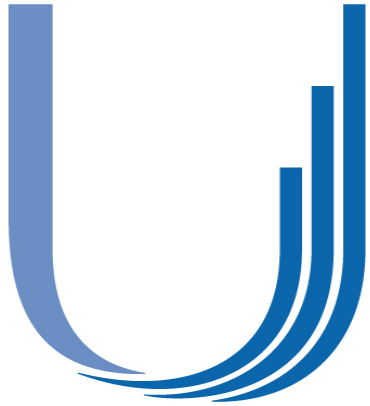


LHC Injectors Upgrade

CERN

LHC Injectors Upgrade

Upgrades of the RF Systems in the LHC Injector Complex

H. Damerau, M. E. Angoletta, T. Argyropoulos, P. Baudrenghien, A. Blas, T. Bohl, A. Butterworth, A. Findlay, R. Garoby, S. Gilardoni, S. Hancock, W. Höfle, J. Molendijk, E. Montesinos, M. Paoluzzi, D. Perrelet, C. Rossi, E. Shaposhnikova

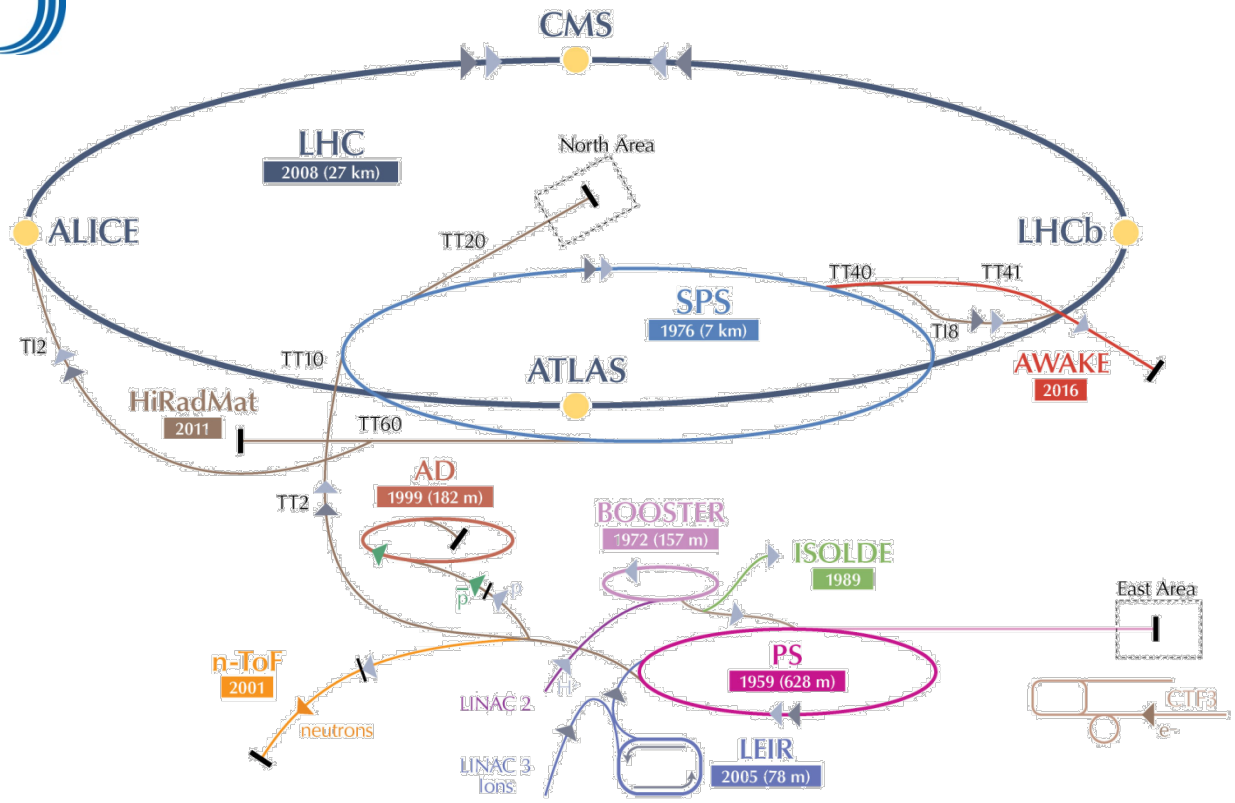
Workshop on High-Intensity, High Brightness and High Power Hadron Beams
November 11, 2014

CERN

Overview

- Introduction and motivation
- PSB
  - Digital beam control
  - Finemet-based accelerating cavities
- PS
  - 1-turn delay feedback systems
  - Coupled-bunch feedback with Finemet wide-band kicker cavity
- SPS
  - RF power upgrade, impedance reduction and bunch rotation
  - Low-level RF upgrade: 800 MHz
- Summary

Introduction and motivation



Proton injectors	
Linac2/4	50 MeV → **160 MeV**
PS Booster	1.4 GeV → **2 GeV**
PS	26 GeV/c
SPS	450 GeV/c
LHC	7 TeV
Intensity with 25 ns	$1.3 \cdot 10^{11}$ ppb → **$>2 \cdot 10^{11}$ ppb**

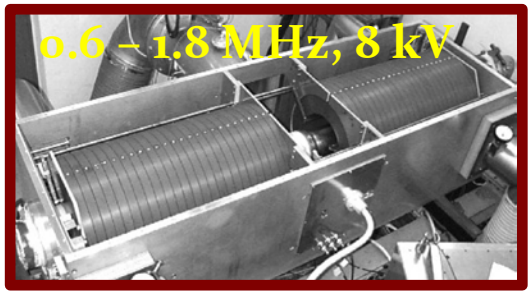
25 ns spacing, LIU project

- **With more than $2.0 \cdot 10^{11}$ ppb → longitudinal density almost doubled**
- **After LS2 → Reliable beam delivery to the high-luminosity (HL) LHC**

→ Extensive upgrades of the RF system in the whole injector chain

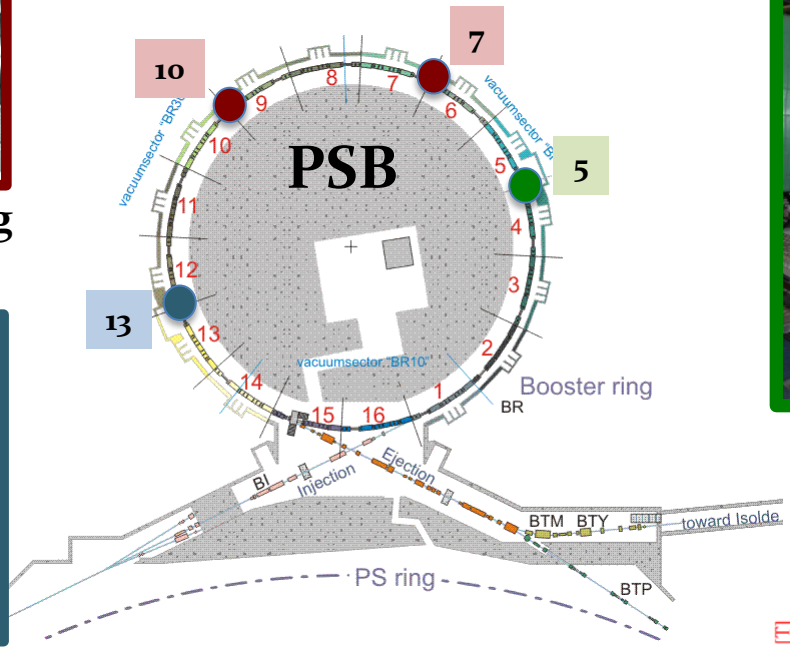
PS Booster

RF systems in the PS Booster

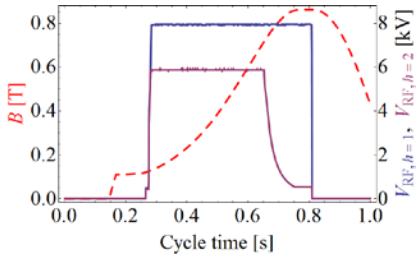


Acceleration and splitting

Acceleration and splitting



Longitudinal blow-up



→ 4 rings with 3 cavities

→ Present PS Booster RF systems based on ferrite-loaded cavities

RF upgrades in the PSB

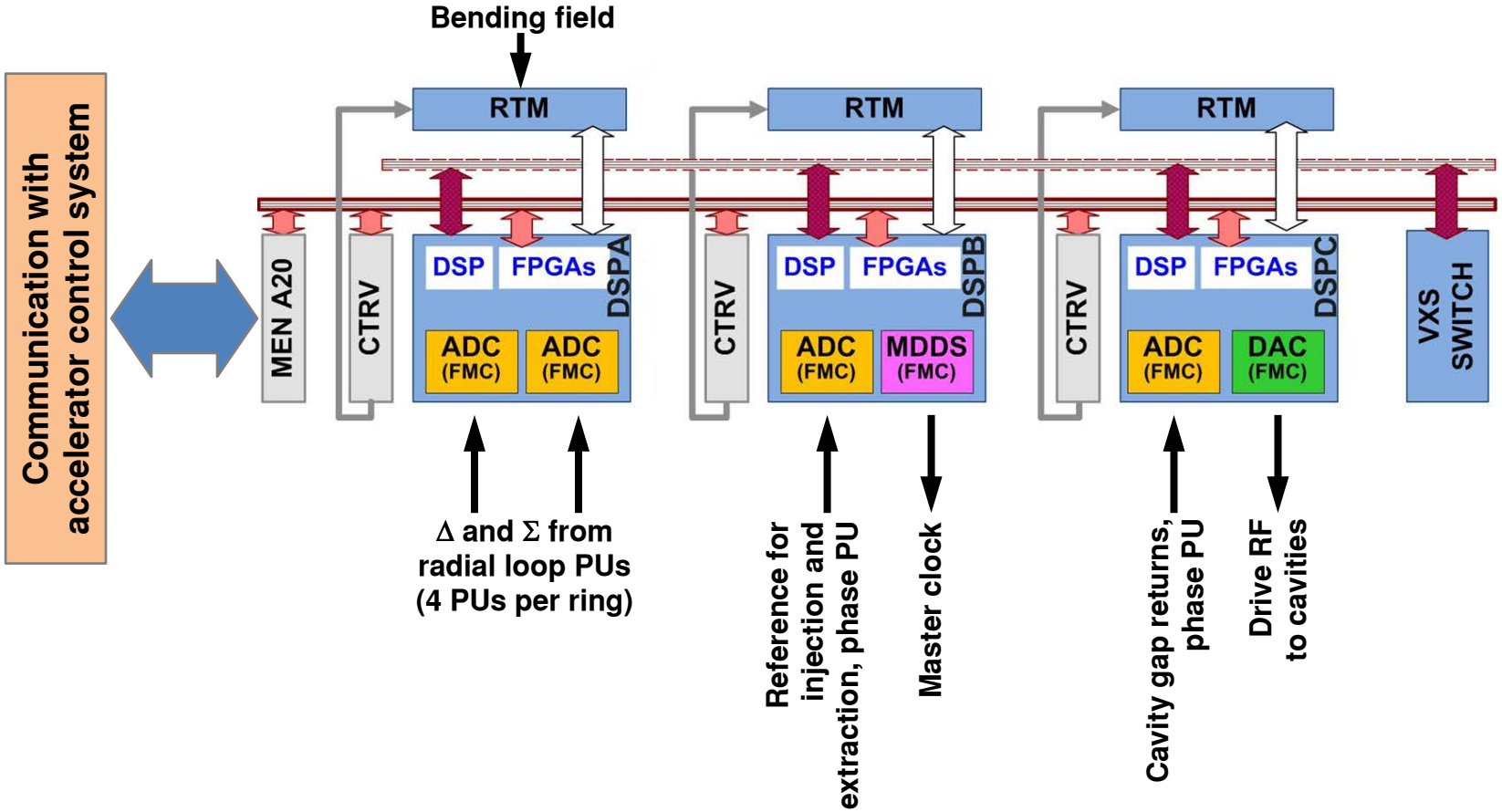
Upgrade	Expected/achieved benefit
• Replacement of beam controls by **fully digital low-level RF (LLRF) system**	→ **Flexibility and reliability** → Injection of chopped beams from Linac4 → **Voltage control** and **feedback for Finemet cavity**
• Upgrade of **ferrite-loaded cavities** or **replacement by Finemet cavities**	→ **Double intensity** to $2 \cdot 10^{13}$ ppp (ISOLDE) → Reliability

