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. Bartosik, Y. Pappaphilipou + speakers

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

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

TE/ABT: M. Barnes, B. Balhan, R. Barlow, J. Borburgh, BE/BI

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

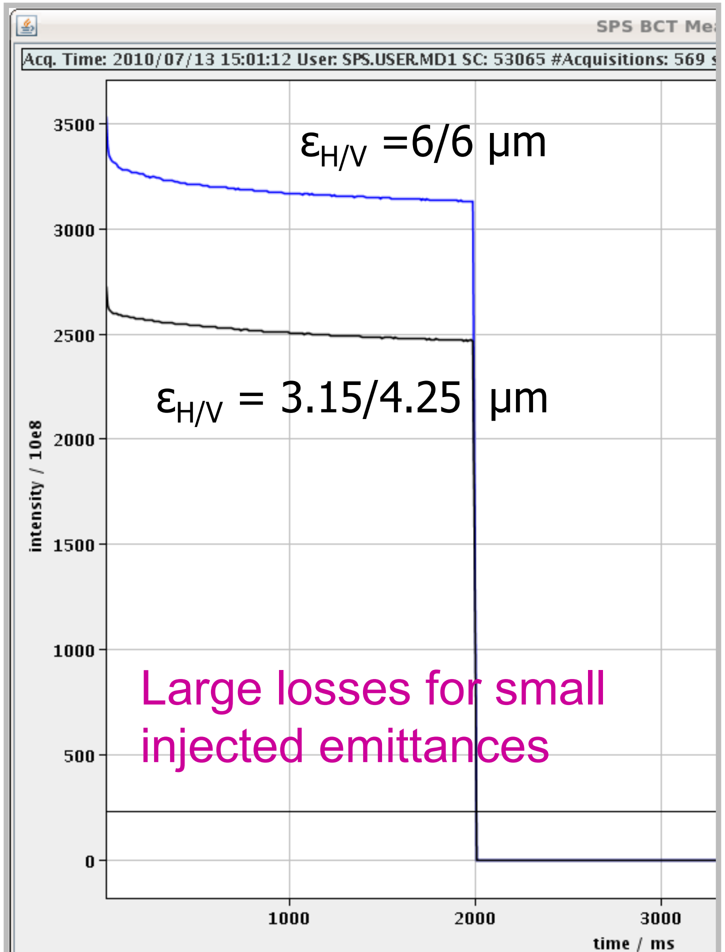
3. p/b and emittance as a function of the distance between bunches today and after upgrade

4. What should be done for delivering smaller transverse emittances at ultimate beam current?

Known intensity limitations and 2010 studies

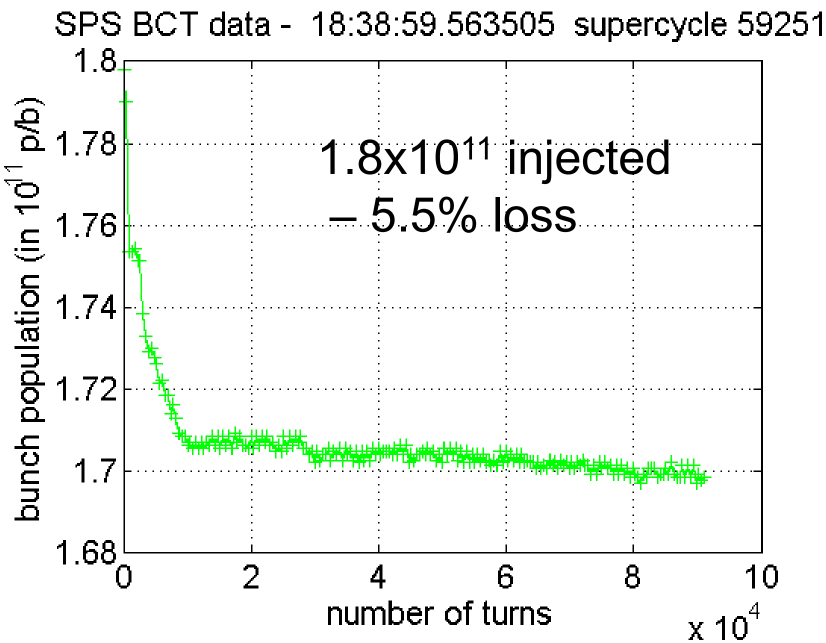
- Single bunch
  - TMCI (transverse mode coupling instability)
  - loss of Landau damping
  - space charge
  - longitudinal instability
- ➢ Studies with high (twice ultimate) intensities, nominal and small transverse emittances; γ_t=22.8 (nominal) and γ_t=18 ("low") optics
- Multi-bunch
  - e-cloud → 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
- ➢ Studies with 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 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 ~ 1.6×10^{11} for $\xi_V \sim 0$
(close to prediction from the SPS transverse impedance model)

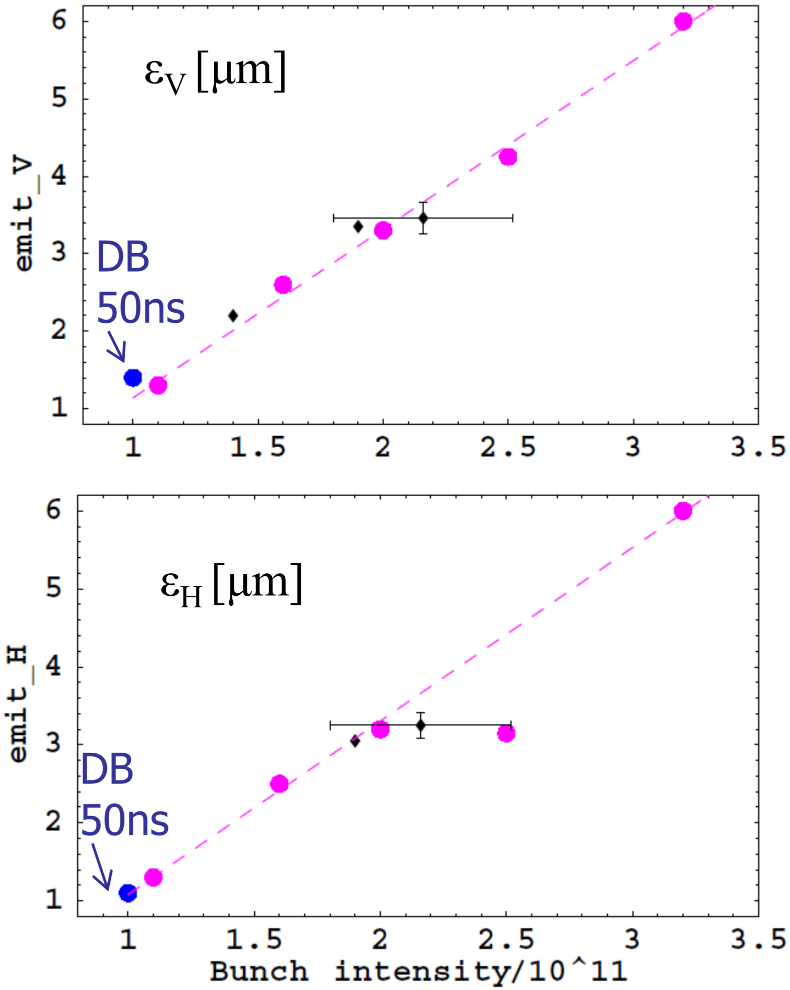
- TMCI threshold ~ $\varepsilon_L\ |\eta|$, $\eta = 1/\gamma^2 - 1/\gamma_t^2$
- Cures:
  - higher chromaticity ξ_V
  - higher η (lower γ_t)
  - larger ε_L (capture losses)
  - impedance reduction (if known)
  - wide-band FB (W. Hofle & LARP)

- End FB intensity (2.25-3.3)x10^{11} for ξ_V =(0.05-0.3), ξ_H=0.25
- Emittance blow-up?

