Update on CERN LHC operation with a focus on the impact of beam dynamics collective effects

Benoit Salvant, for the CERN collective effects team (BE-ABP/HSC)

with a lot of material and help from many CERN colleagues and collaborators

DESY Accelerator R&D Lunchseminar

23rd March 2017
Content

- The LHC complex

- LHC performance

- Impact of collective effects
  - Longitudinal instabilities
  - Transverse instabilities
    - Linear coupling
    - “16L2”
    - Destabilizing effect of transverse damper
  - Beam induced heating
    - Arcs
    - Other devices
    - Issues with PT100 readings

- LHC operation
  - Availability
  - MD Studies
LHC? \rightarrow \text{Large Hadron Collider}

- World’s largest and most powerful particle accelerator:
- 4 large experiments to monitor the collisions
- Thousands of superconducting magnets:
  - Dipoles to bend the beam
  - Quadrupoles to focus the beam
  - Sextupoles and octupoles to keep the single particle, multiparticle and multibunch trajectories stable.
  - Insertion region magnets to make beams collide and squeeze their beam size down to 17 µm.
- 16 RF cavities to accelerate the beam to 6.5 TeV and keep its energy
- 80 collimators to protect the cold magnets from beam losses
- Thousands of monitors to measure beam position, size, losses
- Fast kickers to inject and extract the beams
- Bunch by bunch transverse feedback system to keep bunches on their trajectory.
LHC → Challenges at all levels!!!

- Requires high power and stability from electrical network
- High reliability of the cryogenics system (largest refrigerator of the world)
- Very long magnet quench training campaigns (unexpected)
- Sudden losses attributed to Unidentified Falling Objects (UFO), potentially dust, which cause dumps and quenches and collisions generate significant radiation
  - Increased problems for electronics and access for intervention and visits

- High energy and high intensity beam → high damage power
  → machine protection is a key player

- Running close to collective effects limits:
  - Transverse stability
  - Longitudinal stability
  - Beam induced heating
  - Emittance growth

- Choice of crossing angle
  - Sensitive trade-off between stability, mechanical, dynamic and protected aperture.
Context of CERN and LHC

The LHC footprint superimposed on Paris map

~ 8.4 km

0.4 km

CERN Large Hadron Collider

Jura mountains

Mont Blanc

Lac Léman

Geneva Airport
Context of CERN and LHC

Mont Blanc
Lac Léman
Geneva
Airport

CERN Large Hadron Collider
Jura mountains

The LHC footprint superimposed on Hamburg map

~ 8.4 km
Context of CERN and LHC

View from inside the LHC tunnel

Underground LHC Experiments

“Beam pipes” in which the beam travels

Between 50 and 175 m underground!
CERN complex: not just the LHC

- Antimatter (AD, ELENA)
- Neutrino physics (ex-CNGS)
- Nuclear physics (ISOLDE, n-TOF)
- Precision particle measurements (North Area)
- Environment (CLOUD)
- tests for accelerator hardware (e.g. radiation to materials, detectors, instrumentation, crystal collimation) HIRADMAT

- Project of hadrotherapy research
- Plasma Wakefield acceleration (AWAKE)

... and of course particle physics and high energy frontier with the LHC

- Need to deliver all sorts of primary and secondary beams to these users
- Versatile accelerators with complex manipulations, controls and timings
- Very high power in SPS and LHC, need of stringent machine protection
Context of CERN and LHC: the injector chain

"The journey of a proton in the LHC: from the source to the CMS collision point"

Average proton velocity in fraction of speed of light $c$

- Proton Source: 0 c
- Linac 2: 0.015 c
- PS Booster: 0.31 c
- PS: 0.91 c
- SPS: 0.9993 c
- LHC: 0.999998 c
- (nominal) LHC: 0.999999993 c

→ LHC performance is measured by its luminosity: ability to produce physics events of interest in a given amount of time.
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LHC performance

→ characterized by the luminosity:
  rate of interesting physics events that can be produced

\[ \mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi \sigma_x \sigma_y} \cdot S \]

What can we do to increase luminosity?

→ increase bunch intensities \( N_1 \) and \( N_2 \)
→ increase number of bunches \( N_b \)
→ reduce beam sizes \( \sigma_{x,y} \) at the collision point
  
  \[ \text{[→ reduce transverse emittance or } \beta^*] \]
→ increase luminosity reduction factor \( S \)
  
  \[ S = \frac{1}{\sqrt{1 + \left( \frac{\sigma_s}{\sigma_x} \tan \frac{\phi}{2} \right)^2}} \]

… and maximize time with collisions at highest luminosity
LHC performance

- Despite lower beam energy (4 TeV) and half the number of bunches until the shutdown in 2012, peak luminosity was at 77% of design.
- After LHC restarted in 2015 with 6.5 TeV, peak luminosity in high luminosity experiments surpassed design by more than 50%, and doubled it for two test fills.

From CERN LPC website
LHC performance

- Despite lower beam energy (4 TeV) and half the number of bunches until the shutdown in 2012, peak luminosity was at 77% of design.
- After LHC restarted in 2015 with 6.5 TeV, peak luminosity in high luminosity experiments surpassed design by more than 50%, and doubled it for two test fills.
- The total integrated luminosity since the start of LHC is approaching 125 fb$^{-1}$

→ beyond expectations

Courtesy R. Steerenberg, LHC Operation workshop, Evian 2018
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CERN LHC: a testbed for instabilities

- **Longitudinal instabilities**
  - Single bunch loss of Landau damping instabilities (not limiting)
  - Longitudinal oscillations of colliding pairs (*Las Ketchup*, 2016)

- **Transverse loss of Landau damping** (*rise times of 1 to 10 s*)
  - End of squeeze instability (2012)
  - Snowflakes (2012, beam-beam with offset)
  - Linear coupling with collision tunes (2015)
  - CB$^2$ (coupled bunch coupled beam instability, 2016)
  - Weird B1V instability (2016), weird B1H instability (2017)
  - Popcorn instability

- **Mode coupling instability with colliding beams** (2012, $\sim$1 s, see talk of Xavier)

- **Electron cloud instabilities** ($\sim$1 s)

- **16L2 instability** ($\sim$20 turns)
Main LHC limitations from collective effects

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam induced heating</th>
<th>Longitudinal instabilities</th>
<th>Transverse instabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Impedance</td>
<td></td>
<td></td>
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<tr>
<td>2012</td>
<td>Impedance</td>
<td></td>
<td>Linear coupling + ?</td>
</tr>
<tr>
<td>2015</td>
<td>Impedance addressed during shutdown</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Heating in arcs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2017</td>
<td>Heating in arcs</td>
<td></td>
<td>16L2</td>
</tr>
<tr>
<td>HL-LHC upgrade &gt;2025</td>
<td>Heating in arcs</td>
<td>Bunch length 1 ns $\rightarrow$ 1.2 ns</td>
<td>Impedance reduction of collimators</td>
</tr>
</tbody>
</table>

- **Limited operation**
- **Constrained some parameters**
- **Observed but not limiting**
- **Not observed**
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Longitudinal instabilities

- Have not been limiting so far but could become limiting for HL-LHC

Stability threshold at flat top (6.5 TeV) according to $N_{th} \propto \tau^5$
Longitudinal instabilities

Loss of Landau damping for LHC beams

- Instability observed in 2015 and 2016 during long physics fills
  - Bunch length shrinkage due to synchrotron radiation damping

![Graph showing bunch length evolution, stability threshold, and number of unstable bunches at flat top (6.5 TeV, 2015)]

- Compatible with loss of Landau damping
  - Very good agreement with measured single-bunch threshold
  - No coupled-bunch modes observed
Longitudinal instabilities

- Persistent injection oscillations & instabilities observed
  - Survives the ramp!

