Beam dynamics issues and present limits

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LIU Day, 1.12.2010

Outline

- Present limits from observations (preliminary)
- Do we understand them? => Beam dynamics issues

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

+ all speakers + OP shifts for help in MDs

RF: T. Argyropoulos, T. Bohl, E. Ciapala, H. Damerau W. Hofle, E. Montesinos, J. Tuckmantel +

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

Limits for LHC beam variants

- At least 3 different bunch spacings (25 ns, 50 ns and 75 ns) should be considered for future LHC operation
- Single bunch limitations are the same for the same bunch parameters
  - not the case for transverse emittance at injection so far
- Multi-bunch limitations depend on
  - total intensity (resistive wall, HOMs, …)
  - local density (beam loading, HOMs with low Q)
  - specific resonant conditions (e-cloud)

    → for all these cases the 25 ns beam is the worst (with 4 batches)
  - beam spectrum

    → MKDV outgassing/heating for 50&75 ns spacings

Beam studies: what is new in 2010?

- Single bunch:
  - up to 3.5×10^{11} injected – a lot of studies & data
  - low gamma transition optics
- LHC beams:
  - 25 ns spacing
    - no limitation from ZS after a few first MDs
    - small losses (~5%) for nominal intensity
    - ultimate intensity injected: MD3.06: >20% losses (more for more batches), ε_H=5 μm, 0.4 eVs unstable on FB with 800 MHz on
  - 50 ns spacing
    - ultimate intensity inject. – 1 MD in || with setting-up for LHCFast

Intensity limitations for 25 ns beam -2010

intensity /bunch	Origin	Leads to	Present/future cures/measures
$0.2x10^{11}$	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
$0.5x10^{11}$	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) - a-C coating ($\delta \rightarrow 1.0$)
$1.2x10^{11}$	not known exactly e-cloud/impedance/SC(?)	- flat bottom/capture beam loss (>5%)	- (lower chromaticity) - WP, RF gymnastics - collimation
$1.5x10^{11}$	beam loading in 200 MHz RF system	- voltage reduction on FT - phase modulation	- Feedback & FF - RF cavities shortening
$1.6x10^{11}$	TMCI (transverse mode coupling instability) due to transverse impedance	- beam losses - emittance blow-up	- higher chromaticity - high voltage - transverse high bw FB

Intensity limitations

- Single bunch
  - space charge
  - TMCI (transverse mode coupling instability)
  - loss of Landau damping due to incoherent frequency shift
  - longitudinal/microwave instability
- Multi-bunch
  - e-cloud → Mauro's talk
  - beam loss (many reasons)
  - longitudinal coupled bunch instabilities
  - beam loading in the 200 MHz and 800 MHz RF systems
  - heating of machine elements (MKE, MKDV kickers, …)
  - vacuum (beam dump and MKDV outgassing), septum sparking (ZS was a main limitation in 2008 and 2009)

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 ($N=1.2\text{x}10^{11}$, 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) $2.5\text{x}10^{11} \rightarrow \Delta Q=0.1$ for $\varepsilon=3.5$ μm
- LHC ions in the SPS: $\gamma=7.31$, $N_e=1.5\text{x}10^{10}$, (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)

TMCI

- Threshold scales (matched voltage) $\sim \varepsilon_L \eta$
- Cures: high chromaticity, ε_L, impedance reduction… but 30-40% of transverse SPS impedance is still unknown → ongoing work (impedance team of E. Metral), transverse wide-band FB (W. Hofle with LARP)

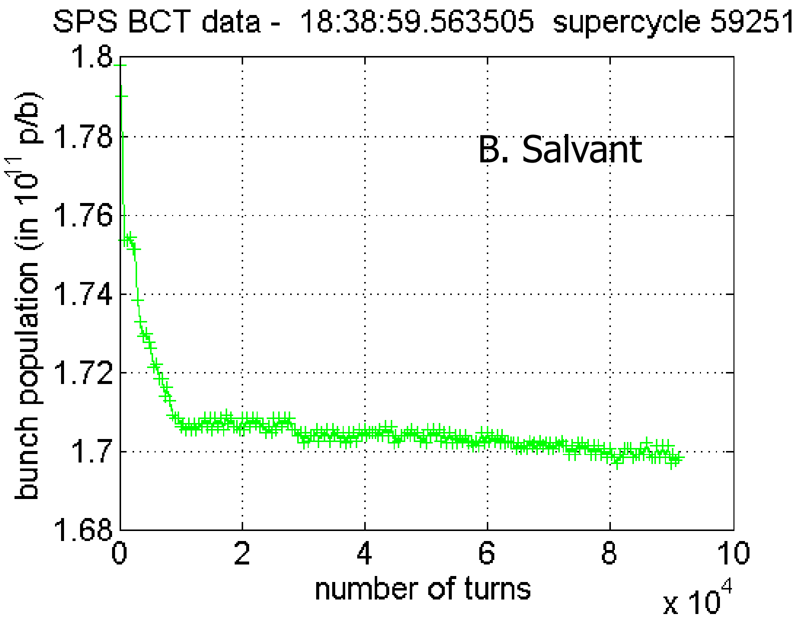
Preliminary results of MDs in 2010 (B. Salvant et al.)

- Threshold ~ $1.6\text{x}10^{11}$ for zero chromaticity – as expected
- Intensity from PS ~$3.5\text{x}10^{11}$, ε_L =0.35 eVs, τ=3.8 ns
- SPS end FB: $(2.25\text{-}3.3)\text{x}10^{11}$ for ξ_V in range 0.0-0.3, ξ_H=0.25
- Higher TMCI threshold was expected (from theory and simulations) for smaller transverse emittances due to space charge effect, opposite effect was observed on FB for small and nominal transverse emittances (not directly comparable due to different RF → more measurements)

Ultimate single bunch

Losses

- N=1.8×10^{11} injected – 5.5% loss
- N=1.4×10^{11} - no visible loss on FB



Bunch parameters

- PS (ext): $\varepsilon_{H/V}$=2.5/2.6 μm
- SPS (ext) $\varepsilon_{H/V}$=3.2/3.3 μm
- Need to blow up the transverse emittance in the PS to reduce the transverse emittance blow-up in the SPS
- $\varepsilon_{H/V}$=3.3/3.6 μm for N >1.8 10^{11}
- $\varepsilon_{H/V}$=5-6 μm for N >2.5 10^{11}
- Longitudinal instability N >1.4 10^{11} (in single and double RF)
- A lot of data, need careful analysis and interpretation

Single bunch data (C. Bhat)

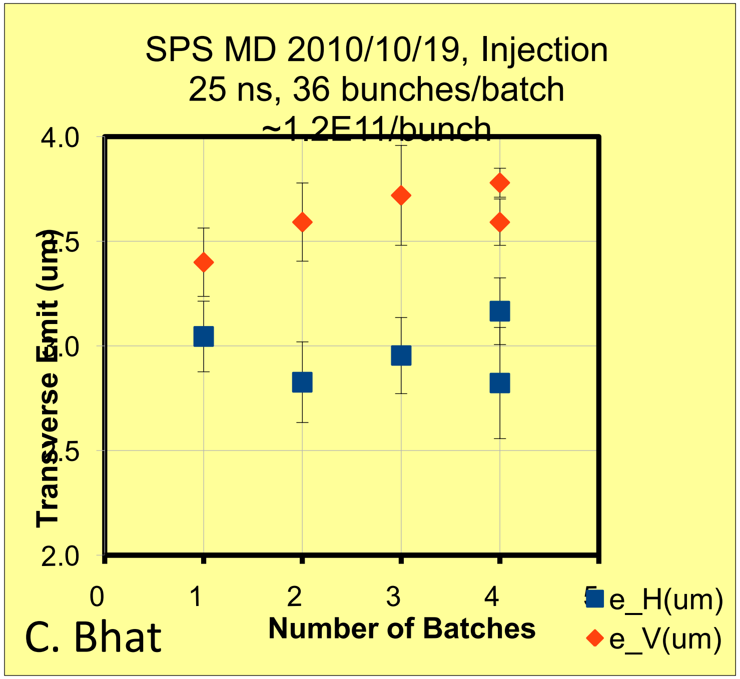
Date		Ave. Bunch Intensity	e_H(Inj) (μm)	e_H(Eject.) (μm)	e_V(Inj) (μm)	e_V(Eject.) (μm)	Accel. Eff.
20101012	PS#	1.90E+11		2.92		1.97	
	LE=0.31 eVs			0.2		0.15	
	SPS*	1.5-1.83E11	3.05	3.28	3.35	3.14	96%
20101025	PS*	2-2.5E11		2.45		1.35	
	LE=0.32 eVs						
	SPS#	1.8-2.52E11	3.25	3.08	3.46	3.61	97%
			0.17	0.13	0.21	0.26	
	# Average over many measurements						
	* Single Measurement, which represents typical case						

LHC beams in 2010

50 ns spacing

- nominal intensity (MD19.10)
  emittances:
  inj. H/V 2.5/2.9 ±0.4,
  extracted: 2.2/2.8 ± 0.4
  → no emittance blow-up
- ultimate intensity (MD3.09)
  - capture losses 10-12%
  - 1.5×10^{11} on flat top
  - very small increase of e-cloud signal (in agreement with simulations of G. Rumolo)
- back to nominal→3-4 % losses

