28th US-LARP Collaboration Meeting - CM28
April 24th-26th, 2017
Embassy Suites by Hilton Napa Valley, Napa, CA, USA

Plans for e-lens at HL-LHC

— Summary of collimation session —

S. Redaelli on behalf of the WP5 collimation teams at CERN and FNAL

Acknowledgements: various teams from CERN, US-LARP colleagues.
Oliver and Lucio for the support!

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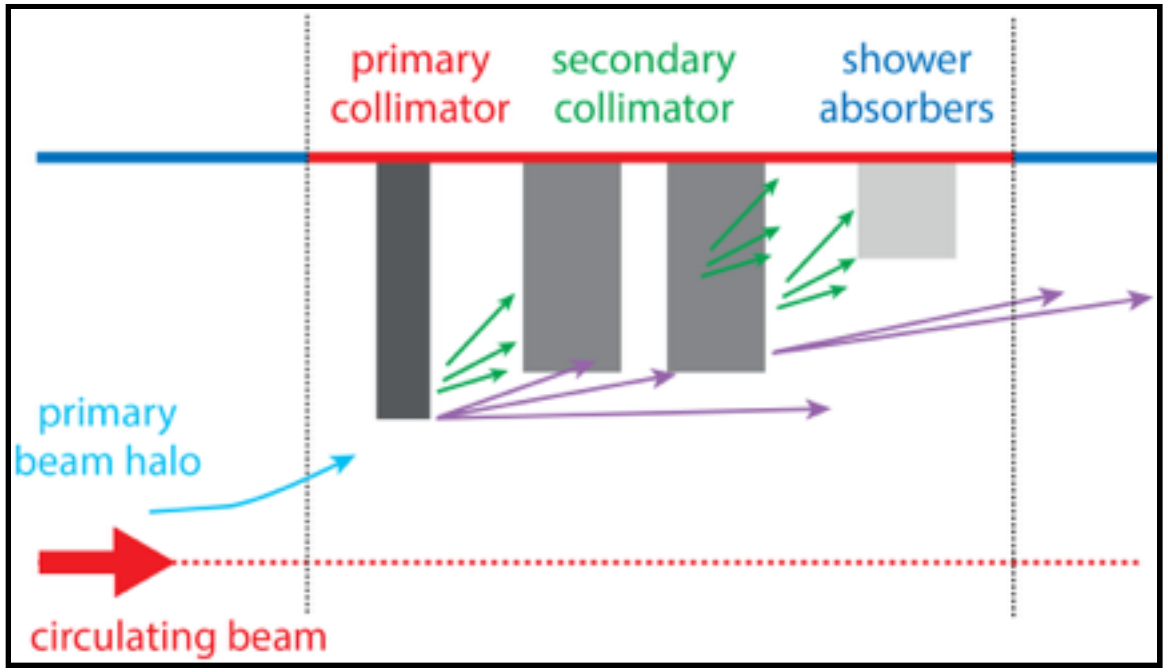
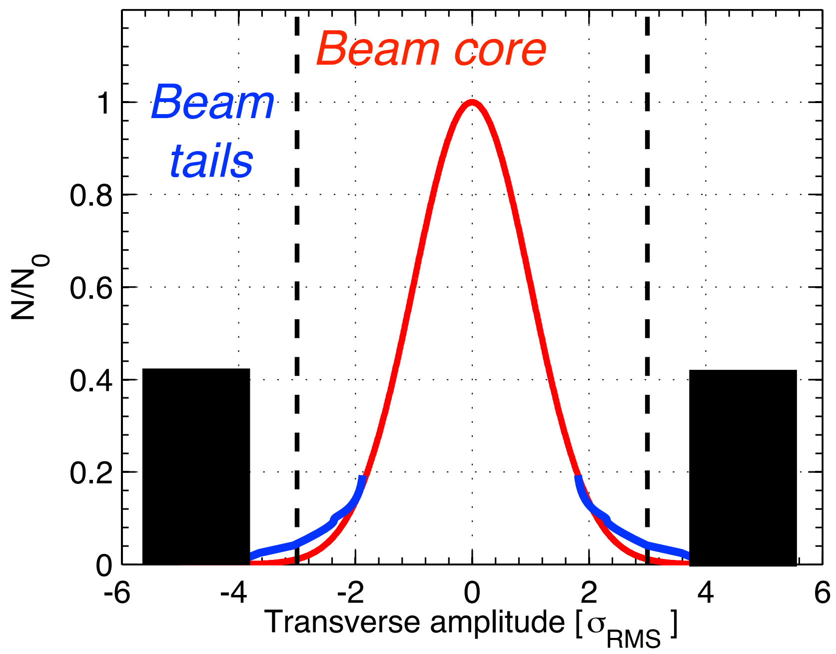
Concept of active halo depletion

Present system





Halo cleaning is a 'passive' response to beam losses.
Halos (over-populated tails) fill the gaps of primary collimators.
Can lead to sudden losses in dynamics phases *(orbit jitters, change of collimator jaw positions, onset of collision, changes of long-range beam-beam, …)*

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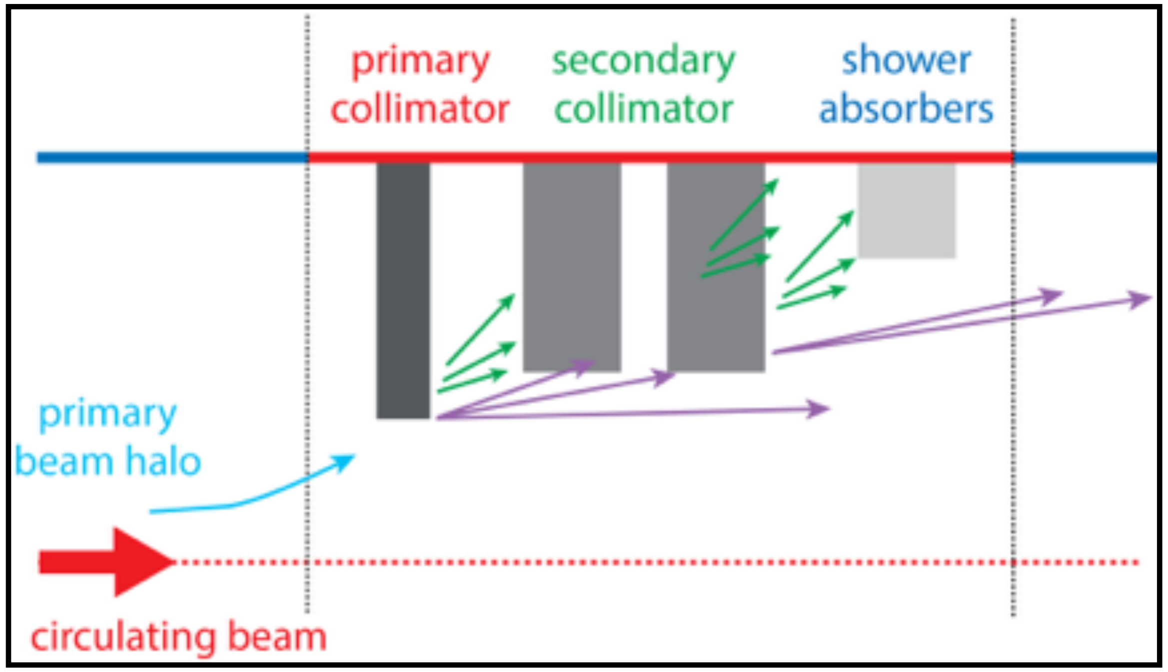
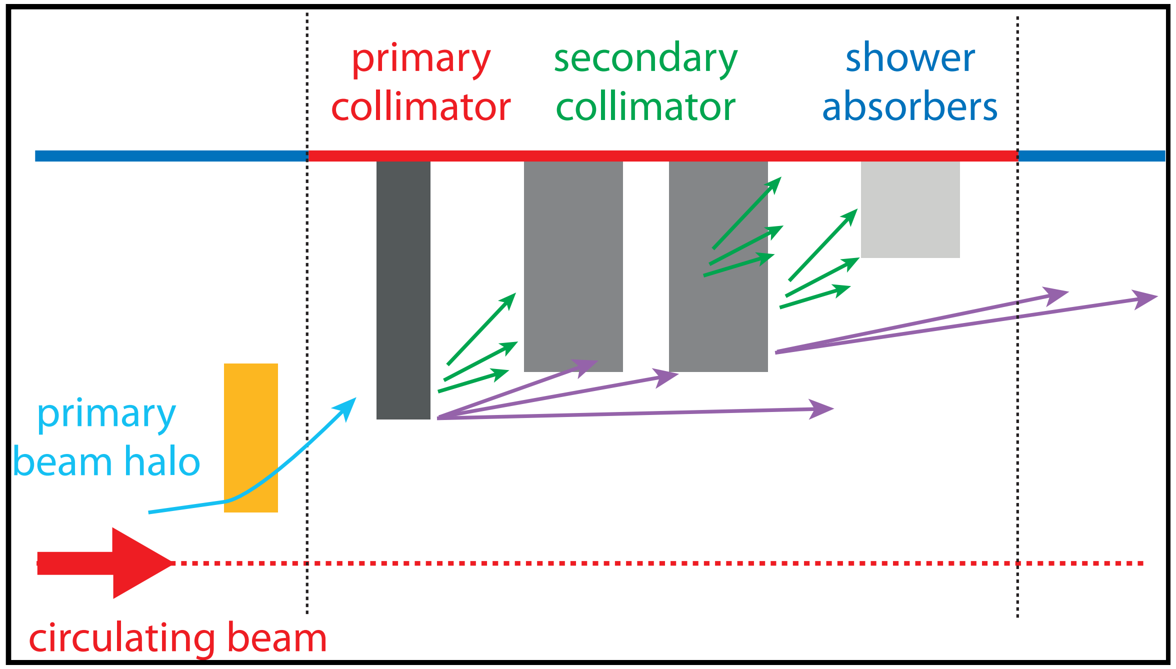


Collimation with active halo control



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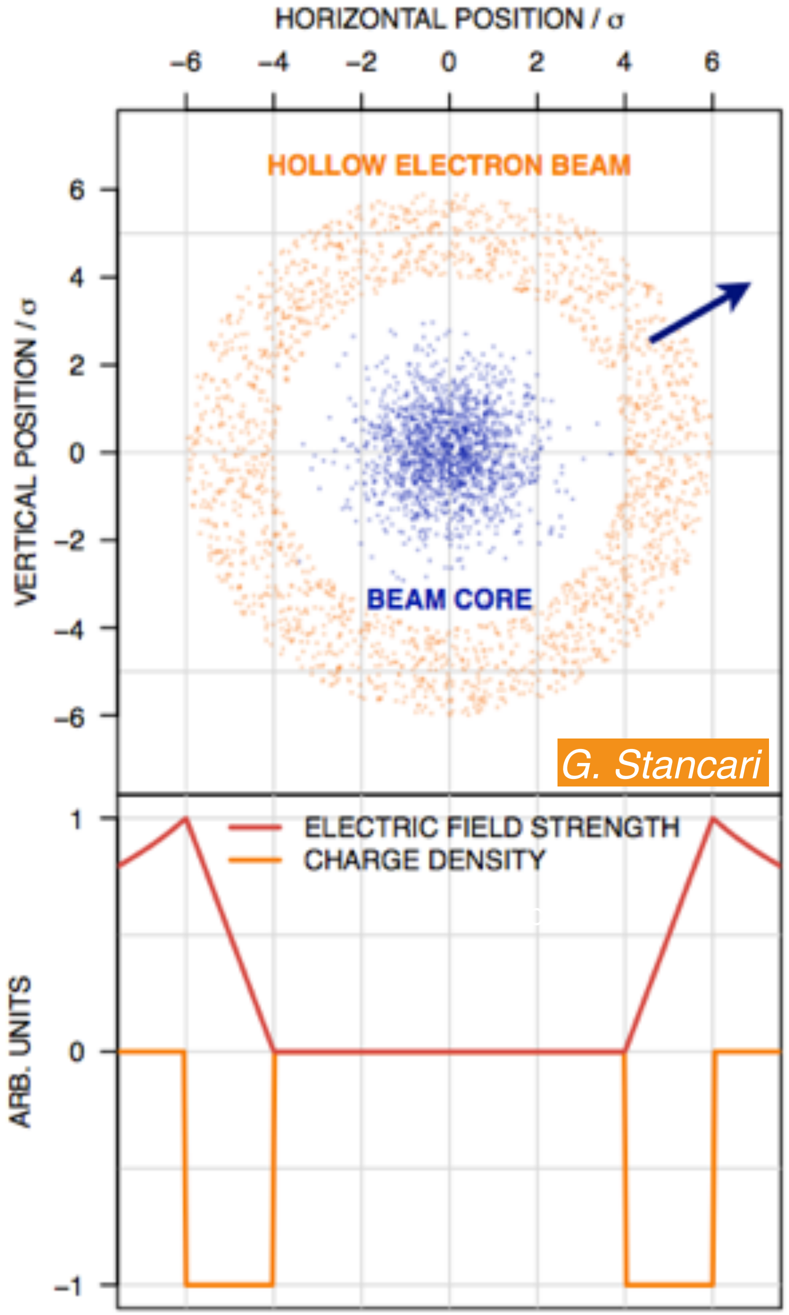
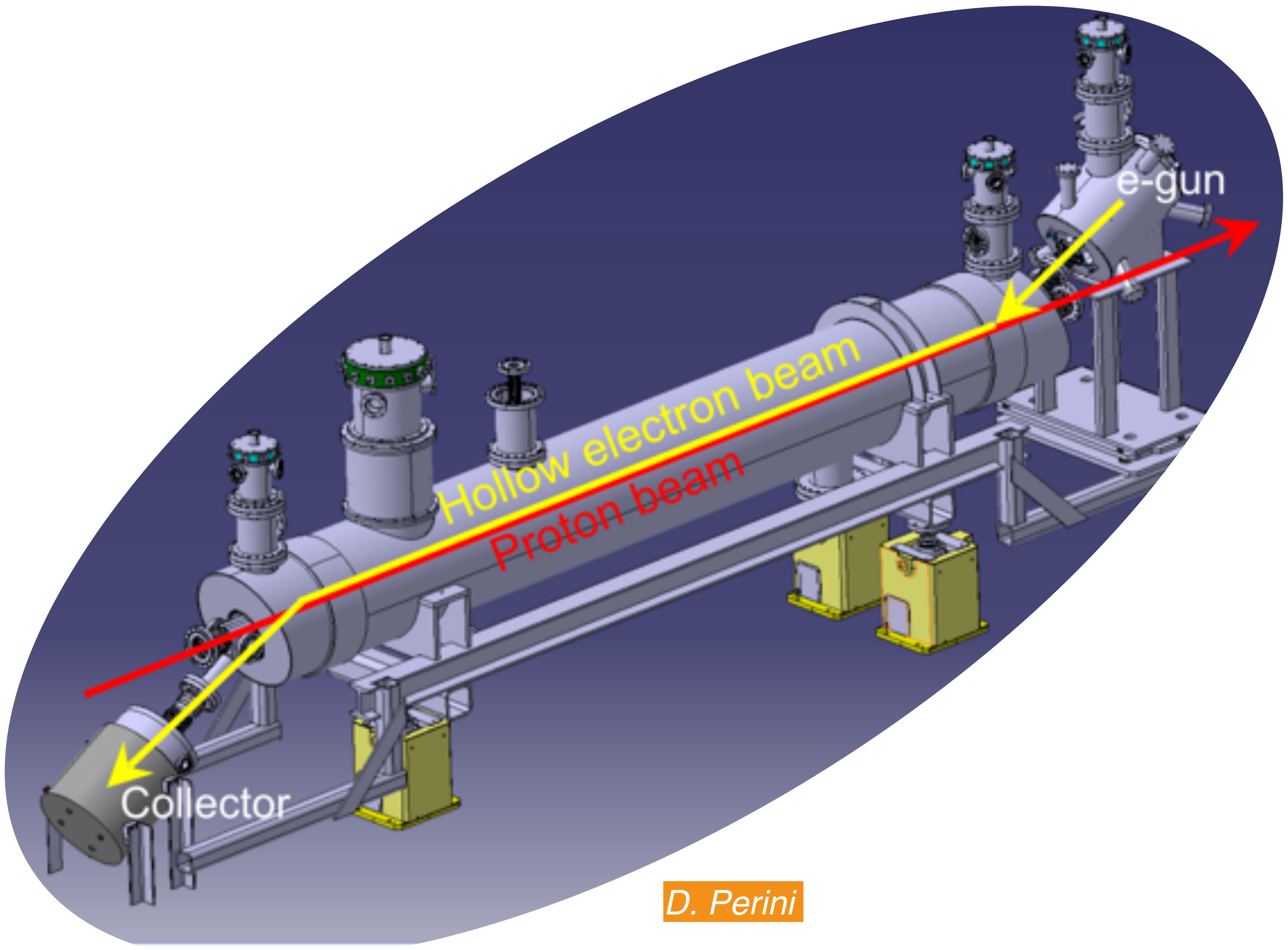
Active halo depletion: control of diffusion speed, selective by transverse amplitude.
Allows:

— distributing losses over a desired time interval.
— control static tail population close to collimator jaws (deplete tails).
— transparent integration into the system responsible for cleaning.

Hollow e-lens for collimation





"Non-material" scraper — adds scraping functionality but particles are disposed of by the present collimation system.

Can be installed anywhere in the ring, because kicks per turn are small.

It requires overlap of e- and proton beam over ~3 meters.

Recent history

Timeline for the definition of a CERN strategy for **hollow e-lenses (HE)** for **beam collimation** at the HL-LHC:

- **CERN internal review in Nov. 2012** (Special ColUSM meeting — link)
  Triggered by 'availability' of TEL2 after Tevatron shutdown: can we use it as CERN?
  Brought up comprehensively technical aspects for installation in LHC or SPS.
- **HiLumi annual meeting in Frascati, end of Nov. 2012**
  CERN iterated the strong interest to pursue the option HEL for HL-LHC.
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  (Following discussions with the directorate in light of 2012 review). New strategy: focus resources on a technical design for the LHC, decision on needs in Run II.
- **End of 2014**
  Publication of conceptual design report. Following that, design work started at CERN within EN/MME: optimised design for LHC + gun developments
- **October 2016**
  External review on the needs for hollow lenses for HL-LHC.
  2016: first year with pushed operational performance the LHC, as 2015 was a "commissioning" year after first long shutdown (LS1).

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Key role of US-LARP

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External review: October 6th-7th 2016

Review of the needs for a hollow e-lens for the HL-LHC

HiLumi HL-LHC PROJECT

6-7 October 2016
CERN
Europe/Zurich timezone

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Following the experience of the 2016 LHC operation, this review aims to discuss the need and potential benefits of an active halo depletion system for the HL-LHC and give a recommendation for adopting it into the HL-LHC baseline.

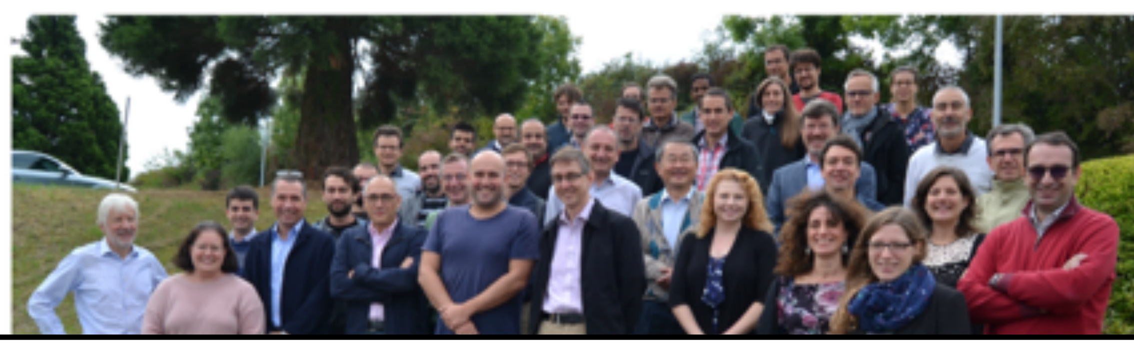
The scope of this review is to examine the two initial motivations (loss spikes during operation and machine protection aspects for operation with Crab Cavities), to evaluate the needs in view of the recent project re-scoping and to compare the projected needs with the operational experience from the LHC during Run I and Run II.

Following the close-out by the review chair, the committee is required to compile a short report with findings, comments and recommendations within one month. The report will be delivered to Lucio Rossi, HL-LHC Project leader.

Review panel: Rudiger Schmidt (CERN, Chair), Rob Appleby (UNIMAN), Wolfram Fischer (BNL), Mike Lamont (CERN), Katsunobu Oide (CERN), Mike Seidel (PSI)

Oliver Bruning (CERN) is the link person.

The review is scheduled on **6th and 7th October 2016**, at CERN.



https://indico.cern.ch/event/567839

External review panel:
R. Schmidt (CERN, Chair), R. Appleby (UNIMAN), W. Fischer (BNL), M. Lamont (CERN), K. Oide (CERN), M. Seidel (PSI)
Project link person: O. Brüning

Charge to review (see link): address needs for active halo depletion at the HL-LHC and comment on solutions based on hollow electron-lenses.

The Review Panel document is available on the review web page.

Timing of review: far enough into Run II to have operational experience at 7 TeV, still in time for actions in LS2 + LS3.

Program of hollow e-lens review

1. Overview and introduction, Stefano Redaelli (CERN)
2. Loss and lifetime observations during nominal operation and their extrapolation to HL-LHC parameters, Belen Salvachua (CERN)
3. What did we learn about HALO population during LRBB studies and MDs? Y. Papaphilippou (CERN)
4. What did we learn about HALO population during MDs and regular operation? Gianluca Valentino (University of Malta (MT))
5. Observations and measurements on the impact of earthquakes and cultural noise on the LHC operation, Michaela Schaumann (CERN)
6. Operational experience from HERA and their extrapolation to the HL-LHC, Mike Seidel (PSI)
7. Operational experience of RHIC electron lenses and their effect on collimation and halo populations, Wolfram Fischer (BNL)
8. Operational experience from Tevatron and relevance for HL-LHC, Alexander Valishev (FNAL)
9. Expectations for the beam lifetime and halo population based on scaling from the LHC observations, Fanouria Antoniou (CERN)
10. RF overview of the Crab Cavity system for HL-LHC with presentation on potential failure modes and summary of the KEK operation experience, Rama Calaga (CERN)
11. Potential failure scenarios in the HL-LHC machine that can lead to very fast orbit changes (e.g. missing beam-beam kicks, damper failure scenarios, Crab cavity failure scenarios etc) and the resulting machine protection requirements for HL-LHC operation (with input from collimation team), Daniel Wollmann (CERN)
12. Measured effects of depleted halo population with hollow e-lens and relevance for HL-LHC, Giulio Stancari (FNAL)
13. Alternative methods for halo depletion (damper and tune modulation)and comparison of their performance / reliability to that of a hollow electron lens, Roderik Bruce (CERN)
14. Potential performance reach for the HL-LHC in case of a depleted beam halo, Gianluigi Arduini (CERN)

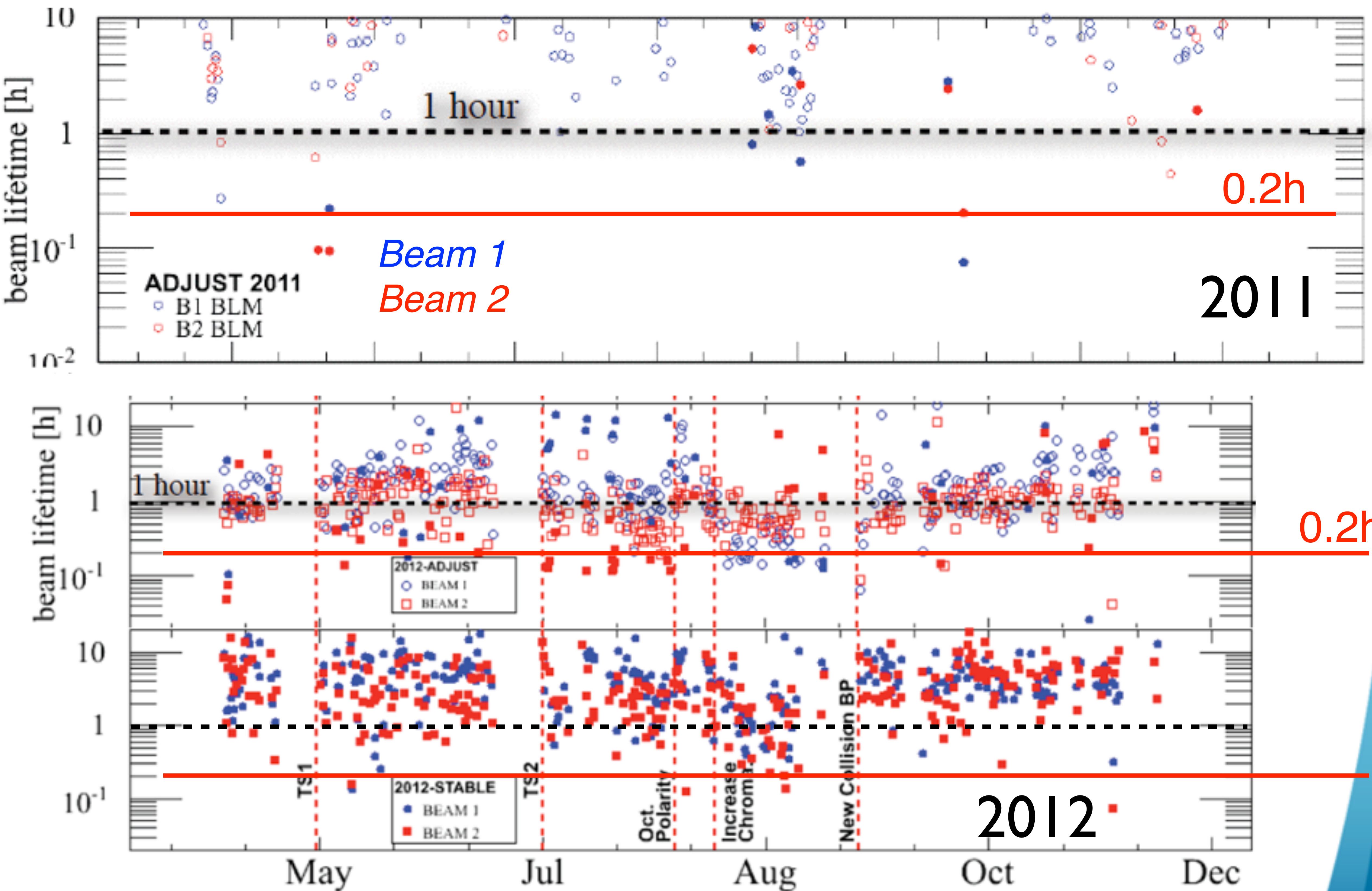
Operational experience and extrapolation to HL-LHC

HL-LHC specific systems/constraints

Many thanks to all the speakers!

A set of <u>key excellent talks</u> was crucial to convey important messages.