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 2nd 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

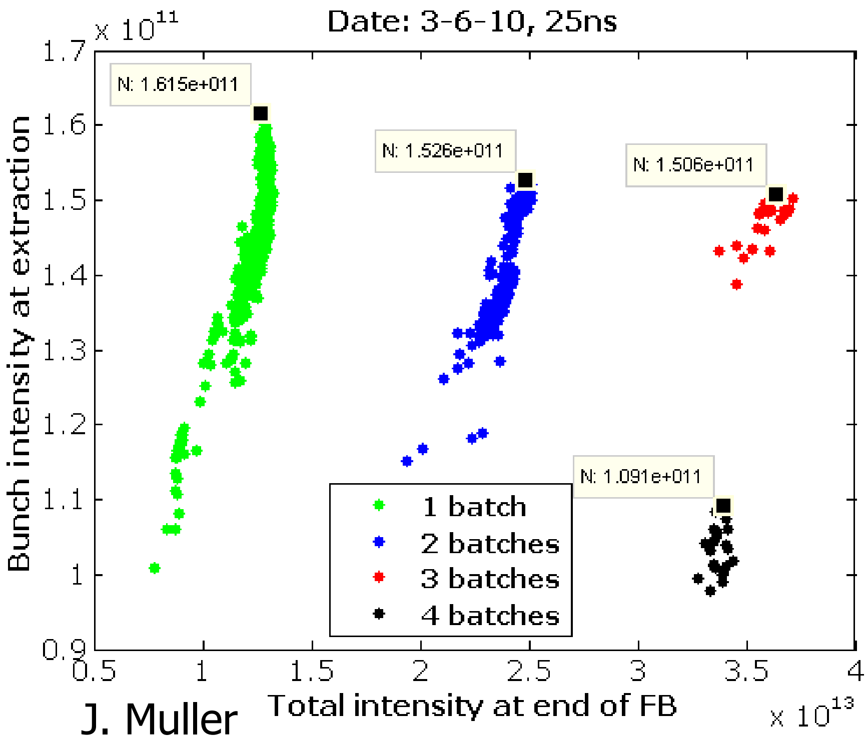
Linear fit:
H: $\varepsilon = -1.14 + 2.22\,(N/10^{11})$
V: $\varepsilon = -1.03 + 2.17\,(N/10^{11})$

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

SPS MDs with LHC beams in 2010 – v1.9

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

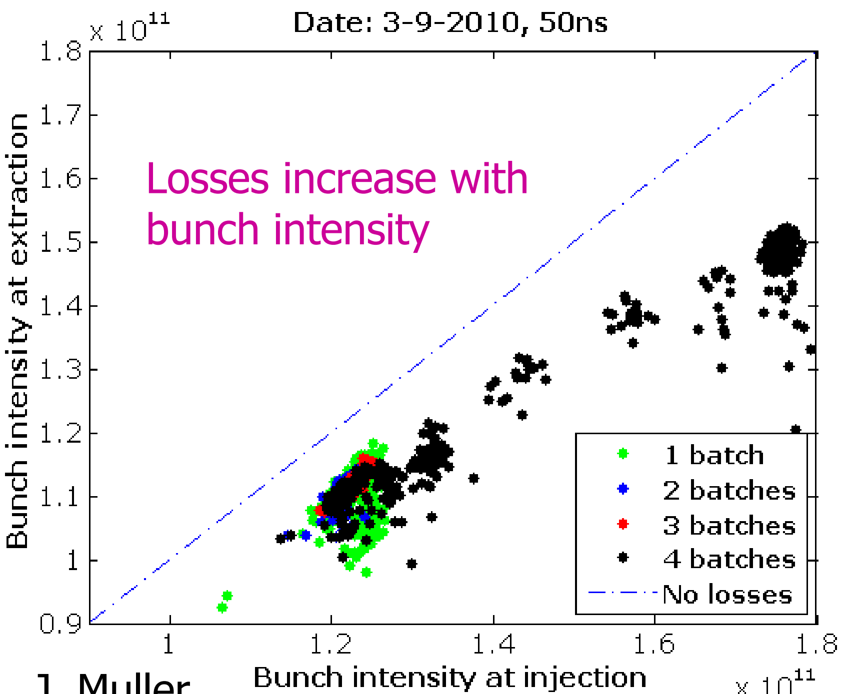
Bunch intensity on flat top decreases with number of batches: $1.62x10^{11}$ -1 batch, $1.51x10^{11}$ - 3
Beam losses: 30% → 20%

- Large efforts in whole inject. chain
- Up to $1.9x10^{11}$/bunch injected, ε_L~0.4 eVs, $\varepsilon_{H/V}$~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

