HEL functional specifications

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A. Rossi, G. Stancari, on behalf of WP5

HL-LHC Hollow Electron Lens kick-off meeting
13 April 2021
CERN, Geneva, Switzerland

Recap. of timeline and key events

<u>General concern for loss spikes in high-intensity proton colliders</u>

- HEL concept proposed for LHC in 2006 (V. Shiltsev, CARE meeting)
- Extensive pioneer experimental tests at the Tevatron (G. Stancari et al.)

<u>Recent history of HEL-related WP5 reviews</u>

- Internal **HEL review 2012** → triggered preparation of conceptual design (2014)
- External **Collimation review 2013**: looking at LHC Run I
  - → Severe issues of operational losses
  - → Such <u>beam losses</u> <u>not</u> 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**

<u>HEL discussions coming up at different cost&schedule reviews</u>

- 2018: recommendation to find funding mechanisms to implement it.
- 2019: Endorsement for integration in baseline, approved by Dec. 2019 council.

<u>Recent activities / news:</u>

- Working on establishing the framework for in-kind contribution from Russia
  - → Good progress in 2019, slower response in 2020 because of delays
- Kickoff now to converge on a reference parameter set

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- Introduction
- Beam collimation requirements
- Main HEL specifications
- Operational scenarios
- Beam diagnostics
- Conclusions

Based on EDMS 2514085 document issued for engineering checks on March 31st, collecting present up-to-date information.

Motivation

HL-LHC target 700 MJ stored beam energy (~ x2 LHC)

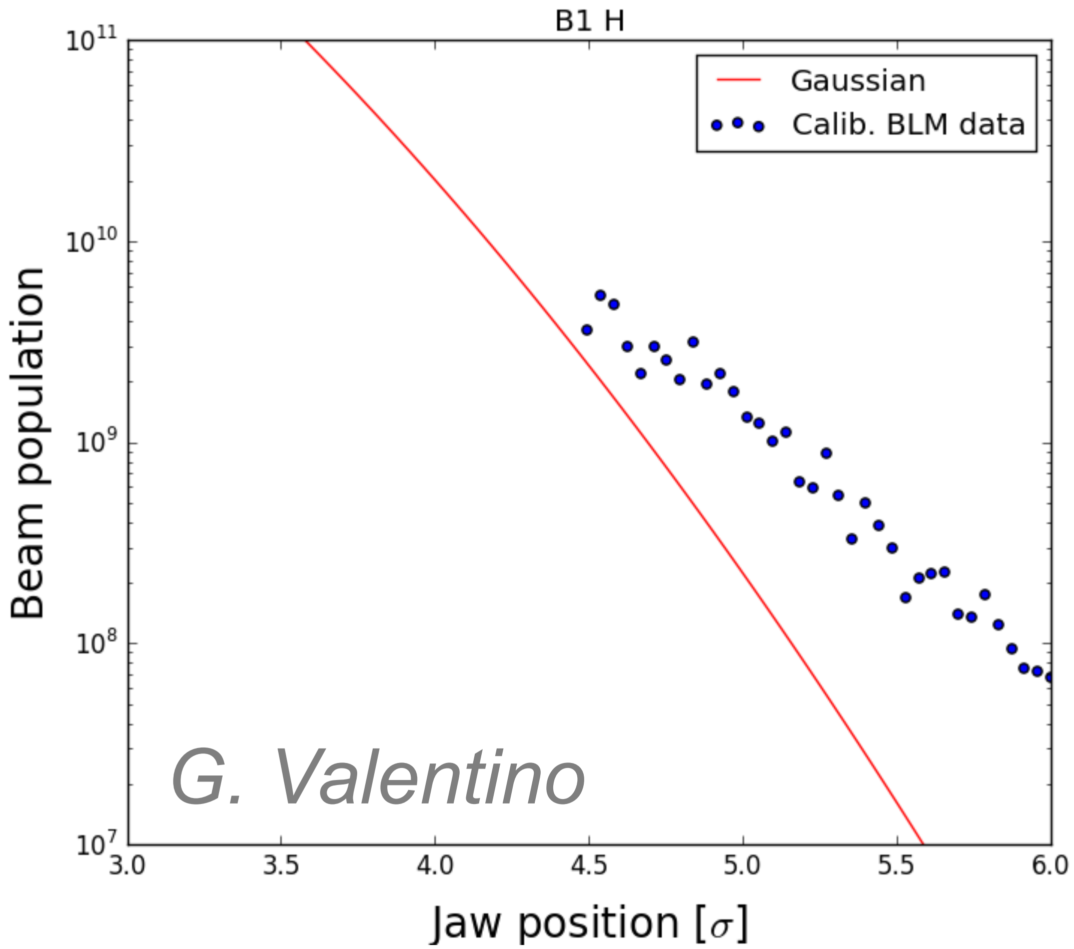
New collimation challenges, new failure scenarios

Consistent indications of over-populated tails in the LHC's Run 1 and Run 2 (collimator scan measurements)

- Up to 5% of total beam current *statically* stored in the tails
- Obvious concerns for machine availability (dumps from loss spikes)
- High potential of damage

Need to continue the monitoring in Run 3 to improve understanding and study scaling with LIU beam parameters.

Need for an active tail control at the HL-LHC deemed necessary, assessed through different review panels.



Beam collimation requirements

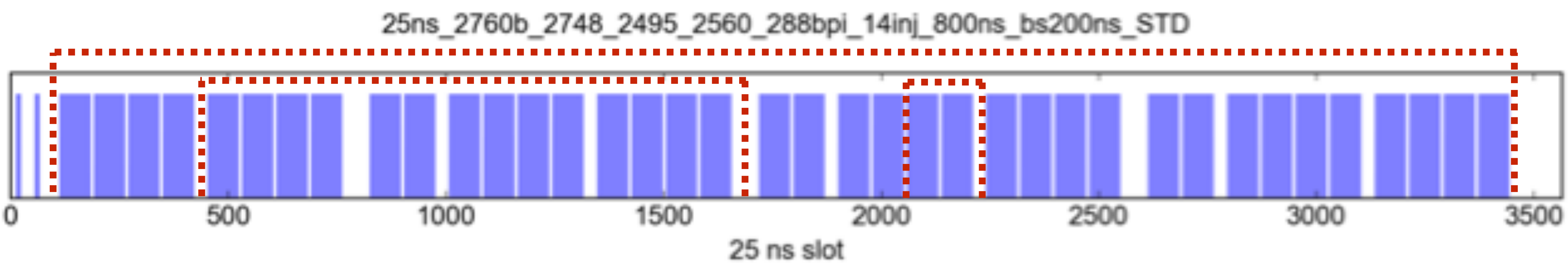
— Depletion of tails by ~90% in time scale of ~ 5 minutes
Even with linear machine and beams non colliding

— Transverse operational range: above 3.6 σ at 7 TeV

— Selection of batches within LHC bunch time structure
Leave "witness" halo for monitoring purposes
Allow for excitation of batches within the LHC trains
Leave the non-colliding bunches un-touched

— Negligible core blow-up during operation in stable beams

— Operation starting at the end of the ramp above 5 TeV:
Usage at injection as commissioning scenario



Review on needs (2016) indicated that HEL are the best solution presently available to address these points.

Additional prospects

HELs offer additional benefits beyond the initial driving motivations:

— 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.

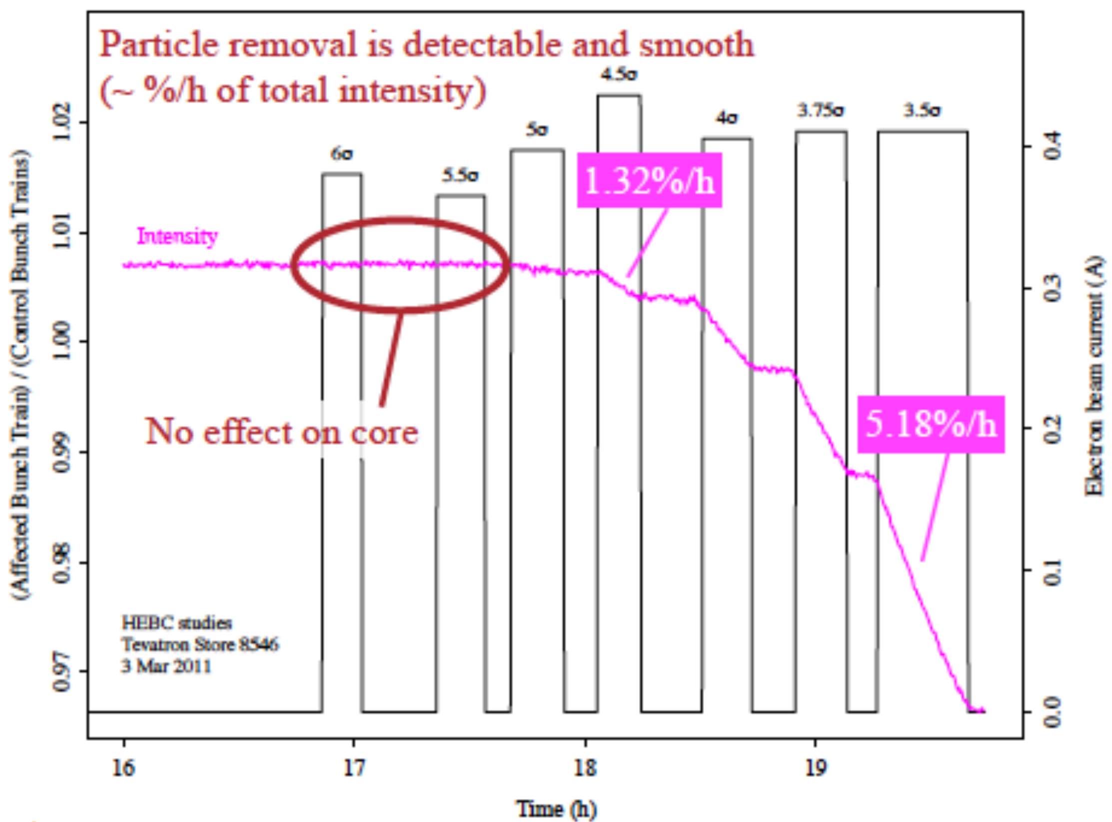
— Tighter collimator settings for even further beta* reach (if other known limitations are under control / fixed)

