LHC Injectors Upgrade

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LHC Injectors Upgrade

Additional (beyond baseline) PS upgrade options

H. Damerau, A. Lasheen
SPS injection losses review
30/11/2017

Many thanks to G. Favia, C. Rossi, E. Shaposhnikova

Overview

- Introduction
- Observations motivating additional upgrades
  - Open issues with beam
  - Observations of limitations with feedbacks
- Higher-harmonic Landau RF system
  - Beam tests and expected benefits
  - RF system parameters
- Additional RF systems
  - Feasibility of adiabatic bunch shortening at PS-SPS transfer
  - Potential voltage and frequency ranges
- Summary

Introduction and motivation

Issues with LHC-type beams in the PS, even with partly implemented longitudinal LIU improvements

1. **Preserve longitudinal beam quality at highest intensities**
   - **Coupled-bunch instabilities at $N_b > 2 \cdot 10^{11}$ ppb**
   - **Uncontrolled emittance blow-up**
2. **Avoid bunch shape distortion of caused by bunch rotation prior to PS-SPS transfer**
   - **Distorted bunch distribution at PS ejection due to rotation**

→ Difficult to reach $N_b = 2.6 \cdot 10^{11}$ ppb with LIU baseline improvements

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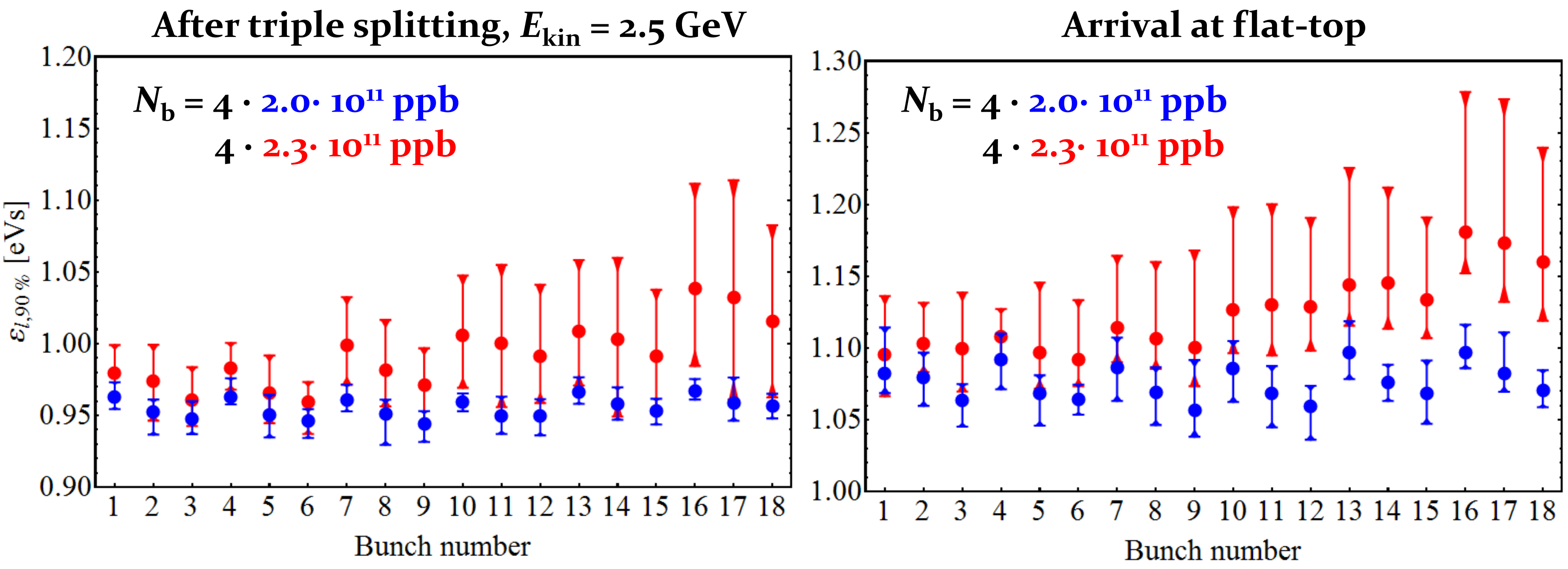
Longitudinal emittance along batch

- **Above bunch intensities of $2 \cdot 10^{11}$ ppb beam quality degrades**
- **Emittance along batch increase**



After triple splitting, $E_{\mathrm{kin}} = 2.5$ GeV

Arrival at flat-top

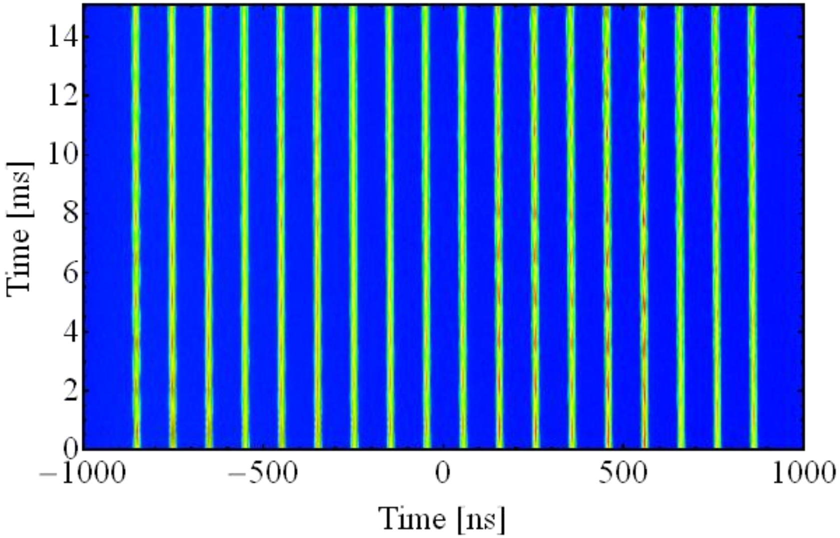
→ Again first few bunches much less affected than tail of batch

Quadrupole oscillations after transition

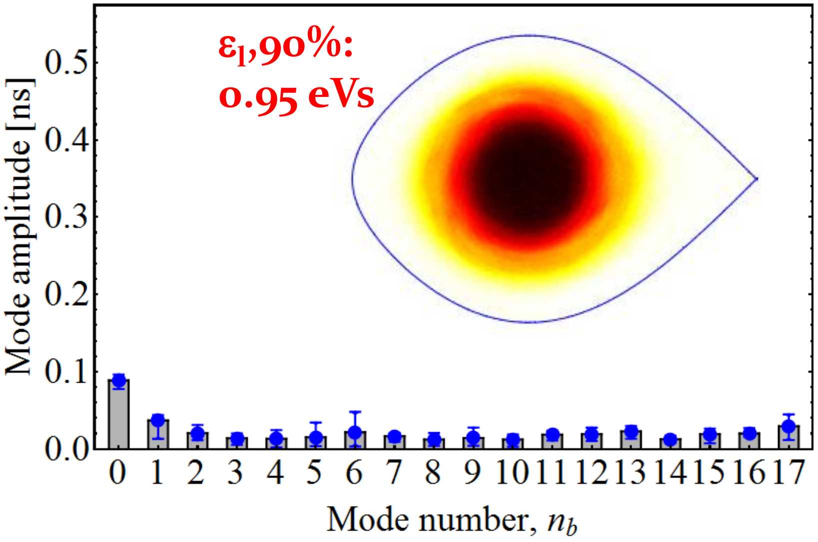
- **Emulating higher intensity by increasing density N_b/ε_l**

→ Quadrupole instabilities observed right after transition crossing

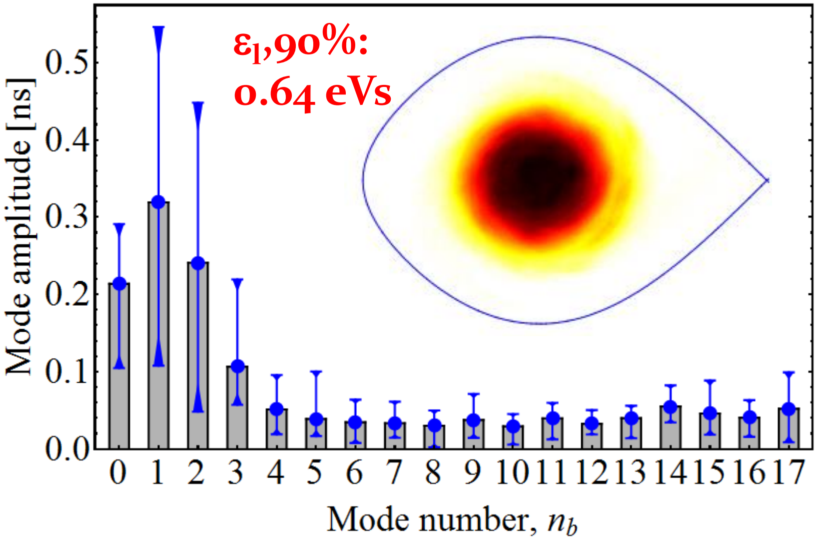
→ Measurements at $4 \cdot 2.0 \cdot 10^{11}$ ppb