H. Timko, LHC operation, Evian workshop 2016, 2017
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Transverse instabilities: impact of linear coupling

- Factor 4 more octupole needed to stabilise in 2012 at end of squeeze.

- Issues in 2015 at injection with emittance blowup when transverse tunes not well separated \(\rightarrow\) Motivated a further study into effect of linear coupling on transverse stability.

- Unstable modes must be within the tune footprint to be Landau damped. Tune spread dominated by octupoles (when not in collisions).

- Bottom left: PyHEADTAIL simulations showing required stabilising octupole current as function of the tune separation for different strengths of global coupling.

- Bottom right: MADX footprint as a function of \(|C^-|\) tracked out to 10sigma.

See L.R. Carver, LHC operation workshop, Evian 2016.
Linear Coupling – Single Bunch Measurement at Flat Top

Can we make a single bunch at flat top unstable using linear coupling?

Before

• Introduced coupling and measured by tune crossing.
• B2H became unstable when moving tunes together despite 283A in octupoles, norm. current of 254A.
• Norm. threshold for no coupling: 63.4A. Expected factor 1.5 increase from PyHT with these settings, measured factor 4.
• Still some work to do!

After

See L.R. Carver, LHC operation workshop, Evian 2016.
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16L2: the main facts

• Since the restart in 2017 after the Christmas stop, abnormal losses were observed in the LHC and were localized near “16L2”.

• With larger stored beam intensities, many beam dumps and a quench occurred, always initiated by large losses in “16L2”.

• Since a beam screen warm-up around “16L2” (August 10th), the situation worsened.

• Now the LHC is limited to 1300 to 1900 bunches (instead of more than 2500) to avoid premature dumps

➔ LHC performance has decreased by 30% to 50% due to “16L2” related dumps
“16L2”? 

- **16L2 → half-cell 16 left of point 2**
- **16L2** is an LHC half cell in the middle of arc 12, made of 3 main dipoles, 1 quadrupole, 1 sextupole and correctors.
- Nothing special compared to other half cells.

![LHC machine](image)

Point 2

Point 1

Arc 12
16L2: the losses
16L2: the losses

BLMs: losses must be either in MCB.16L2 corrector or in QQBI.16L2 interconnect (i.e. between $s=2630.7m$ and $s=2632m$)

→ expect highest energy deposition density in neighboring dipoles (gammas, neutrons)

Courtesy: Anton Lechner (EN-STI), 16L2 task force meeting Sept 5th 2017
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Courtesy: Anton Lechner (EN-STI), 16L2 task force meeting Sept 5th 2017

superposition of several layout drawings
16L2: a complicated loss pattern that links losses and instabilities

- Affecting alternatively both apertures at the same location (while not directly connected) → always B1V or B2H
- Starts like an object entering the beam path (“UFO”)
- Ends up provoking a very fast transverse instability that causes large losses at the collimators and a dump (once a quench)

→ Very few observables (in particular from the vacuum levels)
→ Many exotic theories
Example of instabilities at injection and during the ramp (thanks to BE-RF and BE-BI colleagues for the diagnostics!)

→ ADTObsBox: Impressive propagation of the coherent motion on these few turns
→ Quite clear coupled bunch motion with single bunch positive tune shift

→ Headtail monitor: TMCI-like intra-bunch motion that affects the end of the bunch
16L2: What we think happened?

- During the Christmas shutdown, sector 12 was warmed up to exchange a magnet (in 31L2).
- During the cooldown/pumpdown of the sector an issue with a pump connected to both apertures may have let a large amount of air inside the beam vacuum.
- In cryogenic conditions, air may have frozen and generated flakes that could then interact with the beam.

![Diagram of cryogenic system with labels for plug-in module, cold bore, beam screen, thermal anchor, and pumping port valve.](image)
16L2: attempts at mitigation

- Loss spikes were observed to be correlated to the field of the corrector magnets, and dumps could be prevented with high current in the corrector before the beam screen warm-up took place.
16L2: attempts at mitigation

- Loss spikes were observed to be correlated to the field of the corrector magnets, and dumps could be prevented with high current in the corrector before the beam screen warm-up took place.

- The beam screen warm-up was performed to see if the issue could be solved, but in fact it got much worse. At this point safe operation with more than 1100 bunches was not guaranteed and most fills were dumped during the energy ramp.

  ➔ moments of despair.
16L2: attempts at mitigation

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- The beam screen warm-up was performed to see if the issue could be solved, but in fact it got much worse. At this point safe operation with more than 1100 bunches was not guaranteed and most fills were dumped during the energy ramp.

  → moments of despair.

- A test with 50 ns beam indicated that the situation was better without electron cloud and this was confirmed by using the 8b4e filling scheme and the solenoid, which reduce electron cloud.

![Graph](image.png)
Instability modelling

- For a tune shift of $10^{-2}$, the required electron density is $\sim 5e17 \text{ m}^{-3}$ over 10 cm
  - Estimated based on formula for ion trapping in electron machines
    
- An equivalent broad-band resonator impedance model for an e-cloud
  - Based on F. Zimmermann et al
  - Shunt impedance $R_s = 150 – 500 \text{ MΩ/m}$ at frequency $f_r = 2.6 \text{ GHz}$
  - Could reproduce observed rise time and intra-bunch motion

- Electron cloud simulations confirm that a density of $10^{17} \text{ m}^{-3}$ over 10 cm may lead to
  - A positive tune shift of $10^{-2}$, instability rise times below 100 turns, and intra-bunch motion at the tail of the bunch
Instability modelling

- An electron density of $10^{17}$ m$^{-3}$ over 10 cm can explain several of the observations, but simulations also show that such a large electron density cannot easily be sustained
  - After each bunch passage, when the electrons hit the wall, the density is reduced by several orders of magnitude
  - Need either a mechanism that affects the electron dynamics and/or a recurring source of electrons in the chamber
    → the presence of gas in the chamber can possibly provide both

- Beam-induced ionization generates electrons and an equal amount of ions
  - We cannot yet simulate both species together (work is on-going)
  - Some conclusions can be drawn from simulations with single species

Average electron density, during bunch passage with beam-induced ionization for different gas densities
16L2: happy ending?

- The sector was warmed up during the winter shutdown, and a lot of air came out, confirming the suspicions.
- Fingers crossed!
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Transverse instabilities: impact of transverse damper

- Recent work by E. Métral et al on the destabilizing impact of transverse damper. [https://indico.cern.ch/event/714412/](https://indico.cern.ch/event/714412/)
MOTIVATION

LHC single-bunch instabilities with $Q' \sim 0$ (2015)

Predictions

$\Rightarrow$ 2 questions:

1) What is the (exact) predicted instability mechanism?

2) Is Landau damping well computed (stability diagram $\Rightarrow$ 1-mode approach)?

