Lessons from SPS studies in 2010

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Chamonix'11

session 09: LHC injectors upgrade

Outline

- Review of the SPS MD studies in 2010
- Expectations for possible SPS upgrades

Acknowledgments:

SPSU SG: G. Arduini, J. Bauche, C. Bhat, F. Caspers, S. Calatroni, P. Chiggiato, K. Cornelis, S. Federmann, E. Mahner, E. Metral, G. Rumolo, B. Salvant, M. Taborelli, C. Yin Vallgren, F. Zimmermann + H. Neupert, H. Bartosik, Y. Pappaphilipou

BE/RF: T. Argyropoulos, T. Bohl, E. Ciapala, H. Damerau, W. Hofle, E. Montesinos, G. Papotti (OP), J. Tuckmantel, U. Wehrle, G. Hagmann, J. F. E. Muller

LIU/TF: R. Garoby, B. Goddard, V. Mertens

EN/BT: M. Barnes, B. Balhan, R. Barlow, J. Borburgh

PS&PSB teams and OP shifts for help in MDs

Questions

1. Source of limitations/bottlenecks (up to ultimate intensity)

2. Possible cures and mitigation measures

3. p/b and emittance as a function of the distance between bunches today and after upgrade
   (extracted emittance depends on intensity, injected emittance, distance between bunches, number of batches and machine settings…)
4. What should be done for delivering smaller transverse emittances at ultimate beam current?

Known intensity limitations and 2010 studies

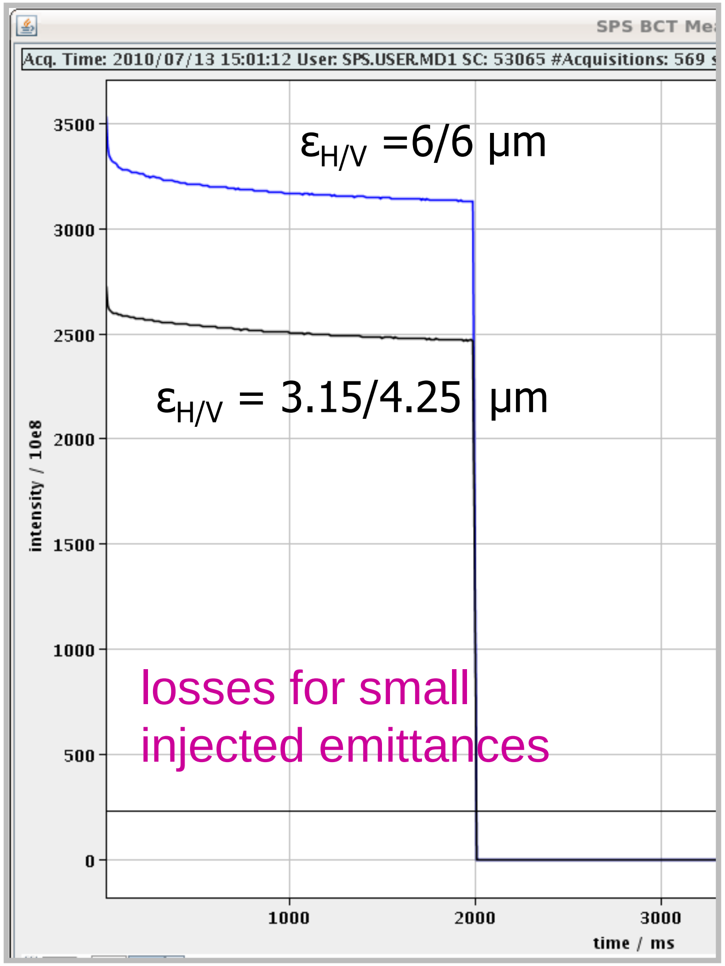
- Single bunch
  - TMCI (transverse mode coupling instability)
  - loss of Landau damping
  - space charge
  - longitudinal instability

➢ High (twice ultimate) intensities, nominal and small transverse emittances, γ_t=22.8 (nominal) and γ_t=18 (“low”) optics

- Multi-bunch
  - e-cloud → talk of J.M. Jimenez
  - beam loss (many reasons)
  - longitudinal coupled bunch instabilities
  - beam loading in the 200 MHz and 800 MHz RF systems
  - heating and outgassing of machine elements, septum (ZS) sparking

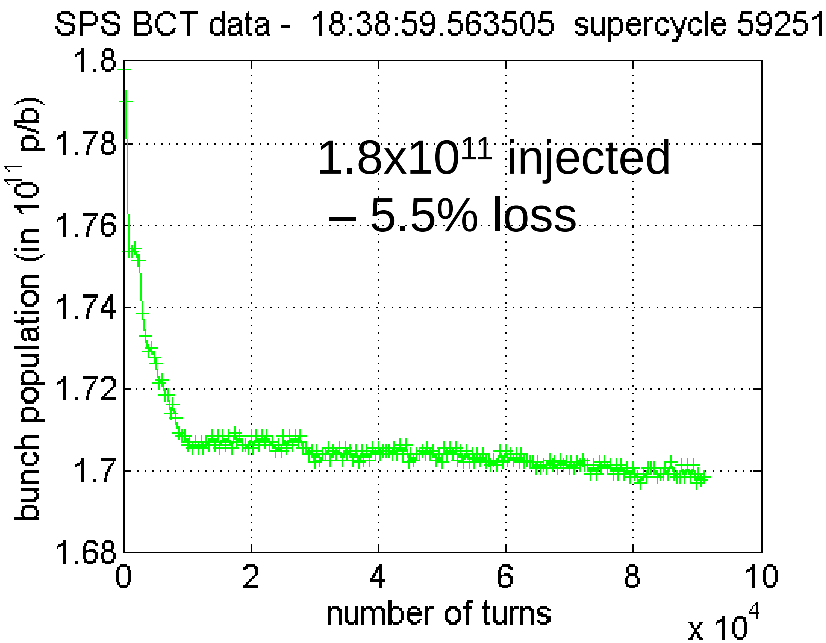
➢ Nominal 25, 50, 75, (150) ns spaced LHC beam,
Ultimate (injected) 25&50 ns spaced beam

Very high intensity single bunch



- Many parallel MD sessions (B. Salvant et al.) → TMCI
- Injected bunch:
  - intensity up to 3.5×10^{11}
  - $\varepsilon_{H/V}$ ~1.3 µm, then 2.5/2.6 µm (to reduce losses and emittance blow-up in SPS)
  - ε_L =0.35 eVs, τ=3.8 ns (nominal LHC)
- Long. instability N > 1.4×10^{11}
- Issue with MOPOS before BI upgrade at the end of run

Transverse Mode Coupling Instability (TMCI)



