Electron cloud effects and expected limitations in the HL-LHC era (stability, heat load in existing and new components, countermeasures)

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11 November 2013

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

This work is part of HiLumi LHC Work Package 2: Accelerator Physics & Performance.

The electronic version of this HiLumi LHC Publication is available via the HiLumi LHC web site <http://hilumilhc.web.cern.ch> or on the CERN Document Server at the following URL: <http://cds.cern.ch/search?p=CERN-ACC-SLIDES-2014-0074>
Electron cloud effects at the HL-LHC

G. Iadarola, G. Rumolo

Thanks to:


ABP, Collimation, Cryogenics, EN/STI, Injection, Operation, Transverse Damper, Vacuum teams for their help during 25 ns run

3rd Joint HiLumi LHC-LARP Annual Meeting 2013
Daresbury Laboratory, Daresbury, 11-15 November 2013
Outline

• Introduction

• Electron Cloud effects in the arcs
  o Experience with 25 ns beams during Run 1
  o Prospective for the HL-LHC era

• Electron cloud effects in the inner triplets
  o Simulations for the present inner triplets
  o Heat load observations during Run 1
  o Simulations for the HL-LHC triplets
• **Introduction**

• **Electron Cloud effects in the arcs**
  - Experience with 25 ns beams during Run 1
  - Prospective for the HL-LHC era

• **Electron cloud effects in the inner triplets**
  - Simulations for the present inner triplets
  - Heat load observations during Run 1
  - Simulations for the HL-LHC triplets
• When the an accelerator is operated with bunches closely spaced an **Electron Cloud** can develop in the beam chamber due to **Secondary Electron Emission**

• Depending on the **Secondary Electron Yield (SEY)** of the beam chamber electrons can accumulate with adverse consequences i.e.:
  
  o **Beam quality degradation** (instabilities, losses, emittance growth)
  
  o **Dynamic pressure rise**
  
  o **Heat load** (on cryogenic sections)

• **SEY reduces with electron bombardment**

  → Mitigation by beam induced **scrubbing**
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The “multipacting threshold” for 25 ns beams is significantly lower than for 50 ns.

In 2011, 4 days of scrubbing with 50 ns beams + 2 days of tests with 25 ns beams lowered the SEY enough to allow “EC free” operation with 50 ns also in 2012.

PyECLOUD simulations
In 2012 heat load measurements on arc beam screens arcs confirm the absence any strong EC activity with 50 ns beams.
First scrubbing tests with 25ns (450 GeV):

- Running with high chromaticity to avoid EC driven instabilities
- Injected up to **2100b.** for B1 and **1020b.** for B2
- Strong heat load observed in the cryogenic arcs

Thanks to L. Tavian
First scrubbing tests with 25ns (450 GeV):

- Running with **high chromaticity to avoid EC driven instabilities**
- Injected up to 2100b. for B1 and 1020b. for B2
- **Strong heat load observed in the cryogenic arcs**

**x15 stronger than heating due to impedance**

*Heat load measurement from cryogenics*

*Estimation (impedance + synchrotron rad.)*

Thanks to L. Tavian

Thanks to C. Zannini
First scrubbing tests with 25ns (450 GeV):

- SEY_{max} in dipoles could be lowered to \sim 1.5

Reconstruction based on measured beam parameters, heat load meas. and PyECLOUD sims.
First scrubbing tests with 25ns (450 GeV):

- **$SEY_{\text{max}}$ in dipoles** could be lowered to $\sim 1.5$

Beam degradation still important:

- Poor bunch by bunch lifetimes
- Large emittance growth

Thanks to F. Roncarolo
The “25 ns run” in 2012

All experiments with 25 ns beams with large number of bunches were concentrated the last two weeks of the run.
3.5 days of scrubbing with 25ns beams at 450 GeV (6 - 9 Dec. 2012):

- Regularly filling the ring with up to 2748b. per beam (up to $2.7 \times 10^{14}$ p)
- Slow improvement visible on beam quality and heat load in the arcs

Average over the last 72 bunches of the first 3 injections

The 2012 scrubbing run
The 2012 scrubbing run

3.5 days of scrubbing with 25ns beams at 450 GeV (6 - 9 Dec. 2012):

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The 2012 scrubbing run

3.5 days of scrubbing with 25ns beams at 450 GeV (6 - 9 Dec. 2012):

- Beam 1: filling the ring with up to 2748b. per beam (up to $2.7 \times 10^{14}$ p)
- Slow improvement visible on beam quality and heat load in the arcs

Beam 1
Beam 2

- Sector 5: 29/06 - 07/10
- Heat load measurement from cryogenics
- Estimation (impedance + synchrotron rad.)