— Synergy with studies on Landau stabilisation with different e-beam shapes

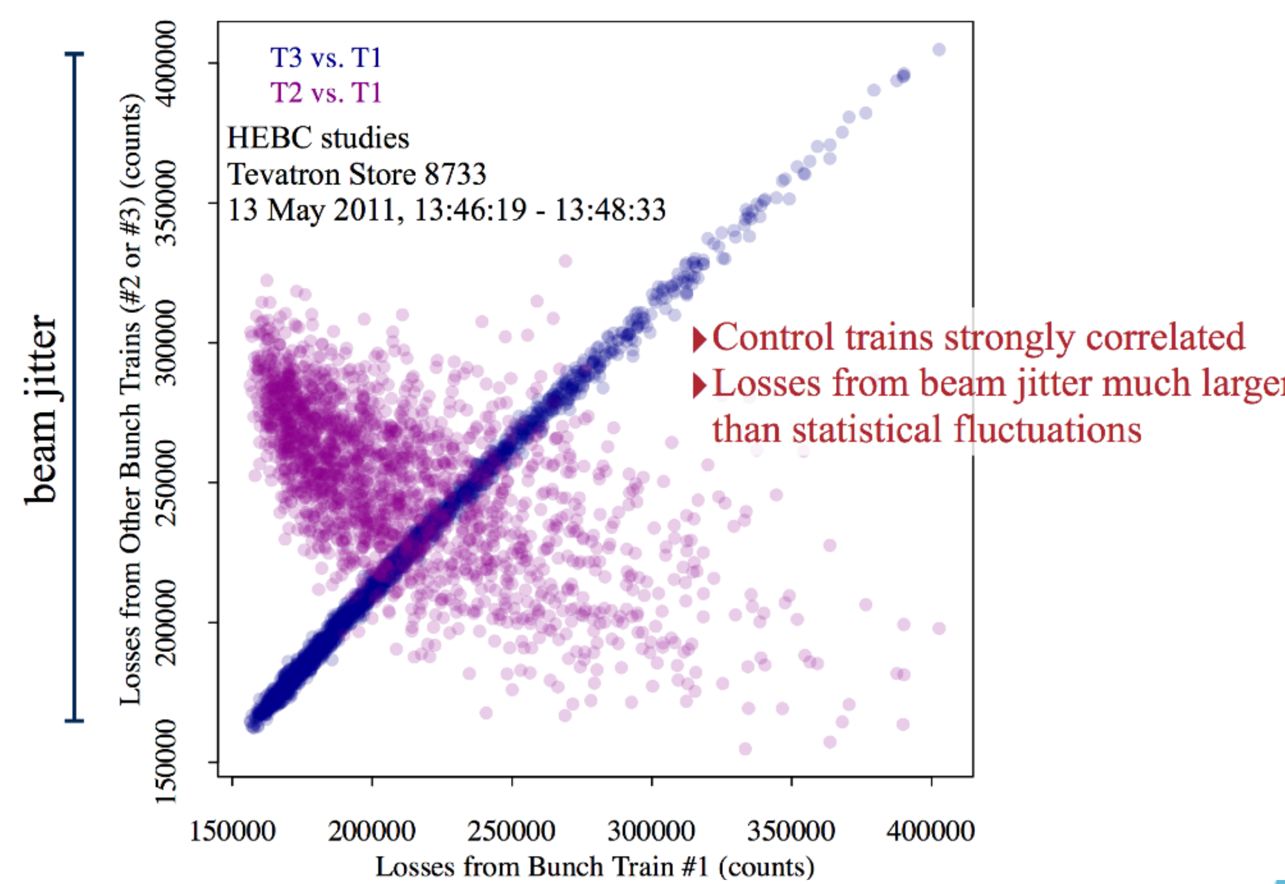
One more tool to “fight” known and unknown challenges of the HL-LHC!

Experience from the Tevatron

Depletion with no effect on beam core



Removes correlation of losses to orbit jitter



G. Stancari et al.

Very convincing results from beam tests at the Tevatron!

Other active tail-depletion schemes disregarded.

Tevatron feedback

Important feedback accumulated from the Tevatron experience:

- the use of HEL was compatible with collider operation during physics data taking;
- the alignment of the electron beam with the circulating beam was accurate and reproducible;
- the halo removal rates were controllable, smooth, and detectable;
- with aligned beams, there was no lifetime degradation or emittance growth in the core;
- loss spikes from beam-orbit jitters and tune adjustments were suppressed;
- the local effect of the electron beam on beam halo fluxes and diffusion speed were directly measured with collimator scans.
- the hardware reliability of e-lenses was demonstrated through regular operation during several years, as abort-gap cleaner.

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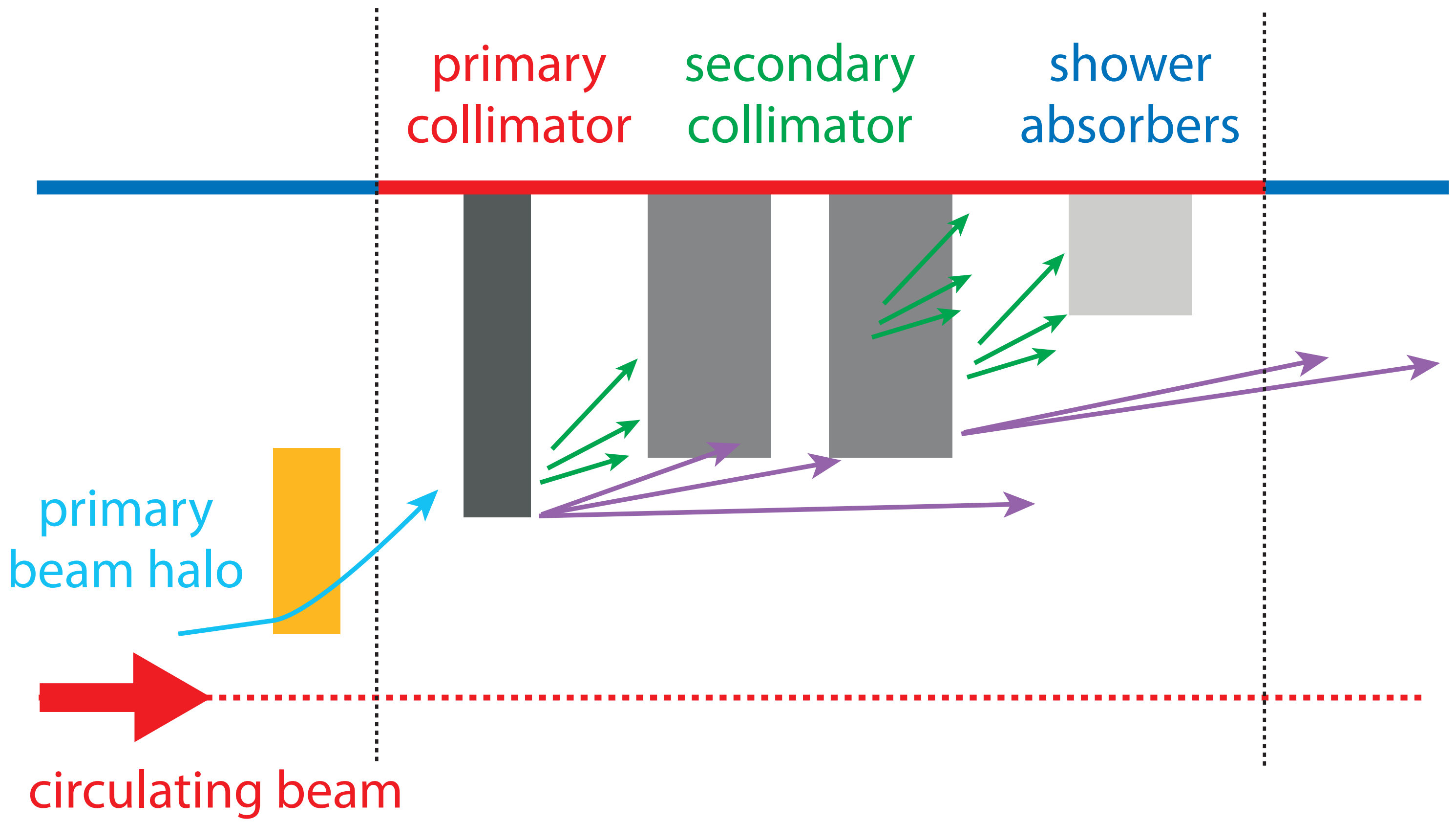
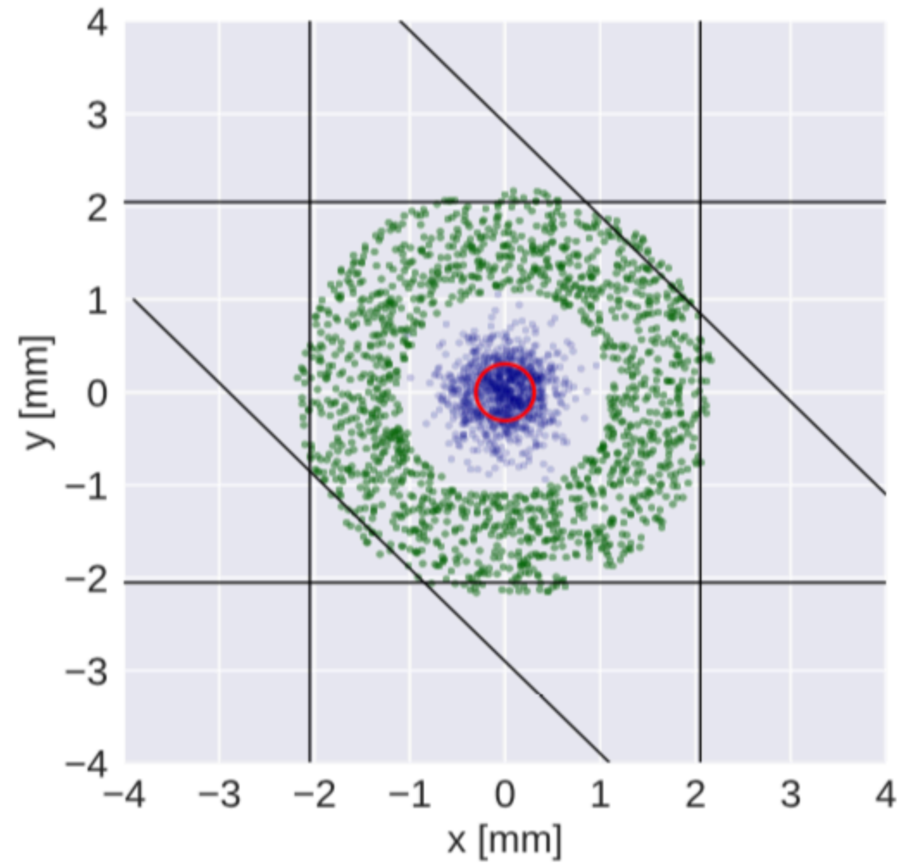
The HEL-based collimation concept





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.
- Constraints from tight transverse aperture determine the requirement on the small electron beam size.

