SPS collective effects and limitations

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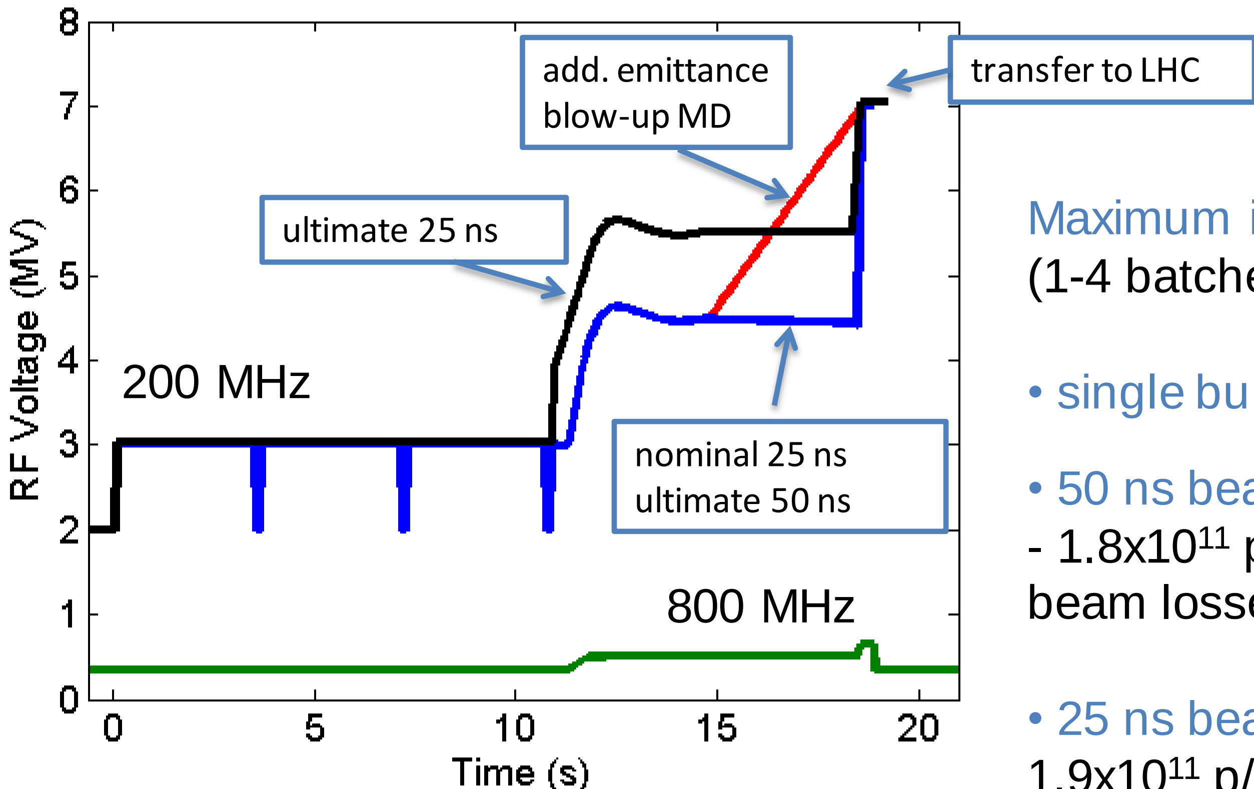
LHC beams in the SPS: acceleration from 26 to 450 GeV/c



Maximum intensity achieved (1-4 batches) at 450 GeV/c :

- single bunch – 3.0×10^{11}
- 50 ns beam (2011)

- 1.8×10^{11} p/b (not stabilized), beam losses ~ 10%

- 25 ns beam (2010): injected 1.9×10^{11} p/b, losses ~ 20-30% (more for more batches)

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SPS beams in 2011

Beam parameters		SPS at 450 GeV/c (stable beam)			
		LHC	LHC	FT	indiv
bunch spacing	ns	25	50	5	23040
bunch intensity	10^{11}	1.2	1.6	0.1	3.0
number of bunches		4x72	4x36	2x2100	1
total intensity	10^{13}	3.5	2.3	4.2	0.04
long. emittance	eVs	0.7	0.5	0.8	0.4
norm. h/v emittance	μm	2.5/3.0	2.0/1.9	8/5	2.5*

* Q20 optics

Intensity and beam quality (BQM!) limitations

- Single bunch effects
  - space charge → working point optimisation (H. Bartosik et al. + study of G. Franchetti, GSI)
  - TMCI (Transverse Mode Coupling Instability)
  - loss of Landau damping
  - longitudinal/microwave instability
- Multi-bunch effects (total intensity or local density)
  - e-cloud
  - beam loss (many possible reasons) → PS-SPS beam transfer studies
  - 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), ZS septum sparking

