Halo removal and effects on beam core of electron lens in HL-LHC

D. Mirarchi, R. Bruce, M. Giovannozzi, A. Mereghetti, S. Redaelli
Acknowledgments: G. Stancari

We greatly acknowledge all BOINC volunteers who supported LHC@Home project, giving for free their CPU time and allowing these results to be produced.

joint WP2-WP5 Meeting, 15th September 2020, CERN
Outline

I. Introduction

II. On-going studies

III. Halo removal

IV. Effects on beam core

V. Towards operational scenario

VI. Conclusions
Outline

I. Introduction

II. On-going studies

III. Halo removal

IV. Effects on beam core

V. Towards operational scenario

VI. Conclusions
Introduction

- Design **stored energy** in HL-LHC beams \(~700\,MJ\)
- **How much** of this energy is **in the tails**?

Halo population probed by means of **collimator scans**

\(~5\%\) of the beams in the tails \((>3.5\ \sigma)\)
while \(0.22\%\) if Gaussian

**Scaling to HL-LHC parameters:**
\(~33.6\,MJ\) in the tails!

**Fast failure scenarios:**
- Orbit jitter
- Crab cavity phase slip

**Possible consequences:**
- Magnet quench
- Permanent damage to TCPs
**Hollow e-lens assisted collimation**

**Working principle:** hollow electron beam as additional hierarchy layer

<table>
<thead>
<tr>
<th>TCP</th>
<th>TCSG</th>
<th>TCLA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Hollow e-lens**
- **Circulating beam**
- **Secondary halo + hadronic shower**
- **Tertiary halo**

**em-field acting only on halo particles**

**Increased diffusion speed and depleted halo population**

**Beam population density, f(x, t)**
**Diffusion coefficient, D(x)**

---

D. Mirarchi, joint WP2-WP5 Meeting
Possible pulsing pattern

- **Continuous (DC):** always ON and with same $e^-$ beam current

  **Two main modulation can be envisaged:**

  **Tuning the switching while keeping constant current**
  - **Stochastic-ONOFF:**
    - **Resonant-turn:**

  **Tuning $e^-$ beam current while keeping always ON**
  - **Stochastic-amplitude:**
    - **Resonant-tune:**

Main focus

Challenging HW!
Requested functionality

Baseline HL-LHC filling pattern

Machine protection constraints:
- Leave **witness trains** for an early loss detection
- **pulse rise-time** (10%-90%) of **200 ns** due to internal structure of SPS batches
- **pulse length** in the range from **1.2 µs to 86 µs** (48 bunches to entire beam w/o AG)
- Full range of current **0 – 5 A always available**

Main requirements on **halo depletion**:

**Crab cavity (CC) failure**
- 2 σ depleted halo before TCP
- **Always ON when CC ON**

**Orbit jitter**
- More aggressive pulsing patterns needed **before going to collision**
- Compromise between removal rate and effects on core
Outline

I. Introduction

II. On-going studies

III. Halo removal

IV. Effects on beam core

V. Towards operational scenario

VI. Conclusions
Strategy of on-going studies

Main aim:

Define possible operational scenario and parameters of e-lens in HL-LHC, that provide optimal removal rate of beam tails in each point of the cycle

Best compromise between operational needs and hardware feasibility to be found, parameter space diverge quickly (excitation modes, e beam current and radius, MO, Q’, …)

Simulations approach used:

1. Dynamic Aperture simulations and Frequency Map Analysis
   - Fast simulations to explore the parameter space and guide the choice of a subset

2. Complete tracking simulations tacking into account collimation
   - Detailed evaluation of beam tail depletion and effects on the core
Recap of previous studies

- **Good qualitative agreement** between halo removal performance and DA

- **Significant effect of non linearity** on loss rate depending on pulse used

- **Main qualitative observations from FMAs:**
  - Clear distortion of Q phase space
  - e-lens enhances effects due to non linearity
Estimation of removed halo from DA simulations underestimate if DA > inner radius \( (r_1) \)

