×10^{9}
Source transverse emittance	0.2 π mm mrad
Linac transverse emittance	0.4 π mm mrad

- **LINAC4:**
  - **would allow removing the first bottleneck towards higher brightness for the LHC**
  - **would solve the reliability issues (LINAC2 vacuum leaks)**

Summary and Conclusions

- From the point of view of the HW the LHC injectors are ready for the LHC.
- The Commissioning and Early Physics Beams have been tested during machine studies and can be provided.
- Need to turn their operation mode from occasional (MD/expert type) into routine during the 2007 run.
- Nominal beam is feasible but we have to create more margin for a reliable operation in PS and particularly in the SPS where e-cloud together with impedance are the main limitations.

Summary and Conclusions

- **Operation above nominal is for the time being out of range and likely requires a more drastic upgrade programme of the injectors.**
- **Aging of the injectors is a major concern and a consolidation programme and upgrade studies are ongoing.**
- **Not only beam physics considerations drive the choices for the upgrade.**
- **The first step of this upgrade programme is logically the proposed construction of the LINAC4**