Thanks to C. Zannini
Experience with 25 ns beams at 4 TeV

The accumulated scrubbing made possible to have machine studies and a pilot physics run with 25 ns at 4 TeV

Machine Studies
with 25 ns beams at 4TeV
(12 – 15 Dec 2012)

Pilot physics run
with 25ns beams
(15 – 17 Dec 2012)
Experience with 25 ns beams at 4 TeV

- A strong enhancement on the heat load is observed on the energy ramp

fill 3429 started on Thu, 13 Dec 2012 18:16:27

Thanks to L. Tavian
Experience with 25 ns beams at 4 TeV

- A **strong enhancement on the heat load** is observed on the energy ramp
- Large electron cloud density in the arcs **does not show a strong effect on the beam** (due to increased beam rigidity)
  - **Emittance blow-up** in collision very similar to 50 ns → likely not due to EC

![Graph showing ATLAS data](image)

Thanks to D. Banfi
Experience with 25 ns beams at 4 TeV

- A **strong enhancement on the heat load** is observed on the energy ramp
- Large electron cloud density in the arcs does not show a strong effect on the beam (due to increased beam rigidity)

A look to **bunch by bunch emittances**

- **Blow-up on trailing bunches** is observed mainly at injection energy
- Blow up in **stable beams** more severe for brighter bunches at the beginning of trains (although they see less EC) → possibly related to beam-beam

Thanks to D. Banfi
Scrubbing: we need to do better!

- Experience in Run 1 showed that the electron cloud can limit the achievable performance with 25 ns beams mainly through:
  - beam degradation (blow-up, losses) at low energy
  - high heat load on arc beam screens at high energy
- To operate with 25 ns beams (~2800b.) it is mandatory to achieve lower values in SEY
  - Dedicated scrubbing beams with hybrid bunch spacing are presently under study (e-cloud enhancement shown experimentally at SPS)

**Scrubbing dose (50eV) [mA/m]**

- 0.50e11 ppb
- 0.60e11 ppb
- 0.70e11 ppb
- 0.80e11 ppb
- 0.90e11 ppb
- 1.00e11 ppb
- 1.10e11 ppb

**Electron density [a. u.]**

- Scrubbing beam (5+20) ns
- Standard beam 25 ns

**Time [ns]**

- PyECLoud simulations
What will be different in the HL-LHC era?

- The arcs will be practically the same but we need to cope with ~double bunch intensity
  - Provided that we manage to access a low SEY regime, increased bunch intensity should be acceptable for heat load, effect on the beam still to be assessed
What will be different in the HL-LHC era?

- The arcs will be practically the same but we need to cope with ~double bunch intensity
  - Provided that we manage to access a low SEY regime, increased bunch intensity should be acceptable for heat load, effect on the beam still to be assessed
  - If option with 200 MHz main RF is adopted, longer bunches will have a positive impact also on electron cloud

![PyECLOUD simulations](image)
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Machine layout and optics near IP1

IP1, 4 TeV, $\beta^* = 0.6$ m
Machine layout and optics near IP1

3R1 4000.0 GeV (2sigma beam shape)

IP1, 4 TeV, $\beta^* = 0.6$ m
Machine layout and optics near IP1

IP1, 4 TeV, $\beta^* = 0.6$ m
Machine layout and optics near IP1

1R1 4000.0 GeV (2σ beam shape)

1R1 A2R1 B2R1

IP1, 4 TeV, $\beta^* = 0.6$ m
PyECLOUD simulations for the inner triplets

Quite a **challenging simulation scenario**:

- **Two beams** with:
  - Different transverse position (off center)
  - Different transverse shape
  - Arbitrarily delayed with respect to each other (no real bunch spacing)

- **Quadrupolar** magnetic field

- **Non elliptical chamber**

Beam properties (delay, position, size) changing along the structure:

- Simulated **10 slices per magnet**
- **SEY = 1.0, 1.1, ..., 2.0**
- **50 ns and 25 ns**

