52nd ICFA Advanced Beam Dynamics Workshop HB2012

Longitudinal instabilities in the SPS and beam dynamics issues with high harmonic RF system

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Thanks to A. Burov, C. Bhat, H. Damerau, G. Papotti,
J. Tuckmantel, ABP and Operation teams

Outline

- CERN SPS performance
- Longitudinal instabilities
  - observations
  - cures
- Issues with high harmonic RF system
  - phase control
  - synchrotron frequency distribution
- Summary

Present and future SPS performance

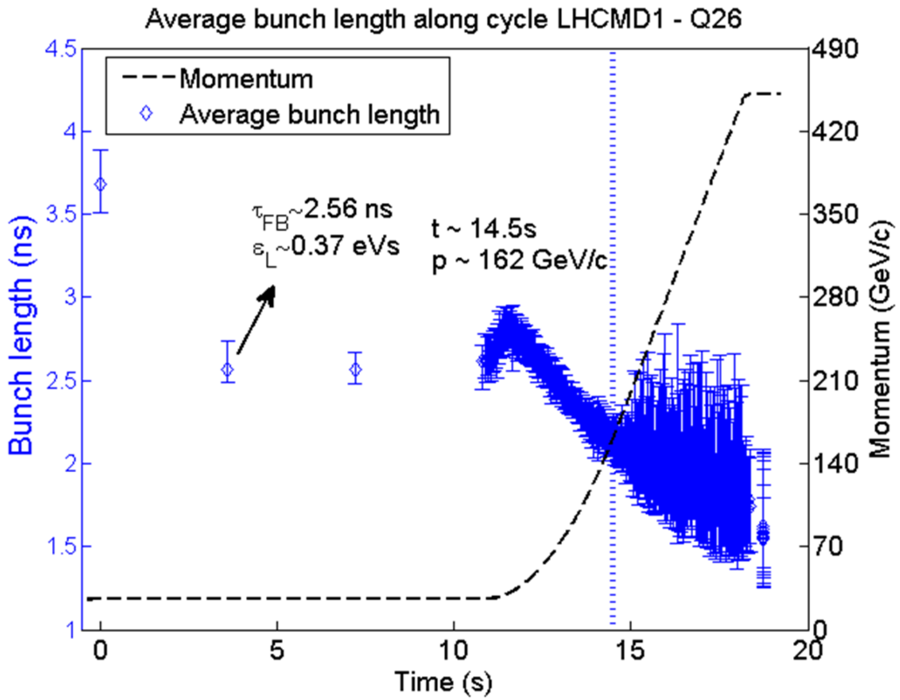
	Present operation		SPS record		Aim after LIU	
	LHC	CNGS	LHC	CNGS	LHC	LHC
SPS beam energy [GeV]	450	400	450	400	450	450
bunch spacing [ns]	50	5	25	5	25	50
bunch intensity/10^{11}	**1.6**	0.1	**1.3**	0.13	**2.2**	**3.6**
number of bunches	4x36	2x2100	4x72	2x2100	4x72	4x36
SPS beam intensity/10^{13}	2.3	4.2	3.75	**5.3**	6.35	5.2
SPS cycle length [s]	21.6	6.0	21.6	6.0	21.6	21.6

- LHC beams: beam brightness and quality
- CNGS-type beams: beam power and proton flux

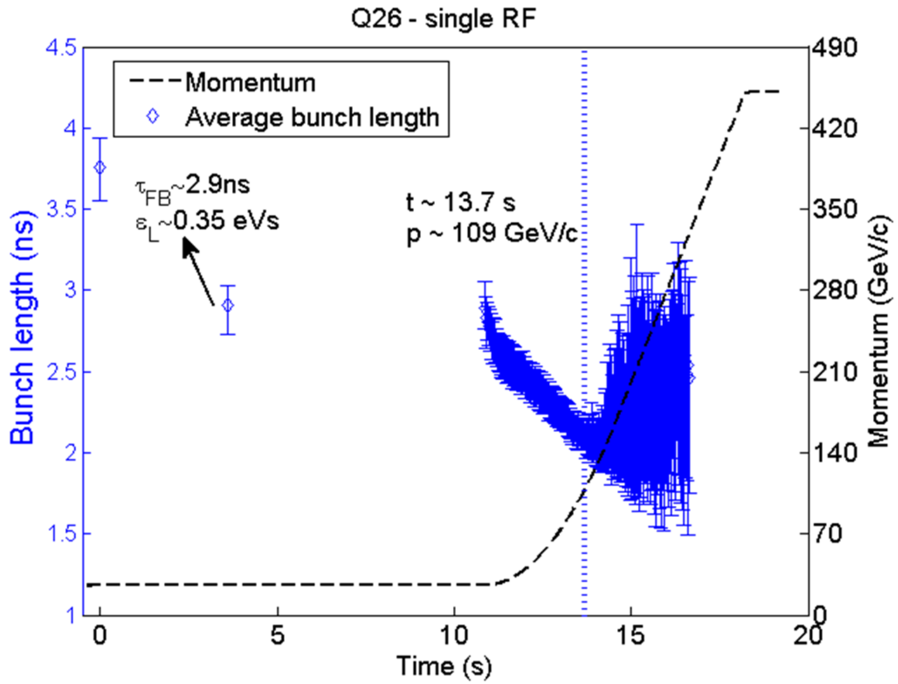
- Longitudinal instabilities are one of the main intensity limitations, much higher intensities are required in future => LIU project (2020)
- Source of instability is unknown and no mode could be identified

Longitudinal multi-bunch instability
Single 200 MHz RF system

50 ns beam, 1.6x10^{11} p/b



25 ns beam, 1.2x10^{11} p/b



$\Rightarrow$ Instability starts at **energy ~ 1/N$_{tot}$ => multi-bunch effect**

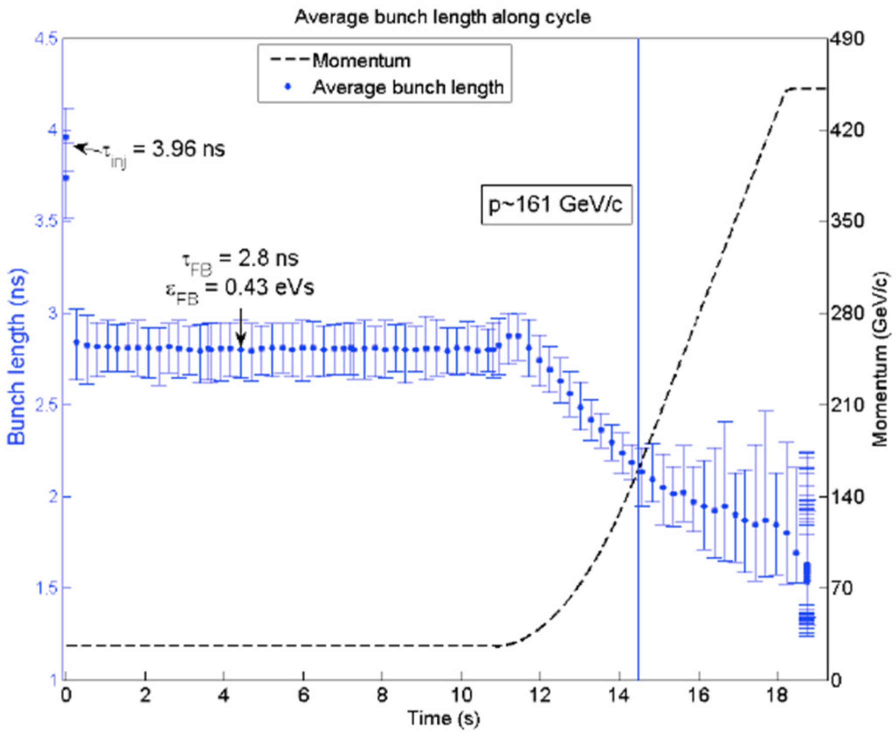
(P1/P2 = 162/109 = 1.49 and N2/N1=2x1.2/1.6 = 1.5)

- **Low threshold**: single batch 2-3x10^{10} p/b unstable at flat top (450 GeV/c)
- Single bunch N_{th} ~ 1.3x10^{11}

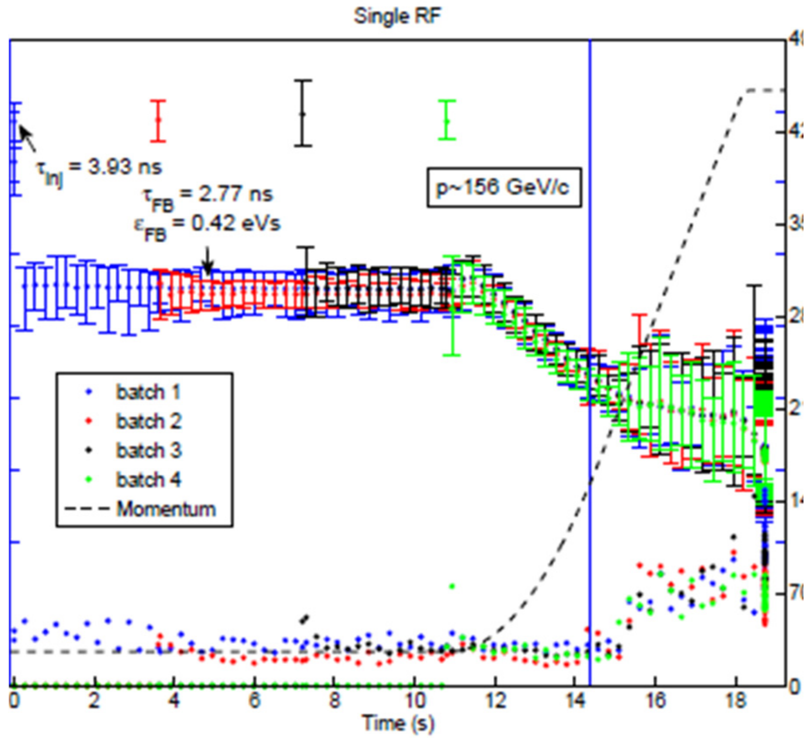
Multi-bunch instability

Single RF, LHC beam with 50 ns spacing, 1.6×10^{11}p/b

1batch x 36 bunches



4 x 36 bunches, 250 ns batch gaps

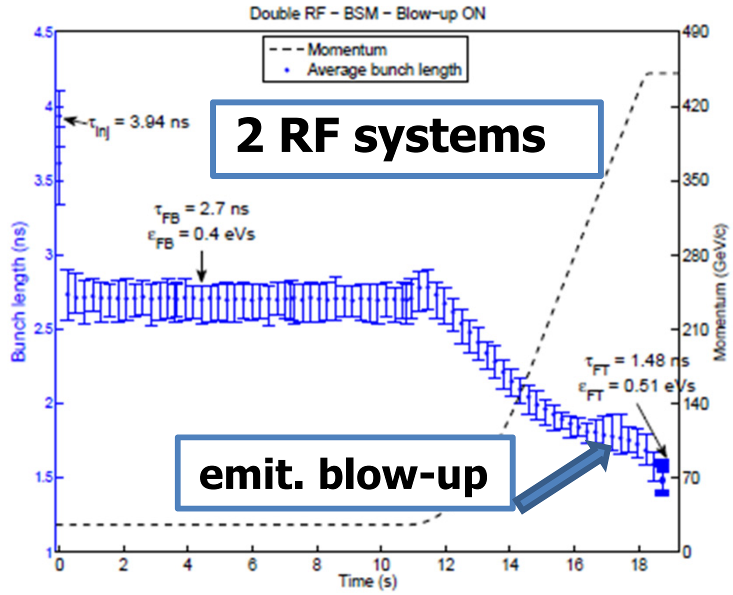


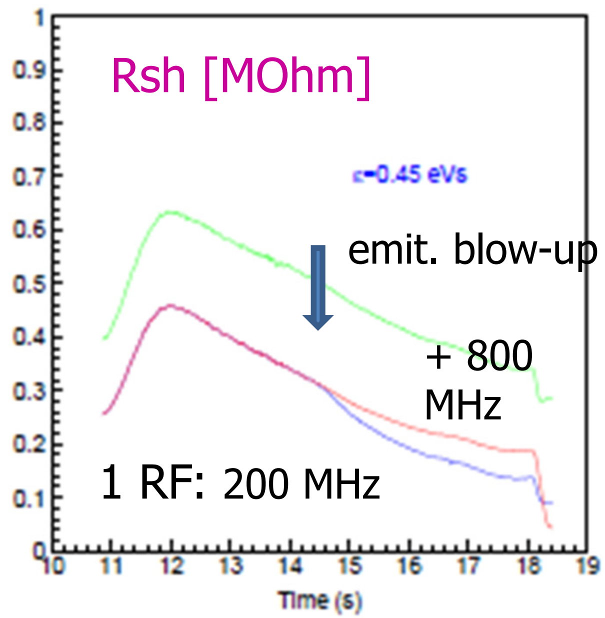
⇒ Instability starts at the same energy for 1 and 4 batches,
6 bunches unstable over wide range (240-410) GeV/c

⇒ short-range wake => SPS TW RF systems (Q=150, 300)?