B. Salvant et al.

→Threshold ~ 1.6x10[11] for $\xi_V = 0$

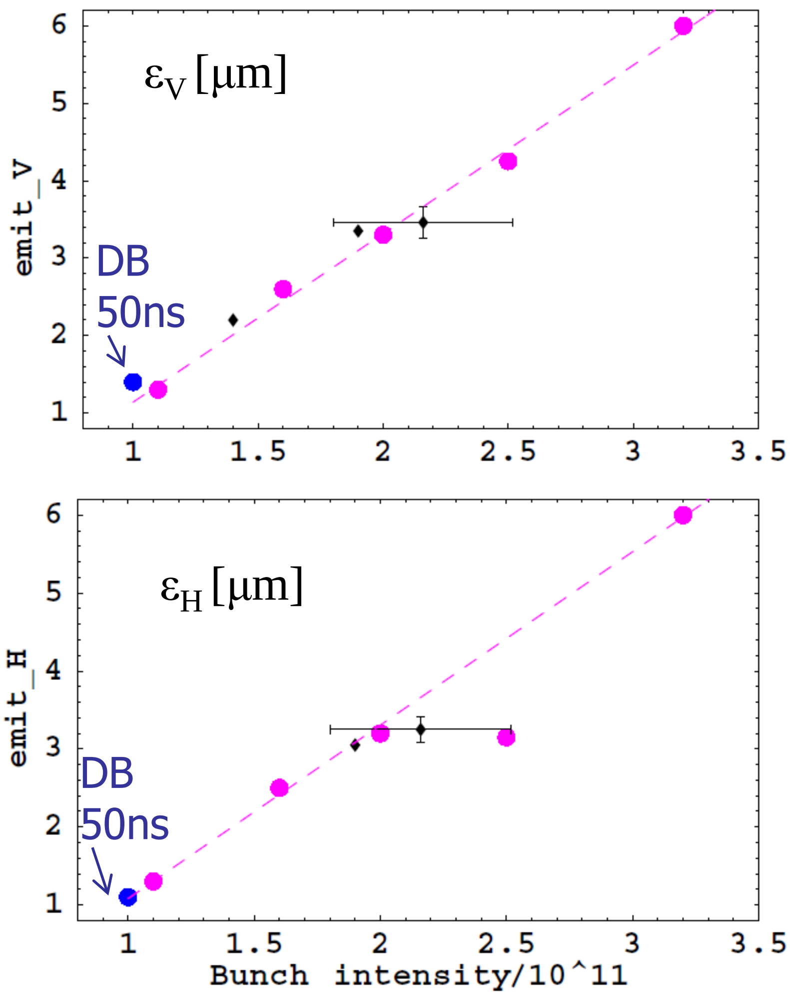
- TMCI threshold ~ $\varepsilon_L\ |\eta|$,
  $\eta = 1/\gamma^2 - 1/\gamma_t^2$
- Cures:
  - higher chromaticity ξ_V
  - higher η (lower γ_t)
  - larger ε_L (capture losses)
  - impedance reduction (if known)
  - wide-band FB (W. Hofle&LARP)

- Intensity (2.25-3.3)x10[11] (end FB) for ξ_V =(0.0-0.3), ξ_H=0.25

Transverse emittance measurements in the SPS

- Measurements during the cycle and along batch(es) are essential to study origin of emittance blow-up (if any)
- Measurements with Wire Scanners (WS) in 2010:
  - Average for all bunches (no bunch-by bunch)
  - One measurement per cycle (difference between “in” & “out”)
  - First measurement at 10 ms after injection
- BI improvements for 2011 (L. Jensen):
  - new electronics for 2^{nd} WS (linear, now broken) with possibility to gate acquisition (over 50-100 ns, as in the past)
  - cross-calibrations (WS 1&2, “in”&“out”, PS&LHC)
  - expert involvement (settings are critical) plus fellow(?)
  - BGI (rest gas) monitor – continuous beam profile measurements during cycle, average for all bunches over 20 ms

Transverse emittance vs bunch intensity for a single bunch



•Data from single bunch MDs in 2010 (C. Bhat, B. Salvant et al.,) + 50 ns beam (PS Double Batch, E. Metral et al., 2008)
•Settings optimised up to 2×10^{11}
•ξ_V in range 0.0-0.3, ξ_H=0.25

nominal int. $\varepsilon_{H/V}$ ~1.2 μm
ultimate int. $\varepsilon_{H/V}$ ~3.0 μm

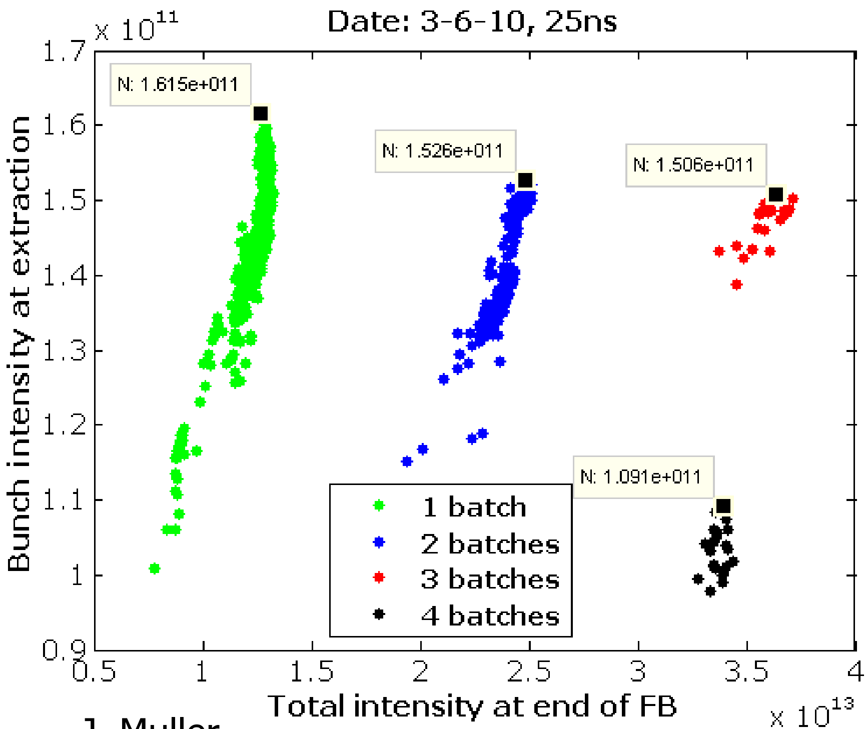
Linear fit:
H: ε= -1.14+2.22 ($N/10^{11}$)
V: ε= -1.03+2.17 ($N/10^{11}$)

→ Emittance blow-up above space charge limit (N/ε=const)

SPS MDs with LHC beams in 2010

Week	Date	Spacing	Max. inj. intensity	Comments/Results
17	27-29.04	25 ns	nominal	“scrubbing”, dedicated SC, 1-4 batches, low beam loss (5%)
22	02-03.06	25 ns	ultimate	36 h, part. dedic. SC, 1-3 batches
29	20-21.07	25 ns	nominal	practically lost
35	03-04.09	50 ns 25 ns	ultimate nominal	8 h, 4 batches
42	19-20.10	25 ns 50 ns	nominal nominal	36-72 bunches; dedicated SC → 1-2 batches
45	09.11	50 ns	nominal	floating MD
46	17-18.11	75 ns	nominal	

Ultimate 25 ns beam



J. Muller

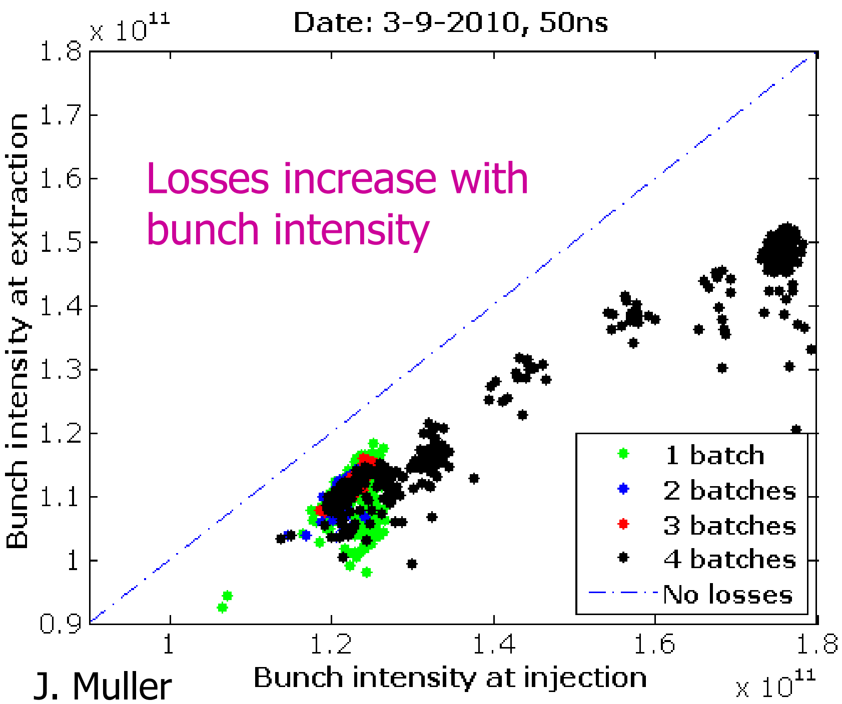
Bunch intensity on flat top decreases with number of batches: $1.62 10^{11}$ -1 batch, 1.51×10^{11} - 3
Beam losses: 30% → 20%