$L. R. Carver et al.$
NEW VLASOV SOLVER: GALACTIC
(GArnier-LAclaire Coherent Transverse Instabilities Code)

- Approximated model with $Q' = 0$ (no damper)

\[
\begin{pmatrix}
-1 & -0.23 j x \\
-0.55 j x & -0.92 x
\end{pmatrix}
\]

α bunch intensity

TMCI
(Transverse Mode-Coupling Instability)
NEW VLASOV SOLVER: GALACTIC
(GArnier-LAclaire Coherent Transverse Instabilities Code)

- Approximated model with $Q' = 0$
  (with damper: $n_d = 50$ turns)

\[
\begin{pmatrix}
-1 & -0.23 j x \\
-0.55 j x & -0.92 x + 0.48 j
\end{pmatrix}
\]

New ISR instability
(Imaginary tune Split & Repulsion)
IMPACT ON LANDAU DAMPING

1-mode approach (usual stability diagram)
2-mode approach

Required tune spread to reach bunch stability

~ threshold for TMCI (without damper)
CONCLUSION

◆ 1st step: new (single-bunch) instability mechanism => Confirmed and finalised

◆ 2nd step: Landau damping => To be confirmed and finalised
  ▪ Below ~ TMCI intensity threshold (without damper), 1-mode approach (usual stability diagram) seems fine
    • LHC currently operated below TMCI (without damper)
    • In agreement with tracking results (X. Buffat, HSC, 15/01/18)
  ▪ Above ~ TMCI intensity threshold (without damper), 2-mode approach needed => More tune spread required

◆ Seems that destabilising effect of LHC (resistive) transverse damper (alone) cannot explain LHC observations with Q’ ~ 0

=> Another mechanism needs to be identified / added...
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+ interesting work on impact of noise and high bandwidth feedback on stability

Xavier Buffat et Kevin Li
Uneven heat load to arc beam screens

→ Difference between low load and heat load sectors can reach a factor of 2.5
→ If this scales with bunch intensity, there is not enough cooling capacity for HL-LHC
→ In instrumented cells, difference can be narrowed down to 1 good magnet aperture next to a bad one

G. Iadarola et al, LMC August 30
Were the differences always there? – situation before LS1

- A one-week test **period with 25 ns beams took place in 2012**
- We used the raw data recorded at that time **to reconstruct the cell-cy-cell heat load**, that can be directly compared with Run 2 data

**2012** (after 3 d of scrubbing at 450 GeV)

**2017** (after 7 d of scrubbing at 450 GeV)

Differences were not present in 2012!

In the high load sectors, present loads are **4 times larger than before LS1**

More information on 2012 vs Run 2 comparisons can be found [here](#)
Uneven heat load disappears with 50 ns bunch spacing!

→ Clear signature of electron cloud.
→ Nevertheless, can not reproduce such an SEY in the lab
→ We are missing something!

G. Iadarola et al, LMC August 30
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Beam induced RF heating?

- When the LHC beam traverses a device which
  - is not smooth
  - or is not a perfect conductor,
  it will produce wakefields that will perturb the following particles
  \rightarrow resistive or geometric wakefields (in time domain) and impedance (in frequency domain).

- 3D simulation of electromagnetic perturbation caused by an obstacle beam pipe:

  In a round beam pipe

  In a round beam pipe with sharp obstacle
  \rightarrow resonant RF mode
  \rightarrow energy left behind by the bunch
  \rightarrow eventually dissipates in the surrounding walls

\rightarrow Energy lost by the bunch heats up the surrounding walls
Beam induced RF heating?

→ Can be computed from the impedance and the longitudinal beam spectrum

Power lost by a beam of intensity $I_{beam}$ and normalized power spectrum $\lambda^2$ in a device of longitudinal impedance $Z_{long}$

$$P_{loss} = 2 \sum_{f=f_{rev}}^{\infty} \text{Re}[Z_{long}(f)] \times I_{beam}^2 \times \lambda^2(f)$$

For 2248 bunches with 1.15 p/b, we would compute:

- TDI8 in 2015: $P_{loss} \sim 3$ kW
- TDI8 in 2016: $P_{loss}$ barely measurable

Beam spectrum measurement is critical → need to solve recurring hardware problems!
Depending on available cooling at the location of the dissipated power, could lead to problems or not
→ outgassing, structural issues
Reminder: heating issues in LHC before LS1

- **Damaged vacuum modules** → Design not robust
- **Damaged injection collimators** → Design not robust
- **ATLAS-ALFA detector almost reached damage level** → Design not robust
- **One injection kicker delays injection** → Non conformity
- **2 collimators reached temperature interlock dump levels** → Cooling non conformity
- **Spurious temperature readings**
- **One single cryogenic module (Q6R5) has no margin for cooling, likely linked to TOTEM outgassing.** → TOTEM ferrite not baked

→ Many actions taken during LS1 and 2015-2016 YETS by all involved equipment groups!
Actions taken in LS1 and 2015-2016 YETS and outcome

• Shielded and cylindrical **Roman pots** (both ATLAS-ALFA and TOTEM)
  → a lot of margin gained in 2015 for ALFA and no vacuum problems with Q6R5 for TOTEM

• New design for **synchrotron light telescope** (BSRT) *followed up with BI-TB*
  → barely any temperature increase (compared to more than 300C in 2012)

• New **collimator design with ferrite** (TCTP), *followed up with collimation WG*
  → no significant difference observed so far with respect to the design without ferrite

• 2 **collimator cooling non-conformities** were identified and solved.

• **Full shielding of ceramic tube for injection kickers** (MKI) – 24 instead of 15 screen conductors.
  *followed up with MKI strategy meetings*

• Additional **monitoring tools** in CCC

• New **TDI jaws** in copper coated graphite (YETS)
  → *not anymore a limitation*

→ Great success and big relief that new designs have worked so far!
### Beam induced heating status

<table>
<thead>
<tr>
<th>equipment</th>
<th>Problem</th>
<th>2011</th>
<th>2012</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>HL-LHC?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum modules</td>
<td>Damage</td>
<td></td>
<td></td>
<td>VMTSA removed</td>
<td>Spring on VMSI gone</td>
<td>Spring on VMSI gone again</td>
<td>New design underway</td>
</tr>
<tr>
<td>TDI</td>
<td>Damage</td>
<td>Beam screen bent</td>
<td>Beam screen bent</td>
<td>non-conformity with hBN material</td>
<td>vacuum behavior with 55mm gap, could be e-cloud related</td>
<td>New design underway with efficient cooling</td>
<td></td>
</tr>
<tr>
<td>MKI</td>
<td>Wait for injection or reduce intensity</td>
<td></td>
<td></td>
<td></td>
<td>Beam screen upgrade and non conformance solved</td>
<td>Current design marginal, new design underway</td>
<td></td>
</tr>
<tr>
<td>Collimators</td>
<td>Few dumps</td>
<td></td>
<td></td>
<td></td>
<td>Non conformance solved. TCTVB removed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam screen</td>
<td>Regulation at the limit</td>
<td>Q6R5 affected by TOTEM</td>
<td>Q6R5 affected by TOTEM</td>
<td>Upgrade of the valves + TOTEM check</td>
<td>Some sectors heating more</td>
<td>Some sectors heating more (not impedance)</td>
<td></td>
</tr>
<tr>
<td>Roman pots (ALFA and AFP)</td>
<td>Risk of damage and outgassing</td>
<td>ATLAS-ALFA close to limit</td>
<td>ATLAS-ALFA close to limit</td>
<td>New design for ATLAS-ALFA + cooling</td>
<td></td>
<td>Forward physics plans after LS3?</td>
<td></td>
</tr>
<tr>
<td>BSRT</td>
<td>Deformation suspected</td>
<td></td>
<td>Mirror damage</td>
<td>New design + cooling</td>
<td></td>
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<tr>
<td>BGI</td>
<td>vacuum increase</td>
<td></td>
<td></td>
<td>To be followed up</td>
<td>BGI heats up and damaged</td>
<td>BGIs removed</td>
<td>To be followed up</td>
</tr>
</tbody>
</table>

→ Some topics to follow up, but no limitation anymore
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LOCALISATION PT 100 TDI

<table>
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<th>Upstream</th>
<th>Centre</th>
<th>Downstream</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poutre DOWN</td>
<td>T1</td>
<td>T2</td>
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<tr>
<td>Segment hBN DOWN</td>
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<td>Segment Al DOWN</td>
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<tr>
<td>Ecran coté passage</td>
<td>T7</td>
<td></td>
<td>T8</td>
</tr>
</tbody>
</table>
TDI (injection protection collimator)

→ Strong change of temperature readings when changing the jaw gap
Suspicious TDI temperature readings