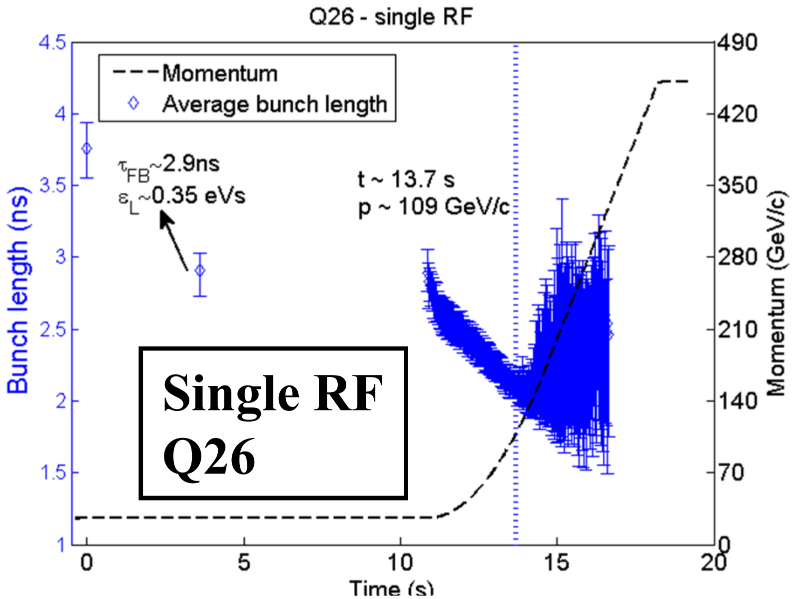
Beam stabilisation - cures

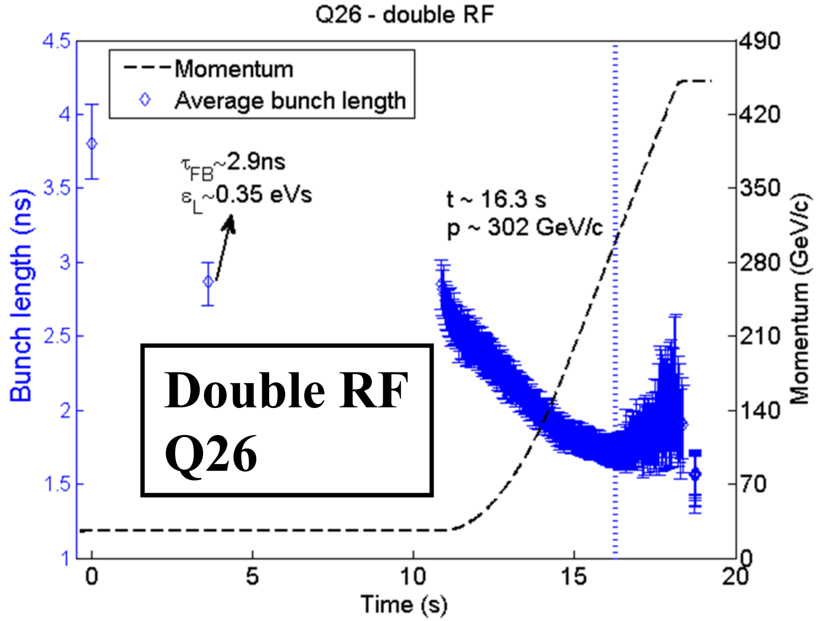
- ✓ Active damping (low mode number): RF feedback, feed-forward, longitudinal damper
- ✓ **4th harmonic RF system (800 MHz) in bunch-shortening (BS) mode**
- ✓ Larger injected emittance => PS-SPS transfer (talk of H. Timko). Large emittance at 450 GeV/c => capture losses in the LHC 400 MHz RF system => controlled emittance blow-up in the SPS by factor 2.5
- ✓ Optics ("Q20") with lower transition energy (γ_t=22.8 -> 18 (talk of H. Bartosik) => N_{th} ~|η| (factor 2.8 – 1.6), but one still needs the double RF and blow-up
- Impedance reduction (measurements of HOMs in 2 RF systems in 2013-2014)

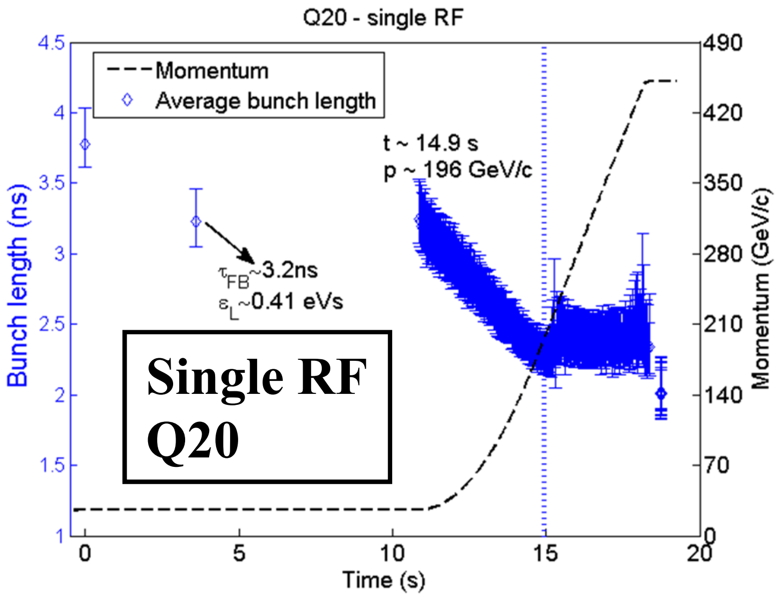


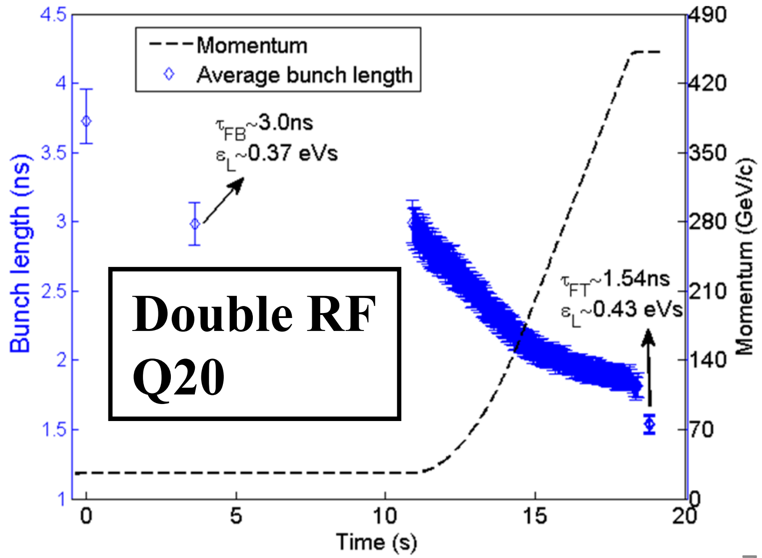


Beam stabilisation (25 ns, 1.2×10^{11} p/b)
Q20 and double RF (BS-mode), V_2/V_1=1/10



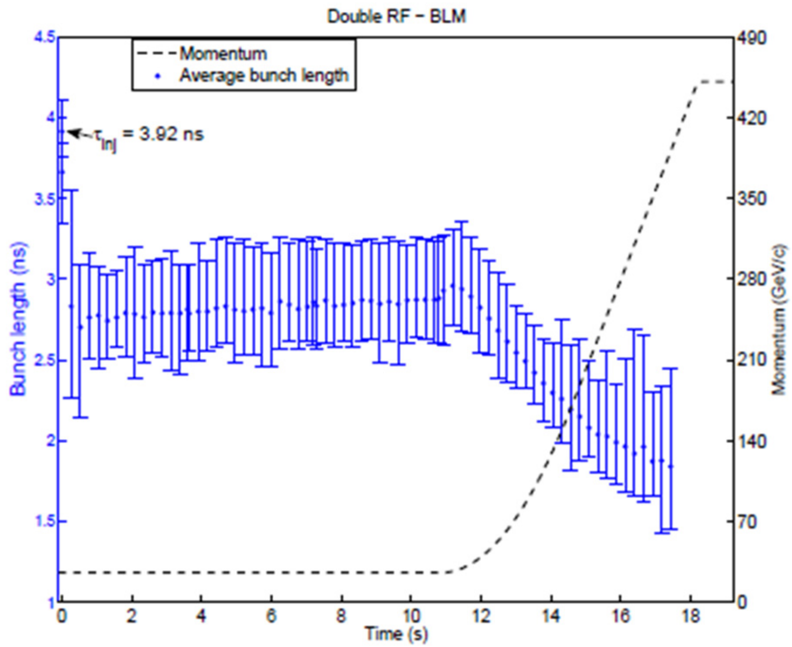






Operation modes of high harmonic RF system in the SPS

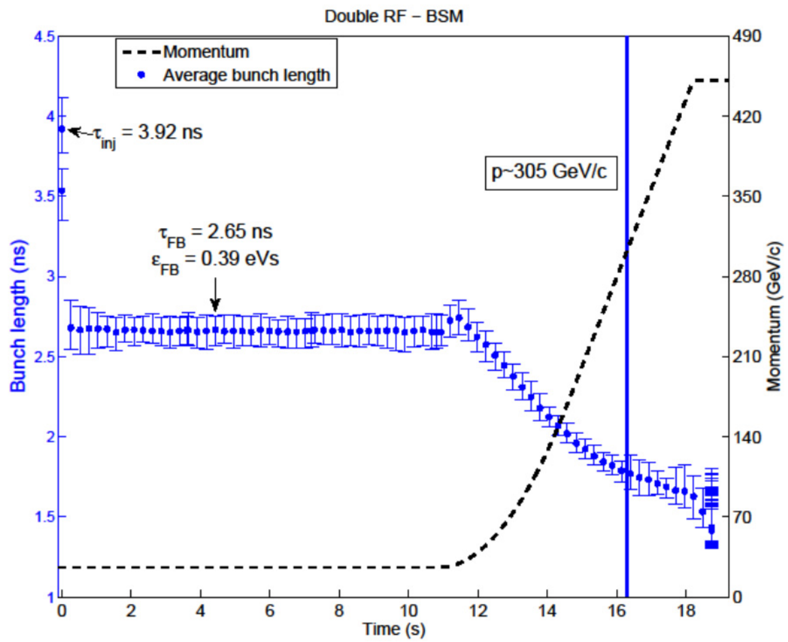
Bunch-lengthening



Used in most/all accelerators in the world
- larger synchrotron frequency spread
- larger bucket in BL-mode
- smaller peak density (SC, heating,…)

but unstable in the SPS => beam dump!

Bunch-shortening



Stable with $V_2/V_1 = 1/10$
=> Can we increase this ratio?

Landau damping with a high harmonic RF: bunch-shortening or bunch-lengthening mode?

