Status of the HL-LHC hollow electron lenses (HEL)

Stefano Redaelli, BE-ABP, on behalf of WP5
O. Brüning, D. Perini, A. Rossi, G. Stancari

9th HL-LHC Collaboration Meeting
14-16 October, 2019
Fermilab, Batavia, USA
Acknowledgements

Many thanks to the crucial contribution from FNAL to the hollow electron lens (HEL) studies!
— Initially through US-LARP
— Important contributions from Toohig fellows
— No continuing with direct collaboration
More recently: contributions also from BNL.

FNAL: G. Stancari, A. Valishev
HL-UK: UNIMAN, RHUL (H. Garcia, D. Mirarchi)
BNL-RHIC: X. Gu, W. Fischer
Thanks to the great contribution/support from CERN groups (TE/MSC, TE/EPC, TE/VSC, TE/CRG, TE/ABT, TE/MPE, EN/MME, BE/BI, BE/ABP, BE/RF), from WP2 and from the HL-LHC project.
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- Introduction
- HEL-assisted beam collimation
- The HEL design for HL-LHC
- Recent results
- Conclusions
Motivation

HL-LHC target 700 MJ stored beam energy (~ x2 LHC)
New collimation challenges, new failure scenarios
Consistent indications of over-populated tails in the LHC’s Run I and Run II (collimator scan measurements)
  — Up to 5% of total beam current \textit{statically} stored in the tails
  — Obvious concerns for machine availability (dumps from loss spikes)
  — High potential of damage

\textbf{Need for an \textit{active tail control} at the HL-LHC deemed \textit{necessary}, assessed through different review panels.}
Recent history and overall status

General concern for loss spikes in high-intensity proton colliders
  - HEL concept proposed for LHC in 2006 (V. Shiltsev, CARE meeting)
  - Extensive pioneer experimental tests at the Tevatron (G. Stancari et al.)

Recent history of HEL-related WP5 reviews
  - Internal HEL review 2012 → triggered preparation of conceptual design (2014)
  - External Collimation review 2013: looking at LHC Run I
    → Severe issues of operational losses
  - Beam losses not confirmed in Run II: what to expect for the next runs?
  - External review on needs for halo control in 2016 (“best year for losses”)
    → Recommendation to implement HEL
  - External technical review on readiness in 2017

HEL coming up at different cost&schedule reviews
  - 2018: recommendation to find funding mechanisms to implement it.

Activities in the last ~year:
  - Working on establishing the framework for in-kind contribution from Russia
    and assuring availability of CERN manpower for core activities
  - Pass technical design “ownership” to collaborators: e-beam design
  - Beam tests: gun/cathode tests + measurements at RHIC
  - Implementations from technical review and progress in design
Requirements

— Depletion of tails by ~90% in time scale of ~ 1-2 minutes
  Even with linear machine and beams non colliding
— Selection of batches within LHC bunch time structure
  Leave “witness” halo for machine protection purpose
— Negligible core blow-up during continuous operation in stable beams
— Operation starting at the end of the ramp
  Option for operation at injection as commissioning scenario

Main parameters in a nutshell:
— Rise time of electron beam ~ 200ns
— Various pulsing/modulated modes, turn-by-turn modulation of current
— 5A electron beam current, 3m overlap to proton beam
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Review on needs (2016) indicated that HEL are the best solution presently available to address these points.
Additional prospects

Once the HEL is in the baseline, it offers additional benefits beyond the motivation/scope:

— More operational flexibility, e.g. to move primary collimators during the HL-LHC cycle
— Potential further improvement of collimation cleaning through the control of the impact parameter on primary collimators.
— Tighter collimator settings for even further beta* reach (if other known limitations are under control / fixed)
— Synergy with studies on Landau stabilisation with different e-beam shapes

One more tool to “fight” known and unknown challenges of the HL-LHC!
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Three-stage cleaning in warm **cleaning insertions**: betatron (IR7) and off-momentum (IR3); local “tertiary” collimators at inner triplet.

Well-defined **collimation hierarchy** that integrates injection and dump protection collimators (as well as Roman pots). **Five stages**!

