PS beam dynamics issues in view of LHC beams upgrade: brief status and prospects

G. Rumolo (Beam Dynamics for the PSB/PS Upgrade Working Groups),
based on discussions with several colleagues

- Upgrade of the PSB injection and extraction energy:
  - ✦ Expected impact on space charge at PS injection
  - ✦ What parameter space was explored during the 2010 MDs with LHC-type beams (and not only)
- Can the PS digest LHC beams with increased brilliance?
  - ✦ **Space charge emittance growth and slow losses at the flat bottom** (not expected to become worse)
  - – **Head-tail instabilities** at the flat bottom with high chromaticity
  - – **TMCI close to transition crossing**.
  - – **Transient beam loading during splittings and longitudinal coupled bunch instabilities**
  - – **Electron cloud and transverse instabilities at flat top** (horizontal) when the full bunch length is below 11ns.

Space charge at the PS injection

- An increase of PSB extraction energy is beneficial, as it could allow for transfer of higher intensities to the PS (available with Linac4). Note that:
  - Injection at 2GeV **lowers** space charge effect by a factor $(\beta\gamma^2)_{2GeV}/(\beta\gamma^2)_{1.4GeV} \approx 1.63$. Seems we can inject beams ~65% more intense keeping the same space charge tune spread as now
  - If we assume to conserve the longitudinal emittance (e.g., 1.3 eVs, LHC beam h=1), the bunch at 2GeV will be 33% shorter at the exit of the PSB, which would in principle limit the above gain to less than 40%!! However, the **PS bucket acceptance** at injection also increases by 50%, which allows for injection of larger longitudinal emittances, recovering the desired gain (50% larger longitudinal emittance required)
  - Larger **transverse emittances** acceptable at the PS injection, if the final transverse emittances to the LHC are the same? Unlikely, as the previously PSB specified transverse emittances have meanwhile become the “nominal” LHC emittances!

$$\Delta Q_x = \frac{R_p N_b}{(2\pi)^{3/2}\gamma^3\beta^2\sigma_z} \oint \frac{\beta_x(s)\,ds}{\sigma_x(s)\left[\sigma_x(s)+\sigma_y(s)\right]}$$

$$\Delta Q_y = \frac{R_p N_b}{(2\pi)^{3/2}\gamma^3\beta^2\sigma_z\sqrt{\epsilon_y}} \oint \frac{\sqrt{\beta_y(s)}\,ds}{\sigma_x(s)+\sigma_y(s)}$$

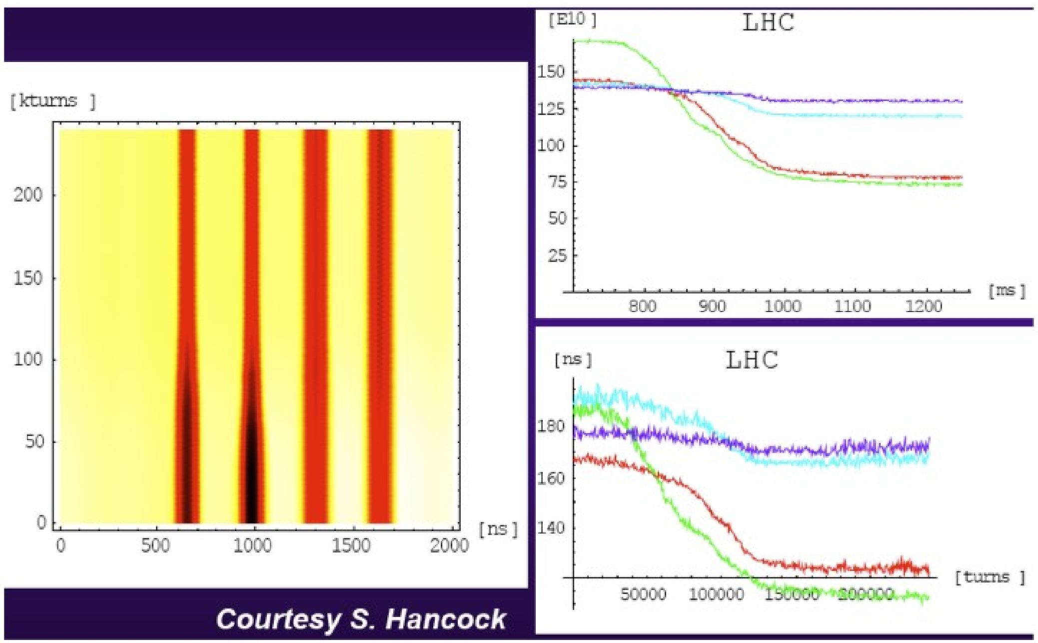
$$\begin{cases} \sigma_x(s) = \sqrt{\epsilon_x\beta_x(s) + D_x^2(s)\left(\frac{\delta p}{p_0}\right)^2} \\ \sigma_y(s) = \sqrt{\epsilon_y\beta_y(s)} \end{cases}$$

$$\epsilon_{x,y} = \frac{\epsilon_{xn,yn}}{\beta\gamma}$$

$1/\beta\gamma^2$ $1/\sigma_z$ $1/\varepsilon$

Space charge at the PS injection

- What we know experimentally from the past years
  - ✦ **Slow losses at the flat bottom** believed to be caused by space charge
  - ✦ The problem should not become worse if they are caused exclusively by space charge and if we conserve $N/(\sigma_z \varepsilon_n \beta\gamma^2)$
  - ✦ At flat bottom emittance growth can be driven by strong space charge:
    - ❼ 2010 measurements
    - ❼ It has been proposed to carry out simulations with self-consistent space charge model in collaboration with LARP to benchmark existing data and extrapolate to new scenarios



Courtesy S. Hancock

From E. Métral

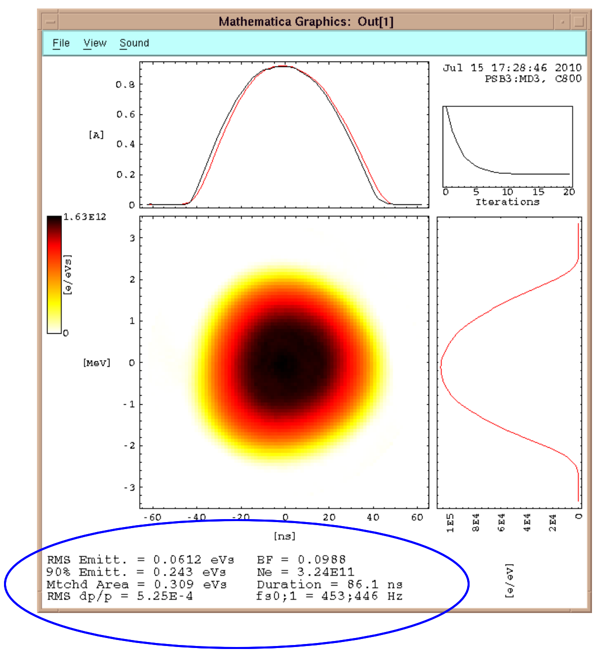
- Slow loss accompanied by bunch shortening seems to point to periodic resonance crossing induced by space charge
- In the MDs with LHC25 ultimate intensity, losses at flat bottom could be suppressed through working point correction

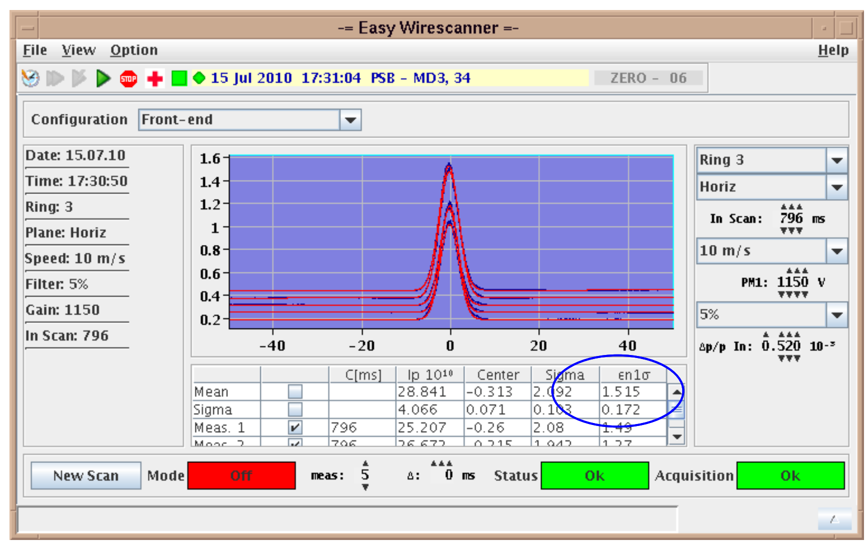
2010 MDs with LHC-type beams: space charge @PS injection and observations