Voltage in a double RF system:

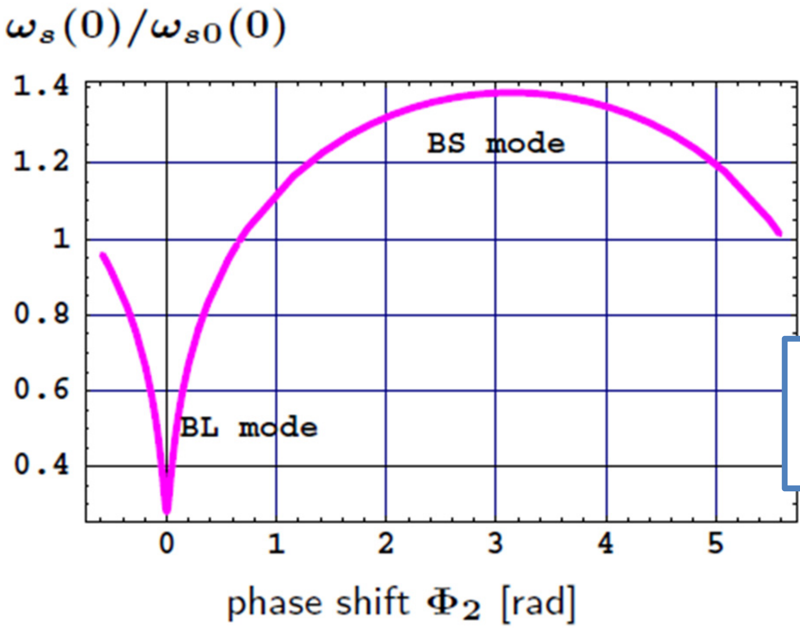
$$V = V_1 \sin\varphi + V2 \sin(n\varphi + \phi_2)$$

$n = h_2/h_1$ and above transition:

BL-mode: $\phi_2 = 0$

BS-mode: $\phi_2 = \pi$

(1) Phase: very tight control in BL-mode

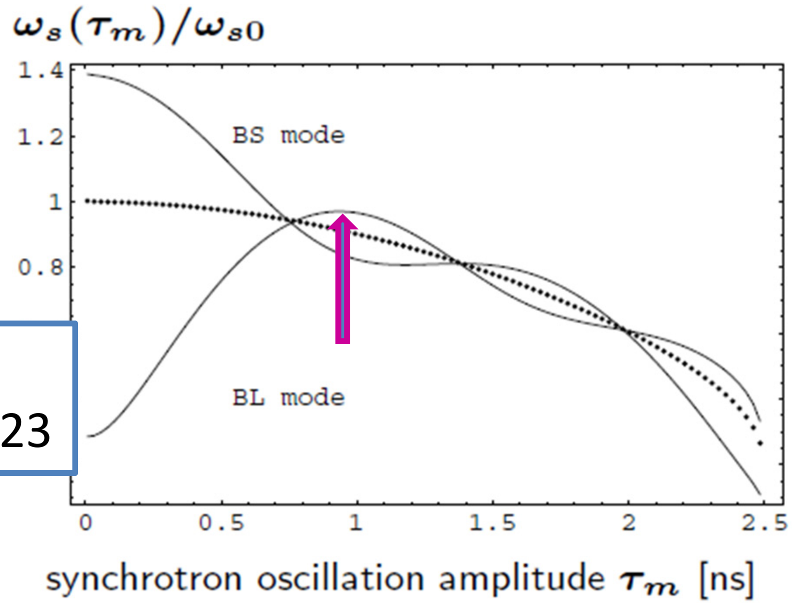


(2) Synchrotron frequency distribution:

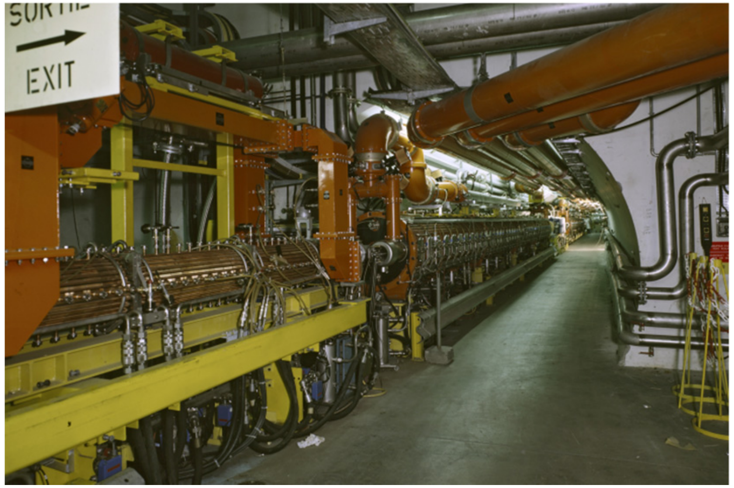
- In BL-mode region $\omega_s'(J_{cr})=0$ exists for any voltage ratio => loss of Landau damping for long bunches (> 1.8 ns)
- Same in BS-mode for large V_2/V_1

$\Rightarrow$ $V_2/V_1 = 1/10$ during the SPS cycle

$h_2/h_1 = 4$
$V_2/V_1 = 0.23$



4^{th} harmonic RF system in the SPS

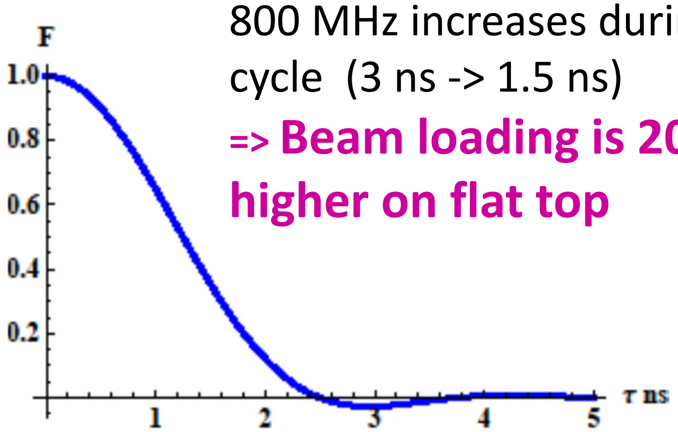


Two 800 MHz travelling wave RF structures were installed in the SPS as "Landau cavities" in 1979, in real operation for LHC beams from 2010

Only one cavity is used (has RF power)

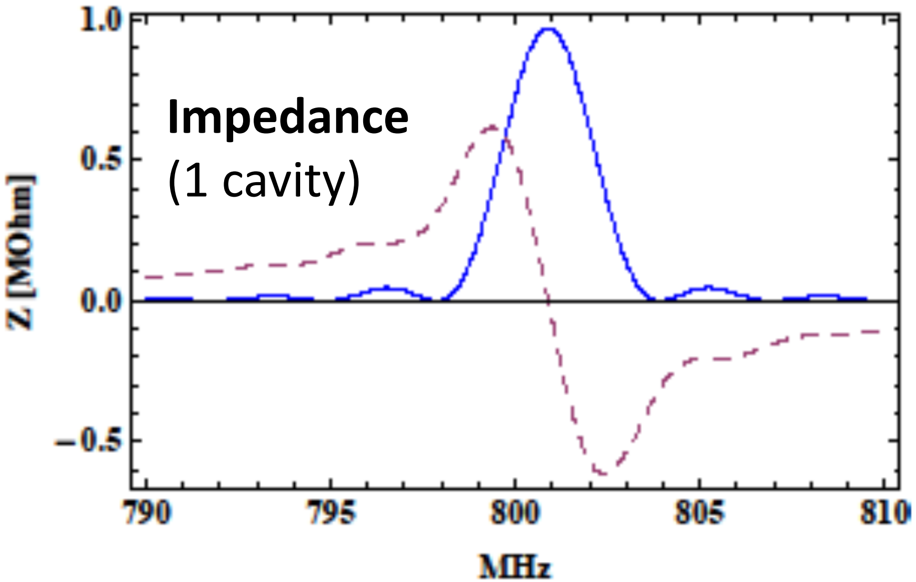
V_{max}=650 kV, 2^{nd} cavity is idle

=> induced voltage in 2 cavities

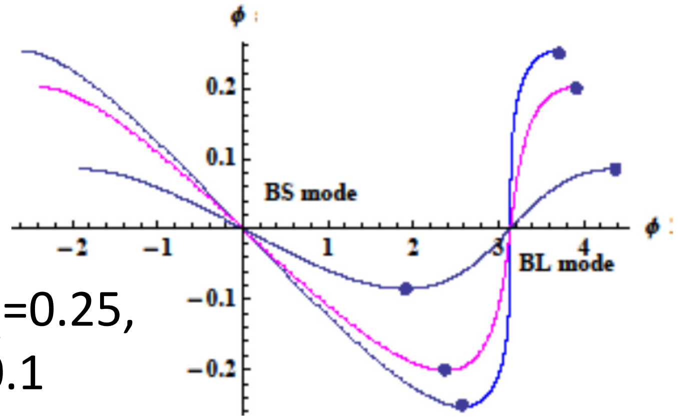


Beam current component at 800 MHz increases during cycle (3 ns -> 1.5 ns)

=> Beam loading is 20 higher on flat top

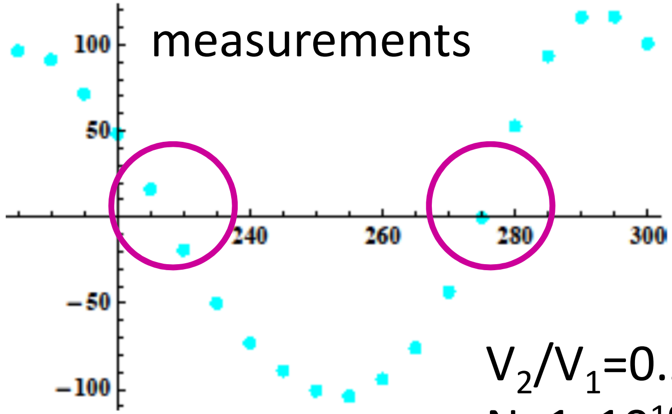


Phase calibration of 4th harmonic RF system



V_2/V_1=0.25, 0.2, 0.1

bunch tilt measurements

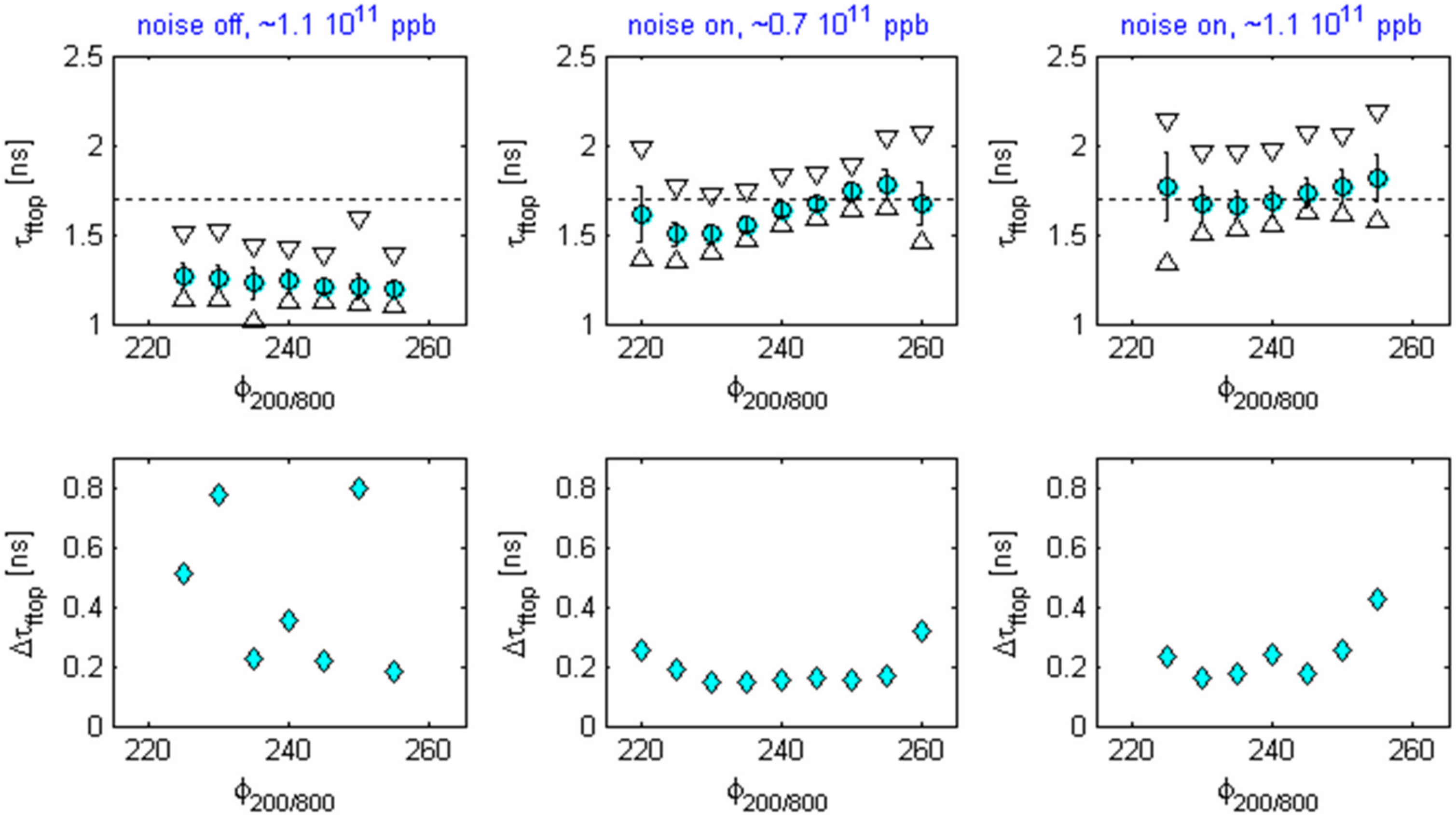


V_2/V_1=0.2
N=1×10^{10}

- Phase shift is known up to some offset determined from measured bunch tilt at low intensity and large ratio V_2/V_1
- Beam calibration done each year, then phase is adjusted for the best beam stability during cycle
- **Relative phase is programmed** through the cycle (BS-mode above transition):