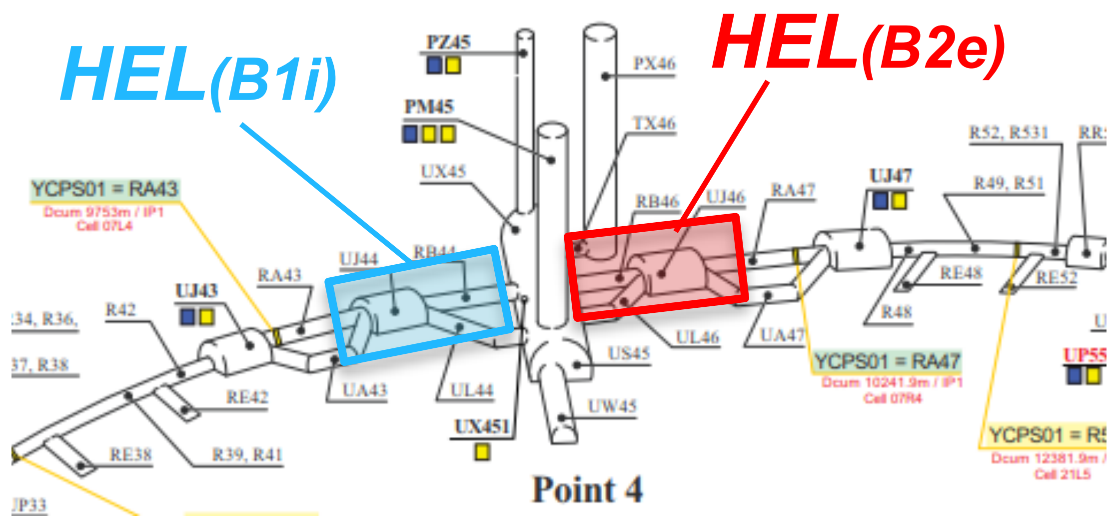
Hollow electron lenses:

"Non-material" scraper; small kick per turn → safe device

Does not need to be in IR7: enhanced diffusion brings losses in IR7

Ring locations and optics

Property	HEL B1	HEL B2
Longitudinal position from IP1, m	9957.0	10037.2
Hadron beam energy, Z TeV	7.0	
Horizontal / vertical β functions, m	280 / 280	
RMS horizontal / vertical beam size (at 7 TeV, ε=2.5μm), μm	306 / 306	
Maximum acceptable β–beating (percent)	20	
Horizontal dispersion function, m	0.0 †	
RMS horizontal / vertical beam divergence (1 σ), μrad	1.3 - 1.5	
Intra-beam distance, mm	420	
Vacuum beam aperture radius, mm	30	



†*: Tolerance on acceptable dispersion errors being finalised with WP2.*

Installation in P4 motivated by various salient aspects:

- Availability of cryogenics;
- Larger inter-beam distance for the RF system;
- Optics flexibility; optics can be kept constant during full cycle;
- Necessary longitudinal space could be found for integration.

Thanks to the great support from the integration team and WP2 for new optics.

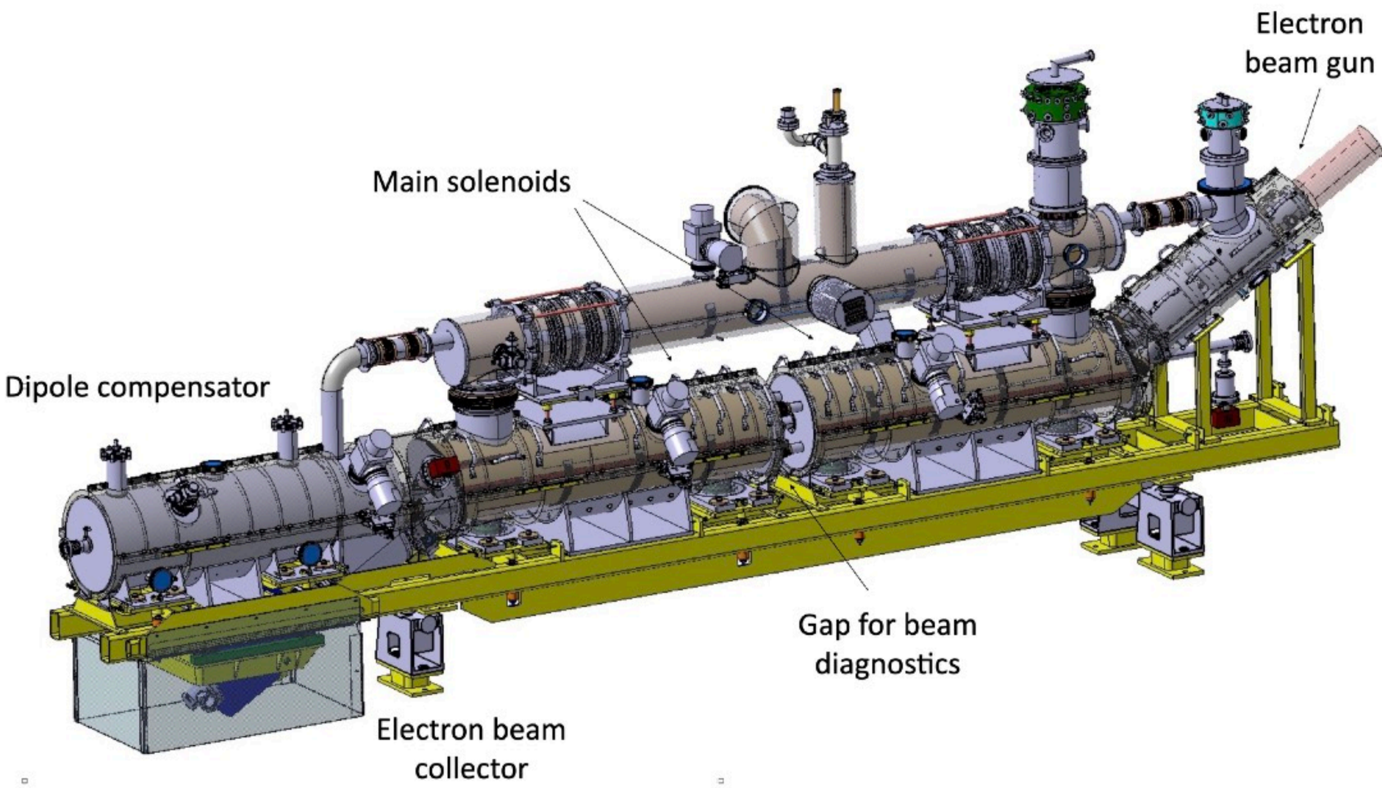
Main HEL parameters

Property	Specification	Comments
Maximum electron beam current	5 A	> 4.5 A
Interaction length	3 m	
Minimum inner electron beam radius	1.1 ± 0.01mm	
Electron beam rise time	< 200 ns	
Electron pulse length	1.2-86 μs	Also compatible with DC
Maximum number of pulses for LHC turn	3	
Repetition rate	11.4kHz – 34.2kHz	
Maximum electron beam energy	15 keV	
Tolerated integrated dipole kick in the core	3 nrad	Request from WP2: 1nrad
Electron current stability over a pulse	0.5%	
Electron current stability pulse-to-pulse	0.5%	

Still pending: study of tolerance on higher-order multipoles from e-beam imperfections and magnet field errors.

Considerations on magnet system

Property	Specification
Main solenoidal field	5 T
Inner cold bore radius	79 mm
Inner warm bore radius	60 mm
Warm beam aperture radius	30 mm
Range of gun solenoid field	0.2 – 4.0 T
Magnetic compression factor range	1.1 – 5
Target compression factor for 7 TeV operation	3.7 (0.375 T at gun)
Range of collector solenoid fields	0.2 – 0.4 T

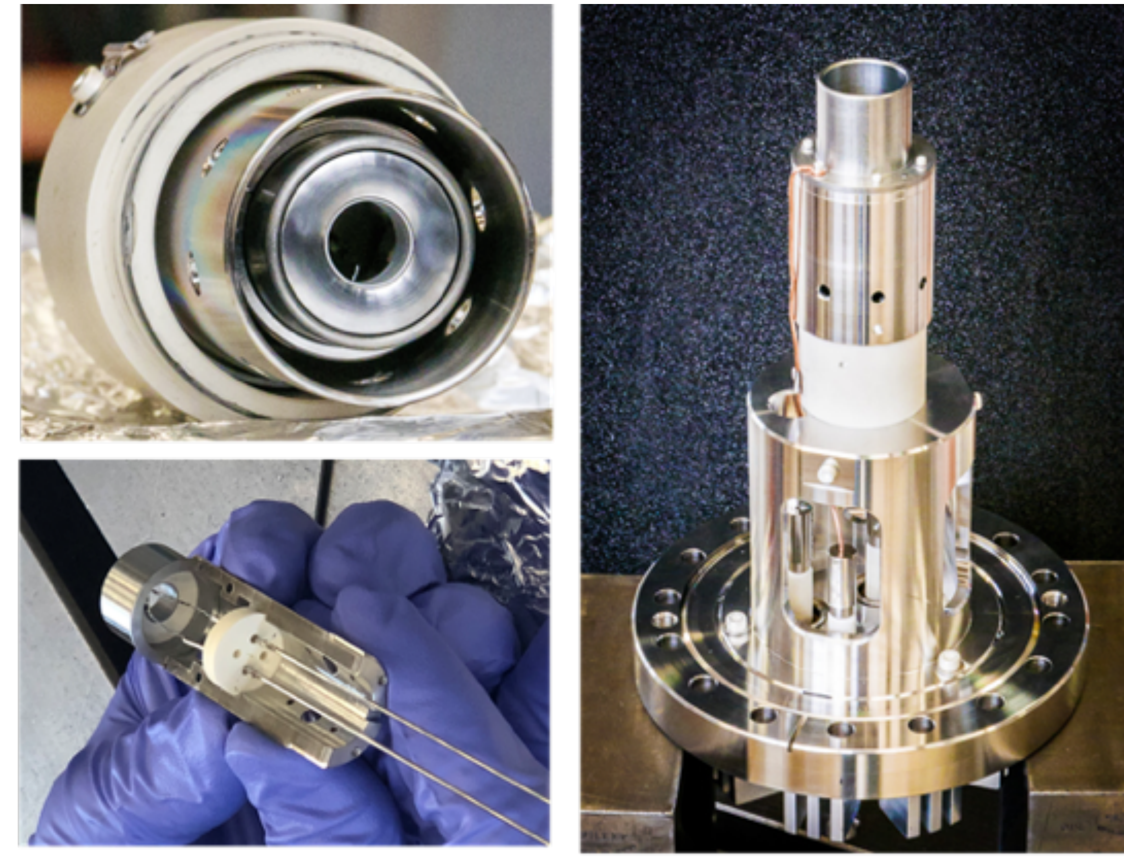


Observations relevant for HEL magnet system specifications:

- Requirement for **5 T solenoid field** for e-beam stability;
- Identified **smallest hollow cathode** that could provide 5A ($r_i = 4$mm);
- Followed the finalization of the magnetic field arrangement that gives the desired **compression factors** for the operation at 7 TeV;
- Addition of a dipole compensator for the components of tilted solenoids that minimise residual field on protons.