- In 2010 several **LHC beam high intensity MDs** took place in order to check intensity limitations for LHC-type beams along the injector chain
  - Single bunch LHC-type beams
  - Multi-bunch LHC-type beams
    - ✓ Single batch transfer to the PS (50, 75, 150ns bunch spacing)
    - ✓ Double batch transfer to the PS (25ns bunch spacing)
  - Neither single bunch nor multi-bunch LHC-type beams with single batch transfer need the (longer than) 1.2s flat bottom in the PS, during which a strong space charge could play a detrimental role in terms of beam quality

Single bunch LHC-type beams (PSB)

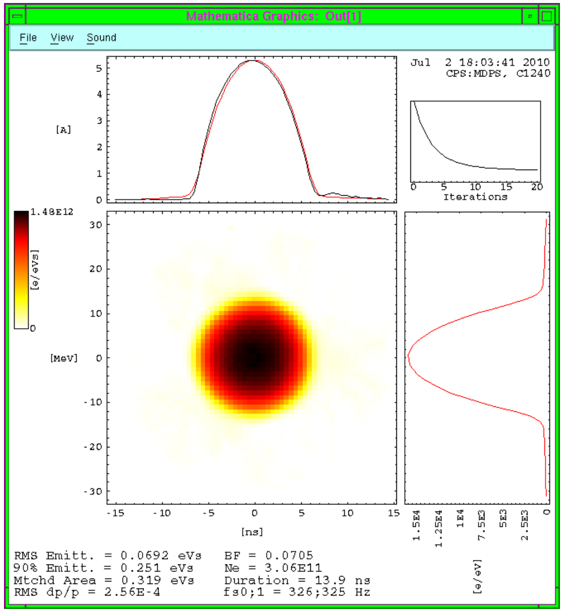
- The LHCINDIV beam, originally limited in intensity between 2e10 and 1.3e11 p, was produced in the PSB up to **3.5e11** p, preserving its longitudinal properties (i.e. ε_z=0.3eVs) and within transverse emittances of <1.5μm.
- The transverse emittances can be easily blown up to values around the nominal $\varepsilon_{x,y}$=3μm by mis-steered injection into the PS. This was requested during some SPS MD sessions with high intensity single bunch
- This variant of the LHCINDIV is presently an archived MD beam that can be loaded on request on any of the PSB MD users (e.g. MD3, MDPSB)

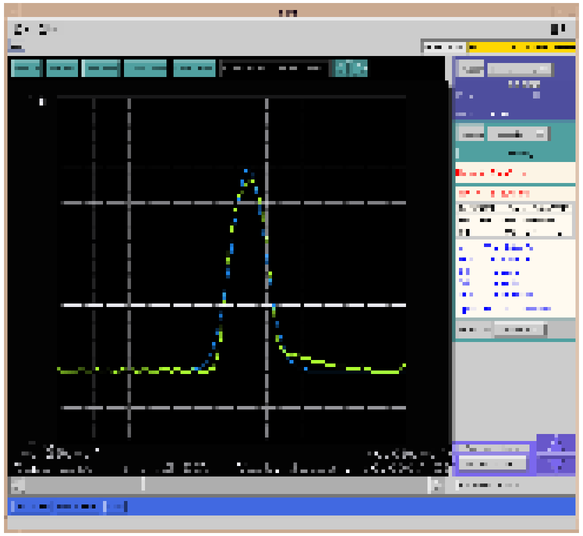




Single bunch LHC-type beams (PS)

- The high intensity LHCINDIV went to the PS, where it could be accelerated and rotated at flat top
- The resulting beam had the nominal longitudinal specs to be injected into the SPS (bl=4ns at extraction)
- Transversely no significant emittance blow up was observed along the cycle





Single bunch LHC-type beams in the PSB/PS General remarks

- The high intensity LHCINDIV is still a low intensity beam at the PSB and its production was not expected to cause major problems
- Space charge tune spread at the PS injection with N=3.5e11p and $\varepsilon_{x,y}$=1.5μm is

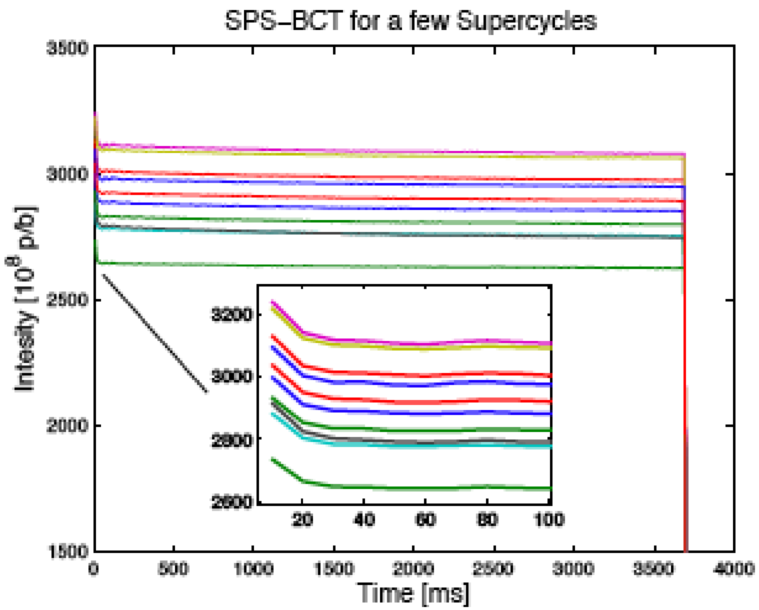
$$\Delta Q_y^{\mathrm{LHCINDIV}} \mathbf{@PSinj} = -0.2$$

and therefore this beam is comparable in brilliance to other beams

- The main interest for this beam lies in the SPS (and perhaps one day in the LHC, too?) to study single bunch intensity limits for LHC beams (wide range tune shift measurements, instability thresholds in both the longitudinal and the transverse plane, impedance localization studies, etc.)

Single bunch LHC-type beams (SPS)

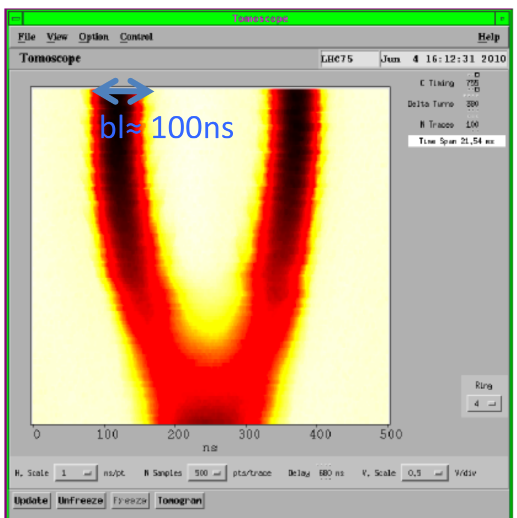
- The high intensity LHCINDIV was injected into the SPS several times to test single bunch limitations with nominal and low γ_t optics.
- Measurements
  - With nominal optics on MD (4s injection plateau) or LHCFAST cycle:
    - A longitudinal high order instability is observed to develop above a threshold of about 1.9e11 p
    - A transverse instability (TMCI) at injection causes a sharp loss if we inject with 0 chromaticity and currents above 1.7e11. Vertical chromaticity of 0.3 permits stable injection of bunches up to ~3e11 (with losses on the flat bottom)
    - Significant emittance growth observed on the 4s flat bottom for intensities above 2e11 p
  - With low γ_t optics on MD (4s injection plateau) or LHCFAST cycle:
    - TMCI threshold above 3e11
    - No significant emittance growth over the 4s long flat bottom, even for the highest intensities
    - More longitudinal studies needed

