LHC Injectors Upgrade

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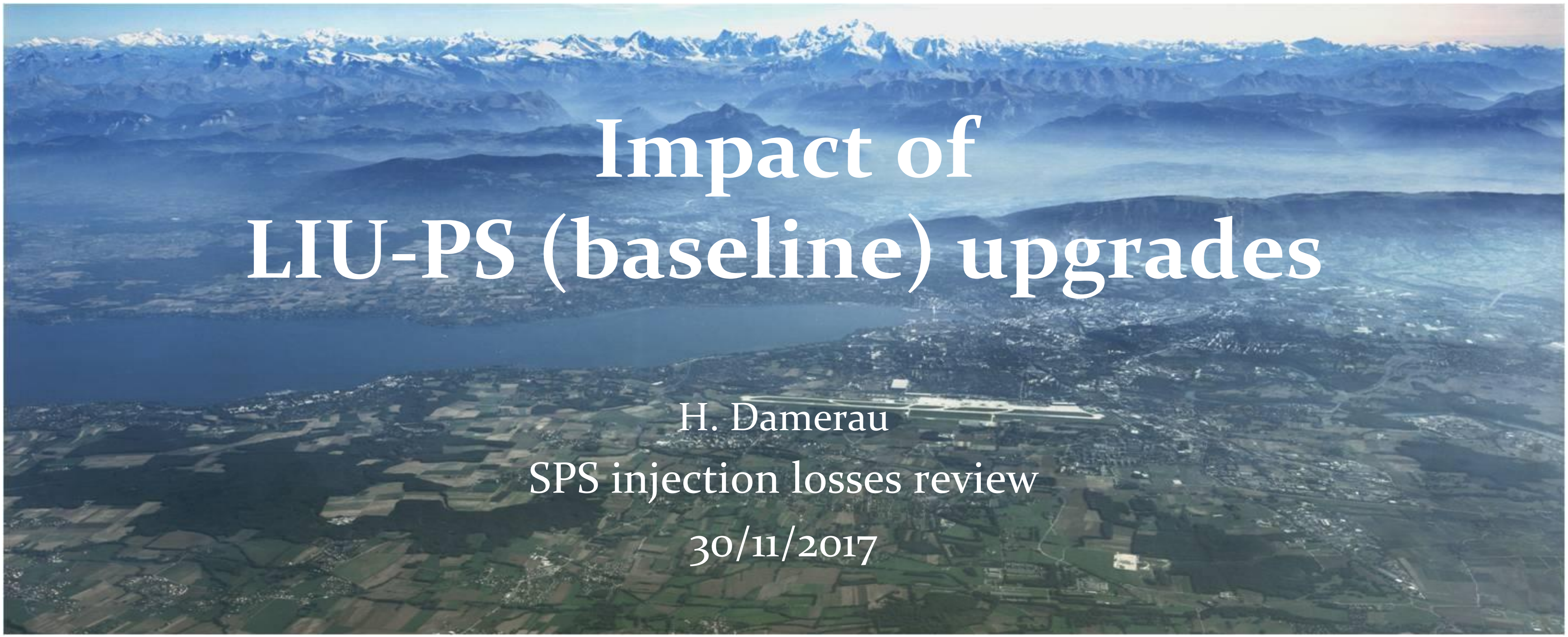

Impact of LIU-PS (baseline) upgrades

H. Damerau

SPS injection losses review

30/11/2017

Many thanks to F. Bertin, G. Favia, S. Hancock, A. Huschauer, A. Lasheen, M. Migliorati, M. Morvillo, M. Paoluzzi, D. Perrelet, C. Rossi, E. Shaposhnikova, H. Timkó, L. Ventura

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Overview

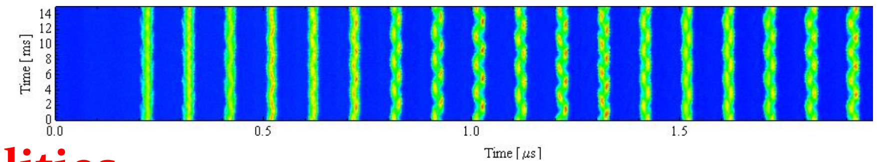
- **Introduction and motivation**
  - Effect of PS beam quality on SPS injection losses
- **Present performance**
  - Maximum intensity with good and compromised quality
- **Impact of longitudinal upgrades**
  - 10 MHz feedbacks
  - Wide-band coupled-bunch feedback
  - 20 MHz, 40 MHz and 80 MHz multi-harmonic feedbacks
- **Summary**

Introduction

- **PS Beam quality: essential contribution to losses in SPS**
  - Target: 72 bunches with $2.6 \cdot 10^{11}$ ppb, $\varepsilon_l = 0.35$ eVs, $4\sigma = 4$ ns, $\varepsilon_{h/v} = 1.9$ μm
- **Transverse**
  - Beam size/emittance twice larger than expected after 2 GeV upgrade
  - Instabilities (e.g., e-cloud) controlled by upgraded transverse damper
- **Longitudinal**
  - Longitudinal emittance is key: 0.35 eVs/bunch
  - Distortion of distribution due to bunch rotation } → A. Lasheen
  - Uncaptured/large amplitude particles } → A. Lasheen
  - Phase jitter of bunches with respect to SPS buckets → G. Papotti

Where do we stand? What to expect?

Intensity/beam quality limiting effects in PS



Acceleration/Bunch splittings

Longitudinal coupled-bunch instabilities

Uncontontrolled emittance growth

Transient beam loading

Transition crossing

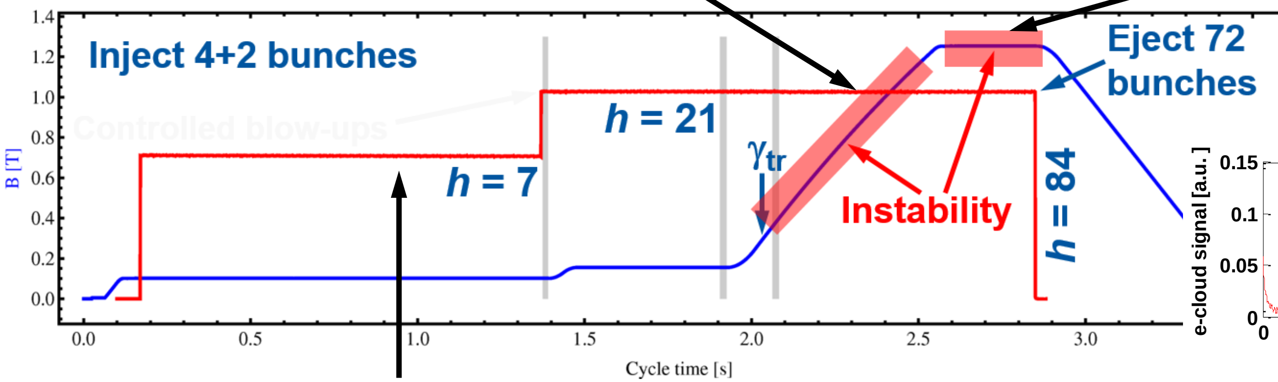
Flat top

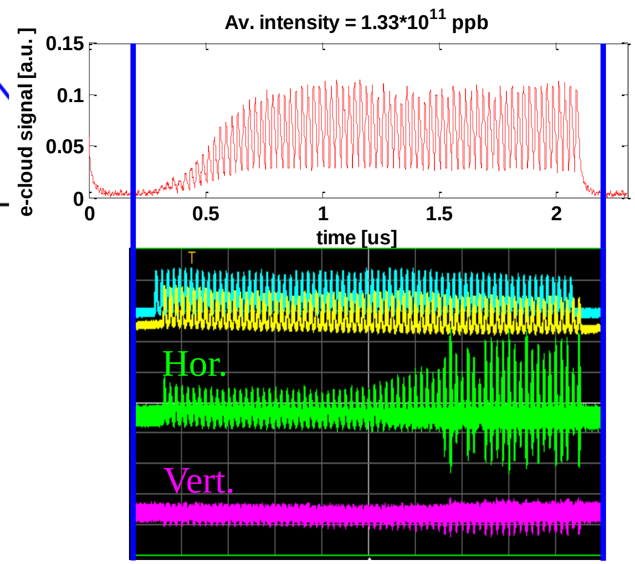
Longitudinal CBI

Emittance growth

Transv. instabilities

Electron cloud

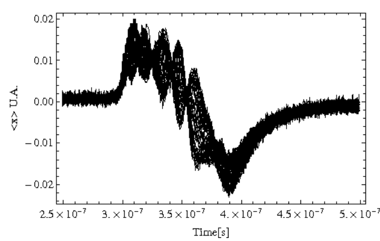




Injection flat bottom

Space charge

Headtail instability



Longitudinal effects in PS

Beam quality degradation

- **Coupled-bunch instabilities**
  - **Dipole**
    - During acceleration
    - At flat-top
  - **Quadrupole**
    - During acceleration
    - At flat-top
- **Emittance growth**
  - **High-frequency cavities**
    - Mainly above transition?
  - **Unknown, e.g. kickers?**
    - ?

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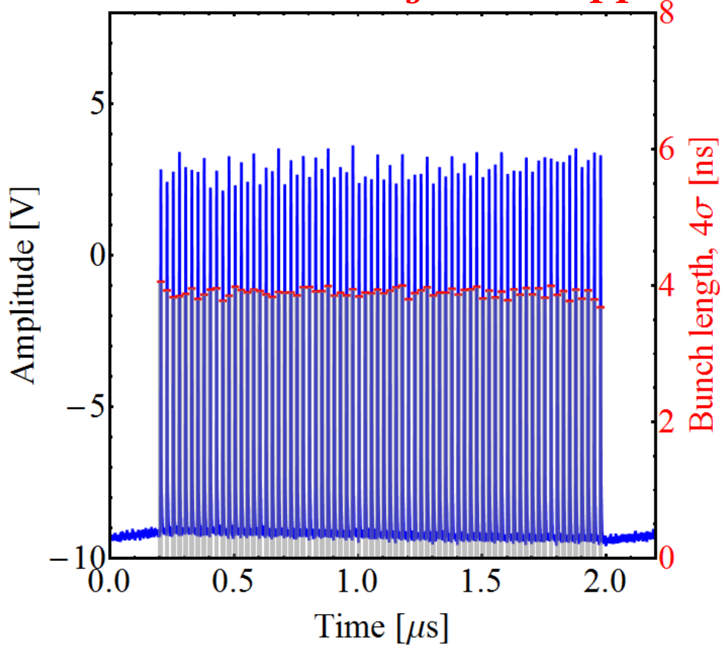
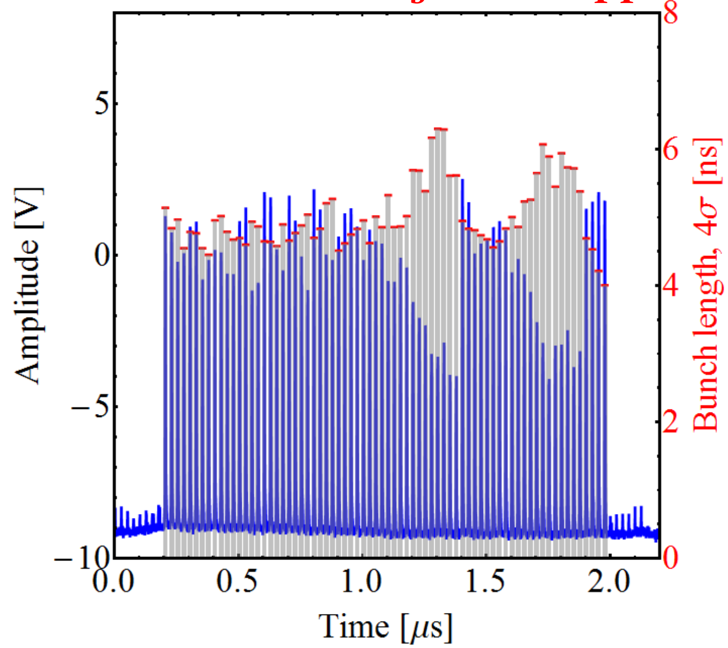
Maximum intensity at extraction

- **Coupled-bunch feedback** significantly improves beam stability
  - → **Regularly delivered** ~$2 \cdot 10^{11}$ ppb with nominal longitudinal emittance of $\varepsilon_l = 0.35$ eVs **and** bunch length of $4\sigma = 4$ ns (Gaussian fit)
  - → **Beam quality as at ~$1.3 \cdot 10^{11}$ ppb without feedback**

