RF Upgrade Paths

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... and special thanks to
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E. Montesinos, K. Schirm, H. Timkó, R. Tomás, D. Valuch

LHC Performance Workshop (Chamonix 2016)
28-Jan-2016
Outline

• The baseline HL-LHC upgrade
• How does the full detuning scheme affect crab cavity operation?
• What are the risks/limitations of the baseline?

• Harmonic systems:
  • Alternative A: 200 MHz + 400 MHz
  • Alternative B: 400 MHz + 800 MHz
• Do we need an upgraded transverse damper (ADT)
• Conclusions
Baseline RF systems for HL-LHC (1):

Existing 400 MHz system “ACS-400” (+ Crab Cavities 400 MHz “ACF” + Existing Transverse Damper system “ADT”)

- Nominal beam parameters “HL-LHC 25 ns standard”:
  - \( N_b = 2.2 \cdot 10^{11}, n_b = 2748, I_b = 1.1 \, \text{A}, \, \varepsilon_L = 2.5 \, \text{eVs}, \, \sigma_L = 7.55 \, \text{cm} \).

- ACS-400 nominal:
  - 8 single-cell cavities per beam, 2 MV per cavity, \( \leq 300 \, \text{kW} \) per cavity, CW.
  - Controlled longitudinal \( \varepsilon \) BU by a factor 6 using band-limited phase noise.

- But: 1.1 A beam transient beam loading with half-detuning would require 560 kW per cavity!

- Mitigate using optimal (full) detuning!
  - Reduces required power to \( \leq 200 \, \text{kW} \) per cavity (klystron)
  - Results in bunch arrival time variation by \( \approx \pm 50 \, \text{ps} \) (7.2°, 15 mm)
  - Was tested in past MD’s – still to be fully validated in physics!
Baseline RF systems for HL-LHC (2):

• Since we do not have HL-LHC beam today, we can not yet fully validate beam stability limits, but we’re about OK.

• Subsystems and components (cavities, couplers, amplifiers,...) will age already before and during HL-LHC – this requires an additional effort in maintenance and consolidation.

• The same is true for the Transverse Damper system ADT.
Baseline RF systems for HL-LHC (3):

- **RF Systems Consolidation – ongoing:**
  - Existing spare module fully validated (→ Andy’s talk)!
  - 4 new dressed cavities under development
  - A 2nd spare module is in construction (yes – this is a priority!)
  - P4 cryogenic upgrade in progress
  - Potential replacement of power couplers & HOM couplers (aging, ?)
  - Regular replacement of HV and klystrons ...

K. Schirm, M. Karppinen
Concern: Lifetime of power couplers (FPCs)?

- 16 (variable) high power couplers in operation in LHC, 8 spares available, tested to 330 kW max.
- Start of HL-LHC is in 10+ years → Replacement of couplers!
- Change of FPC takes months!
- Plan to build roughly 1/year now! (necessary consolidation!)

Maximum lifetime before first failure: 15-20 years?

E. Montesinos
Planning ACS-400 MHz (checked with K. Schirm)

- **Ongoing:** Fabrication of 4-8 Spare Dressed Cavities (Fabrication, sputtering, joining, dressing, assembly, tests)!
- **Finish 2nd spare module** – it should be ready after LS2 in case of urgency!
Crab cavity and full detuning

... replying to a question by Oliver Brüning on Monday
Bunch crossing with non-zero X-ing angle
Effect of Crab Cavity
Effect of Crab Cavity with late bunch arrival (symmetric)
No loss of $\mathcal{L}$ to first order – slight transverse offset

$c \, 1 \text{ ns} = 300 \text{ mm}$

$\text{IP}$

$4.5 \, \mu\text{m}$

$c \, 50 \text{ ps} = 15 \text{ mm} = 7.2^\circ \frac{c}{\omega}$

transverse offset: $\frac{\theta c}{2} \Delta \varphi \frac{c}{\omega}$
Effect of Crab Cavity with phase error (asymmetric)

longitudinal offset: $\Delta \varphi \frac{c}{\omega}$

$c \ 50 \text{ ps} = 15 \text{ mm}$
Risks/limitations of baseline
Is the full detuning scheme fully OK for experiments?

