Electron Cloud Stability: Single Bunch Effects

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Acknowledgements: L. Mether, K. Paraschou
Outline

- Introduction
- Convergence Studies
- Bunch Length and RF voltage
- Effect of SEY and Bunch Charge
- Chromaticity and Damper
- Octupoles
- Frequency Analysis
- Conclusions and Future Developments
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Introduction: Motivation

- The electron motion is fast enough to act as a coupling mechanism between the head and the tail of the bunch (dominated by electrons at the beam location)
  - Stronger at injection energy due to lower beam rigidity
The possibility of lowering the RF voltage at injection is being considered to cope with RF power limitations.

→ An extensive simulation study has been conducted to address the impact on e-cloud driven instabilities.

In the simulations the bunch length has been adapted to the RF voltage following the dependence measured at the LHC.

- In all simulations the longitudinal distribution is matched to the bucket.
Introduction

- Electrons in the **arc quadrupoles** are expected to be the **strongest contributor** (quadrupolar field concentrates a large electron density at the beam location)
  - Instabilities driven by **e-cloud in the quadrupoles** will be considered in the following
Introduction: Simulation Parameters

- $\varepsilon_{nx} = \varepsilon_{ny} = 2.5 \mu m$
- $\beta_x = 92.7 \text{ m}$ and $\beta_y = 93.2 \text{ m}$
- Energy: 450 GeV
- Magnetic Field (Arc Quadrupoles): 12.1 T/m
- Electron density: from build-up simulation
- SEY: 1.30 - 1.40
- Bunch Intensity: $1.2e11 - 2.3e11$ protons per bunch
- Scan: $4\sigma_t (1.37 – 1.02 \text{ ns}) / \text{RF voltage (3 - 8 MV)}$
Introduction: Instability Study Observables

- **Blow-up time**: time required for observing an emittance blow-up of 12% (2.5 µm → 2.8 µm)

![Blow-up time graph](graph)

- No EC kick on the vertical plane
- The maximum number of turns is fixed: 20,000
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Electron cloud stability: Single bunch effects
Convergence Studies
The motivation of these convergence studies is to find the lowest acceptable values for the numerical parameters:

1. number of slices of the bunch
2. number of MacroParticles (MPs) / slice
3. number of kicks (or segments) for each e\(^{-}\) cloud element
4. number of electron MPs for each kick
5. transverse grids (Multigrid [1])

Convergence Studies

Strategy

Scan every numerical parameter, using conservative values for the other parameters:

- Slices = 750
- MPs/slice = 5,000
- Segments = 8
- e⁻ MPs = 500,000
- Transverse Grid: $T_0$
Convergence Studies: Slices

- Old setting 150 slices is not adequate
- 500 slices is chosen

No instability observed over 20k turns

Simulated number of turns

Electron cloud stability: Single bunch effects
Convergence Studies: MPs/Slice

- 2,500 MPs/slice is chosen

No instability observed over 20k turns
Convergence Studies: Kicks

- 8 kicks is chosen

No instability observed over 20k turns
Convergence Studies: $e^-$ MPs

- 500,000 $e^-$ MPs is chosen

No instability observed over 20k turns
## Convergence Studies: Transverse Grid

**Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$T_0$</th>
<th>$T_{inj} \Delta h=0.2\sigma$</th>
<th>$T_{inj} \Delta h=0.1\sigma$</th>
<th>$T_{inj} \Delta h=0.05\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal grid coverage [mm]</td>
<td>6.95 (10\sigma)</td>
<td>10.5 (15\sigma)</td>
<td>10.5 (15\sigma)</td>
<td>10.5 (15\sigma)</td>
</tr>
<tr>
<td>Internal grid cell size [mm]</td>
<td>0.139 (0.2\sigma)</td>
<td>0.139 (0.2\sigma)</td>
<td>0.0697 (0.1\sigma)</td>
<td>0.0349 (0.05\sigma)</td>
</tr>
<tr>
<td>External grid cell size [mm]</td>
<td>0.8</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

No instability observed over 20k turns.