Feedback on, $N_b = 2 \cdot 10^{11}$ ppb



Feedback off, $N_b = 2 \cdot 10^{11}$ ppb



Maximum intensity at extraction

- **Coupled-bunch feedback significantly improves beam stability**
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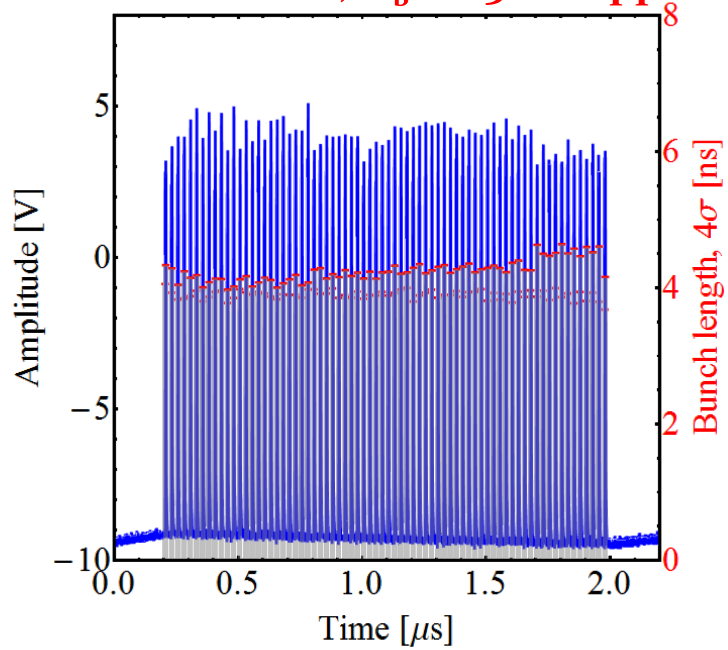
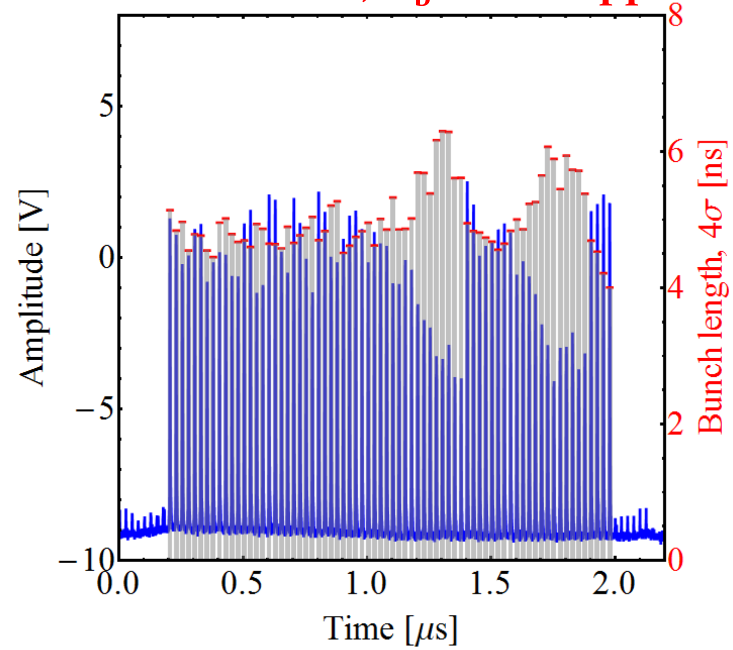
Feedback on, N_b = 2.3 · 10^{11} ppb



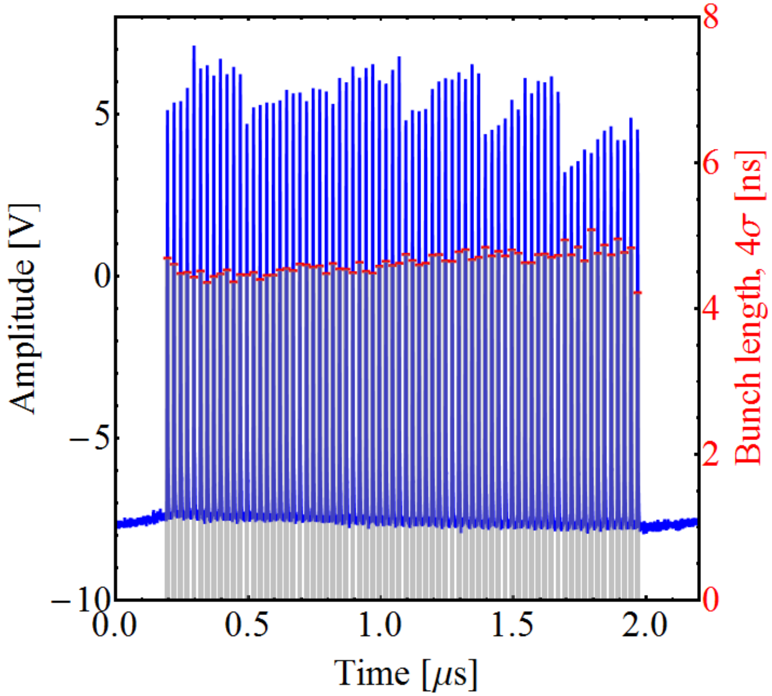
Feedback off, N_b = 2 · 10^{11} ppb



Degradation of longitudinal beam quality

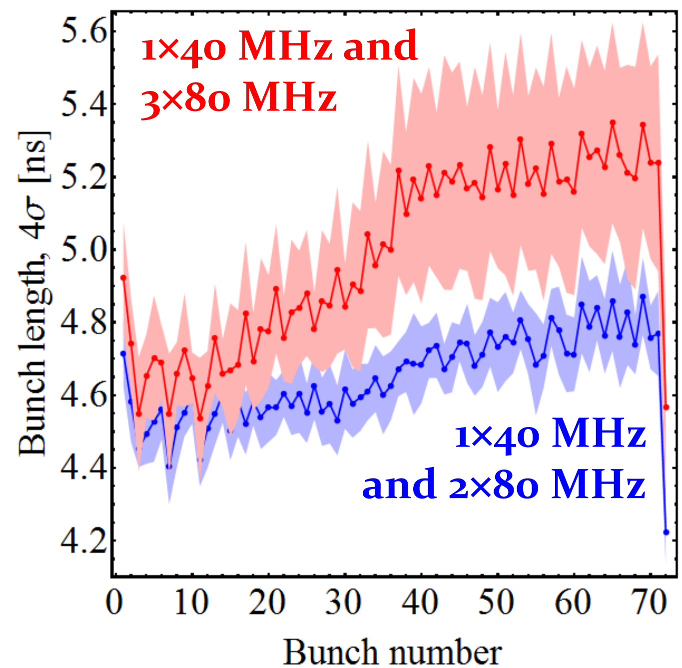
Parameters at LIU/HL-LHC baseline intensity: 2.6 · 10^{11} ppb

→ Additional longitudinal blow-up needed for stabilization



- **Bunch length increase along the batch**
  - **→ Onset of instability**

- **Average ε_l at arrival on flat-top: 0.3 eVs (RMS, 4 final bunches)**
- **Corresponds to ~0.45…0.5 eVs per bunch in usual convention**



→ Longitudinal emittance far outside specification of 0.35 eVs

LIU-PS baseline RF upgrades

Limitation	Mitigation
• Longitudinal **beam stability** • **Coupled-bunch** oscillations	1. Reduced impedances of all RF cavities → Improved **wide-band feedback 10 MHz** ✓ Replaced **1-turn delay feedbacks 10 MHz** → New **Multi-harmonic feedbacks for 20, 40 and 80 MHz** cavities 2. Dedicated coupled-bunch feedback ✓ **Wide-band Finemet** longitudinal **kicker**
• **Bunch-to-bunch equalization**	→ 1-turn delay and multi-harmonic feedbacks
• **PS-SPS transfer**	✓ Bunch rotation with **both 40 MHz cav.**
• **Availability of 80 MHz cavities** for protons and ions	→ New fast **ferrite tuners**
• **Reliability** and **long-term maintainability**	→ Replace **anode power supplies for 40 MHz and 80 MHz RF systems** → Upgrade to a **digital beam control**

- **Most PS RF systems affected by upgrades:**

  → **Improve longitudinal beam quality for LHC-type beams**

Longitudinal effects in PS

Beam quality degradation

- **Coupled-bunch instabilities**
  - **Dipole** → Coupled-bunch feedback, cavity feedbacks
  - **Quadrupole** → Cavity feedbacks, Landau cavity?
- **Emittance growth**
  - **High-frequency cavities** → Multi-harmonic feedbacks (20, 40, 80 MHz)
  - **Unknown, e.g. kickers?** → Impedance identification, reduction?

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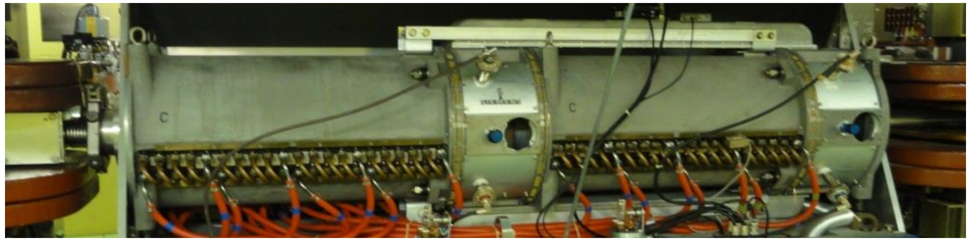
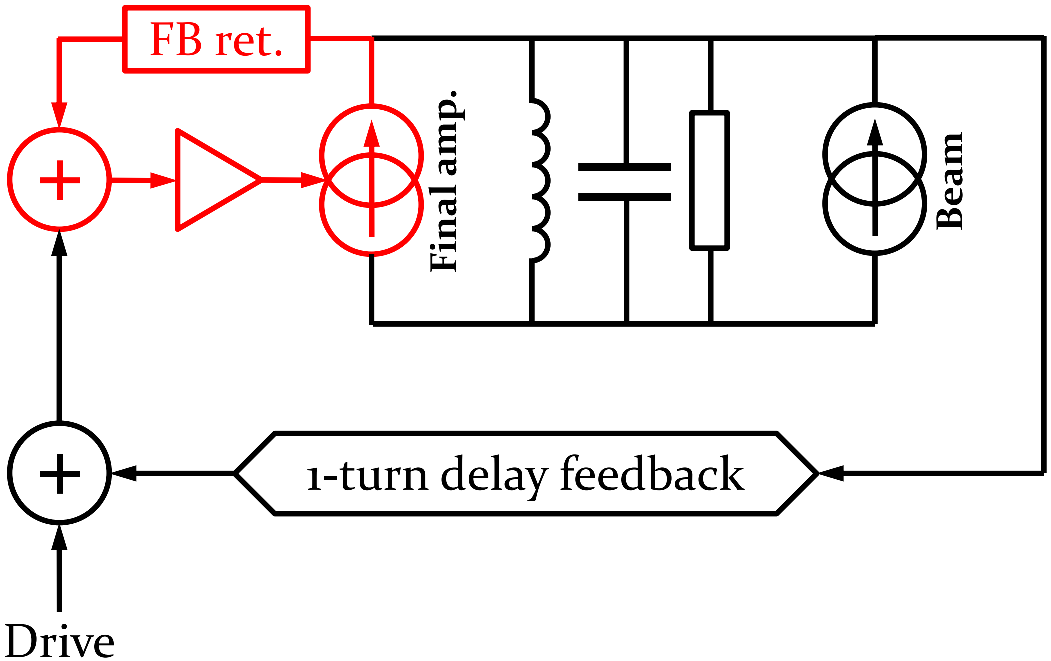
Main 10 MHz RF system