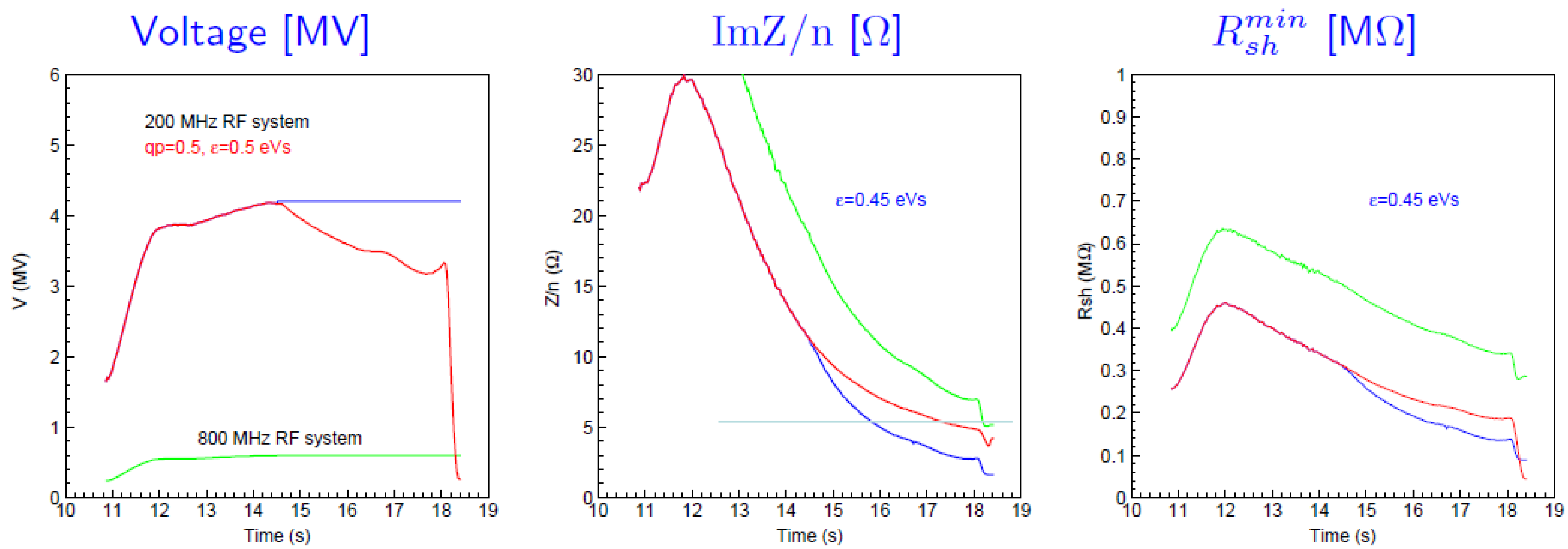
25 ns spacing



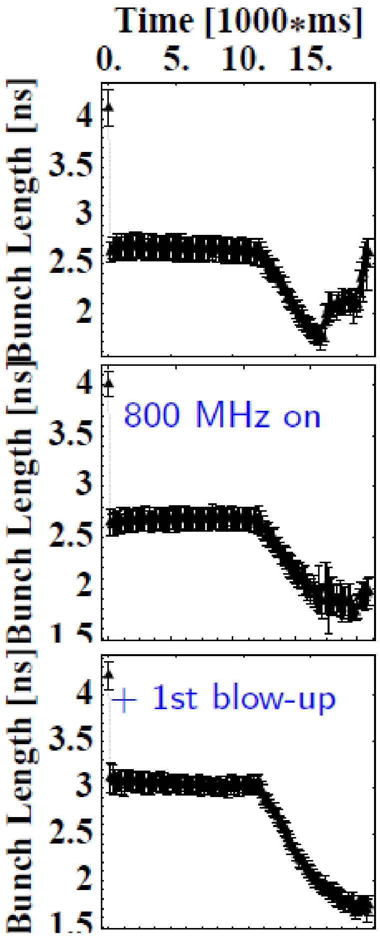
Vertical emittance increase with number of batches, measurement at 0.55 s (26 GeV)

Loss of Landau damping towards the end of the ramp => instability

Threshold impedances for nominal LHC intensity



Multi-bunch instability and its cures

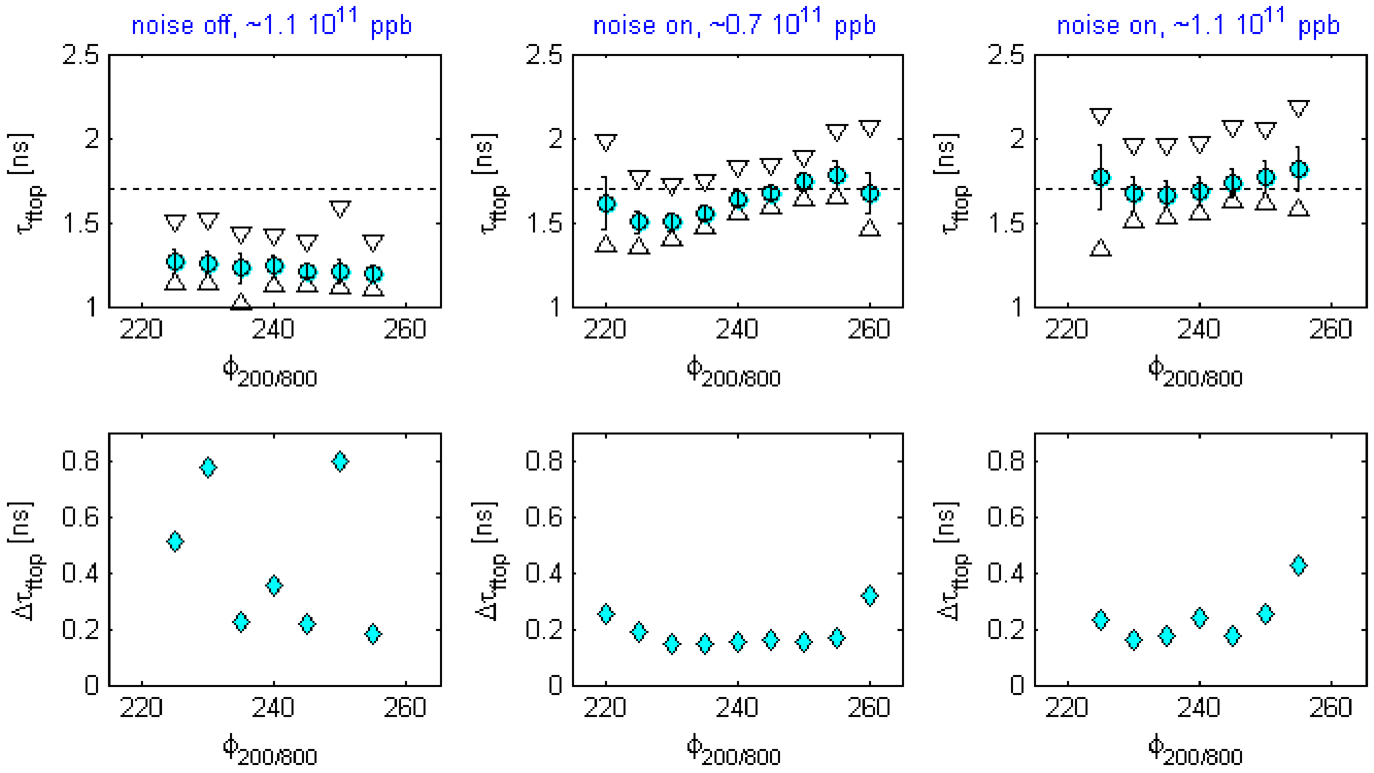


•Threshold: single batch (25 ns spacing) with $2x10^{10}$/bunch (2006, $3x10^{10}$ before) is unstable at the end of the ramp

•Possible source: fundamental or HOMs of
•200 MHz (629, 912 MHz) or 800 MHz (RF systems – not known

•Cures:
- FB, FF, longitudinal damper for 200 MHz
- 800 MHz RF system in bunch shortening mode through the cycle
- controlled longitudinal emittance blow-up (0.35 → 0.42 eVs → 0.65 eVs)