Still running (3)

**Graph:**

- *Inj Quad Slices = 750 Segments = 8 MPs/Slice = 5e3 e^- MPs = 5e5*

**Legend:**
- Grid
- $T_0$
- $T_{inj} \Delta h=0.2\sigma$
- $T_{inj} \Delta h=0.1\sigma$
- $T_{inj} \Delta h=0.05\sigma$

**Table:**

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</tbody>
</table>
Convergence Studies: 16% - 26%

No instability observed over 20k turns

- Scans of the length of the quadrupoles (equivalent to have stronger electron cloud kicks) for each numerical parameter
- They confirm the previous conclusions
Convergence Studies: Summary

- 378 multi-core simulations
- Total computational time: ~ 32672 CPUcores*days
- It took months using the full CNAF cluster
- ~127 GB stored
Convergence Studies: Chosen Parameters

<table>
<thead>
<tr>
<th>Numerical Parameter</th>
<th>Chosen Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slices/bucket</td>
<td>500</td>
</tr>
<tr>
<td>MPs/Slice</td>
<td>2,500</td>
</tr>
<tr>
<td>Segments</td>
<td>8</td>
</tr>
<tr>
<td>e⁻ MPs</td>
<td>5e5</td>
</tr>
<tr>
<td>Transverse Grid</td>
<td>T₀</td>
</tr>
<tr>
<td></td>
<td>Internal grid coverage: 6.95 mm (10σ)</td>
</tr>
<tr>
<td></td>
<td>Internal grid cell size: 0.139 mm (0.2σ)</td>
</tr>
<tr>
<td></td>
<td>External grid cell size: 0.8 mm</td>
</tr>
</tbody>
</table>
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10th December 2019

Electron cloud stability: Single bunch effects
Increasing $V_{RF}$ and decreasing the bunch length, the bunch is more stable
→ Which is dominant?
Bunch Length and RF voltage

Increasing $V_{RF}$, we change

- Faster synchrotron tune $Q_s$
  - Stabilising mechanism
- Bunch length
  - EC dynamics
    - Longer bunches $\rightarrow$ more $e^{-}$
    - Shorter bunches $\rightarrow$ less $e^{-}$

We study the two effects separately
Bunch Length and RF voltage

$1.2 \times 10^{11}$ p/bunch, $\text{SEY} = 1.3$

4 \cdot \sigma_t [\text{ns}]

$1.35 \quad 1.30 \quad 1.25 \quad 1.20 \quad 1.15 \quad 1.10 \quad 1.05 \quad 1.00$

• Changing bunch length
• Changing $V_{RF}$ ($Q_s$)

10^4

10^3

10^2

3 4 5 6 7 8

$V_{RF}$ [MV]

 Blow-up Time [Turns]

• Fixed bunch length (same e⁻ pinch)
• Changing $V_{RF}$ ($Q_s$)

• Fixed $V_{RF}$ ($Q_s$)
• Changing bunch length

→ the dominant stabilizing factor is the change of $Q_s$
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Effect of SEY and Bunch Charge

- Increasing the SEY, the bunch is more unstable
- No instability for $2.3 \times 10^{11}$ ppb in this entire range of parameters
Effect of SEY

- Increasing the SEY, the bunch is more unstable.
- No instability for $2.3 \times 10^{11}$ ppb in this entire range of parameters.
Why no Instability at High Intensity?

- The electron density close to the bunch, during the pinch, is significantly smaller for high intensity
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Chromaticity and Damper

- Scanned around these points
Chromaticity and Damper

- $V_{RF} = 4 \text{ MV}$
- $SEY = 1.3 - 1.4$
- Feedback damping time is 10 turns

For the case of LHC intensity (which an instability could be observed) the effectiveness of different mitigation measures has been investigated:

- The instability is strongly mitigated by increasing the chromaticity settings
Chromaticity and Damper

- $V_{RF} = 4\, MV$
- $SEY = 1.3 - 1.4$
- Feedback damping time is 10 turns

For the case of LHC intensity (in which an instability could be observed) the effectiveness of different mitigation measures has been investigated:

- The instability is strongly mitigated by increasing the chromaticity settings
- The transverse feedback is mostly ineffective → cannot damp intra-bunch motion
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Octupoles

