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

Tevatron control room, 2011

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.

CERN: R. Bruce, **B. Di Girolamo**, D. Mirarchi, M. Giovannozzi, G. Gobbi, G. Kirby, A. Kolehmainen, A. Mereghetti, **D. Perini**, **A. Rossi**, S. Sadovich.
FNAL: **G. Stancari**, A. Valishev
HL-UK: UNIMAN, RHUL (H. Garcia, D. Mirarchi)
BINP: A. Levichev, M. Arsentyeva, A. Barnyakov, D. Nikiforov, *et al.*
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.

Table of contents

Motivation

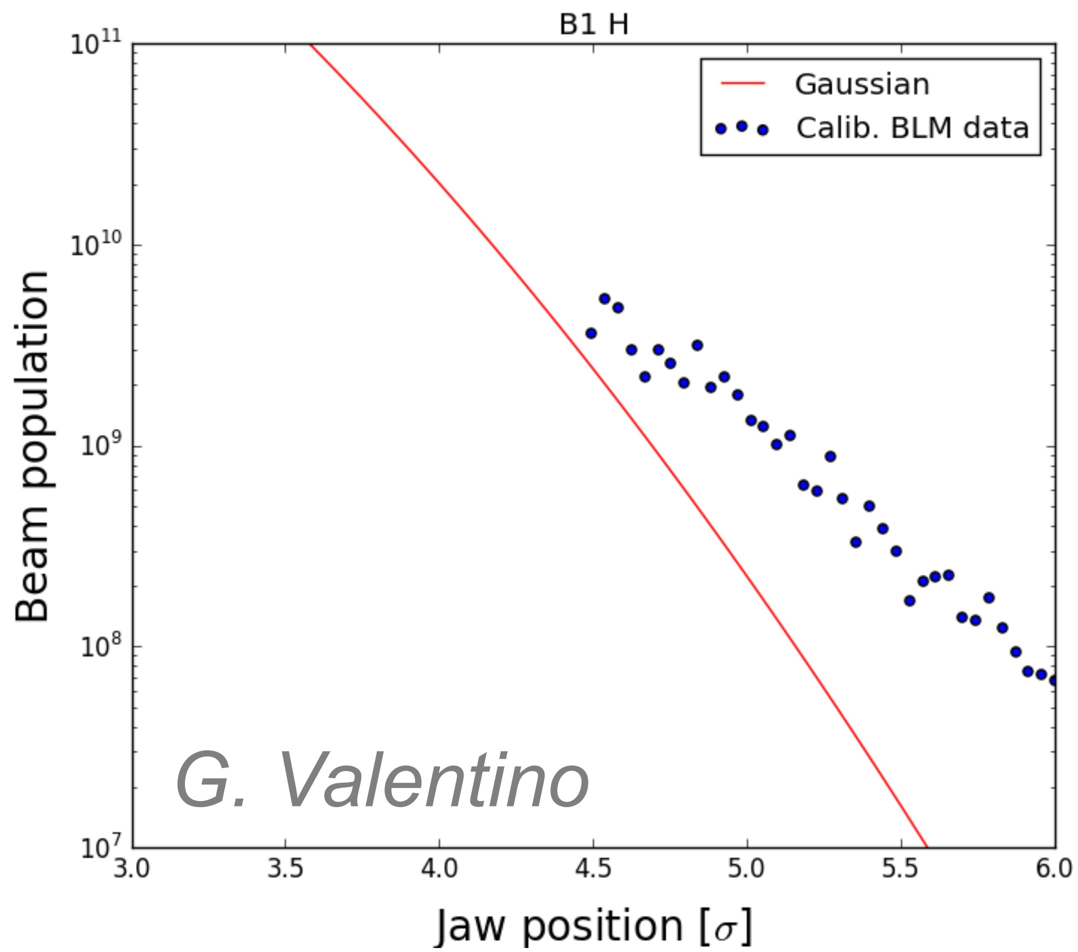
HL-LHC target 700 MJ stored beam energy (~ x2 LHC)

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 *statically* stored in the tails
- Obvious concerns for machine availability (dumps from loss spikes)
- High potential of damage

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



Recent history and overall status

<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
— <u>Beam losses 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 coming up at different cost&schedule reviews</u>

— 2018: recommendation to find funding mechanisms to implement it.