Intensity limitations for 25 ns beam - 2011

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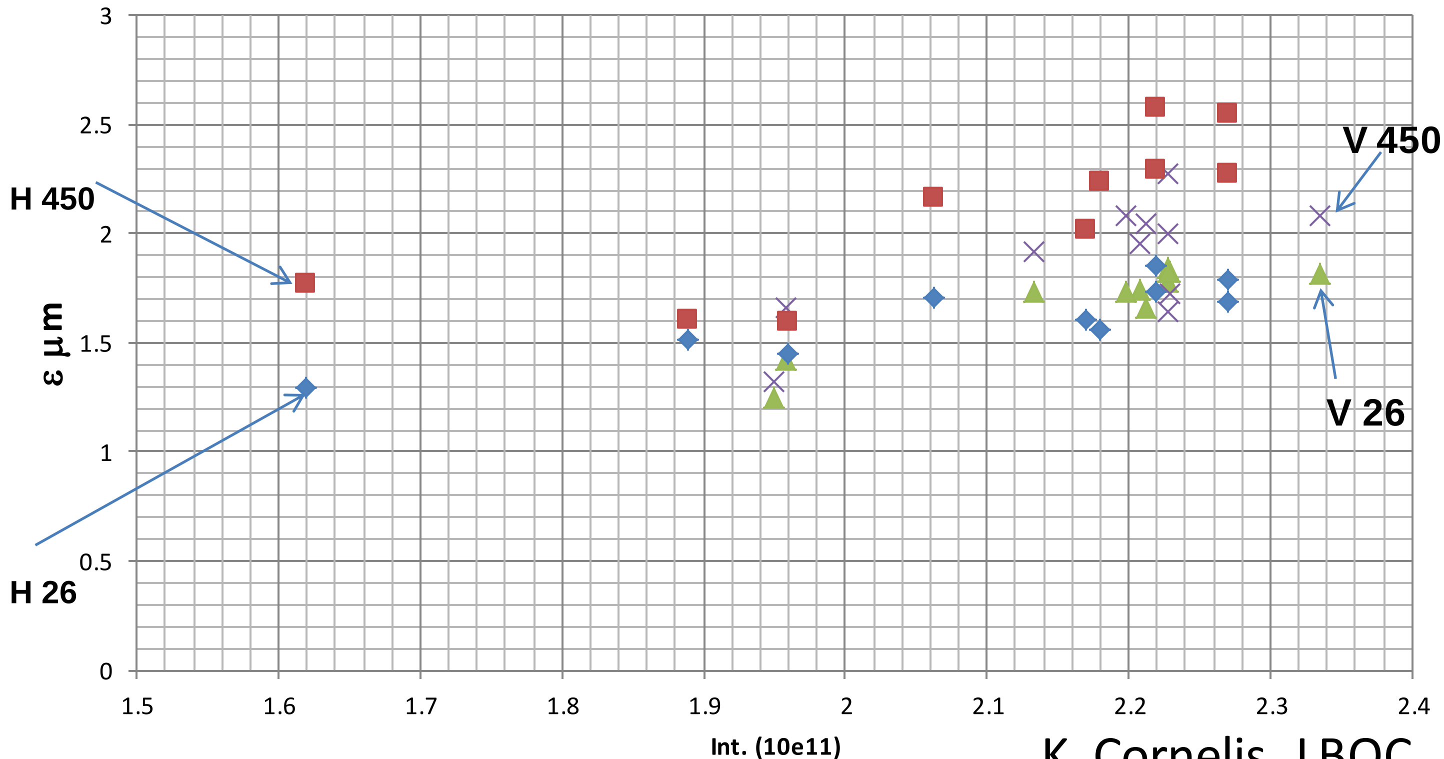
intensity /bunch	Origin	Leads to	Present/future cures/measures
$0.2x10^{11}$	loss of Landau damping / longitudinal multi bunch instability due to longitudinal impedance	- beam loss during ramp - bunch variation @450GeV/c	FB, FF, longitud. damper - 800 MHz RF system - emit. blow-up → RF
$0.5x10^{11}$	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 - beam losses	- scrubbing run ($\delta \rightarrow 1.6$) - high chrom. (0.2/0.4) - transv. damper (H) - (50/75 ns spacing) - a-C coating ($\delta \rightarrow 1.0$)
$>1.2x10^{11}$	beam loading / ecloud / impedance / space charge (?)	- 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 - b-by-b 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

Cures

- Understanding the limitations: MD studies, simulations, calculations
- Impedance identification and reduction (MKE kickers, MKDV, 200 MHz RF)
- Low γ_t (Q20 optics) $\longrightarrow$ talk of H. Bartosik
- e-cloud mitigation $\longrightarrow$ talk of M. Taborelli
- Upgrade of the 200 MHz RF system $\longrightarrow$ talk of E. Montesinos
- Landau cavities (800 MHz RF system)
- Controlled longitudinal emittance blow-up
- High bandwidth transverse feedback (e-cloud, TMCI)

Single bunch: transverse emittance versus intensity

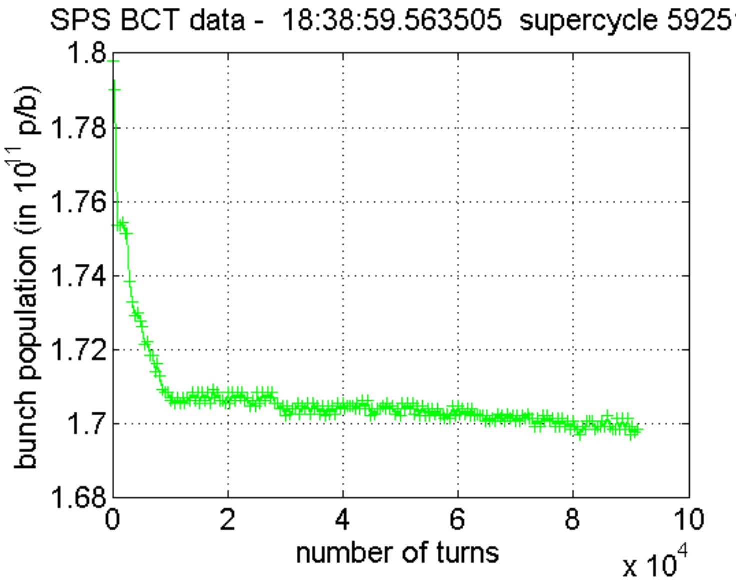


K. Cornelis, LBOC

- injected emittance is increasing with intensity (~ 30%)
- emittance blow-up in SPS above $2x10^{11}$, more in H-plane