**Probe on TDI8**

<table>
<thead>
<tr>
<th>Probe</th>
<th>deltaT in 10 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>T3</td>
<td>55 -&gt; 50</td>
</tr>
<tr>
<td>T6</td>
<td>100 -&gt; 68</td>
</tr>
<tr>
<td>T8</td>
<td>47 -&gt; 39</td>
</tr>
<tr>
<td>T7</td>
<td>37 -&gt; 34</td>
</tr>
<tr>
<td>T4</td>
<td>70 -&gt; 45</td>
</tr>
<tr>
<td>T1</td>
<td>43 -&gt; 37</td>
</tr>
<tr>
<td>T2</td>
<td>55 -&gt; 38</td>
</tr>
<tr>
<td>T5</td>
<td>141 -&gt; 59</td>
</tr>
</tbody>
</table>
Impact of bunch length on temperature readings

→ Strong, immediate, inconsistent impact of bunch length on temperature readings
→ Cannot be linked to the massive TDI block heating up
→ What are we measuring?
Content

• The LHC complex

• LHC performance

• Impact of collective effects
  • Longitudinal instabilities
  • Transverse instabilities
    • Linear coupling
    • “16L2”
    • Destabilizing effect of transverse damper
  • Beam induced heating
    • Arcs
    • Other devices
    • Issues with PT100 readings

• LHC operation
  • Availability
  • Levelling schemes
  • MD Studies
Availability: maximization of time with useful collisions for physics

- Minimize downtime due to planned stops
  → planning optimization
- Minimize downtime due to faults
  → identification of major contributors to downtime
  → Accelerator Fault Tracking tool
- Minimize time of all cycle processes, except “STABLE BEAMS”
  → dump, ramp down, injection, ramp, squeeze, adjust
Identification of main contributors

- Accelerator Fault tracking tool
- LHC operation workshop every year to review operation and highlight the major availability issues during the year, and progress of equipment groups.
  → very efficient to motivate equipment groups not to be in the top list of contributors
Timeline of availability working group and accelerator fault tracking

<2012: generally poor data

2012: Availability Working Group (AWG) launched

2013: AWG proposed Accelerator Fault Tracker (AFT) to solve data issues

2014: AFT launched

2015: AFT extensively used for data analysis

2016: AWG began periodic reporting for LHC

2017: AWG began data capture for injectors

B. Todd, Chamonix workshop 2018
Availability week

8b4e all week

TDE access

30cm

Excellent availability also from injectors
8b4e: excellent quality from injectors!

weekly availability: 94.1 %
stable beams 60 %
Clustered Pareto - Fault Duration and Root Cause Duration vs System

Fault Duration = Integrated fault time logged

Root Cause Duration = Corrects for dependencies parent / child / shadow

B. Todd, Chamonix workshop 2018
### Top Faulty Systems

<table>
<thead>
<tr>
<th>Root Cause System</th>
<th>Root Cause Duration [h]</th>
<th>% of Total Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector Complex</td>
<td>140.2</td>
<td>17.5</td>
</tr>
<tr>
<td>Cryogenics</td>
<td>107.7</td>
<td>13.5</td>
</tr>
<tr>
<td>Power Converters</td>
<td>98.9</td>
<td>12.3</td>
</tr>
<tr>
<td>Quench Protection</td>
<td>63.8</td>
<td>8.0</td>
</tr>
<tr>
<td>Beam Dumping System</td>
<td>60.6</td>
<td>7.6</td>
</tr>
</tbody>
</table>

= 471.2 hours = 58.8%

B. Todd, Chamonix workshop 2018
Minimize time of all cycle processes

Time to minimize

Mode breakdown in 2017

Fault / Downtime 19%
Operations 30%
Pre-Cycle 2%
Stable Beams 49%

Mode breakdown in 2016

Fault / Downtime 26%
Operations 23%
Pre-Cycle 2%
Stable Beams 49%
Example: minimizing ramp time

→ Ramp time **to 6.5 TeV** in 2017: 1210 s (20 min), including beta* squeeze
→ Plan to decrease ramp time to 1100 s in 2018.

M. Solfaroli, Evian workshop 2013
2016 vs 2017 Turnaround

B. Todd, Chamonix workshop 2018
Content

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- LHC operation
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  - MD Studies
Maximize integrated luminosity

- Luminosity decreases during a fill (hopefully mainly due to proton burn off)
  - Find and operate at the optimal fill length after which it is better to dump the fill and reinject
- Use leveling schemes to increase luminosity during the fill while staying in “stable beams”
  - let bunch length naturally reduce during fills (bunch length levelling needed to keep luminous region constant in certain conditions)
  - crossing angle reduction during fills used in 2017
  - beta* leveling during fills tested in MD in 2017, to be put in operation in 2018
2016 vs 2017 Stable Beams

End of Fill Stable Beams Duration Histogram

Aborted Fill vs End of Fill Stable Beams Duration Histogram

B. Todd, Chamonix workshop 2018
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• LHC operation
  – Availability
  – Levelling schemes
  – MD Studies
Organization of MDs

• 2 Working Groups with the mandate to organize and prioritize machine studies (“machine development”: MDs): one for injectors, one for LHC

• Set up is quite different for LHC and other machines:
  – In LHC, no possibility for parallel studies: 3 or 4 MD sessions of 4 to 5 days per year (24/7).
  – In injectors, parallel studies on short supercycles are possible + dedicated MDs for studies that require longer supercycles or hardware incompatible with standard operation (ex: insertion in-beam of goniometers, crab cavities for HL-LHC studies in SPS or COLDEX, a set-up to test beam pipes at cryogenic temperatures).
# Summary Table 2018 - 2017 - 2016

<table>
<thead>
<tr>
<th>Phase</th>
<th>2018</th>
<th>2017</th>
<th>2016</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Days</td>
<td>Ratio [%]</td>
<td>Days</td>
</tr>
<tr>
<td>Comm. &amp; Intensity ramp up</td>
<td>34**</td>
<td>14.1</td>
<td>35</td>
</tr>
<tr>
<td>Scrubbing</td>
<td>1</td>
<td>0.4</td>
<td>7</td>
</tr>
<tr>
<td><strong>25 ns Proton Physics</strong></td>
<td>124</td>
<td>51.4</td>
<td>127</td>
</tr>
<tr>
<td>Special Physics Runs</td>
<td>17</td>
<td>7.0</td>
<td>18</td>
</tr>
<tr>
<td>Setting up Pb-Pb ion run</td>
<td>4</td>
<td>1.7</td>
<td>-</td>
</tr>
<tr>
<td>Pb-Pb ion run</td>
<td>24</td>
<td>10.0</td>
<td>-</td>
</tr>
<tr>
<td>Machine Developments (MD)</td>
<td>20</td>
<td>8.3</td>
<td>18</td>
</tr>
<tr>
<td>Technical Stops (3x)</td>
<td>13</td>
<td>5.4</td>
<td>8</td>
</tr>
<tr>
<td>Technical Stop Recovery (3x)</td>
<td>4</td>
<td>1.7</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>241</td>
<td>100</td>
<td>217</td>
</tr>
</tbody>
</table>

**Integrated luminosity [fb⁻¹]**

- 2018: ~58
- 2017: 50.2
- 2016: 39.7

* Did not fully include intensity ramp up – interleaved commissioning and interleaved intensity ramp up was as of 2017
** With 1200 bunches per beam, previously with 3 bunches
LHC schedule 2018
Version 1.2
Injector schedule 2018
Outlook

• LHC in production mode
  – optimizing all processes to harvest as much integrated luminosity as possible

• High luminosity LHC and LHC injectors upgrade are knocking at the door.
  – Exciting challenges for collective effects!