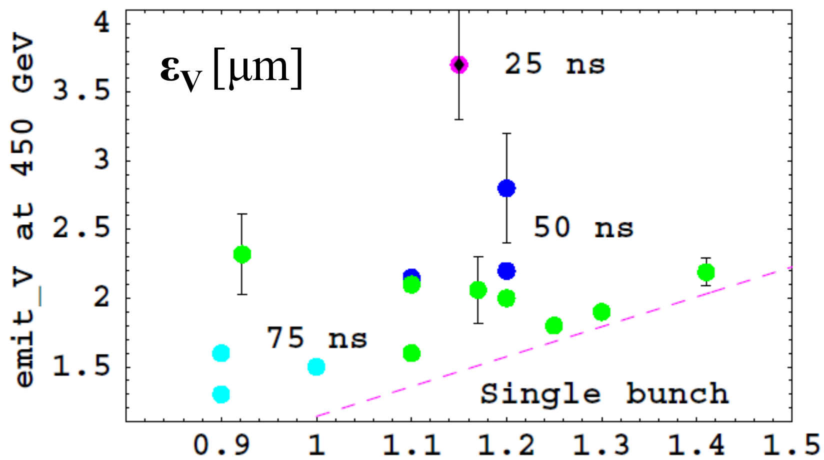


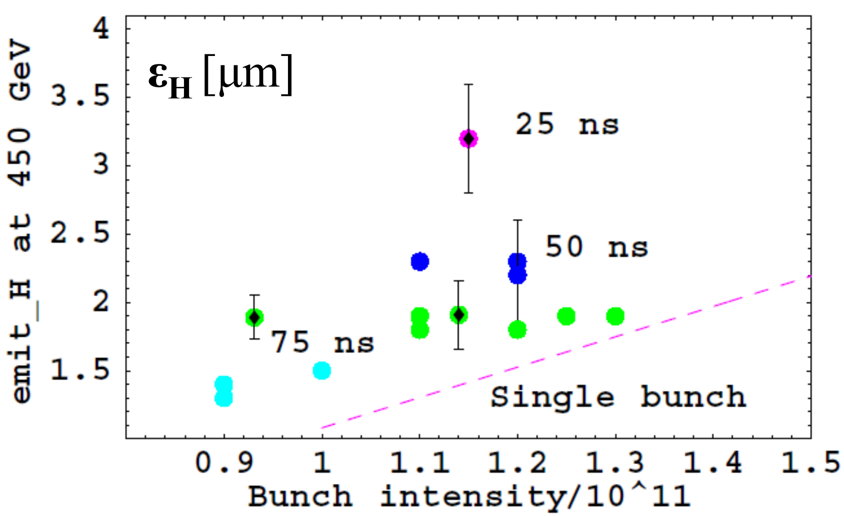
J. Muller

- 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 ultim.: 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





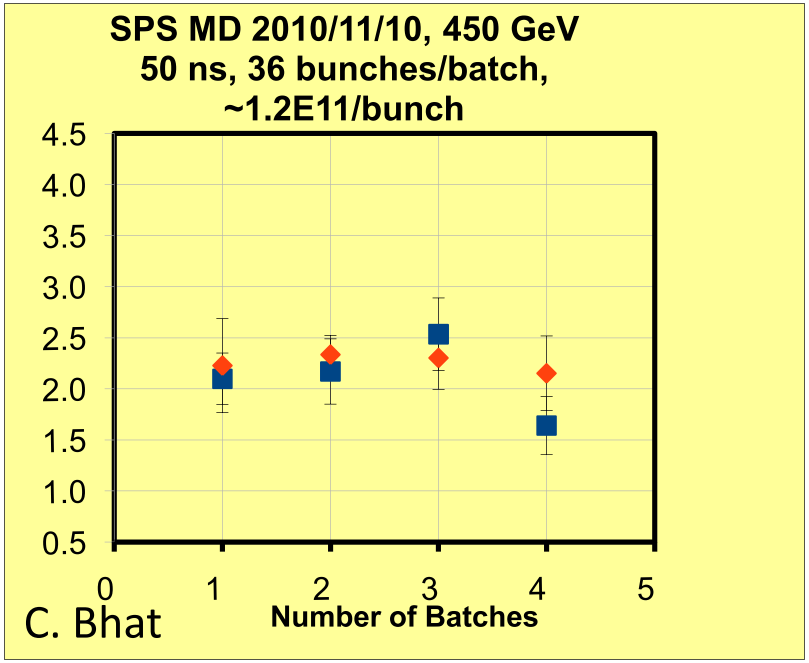
- Nominal 50&75 ns beam: extracted emittances determined by injected with no/small blow-up
- Nominal 25 ns beam: blow-up
  PS ext. $\varepsilon_{H/V}$ =2.0/1.5 μm →
  SPS (t=0.55 s) $\varepsilon_{H/V}$ = 3.2/3.3 μm
  flat top: $\varepsilon_{H/V}$ = 3.2/3.6 μm
- Larger emittances in V-plane

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

25 ns beam - can hope for same after e-cloud mitigation

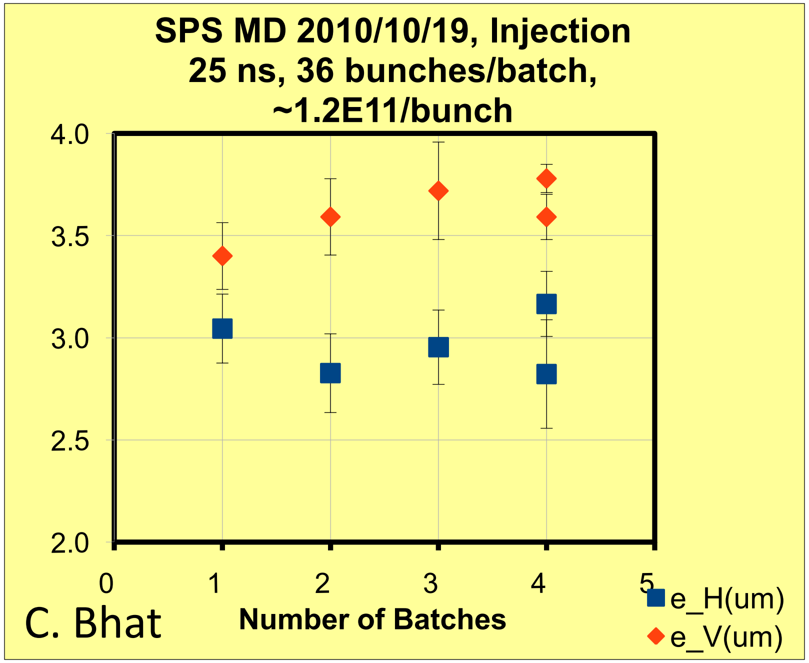
Transverse emittances vs bunch spacing for the same total and bunch intensities

50 ns spacing



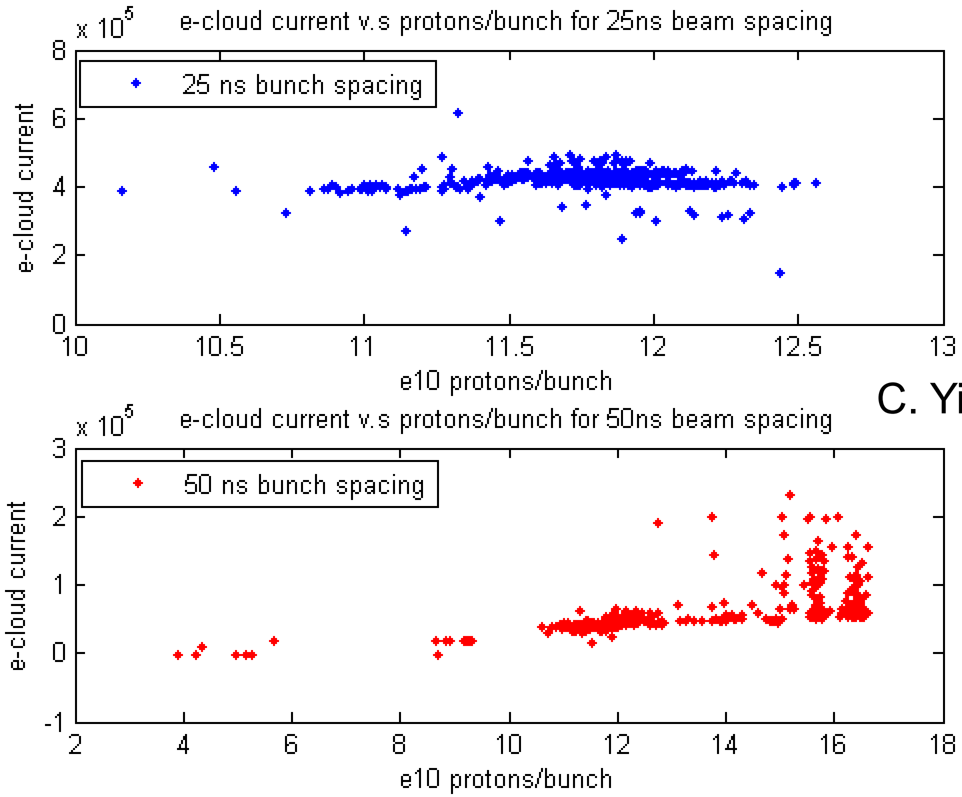
No emittance increase with n batches, small (<10%) blow-up during the cycle