Transverse Mode Coupling Instability

- **Measurements** (B. Salvant et al.): threshold @26 GeV/c - 1.6×10^{11} for $\xi_V = 0$ ($\varepsilon_L = 0.35$ eVs, $\tau = 3.8$ ns); $(2.25\text{-}3.3) \times 10^{11}$ for ξ_V in range 0-0.3, $\xi_H = 0.25$
- Threshold scales (matched V) $\sim \varepsilon_L \eta$, where $\eta = 1/\gamma^2 - 1/\gamma_t^2$
- **Cures:**
  - high ξ_V, ε_L and η → lower γ_t (Q20 optics!)
  - impedance reduction… but ~30% of transverse SPS impedance is still unknown → ongoing work (B. Salvant et al.)
  - transverse wide-band FB (W. Hofle et al. with LARP)

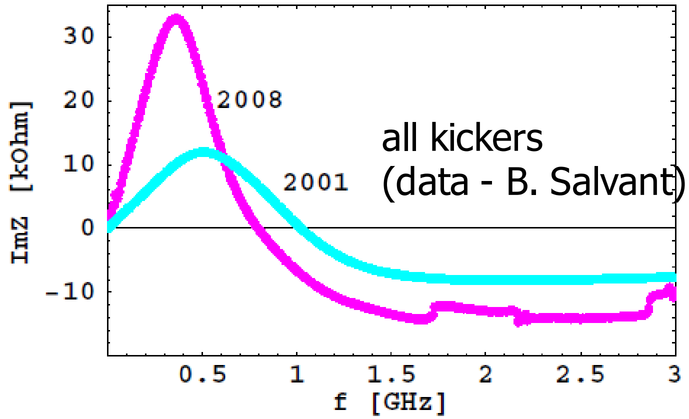


SPS impedance

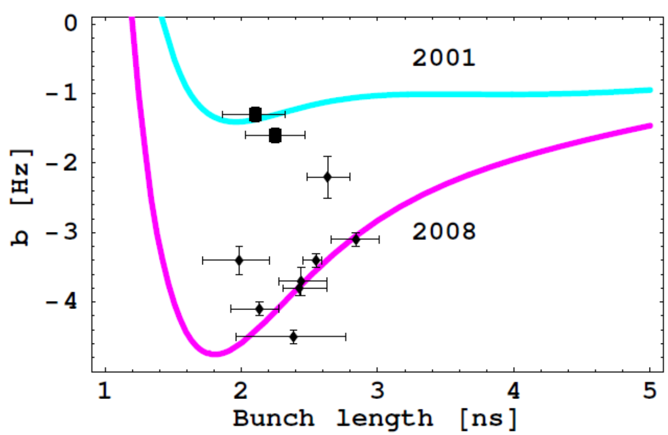
- Reduce known high impedance → loss of Landau damping, heating
  - MKE: serigraphy – the last after LS1 (M. Barnes et al.)

    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 (2014?)
  - 200 MHz TW cavities: reduction by 20% due to modifications
- Search for unknown impedances:
  - transverse (broad-band and narrow-band)
  - longitudinal (narrow-band?)

