Beam Quality Preservation in the CERN PS-SPS Complex

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6th July 2004 – G. Arduini

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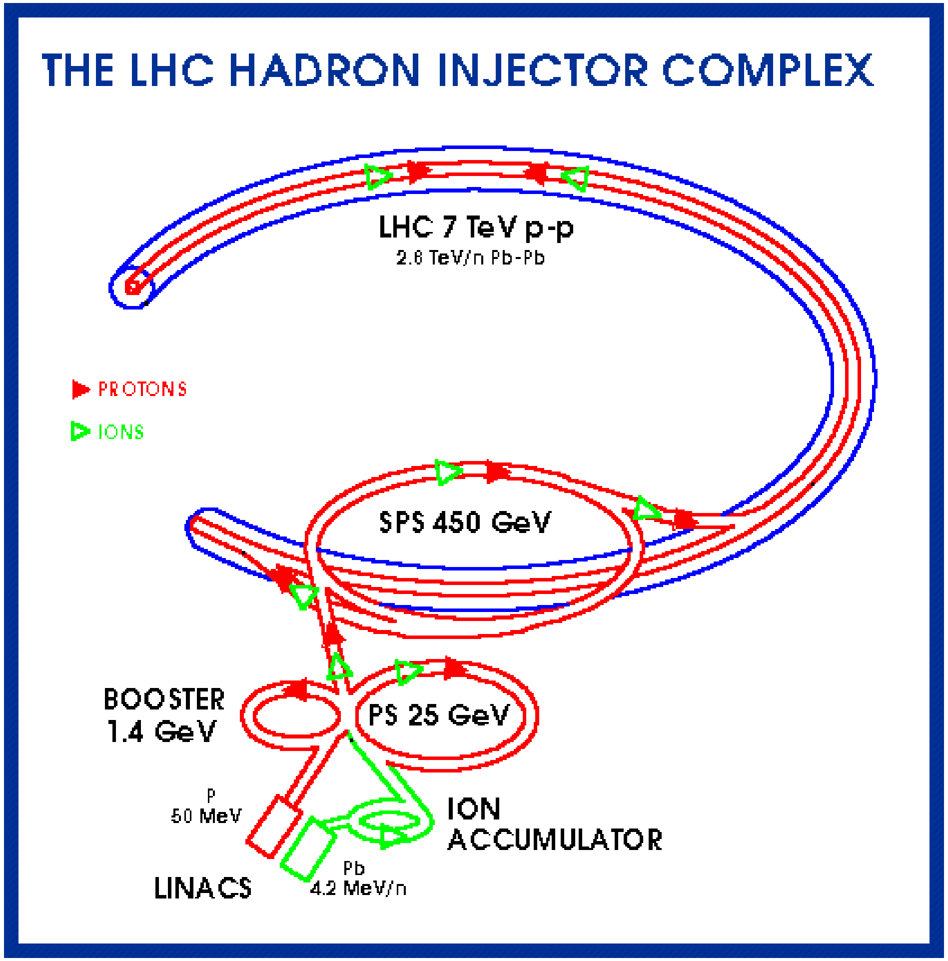
The LHC Proton Injector Chain



The LHC Proton Injectors:

Linac 2 (1979)

Proton Synchrotron Booster - PSB (1972)

Proton Synchrotron – PS (1959)

Super Proton Synchrotron – SPS (1976)

The LHC proton beam in the Injectors

	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		26.18/26.13	
γ_{tr}	4.15		6.11		22.83	
bunches/ring	1	1	6	72 24	2-4×72 2-4×24	2-4×72 2-4×24
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

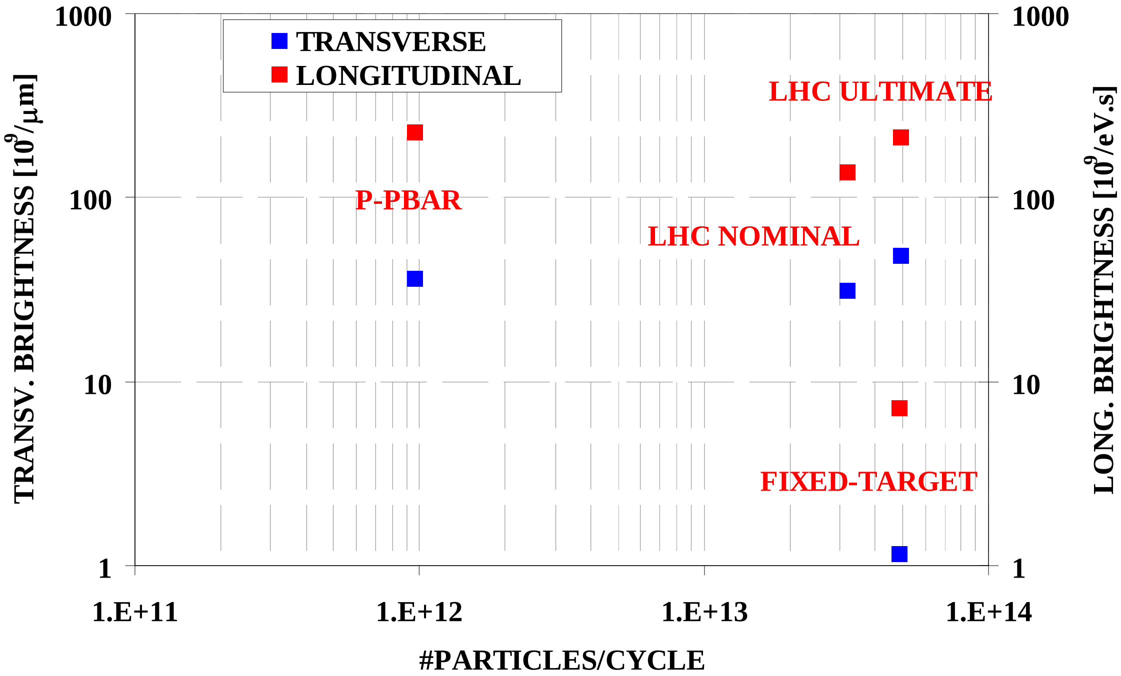
75 ns LHC beam / Nominal 25 ns LHC beam / Ultimate 25 ns LHC beam