- 10 + 1 ferrite loaded cavities, tunable from 2.8…10 MHz

G. Favia, D. Perrelet





- Fast wide-band feedback around amplifier (internal)
→ Gain limited by delay

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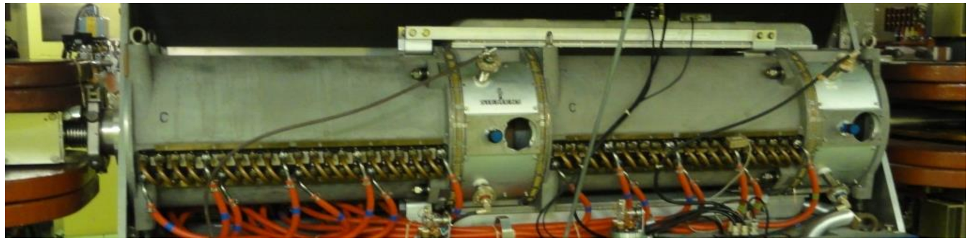
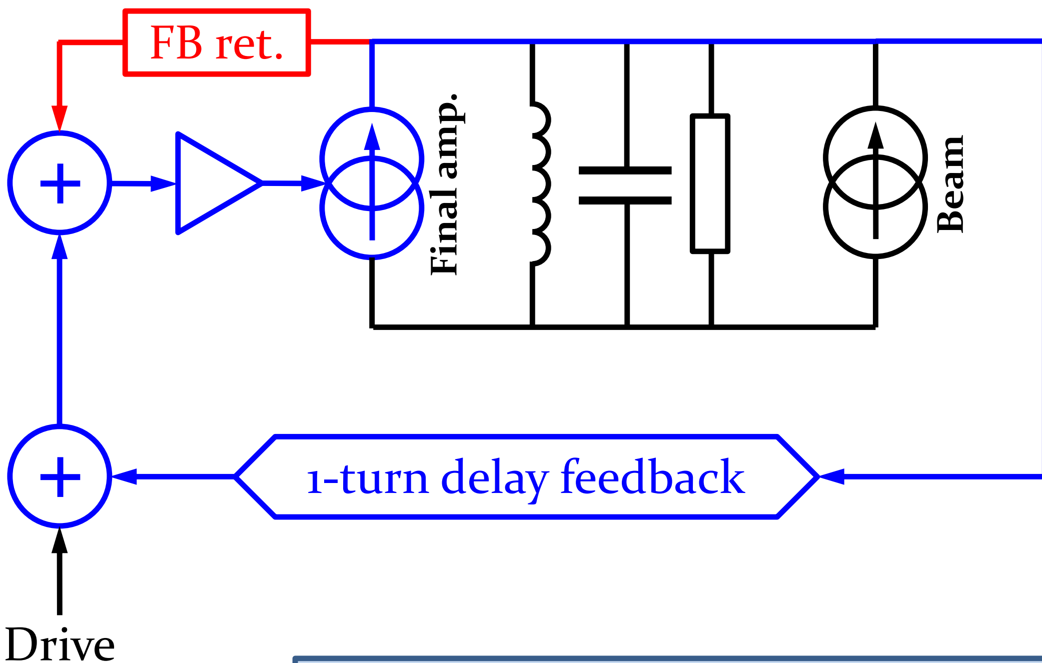
- 10 + 1 ferrite loaded cavities, tunable from 2.8…10 MHz

G. Favia, D. Perrelet





- Fast wide-band feedback around amplifier (internal)
  → Gain limited by delay

- 1-turn delay feedback
  → High gain at n × f_{rev}

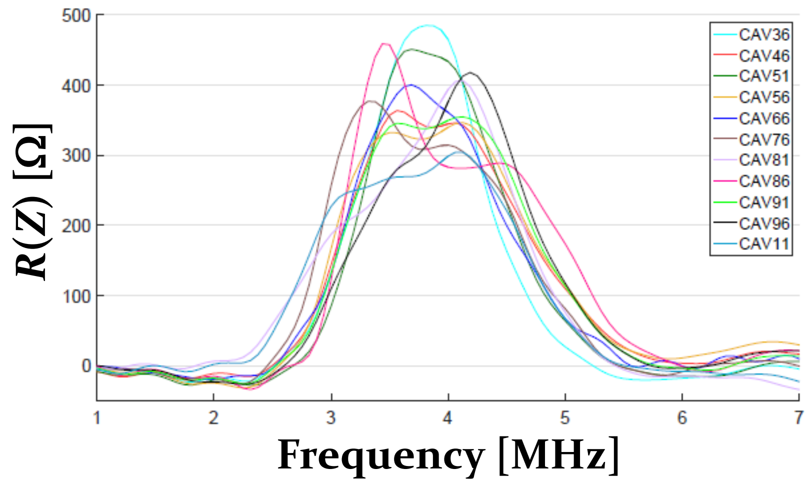
1. Maximize loop gain of direct wideband feedback
2. 1-turn delay feedback operational since LS1

Wide-band feedback of 10 MHz cavities

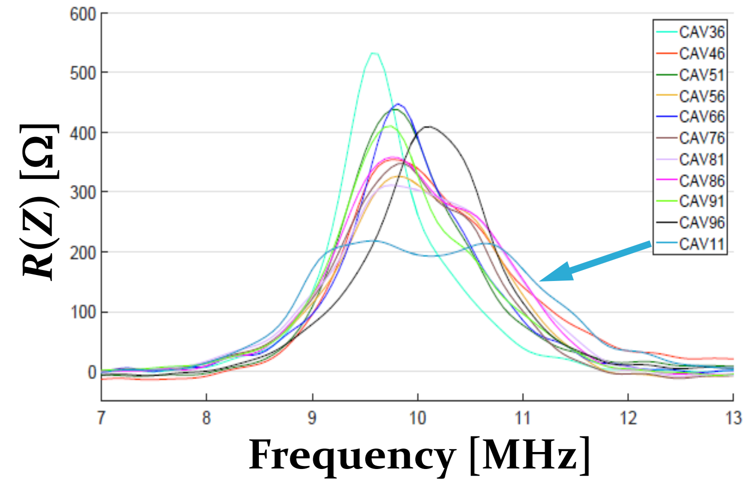
G. Favia

- **Power amplifier upgrade: New working point and grid resonator**
  - → **Increased gain of direct RF feedback around amplifier**

Impedance at *h* = 8, ~3.8 MHz



Impedance at *h* = 21, ~10 MHz



- **Prototype amplifier installed during 2016 and (partly) 2017 runs**
  - → **Impedance reduction by factor of ~2 (*h* = 21) with beam**
- **Full implementation during LS2**
- **One single upgraded cavity has insignificant effect on stability**

→ **What to expect after LS2?**

→ **Benefit mainly during acceleration**

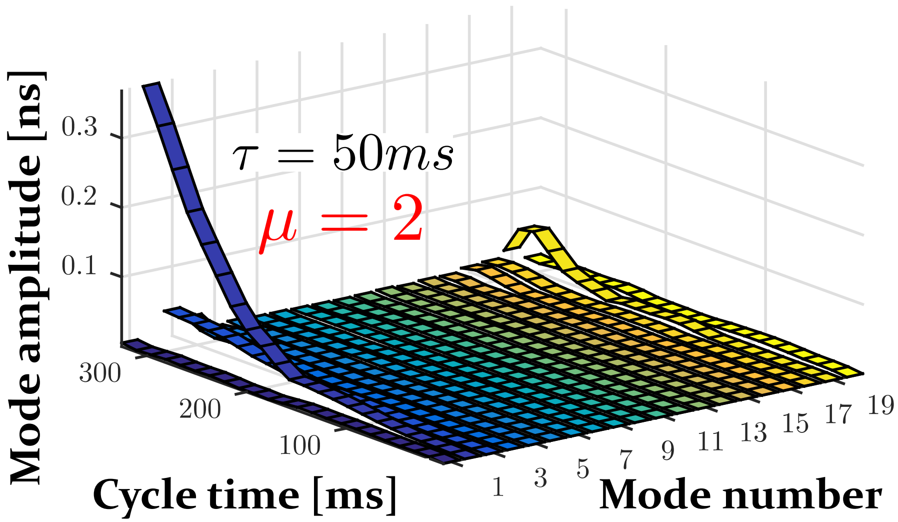
Multi-bunch simulations (MuSiC)

M. Migliorati, L. Ventura

Study case: 21 bunches in h =21

→ Multiple particles per bunch, length ~ 1 m

- Intensity, $N_b = 4 \cdot 2.6\ 10^{11}$ ppb

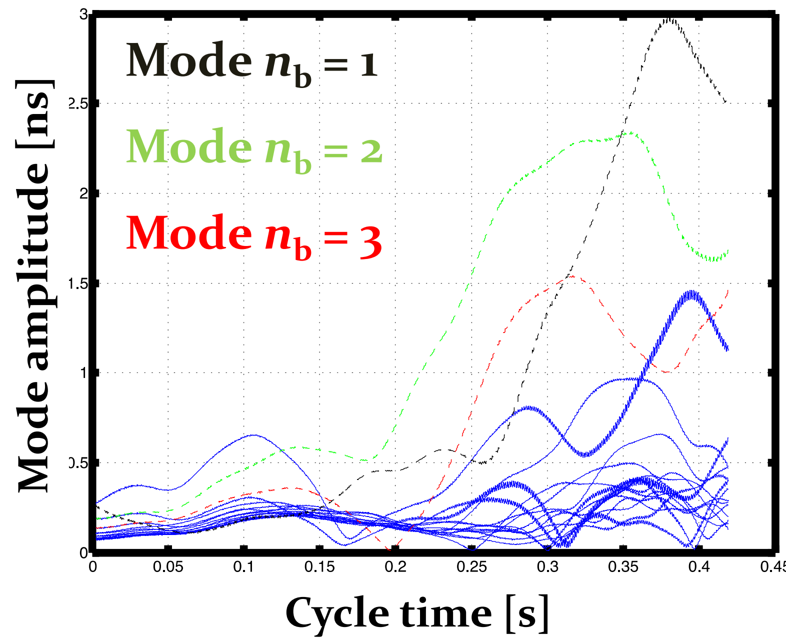


→ Mode 2 grows faster than mode 1, as expected

→ Four times larger impedance translates in three times shorter rise time

18 bunches in h = 21

→ Multiple particles per bunch, length ~ 1 m



→ Rise times not well defined

→ Stay of the order of ~50 ms

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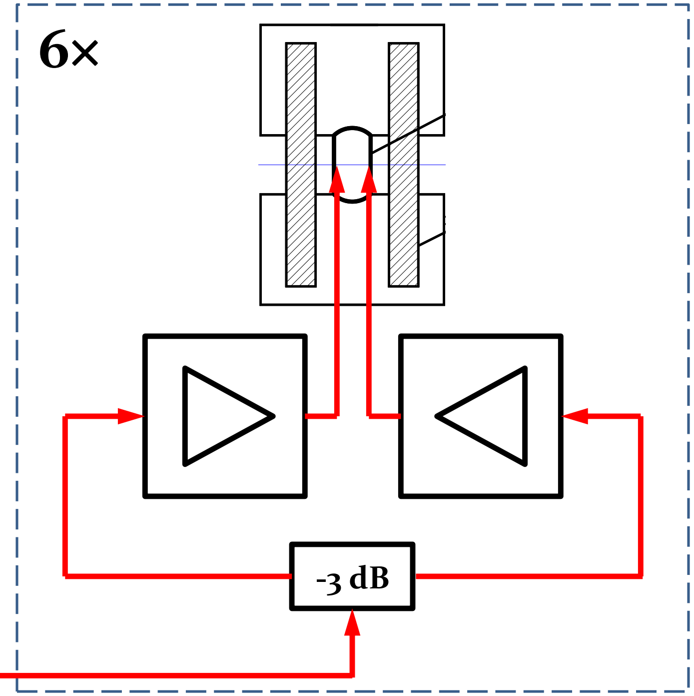
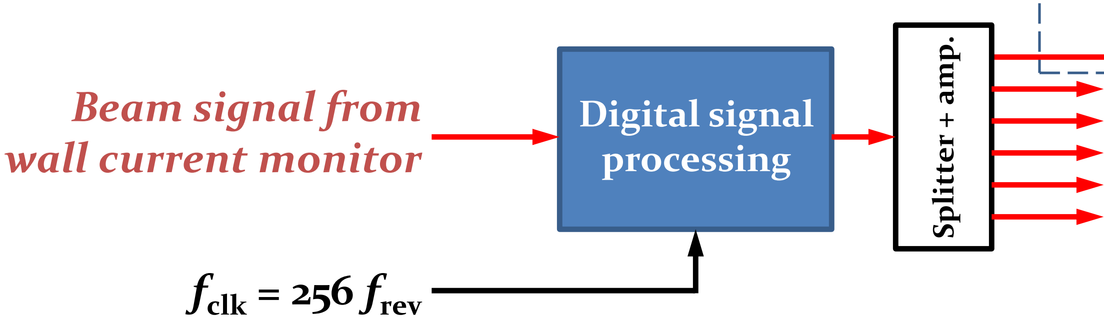
PS coupled-bunch feedback overview