• Studies in parallel to increase beam energy in order to probe new physics:
  – FCC: 100 km tunnel filled with 16 T dipole magnets $\rightarrow$ 100 TeV p-p collider
  – HE-LHC: LHC tunnel with 16 T dipole magnets $\rightarrow$ 27 TeV p-p collider
Many thanks for your attention!
Comparison between range of relevant machine parameters at ALS, SOLEIL, PETRA and CERN LHC complex

<table>
<thead>
<tr>
<th>Machine</th>
<th>RMS Bunch length</th>
<th>Transverse emittance</th>
<th>Intensity/bunch</th>
<th>Number of bunches</th>
<th>Total intensity</th>
<th>Frev</th>
<th>Beam freq</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOLEIL</td>
<td>~20 ps</td>
<td>3.9 nm.rad</td>
<td>1.36+5 mA</td>
<td>312+1</td>
<td>0.4 A</td>
<td>846 kHz</td>
<td>350 MHz</td>
</tr>
<tr>
<td>ALS</td>
<td>50 to 60 ps</td>
<td>0.03-2 nm.rad</td>
<td>~2 -17.5 mA</td>
<td>284</td>
<td>0.5 A</td>
<td>1520 kHz</td>
<td>500 MHz</td>
</tr>
<tr>
<td>PETRA III</td>
<td>44 ps</td>
<td>0.012-1.2 nm.rad</td>
<td>0.1 mA</td>
<td>960, 480,40</td>
<td>0.1 A</td>
<td>130 kHz</td>
<td>500 MHz</td>
</tr>
<tr>
<td>ALS-U</td>
<td>120 ps</td>
<td>0.05 nm.rad</td>
<td>~2 mA</td>
<td>284</td>
<td>0.5 A</td>
<td>1520 kHz</td>
<td>500 MHz</td>
</tr>
<tr>
<td>LHC</td>
<td>~270 ps</td>
<td>~2000 nm.rad</td>
<td>~0.25 mA</td>
<td>~2000</td>
<td>~ 0.5 A</td>
<td>11 kHz</td>
<td>20 or 40 MHz</td>
</tr>
<tr>
<td>SPS</td>
<td>300 to 1000 ps</td>
<td>~2000 nm.rad</td>
<td>0.25 mA</td>
<td>~200</td>
<td>~0.05 A</td>
<td>44 kHz</td>
<td>20 or 40 MHz</td>
</tr>
<tr>
<td>CLIC damping ring</td>
<td>6 ps</td>
<td>4.8 nm.rad</td>
<td>0.4 mA</td>
<td>312</td>
<td>0.1 A</td>
<td>700 kHz</td>
<td>1 GHz</td>
</tr>
</tbody>
</table>

→ Very different range of parameters!
→ Range of frequencies excited by the bunch is much larger in light sources, compared to LHC
→ Task is much more difficult for simulations and bench measurements
Content

- Context
  - The LHC complex

- Update on LHC operation
  - Availability
  - Machine protection
  - Studies

- Impact of collective effects
  - Instabilities
  - Beam induced heating
Update on LHC operation
Content

- **Context**
  - The LHC complex

- **Impedance models**
  - Impedance
  - Impedance models
  - Procedure for hardware installation at CERN
  - Building the model
  - Examples for CERN machines

- **Methods used by the impedance team to assess impedances**
  - Theories
  - Simulations
  - RF measurements on testbench
  - Measurements with beam

- **Main questions and issues for the future**
Impedance?

- When a beam of particles traverses a device which
  - is not smooth
  - or is not a perfect conductor,
  it will produce electromagnetic wakefields that will perturb the following particles

  → wakefields (in time domain) or impedance (in frequency domain).

- Example of wakefield perturbation caused by an obstacle in a beam pipe:

  ![In a smooth beam pipe](image1)

  ![In a beam pipe with a sharp obstacle](image2) → resonant RF mode

Impact of impedance?

1) Energy is lost by the beam
2) Resonant kicks to following particles

→ Are these impedance perturbations an issue?
Impact of impedance?

1) Energy is lost by the beam → dissipated in surrounding chambers → beam induced heating
2) Resonant kicks to following particles → instabilities → beam loss and blow-up

→ More beam intensity → more perturbations → more damage and beam quality issues
→ Impedance is a critical limit to increase the performance of several CERN accelerators
→ Requires strict follow-up and support → mandate of the impedance working group at CERN
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- **Main questions and issues for the future**
What is an impedance model?

- Also called “impedance budget”

- Gives the necessary information on the status of criticality of the impedance of a machine with respect to beam dynamics thresholds

- Depending on the need, an impedance model can be anything between:
  - A single number (for instance \(\text{Im}(Z/n)\) at low frequency),
  - And an elaborated tool that is able to recompute many impedance contributions as a function of frequency and related thresholds with slight changes of machine configuration

<table>
<thead>
<tr>
<th>element</th>
<th>Ref.</th>
<th>(b)</th>
<th>(\text{Im}(Z/n))</th>
<th>(\text{Im}(Z_1))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping slots</td>
<td>[23]</td>
<td>18</td>
<td>0.017</td>
<td>0.5</td>
</tr>
<tr>
<td>BPM’s</td>
<td>[24]</td>
<td>25</td>
<td>0.0021</td>
<td>0.3</td>
</tr>
<tr>
<td>Unshielded bellows</td>
<td></td>
<td>25</td>
<td>0.0046</td>
<td>0.06</td>
</tr>
<tr>
<td>Shielded bellows</td>
<td></td>
<td>20</td>
<td>0.010</td>
<td>0.265</td>
</tr>
<tr>
<td>Vacuum valves</td>
<td></td>
<td>40</td>
<td>0.005</td>
<td>0.035</td>
</tr>
<tr>
<td>Experimental chambers</td>
<td></td>
<td>-</td>
<td>0.010</td>
<td>-</td>
</tr>
<tr>
<td>RF Cavities (400 MHz)</td>
<td></td>
<td>150</td>
<td>0.010</td>
<td>(0.011)</td>
</tr>
<tr>
<td>RF Cavities (200 MHz)</td>
<td></td>
<td>50</td>
<td>0.015</td>
<td>(0.155)</td>
</tr>
<tr>
<td>Y-chambers (8)</td>
<td>[25]</td>
<td>-</td>
<td>0.001</td>
<td>-</td>
</tr>
<tr>
<td>BI (non-BPM instruments)</td>
<td></td>
<td>40</td>
<td>0.001</td>
<td>0.012</td>
</tr>
<tr>
<td>space charge @injection</td>
<td>[2]</td>
<td>18</td>
<td>-0.006</td>
<td>0.02</td>
</tr>
<tr>
<td>Collimators @injection optics</td>
<td></td>
<td>4.4 ± 8</td>
<td>0.0005</td>
<td>0.15</td>
</tr>
<tr>
<td>Collimators @squeezed optics</td>
<td></td>
<td>1.3 ± 3.8</td>
<td>0.0005</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>TOTAL broad-band @injection optics</strong></td>
<td></td>
<td></td>
<td>0.070</td>
<td>1.34</td>
</tr>
<tr>
<td><strong>TOTAL broad-band @squeezed optics</strong></td>
<td></td>
<td></td>
<td>0.076</td>
<td>2.67</td>
</tr>
</tbody>
</table>

LHC design report, chap 5

SPS dipolar and quadrupolar impedance model in 2012

C. Zannini
Why build an impedance model?

- **Estimate the intensity/brightness limits** of new projects and existing accelerators
  - With respect to single bunch and coupled bunch instability thresholds
  - All new projects ask at a very early stage for an estimate of the impedance budget (e.g. ZBASE for LHC, HPPS, TLEP, FCC).

- **Identify large impedance contributors** that could be optimized to improve the performance of existing accelerators

- Design standardized tools to objectively **estimate the criticality of impedance of existing and foreseen hardware**
  - → help the “impedance police” make informed decisions
  - → predict beam induced heating

---

Re(Zydip) for LHC

TMCI thresholds for LHC and HL-LHC

Plots taken from N. Mounet et al
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  - Measurements with beam

- Main questions and issues for the future
Procedure to accept/reject installation of new devices in machines at CERN

- Needs to put a request for installation for all new devices in the tunnel, that has to be signed and agreed by all parties, in particular safety, radiation protection, vacuum, aperture, and now impedance.