Electron beam sizes

Magnetic fields and magnet parameters	
Gun solenoid, B_g [T]	0.2–4.0
Collector solenoid [T]	0.2–0.4
Main solenoids (superconducting), B_m [T]	5
Range of compression factors, $\sqrt{B_m/B_g}$	1.1–5.0
Target compression factors	3.7 (0.375 T)
Electron gun and electron beam	
Inner/outer cathode radius, $r_{i,cathode}$, $r_{o,cathode}$ [mm]	4.0/8.0
Peak yield at 10 kV, I [A]	5
Maximum electron beam density [A/mm^2]	0.44



Considerations:

- Nominal e-beam size of 1.1mm achieved with a compression of 3.7;
- Larger e-beam sizes can be obtained by changing just the gun field: target to keep constant all the fields affecting the proton beams!
- Significant simplification of operational aspects (See 103rd TCC)

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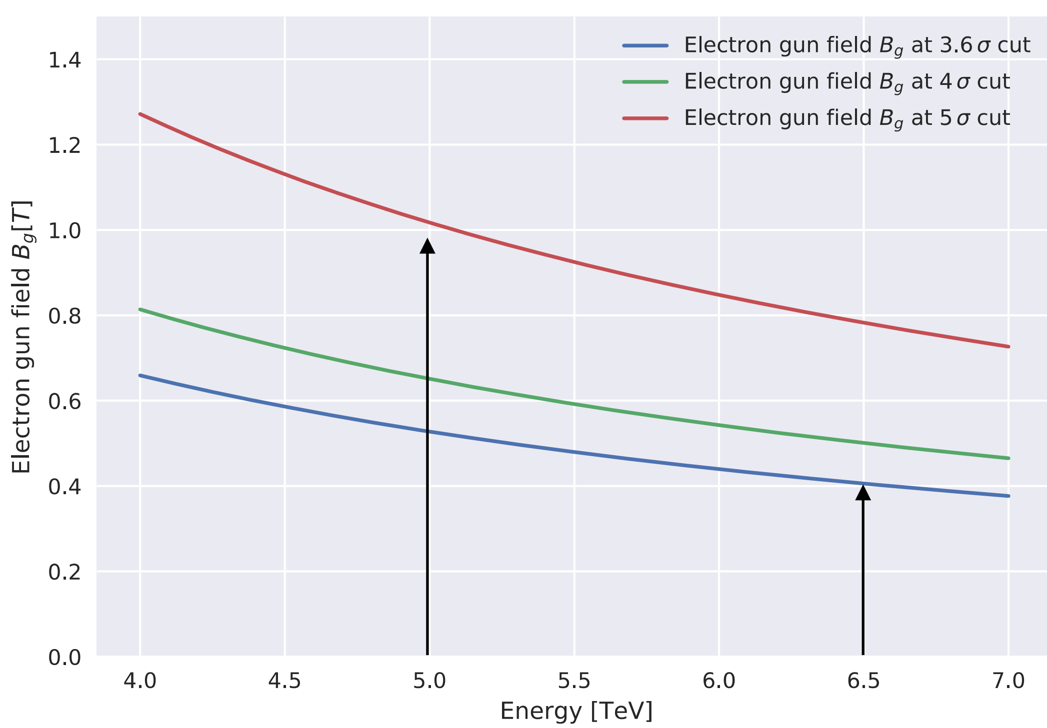
Operational scenarios

Initially specified to be able to tail deplete tails at 7 TeV

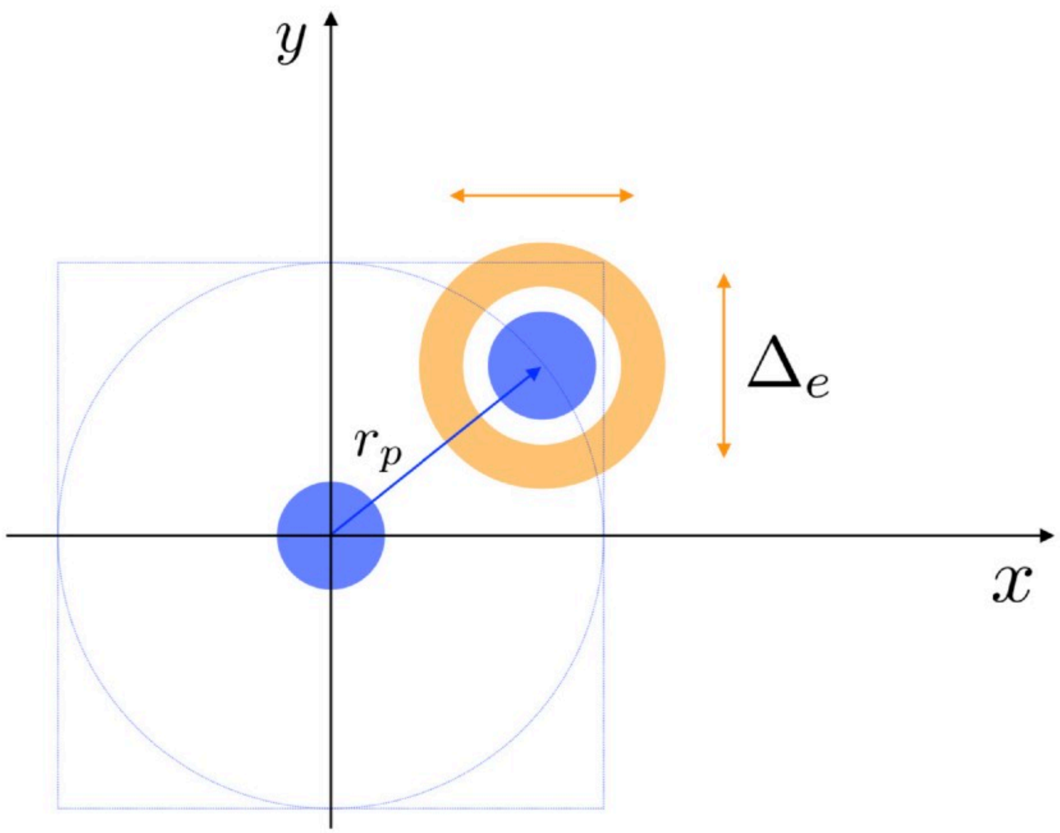
- Operational range set for energies > 5 TeV that leaves ~ 5 min to deplete tails during the ramp (reaching optimum conditions at flat top)
- Following shrinking beam sizes compatible with small adjustment at gun!
- Operations at injection = commissioning scenario.

Recent issue of flux jumps in Nb_3Sn magnets → reviewed specs.

- Checked smallest beam energy compatible with present design: 3.6 σ cut achievable at energies above ~0.8 TeV without changing the specs.
- Keep maximum flexibility in e-beam correctors to ensure this scenario.



Positioning requirements



Property	Specification
Electron beam position range	±4 mm
Electron beam position stability	0.03 mm
Electron beam angle range	± 2 mm / 3 m
Rate of position change	0.1 mm / s

Specification for the e-beam positioning to follow the proton beam for orbit variations up to ± 2 mm

- Standard assumption adopted for HL-LHC. No obvious possibility in P4 to correct locally to better levels.
- Additional 2mm range needed for relative alignment purposes.

Discussions started at the Alignment WG to elaborate precise alignment strategy and targets for HELs.

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- **Beam diagnostics**
- Conclusions

Key diagnostics for HEL:
- Beam position measurements (BPM);
- Beam-gas curtain (BGC);
- Beam loss monitors (BLMs);
- Coronagraph (not part of today meeting).

Beam diagnostics — BPMs

Parameter	Specification
BPM range	+/- 10 mm
BPM resolution	30 µm
BPM accuracy	500 µm
Time response	2 µs
BPM sensitivity — electrons	0.1 A — 5 A
BPM sensitivity — protons	Single bunch to full beam
Relative position measurement accuracy	< 100 µm (TBD)

Important to address, and ensure flexibility for

- Commissioning scenarios with few bunches
- Nominal operation at maximum beam current

Electron beam: cover range up to maximum current.

Beam diagnostics — BGC

Parameter	Specification
Beam energy (proton / electron)	7 TeV / 15 keV
Beam size (proton / electron)	300 µm / 4-8 mm (annular)
Intensity (proton / electron)	1.1 A / 5 A
Time to acquire 2D images	10 s
Synchronization proton electron images	1 s
Beam centroid accuracy	< 100 µm

From EDMS 2369616, "acceptance criteria for BGC".

Same considerations made for BLM apply — see detailed talk.

Looking forward to seeing the beam tests in Run 3 at the LHC

- Important to assess if BGC can be used in commissioning phases at low proton beam intensities.