→ **Entirety of PS Booster RF system affected by upgrades:**

- **Beam control system exchanged by digital LLRF during LS1**
- **Renovation or replacement of cavities and power amplifiers**

Beam control upgrade

- Largely independent beam control per ring
- Since restart 2014: fully digital beam control on all four PSB rings

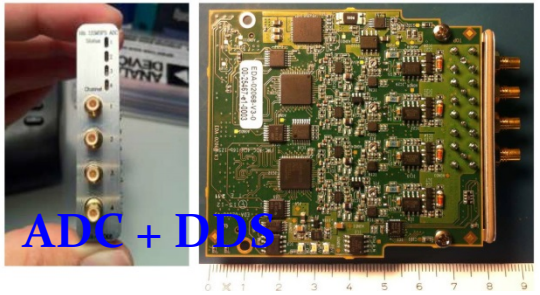


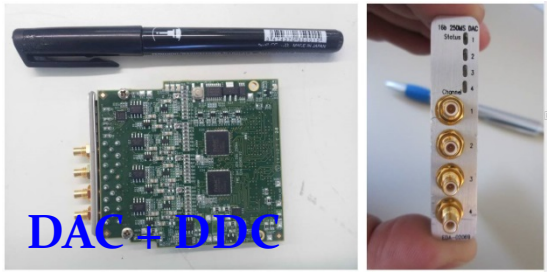
→ Three DSPs per ring: beam phase, radial, injection/ejection synchronization and cavity loops → All loops in firmware

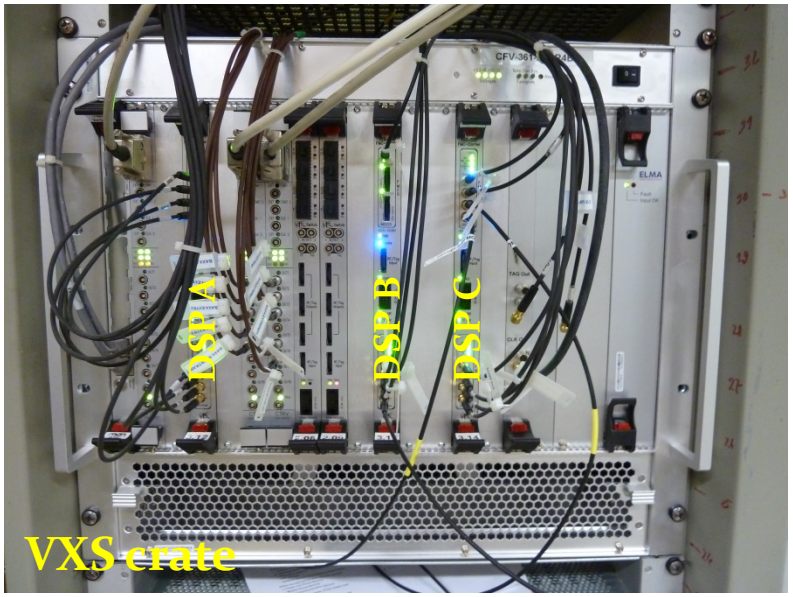
Digital beam control system

- Sweeping tagged clock, switchable h_{clk}, presently $h_{clk} = 64$
- DSP motherboard with 2 mezzanine slots

  → Master DDS, Digital down converter (DDC), Slave DDS (ADC)







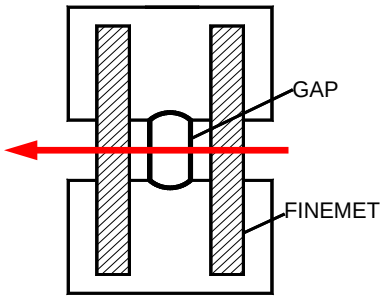
→ **Flexible:**
- All loop parameters adjustable in pulse-to-pulse mode
- Reconfigurable loop algorithms by firmware

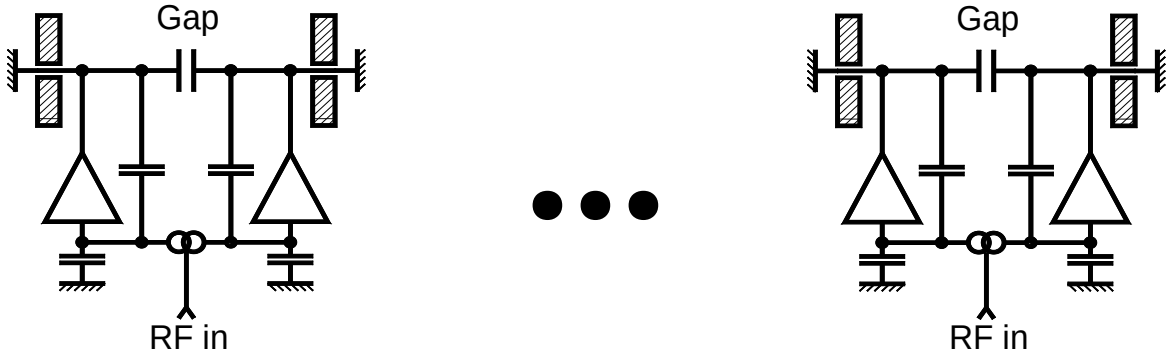
→ **Stable:** No analog drift, direct conversion and digital processing

→ **Modular:** 4th DSP board added to drive Finemet cavity

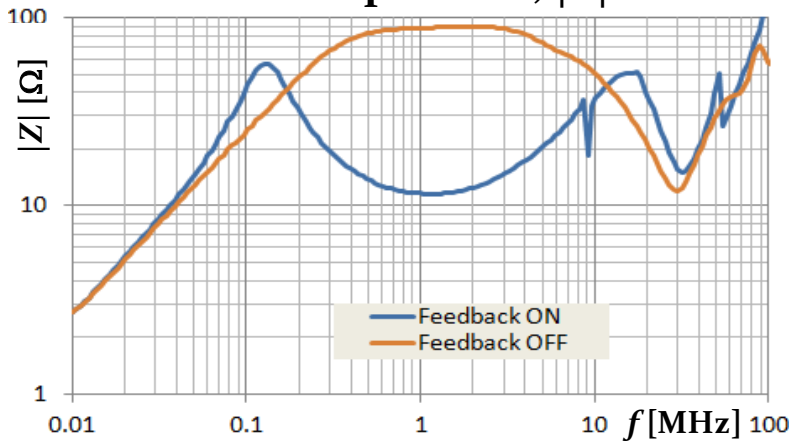
Wide-band Finemet cavity for the PSB

- **Large bandwidth:** covers $h = 1$ and $h = 2$ without need for tuning
- **Moderate voltage per gap, many gaps →** Solid state amplifiers





Cell impedance, $|Z|$

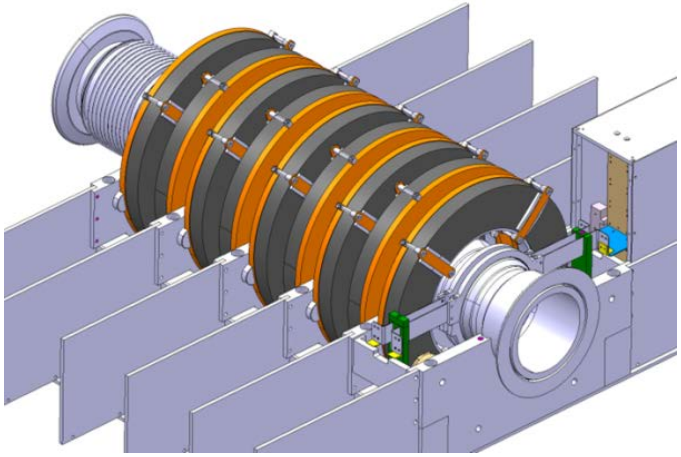


PSB-type Finemet cell	
Frequency range	0.6 - 4 MHz
RF power	2 × 670 W
RF voltage	0.7 – 1 kV
Length	13 cm

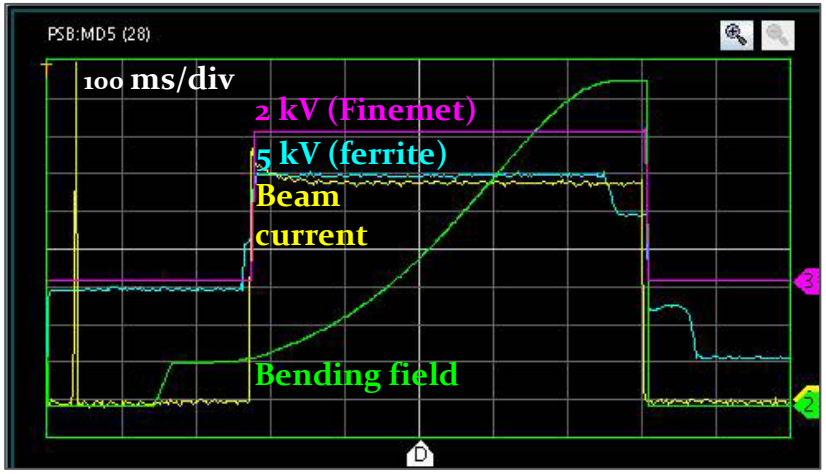
→ **Modular approach: total RF voltage scales with number of cells**