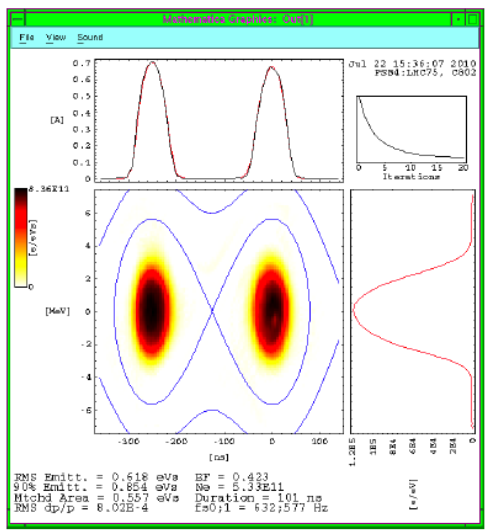


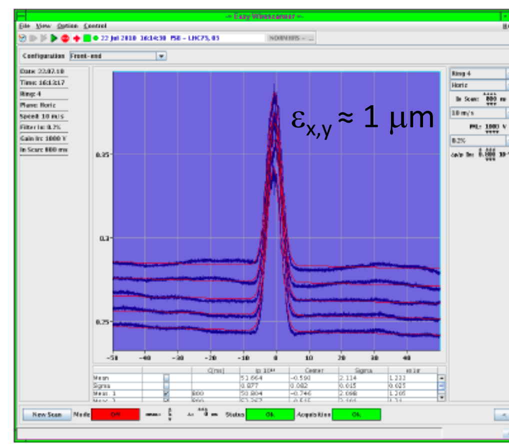
H. Bartosik *et al.*, SPSU-ST Meeting

Multi-bunch LHC-type beams
The 150ns beam

- The 150ns beam was produced for the first time this year under request of LHC. It is presently under the LHCPILOT user both in the PSB and PS (planned changed of username to LHC150).
  - Successfully produced within longitudinal specs (and lower trensverse emittances) at the PSB and transferred in single batch to the PS and stably to the SPS (with nominal longitudinal emittance)
  - This beam has been taken for LHC physics fills until the end of the proton run (obviously excluding the 5-day long 50ns tests prior to the switch to ions and the 3-day return to protons during the ion oven refill)

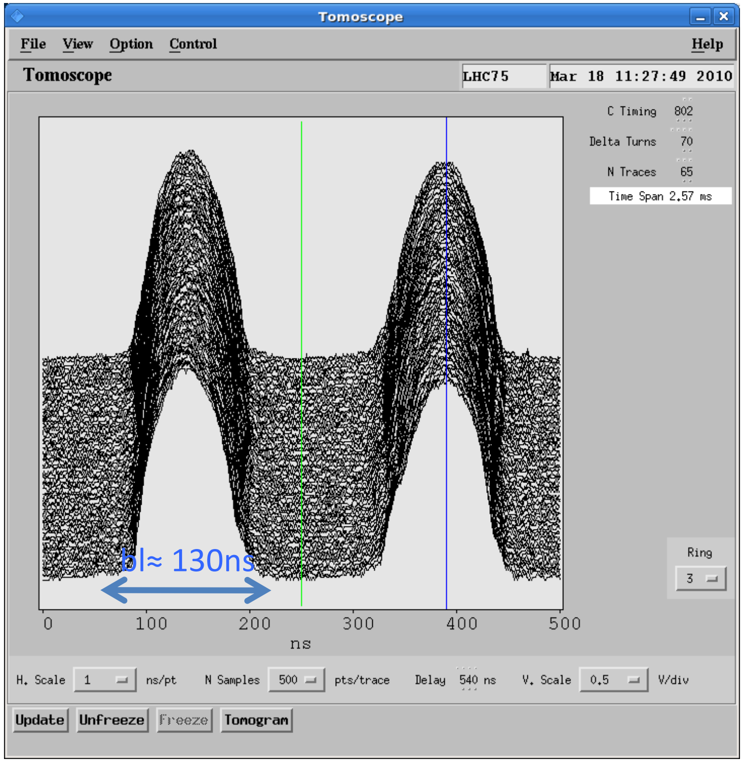


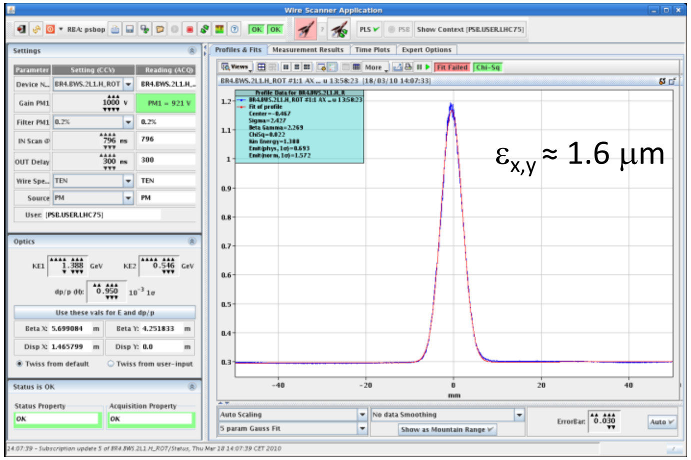




Multi-bunch LHC-type beams
The 75ns beam

- The 75ns beam was first checked at the beginning of the 2010 run, but it was never taken by the SPS during the MDs
- Later on, it was resumed for LHC electron cloud tests. It was used in the range of intensities from 9e10 to 1.3e11 ppb (@SPS → LHC)





Multi-bunch LHC-type beams
The 150 and 75ns beams

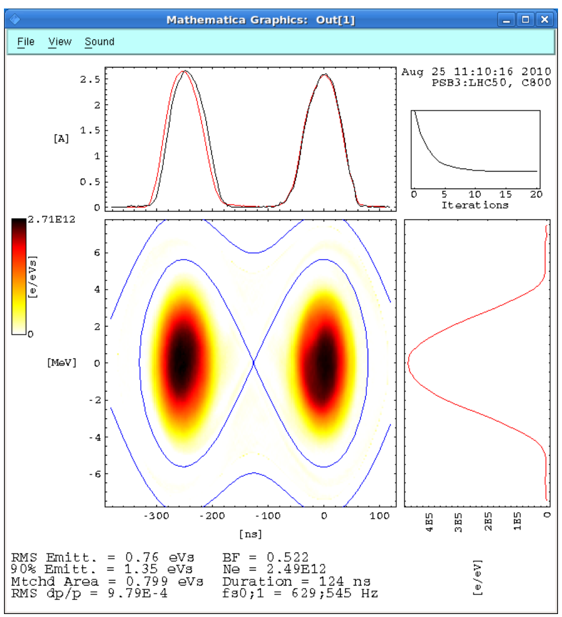
- Both the 150ns and the 75ns beams have a relatively small space charge tune spread at injection into the PS
- Even if there is a factor 2 in the intensity between these two types of beams, the tune spread scales by a lower factor due to the different transverse emittances and bunch length (see previous slides)

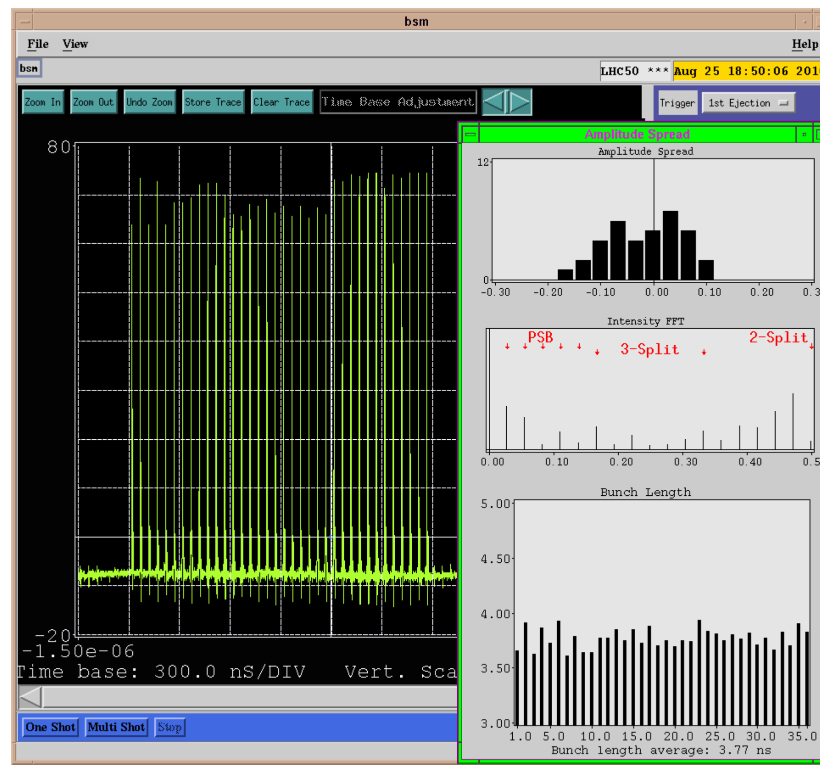
$$\Delta Q_y^{\mathrm{LHC150}}@\mathrm{PSinj} = -0.16$$

$$\Delta Q_y^{\mathrm{LHC75}}@\mathrm{PSinj} = -0.171$$

Multi-bunch LHC-type beams
The 50ns beam

- The 50ns is available within specs in single batch transfer to the PS (bl=130ns, $\varepsilon_{x,y}$=2.5μm)
- This year its intensity has been pushed from the nominal 1.6e12 per ring to the “ultimate” **2.4e12** per ring within transverse emittances of ~3.5μm.
- The ultimate was taken and accelerated in the PS, resulting in a train of bunches with **1.9e11** ppb at the PS exit





A. Findlay & H. Damerau

Multi-bunch LHC-type beams
The 50ns beam

- This gives the limit of what can be produced in terms of LHC50 beam “within specs” with the present injectors
- It is very useful for SPS studies (electron cloud, high single bunch intensity in multi-bunch mode), it was used on one MD session. It may be interesting for LHC, too, to combine physics with efficient scrubbing against the electron cloud (larger emittances are more stable, higher current gives high luminosity)
- Not too challenging for space charge at the PS injection
- The LHC50 double batch hasn’t been produced in the last two years in the PSB. With lower transverse emittances (~1.2μm per plane), but longer bunch length, it has the same space charge at PS injection as the single batch variant.