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

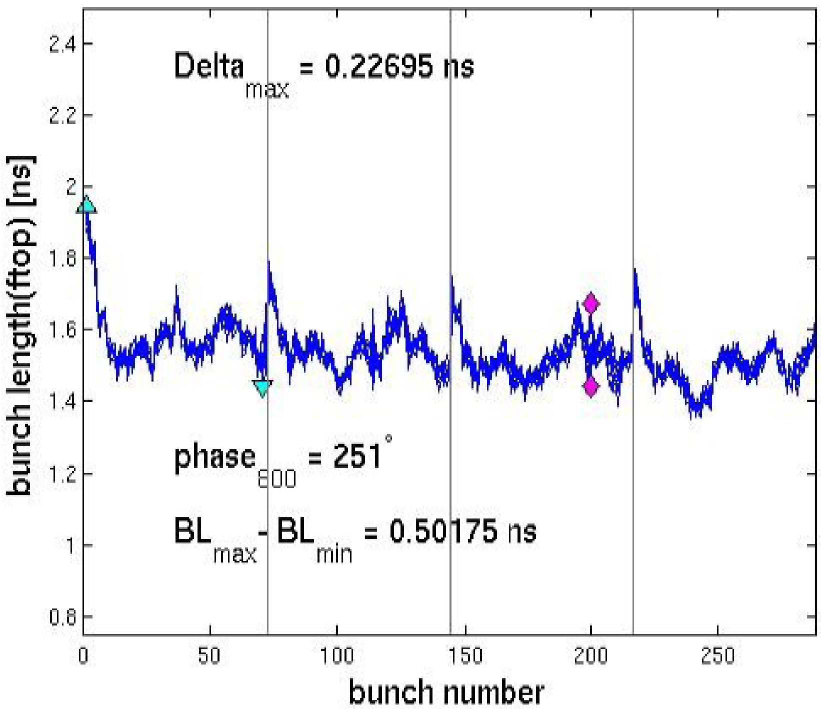
- A factor 3-5 difference between 25 ns and 50 ns beams
- Some increase of e-cloud current with intensity for 50 ns beam

Nominal LHC beams: beam quality issues

- 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 dedicated LHC filling)
  - no limitations from ZS after change of settings by ABT group
- 50 ns beam
  - beam stability issue: need of controlled emittance blow-up in addition to the 800 MHz RF

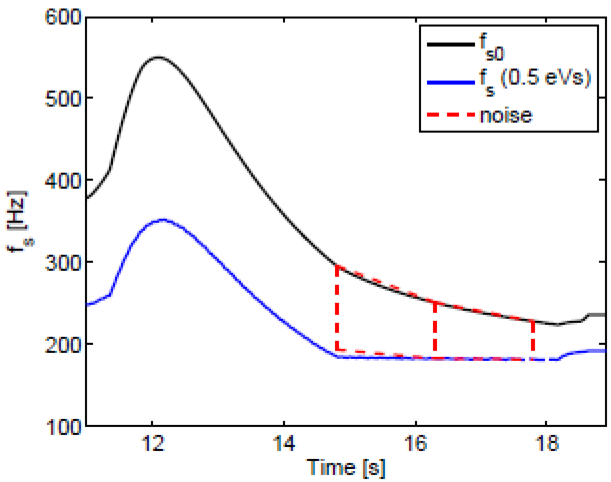
Bunch length on flat top

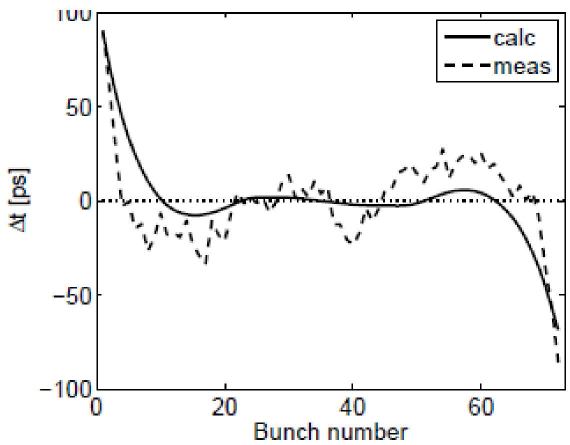
25 ns nominal beam, 4 batches, V_{200}=5.5 MV, V_{800}=0.5 MV, blow-up

