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

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 spacing: 1.3 \(\cdot 10^{11}\) ppb → >2 \(\cdot 10^{11}\) ppb

- **Key points**
  - 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
  - 0.6 – 1.8 MHz, 8 kV

- 1.2 – 3.8 MHz, 8 kV

- Longitudinal blow-up
  - 6 – 16 MHz

→ 4 rings with 3 cavities
→ Present PS Booster RF systems based on ferrite-loaded cavities
## Overview - PSB

<table>
<thead>
<tr>
<th>Limitation</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• <strong>Compatibility</strong> of RF with Linac4 intensity and 2 GeV</td>
<td>• Replace all ferrite loaded cavities by <strong>Finemet cavities</strong></td>
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<td>• <strong>Reliability</strong> and long-term maintainability</td>
<td>• <strong>Finemet cavities</strong></td>
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<td>• Replacement of beam controls by <strong>fully digital low-level RF (LLRF)</strong> system</td>
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<td>• New operation modes:</td>
<td>• <strong>Digital beam control</strong></td>
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<td>• Injection painting</td>
<td>• Dynamic <strong>redistribution of RF voltage</strong> available at different harmonics simultaneously</td>
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<tr>
<td>• Controlled blow-up for transfer to PS</td>
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→ **Entirety of PS Booster RF system affected by upgrades:**
   • **Beam control system exchanged by digital LLRF during LS1**
   • **Replacement of all main RF systems**
→ 3 straight sections equipped with Finemet cavities
→ 1 Straight section in standby
RF systems in the PS Booster after LS2

**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

Collaboration with KEK/JPARC
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
Beam control for Finemet tests

Operational beam control (since LS1)

→ 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 $\varepsilon_l = 1.8$ 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 to SPS

RF Manipulations

2.8 – 10 MHz

Longitudinal blow-up

200 MHz

20 MHz

0.4 – 5 MHz

0.4 – 5 MHz
The LHC25ns cycle in the PS

Inject 4+2 bunches

Controlled blow-ups

$h = 7$

Cycle time [s]

$h = 21$

$\gamma_{tr}$

Instability

Eject 72 bunches

$h = 84$

Split in four at flat top energy

Triple splitting at $E_{\text{kin}} = 2.5 \text{ GeV}$

2nd injection

Transients beam-loading

26 GeV/c

$\rightarrow$ Each bunch from the Booster split in $12 \rightarrow 6 \times 3 \times 2 \times 2 = 72$
## Overview - PS

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

• **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

![Graphs showing gain vs. frequency comparison between standard and upgraded prototype amplifiers.]

**Standard amplifier: 3 MHz**

- **Upgraded prototype: 3 MHz**

  ~24 dB

  ~25 dB

- **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
  → Increased gain of direct RF feedback around amplifier

<table>
<thead>
<tr>
<th>Frequency [MHz]</th>
<th>Standard amplifier: 10 MHz</th>
<th>Upgraded prototype: 10 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>open loop</td>
<td>open loop</td>
</tr>
<tr>
<td></td>
<td>closed loop</td>
<td>closed loop</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
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<tr>
<td>8.5</td>
<td></td>
<td></td>
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<tr>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>~24 dB</td>
<td>~30 dB</td>
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<tr>
<td>10.5</td>
<td></td>
<td></td>
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<tr>
<td>11</td>
<td></td>
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<tr>
<td>11.5</td>
<td></td>
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<tr>
<td>12</td>
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</tr>
</tbody>
</table>

- 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
1-turn delay feedbacks

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

→ 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
→ Two feedbacks: 1. Beam → Finemet cavity, 2. Cavity return → cavity
→ Frequency domain approach
→ Suppress synchrotron frequency side-bands at n · 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

→ 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
     • $5 \times 25$ kV, 8 A
     • CERN standard design
     • Modular
   → Complete installation during LS2

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
RF systems in the SPS

- All cavities in same straight section
- 200/800 MHz travelling wave cavities
  - Filling time much shorter than $f_{rev}$ → pulsed operation

Acceleration and controlled blow-up

800 MHz

4th harmonic Landau cavity
## Overview - SPS

<table>
<thead>
<tr>
<th>Limitation</th>
<th>Mitigation</th>
</tr>
</thead>
</table>
| • RF power during acceleration for $1.3 \times 10^{11}$ ppb → $2.4 \times 10^{11}$ ppb | 1. Rearrangement of main 200 MHz cavities  
  • 6 shorter travelling wave cavities  
  2. Installation of 2 additional RF power plants  
  • $2 \times 1.6$ MW at cavity input |
| • Longitudinal bucket area | 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 |
| • Insufficient RF voltage at transfer to LHC at $2.3 \times 10^{11}$ ppb | • 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