Cures for multi-bunch instability
25 ns beam



Bunch length
(av., max-min)
at 450 GeV/c

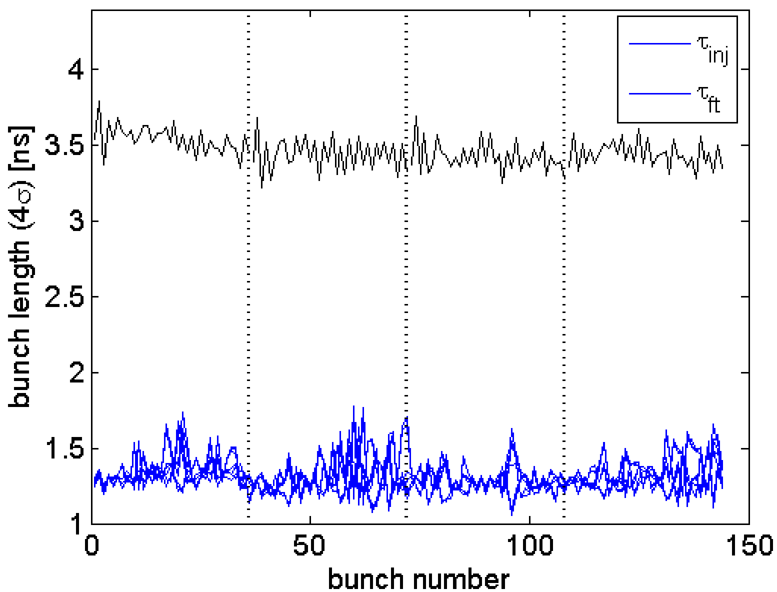
Beam stability
from $\Delta\tau$

G. Papotti et al.

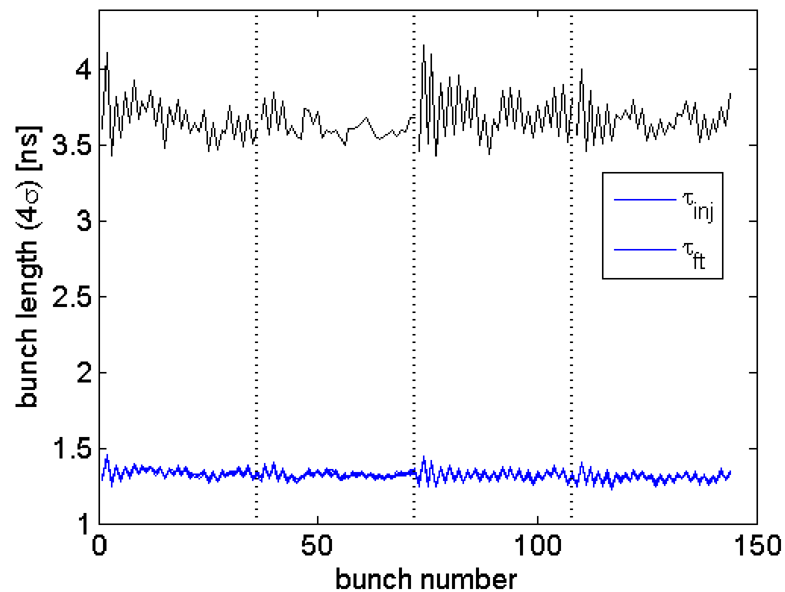
→ larger emittance (0.9 eVs for ult.) for higher intensities – more RF!

Longitudinal multi-bunch instability
50 ns beam, 2 RF systems, no RF noise

Short PS bunches



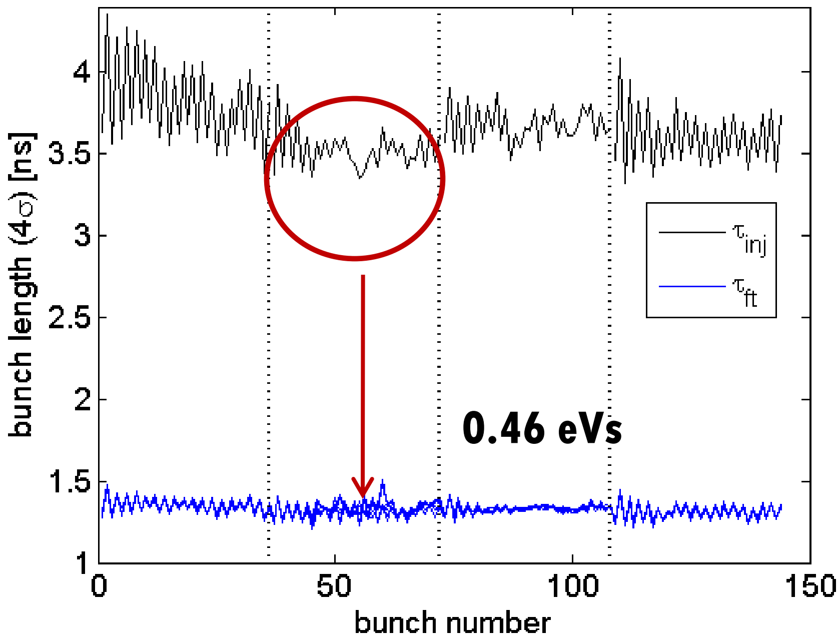
Long PS bunches



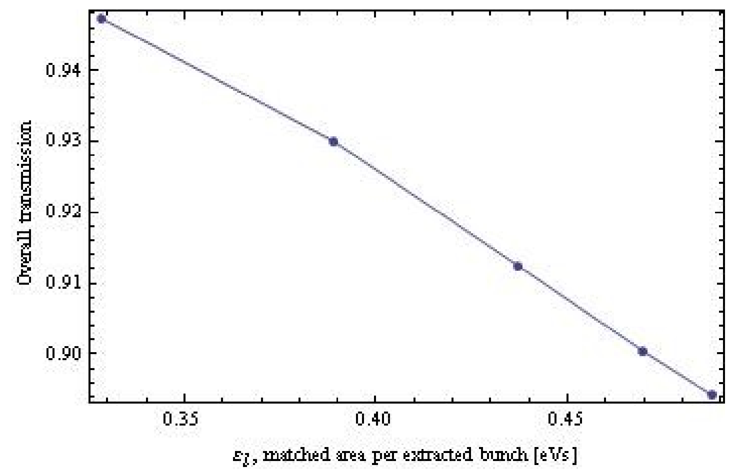
T. Argyropoulous et al.

Multi-bunch instability due to loss of Landau damping?

50 ns beam



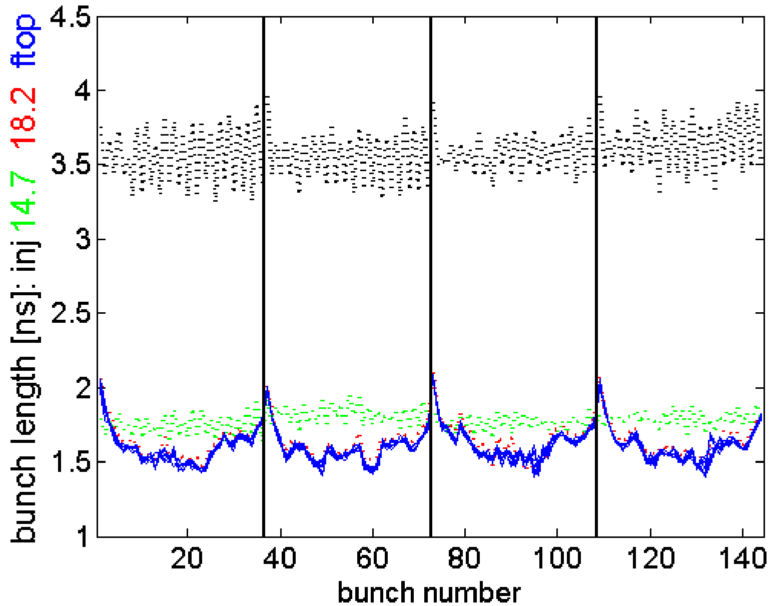
- There is a narrow window for the injected parameters – losses increase for larger bunch length and beam is unstable for lower emittance (blow-up is required also for 50/75 ns beam)



H. Damerau et al.

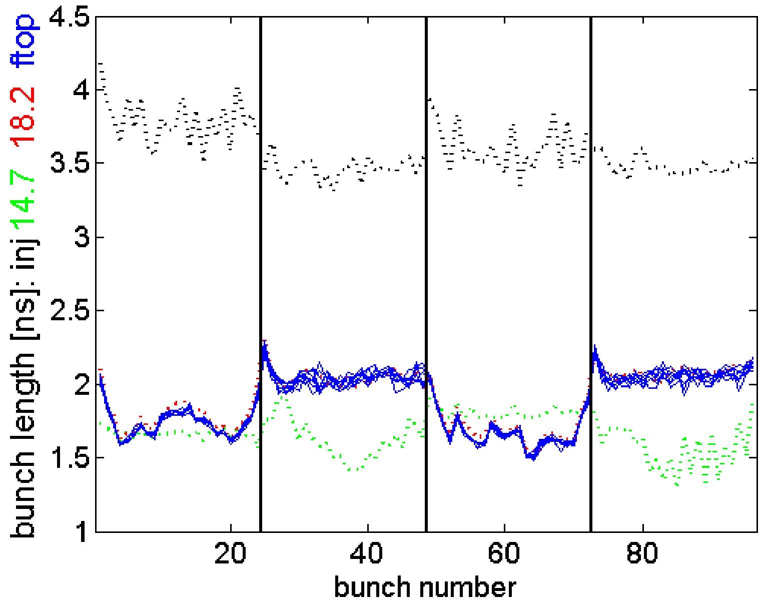
Controlled longitudinal emittance blow-up in a double RF system

50 ns beam



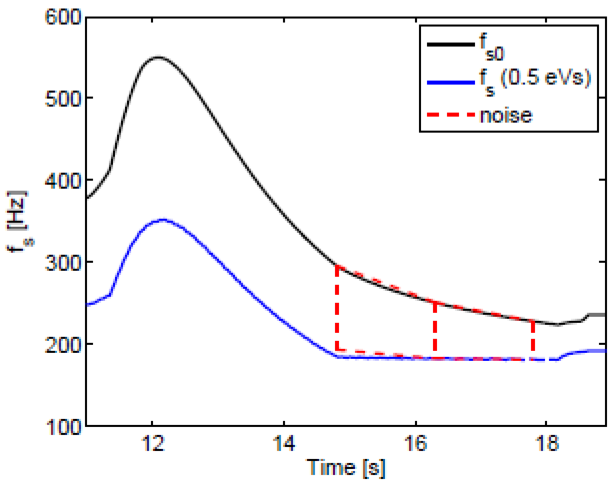
Non-uniform emittance blow-up due to beam loading in a double RF system