Exploded starting from this point

\[ V_{RF} \text{ [MV]} \]

\[ \text{Blow-up Time [Turns]} \]

- SEY = 1.3
- SEY = 1.4
Octupoles

- $V_{RF} = 4$ MV
- SEY = 1.4
- Damper = 10 turns

For the case of LHC intensity the octupole current has also been scanned → less effective compared to chromaticity

- Large oscillations for high chromaticity driven by random component

No instabilities over 20,000 turns
Octupoles

- $V_{RF} = 4$ MV
- $SEY = 1.4$
- Damper = 10 turns
- 20 repetitions

- To mitigate dependence on initial random seed (bunch MP coordinates) we repeat each simulation 20 times
- Reveals non-trivial dependence on octupole current for high chromaticity
  → to be further investigated

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Frequency Analysis

- An \textit{exponential rise} is visible on the transverse emittance.
- The centroid motion does not show clear signs of instability.
Frequency Analysis

- An \(~\text{exponential rise}\) is visible on the \textit{transverse emittance}.
- The centroid motion does not show clear signs of instability.
- The development of the instability is visible on the \textit{intra-bunch motion}.
Frequency Analysis

We perform a **Fourier transform of the intra-bunch motion**

- We are measuring the number of the intra-bunch oscillations
Frequency Analysis

We perform a Fourier transform of the intra-bunch motion

• We are measuring the number of the intra-bunch oscillations

Not much activity on the “rigid bunch” line
Frequency Analysis

We perform a **Fourier transform of the intra-bunch motion**
- We are measuring the number of the intra-bunch oscillations

Instability clearly visible on higher intra-bunch "mode"
Frequency Analysis

We perform a **Fourier transform of the intra-bunch motion**
- We are measuring the number of the intra-bunch oscillations

Instability clearly visible on **higher intra-bunch ”mode”**
Frequency Analysis

We perform a Fourier transform of the intra-bunch motion

- We are measuring the number of the intra-bunch oscillations

We apply another Fourier transform w.r.t. turn number

- The rigid bunch line that has a positive tune shift (typical for e-cloud)
- The unstable “”mode”” has a negative tune shift
Frequency Analysis

These features are **observed systematically over the simulation set**

- The tune of the unstable line seems **correlated to** $Q_s$

---

**SEY 1.3 - 3.0 MV**

![Frequency Analysis Diagram](image)

- **Tune machine:** 0.2700
- **Synchrotron tune:** 3.469e-3 (V RF: 3.0 MV)
- **Tune centroid:** 0.2724 (2.37e-3)
- **Tune mode (cos):** 0.2675 (-2.46e-3)
- **Tune mode (sin):** 0.2676 (-2.35e-3)
Frequency Analysis

These features are observed systematically over the simulation set:

- The tune of the unstable line seems correlated to $Q_s$.

SEY 1.3 - 4.0 MV

- **Tune machine**: 0.2700
- **Synchrotron tune**: 4.005e-3 ($V_{RF}$: 4.0 MV)
- **Tune centroid**: 0.2717 (1.68e-3)
- **Tune mode (cos)**: 0.2667 (-3.31e-3)
- **Tune mode (sin)**: 0.2667 (-3.31e-3)
Frequency Analysis

These features are observed systematically over the simulation set

- The tune of the unstable line seems correlated to $Q_s$
Frequency Analysis

These features are **observed systematically over the simulation set**

- The tune of the unstable line seems **correlated to** $Q_s$
Frequency Analysis

These features are **observed systematically over the simulation set**

- The tune of the unstable line seems **correlated to** $Q_s$

---

**SEY 1.3 - 7.0 MV**

- **N. oscillations in 4 sigmaz**
  - Turn: $0, 5000, 10000, 15000, 20000$

- **Centroid position [mm]**
  - Turn: $0, 5000, 10000, 15000, 20000$

- **P.U. signal**
  - Turns: 13780 - 13794

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**Tune machine: 0.2700**

- Synchrotron tune: 5.298e-3 (V_RF: 7.0 MV)
- Tune centroid: 0.2715 (1.52e-3)
- Tune mode (cos): 0.2715 (1.52e-3)
- Tune mode (sin): 0.2682 (-1.85e-3)
Footprints - Effect of the Octupoles

There is little overlap between the spread and the unstable frequency.
Footprints - Effect of the Octupoles

There is little overlap between the spread and the unstable frequency.
Footprints - Effect of the Octupoles

There is little overlap between the spread and the unstable frequency.