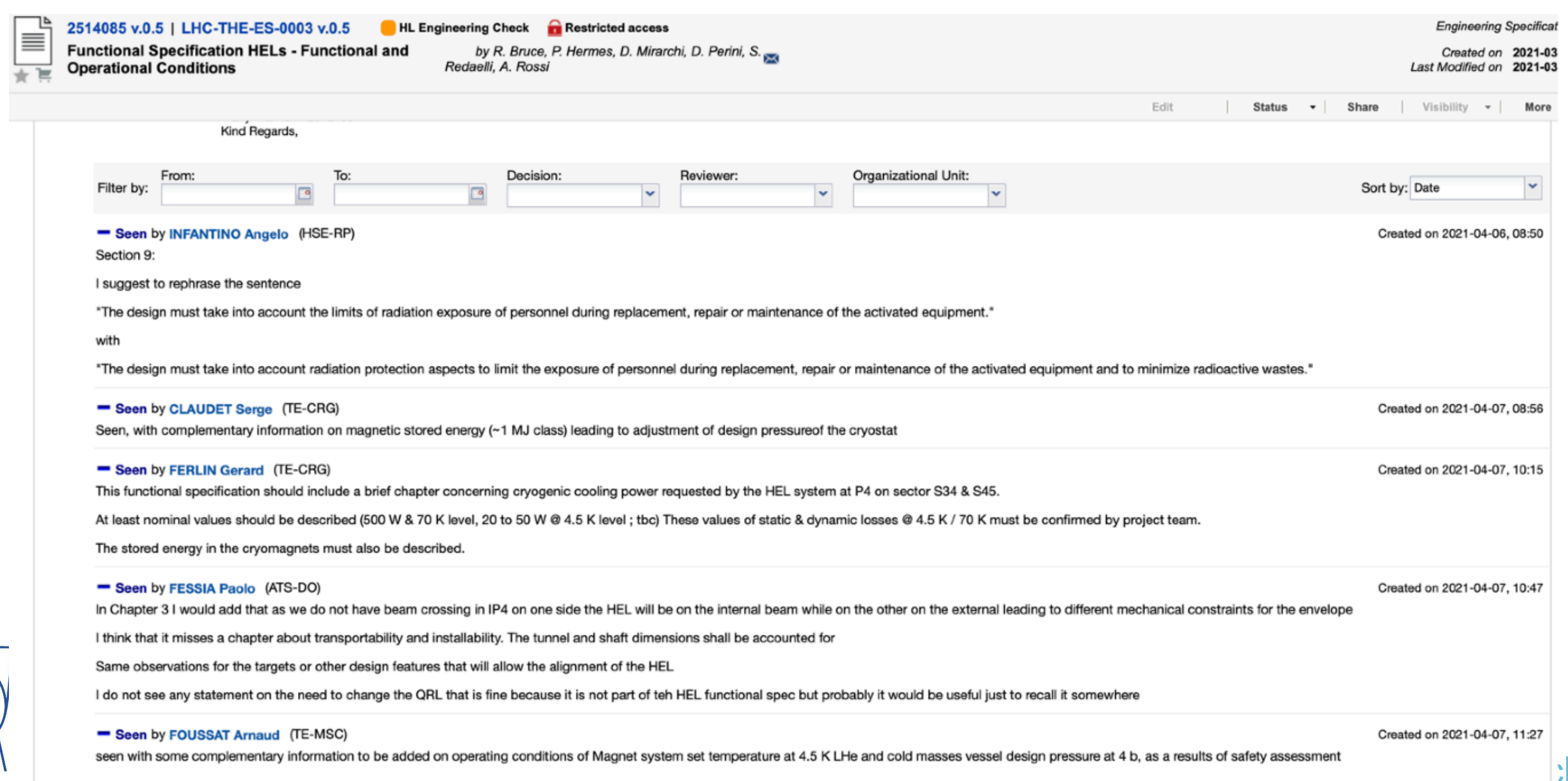
Comments received and further studies

Several feedback received on the specification document

- *Detailed comments from SY/BI and HL-WP2, being addressed*
- *Various suggestions to add more technical information on specific sub-systems (cryo loads, survey requirements, …)*
- *Many thanks for the prompt feedback!*

Presently reviewing with WP2 simulation campaigns for the latest HL-LHC layout and optics

- *Final optics at the HELs, with layouts V1.5*
- *Refine specifications of tolerances in the next months*
- *Add beam-beam for studying depletion in the collision mode.*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Functional Specification HELs - Functional and Operational Conditions
by R. Bruce, P. Hermes, D. Mirarchi, D. Perini, S. Redaelli, A. Rossi
Created on 2021-03
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Kind Regards,

Filter by: From: To: Decision: Reviewer: Organizational Unit: Sort by: Date

Seen by INFANTINO Angelo (HSE-RP) — Created on 2021-04-06, 08:50
Section 9:
I suggest to rephrase the sentence
"The design must take into account the limits of radiation exposure of personnel during replacement, repair or maintenance of the activated equipment."
with
"The design must take into account radiation protection aspects to limit the exposure of personnel during replacement, repair or maintenance of the activated equipment and to minimize radioactive wastes."

Seen by CLAUDET Serge (TE-CRG) — Created on 2021-04-07, 08:56
Seen, with complementary information on magnetic stored energy (~1 MJ class) leading to adjustment of design pressureof the cryostat

Seen by FERLIN Gerard (TE-CRG) — Created on 2021-04-07, 10:15
This functional specification should include a brief chapter concerning cryogenic cooling power requested by the HEL system at P4 on sector S34 & S45.
At least nominal values should be described (500 W & 70 K level, 20 to 50 W @ 4.5 K level ; tbc) These values of static & dynamic losses @ 4.5 K / 70 K must be confirmed by project team.
The stored energy in the cryomagnets must also be described.

Seen by FESSIA Paolo (ATS-DO) — Created on 2021-04-07, 10:47
In Chapter 3 I would add that as we do not have beam crossing in IP4 on one side the HEL will be on the internal beam while on the other on the external leading to different mechanical constraints for the envelope
I think that it misses a chapter about transportability and installability. The tunnel and shaft dimensions shall be accounted for
Same observations for the targets or other design features that will allow the alignment of the HEL
I do not see any statement on the need to change the QRL that is fine because it is not part of teh HEL functional spec but probably it would be useful just to recall it somewhere

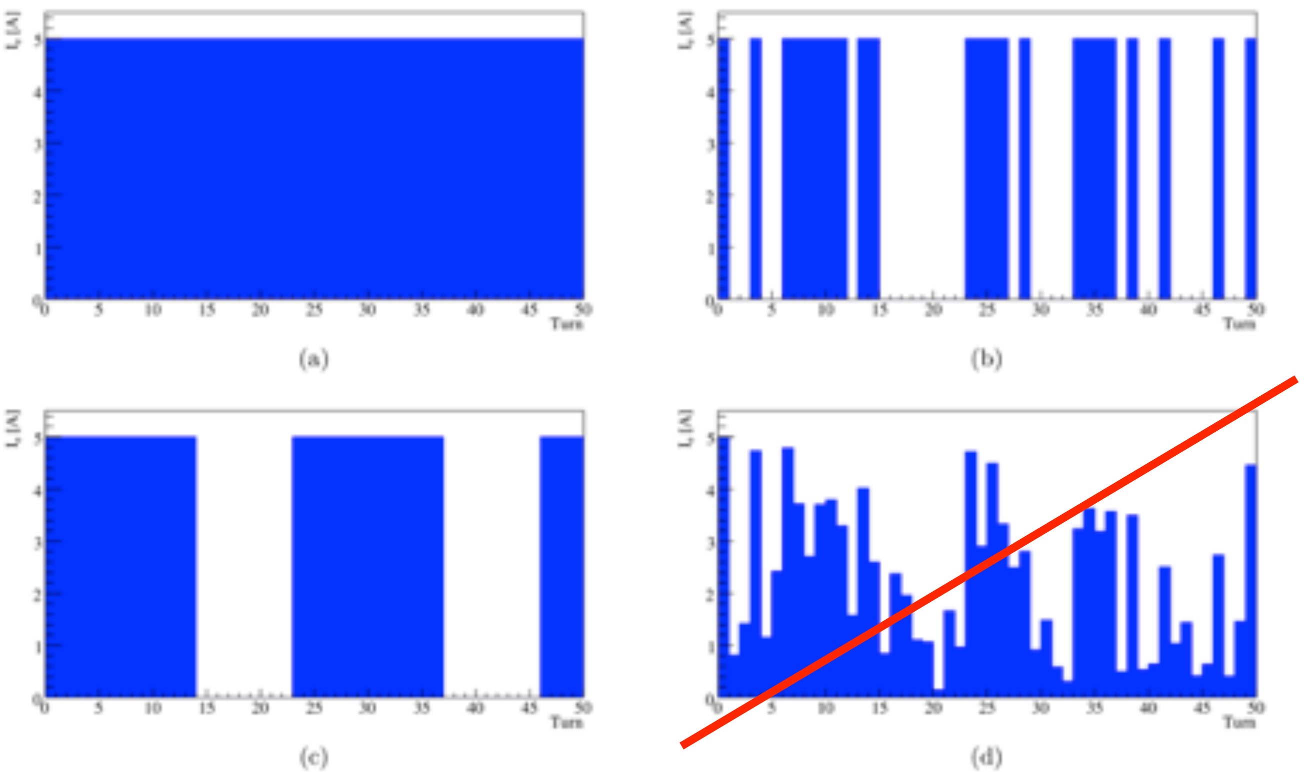
Seen by FOUSSAT Arnaud (TE-MSC) — Created on 2021-04-07, 11:27
seen with some complementary information to be added on operating conditions of Magnet system set temperature at 4.5 K LHe and cold masses vessel design pressure at 4 b, as a results of safety assessment

Conclusions

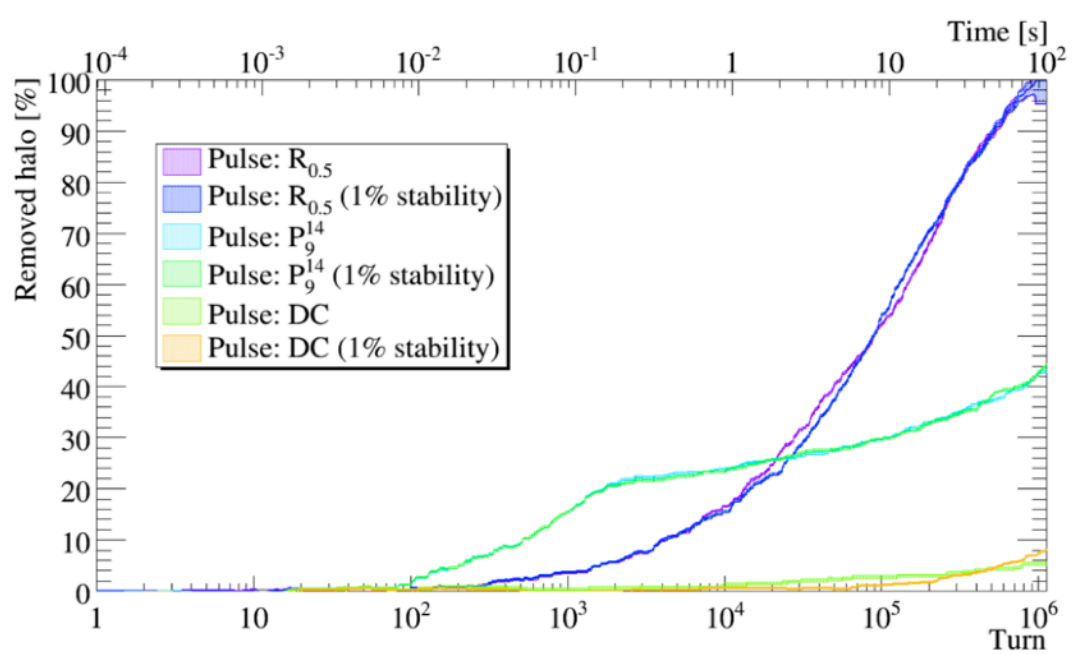
- The functional specifications for the HEL were presented
  - Collected consistently information available from various sources
  - Additional information provided on tolerances and operational scenarios
  - Many thanks for the people who contributed with a lot of useful feedback!
- Key design parameters reviewed
  - Stable from last design changes that followed review at the end of 2017.
- Important details need further iterations with key stakeholders
  - Specifications for beam diagnostics.
  - Iterations on beam dynamics and optics.
- More technical details planned in the next presentations.