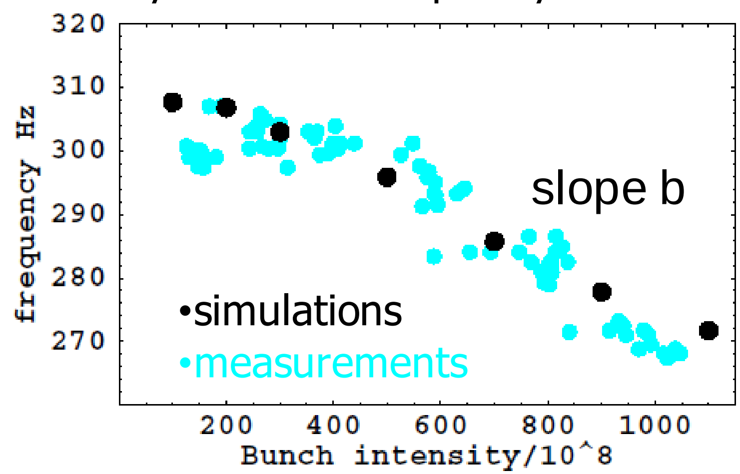
Longitudinal impedance: reactive part



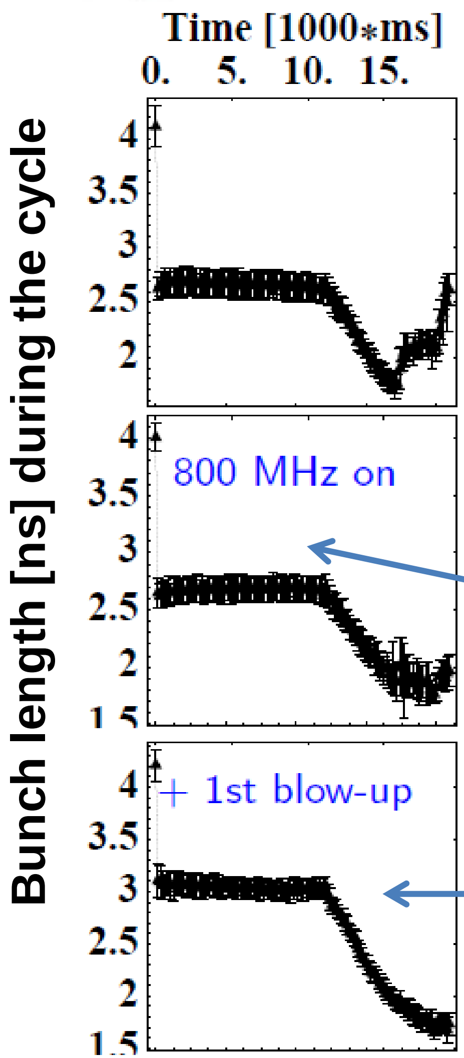
- Kickers - main contribution to ImZ → loss of Landau damping
- Not much room for extra impedance ,
- Similar for resistive impedance (stable phase shift measurements)



Quadrupole
synchrotron frequency shift



Longitudinal multi-bunch instability and its cures



- **Threshold:** reduces with energy ~1/E, single batch (25 ns spacing) with $2x10^{10}$p/b is unstable at the end of the ramp, beam is lost at nominal intensity

Possible source: fundamental /HOMs of 200 MHz or 800 MHz RF systems

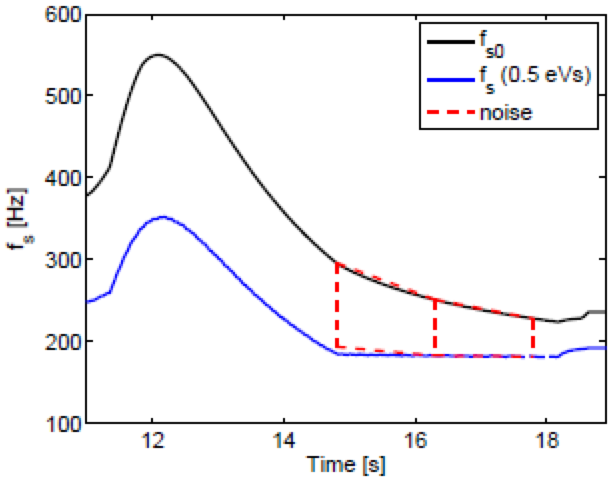
Cures:

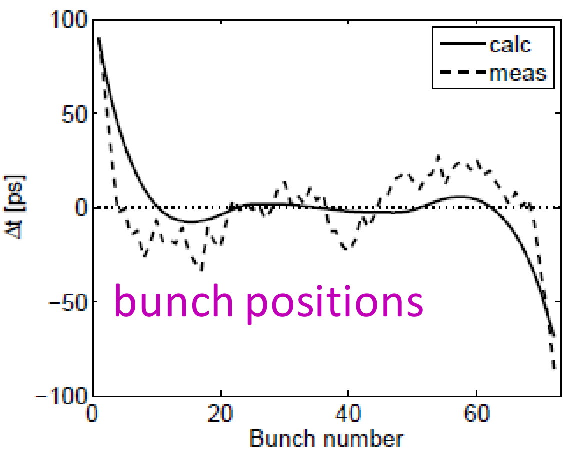
- FB, FF, longitudinal damper for 200 MHz
- 800 MHz RF system in bunch shortening mode through the cycle, $V_{800} \sim 0.1\ V_{200}$, $V_{800} \sim 0.15\ V_{200}$ in the last MD
- controlled longitudinal emittance blow-up (0.35 → 0.42 eVs → 0.65 eVs)

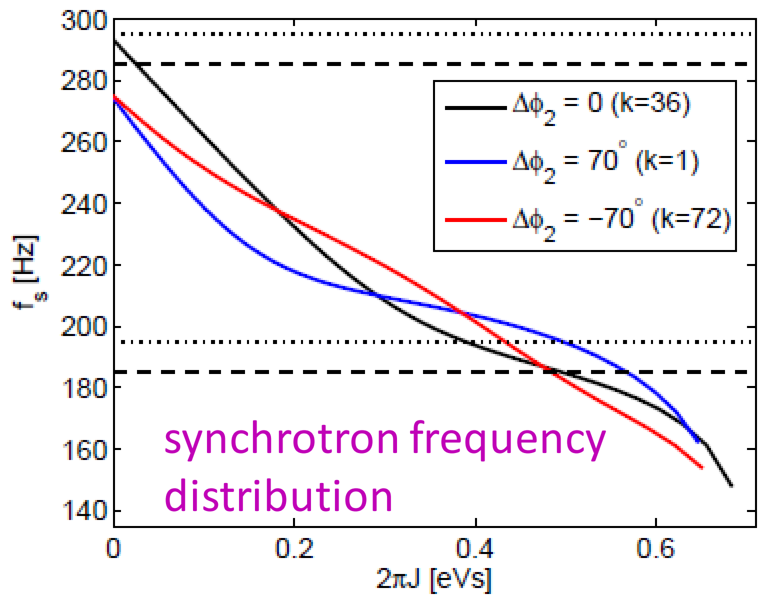
T. Bohl et al.