- 2 x 4 sections
- 2 x 5 sections
- 3 spare sections

Existing amplifiers (after upgrades):
- 0.7 MW continuous
- 1.05 MW pulsed

After LS2: 6 cavities

- 2 x 4 sections
- 4 x 3 sections
- 1 spare sections

New amplifiers
- 1.6 MW pulsed
→ New building
Maximum intensity during acceleration

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

$N_b = 2.4 \cdot 10^{11}$ ppb
$q_p = 0.8$

$P_{RF} + V_{ind}$
$V_{RF}$
$\tau [\text{ns}]$

$V_{RF}$
$P [\text{MW}]$

$N_b = 2.4 \cdot 10^{11}$ ppb
$q_p = 0.8$

$\varepsilon_l [\text{eVs}]$

→ Acceleration of $2.4 \cdot 10^{11}$ 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**

24 bunches at flat-top, bunch shortening mode

\[ V_{200\text{MHz}} = 7 \text{ MV}, \ V_{800\text{MHz}} = 0.7 \text{ MV} \]

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 \((2 \times 1.6 \text{ MW})\)

- 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 → Impedance reduction
   • Feedforward

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

<table>
<thead>
<tr>
<th>Correlations from loops</th>
<th>Master DDS</th>
<th>Slave DDS</th>
<th>Slave DDS</th>
<th>Slave DDS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( 2^{13}f_{rev} )</td>
<td>( f_{RF,avg} )</td>
<td>( f_{RF,FSK1} )</td>
<td>( f_{RF,FSK2} )</td>
</tr>
</tbody>
</table>

→ 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

→ 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 $\sim 2.8 \cdot 10^{11}$ 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
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*

- **Co2 Rings 1 and 3**
- **Co2 Rings 2 and 4**
- **Co4 All rings**
- **C16 All rings**
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.
Proposed layout in the ring.

5L1

M. Paoluzzi
December 10th - 2015
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 $\rightarrow$ Solid state amplifiers

![Diagram of Finemet cavity](image)

**Cell impedance, $|Z|$**

<table>
<thead>
<tr>
<th>Frequency range</th>
<th>0.6 - 18 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF power</td>
<td>$\sim 3$ kW</td>
</tr>
<tr>
<td>RF voltage</td>
<td>700 V (&lt; 4 MHz)</td>
</tr>
<tr>
<td>Length</td>
<td>13 cm</td>
</tr>
</tbody>
</table>

$\rightarrow$ 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
Finemet cavity prototype tests in ring 4

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→ Decision to replace all RF systems by Finemet cavities
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)

→ Combined operation of Finemet prototype with ferrite cavity
  • Capture and acceleration \((V_{RF} = 2\, \text{kV} \text{ from Finemet cavity})\)
  • Beam phase loop at \(h = 1\) closed around Finemet cavity
  • Beam-induced voltage studies
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.

- 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. Oefriger & S. Hancock

http://tomograp.web.cern.ch
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:** 
    \[ f_{\text{out}} = h_{\text{RF}} \frac{f_{\text{clk}}}{256} - f_{\text{in}} \]

  → **Excitation sweeps upwards** from \( 10.5f_{\text{rev}} \) to \( 20.5f_{\text{rev}} \)

  ← **Detection sweeps downwards** from \( 10.5f_{\text{rev}} \) to \( 0.5f_{\text{rev}} \)

• **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: $20 f_{\text{rev}} \rightarrow f_{\text{rev}}, 19 f_{\text{rev}} \rightarrow 2 f_{\text{rev}}$
  - Inversion of side-bands
  - Lock all numerical local oscillators to $f_{\text{rev}}$
  - Test with 21 bunches in $h = 21$

→ With all RF sources synchronized cross-damping works as expected
First damping of coupled-bunch oscillations

- Single signal processing chain at $20 f_{\text{rev}}$, digital LLRF + Finemet cavity
- Nominal LHC25 ns beam, 18 bunches, $1.3 \cdot 10^{11}$ ppb, reduced $\varepsilon_l$