- Large efforts in whole inject. chain
- Up to 1.9×10^{11}/bunch injected, $\varepsilon_L \sim 0.4$ eVs, $\varepsilon_{H/V} \sim 4.5/5$ μm
- Emittance blow-up 5 → 10 μm

  (larger in H-plane and for more batches) with $\xi_{H/V}=0.2/0.3$
- Voltage increased during cycle 0.65 → 0.75 eVs to reduce losses & reduced on flat top: 7.2→5.5 MV to reduce outgassing and heating in kickers
- Beam unstable longitudinally on flat bottom with 12 bunches
- 36 hours MD – stopped due to MKE heating to 70 deg

Ultimate 50 ns beam

Bunch intensity on flat top
vs injected bunch intensity

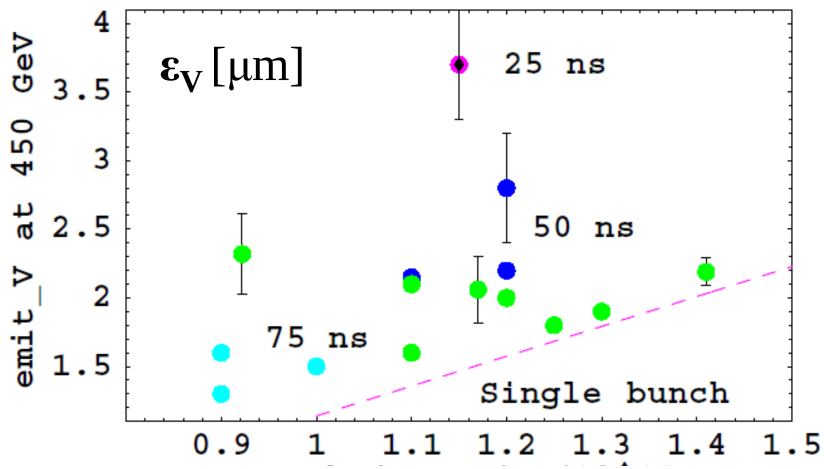


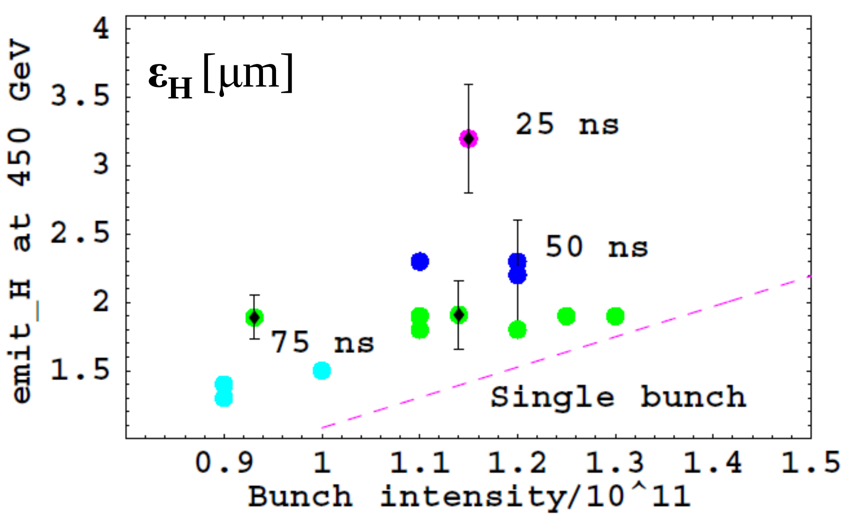
J. Muller

- Only 8 h MD at the end of block - in || to LHC set-up (150 ns beam)
- 1.8×10^{11}/bunch injected → maximum 1.52×10^{11}/bunch on FT, 15% losses for ultimate intensity
- Nominal: $\varepsilon_{H/V}$ =2.7/2.8 μm on FT ultimate: injected $\varepsilon_{H/V}$ = 3.2/3.9 μm
- Voltage programme as for 25 ns nominal beam
- Increase in $\xi_{H/V}$ from (0.05/0.18) had no effect on losses

→ More time for optimisation in 2011

Nominal LHC beams in 2010
Transverse emittance vs bunch intensity





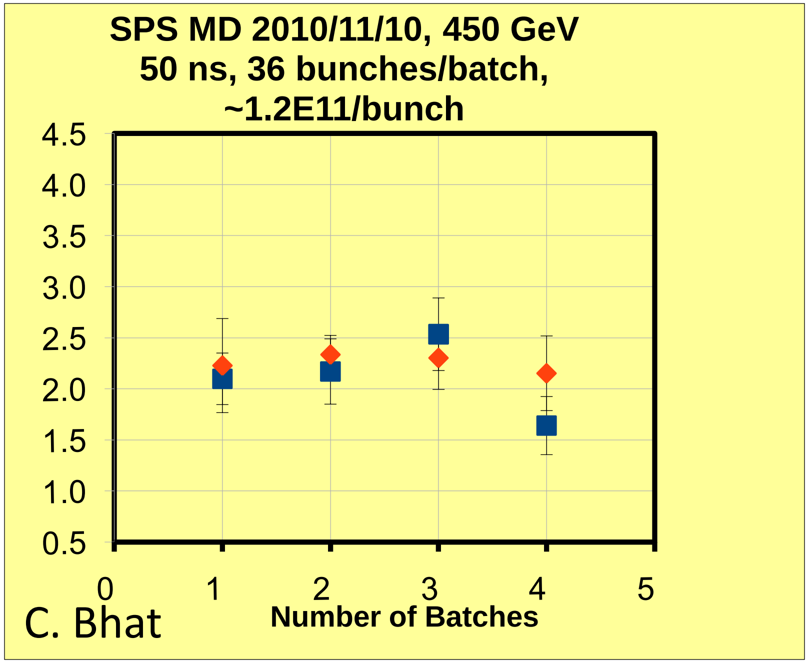
- Nominal 50&75 ns beam: extracted emittances determined by injected with no/small blow-up
- Nominal 25 ns beam: blow-up
  PS ext. $\varepsilon_{H/V}$ =2.0/1.5 μm →
  SPS (t=0.55 s) $\varepsilon_{H/V}$ = 3.2/3.3 μm
  flat top: $\varepsilon_{H/V}$ = 3.2/3.6 μm
- Larger emittances in V-plane

→ 50 ns and 75 ns beams: one can hope to get single-bunch emittances (~3 μm for ultimate intensity)

25 ns beam - same after e-cloud mitigation

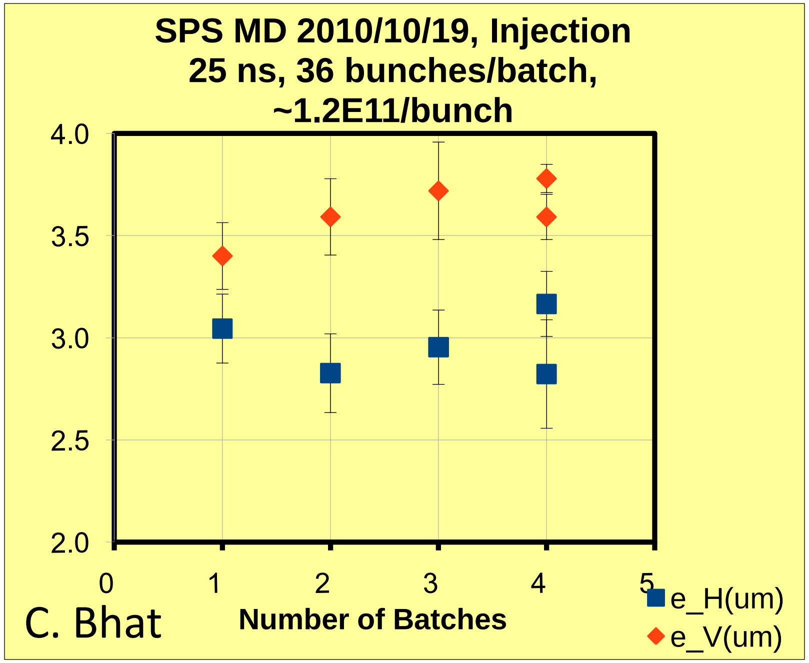
Transverse emittances vs bunch spacing for the same total and bunch intensities