![Graph showing effect of octupoles](image)

- Machine tune
- Instability freq.
- Centroid freq.

Koct = -3.0 - \( I_{LOF} = 39.1 \text{A} \)
Footprints - Effect of the Octupoles

There is little overlap between the spread and the unstable frequency

K_{oct} = -6.0 - I_{LOF}=78.2A
Footprints - Effect of the Octupoles

There is little overlap between the spread and the unstable frequency.

$K_{oct} = 6.0 \cdot I_{LOF} = -78.2A$

Machine tune  --  Instability freq.  --  Centroid freq.

$Q_x \quad Q_y$

$z \ [\text{cm}]$

$z \ [\text{cm}]$

$z \ [\text{cm}]$

$z \ [\text{cm}]$
Footprints - Effect of the Octupoles

$K_{OCT} = +6.0 \ (I_{LOF} = -78 \ A)$

Summary:
- The e-cloud is pushing the tune spread away from the instability frequency.
- Effect of octupole polarity is minor but visible.

Graphs showing:
- $K_{OCT} = +6.0 \ (I_{LOF} = -78 \ A)$
- $K_{OCT} = -6.0 \ (I_{LOF} = +78 \ A)$
Footprints - Effect of the Octupoles

- The instability risetime looks correlated with the tune-spread population around the unstable frequency

**Tune spreads**

**Coherent instability (Q’ = 2.5)**
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Conclusions

- Extensive convergence studies at injection are carried out
- Decreasing $V_{RF}$ the bunch is more unstable
  - dominant factor is the de-stabilising effect due to the change of the synchrotron tune
- No instability for $2.3e11$ ppb in the entire range of parameters
  - electron density at bunch location is smaller for high intensity
- Damper does not affect significantly the instability (unable to suppress intra-bunch motion)
- Positive chromaticity strongly mitigates the instability
- Octupoles are less effective compared to chromaticity
- Frequency analysis reveals that
  - The unstable line has a negative tune shift
  - E-cloud pushes the tune spread away from the unstable line, fighting against Landau damping
Thanks for your attention
Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   • Single grid
     - PyPICmode = ‘FiniteDifference_ShortleyWeller’
     - Dh_sc_ext
Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   • Multigrid [1]:

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   • Multigrid:

---

**Introduction: Numerical Parameters**

Courtesy of E. Belli

- Multigrid with more nodes around the beam and less dense towards the pipe borders.
- For LHC at injection: $\sigma_{x,y} \sim 10^{-4}m$.
- High energy LHC and FCC-ee case very demanding.
- Arc dipole ($\beta_y = 55m$)
  - $\epsilon_y = 1pm@ 45.6 GeV$
  - $\sigma_y \sim 2 \cdot 10^{-8} m$
  - $\Delta h \sim 10^{-8}$
  - $N_y = \frac{d_{pipe}}{\Delta h} \sim 700000$

---

At least 2-3 meshes inside the beam.
Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   • Multigrid:
     - PyPICmode = ‘ShortleyWeller_WithTelescopicGrids’
     - f_telescope
     - target_grid
       ▪ target_size_internal_grid_sigma
       ▪ target_Dh_internal_grid_sigma
     - N_nodes_discard
     - N_min_Dh_main
     - Dh_sc_ext
The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Multigrid:
     - \( f_{\text{telescope}} \): Magnification factor between grids \( 0 < f < 1 \)

\[
S_i = f \cdot S_{i-1} \quad (0 < f < 1)
\]

\[
S_n = f^n S_0
\]

\( f \): Magnification factor between grids \( 0 < f < 1 \)

Courtesy of E. Belli
Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   • Multigrid:
     - **target_grid**: dictionary with the internal grid parameters: ‘x_min_target’, ‘x_max_target’, ‘y_min_target’, ‘y_max_target’, ‘Dh_target’

Parameters of the target grid
\[ x_{\text{min}}, x_{\text{max}}, y_{\text{min}}, y_{\text{max}}, \Delta h_{\text{target}} \]

