LHC Injectors Upgrade

CERN

LHC Injectors Upgrade

LIU - RF systems along the injector chain and outlook for post-LS2 performance

H. Damerau for the RF teams in LIU-PSB, PS and SPS

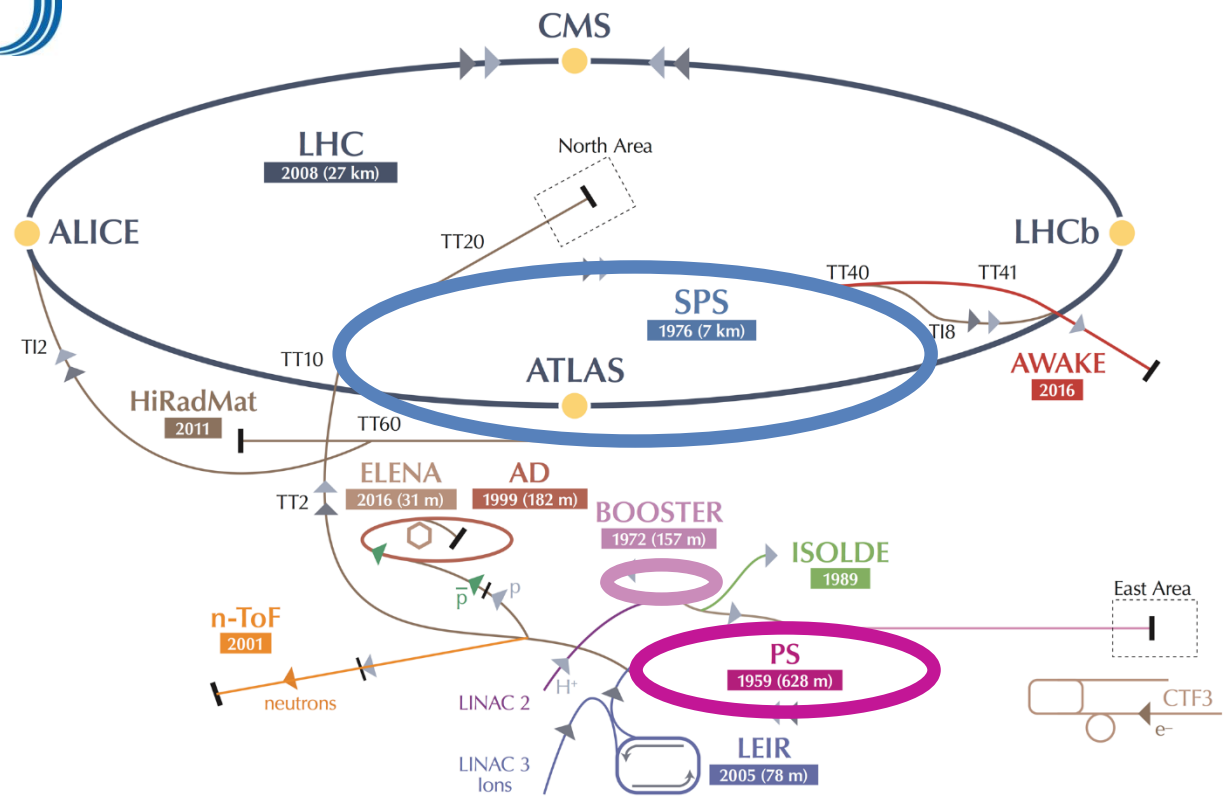
LHC Performance Workshop
Chamonix, 27/01/2016

Many thanks for input and discussions to: **M. E. Angoletta, T. Argyropoulos, P. Baudrenghien, A. Blas, T. Bohl, A. Butterworth, G. Favia, A. Findlay, B. Goddard, S. Gilardoni, M. Haase , G. Hagmann, S. Hancock, W. Höfle, A. Lasheen, J. Molendijk, E. Montesinos, M. Paoluzzi, D. Perrelet, S. Pittet, C. Rossi, E. Shaposhnikova, H. Timko, L. Ventura, C. Völlinger**

Overview

- **Introduction and motivation**
- **PSB**
  - Digital beam control
  - Finemet-based accelerating cavities
- **PS**
  - Direct and 1-turn delay feedback systems, digital beam control
  - Coupled-bunch feedback with Finemet wide-band kicker cavity
  - Increased reliability and flexibility of high-frequency cavities
- **SPS**
  - RF power upgrade: rearrangement of cavities and new RF power plants
  - Upgrade of cavity controllers 200 MHz and 800 MHz
  - Renovation of beam control for slip-stacking
- **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**

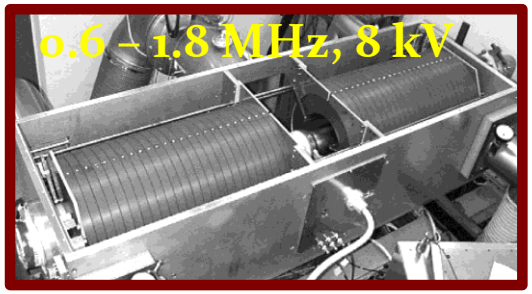
25 ns spacing, LIU project

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

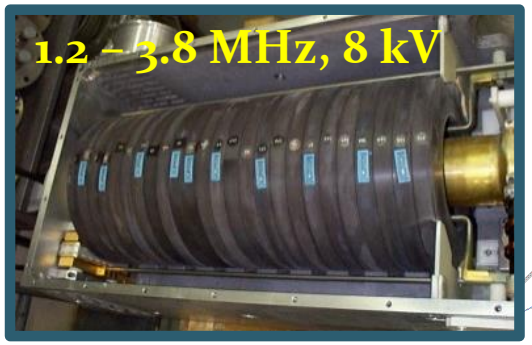
→ Extensive upgrades of the RF systems in the whole injector chain

PS Booster

RF systems in the PS Booster



Acceleration and splitting



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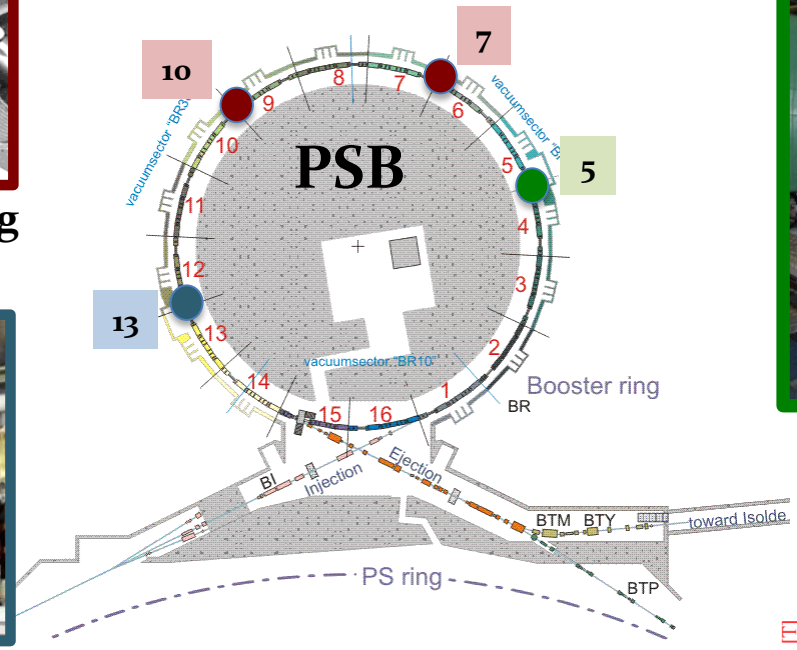
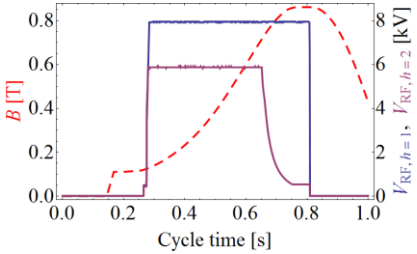


Longitudinal blow-up



→ 4 rings with 3 cavities

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

Overview - PSB

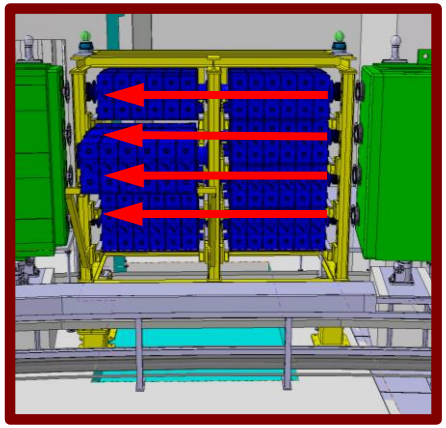
Limitation	Mitigation
• **Compatibility** of RF with **Linac4 intensity and 2 GeV**	• Replace all ferrite loaded cavities by **Finemet cavities**
• **Reliability** and **long-term maintainability**	• **Finemet cavities** • Replacement of beam controls by **fully digital low-level RF (LLRF) system**

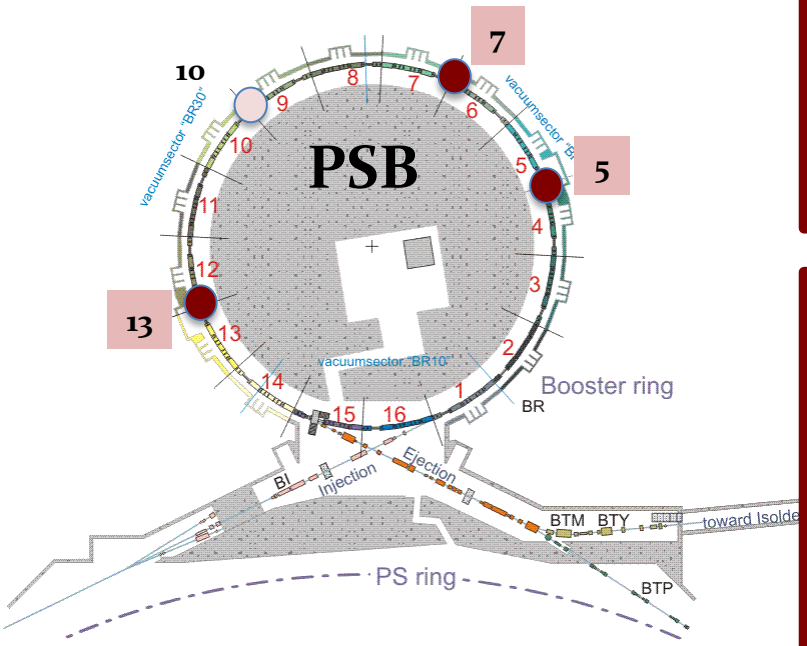
• New operation modes:
  • **Injection painting**
  • **Controlled blow-up** for transfer to PS
	• **Digital beam control**
	• Dynamic **redistribution of RF voltage** available at different harmonics simultaneously

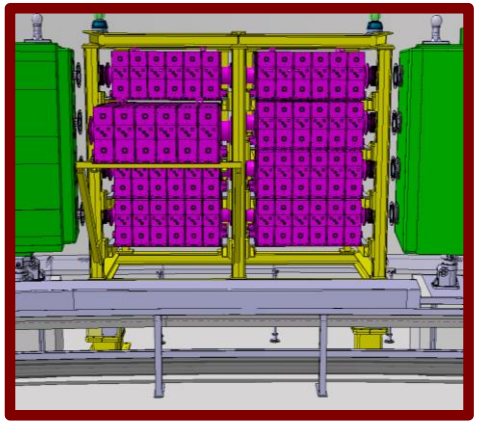
→ **Entirety of PS Booster RF system affected by upgrades:**

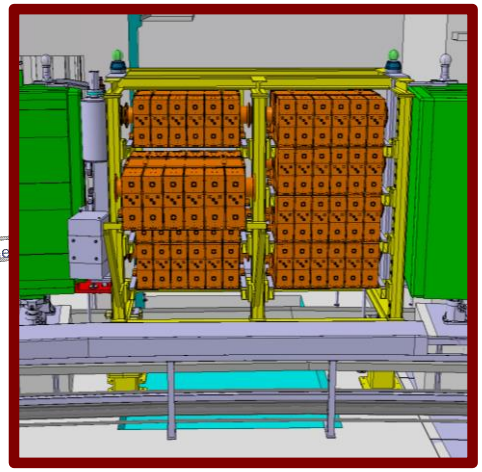
- **Beam control system exchanged by digital LLRF during LS1**
- **Replacement of all main RF systems**

RF systems in the PS Booster after LS2





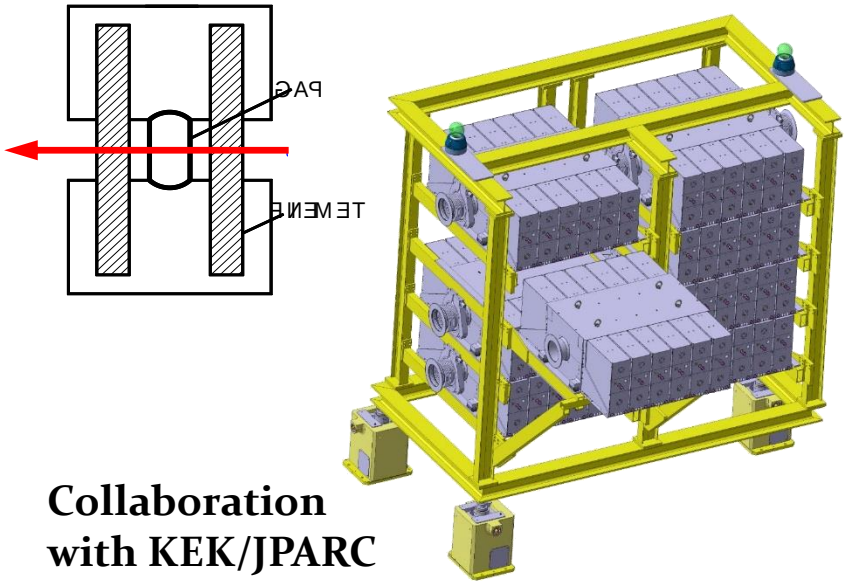




→ 3 straight sections equipped with Finemet cavities

→ 1 Straight section in standby

RF systems in the PS Booster after LS2



Collaboration with KEK/JPARC

PSB-type Finemet cell	
Frequency range	0.6 - 18 MHz
RF power	~3 kW
Peak RF voltage	700 V (< 4 MHz)
RF system arrangement	
Cells per cavity	6
Cavities per ring	6
Total peak voltage	~24 kV

- 'One cavity fits it all' concept
  - → All six cavities per ring identical
  - → Perform as $h = 1$, $h = 2$ or blow-up cavity together
- Designed to operate for intensity with Linac4: $2 \cdot 10^{13}$ p/ring
- Reliability and availability
  - → No need for high voltage nor tuning system
  - → Full voltage achievable with defective gaps

Finemet cavity prototype tests in ring 4

→ **Extensive study program**

- 2012 prototype 5 cells
- 2014 prototype 10 cells

1. **Take over functionality from all ferrite cavities**
2. **Reliability demonstrated during 6 weeks run**

→ **High-power part fully validated**

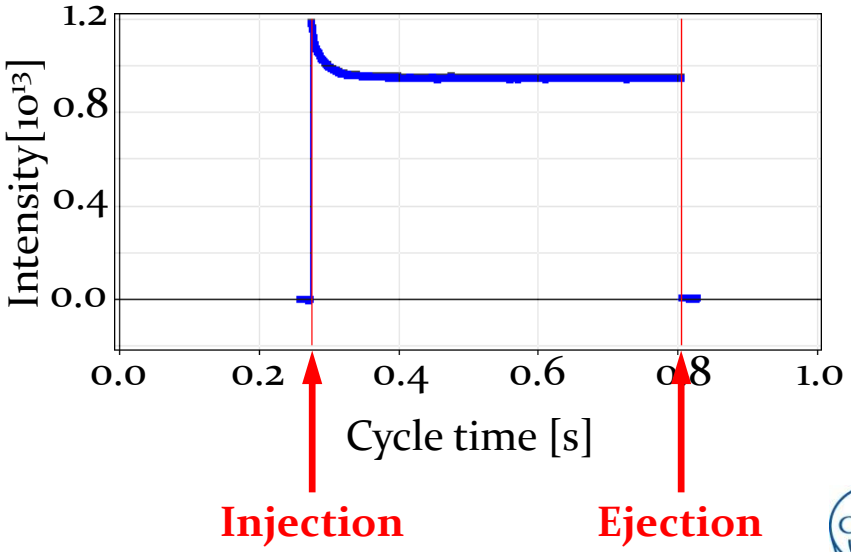
→ **R2E aspects of amplifiers under control**

→ **MD time only for LLRF developments**

→ **Decision to replace all RF systems by Finemet cavities**

10-cell Finemet prototype in ring 4

Intensity with Finemet cavity on $h = 1$



Beam control for Finemet tests

Controls
Local Control Room
Ring

Controls middleware & application programs

Frequency program, radial loop

Beam phase loop (*h*=1,2)
Extraction synchro loop
Injection synchro loop

C02, C04, C16 drive
C04 phase loop, C16 beam blowup, RF trains

Finemet amplitude/phase loops

RTM | MEN A20 | CTRV | DSP | FPGAs | ADC (FMC) | ADC (FMC) | DSPA
RTM | CTRV | DSP | FPGAs | ADC (FMC) | MDDS (FMC) | DSPB
RTM | CTRV | DSP | FPGAs | ADC (FMC) | DAC (FMC) | DSPC
RTM | CTRV | DSP | FPGAs | ADC (FMC) | DAC (FMC) | DSPD
RTM | CTRV | DSP | FPGAs | ADC (FMC) | DAC (FMC) | DSPE

VXS bus
VME64x bus

VXS SWITCH

B_{UP}
B_{DOWN}

TPU 1,2,3,4
Σ & Δ

Extraction reference

Phase PU

C02, C04, C16 Ferrite HLRF

(1:16)

Σ (16:1)

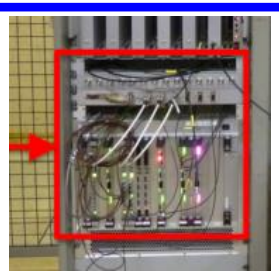
CCI

Finemet HLRF

Timing pulses
VME64x J0/P0 (VXS)
VME64x J2/P2

Operational beam control (since LS1)

Finemet cavity part



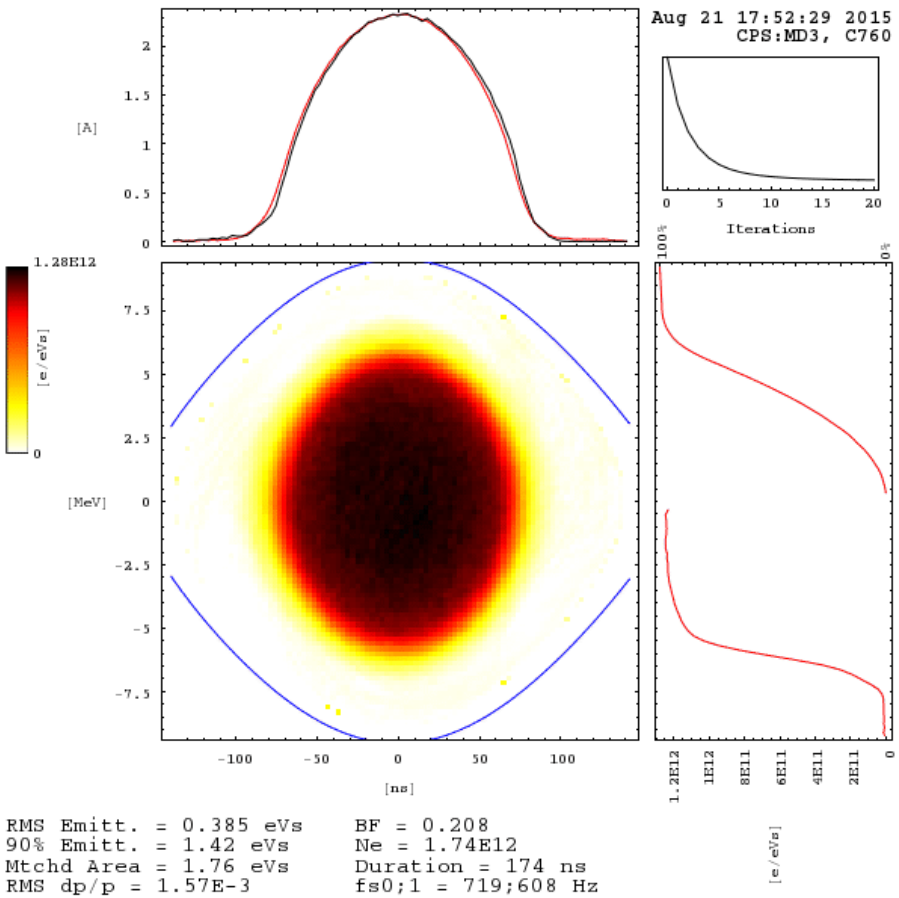
→ **Two extra DSPs for Finemet control:**

→ **Servo-loops at h = 1, 2, 3 and 5 simultaneously**

→ **Operational system will be more compact**

Controlled longitudinal emittance blow-up

- **Reduce space charge at PS flat-bottom**
  - → **Large longitudinal emittance of 2.8 eVs needed for LIU**



