Do we need a Wide-Band Transverse Feedback in the LHC/HL-LHC?

K. Li, W. Hofle, J. Kamppolou, E. Metral

WP2 Meeting, 23. August 2016, CERN
Context:

The HL-LHC upgrade features a **doubling of the nominal LHC intensity together with reduced emittances** with the goal of delivering higher brightness beams to considerably increase the luminosity. **Intensity effects and possible limitations** are likely to become **more pronounced**. For this it will be important to draw up **adequate mitigation measures**. One of the potential options is a **wideband feedback system** which will be discussed more closely here.

Outline:

1. Introduction
2. Instabilities from impedance
3. Instabilities from electron cloud
4. Performance of demonstrator system
5. Specification together with need, capabilities and cost
Context:
Brief outline of what is meant by wideband feedback system.

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Brief description of a wideband feedback system

- Active damping of single or coupled bunch instabilities
- High frequency allows damping of intra bunch motion
- No introduction of additional tune spread
- No introduction of additional non-linearities

- Technically challenging and complex system → close follow-up required during operation
- Imperfections can lead to loss of stabilization (i.e. noise or saturation)
- Impedance contribution of kickers must be addressed
More applications not mentioned:

• Active damping of single or coupled bunch instabilities
• High frequency allows damping of intra bunch motion
• No introduction of additional tune spread
• No introduction of additional non-linearities
• More applications not mentioned:
  • Excitation of intra-bunch motion – measure beam response ➔ diagnostics for impedance, machine optics...
  • Elimination of individual bunches with high selectivity
  • Individual controlled blow-up of bunches
  • ...

Complex system ➔ close follow-up required during operation

• Imperfections can lead to loss of stabilization (i.e. noise or saturation)
• Impedance contribution must be addressed
The present transverse feedback system – “ADT”

• Primarily designed for:
  • Damping of injection oscillations
  • Damping of oscillations driven by coupled bunch instability
  • Important role in preservation of the beam’s transverse emittance

• Since the LHC start in 2008 it grew into (view from the CCC):

- Injection oscillation damping
- Injection cleaning
- Abort gap cleaning
- Transverse blow-up (used for loss maps)
- Instabilities detection (with the damper PU)
- Tune measurement

From D. Valuch, EVIAN 2014
The present transverse feedback system – “ADT”

- **Transverse damper:**
  - operational experience has also shown, it is also absolutely essential for control of instabilities and emittance blow-up for coupled as well as single bunches.

- Since the LHC start in 2008 it grew into (view from the CCC):

  - Injection oscillation damping
  - Injection cleaning
  - Abort gap cleaning

- After switching to optimized settings of the transverse damper – impeccable fill
HL-LHC challenges

• HL-LHC targets for high luminosity:
  • Intensity 1.15e11 → 2.2e11
  • Emittance 3.75um → 2.5 um

• Intensity effects are detrimental for performance:
  • Instabilities
  • Beam-beam tune spread
  • IBS

• Can HL-LHC sustain the high brightness beams without loss of performance?
• Do we require means of additional beam stabilization?
• Impedances:
  • Simulations based on the present HL-LHC impedance model predict that the present means of stabilization (i.e. Landau octupoles and transverse damper) are sufficient to ensure beam stability

• E-cloud:
  • Simulation work is ongoing
  • E-cloud in dipoles: main source of instabilities (at least at flat top) – ‘scrubbable?’
  • E-cloud in quadrupoles: less crucial for instabilities
  • E-cloud in triplets: triplets are coated

• Incoherent effects:
  • Tune spread significant due to high chromaticities and octupoles
  • In addition enhanced by LR and HO collisions
  • Means of compensation are under investigation (i.e. wires)
HL-LHC predictions

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Wideband feedback:
  • Do we need it? Let's tackle this at the end...
  • Can it work? We look at this first...
Context:

We investigate instabilities expected from pure impedance effects and identify whether a wideband feedback system could theoretically provide sufficient cure.