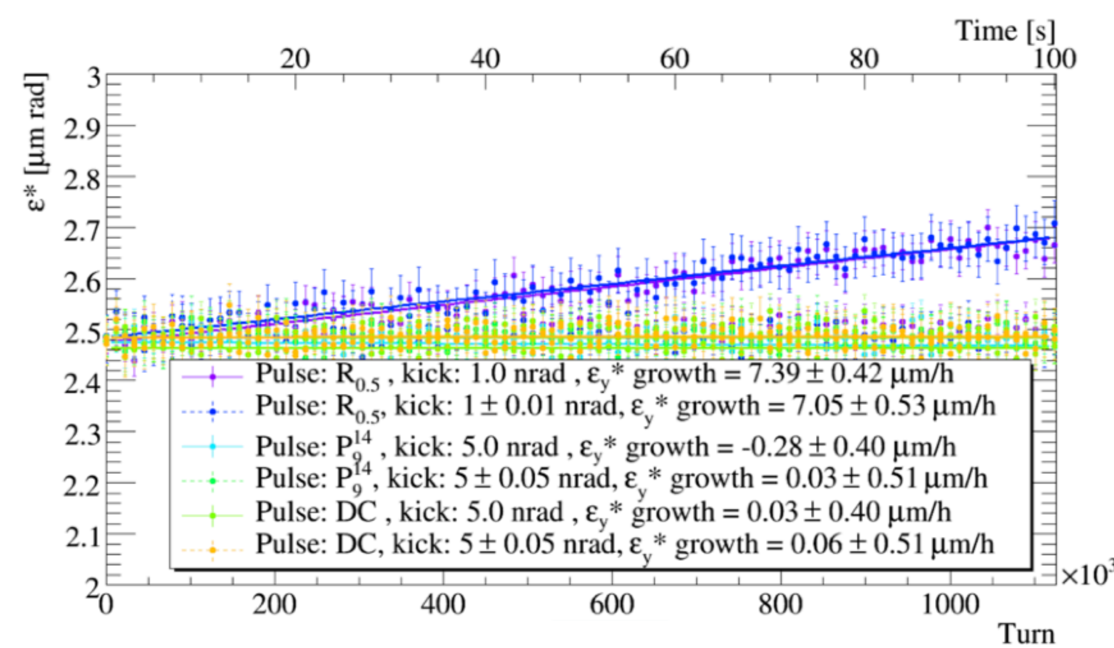
Reserve slides

Simulations for HL-LHC



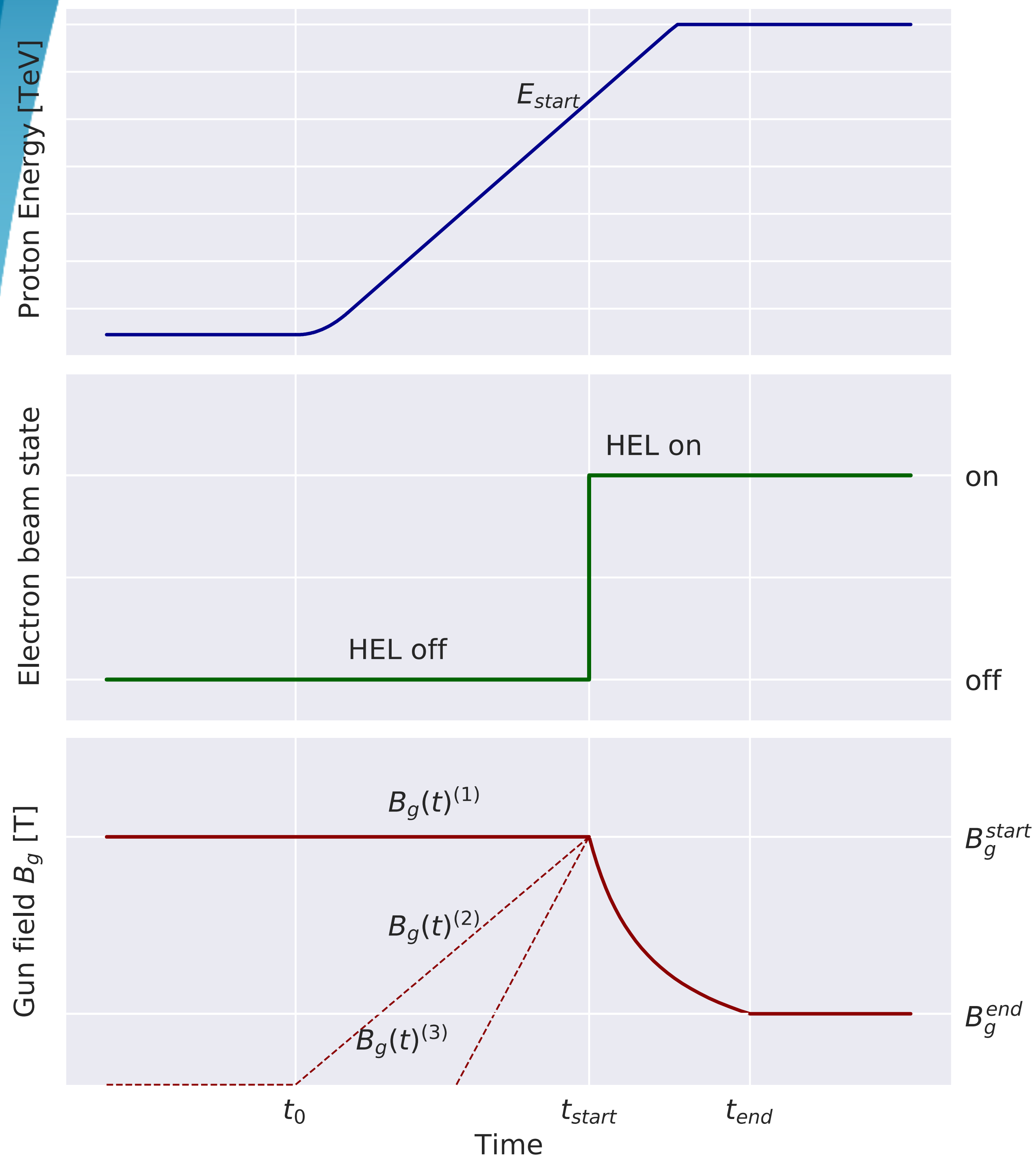
Different e-beam powering schemes tested in simulations. Converged to a specs with ON/OFF schemes for different turns at the same electron beam current, to avoid turn-by-turn variations. Pre-defined numbers of turns for ON and OFF or random.





Simulation effort done through support from HL-UK: funding for ~1y D. Mirarchi.