→ **Extensive beam tests of controlled blow-up in PSB**

→ **Maximum emittance of only ε_l = 1.8 eVs achieved so far**

→ **Close to textbook water-bag distribution: constant phase space density**

→ **Studies to continue in 2016 to produce up to 2.8 eVs**

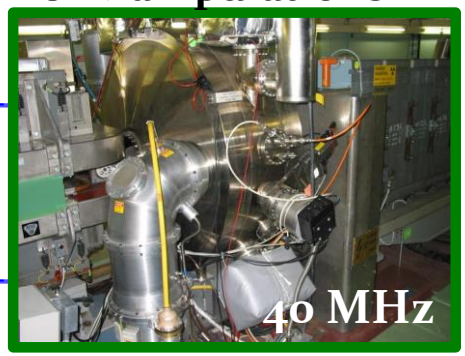
→ **Critical for PS space charge**

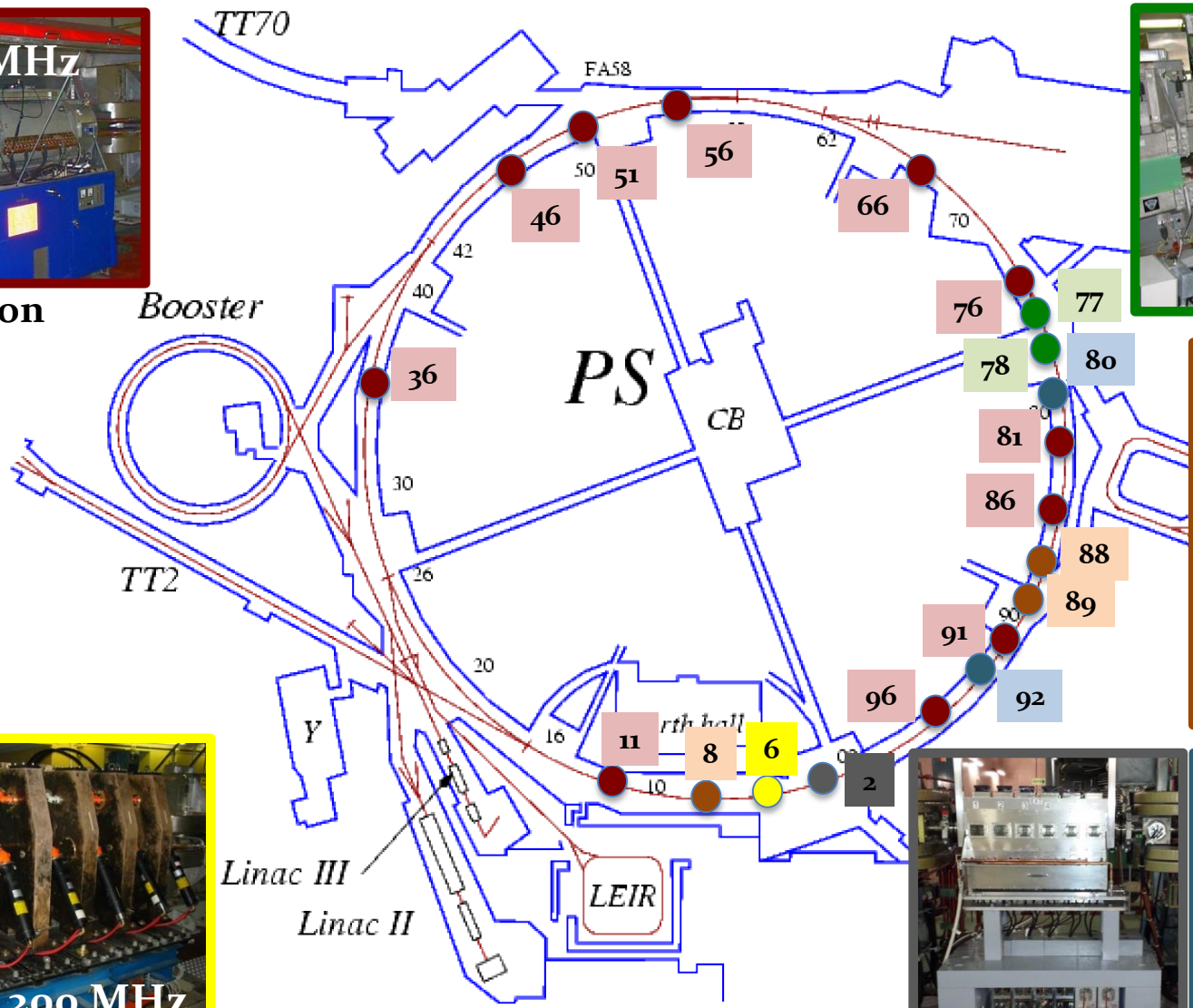
PS

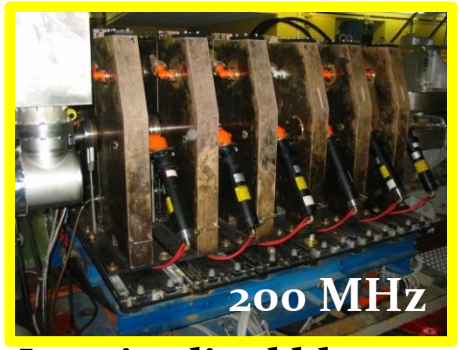
RF systems in the PS

Acceleration

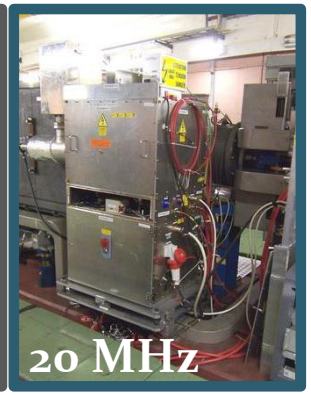
RF Manipulations



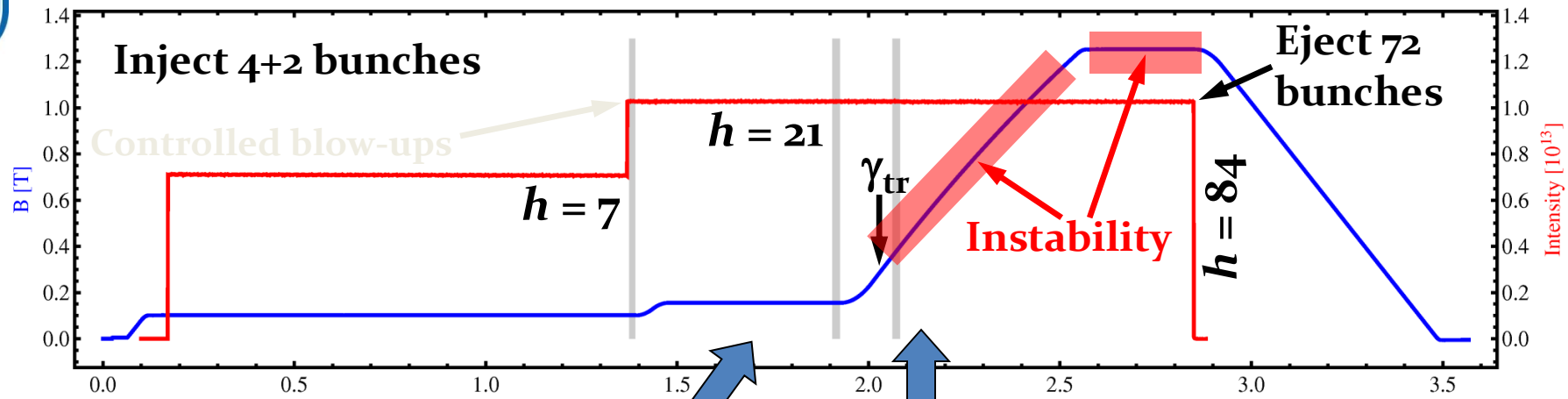




Longitudinal blow-up



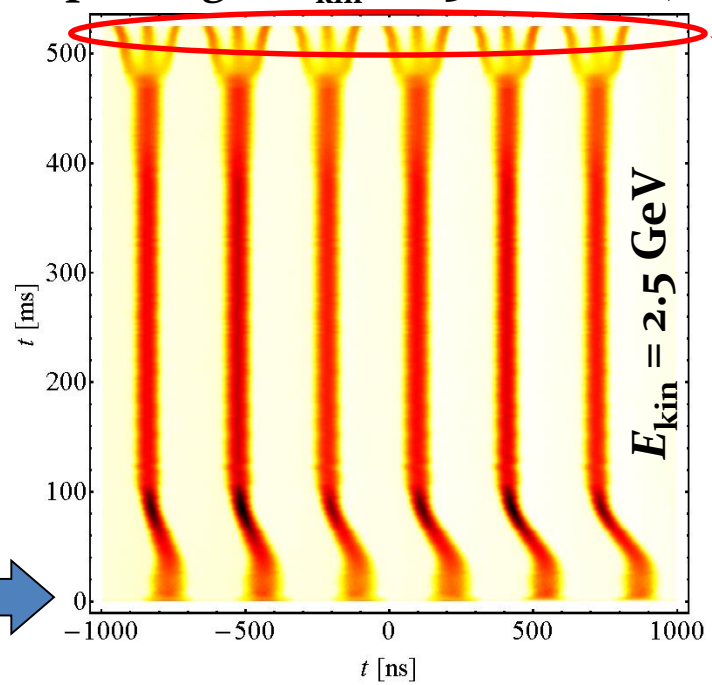
The LHC25ns cycle in the PS



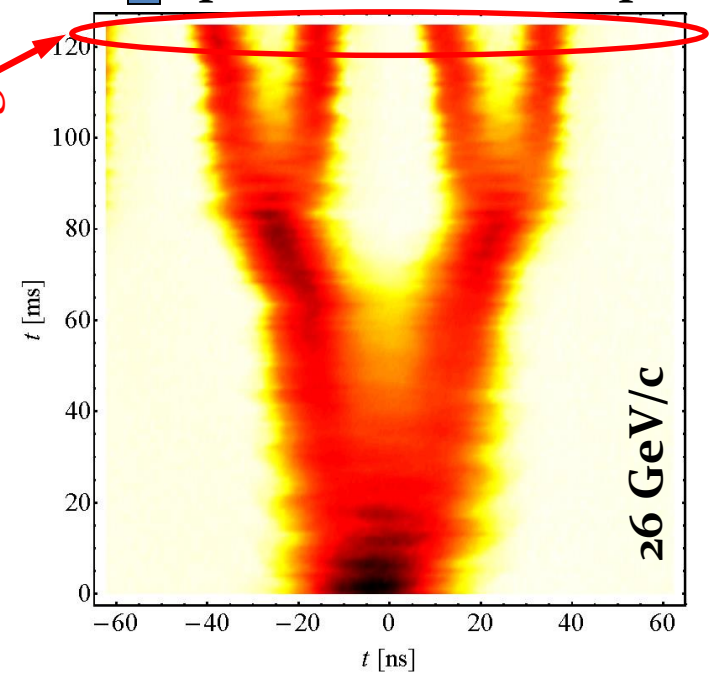
Triple splitting at E_{kin} = 2.5 GeV

Split in four at flat top energy

2nd injection



Transient beam-loading



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

Overview - PS

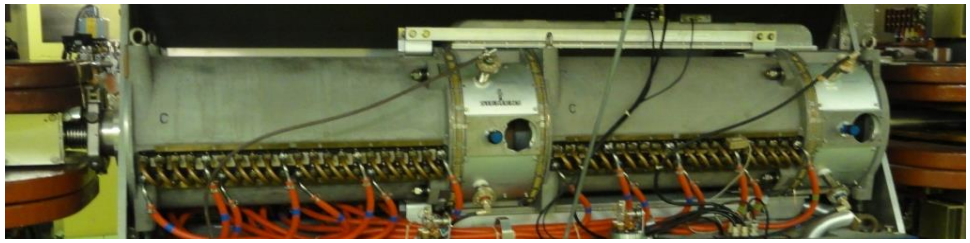
Limitation	Mitigation
• Longitudinal **beam stability** • **Coupled-bunch** oscillations	1. **Reduced impedances of all RF cavities** → Improved **wide-band feedback 10 MHz** → Replaced **1-turn delay feedbacks 10 MHz** → New **1-turn delay feedbacks for 20, 40 and 80 MHz** cavities 2. **Dedicated coupled-bunch feedback** → **Wide-band Finemet** longitudinal **kicker** 3. **Increased longitudinal emittance** → PS-SPS transfer with **both 40 MHz cav.**
• **Bunch-to-bunch equalization**	→ 1-turn delay feedbacks
• **Reliability** and **long-term maintainability**	→ Replace **anode power supplies for 40 MHz and 80 MHz RF systems** → Upgrade to a **digital beam control**
• **Availability of 80 MHz cavities** for protons and ions	→ New fast **ferrite tuners**

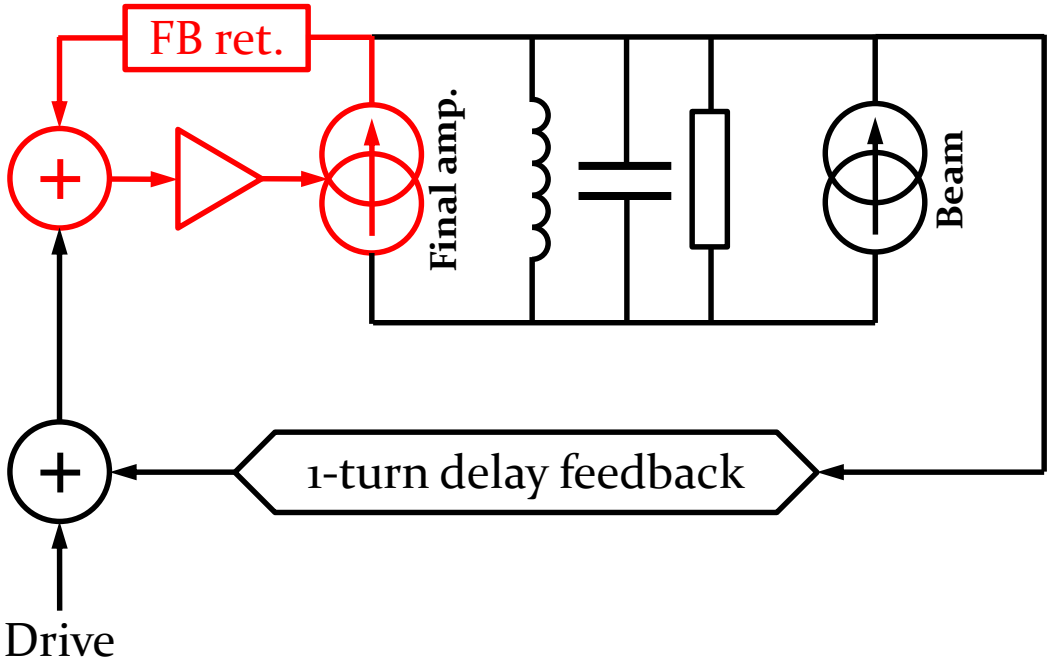
- **Most PS RF systems affected by upgrades:**

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

Main 10 MHz RF system

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

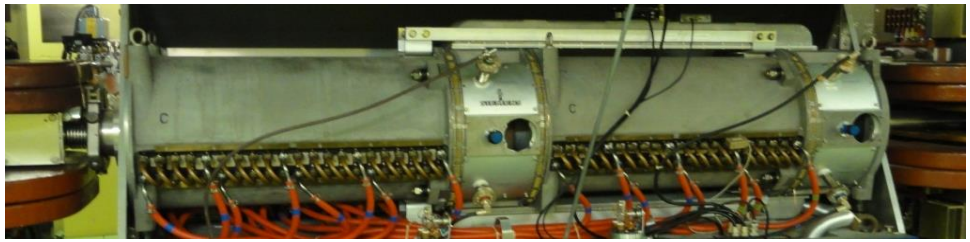


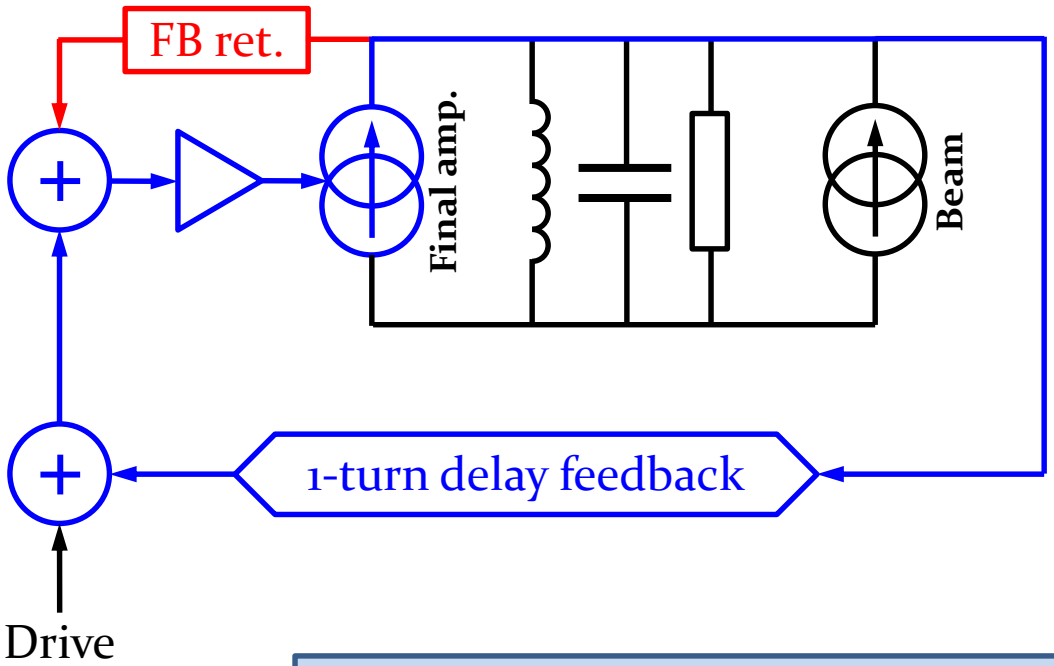


- Fast wide-band feedback around amplifier (internal)
  → Gain limited by delay

Main 10 MHz RF system

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





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

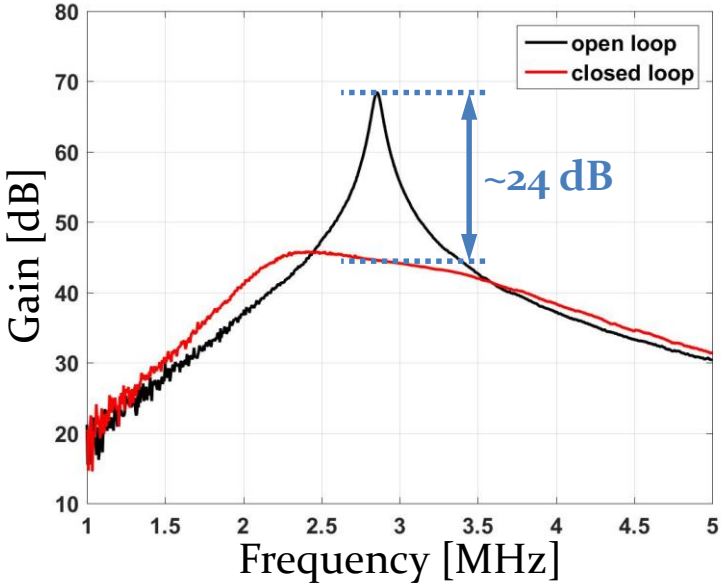
- 1-turn delay feedback
  → High gain at n × f_{rev}

1. Maximize loop gain of direct wideband feedback
2. Add 1-turn delay feedback

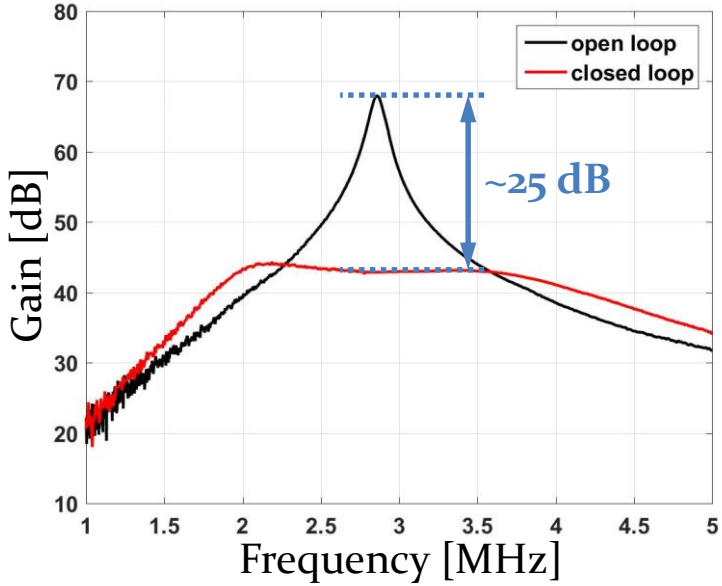
Wide-band feedback of 10 MHz cavities

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

Standard amplifier: 3 MHz



Upgraded prototype: 3 MHz



- **Prototype amplifier**
  - → **Impedance reduction by factor of ~2 (at 10 MHz → h = 21)**
  - → **First cavity being upgraded during YETS2015/16**
  - → **Ready for beam tests on one cavity in 2016**
- **Full implementation during (E)YETS and LS2**

Wide-band feedback of 10 MHz cavities

- **Power amplifier upgrade: New working point and grid resonator**
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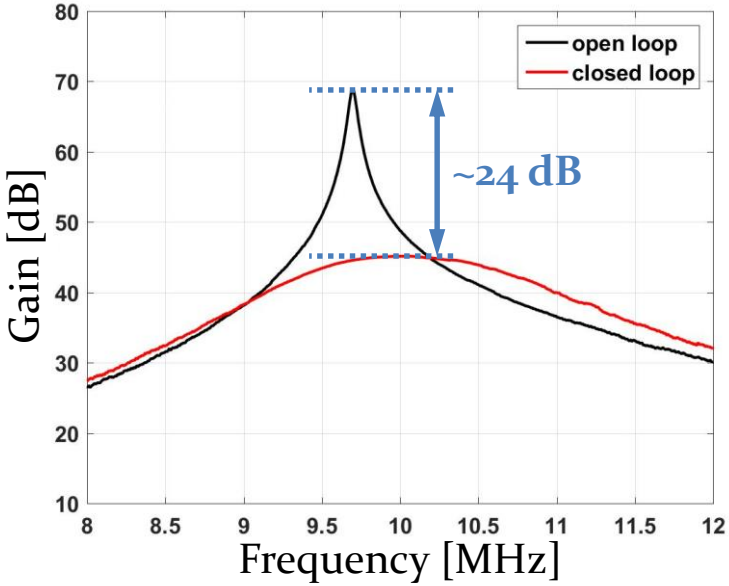
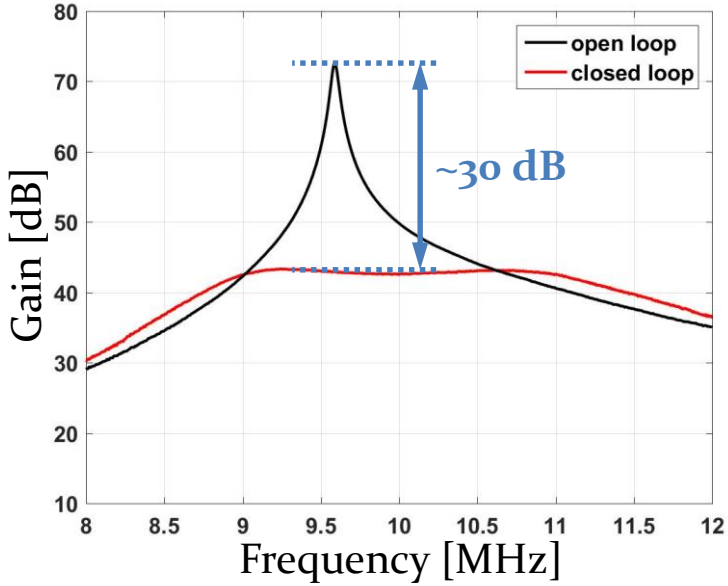
Standard amplifier: 10 MHz



Upgraded prototype: 10 MHz



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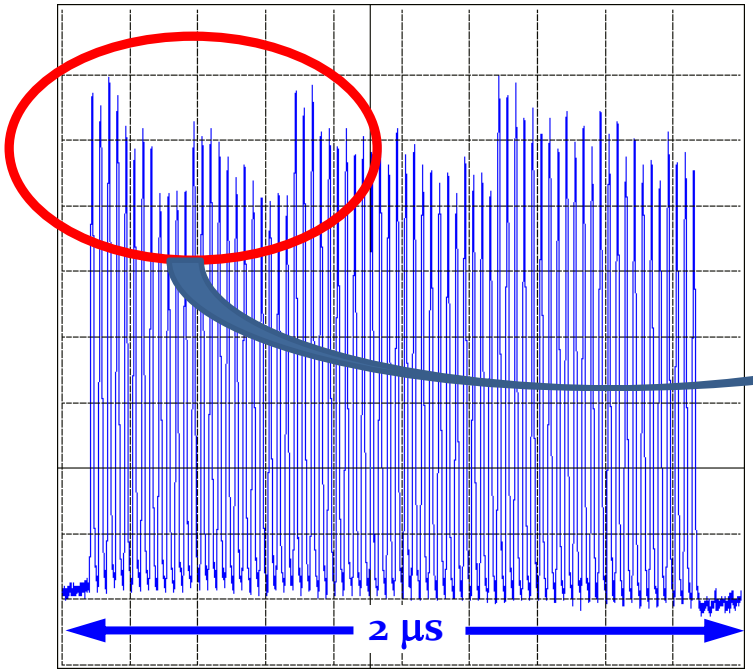
1-turn delay feedbacks

- **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



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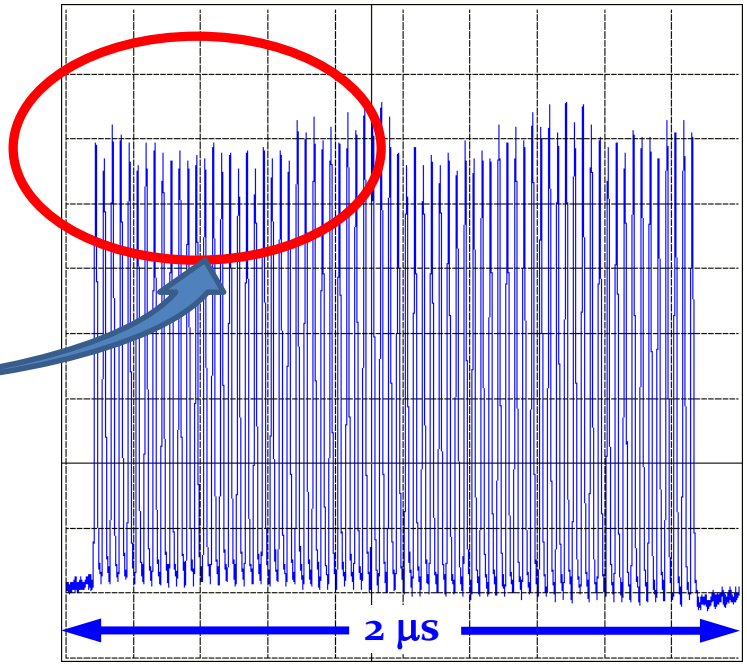
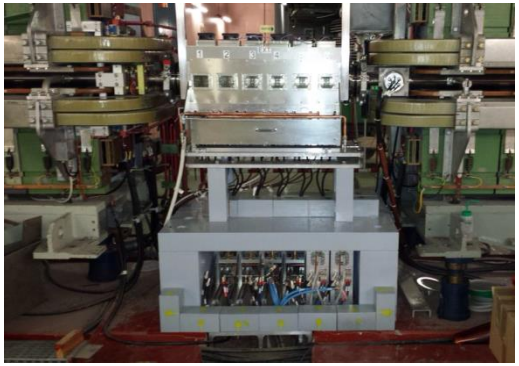