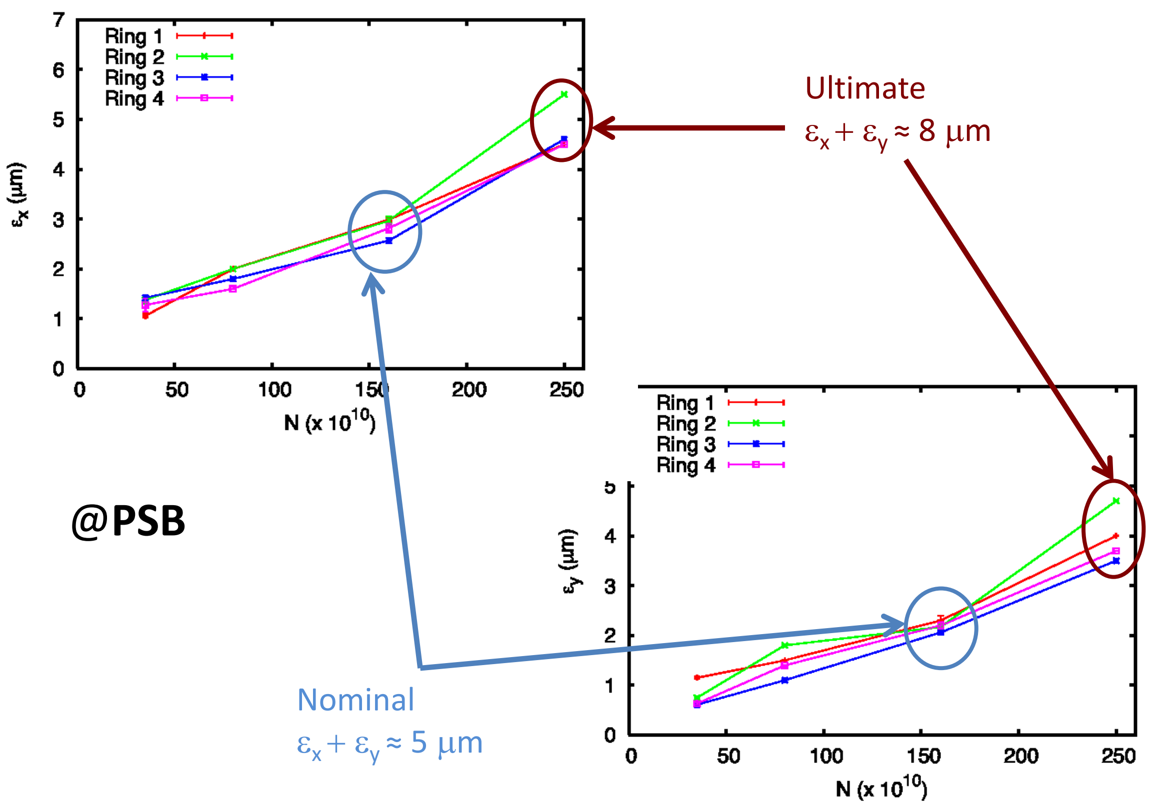
$$\Delta Q_y^{\mathrm{LHC50}} \mathrm{@PSinj} = -0.175$$

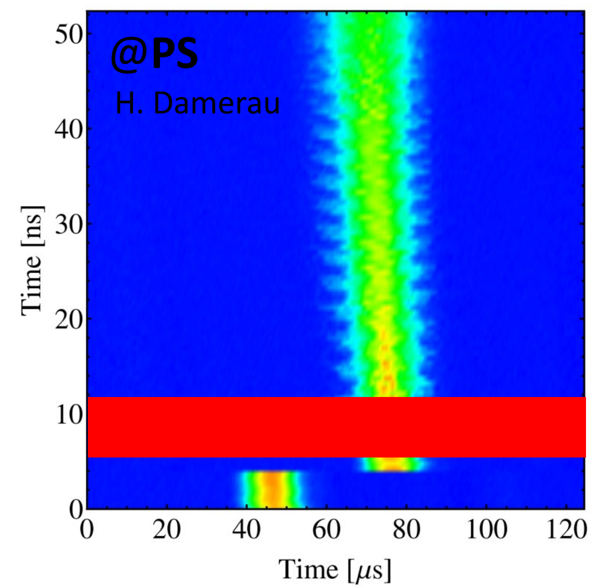
$$\Delta Q_y^{\mathrm{LHC50ult}} \mathrm{@PSinj} = -0.21$$

$$\Delta Q_y^{\mathrm{LHC50db}} \mathrm{@PSinj} = -0.185$$

Multi-bunch LHC-type beams
The 25ns beam

- This is presently the only beam still transferred in double batch to the PS (with 4+2 rings from the PSB, each one with one bunch 1.6e12 p, bl=180ns, $\varepsilon_{x,y}$=2.5μm)
- A sort of ultimate version (~**2.5e12 p**) has been produced at the PSB within longitudinal specs and relaxed transverse emittances $\varepsilon_{x,y}\approx$4μm
- This ultimate variant went successfully through the PS, up to 3 batches were injected into the SPS (but even one batch alone exhibits significant losses –needs optimization)





With additional blow-up after transition
Ultimate not perfectly stable, but acceptable

Multi-bunch LHC-type beams
The 25ns beam

- While this "ultimate" beam has proved very useful in the PS and SPS to study longitudinal instabilities and intensity effects expected not to be dependent on the transverse emittances (e.g. e-cloud, TMCI in multi-bunch), the space charge limit at the PS injection has not been pushed much further....

$$\Delta Q_y^{\mathrm{LHC25}} @\mathrm{PSinj} = -0.208$$

$$\Delta Q_y^{\mathrm{LHC25ult}} @\mathrm{PSinj} = -0.213$$

Beams with strong space charge effect at the PS injection

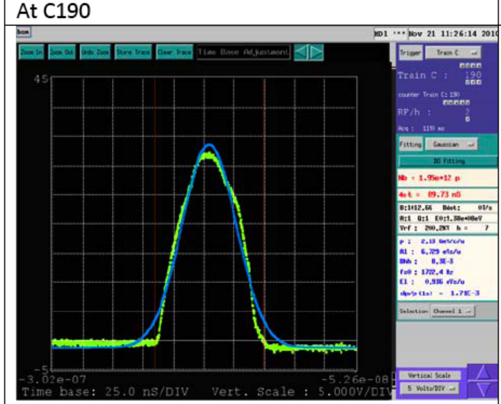
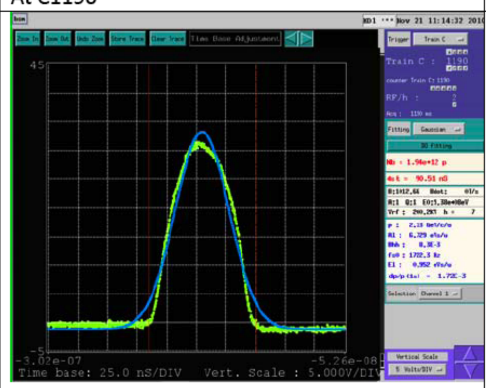
- From normal operation, the TOF beam is the one that is injected into the PS with the largest tune spread (N=800e10 p). It has, however, a 1bp cycle in the PS and sits on a very short flat bottom before being accelerated. For its high intensity, the TOF beam is also interesting for instability at transition (see following slides)
- From 2010 MDs, on June 24th there was a first joint PSB/PS MD (S. Hancock, A. Findlay, *et al*) on the LHC25 single-batch intensity limit at PS injection
  - The beam was produced in the PSB from the LHC50. The ~1.6e12 p accelerated on h=1 are re-bucketed in one of the two available buckets of h=2, instead of being equally split between the two. This gave more than 1.6E12 p longitudinally confined in 135ns and 0.9 eVs, and transversely in $\varepsilon_{x,y} \approx 2.5\mu m$
  - This beam was injected into the PS on a 3bp cycle and a transverse emittance increase of only 10% was observed at the end of the flat bottom, with no discernible blow up in the longitudinal plane