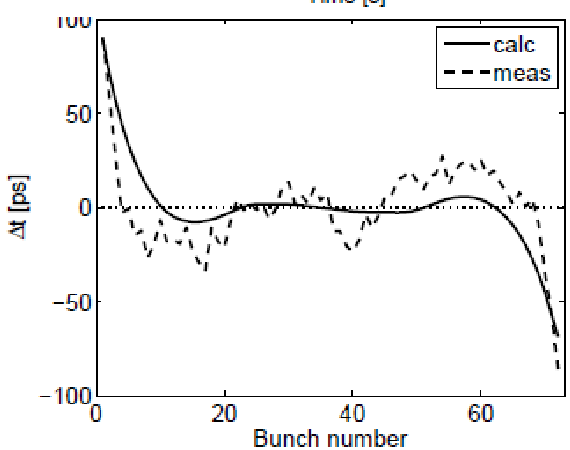
75 ns beam

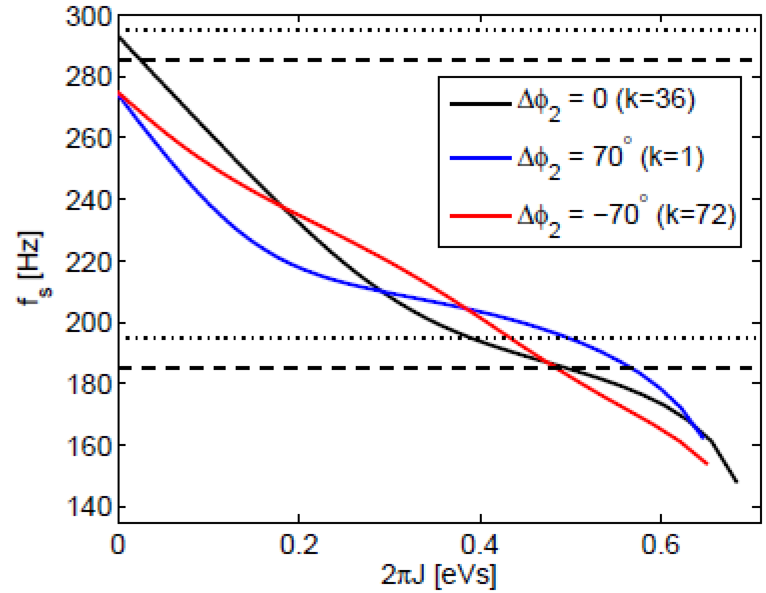


Non-uniform emittance blow-up and beam instability (?) for short injected bunches

Effect of beam loading in the 200 MHz RF on emittance blow-up by band-limited noise







T. Argyropoulos et al., HB2010

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

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

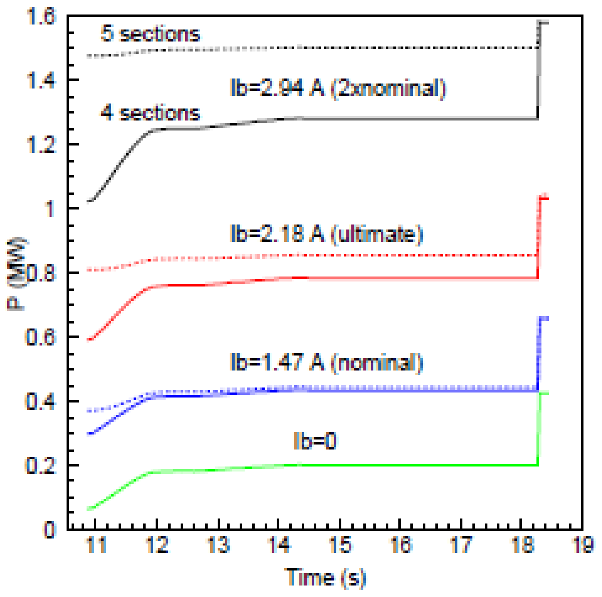
Beam loading in the 200 MHz RF system

- Power (1 MW) and voltage (7.5 MV) limitations are still OK for acceleration of the ultimate beam, but not for FT
- If larger emittances ($\varepsilon \sim \sqrt{N}$) required for beam stability in SPS or in LHC then beam transfer to the LHC 400 MHz RF system is critical: since

  $\tau \sim (\varepsilon / V^{1/2})^{1/2} \longrightarrow$ for $\tau = \text{const}$

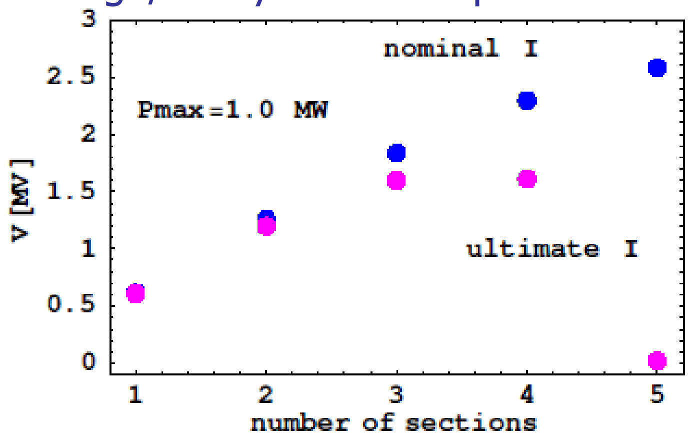
  $V = V_1 \, N_{ult}/N_{nom} = 1.48 \, V_1 = 10.3$ MV
- Possible solutions:
  - install the 200 MHz RF system in the LHC (problems → LHC)
  - rearrange the SPS 200 MHz RF

Power/cavity (LHC cycle) for different intensities

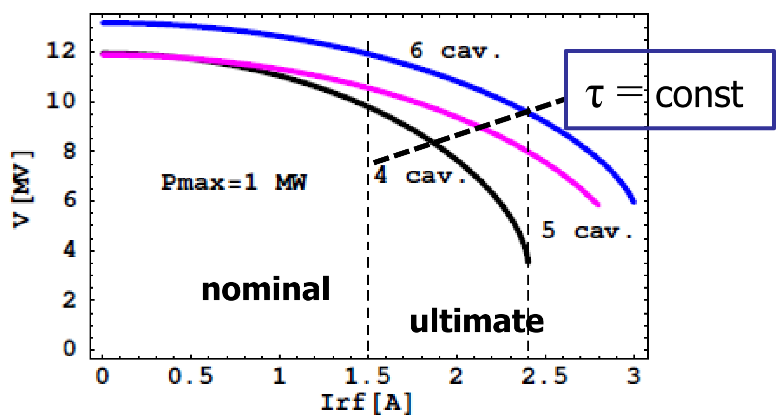


200 MHz TW RF system upgrade

Voltage/cavity on Flat Top



Total voltage on Flat Top



- Now: 2x4+2x5 sections
- Power/cavity (E. Montesinos):
  - 700 kW cw (full ring, used)
  - 1.05 MW pulsed (half ring, not tested)
- 5-section cavities are useless for ultimate intensities and 1 MW limit
- 7.5 MV used @450 GeV for beam transfer to LHC → more (~ √N) for higher intensities (up to 0.9 eVs)

→ Rearrange 4 cavities (+ 2 spares) into 6 shorter cavities of 2x4+4x3 sections with 2 extra power plants (LSS3) to

- reduce beam loading/cavity and beam coupling impedance (~L^2)
- restore voltage for LHC ultimate beam
- improve performance for CNGS/FT

SPS RF system modification: impedance reduction

Total beam (peak) impedance of the 200 MHz TW RF system

$$Z = R/8 \sum L_n^2 = RL^2/8 \sum (n-1/11)^2$$

$R = 27.1$ kOhm/m^2,

n - number of sections per cavity

$L_n = L\,(n-1/11)$, $L = 11 \times 0.374$ m, $RL^2/8 = 57.3$ kOhm

4 cav.	2x5 & 2x4:	Z = 4.5 MOhm	- now
5 cav.	2x3 & 3x4:	Z = 3.6 MOhm	- 20% less
6 cav.	4x3 & 2x4:	Z = 3.7 MOhm	- 18% less

→ We have two more cavities in the SPS and reduce impedance!
(To compare with installation of the 200 MHz in LHC)