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• The **HL-LHC impedance model**
  • 7 TeV
  • 15 cm beta*
  • 5um Mo and MoC coated TCTs

• Predictions on **single bunch stability** from **PyHEADTAIL simulations**
  • 7 TeV with present impedance model
  • Perfect transverse damper – damping rate 50 turns, single bunch
The **HL-LHC impedance model**

- 7 TeV
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- 5um Mo and MoC coated TCTs

**Predictions on single bunch stability from PyHEADTAIL simulations**

- 7 TeV with present impedance model

**Perfect transverse damper** – damping rate 50 turns

**Impedance and instabilities**

Mode pattern: (0, 2)

Intensity: 2.3e11

23/08/2016

75th HiLumi WP2 Meeting

Kevin Li
Impedance and instabilities

- The **HL-LHC impedance model**
  - 7 TeV
  - 15 cm beta*
  - 5um Mo and MoC coated TCTs

- Predictions on single bunch stability from PyHEADTAIL simulations

- 7 TeV with present impedance model

- Perfect transverse damper – damping rate 50 turns

- Mode pattern: (0, 2)
  - MD example – in LHC, it actually exists!

- Intensity: 2.3e11

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Kevin Li
• The HI-LHC impedance model
  • 7 TeV
  • 15 cm beta*
  • 5µm Mo and MoC coated TCTs

• Predictions on single bunch stability from PyHEADTAIL simulations
  • 7 TeV with present impedance model

• Perfect transverse damper – damping rate 50 turns

Mode pattern: (0, 2)
• Spectrogram reveals frequency components up to 1 - 1.5 GHz for this mode
• Can this mode be damped by a transverse damper and what is the necessary bandwidth?
New PyHEADTAIL Feedback module

- New module to handle the feedback loop.
- Concept of list of abstract signal processors.
- Several pickups and kickers at different positions possible.
- To date – filter functions, delay/registers, noise, gain functions.

J. Komppula
The HL-LHC impedance model

- 7 TeV
- 15 cm beta*
- 5um Mo and MoC coated TCTs

Predictions on single bunch stability from PyHEADTAIL simulations

- 7 TeV with present impedance model
- Perfect transverse damper – damping rate 50 turns

Bandwidth limitation via a 1-pole roll-off TF

Bandpass gain
- 0.001
- 0.01

J. Komppula

23/08/2016
Impedance and instabilities

Bandwidth limitation via a 1-pole roll-off TF

J. Komppula

23/08/2016
- Stabilisation is **achieved with very low gains** – the risetimes at flat top are very long.
- Even for lower cut-off frequencies, the gain around 1 GHz is still sufficient.
- The model includes the frequency roll off **but is ideal in the sense** that there is:
  - No noise
  - No delay
  - Perfect phasing between pick-up and kickers
- We still need to include some margin in these estimates, but a bandwidth of <2 GHz seems reasonable.
Context:
We outline the status and plans for investigating the **impact of electron cloud on beam stability** and how we want to include a **wideband feedback system** into the model.

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E-cloud and instabilities

- Ongoing simulation campaign with PyHEADTAIL + PyECLOUD (G. Iadarola, A. Romano)
- Studying stability limits in dipoles, quadrupoles and the impact of chromaticity, octupoles and, new, also the transverse damper
E-cloud and instabilities

• Ongoing simulation campaign with PyHEADTAIL + PyECLOUD (G. Iadarola, A. Romano)

• Studying stability limits in dipoles, quadrupoles and the impact of chromaticity, octupoles and, new, also the transverse damper

• Simulations in the past have shown chromaticity to be the main stabilizing parameter with octupoles virtually ineffective (K. Li, G. Rumolo, IPAC 2012)

Figure 2: The vertical coherent motion under the influence of electron clouds at an energy of 3.50 TeV for different chromaticities.

Figure 5: The vertical coherent motion under the influence of electron clouds at an energy of 3.50 TeV for different octupole currents.
E-cloud and instabilities

• Ongoing simulation campaign with PyHEADTAIL + PyE CLOUD (G. Iadarola, A. Romano)
• Studying stability limits in dipoles, quadrupoles and the impact of chromaticity, octupoles and, new, also the transverse damper
• Simulations in the past have shown chromaticity to be the main stabilizing parameter with octupoles virtually ineffective at high energies (K. Li, G. Rumolo, IPAC 2012)
• What do we want to learn from these simulations?
  • Identify a possible scenario with limitation from e-cloud
  • Include new feedback module and make a bandwidth – gain study
• Ongoing simulation campaign with PyHEADTAIL + PyECLOUD (G. Iadarola, A. Romano)
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Example from scrubbing runs: in the LHC, it is real!
E-cloud and instabilities

Simulations:
- E-cloud in dipoles with chromaticity
- Horizontal shows strong centroid motion – this can be damped by the conventional system
- Vertical motion shows higher frequency content at ~600 MHz – this cannot be damped by the conventional system
- We will identify a representative scenario and add the new feedback to investigate bandwidth requirements

A. Romano, G. Iadarola
Context:

We briefly describe the **wideband feedback demonstrator system** developed in collaboration with SLAC (within the US-LARP) and highlight some recent MD results that indicate **successful damping of intra-bunch** as an **experimental proof-of-principle**.