Nominal emittance: ε_l,90%: = 0.95 eVs



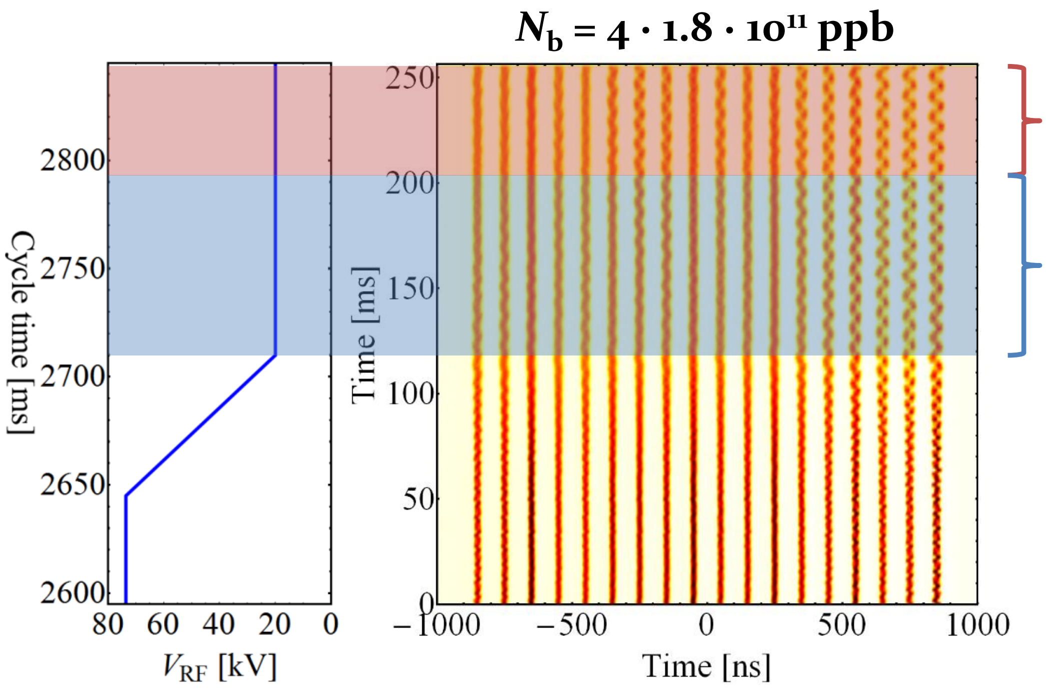
Reduced emittance: ε_l,90%: = 0.64 eVs



→ No damping from coupled-bunch feedback

Instability at flat-top

- **Stop RF manipulations at flat-top to observe evolution of stability**



$N_b = 4 \cdot 1.8 \cdot 10^{11}$ ppb

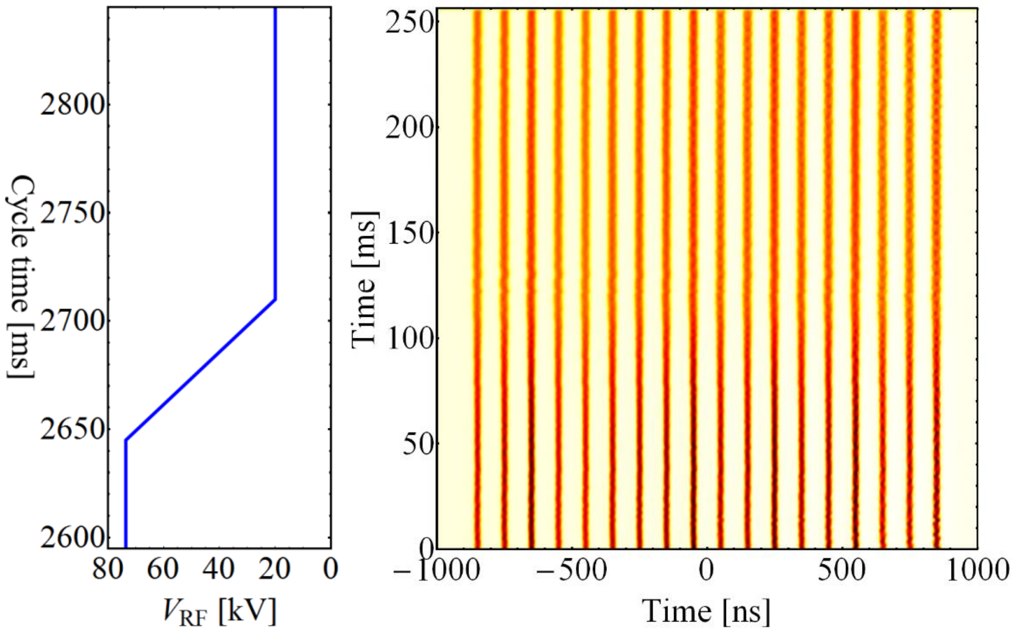
2nd splitting, $h = 42 \rightarrow 84$

1st splitting, $h = 21 \rightarrow 42$

- **Dipole coupled bunch oscillations build up along the batch**
  - → **Low $2Q/\omega_0$ impedance source decaying during ~400 ns gap**
- **Already well developed at start of first splitting manipulation**

Instability at flat-top

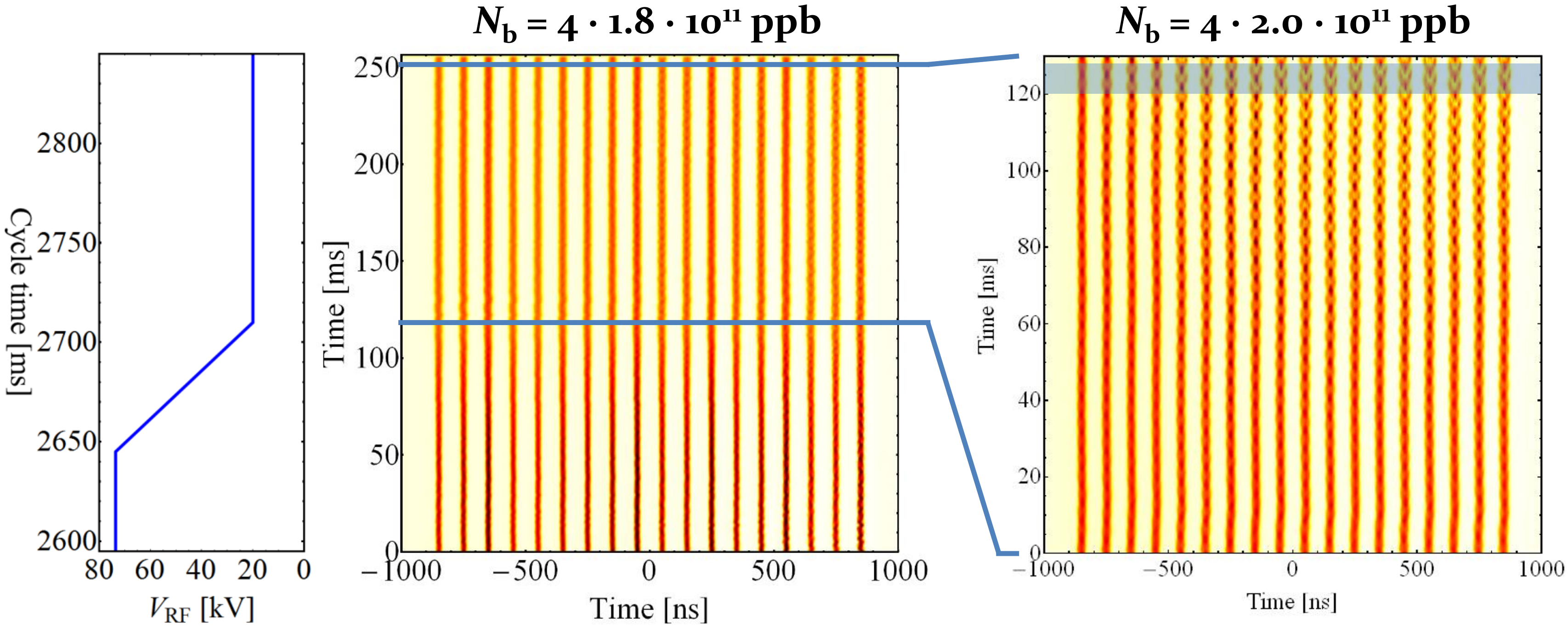
- **Stop RF manipulations at flat-top to observe evolution of stability**
- **Coupled-bunch feedback enabled → significant improvement**



$N_b = 4 \cdot 1.8 \cdot 10^{11}$ ppb

Instability at flat-top

- **Stop RF manipulations at flat-top to observe evolution of stability**
- **Coupled-bunch feedback enabled → significant improvement**



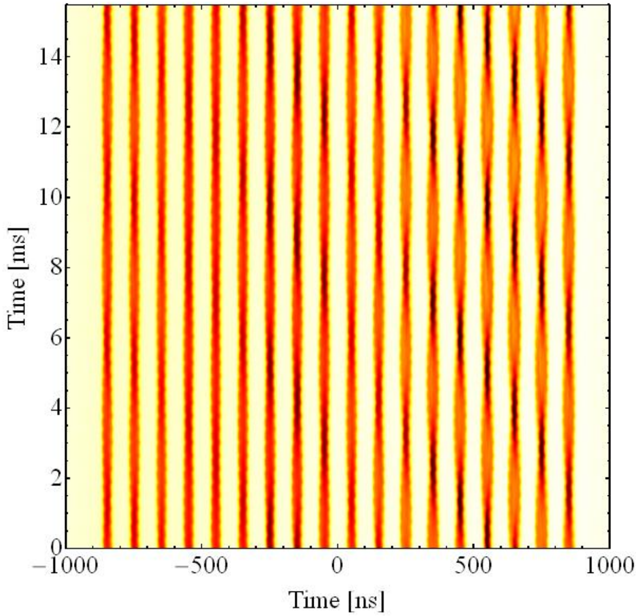
- **Dipole coupled-bunch oscillations well damped**
- **Again quadrupolar oscillations at ~$4 \cdot 2 \cdot 10^{11}$ ppb**

  → Not damped by feedback system? → Mode analysis

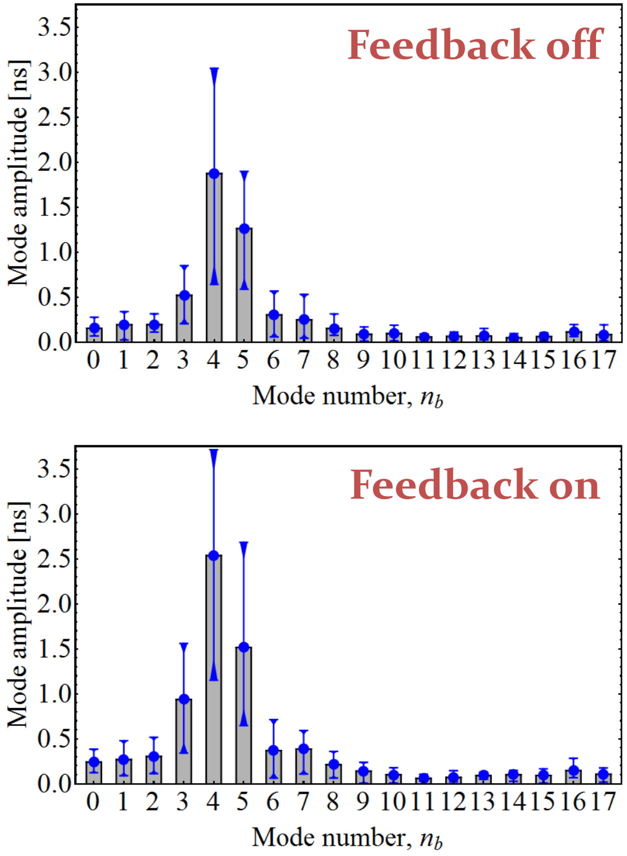
Quadrupole oscillations with feedback?