- Document is circulated electronically for 2 weeks, before its status is reviewed one by one by managerial committees.

- Consequences for impedance team:
  - Need to take responsibility for the possibility to modify the machine
  - Need efficient tools to be able to answer very fast on the predicted impact on the performance and protection of the machine:
    - longitudinal stability for single bunch and coupled bunch,
    - transverse stability for single bunch and coupled bunch,
    - beam induced heating to the device itself, and maybe also neighboring devices
  - Need objective criteria to accept or reject the installation of new devices
Procedure put in place by the CERN impedance team to address these requests

- Ask for geometry (3D models, drawings) and material properties.
- Decide which code to use:
  - Analytical models for simple geometries (ImpedanceWake2D for round/flat chambers)
  - 2D models for axisymmetric geometries (ABCI, ECHO)
  - 3D models for more complex geometries (CST, GdfidL, ACE3P) ⇒ most of the cases unfortunately
- Obtain all impedance contributions as a function of frequency (up to XXX GHz):
  - Longitudinal
  - Horizontal (dipolar, quadrupolar)
  - Vertical (dipolar, quadrupolar)
  - Coupled terms (if needed, dipolar, quadrupolar)
- Discuss the results, margins, critical points (RF fingers contact, potential non-conformities) with impedance experts
- Give decision to approve/reject for the Engineering Change Request
- Validate the installation through bench impedance measurements compared to simulated

⇒ Lot of studies required, and difficult to answer correctly in two weeks!
⇒ Requires industrial tools and industrial organization
⇒ Unavoidable conflicts between answering to numerous urgent requests and continuing research

N. Mounet
Content

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  - Simulations
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  - Measurements with beam

- Main questions and issues for the future
How to build a longitudinal impedance model?

1. Identify main impedance contributors
2. Assess impedance of individual elements
3. Sum the impedance contributions
4. Longitudinal impedance model
5. Compute beam observables
6. Measurements of observables with bench

Is there agreement?

If not (most of the time), need to reconsider...
How to build a transverse impedance model?

1. Identify main impedance contributors
2. Assess impedance of individual elements
3. Sum the weighted impedance contributions
4. Measure the transverse impedance model
5. Compute beam observables
6. Measure observables with bench
7. Measure observables with beam

Is there agreement?

If not (most of the time), need to reconsider...

Machine optics (β functions)
There are challenges at all levels!

**Identify main impedance contributors**

**Assess impedance of individual elements**

**Sum the weighted impedance contributions**

**Transverse impedance model**

**Compute beam observables**

---

**Do we know the machine well enough?**
- Some changes sometimes not well recorded
  → Layout database not up to date
- Non conformities, damage, ageing → unexpected high impedances

---

LHC RF fingers

Conform

Non-conform: reduction of aperture with increase of contact resistance

---

O. Kononenko et al, IPAC13

---

Conform

Non conform

---

Courtesy CERN TE-VSC
There are challenges at all levels!

**Identify main impedance contributors**

**Assess impedance of individual elements**

**Sum the weighted impedance contributions**

**Transverse impedance model**

**Compute beam observables**

---

**Do we know the machine well enough?**
- Some changes sometimes not well recorded → Layout database not up to date
- Non conformities, damage, ageing → unexpected high impedances
- Napolitan proverb: “Many small impedances make large tune shift”
- It takes a while to cover all hardware in large machines

---

**Example of the step transitions in SPS (C. Zannini, J. Varela et al)**

<table>
<thead>
<tr>
<th>Flange Type</th>
<th>Num. of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPV-QD</td>
<td>90</td>
</tr>
<tr>
<td>BPH-QF</td>
<td>39</td>
</tr>
<tr>
<td>QF-MBA</td>
<td>83</td>
</tr>
<tr>
<td>MBA-MBA</td>
<td>14</td>
</tr>
<tr>
<td>QF-QF</td>
<td>26</td>
</tr>
<tr>
<td>QD-QD</td>
<td>99</td>
</tr>
<tr>
<td>QF-QF</td>
<td>20</td>
</tr>
<tr>
<td>BPH-QF</td>
<td>39</td>
</tr>
<tr>
<td>QD-QD</td>
<td>75</td>
</tr>
<tr>
<td>QD-QD</td>
<td>99</td>
</tr>
</tbody>
</table>

---

Small contribution, but many steps!
There are challenges at all levels!

1. Identify main impedance contributors
2. Assess impedance of individual elements
3. Sum the weighted impedance contributions
4. Transverse impedance model
5. Compute beam observables

Can we compute the impedance of a given device correctly?
- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code
There are challenges at all levels!

1. **Identify main impedance contributors**
2. **Assess impedance of individual elements**
3. **Sum the weighted impedance contributions**
4. **Transverse impedance model**
5. **Compute beam observables**

**Can we compute the impedance of a given device correctly?**
- Non-conformities, damage, ageing
- Many limitations of the calculation/simulation code

**→ Limitation in the number of mesh cells**
- Requirement to often drastically simplify the structure
- Decision to remove many details.
- Ideally we should check that every removal does not change the result, but it is not always possible.

**CATIA model for wire scanner**

**Model for 3D simulations**

→ Very important to get validation by comparing bench measurements with simulated bench measurements (with wires and probes)
There are challenges at all levels!

- Identify main impedance contributors
- Assess impedance of individual elements
- Sum the weighted impedance contributions
- Transverse impedance model
- Compute beam observables

Can we compute the impedance of a given device correctly?
- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code

→ Limitation in number of mesh cells
→ Limitation in the maximum frequency

- Not an issue for analytical codes
- Severe limitation for 3D wakefield codes as minimum exciting bunch length related to mesh cell dimension

→ Central question for an impedance model: What is the required maximum frequency?

Several answers:
- Assumed to be linked to the maximum significant frequency of the longitudinal beam spectrum (1-10 fmax?)
- Choose so that the discretization that can be used in the beam dynamics code (100 to 1000 slices per bunch)
- Most of the time: the best we can do with the 3D code

Ideally, a convergence should be found for the whole chain down to the beam dynamics, but again very cumbersome to perform.
There are challenges at all levels!

- Identify main impedance contributors
  - Can we compute the impedance of a given device correctly?
    - Non conformities, damage, ageing
    - Many limitations of the calculation/simulation code

- Assess impedance of individual elements
  - Limitation in number of mesh cells
  - Limitation in the maximum frequency
  - Limitation in the applicability of the code

- Sum the weighted impedance contributions
  - Many codes or features do not work when $\beta < 1$

- Transverse impedance model
  - Many analytical formulae are only valid in a limited range of frequencies and for simple geometries: e.g. thick wall formula (see talk of N. Mounet), formulae for striplines, bellows, Tsutsui/Wang models for kickers, etc.

- Compute beam observables
  - Can we accurately account for connection to external circuits with long cables with 3D models? E.g. kicker and septum plates connection to power supply.
  - Need to separate the dipolar/quadrupolar impedances with the eigenmode solver in non symmetric structures.
  - Recent significant effort in treatment of dispersive materials in both wakefield and eigenmode solvers. Thanks to CST, TEMF and GdfidL!
  - Difficulty to account for coatings in 3D codes.
There are challenges at all levels!

Identify main impedance contributors

Assess impedance of individual elements

Sum the weighted impedance contributions

Transverse impedance model

Compute beam observables

Can we compute the impedance of a given device correctly?
- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code

Limitation in number of mesh cells
Limitation in the maximum frequency
Limitation in the applicability of the code
Limitation when the impedance is very small

- non-physical behaviour (in particular in transverse plane)

→ Not a problem if there is only one device.
→ How about when there are ~1000 of these devices, or when the beta function at their location is very large?
→ What do we do when we can not use ECHO2D or reduce the mesh in GdfidL?

A. Blednykh, TWICE workshop, January 2014

comparison between GdfidL, CST and ECHO for tapered collimator
There are challenges at all levels!