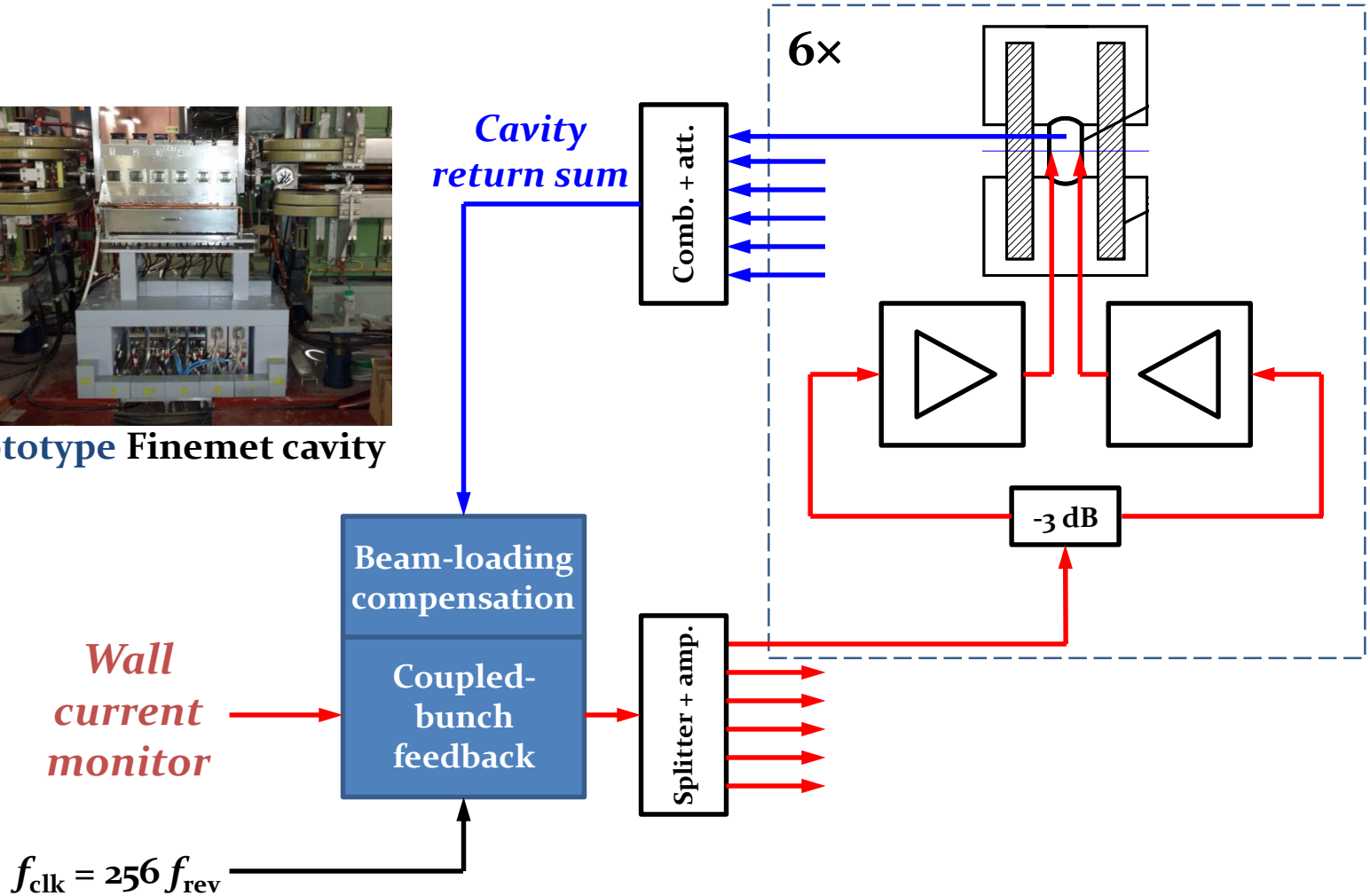
→ **Full commissioning of digital 1-turn delay feedback for all 11 main accelerating cavities in 2015**

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

Coupled-bunch feedback



Prototype Finemet cavity



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

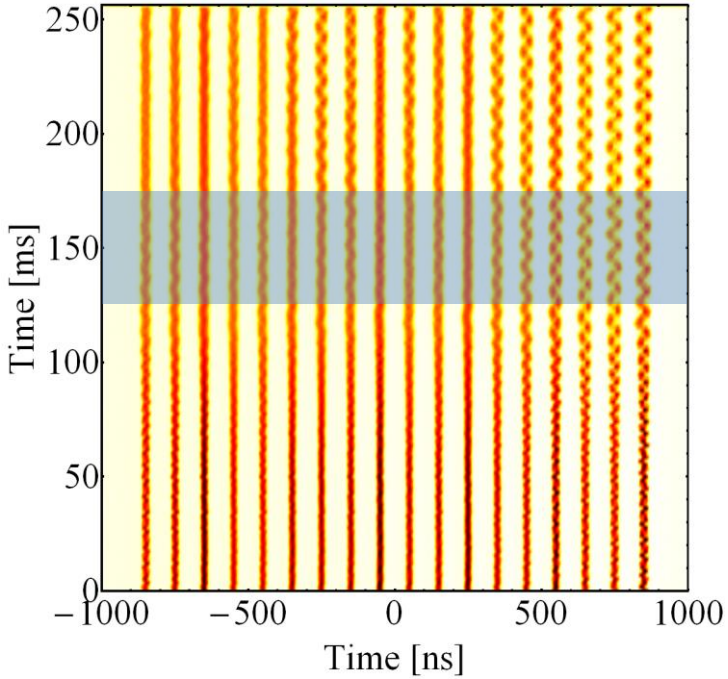
→ Frequency domain approach

→ Suppress synchrotron frequency side-bands at $n \cdot f_{rev}$

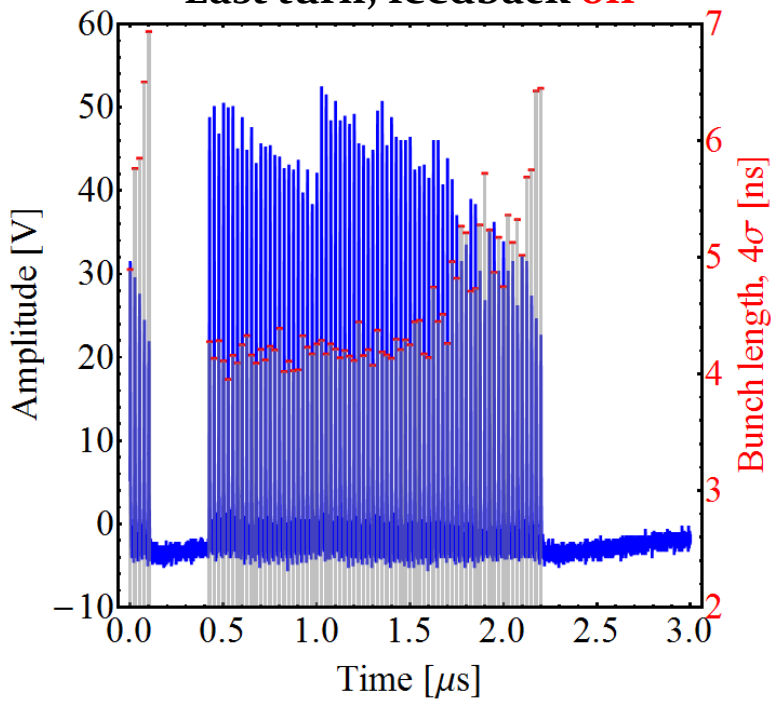
Damping of instability at flat-top

- **Coupled-bunch instability with wide mode spectrum**

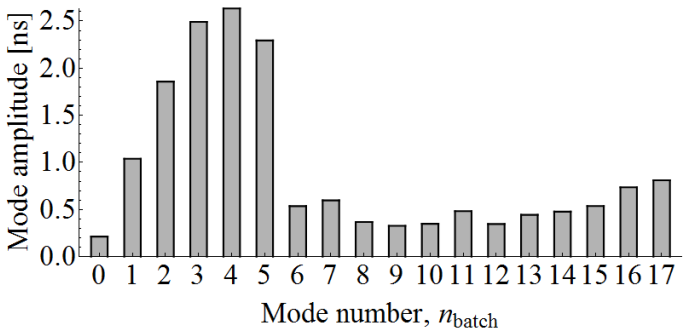
Bunches on flat-top, feedback off



Last turn, feedback off



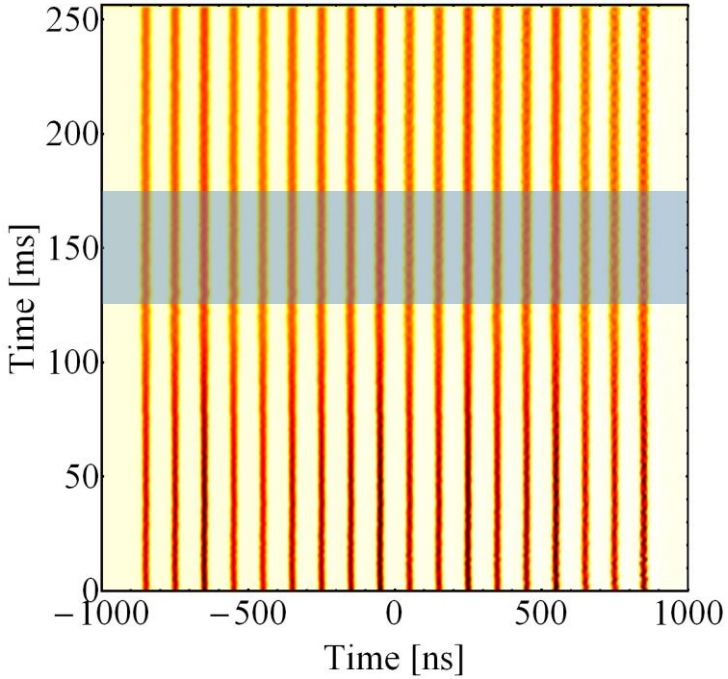
Mode spectrum, feedback off



Damping of all 20 modes on the flat-top

- **Coupled-bunch instability with many modes**

Bunches on flat-top, feedback on



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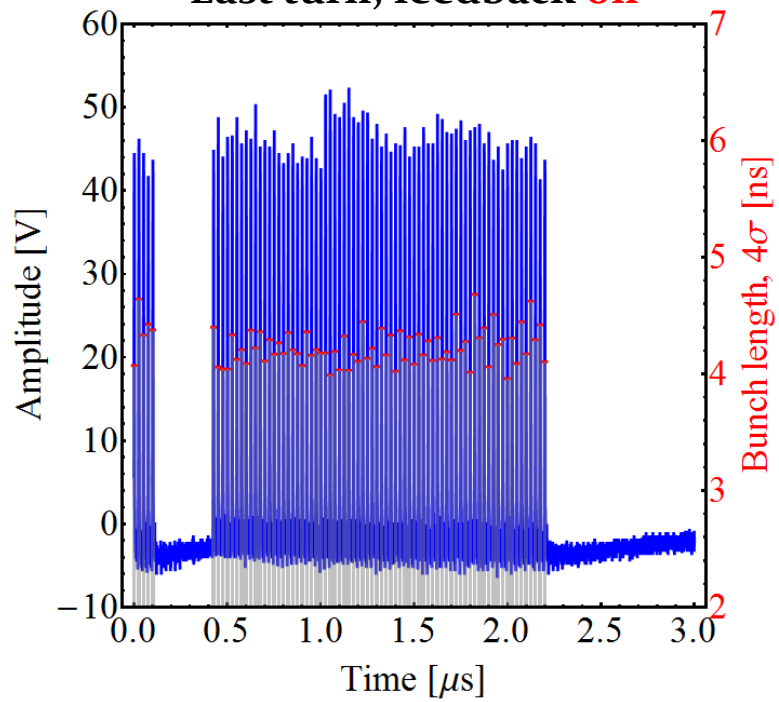

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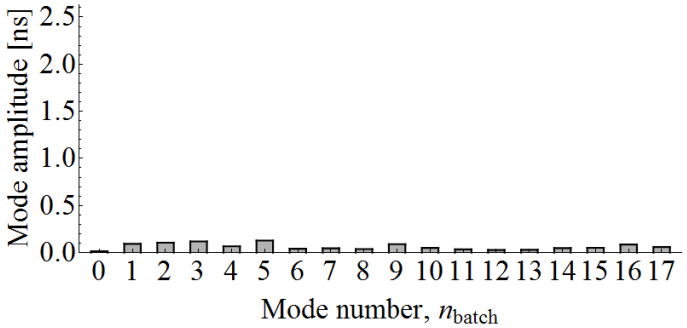


→ **Reached $1.7 \cdot 10^{11}$ ppb with good longitudinal parameters**

→ **Full evaluation of prototype with beam during 2016 run**

→ **Critical to reach LIU baseline**

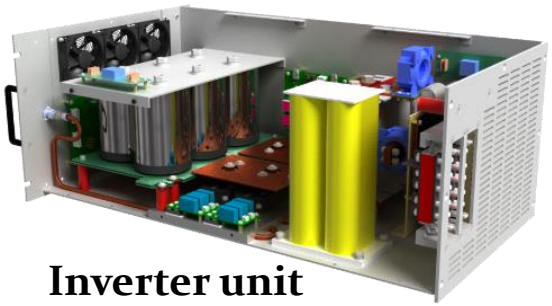
Reliability: 40 MHz and 80 MHz cavities

1. Both 40 MHz cav. to transfer larger longitudinal emittance to SPS

→ New anode power supplies

- 5 × 25 kV, 8 A
- CERN standard design
- Modular

→ Complete installation during LS2



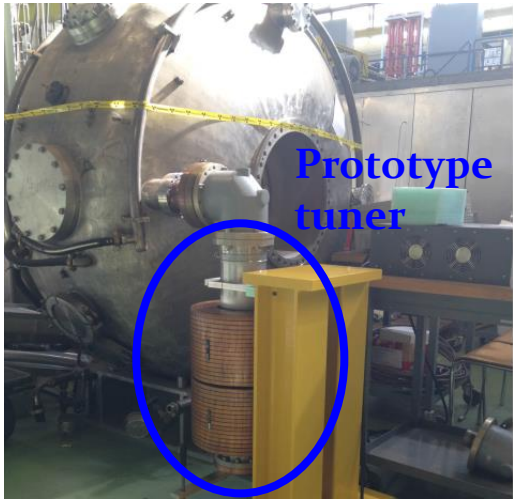
Inverter unit

2. Operate 80 MHz cavities for protons and ions simultaneously

→ Fast ferrite tuner to switch cavity between p^+ and Pb^{54+} frequencies

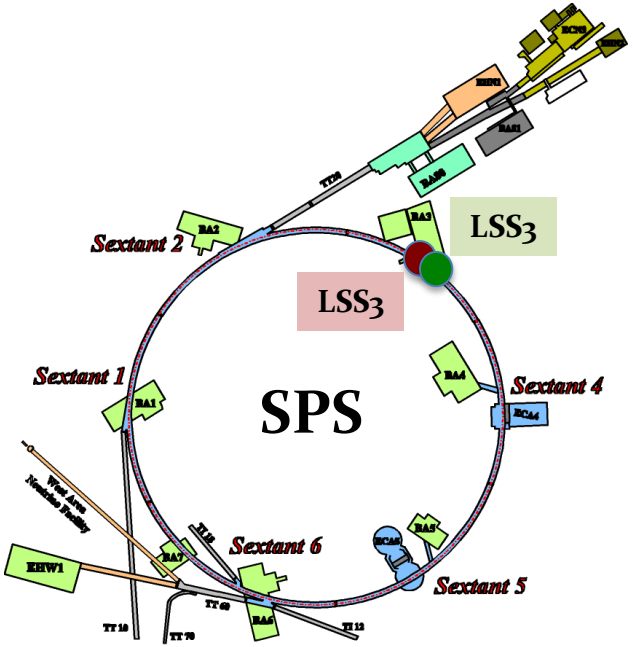
- Inductively loaded coaxial line coupled to cavity with DC bias
- Prototype on test cavity
- 2017: validation on cavity in ring

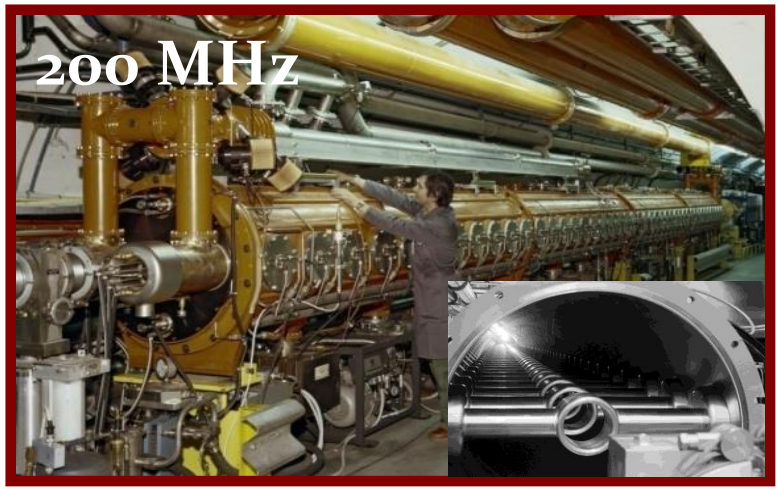
→ Complete installation during LS2



SPS

RF systems in the SPS



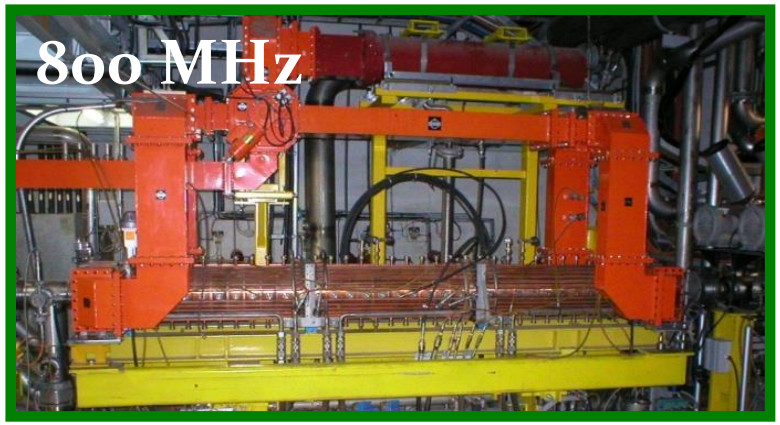


Acceleration and controlled blow-up

→ 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

Limitation	Mitigation
• **RF power during acceleration** for 1.3 10^{11} ppb → ~2.4 10^{11} ppb • Longitudinal **bucket area** • **Insufficient RF voltage at transfer** to LHC at ~2.3 10^{11} ppb	1. **Rearrangement of main 200 MHz cavities** • **6 shorter travelling wave cavities** 2. **Installation of 2 additional RF power plants** • **2 × 1.6 MW at cavity input**
• Longitudinal **beam stability**	1. **Impedance identification and reduction** → **Shielding of vacuum flanges** → **HOM dampers for 200 MHz RF cavities** 2. **LLRF upgrade** → Replace **cavity controllers 200 MHz** → New **cavity controllers 800 MHz** → **Improved relative phase control**
• Ion slip stacking not possible with present beam control	→ **Beam control upgrade**

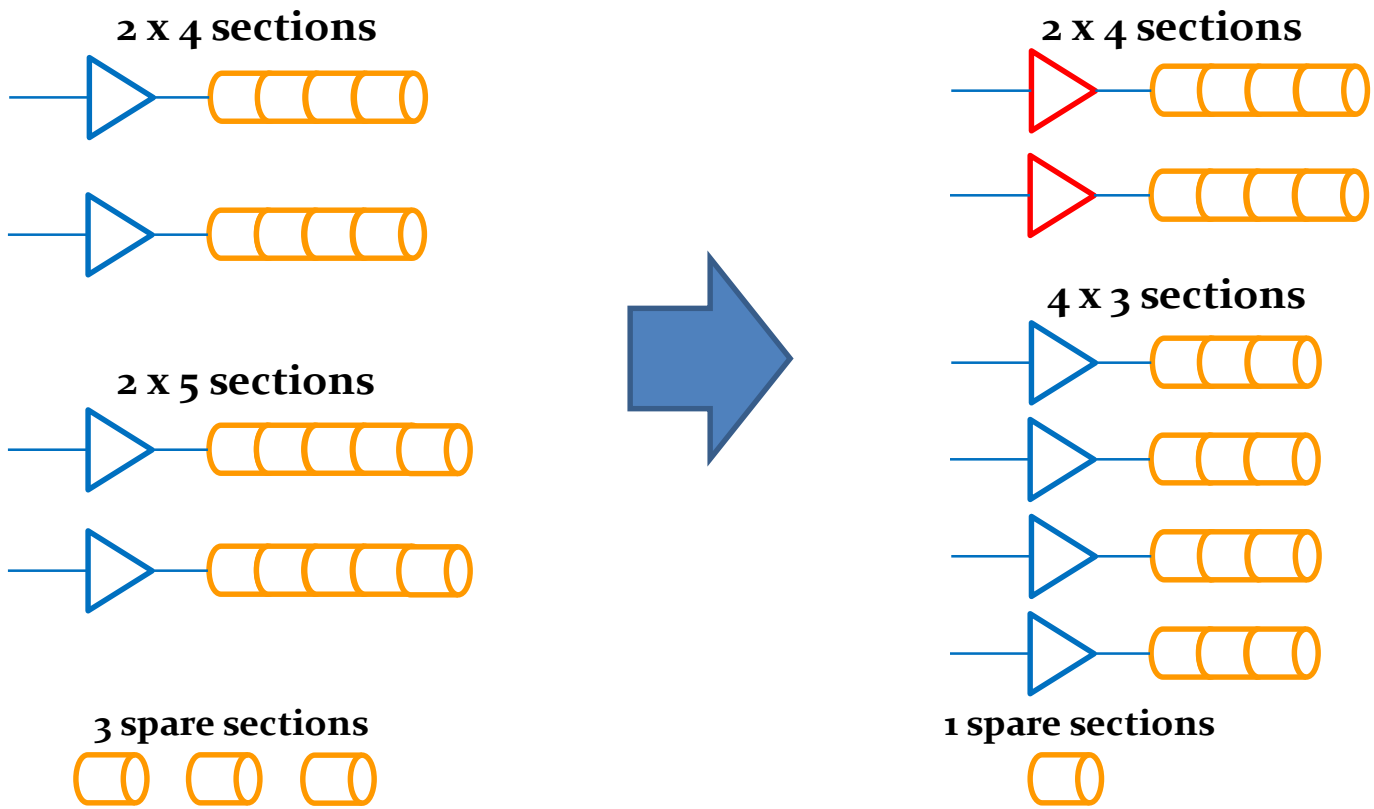
- **Major upgrade of main 200 MHz RF system:**

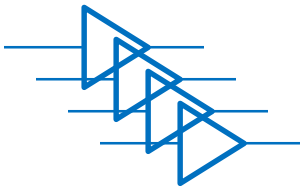
  → **More RF voltage with higher intensity for LHC-type beams**

Rearrangement of cavity sections

Present arrangement: 4 cavities

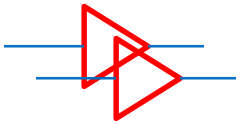
After LS2: 6 cavities





Existing amplifiers (after upgrades):

- 0.7 MW continuous
- 1.05 MW pulsed



New amplifiers

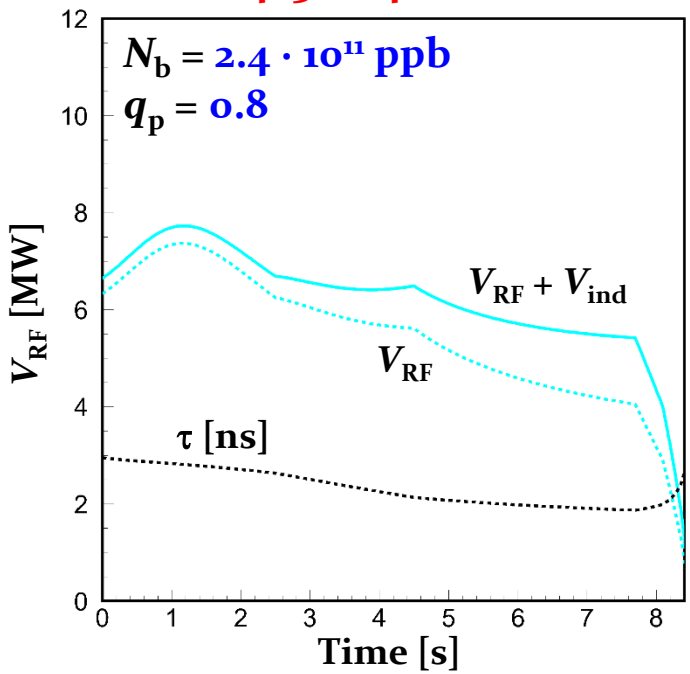
- 1.6 MW pulsed

→ New building

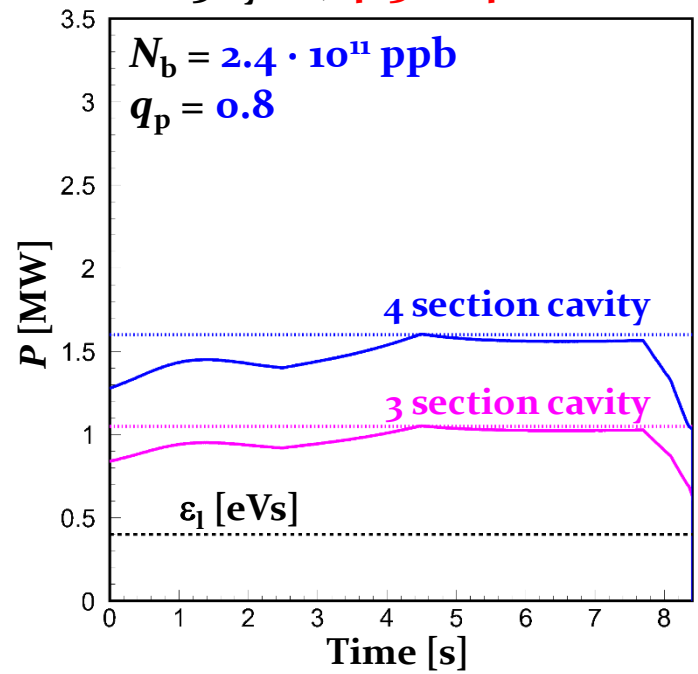
Maximum intensity during acceleration

- RF power related intensity limitation during acceleration
- Assuming constant longitudinal emittance, ε_l = 0.4 eVs