$$\Delta Q_y^{\mathrm{TOF}} @\mathrm{PSinj} = -0.31$$

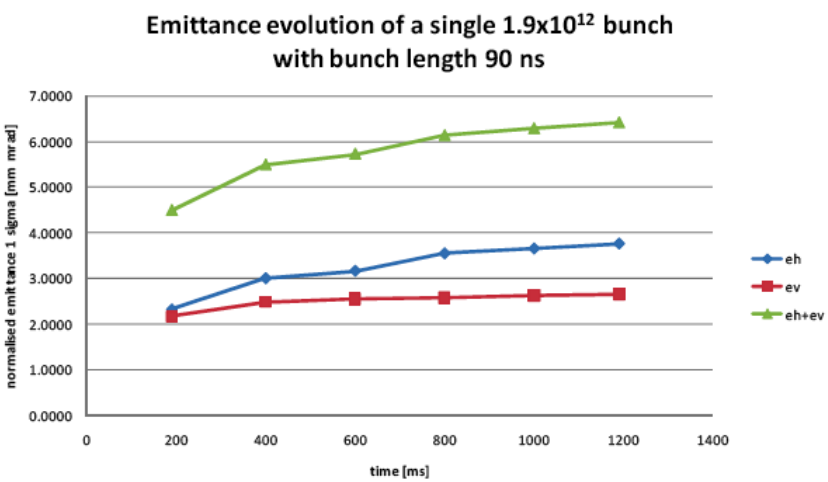
$$\Delta Q_y^{\mathrm{MDLHC25}} @\mathrm{PSinj} = -0.338$$

Beams with strong space charge effect at the PS injection (II)

- On Sunday Nov 21st there was an MD at the SPS to measure the emittance growth at flat bottom in extreme conditions of space charge (S. Gilardoni, R. Steerenberg, H. Damerau, S. Hancock)
- The same beam type as on June 24th was used from the PSB, i.e. LHC50 rebucketed from h=1 to h=2 instead of split before extraction, but with higher intensity
- This beam was also compressed adiabatically after injection into the PS (from 130ns to 95ns) in order to further increase the space charge effect
- An increase of total emittance ($\varepsilon_x + \varepsilon_y$) by ~40% is observed over 1s, scan of working point needed

At C190	At C1190
	
Bunch length = 90 ns dp/p = 1.7	Bunch length = 90 ns dp/p = 1.7

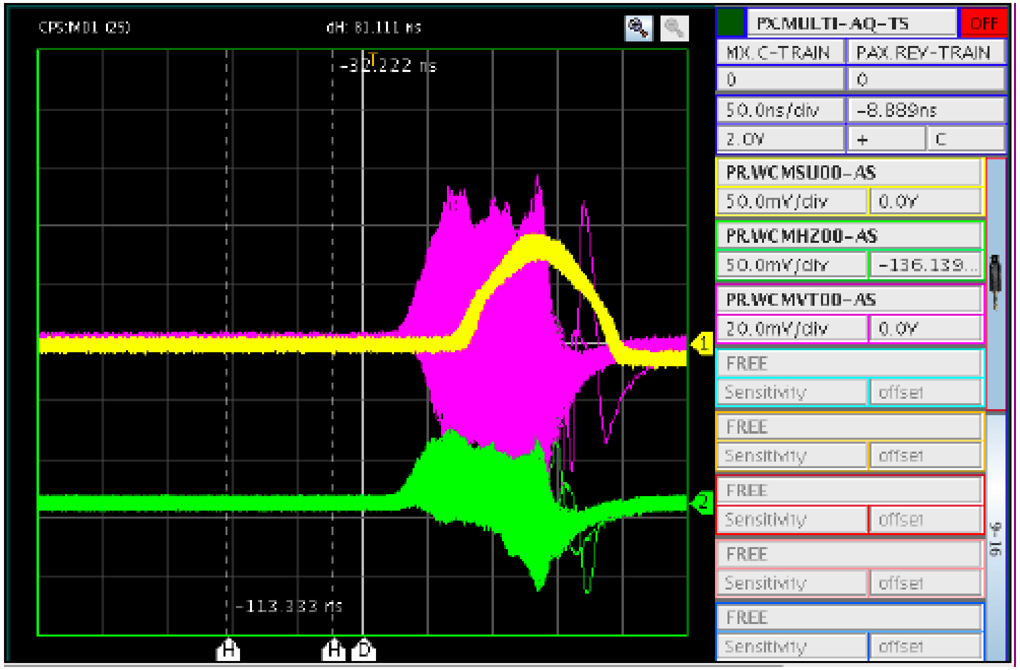
$$\begin{cases} \Delta Q_x^{\mathrm{LHC25MD}}@\mathrm{PS\_FT} = -0.34 \\ \Delta Q_y^{\mathrm{LHC25MD}}@\mathrm{PS\_FT} = -0.56 \end{cases}$$



R. Steerenberg et al.

Beams with strong space charge effect at the PS injection (III)

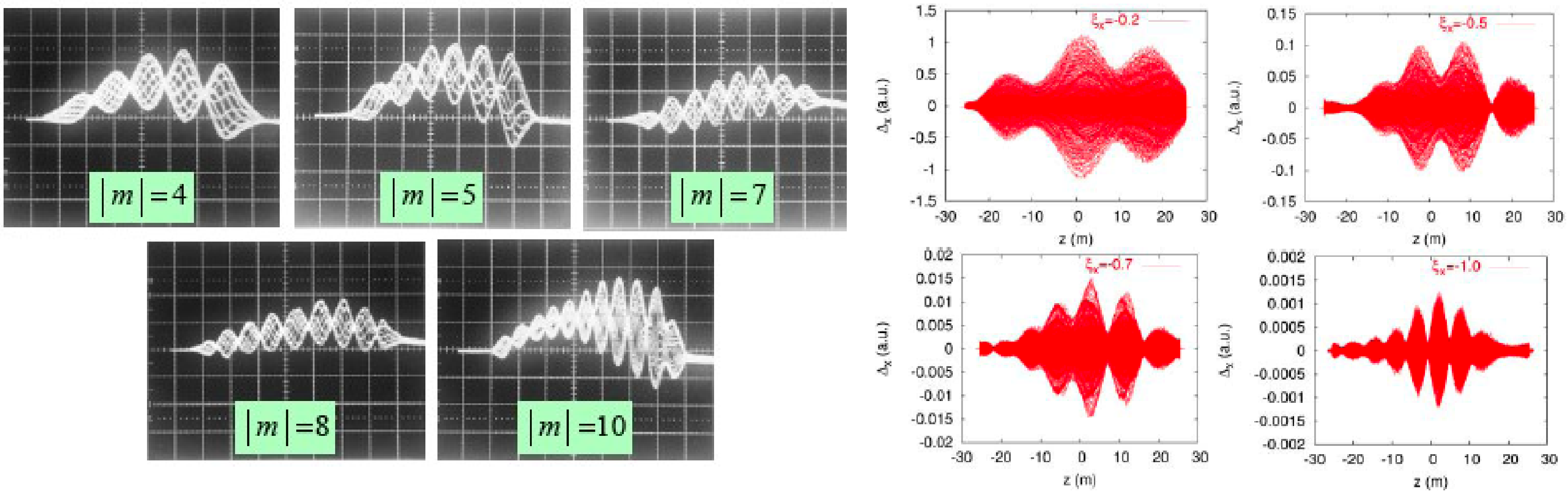
- Another interesting observation from the space charge MD of Nov 21st → During the very first part of the flat bottom a head-tail instability was observed, which however did not cause important transverse blow up and damped quickly (details remain to be investigated).



R. Steerenberg et al.

Head-tail instabilities at the flat bottom

- **Growth rate of head-tail instabilities** at the flat bottom scales like N/γ, which translates into 50% faster instabilities if we inject into the PS twice the intensity at 2 GeV
- So far cured with octupoles (not any longer), linear coupling and working point adjustment, but appeared in high brilliance conditions (see previous slide)
- In future need for skew quadrupoles working at 2 GeV and/or transverse feedback