Can we compute the impedance of a given device correctly?
- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code
- Limitation in the knowledge of the materials and geometry

- Electromagnetic properties of material up to several GHz are usually not a specification and may fluctuate from batch to batch.
- Problem with non isotropic materials (depends on manufacturing process).
- Thickness of thin coatings is not always well controlled.

μ’’ as a function of frequency for samples of TT2-111R ferrites with and without heat treatment

Courtesy Christine Vollinger (CERN)
There are challenges at all levels!

Can we compute the impedance of a given device correctly?
- Non conformities, damage, ageing
- Many limitations of the calculation/simulation code
- Limitation in the knowledge of the materials
- **Impedance of active devices**

- How to account for active feedback on main cavity mode?
- The active feedback acts on the fields around the main mode
- Proposal: keep the same R/Q of the mode, but strongly decrease both R and Q, as beam induced fields at the frequency of the main cavity mode should be damped very fast by the feedback (but not far from this frequency).

- The low frequency component is mostly unchanged, and so should be the single bunch behaviour.
- Can we assume that a damped mode still follows the resonator model?
How to build a longitudinal impedance model?

1. Identify main impedance contributors
2. Assess impedance of individual elements
3. Sum the impedance contributions
4. Measurements of observables with bench
5. Longitudinal impedance model
6. Compute beam observables

Main issue: the probing device perturbs the fields (wire, coil, bead, antenna, loop):
- Difficult to be quantitative
- Not always comparable to simulations
- Would advise performing simulated measurements
There are challenges at all levels!

**Can we aggregate the impedance contributions correctly?**

- Several contributions coming from various analytical or simulation codes
- Results can be in wake functions, “wake functions”, impedances, eigenmode tables
- If beam dynamics tool requires a single bunch wake as input
  → short wake length is ok, but needs small bunch (HEADTAIL single bunch)
- If beam dynamics tool requires a broadband impedance as input
  → long bunch is ok but needs long wake length (Sacherer formula)
- If beam dynamics tool requires both low and high frequency content
  → need for non equidistant FFT to transform impedance into wake
    (see N. Mounet’s PhD, EPFL 2012)
  → need both short bunch and long wake length (Headtail multibunch, DELPHI)
  → when resistive contribution is negligible, can use results of eigenmode
  → when resistive wall contribution is large, better to use wakefields
- Interpolation is required to sum contributions. If many modes and many resonances, the number of points in the wake or in the impedance can be very large (O(10^5) for LHC).
- Requires accurate knowledge of the beta functions of all devices
There are challenges at all levels!

Question:
Should we avoid the direct use of wake functions extracted from simulated wake potential, and fit the impedance by sum of resonators? (as done by several labs)

Advantage of using sum of resonators:
- The wake should respect causality and numerical noise can be avoided
- The number of resonators is not a limitation, but the fit itself is an issue when there are too many peaks

Disadvantage:
- What do we do when the resonator model is not applicable (dispersive materials, β<1)?
- If other contributions to low frequency impedance, how can we account for them?

→ For large machines, these operations cannot be performed “by hand”.
→ Need for an impedance database to store impedance results
→ Need for scripts to efficiently recompute impedances, sum them and plot them as scan of parameters are often needed (optics, collimator aperture, addition of new device)
There are challenges at all levels!

→ Many challenges and traps before reaching an impedance model!

→ Despite these difficulties, there are many impedance models available!

Identify main impedance contributors

Assess impedance of individual elements

Sum the weighted impedance contributions

Transverse impedance model

Compute beam observables

**KEKB low energy ring**

**DAΦNE longitudinal impedance,**
S. Bartalucci et al (1993)

Figure 3. Total longitudinal wake potential for the KEKB LER.

Fig. 11. Imaginary and real part of DAΦNE main ring impedance with superimposed bunch spectrum (solid line).
There are challenges at all levels!

→ Many challenges and traps before reaching an impedance model!

- **Vertical model of APS**
  Y.C. Chae (PAC07)

- **MAXIV longitudinal model**
  (M. Klein, R. Nagaoka et al, IPAC13)

- **ALBA horizontal model**
  T., Guenzel (ESLS 2010)

- **SPS vertical model**
  (C. Zannini et al, )

- **Identify main impedance contributors**

- **Assess impedance of individual elements**

- **Sum the weighted impedance contributions**

- **Transverse impedance model**

- **Compute beam observables**
There are challenges at all levels!

→ Many challenges and traps before reaching an impedance model!

**Identify main impedance contributors**

**Assess impedance of individual elements**

**Sum the weighted impedance contributions**

**Transverse impedance model**

**Compute beam observables**

SPS longitudinal model
J. Varela et al (2014)

Longitudinal model of TPS project
A. Rusanov, EPAC08

HL-LHC horizontal model
N. Mounet et al (2014)

PS vertical model
S. Persichelli et al (TDR PS, 2014)
Content

• Context
  – The LHC complex

• Impedance models
  – Impedance
  – Impedance models
  – Procedure for hardware installation at CERN
  – Building the model
  – Examples for CERN machines

• Methods used by the impedance team to assess impedances
  – Theories
  – Simulations
  – RF measurements on testbench
  – Measurements with beam

• Main questions and issues for the future
PSB transverse impedance and instabilities

Comprehensive talk by C. Zannini and G. Rumolo (BE-ABP/HSC) at the LIU-PSB Meeting 125, 24 May 2015:

Present PSB transverse impedance model

- Elements included in the database:
  - Analytical calculation of the relative wall impedance that takes into account the different PSB vacuum chambers weighted by the respective length and beta function. Also the iron in the magnet is taken into account.
  - Extraction kicker
    - Impedance due to the finite loaded structure
    - Impedance due to the coupling to the external circuits (analytical calculation)
  - Indirect space charge impedance
  - Broadband impedance of step transitions
  - KSW magnets

Vertical tune shift at 160 MeV in ring2

Status

→ Impressive improvement to the impedance model with non trivial contributions (e.g. β<1, coating, external circuit, indirect space charge for PSB chamber shapes, RF bypass).
→ Very good agreement between computations and tune shifts at 160 MeV.
Simulations agree with tune shift measurements at 2 GeV and 26 GeV.

More work needed in particular to understand the dependence of chromaticity

The transverse impedance model of the PS is fully validated by simulation and beam based measurement!

- Measurement and simulation are in excellent agreements (almost 100%) at 2 and 25 GeV!
- At 7 and 13 GeV measurement and simulation are in very good agreement (70-80%)
- Coupling is decreasing with the beam energy: measurement at 7 GeV were probably affected!
SPS longitudinal impedance and instabilities

Many extensive talks by J. Varela, T. Argyropoulos and A. Lasheen et al at the LIU-SPS-BD.

Impedance model

Simulated and measured instability threshold

Status

→ Impressive progress in the last few years: improved impedance model and good agreement between simulations and measurements with single bunches.

→ Limited by coupled bunch instabilities → bellows and flanges targeted by impedance reduction campaign

Is the baseline enough to have the LIU beam stable? → macroparticle simulations
Assessing the impact of reducing the impedance of several elements

Simulations of longitudinal instability threshold with 24 bunches

Double RF at flat top $V_{200} = 7$ MV with full impedance model:

- TW cavities and HOMs
- Kickers
- Vacuum flanges
- Unshielded pumping ports
- BPMs
- Y chambers
- beam scrapers
- resistive wall
- space charge

$\rightarrow$ Tedious simulations
$\rightarrow$ Several parameters are idealized (effective 800 MHz phase and voltage, feedback, no ramp, phase loop)
$\rightarrow$ Should be used as sensitivity analysis, but ... measured thresholds are not far!