50 ns spacing



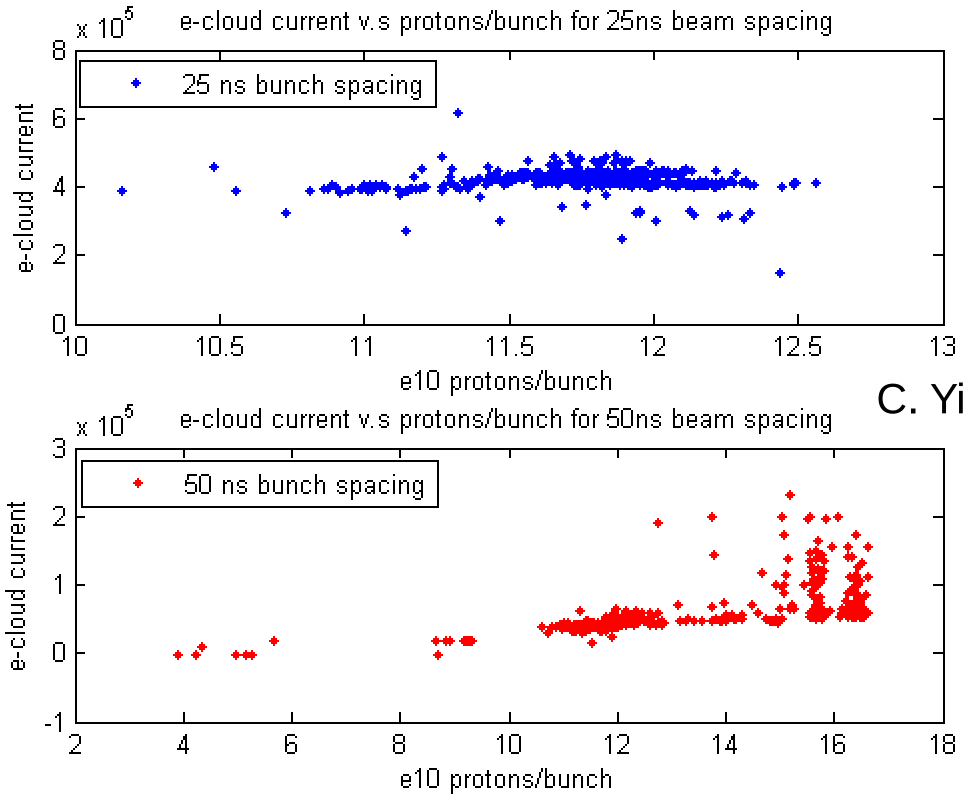
No emittance increase with n batches, small (<10%) blow-up during the cycle

25 ns spacing



Vertical emittance increase with n batches, measurement at 0.55 s (26 GeV)

e-cloud vs bunch intensity for 25&50 ns spacing (MD w35)



C. Yin Vallgren et al

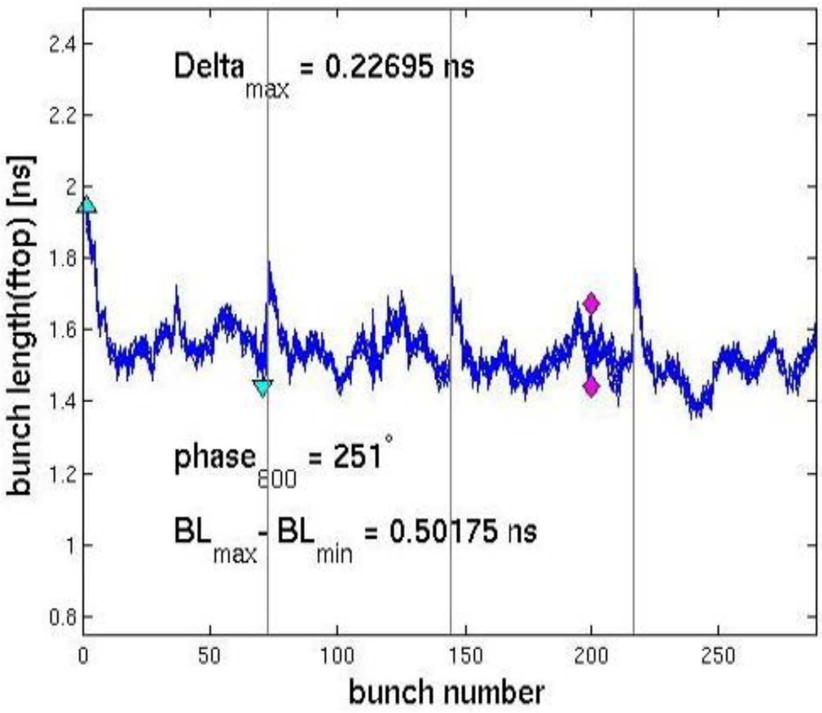
- A factor 3-5 difference between 25 ns and 50 ns beams
- Some increase of e-cloud current with intensity for 50 ns beam

Nominal LHC beams

- 25 ns beam
  - low (5%) losses (with low $\xi=0.1$)
  - heating and outgassing of kickers: MKDH3, MKP and MKE - limitation for dedicated MD cycle (or LHC filling)
  - no limitations from ZS after change of settings by BT group
- 50 ns beam
  - beam stability issue: need of controlled emittance blow-up in addition to the 800 MHz RF

Bunch length on flat top

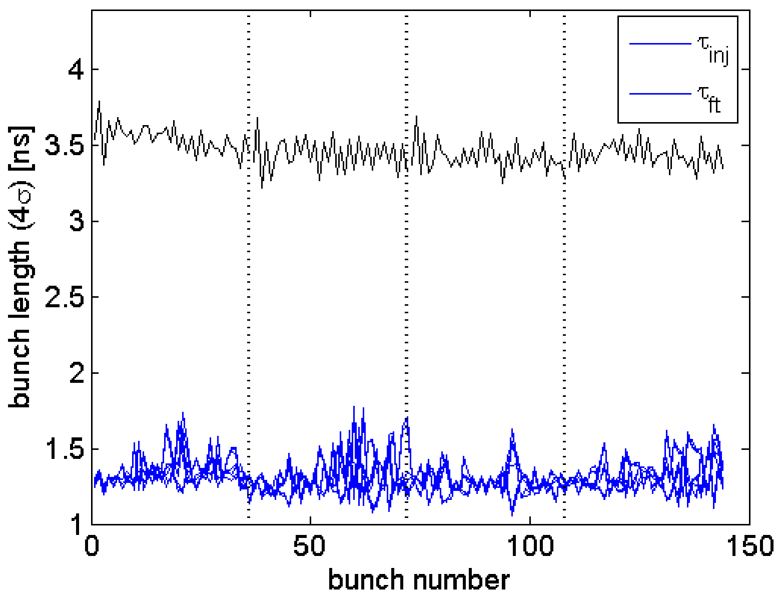
25 ns nominal beam, 4 batches, V_{200}=5.5 MV, V_{800}=0.5 MV, blow-up



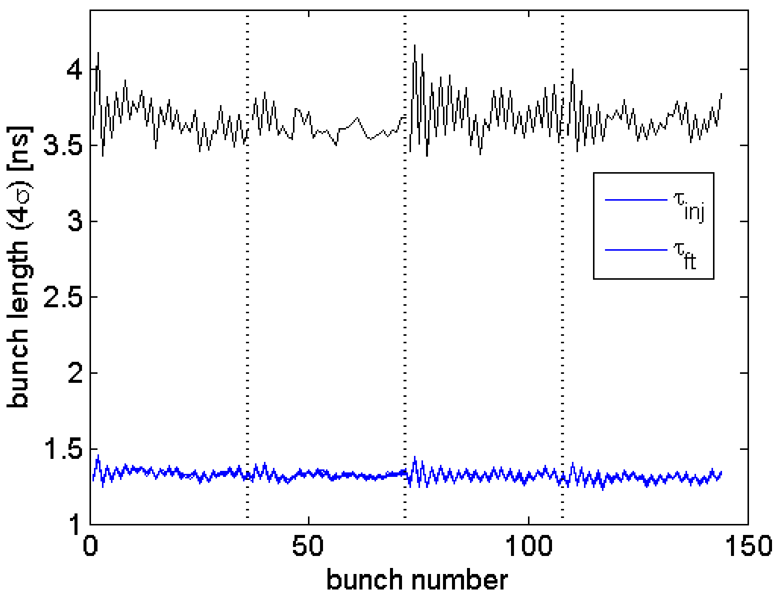
T. Argyropoulous et al.