We are close to single bunch stability limits for short bunches!

Longitudinal BU with single $h$ system is not very robust.

Have to cope with arrival time variations ±50 ps.
No axial offset of vertex if perfectly symmetric.

Must be tested in 2016!

Short bunches become unstable – at about the expected threshold.

$$Z_{th} \propto \frac{\tau^5}{N_b}$$

LHC impedance will be ≈ 40% larger than today!

Longitudinal BU by noise injection/phase modulation critically depends on equal bunches – bifurcation behaviour observed in MDs!

Philippe, 25-Jan-16

Juan, LIU/HiLumi 15-Oct-15
HL-LHC RF, Harmonic Systems

• *Longitudinal beam stability (voltage ratio = 0.5): min emittance*

<table>
<thead>
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<th>$N_b$</th>
<th>Single RF</th>
<th>BSM</th>
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<td><strong>Alternative A:</strong></td>
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<tr>
<td>6 MV @ 200 MHz</td>
<td>$(2.2 \ldots 2.4) \cdot 10^{11}$</td>
<td>3.25 eVs $(1.8 \text{ ns})$</td>
<td>2.38 eVs $(1.31 \text{ ns})$</td>
<td>0.70 eVs $(1.25 \text{ ns})$</td>
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<td>+ 3 MV @ 400 MHz</td>
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<td><strong>Alternative B:</strong></td>
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<tr>
<td>16 MV @ 400 MHz</td>
<td>$2.2 \cdot 10^{11}$</td>
<td>2.16 eVs $(0.97 \text{ ns})$</td>
<td>1.72 eVs $(0.77 \text{ ns})$</td>
<td>$\sim 0.45$ eVs $(0.65 \text{ ns})$</td>
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<td>+ 8 MV @ 800 MHz</td>
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Alternative A: 6 MV @ 200 MHz (+ 3 MV @ 400 MHz)

- **Main RF System 200 MHz, (λ/4-Cavity, to be studied!)**
  - 4-cavities/beam, $V = 1.5$ MV/cavity, $P \leq 450$ kW
  - Minimum bunch length 1.3 ns,
  - A maximum of 1 ACS-400 module needed (3 MV total)
  - Compatible with 400 MHz crabs $\Rightarrow$ R. Tomas: (-8% @2.2 $\cdot 10^{11}$)

**Interest of this option:**
- New bunch length regime of operation with higher current (1.24 A)
- Could allow to return to $\frac{1}{2}$-detuning if preferred.
- Mitigate e-cloud, RF heating, IBS, SPS-LHC transfer + emittance blow-up
- Facilitate longer bunches injection from SPS ($\Rightarrow$ Brennan’s talk)
- What can SPS deliver? Ready for 2.5 $\cdot 10^{11}$ protons/bunch!
- BL- & BS-modes feasible with existing ACS module as 2nd harmonic
- Allows recapturing with 400 MHz (4 h into physics, when 1.5 $\cdot 10^{11}$ left)!
200 MHz cavities ($\lambda = 1.5$ m!) require R&D!

- First ideas: $\frac{1}{4}$-wave cavities – (smaller than present 400 MHz!)

![Diagram of 200 MHz 4-Cavity Module (3.5m)]

![Diagram of ACS-400 MHz Module (7.037m)]

EJ – RF Upgrade Paths – Chamonix '16
Alternative A (200 MHz) - planning

- **Design & Prototyping phase → Feasibility!**
- **To keep this as a valid option, feasibility study should conclude before LS2!**

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- **RF Design**
- **Single Prototype Cavity**
- **Cryomodule II-IV Production**
- **Installation P4**
- **Engineering Design**
  (CM, Cryo, RF Services)
- **Cryomodule Testing**
Alternative B: (16 MV @ 400 MHz +) 8 MV @ 800 MHz

- **Main RF System ACS-400 + 800 MHz voltages**
- 4 additional cavities/beam, 2 MV/cavity.
  with $V = 1$ MV, $P \leq 80$ kW per cavity (in BS-mode).
- Minimum bunch length 0.6 ns, maximum $\approx 1.4$ ns.