- **Side-bands at ±2f_S also pass the filters of the coupled-bunch feedback**
  - **→ BUT: phase advance wrong (set for dipole oscillation damping)**

$N_b = 4 \cdot 2.0 \cdot 10^{11}$ ppb



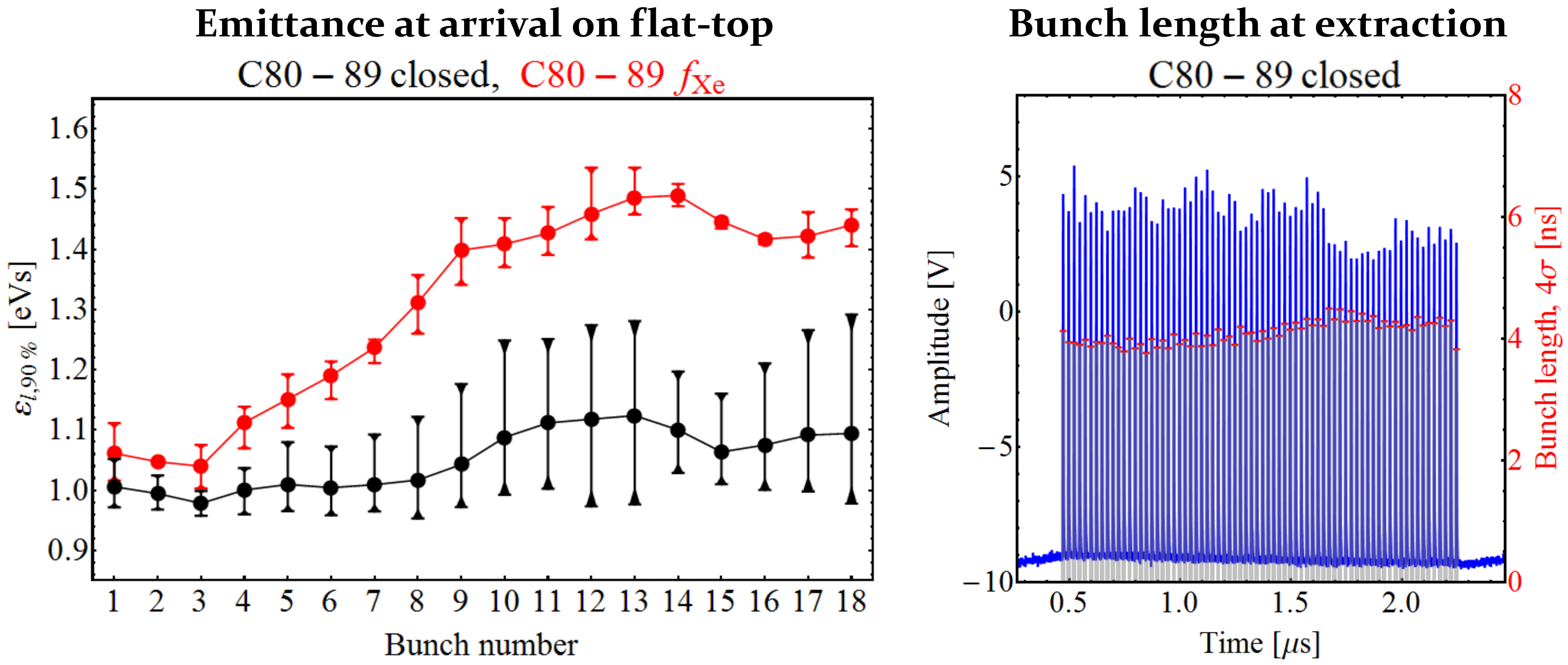
Quadrupole mode spectrum



→ No damping from dipole coupled-bunch feedback

Instability at flat-top

- **Detrimental effect of 80 MHz cavity impedance, $N_b = 2.2 \cdot 10^{11}$ ppb**



- **Bunch length and emittance degradation along the batch**
  - → **With minimum number of high frequency cavities**
  - → **Well below bunch intensities of $N_b = 2.6 \cdot 10^{11}$ ppb**

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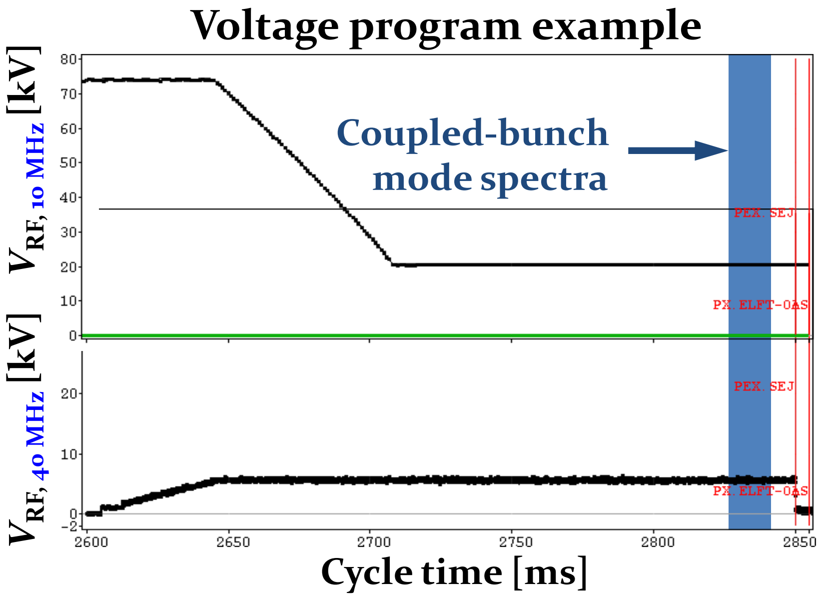
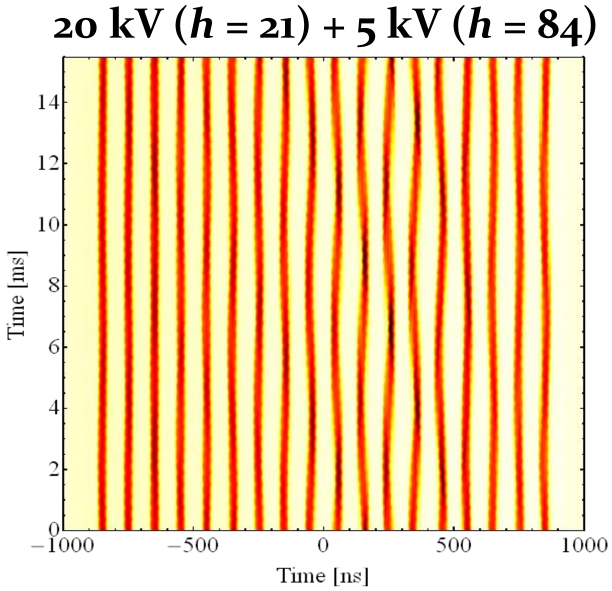
High-frequency cavity as Landau RF system

- **Proof-of-principle test adding 20/40 MHz at flat-top in 2016**
  - → **Nominal intensity of $4 \cdot 1.3 \cdot 10^{11}$ ppb without coupled-bunch feedback**
  - → **Bunch shortening (BS, in-phase) and lengthening (BL, counter-phase)**



Voltage program example

Coupled-bunch mode spectra



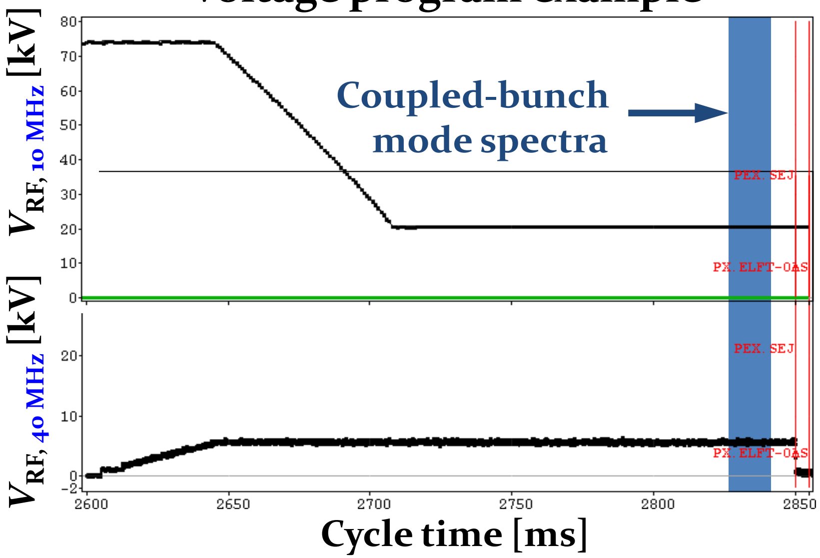
20 kV (h = 21) + 5 kV (h = 84)

→ **No significant stability change in BL mode**

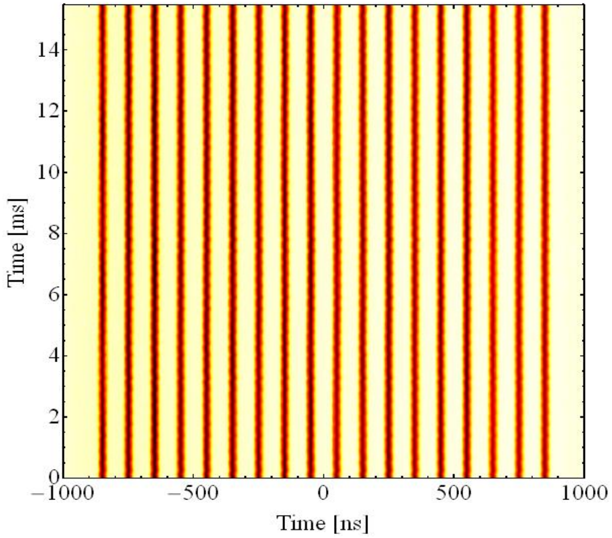
High-frequency cavity as Landau RF system

- Proof-of-principle test adding 20/40 MHz at flat-top in 2016
  - → Nominal intensity of $4 \cdot 1.3 \cdot 10^{11}$ ppb without coupled-bunch feedback
  - → Bunch shortening (BS, in-phase) and lengthening (BL, counter-phase)

Voltage program example



20 kV (h = 21) + 5 kV (h = 84)