Longitudinal multi-bunch instability:
50 ns beam, 2 RF, no controlled blow-up

Short PS bunches



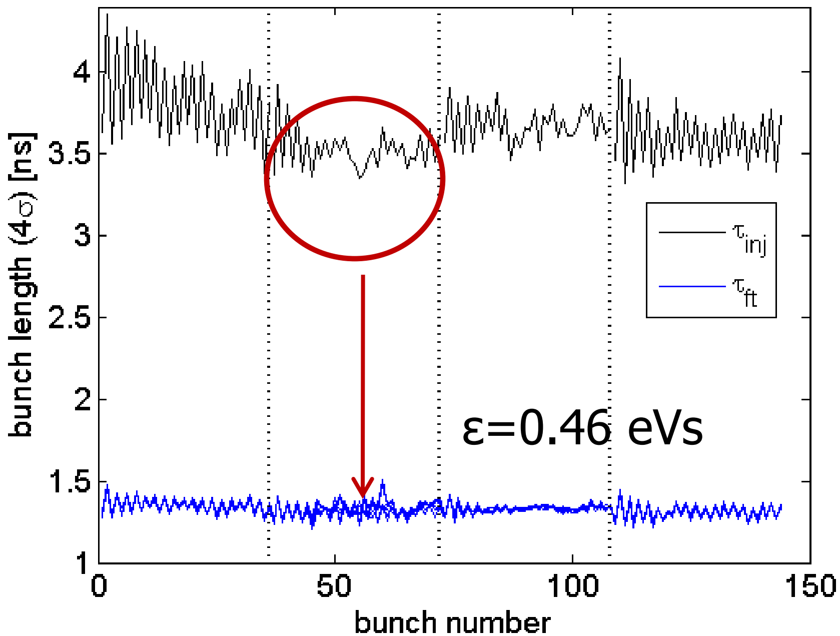
Long PS bunches



T. Argyropoulous et al.

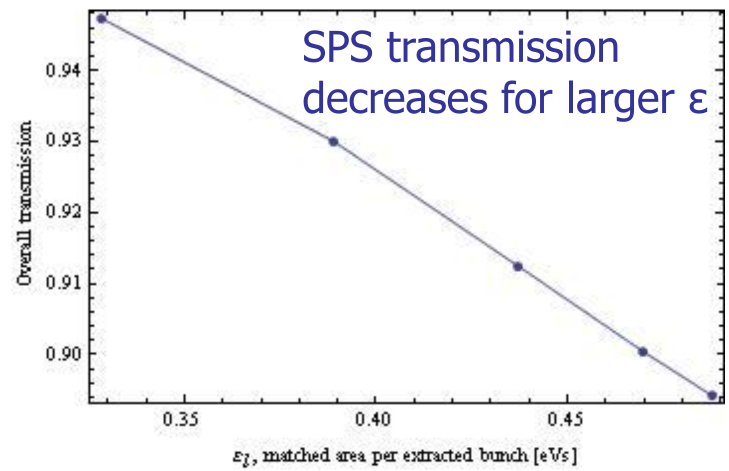
Multi-bunch instability due to loss of Landau damping?

50 ns beam



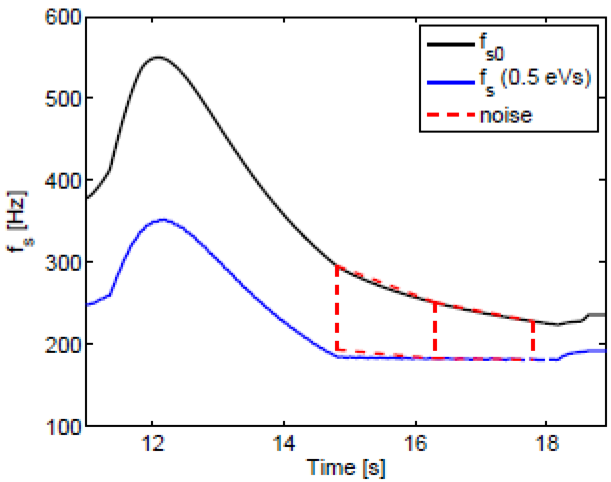
Loss of Landau damping due to inductive impedance (MKE)

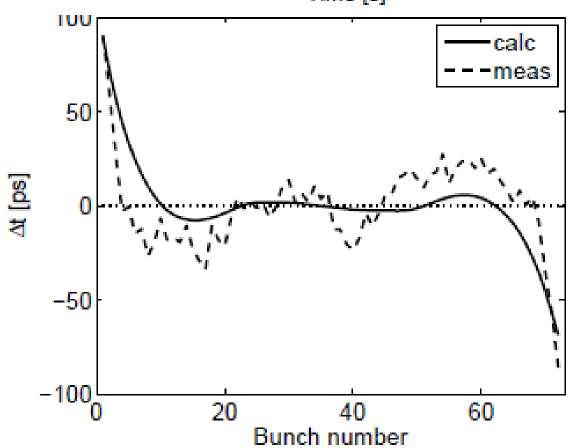
- Narrow window for the injected parameters: losses increase for longer bunches and beam is unstable for lower emittance (blow-up required for 50&75 ns beams)

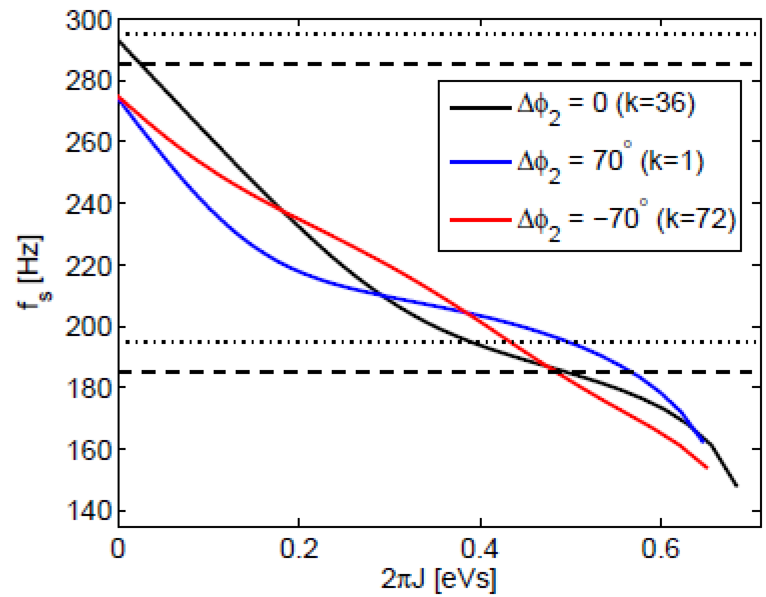


H. Damerau et al.

Bunch length variation on flat top: effect of beam loading in the 200 MHz RF on emittance blow-up by band-limited noise







T. Argyropoulos et al., HB2010

$$V = V_t^{200}\sin\phi + V_t^{800}\sin(4\phi + \Phi_2 + \Delta\phi_2),$$

$$\Delta\phi_2 = 4\Delta\phi_s^{meas}\left(1 + 4\frac{V_t^{800}}{V_t^{200}(-\cos\phi_s)}\right)$$

Intensity limitations for 25 ns beam - 2010

intensity /bunch	Origin	Leads to	Present/future cures/measures
0.2×10^{11}	longitudinal multi bunch instability due to longitudinal impedance	- beam loss during ramp - bunch variation on FT	(FB, FF, long. damper) - 800 MHz RF system - emit. blow-up → RF - low γ_t optics
0.7×10^{11}	e-cloud due to the StSt vacuum chamber (δ_{SEY}=2.5, 1.3 is critical for SPS)	- dynamic pressure rise - transv. (V) emit. blow-up - instabilities - losses (via high chrom.)	- scrubbing run ($\delta \rightarrow 1.6$) - high chrom. (0.2/0.4) - transv. damper (H) - (50/75 ns spacing) - coating ($\delta \rightarrow 1.0$)
1.3×10^{11}	not known exactly e-cloud, impedance, space charge, beam loading	- flat bottom/capture beam loss (>5%)	- (lower chromaticity) - WP, RF gymnastics - collimation
1.5×10^{11}	beam loading in 200 MHz RF system	- voltage reduction on FT - phase modulation	- feedback & FF - RF cavities shortening
1.6×10^{11}	TMCI (transverse mode coupling instability) due to transverse impedance	- beam losses - emittance blow-up	- higher chromaticity - low γ_t optics - transverse high bw FB

Low γ_t - solution for everything?