<u>Activities in the last ~year:</u>

— 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

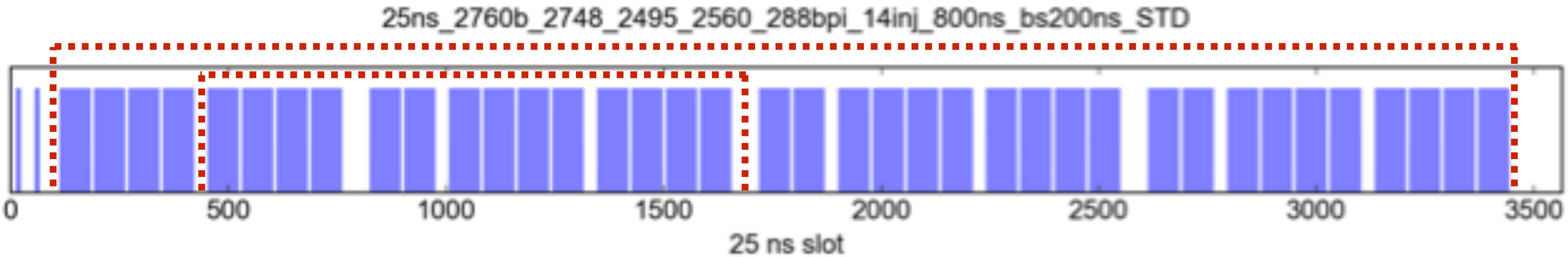
Requirements

- 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, turr
- 5A electron beam current, 3m overlap

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.

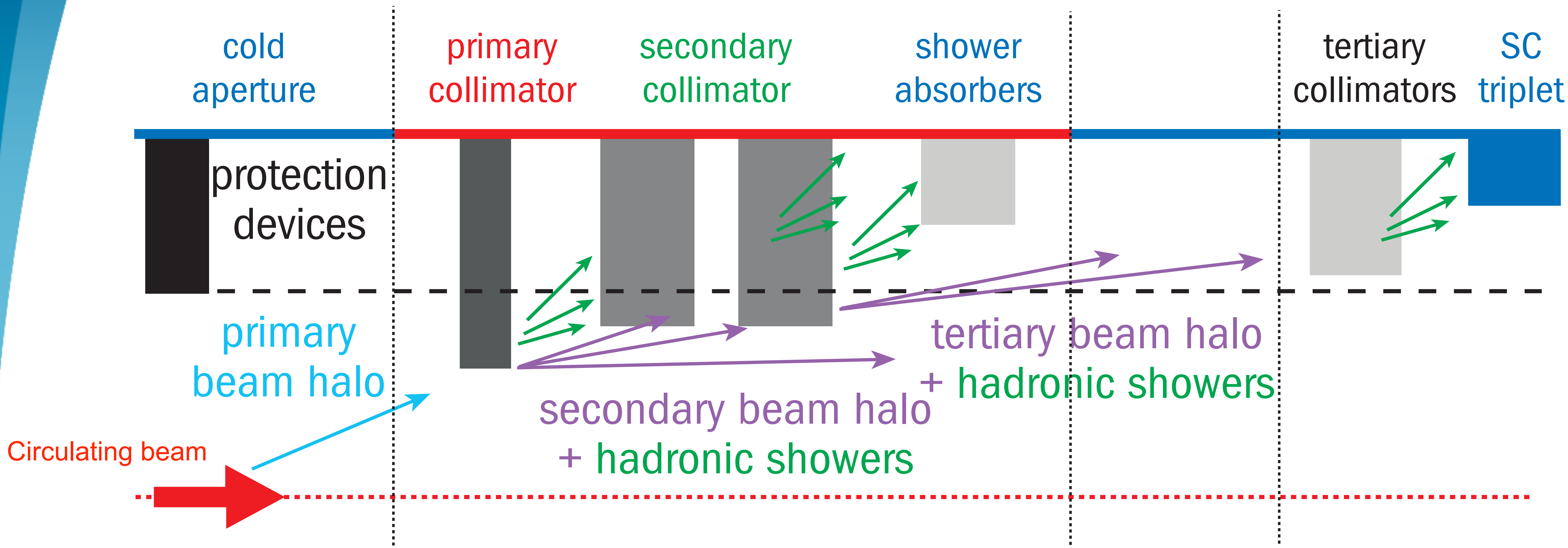
— Tighter collimator settings for even further beta* reach (if other known limitations are under control / fixed)