Required the introduction of new features in PyECLOUD

~1000 simulations, 
~48 h for two bunch trains, 
~120 GB of sim. data
Few snapshots of the electron distribution (50 ns spacing)

A look to the EC buildup
The presence of two beams enhances the multipacting efficiency, especially far enough from the locations of the long range encounters.
Heat load density along the triplet - 25 ns

**Remarks:**

- EC much weaker close to **long range encounters**
- Modules with the **same beam screen** behave very similarly
• High heat load even with 50 ns beams (unlike in double aperture magnets)
• No big change during ramp and squeeze (both for 50 ns and 25 ns spacing)
• High heat load even with 50 ns beams (unlike in double aperture magnets)
• No big change during ramp and squeeze (both for 50 ns and 25 ns spacing)
Comparison against simulations

1.2 < \text{SEY}_{\text{max}} < 1.3

is compatible with all the observations
Crosscheck with single beam MDs

For the estimated SEY value we do not expect nor observe EC in the triplets with only one beam with 50 ns spacing circulating in the LHC.

**Simulations**

**Measurements**

![Graphs showing heat load vs. SEY for 50 ns B2R1 with simulations and measurements for two beams and one beam circulating.](image-url)
Inner triplets for HiLumi upgrade

Present

IP1, 4 TeV, $\beta^* = 0.6$ m

HiLumi

IP1, 7 TeV, $\beta^* = 0.15$ m
Inner triplets for HiLumi upgrade

Quadrupoles

Quadrupoles

Dipole

Thanks to R. De Maria

IP1, 7 TeV, $\beta^* = 0.15$ m

Beta function [m]

Beam position [mm]
**Present**

- **Q1**: Inner triplets for HiLumi upgrade
- **Q2 (A/B)**
- **Q3**: Inner triplets for HiLumi upgrade
- **D1**

**HiLumi**

- **Q1 (A/B)**
- **Q3 (A/B)**
- **D1**

**IP1, 4 TeV, \(\beta^* = 0.6 \text{ m}\)**

**IP1, 7 TeV, \(\beta^* = 0.15 \text{ m}\)**
Inner triplets for HiLumi upgrade

Present

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Present

HiLumi

Inner triplets for HiLumi upgrade

IP1, 4 TeV, $\beta^* = 0.6$ m

IP1, 7 TeV, $\beta^* = 0.15$ m
Inner triplets for HiLumi upgrade

Present

A2R1 7000.0 GeV (2sigma beam shape)

A2R1 7000.0 GeV (2sigma beam shape)

HiLumi

IP1, 4 TeV, $\beta^* = 0.6$ m

IP1, 7 TeV, $\beta^* = 0.15$ m

Beta function [m]

Beam position [mm]

Beta function [m]

Beam position [mm]
Inner triplets for HiLumi upgrade

Present

Q1, 4 TeV, $\beta^* = 0.6$ m

HiLumi

Q1, 7 TeV, $\beta^* = 0.15$ m

Present

1R1 7000.0 GeV (2sigma beam shape)

B1R1 7000.0 GeV (2sigma beam shape)
Inner triplets for HiLumi upgrade

**Present**

- IP1, 4 TeV, $\beta^* = 0.6$ m
- IP1, 7 TeV, $\beta^* = 0.15$ m

**HiLumi**

- Q1 (A/B) Q3 (A/B) D1

Graphs showing the beam shape and beta function for different energy levels.
A look to the EC buildup – HiLumi triplets

Few snapshots of the electron distribution $\rightarrow$ much wider stripes for HiLumi triplets

**HiLumi** ($2.20 \times 10^{11}$ ppb)

**Present** ($1.15 \times 10^{11}$ ppb)
Total heat load on the triplet beam screen

Bunch intensity is larger but also chamber is wider. For the **same SEY**:

- energy of multipacting electrons is quite similar
- number of impacting electrons about x2 larger
- Total **heat load about x2 larger**

**e-cloud suppression** can be obtained using **low SEY coatings and/or clearing electrodes**

**Present triplets**
(1.15 x 10^{11} ppb)

25 ns - 2800 bunches

**Full suppression**
(SEY≈1 or clearing electrodes)

**HiLumi triplets**
(2.20 x 10^{11} ppb)

25 ns - 2800 bunches
Inner triplets in IP2 and IP8 will still have the present design:

- Increase bunch intensity leads to more than $x2$ larger heat load
- e-cloud suppression strategies needed also for these magnets
Summary

• Main magnets in the arcs:
  o Experience in Run 1 showed that with 50 ns beams, electron cloud effects could be fully suppressed by scrubbing
  o Much longer scrubbing time is needed for 25 ns beams (full suppression not achieved in 2012)
  o Dedicated scrubbing beam is under study
  o Hilumi beam parameters not severe for heat load, effect on beam to be assessed

• Inner triplets:
  o The presence of two counter-rotating beams enhances the electron cloud
  o If suppression measures (like low SEY coating or clearing electrodes) not in place, important heat loads are expected on the beam screens
Thanks for your attention!
First injection tests with a train of 48b. on 26/08/2011:

- Beam **unstable** right after injection (dump due to losses)
- Driven by **e-cloud in the dipoles** (mainly vertical motion, trailing bunches of the train) – **reproduced with PyECLOUD-HEADTAIL simulations**
- Beam stable with **high chromaticity settings (Q’=15)**

Thanks to H. Bartosik, W. Höfle and D. Valuch
Experience with 25 ns beams at 4 TeV

Machine Studies with 25 ns beams at 4 TeV
(12 – 15 Dec 2012)

Pilot physics run with 25 ns beams
(15 – 17 Dec 2012)

Standard production scheme from injectors:
- Batches of 72 bunches
- \( \sim 1.15 \times 10^{11} \) ppb
- \( \epsilon_{x,y} = 2.6 \mu m \)

BCMS production scheme from injectors:
- Batches of 48 bunches
- \( \sim 1.0 \times 10^{11} \) ppb
- \( \epsilon_{x,y} = 1.4 \mu m \)
Simulated scenario

25 ns beam – $2.20 \times 10^{11}$ ppb

Other beam parameters:

- Beam energy: 7 TeV
- Transverse emittance: 2.5 μm
- Bunch length: 1.0 ns
- Optics with $\beta^* = 0.15$ m
Heat load along the triplet

25 ns - 576 bunches

Present triplets

Locations of long range encounters

HiLumi triplets

Average heat load [W/m]

25 ns - 576 bunches

sey = 1.00
sey = 1.20
sey = 1.40
sey = 1.60
sey = 1.80
sey = 2.00
The longitudinal direction

The **delay between two following bunch passages** changes along the machine elements

- Locations of **long range encounters** spaced by half the bunch spacing

![Diagram showing beam passages and timing](image-url)
Heat load density along the triplet - 25 ns

Remarks:

- EC much weaker close to long range encounters
- Modules with the same beam screen behave very similarly

As in the other quadrupoles in the LHC, the multipacting threshold is already quite low even for a single beam with 25 ns spacing
Machine layout and optics near IP1

IP1, 4 TeV, $\beta^* = 0.6$ m
For each triplet we get:

Remark:

- Above threshold values are very similar → enhancement from hybrid spacings much stronger on the 50 ns than on 25 ns
When the an accelerator is operated with close bunch spacing an **Electron Cloud (EC)** can develop in the beam chamber due to the Secondary Emission from the chamber’s wall.

**Secondary Electron Yield (SEY) of the chamber’s surface:**

- ratio between emitted and impacting electrons
- function of the energy of the primary electron
**Introduction: electron cloud effects and scrubbing**

Scrubbing is a mitigation for the e-cloud effects:

- 😊 Keeping a significant e- flux on the chamber’s walls causes a decrease of the SEY (and hence the e-cloud)
- 😟 The dependence of the SEY on the accumulated dose is logarithm-like

Scrubbing of Cu measured with e\(^-\) at 500eV (CERN TE-VSC)
25 ns beams in the LHC during Run 1

**2011**
- 21/02: Commissioning with beam
- 13/03: 75 ns physics run (nominal)
- 05/04: Scrubbing run 50 ns
- 12/04: Physics run 50 ns (3.5 TeV)
- 29/06: 25 ns MDs
- 07-14-24/10: Scrubbing run 50 ns (4 TeV)
- 30/10: “25 ns run” Scrubbing run + MDs + Pilot physics

**2012**
- 14/03: Commissioning with beam
- 03/04: Physics run 50 ns (4 TeV)
- 10/07: 25 ns MD