Beam tests with first prototype (2012)

5-cell Finemet cavity prototype



Combined acceleration $4.6 \cdot 10^{12}$ ppb



→ **Combined operation of Finemet prototype with ferrite cavity**

- **Capture and acceleration (V_{RF} = 2 kV from Finemet cavity)**
- **Beam phase loop at h = 1 closed around Finemet cavity**
- **Beam-induced voltage studies**

Finemet cavity upgrade program

- Upgrade existing ferrite-loaded cavities or replacement by Finemet cavities? → Finemet preferred

→ Extensive study program
- 2012 prototype 5 cells
- 2014 prototype 10 cells

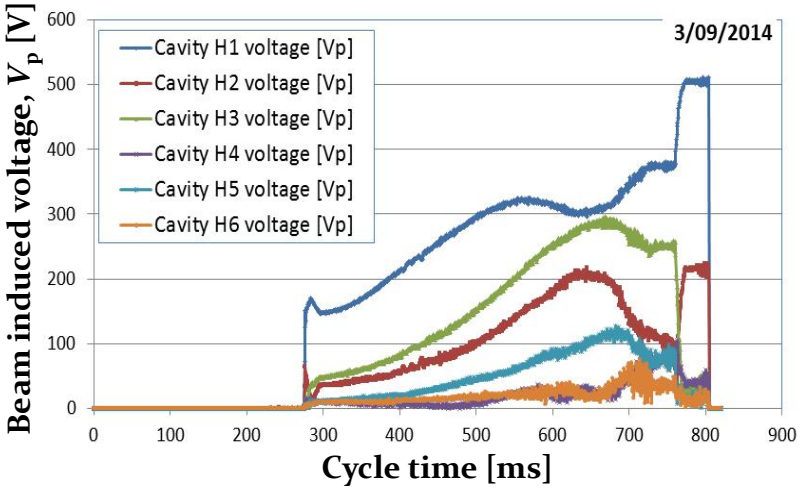
- Take over functionality from $h = 1$ and $h = 2$ ferrite cavities
- Validate reliability
- Radiation damage to solid state amplifiers

→ Decision by end 2015

10-cell Finemet prototype in ring 4

M. Haase

Beam induced voltage (with digital LLRF)

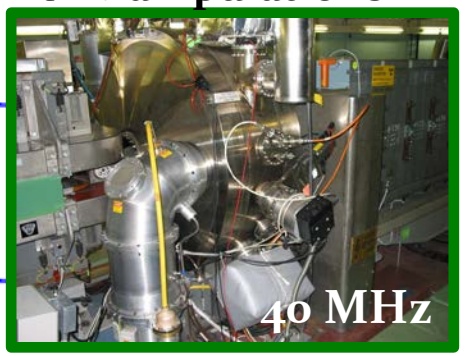


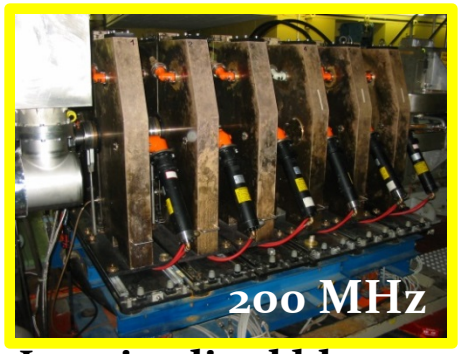
PS

RF systems in the PS

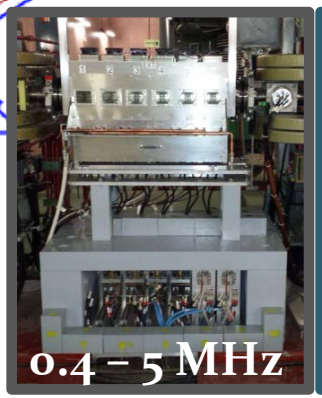
Acceleration

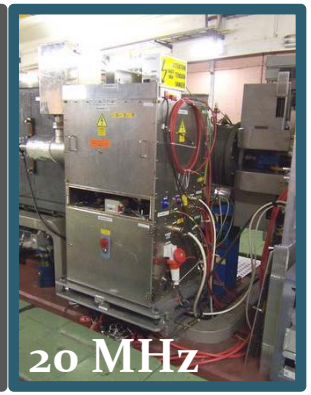
RF Manipulations





Longitudinal blow-up



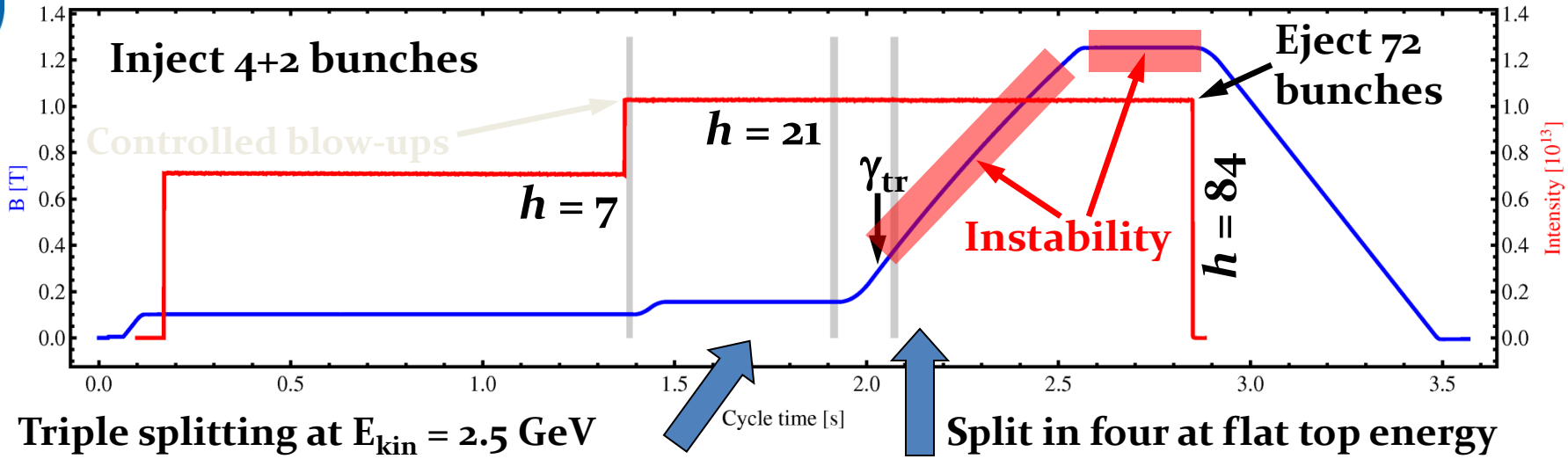


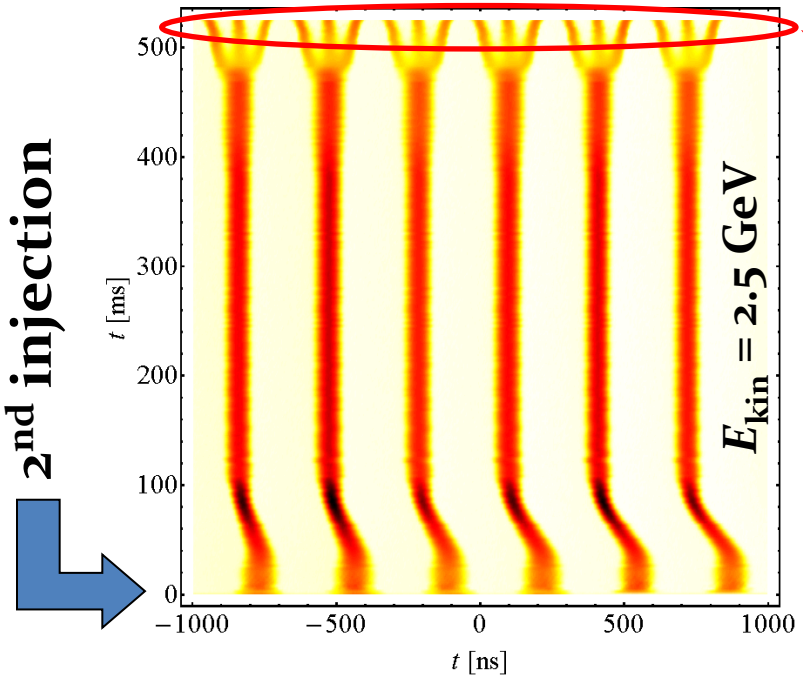
Overview - PS

Upgrade	Expected benefit
• **1-turn delay feedbacks** 10 MHz cavities • Improved **wide-band feedback** (higher gain)	→ Reduction of **transient beam loading** → Bunch-to-bunch **equalization** → Reduction of **coupled-bunch instabilities**
• **1-turn delay feedbacks** 20 MHz, 40 MHz and 80 MHz	→ Reduction of **transient beam loading** → Bunch-to-bunch **equalization**
• **Coupled-bunch feedback** • Wide-band **Finemet longitudinal kicker**	→ Mitigation of **coupled-bunch instabilities**
• Replacement of beam controls by **digital low-level RF (LLRF) system**	→ **Reliability** and **maintainability**

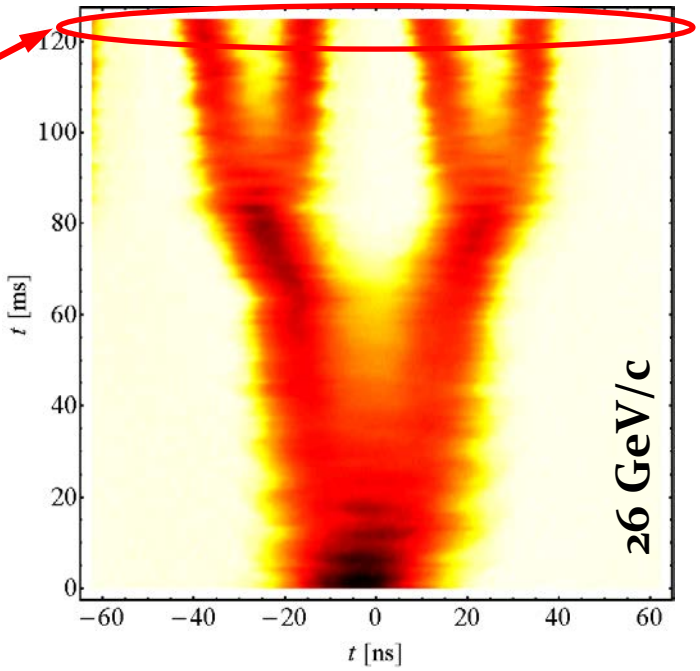
- **Most PS RF systems affected by upgrades:**
  → **Improve longitudinal beam quality for LHC-type beams**