The LHC Beam Challenge in the Injectors

- High Transverse and Longitudinal Brightness to get High Luminosity in the LHC

  ➔ tight ε budget

  ➔ Beam quality preservation



- High Total Intensity

•Longitudinal gymnastics

Low h (for low energy machines) ➔ reduced space-charge, low order CB-modes, large frequency (velocity) range, large acceptance

High h (for high energy machines) ➔ high voltage for acceleration, short bunches for luminosity

Tight transverse emittance budget implies a strict control of the sources of emittance blow-up during transfer from a machine to the next:

Injection errors: $$\frac{\Delta\varepsilon^*_{af}}{\varepsilon^*} = \frac{\Delta X_n^2 + \Delta X_n'^{\,2}}{2\varepsilon^*}\beta\gamma$$ $n \equiv$ normalised

Betatron Mismatch: $$\frac{\Delta\varepsilon^*_{af}}{\varepsilon^*} = \frac{1}{2}\left[\frac{\beta_0}{\beta_m} + \frac{\beta_m}{\beta_0} + \left(\alpha_0\sqrt{\frac{\beta_m}{\beta_0}} - \alpha_m\sqrt{\frac{\beta_0}{\beta_m}}\right)^2\right]$$

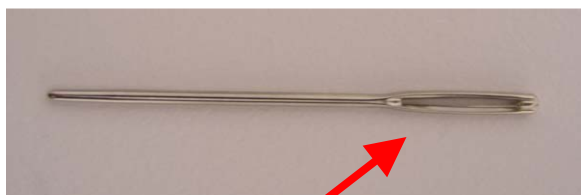
0 = expected

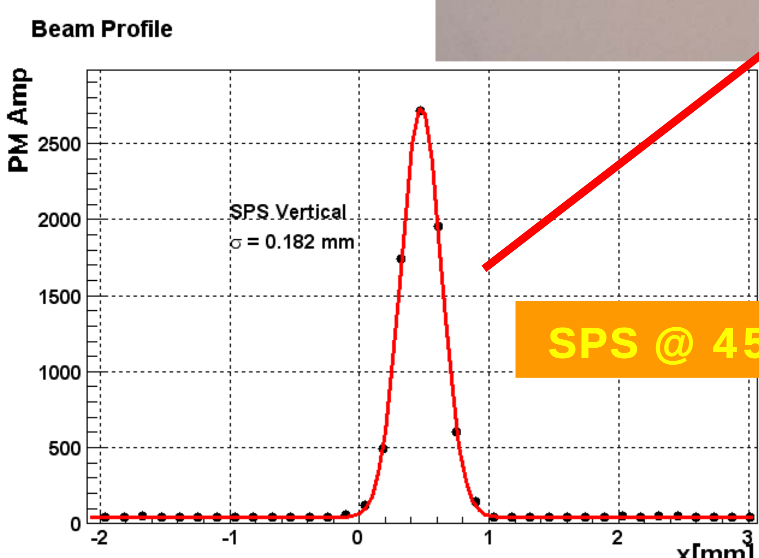
m = measured

Dispersion Mismatch: $$\frac{\Delta\varepsilon^*_{af}}{\varepsilon^*} = 1 + \frac{\left(\Delta D_n^2 + \Delta D_n'^2\right)\left(\frac{\Delta p}{p}\right)^2}{2\varepsilon^*}\beta\gamma$$

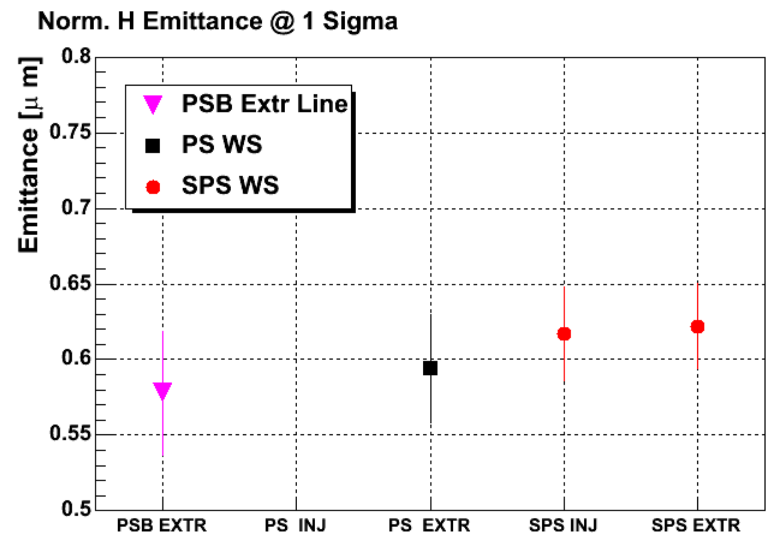
Dispersion mismatch is particularly critical for beam of small ε^* and large $\Delta p/p$ (like the LHC beam) and for high energy machines

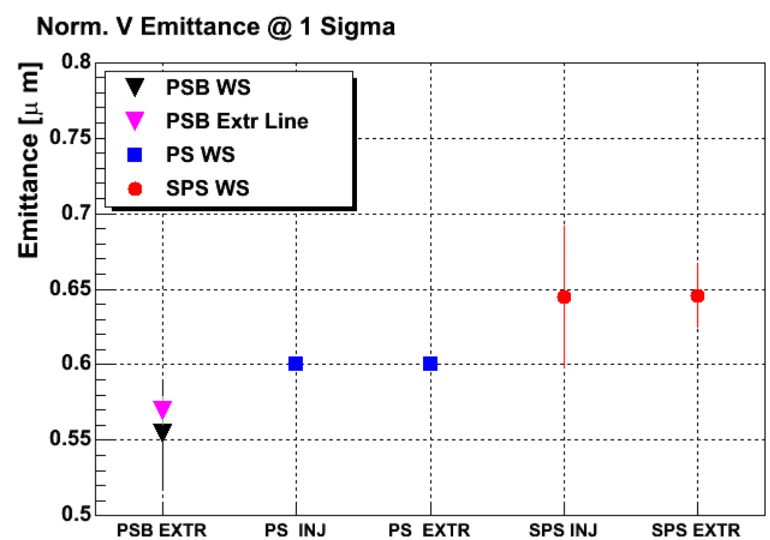
Full scale test of the matching and injection error control through the whole chain: pilot bunch of very small ε^* and $\Delta p/p$ comparable to that of the LHC beam