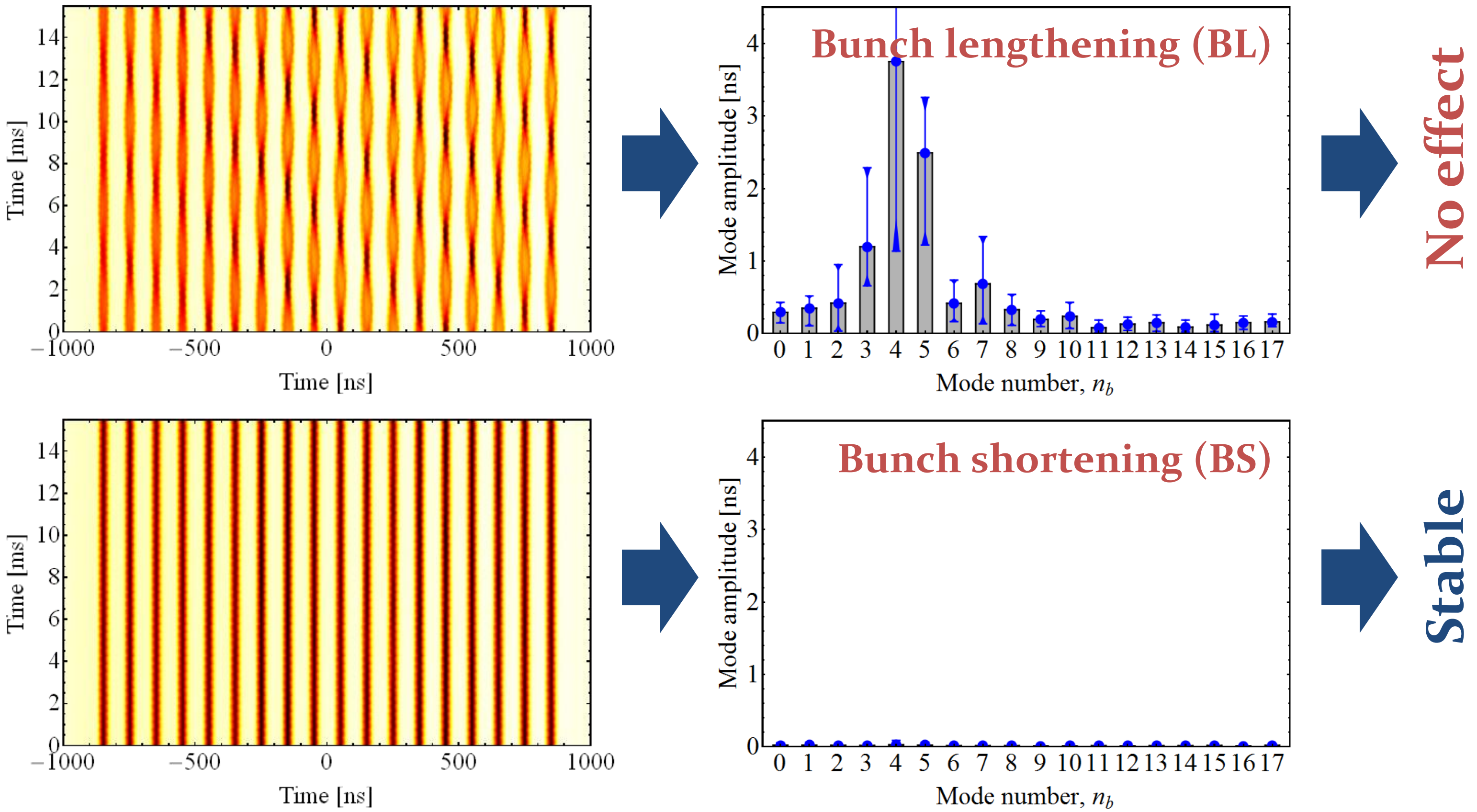
→ Much improved stability in BS mode

→ Similar condition than in the SPS with 200/800 MHz RF systems

E. Shaposhnikova et al., PAC2005

Damping of quadrupole instability

- → $N_b = 4 \cdot 2 \cdot 10^{11}$ ppb together with dipole coupled-bunch feedback
- → Bunch shortening (BS, in-phase) and lengthening (BL, counter-phase)
- → Reduce higher-harmonic voltage down to ratio $V_{40\,\mathrm{MHz}}/V_{10\mathrm{MHz}} = 0.1$



20 kV (h = 21) + 2 kV (h = 84)

Quadrupole mode spectrum

Bunch lengthening (BL) → No effect

Bunch shortening (BS) → Stable

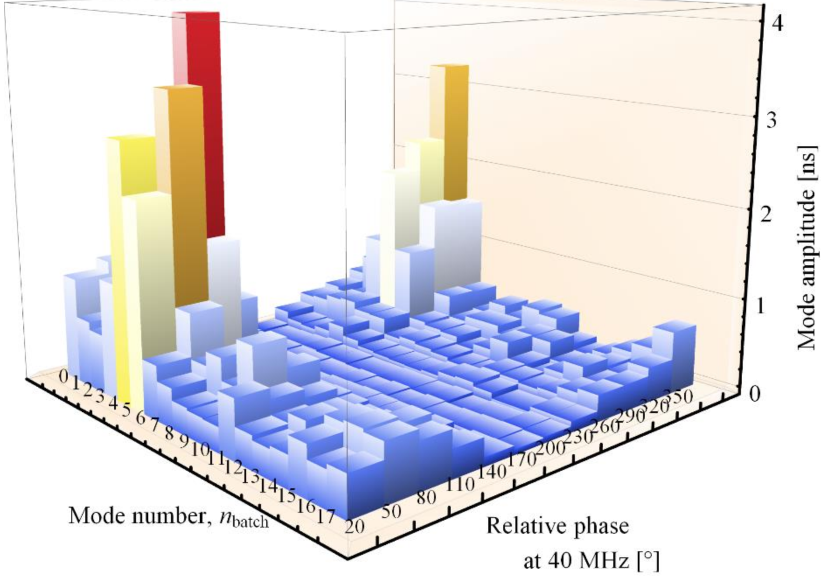
→ Encouraging results with combination 10 MHz/40 MHz

Robustness of Landau cavity approach

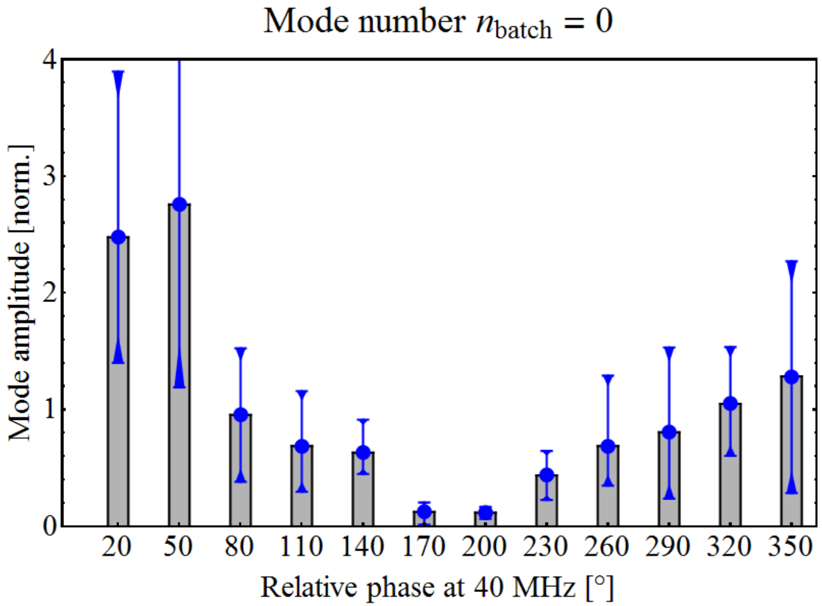
- **Few parameters**: harmonic number, **RF voltage and phase**

→ Scan to explore parameter sensitivity

Mode spectrum versus relative phase



~60° wide valley of stability

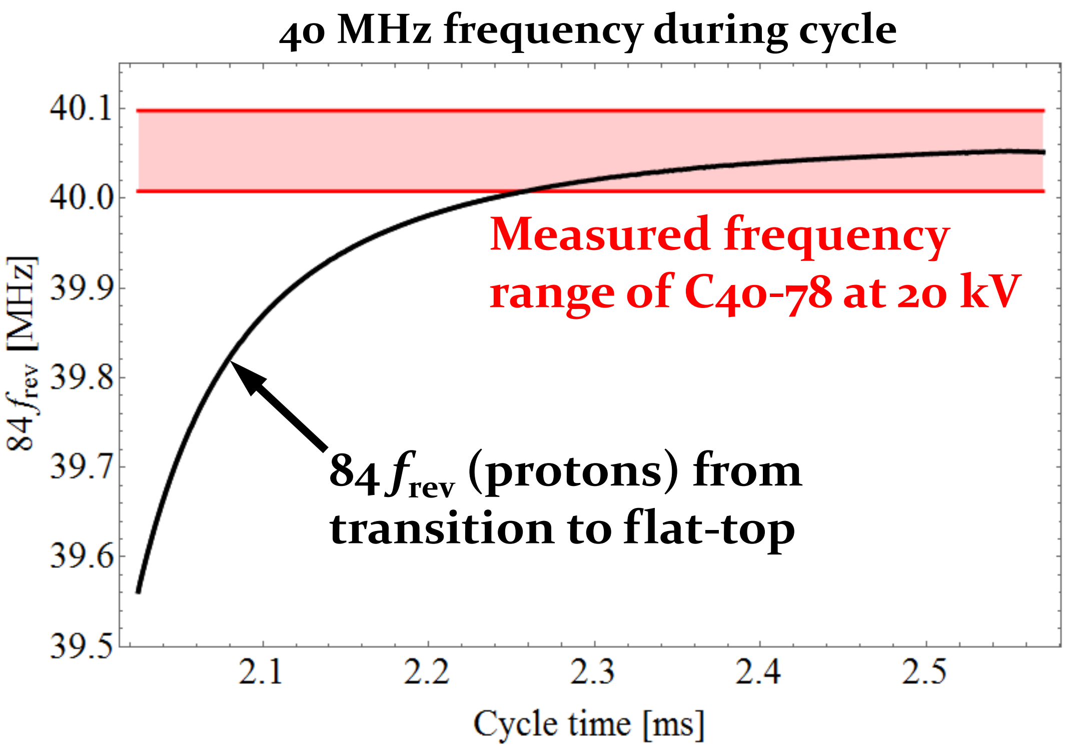


→ **Damp dipole** and **higher-order mode instabilities** simultaneously

→ **Robust** with respect to relative phase

Landau cavity during acceleration?

- **Existing 40 MHz cavities optimized for large RF voltage (~300 kV) at fixed frequency**
- **Measurements to explore frequency range at low RF voltage**



Measured frequency range of C40-78 at 20 kV

84 f_{rev} (protons) from transition to flat-top

Usable frequency range:

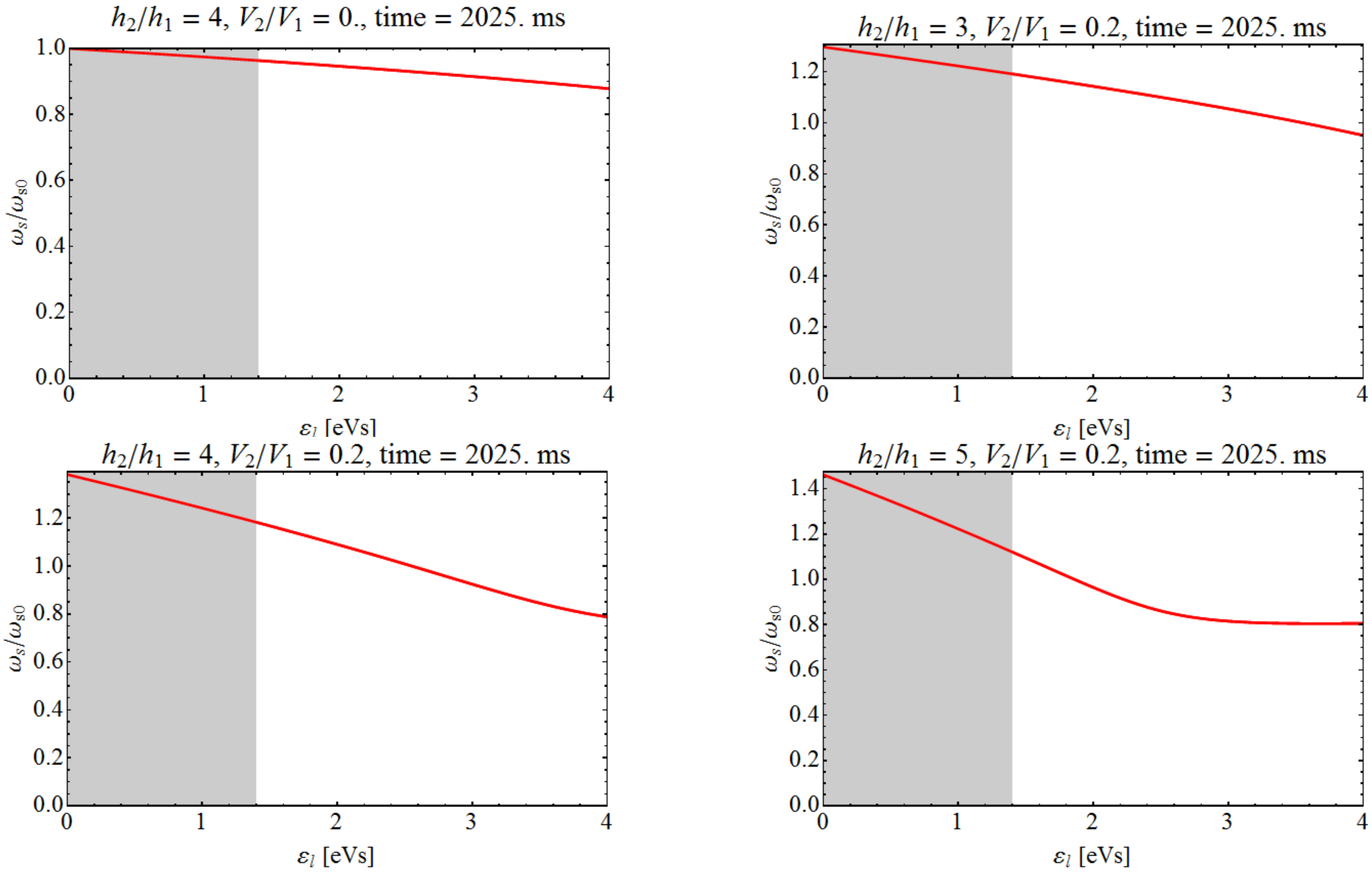
V_{RF}	C40-77	C40-78
10 kV	110 kHz	170 kHz
20 kV	50 kHz	90 kHz

→ Frequency limits confirmed with beam tests

→ Insufficient → Need dedicated RF system for Landau damping

Harmonic number ratio for dedicated cavity

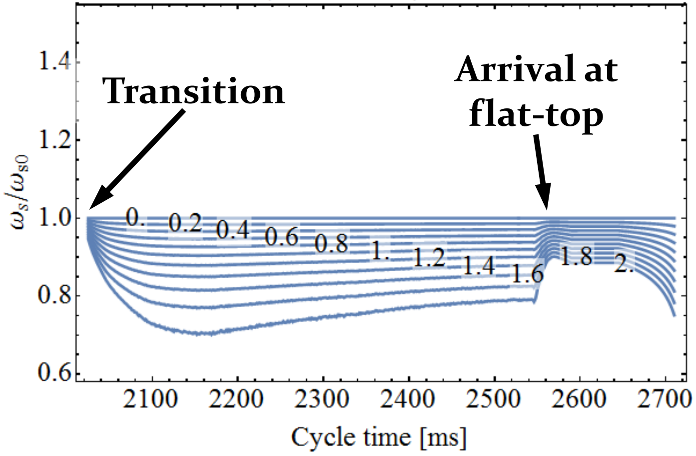
- 1st order calculation: f_s distribution during acceleration



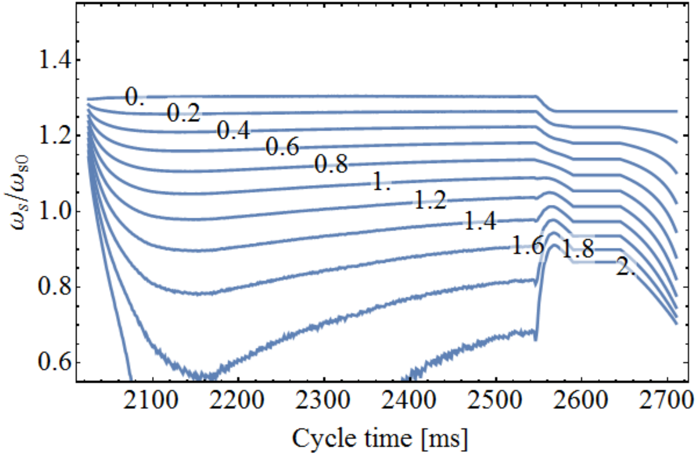
Possible harmonic number ratio

- **Synchrotron frequency spread versus emittance**

$h_2/h_1 = 4,\ V_2/V_1 = 0.$



$h_2/h_1 = 3,\ V_2/V_1 = 0.2$



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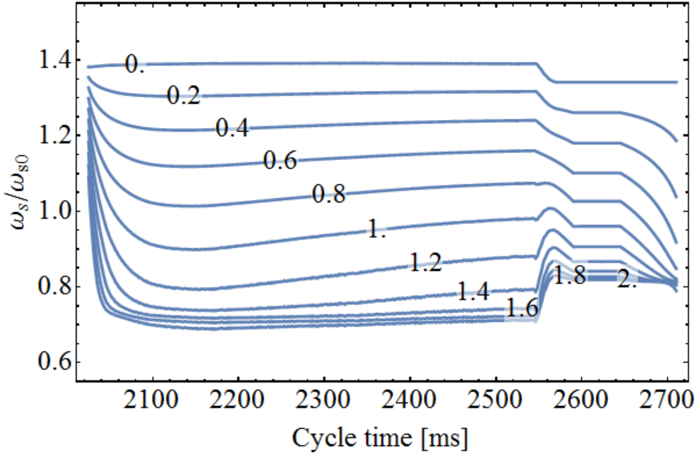
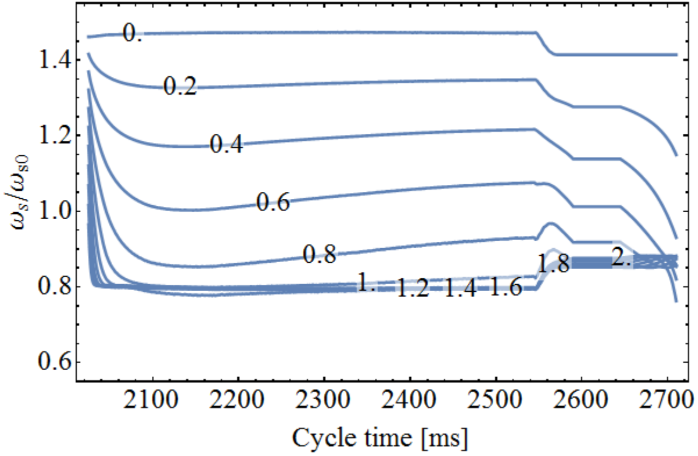


$h_2/h_1 = 5,\ V_2/V_1 = 0.2$



→ 3rd harmonic not very efficient, 5th harmonic too high for 1.4 eVs

→ 4th harmonic (*h* = 84) seems interesting compromise

Possible Landau RF system parameters

- Frequency ranges and preliminary RF voltages

	$\Delta f/f$ [%]	$h_2/h_1 = 3, h = 63$	$h_2/h_1 = 4, h = 84$	$h_2/h_1 = 5, h = 105$
2 GeV to 26 GeV	5.3	28.49…30.04 MHz	37.98…40.05 MHz	47.48…50.07 MHz
Transition to 26 GeV	1.3	29.65…30.04 MHz	39.53…40.05 MHz	49.42…50.07 MHz
RF voltage		~60…80 kV ($V2/V1 = 0.3…0.4$)	~40…50 kV ($V2/V1 = 0.2…0.25$)	< 40 kV ($V2/V1 < 0.2$)

- Vaccum cavity similar to 40 MHz with ferrite tuners?
  → Moderate voltage, relatively large tuning range and duty cycle
- Technically feasible, similar RF systems exist, e.g.:

→ FNAL Main Injector:	240 kV, 52.8…53.1 MHz	($\Delta f/f$ ~ 0.6%)
→ FNAL Booster:	55 kV, 37.8…52.8 MHz	($\Delta f/f$ ~ 30%)
→ CERN study:	up to 60 kV, 18…40 MHz	($\Delta f/f$ ~ 70%)

- Launch study for conceptual technical design of RF system?

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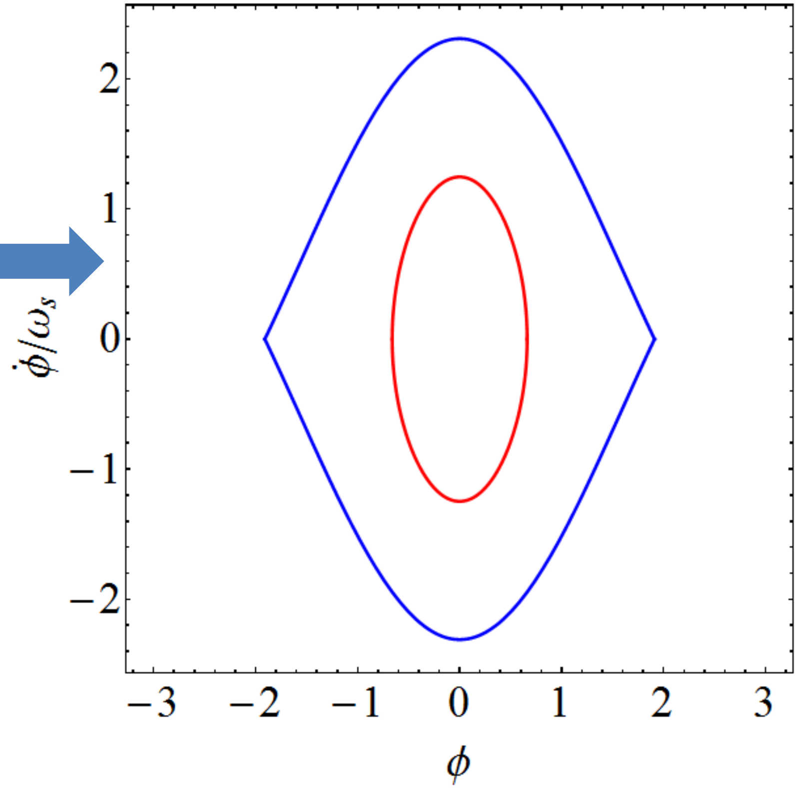
Adiabatic bunch shortening

- **Assumption:** nominal longitudinal emittance of 0.35 eVs

RF voltage 40 MHz [kV]	RF voltage 80 MHz [kV]	Bunch length [ns]
600	0	7.3
600	600	5.7
600	**900**	5.3
(2160)	(0)	5.3
(0)	(1210)	5.3