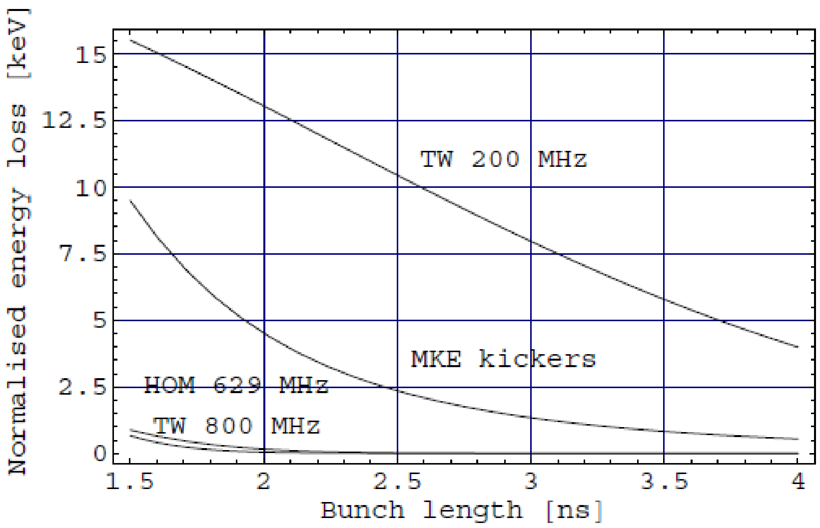
SPS impedance

- Reduce known high impedances → loss of Landau damping, heating
  - MKE: serigraphy – 3 done, 5 more in 3 years (M. Barnes et al.) Transverse impedance issue. New design (B. Goddard)?
  - MKDV, MKDH: complete transition pieces between magnet and tank (heating, outgassing)
  - 800 MHz TW cavities: active damping → new FB and FF (2011?)
  - 200 MHz TW cavities: reduction by 20% due to modifications

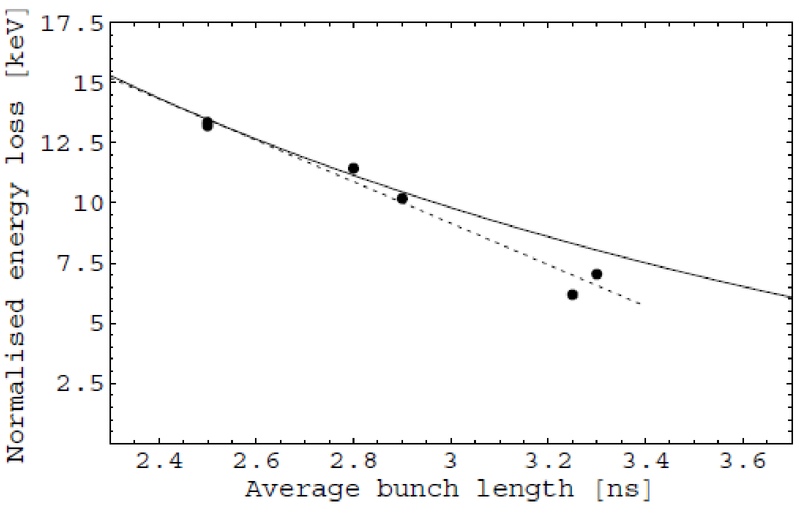
- Search for unknown impedances:
  - transverse (broad-band and narrow-band): E. Metral's team
  - longitudinal (narrow-band?): RF team

Longitudinal impedance: resistive part

known impedance

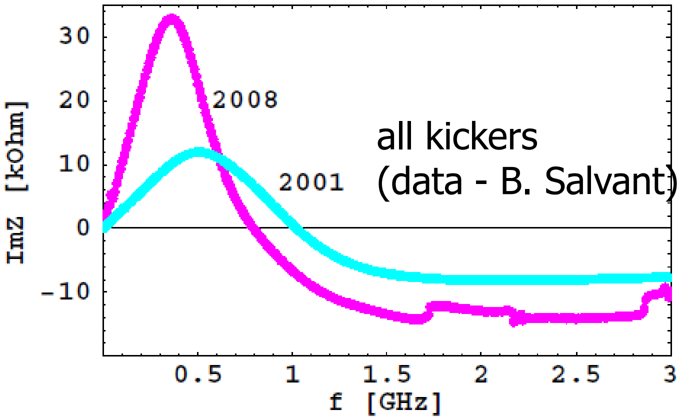


comparison with measurements

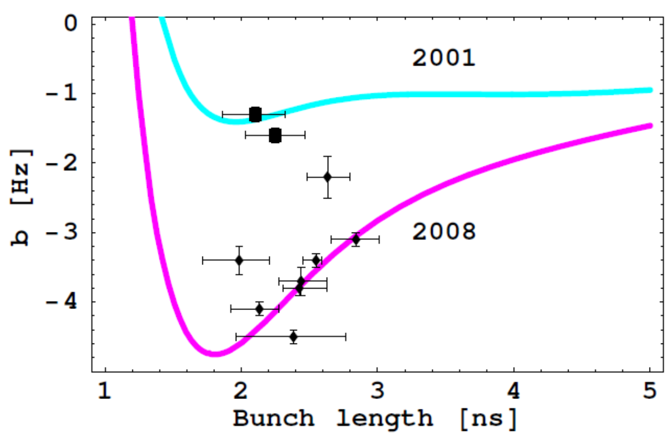


→ no room for extra impedances

Longitudinal impedance: reactive part

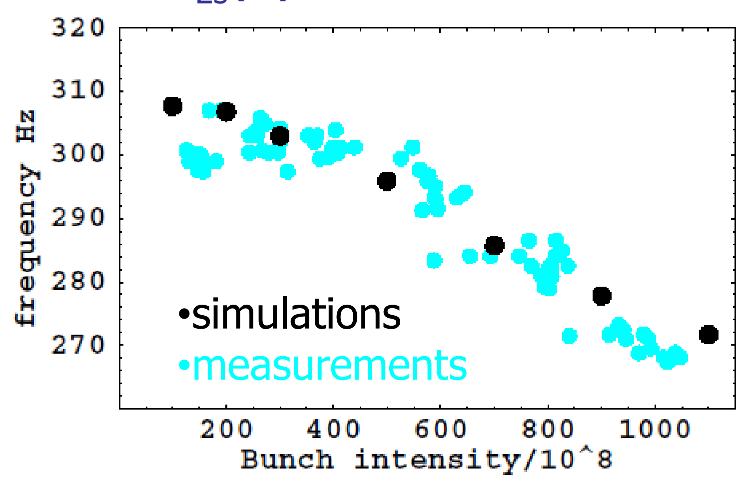


- Kickers - main contribution to ImZ → loss of Landau damping
- Not much room for extra impedance (for space charge term < -0.2 Ohm)