Six-cell Finemet cavity:

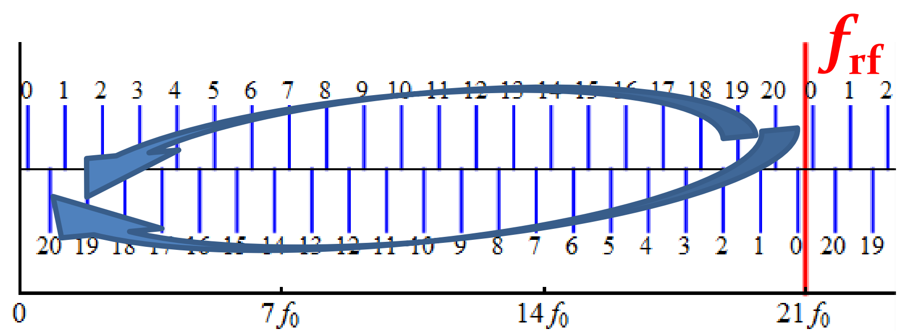
→ V_{RF} up to 6 kV from 0.4 to 5 MHz

M. Hasse, M. Paoluzzi



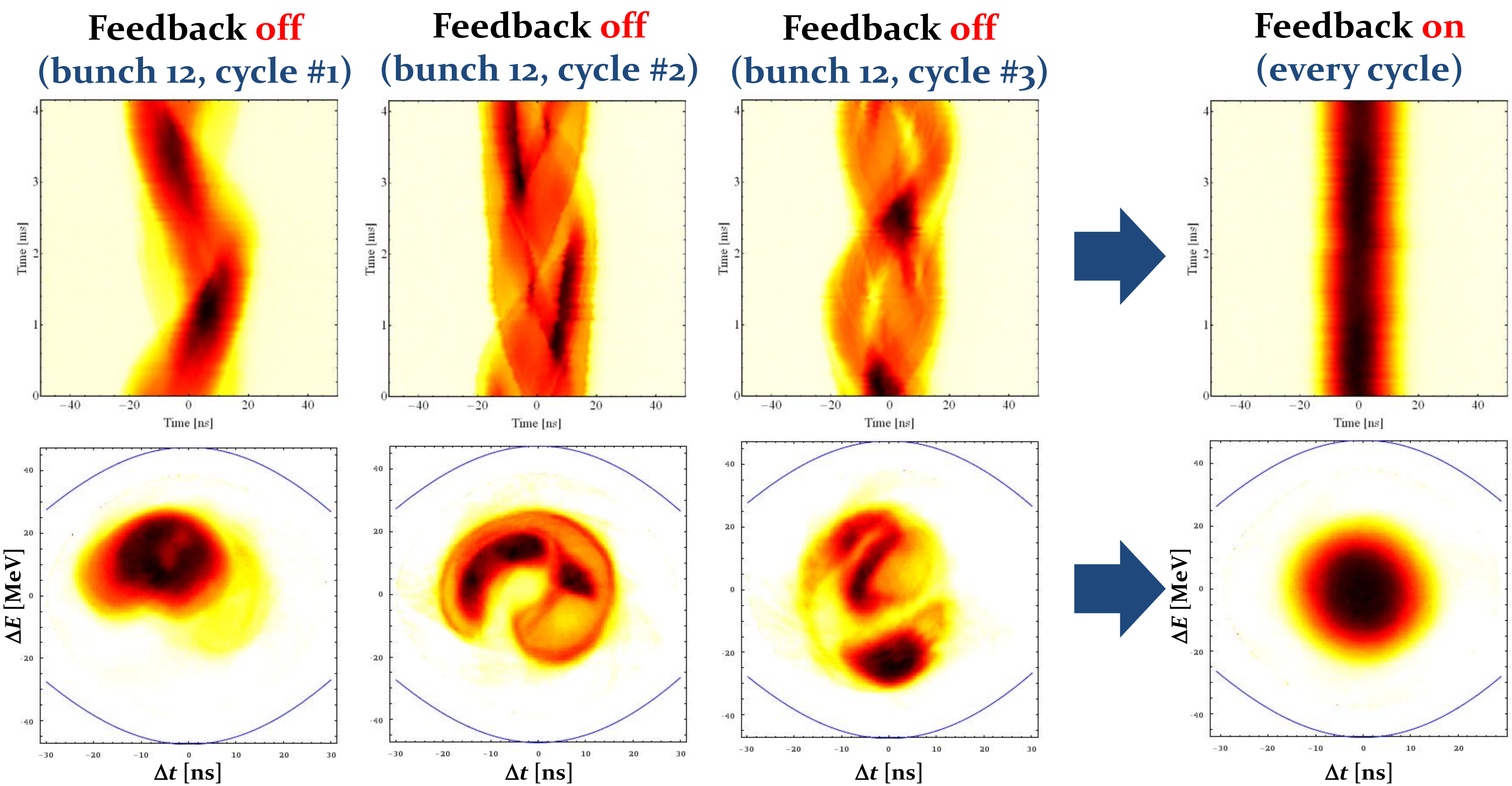


- **Detect f_s sidebands at 11…20 f_{rev}**
- **Drive kicker cavity at 1…10 f_{rev}**



Stability during acceleration

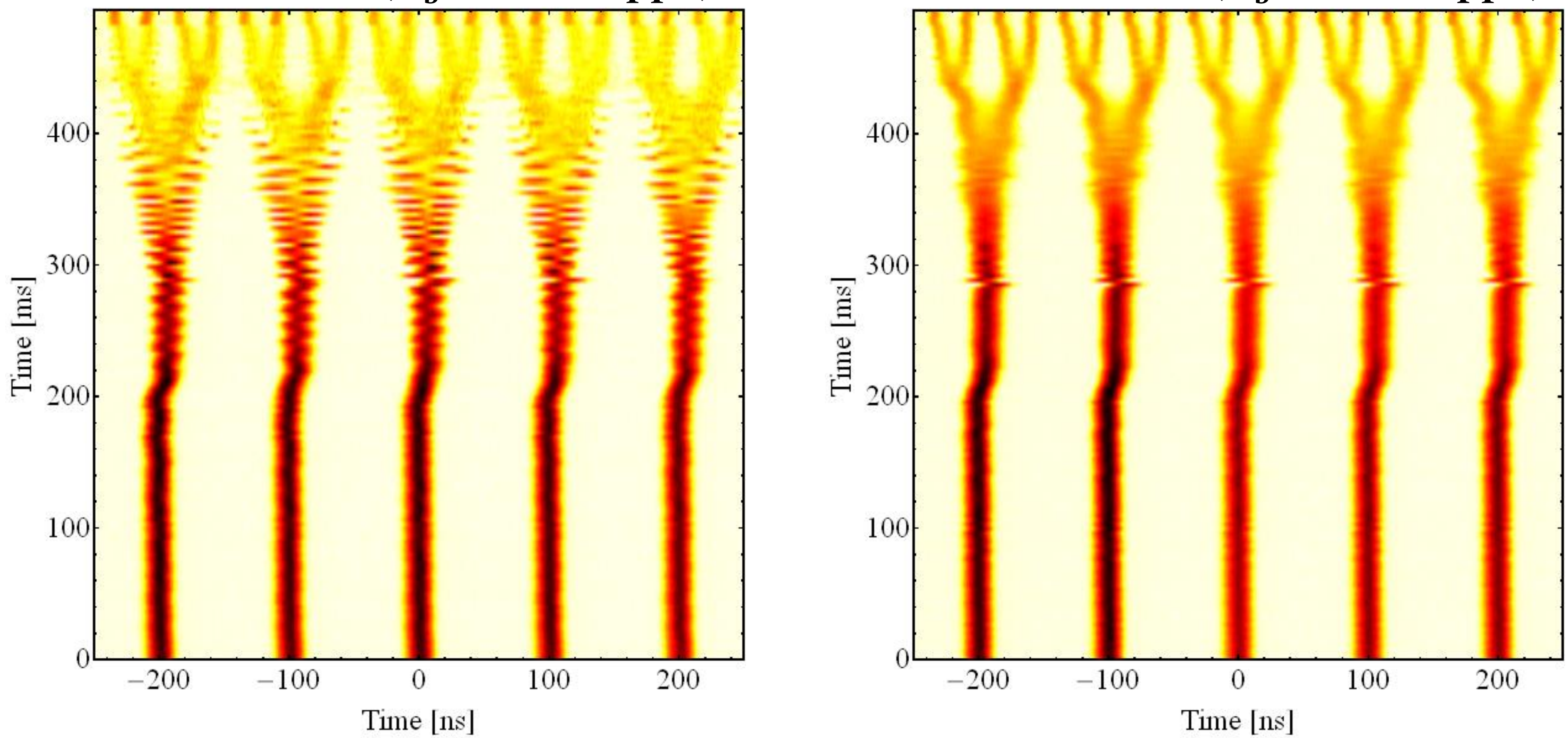
- **Longitudinal stability at arrival on flat-top, $N_b = 4 \cdot 2.0 \cdot 10^{11}$ ppb**



Final part of acceleration and flat-top

- **Arrival at flat-top and high-energy splittings**
- **Mode pattern changes due to impedance**

Feedback off ($N_b = 1.8 \cdot 10^{11}$ ppb) **Feedback on ($N_b = 1.8 \cdot 10^{11}$ ppb)**



→ **Significant improvement of longitudinal stability with feedback**

→ **Above $N_b = 4 \cdot 2 \cdot 10^{11}$ ppb again dipole and quadrupole coupled-bunch instabilities**

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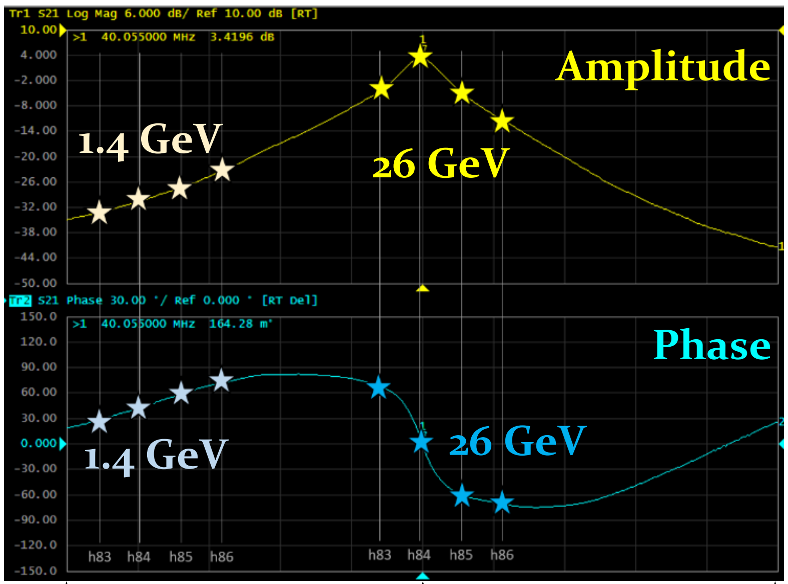
Feedbacks for 40/80 MHz

- **Impedance reduction of high frequency cavities**
  - → **Potential margin for direct feedback gain ~6 dB (already > 40 dB)**
  - → **Need 1-turn delay like LLRF feedback beyond**