Total RF voltage, 2015 cycle
4×3+2×4 cavities



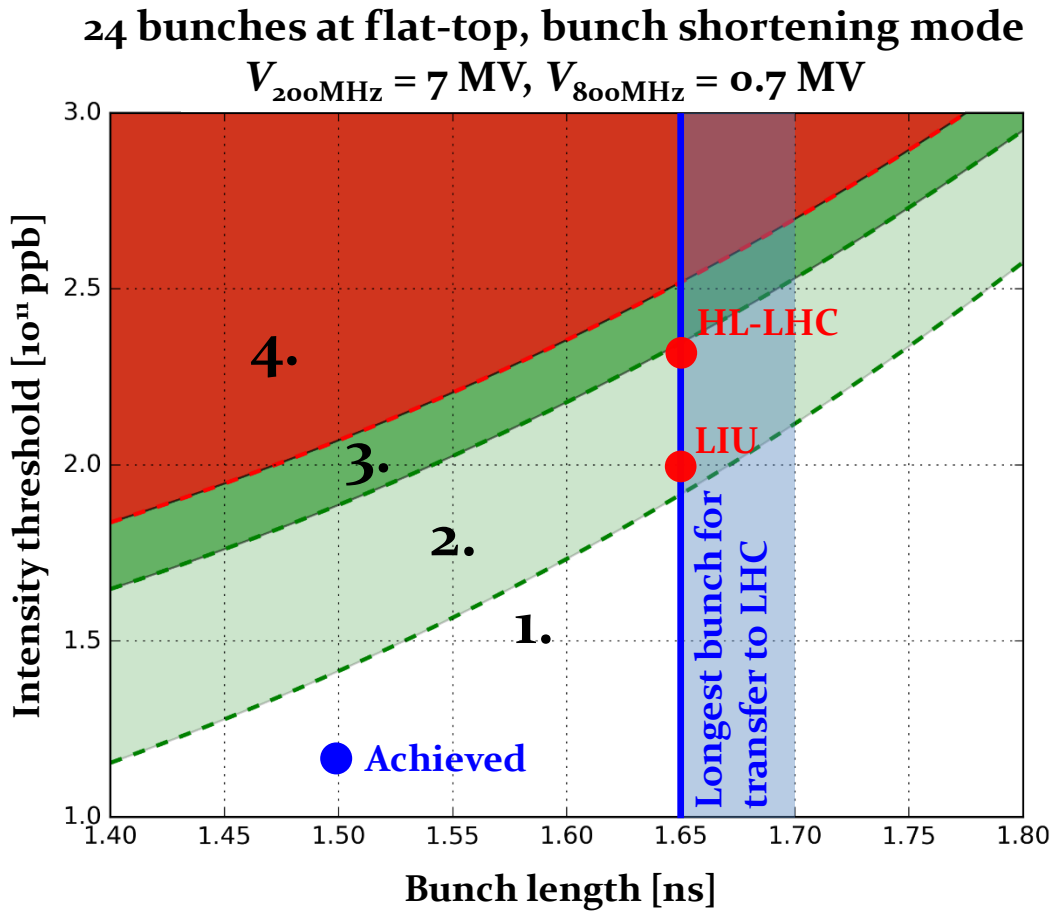
RF power and long. emittance
2015 cycle, 4×3+2×4 cavities



→ Acceleration of 2.4 · 10¹¹ ppb with 2015 cycle at power limit after LS2

Bunch length and intensity at extraction

- **Bunches at extraction must be stable and fit into LHC buckets**



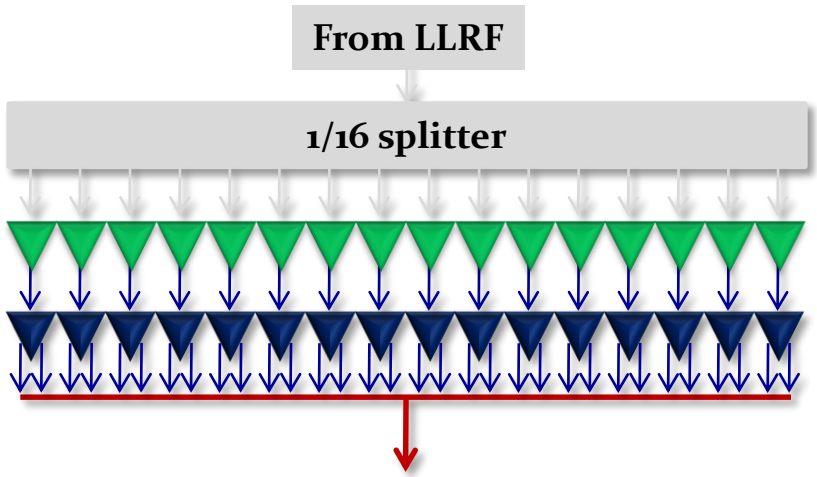
1. **No impedance reduction**
2. **Impedance reduction**
   - **QF flanges**
   - **Main cavity higher order mode at 630 MHz divided by 3**
3. **Additional reduction of injection kicker (MKP) by 2**
4. **Not accessible**

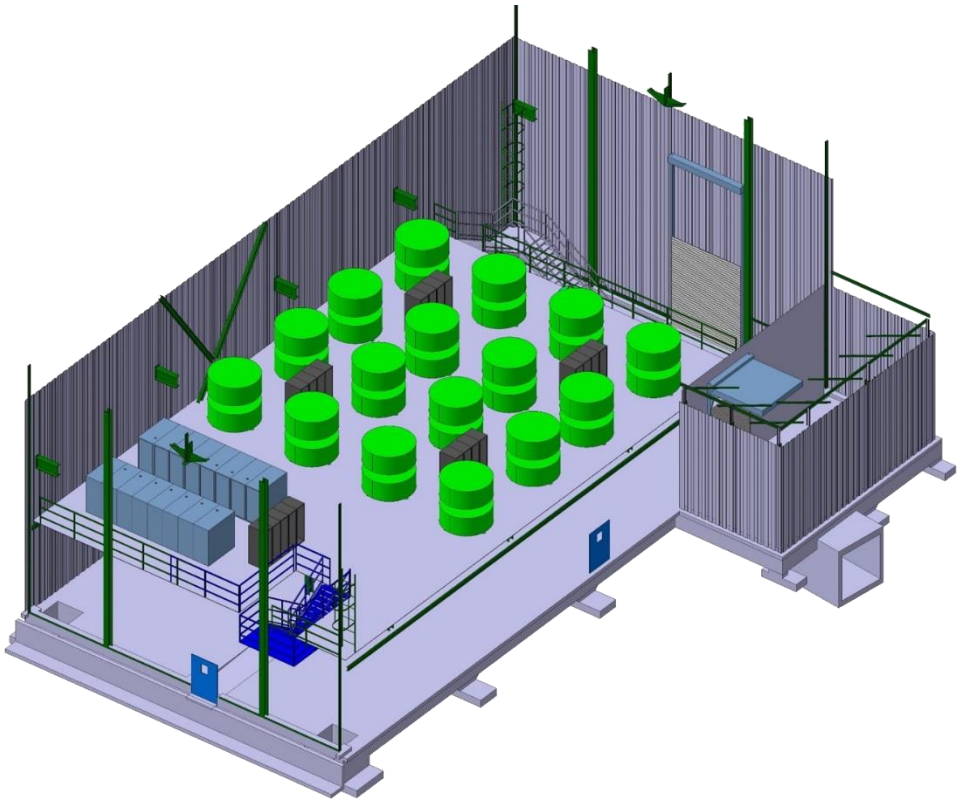
→ **Impedance reduction required**

→ **Next: Tracking studies with full 72 bunch batches (BLonD code)**

RF power plant (2 × 1.6 MW)

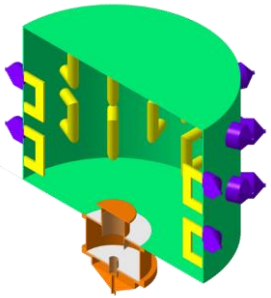
- Two additional RF cavities must be powered





1.6 MW at cavity input

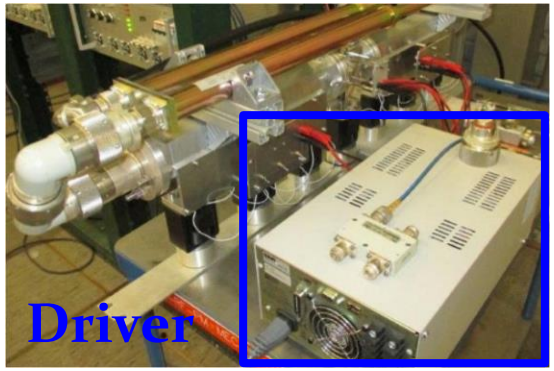
32 → 1 VHPCC
Very High Power Cavity Combiner



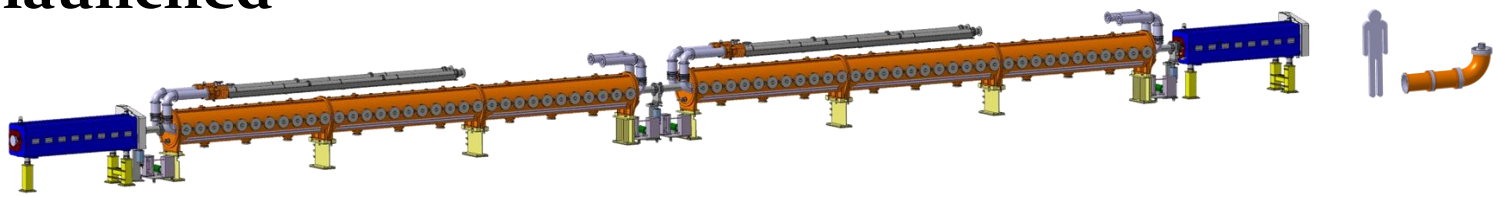
→ Solid state technology chosen, contract awarded
→ 16 towers with 2×80 kW for each amplifier
→ Ready after LS2

RF power upgrade

- New building BAF3 completed, services being installed, cooling defined and funded
- Procurement strategy for power couplers, coaxial lines and combiners defined
- Prototyping of new driver amplifiers completed



- LSS3 layout defined and space reservation request issued
- Integration studies for coaxial transmission lines launched

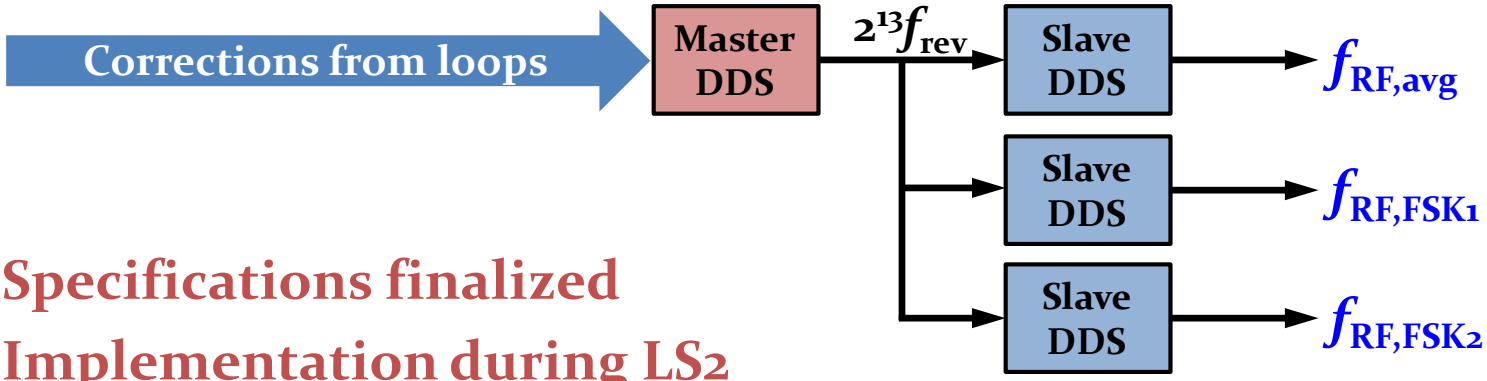


200 MHz cavity controller and beam control

1. New cavity controller for all 6 cavities after LS2
   - Based on cavity controller for 800 MHz
   - Polar loop → Linearize amplifier chain
   - 1-turn delay feedback
   - Feedforward

   ↘ ↗ Impedance reduction

2. New beam control
   - Beam phase, radial and synchronization loops → Replace obsolete hardware to make it PPM compatible
   - New master oscillator to generate multiple frequencies synchronously: $f_{RF,avg}$ and $f_{RF,FSK}$ → Slip stacking with ions

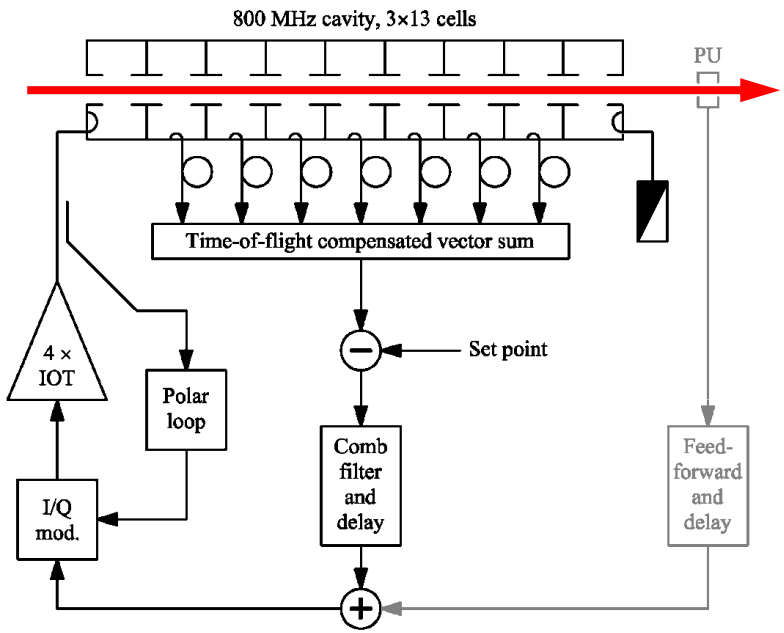


→ Specifications finalized

→ Implementation during LS2

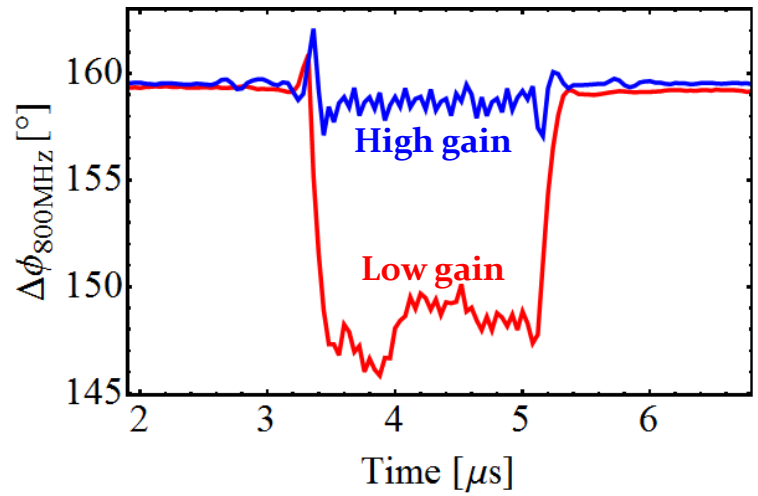
800 MHz cavity controller

- **2014: First beam tests with 800 MHz 1-turn delay feedback**
- **2015: Operational on one cavity; 2nd cavity during after restart 2016**



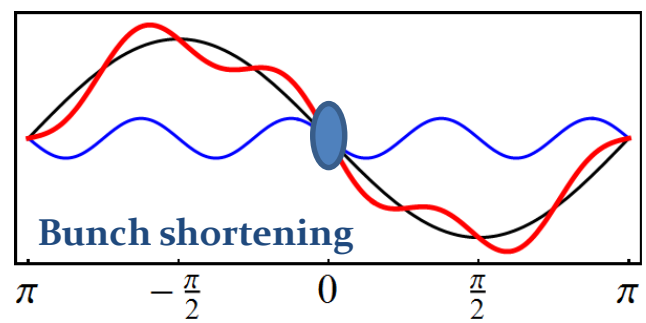
Benefit of 1-turn delay feedback

Passage of 72b, 25 ns trough 800MHz



→ **Reduces beam induced phase modulation more than an order of magnitude with linear voltage gain ~20**

→ **Critical to keep RF phase correct in bunch shortening mode for all bunches → Stability**



Summary

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

- Challenges for LHC-type beams
  - PSB: Achieve large longitudinal emittance for PS space charge
  - PS: Longitudinal stability to reach ~$2.8 \cdot 10^{11}$ ppb
  - SPS: RF power and longitudinal stability to extract $2.3 \cdot 10^{11}$ ppb
    Slip stacking with ions

- Key upgrades
  - PSB: Cavity upgrades → new Finemet cavities
  - PS: Power upgrades and feedbacks
  - SPS: 200 MHz power upgrade and LLRF upgrade

→ Major part of RF upgrades: LS2

→ Lots of new hardware to commission afterwards

LHC Injectors Upgrade

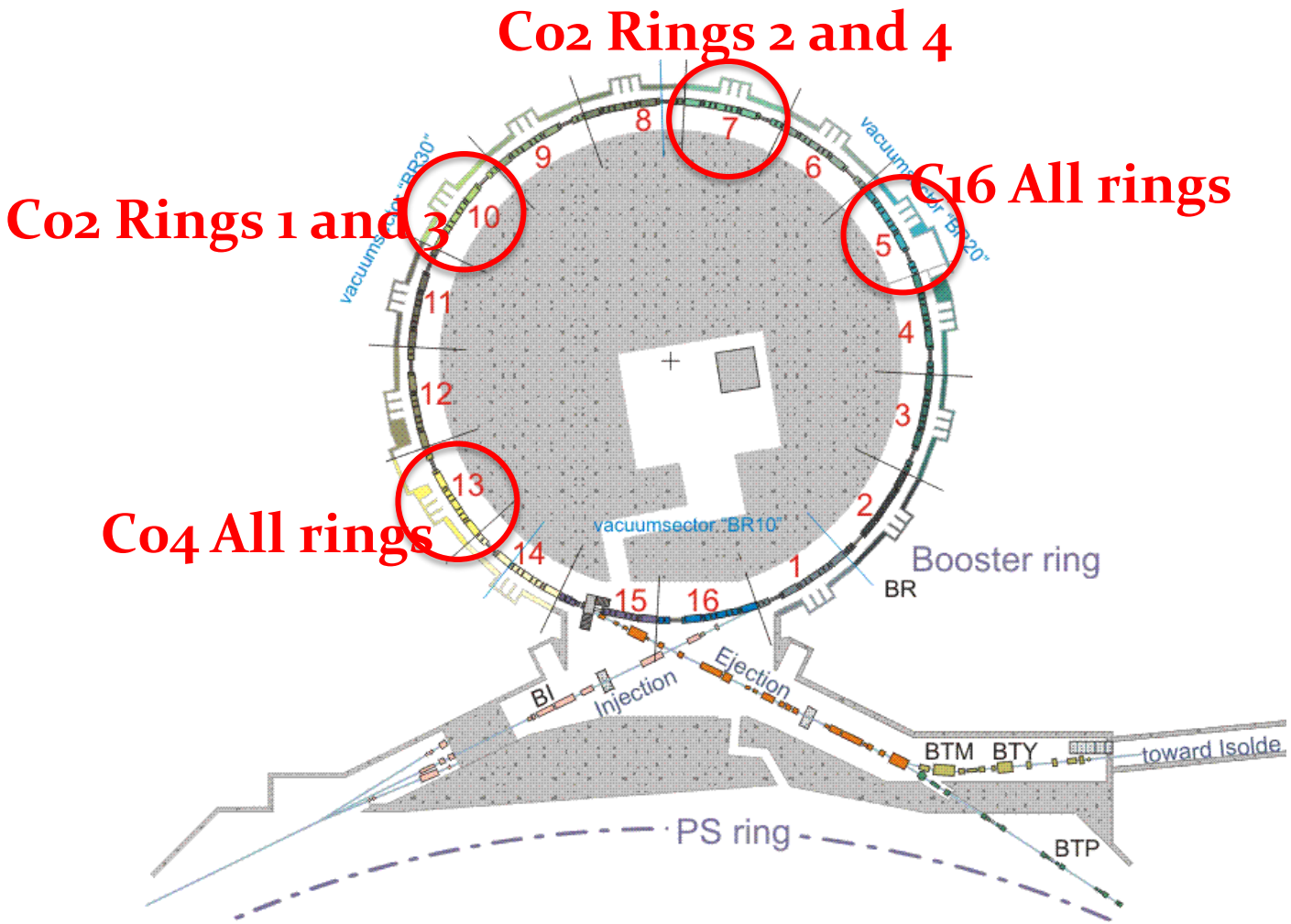
THANK YOU FOR YOUR ATTENTION!

Spare slides

PS Booster

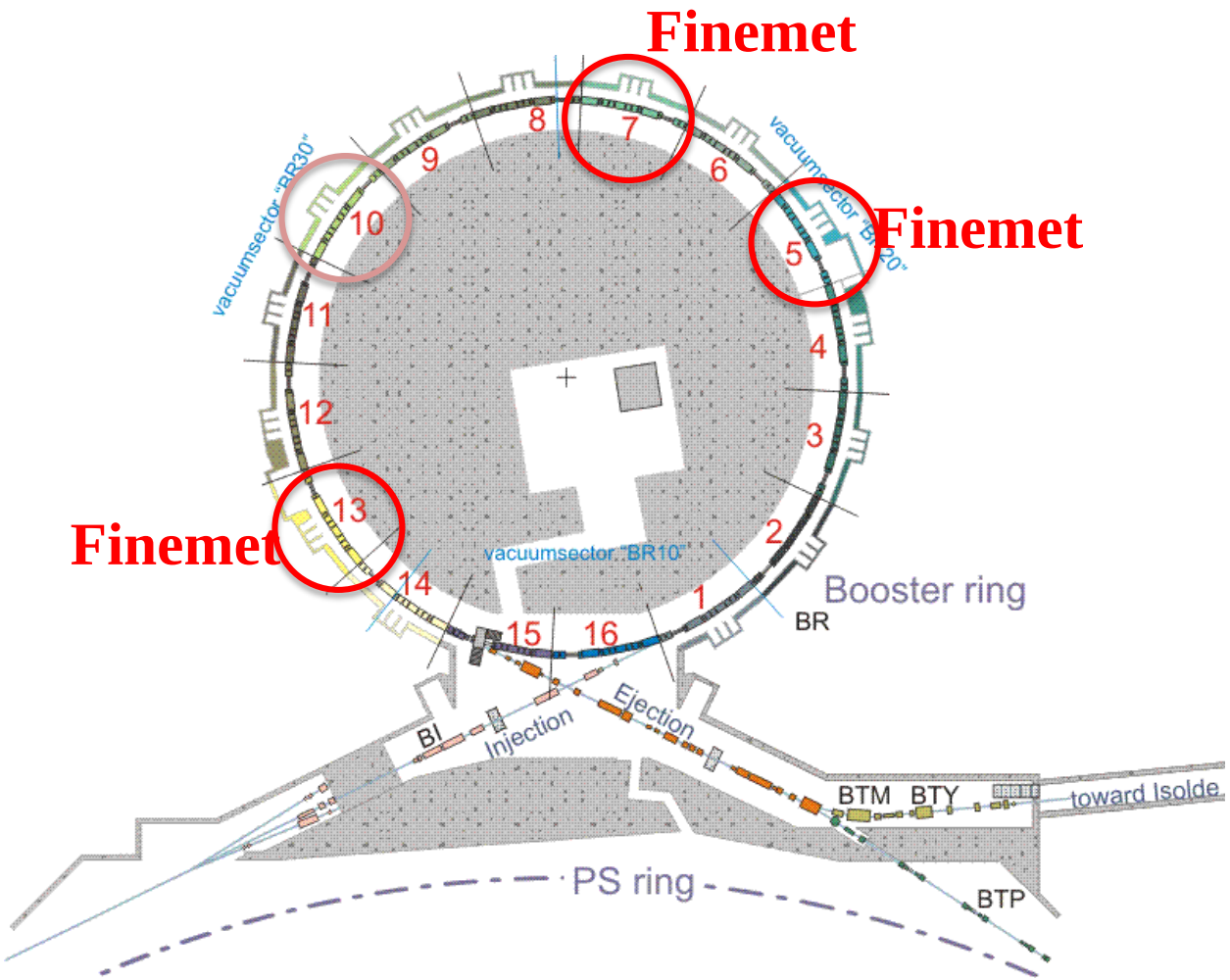
Present RF systems in the PSB

Four sections presently attributed to RF systems: 5L1, 7L1, 10L1 and 13L1

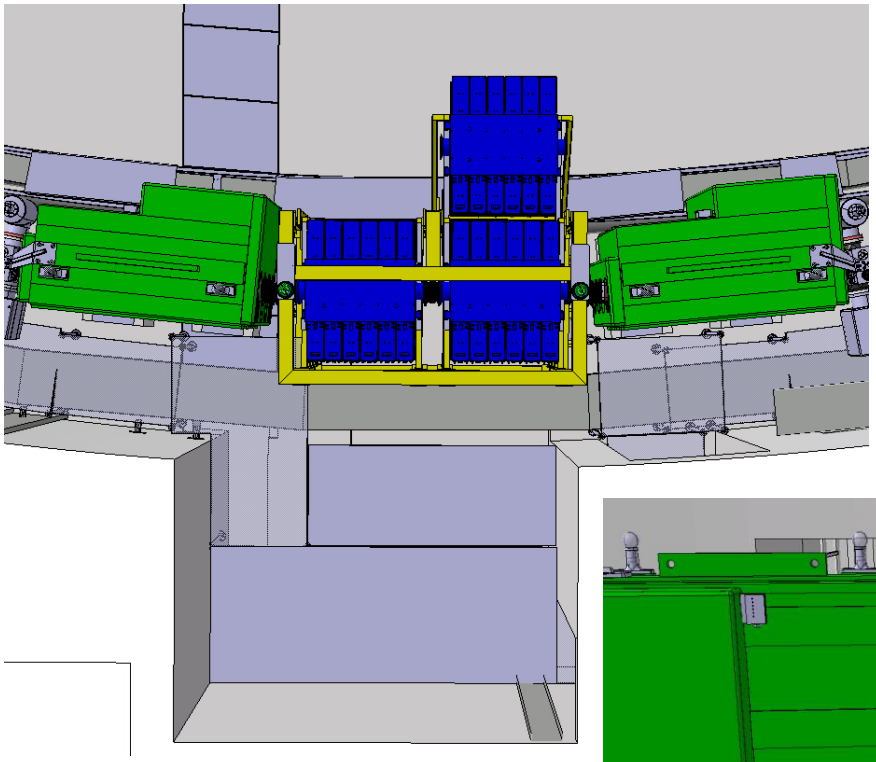


Future RF systems in the PSB

Use of three sections for new RF systems: 5L1, 7L1 and 13L1. Section 10L1 in stand-by.