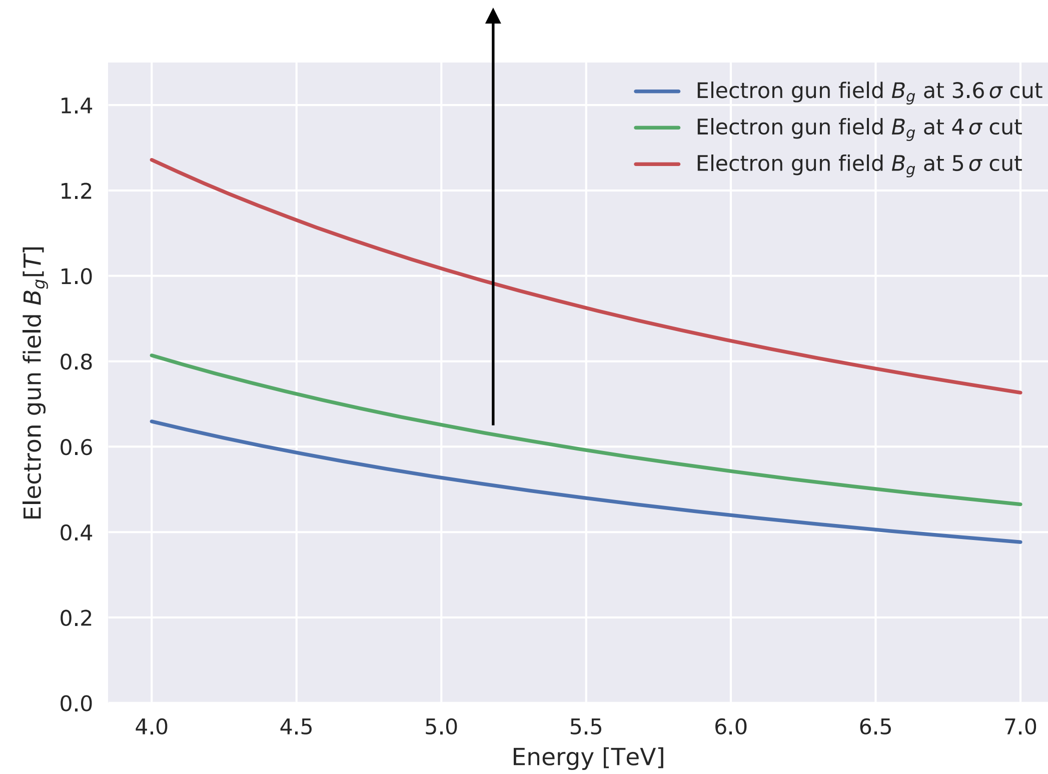
Example of ramp operation



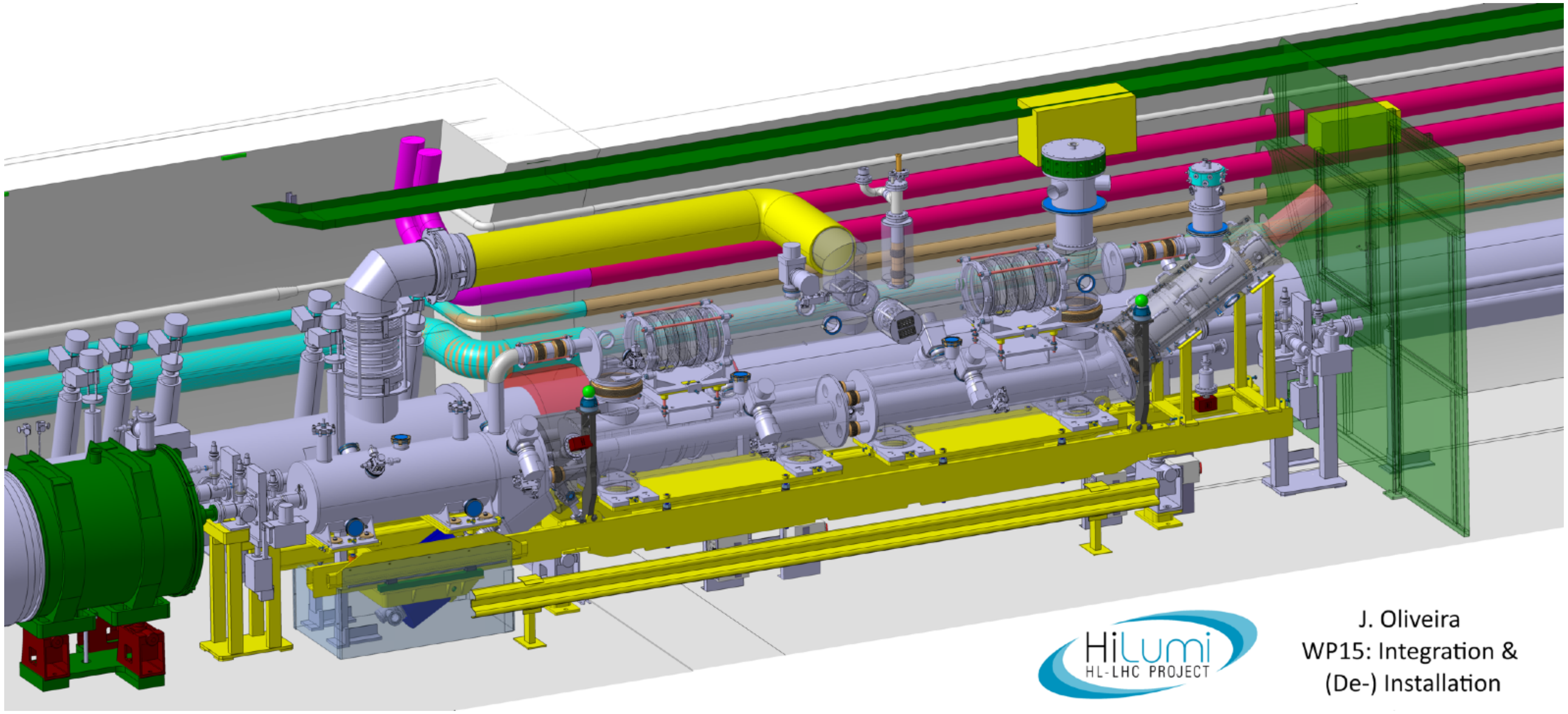
If HEL are used only at top energy, all magnets can be kept at constant current, asynchronously from LHC operational cycle.

Example for operation with E_{start} = 5 TeV

- magnets "seen" by protons kept constant
- Synchronise "start even" for e-beam at the corresponding time in the ramp
- Dedicated cycle for gun solenoid
- To be assessed: needs for pre-cycle after beam dump for the gun and orbit correctors used



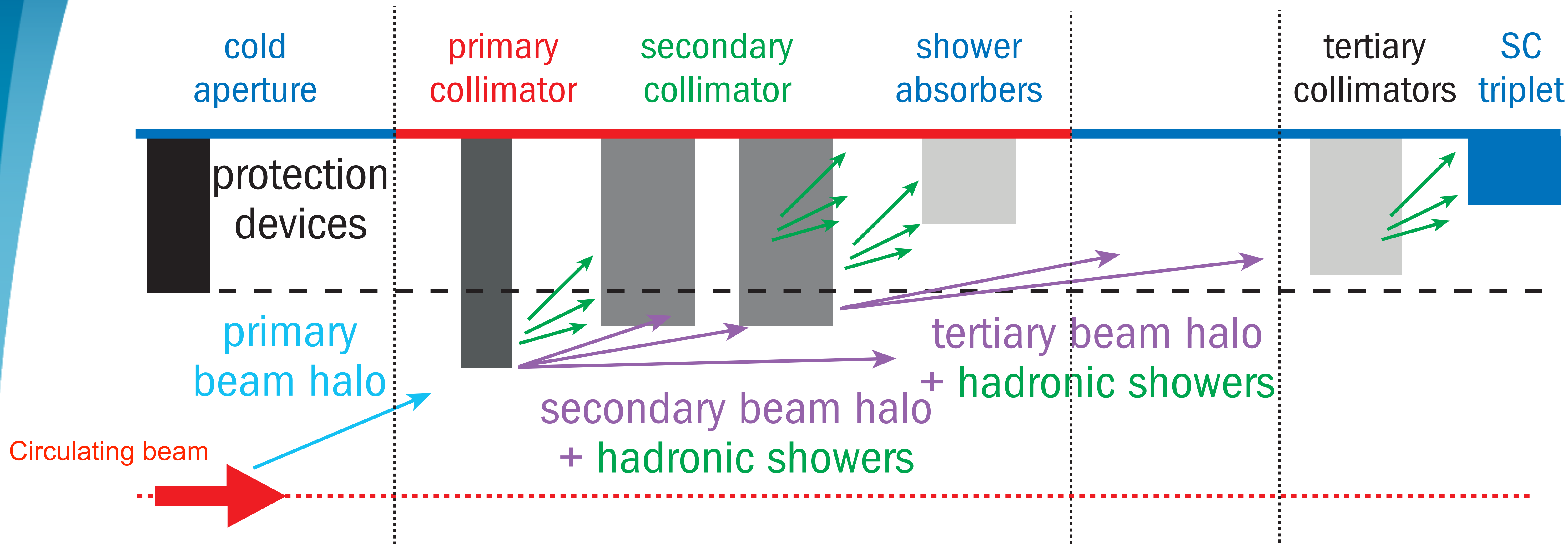
Integration and interfaces



Ongoing topics/issues (see also talk by Joao):

- *Longitudinal space constraints: < 8m*
- *Interface to cryogenics system: 4.5K; ~4.5 bar*
- *compatibility with survey system*
- *3D integration issues being addressed, P4-R in particular*
- *Cabling and UA space and interfaces to ancillary systems*

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.

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)