Recap.: losses in 2011 and 2012



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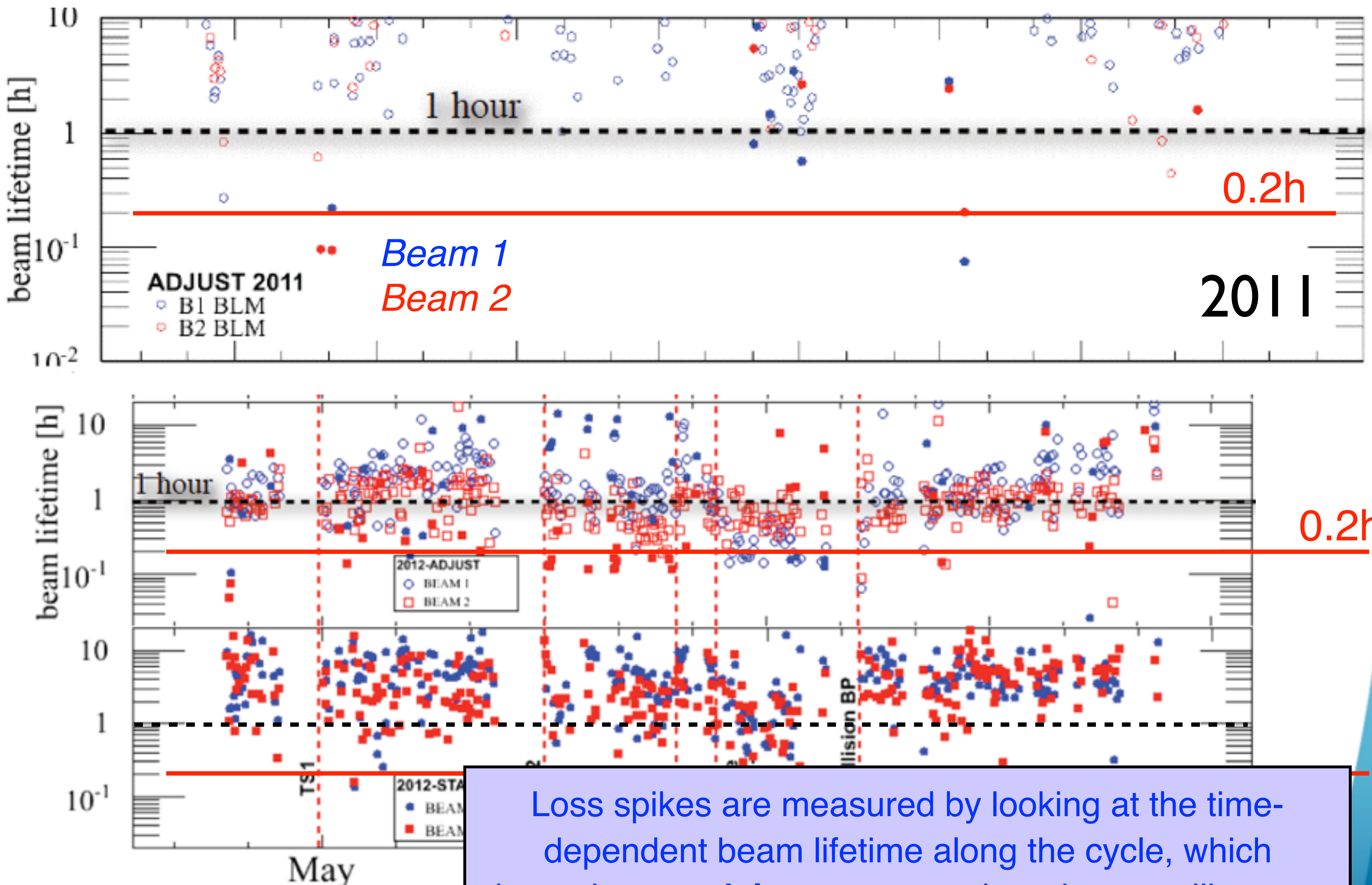
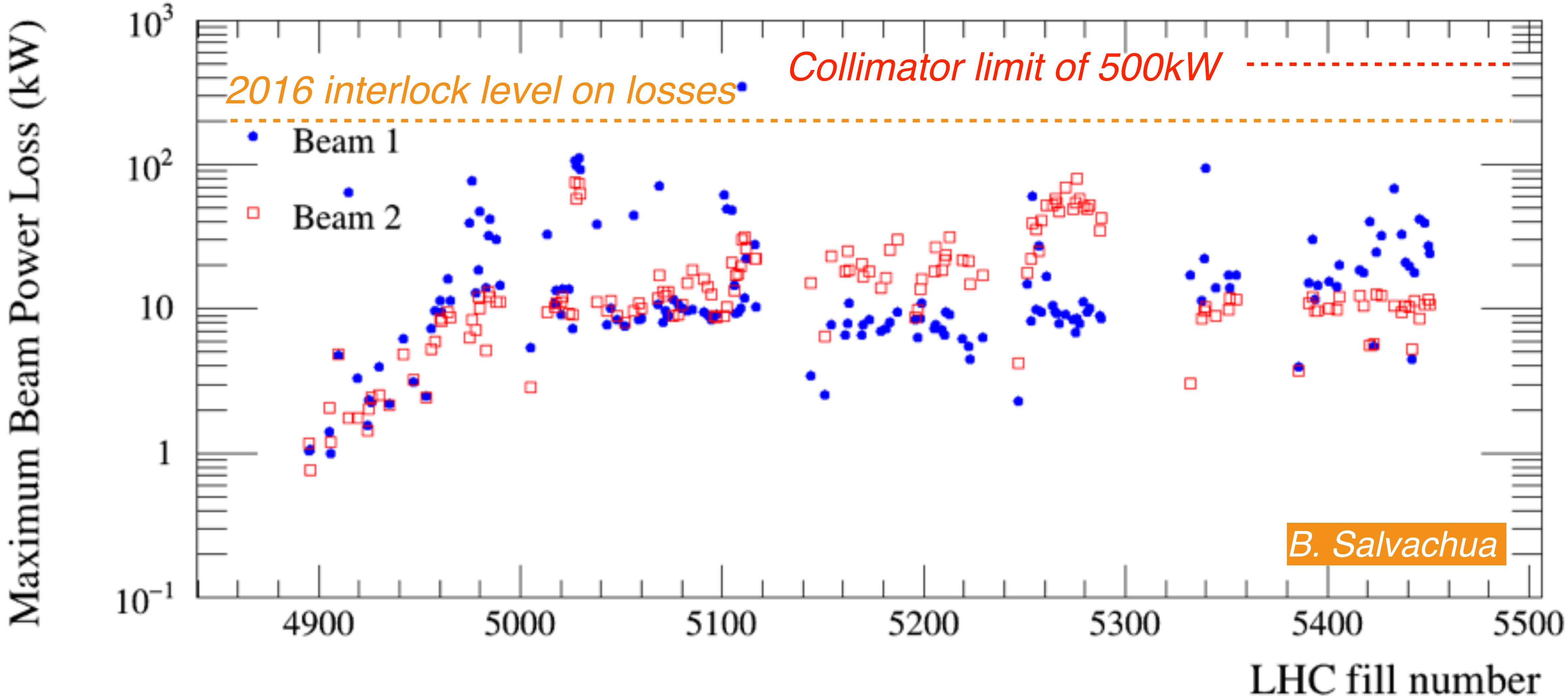


Loss spikes are measured by looking at the time-dependent beam lifetime along the cycle, which determines **peak loss rates** on the primary collimators.

Beam lifetime and losses in 2016



Conservative linear scaling to HL-LHC

How many fills did we have with 500 kW HL-LHC equivalent in 2016?

This corresponds to 166kW in 2016 --> 1 out of 135 fills in ADJUST (<1% of fills)

How many fills did we have with 500 kW HL-LHC equivalent in 2012?

This corresponds to 70kW in 2012 --> 45 out of 282 fills in ADJUST (15% of fills)

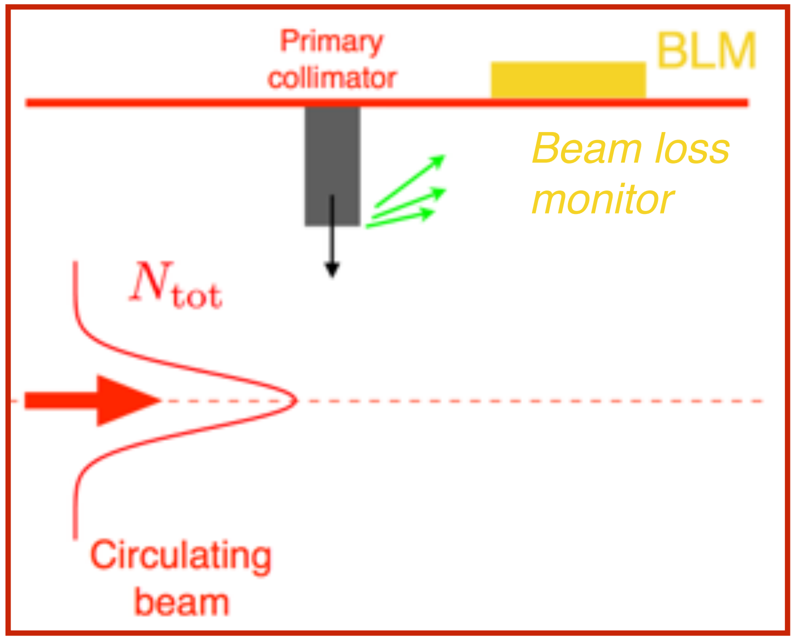
How many fills did we have with 200 kW HL-LHC equivalent in 2012?

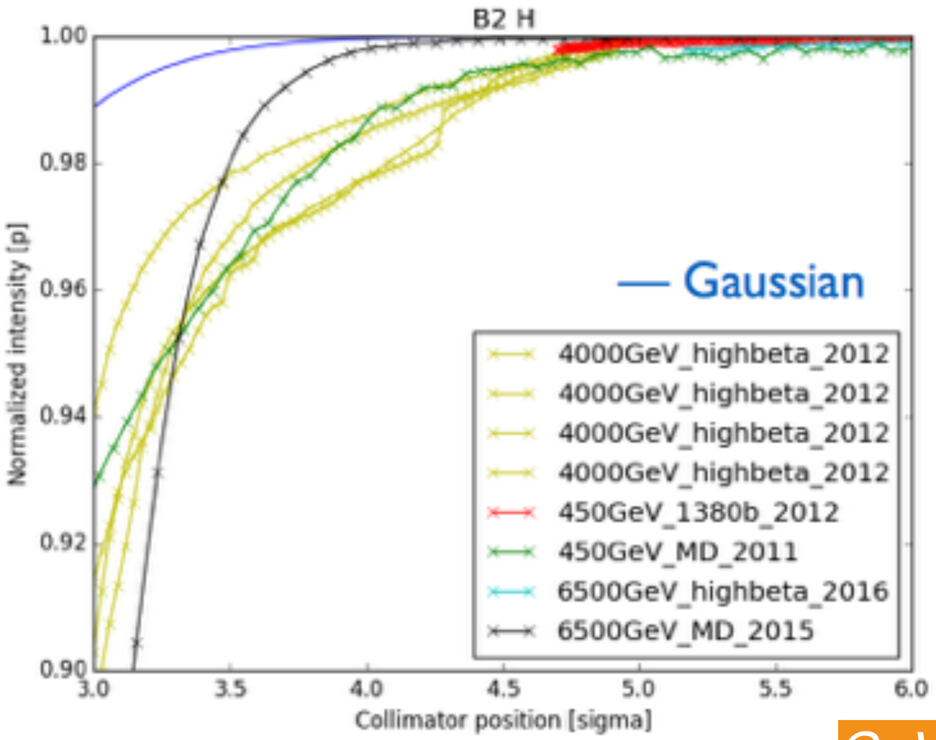
This corresponds to 35kW in 2012 --> 157 out of 282 fills in ADJUST (55 % of fills)

LHC beam tail population

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

- 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

The review panel pointed out the risks associated, in particular because crab cavities add new categories of fast failures that need to be understood.

Review recommendations

1. Implement active beam halo control using a hollow e-lens

- The extrapolation of the observed losses to HL-LHC are close to the limit of what is acceptable during operation. This does not even consider halo generating effects related to higher bunch intensity and new failure modes due to operation with crab cavities. These risks and the potentially large energy stored in the beam halo of order 35 MJ justify an active control of the beam halo.
- The hollow e-lens is by far the best technology to achieve this objective, as clearly demonstrated in the Tevatron.
- An e-lens available in Run 3 would allow exploration of halo cleaning in the HL-LHC beam parameter regime.

2. Address with high priority failure modes of the crab cavities

- The failure modes of crab cavities are not well understood. Beam induced oscillations in case of a cavity failures observed at KEK should be analysed and a model should be developed to understand failure modes and resulting oscillations. Failure modes of the HL-LHC crab cavities should be investigated experimentally during the SPS tests, including tests with high beam current.

3. Pursue tests with bunch intensities as planned for HL-LHC during Run 2

- Consider machine development sessions with bunch trains to test beam losses, tail formation and beam stability with beams similar to HL-LHC. The committee recognizes that these tests would have to respect the limitations of beam that can be delivered by the injectors (e.g. 50 ns bunch spacing in case of high bunch intensity).

Specific questions and follow up points

- **Are there sufficient indications that active halo cleaning for HL-LHC is required? Yes.**
  - The committee considers that there are considerable risks for HL-LHC to reach design performance with the proposed baseline related to beam halo population.
  - There are clear observations that the tails are overpopulated. Double Gaussian beams have been measured in all phases of operation. Scaled with HL-LHC beam parameters, the energy stored in the beam halo above 3.5 σ would amount to 35 MJ.
  - During some phases in the cycle, in particular during squeeze and adjust, beam losses were observed in 2012 and 2016. When scaling the observations to the HL-LHC parameters from 2012, this would lead to an unacceptable performance in operation.

— Continue studies of tail populations.

— Study parameter scaling, in particular dependence on bunch population, to improve scaling to HL-LHC regimes.

— SPS tests with crab cavities: get experience on failure modes.

— Continue halo studies and alternative excitation techniques.

— Study further mitigations of losses:

fast feedback (in collimator region).

— Recommendation on various simulation fronts (effects on core, halo dynamics, etc.)

Important to get MD support for these topics!

Outcome of additional reviews

- **Second HL-LHC Cost & Schedule review**

  Continued encouragement to study HEs:

  > - **Collimation:** Besides installing new collimators ensure a high level of availability for installed systems as well. Develop crystal collimation and hollow e-beam as supporting measures.

- **CMAC @ Chamonix 2017**

  Very encouraging statement on the HEs, re-iterated in March by CERN management (ATS sector: see Chamonix summary *by F. Bordry).*

> **Comments - High Luminosity Project (HL-LHC) - Status and planning**
>
> The scope changes from the re-baseline in September of 2016, while increasing risks and narrowing margins in several areas, do not affect the ability to achieve the ultimate Luminosity goal of HL-LHC as far as we can assess.
>
> Uncertainties in predicting the halo require large design margins for the collimators. Hollow electron lenses, a proven technology, can further mitigate this risk. The HL-LHC team should further evaluate (calculate and measure) the necessity and management might want to consider inclusion into the baseline, even at increased cost.

Status and next steps

We are working on integrating hollow e-lenses into the project baseline! (we would have done it, if we did not have the June 2016 re-baseling)

Conceptual design:	Done (Dec. 2014)
Assess needs based on LHC operation	Done (Review 2016)
Improve technical design, integration into the HL-LHC layout, effect on beams	Ongoing
Assess of technical design and of readiness of involved CERN teams	Autumn 2017
Assess of cost, including possible external contributions, and decision	Next C&S review

Autumn review being organised by O. Brüning: in the process of contacting reviewers. Dates: 2-day event in **Oct. 17th-20th**!

