Dynamic Aperture simulations at the HL-LHC with hollow e-lens

D. Mirarchi,
M. Giovannozzi, A. Mereghetti, S. Redaelli

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

- Present collimation system designed to handle up to 360 MJ, HL-LHC design ~700 MJ
- How much of this energy is in the tails?

Halo population probed by means of collimator scans
BLM signal calibrated using BCT signal

~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 surrounds the p beam as additional hierarchy layer

---

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

---

**Increased diffusion speed and depleted halo population**

---

**TCP**

**TCSG**

**TCLA**

---

**Circulating beam**

---

**Hollow e-lens**

---

**Secondary halo + hadron shower**

---

**Tertiary halo**

---
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

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

• **Complete simulations** to evaluate halo depletion rate and effects on beam core:
  - Time consuming
  - Large computing power required

• **Main aim of these studies:**
  Use Dynamic Aperture (DA) simulations (much faster) to explore the parameter space and guide the choice of a subset for complete simulations
Parameters explored

• **Studies of DA and DA vs Turns** have been carried out for:

  ✓ **Inner radius \( r_1 \) scan** for different excitation modes:
    - \( r_1 = 3, 5, 7, 9 \) σ
    - Mode: Random ON-OFF (RND), Continuous (DC), pulsed every 1, 2 or 3 turns

  ✓ **Octupole current and Chromaticity scans**:
    - \( r_1 = 3, 5 \) σ
    - Mode: Random ON-OFF (RND), Continuous (DC), pulsed every 1, 2 or 3 turns

**HOW TO READ NAMING CONVENTION USED:**

\[
\text{HEL}_\text{Q'}p_2\text{MO}_0??_s
\]

- \( Q' = 2 \)
- \( r_1 = 3, 5, 7, 9 \) σ
- \( \text{MO} = 0 \) A
- Pulsing pattern = DC, RND, 1t, 2t, 3t

• **Machine** and **e-lens settings** reported in **backup** as reference
Two ways to show results

What you get from the 60 seeds simulated with SixTrack:

- Average DA over all seeds vs angle
- Envelope defined by absolute min and max DA over all seeds for each angle
- Average DA over all seeds and angles
- Error bars defined by absolute min and max DA over all seeds and angles
Reference case, HL-LHC v1.3, $Q' = 2$, MO = 0 A, without HEL
Summary r1 scan for different exc. modes

The larger $r1$, the worse the field quality $\rightarrow$ reduced difference of efficiency for btw exc. modes
Qualitative observations r1 scan

- **Clearly visible effect** of e-lens on DA
- The larger r1, the smaller the difference between excitation modes
- Ranking of efficiency:
  1) RND
  2) 3t
  3) 1t
  4) DC
  5) 2t

**Ranking confirmed** by on-going simulations of tail population removal rate!

![Average Population Mode scan - 3 σ](chart)

- DC
- RND
- 1t
- 2t
- 3t

R. Cai

ColUSM #119, D. Mirarchi
Summary MO scan

$R1 = 3\sigma$

$R1 = 5\sigma$

(1) MO = -300 A, (2) MO = -150 A, (3) MO = 0 A, (4) MO = 150 A, (5) MO = 300 A

$Q' = 2$

ColUSM #119, D. Mirarchi

The University of Manchester
Qualitative observations MO scan

- **RND** mode cuts always like a **sharp blade at r1**
- For **other pulsing pattern**:
  - DA increases with MO=-150A and back down with MO=-300A at same level of MO=0A
  - DA decreases with positive MO
- Effect of MO **more pronounced when r1 = 5 \( \sigma \) than r1 = 3 \( \sigma \)**

  - Ranking of efficiency confirmed:
    1) RND
    2) 3t
    3) 1t
    4) DC
    5) 2t

- **Next step**: simulations with -450 A and -600 A running (negative MO present HL baseline)
Summary Q’ scan

(1) $Q' = 2$, (2) $Q' = 5$, (3) $Q' = 10$, (4) $Q' = 15$

$MO = 0$ A
• **RND** mode cuts always like a **sharp blade at r1**

• For **other pulsing pattern:**
  - DA and its spread decreases as a function of Q’ for all other modes

• Effect on Q’ **more pronounced when r1 = 5 σ than r1 = 3 σ**

• Ranking of efficiency confirmed:
  1) RND
  2) 3t
  3) 1t
  4) DC
  5) 2t

• **Next step:** simulations with Q’ = 20
Combined effect toward OP config.