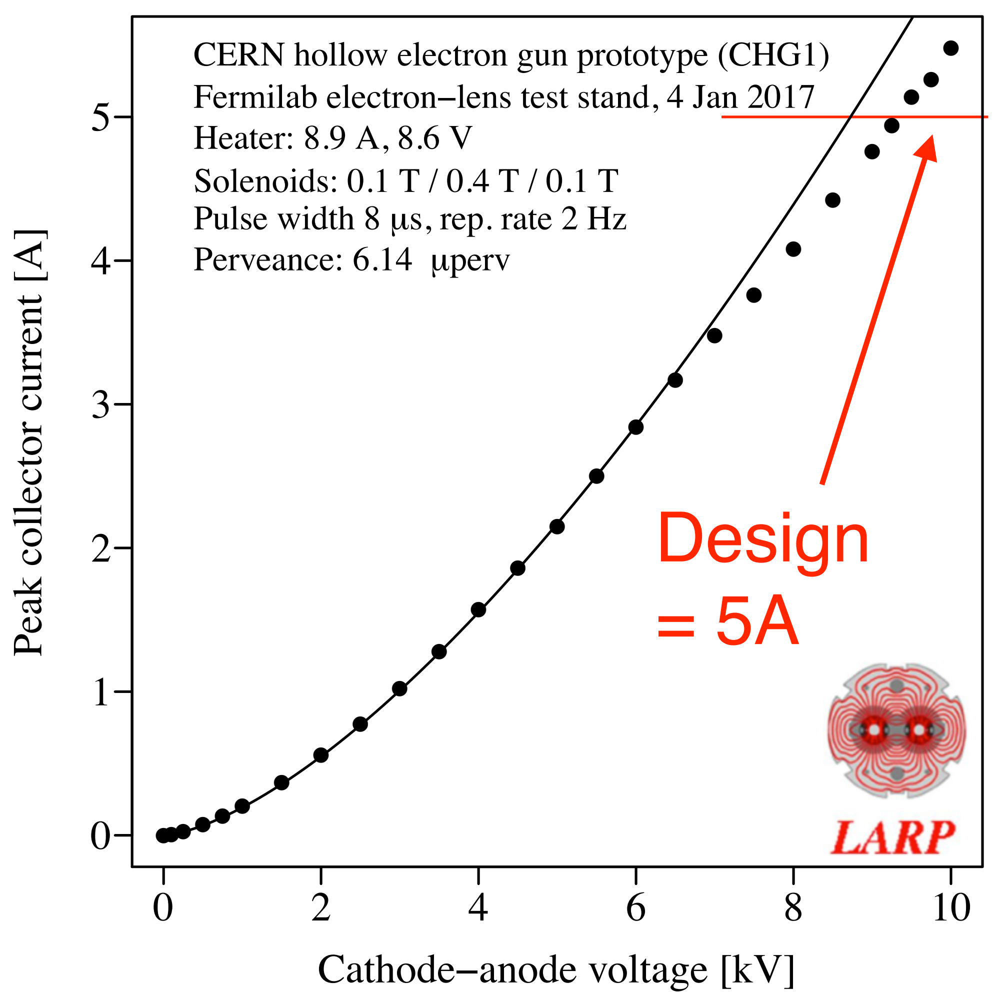
Oct. 2018

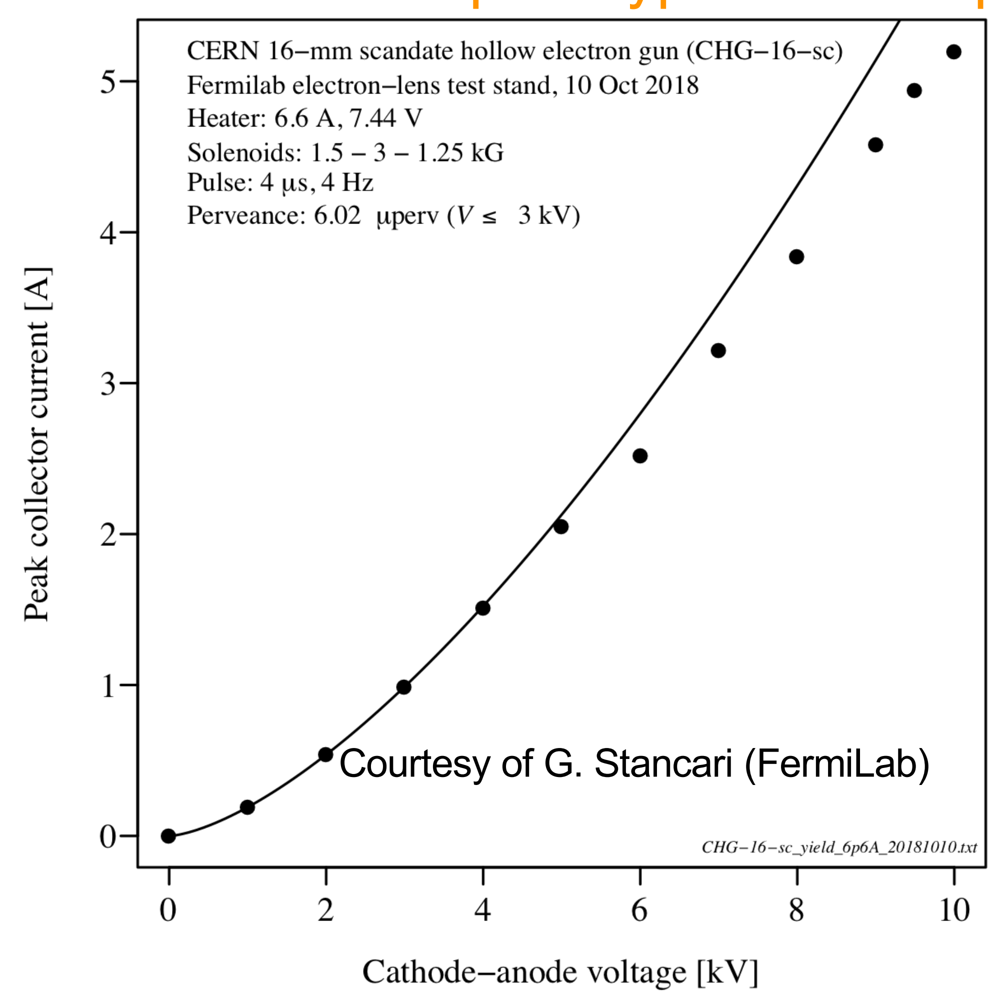
— >5 A with first small cathode and old, bigger gun

2019 (final design): Smaller gun optimised for new cathode

— Presently under test at FNAL and CERN.

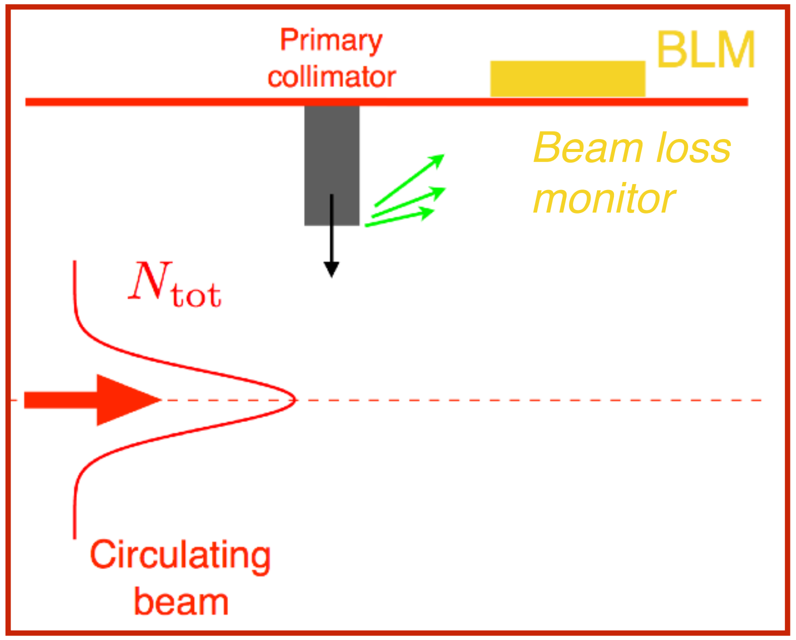
Issue of short on first prototype fixed on paper



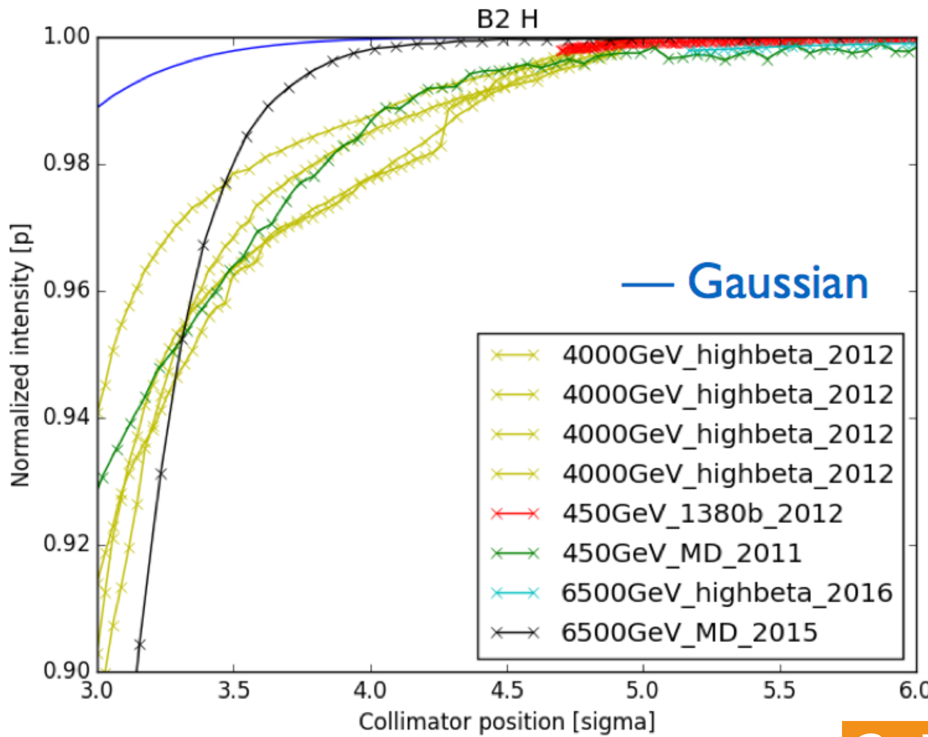


Collimator scans of beam tails

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.



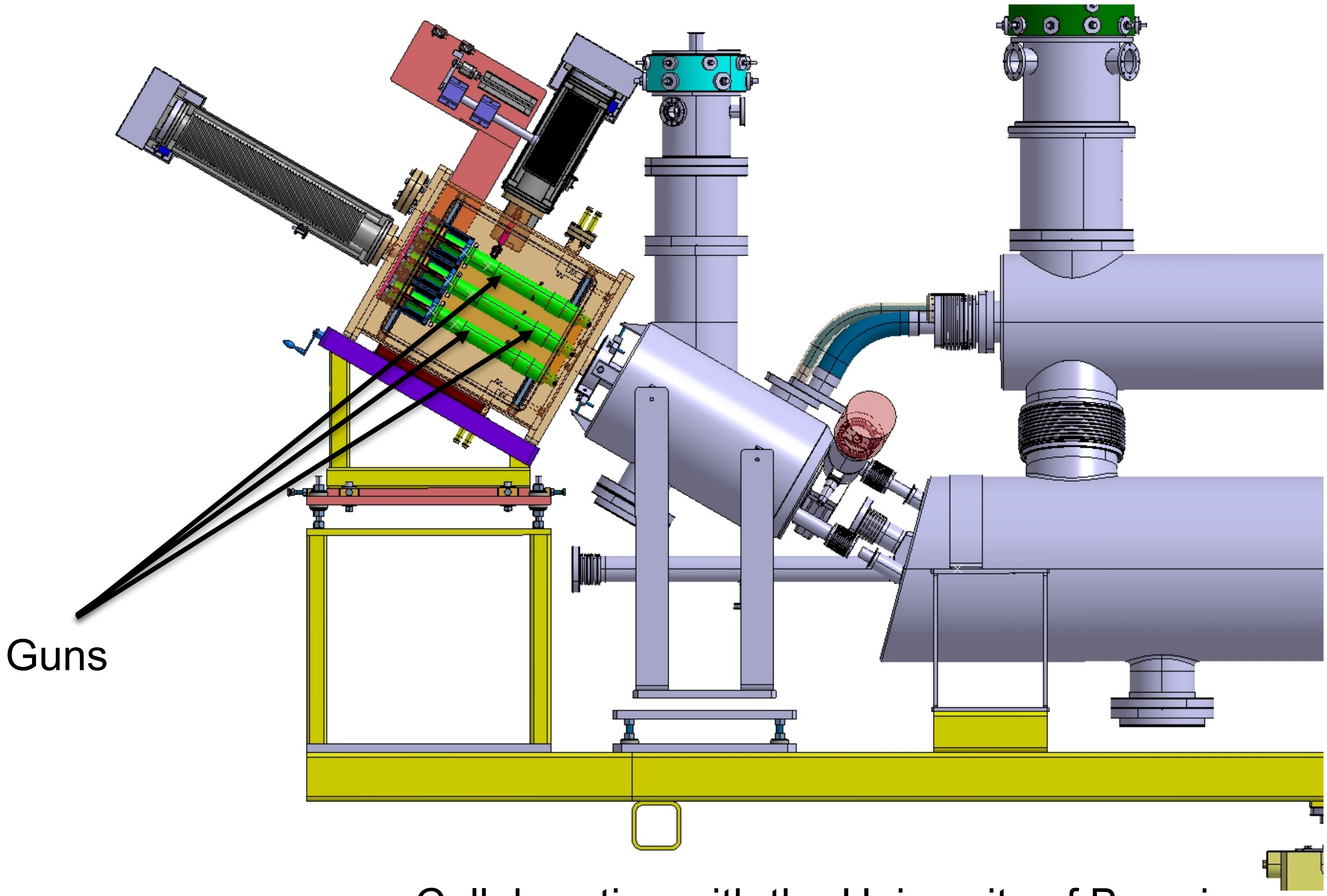
G. Valentino

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

“Crazy” idea of multiple guns



Collaboration with the University of Brescia