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- Outcome of recent reviews
- **Status of LHC hollow e-lenses**
- Other WP5 news
- Conclusions

Update on LHC Electron Lens Design *Diego PERINI*

FNAL measurements with CERN gun *Giulio STANCARI*
Embassy Suites by Hilton Napa Valley

Hollow Electron Lens for HL-LHC: Effect on core *Miriam FITTERER*

Hollow Electron Lens for HL-LHC: Effect on tails *Joschka WAGNER*

Conceptual design for LHC lenses

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ACC-2014-0248

FERMILAB-TM-2572-APC

Conceptual design of hollow electron lenses for beam halo control in the Large Hadron Collider*

G. Stancari, V. Previtali, and A. Valishev
Fermi National Accelerator Laboratory, PO Box 500, Batavia, Illinois 60510, USA

R. Bruce, S. Redaelli, A. Rossi, and B. Salvachua Ferrando
CERN, CH-1211 Geneva 23, Switzerland

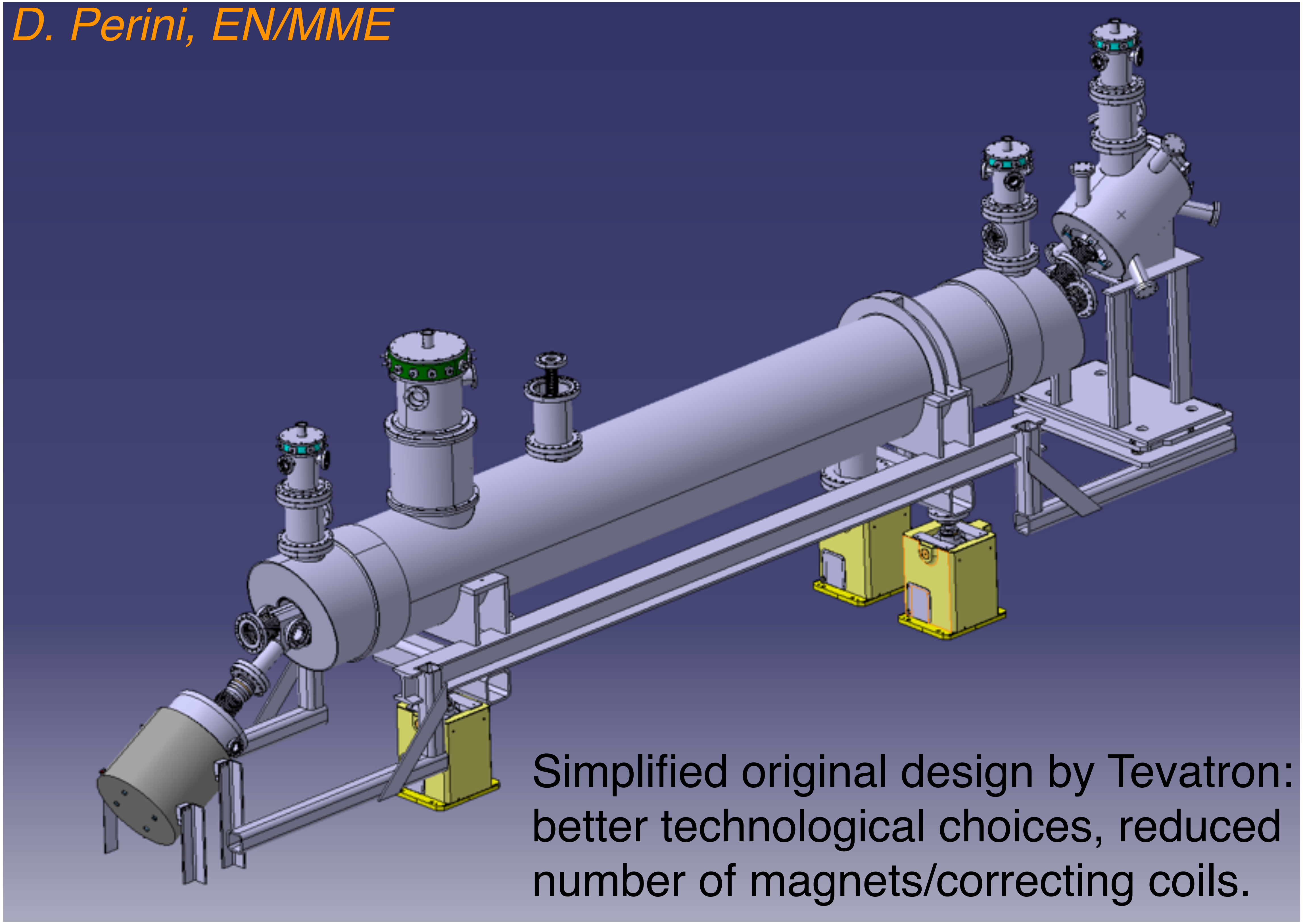
(Dated: October 30, 2014)

Present conceptual design based on achieved parameters

- Range of sigmas — 4-8 (emittance of 3.5 microns)
- Halo depletion time — < a minute
- Electron beam current — 5 A
- Time structure — rise time of 200ns (batch-by-batch)
- Main solenoid field — 4-6 T

New CERN design improves and optimises various aspects!

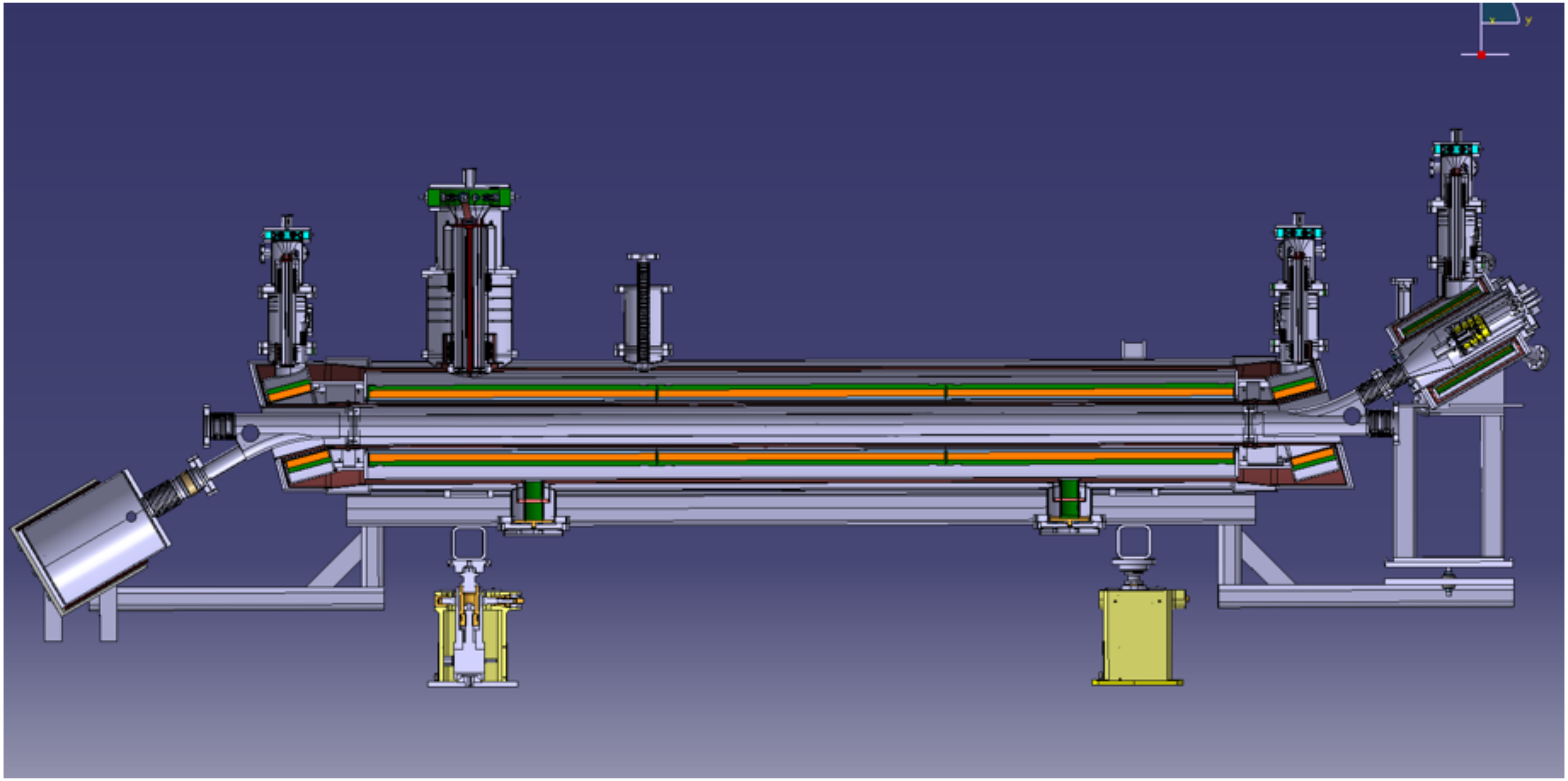
LHC HEL design



D. Perini, EN/MME

Simplified original design by Tevatron: better technological choices, reduced number of magnets/correcting coils.

Detailed component design



D. Perini

Ongoing: study of the possibility to create space to fit a gas jet monitor for transverse beam size measurements (*p*+*e*).

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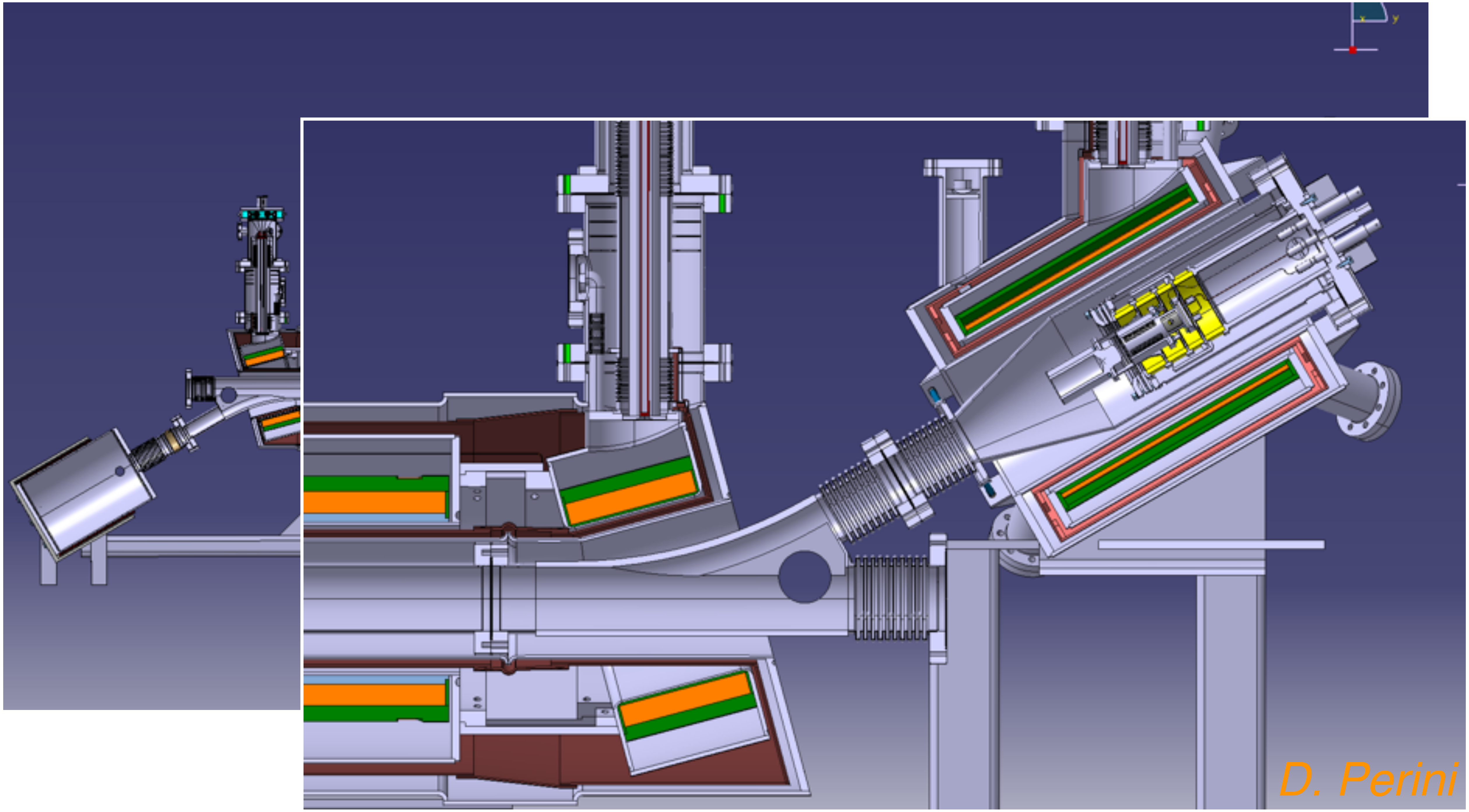

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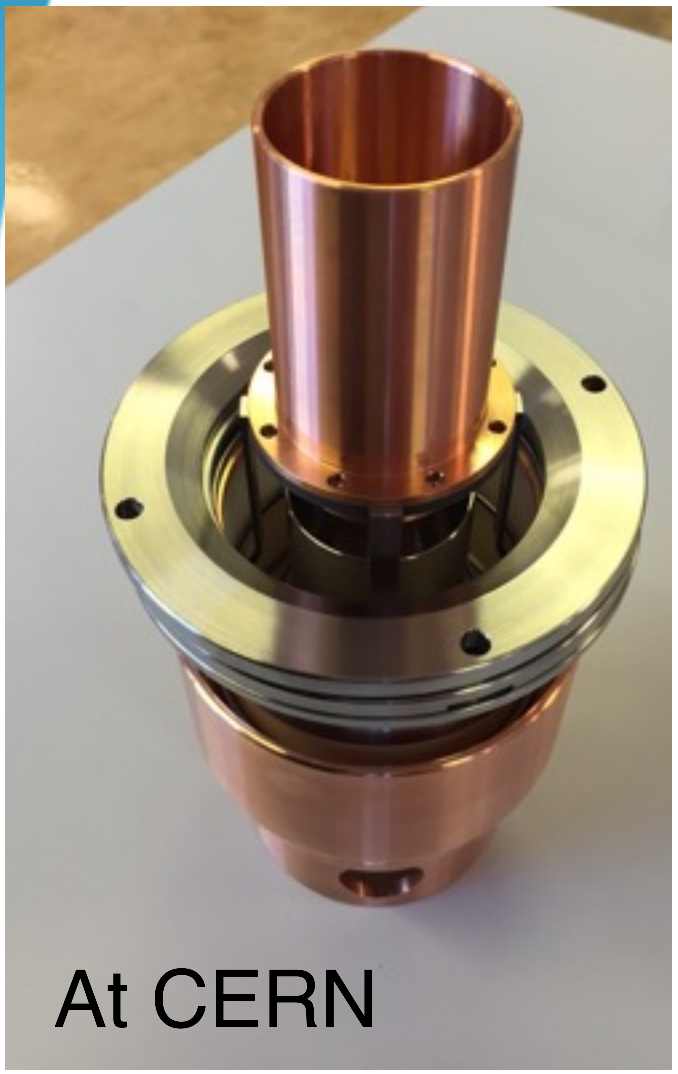
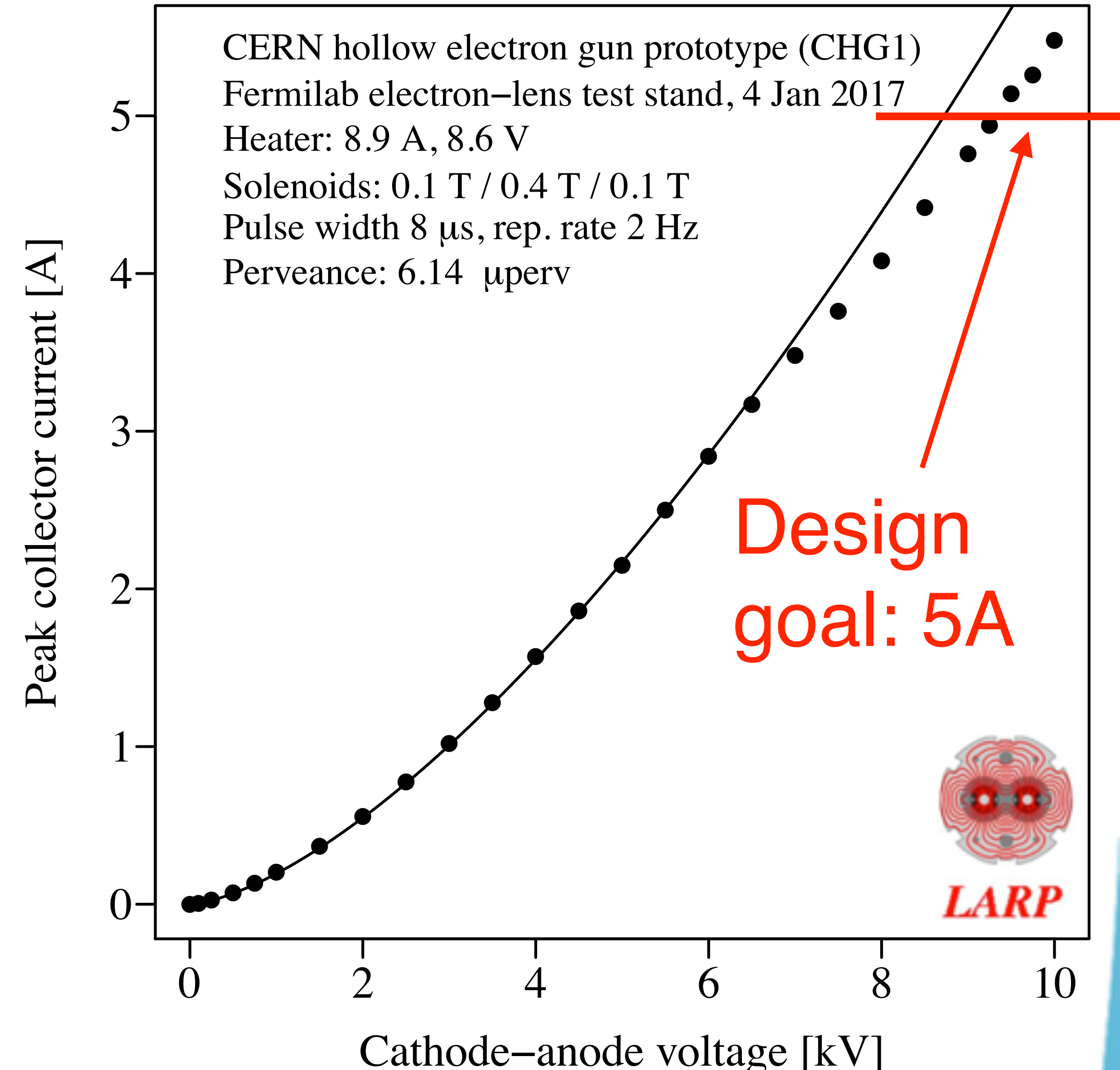
Electron gun developments