Complete halo depletion simulations needed for quantitative evaluation

To be combined with emittance blow-up simulations
Present studies

• **Disclaimer:** present studies to be considered as “academic”
  - Optics v1.3, $\beta^* = 15$ cm, no beam-beam, $Q' = 15$, $MO = -300A$
  - Only H&V TCP at 6.7 $\sigma$ treated as black absorber
  - Ideal e-lens used, with inner radius $r_1 = 5$ $\sigma$ (for halo depletion studies)
  - e-lens replaced with dipolar kick in the V plane (for core blow-up studies)

• **Minimal requirements** to define specifications and operational scenarios:
  - Optics v1.5 (at least v1.4) at each matched point of the HL-LHC cycle

Large computing power needed! Exploiting SixTrack potentiality!

<table>
<thead>
<tr>
<th>Turns</th>
<th>$10^5$</th>
<th>$10^6$</th>
<th>$10^7$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time/job (2p tracked)</td>
<td>$\sim1h$</td>
<td>$\sim$few h</td>
<td>$\sim$few days</td>
</tr>
<tr>
<td>Study:</td>
<td>FMA</td>
<td>DA / Halo / Core</td>
<td>Core</td>
</tr>
<tr>
<td>jobs/case:</td>
<td>$\sim600$</td>
<td>$10200 / 7500 / 5000$</td>
<td>$5000$</td>
</tr>
<tr>
<td>Simulated cases:</td>
<td>$\sim40$</td>
<td>$\sim200 / \sim700 / \sim100$</td>
<td>$\sim20$</td>
</tr>
</tbody>
</table>

Impossible without combining HTC and BOINC!  
>1000 years of CPU used on HTC!
Outline

I. Introduction

II. On-going studies

III. Halo removal

IV. Effects on beam core

V. Towards operational scenario

VI. Conclusions
Halo removed with “stochastic-ONOFF” (RND)

Performance with different probabilities to be ON probed (keeping $e^-$ beam current 5 A):

- **Stable performance** between 35% - 65% of $e^-$ beam ON
- Still **significant** removal with probability < 35% and > 65%

*Useful knob to reduce possible effects on core and power deposition on collector, while keeping efficient halo removal*
Current scan with RND pulse

Performance with different e⁻ beam current probed (keeping 50% prob. e⁻ beam ON):

- Significant margins on e⁻ beam current
  - Current can be reduced while keeping efficient halo removal
- “stochastic-amplitude” pulse equivalent to RND 50% with ~3 A
  - Is it worth keep investigating HW options that would make it possible?
Halo removed with “resonant-turn” (pulsed)

Usually explored patterns with \( N_{\text{ON}} = 1 \text{ turn} \) and \( N_{\text{OFF}} = \# \text{ turns} \)

Studies extended to investigate dependence on both parameters

- Clear “resonances” depending on pulse period
- Highest losses observed for \( T = N_{\text{ON}} + N_{\text{OFF}} = 23 \text{ turns} \)
- Investigated larger \( T = N_{\text{ON}} + N_{\text{OFF}} \) moving on this diagonal
Halo removed vs $T = N_{ON} + N_{OFF}$

- **No effect** changing $Q'$
- $I_{MO}$ modify the “resonance” lines

$I_{MO}$ acts on **detuning with amplitude**

Tried to find a recursive pattern to **build a simple model to find optimal $T$ analytically**

**Harder than expected:**
Strong dependence also on time!
No clear signature observed in FMAs and FFTs

Analytical **model on-hold**
and complete simulations performed

**Any idea** is very welcome!
(on-going work with Univ. Bologna)

D. Mirarchi, joint WP2-WP5 Meeting
Outline

I. Introduction

II. On-going studies

III. Halo removal

IV. Effects on beam core

V. Towards operational scenario

VI. Conclusions
Core blow-up

- Ideal e-lens replaced with **vertical dipolar kick** dynamically tuned according to pulsing pattern
- Estimates **residual kick** using present magnetic design (**A. Mereghetti at e-beam WG**):
  - **V plane: 5.22(3.78) nrad** for a symmetric(entire) map
  - **H plane: 0.085(0.082) nrad** for a symmetric(entire) map
- **Tolerated emittance blow-up in HL-LHC = 0.05 μm/h ≈ 1.39 × 10^{-5} μm/s**