Emittance blow-up by band-limited noise: intensity effects

synchrotron frequency spread during the cycle







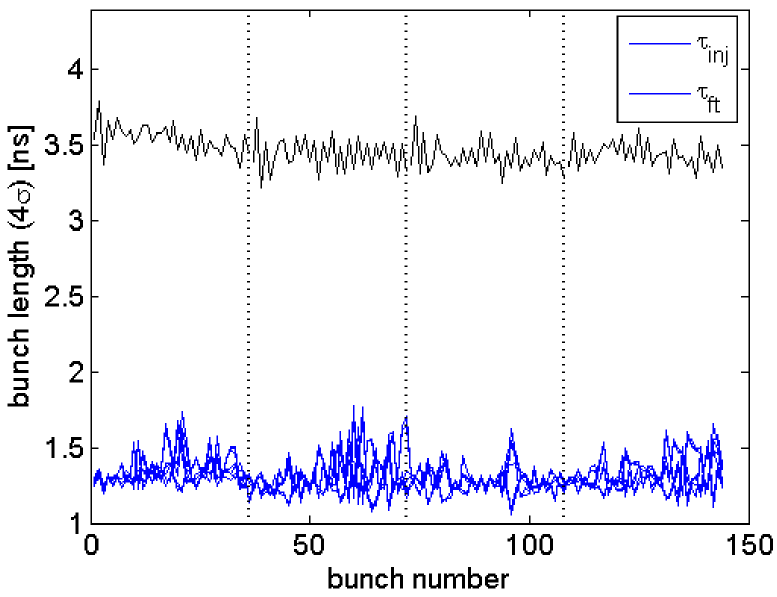
T. Argyropoulos et al., HB2010

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

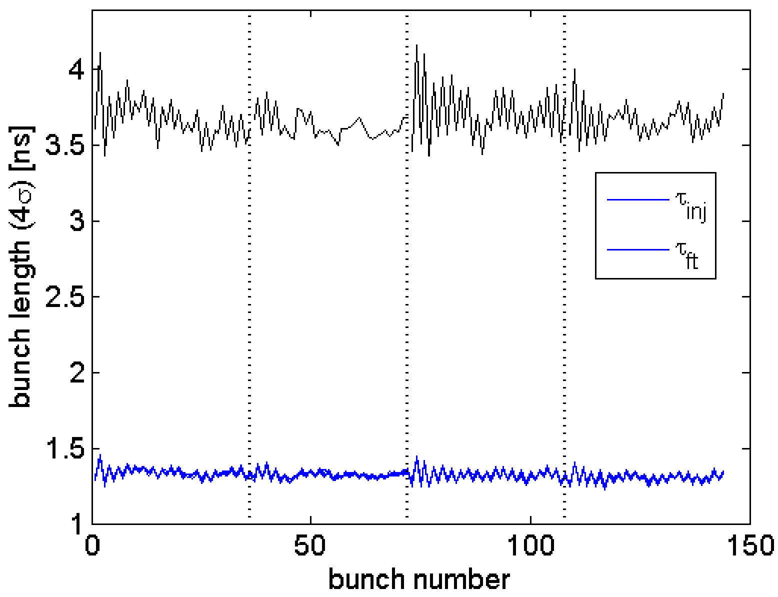
Synchrotron frequency distribution is modified by potential well distortion and beam loading (depending on bunch position in the batch) effects