Machine aperture sets the scale for collimation hierarchy

Critical **beam-based alignment** to determine local orbit and beam size.
LHC multi-stage collimation

Three-stage cleaning in warm cleaning insertions: betatron (IR7) and off-momentum (IR3); local "tertiary" collimators at inner triplet.

Well-defined collimation hierarchy that integrates injection and dump protection collimators (as well as Roman pots).

Five stages!

Machine aperture sets the scale for collimation hierarchy

Critical beam-based alignment to determine local orbit and beam size.

Circulating beam

primary beam halo

protection devices

cold aperture

primary collimator

secondary collimator

shower absorbers

tertiary collimators

SC triplet

primary beam halo

secondary beam halo

tertiary beam halo + hadronic showers

Collimation cleaning (protons)

~ $10^{-4}$

R. Rossi
Active halo depletion: control diffusion speed, selective by amplitude.
— it is integrated into the hierarchy of the collimation system that remains responsible for the halo disposal.
— it allows distributing losses over a desired time interval.
— it controls tail populations close to collimator jaws (deplete tails).

Hollow electron lenses:
“Non-material” scraper; small kick per turn → safe device
Can be installed in other points than IR7
Experience from the Tevatron

Depletion with no effect on beam core

Particle removal is detectable and smooth (~ %/h of total intensity)

No effect on core

Removes correlation of losses to orbit jitter

Control trains strongly correlated
Losses from beam jitter much larger than statistical fluctuations

Very convincing results from beam tests at the Tevatron!

G. Stancari et al.
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The HL-LHC HEL design

- Cryogenics and magnetic system;
- Electron gun and collector;
- Electron and proton beam diagnostics;
- Vacuum system;
- Support and alignment systems.

This is a small accelerator!

- “S” shape to compensate effects on core from e-beam asymmetries.
- Small SC dipole to compensate effect on proton orbit from bending.

Talk yesterday by WP13
Design improvement following readiness review

- Higher field main solenoids: 4 T → 5 T
- Split design with 2 shorter mains: reduce stored magnet energy
- Reduced from two to one profile monitor (in the middle)
- Reduced magnet aperture: 80 mm → 60 mm (collaboration with WP2)
- Dipole orbit corrector to compensate tilted solenoids
- Change of cryogenics system pressure (for safety)
- Reduce cathode size: 25 mm → 16 mm outer radius (reduce need for compression)
- Change of local $\beta$: 200 m → 280 m (improve e-beam stability)
- ...
- Significant advance on the design of sub components
- Improvement of magnetic system through e-beam simulations by BINP.

Old design 2017

Many thanks to people involved in the progress, achieved on a “best effort” approach.

## Present parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton beam optics at HEL, $\beta$ [m]</td>
<td>280</td>
</tr>
<tr>
<td>Length of interaction, $L$ [m]</td>
<td>3</td>
</tr>
<tr>
<td>Desired transverse scraping ($&gt; 3.5 \sigma$), $r$ [mm]</td>
<td>1.1 – 2.2 @ 7TeV</td>
</tr>
<tr>
<td>Maximum electron beam current, $I$ [A]</td>
<td>5</td>
</tr>
<tr>
<td>Cathode diameter, inner/outer [mm]</td>
<td>8 / 16</td>
</tr>
<tr>
<td>Gun extraction and modulation voltage [kV]</td>
<td>10</td>
</tr>
<tr>
<td>Cathode-ground voltage [kV]</td>
<td>15</td>
</tr>
<tr>
<td>Collector bias (decelerating) voltage [kV]</td>
<td>in study</td>
</tr>
<tr>
<td>Modulator rise time [ns]</td>
<td>200</td>
</tr>
<tr>
<td>Modulator repetition rate [kHz]</td>
<td>35</td>
</tr>
<tr>
<td>Magnetic field at gun [T]</td>
<td>0.35 @ 7TeV to 4 @ 450GeV</td>
</tr>
<tr>
<td>Magnetic field at bend [T]</td>
<td>3.5</td>
</tr>
<tr>
<td>Magnetic field at main [T]</td>
<td>3 @ 450GeV to 5 @ 7TeV</td>
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See talk

D. Mirarchi et al.
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<td>Magnetic field at main [T]</td>
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</table>

— High target e-beam current compared to e-lenses in other colliders (RHIC, Tevatron): > x5 times
— Small electron beams
— **Pulsed operation mode**, with turn-by-turn variation of e-beam current.