Negative MO partially compensates improvement due to $Q' = 15$
Machine settings

DA vs Turns
• **Main aim:**
  1. Study the behaviour of DA as a function of the simulated turns
  2. Use parametric fit to extrapolate DA at much larger turns

• DA vs Turns extracted by Sixdb and analysed using **two models**:

\[
DA(N) = b \left[ \ln \frac{N}{N_0} \right]^{-\kappa}
\]

\[
DA(N) = b \left[ \ln \mu N + \frac{\kappa}{2} \ln \left( \frac{2}{\kappa} \ln \mu N \right) \right]^{-\kappa}
\]

• **Models do not fit perfectly DA vs Turns using HEL:**
  1. Parametric study on minimum turn for the fit
  2. Minimum turn after which fitting results are stable for all the 60 seeds is chosen

Average DA vs Turns over 60 seeds evaluated and extended to 1e9 turns (24h...)

Checked **difference between two models:** below 4% along the 1e9 turns

---

**Example:** $Q'=2$, MO=0A, 3t, 3sigma (solid lines: fit)
Qualitative observations:

- **RND mode sharp and stable** DA at r1 value (partially true also for 3t)
- **Other** pulsing pattern follow DA decay obtained without e-lens

To be understood:

- Why **DA goes below r1** for all pulsing except than for RND?

On-going investigation: model based on **theorems valid for time-independent systems**

- Simulating 1 seed with RND pattern for 1e9 turns
- Standard DA simulations with DC e-beam but RND modulation of e-beam current
The larger the MO current, the smaller the initial DA and decay rate
Summary $Q'$ scan, $r1 = 5 \sigma$

The larger the $Q'$, the smaller the initial DA and decay rate
Conclusions and next steps

- **DA studies performed for different r1, pulsing pattern, MO and Q’:**
  - Interesting results obtained
  - First step toward definition a subset of parameter for collimation simulations (halo depletion rate and effects on circulating beam core)

- **Next steps/on-going studies:**
  - Same studies extended to e-beam current of 1, 2, 3, 4 A
  - Probe effect of pulsing pattern until 10th turns
  - DC mode but with random e-beam current
  - Extend MO scans to -600 A, and Q’ to 20

- **“From qualitative to quantitative”:**
  - FMA analysis to identify resonances hit as a function of the e-lens pulsing pattern
BACKUP
Machine settings

- Optics = HL-LHC v1.3
- BP = collision
- Beam-beam = NO
- Field errors = MBRB, MBRC, MBRS, MBX, MBW, MQW, MQTL, MQMC, MQX, MQY, MQM, MQML, MQ, MQXF
- MO = 0 A
- Q’ = 2
- Turns = 1e6
- Angles = 17
- Aperture steps = 10 (from 2σ to 22σ with 2σ step)
- Seeds = 60
e-lens settings

- Length = 3 m
- e-beam current = 5 A
- e- kinetic energy = 10 keV
- e- distribution = UNIFORM
- Pulsing patterns = DC, RANDOM, 1 turn, 2 turns (still running), 3 turns (i.e. 1 turn ON and 1 turn OFF, 1 turn ON and 2 turns OFF, 1 turn ON and 3 turns OFF)
- r1 = 3, 5, 7, 9 σ
- r2 = given by magnetic compression using real e-gun dimension (r1=8.05mm, r2=16.1mm)
- Bending solenoids = NO