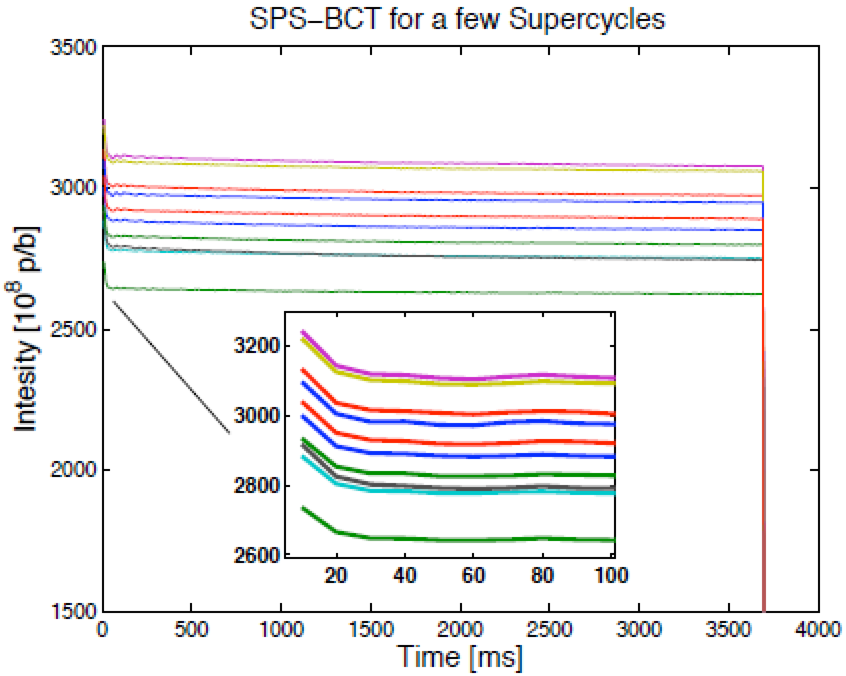
- Successful MDs with a single bunch (H. Bartosik, Y. Papaphilippou et al.): γ_t=22.8 → 18, increase in η: 2.86 @26 GeV/c and 1.6 @450 GeV/c
- Expected increase in beam stability for the same bunch parameters $N_{th} \sim \eta$ for TMCI (observed!) and longitudinal instabilities (to be seen in 2011)
- For the same parameters: $V \sim \eta$. Already maximum voltage (7.5 MV) is used now for extraction to LHC → longer bunches for the same emittance and voltage → RF upgrade should help (2017?)
- But probably emittance blow-up for the same intensity can also be reduced: loss of Landau damping $N_{th} \sim \varepsilon^2 \eta \tau$. Since $\tau \sim (\varepsilon^2 \eta/V)^{1/4} \rightarrow \varepsilon \sim \eta^{-1/2}$ and τ = const for V=const.

Issues:

- If LHC itself needs higher longitudinal emittances at injection
- Fast cycles
- e-cloud effects

Some MD results for low γ_t

No TMCI up to $3.2\text{x}10^{11}$



Small transverse emittances

- FB: no transverse blow-up for
  - $\varepsilon_{H/V}$ = 2.0/2.3, $2.6\text{x}10^{11}$
  - $\varepsilon_{H/V}$ =2.5/2.6, $3.3\text{x}10^{11}$

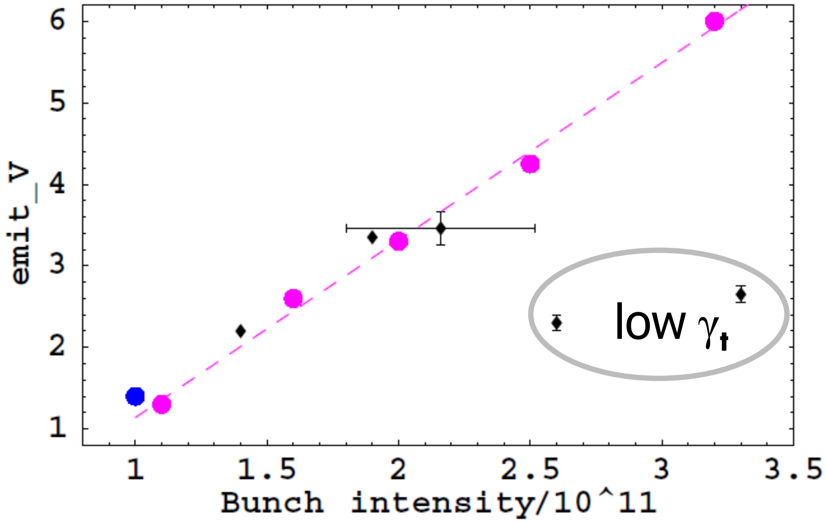
  but too low voltage (1.8 MV) → losses (10-15%) and longer bunch (~30%?)
- Acceleration of $2.5\text{x}10^{11}$
  - 5% capture losses
  - $\varepsilon_{H/V}$ = 2.4/2.9,
  - τ = 1.5 ns on FT

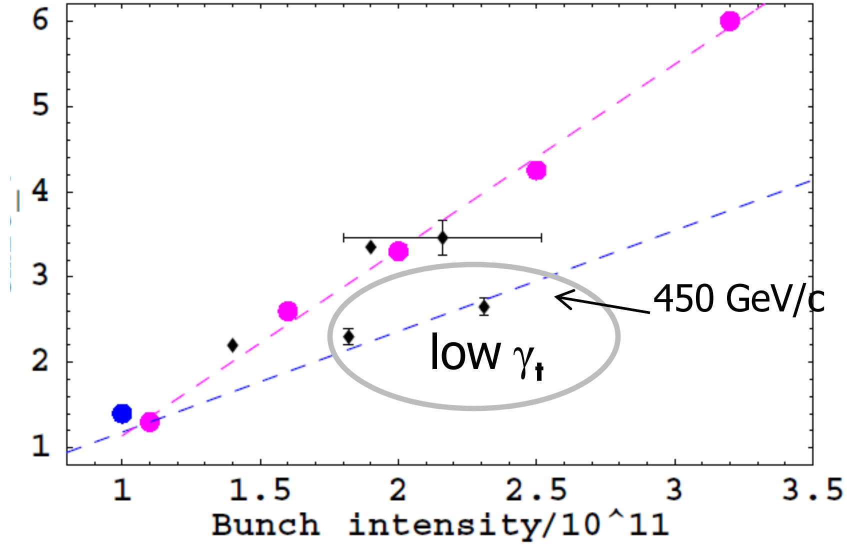
→ Studies with nominal and ultimate LHC beams (long. beam stability)

What is SPS space charge limit at 26 GeV/c?