$$\phi_2 = -4\,\varphi_s + \pi$$

Bunch length and stability at 450 GeV/c as a function of the 800 MHz phase



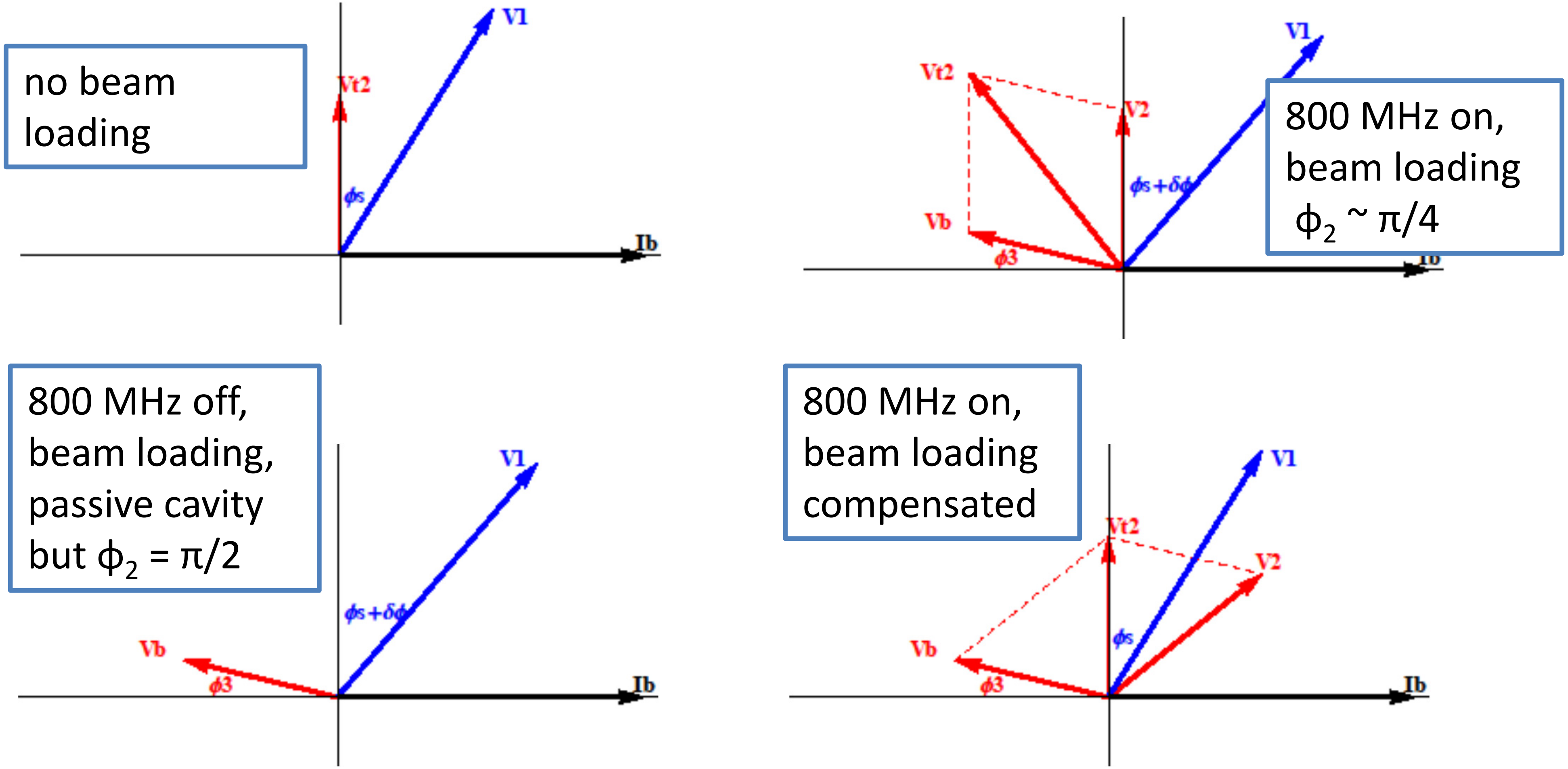
Bunch length
(av., max-min)
at 450 GeV/c

Beam stability
from $\Delta\tau$

G. Papotti et al.

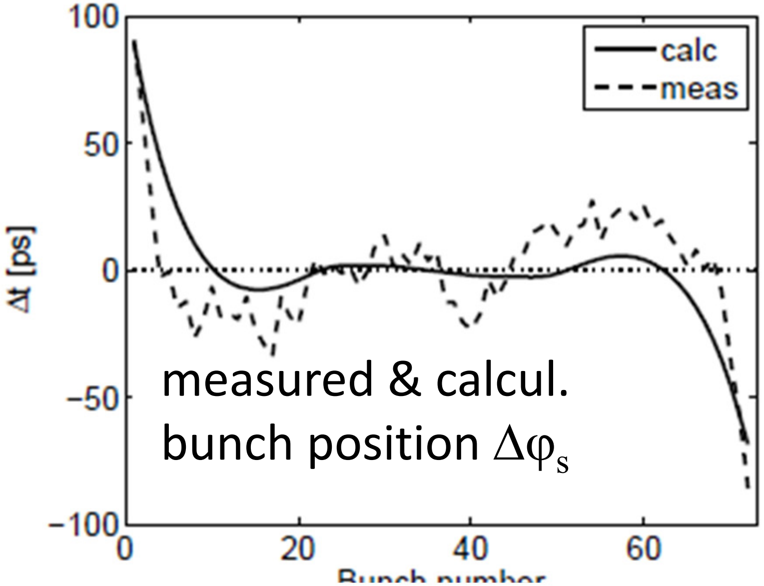
- Phase is changed through the whole cycle (phase offset)
- Large (+/- 20 deg at 200 MHz) phase range of BS-mode
- Short bunches are still unstable on flat top

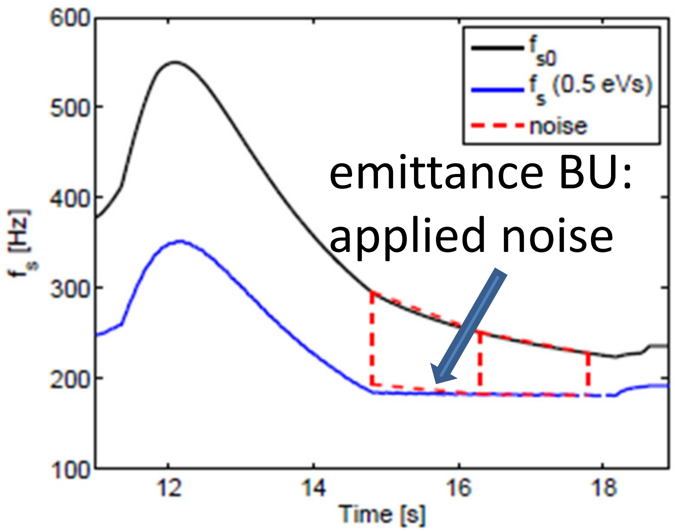
Phase control: effect of beam loading in 800 MHz RF system

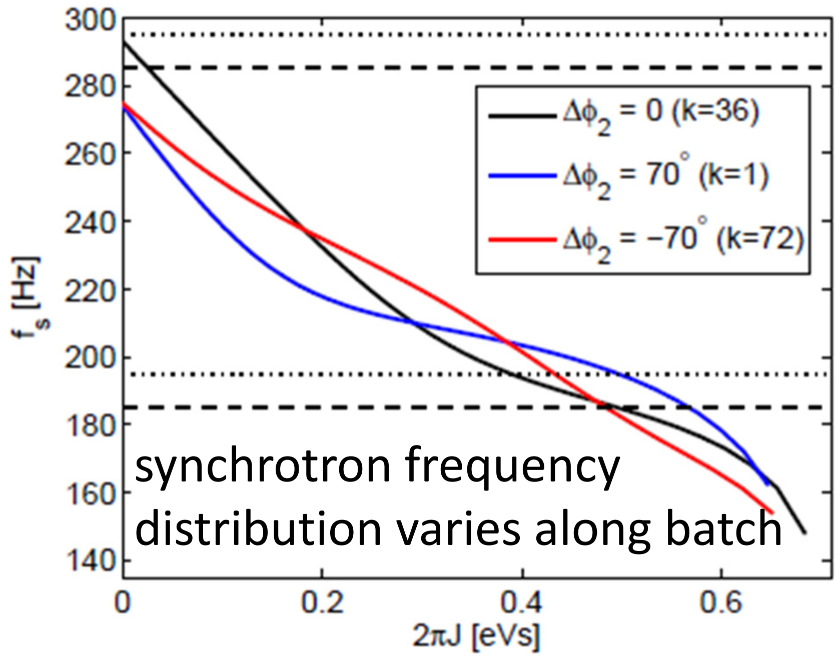


Difficult to program ϕ_2 accordingly => FB and FF (2014)

Phase control: effect of beam loading in 200 MHz RF system







T. Argyropoulos et al., HB2010

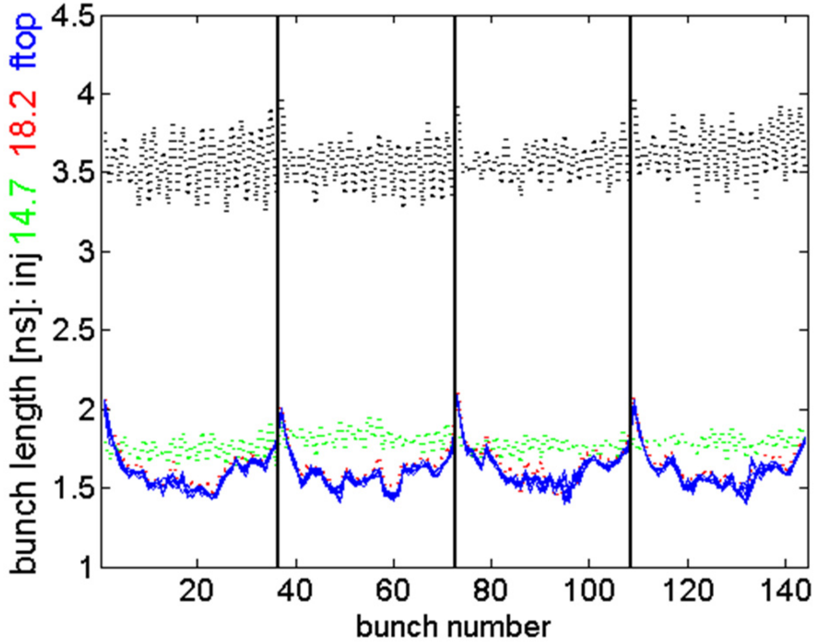
$$\boxed{\Delta\phi_2 = 4\Delta\phi_s^{meas}\left(1 + 4\frac{V_t^{800}}{V_t^{200}(-\cos\phi_s)}\right)}$$