SPS @ 450 GeV/c



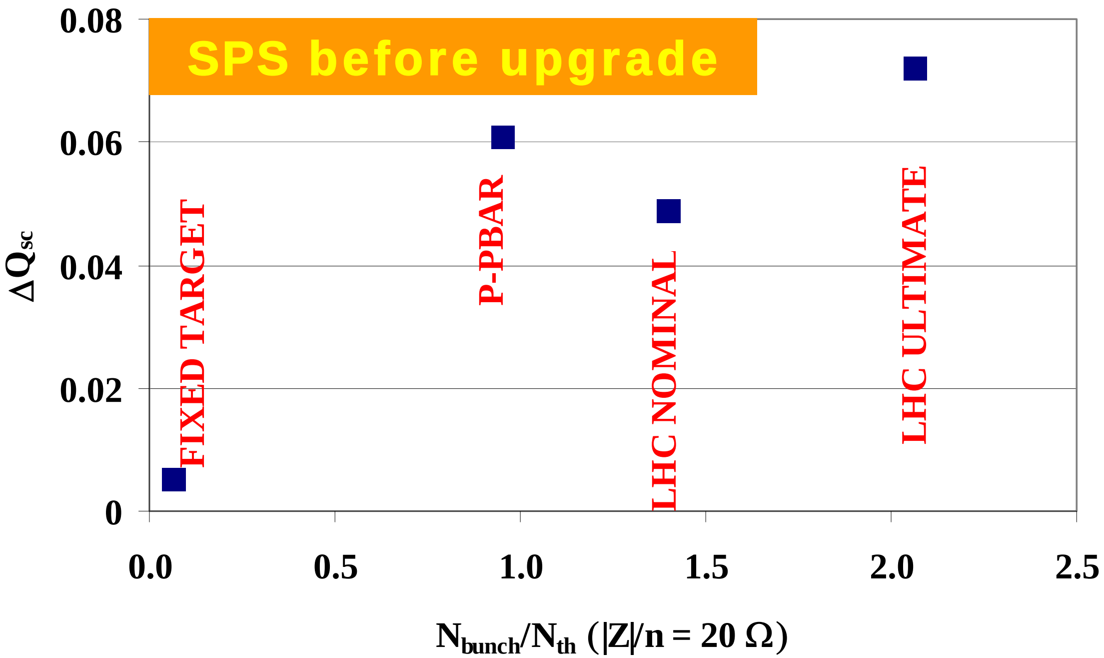


Single Bunch phenomena @ injection because of the high brightness:

- Longitudinal Instabilities (e.g. μ-wave)
- Space charge
- Transverse Instabilities

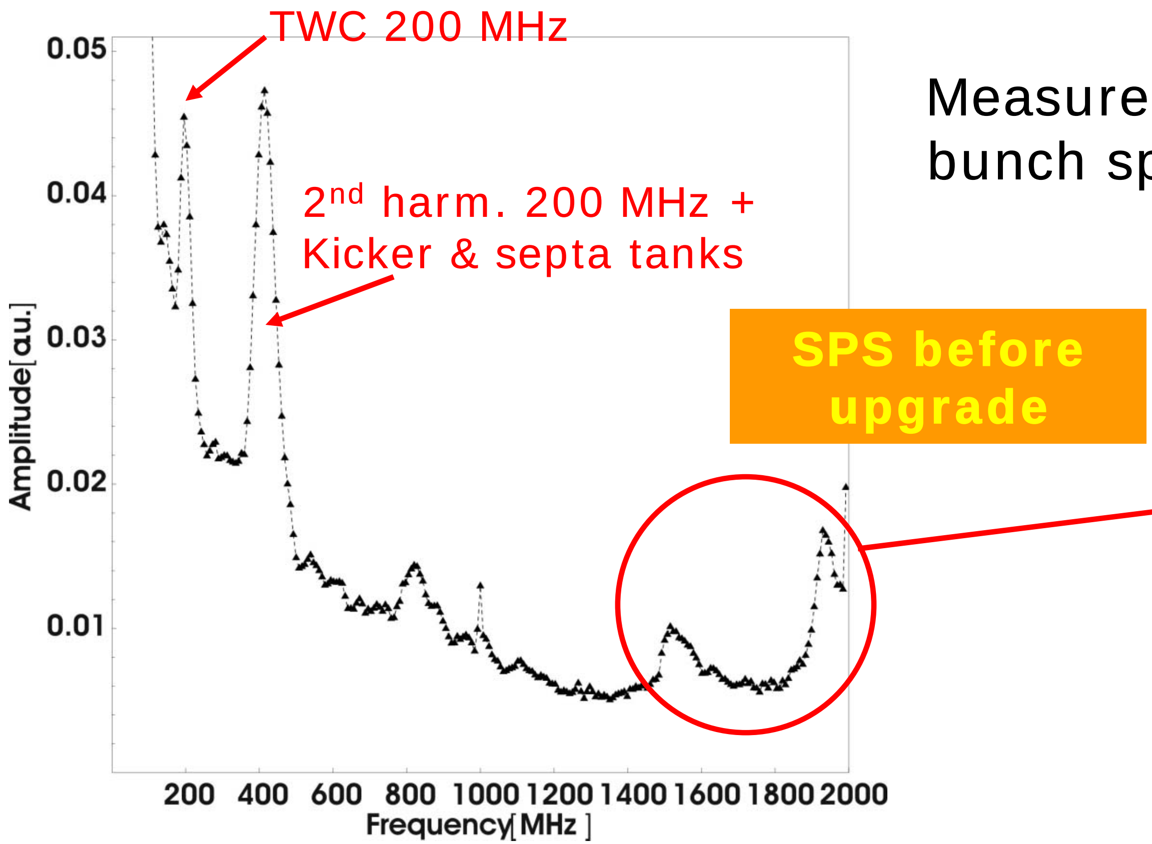
$$\frac{N_b}{N_{th}} \div \frac{N_b}{\left(\frac{\Delta p}{p}\right)^2 \tau} \frac{\frac{|Z_L|}{n}}{pc|\eta|}$$