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2 stripline kickers + 2 x 2 power amplifiers
Power: 250 W
Frequency range: 5 – 1000 MHz

“The Box”:
Complete processing channel from pickups through kicker, running a
digital reconfigurable system up to 4 GS/s is installed and ready for use
at 3.2 Gs/s. Now includes multi-bunch processing of up to 64 bunches
in any configuration.
Observation in the SPS for Q26 single bunch MDs

• Different shorts:
  • Top: delta signal – bottom: sum signal
  • Yellow: early turns – blue: late turns
Observation in the SPS for Q26 single bunch MDs

• Different shorts:
  - Top: delta signal
  - Bottom: sum signal
  - Yellow: early turns
  - Blue: late turns

H. Bartosik: CERN-THESIS-2013-257
Data from the ADC of the Box

- Intensity $\sim 1.6e11 - 1.8e11$
- Low vertical chromaticity
- Low 200 MHz voltage
- Transverse damper active to remove injection oscillations
Data from the ADC of the Box

Open loop
Data from the ADC of the Box

Closed loop
Context:

Based on what we have learned so far, we investigate **specifications and options for wideband feedback system configurations which are suitable for HL-LHC.**

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Potential location in HL-LHC

Some space was already foreseen for a possible damper upgrade

- ~5m at each side of the ADT,
- gallery with ~10 racks for amplifiers)
Kicker specs – examples from the SPS

Some space (~5m at each side of the ADT) was already foreseen for a possible damper upgrade.

<table>
<thead>
<tr>
<th></th>
<th>$N_{\text{mod}}$</th>
<th>$N_{\text{amp}}$</th>
<th>$P_{\text{amp}}$ (W)</th>
<th>$P_{\text{tot}}$ (W)</th>
<th>$V_{\perp}$ (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100 MHz 250 MHz 500 MHz 750 MHz 1000 MHz</td>
</tr>
<tr>
<td>Striplines</td>
<td>4</td>
<td>8</td>
<td>500</td>
<td>4000</td>
<td>7.6 7.3 6.3 4.9 3.2</td>
</tr>
<tr>
<td>Striplines</td>
<td>44</td>
<td>88</td>
<td>100</td>
<td>8800</td>
<td>37.3 35.9 31.1 23.9 15.5</td>
</tr>
<tr>
<td>Slotline</td>
<td>1</td>
<td>2</td>
<td>500</td>
<td>1000</td>
<td>3.2 3.3 3.6 4.2 4.6</td>
</tr>
<tr>
<td>Slotline</td>
<td>1</td>
<td>2</td>
<td>2000</td>
<td>4000</td>
<td>6.4 6.6 7.2 8.4 9.3</td>
</tr>
<tr>
<td>Slotline</td>
<td>6</td>
<td>12</td>
<td>300</td>
<td>3600</td>
<td>14.8 15.3 16.7 19.4 21.5</td>
</tr>
</tbody>
</table>


LHC would of course require a re-design, that could, however, build on the SPS designs.

- Stripline – 10 cm
- Slotline – 1 m
- +/- 5 m on each side
Wideband feedback system – scaled to LHC

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

Millimetre oscillations can still be damped at reasonable rates.
Wideband feedback system – scaled to LHC

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Wideband feedback system – scaled to LHC

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

... transient effects are usually less critical. If detection level is at the <100 um range, we still get reasonable damping rates.
Wideband feedback system – scaled to LHC

• Damper kick strength/voltage:
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• 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
Wideband feedback system – scaled to LHC

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Instabilities observed in the LHC, typically below 2GHz.
Context:
We answer the question whether a wideband feedback system will be needed for HL-LHC and check how this compares to other mitigation measures such as the RF quadrupole.

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  • In addition enhanced by LR and HO collisions
  • Means of compensation are under investigation (i.e. wires)
Simulations using the impedance model suggest it may not be needed.