40 MHz cavity transfer function



-4 MHz f_{res} = 40.053 MHz +4 MHz

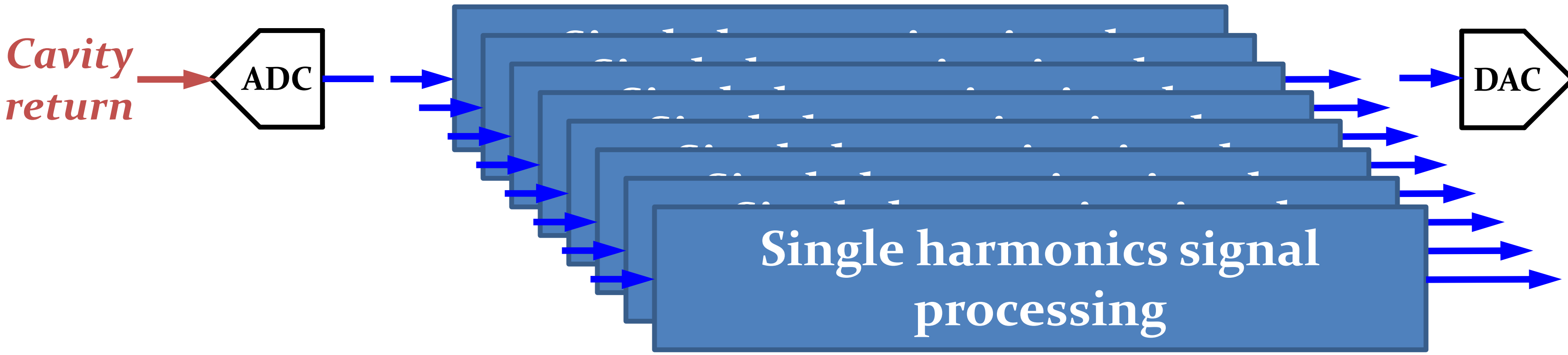
Specific technical difficulties:

- **Fixed resonance cavity resonance while f_{rev} harmonics sweep**
- → **Programmable notch filter with automatic phase calibration**
- **80 MHz beyond 1st Nyqist band for clock frequencies 111…122 MHz**
- → **Operate signal processing in under-sampling mode**

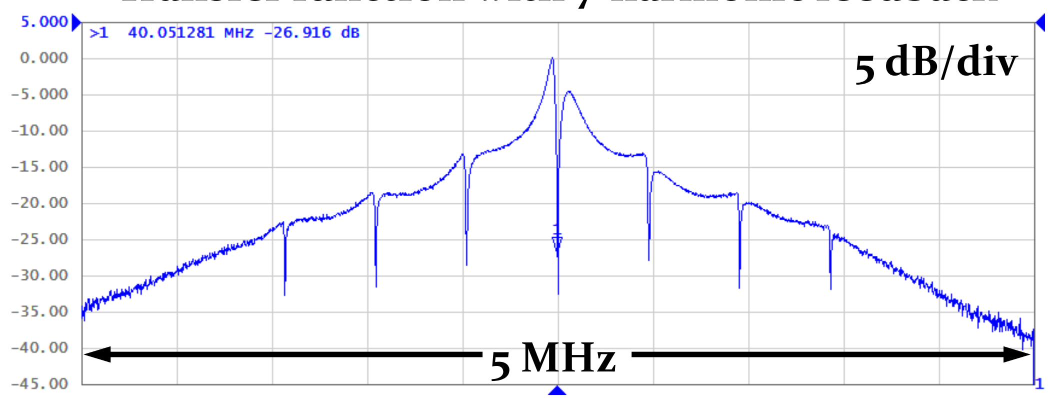
F. Bertin, D. Perrelet

Multi-harmonic feedback

- **Prototype signal processing covering multiple harmonics**
  - → **Automatic calibration to compensate cavity phase**
  - → **Powerful digital signal processing with up to 8 harmonics**



Transfer function with 7-harmonic feedback



→ **Impedance reduction > 20 dB demonstrated at harmonics close to f_{res}**

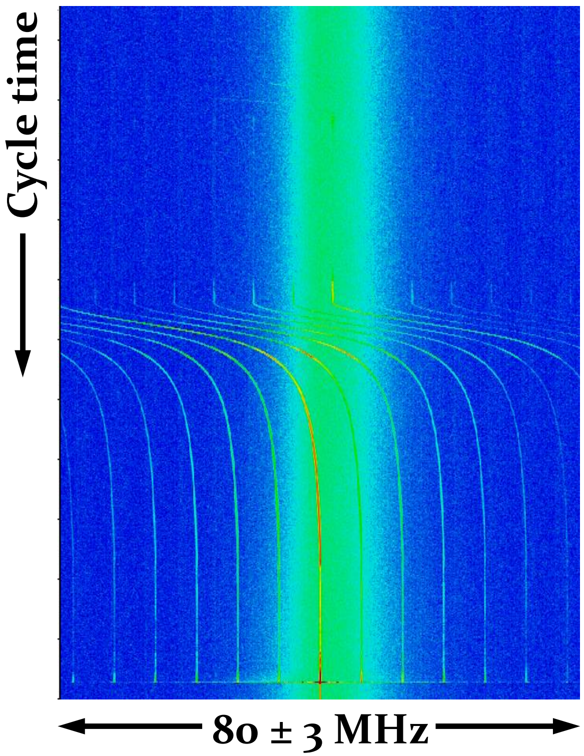
→ **May solve uncontrolled blow-up issues**

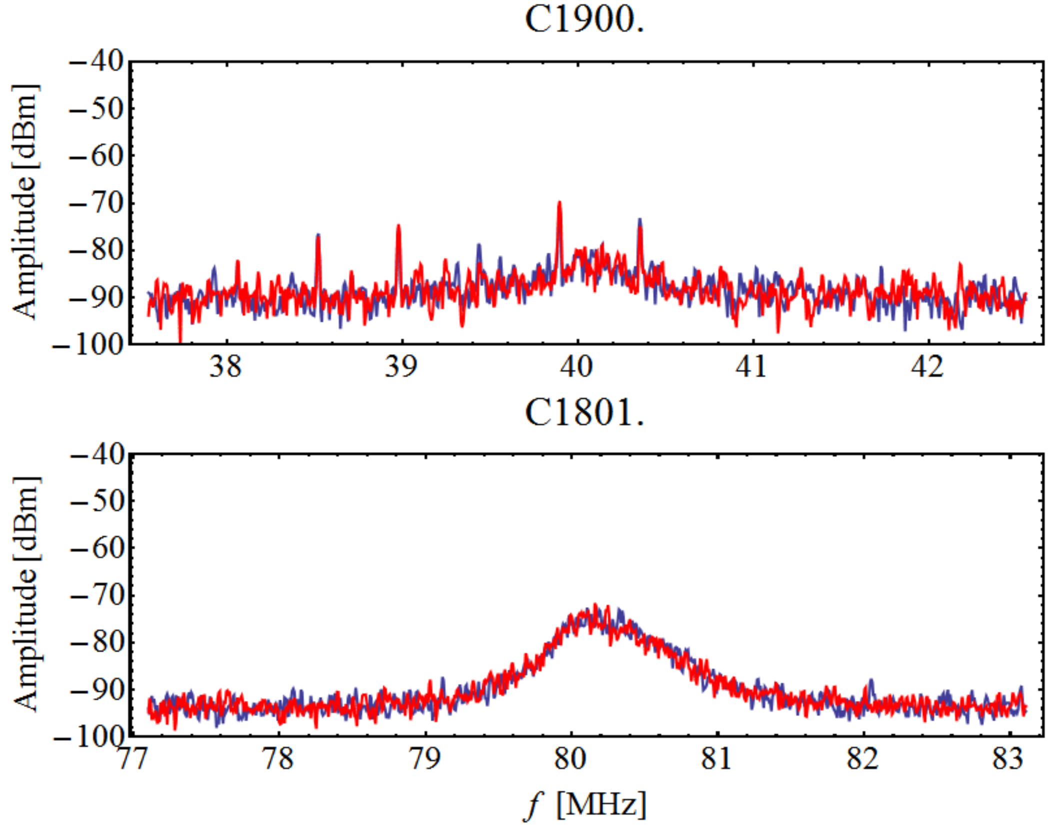
F. Bertin, D. Perrelet

Beam measurements with feedback

- **Observe beam induced voltage with/without feedback**
  - → **Prototype validated for both 40 MHz and 80 MHz RF system**

C80-88, feedback on/off





F. Bertin, D. Perrelet

→ **Implement on all cavities during 1st half of 2018**

→ **Evaluate effect on uncontrolled blow-up before LS2**

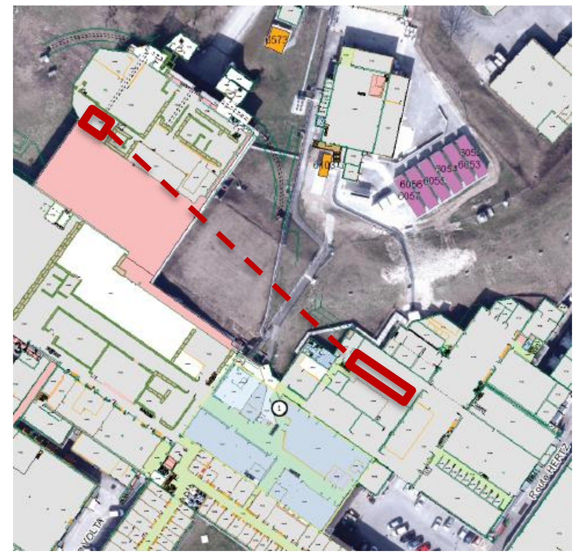
Anode power supplies for 40/80 MHz systems

- Anode power supplied of final amplifiers are weakest part
  - → Differences between converters → 'weak' or 'strong cavities

→ New 25 kV / 200 kW power converters with three times output power to cover the needs of future operation

→ First converter tested during 2017 run

→ Completion during YETS2017/18 (5 more converters)



A. Jibar, L. De Mallac, S. Pittet, C. Rossi

- Improve operational reliability at high beam intensities

→ Remove limitations for MDs: post acceleration, adiabatic shortening

→ Critical: commission early in 2018 to profit for studies

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- **Maximum achieved intensity per bunch: ~2.0 · 10^{11} ppb at ε_l = 0.35 eVs**
  - → Part of LIU baseline improvements already in place for studies
  - → Transverse emittance to become twice smaller with Linac4/2 GeV

- **Strong beam quality degradation above > 2.0 · 10^{11} ppb**
  - → Dipole and quadrupole coupled-bunch instabilities
  - → Significant uncontrolled emittance growth of the tail batches

- **Expected impact of improvements before LS2**
  - → Multi-harmonic feedbacks for 40/80 MHz cavities → Reduce ε_l growth
  - → Anode power supplies → MDs: post-acceleration, adiabatic shortening

- **Expected impact of improvements after LS2**

  10 MHz direct feedback → dipole coupled-bunch growth rate reduction

- **Potentially not covered sufficiently with baseline**
  - → Uncontrolled longitudinal emittance blow-up
  - → Dipole and quadrupole coupled-bunch instabilities

LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!

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Spare slides

Introduction

- **Objectives: HL-LHC request**

	Parameter		Achieved end 2015
Injection	Intensity per bunch (total: **2 10^{13} ppp**)	3.3 10^{12} ppb ($12 \times 2.7\ 10^{11}$)	
	Transverse emittances	1.8 µm	
	Longitudinal emittance	3.0 eVs	
	Bunch length	205 ns	
PS	Beam loss	5%	
	Transverse emittance growth	5%	
	Controlled longitudinal blow-up	~50%	
	Tolerable space charge tune shift, ΔQ_y	-0.31	
Ejection	Intensity per bunch	2.6 10^{11} ppb	1.7 10^{11} ppb
	Transverse emittances	1.9 µm	2.2 µm
	Longitudinal emittance	0.35 eVs	0.35 eVs
	Bunch length	4 ns	4 ns