$$\Delta Q_{sc} \div \frac{N_b}{\tau \varepsilon_n^*} \frac{R}{\beta \gamma^2}$$

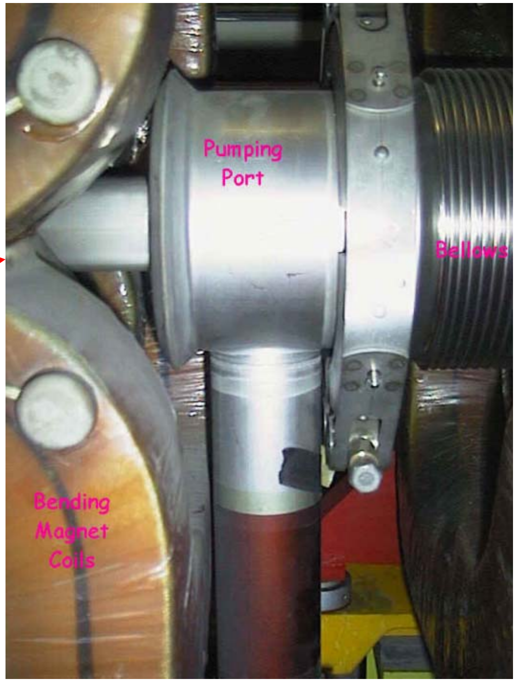


Signs of μ-wave instability (ε_L blow-up and low lifetime) observed with the LHC beam injection in the SPS in 1999

Identification of the responsible sources of Z_L at high frequency



Measurement of the unstable bunch spectra with RF off.



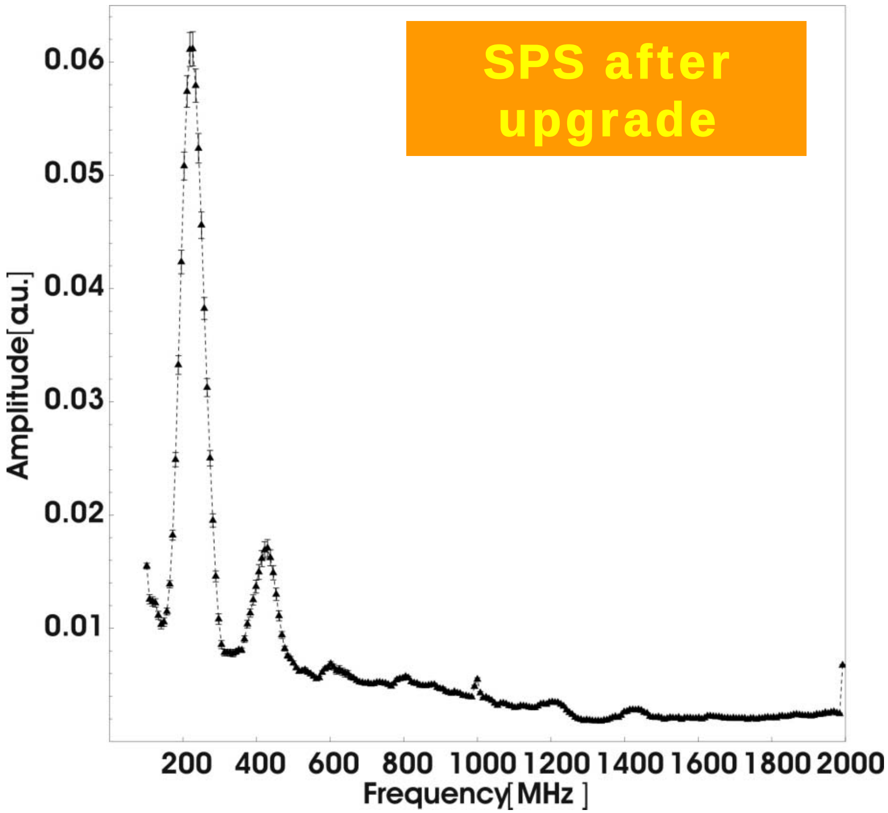
T. Bohl, T. Linnecar, E. Shaposhnikova

Single bunch phenomena
μ-wave instability

Solution for the microwave instability:

• Impedance reduction by shielding of the ~1000 pumping ports and kicker and extraction septa tanks

$$\frac{N_b}{N_{th}} \div \frac{N_b}{\left(\frac{\Delta p}{p}\right)^2 \tau} \, \frac{\frac{|Z_L|}{n}}{pc|\eta|}$$



Suppression of the 1.5-1.8 GHz lines and of the strong 400 MHz mode limited to the second harmonic of the 200 MHz unstable mode.

Disappearance of the signatures of the μ-wave instability up to nominal N_b.