Simulations using e-cloud are still in progress.

Simulations rarely include all relevant effects:
- The real machine tells a different story – running at high chroma, instabilities are still observed throughout the cycle (2012, injection, squeeze, adjust, stable beams)
- The tasks is to identify relevant effects and to include them into the simulations (e-cloud, non-ideal transverse damper, or linear coupling as a recent example)
- Symbiosis between observations and simulations will eventually enable to draw a complete picture

Beam stability corresponding to exclusively the pure impedance, as such, was not yet demonstrated in the machine.

We do not know whether there are any hard limits (e.g. minimum SEY, correction limits).

Strategy
- We need to continue to gather experience with the running machine
- We need to in parallel continue R&D on possible mitigation measures to be ready with a system that can be deployed in case nominal performance turns out to be limited or even excluded.
## Comparison of mitigation techniques

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<th>Active feedback</th>
<th>Passive elements (e.g. RF Quad)</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>Control method</td>
<td>Active – resistive feedback</td>
<td>Passive – tune spread</td>
<td>(*) AF: active feedback</td>
</tr>
<tr>
<td>Additional functionality</td>
<td>High</td>
<td>Low</td>
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<tr>
<td>Control method</td>
<td>Active: resistive feedback</td>
<td>Low</td>
<td>By demonstration only, requires setup and understanding, continuous expert support</td>
</tr>
<tr>
<td></td>
<td>Passive: tune spread</td>
<td>Low</td>
<td>Demos modelled, not demonstrated in experiments</td>
</tr>
<tr>
<td>Complexity</td>
<td>High</td>
<td>Low</td>
<td>Not demonstrated so far, over-the-counter, easy to operate</td>
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<tr>
<td>Flexibility</td>
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<td>Low</td>
<td>General purpose, all-round, generic cure for ‘light’ instabilities – but has inherent limits</td>
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<tr>
<td>Concomitant incoh. effects</td>
<td>Noise by design (tune spread)</td>
<td>Low</td>
<td>Demonstration in simulations</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>Fast</td>
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</tr>
<tr>
<td></td>
<td>E-cloud instability</td>
<td>Low</td>
<td>Demonstration in simulations</td>
</tr>
<tr>
<td>Status</td>
<td>Demonstrator system installed in the SPS</td>
<td>Prototype under study / development</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>???</td>
<td>High</td>
<td>Highly configurable and powerful – can forge the ‘ultimate’ cure</td>
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### Which Pill Do You Choose?

- **Yellow Pill**: Gives you the ability to read anybody’s thoughts inside a 100m radius, can only use 5 times a day for a maximum of 30 minutes.
- **Green Pill**: Gives you the ability to fly, can only use 3 times a day for a maximum of an hour.
- **Blue Pill**: Gives you the ability to master any sport of your choice, but toxins in pill only let you live for 10 more years after consumption.
- **Orange Pill**: Gives you the ability to get high without weed, can only use 4 times a day and lasts for 45 minutes.
- **Red Pill**: Gives you the ability to access the internet with your mind, can only use 6 times a day for a maximum of an hour.
- **Pink Pill**: Gives you the ability to shape-shift into anything, can only use 2 times a day for a maximum of 2 hours.
- **Grey Pill**: Gives you the ability to make someone love you with a single touch, can only use 10 times in your lifetime. Can turn on/off.
- **Black Pill**: Gives you the ability to see into the future by a maximum of 5 years, can use anytime, but using your power publicly causes a lot of hassle to your daily life.
Path of choice

- Continue **R&D on kickers** – target for ~2 GHz
- Exploit the **SPS system** for studies and to gain experience
- Amplifiers can still be investigated, to ultimately favour:
  - Full-blown **wideband feedback** for maximum flexibility and gain – expensive and main cost driver
  - **Band-by-band** approach – less flexible but likely the cheaper solution
• We investigated beam instabilities in the HL-LHC from pure impedances and demonstrated numerically that a wideband feedback system can mitigate these instabilities.

• We sketched a path for investigating instabilities in the HL-LHC from electron cloud and how we want to check whether a wideband feedback system can mitigate these instabilities.

• We showed recent examples for an experimental proof-of-principle using the wideband feedback demonstrator system installed in the SPS.

• We sketched possible scenarios of real systems in the machine.