The LHC25ns cycle in the PS





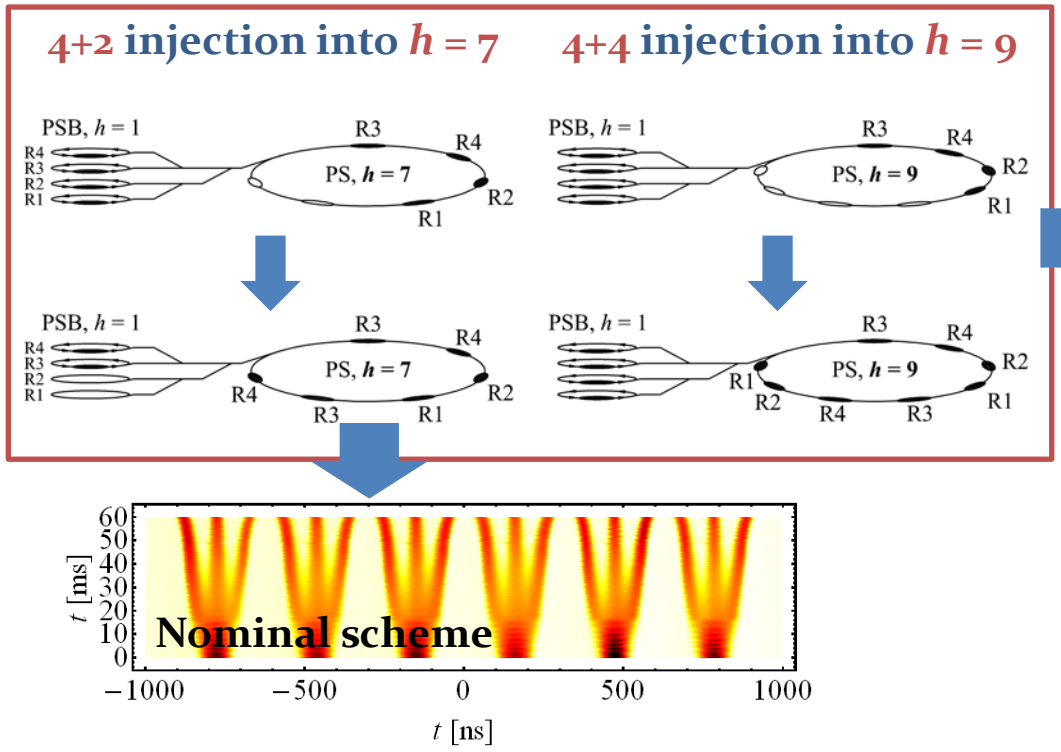
Transient beam-loading

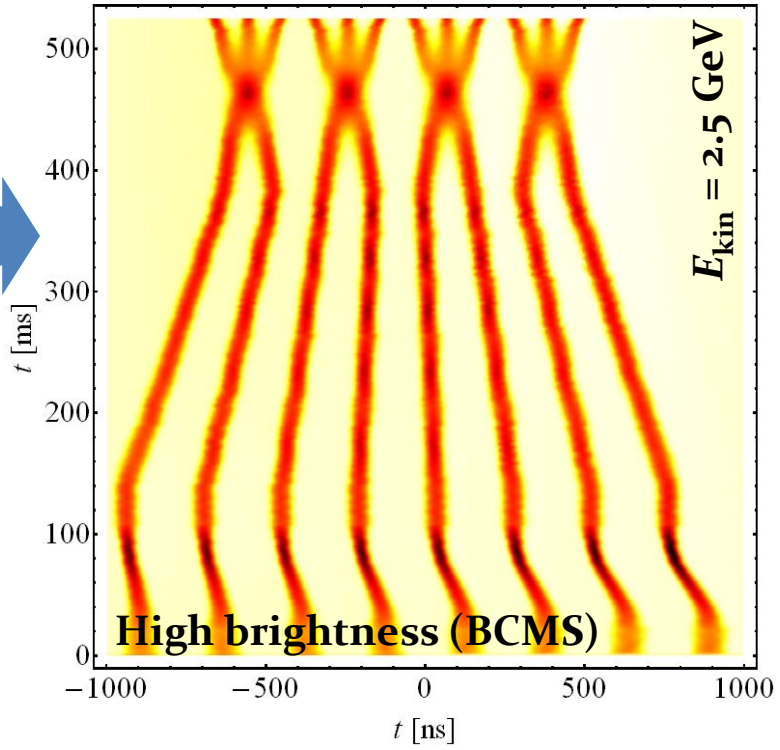


→ Each bunch from the Booster divided by 12 → 6 × 3 × 2 × 2 = 72

RF Manipulations and beam control

- **Advanced RF manipulations for large variety of LHC type beams**
- **Different injection harmonics, many harmonics during cycle**



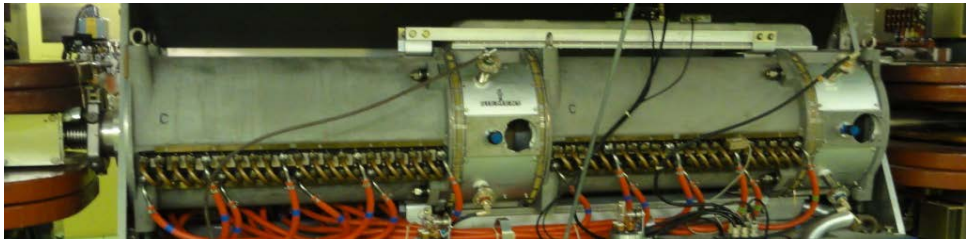


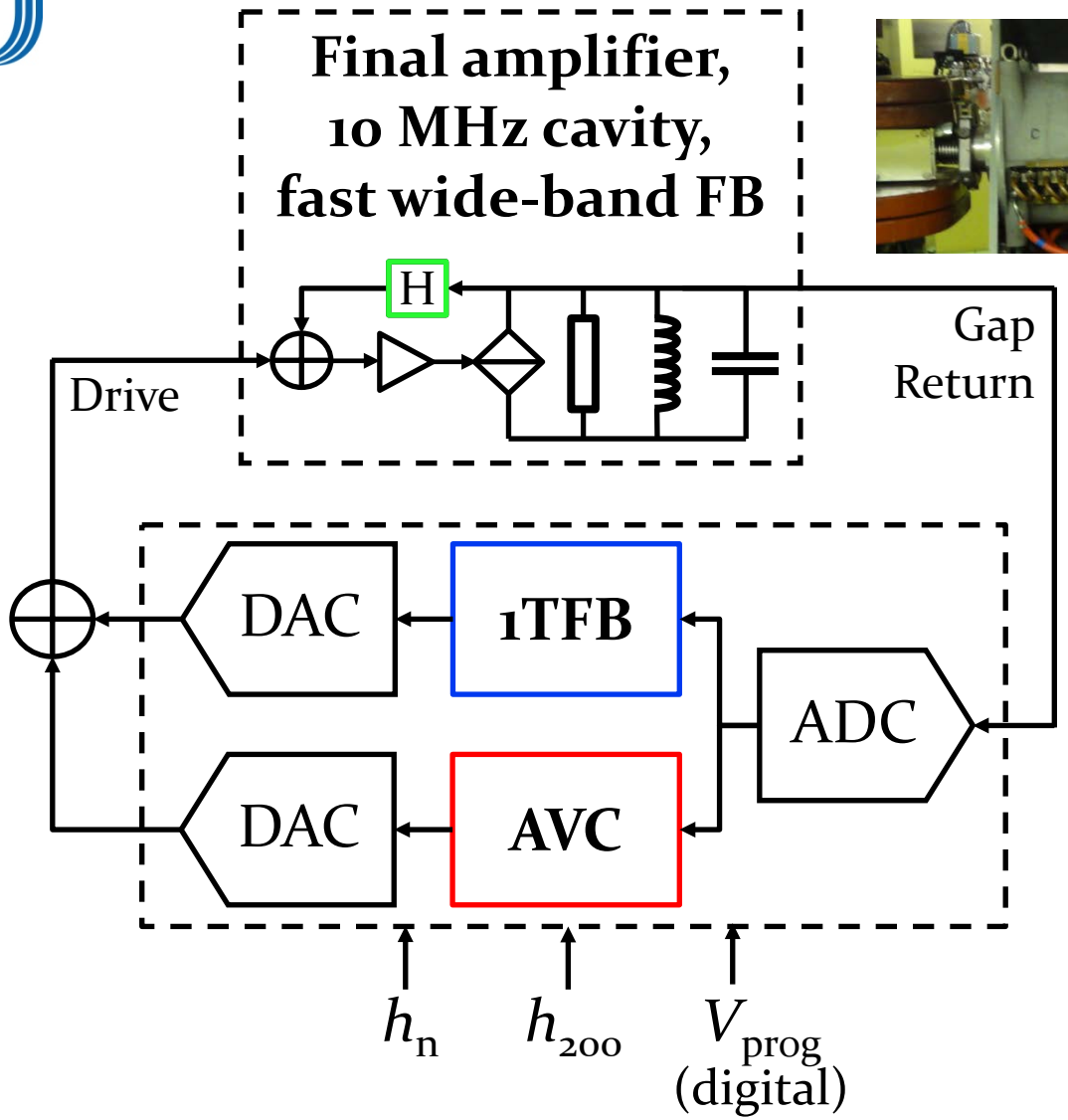
→ **High flexibility of cavity control and low-level RF essential**