Size of target grid
\[ S_n = f^n \cdot N \cdot \Delta h_0 = S_{\text{target}} \]
Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   • Multigrid:
     - target_grid: dictionary with the internal grid parameters

Can be given also in terms of transverse sigma of the beam:
   - target_size_internal_grid_sigma
   - target_Dh_internal_grid_sigma

```python
target_grid_arcs = {
    'x_min_target': -pp.target_size_internal_grid_sigma*sigma_x_smooth,
    'x_max_target': pp.target_size_internal_grid_sigma*sigma_x_smooth,
    'y_min_target': -pp.target_size_internal_grid_sigma*sigma_y_smooth,
    'y_max_target': pp.target_size_internal_grid_sigma*sigma_y_smooth,
    'Dh_target': pp.target_Dh_internal_grid_sigma*sigma_x_smooth
}
```
Introduction: Numerical Parameters

The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Multigrid:
     - \texttt{N_nodes_discard}: number of nodes at the edge of the internal grids which are discarded in the field interpolation

\begin{itemize}
\item An artifact is introduced at the edge of the internal grid, which can be avoided by discarding the most external nodes when interpolating (as described in [1]).
\item The user can define the number of nodes to be discarded: \texttt{(N_nodes_discard to be set \neq 0)}
\item The probe \((r = 6\, \text{mm})\) crosses the edges of the internal grid
\item If \texttt{N_nodes_discard=0} an error is introduced during interpolation
\end{itemize}
The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   - Multigrid:
     - \( N_{\text{min}_Dh_{\text{main}}} \): minimum size of the first internal grid, in number of points of the step of the main grid

\[
S_0 = N \Delta h_0
\]

\( N \): Minimum number of points of the first internal grid in the \( \Delta h_0 \) of the main grid

Courtesy of E. Belli
The motivation of these convergence studies is to find the lower acceptable values for the numerical parameters:

5. transverse grids
   • Multigrid:
     - $D_{h\text{ sc}_\text{ ext}}$: step of the external grid
Introduction: Numerical Parameters

- Scan: $4\sigma_t$ (1.37 – 1.02 ns) / RF voltage (3 - 8 MV)

![Graph showing the relationship between $4\sigma_t$ and $V_{RF}$](image)

[1] H. Timko, “Injection Voltage Reduction In the LHC” – September 5, 2018
Convergence Studies: Pinch

To understand why such a large number of slices is required we look at the electron evolution during the individual pinch.

Electron density average ($|y| < 0.25\sigma_y$ and $x = 0$) along the bunch

- Single passage simulation confirms: 150 slices are not enough
- Smaller electron density peak (around 20%) during the pinch $\Rightarrow$ bunch more stable
Convergence Studies: Slices

Computational Time

1. The simulations are: 108.
2. The finished simulations are: 108. The killed simulations are: 0.
3. Total computational time: 858 days (8 cores).
4. 28.5 GB stored.
Convergence Studies: MPs/Slice

Computational Time

1. The simulations are: 72.
2. The finished simulations are: 72. The killed simulations are: 0.
3. Total computational time: 818 days (8 cores).
4. 24.6 GB stored.
1. The simulations are: 72.
2. The finished simulations are: 72. The killed simulations are: 0.
3. Total computational time: 748 days (number of cores depends on segments).
4. 25.7 GB stored.
Convergence Studies: $e^-$ MPs

Computational Time

1. The simulations are: 54.
2. The finished simulations are: 54. The killed simulations are: 0.
3. Total computational time: 645 days (8 cores).
4. 19.7 GB stored.
**Convergence Studies: Transverse Grid**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( T_0 )</th>
<th>( T_{\text{inj}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>f (magnification factor)</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Internal grid coverage [mm]</td>
<td>6.95 (10( \sigma ))</td>
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<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>N_nodes_discard</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>N_min_Dh_main</td>
<td>10</td>
<td>40</td>
</tr>
</tbody>
</table>

![Diagram of internal and external grids with beam chamber](image_url)
Convergence Studies: Transverse Grid