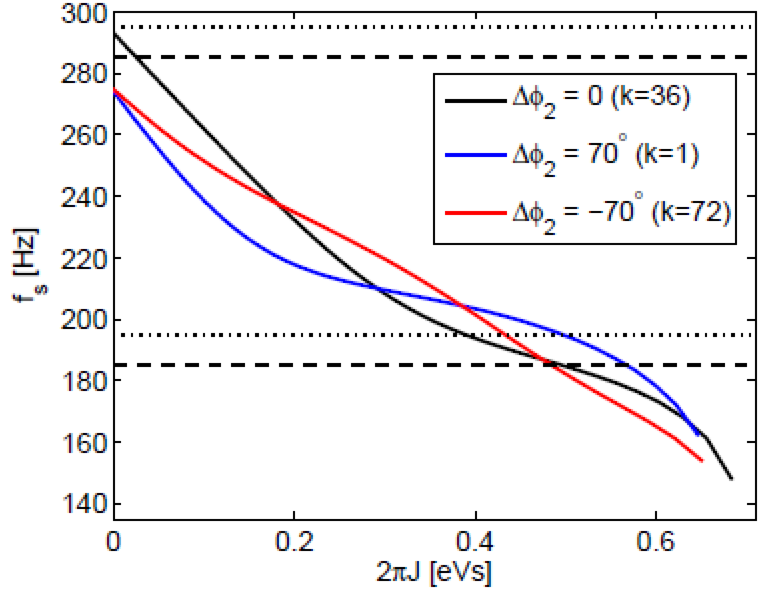


T. Argyropoulous et al.

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







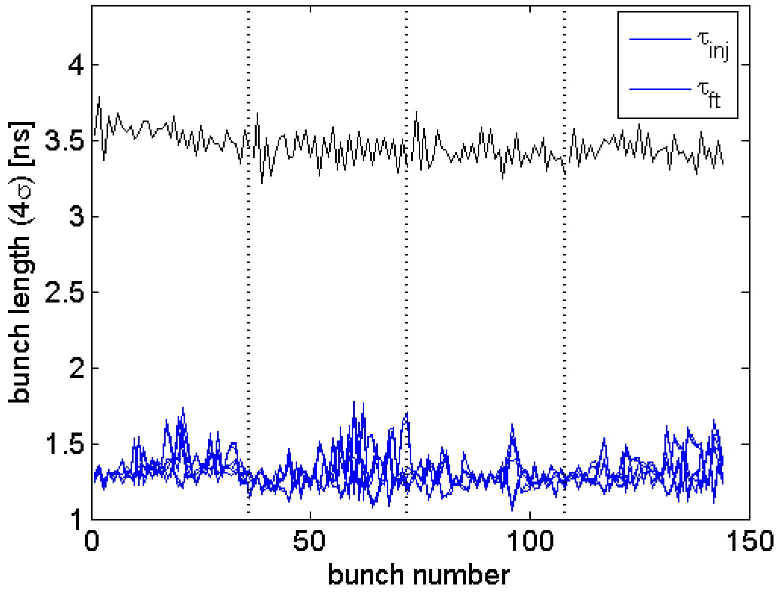
T. Argyropoulos et al., HB2010

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

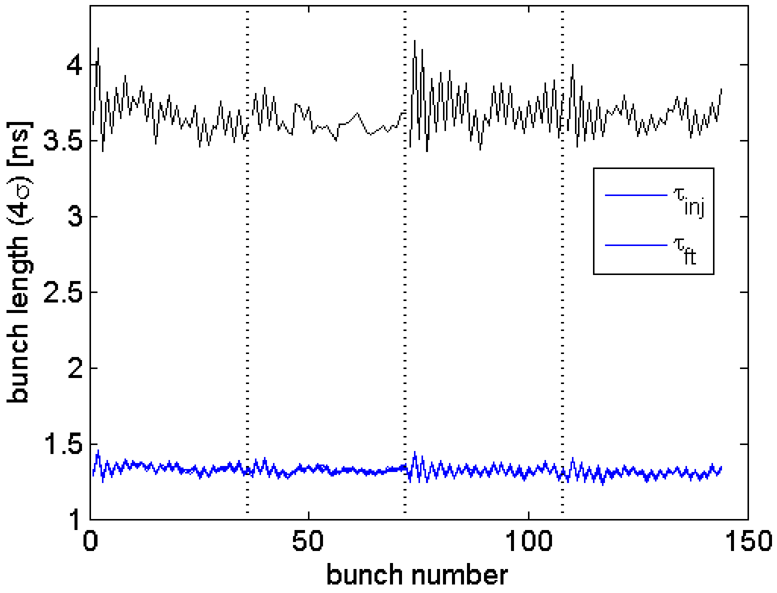
$$\Delta\phi_2 = 4\Delta\phi_s^{meas}\left(1 + 4\frac{V_t^{800}}{V_t^{200}(-\cos\phi_s)}\right)$$

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

Short PS bunches are
unstable in SPS (450 GeV/c)

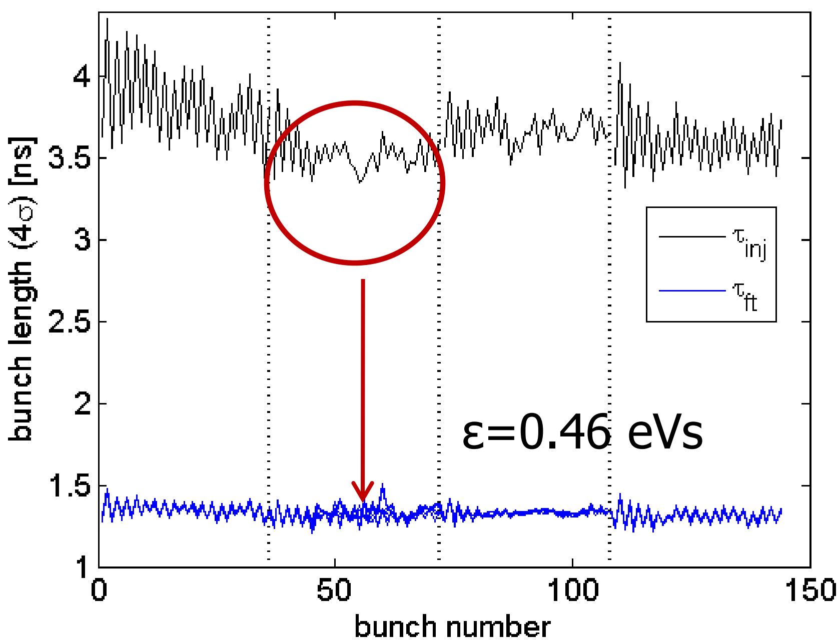


Long PS bunches



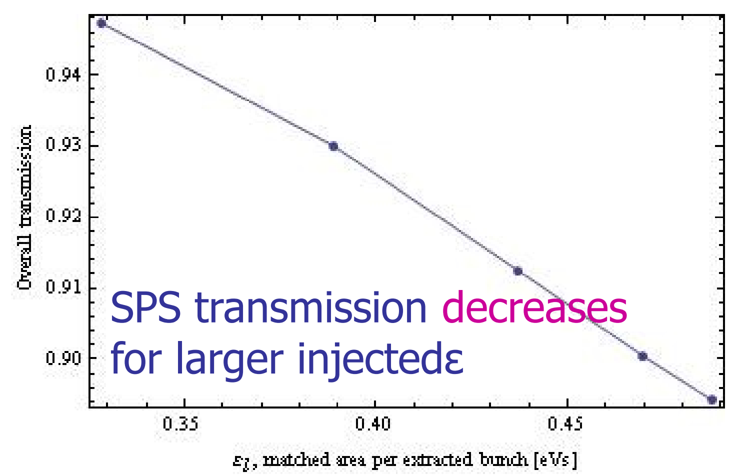
Multi-bunch instability due to loss of Landau damping?

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.