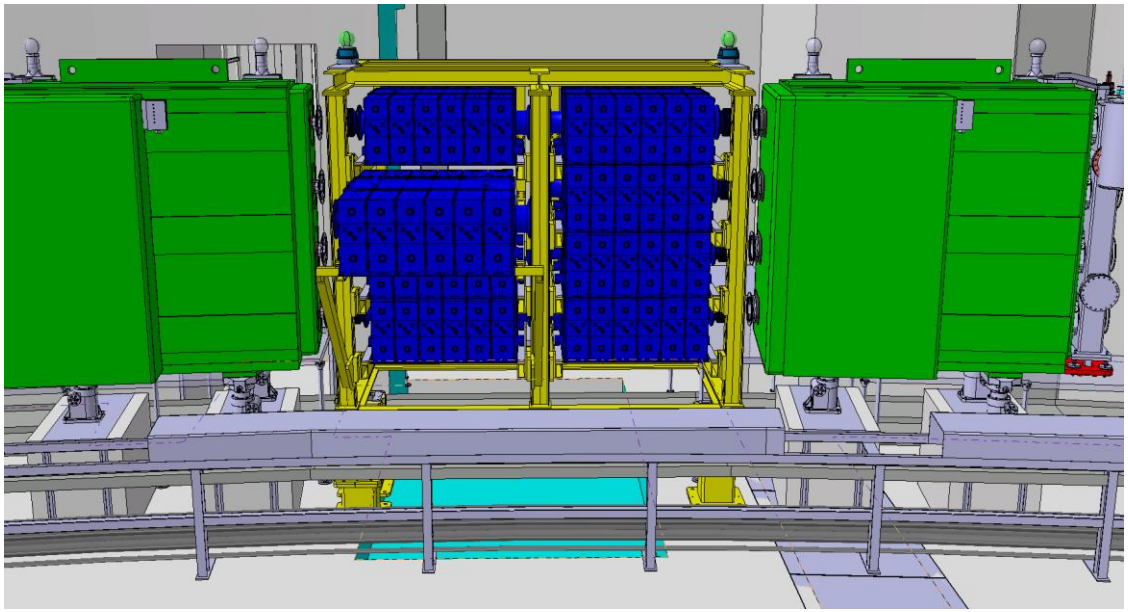


Proposed layout in the ring.



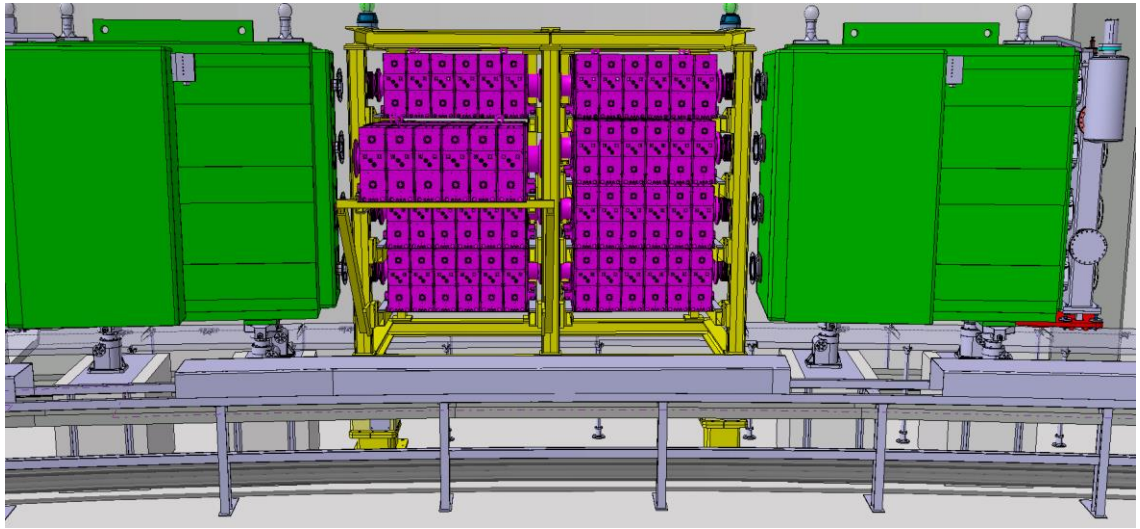
13L

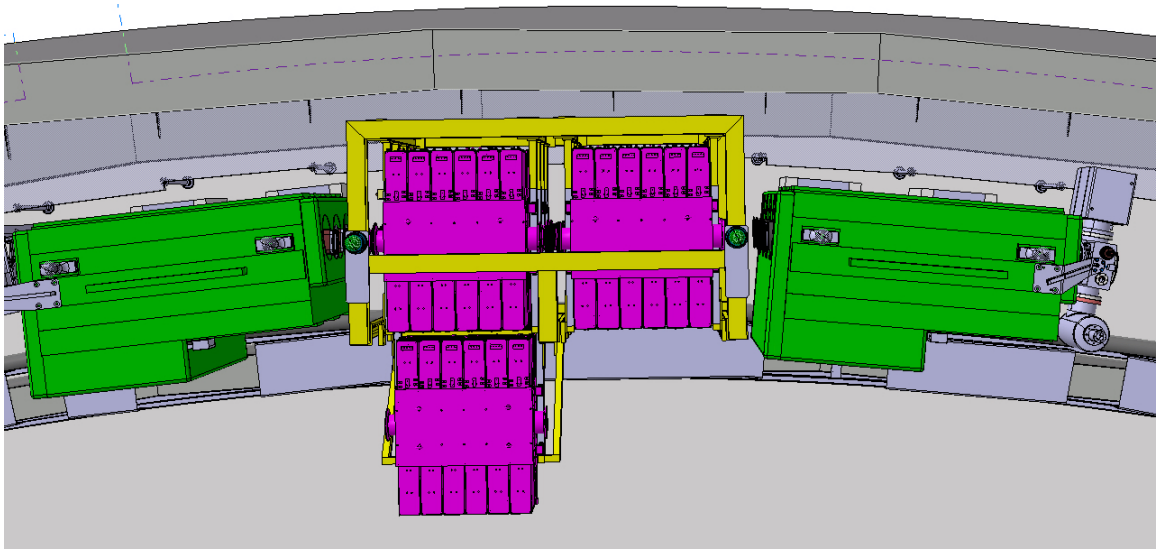
1



Proposed layout in the ring.

7L1





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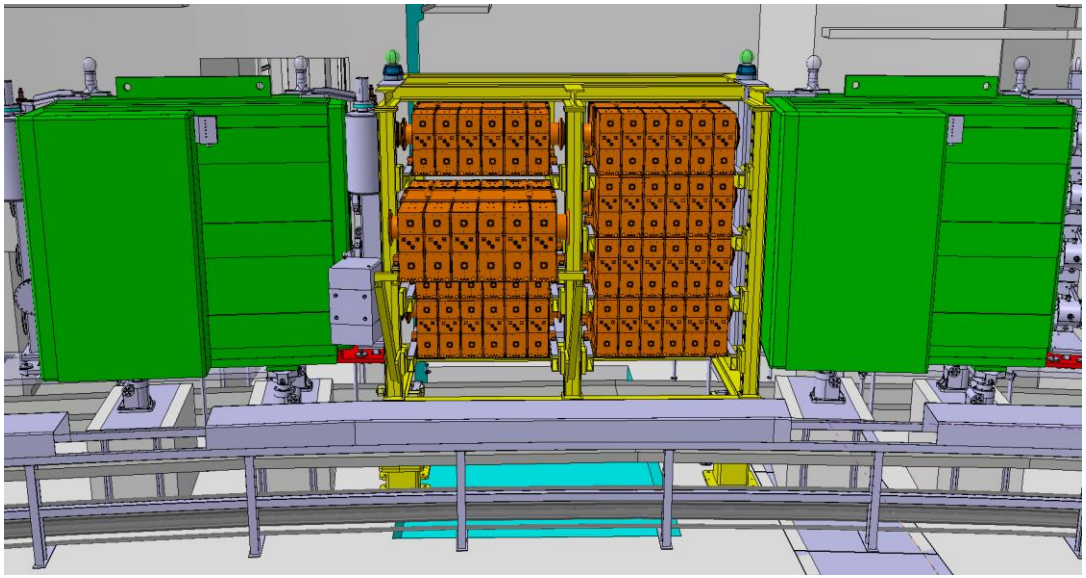
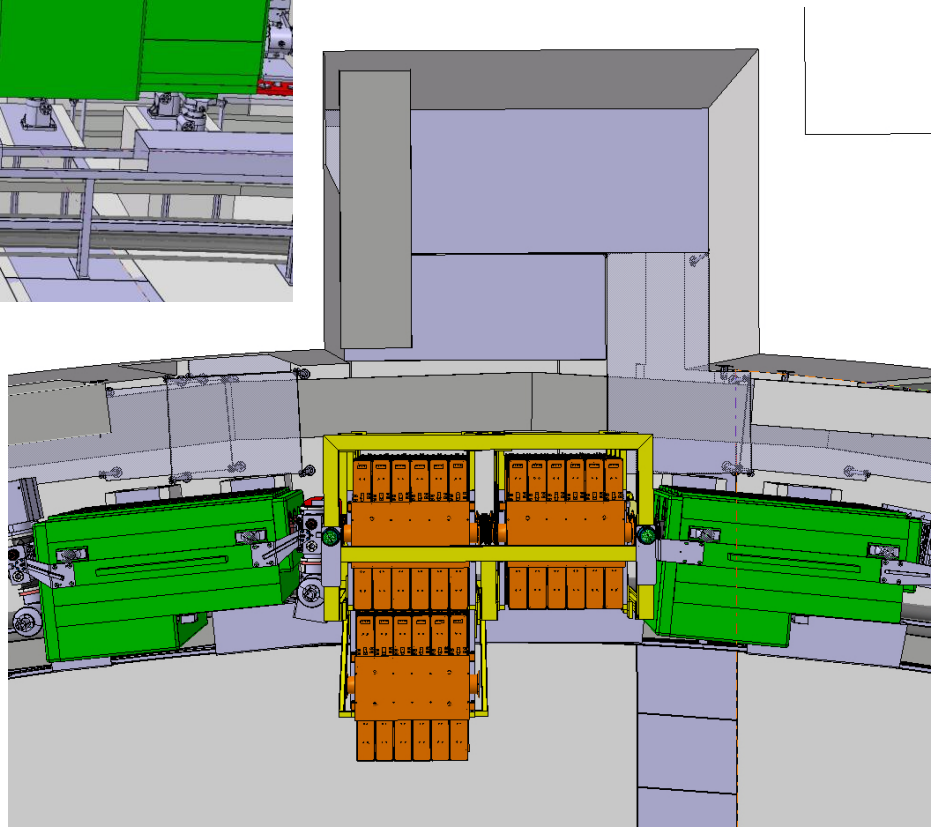
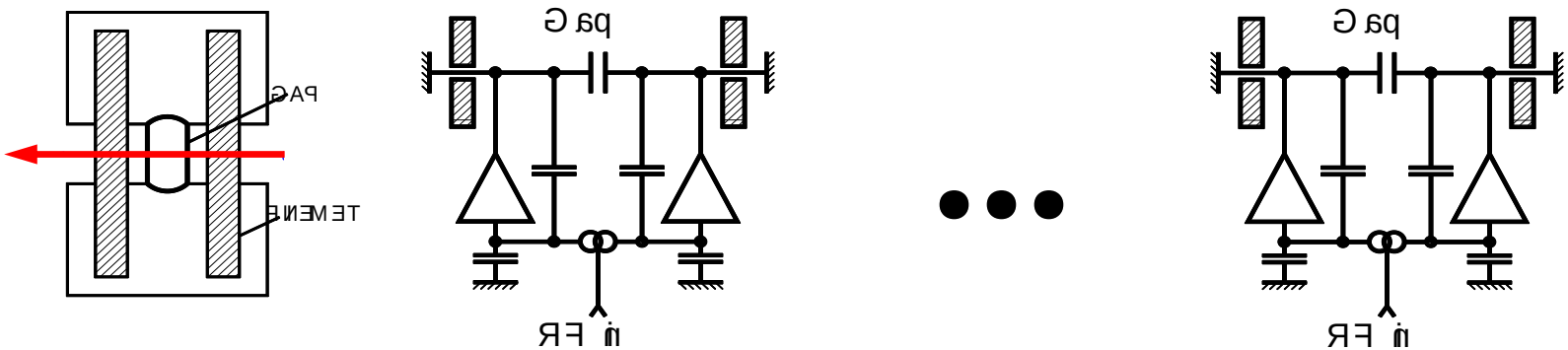


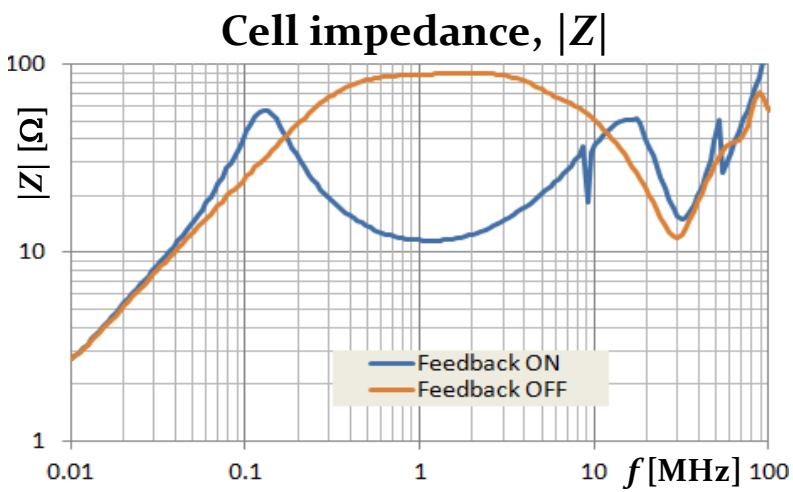


5L1

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**





PSB-type Finemet cell	
Frequency range	0.6 - 18 MHz
RF power	~ 3 kW
RF voltage	700 V (< 4 MHz)
Length	13 cm

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

Finemet cavity prototype tests in ring 4

→ **Extensive study program**

- 2012 prototype 5 cells
- 2014 prototype 10 cells

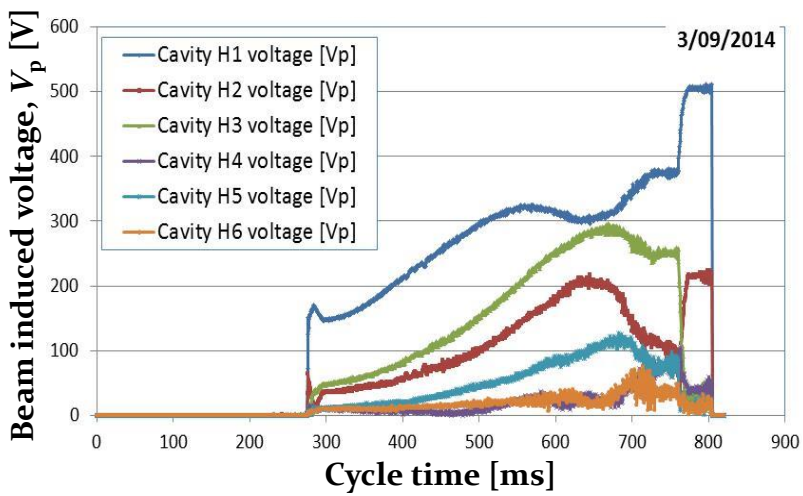
- **Take over functionality from h = 1 and h = 2 ferrite cavities**
- **Reliability fully validated during 6 weeks run**
- **Cover also functionality of blow-up cavity**

→ **No further studies required**

→ **Decision to replace all RF systems by Finemet cavities**

10-cell Finemet prototype in ring 4

M. Haase



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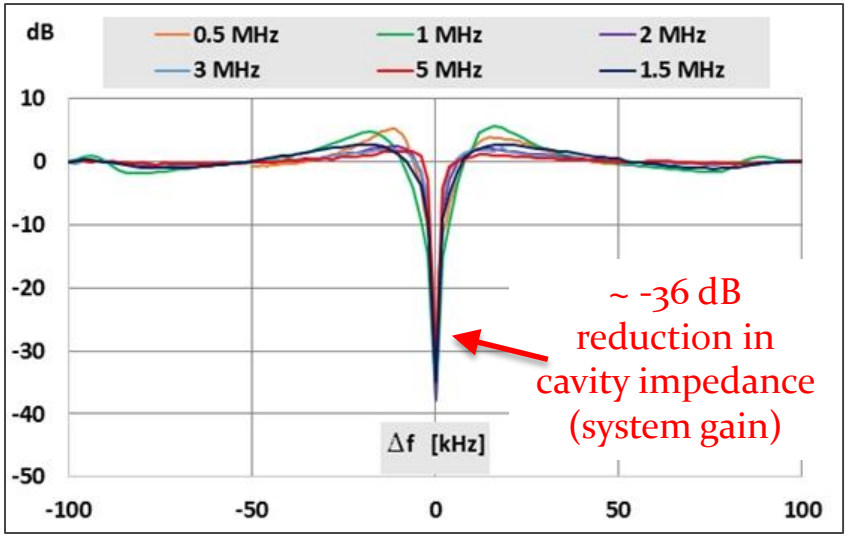
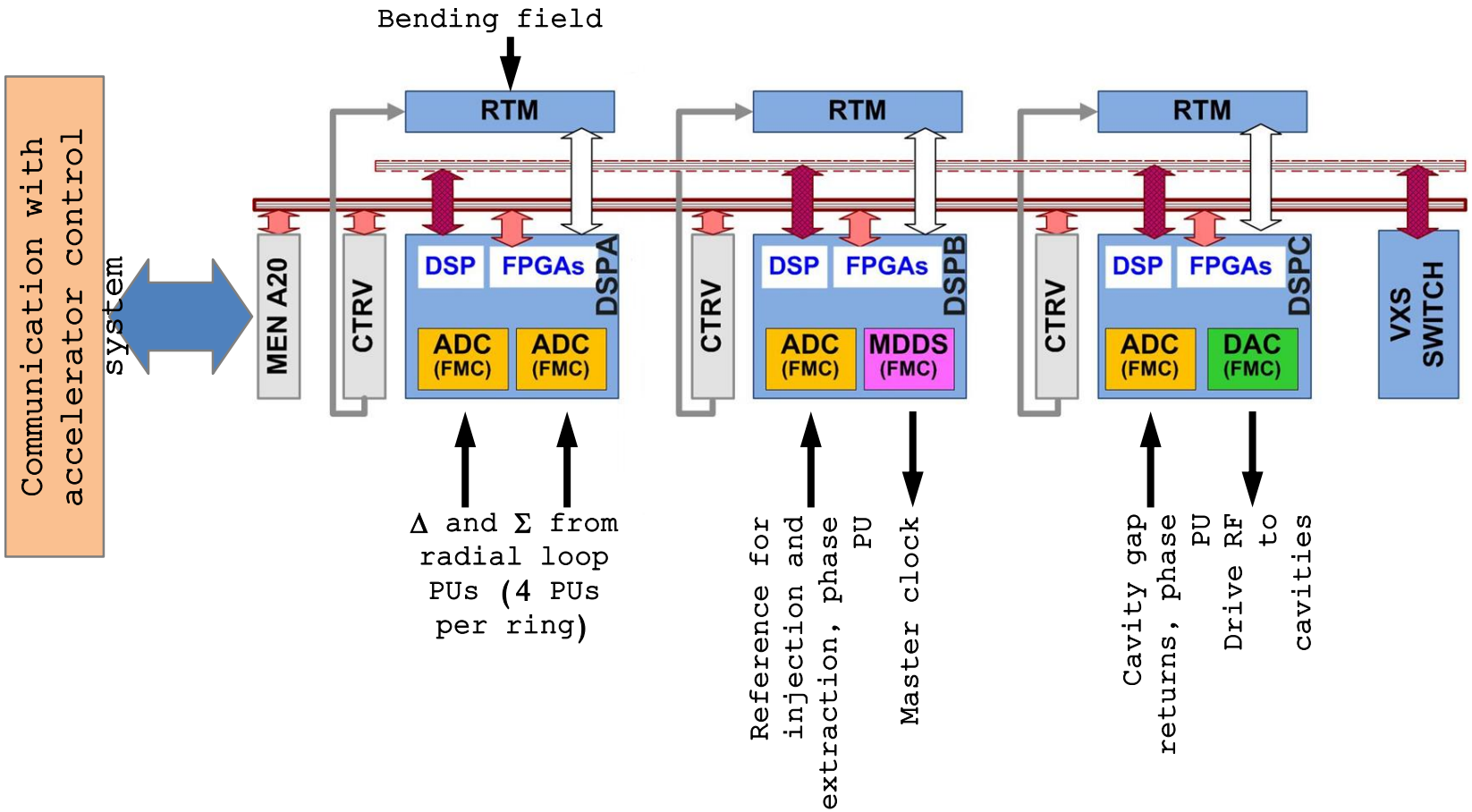


Beam control upgrade

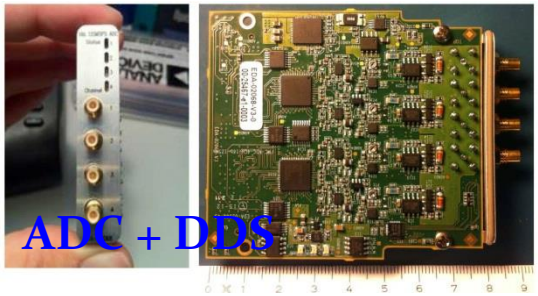
- **Largely independent beam control per ring**
- **Drives present ferrite cavities as well as Finemet cavity**
- **Since restart 2014: fully digital beam control on all four PSB rings**

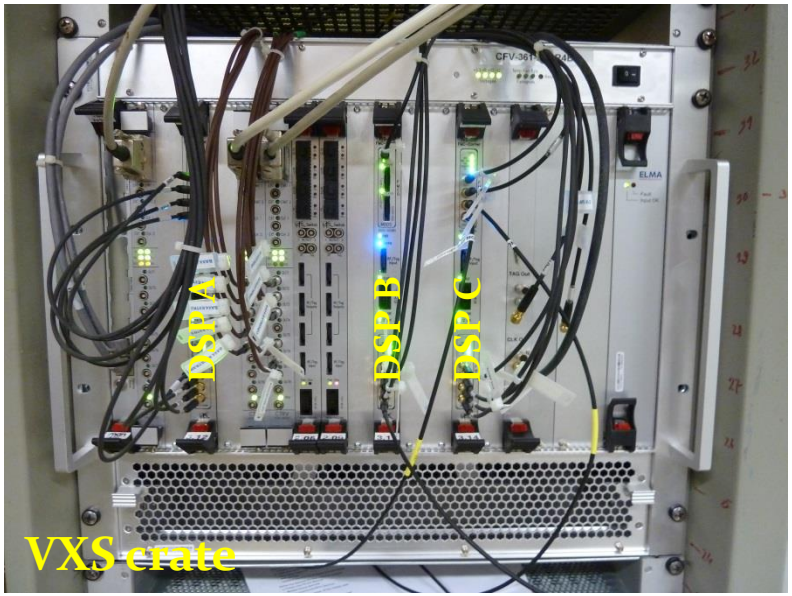


→ **Three DSPs per ring: beam phase, radial, injection/ejection synchronization and cavity loops → All loops in firmware**