**Interest of this option:**
- Robust emittance blowup with phase modulation
- Could allow to return to $\frac{1}{2}$-detuning if preferred
- Will allow for Landau damping & bunch profile manipulations
- **Caveat:** Realistically only BS-mode feasible
Flat bunches in the “bunch shortening mode”? Encouraging simulation results

Phase noise applied in BS-mode in frequency band \((1.2 \ldots 1.4)f_{s1}\)

16 MV @ 400 MHz, 16 MV @ 400 MHz + 8 MV @ 800 MHz, + noise

\(\tau_{FWHH}: 1.13\) ns \(\rightarrow 1.34\) ns

→ Final bunch is flatter than the initial one in a single RF system!

H. Timkó
Possible Layout

- **800 MHz, 2\textsuperscript{nd} Harmonic**

**4-Tetrodes (~300 kW)**

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Possible Layout

Fits within QRL constraints with a square cryomodule

Front View

Top View

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Preliminary CM Integration in P4

Integration with QRL is feasible with rectangular cryostat
Alternative B (800 MHz) - planning

- **Prototyping Phase**
- **Construction (only 2 modules, one for each beam)**
- **Need conclusive results of prototype by LS2.**

![Timeline Diagram]

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- **Finalize RF Design**
- **Single Prototype Cavity**
- **Cryomodule I-II Production**
- **Installation P4**
- **Engineering Design** (CM, Cryo, RF Services)
- **Cryomodule Testing**
Do we need an upgraded transverse feedback during HL-LHC era?
Transverse feedback – what bandwidth?

- Present ADT: up to 20 MHz (limited to bunch-by-bunch)
- It would be great to suppress TMCI instabilities! Tremendous potential!
- In fact - we’re almost there:
  - We have the MIM (multi-band Instability monitor) – BW: 3.2 GHz
  - We have fast DAC/ADC and signal processing
  - We are developing wideband kickers!
  - We have the LARP collaboration on the wideband feedback system, to be tested in SPS.
- We should continue/intensify this study!

PyHEADTAIL simulation from Kevin’s presentation Monday:
Potential of SPS wideband development for HL-LHC

Wideband feedback system – scaled to LHC

Kevin Li, Oct 2015

- Damper kick strength/voltage:
  - With 5 m space – consider installation of 4 slotline kickers \( V \sim 37 \text{ kV} \) with 2 kW amplifiers at 1 GHz
  - Slotline dimensions are smaller for LHC – can gain a factor 2 in kick strength

- Bandwidth:
  - Slotline dimensions are smaller for LHC – can gain a factor 2 in frequency reach

Options:
1. Extension of current system:
   long stripline at 40 MHz for true bunch-by-bunch damping
2. Band-by-band approach:
   Stripline at 400 MHz in combination with slotlines at 800, 1200, 1600, 2000, 2400,... MHz

The SPS system is the fundamental research platform for the development of the required technology. \( \rightarrow \) all work conducted so far will be crucial to serve as basis for deployment for LHC/HL-LHC.
Conclusions

• The baseline (ACS400 & Crab Cavities & ADT) is valid, but ...
• Consolidation program is part of our plan!
• Risks:
  • Aging of power couplers is not known – prepare for failures!
  • Full detuning not yet fully validated in physics run! 2016!
  • Exact multibunch stability limits are not well known,
  • LHC impedance will increase (crabs, IT, ...) after LS3,
  • Controlled emittance BU with single harmonic RF is touchy.
• To keep the harmonic systems (200 MHz, 800 MHz) as valid options, studies/prototyping must be continued – to conclude before LS2!
• Priority: validate 200 MHz cavity with a prototype – 800 MHz study well advanced – exploit collaborations and synergy with FCC.
• A wideband (3 GHz BW) feedback seems in reach – its potential is tremendous – the study should be continued!
The end