**Main focus** given to most promising patterns for operational purposes:

Significant blow-up observed with **RND** mode

**Not usable with present design** (~0.5 μm increase in10s!)

**Longer simulation needed to provide OP specifications**

No emittance growth visible with **DC** and

\[ N_{ON} = 14 - N_{OFF} = 9 \]

with up to 10 nrad kick!
Increasing sensitivity

- Still **no emittance growth** visible with **5 nrad** kick for **DC** and **N_{ON} = 14 – N_{OFF} = 9**!

  - Simulations performed up to 10^7 turns (~16min) for a sensitivity of ~ 2 \times 10^{-5}\mu m/s

- **Visible blow-up** with **1 nrad** kick for **RND** mode!

  - Is there any “threshold”?
Tolerable residual kick with RND mode

Probed the effect of different probabilities to be ON

- Still on the edge tolerated continuous blow-up with residual kick of 0.1 nrad!
- Two possible knobs to mitigate emittance growth
  - Reduce $e^-$ beam current (assuming linear scaling of the residual kick)
    - About a factor 2 less blow-up going from 50% to 15% probability to be ON
Outline

I. Introduction
II. On-going studies
III. Halo removal
IV. Effects on beam core
V. Towards operational scenario
VI. Conclusions
Combining core and halo performance

- **Significant** fraction of halo removed with 15% probability (see also slide 13)
- Pulse $N_{ON} = 14 - N_{OFF} = 9$ much more efficient than DC without inducing blow-up!

**Possible strategy:**
1. **Short** use of RND mode until adjust (few s) tuning $e^-$ beam current and probability
2. **Continuous** depletion using $N_{ON} = 14 - N_{OFF} = 9$ while colliding
Considering pulse-to-pulse stability

Random component with Gauss distribution cut at a $3 \sigma$ and $\sigma = 1\%$ of considered:

- $\text{e}^-$ beam current
- Dipolar kick

Minor effect on halo depletion with DC pulse
(adding random $\text{e}^-$ beam current component)

No effect expected on emittance growth

1% pulse-to-pulse stability should be within reach: to be confirmed at the test stand
Introducing linear coupling

Dipolar kick acting only on V plane: invariant provided by $\varepsilon_x^* + \varepsilon_y^*$

- The larger the amplitude, the larger the sharing between planes
- The larger the amplitude, the smaller the sharing between planes
- The larger the amplitude, the larger the sharing between planes, but most of the growth still in the excitation plane

Useful knob to distribute eventual blow-up between planes:

phase roughly $315^\circ$ - $45^\circ$ would prevent $\mathcal{L}$ unbalance in IP1-5 due to Xing form factor
Outline

I. Introduction
II. On-going studies
III. Halo removal
IV. Effects on beam core
V. Towards operational scenario
VI. Conclusions
Conclusions

**Halo removal:**
- RND pulse confirmed to be the most efficient

**Significant margins** on e⁻ beam current and probability to be ON
- RND modulation of e⁻ beam current do not justify efforts to investigate HW options
- Very poor performance of DC mode
- Pulse $N_{ON} = 14 - N_{OFF} = 9$ much more efficient than DC and other resonant

**Effects on core:**
- RND pulse lead to unacceptable emittance growth with present magnetic design
- No emittance growth visible with DC and $N_{ON} = 14 - N_{OFF} = 9$ with up to 10 nrad kick!

**Pulse-to-pulse stability:** Negligible effects expected with 1% stability

**Linear coupling:** Useful knob to distribute eventual blow-up between planes

**Conceptual operational strategy based on present studies:**
1. Find best compromise between magnetic design, e⁻ beam current and probability to be ON to use RND mode until adjust for few s when needed
2. Constant depletion using $N_{ON} = 14 - N_{OFF} = 9$ with colliding beams
Next steps

Much clearer path of studies needed to draw OP specs! But plenty of work to be done!