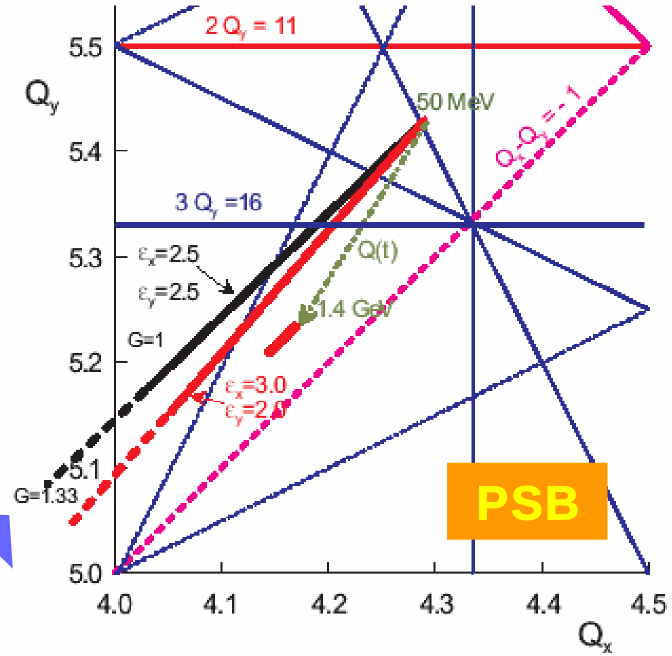
T. Bohl, T. Linnecar, E. Shaposhnikova

Max. acceptable ΔQ_{SC} depends on the time spent at low energy and on the strength of the resonances close to the working point. To get acceptable tune spreads at injection in PSB (<0.5) and PS (<0.3) (respectively) for the ultimate intensity:

- Double batch injection into the PS
- Increase of the PSB extraction energy from 1 to 1.4 GeV

	ΔQ_{SC}	Inj. plateau [ms]	Ramp [ms]
PSB	0.3 0.5	0	590
PS	0.2 0.3	1273	679
SPS	0.05 0.07	10860	7500

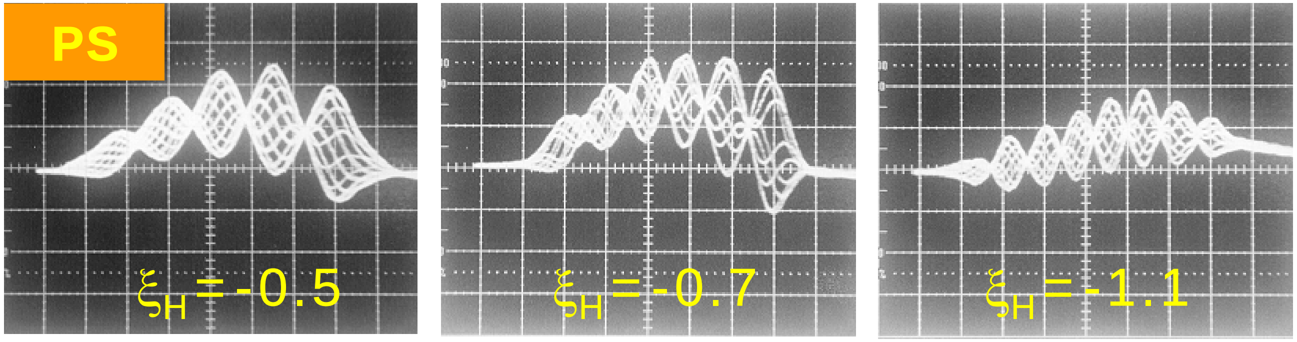
Nominal LHC beam / Ultimate LHC beam



K. Schindl

Drawback of double-batch injection ➔ First PSB batch for 1.2 s at inj. Energy ➔ Transverse Single Bunch Instabilities.

In the PS radial head-tail modes observed @ 1 GeV as expected from impedance model:



E. Métral

Stabilized only for a narrow range of positive chromaticities ($0<\xi_H<0.05$) ➔ impractical

Cures:

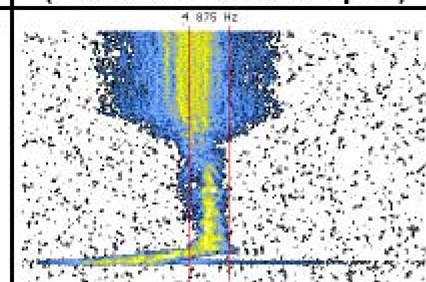
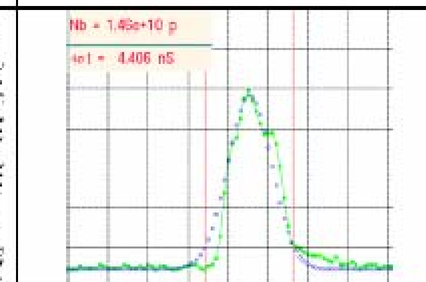
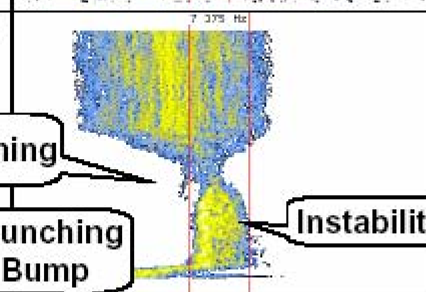
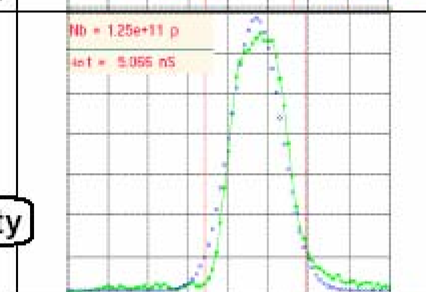
- Increase the PS injection energy from 1.0 to 1.4 GeV
- Linear coupling

The LHC Beam Challenge
Longitudinal gymnastics

Initial scheme:

- Adiabatic debunching (h=16) and recapture (h=84 - 40 MHz) at extraction energy in the PS
- No gap for the extraction kicker (3 bunches lost at extraction and 2-3 badly kicked bunches injected in the SPS)

μ-wave instability during debunching ➔ controlled ε_L blow-up to avoid instabilities ➔ 5 ns long bunches (too long) at nominal N_b