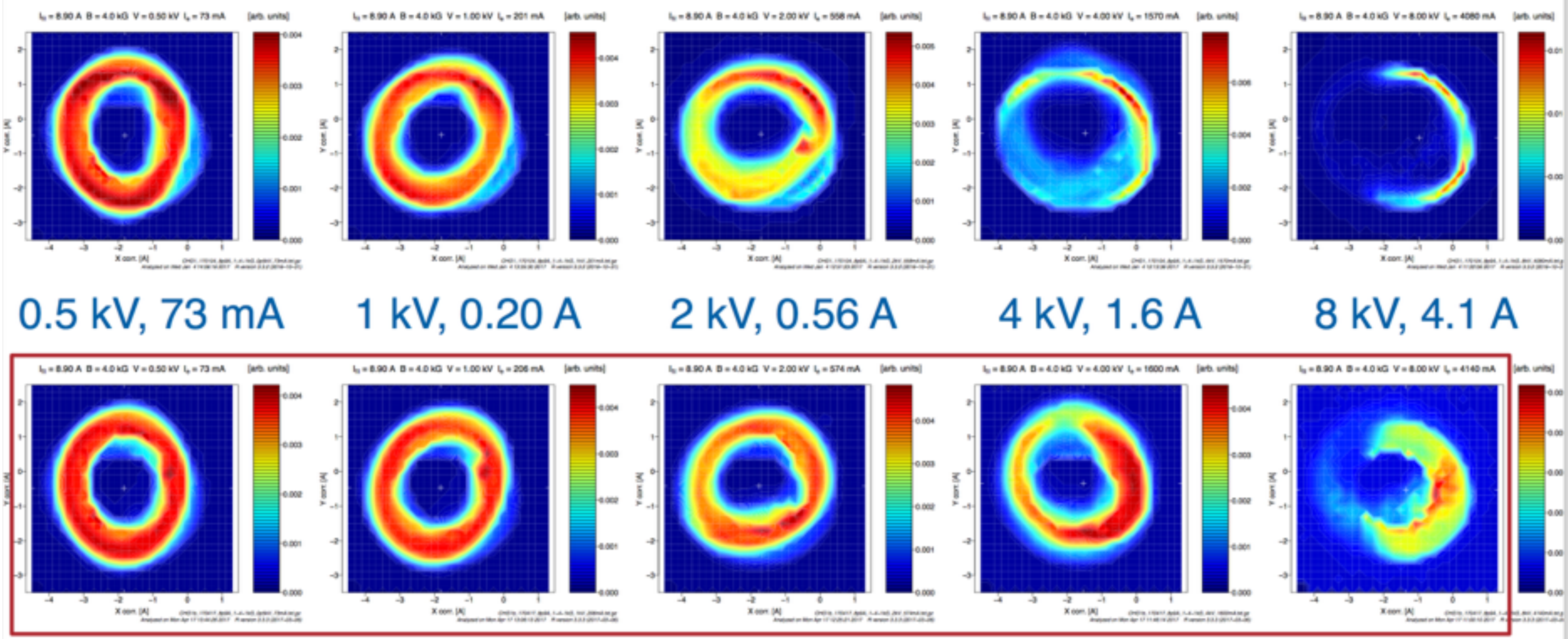




The first CERN hollow electron gun was tested in the Fermilab electron beam test-stand. Achieved output current **5.4 A (new record)**.

Thanks to US-LARP support and to G. Stancari.

Results of recent tests



G. Stancari

Added shield removes effect of supports,
reducing systematics on space-charge evolution

Planned CERN visits to FNAL to support beam tests and <u>transfer know-how</u>:
J. Wagner (PhD, BE/ABP), A. Rossi (BE/BI), G. Gobbi (fellow, EN/MME).

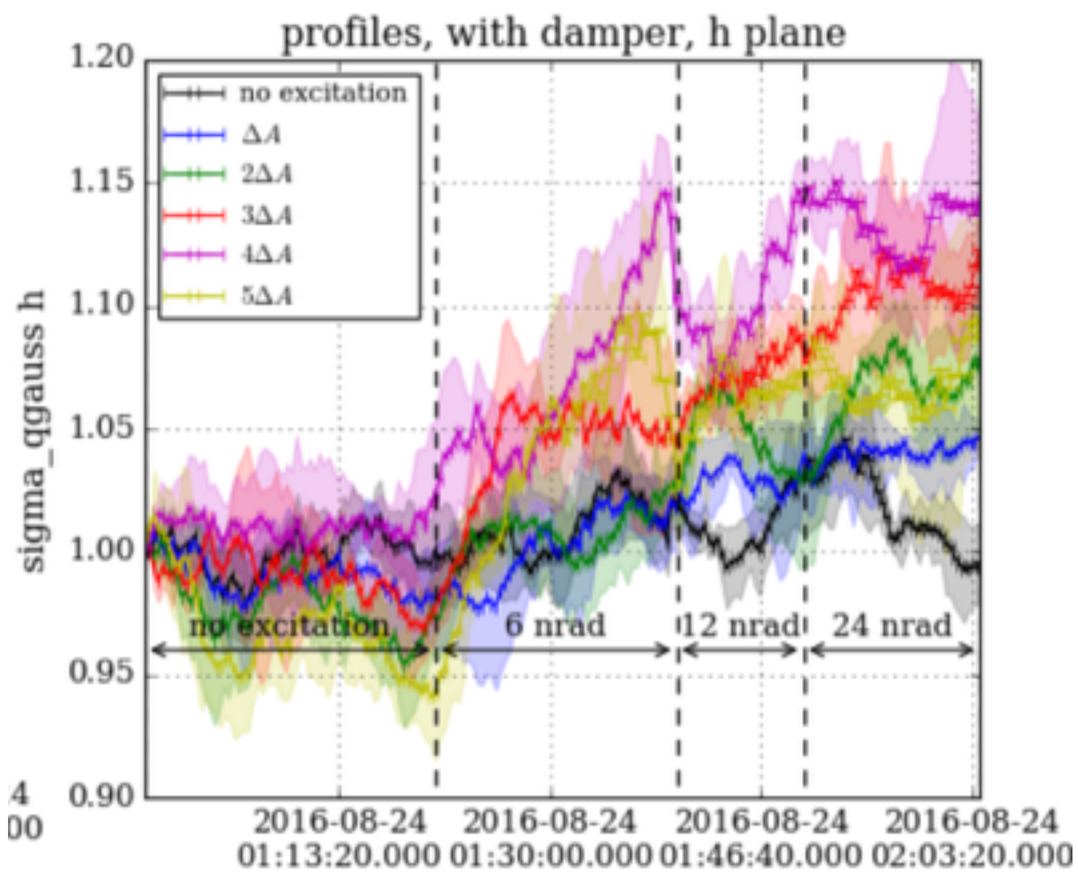
Program and main goals:

find optimum working point (temperature) and optimise shape vs magnetic fields.

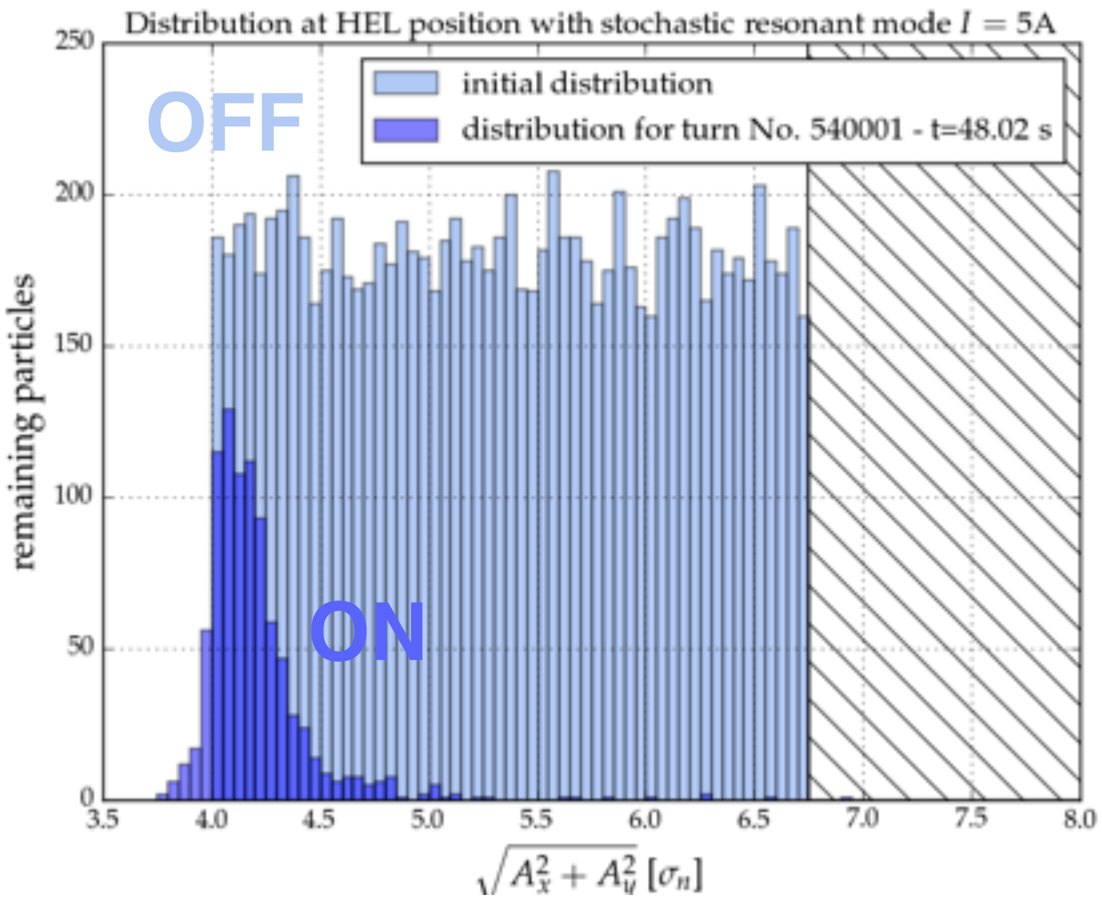
Measurements and simulations

Beam core
(M. Fitterer)

Beam tails
(J. Wagner)



Measured beams size in MD: damper excitation to mimic effect of HE on core.



Simulation of tail depletion t HL-LHC with HE.

Excellent team work on code development (Lifetrac, SixTrack) and benchmarks. Lots of new results on core and tail simulations.

Thanks to FNAL support to LHC MDs!