- **Presently based combination of analogue and digital hardware**

→ **Upgrade to digital beam control hardware during LS2**

Feedbacks of 10 MHz RF system





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

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

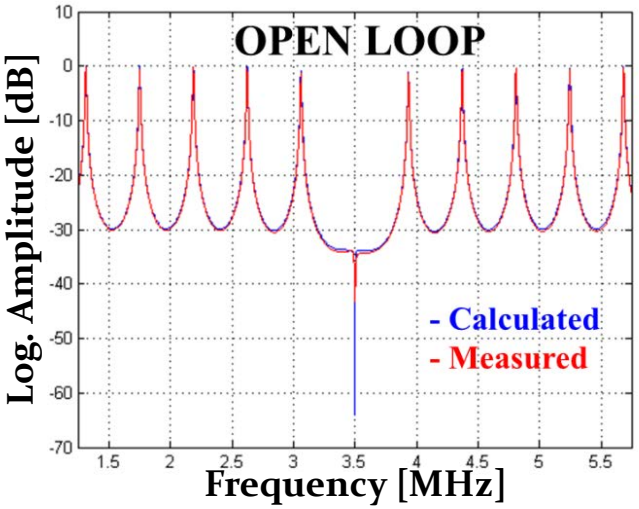
- **Slow voltage control loop (AVC)**
  → **Gain control at f_{RF}**

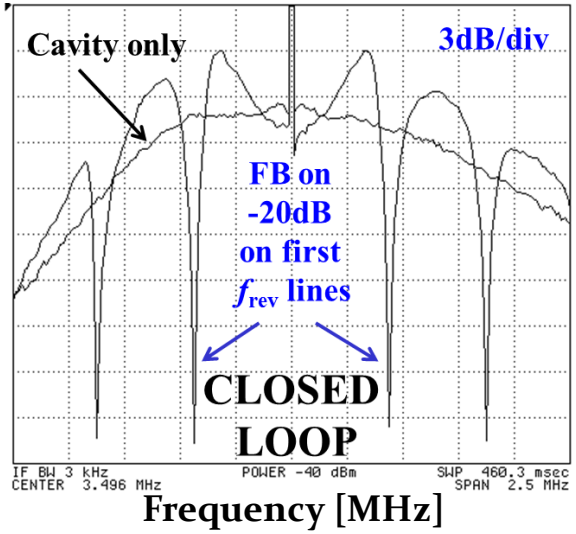
→ **Digital 1-turn delay feedback and AVC loops commissioned on all 11 main accelerating cavities during 2014 start-up**

10 MHz 1-turn delay feedbacks

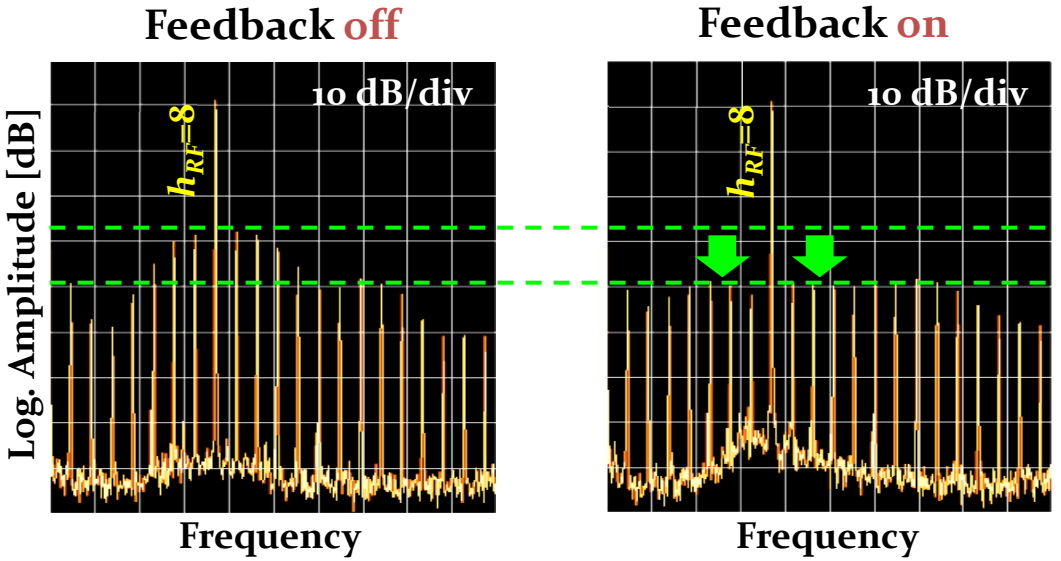
→ **Reduce cavity impedance beyond stability limit of wide-band FB**

Open/closed loop transfer functions





Spectrum at cavity gap return



→ **Important impedance reduction**

→ **Beneficial for**

- **Transient beam loading**
- **Coupled-bunch instabilities driven by 10 MHz cavities**

→ **Measurements with LHC beams**

Coupled-bunch feedback

→ Two feedbacks: 1. Beam → Finemet cavity, 2. Cavity return → cavity

→ No detrimental effect on beam stability expected

→ But: beam-loading reduction essential to reduce induced voltage

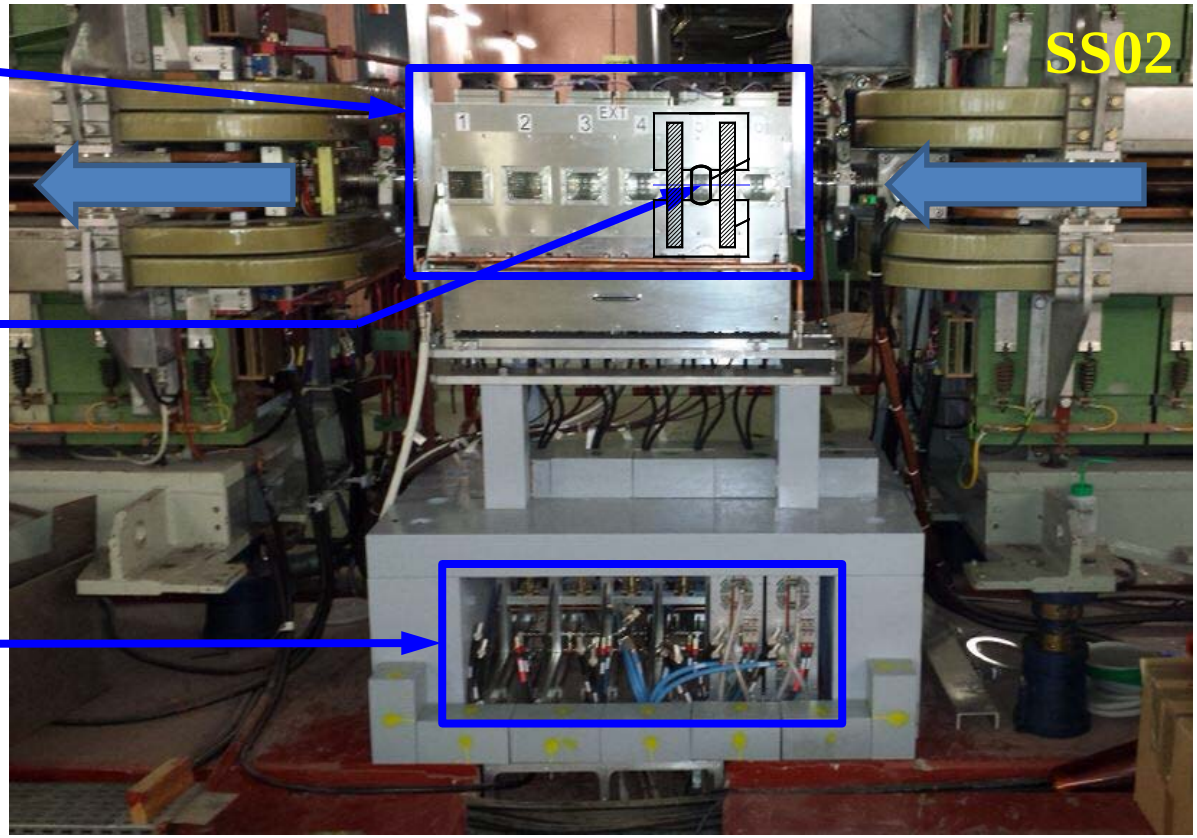
Wide-band Finemet longitudinal kicker

- **Wide-band Finemet cavity: 0.4 MHz (f_{rev}) – 5 MHz ($f_{RF}/2$), $V_{RF} \approx 5$ kV**
- **No acceleration, but damping of coupled-bunch oscillations**

6-cell cavity unit

Accelerating gap

Power amplifiers
(solid state)

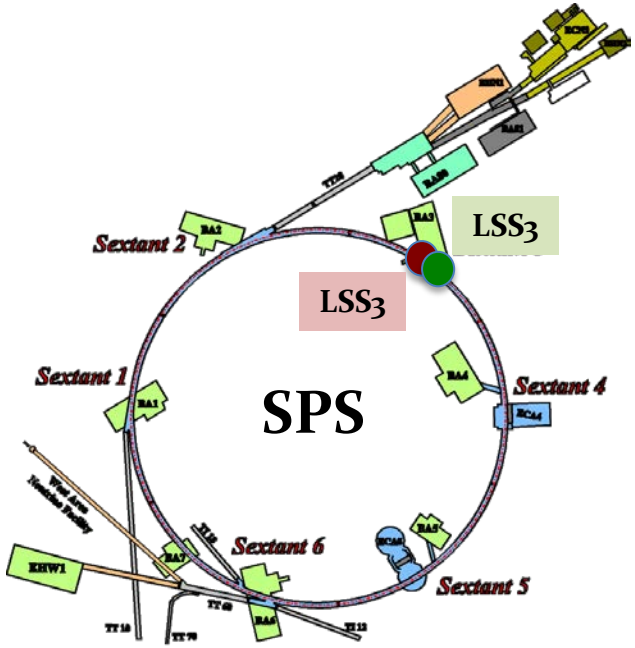


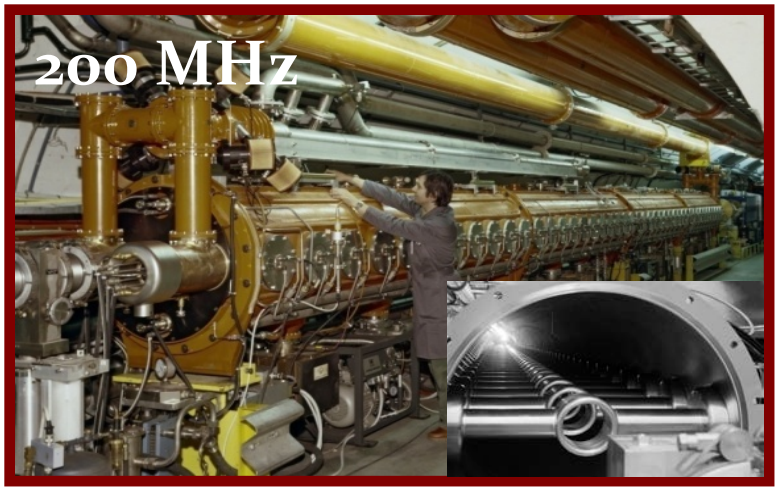
→ **First installation of solid state power amplifiers close to beam in PS**