See talk

D. Mirarchi et al.
Component design: magnetic system

Reviewed with the circuit and machine protection teams, see TCC meeting April 2019: https://indico.cern.ch/event/814368

On-going optimisation of the e-beam correctors based on simulations at BINP. Planned an internal technical review at the end of Nov. (visit by Giulio at CERN).

Thanks: G. Kirby et al.
Component design: electron collector

Present design can sustain the full beam power of 75kW without damage. Under study (BE/BI, BINP): bias voltage to reduce loads, for a possible simplification.
Component design: electron collector

Present design can sustain the full beam power of 75kW without damage. Under study (BE/BI, BINP): bias voltage to reduce loads, for a possible simplification.
Component design: gun and cathode

Rich program in the last 5 years, in collaboration with FNAL (e-beam test facility), and China → new, high-current cathode with inner radius of 8 mm.

— Challenge of high current density to match small beam sizes at the LHC.
Results of gun/cathode development

2015-2016
— CERN acquiring know-how on LHC cathode/gun design from FNAL (1” cathode used in Tevatron)
— Record current >5A with first CERN-built gun

2016-17
— New LHC design with smaller, high-current cathode (collaboration with China)

Oct. 2018
— >5 A with first small cathode and old, bigger gun

2019 (final design): Smaller gun optimised for new cathode
— Presently under test at FNAL and CERN.

Issue of short being investigated.

CERN hollow electron gun prototype (CHG1)
Fermilab electron–lens test stand, 4 Jan 2017
Heater: 8.9 A, 8.6 V
Solenoids: 0.1 T / 0.4 T / 0.1 T
Pulse width 8 μs, rep. rate 2 Hz
Perveance: 6.14 μperv

CERN 16–mm scandate hollow electron gun (CHG–16–sc)
Fermilab electron–lens test stand, 10 Oct 2018
Heater: 6.6 A, 7.44 V
Solenoids: 1.5 – 3 – 1.25 kG
Pulse: 4 μs, 4 Hz
Perveance: 6.02 μperv (V ≤ 3 kV)

Design = 5A

Courtesy of G. Stancari (FermiLab)
Ion beam tests at RHIC

Hollow cathode in one of the RHIC lenses in 2018 for tests with ion beams!
- Reviewed beam-based alignment procedures.
- First set of measurements with various excitation types.
- Analysis ongoing for an upcoming publication.
A big thank to Wolfram and Xiaofeng who made this possible!

Visits from CERN team: excellent opportunity for cross-fertilisation and to get experience!
Integration in the HL-LHC

HEL(B1i) HEL(B2e)

Point 4

CMS

Point 5

Point 6

Point 2

ALICE

Point 3.3

Point 3.2

Point 1

Point 1.8

Point 8

LHC

LHCb

SPS

HiLumi HL-LHC Project

CERN

S. Redaelli, 9th HL-LHC Collaboration Meeting, 16/10/2019
Integration in the HL-LHC

— To be updated with the new design
— Need to address a conflict with the “line of sight” for the survey team;
— Detailed integration of cabling and integration of beam instrumentation.
Established in 2016, basic R&D design phase still actual
   — Hardware: completion of Guin design validation in Q1 of 2020
   — Decided to add additional prototyping of components: collector, vacuum chamber.
   — Detailed schedule beyond to be established with BINP

**Goal for 2020**
   — Pass design “ownership” to colleagues from BINP

**Status of simulations of electron and proton beams for “iteration on the design”**
   — Some delays accumulated: people leaving + time to pass the design to BINP.
Conclusions

- Presented the status of the hollow electron lens project
  Still an “option” within WP5 — we are looking forward to the feedback on the possibility to have the HL-LHC HELs built in BINP as in-kind.

- Very mature design that is essentially completed
  A few technical open points identified, mainly related to the number of correctors.
  Need a review of the complete magnetic system → end of Nov. 2019.
  Reviewing the required pulsing schemes: efficient halo depletion vs core effects.
  → Input to modulator design.