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

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

Table of contents

LHC multi-stage collimation



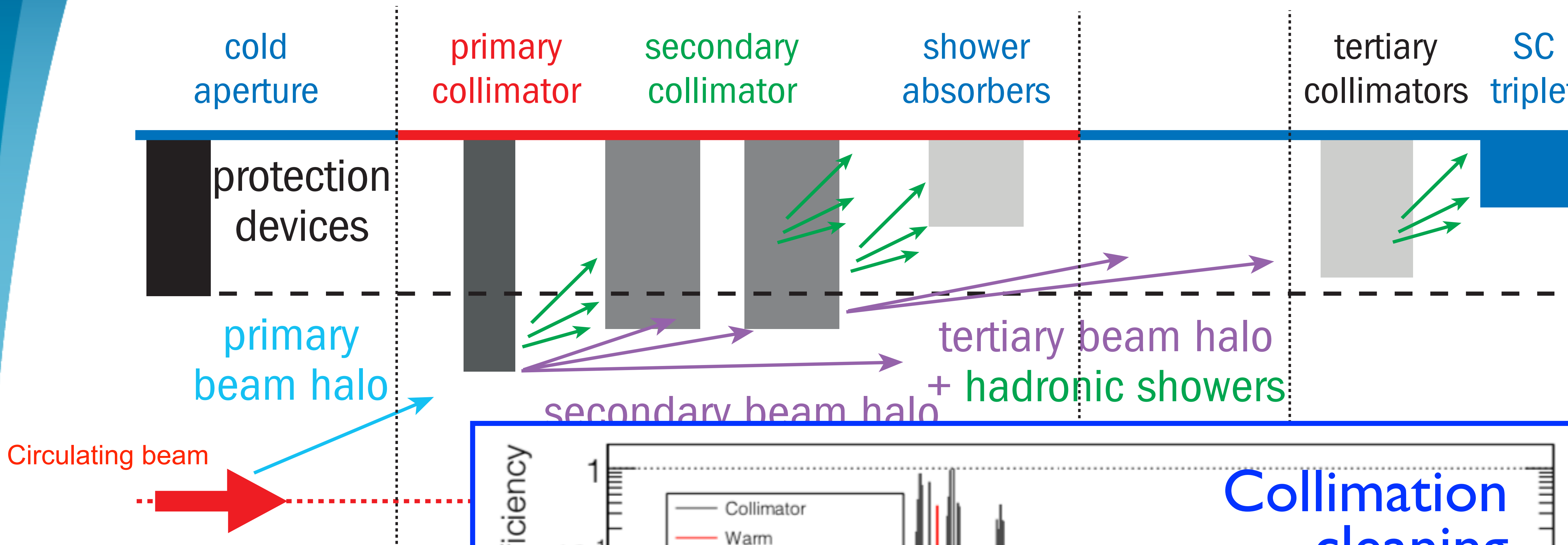
Three-stage cleaning in warm **cleaning insertions**: betatron (IR7) and off-momentum (IR3); local "tertiary" collimators at inner triplet.