Separatrix and 0.35 eVs trajectory

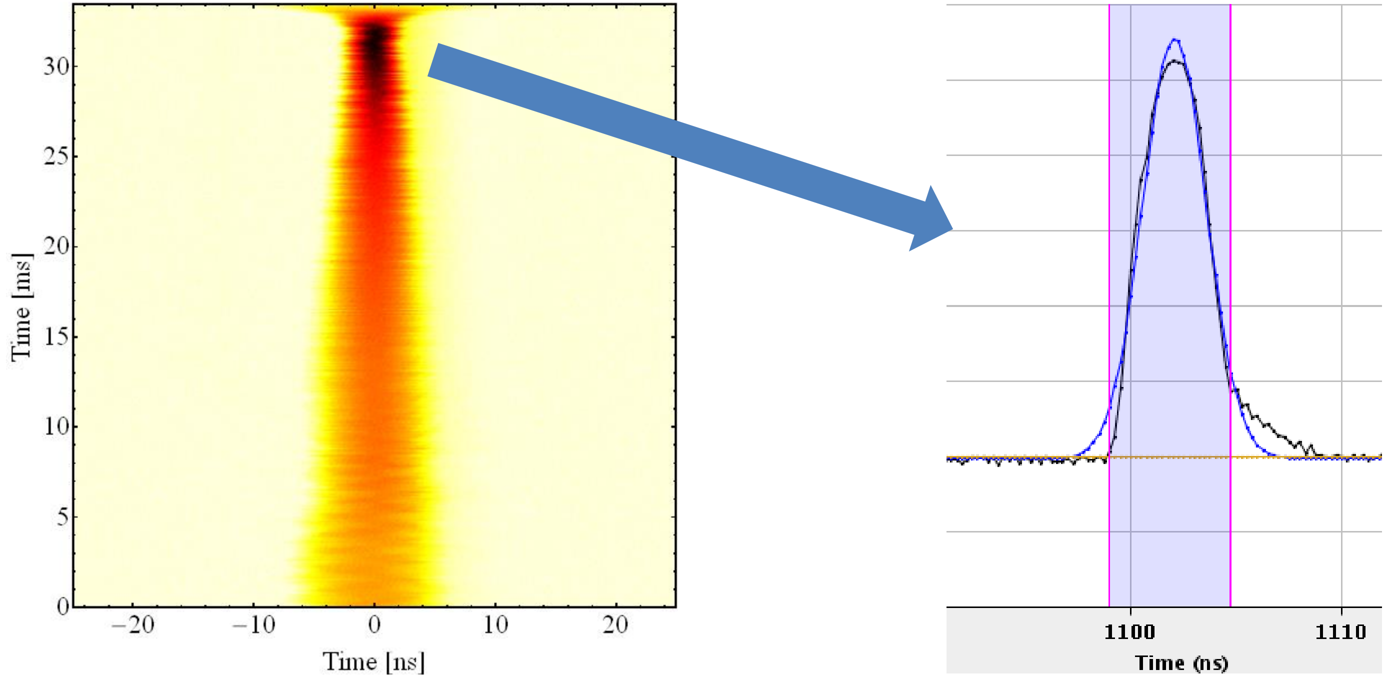


→ Bunches with 40 MHz alone short enough to fit into 80 MHz wavelength

→ Beam test with 600 kV at 40 MHz and 600 kV at 80 MHz

Single-bunch test

- **Objective:** Check minimum bunch length without intensity effects


Adiabatic shortening

Shortest bunch: 4σ ~ 6 ns

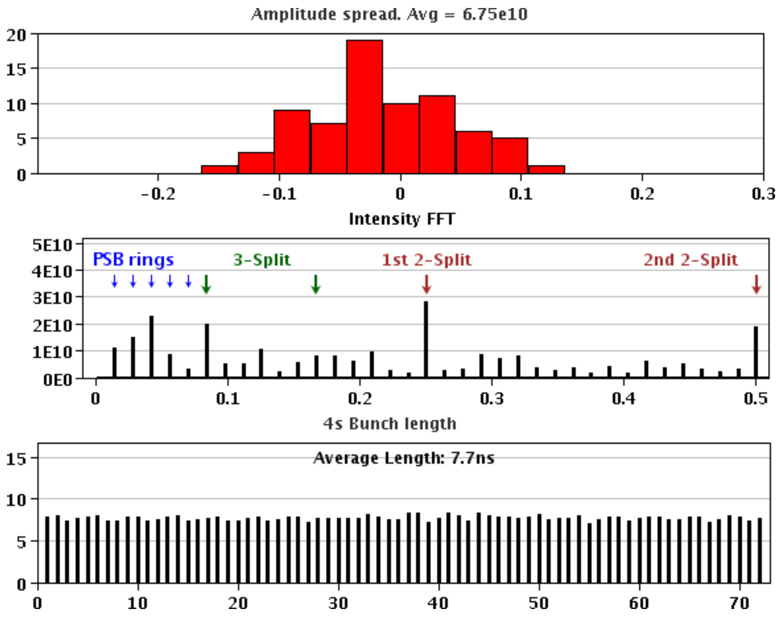
→ Measured bunch length with ~0.35 eVs emittance becomes 6 ns

→ Corresponds well to estimate from trajectory of 5.7 ns

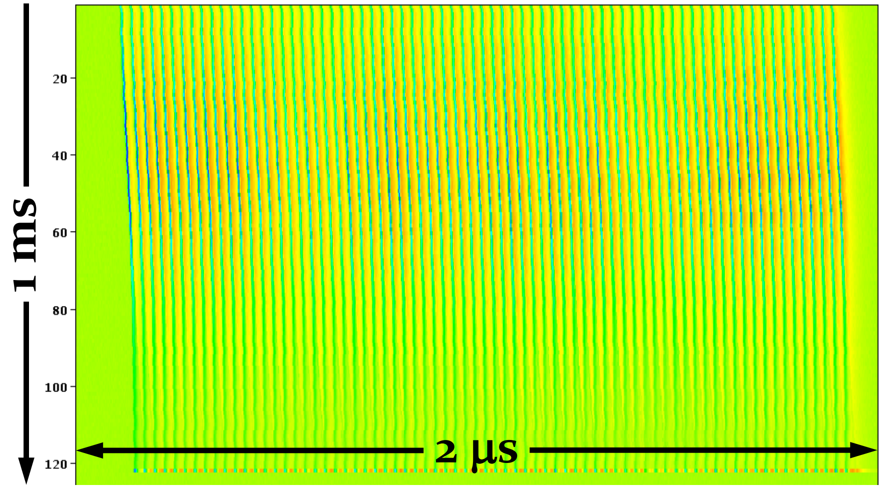
Short multi-bunch beams

- **LHC 25 ns beam at nominal intensity, $N_b = 1.3 \cdot 10^{11}$ ppb**
- **Limited by energy from present anode power converters**

600 kV at 40 MHz



Pick-up (SS00), hor. last 500 turns

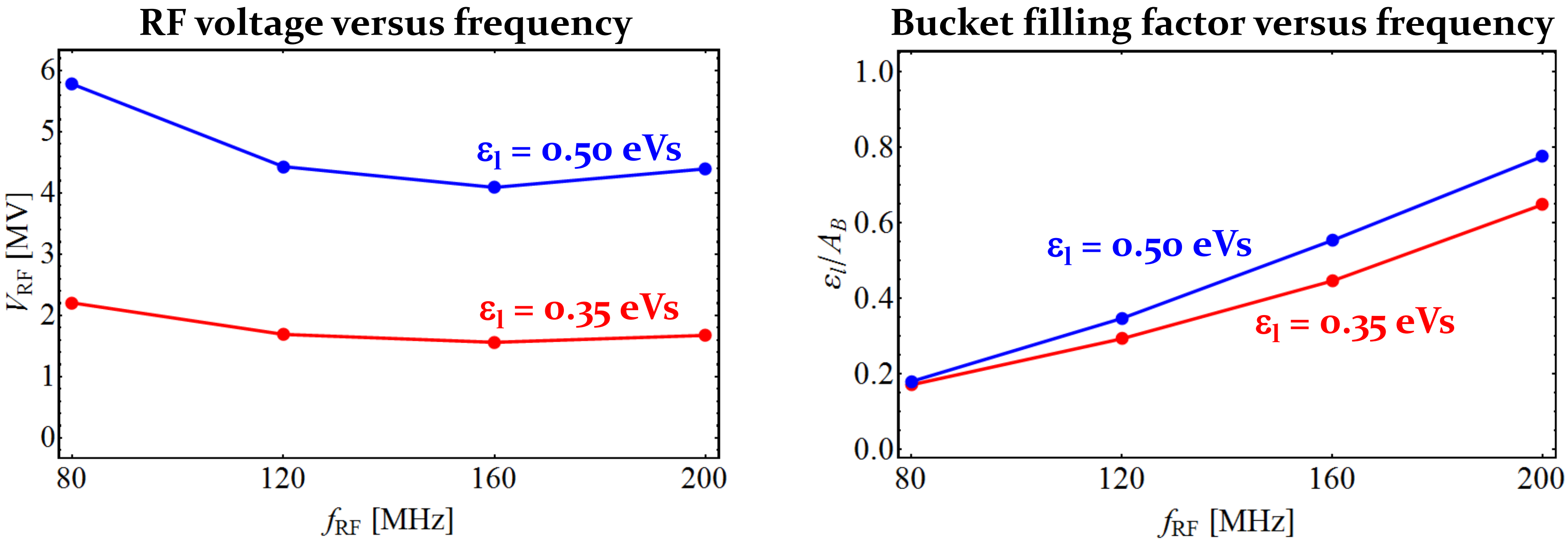


→ **Measured bunch length longer (7.7 ns) than expected (7.3 ns)**

→ **Transverse instabilities (probably e-cloud) with short bunches**

Matched PS-SPS transfer

→ **RF voltage in addition to 600 kV at 40 MHz and 900 kV at 80 MHz for adiabatic compression to 4 ns bunches at PS extraction**



→ **Longitudinal emittance increase requires excessive RF voltage**

- **Whichever options is considered:**
  - → **Important multi-cavity (3...9 cavities) installation**
  - → **Feasible in terms of space and cost?**

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- **Difficulties to reach LIU parameters with baseline upgrades**
  - → Emittance growth along the batch already at 2.5 GeV
  - → Dipole and quadrupole instabilities above $2 \cdot 10^{11}$ ppb
  - → Uncontrolled longitudinal emittance blow-up along the batch
- **Higher-harmonic Landau cavity**
  - → Proven damping of dipole and quadrupole instabilities at flat-top
  - → Stability beyond coupled-bunch feedback
  - → Potential of even smaller longitudinal emittance for PS
  - → Needs technical design study to define manpower, cost and schedule
- **RF system for adiabatic shortening or reduced bunch rotation**
  - → MV range: large multiple cavity installations
  - → Issues with short bunches in the PS: e-cloud, microwave instabilities
- **Open questions and beam studies before LS2**
  - → Refine parameter choices for Landau RF system
  - → Beam studies with new 40/80 MHz power converters in 2018

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

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Spare slides

RF system parameter example

- 6× less voltage → 36× smaller shunt impedance at constant power
- Smaller cavity then present 40 MHz: R/Q ↓ and Q ↓