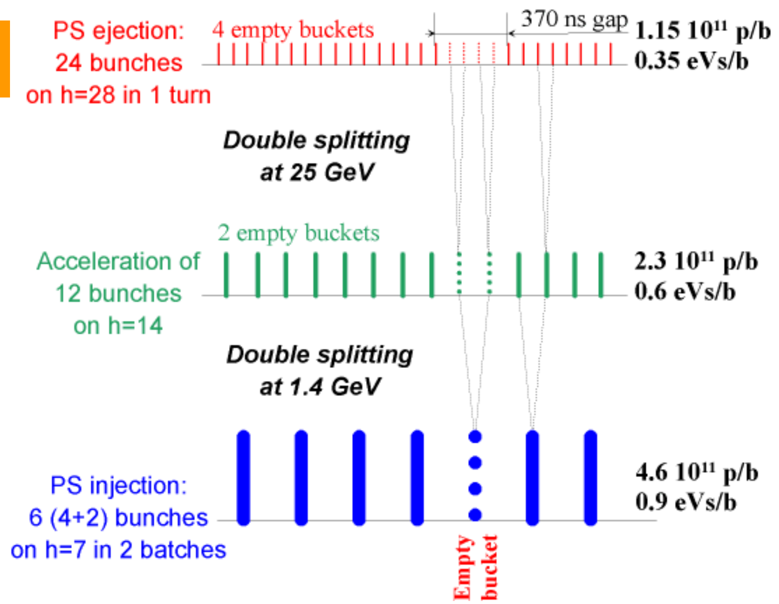
H^+ / bunch	E_L(h=16)	Schottky spec. @ 26 GeV/c (395 MHz – 50 kHz span)	Bunch @ ejection
~ 1×10^{10} H^+ @ ejection	0.85 eVs		
~ 10×10^{10} H^+ @ ejection PS	1.15 eVs		

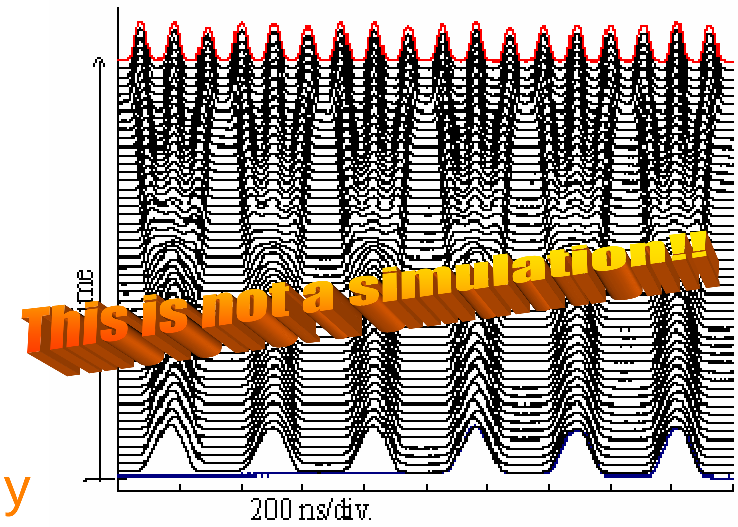
R. Garoby/E. Métral

PS

Bunch splitting:

- Gap for extraction kicker
- No μ-wave instability
- Very flexible scheme to produce alternative bunch spacings (75 ns)
- Careful control of coupled bunch instabilities to avoid asymmetries (tolerance: ±10%) in the splitting process or generation of satellite bunches
  ➔ Controlled ε_L blow-up (e.g. after transition) / longitudinal CB feed-back (mode n=1)



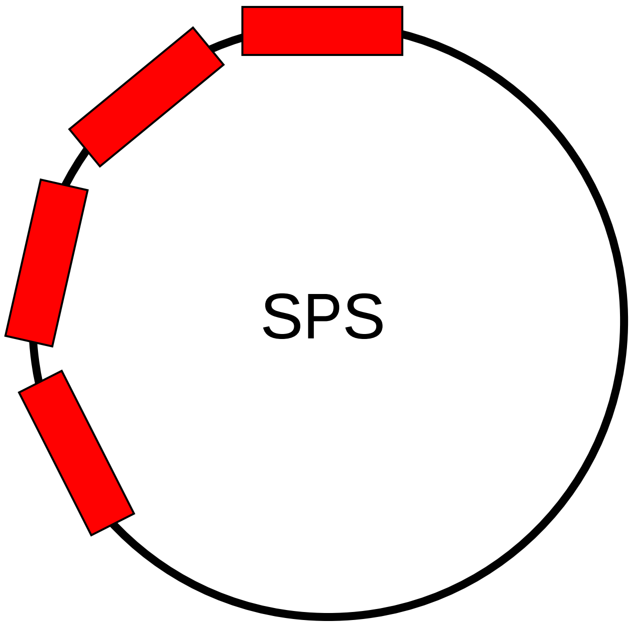


R. Garoby

The LHC Beam Challenge
Multi-bunch phenomena

The high bunch population, the large number of bunches and the tight spacing in the SPS at injection make the LHC beam more prone to multi-bunch phenomena in the longitudinal plane:

- Beam-loading
- Longitudinal coupled-bunch instabilities



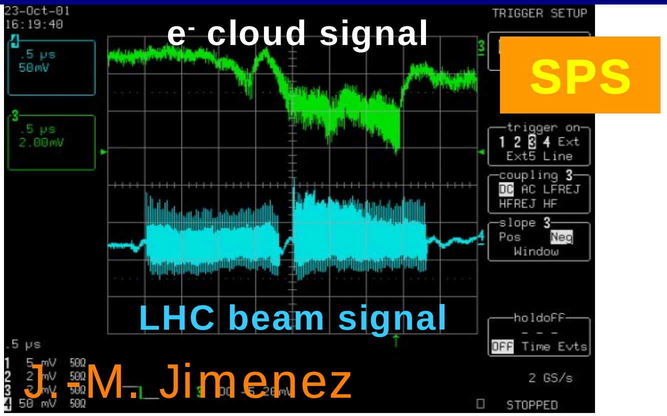
and in the transverse plane:

- Resistive Wall Instability
- Electron-Cloud Instability

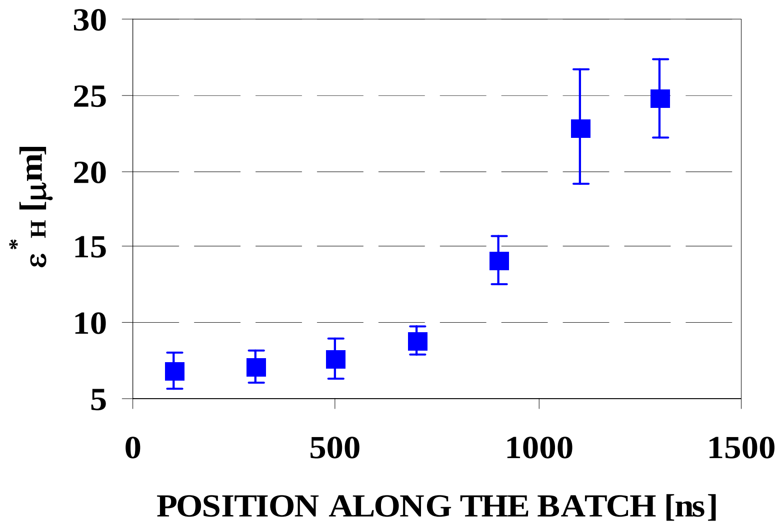
Above a given threshold (~ 0.2×10^{11} p) an electron cloud builds-up along the LHC bunch train in the SPS and couples subsequent bunches or the head and the tail of each bunch in the trailing edge of the batch

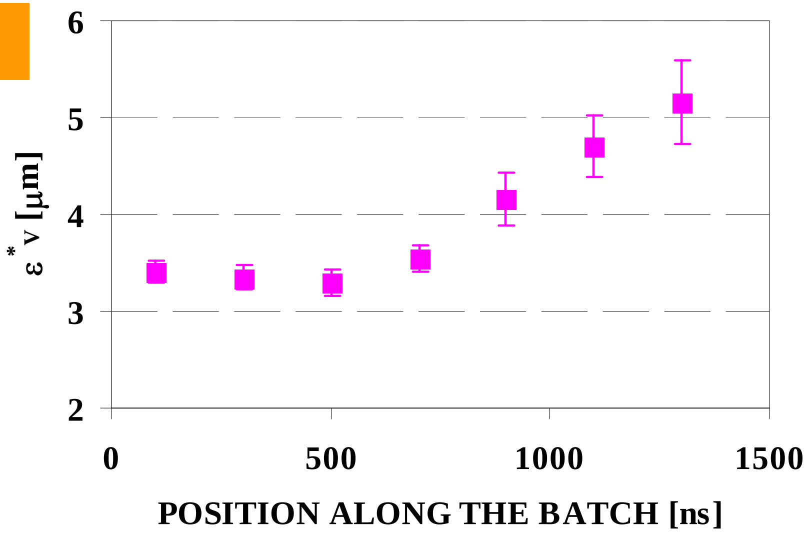
➔ instabilities

➔ blow-up of the tail of the batch.



SPS





Cures for the electron cloud effects exist:

- Larger bunch spacing (e.g. 75 ns) – ....but it costs luminosity

- Modification of the surface properties of the vacuum chamber (reduction of the Secondary Electron Yield) by electron bombardment induced by the beam ➔ Scrubbing

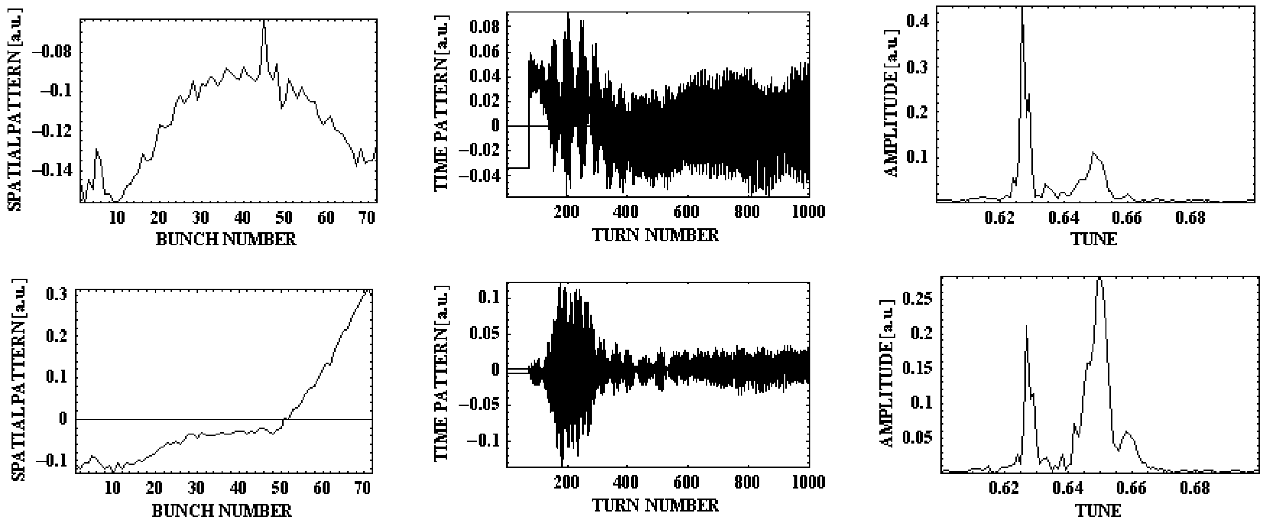
- A scrubbing run (~ 10 days) is routinely performed in the SPS at the beginning of the machine run: that increases the threshold for electron multipacting from $\sim 0.2\times10^{11}$ p to $\sim 0.8\times10^{11}$ p

- It significantly easies operation although it does not eliminate completely the phenomenon for the nominal bunch population, for that reason cures for the ECI have been developed.