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 loss of Landau damping (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 → 200 MHz RF upgrade should help
- 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

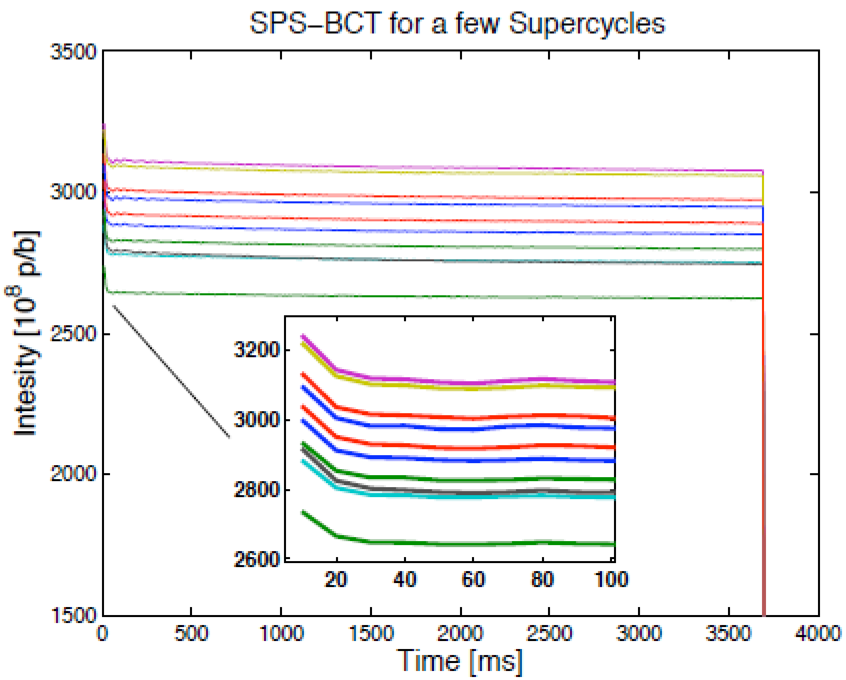
Issues:

- If LHC itself needs higher longitudinal emittances at injection
- Fast cycles in SPS

…

Some MD results for low γ_t

No TMCI up to 3.2x10^11



H. Bartosik et al.

Small transverse emittances

- FB: no transverse blow-up for
  - $\varepsilon_{H/V}$ = 2.0/2.3, 2.6x10^11
  - $\varepsilon_{H/V}$ =2.5/2.6, 3.3x10^11

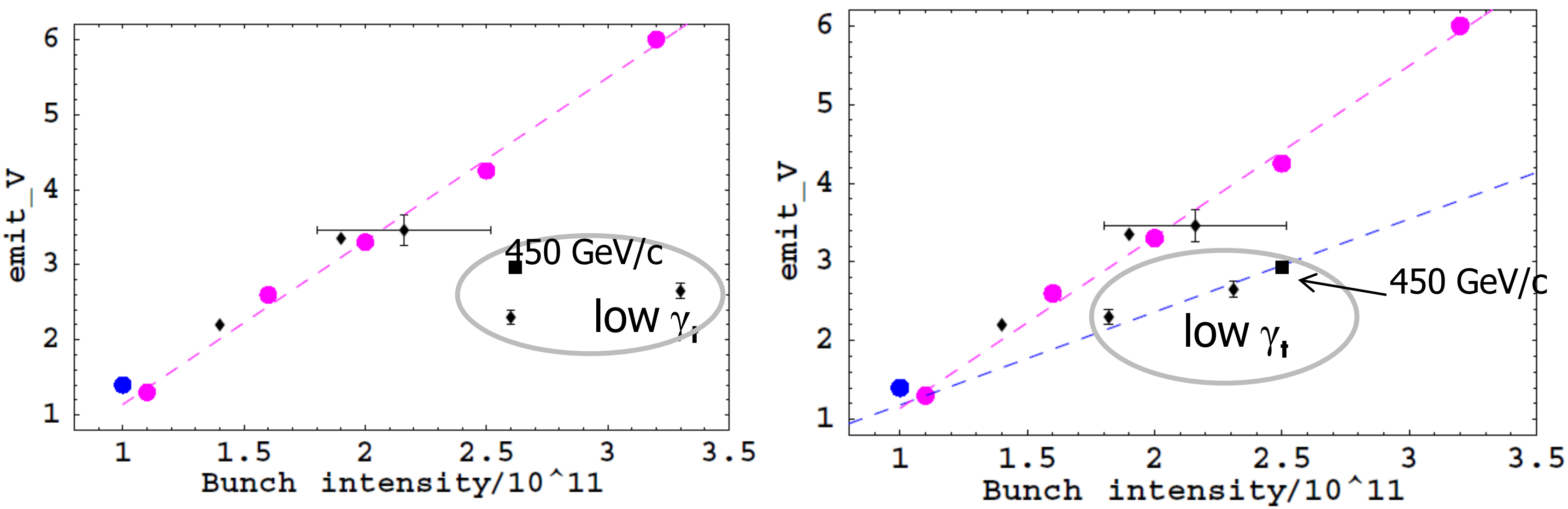
  but too low voltage (1.8 MV) → losses (10-15%) and longer bunch (~30%?)
- Acceleration of 2.5x10^11
  - 5% capture losses
  - $\varepsilon_{H/V}$ = 2.4/2.9,
  - τ = 1.5 ns on FT

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

What is the 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= 1.4 ($N/10^{11}$)
→ space charge limit ΔQ_{sc} > ~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**	**1.5**	**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, $1.5x10^{11}$/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

MDs issues: transverse emittance measurements, time allocation, data analysis

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); > 4 μm for 25 ns ultimate beam