→ **Commissioning with low-intensity beam started**

SPS

RF systems in the SPS



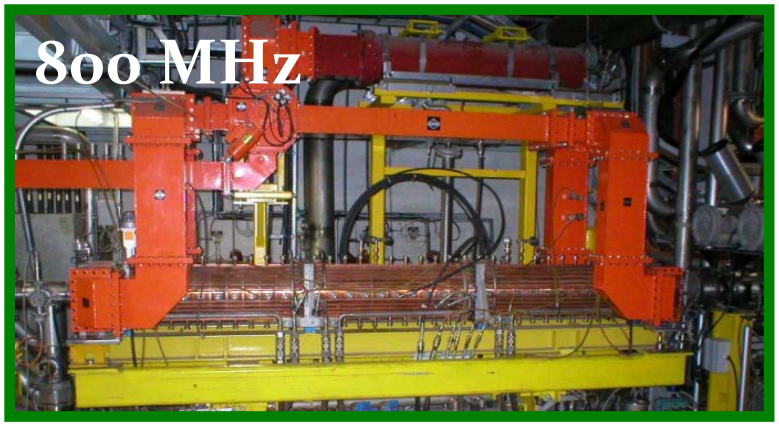


Acceleration and controlled blow-up

→ All cavities in same straight section

→ 200/800 MHz travelling wave cavities

- Filling time much shorter than f_{rev} → pulsed operation



4th harmonic Landau cavity

Overview - SPS

Upgrade	Expected benefit
• **Rearrangement of main 200 MHz cavities** • 2 new **RF power plants**	→ **Increased voltage** at transfer to LHC → **Increased RF power** during acceleration → 1.3 10^{11} ppb → > 2.0 10^{11} ppb → **Accept larger** longitudinal **emittance**
• New **beam controls for 200 MHz and 800 MHz RF systems**	→ Suppression of **transient beam loading** → Improved relative **phase control** → **Pulsed** cavity **operation**
• **Impedance identification** and improvement campaign	→ Vacuum flanges with **1.4 GHz resonance identified** → Possible **shielding being investigated**

- **Major upgrade of main 200 MHz RF system:**
  → **More RF voltage with higher intensity**

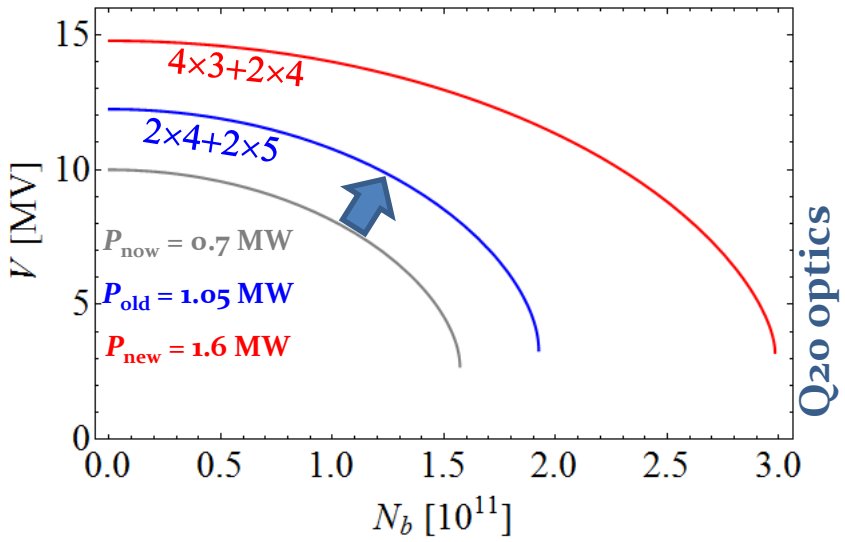
Maximum intensity at transfer to LHC

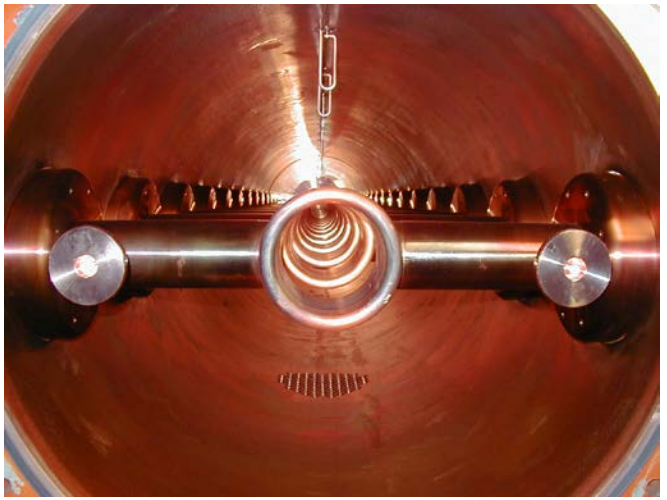
- Fixed bunch length required at SPS → LHC transfer: 1.7 ns (4σ)

- Available RF voltage decreases with
- Required RF voltage increases with

increasing beam intensity

RF voltage at transfer to LHC (25ns)





- Pulse amplifiers at f_{rev} for more power during beam passage
- Maximum RF power from existing amplifiers 0.7 MW → ~1.05 MW

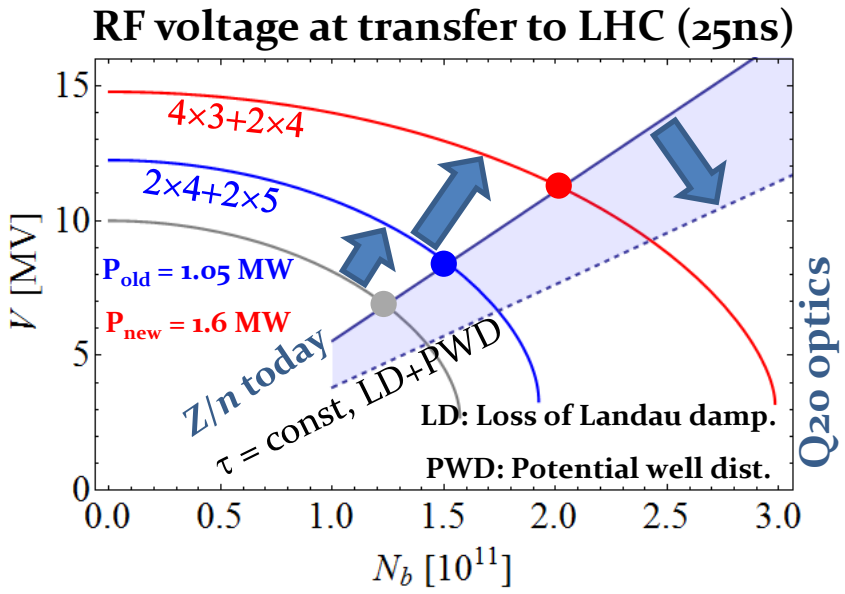
→ New low-level RF for beam synchronous pulsing during LS2

Maximum intensity at transfer to LHC

- **Fixed bunch length required at SPS → LHC transfer: 1.7 ns (4σ)**

- **Available RF voltage decreases with**
- **Required RF voltage increases with**

increasing beam intensity



1. **Rearrangement of cavity sections and 2 × 1.6 MW power plants**

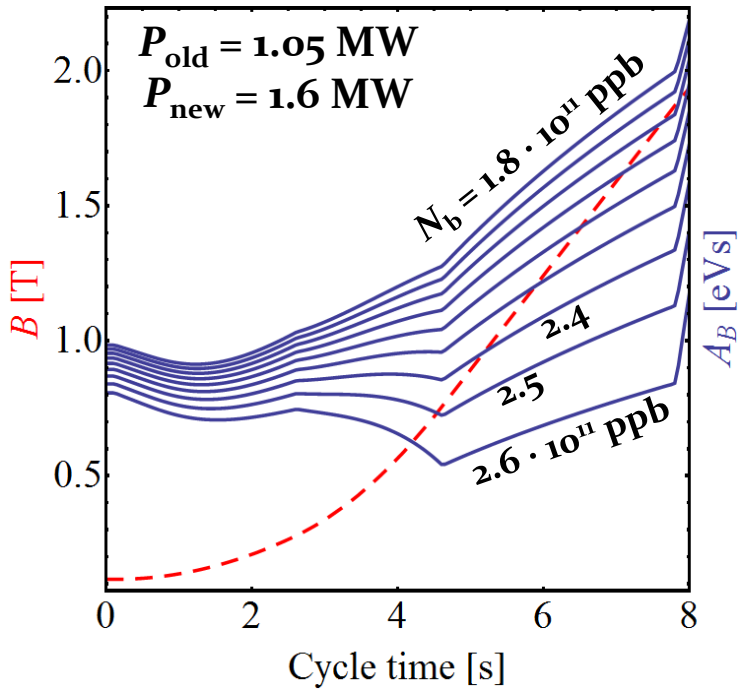
2. **Impedance identification and reduction (smaller ε_l)**