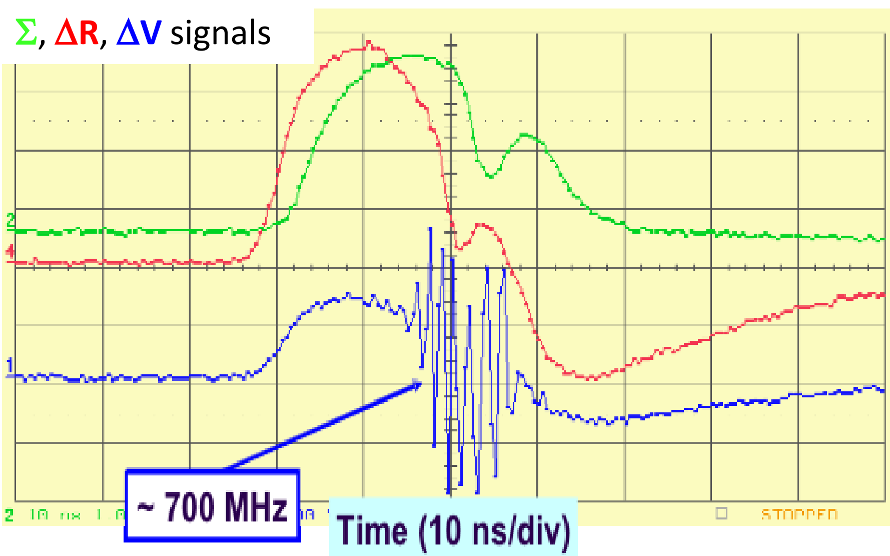


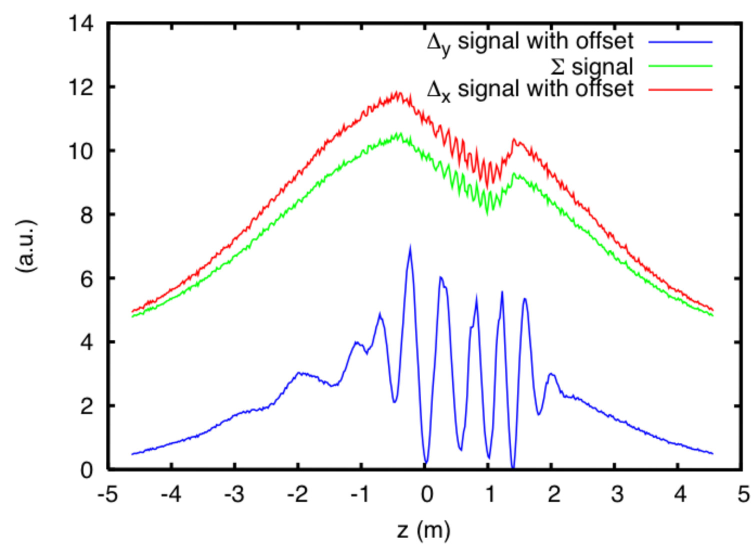
Measurement (left) and simulations (right) of head-tail modes becoming unstable for different chromaticity values

From E. Métral, GR, B. Salvant & R. Steerenberg
"Simulation study of the horizontal head-tail instability observed at injection in the CERN -PS", PAC 2007

Fast instability close to transition crossing

- **Vertical TMCI close to transition crossing** has been observed in the PS on TOF beams (S. Aumon Ph.D. thesis)
- What we presently know:
  - Intensity threshold of ~9 x 10^{11} ppb within ε_z=1.8 eVs without the γ-jump
  - Intensity threshold of ~7 x 10^{12} ppb within ε_z=2.1 eVs with γ-jump
- Assuming a scaling law of the threshold like ε_z, the value 0.7 eVs after the triple splitting is expected to be stable with up to ~2 x 10^{12} ppb. Therefore, twice the nominal intensity (~1.1 x 10^{12} ppb after the triple splitting) should be stable within about a factor 2.
- However, we should be careful applying scaling laws close to transition… Simulations with the LHC beam parameters to be done!

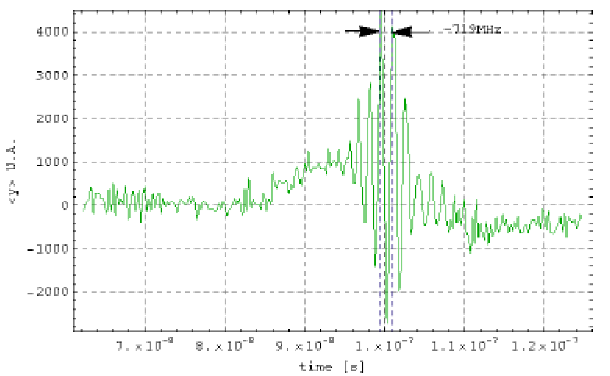


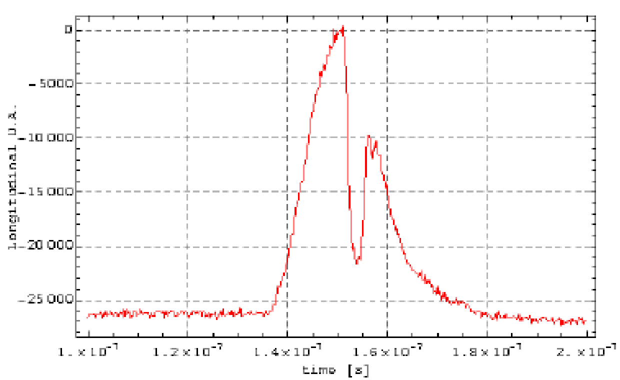


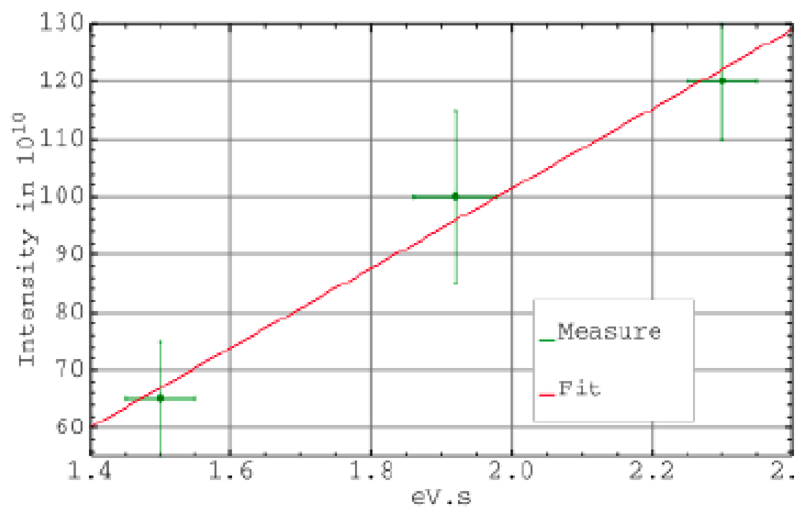
From GR & E. Métral "Recent developments of HEADTAIL" ICAP 2006

Fast instability close to transition crossing (II)

- 2009/2010 measurement by S. Aumon:
  - Dependence of the threshold on longitudinal emittance has been studied (w and w/o γ-jump)
  - Different chromaticity trims
  - Contrary to previous measurements, it seems now that the instability sets in after transition crossing (to be understood)
  - Simulations on the accelerating ramp have validated once more the existing broad-band impedance model of the PS, and only show the instability after transition if the vertical chromaticity is trimmed from significantly negative to about 0 upon transition crossing