	Existing	Estimate
	PS 40 MHz	**Landau 40 MHz**
RF voltage	300 kV_p	50 kV_p
Frequency, f_{res}	40.053 MHz	37.98…40.05 MHz
Tuning range	Fixed frequency	Ferrite tuner, 5%
Geometrical parmeter, R_S/Q_o	33 Ω	10 Ω
Loaded quality factor, Q_L	~10000	~2000
Shunt impedance, R	~330 kΩ	~20 kΩ
Power for nominal voltage, P	~140 kW	~65 kW

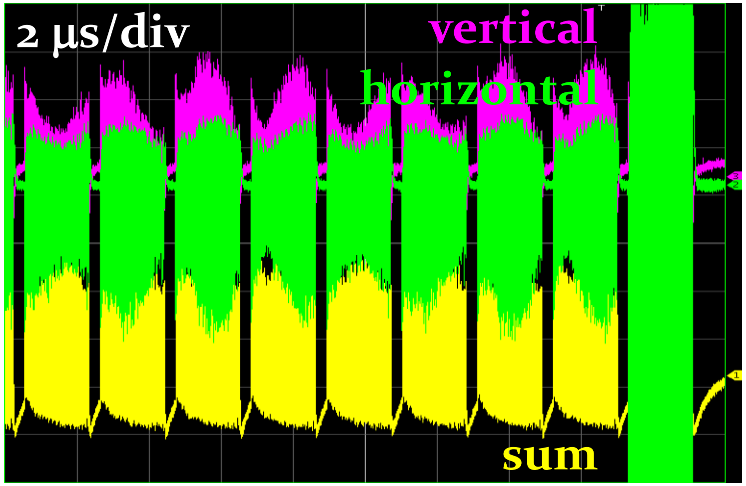
- Cost estimate: ~2 to 3 MCHF
- Development time: ~4…5 years

} **Preliminary, not based on technical design**

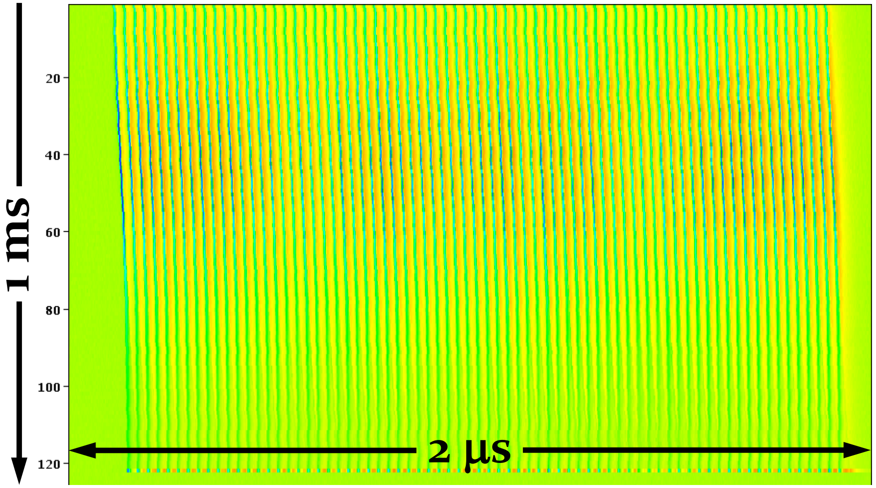
Transverse observations (Guido)

- **As expected, beam transversely unstable**

Wide-band pick-up (SS00), last turns



Pick-up (SS00), hor. last 500 turns



→ **Data yet to be analysed**

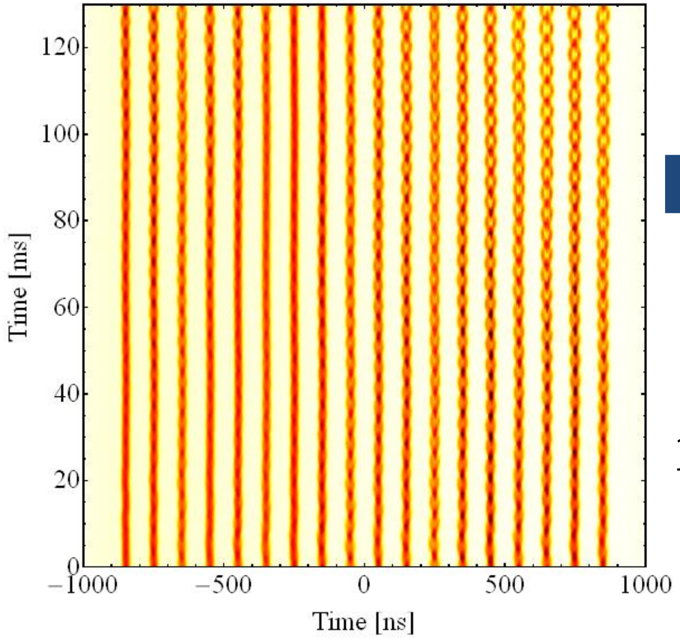
→ **First signals from electron cloud monitor in SS98, but no systematic data taken so far → MD next week**

→ **Transverse feedback set-up for operation at flat-top → next week**

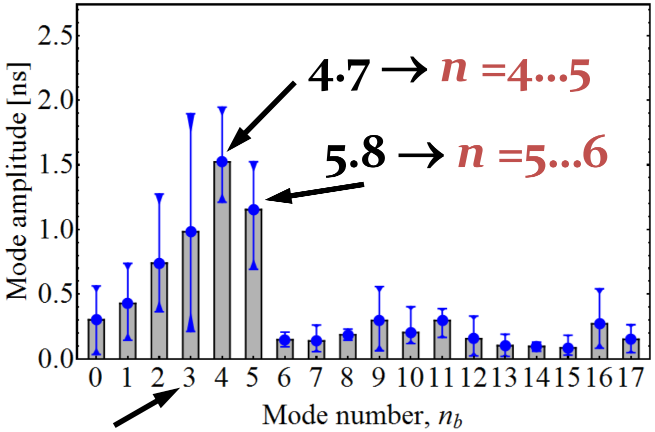
Dephasing test with coupled-bunch feedback

→ Scanned phase of signal processing channels trying to act on quadrupole modes of specific mode number

Quadrupole oscillations at flat-top



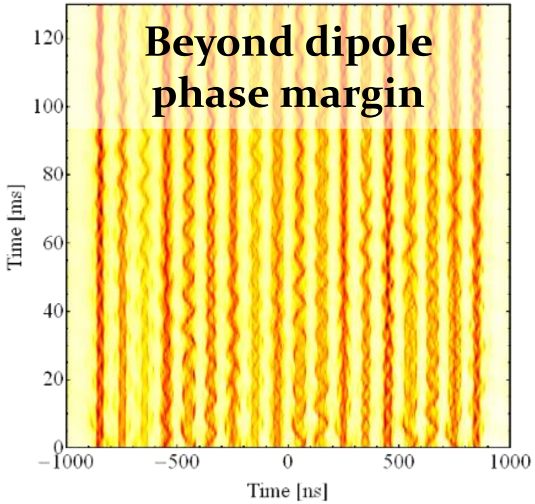
Quadrupole mode spectrum ($N_b = 4 \cdot 1.8 \cdot 10^{11}$ ppb)



4.7 → $n = 4 \ldots 5$

5.8 → $n = 5 \ldots 6$

$3 \cdot 7/6 = 3.5$ → $n = 3 \ldots 4$



Beyond dipole phase margin

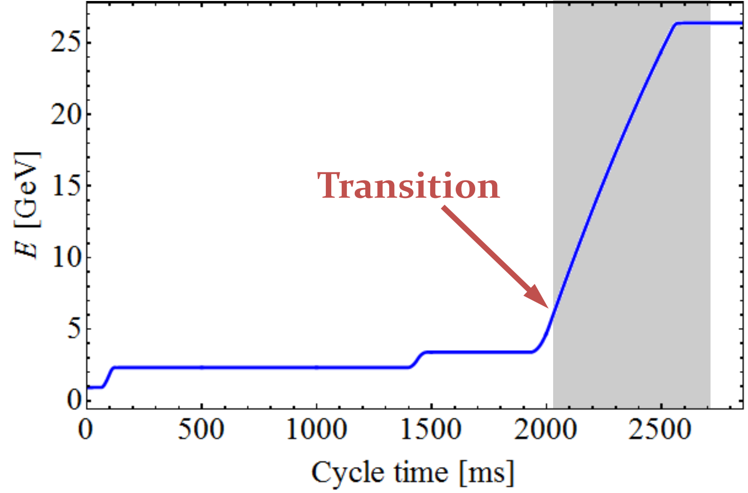
→ No beneficial effect on quadrupole oscillations of feedback in range of ~135°

→ Drives dipole instability beyond

Acceleration of LHC multi-bunch beams

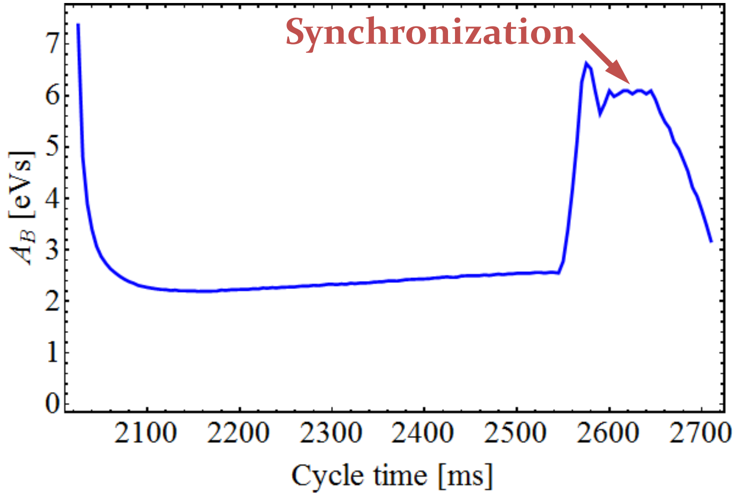
- **Longitudinal parameters of the present acceleration cycle**