Outline

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New collimators for 2017

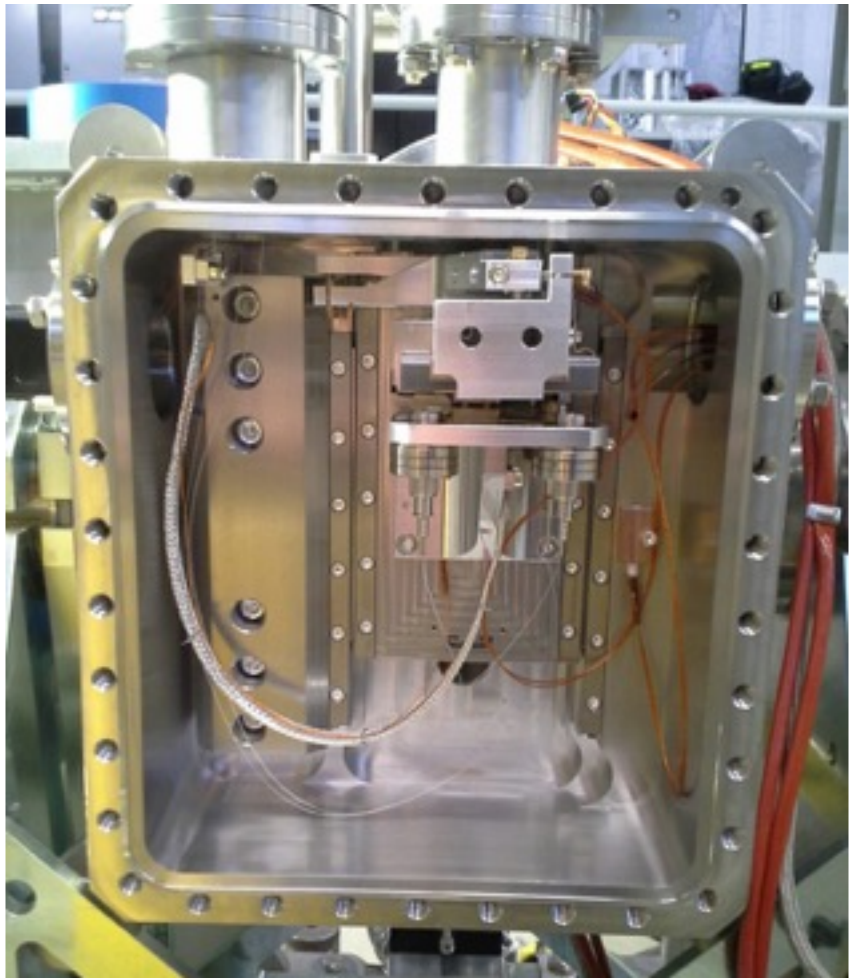
In the EYETS2016, we succeed to install **6 new collimator devices**:

- 1 *primary collimator with BPMs (TCPP) ↦ consolidation*
- 1 *low-impedance prototype (TCSPM) in IR7*
- 2 *crystal collimator primaries (TCPC) in IR7, beam 2*
  2017: complete system with 4 crystals for collimation studies: 2 per beam!
- 2 *wire collimators for long-range beam-beam (TCTPW)*

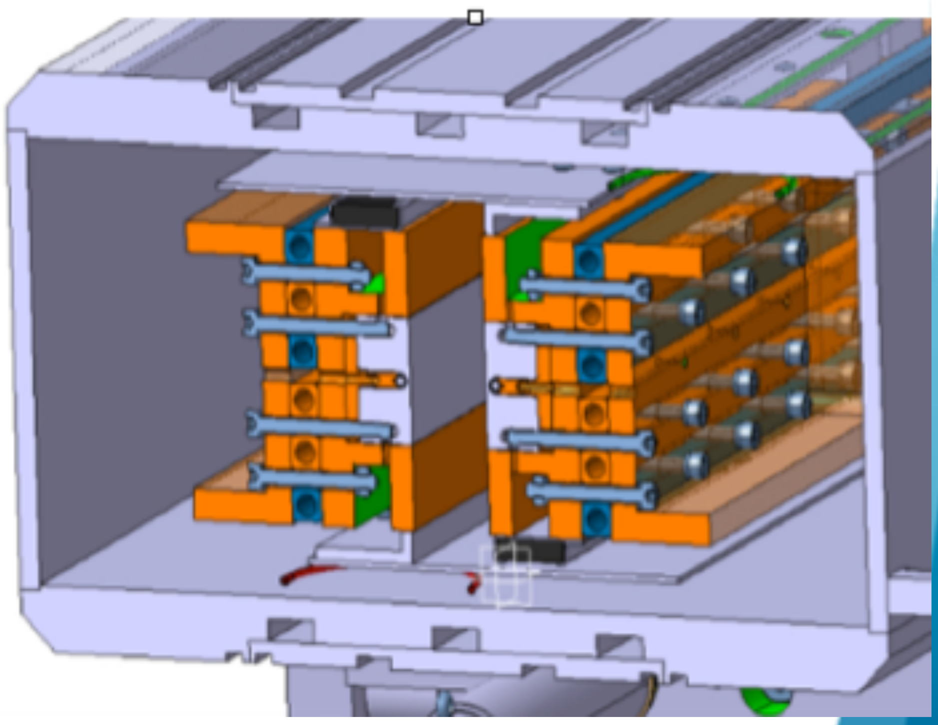
Exciting beam tests ahead!

TCSPM jaw

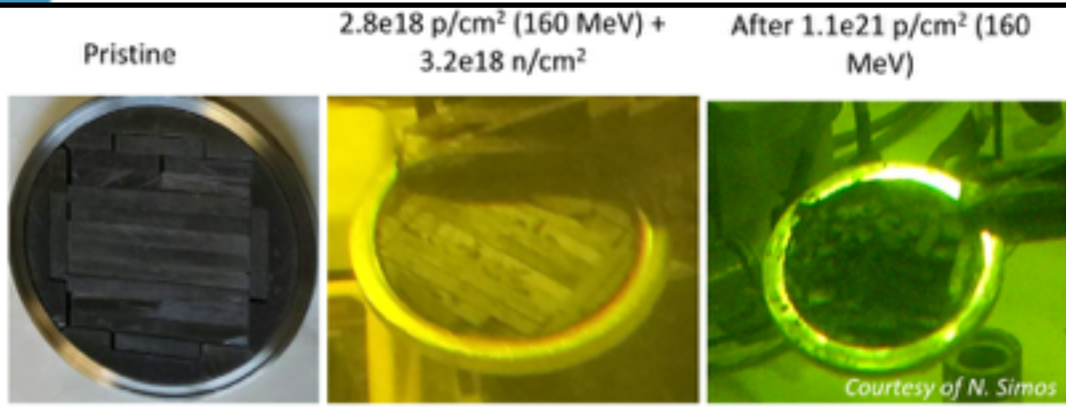
Crystal goniometer (TCPC)



TCTPW cross section

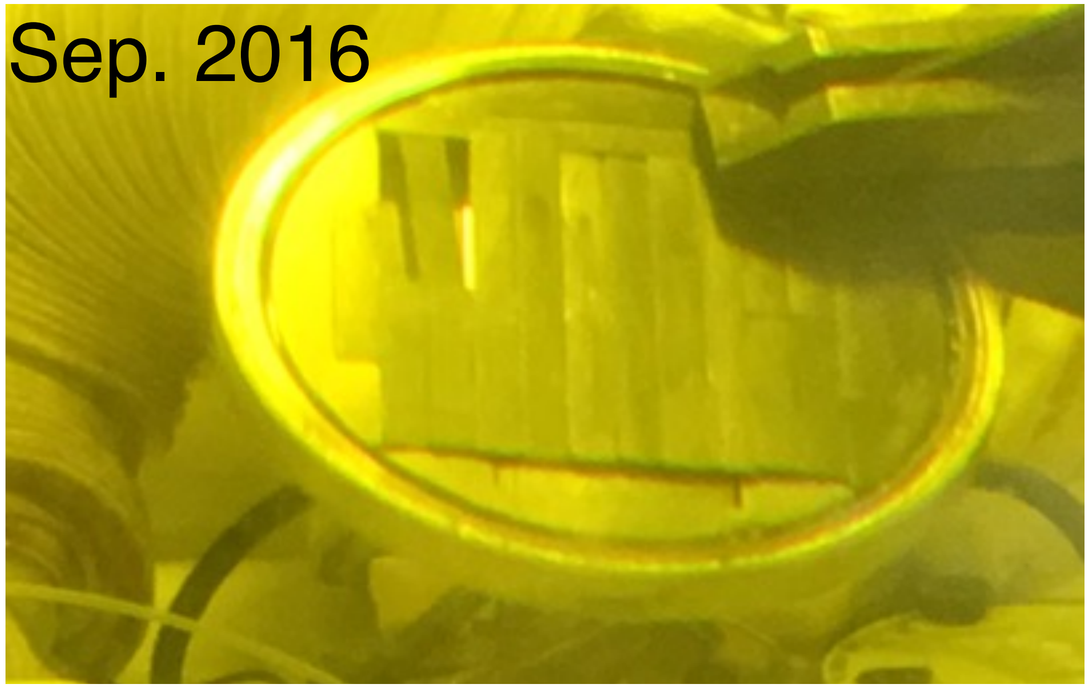


News from LARP: material irradiation



One sample had to be taken out because of problems with the target. Left with important uncertainties on the threshold for net of damage.

New irradiation campaign: (1) several doses; (2) direct comparison to CFC presently used in TCP/TCSG collimators.



6 remaining MoGR target capsules

ALL (macroscopically at least) SURVIVED - that means both NEW grades

Peak fluence to be determined.

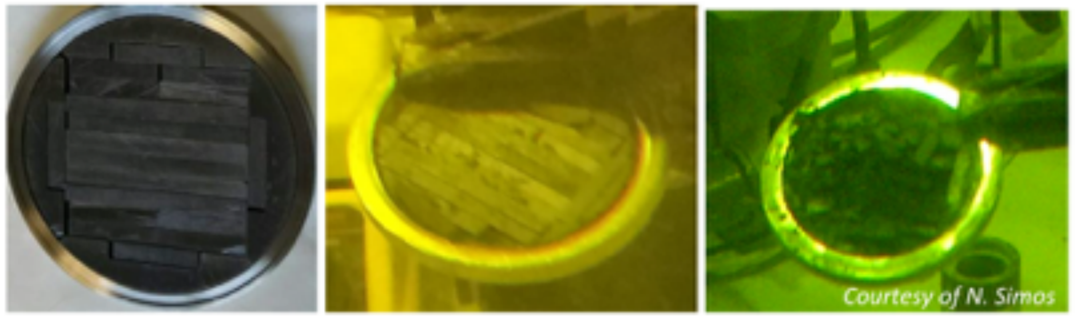
Should be in excess of 10^20 p/cm2 (but what exactly needs time)

Excellent result! We are waiting for more news — present inspections are limited by HIGH RESIDUAL DOSES that also prevented measurements of macroscopic thermo-mechanical properties.

Excellent example of <u>cross-fertilisation</u>: 2 students joined the tests at BNL. Recently completed PhD by E. Quaranta "Investigation of collimator materials for the HL-LHC" (1 chapter on BNL results!). Hope to see this continuing in LARP2!

News from LARP: material irradiation

Pristine	2.8e18 p/cm² (160 MeV) + 3.2e18 n/cm²	After 1.1e21 p/cm² (160 MeV)



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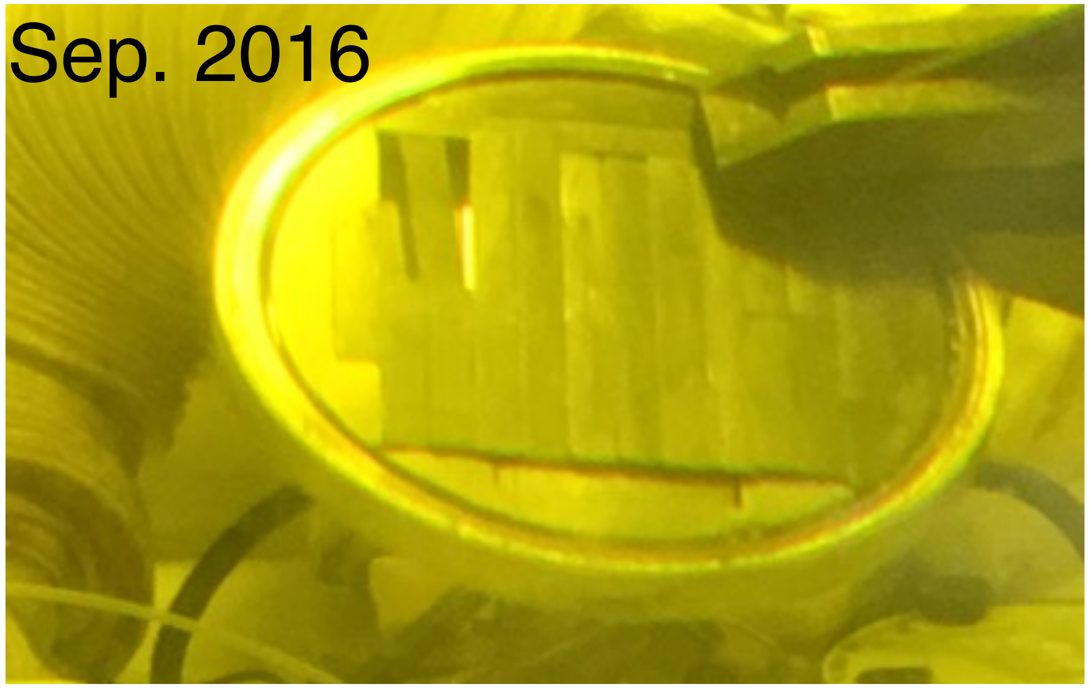

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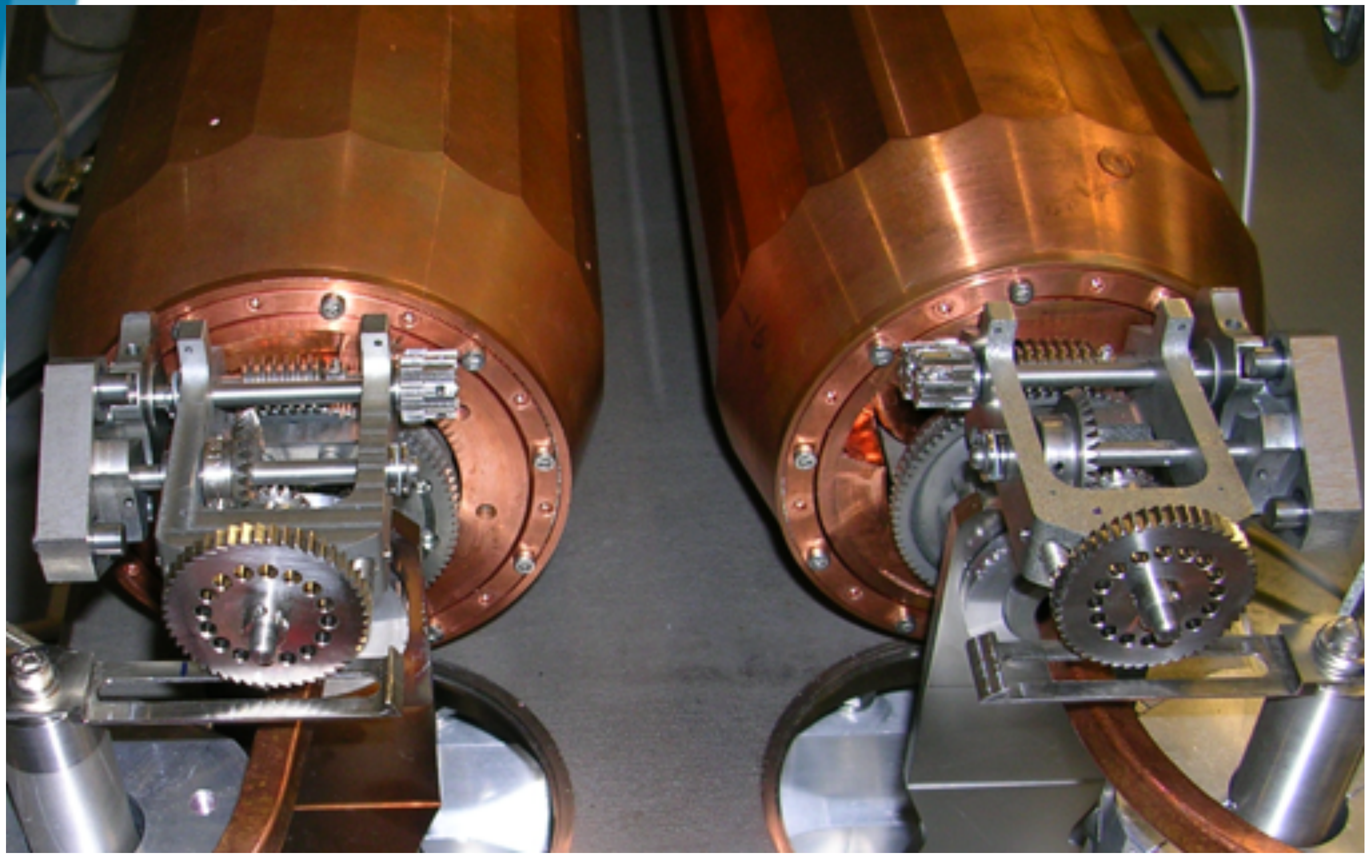
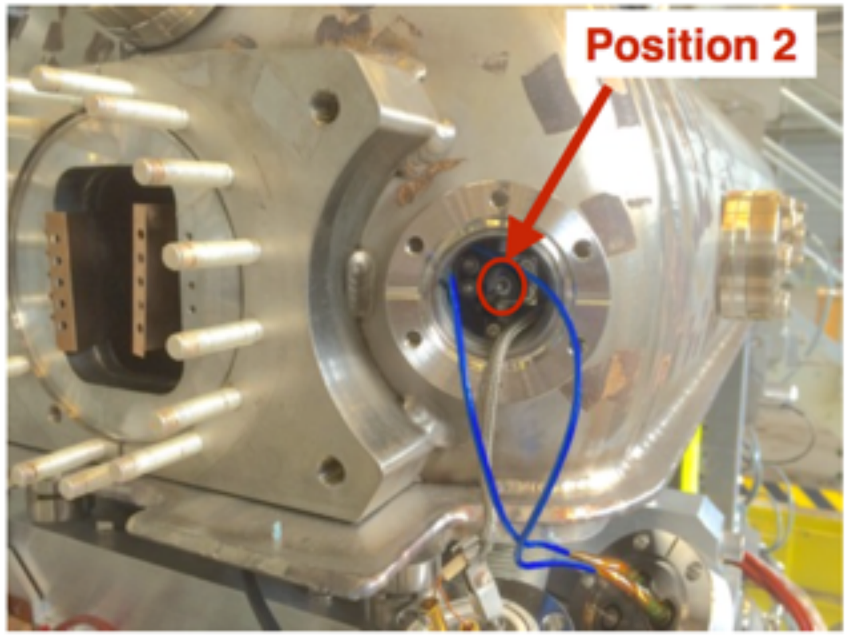
Tonight I go to BNL to discuss with Nick the next steps: **post-irradiation analysis** and new tests on **coated samples.**