• Repeat present studies in realistic machine configurations (no drastic changes expected):
  ✓ Mask for Flat Top optics needed
  ✓ Mask needed for different matched point of $\beta^*$ levelling, including beam-beam
  ✓ Still asymmetric $\beta$ at e-lens in HLv1.3…at least HLv1.4 needed
  ✓ Use three primary collimators (skew TCP not considered yet)
  ✓ Use $4.7\sigma$ as inner radius (present studies done with $5.0\sigma$)
  ✓ Mask during ramp to study solutions for 11T flux jump?

• Additional checks done/open points:
  ➢ Tested pulse with frequency content tuned on halo spectrum
    ➢ Quite fast effect that vanishes once halo starts drifting
    ➢ Frequency content able to drift the until collimators needed
    ➢ It becomes essentially the RND pulse
  ➢ Why $T = N_{\text{ON}} + N_{\text{OFF}} = 23$ turns is so more efficient than others?
    o No clear differences observed in FMAs
    o No clear correlation with FFT: other $T$ have a peak falling into the halo spectrum but are less efficient
Thank you for your attention!
Outline

Backup
Double gauss to study effects on core? (I)

- Best distribution to be used for tracking?

Double gaussian distribution used for halo removal studies:

Solid “dots”: H plane
Dashed “dots”: V plane

Unstable parameters for the core gauss (particularly when increasing the kick) (maybe more stat needed?)
Double gauss to study effects on core? (II)

- Thus, let's try to fit only the core of the double gauss (i.e. within $2\sigma$)

**Solid “dots”: H plane**
**Dashed “dots”: V plane**

Much more stable fit of $\varepsilon^*$ core (but still quite large errors on blow-up)

Absolute $\varepsilon^*$ value faked by single gauss fit on double gauss distribution

D. Mirarchi, joint WP2-WP5 Meeting
Single gauss to study effects on core?

- Thus, let's try a single gauss distribution

Global fit quality "not bad"

- $\varepsilon^*$ growth consistent with evaluation on core of double gauss distribution
- Correct absolute $\varepsilon^*$ value

Single gauss distribution used!
Can we mitigate blow-up using the ADT?

<table>
<thead>
<tr>
<th>Device</th>
<th>s</th>
<th>(\mu_x)</th>
<th>(\mu_y)</th>
<th>(\Delta \mu_x) [deg]</th>
<th>(\Delta \mu_y) [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELENS.5L4.B1</td>
<td>3292.28</td>
<td>7.466278428</td>
<td>6.7572551707</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>12048</td>
<td>864</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADTKH.D5L4.B1</td>
<td>3301.32</td>
<td>7.4738931149</td>
<td>6.7639960052</td>
<td>2.7</td>
<td>2.4</td>
</tr>
<tr>
<td>ADTKH.C5L4.B1</td>
<td>3302.92</td>
<td>7.4753139135</td>
<td>6.7651802462</td>
<td>3.3</td>
<td>2.9</td>
</tr>
<tr>
<td>ADTKH.B5L4.B1</td>
<td>3305.52</td>
<td>7.4776707173</td>
<td>6.7670976714</td>
<td>4.1</td>
<td>3.5</td>
</tr>
<tr>
<td>ADTKH.A5L4.B1</td>
<td>3307.12</td>
<td>7.4791510622</td>
<td>6.7682731552</td>
<td>4.6</td>
<td>4.0</td>
</tr>
<tr>
<td>ADTKV.B5R4.B1</td>
<td>3359.85</td>
<td>7.5418160633</td>
<td>6.8044866706</td>
<td>27.2</td>
<td>17.0</td>
</tr>
<tr>
<td>ADTKV.C5R4.B1</td>
<td>3362.45</td>
<td>7.5455808033</td>
<td>6.8061216557</td>
<td>28.5</td>
<td>17.6</td>
</tr>
<tr>
<td>ADTKV.D5R4.B1</td>
<td>3364.05</td>
<td>7.5479231025</td>
<td>6.8071200295</td>
<td>29.4</td>
<td>18.0</td>
</tr>
</tbody>
</table>
Measured emittance blow-up in LHC