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	Parameter		Achieved 08/2016
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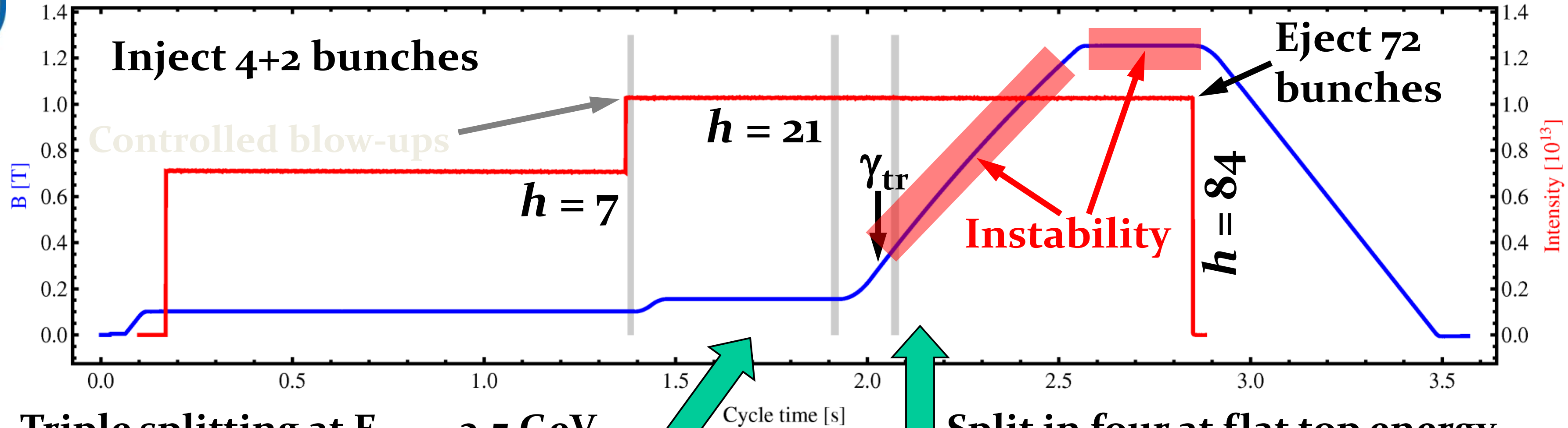
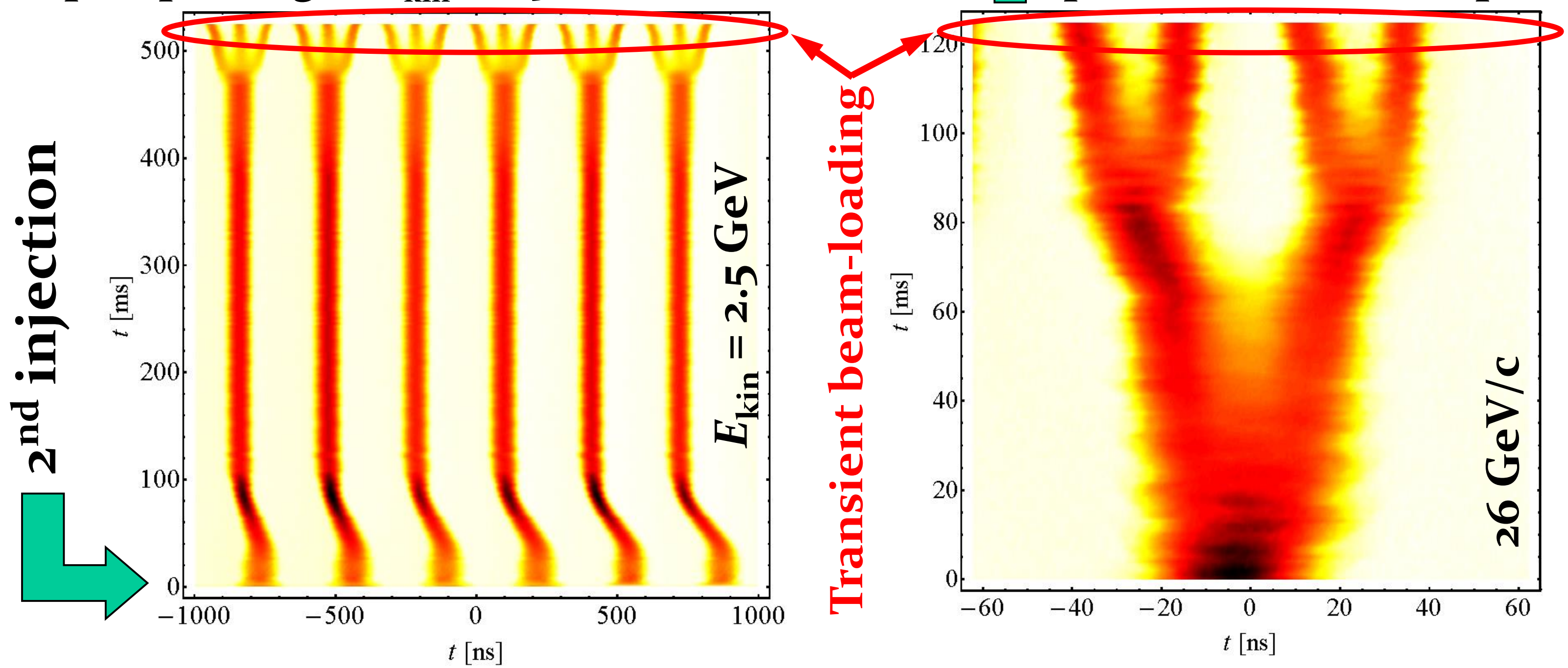
	Longitudinal emittance	3.0 eVs	
	Bunch length	205 ns	
PS	Beam loss	5%	
	Transverse emittance growth	5%	
	Controlled longitudinal blow-up	~50%	
	Tolerable space charge tune shift, ΔQ_y	-0.31	
Ejection	Intensity per bunch	2.6 10^{11} ppb	2.0 10^{11} ppb
	Transverse emittances	1.9 µm	not checked
	Longitudinal emittance	0.35 eVs	0.35 eVs
	Bunch length	4 ns	4 ns

The LHC25ns cycle in the PS



Triple splitting at E_{kin} = 2.5 GeV | **Split in four at flat top energy**

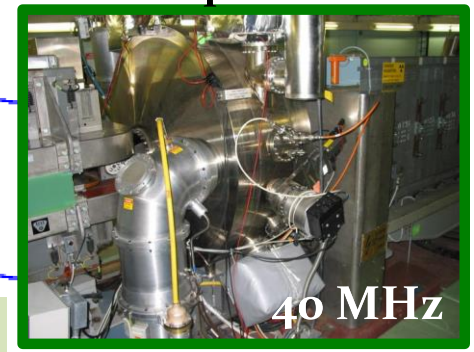


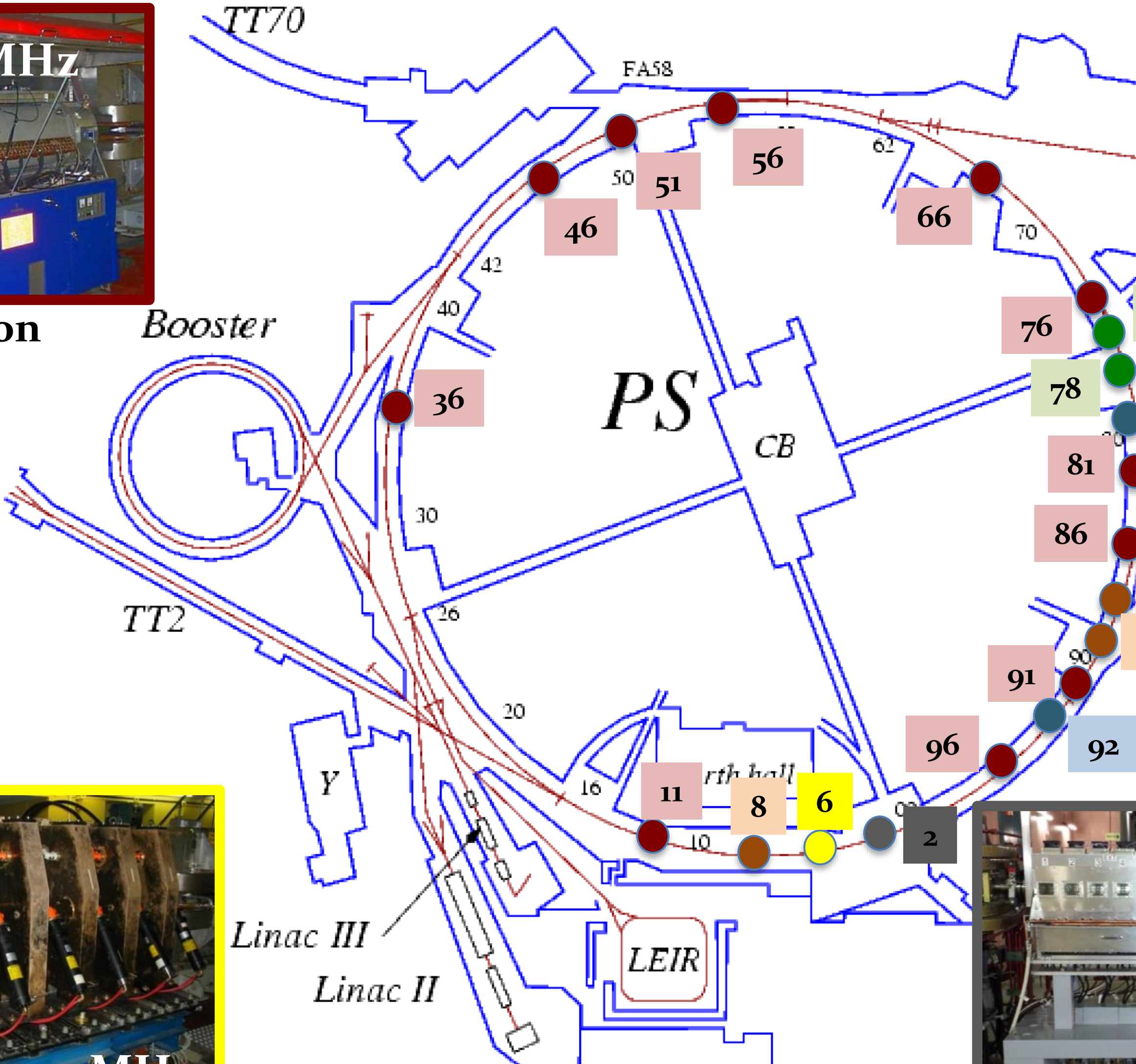
→ Each bunch from the Booster split in 12 → 6 × 3 × 2 × 2 = 72

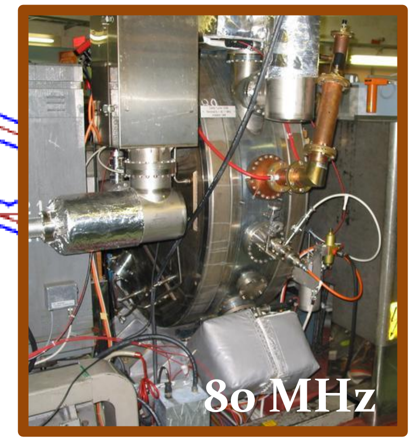
RF systems in the PS

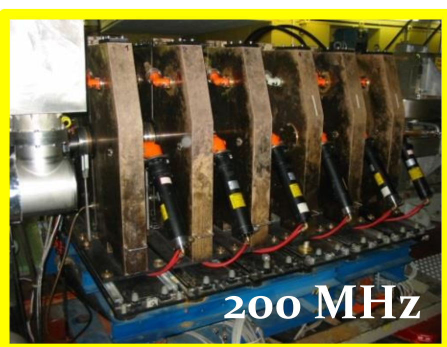
Acceleration

RF Manipulations









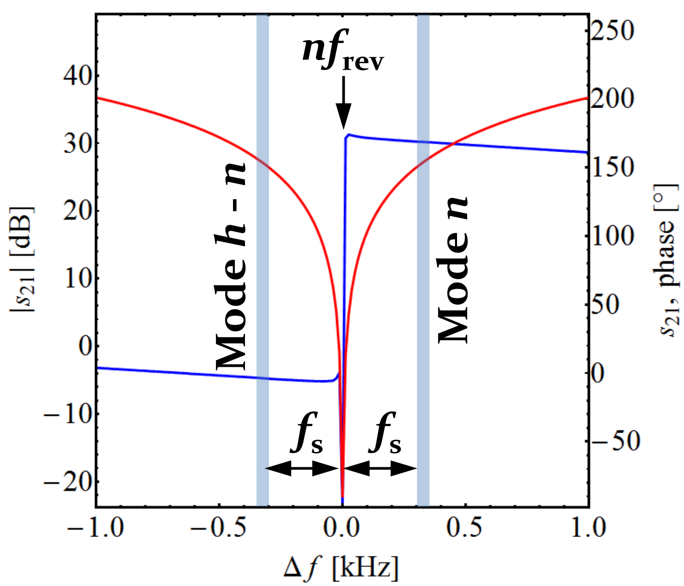
Longitudinal blow-up

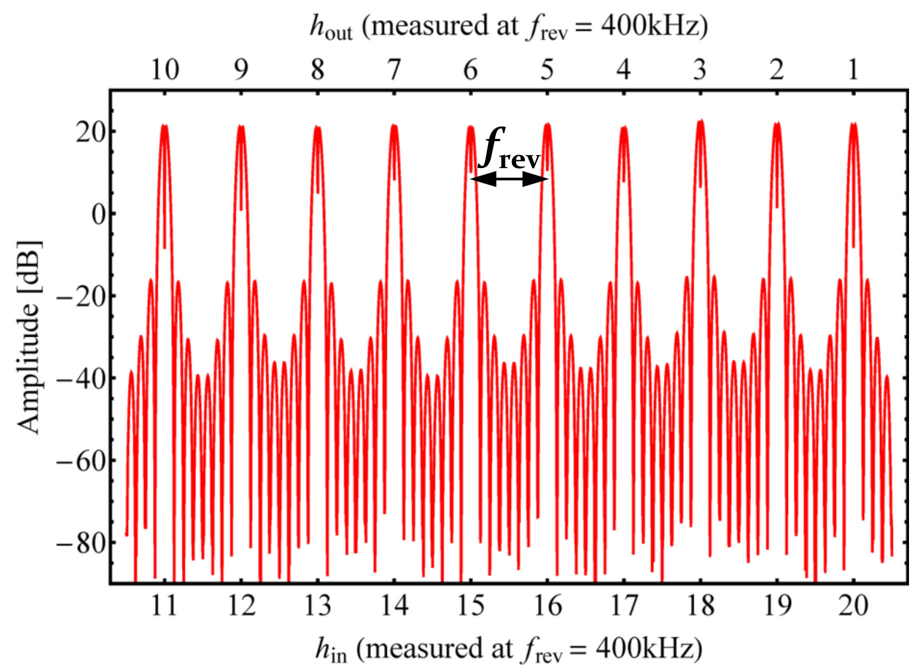
Frequency domain feedback

- Suppress f_s side-bands by actively compensating them
  - → Remove spectral components at $n \cdot f_{rev}$ and amplify $n \cdot f_{rev} \pm f_s$
  - → Robust: insensitive to bunch positions and filling pattern