Synchrotron frequency shift

$f_{2s}(N) = a + b\, N/10^{10}$

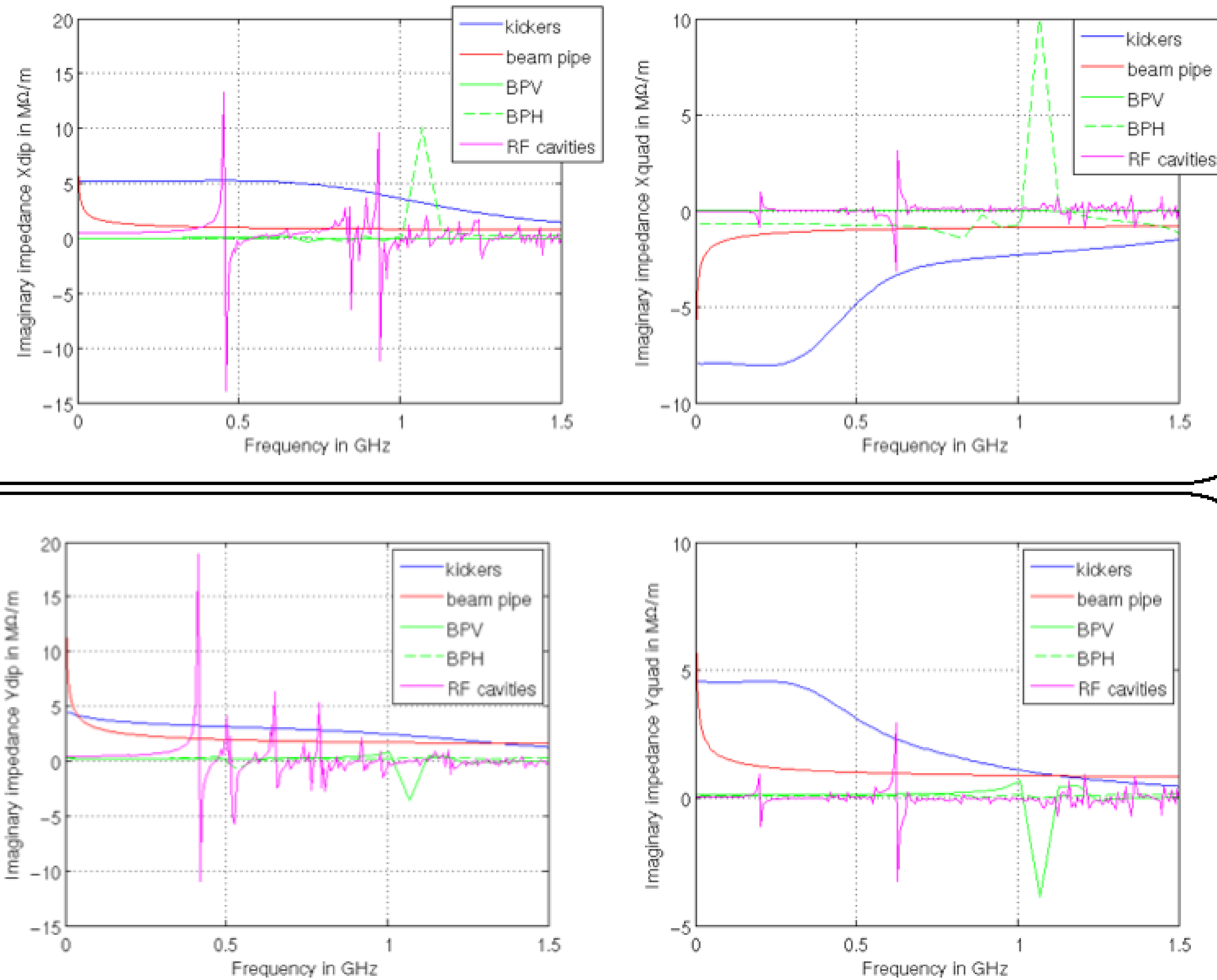


Imaginary impedance for the current SPS model

E. Metral, talk at SPSU SG

Imaginary Horizontal impedance

Imaginary Vertical impedance



Dipolar contribution

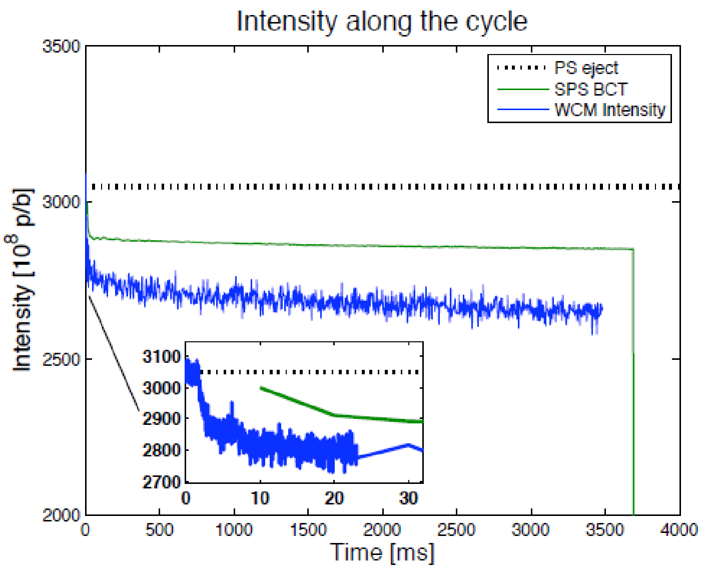
Quadrupolar contribution

Low γ_t - solution for everything?

- Successful MDs with a single bunch (H. Bartosik, Y. Papaphilippou et al.): γ_t=22.8 → 18, η increase 2.86 (26 GeV/c) to 1.6 (450 GeV/c)
- Expected increase in beam stability for the same bunch parameters $N_{th} \sim \eta$ for both TMCI (observed!) and longitudinal instabilities
- To have the same longitudinal parameters (bucket area) $V \sim \eta$ → can be a problem for extraction to LHC of the same longitudinal emittance as now (now 4σ bunch length limit is 1.7 ns)
- But emittance blow-up for the same stability in the SPS can be reduced: for 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 $\tau = \text{const}$ for V=const.
- If LHC itself needs higher longitudinal emittance at injection (IBS, stability) → 200 MHz RF system in LHC?
- Fast cycles are not possible (3 s or 4.2 s acceleration time)
- Space charge limit, e-cloud - ?

Low γ_t - solution for everything?

No TMCI



Emittances

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

  but too low voltage (1.8 MV) → losses (10-15%)
- Acceleration of 2.5×10^{11}
  - 5% capture losses
  - $\varepsilon_{H/V}$ = 2.4/2.9,
  - τ = 1.5 ns on FT
- Very promising → more studies

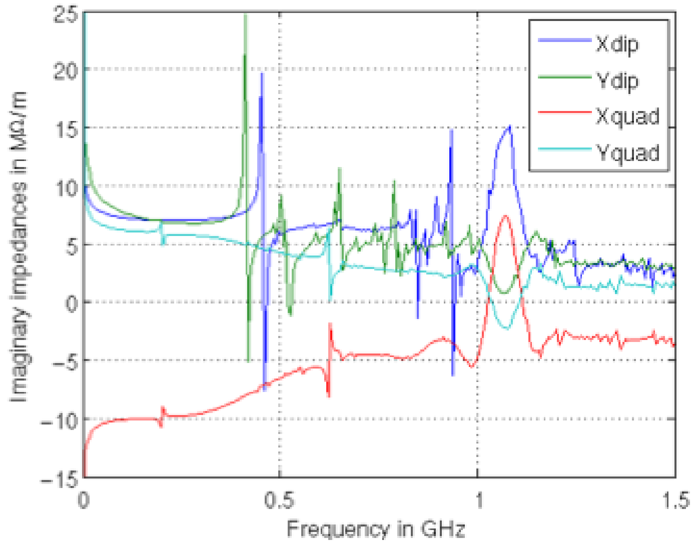
Proposed beam dynamics studies

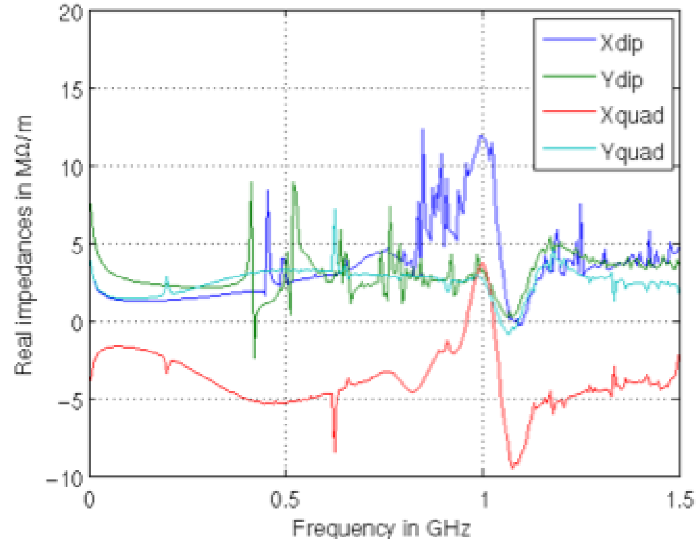
- limitations with “above nominal” intensity beams – more MDs, increase of intensity in steps with time for optimisation
- beam loss origin
- transverse emittance blow-up:
  - accurate and systematic measurements
  - minimisation
  - origin if unavoidable
- impedance identification (transverse + HOM longitudinal)
- TMCI
  - threshold in a double RF system
  - multi-bunch stability
  - feasibility of damping by transverse FB
- longitudinal stability in a double RF system and emittance blow-up
- low gamma transition

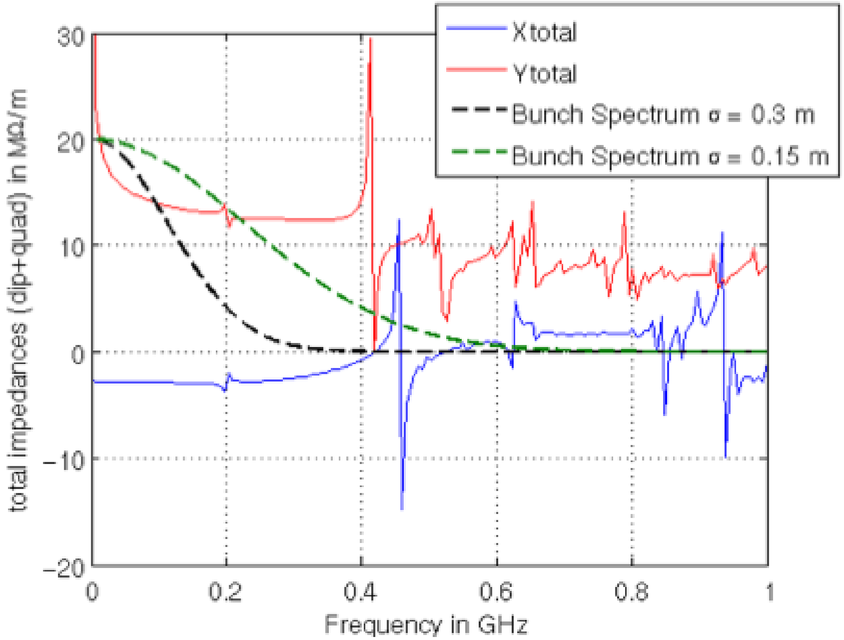
Summary

- Main SPS limitations for ultimate intensity with nominal transverse emittances have been identified and possible cures suggested
- MDs needed to see other possible limitations
- MDs with small injected transverse emittance beam and proper instrumentation are required to study origin of blow-up for high intensities
- Cures for longitudinal instability (800 MHz and emittance blow-up) are limited – consider other solutions to recover Landau damping
- Kickers give dominant contribution to impedance – reduction
- Low gamma transition optics is a very promising solution for beam stability, transfer to LHC should be studied
- Still more results to come for 2010 MDs (ultimate 25 ns,...)