Table 3: Measured and extra emittance growth in collisions.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured</td>
<td>0.04</td>
<td>0.04</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>on top of model</td>
<td>0.02</td>
<td>0.07</td>
<td>0.03</td>
<td>0.09</td>
</tr>
</tbody>
</table>
FMA, $N_{ON} = 14 - N_{OFF} = 9$

5D, $E = 7$ TeV, $I_{\text{oct}} = -300$ A, $\varepsilon_n = 2.5$ $\mu$m rad, $Q' = 15$, $N_b = 2.2 \times 10^{11}$

$(Q_x, Q_y) = (62.31, 60.32)$, 99 angles, 0.1 – 6.1, HEL pulse = 14ON – 9OFF

Resonance line drawn up to 23rd order
Machine settings

• Optics = HL-LHC v1.3
• BP = collision (but still separated beams)
• Beam-beam = NO
• Field errors = MBRB, MBRC, MBRS, MBX, MBW, MQW, MQTL, MQMC, MQX, MQY, MQM, MQML, MQ, MQXF
• Collimators = only H&V TCPs treated as black absorbers
• Turns = 1e6
• Angles = 17
• Aperture steps = 10 (from $2\sigma$ to $22\sigma$ with $2\sigma$ step)
• Seeds = 60
e-lens settings

- Length = 3 m
- e-beam current = 5 A
- e- kinetic energy = 10 keV
- e- distribution = UNIFORM
- r1 = 5 σ
- r2 = given by magnetic compression using real e-gun dimension (r1=4.025mm, r2=8.05mm)
- Bending solenoids = NO
3D Map of Electrical Field

- 3D map of Ex, Ey and Ez is necessary to evaluate:
  - Integrated strength along the longitudinal axis of e-Lens → first idea of effects on core of proton beam;
  - Maps of longitudinally-integrated kicks as effect of asymmetries in electron beam profile (e.g. regions of injection/extraction of electrons), or non-ideal electron beam distributions (e.g. towards the end of e-Lens);
- Map received by D. Nikiforov, 2019-10-11;
- Very detailed mesh: x=[-5:5:0.1] mm, y=[-5:5:0.1] mm, z=[-1900:1950:0.1] mm;
- .txt file at 30 GB → split into 4 pieces:

Collector bend: z=[1750:1950] mm;
Gun bend: z=[-1900:-1750] mm;
Main solenoid 2: z=[0:1750] mm;
Main solenoid 1: z=[-1750:0] mm;
Longitudinal Profile (1D) of $E_{\text{tot}}$ at $x=0$, $y=0$

$E_{\text{tot}}^2 = E_x^2 + E_y^2 + E_z^2$

Discontinuity at entrance of main solenoid 1 (mainly on $E_x$ and $E_y$)

Collector bend: $z=[1750:1950]$ mm;

Main solenoid 1: $z=[-1900:-1750]$ mm;

Main solenoid 2: $z=[0:1750]$ mm;

Main solenoid 1: $z=[-1750:0]$ mm;

Gun bend: $z=[-1900:-1750]$ mm;
Longitudinal Profile (2D, Ver view) of $E_{\text{tot}}$ at $x=0$

Discontinuity at entrance of main solenoid 1 (mainly on $E_x$ and $E_y$)

Collector bend: $z=[1750:1950]$ mm;

Main solenoid 2: $z=[0:1750]$ mm;

Main solenoid 1: $z=[-1750:0]$ mm;

Gun bend: $z=[-1900:-1750]$ mm

Vertical offset of e-beam at entrance and exit of main solenoids (1-2 mm)

$E_{\text{tot}}^2 = E_x^2 + E_y^2 + E_z^2$
Transverse Profile (2D) of $E_{tot}$

$$E_{tot}^2 = E_x^2 + E_y^2 + E_z^2$$

- **Collector bend**: $z=[1750:1950]$ mm;
- **Gun bend**: $z=[-1900:-1750]$ mm;
- **Main solenoid 2**: $z=[0:1750]$ mm;
- **Main solenoid 1**: $z=[-1750:0]$ mm;
- **Vertical offset of e-beam at entrance and exit of main solenoids (1-2mm)**