F. Pedersen et al., PAC1977

Filter transfer function





→ Harmonic of f_{rev} attenuated by more than 40 dB compared to sidebands at $\pm f_s$ (~300 Hz) → Extremely narrow: $f_s / f_0 \sim 6 \cdot 10^{-4}$

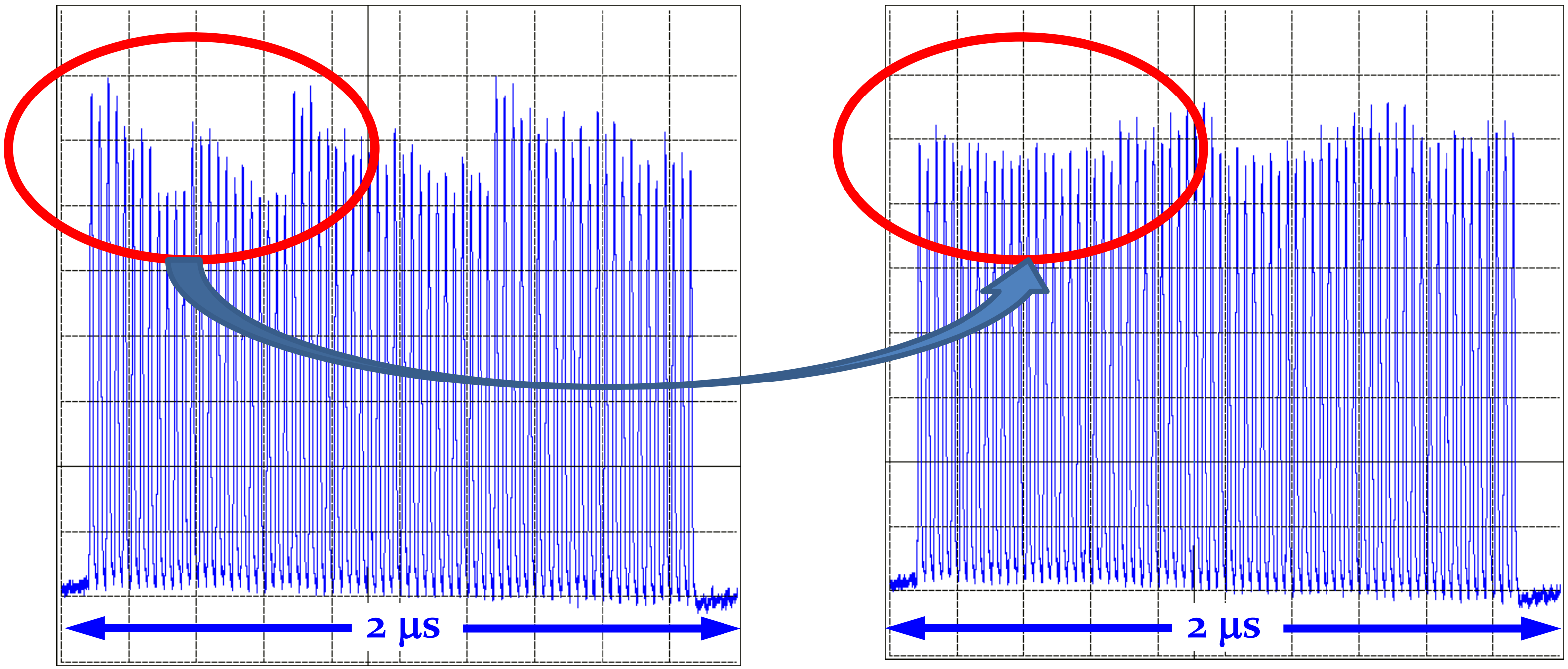
→ Precise 180° phase jump at center frequency

→ Ten notches covering all 20 possible modes (h = 21), other than n = 0

1-turn delay feedbacks

- **Further reduce impedance at harmonics of f_{rev} (comb filter feedback)**
  → Transient beam loading fully suppressed at $1.3 \cdot 10^{11}$ ppb

72 bunches, Feedbacks off | **72 bunches, feedbacks on**



→ Full commissioning of digital 1-turn delay feedback for all 11 main accelerating cavities in 2015

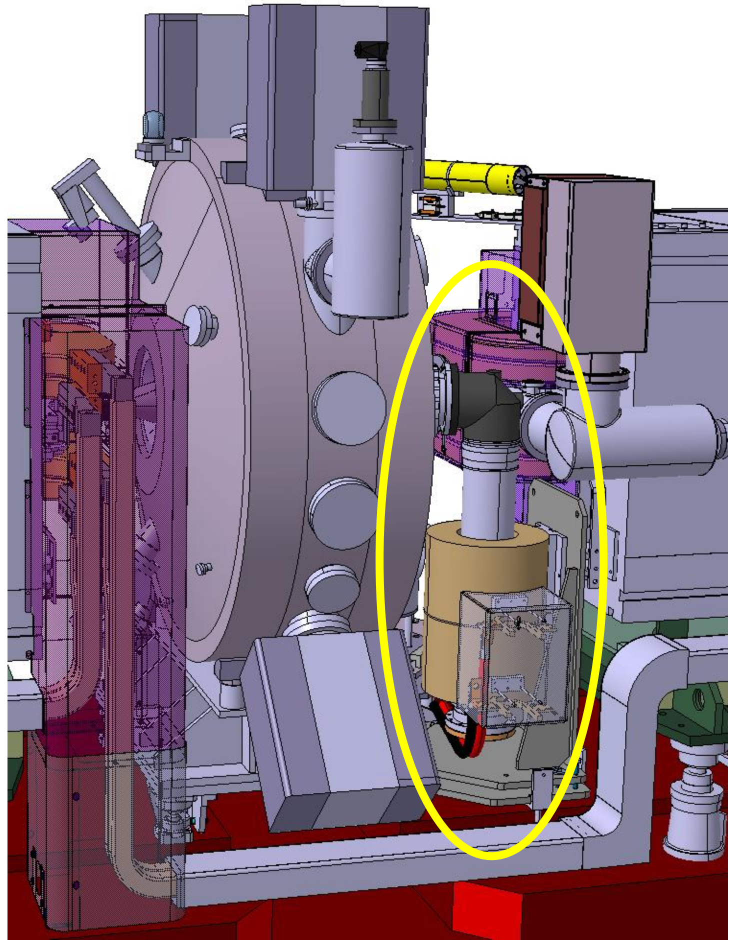
→ New 1-turn delay feedbacks on 20 MHz, 40 MHz and 80 MHz cavities in 2016/17

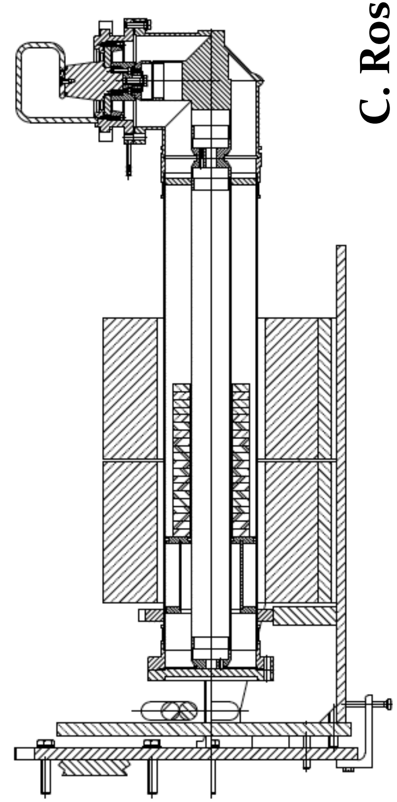
Ferrite tuner for 80 MHz cavities

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

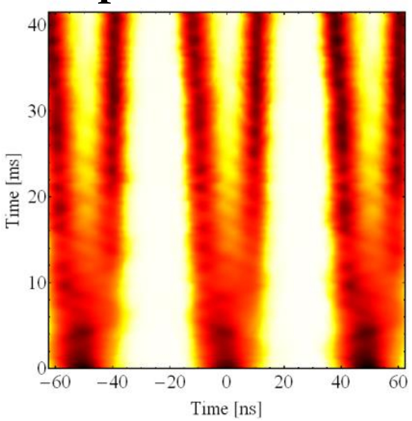
C. Rossi, C. Völlinger

Effect of 80 MHz cavity impedance

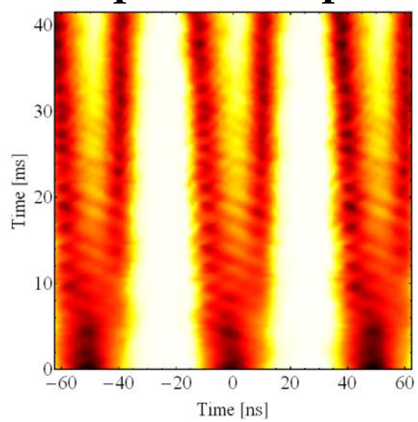
- **80 MHz cavity for lead ions tuned to 135 kHz below proton frequency, but 3 dB bandwidth about 0.7 MHz**