Total energy



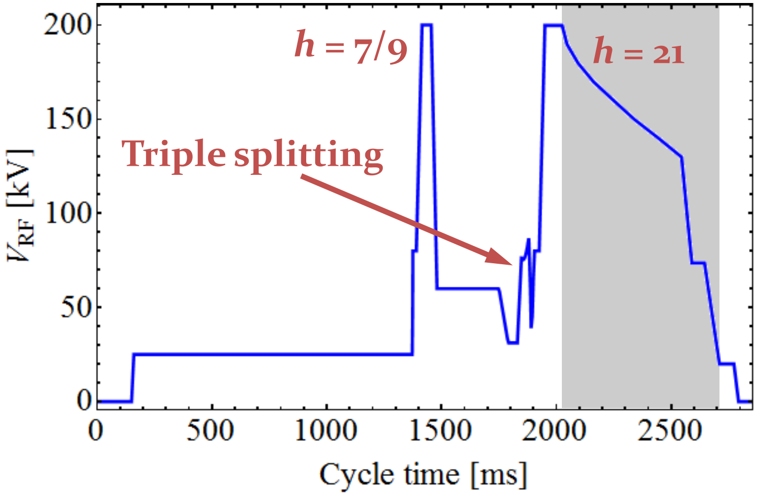
Transition

Single-harmonic bucket area



Synchronization

Total RF voltage, all harmonics

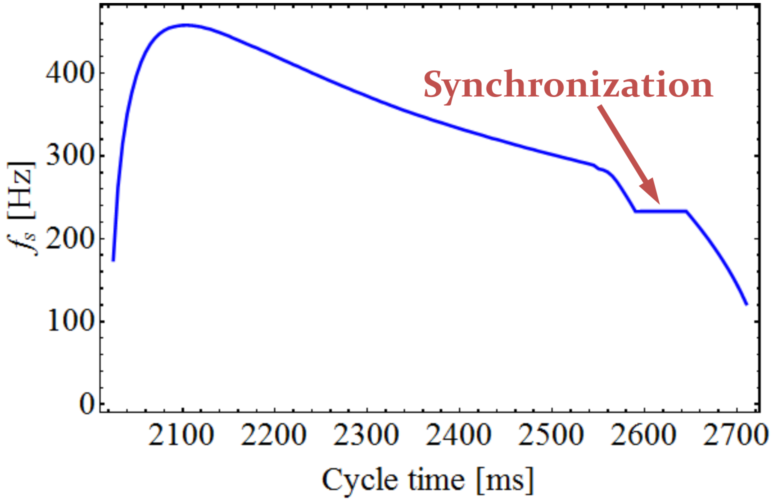


$h = 7/9$

$h = 21$

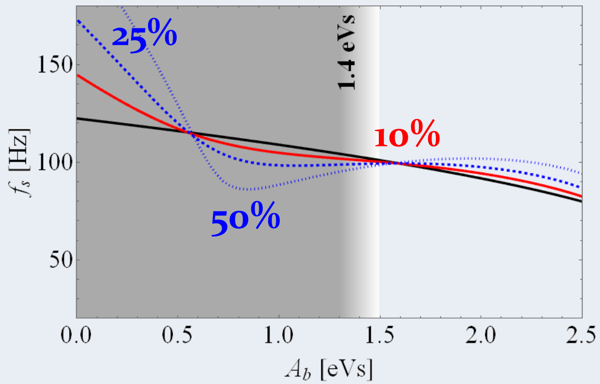
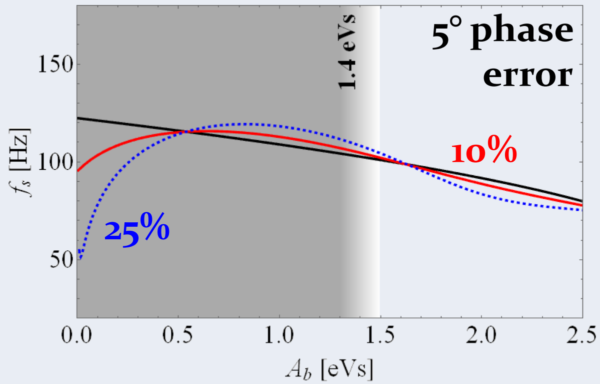
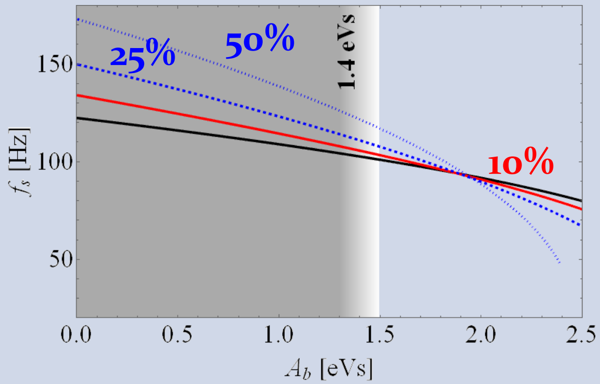
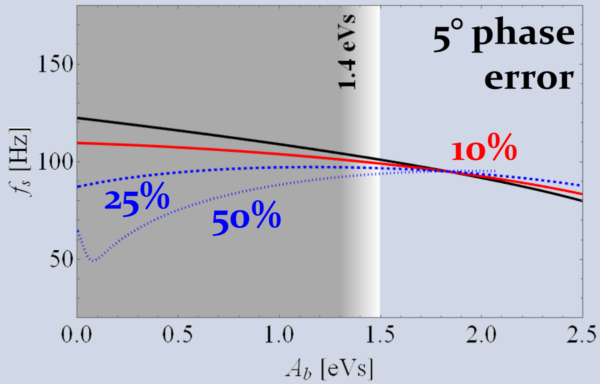
Triple splitting

Central synchrotron frequency



Synchronization

Synchrotron frequency distributions

	In-phase (bunch shortening)	Counter-phase (lengthening)
h = 21 (20 kV) + h = 84 (harmonic ratio: 4)	 → Much improved stability	 → Little effect on stability
h = 21 (20 kV) + h = 42 (harmonic ratio: 2)	 → Slightly improved stability	 → Slightly improved stability

- Only one MD in 2016: promising → Study systematically in 2017

Ferrite tuner for 80 MHz cavities

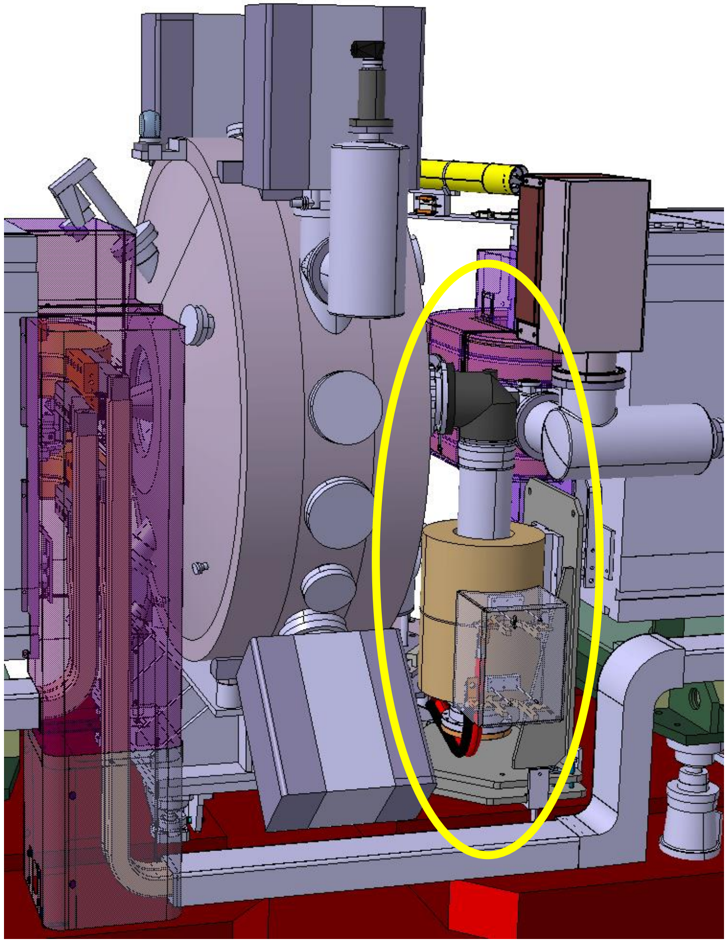
Operate 80 MHz cavities for protons and ions simultaneously

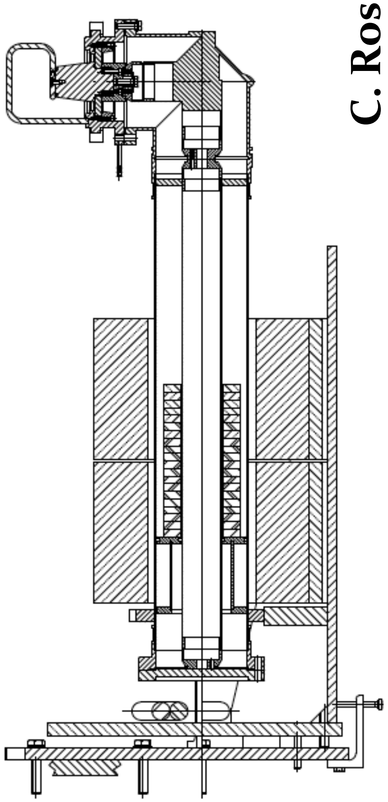
→ Fast ferrite tuner to switch cavity between p$^+$ and Pb^{54+} frequencies in PPM ($\Delta f/f = 0.29\%$)

- Inductively loaded coaxial line coupled to cavity with DC bias
- Prototype on test cavity validated
- Difficulties with installation on C80-08

→ Installation on all cavities during LS2

→ Flexibility to operate 3rd 80 MHz with protons



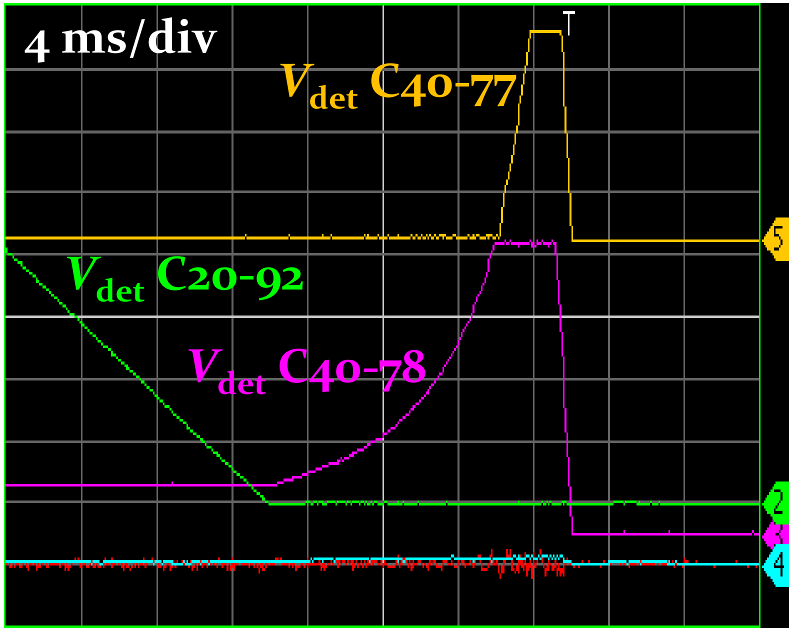


C. Rossi, C. Völlinger

25 ns multi-bunch beam tests

→ Move voltage programs to 72-bunch cycle with N_b = 1.3 10^{11} ppb

- Iso-adiabatic rise of both 40 MHz cavities in sequence
  → First C40-78, then C40-77
- Difficulties to pulse the 80 MHz cavities with beam
  → Maximum voltage of only 100 kV from each cavity
  → C80-89 weaker than C80-88



- Bunch length with 600 kV at 40 MHz alone:
  → ~7.7-8 ns (measured) versus 7.3 ns expected
- Adding 200 kV at 80 MHz shortens to ~6.7 ns