Longitudinal multi-bunch instability due to loss of Landau damping

Short PS bunches



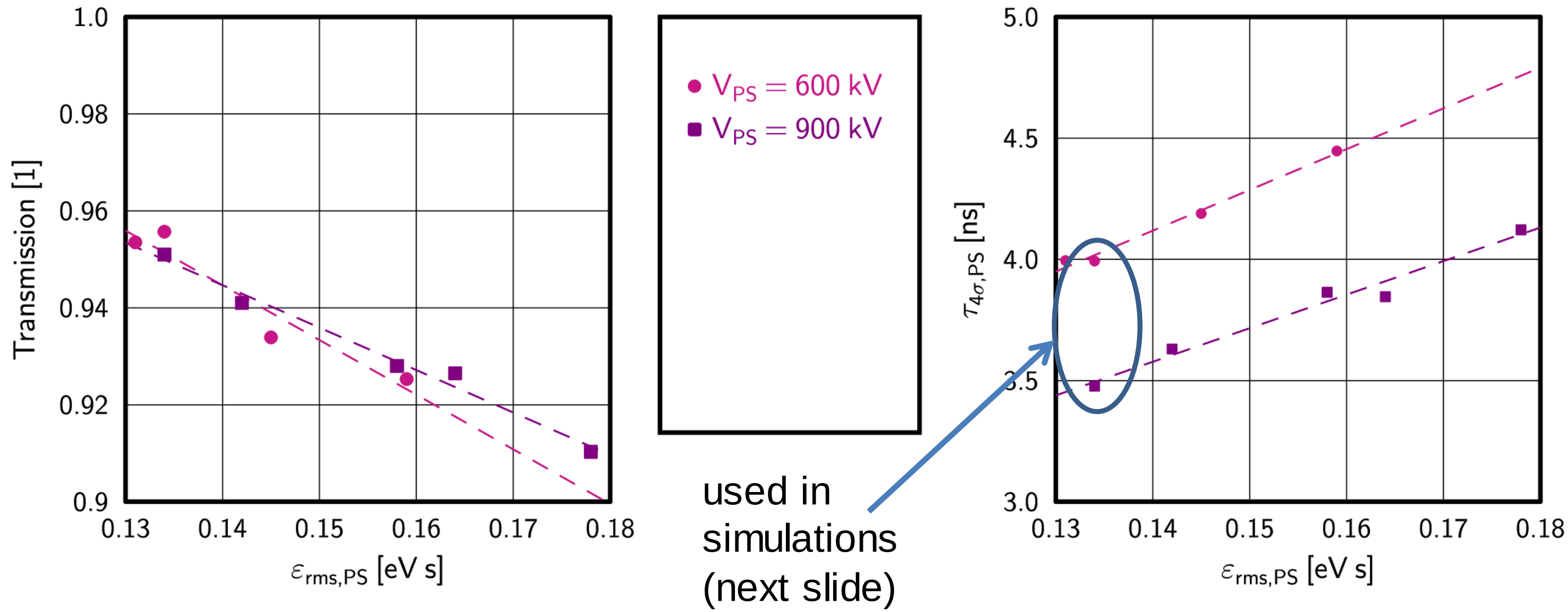
Long PS bunches



T. Argyropoulous et al.

PS-SPS transfer: capture loss - measurements

Experimental results: MD measurements from July 2011



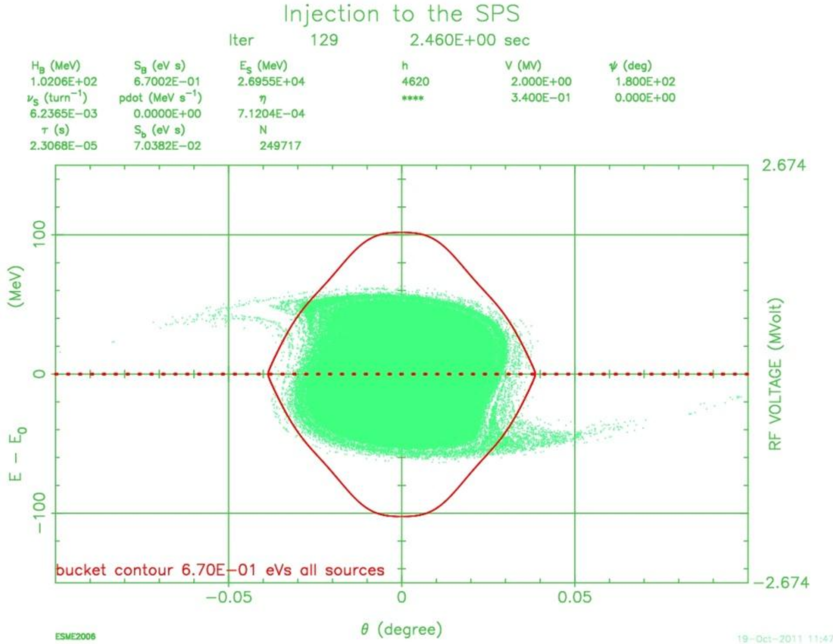
(a) Transmission PS → SPS

(b) Bunch length in PS

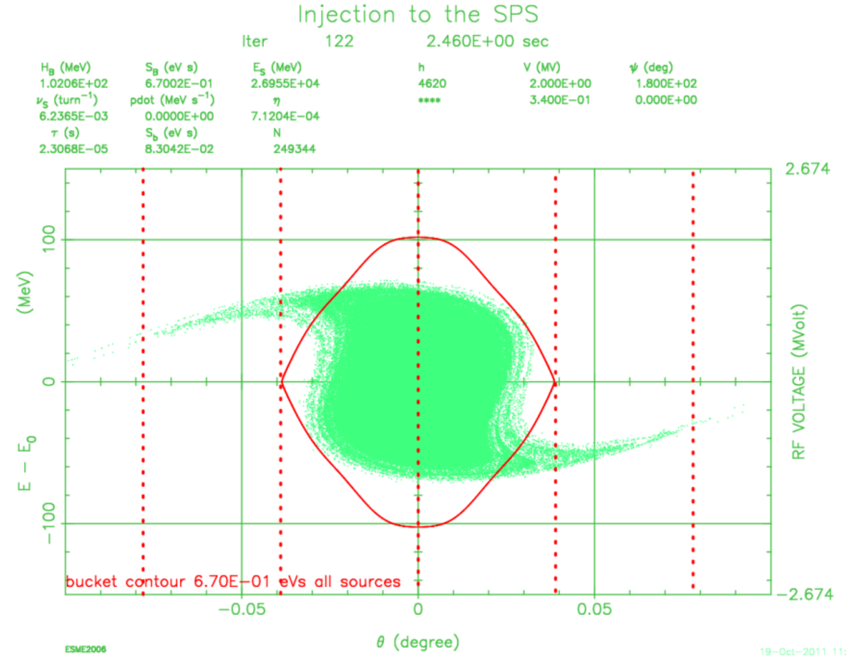
H. Damerau et al.

PS-SPS transfer: capture loss - simulations

long (nominal) PS bunches (600 kV)



short PS bunches (900 kV)



- PS RF gymnastics simulated with measured particle distribution (H. Timko)

→ Measured SPS transmission is reproduced with 20% emittance blow-up!