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)





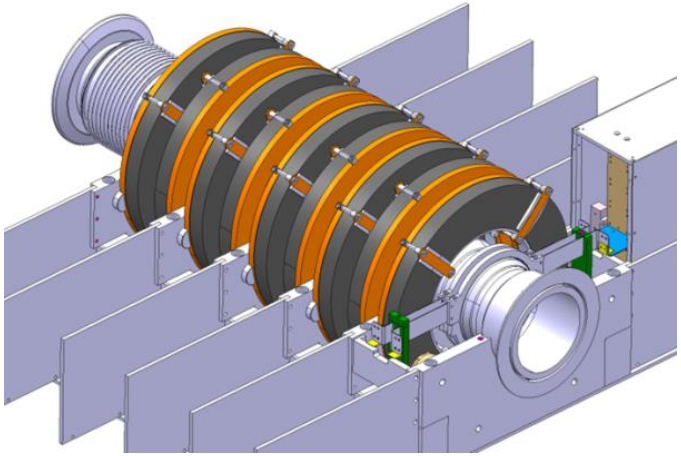
→ **Flexible:**
- All loop parameters adjustable in pulse-to-pulse mode
- Reconfigurable loop algorithms by firmware

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

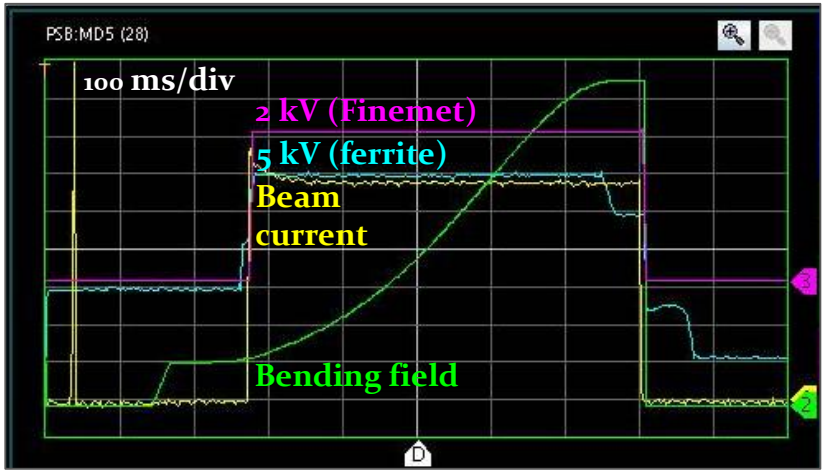
→ **Modular:** 4th DSP board added to drive Finemet cavity

Beam tests with first prototype (2012)

5-cell Finemet cavity prototype



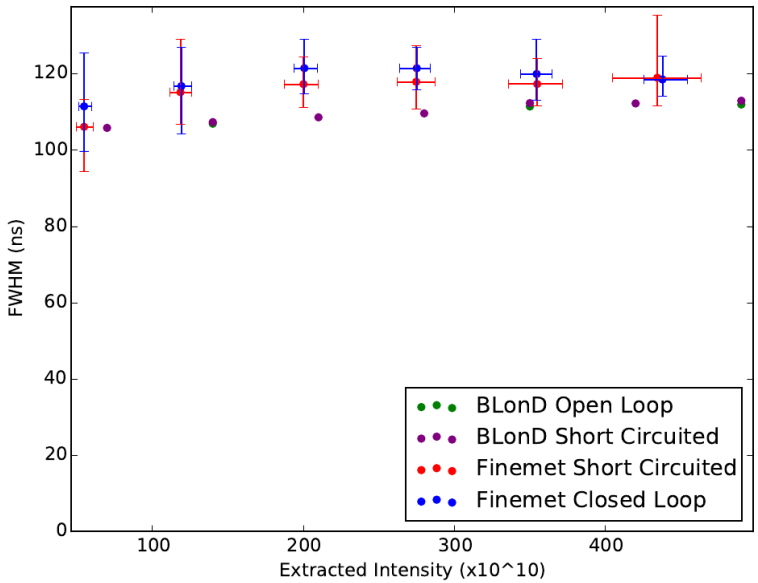
Combined acceleration $4.6 \cdot 10^{12}$ ppb

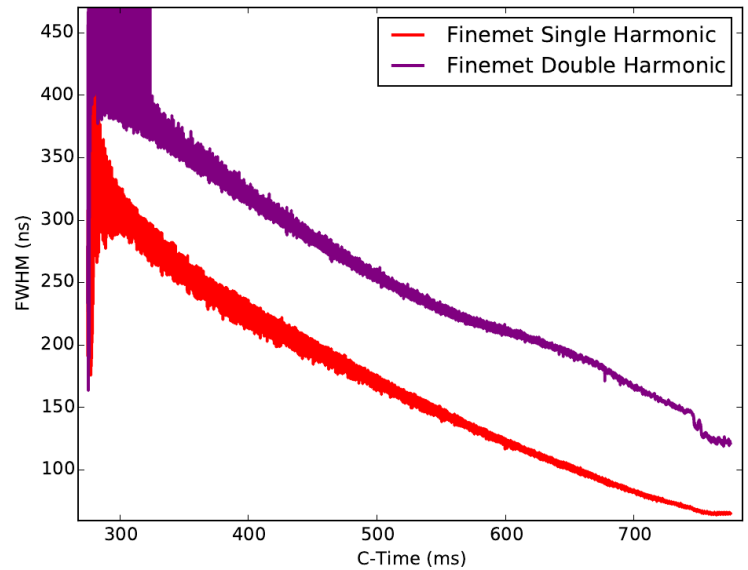


→ Combined operation of Finemet prototype with ferrite cavity

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

PSB: studies for Finemet RF



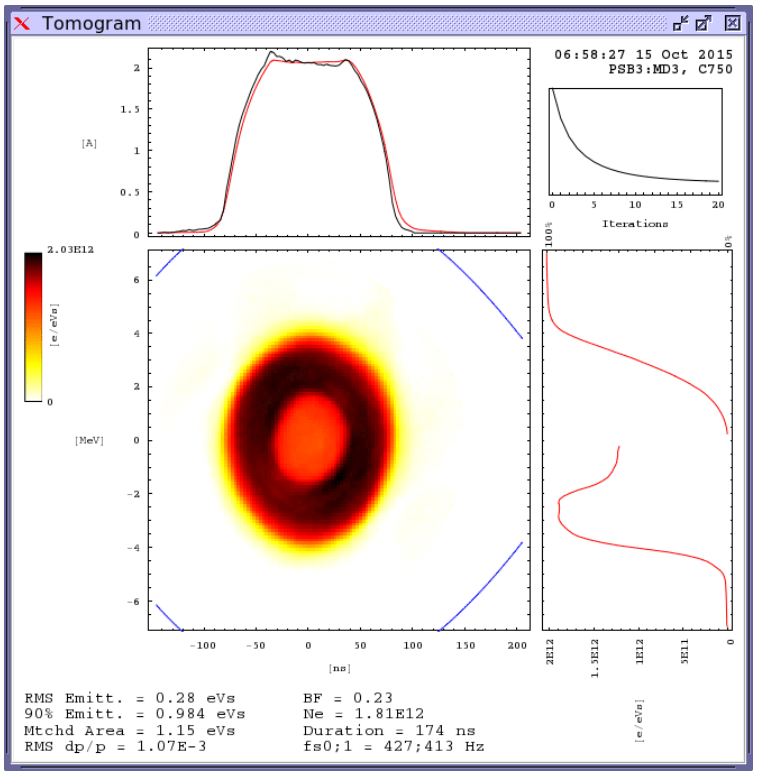


Present operation: good agreement between **measured and simulated bunch length** at extraction for different configurations of Finemet cavities

After LS2: stable operation with Finemet cavities in a single (V=8 kV) and double (8kV + 4 kV) RF mode for N = 9E12 during the ramp from 160 GeV to 2 GeV

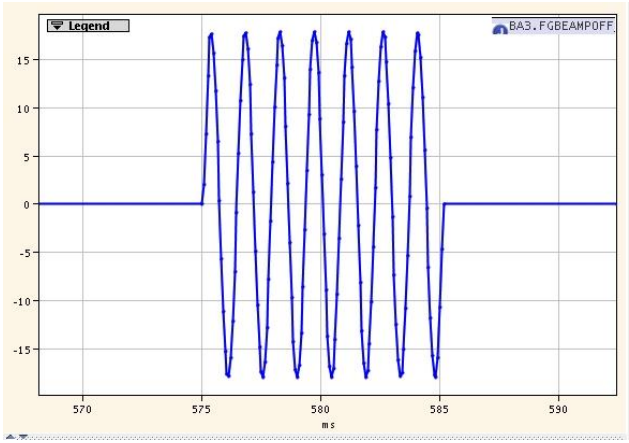
Beam examples: hollow bunches (studies)

- **Hollow (flat-topped) bunches generated in the PSB to gain space charge margin by reducing the bunch peak current.**
- **Important for the PS (i.e. next machine) which has transverse space charge limitations at injection for the beams foreseen for HL-LHC.**



http://tomograp.web.cern.ch

- **Generated via beam phase loop modulation to shake particles out of centre.**



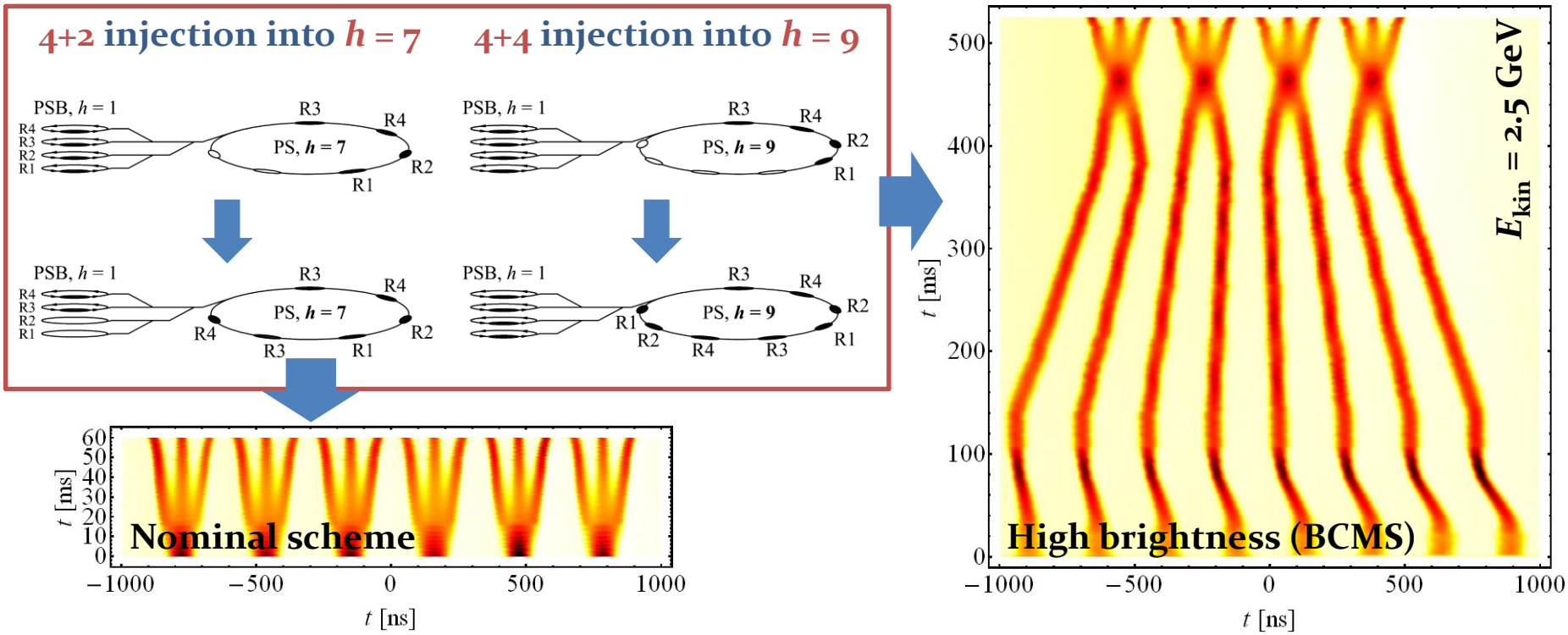
- **C16 blowup to smooth-up distribution.**

Hollow bunch in the PSB towards the end of acceleration. Picture & MDs from A. Oeftiger & S. Hancock

PS

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**

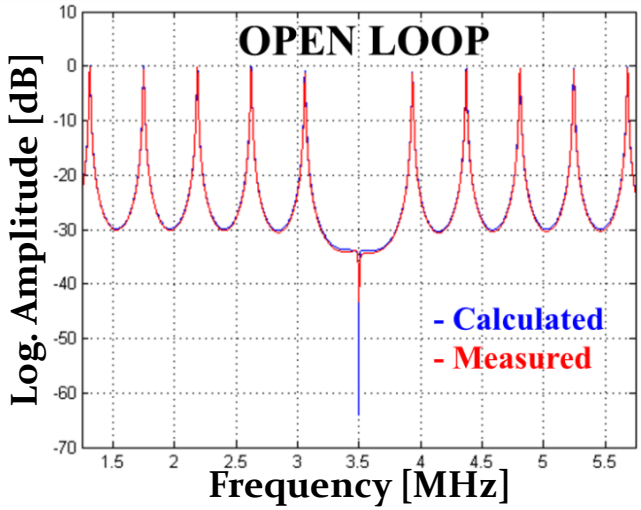
- **Presently based combination of analogue and digital hardware**

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

10 MHz 1-turn delay feedbacks

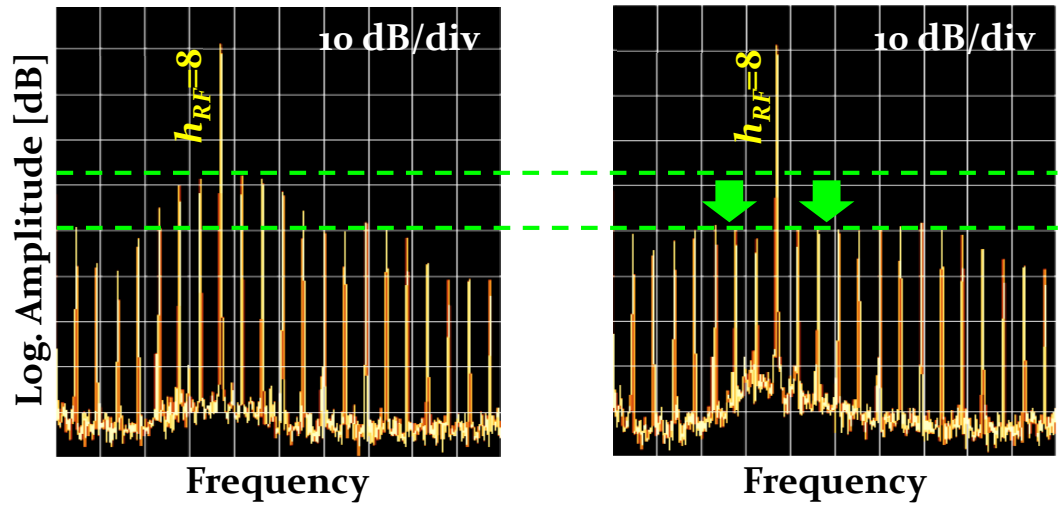
→ **Reduce cavity impedance beyond stability limit of wide-band FB**

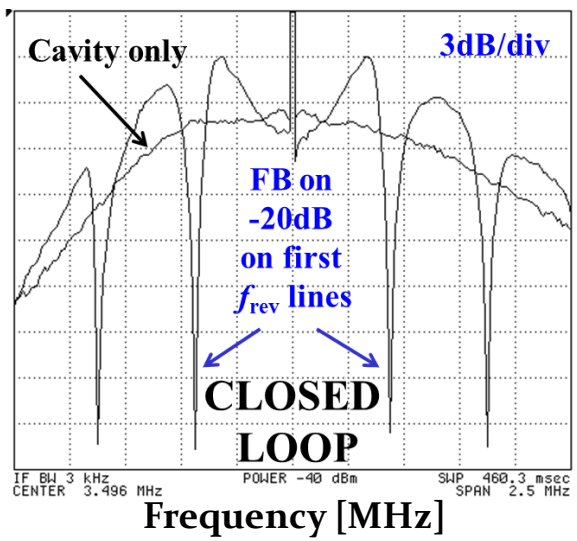
Open/closed loop transfer functions



Spectrum at cavity gap return

Feedback off | Feedback on





→ **Important impedance reduction**

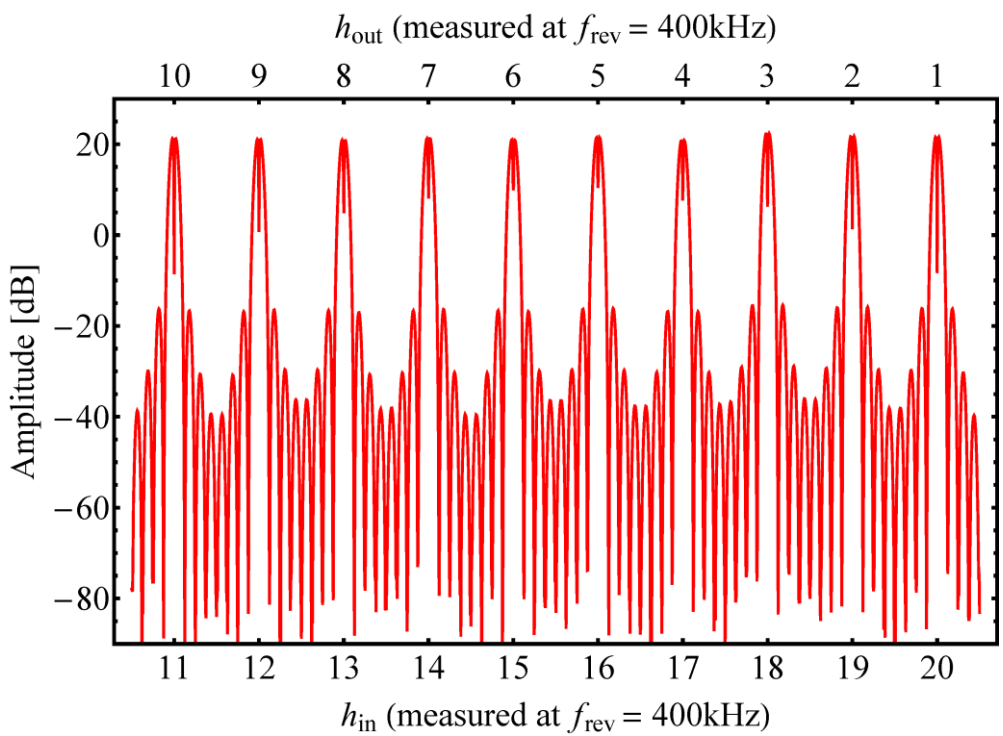
→ **Beneficial for**

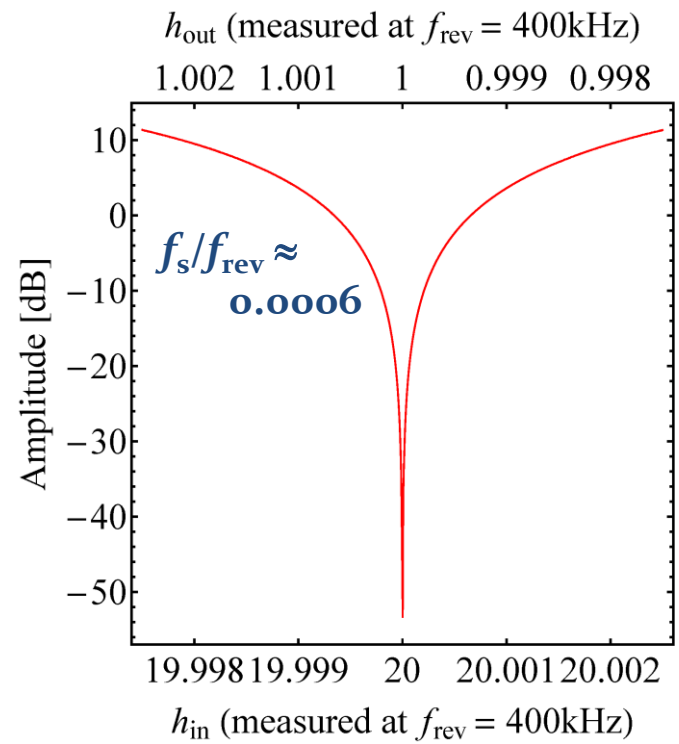
- **Transient beam loading**
- **Coupled-bunch instabilities driven by 10 MHz cavities**

→ **Measurements with LHC beams**

Measured transfer function of all harmonics

- **Difficult to measure due to freq. conversion:** $f_{out} = h_{RF} f_{clk}/256 - f_{in}$
  - → **Excitation sweeps upwards from** $10.5 f_{rev}$ **to** $20.5 f_{rev}$
  - ← **Detection sweeps downwards from** $10.5 f_{rev}$ **to** $0.5 f_{rev}$



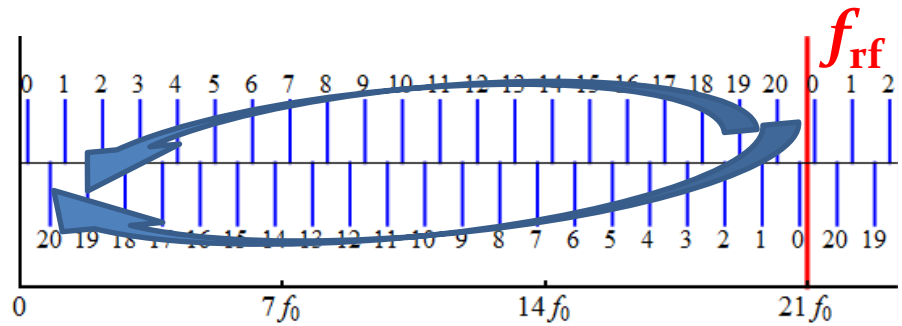


- **Works only thanks to symmetry of the beam spectrum**
- **Independent control of gain, phase and delay for each channel**

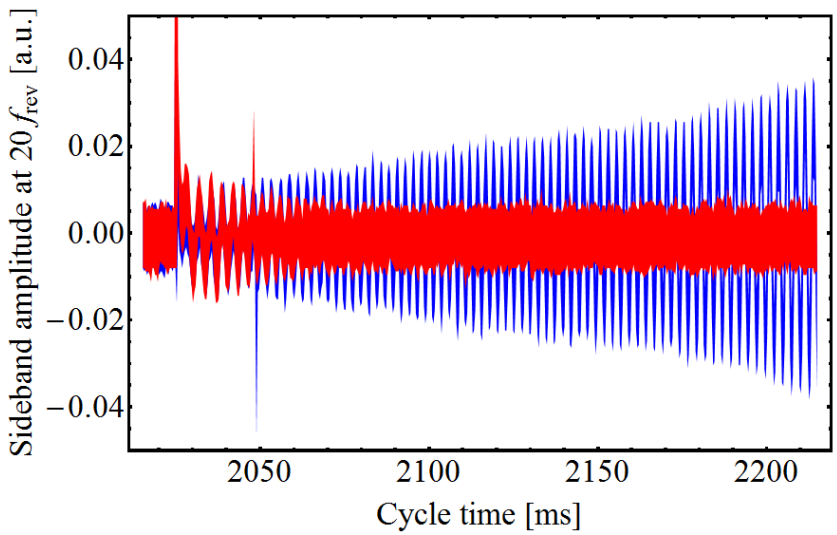
Cross-damping

- **Two parallel signal processing chains:** $20\,f_{rev} \rightarrow f_{rev}$, $19\,f_{rev} \rightarrow 2\,f_{rev}$
  - → **Inversion of side-bands**
  - → **Lock all numerical local oscillators to f_{rev}**