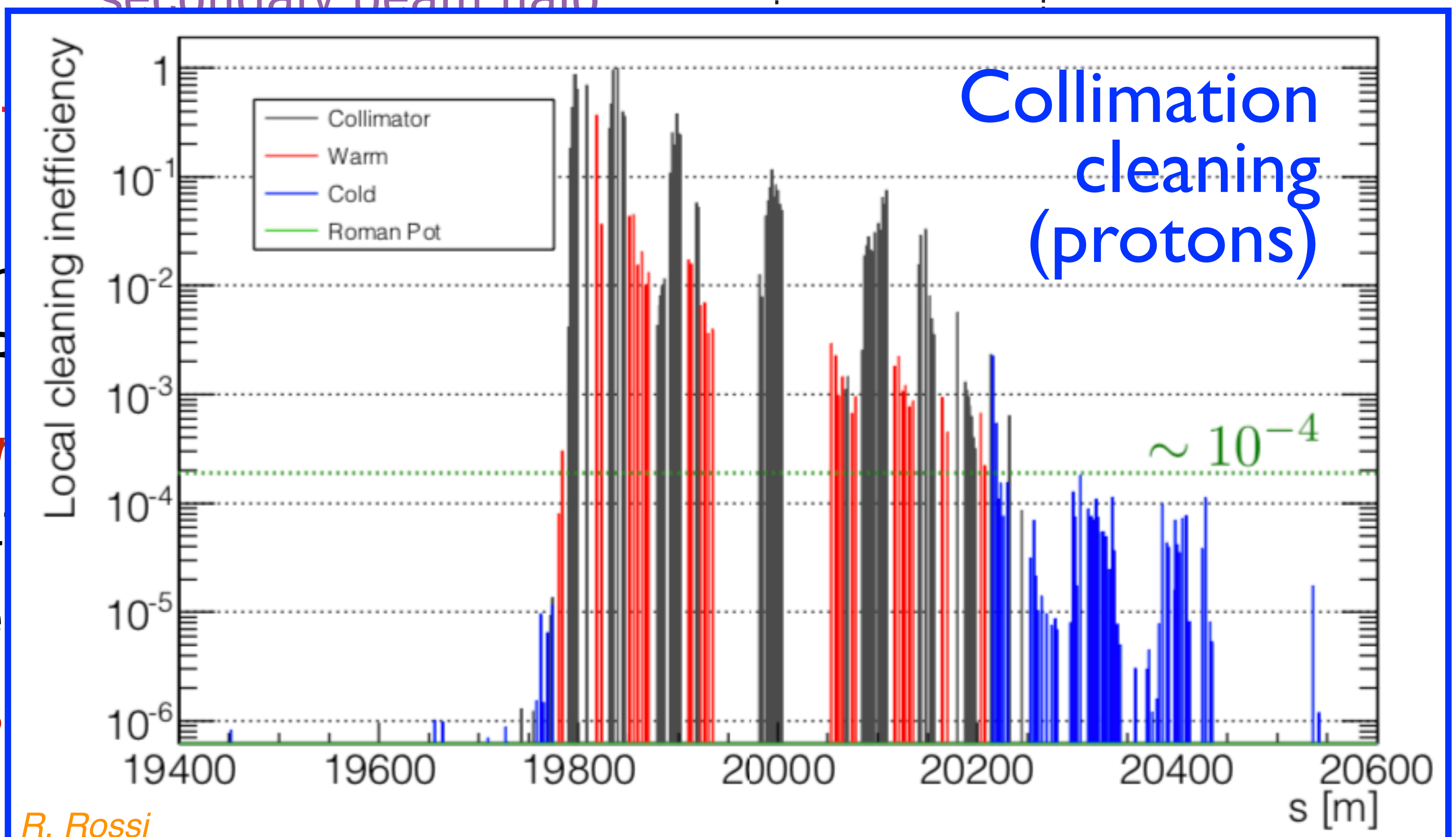
Well-defined *collimation hierarchy* that integrates injection and dump protection collimators (as well as Roman pots). **Five stages**!