Feedback off $\rightarrow$ unstable

Feedback on $\rightarrow$ stable

Drive signal to Finemet cavity

$f_s$ sideband amplitude at $20 f_{\text{rev}}$
First damping of coupled-bunch oscillations

- Single signal processing chain at $20 f_{\text{rev}}$, digital LLRF + Finemet cavity
- Nominal LHC25 ns beam, 18 bunches, $1.3 \cdot 10^{11}$ ppb, reduced $\varepsilon_1$

→ 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: $0.4 \text{ MHz} (f_{\text{rev}}) - 5 \text{ MHz} (f_{RF}/2)$, $V_{RF} \approx 5 \text{ kV}$
- No acceleration, but damping of coupled-bunch oscillations

→ 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

Coupler to cavity

Ferrite-filled part (makes use of area of homogeneous magnetic field)

Support structure

Mechanical plug

\[
|s21| \text{ in dB}
\]

- I_{bias} = 235 A (87.78 MHz)
- I_{bias} = 215 A (88.06 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 increasing beam intensity
- Required RF voltage increases with increasing beam intensity

- Pulse amplifiers at $f_{\text{rev}}$ 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 increasing beam intensity
- Required RF voltage increases with increasing beam intensity

1. Rearrangement of cavity sections and $2 \times 1.6$ MW power plants
2. Impedance identification and reduction (smaller $\varepsilon_1$)
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

\[ P_{\text{old}} = 1.05 \text{ MW} \]
\[ P_{\text{new}} = 1.6 \text{ MW} \]

\[ N_b = 1.8 \cdot 10^{11} \text{ ppb} \]
\[ q_p = 0.75 \]

→ Bucket area allows no emittance growth beyond \( 2.5 \cdot 10^{11} \text{ ppb} \)
Maximum intensity during acceleration

- RF power related intensity limitation also during acceleration

Bucket area at max. RF power

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

→ Bucket area allows no emittance growth beyond $2.5 \cdot 10^{11}$ ppb
→ Should become possible with longer acceleration ramp

$P_{\text{old}} = 1.05$ MW

$P_{\text{new}} = 1.6$ MW

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

$q_p = 0.75$

Twice longer ramp
RF in SPS and LHC

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

**Relevant time scale:**

<table>
<thead>
<tr>
<th></th>
<th>$\tau$ [\mu s]</th>
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</thead>
<tbody>
<tr>
<td>SPS, 4-section cav.</td>
<td>0.6</td>
</tr>
<tr>
<td>SPS, 3-section cav.</td>
<td>0.43</td>
</tr>
<tr>
<td>LHC, loop bandwidth</td>
<td>~1</td>
</tr>
</tbody>
</table>

→ Bucket area allows no emittance growth beyond $2.5 \times 10^{11}$ ppb with 25 ns averaged over $\sim 430$ ns in SPS

→ Effective duty cycle increase by $\sim 10\%$ with 8b+4e and 80b scheme in SPS
Impedance identification and reduction

- Inject long (4σ ≈ 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: \( f_{\text{res}} = 1.2...1.6 \text{ GHz} \)
→ 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 $V_{RF}^{\frac{1}{2}}$ instead of $V_{RF}^{\frac{1}{4}}$

- Simulations including SPS impedance, feed-forward and feedback

→ 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
→ Building ready since July 2015
Peak and average power of LHC-type beams

(Cavity = Amplifier – 0.5 dB = 1.6 MW)

Ramp Average 770 kW

1.8 MW

1.0 MW

Flat bottom
Average 430 kW

10 kW

Beam

RF duty cycle = 9.8 μs / 23.04 μs (43.4 kHz)

3.6 s  3.6 s  3.8 s

11.0 s  17.0 s  3.2 s

31.2 s

Cycle Average 575 kW

Line capability 750 kW
Slip stacking for ions

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

1. Accelerate/decelerate batches
   One phase loops per batch

2. Cogging at off-center orbits
   Design separation: $\pm 6$ mm for 0.8 s process

3. Final approach without phase loop

4. Recapture at average frequency

2015 beam studies for ion slip stacking

- **Momentum clearance** measurements for cogging at flat-top
  $\rightarrow$ Acceptable radial position range: $\pm 10$ mm

- **Phase loop off**
  $\rightarrow$ No dramatic beam quality degradation
  $\rightarrow$ Minor bunch length increase (7%)

$\rightarrow$ Challenging recommissioning for ion run in 2021