Single bunch data
with nominal (γ_t =22.8)
and "low γ_t" optics (γ_t =18)

"Low γ_t" data scaled by 30% in intensity (for low V and losses)
linear fit: ε= 1.2 ($N/10^{11}$)
→ space charge limit ΔQ_{sch} ~ 0.13
(nominal LHC beam ΔQ =0.05)





→ preliminary results, accurate measurements in 2011

LHC beams in SPS

Beam parameters		SPS @ 450 GeV/c (intensity maximum injected minus losses)					
		nom.	nom.	nom.	2010	2010	2010
bunch spacing	ns	25	50	75	25	50	indiv
max bunch intensity	10^{11}	1.2	1.2	1.2	**1.5**	**1.52**	**3.2**
number of bunches		4x72	4x36	4x24	**3**x72	4x36	1
total intensity on FT	10^{13}	3.5	1.7	1.2	3.2	2.2	0.03
long. emittance	eVs	0.7	0.5	0.4	0.8	0.6	0.4
norm. h/v emittance	µm	**3.6**	2.0*	2.0*	~10	>3.2/3.9	**6.0**

* double batch injection in PS: 1.1/1.4

Main lessons/results from 2010

- Nominal 25 ns beam in good shape: low beam losses (5%) with low ξ_v = 0.1
- Ultimate (injected) beam - needs studies
  - 25 ns: large losses and emittances, instabilities
  - 50 ns: 15% losses, $1.5\text{x}10^{11}$/bunch at 450 GeV/c in 4 batches
- TMCI threshold is at ultimate intensity (low ξ). Ultimate single bunch accelerated to 450 GeV/c with low loss and ξ_v, but with some emittance blow-up. More problems for small injected emittances.
- New low γ_t optics: promising results for beam stability and brightness
- Loss of Landau damping for small inj. long. emittances, bunch length variation on flat top after controlled emittance blow-up in 2 RF

Limitations for dedicated LHC filling/MD: MKE, MKP, MKDH3 heating/outgassing

MD issues: transverse emittance measurements, time allocation

Conclusions - Q&A

- p/b and emittance as a function of the distance between bunches today and after upgrade

  - now one can hope to get single-bunch emittances for 50&75 ns beams with 3 μm for ultimate intensity; probably less (2.5 µm) with low γ_t (RF voltage limit to be seen)

  - after upgrades (e-cloud and impedance reduction) one can hope to be at the space charge limit (~2.5 µm for ultimate intensity) for 50&25 ns beams

- what should be done for delivering smaller transverse emittances at ultimate current?

  - studies, smaller PS beam, improvement of trans. emittance measurement

  - e-cloud mitigation, transverse impedance reduction, strong transverse damper/FB

  - low γ_t optics with 200 MHz RF upgrade

Spare slides

Some data for space charge

- ppbar time - $\Delta Q=0.07$
- Protons at 14 GeV/c (H. Burkhardt et al., PAC 2003) $\Delta Q=0.14/0.18$ with 10% losses ($N=1.2\times10^{11}$, 3 ns, $\varepsilon_{H/V}=3.43/3.75$ μm – 30%?,)
- Nominal LHC bunch $\Delta Q=0.05$, ultimate $\Delta Q=0.07$
- 50 ns nominal intensity beam with single batch injection in PS (2008): $\varepsilon_{H/V}=1.1/1.4$ μm at 450 GeV/c (E. Metral) $\rightarrow \Delta Q=0.15$
- Recent studies with high intensity single bunch (B. Salvant et al., 2010) $2.5\times10^{11} \rightarrow$ $\Delta Q=0.1$ for $\varepsilon=3.5$ μm
- LHC ions in the SPS: $\gamma=7.31$, $N_e=1.5\times10^{10}$, (50% more than nominal), $\varepsilon=0.5$ μm (1/2 nominal). In DR $\Delta Q=0.08$ $\rightarrow$ $\Delta Q=0.24$… but with 25% losses

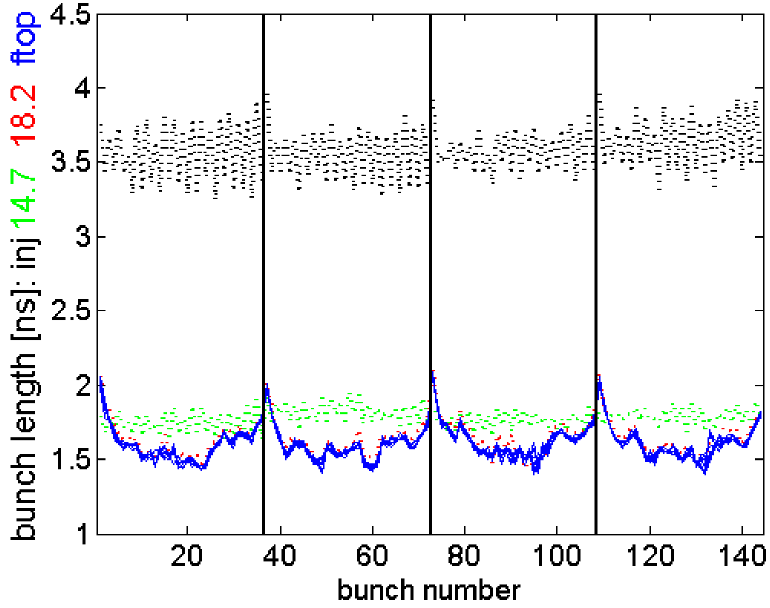
→ Space charge limit alone seems to be more close to $\Delta Q=0.15$

→ Interplay with other effects (multi-bunch) is probably also important

Reminder: significant loss reduction for nominal LHC beam by change of the WP (G. Arduini et al., 2004)

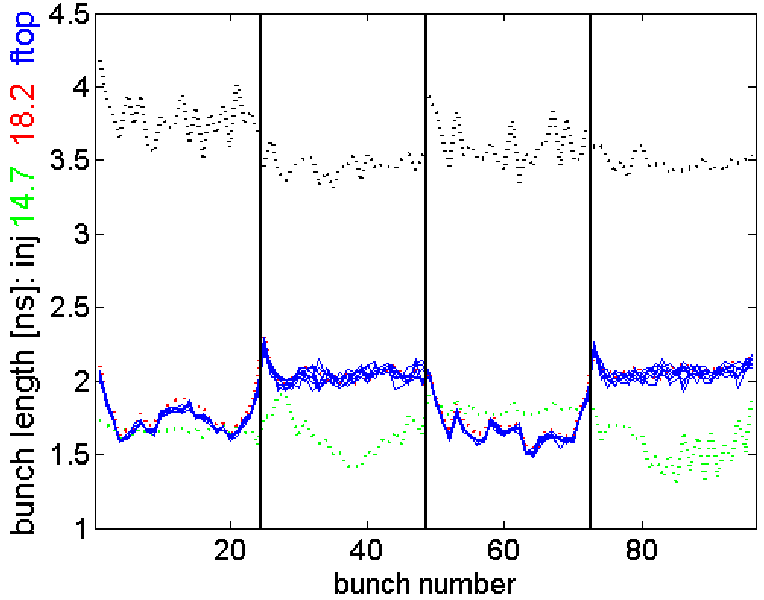
Possible issues with controlled longitudinal emittance blow-up

50 ns beam



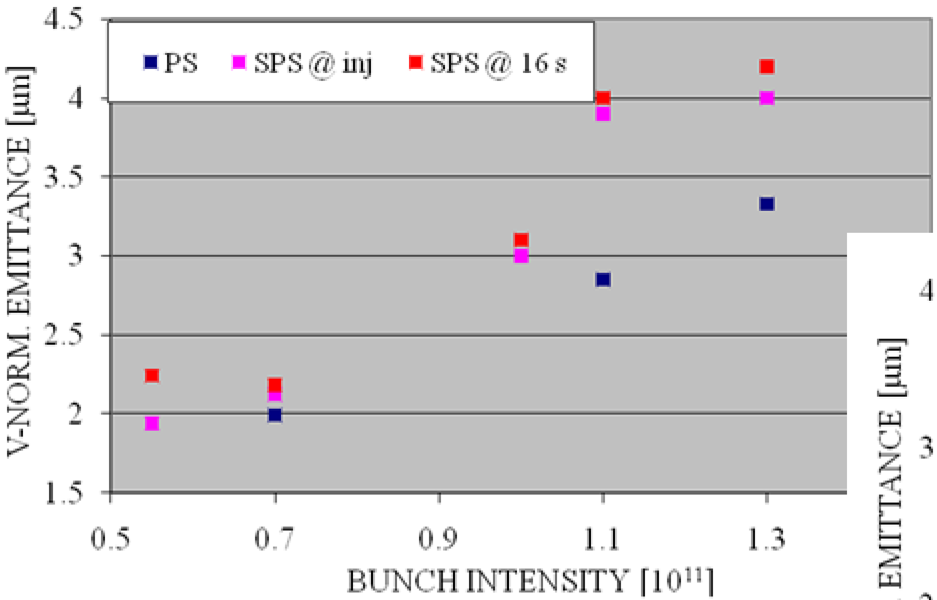
Non-uniform emittance blow-up due to beam loading in a double RF system