Multi-bunch phenomena
Electron Cloud Instability

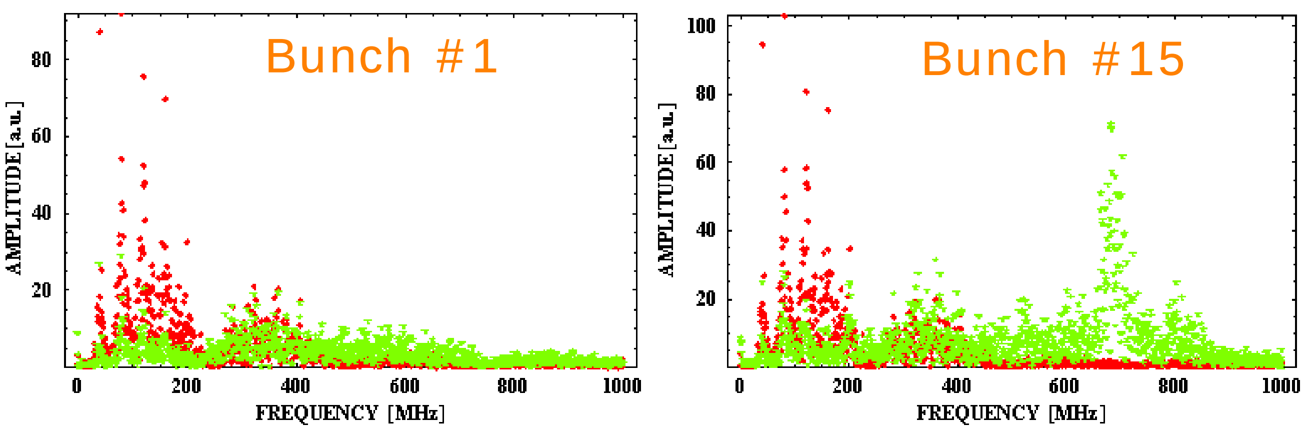
SPS

Horizontal plane



- Low order (~1-2 MHz) CB-mode
- Cures: Transverse feedback (bandwidth 0–20 MHz)

Vertical plane



- TMCI like instability (~700 MHz) affecting trailing bunches.
- Cures: (ξ_V > 0.5).

SPS

Impedance of the TWC 200 MHz system responsible for:

- Beam loading: 6 MV induced within 800 ns (~filling time)
- Coupled bunch dipolar instabilities (~ 2MHz) at low energy

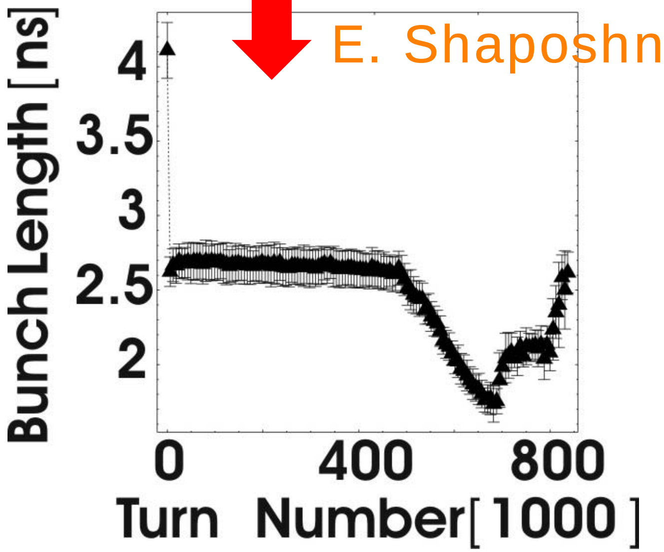
Impedance reduced by:

- Feedforward system
- 1-turn-delay feedback

Additional cures:

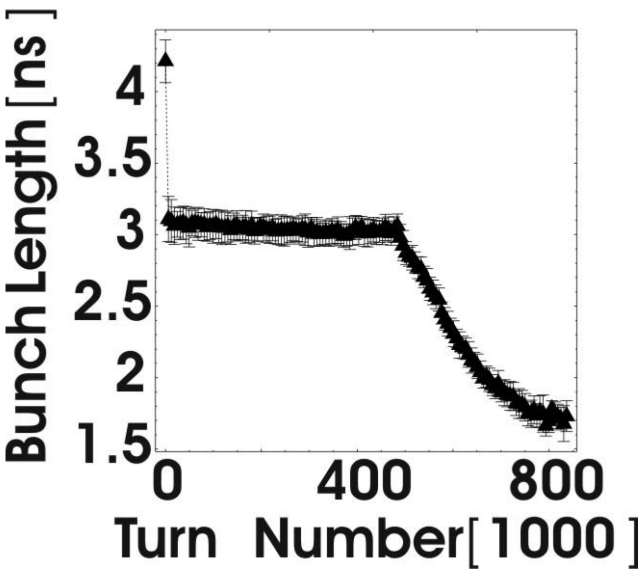
- New power couplers 1 MW-CW (instead of 700kW-CW) and with improved multipactoring control allowing low voltage w.o. counterphasing ➔ easier operation under beam loading
- Longitudinal damping system (for dipole modes up to 3 MHz) built around the TWC 200 MHz

CB-instabilities (at higher frequency) for p>280 GeV/c and at flat-top when the RF voltage is raised to match the LHC 400 MHz bucket. To-date source of the instability unknown.



E. Shaposhnikova

SPS



Cures:

- ΔQs by 4th harmonic RF system in bunch shortening mode
- Emittance blow-up by injection on mismatched bucket
- Controlled emittance blow-up [MOPLT033]

- The LHC beam presents several challenging aspects in all the injectors. Only a selection of the main issues, cures and of the dedicated work of several colleagues has been presented here.
- The beam experiments performed since the early 90's have provided the necessary input to upgrade the LHC injectors which have been built more than 20 years ago.
- Nominal longitudinal and transverse parameters have been achieved in the PSB and PS. Longitudinal emittances well below the target have been obtained in the SPS and the transverse emittance is close to the target for the nominal 25 ns LHC beam and below the nominal values for the 75 ns beam at the extraction energy.
- Efforts are now directed in further improving the performance (in particular transverse emittance and capture losses [WEPLT035-36]) and the reproducibility of the beam properties both on a bunch-by-bunch and a cycle-by-cycle basis.