- different bunch lengths but similar emittances; SPS: V = 2 MV
- no intensity effects, beam loading or injection phase errors

Low γ_t (Q20) optics

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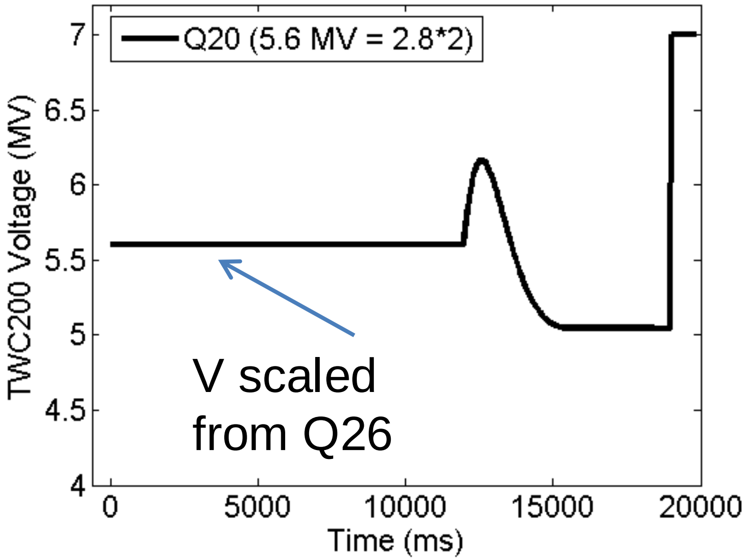
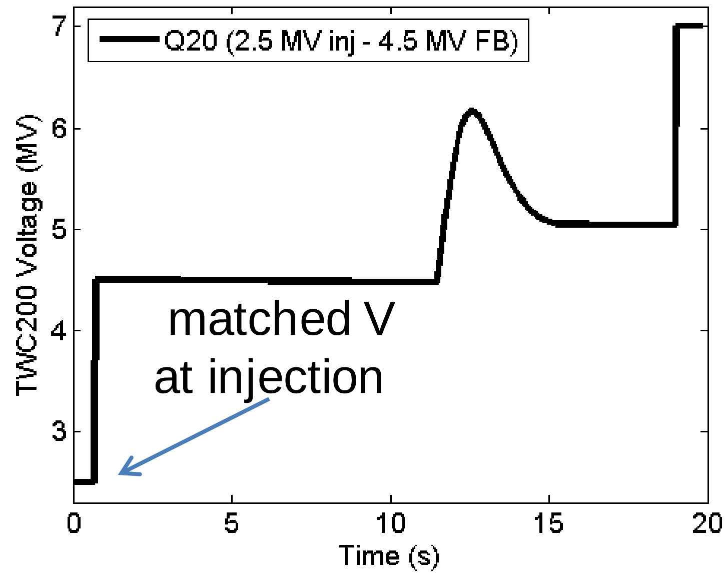


For the same longitudinal parameters required $V \sim \eta$
- limit at 450 GeV/c to 7.5 MV
 → 200 MHz RF upgrade
 → more 800 MHz voltage also

Emittance blow-up for the same intensity can also be reduced: loss of Landau damping $N_{th} \sim \varepsilon^2 \eta \tau$. Since $\tau \sim (\varepsilon^2 \eta / V)^{1/4}$
→ $\varepsilon \sim \eta^{-1/2}$ and τ = const for V=const.



Q26/Q20 comparison
50 ns beam (1.9x10^{11} p/b)

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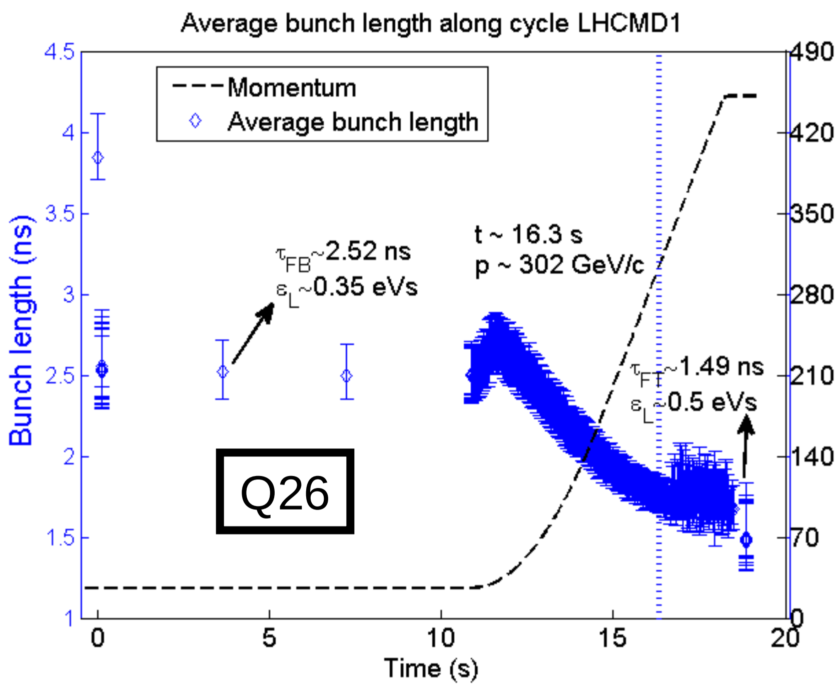