- Ready to launch the production with the collaborators.
  In the next 12 months, specs and design need to be passed to the collaborators.
  Expect potential iterations on the design, respecting the “boundaries” defined by CERN teams that will eventually become owners.

- Plan to organise an HEL workshop around mid 2020, if lenses are integrated in the project baseline
  Stay tuned!
Reserve slides
Component design: cryogenics
HEL location around the ring

M. Gonzalez de la Aleja, Paolo Fessia
Aim
→ cathode that provides high emission, working at temperature as low as possible

<table>
<thead>
<tr>
<th>Cathode type</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>Phase 3</th>
<th>Phase 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ba-W impregnated</td>
<td>Impregnated scandate</td>
<td>Scandia doped dispenser</td>
<td></td>
</tr>
<tr>
<td>Inner diameter</td>
<td>12.5 mm</td>
<td>8.05 mm</td>
<td>8.05 mm</td>
<td>4 mm</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>25 mm</td>
<td>16.1 mm</td>
<td>16.1 mm</td>
<td>8 mm</td>
</tr>
<tr>
<td>Surface area</td>
<td>3.68 cm²</td>
<td>1.5 cm²</td>
<td>1.5 cm²</td>
<td>0.38 cm²</td>
</tr>
<tr>
<td>Working T</td>
<td>1100 °C</td>
<td>950 °C</td>
<td>950 °C</td>
<td>850 °C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gun Design</th>
<th>Diameter</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200 mm</td>
<td>25 kg</td>
</tr>
<tr>
<td></td>
<td>200 mm</td>
<td>24 kg</td>
</tr>
<tr>
<td></td>
<td>50 mm</td>
<td>&lt; 1 kg</td>
</tr>
<tr>
<td></td>
<td>50 mm</td>
<td>&lt; 1 kg</td>
</tr>
</tbody>
</table>
### HEL cathode nominal dimensions

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer diameter</td>
<td>16.1 mm</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>8.05 mm</td>
</tr>
<tr>
<td>Lifetime</td>
<td>≥ 7000 h</td>
</tr>
</tbody>
</table>

- The cathode and all the electrodes are mounted on a support made in aluminium nitride ceramic Shapal™ → good thermal conductivity
- The electron gun fits in a 60 mm diameter vacuum chamber
Electron gun 5Ax15kV

---→ Electron beam

←←→ Hadron beam

Cathode

PC

Cathode / Collector PC

+ V_{CO} - V_{CA} = 10kV
High current I_{beam}=5A

Cathode / Repellers PC

+ V_{R} - V_{CO} = 7kV

Insulation transformer

Cathode Heater
10Ax40V

Anode modulator

Control electrode
4kVx40mA

5kV

Cathode PC

V_{CA}=-15kV
Low current (losses) ~ mA

V_{A}\leq10.5kV,
\langle I_{A}\rangle \geq 100mA,
Peak I_{A} \sim \text{few } 100A,
33kHz, 200ns rise time

+\quad-\quad+

V_{R}

V_{CO}

Collector

LHC tunnel

UL44/46

CA=Cathode
A = Anode
CO=Collector
R = Repeller

Cartoon of the HEL HV System
A. Rossi 02/10/2019
Collimator scans of beam tails

Method: use robust primary collimators to scan tails, record losses, infer number of protons as a function of amplitude.

Various measurements done throughout the years, in different conditions. Below: single bunch.

Scaling to HL-LHC beam parameters in very tricky…

- Around 5% of the beams is in the tails (> 3.5 sigma), compared to 0.22% for Gaussian
- Factor 22 difference: scaling to HL-LHC parameters = 33.6 MJ vs 1.48 MJ

15 times the SPS beam, >10 Tevatron beams
Beam gas curtain monitor

- Beam-Gas Fluorescence on target gas curtain
- Looking at Ne and Ar as gas
- Prototype to be installed in LHC

Nitrogen gas jet test

- Final design scaled to fit

Moveable gauge measurement of the gas jet. This will be smaller in the interaction chamber.

Courtesy of R. Veness, T. Dodington, H. Zhang, S. Udrea and BGC collaboration
8th HL-LHC Collaboration meeting, 15-16 October 2018
IBIC 2017
“Crazy” idea of multiple guns

Collaboration with the University of Brescia