3. **Bunch rotation at extraction**

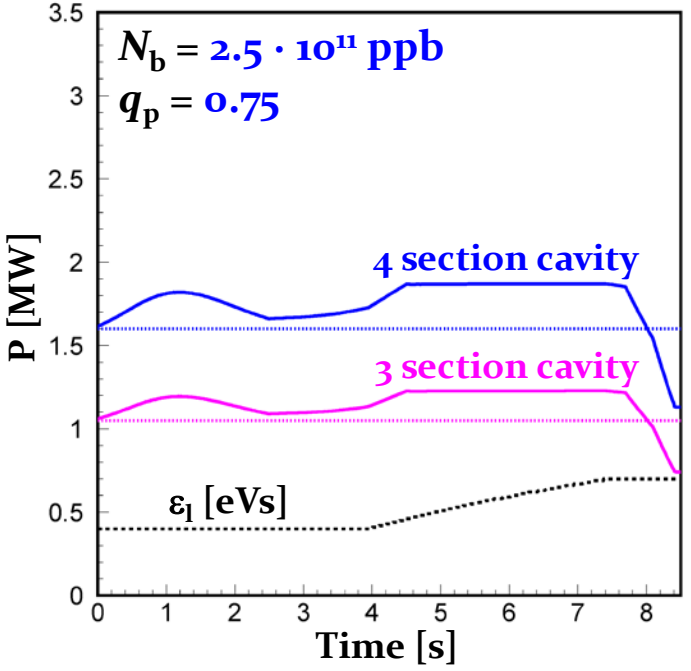
Maximum intensity during acceleration

- **RF power related intensity limitation also during acceleration**

Bucket area at max. RF power
4×3+2×4 cavities



RF power and long. emittance
2014 cycle, 4×3+2×4 cavities

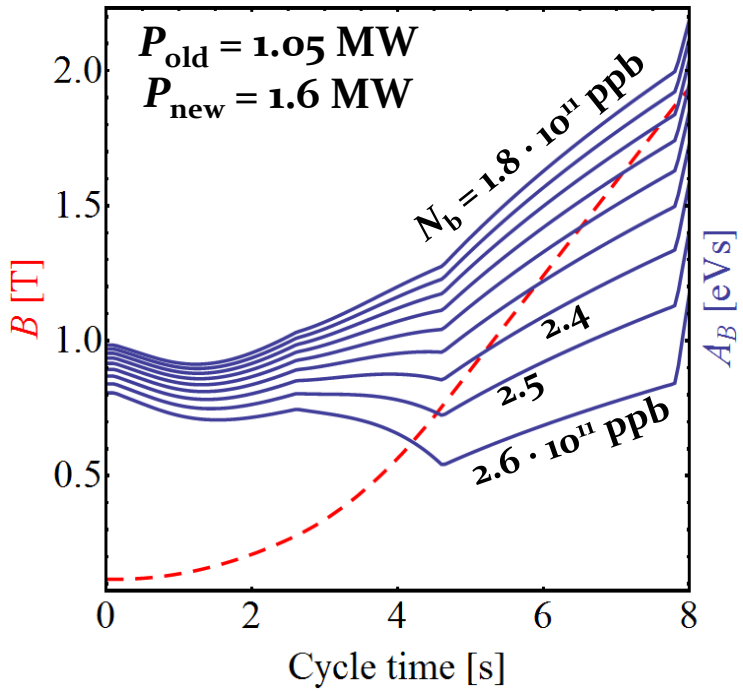


→ **Bucket area allows no emittance growth beyond 2.5 · 10¹¹ ppb**

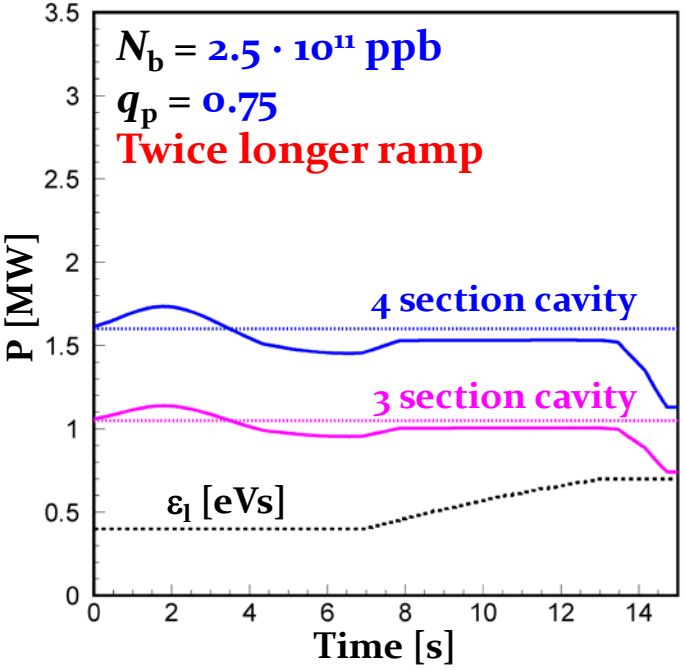
Maximum intensity during acceleration

- **RF power related intensity limitation also during acceleration**

Bucket area at max. RF power
4×3+2×4 cavities



RF power and long. emittance
2014 cycle, 4×3+2×4 cavities



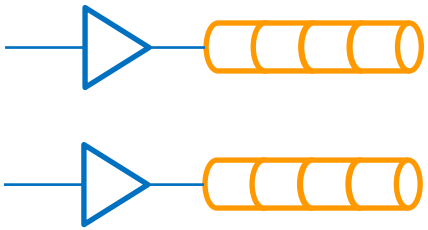
→ **Bucket area allows no emittance growth beyond 2.5 · 10¹¹ ppb**

→ **Should become possible with longer acceleration ramp**

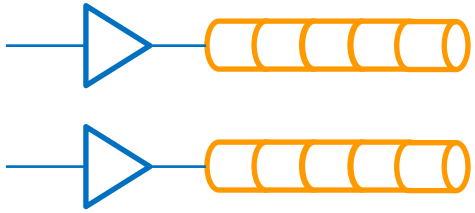
Rearrangement of cavity sections

Present arrangement: 4 cavities

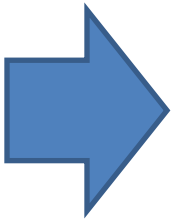
2 x 4 sections



2 x 5 sections

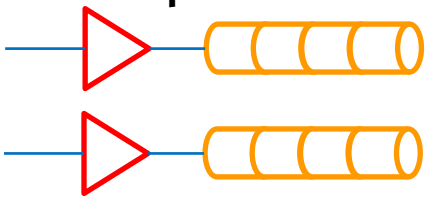


3 spare sections

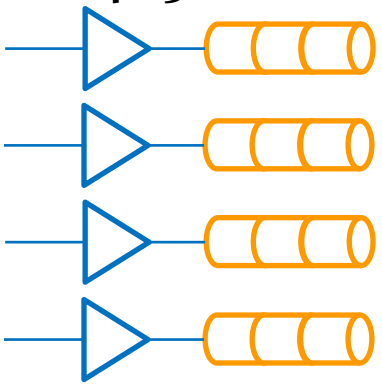


After LS2: 6 cavities

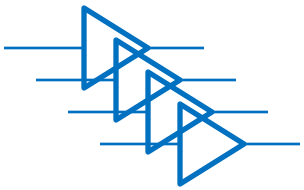
2 x 4 sections



4 x 3 sections

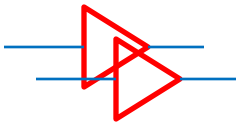


1 spare sections



Existing amplifiers:

- 0.7 MW continuous
- 1.05 MW pulsed



New amplifiers

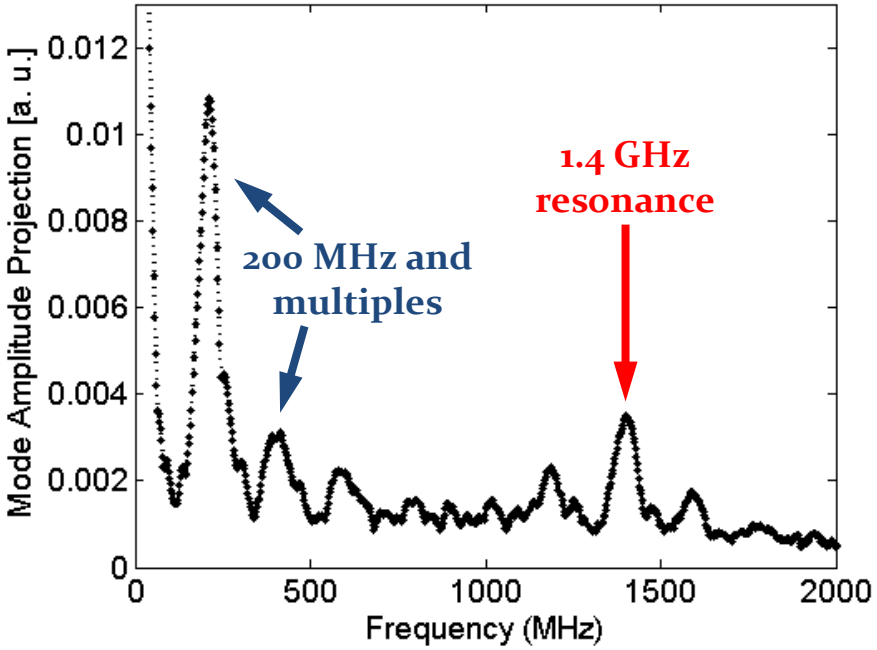
- 1.6 MW pulsed

→ New building

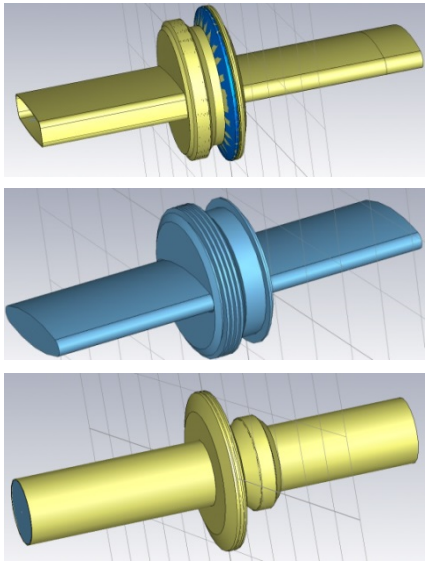
Impedance identification and reduction

- Inject long ($4\sigma \approx 25$ ns) long bunch with RF off
- Observe spectrum