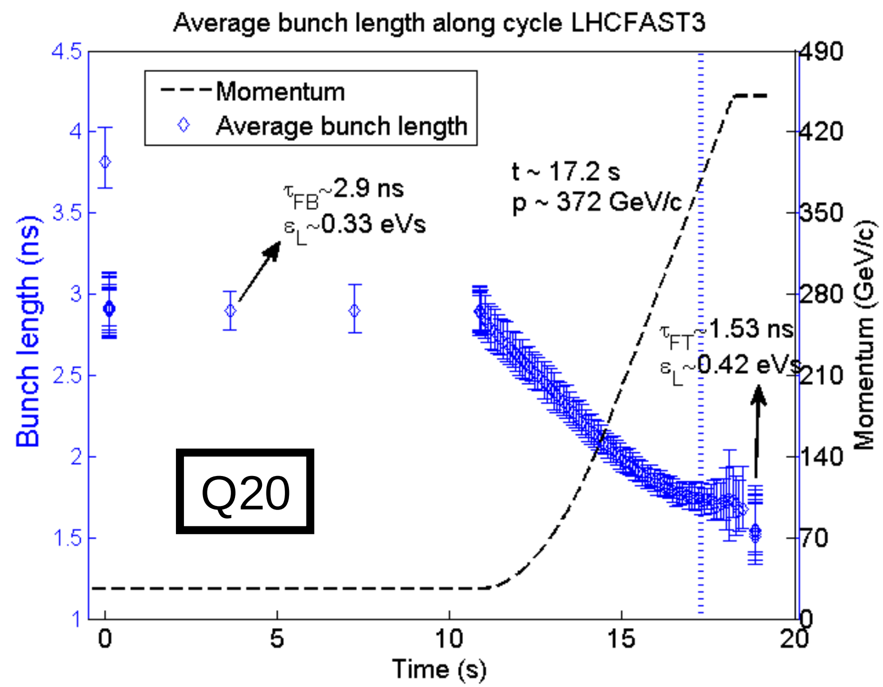

- 800 MHz needed for both cycles
- In Q20 instability starts later but controlled emittance blow-up (smaller) is still required
- Losses ~ (8 – 9)%

T. Argyropoulos et al.
MD Nov. 2011

Q26 – 1.49 ns
Q20 – 1.53 ns

200 MHz TW RF system upgrade

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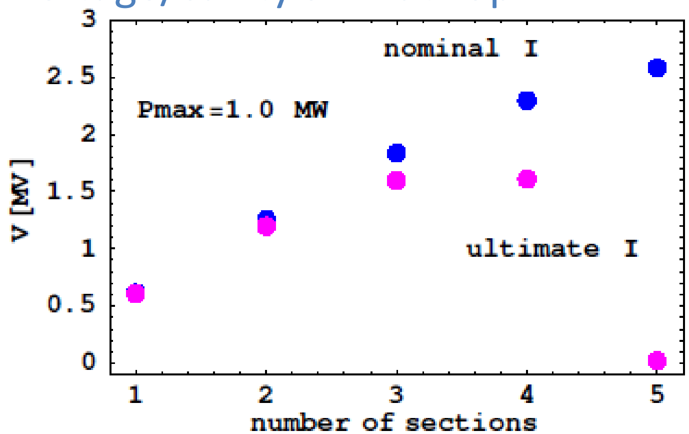
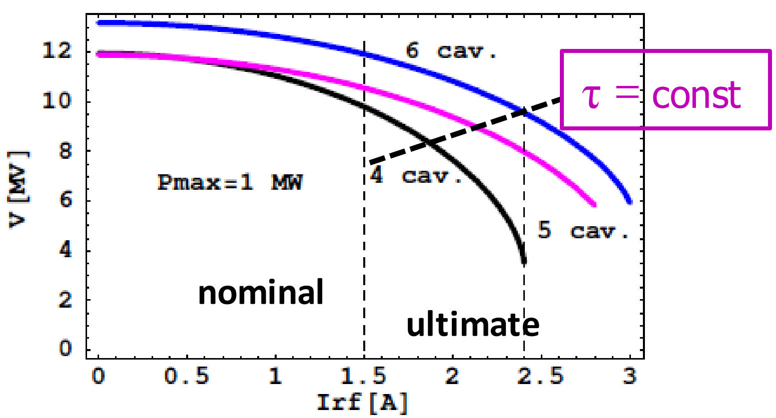
Voltage/cavity on Flat Top



Total voltage on Flat Top



- Now: **2x4+2x5 sections**
- Power/cavity (E. Montesinos):
  - 1.05 MW pulsed
- 5-section cavities are useless for ultimate intensities and 1 MW limit
- 7.5 MV used @450 GeV for beam transfer to LHC → more V needed for higher intensities (larger emittance)

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

- ➢ reduce beam loading/cavity and beam coupling impedance (~L^2)
- ➢ restore voltage for ultimate beam
- ➢ more voltage for Q20 optics

Summary

- High bunch intensities were achieved in 2011 for 50 ns beam
- Beam loss is important limitation for high intensity beams
- More MD time needed for optimisation of high intensity and high brightness beams
- Cures for longitudinal instability (800 MHz and emittance blow-up) are limited – need additional improvements (e.g. Q20, impedance reduction)
- MKE kickers give dominant contribution to longitudinal broad-band impedance, improvement is expected after LS1
- Q20 optics is a very promising solution for beam stability, need more optimisation, transfer to LHC should be studied

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