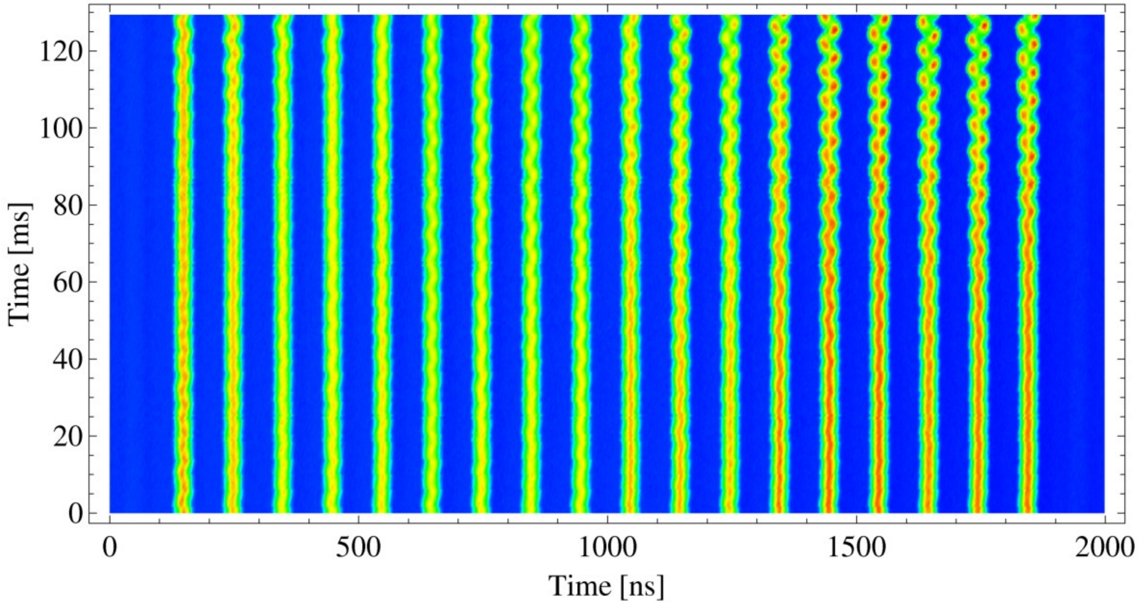




S. Aumon MSWG Meeting

Longitudinal coupled bunch instabilities

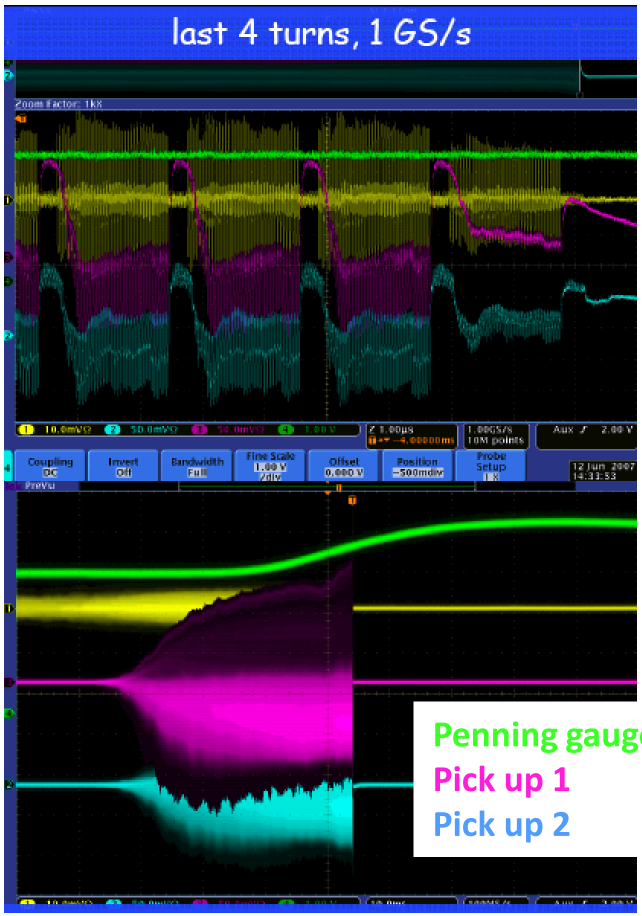
- **Longitudinal coupled bunch instabilities**: presently, the nominal LHC25 is at the limit of stability both along the ramp and at flat top before the double splitting
- Methods of stabilization under consideration:
  - Broad-band cavity to act as a longitudinal feedback system. Requires more feasibility studies to prove that it would not introduce more problems of beamloading and longitudinal impedance
  - Much more details to come in Heiko's presentation….

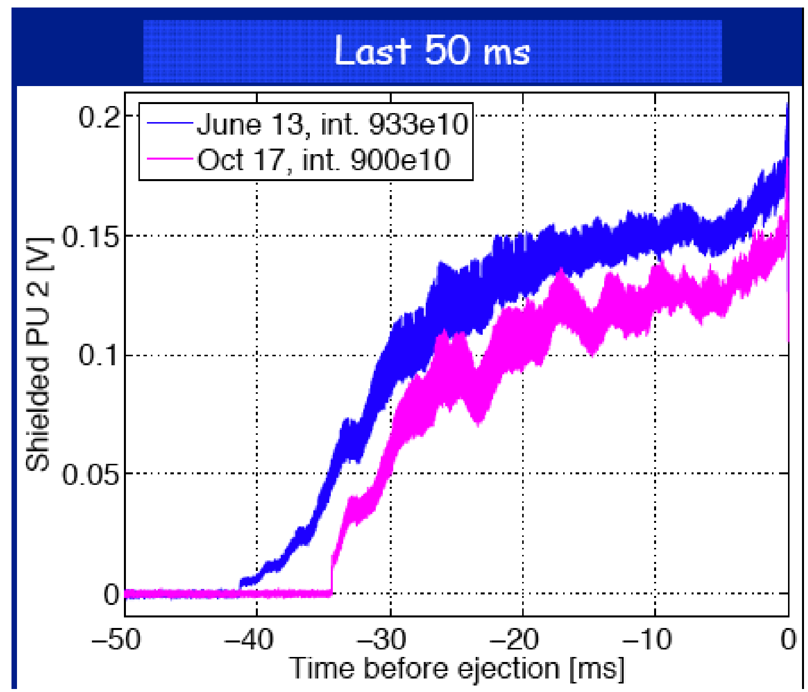


From H. Damerau, MSWG 27/03/2009

Electron cloud during the production of multi bunch LHC beams

- Following 2001 observations in the PS after bunch rotation and in TT2, dedicated electron cloud measurements were set up and conducted in the PS (F. Caspers, T. Kroyer, E. Mahner) with a Penning gauge and shielded pick-ups
- An electron cloud signal is observed after the second double splitting, with little conditioning effect over 1 year run





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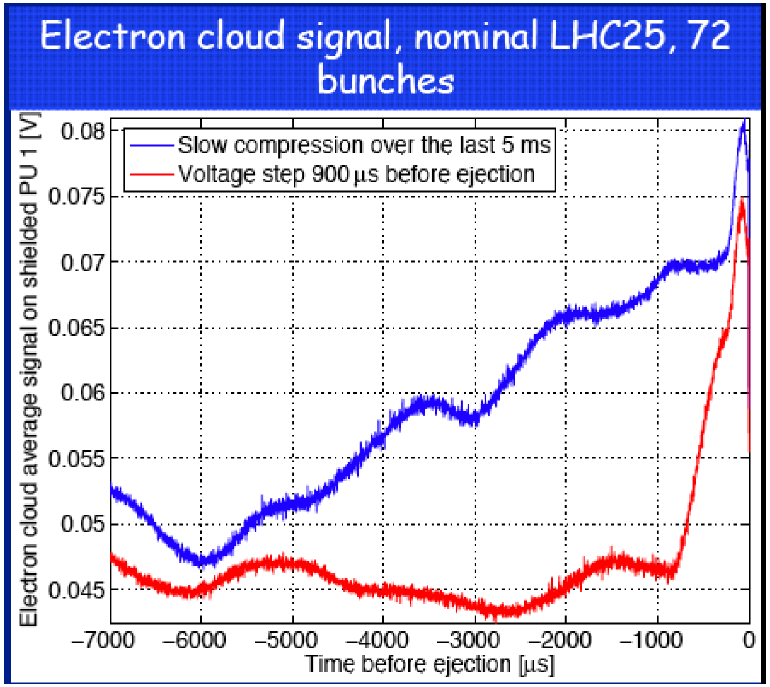
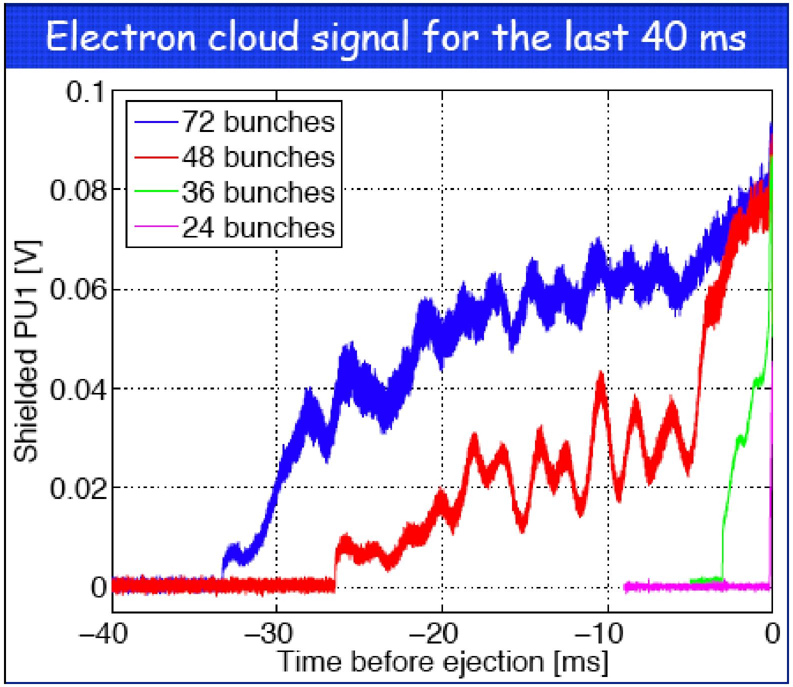
Electron cloud during the production of multi bunch LHC beams (II)

- However, the electron cloud signal steps up during the adiabatic bunch compression (last 5ms before extraction) and even more during the fast bunch rotation (900μs before extraction)
- It also depends on the number of bunches: with nominal intensity, the cloud gives high signal after triple splitting with trains of 48 or 72 bunches, but it only appears during adiabatic compression with 36 bunches and during the fast rotation with 24 bunches.