News from LARP: SLAC RC



- Delivered to CERN in Dec. 2013
- Extensively tested in lab (vacuum, rotation, impedance, …)
- Excellent results of beam tests with circulating beams in the SPS (alignment, BPMs, impedance, …)
- HiRadMat (destructive) tests planned in <u>June 2017</u>, delayed because of SPS dump issues in 2016.

Tests done on 18th April 2016



Improved instrumentation: thermal probes, static pressure sensors, ***rad-hard camera****, accelerometers (to monitor rotation), …*

Thanks to CERN teams that supported this work: BE/ABP, EN/MME, EN/STI.
Collaboration with Malta University (G. Valentino). See ColUSM Apr. 21st, 2017.

Conclusions

- ☑ **Reviewed the CERN plans for HL-LHC hollow e-lenses**
- ☑ **A recent external review acknowledged the needs for active halo control at the HL-LHC, followed by support from CMAC**

  HL-LHC: beam tails with tens of MJ in unexplored operational regimes and in presence of new fast failure scenarios.

  "The hollow e-lens is by far the best technology to achieve this objective, as clearly demonstrated in the Tevatron".

  "… consider inclusion into the baseline, even at increased cost."

- ☑ **We have followed up this strong encouragement and are developing a complete technical design, integrated in HL-LHC**

  Plan now a technical review, assessing readiness of CERN teams: Oct. 2017.

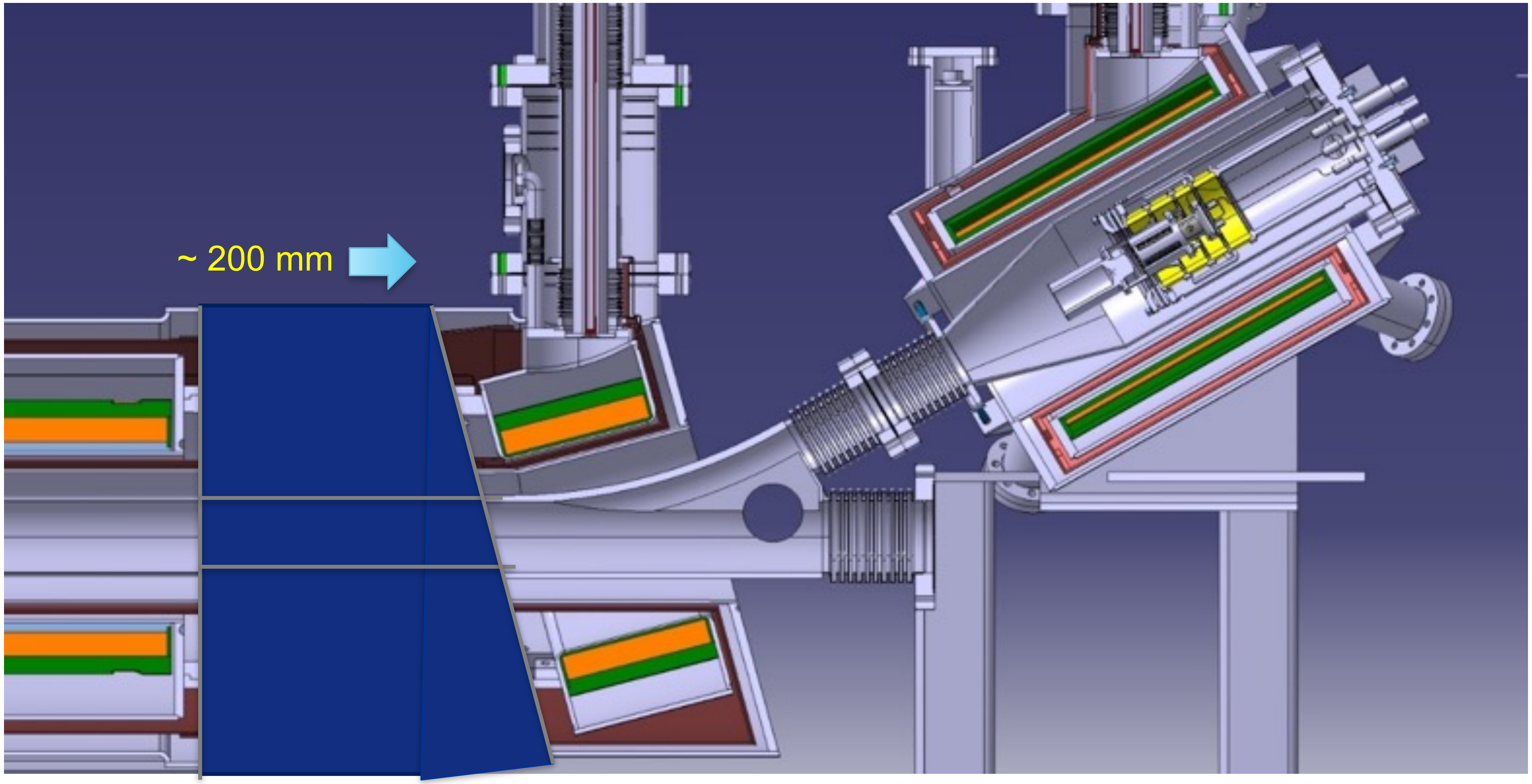
  Discussion on possible inclusion into baseline will follow, at the 2018 C&S review.

- ☑ **Collaborators and in-kind contributions are key ingredients!**
- ☑ **Emphasised excellent collaboration on various US-LARP fronts**

  Looking forward to continue in this way.

Reserve slides

Space of diagnostics



Ideally, need to find some space (to be defined by BE/BI) to insert a gas get monitor.

Experience from other machines

Talks from HERA, Tevatron and RHIC

- *Review of concerns from spikes in other machines*

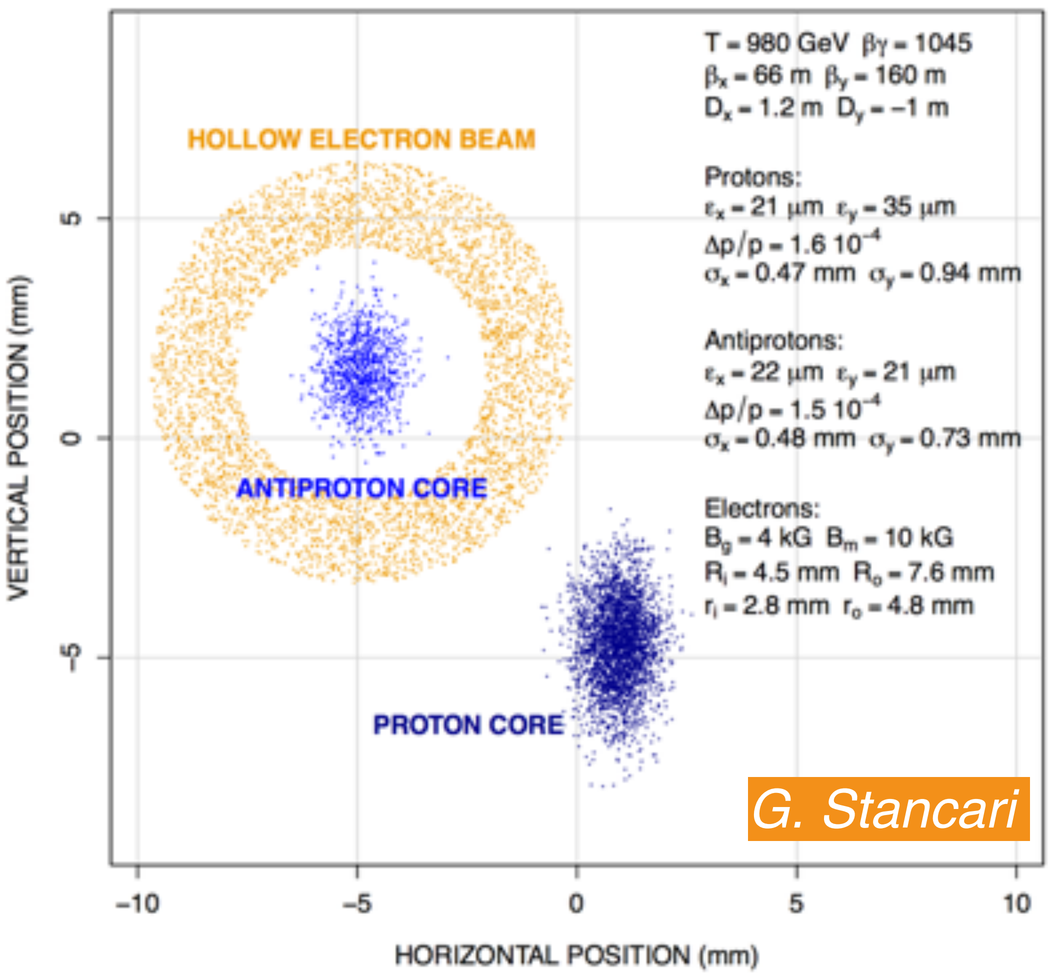
Presented reliability of electron lenses operation in colliders

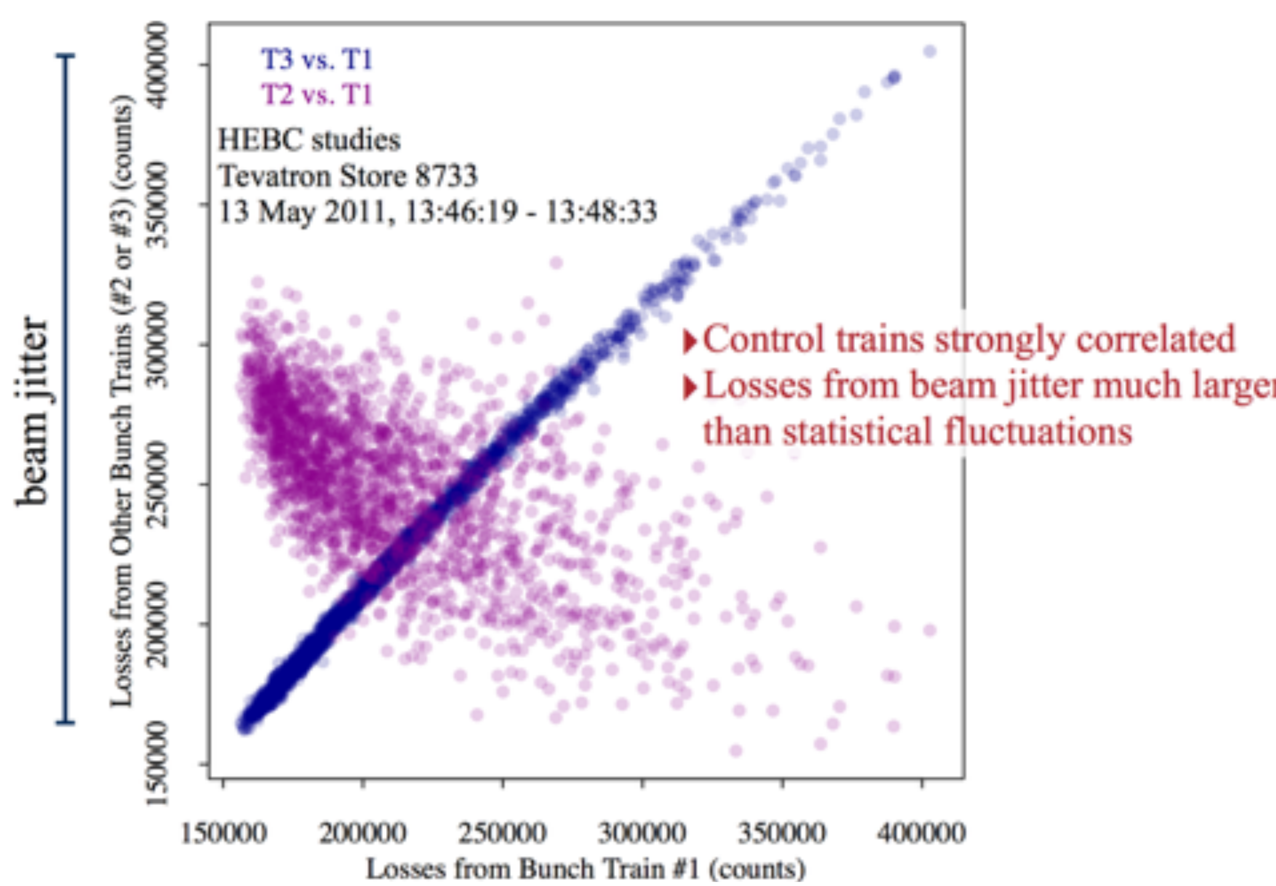
- *Used for more than 10 year at Tevatron. Also good at RHIC.*

Review of collimation tests with hollow e-lens tests at Tevatron

- *Convinced the reviewer that this can work!*

New concerns from vibration noise, addressed in P. Fessia's talk.