Impedance model







Conclusions:

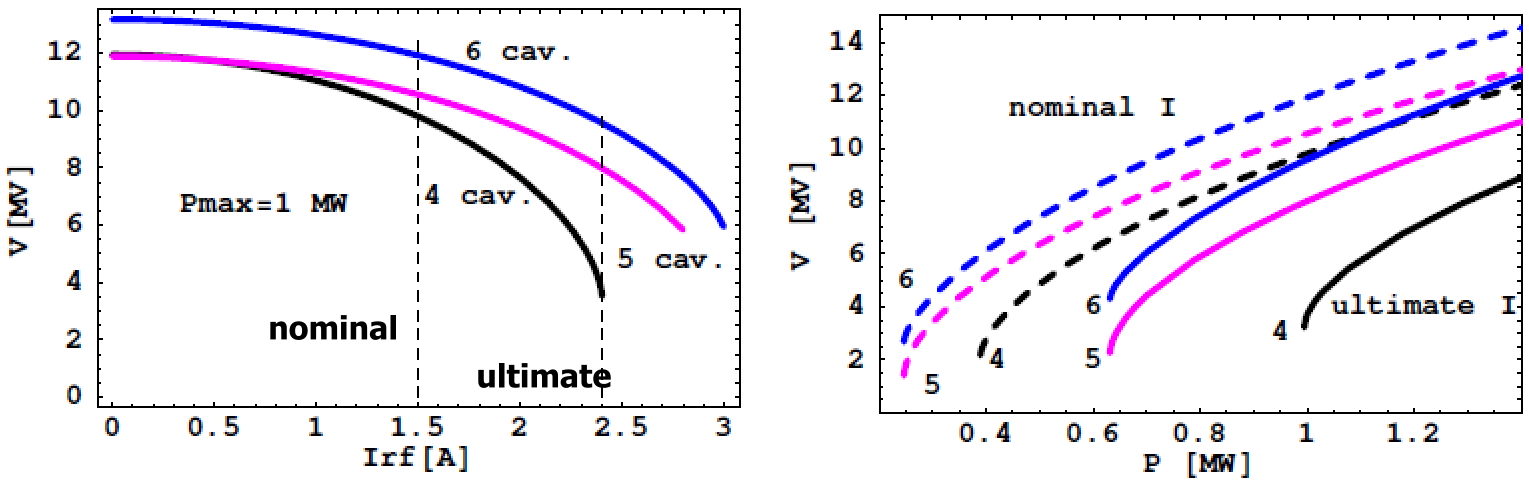
- impedance and wakes have complicated shapes
  → complicated beam dynamics

- negative horizontal impedance at low frequencies
  → positive tune shift in the horizontal plane

- smaller bunch → wider bunch spectrum
  → smaller effective impedance

0.3 m → Zeff = 14.3 MΩ/m (Sacherer equation for mode 0)
0.15 m→ Zeff = 13.4 MΩ/m (Sacherer equation for mode 0)

Total 200 MHz voltage on SPS flat top



- Existing configuration will have problems at ultimate LHC current even at 1 MW

- The same voltage for ultimate current as for nominal could be obtained with 6 cavities and power of 1 MW

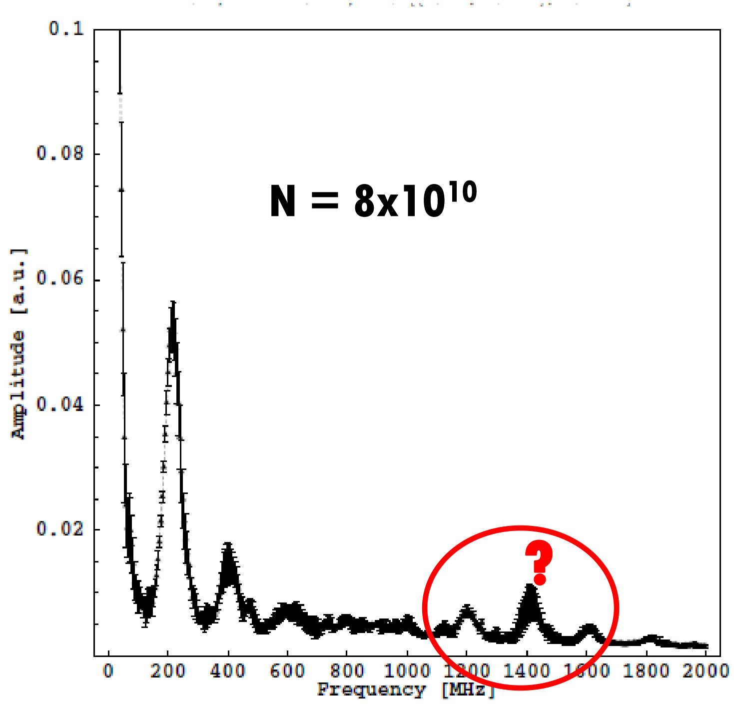
SPS beams now and in future

Beam parameters		SPS at 450 GeV/c (maximum injected minus losses)					LHC ultim./+
		LHC	LHC	LHC	FT	LHC	LHC
bunch spacing	ns	25	50	75	5	indiv	25
bunch intensity	10^{11}	1.2	1.2	1.2	0.13	**1.8**	1.9(2.3)
number of bunches		4x72	4x36	4x24	4200	1	288
total intensity	10^{13}	**3.5**	1.7	1.2	**5.3**	0.02	5.5(6.6)
long. emittance	eVs	0.7	0.4	0.4	0.8	0.3	<1.0
norm. h/v emittance	μm	**3.6**	2.0* 1.1/1.4	2.0*	8/5	?	**3.5**

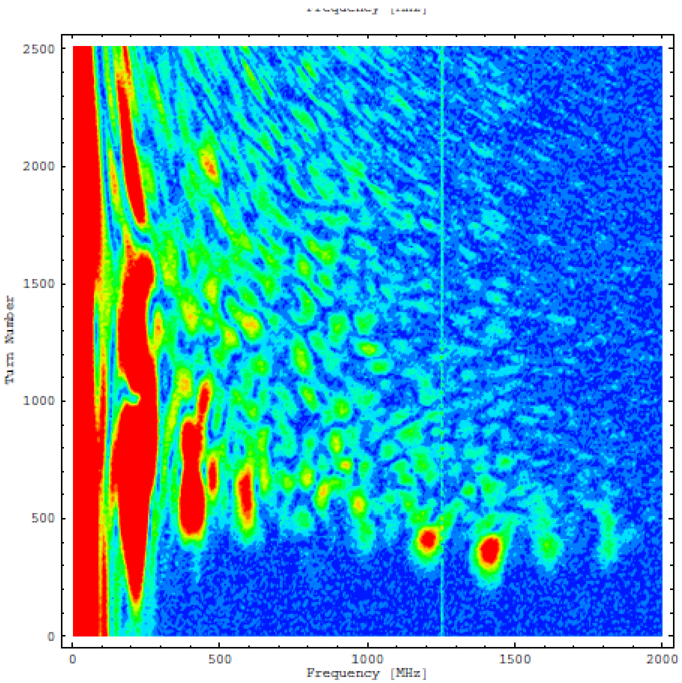
* single batch injection in PS

Unstable bunch spectra

Projection

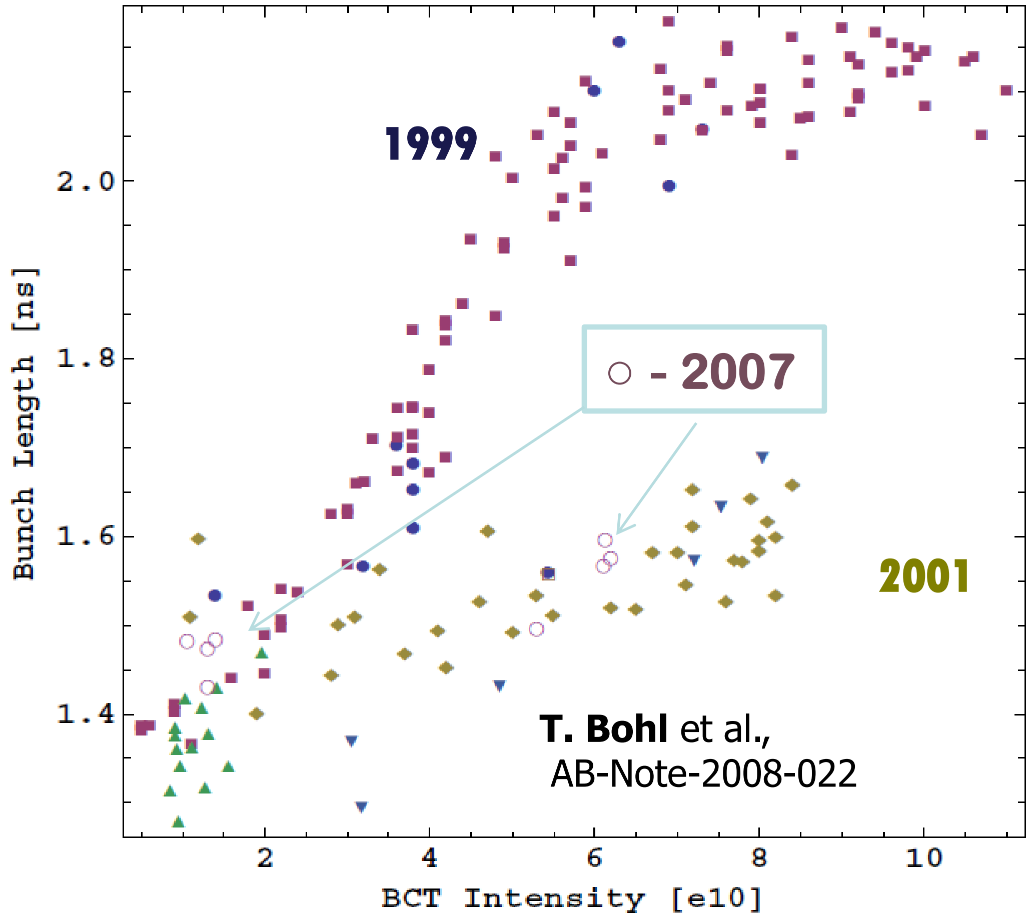


Contour plot



T. Bohl, 2007

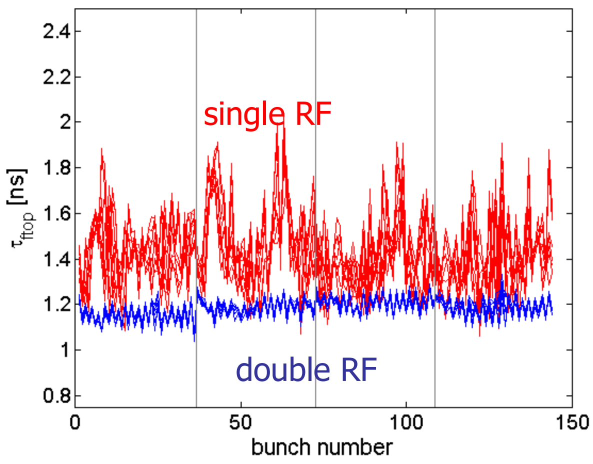
Bunch lengthening
(at 600 ms, 900 kV, ε = 0.15 eVs, 26 GeV/c)