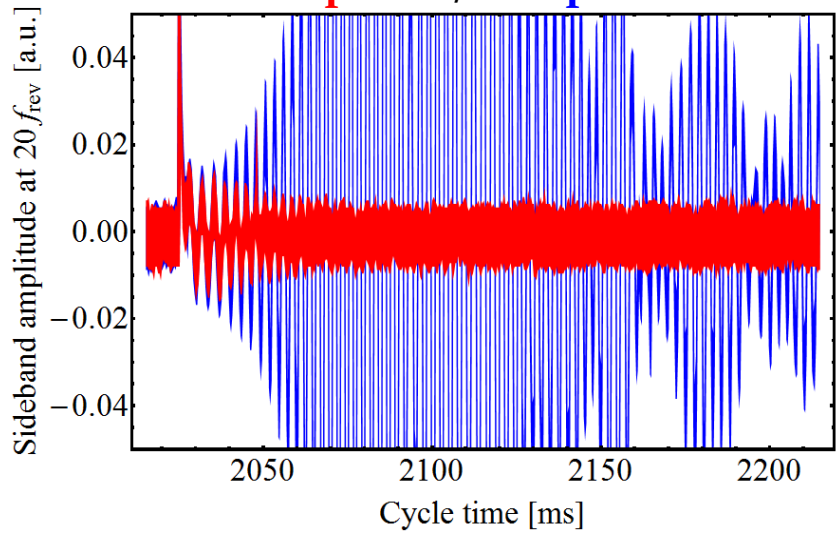
→ **Test with 21 bunches in $h = 21$**



Feedback on and off



In phase /anti-phase

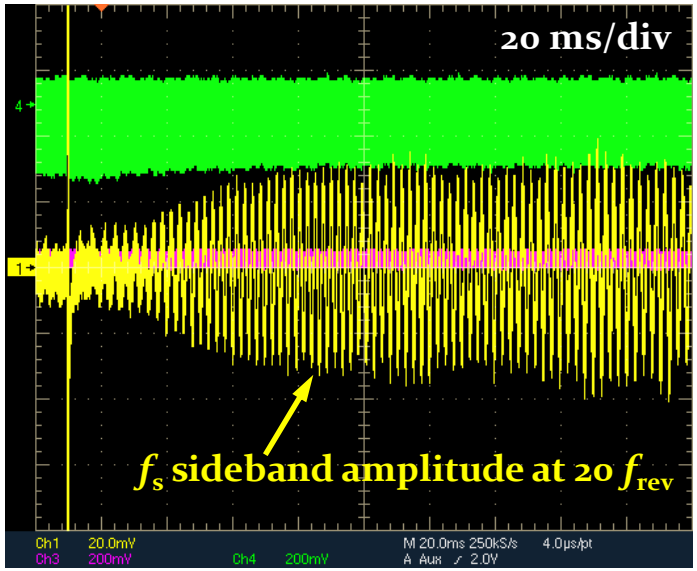


→ **With all RF sources synchronized cross-damping works as expected**

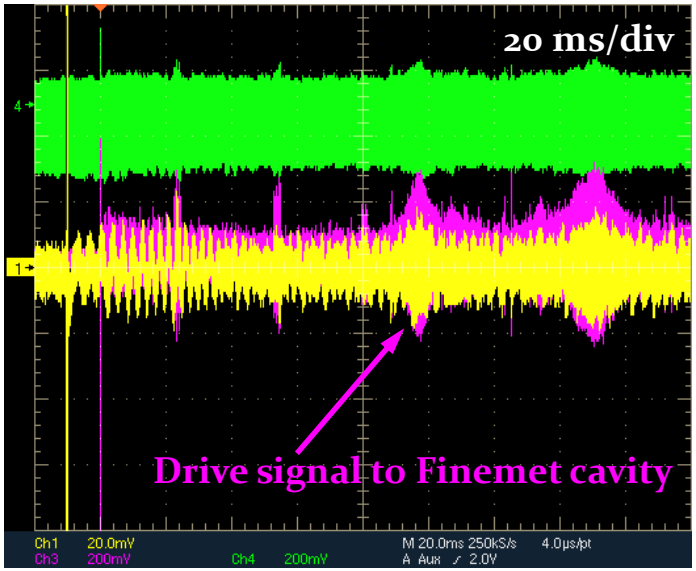
First damping of coupled-bunch oscillations

- **Single signal processing chain at 20 f_{rev}, digital LLRF + Finemet cavity**
- **Nominal LHC25 ns beam, 18 bunches, 1.3 · 10^{11} ppb, reduced ε_l**

Feedback off → unstable



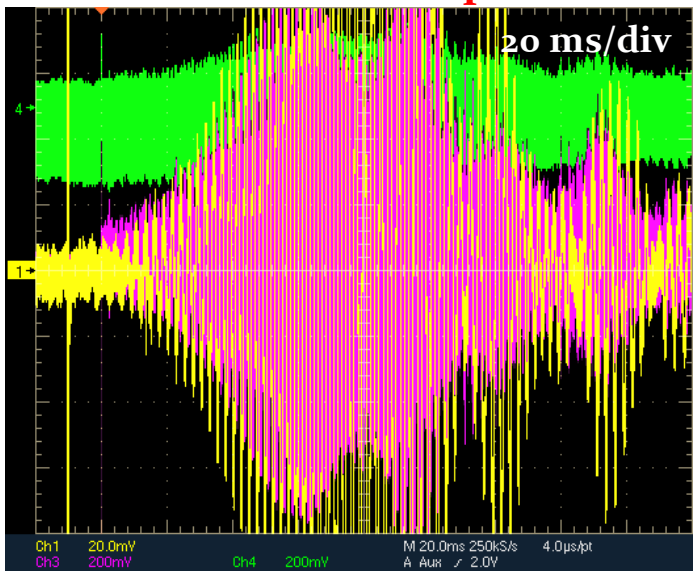
Feedback on → stable



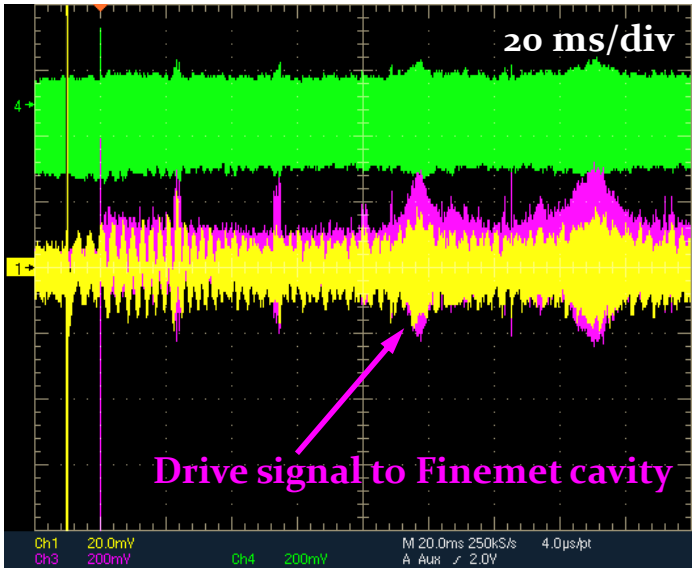
First damping of coupled-bunch oscillations

- **Single signal processing chain at 20 f_{rev}, digital LLRF + Finemet cavity**
- **Nominal LHC25 ns beam, 18 bunches, 1.3 · 10^{11} ppb, reduced ε_l**

Feedback in anti-phase



Feedback on → stable



→ **Coupled-bunch instabilities damped by Finemet cavity in closed loop**

→ **No residual carrier in drive signal as observed with previous feedback**

→ **All 10 parallel signal processing chains tested with beam**

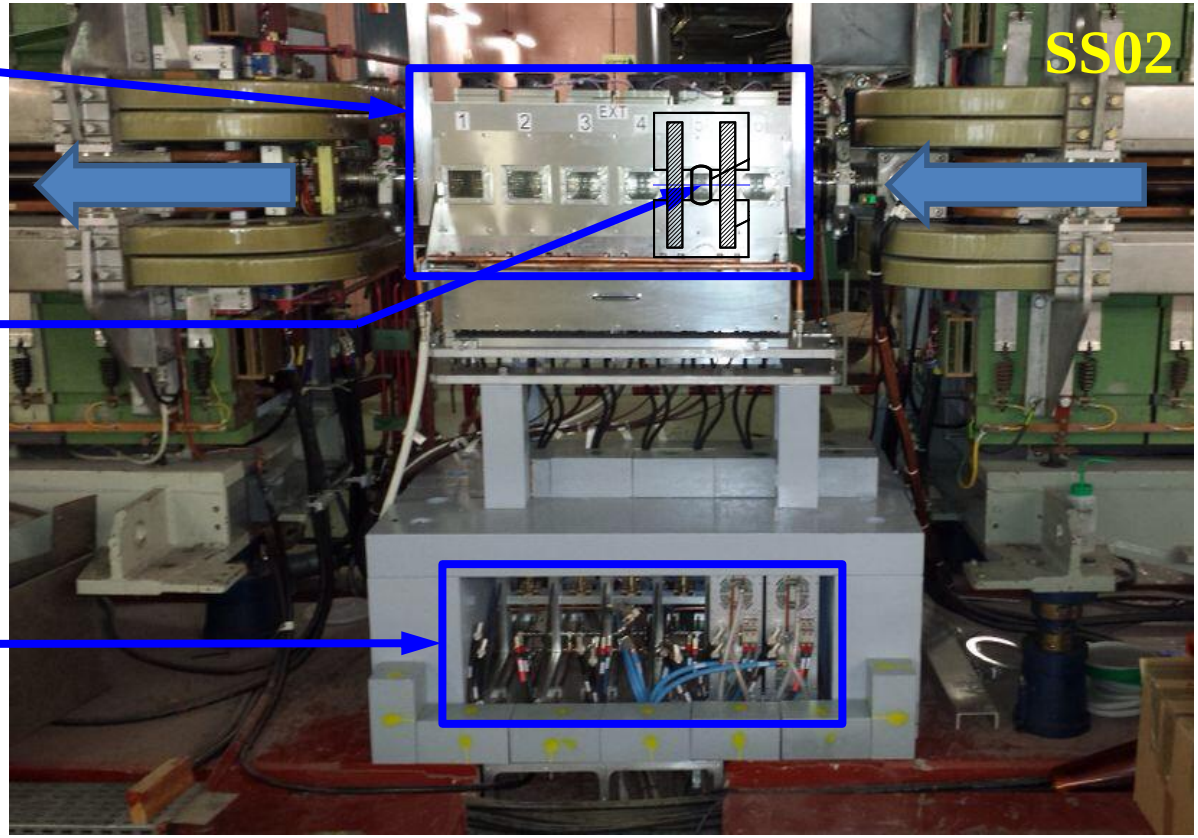
Wide-band Finemet longitudinal kicker

- **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)



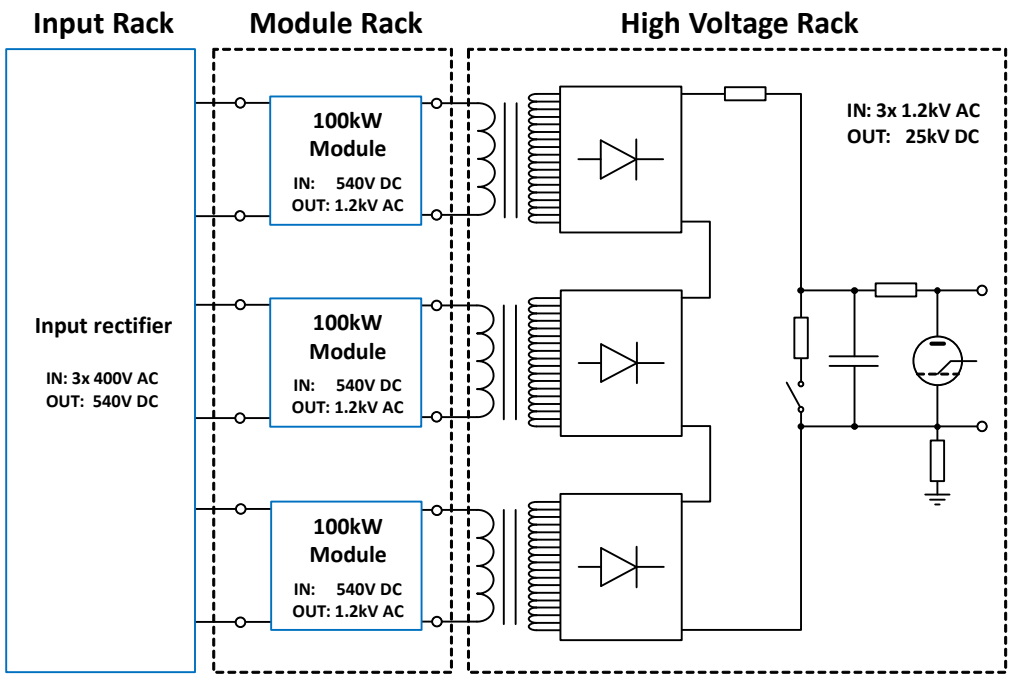
→ **First installation of solid state power amplifiers close to beam in PS**

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

Reliability: 40 MHz and 80 MHz cavities

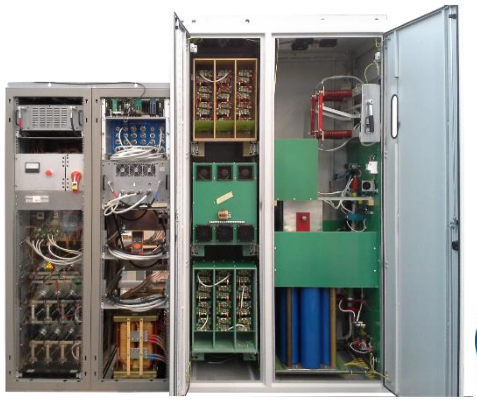
- Present anode power supply (22 kV) identified as main weakness
- New converters: standard CERN design

- 25kV / 8A / 200kW
- N + 1 redundant modular structure
- 3x 100kW resonant inverter modules
- Medium frequency transformers
- HV diode rectifiers
- 5 converters

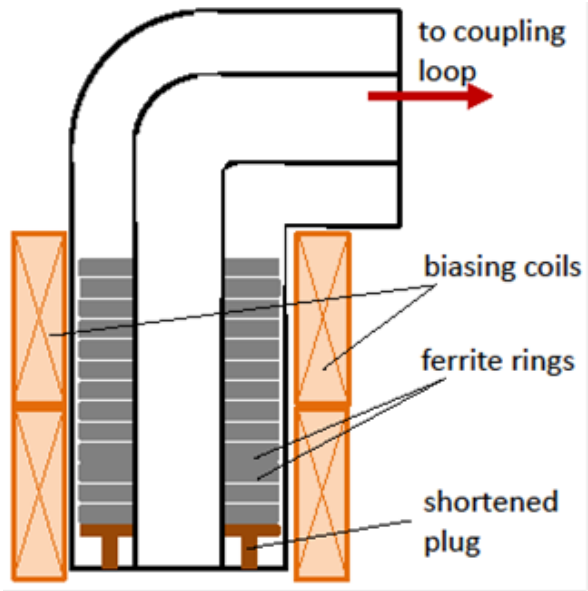


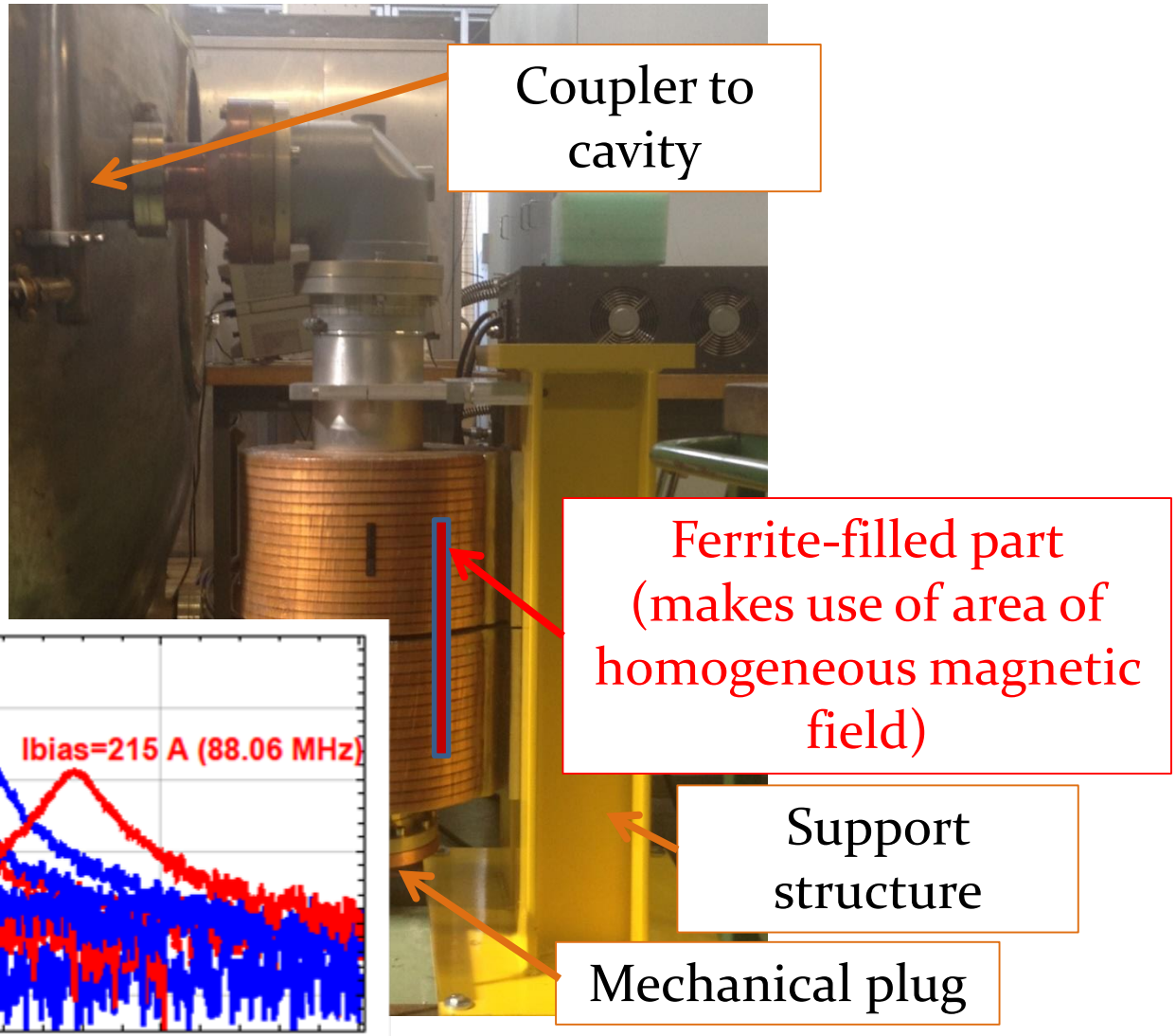
→ Complete installation during LS2

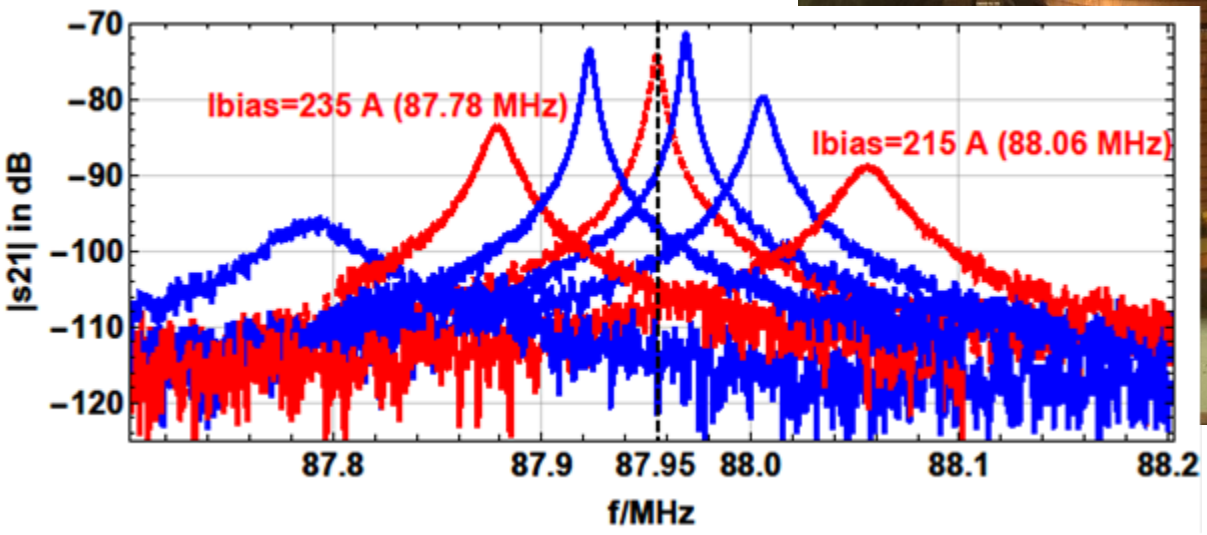
→ Important for operation with both 40 MHz cavities



Availability: Fast ferrite tuner 80 MHz







SPS

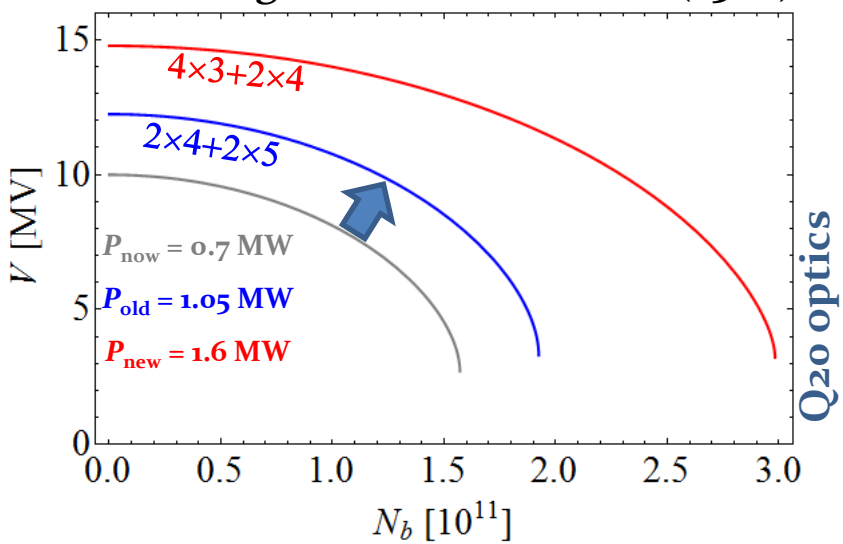
Maximum intensity at transfer to LHC

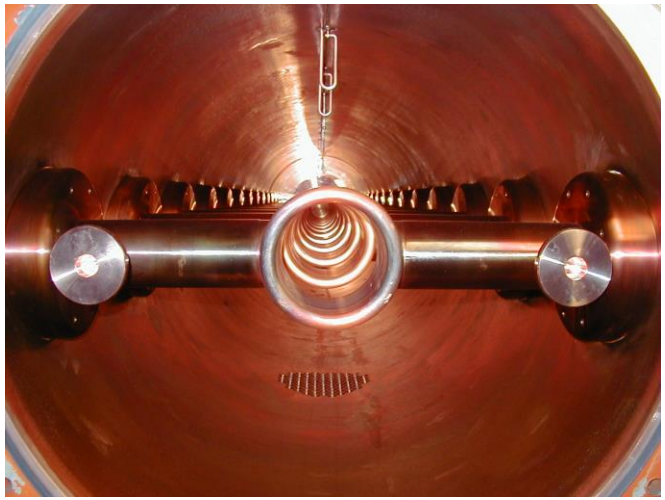
- **Fixed bunch length required at SPS → LHC transfer: 1.7 ns (4σ)**

- **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**

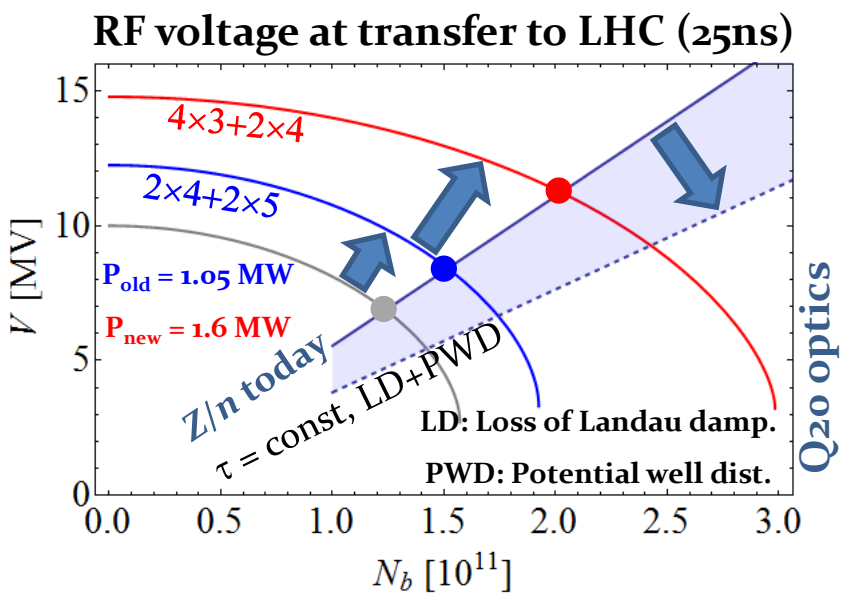
→ New low-level RF for beam synchronous pulsing during LS2