Fast failures at the HL-LHC

Fast and ultra fast failures for HL-LI

Failure type	criticality
Injection failures and **Asynchronous** beam dumps	• Upgrade of protection devices un foreseen; machine configuration to accommodate failures
Crab Cavity failures	• Single CC failure probably manageable • Combined failures of multiple CC → high risk for damage • Higher operating voltages increase criticality significantly
Missing **beam-beam kick**	Low risk - depends on halo distribution and collimator gaps
Kick due to **quench heater firing** in MB and new HL-LHC magnets	Not critical
Discharge of CLIQ (variation of magnet currents by few kA for 100 – 200 ms)	Not critical in case of foreseen connection schemes
Warm **D1 powering failure**	superconducting D1 → mitigated

D. Wollmann, R. Calaga

Outstanding concern for the operation with crab-cavities that is being addressed systematically by various teams *(hardware team with accelerator physics & machine protection): studying extent of issue and possible mitigations.*

It will be crucial to address these aspects in beam studies at the SPS. Strongly recommended by review! Unknown: beam induced failures.

From the review panel recommendation

Crab cavities are likely to introduce a new class of very fast failures, due to phase and/or voltage changes, possibly induced by the beams. This would lead to an excitation of betatron oscillations with large amplitudes (depending on the failure mode, more than 1.5 σ). The reaction time of the machine protection system is not sufficient to fully mitigate these failures in case of overpopulated tails that could damage collimators. A hollow e-lens will mitigate such failures if the oscillation amplitude is below, say, 2 σ. If failure modes exist that lead to larger amplitudes, other mitigation measures need to be found.

Loss spike concern

The present LHC collimation system is designed to withstand peak losses of **500kW**:

minimum allowed lifetime of 0.2 h at 7TeV with full intensity

HL-LHC: factor 2 larger losses for same loss assumption.

Concerns from fast failures in presence of over-populate tails.

- **The success of HL-LHC relies on pushing parameter and operational scenarios well beyond LHC**
  - Double bunch intensity in smaller emittance
    How halo population and beam lifetime scale?
  - Operation with crab cavities
    No experience with proton beams. Implications for machine protection?
  - Luminosity levelling
    Must ensure a loss-free operation while levelling at $5x10^{34}cm^{-2}s^{-1}$

  This makes extrapolation of loss from LHC complex.

- **Re-baselining of June 2016 added some uncertainties**

  See next talk by R. Bruce.

Organized an external project review to address needs of halo depletion with hollow e-lenses at the HL-LHC.

Scaling to HL-LHC — complex!

	Energy	Beta Star	Bunch Spacing	Bunch Intensity	Total Number Bunches	IP7 Collimation Primary Cut @ Top Energy
2011	3.5 TeV	1.5 m	50 ns	1.40E+11	1374	5.7σ
2012	4 TeV	0.6 m	50 ns	1.50E+11	1374	4.3σ
2015	6.5 TeV	0.8 m	25 ns	1.20E+11	2244	5.5σ
2016	6.5 TeV	0.4 m	25 ns	1.10E+11	2220	5.5σ

2012: Year of worst losses!

Same primary cut in mm since 2012

Key parameter changes:

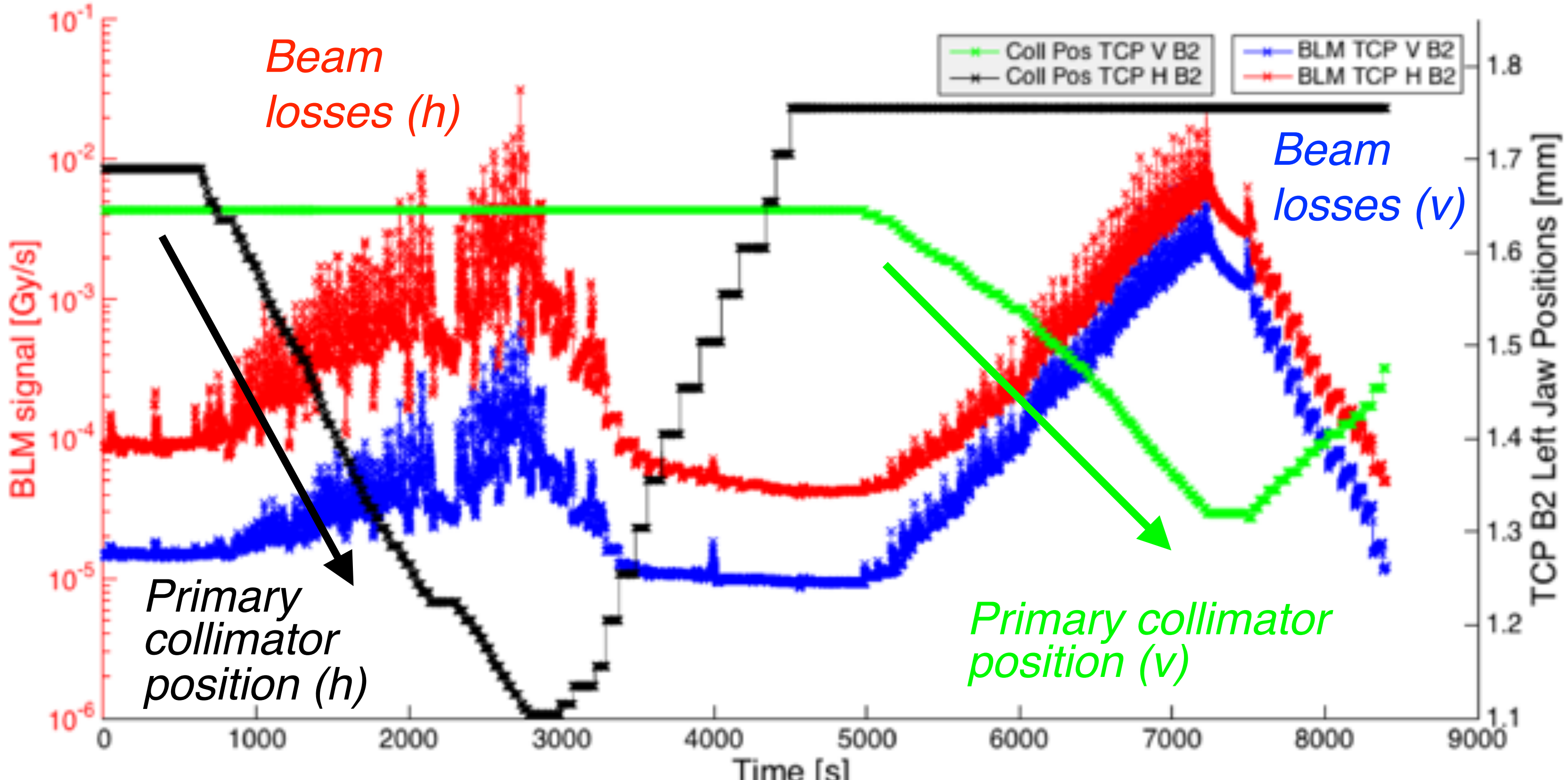
- Optics and betastar
- Beam energy
- Bunch population
- Bunch spacing: 50ns vs 25ns
- Collimator settings in units sigma

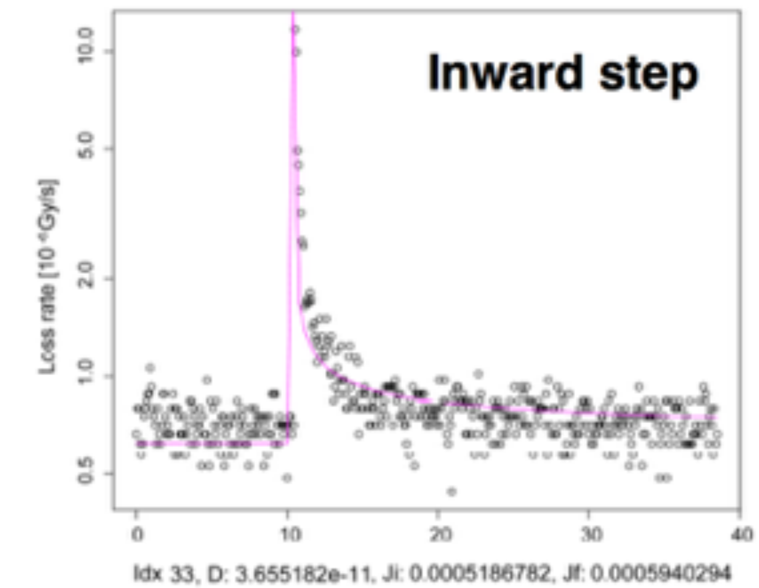
For 2017, we propose to reduce by 0.5 σ the primary betatron cut — get important new insight, with a small risk (setup **tested in MD** with trains brought in collision)

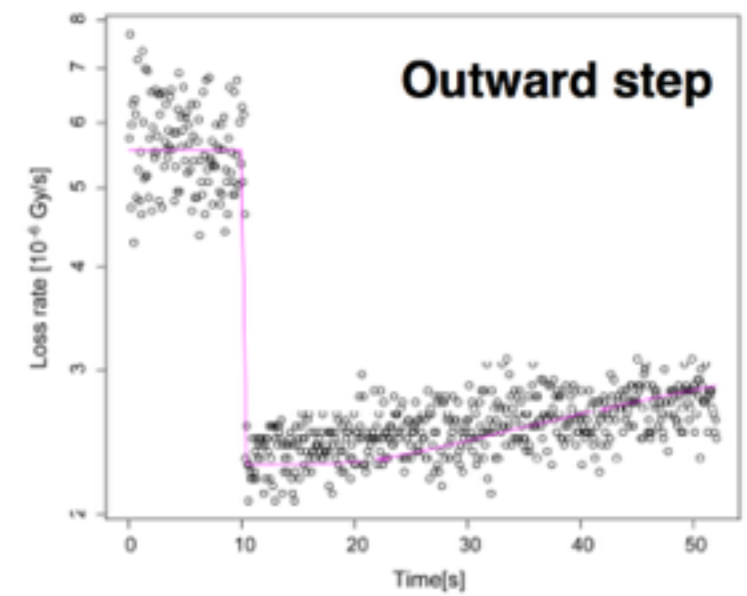
Review panel recommended study with high priority parameter scaling (Request MDs with 8b+4e and 1.6e11 protons per bunch!)

First measure of LHC diffusion at 6.5TeV

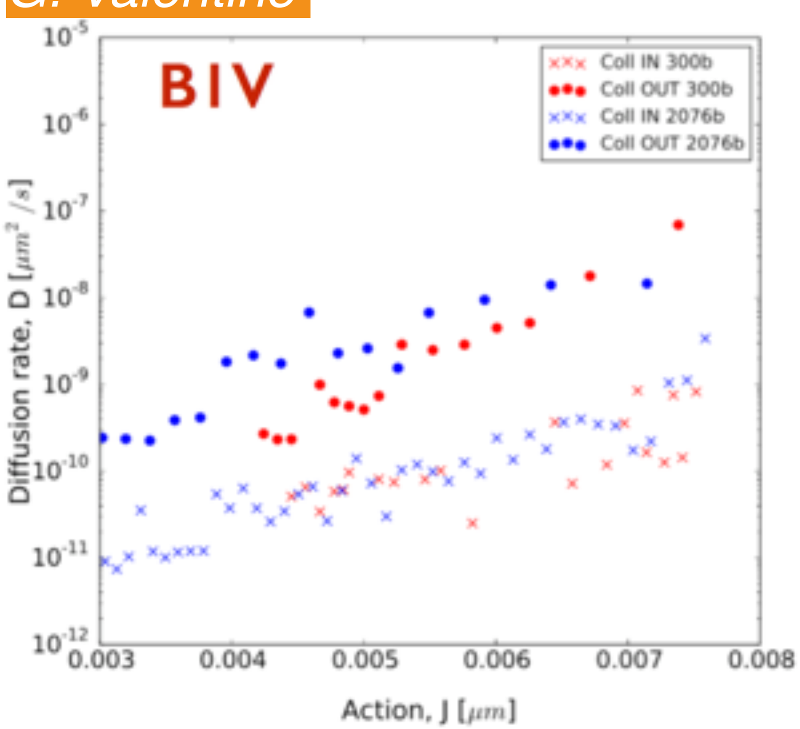
Primary collimator scan performed at 6.5TeV:
2076 bunches = 170 MJ beam in collision!

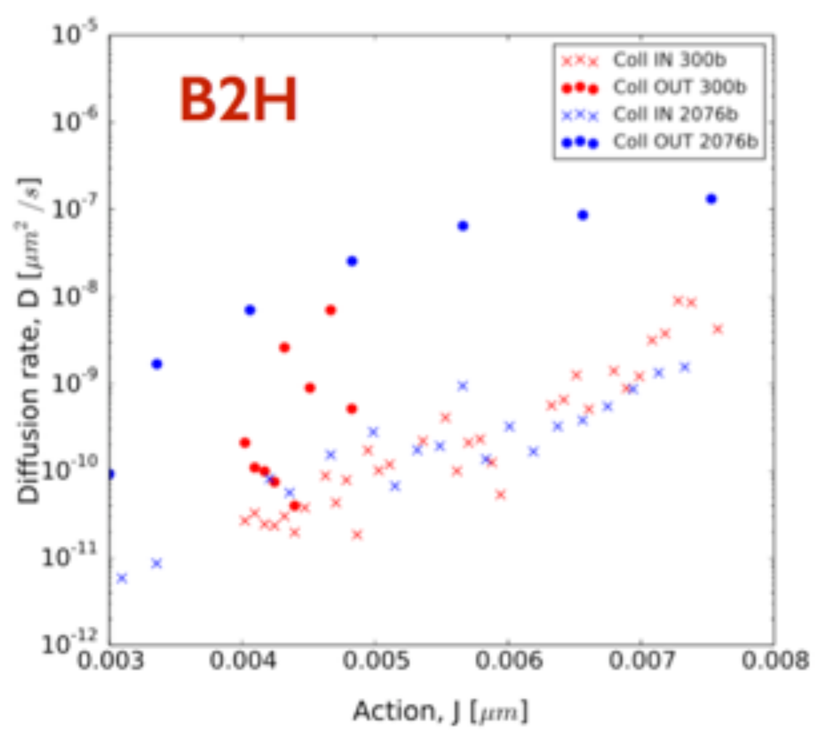






G. Valentino





LHC tails: over-populated but very quiet!

Thanks: Physics coordinators (and MD coordination)

Other benefits from hollow e-lenses

Combined with baseline upgrade of the collimator impedance, can allow tighter collimator hierarchy
- One promising way to re-gain beta* at HL-LHC

G. Arduini

Halo control will provide more flexibility in various operational phases.

Strong synergy with other studies within HL-LHC: halo diagnostics (baseline), long-range beam-beam compensation (non-baseline).

Better control of impact parameter on collimators, for ions and for protons.
- To be studied: can one recover collimation cleaning for new layout with only one 11T dipole “cryo-unit”?