  - 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 FB

  - low γ_t optics with 200 MHz RF upgrade

Spare slides

Some data for space charge

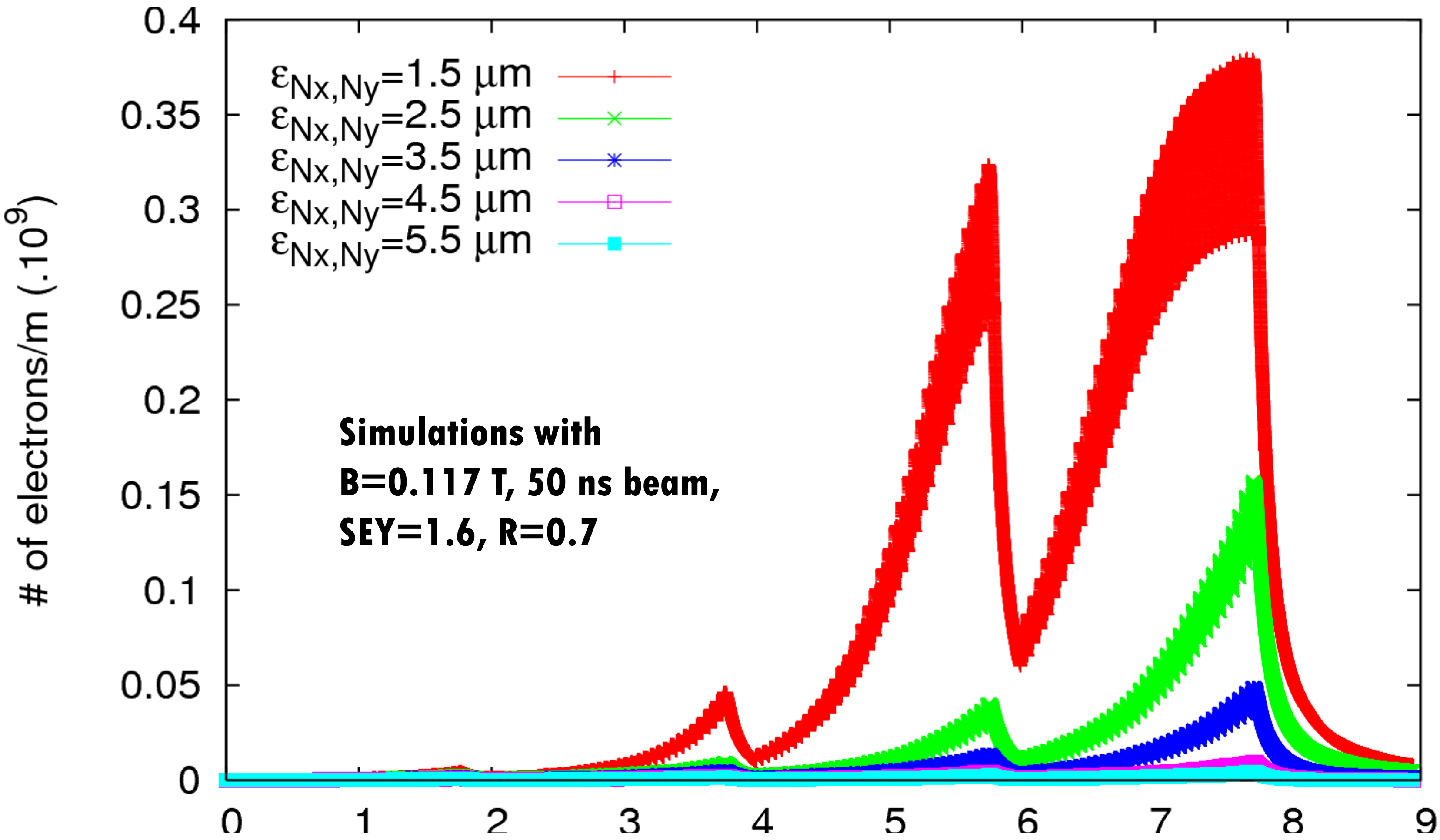
- ppbar time - $\Delta Q=0.07$
- Protons at 14 GeV/c (H. Burkhardt et al., PAC 2003) $\Delta Q=0.14/0.18$ with 10% losses ($N=1.2\times10^{11}$, 3 ns, $\varepsilon_{H/V}=3.43/3.75$ μm)
- Nominal LHC bunch $\Delta Q=0.05$, ultimate $\Delta Q=0.07$
- 50 ns nominal intensity beam with single batch injection 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