• We presented a strategy on how to proceed with this type of systems and how they compare to an RF quadrupole.
Open questions and future studies

- Include the system in e-cloud simulations.
- Refine the system to add delays, real DSP, noise etc.
- Investigate the impact of noise on the emittance.
- Check saturation effects.
- Any other items linked to this that urgently need to be checked?
BACKUP
HL-LHC impedance horizontal plane – 7 TeV

N. Biancacci
HL-LHC impedance vertical plane – 7 TeV

N. Biancacci

23/08/2016
HL-LHC impedance longitudinal plane — 7 TeV

N. Biancacci

23/08/2016 75th HiLumi WP2 Meeting - Kevin Li 52/50
Data from the ADC of the Box

Open loop

BOX data - SnapShot_07-01-2016-0227

BPM signal

Turn No.  Slice No.

128.  128

2.00e+03  16.0

Fast losses - 2016-07-01 02:27:33

Amplitude [arb. units]

0  20000  40000  60000  80000  100000  120000  140000  160000

BOX data - SnapShot_07-01-2016-0227

Signal [arb. units]

0  2  4  6  8  10  12  14

Deltal signal [arb. units]

-60 -40 -20 0 20 40 60

Channels
Data from the ADC of the Box

Closed loop

BOX data - SnapShot_07-01-2016-0228

BPM signal

128. 128
2.008+03

Turn No. 0.00 0.00  Slice No. 16.0
Do we need it?

- Scalings based on available system in the SPS
- Assuming 1 GHz frequency range based on simulations
- Using slotline kicker with higher power amplifiers
- Other scenarios can be thought of, i.e. slotlines in combination with short striplines
- Kicker design and manufacturing expected to be feasible
- Power amplifiers with specified power over the full frequency range is more challenging
Do we need it? – HL-LHC predictions

- Simulations using the impedance model suggest it may not be needed.
- Simulations using e-cloud are still in progress.
- Simulations rarely include all relevant effects:
  - The real machine tells a different story – running at high chroma, instabilities are still observed throughout the cycle (2012, injection, adjust, squeeze, stable beams)
  - The tasks is to identify relevant effects and to include them into the simulations (e-cloud, linear coupling, non-ideal transverse damper)
  - Symbiosis between observations and simulations will eventually enable to draw a complete picture
- Beam stability corresponding to pure impedance was never demonstrated in the machine.
- We do not know whether there are any hard limits (e.g. minimum SEY, correction limits).
- Strategy
  - We need to continue to gather experience with the running machine
  - We need to in parallel continue R&D on possible mitigation measures to be ready with a system that can be deployed in case nominal performance turns out to be limited or even excluded.
Instability in the machine - LHC

- Stability predictions using the LHC impedance model show good agreement. However...

Courtesy of N. Biancacci, L. Carver

\[ t = 15 - 20 \text{ s} \]
Instability in the machine - LHC

- Stability predictions using the LHC impedance model show good agreement. However...
- Additional effects (e.g. e-cloud) can considerably alter the predicted behaviour

Horizontal instability
Instability in the machine - LHC

- Fill 4642 with uncorrected tune drift → blow-up during injection

- Fill 4643 with tune correction → no blow-up

- Coupling C- for these fills was below 0.004

**Tune separation and coupling correction**
- At injection, when tunes approach each other and coupling is not well corrected, instabilities and **emittance blow-up**.
- The instability mechanism was **studied in simulations** and identified as a **loss of Landau damping**.
- This observation was **confirmed in MDs**.
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<td>Flexibility</td>
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<td>Low</td>
<td>AF: constitutes a programmable impedance</td>
</tr>
<tr>
<td>Concomitant incoh. effects</td>
<td>Noise</td>
<td>By design (tune spread)</td>
<td></td>
</tr>
<tr>
<td>Slow headtail</td>
<td>Demonstrated in simulations</td>
<td>Demonstrated in simulations</td>
<td></td>
</tr>
<tr>
<td>Fast headtail</td>
<td>Demonstrated in experiments</td>
<td>Not demonstrated so far</td>
<td></td>
</tr>
<tr>
<td>E-cloud instability</td>
<td>Demonstrated in simulations</td>
<td>Not demonstrated so far</td>
<td></td>
</tr>
<tr>
<td>Status</td>
<td>Demonstrator system installed in the SPS</td>
<td>Prototype under study / development</td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>???</td>
<td>???</td>
<td></td>
</tr>
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