- e-beam fine in the middle of main solenoid

A. Mereghetti
D. Mirarchi, joint WP2-WP5 Meeting
Integrated Vertical Kicks

Gun bend: \( z = [-1900, -1750] \) mm;

Main solenoid 1: \( z = [-1750, 0] \) mm;

Main solenoid 2: \( z = [0, 1750] \) mm;

Collector bend: \( z = [1750, 1950] \) mm;
Remarks

- 3D map seems fine, apart from discontinuity at ~entrance of first main solenoid (~-1600mm) → D. Nikiforov, can you check this in your generation chain?
  - All plots are available on CERNbox at (you should all have received an e-mail with a direct link): your projects → collimation-team → eLens → ChebyshevMaterial → 3D maps → 2019-10-11
- Large vertical offsets of electron beam at entrance/exit of main solenoid (1-2mm):
  - Can we do anything about it?
  - Is this configuration without correctors? (D.Nikiforov)
- Integrated fields computed → values at gun/collector bends are comparable to those computed by G. Stancari;
- Integrated kicks computed:
  - At (x,y)=(0,0): values are in the order of few nrad (similar to what computed by G. Stancari);
  - Maps of integrated kicks are affected by vertical offsets of e-beam → shall we extend transversally the range covered by the maps?
- How does the picture change when varying (D. Nikiforov):
  - Electron current;
  - Electron energy;
- SixTrack:
  - Kicks at (x,y)=(0,0) could be used to have a first estimate of effects on beam core → Reference system in maps is that of the electron beam! To use data, please keep in mind the rotation by 180° about the y-axis (vertical);
  - Chebyshev fitting still to be done – numpy allows only fitting on a domain in 1D, I have to work out the fitting in a 2D domain…
## HEL specs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geometry</strong></td>
<td></td>
</tr>
<tr>
<td>Length of the interaction region, $L$ [m]</td>
<td>3</td>
</tr>
<tr>
<td>Desired transverse scraping range $[\sigma, \epsilon = 2.5\mu m]$</td>
<td>3.5–7.1</td>
</tr>
<tr>
<td>Inner/outer electron beam radii at 7 TeV [mm]</td>
<td>1.1–2.2</td>
</tr>
<tr>
<td>Inner/outer cryostat diameter [mm]</td>
<td>132 / ≈ 500</td>
</tr>
<tr>
<td>Inner vacuum chamber diameter [mm]</td>
<td>60</td>
</tr>
<tr>
<td><strong>Magnetic fields at 7 TeV and magnet parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Main solenoid field, $B_m$ [T]</td>
<td>5.0</td>
</tr>
<tr>
<td>Gun solenoid field, $B_g$ [T]</td>
<td>0.35–4.0</td>
</tr>
<tr>
<td>Beanding solenoid field [T]</td>
<td>3.5</td>
</tr>
<tr>
<td>Compression factor , $\sqrt{B_m/B_g}$</td>
<td>3.8</td>
</tr>
<tr>
<td>Maximum current in main solenoid [A]</td>
<td>330–350</td>
</tr>
<tr>
<td><strong>Electron gun</strong></td>
<td></td>
</tr>
<tr>
<td>Inner/outer cathode diameters [mm]</td>
<td>8.05–16.1</td>
</tr>
<tr>
<td>Peak yield at 10 kV, $I$ [A]</td>
<td>5</td>
</tr>
<tr>
<td><strong>High-voltage modulator</strong></td>
<td></td>
</tr>
<tr>
<td>Cathode-anode voltage [kV]</td>
<td>15</td>
</tr>
<tr>
<td>Rise time (10%–90%) [ns]</td>
<td>200</td>
</tr>
<tr>
<td>Repetition rate [kHz]</td>
<td>35</td>
</tr>
</tbody>
</table>