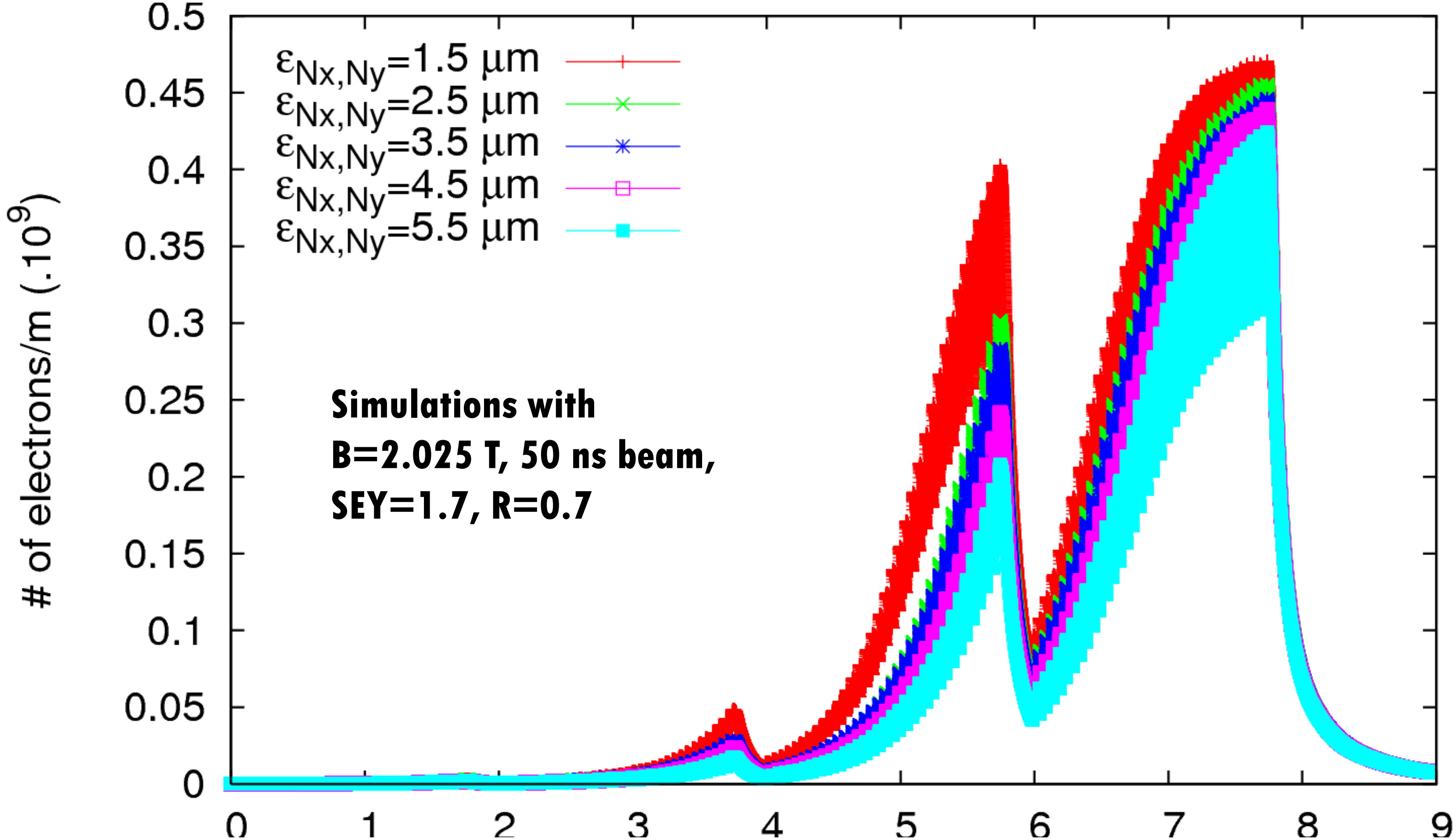
e-cloud build-up for low emittances

C.Octavio Domínguez, Giovanni Rumolo, Frank Zimmermann

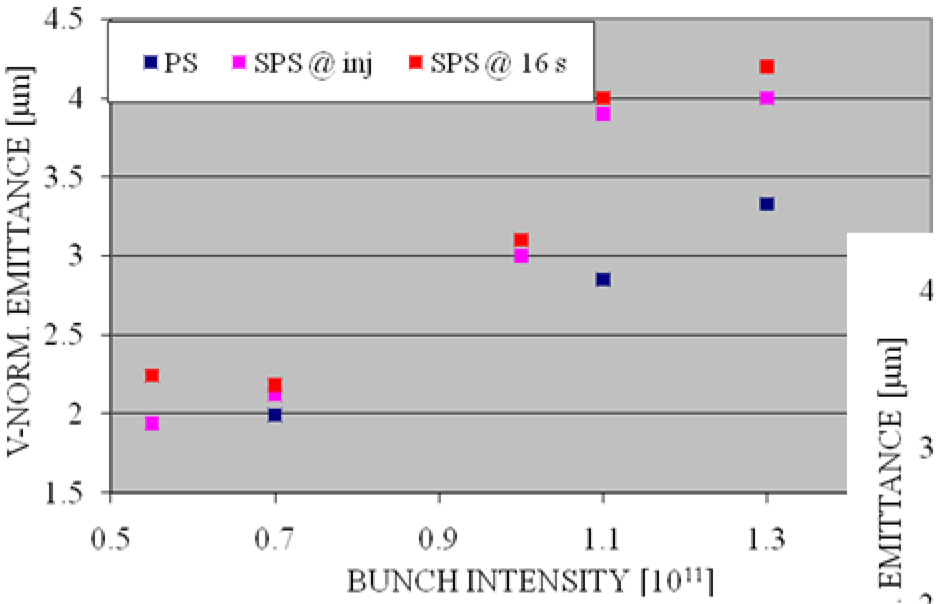


e-cloud build-up for low emittances

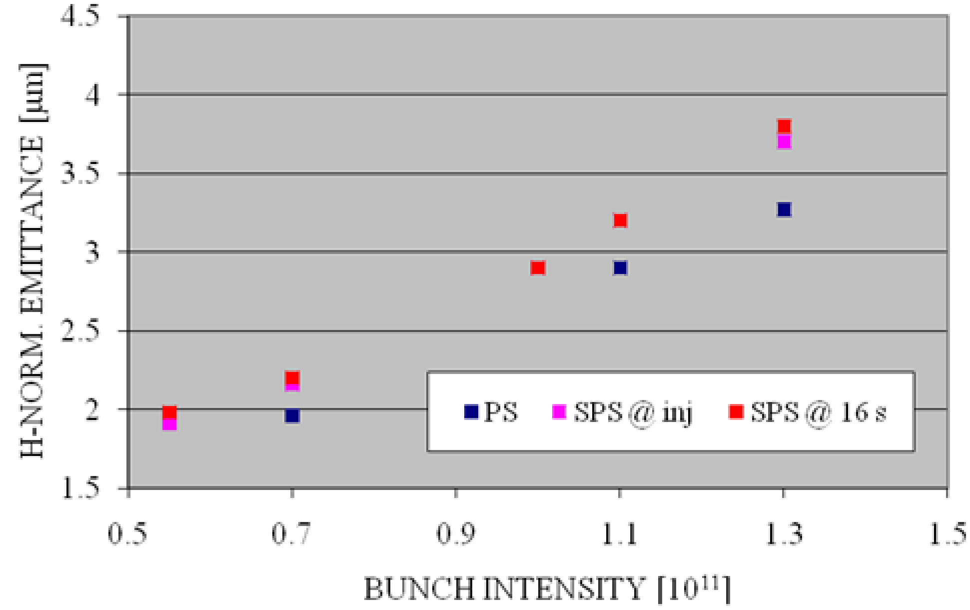
C.Octavio Domínguez, Giovanni Rumolo, Frank Zimmermann



SPS scrubbing run in 2002

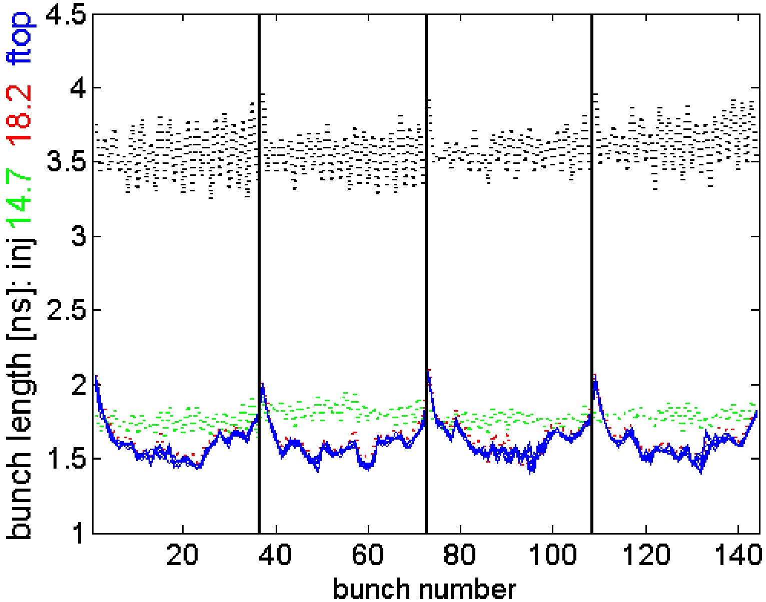


First measurement in SPS 10 ms after injection - G. Arduini



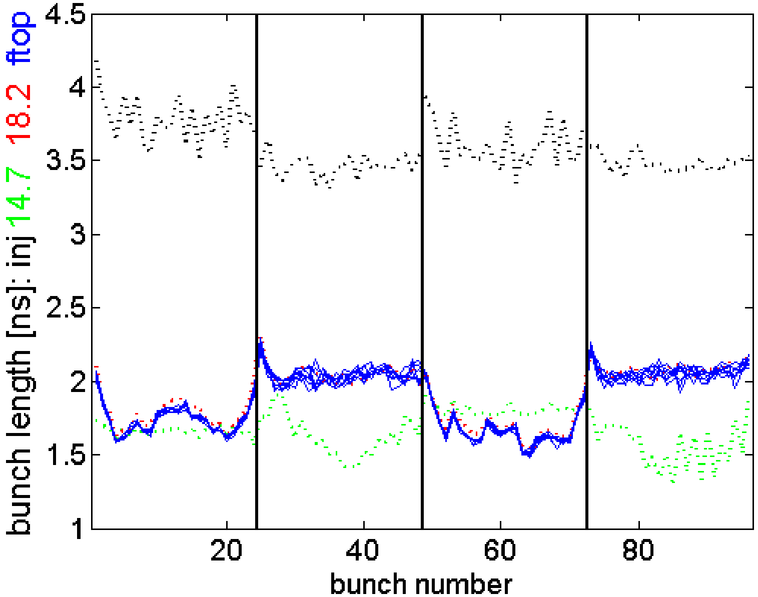
Possible issues with controlled longitudinal emittance blow-up

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

T. Argyropoulous et al.

Nominal and low γ_t optics

(H. Bartosik, Y. Papaphilippou)

– Nominal working point for LHC beams (Q26): Q_x=26.13, Q_y=26.18, γ_t=22.8, η(@26GeV)=0.63E-3,
– maximal horizontal dispersion ~4.8m

- New working point for LHC beams (Q20): Q_x=20.13, Q_y=20.18, γ_t=18, η(@26GeV)=1.8E-3,
- maximal horizontal dispersion ~8m