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

$\Delta\phi_2$~ π/4 for bunch displacement of 100 ps and V_{800}/V_{200}=0.1

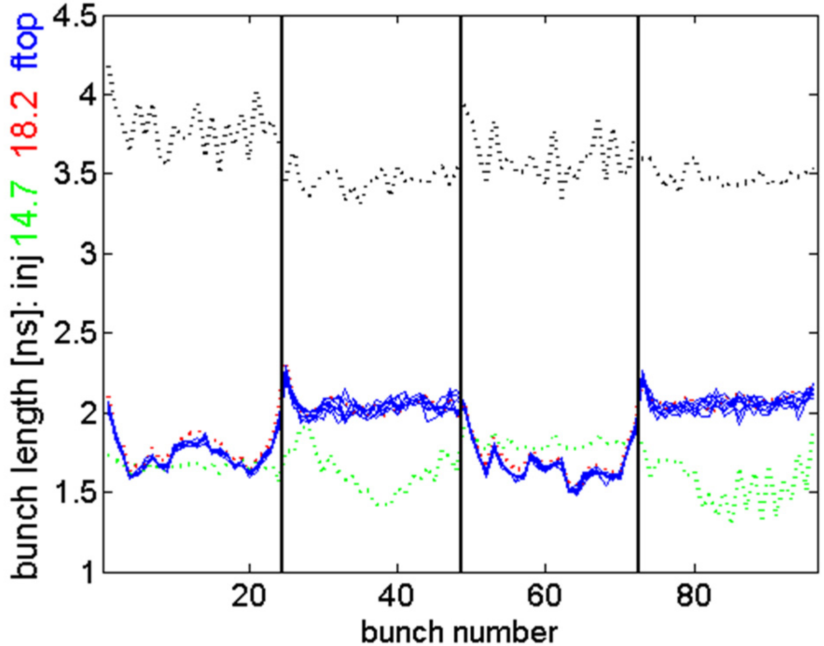
Phase control in a double RF system: issues with controlled emittance blow-up

50 ns spaced LHC beam



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

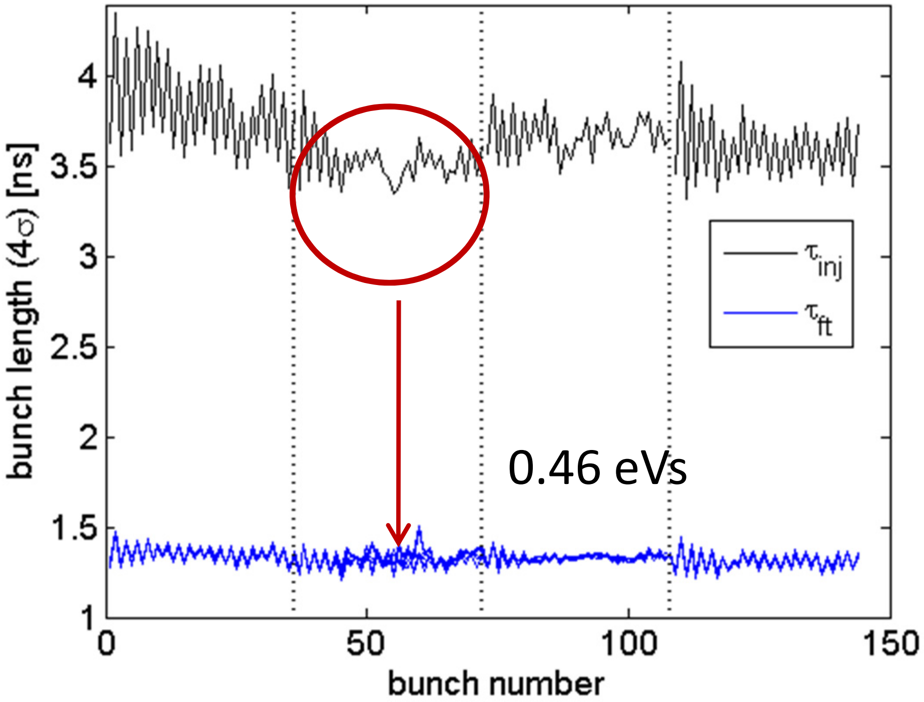
75 ns spaced LHC beam



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

Multi-bunch instability double RF (BS-mode)

50 ns beam, 2 RF, $1.3x10^{11}$ p/b



In a single RF (200 MHz):

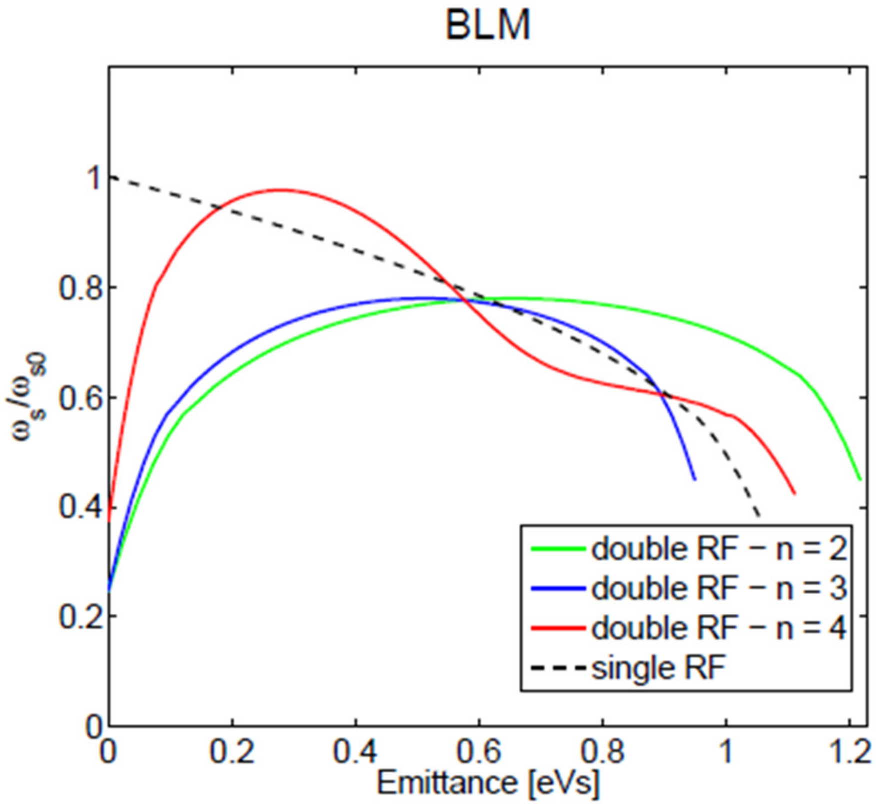
- threshold for 50 ns beam at flat top is factor 5 lower than for a single bunch ($\sim 1.1x10^{11}$)

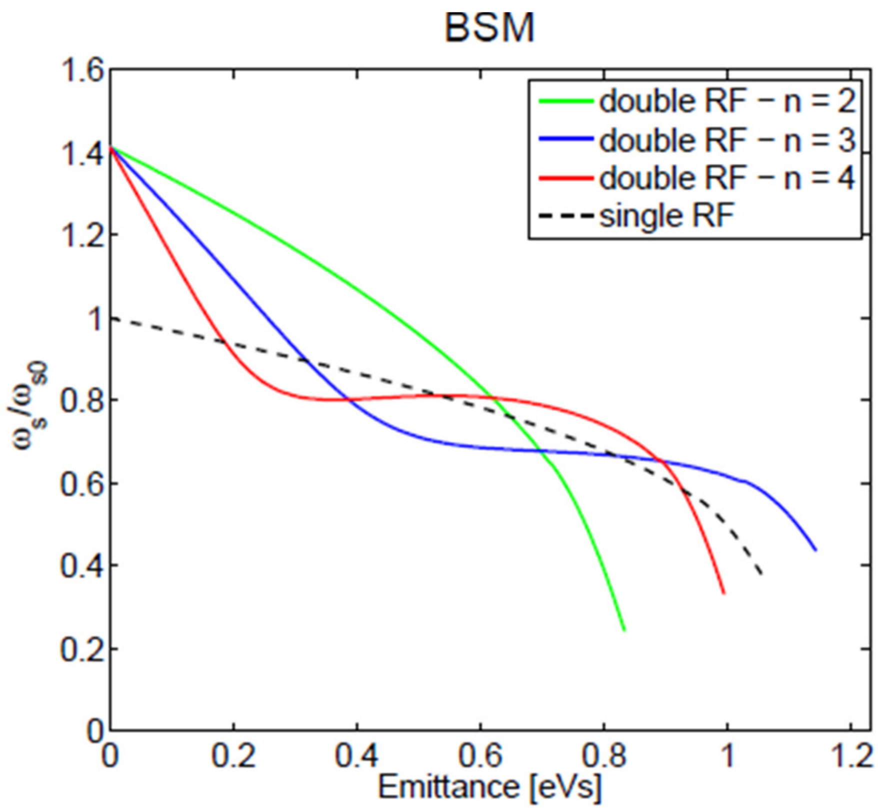
In a double RF (BS-mode):

- these thresholds are very close
- the instability is often observed on individual bunches only (with smallest emittances)

$\Rightarrow$ Single bunch phenomenon?

Synchrotron frequency distribution in a double RF system with $V_2/V_1=h_1/h_2$



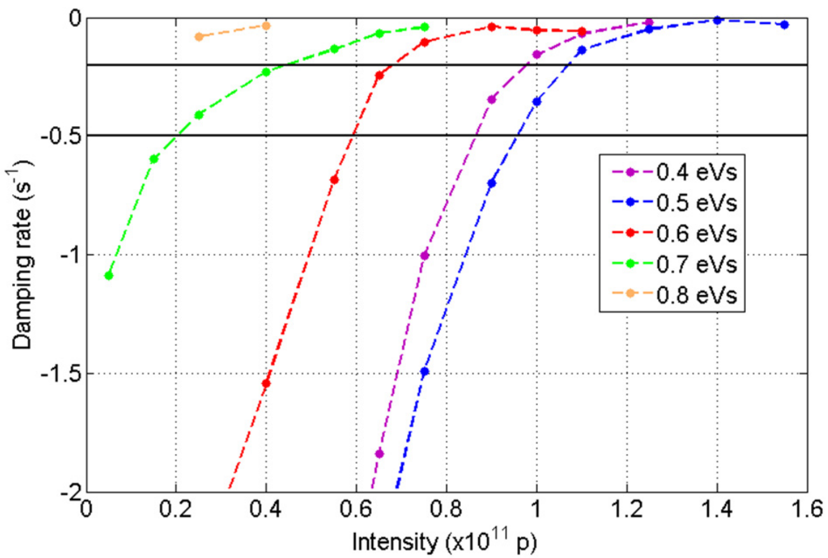


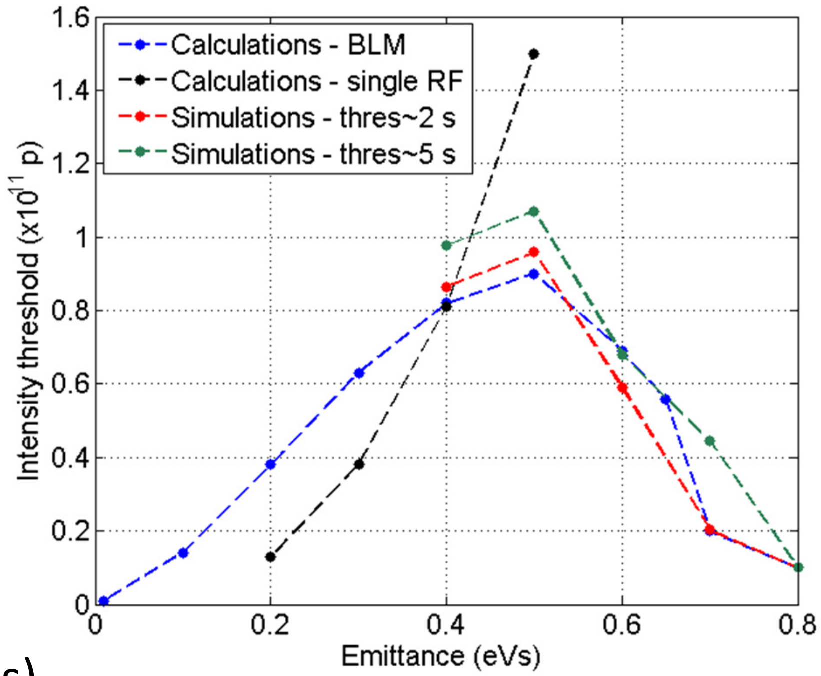
Higher is h_2/h_1 - larger is spread for the same voltage V_2, but a region with zero derivative is closer to the bunch center