→ **80 MHz structure during $h = 42 \rightarrow 84$ splitting**

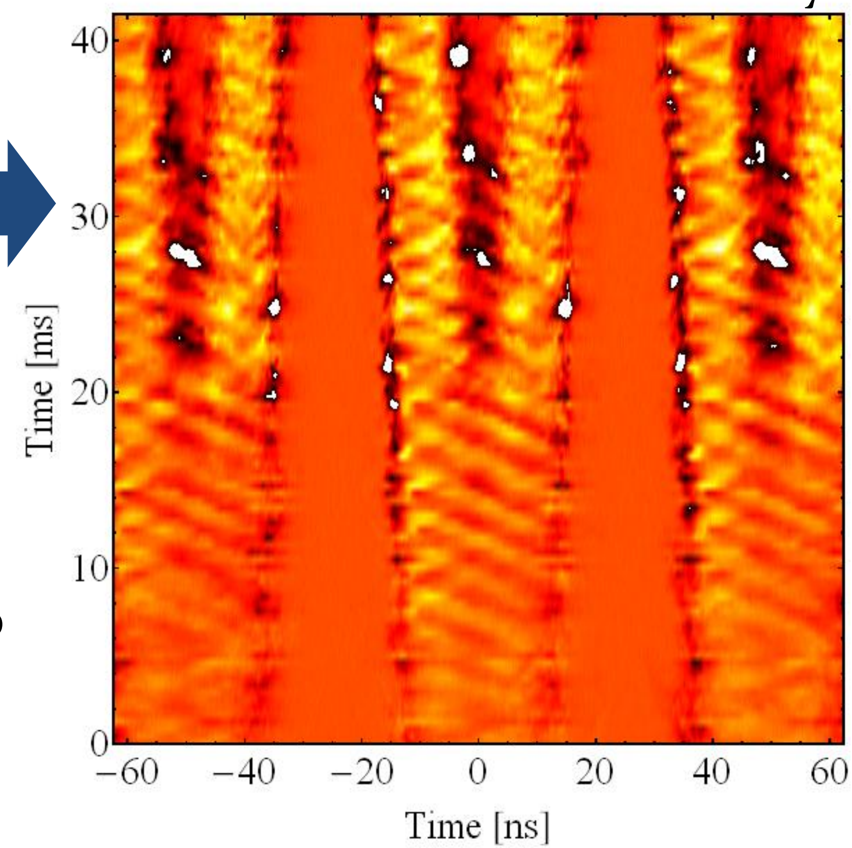
Gap C80-08 closed



Gap C80-08 open



Averaged difference, with and without effect of 80 MHz ion cavity



- **Perturbation visible at $1.6 \cdot 10^{11}$ ppb**

→ **Effect on beam quality?**

80 MHz cavity impedance

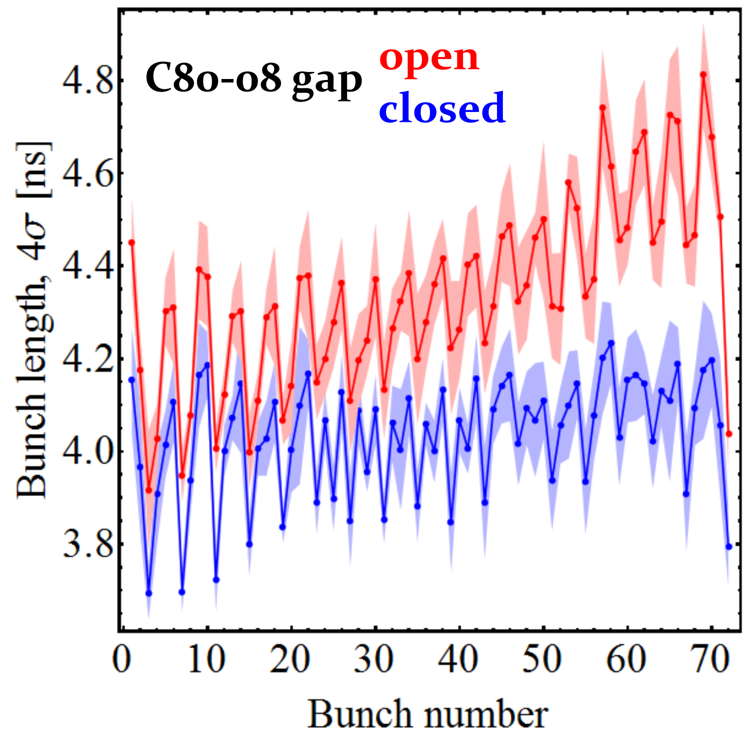
Emittance at arrival on flat-top (4 final bunches)

Cavities with gap open	ε_{RMS} [eVs]
C40-78, C80-88, C80-89	0.231
C40-78, C80-88, C80-89 **and C80-08** (at ion frequency)	0.238

Average bunch length at extraction

Cavities with gap open	$4\sigma_{Gauss}$ [ns]
C40-78, C80-88, C80-89	4.03
C40-78, C80-88, C80-89 **and C80-08** (ion frequency)	4.34

Bunch length at extraction



http://cds.cern.ch/record/1141522/files/AB-Note-2008-052-MD.pdf

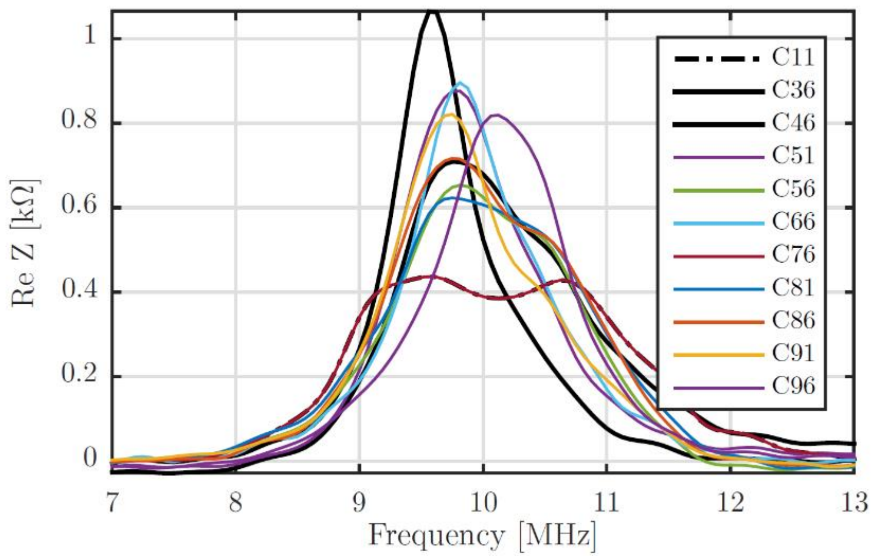
→ **Minor emittance blow-up at arrival on flat-top, but**

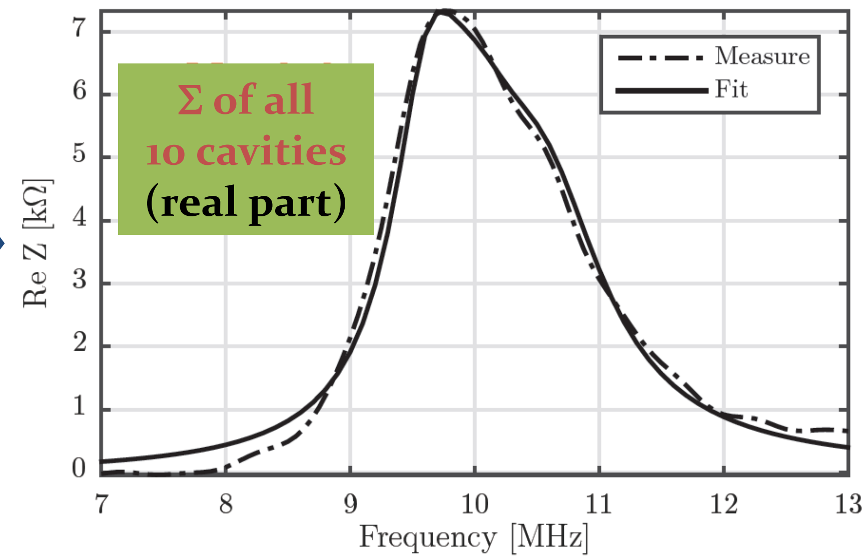
→ **~0.3 ns longer bunches due to impedance of additional 80 MHz cavity**

→ **Expect improvement with new multi-harmonic feedbacks**

New 10 MHz cavity impedance model

- **Studies revealed that 10 MHz cavity impedance four times larger than previously assumed (G. Favia)**





$$Z(\omega) = \sum_{i=1}^{3} \frac{R_{Si}}{1 + iQ_i\left(\frac{\omega_{Ri}}{\omega} - \frac{\omega}{\omega_{Ri}}\right)}$$

Q	R_S [kΩ]	f_{RF} [MHz]
14	4	9.6
9.5	3.5	10
9	3.15	10.6

G. Favia, M. Migliorati, L. Ventura

→ Total impedance modelled as three resonators (fit of real part of impedance)

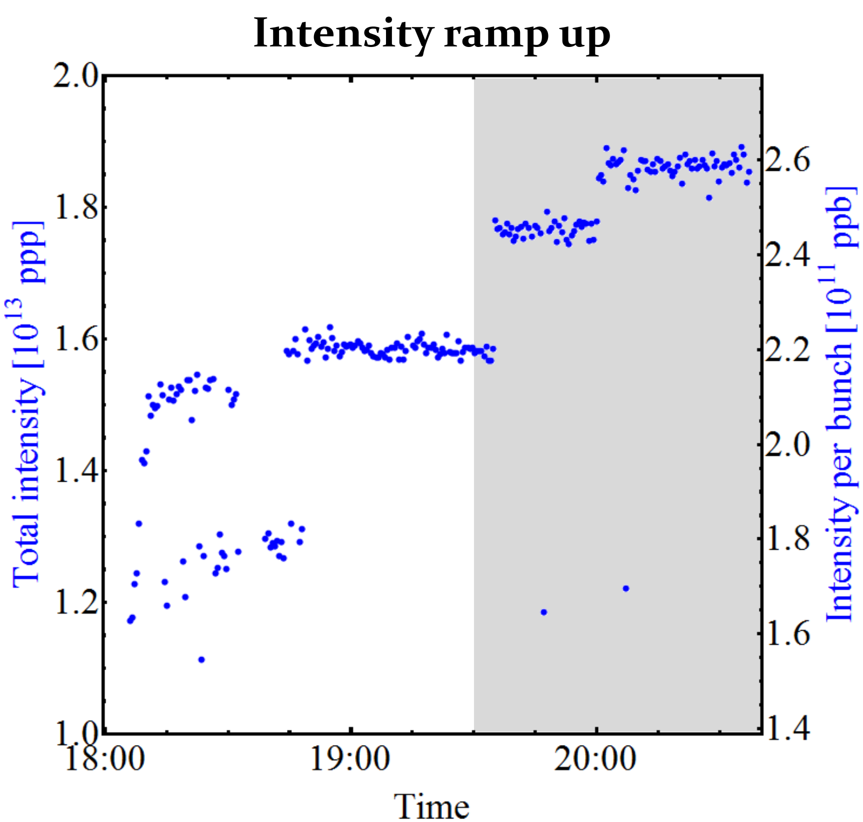
→ Input for MuSiC code (M. Migliorati)

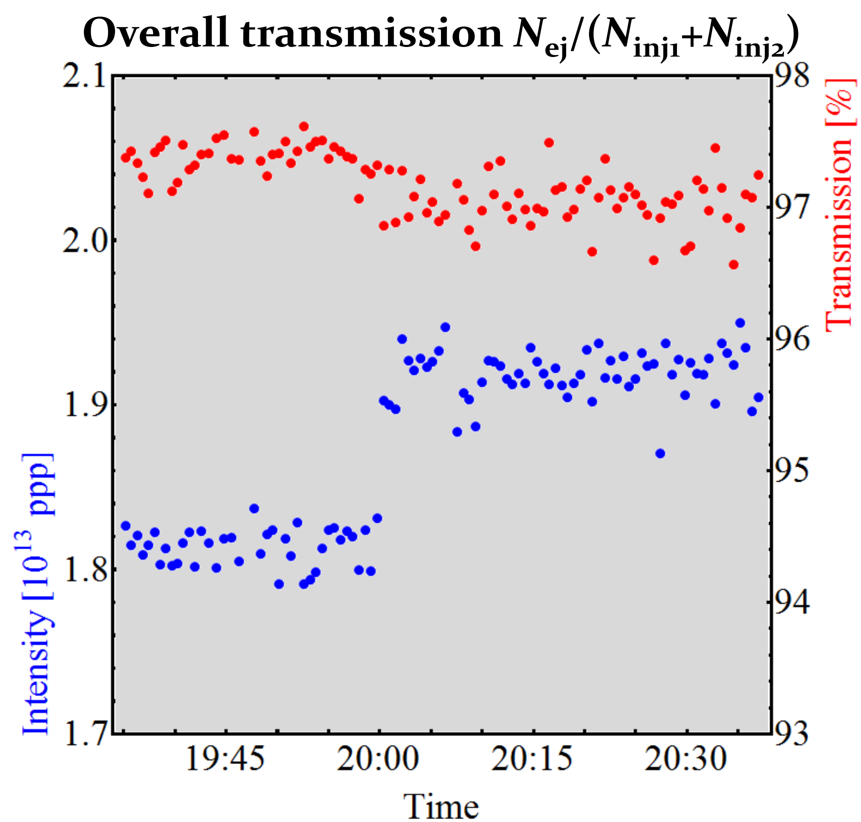
Higher intensity?

Pushing intensity at expense of larger longitudinal emittance

→ Bare minimum of 40/80 MHz cavities with gap open

→ Trips of remaining cavities 40 MHz or 80 MHz due to beam loading





→ **Excellent transmission up to $2.6 \cdot 10^{11}$ ppb, even with $\varepsilon_l > 0.35$ eVs**

→ **No further RF issues related to high intensity**