- **1999** – bunch lengthening due to microwave instability
- **1999/2000** – pumping port shielding: factor 7 decrease in slope
- **2001** - bunch lengthening due to potential well distortion (Im Z/n)
- **2007** – no microwave instability and bunch lengthening is similar to 2001

LHC beam with 50 ns bunch spacing

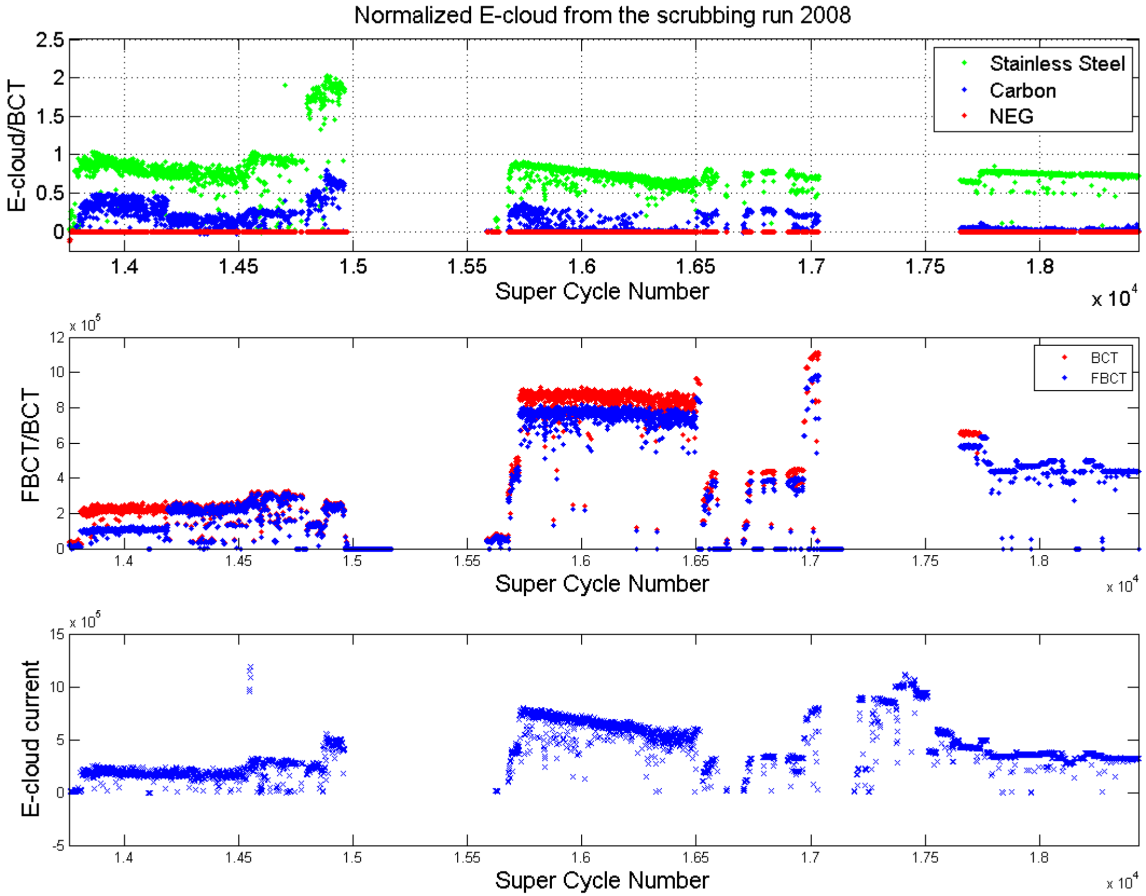
bunch length on flat top



T. Argyropoulos et al.

- small emittances ($1.2x10^{11}$/b):
  - transverse H/V:
    2.0 μm (single batch injection in PS)
    1.1/1.4 μm (double batch inj., E. Metral)
  - longitudinal: 0.4 eVs , 1.2 ns (FT)
    (stable in double RF system, BSM)
- small beam losses (< 5%)
- no e-cloud signal (only before scrubbing), no degradation is expected for increased intensity from simulation (G. Rumolo) – also verified in recent MDs in SPS
- 200 MHz beam loading limit: $3x10^{11}$/bunch

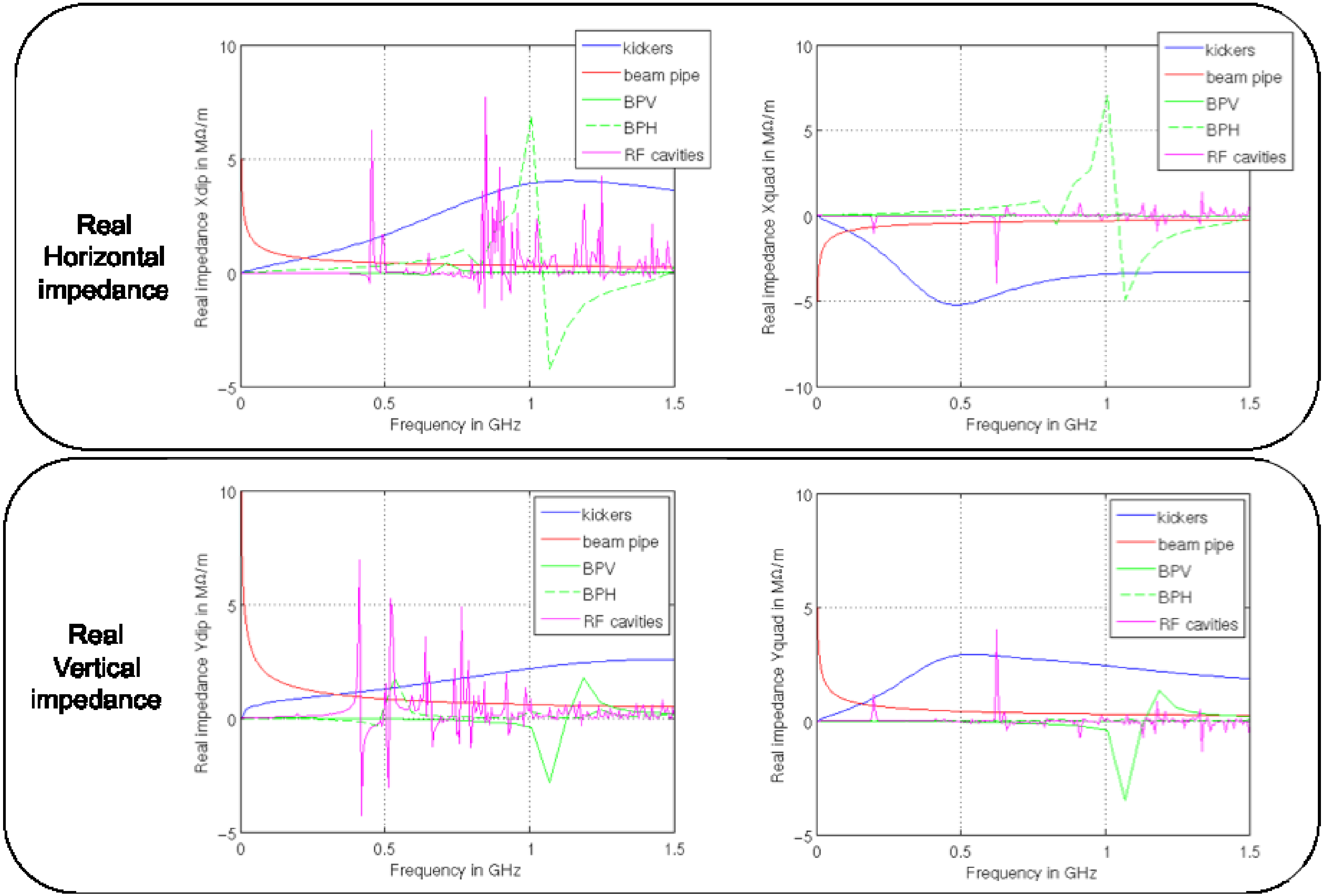
Beam loss and e-cloud



LIU Day

Real impedance for the current SPS model

(note: the simulated BPMs wake was optimized for HEADTAIL, and too short to get an accurate impedance)



Dipolar contribution

Quadrupolar contribution