$\Rightarrow$ limitation to the voltage ratio or bunch length in BS-mode

$\Rightarrow$ limitation to the bunch length in BL-mode

Loss of Landau damping in BL-mode for inductive impedance above transition





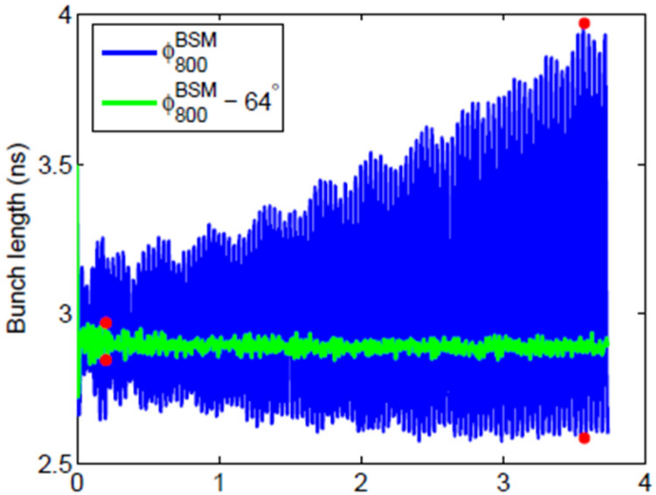
Simulations and calculations (Van Kampen modes) confirm observations in the SPS for BL-mode in (100 + 200) MHz RF at 26 GeV/c during ppbar:

- Unstable bunches with emittance > 0.65 eVs
- Can be stabilised by phase shift from BL-mode

(T. Argyropoulos, A. Burov, E. S.)

Similar behavior to the resistive wake in a double RF
(A. Burov, HB2010)

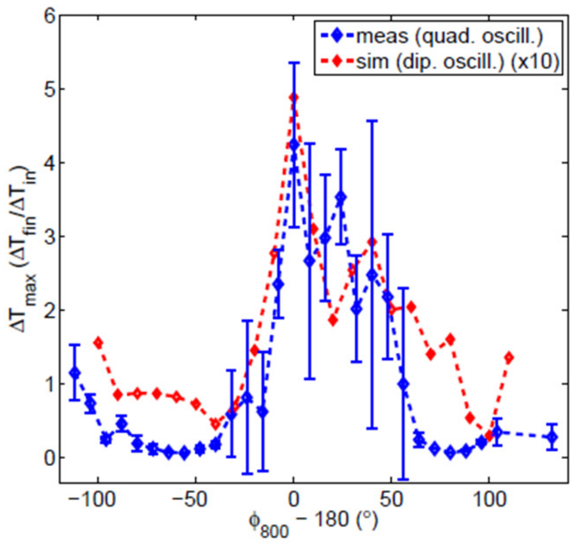
Synchrotron frequency distribution and phase between 2 RF systems in BS-mode

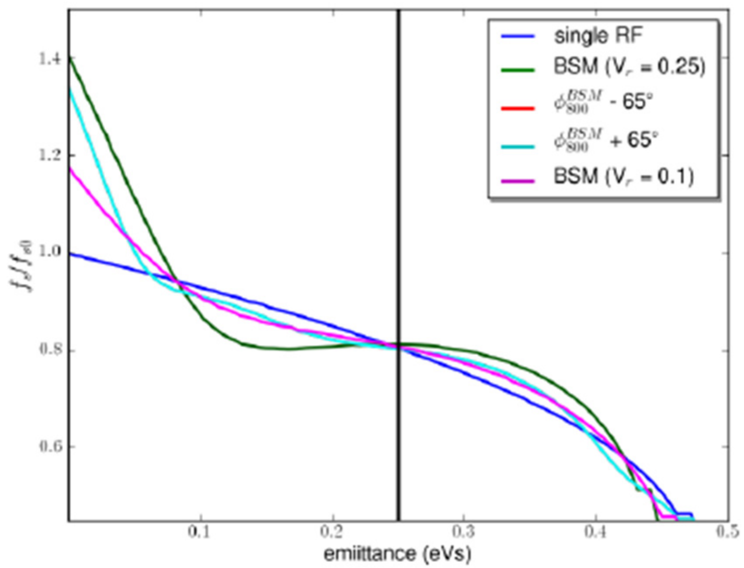


Very good agreement between measurements and simulations (with SPS impedance model):

- single bunches are unstable in BS-mode with V2/V1=4
- can be stabilised by significant phase shift of 800 MHz RF system

(T. Argyropoulos et al., IPAC'12)





Summary

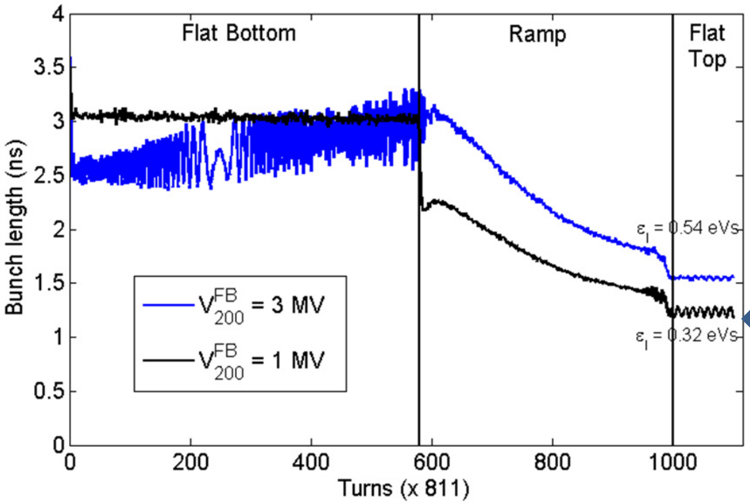
- The SPS produces a good quality LHC beam at intensities by order of magnitude above the threshold of the longitudinal multi-bunch instability.
- The SPS beam is stabilised by the 4th harmonic RF system in BS-mode, efficient even in the presence of strong beam loading in both RF systems; FB and FF systems should improve stability at high energies (less controlled emittance blow-up).
- In the SPS, due to choice of harmonic (4^{th}), the working parameter space is very limited for both BL-mode (emittances) and BS-mode (voltage ratio or emittances).
- BL-mode cannot be used in the SPS with present beam loading and even in future with FF and FB for 800 MHz due to long bunches.
- The 2^{nd} harmonic RF system can have the largest bucket filling factor, but needs a very accurate phase control in BL-mode.

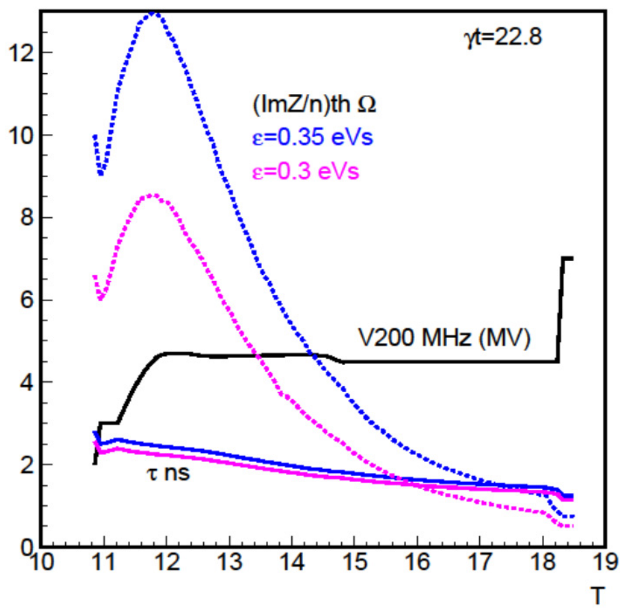
Future plans

- Implementation of the Q20 optics – ongoing
- Measurements of HOMs in 200 MHz and 800 MHz RF systems – during 2013-2014
- FB and FF for the 800 MHz RF system - 2014
- Upgrade of the 200 MHz RF system (double power, shorter cavities, new beam control and impedance reduction by 20%) – 2020
- Search for other impedance sources
- Comparison of measurements and simulations (single bunch) to refine the SPS impedance model
- Design study of the 2nd harmonic RF system for HL-LHC

Additional Material

Loss of Landau damping for a single bunch in a single RF system





Measurements:

- similar N_{th}~$1x10^{11}$ for the loss of Landau damping on flat bottom (V=2 MV) and flat top
- strong dependence on capture voltage (1 - 3 MV)

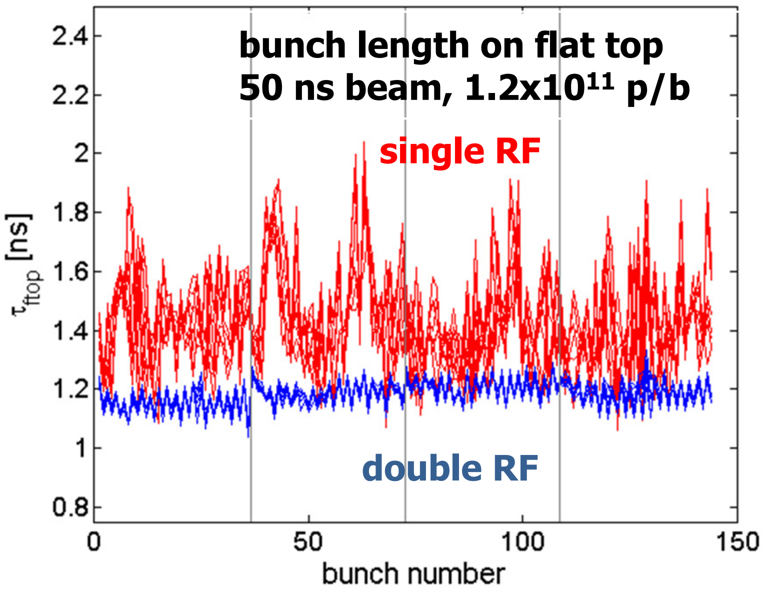
Sacherer' criteria:

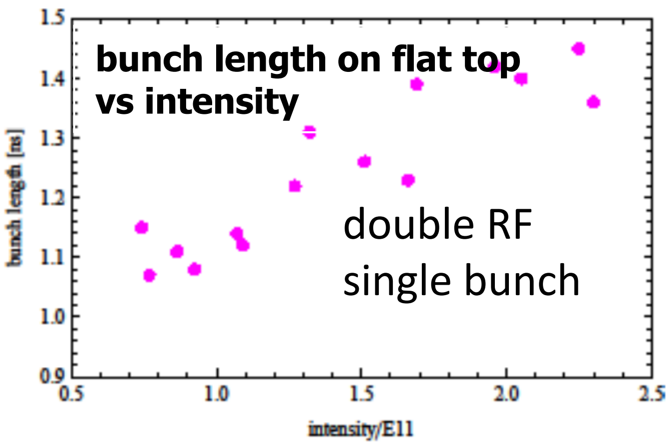
- Predicts factor 6 higher thresholds at injection (26 GeV/c)
- Only 10% difference for 1 - 3 MV
- 15% emittance blow-up during cycle but effective inductive impedance also depends on on bunch length (~2)

→ **initial distribution?**

Indeed, modulated bunch profile after bunch rotation in the PS, confirmed by simulations (talk of H. Timko)

Multi-bunch and single bunch thresholds





- In a single RF (200 MHz):

  threshold for 50 ns beam at flat top is factor 5 lower than for a single bunch (~1.1x10^{11})

- In a double RF (BS-mode)

thresholds are more close at flat top

50 ns beam:

– 1.2 ns (0.36 eVs): 1.2x10^{11} p/b

single bunch:

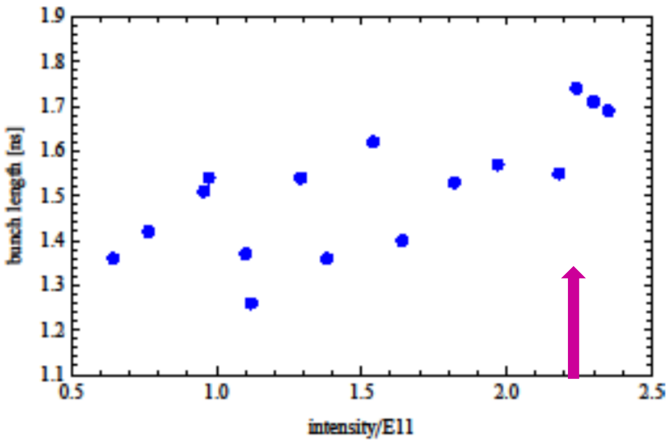
– 1.1 ns (0.3 eVs): 1.2x10^{11} p/b

flat bottom, 50 ns beam:

- 3 ns (0.35 eVs): 1.3x10^{11} p/b

Single bunches on flat top, 800 MHz in BS-mode, no controlled emittance blow-up

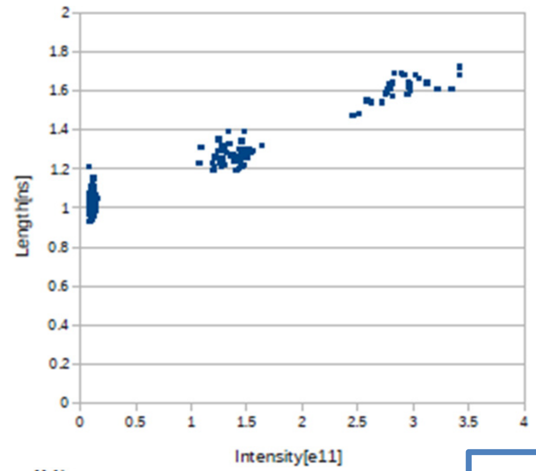
Q26: FT bunch length vs intensity
V200=4.5MV, V800= 0.5MV

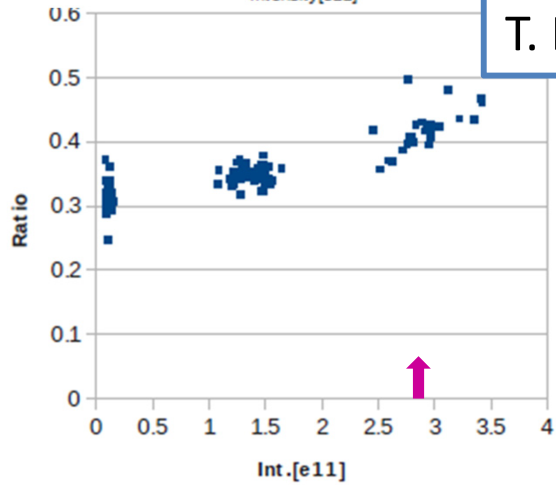


- In Q26 on FT N_{th}= 2.2×10^{11}
- FB – probably Nth= 2.7x10^11
- In Q20 N_{th}= 2.7×10^{11}

=> similar thresholds for the same bunch length ~1.55 ns but higher threshold is expected

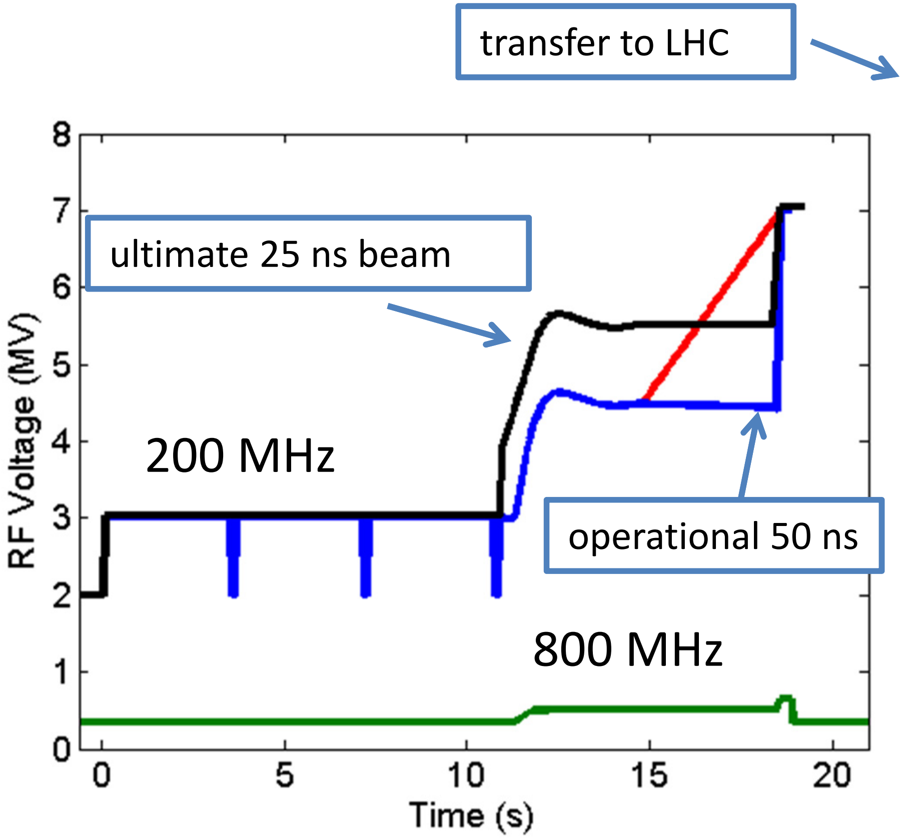
Q20: FT bunch length vs intensity
V200=7 MV, V800= 0.7MV





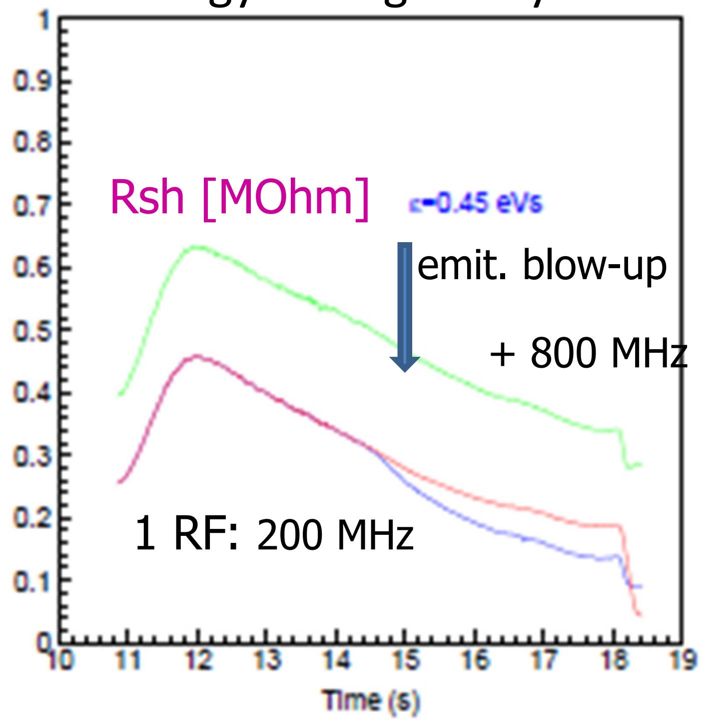
T. Bohl

SPS operational cycle for LHC beams: voltage programs

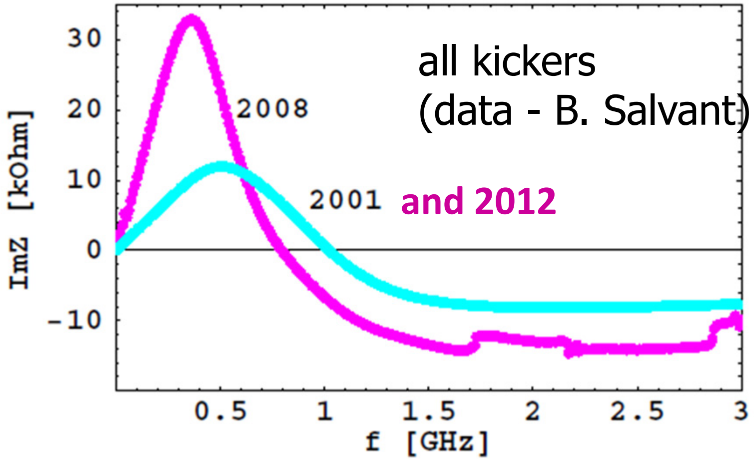


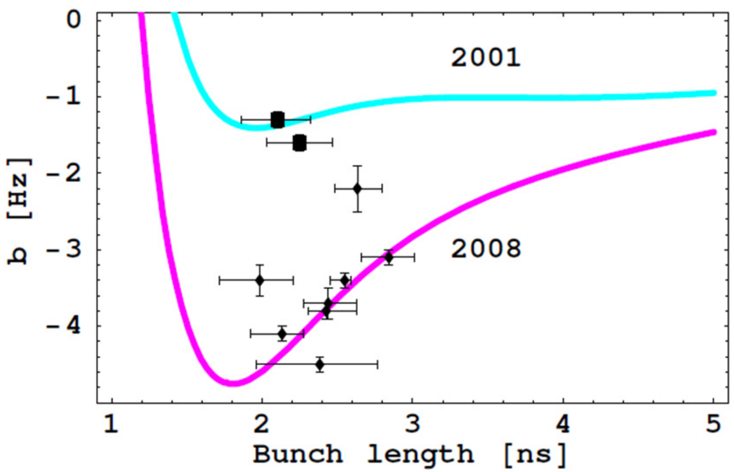
800 MHz used in bunch-shortening mode
Phase shift is programmed through the cycle

CBI threshold decreases with energy during the cycle



SPS longitudinal impedance: reactive part

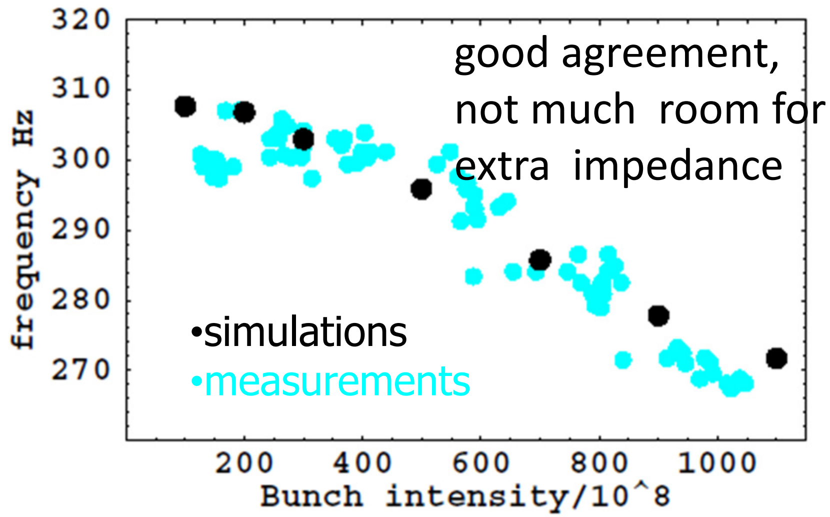




7 from 8 MKE kickers - main contributors to the SPS inductive impedance ImZ - were serigraphed this year but the instability threshold didn't change!