75 ns beam

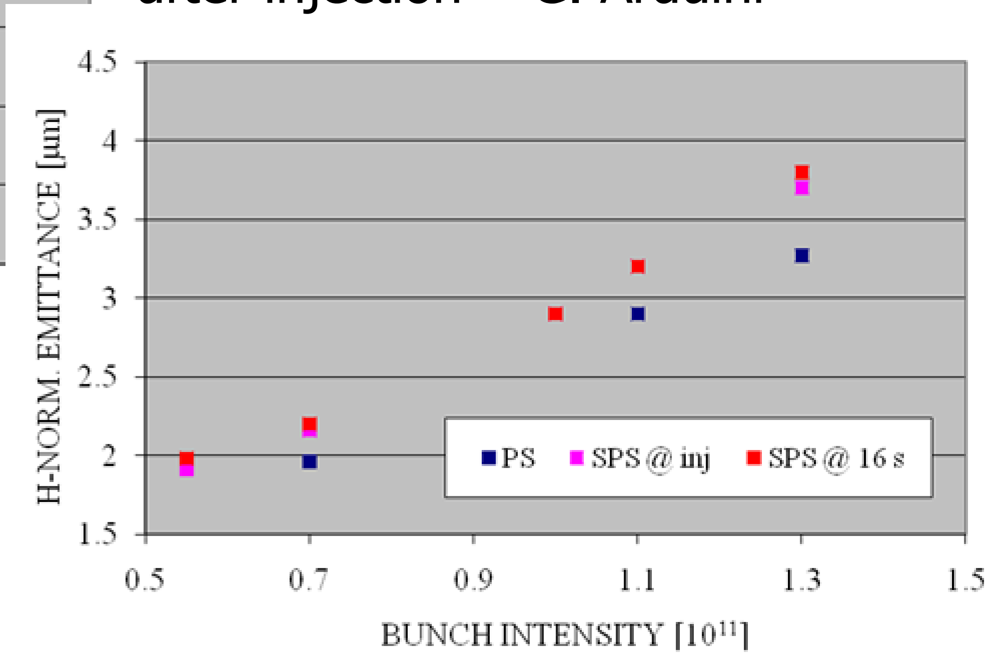


Non-uniform emittance blow-up and beam instability (?) for short injected bunches

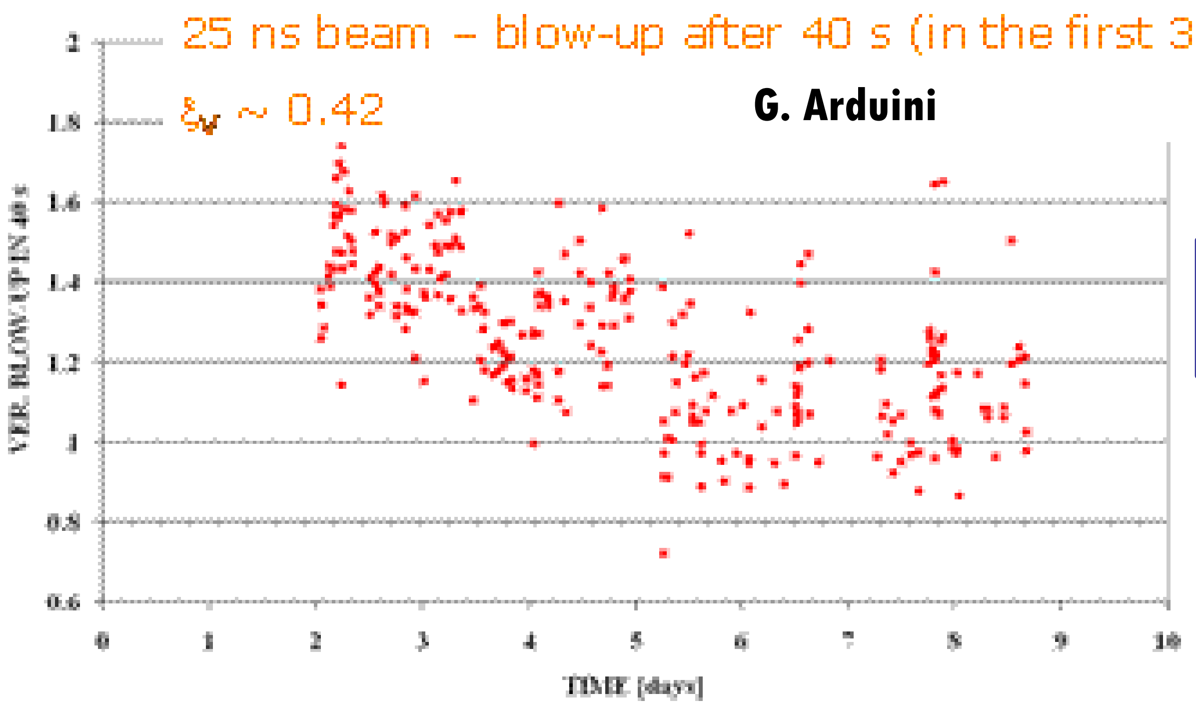
SPS scrubbing run in 2002



First measurement in SPS 10 ms after injection - G. Arduini



Scrubbing effects on the beam



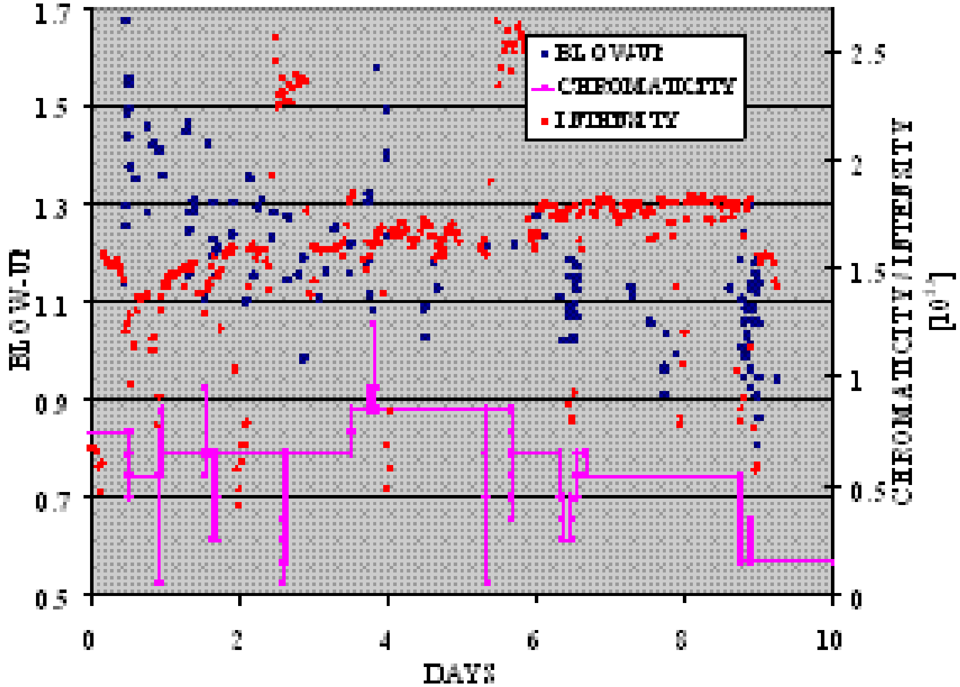
In what regime are we now?

The positive effects of the scrubbing are visible on the beam :

Vertical instability is getting weaker with the reduction of the SEY

Cures for ECI

- Of course eliminating the cause of the ECI is even better …➔ Scrubbing (see J.M. Jimenez talk). Although an electron-cloud free environment cannot be achieved.



Reduction of the V-emittance blow-up along a 15 s injection plateau during the SPS scrubbing run in 2002.

Note: the intensity is increasing and the V-chromaticity is reduced.

G. Arduini

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