$\rightarrow$ HL-LHC beam clearly unstable, and there is margin for nominal LHC beam
$\rightarrow$ Margins are smaller in measurements than simulations (~20%)
Assessing the impact of reducing the impedance of several elements

Baseline: elliptical flange shielding + reduced HOM of TW cavities at 630 MHz

→ HL-LHC beam barely stable, no margin with 7 MV
Assessing the impact of reducing the impedance of several elements

Baseline together with shielding injection kickers MKP

→ Significant margin increase with 7 MV
SPS longitudinal impedance and instabilities

Baseline + MKPs + damping all remaining HOMs + shielding MKPs and circular flanges

→ Even more margin increase for LIU beam with 7 MV
Impact of not using double RF

Even with impedance reduction, the nominal beam is expected to be unstable without double RF.
SPS transverse impedance and instabilities

Comprehensive talks and papers by C. Zannini et al (IPAC’15, MSWG).

Status
→ Impressive progress in the last few years: improved impedance model and successful comparison with single bunch measurements for tune shift and headtail instability growth rates.
→ Switch to Q20 optics removed the TMCI bottleneck and improved stability in general.
LHC impedance model

The impedance model contains contributions from collimators, beam screens, warm beam pipe and a broadband impedance model (from design report).

Longitudinal impedance model at 450 GeV

Transverse impedance model at 4 TeV

→ Studies in 2015 and 2016 have identified the important role played by electron cloud, non linear chromaticity and linear coupling and in the transverse stability of the LHC beam.
2017 stability scenarios

Beam and machine parameters:

- Single nominal bunch of 1.2e11 ppb in 2um emittance.
- Gaussian and parabolic (3.2 sigma cut) transverse profiles.
- Positive octupole sign.
- Variable bunch-by-bunch damper gain.

\[ \text{Gaussian: } \sim 150A, \text{ Parabolic: } \sim 175A \text{ max for } Q' \text{ in (5-15)}. \]

N. Biancacci et al.
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• Main questions and issues for the future
Tools at our disposal for impedance assessment

- **Electromagnetic theories**
  - Formulae for *circular multilayer beam pipes* (Zotter/Métral with Mounet implementation, Burov/Lebedev, Ivanyan, Hahn etc.)
  - Formulae for *flat multilayer beam pipes* with generalized form factors (Mounet)
  - Mode matching formulae for various inserts (Biancacci/Vaccaro)
  - Formulae for *kickers* (Tsutsui/Wang/Biancacci)
  - Formulae for *inserts* (Chin/Shobuda)
  - Formulae for *bellows* (Bane and Ng)
  - Formulae for *tapers* (Stupakov, Podobedov)
  - Formulae for *laminations* (Burov)

- **Electromagnetic Simulations**
  - Ansys HFSS (eigenmode and frequency domain + thermomechanical)
  - CST Studio (wakefield + eigenmode and frequency domain + thermomechanical)
  - ABCI (axisymmetric)
  - MAFIA (axisymmetric)
  - Ace3P and Omega3P

- **Bench measurements**
  - Wire measurements with VNA (with matching resistor to minimize reflexions)
  - Probe measurements (in case of cavity type resonance)
  - Loop measurement (for low frequency transverse impedance)
Tools at our disposal

- Bench measurements
  - Wire measurements with VNA (with matching resistor to minimize reflexions)
  - Probe measurements (in case of cavity type resonance)
  - Coil measurement with LCR meter (for low frequency transverse impedance)
Example of benchmarks

• Comparison of impedance from PS kicker wire measurement (2000) and from simulation (M. Migliorati, 2013)

→ Very good agreement
Example of benchmarks: SPS ferrite kickers

Figure 2.2: Drawing showing the transverse cross-section of an SPS MKE kicker (left) and the longitudinal segmentation into seven assembled ferrite cells mounted with the hot and cold conductors (right). Courtesy T. Kroyer.

Figure 2.13: Comparison between theoretical and simulated transverse impedances for the SPS extraction kicker MKE.41651 with Tsutsui’s kicker geometry model: horizontal driving (top left), vertical driving (bottom left), horizontal detuning (top right) and vertical detuning (bottom right). Real parts of the impedance are full lines, imaginary parts are dashed lines.
Tools at our disposal

- Beam measurements
  - Tune shift vs intensity $\rightarrow \text{Im}(Z\text{trans})$
Tools at our disposal

- Growth rate vs chromaticity $\rightarrow$ Re ($Z_{\text{trans}}$)

Figure 17: Comparison between the measured (dots) and computed (full black curve) real part of the effective vertical impedance vs. chromaticity. The computation was made using the fitted resonator for 2006, i.e. with a shunt impedance of 3.5 M$\Omega$/m, a resonance frequency of 2.3 GHz and a quality factor of 0.6.

E. Metral et al, PAC2007
Tools at our disposal

- Quadrupole frequency shift $\rightarrow \text{Im}(Z_{\text{long}})$
Tools at our disposal

- Synchronous phase shift (green curve) → Re(Zlong)

Power lost by the full beam when moving the TDI out (red curve):

In the case of the MD:

\[ V = 6 MV \]
\[ f_{rev} = 11245 \]
\[ M = 1236 \text{ bunches} \]
\[ N_b = 1.34 \times 10^{11} \text{ p/b} \]

\[ \Delta P_{TDI} = eVf_{rev}N_bM(\sin(\Phi_{TDI_{out}}) - \sin(\Phi_{TDI_{in}})) \]

\[ \Delta P_{TDI} \approx 1 kW \pm 300 W \]
Localization of transverse impedance from phase beating vs intensity

Identification of 2 kickers (need of good BPMs, good decoherence, large intensity scan and not so small impedance) → works well for PS, but not so much for SPS or LHC (in 2012)
Ongoing issues

• Improve expertise on 3D codes for complicated geometries
  ➔ ongoing with an increased amount of users at CERN
  ➔ we profit from the collaboration with GSI/TU Darmstadt and SLAC
  ➔ now larger computing power thanks to dedicated machines

• Assess the properties of materials at high frequencies
  (as it is usually not a specification by manufacturer of dielectrics and ferrites)
  ➔ ongoing with several methods (F. Caspers, C. Vollinger, C. Zannini , E. Koukovini, G de Michele)

• Understand where the heat load is deposited in the presence of ferrite
  ➔ done (with Hugo Day and Serena Persichelli).
  ➔ collaboration ongoing with thermal simulations experts to predict temperature

• Issues of bench measurements
  ➔ often the measured signal is too small, especially for high Q modes damped with ferrites.
  ➔ the modes are perturbed by the wire.
     ➔ Need to simulate the wire measurement
     ➔ working on new types of measurement with Vittorio Vaccaaro
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Outlook

• An accurate impedance model is the key to find ways to improve performance with respect to related instabilities

• Fundamental to obtain all relevant wake or impedance contributions as a function of frequency
  – Longitudinal, dipolar, quadrupolar, coupled terms.

• Many challenges are experienced in all phases of building an impedance model, in particular:
  – difficult to know what is really in the machine (device, material, geometry, non conformities)
  – Issues with modelling/simulating accurately a device in the full frequency range (in particular for $\beta<1$)
  – Issues in preparing the model for beam dynamics codes

• So many challenges that it is fundamental to compare observables with bench measurements and beam measurements.

• Many crucial open questions, among which:
  – Should we fit all impedances with resonators?
  – Up to what frequency should we assess the impedance?
  – Can we model accurately the impact of external circuits?
  – Can we improve the simulation of low impedance devices?
Hot topics

• HiLumi LHC foresees a factor 2 increase in bunch intensity by 2026 → challenging for collective effects in all machines!

• Ongoing studies to understand
  → current margins and main bottlenecks for the HiLumi era
  → the interplay between all players in transverse stability:
    - electron cloud
    - head-on and long range beam-beam effects
    - linear and non-linear chromaticity
    - octupole current
    - transverse feedback gain
    - linear coupling
    - impedance
  → how to better measure the tune and stability bunch by bunch, in order to choose the best mitigation strategy