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

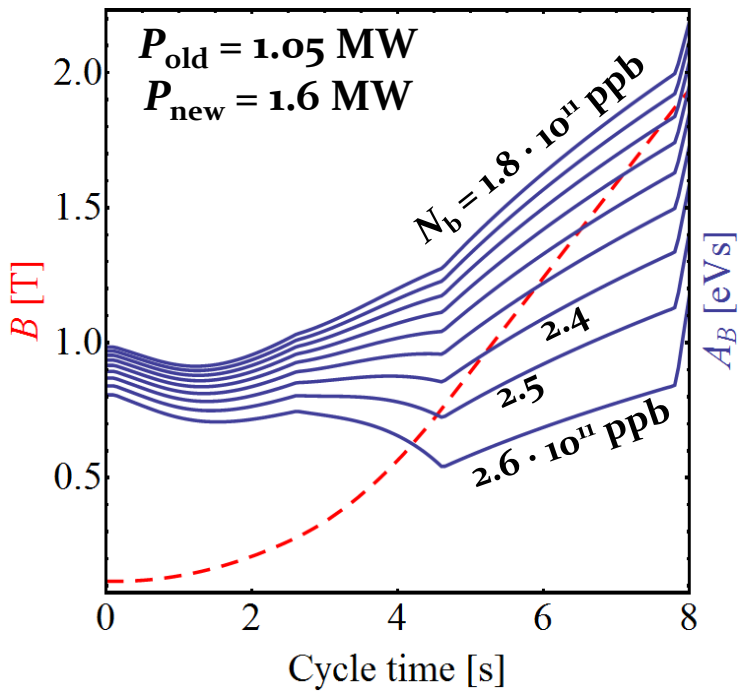


1. **Rearrangement of cavity sections and 2 × 1.6 MW power plants**
2. **Impedance identification and reduction (smaller ε_l)**
3. **Bunch rotation at extraction**

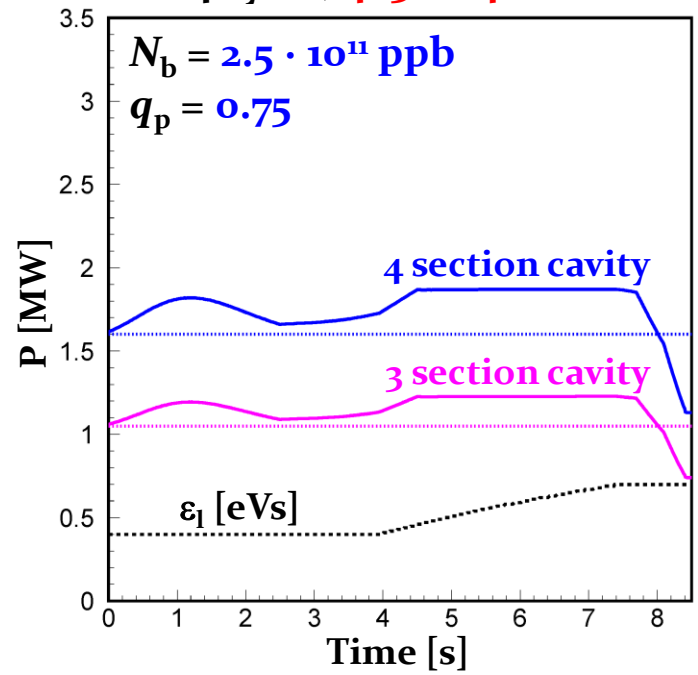
Maximum intensity during acceleration

- **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

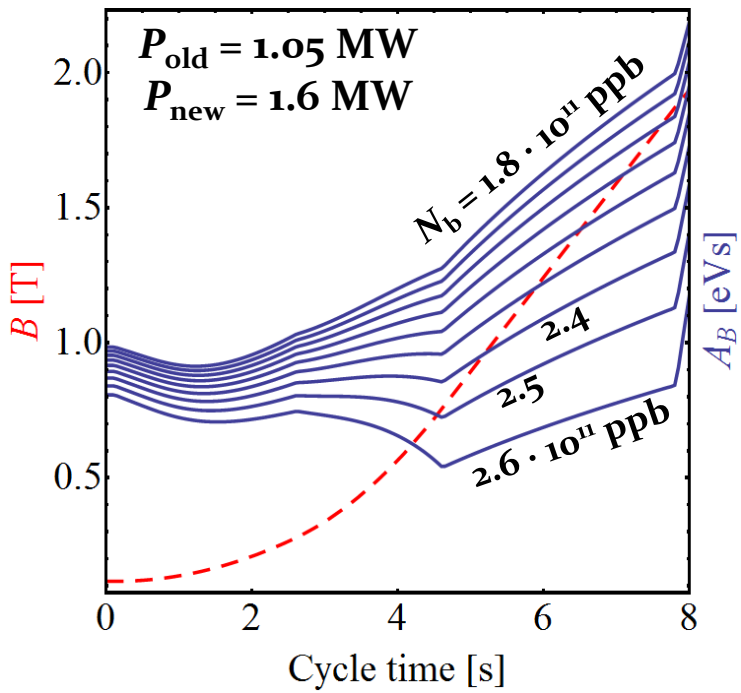


→ **Bucket area allows no emittance growth beyond 2.5 · 10¹¹ ppb**

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
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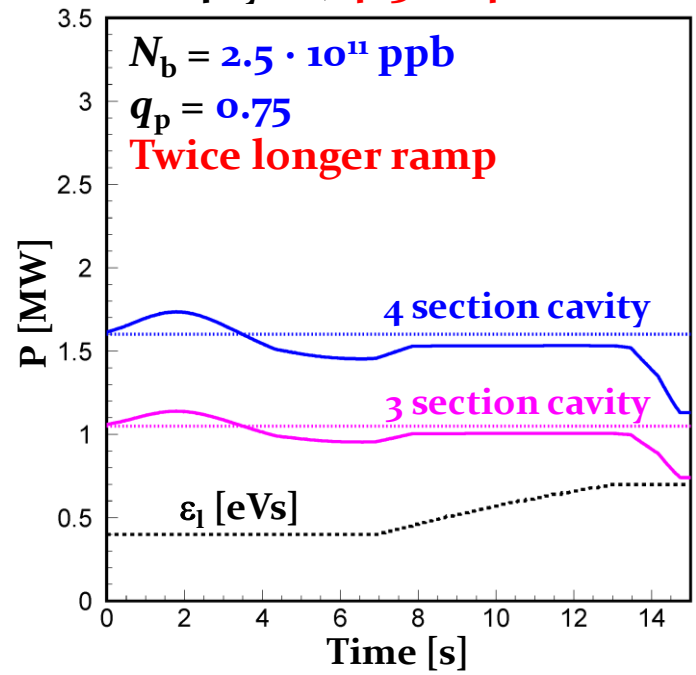


→ **Bucket area allows no emittance growth beyond 2.5 · 10¹¹ ppb**

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

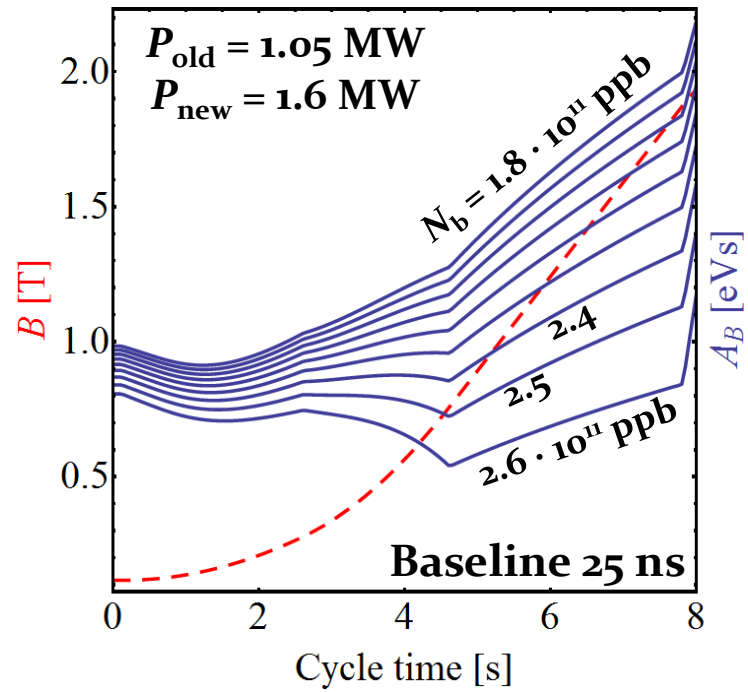
RF in SPS and LHC

- Average RF beam current relevant on time scale of cavity 'reaction time'

Relevant time scale:

	τ [μs]
SPS, 4-section cav.	0.6
SPS, 3-section cav.	0.43
LHC, loop bandwidth	~1

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



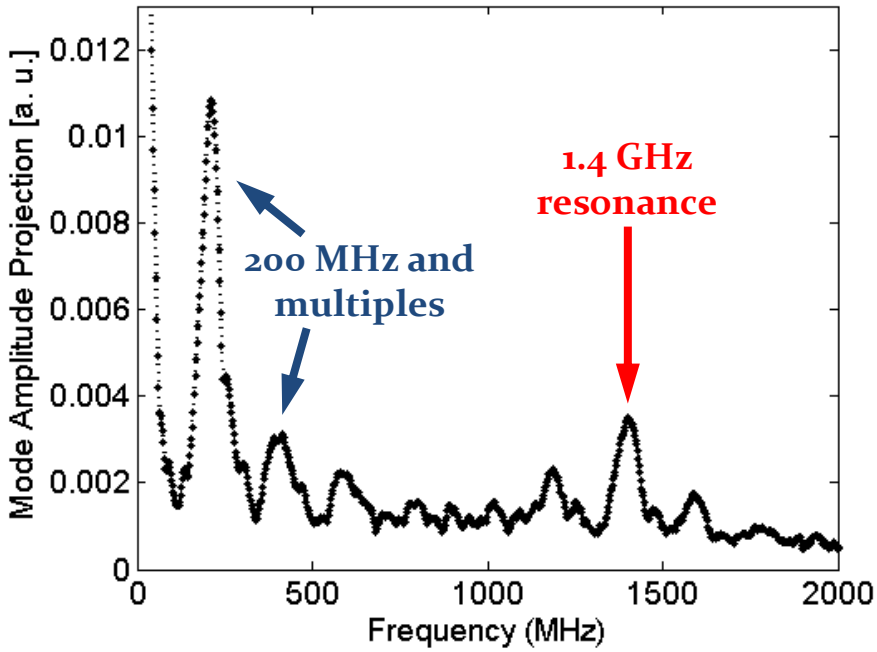
→ **Bucket area allows no emittance growth beyond 2.5 · 10¹¹ ppb with 25 ns averaged over ~430 ns in SPS**

→ **Effective duty cycle increase by ~10% with 8b+4e and 80b scheme in SPS**

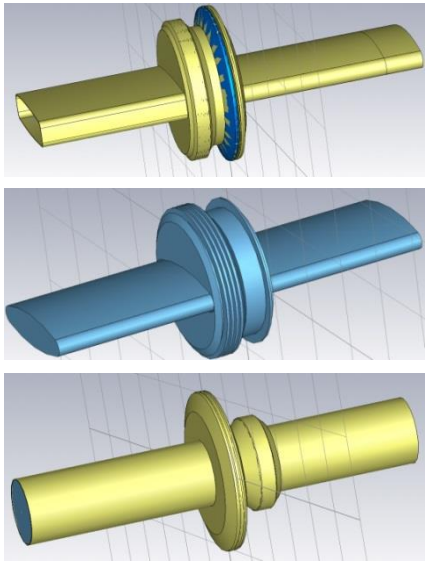
Impedance identification and reduction

- 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

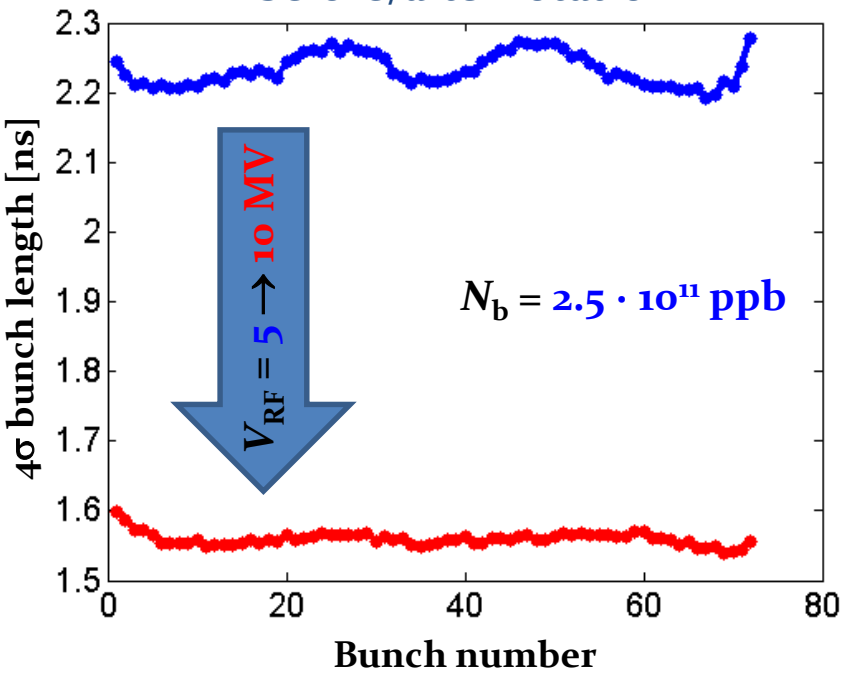
→ Possible shielding being investigated

Bunch rotation before transfer to LHC

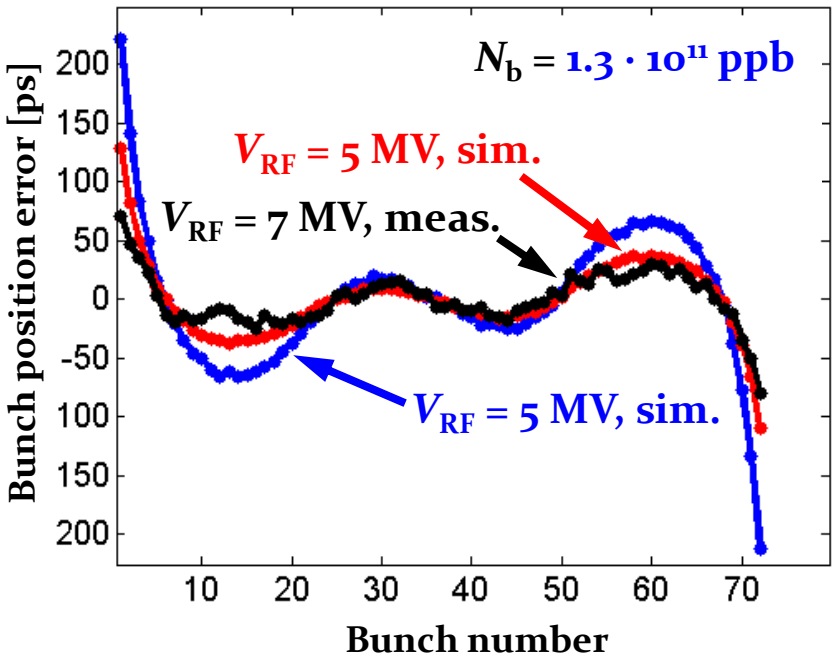
- **Save RF voltage and power by bunch rotation**
- **Voltage step: bunch length proportional to $V_{RF}^{1/2}$ instead of $V_{RF}^{1/4}$**

- **Simulations including SPS impedance, feed-forward and feedback**

Simulated bunch length before/after rotation



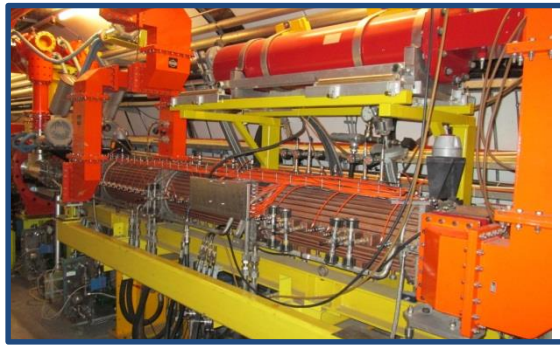
Simulation calibration: bunch position along batch



→ **Promising in simulation → Possible beam test already in 2015**

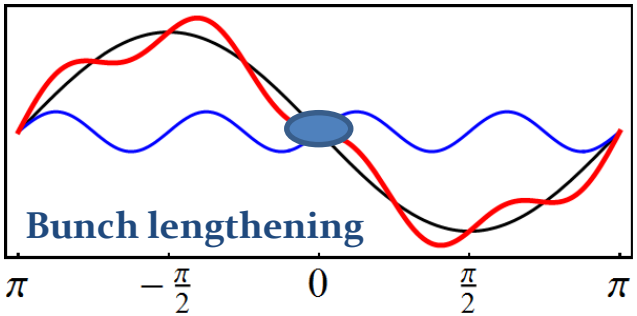
800 MHz RF system

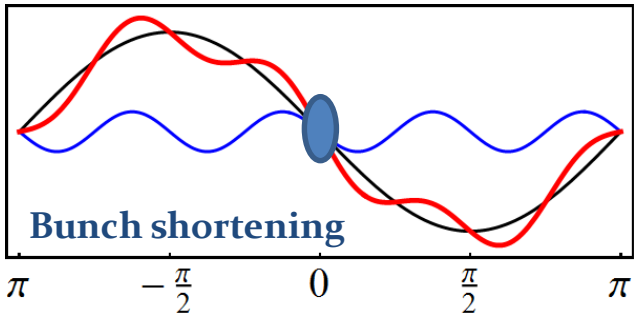
- **Two 800 MHz Landau cavities for beam stabilization**



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

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



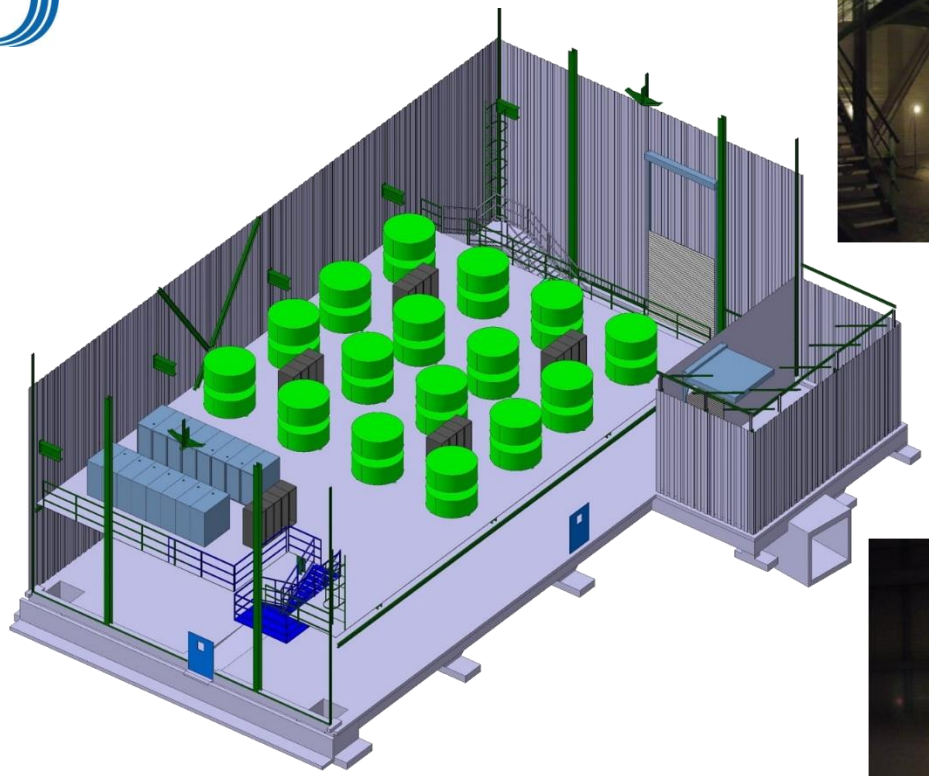


→ Requires good phase control of 800 MHz with respect to 200 MHz

→ Constant relative phase for all bunches, equal f_S distribution

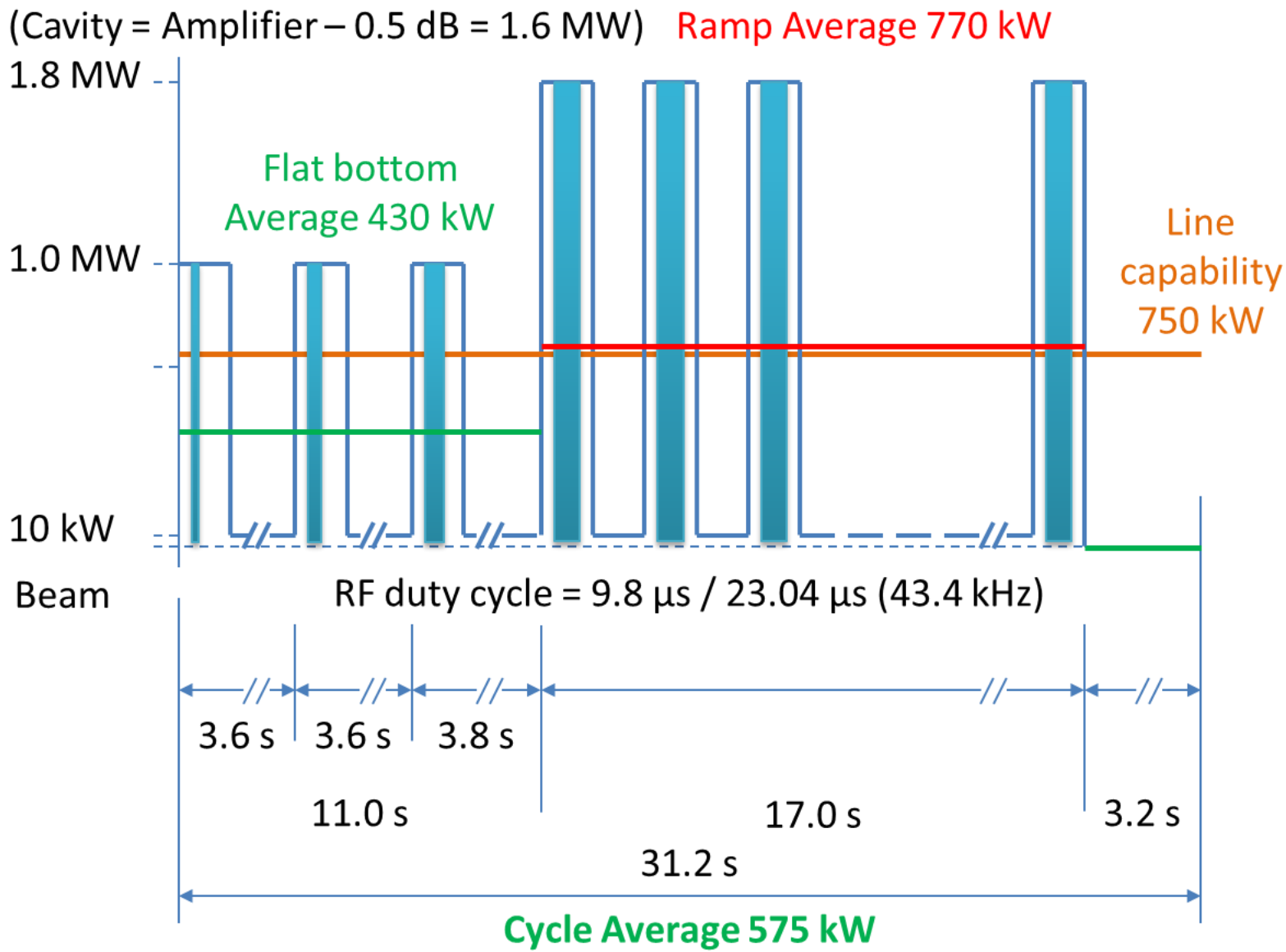
→ New feedback, feed-forward and amplifier polar loops

BAF3



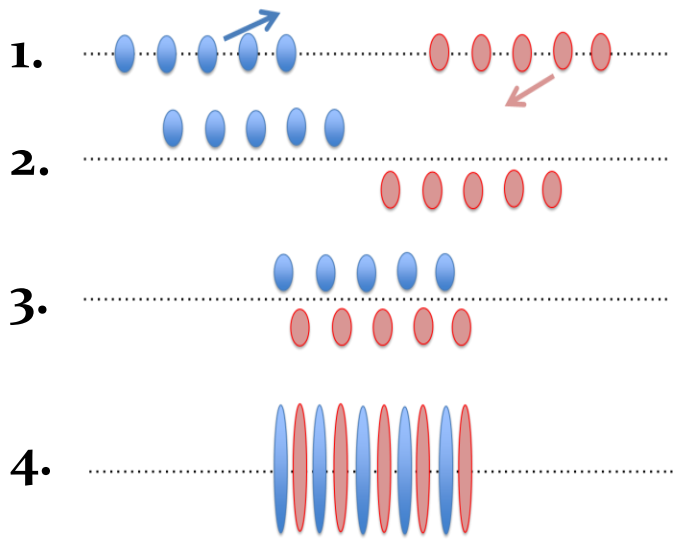
→ **Building ready since July 2015**

Peak and average power of LHC-type beams



Slip stacking for ions

- **Convert two batches with 100 ns spacing to one batch of 50 ns**



Accelerate/decelerate batches
One phase loops per batch

Cogging at off-center orbits
Design separation: ~±6 mm for 0.8 s process

Final approach without phase loop

Recapture at average frequency

2015 beam studies for ion slip stacking

✓ **Momentum clearance measurements for cogging at flat-top**
→ **Acceptable radial position range: ±10 mm**

✓ **Phase loop off**
→ **No dramatic beam quality degradation**
→ **Minor bunch length increase (7%)**

→ Challenging recommissioning for ion run in 2021