Bunch spectrum shortly after injection



SPS vacuum flanges



→ In total about 550 vacuum flanges of 7 different types: f_{res} = 1.2…1.6 GHz

→ Most probable source of impedance at 1.4 GHz

→ Possible shielding being investigated

→ Th. Argyropoulos, THO4LR01

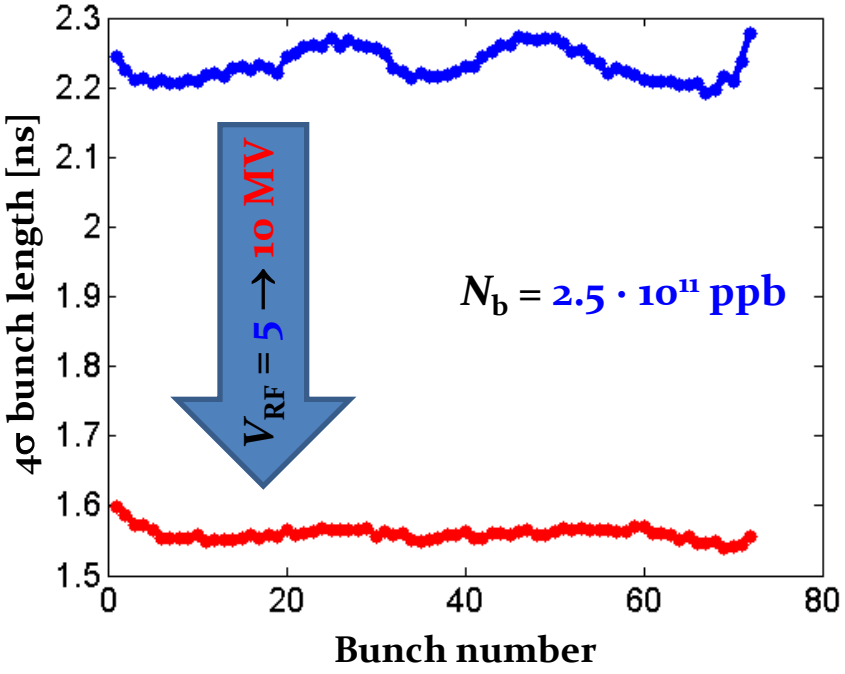
→ A. Lasheen, THO4LR02

Bunch rotation before transfer to LHC

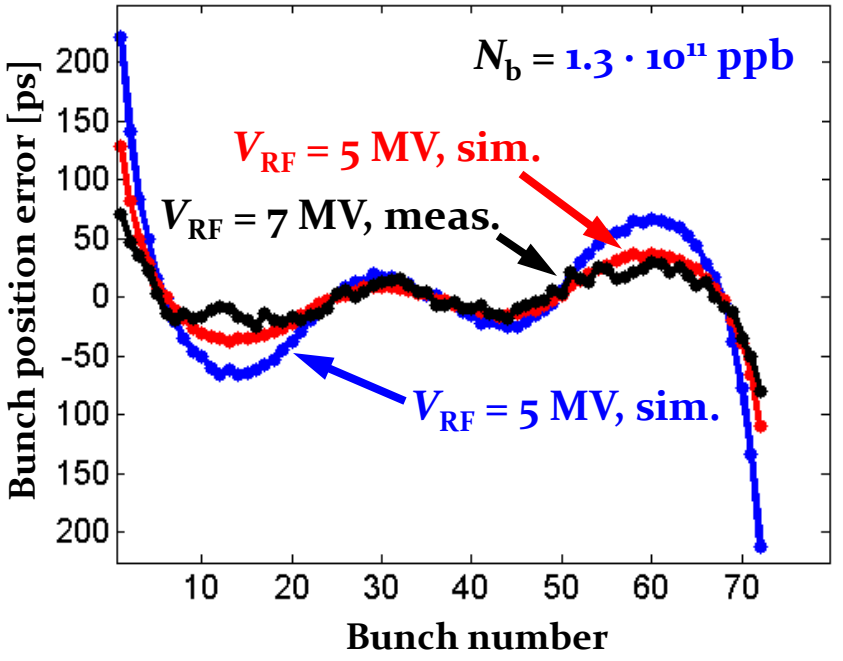
- Save RF voltage and power by bunch rotation
- Voltage step: bunch length proportional to $V_{RF}^{1/2}$ instead of $V_{RF}^{1/4}$

- Simulations including SPS impedance, feed-forward and feedback

Simulated bunch length before/after rotation



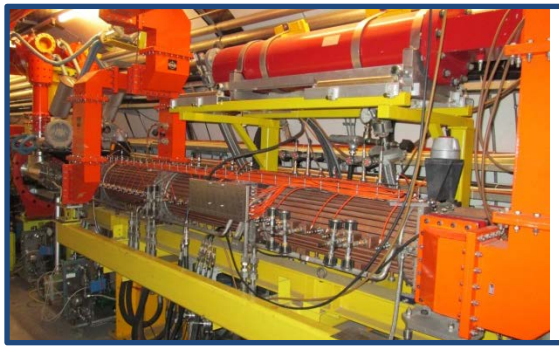
Simulation calibration: bunch position along batch



→ Promising in simulation → Possible beam test already in 2015

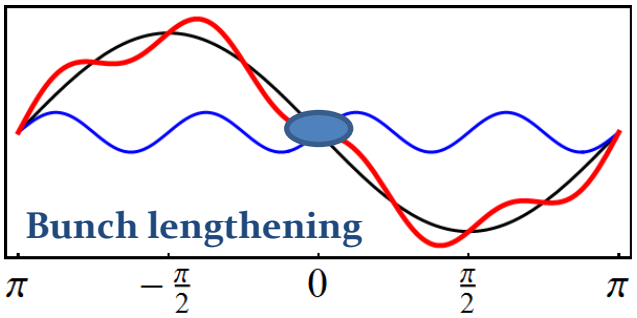
800 MHz RF system

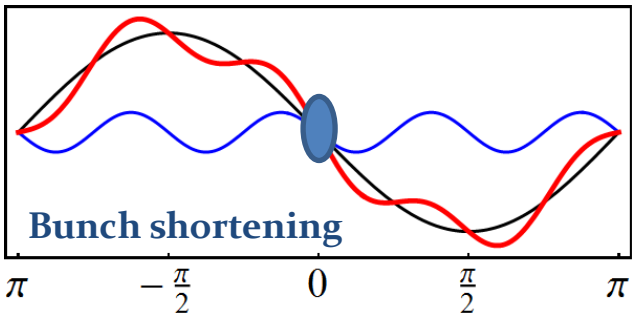
- **Two 800 MHz Landau cavities for beam stabilization**



- 39 cells, 800 MHz
- IOT-based power amplifiers
- 200 kW per cavity

- **10 – 15% of main RF voltage at 200 MHz**





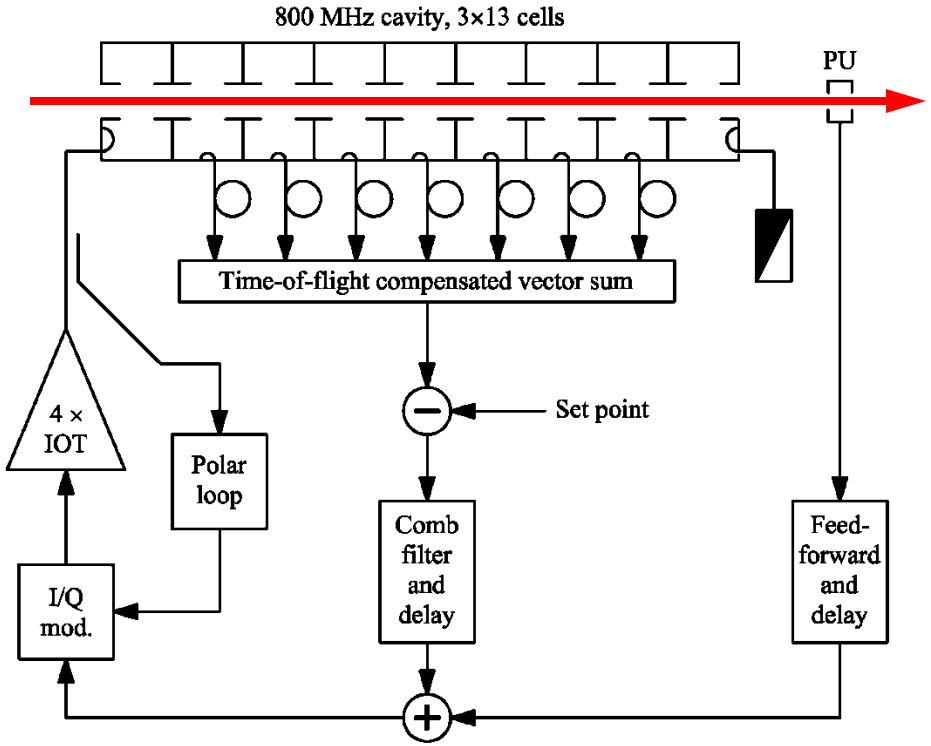
→ Requires good phase control of 800 MHz with respect to 200 MHz

→ Constant relative phase for all bunches, equal f_S distribution

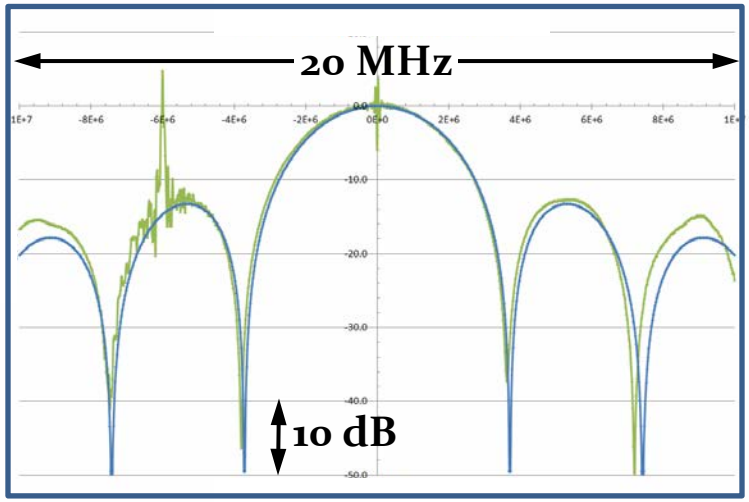
→ New feedback, feed-forward and amplifier polar loops

800 MHz LLRF upgrade

- Feedback and feed-forward → reduce beam-loading
- I/Q polar loop → compensate power amplifier gain/phase drift



Transfer function with vector combiner



G. Hagmann

→ No feedback gain at transfer function notches

→ Expected stability improvement and better blow-up uniformity

→ New feedback controller being commissioned on one cavity

→ Both cavities ready by mid 2015

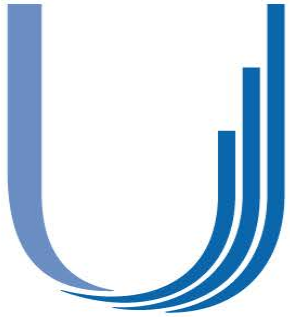
Summary

- RF upgrades to prepare injectors for an intensity beyond $2 \cdot 10^{11}$ ppb with 25 ns spacing for LHC
- Extensive beam studies in all accelerators

- Long shutdown 1:
  - PSB: Digital LLRF, prototype Finemet cavity
  - PS: 1-turn delay and coupled-bunch feedbacks, Finemet cavity
  - SPS: 800 MHz upgrade, LLRF and amplifiers

- Long shutdown 2:
  - PSB: Cavity upgrades → new Finemet cavities
  - PS: Power upgrades, digital LLRF
  - SPS: 200 MHz power upgrade and feedbacks

→ Great progress during LS1, but major part of upgrades: LS2



LHC Injectors Upgrade

THANK YOU FOR YOUR ATTENTION!