**Parameter** | **Value**
---|---
f (magnification factor) | 0.3
$S_N$ [mm] | $6.95 \ (10\sigma)$
$\Delta h_N$ [mm] | $0.139 \ (0.2\sigma)$
$\Delta h_0$ [mm] | 0.8
N_nodes_discard | 5
N_min_Dh_main | 10
Convergence Studies: Transverse Grid

Computational Time

1. The simulations are: 72.
2. The finished simulations are: 69. The killed simulations are: 0.
3. Total computational time: 1035 days (8 cores).
4. 25.4 GB stored.
5. The slowest simulation needs 35 days to reach 20,000 turns.
6. The fastest simulation needs 26 days to reach 20,000 turns.
7. (last download 19/11/2019)
Convergence Studies: 16% - 26%

**Slices**

- Inj Quad T0 Segments = 8 MPS/Slice = 5e3 e− MPs = 5e5

**MPs/Slice**

- Inj Quad T0 Slices = 750 Segments = 8 e− MPs = 5e5

**Segments**

- Inj Quad T0 Slices = 750 MPS/Slice = 5e3 e− MPs = 5e5

**e− MPs**

- Inj Quad T0 Slices = 750 Segments = 8 MPS/Slice = 5e3
Convergence Studies: 16% - 26%

Transverse Grids

Electron cloud stability: Single bunch effects
Why no Instability at High Intensity?

- It can be related to the number of electrons around the chamber centre (from build-up simulations)

**Useful Parameter in PyECLoud**

- `cen_density [e^-/m^3]`: electron volumetric density in a sphere around the chamber centre with radius `r_center` (input simulation parameter)
- `r_center = 1 mm`
Why no Instability at High Intensity?

Build-up: Full Plot

1.2e11 ppb  SEY = 1.30  \( V_{RF} = 3 \) MV

Electron cloud stability: Single bunch effects
Why no Instability at High Intensity?

Build-up: Full Plot

- The combined build-up status are: 196 – 204 bunches
- Build-up in saturation

1.2e11 ppb \ SEY = 1.30 \ V_{RF} = 3 \text{ MV}

Electron cloud stability: Single bunch effects

10th December 2019
Why no Instability at High Intensity?

1.2e11 ppb  SEY = 1.30  $V_{RF} = 3$ MV

Build-up: Zoom Plot
Why no Instability at High Intensity?

1.2e11 ppb  SEY = 1.30  $V_{RF} = 4$ MV

Build-up: Zoom Plot

- **Mask**: points only when the number of the proton bunch is larger than 10% of the maximum

Electron cloud stability: Single bunch effects
Why no Instability at High Intensity?

1.2e11 ppb  SEY = 1.30  $V_{RF} = 4$ MV

Build-up: Zoom Plot

- Average of these values

Electron cloud stability: Single bunch effects
Chromaticity

- $V_{RF} = 6$ MV
- $SEY = 1.4$
- Damper = 10 turns

![Graph showing blow-up time versus $Q'_{x,y}$]
Chromaticity and Damper

- $V_{RF} = 4 \text{ MV}$
- $\text{SEY} = 1.3 - 1.4$
- Feedback damping time is 10 turns

No instability observed over 20k turns for $Q' > 12.5$!

For the case of LHC intensity (which an instability could be observed) the effectiveness of different mitigation measures has been investigated:

- The instability is strongly mitigated by increasing the chromaticity settings
- The transverse feedback is mostly ineffective $\rightarrow$ cannot damp intra-bunch motion
For the case of LHC intensity (which an instability could be observed) the effectiveness of different mitigation measures has been investigated:

- The instability is strongly mitigated by increasing the chromaticity settings.
- The transverse feedback (bunch-by-bunch, damping time of 10 turns) is mostly ineffective → cannot damp intra-bunch motion.
Positive *chromaticity strongly mitigates the instability*

The damper does not affect significantly the blow-up time (unable to suppress intra-bunch motion)

- $V_{RF} = 4\,\text{MV}$
- $\text{SEY} = 1.3 - 1.4$
- Feedback damping time is 10 turns

No instability observed over 20k turns for $Q' > 12.5$!
Chromaticity and Damper

SEY = 1.4, Damper ON

Electron cloud stability: Single bunch effects