Synchrotron frequency shift

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



4^{th} harmonic (800 MHz): phase calibration

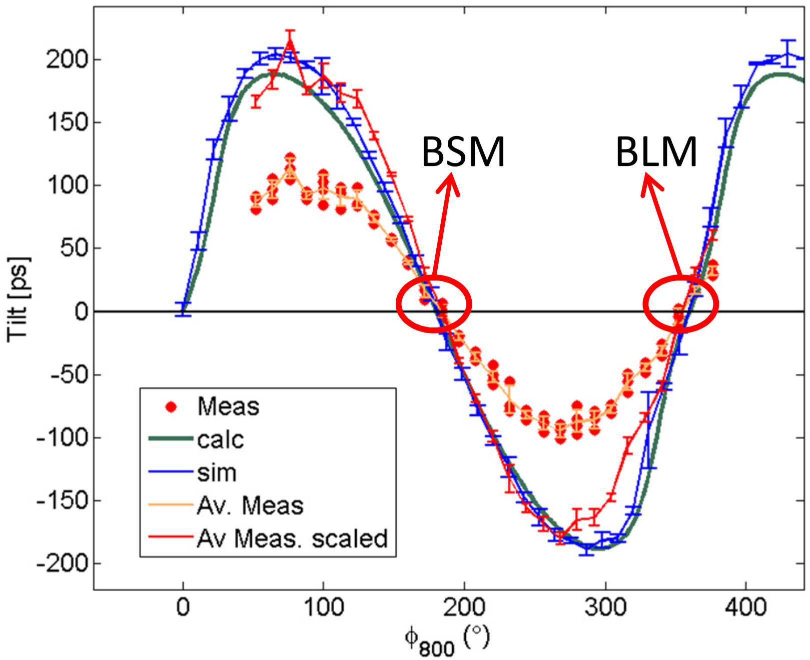
In reality what we measure is

$$\Phi_{800} = \varphi_{800} + \varphi_0 \,,$$

where φ_0 is an unknown offset which has to be calibrated

Calibration is done by measuring the symmetry of the bunch (bunch tilt) while varying the phase Φ_{800} with:

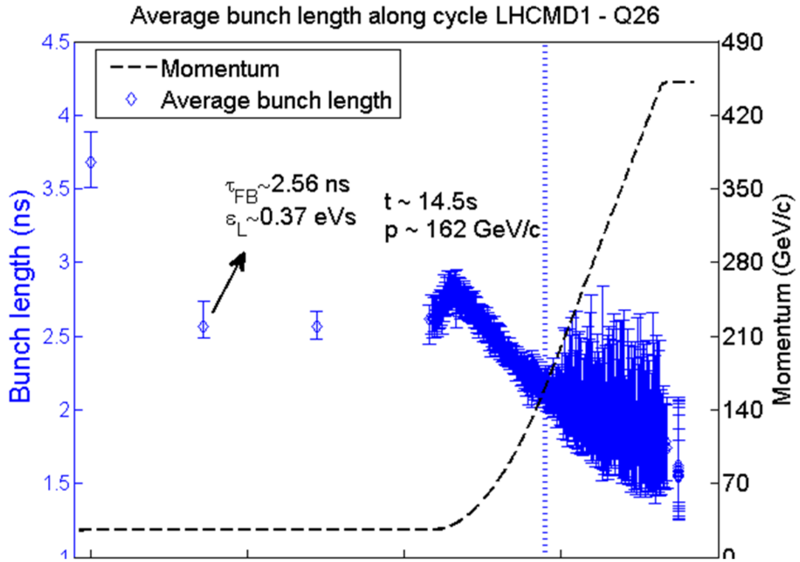
- Single proton bunch at low intensity (N_p~1. x10^{10} p/b)
- Voltage ratio between the two RF systems $V_{200}/V_{800} = 0.25$

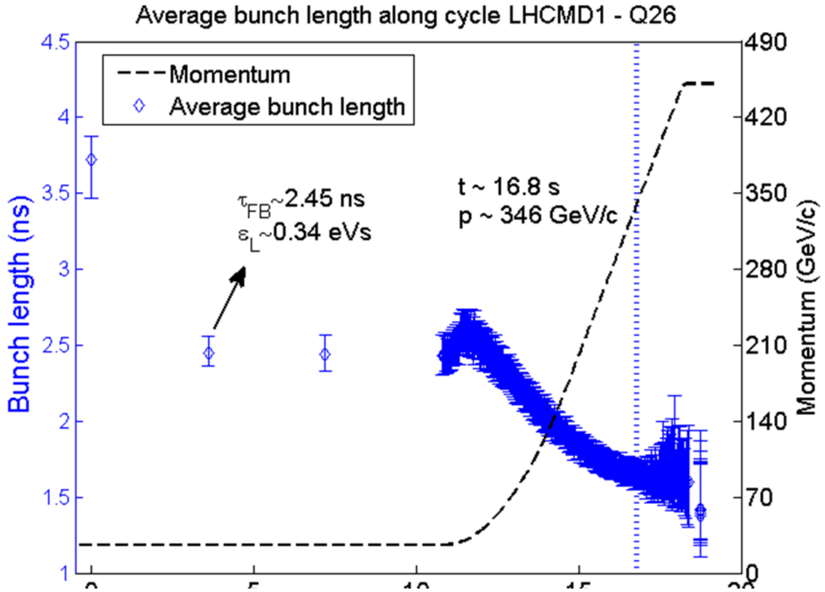


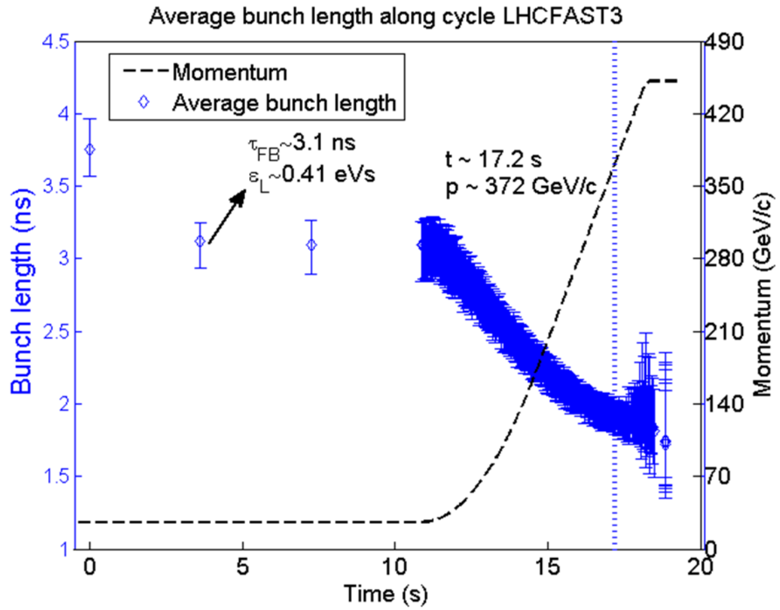
- ➢ Very good agreement between simulations and calculations
- ➢ Good agreement also with the measurements (after scaling)

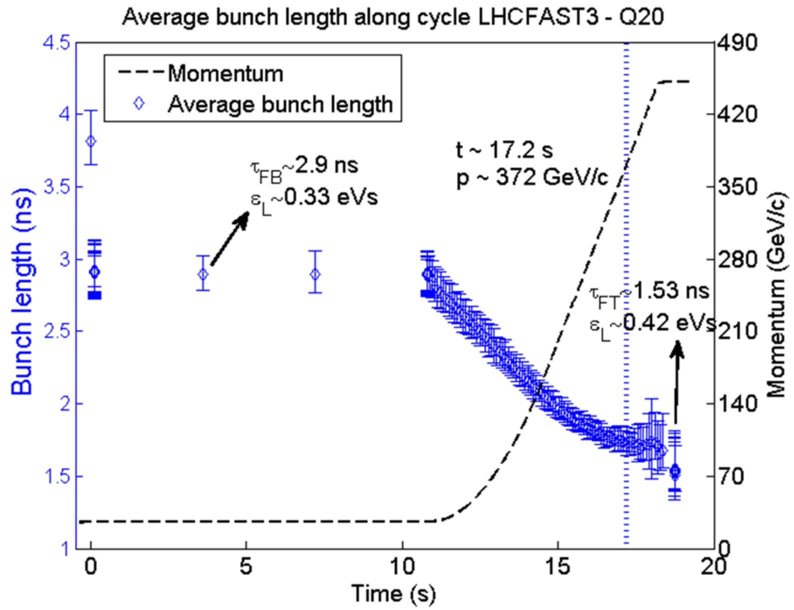
Beam stabilisation

50 ns beam, 1.6×10^{11} p/b

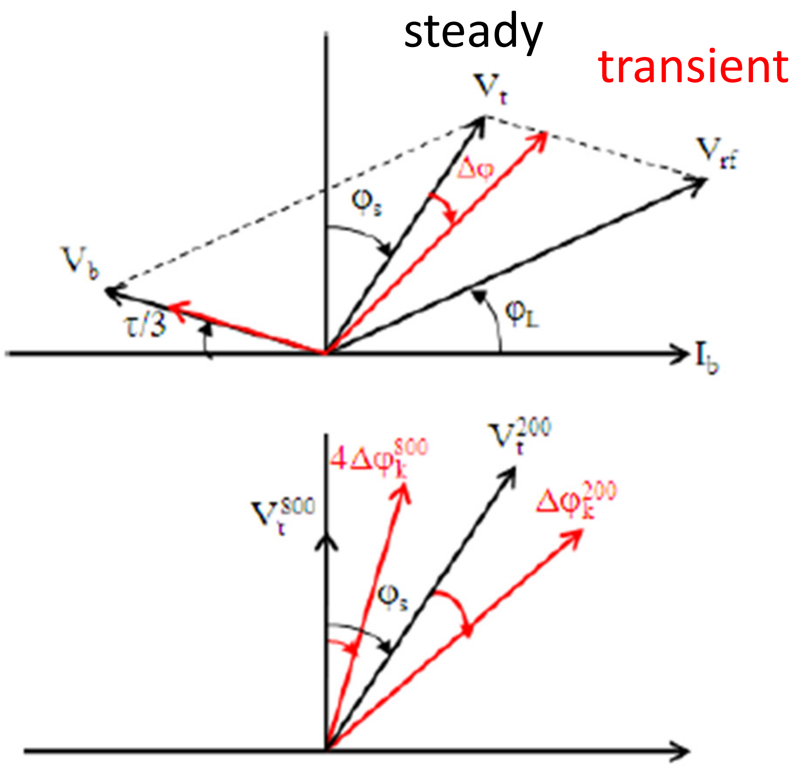


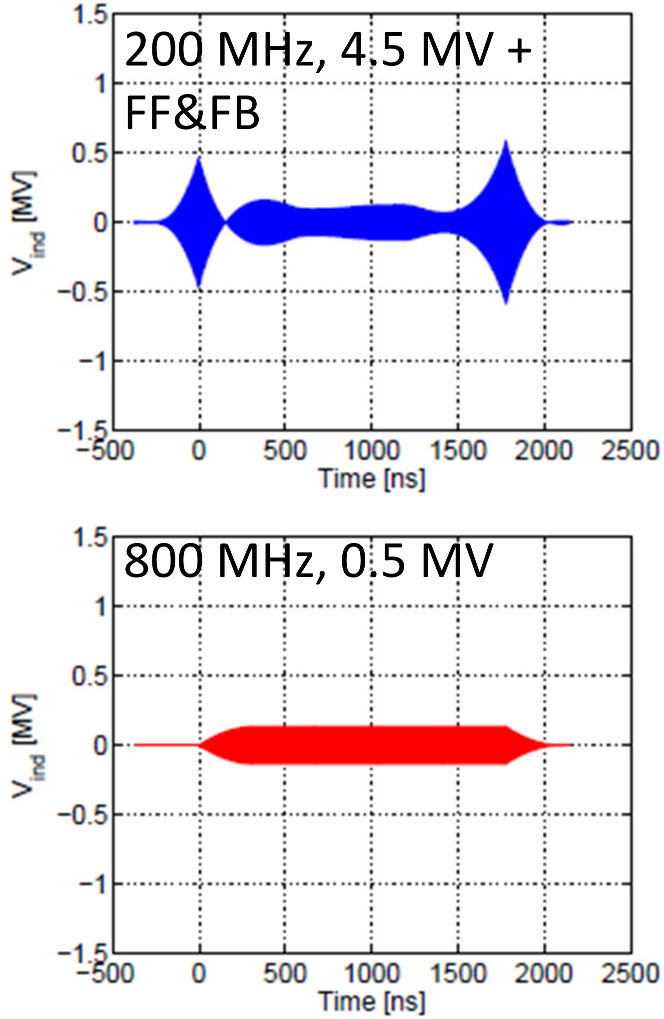






Beam induced voltage during ramp





Now the reference signal is sampled outside the beam

T. Argyropoulos et al., HB2010