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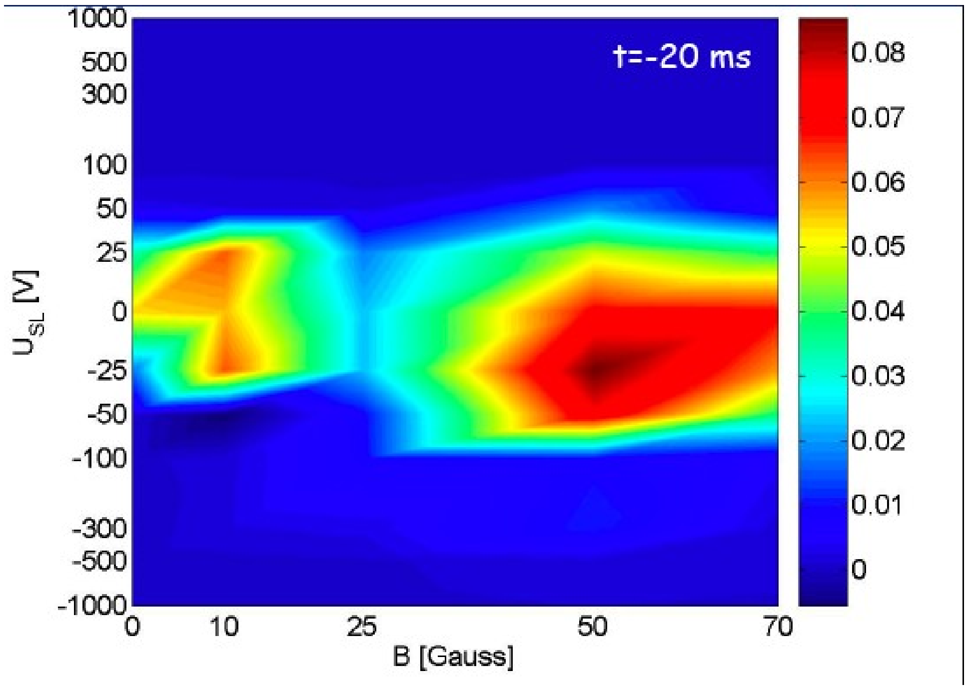
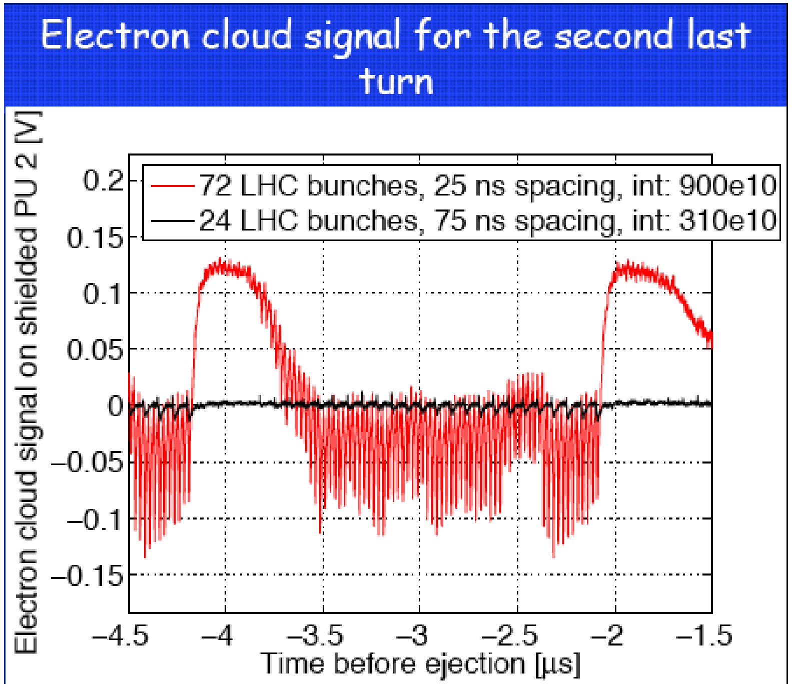
Electron cloud during the production of multi bunch LHC beams (III)

- The dependence of the electron cloud build up on the external magnetic field and the voltage applied to the stripline PU was also studied
  - The electron cloud is stronger in presence of B
  - The electron cloud is suppressed by the voltage (clearing electrode)
- Electron cloud for different bunch spacings (25 and 75ns) was also studied

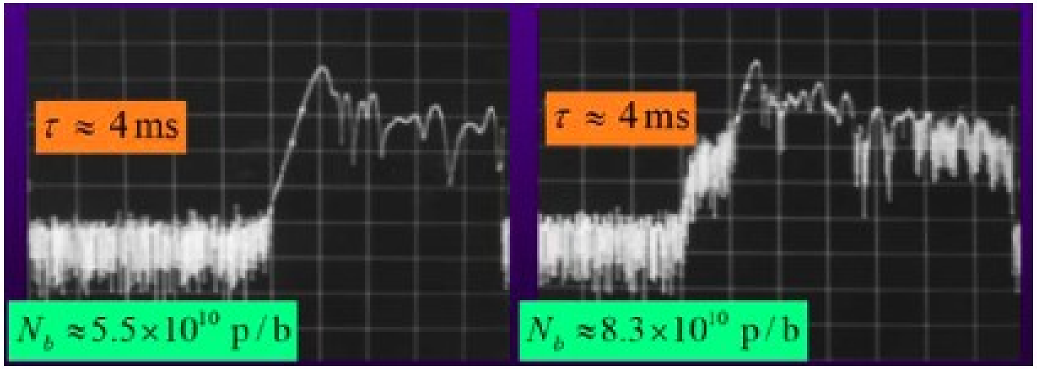




T. Kroyer et al., APC Meeting

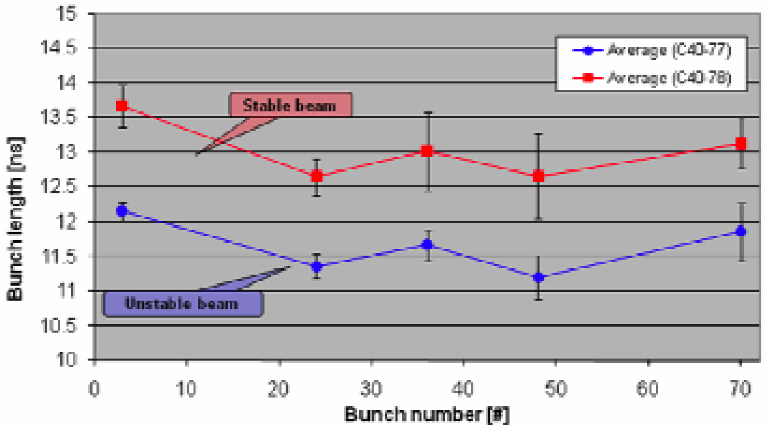
Transverse instabilities at flat top

- **Transverse instabilities at flat top** observed in 2001, 2004 and again 2006.
- Appears in the horizontal plane with rise times of the order of few ms
  - ✓ Probably related to **electron cloud** (but this would not explain why it is mainly horizontal and why it is not cured by chromaticity)
  - ✓ Coupled bunch or single bunch?
  - ✓ Full bunch length must be below 11ns with the present intensities
  - ✓ Threshold of 4.5 x 10^{10} ppb for a bunch length of 10ns.



2001 measurements with 10ns bunches:
In 2001 LHC bunches are rotated before extraction from 16 to 4ns. The instability was observed on a special cycle in which the bunches were just shortened to 10ns and kept for about 100ms inside the machine

2004-2006 instabilities:
Bunches are adiabatically shortened to 12.5ns before rotation. The instability was observed when the bunches were accidentally made too short!



From R. Cappi, M. Giovannozzi, E. Métral, GR, R. Steerenberg, et al., in ECLOUD'02, APC Meetings, …

Conclusions

- With the upgrade of the injection and extraction energy of the PSB, in principle the PS will be able to receive intensities about twice the present intensities, as the space charge tune shift will stay the same
- Points to be investigated:
  - Space charge emittance growth and slow losses
    - Previous and 2010 MDs seem to show that this is no obvious bottleneck with a good choice of working point and if the 1.2s long front porch can be avoided
  - Head-tail instabilities at injection
    - Already present with most of the PS beams at injection, although not always detrimental
    - Rise time scales unfavorably and they become worse at 2 GeV with double intensity
  - TMCI at transition
    - Seems safe with naïve ε_z scaling (also experimentally confirmed)
    - Simulations needed
  - Longitudinal issues (transient beam loading and coupled bunch instabilities)
    - See Heiko's talk
  - Electron cloud at flat top with LHC25 beams
    - It will probably become worse with higher intensities (though not trivial scaling)
    - What about the 50ns beams?
    - How far can it affect the beam?
  - Instabilities at flat top
    - Need to be studied in detail
    - They will certainly become worse with higher intensity and maybe smaller emittances
- Several studies have been already undertaken and can be continued with the tools presently available
  - High intensity beams through the PSB/PS
  - Simulation codes (HEADTAIL, LARP collaboration for space charge)

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