Machine aperture sets the scale for collimation hierarchy

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

LHC multi-stage collimation





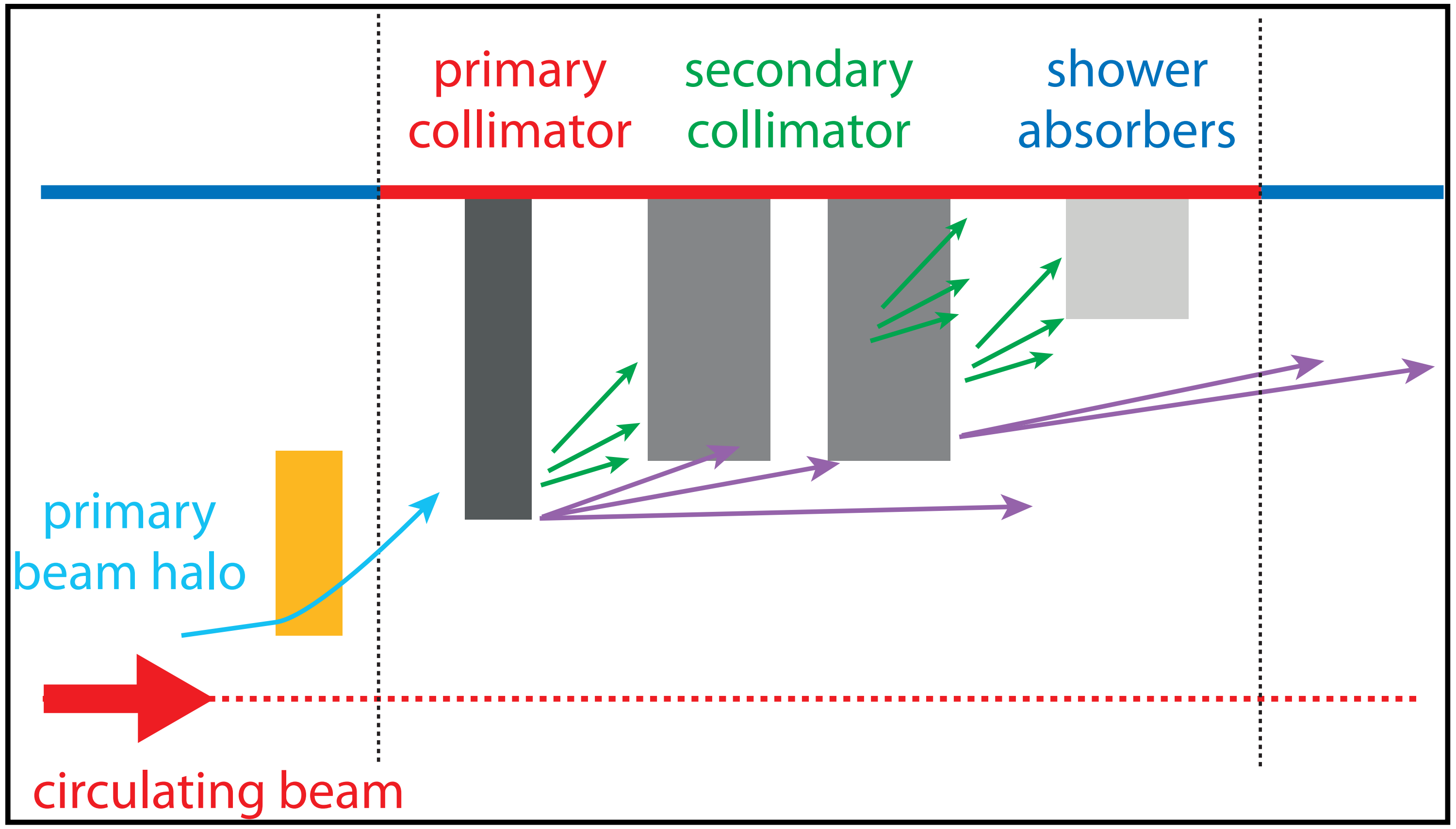
Three-stage clear
off-momentum (IF

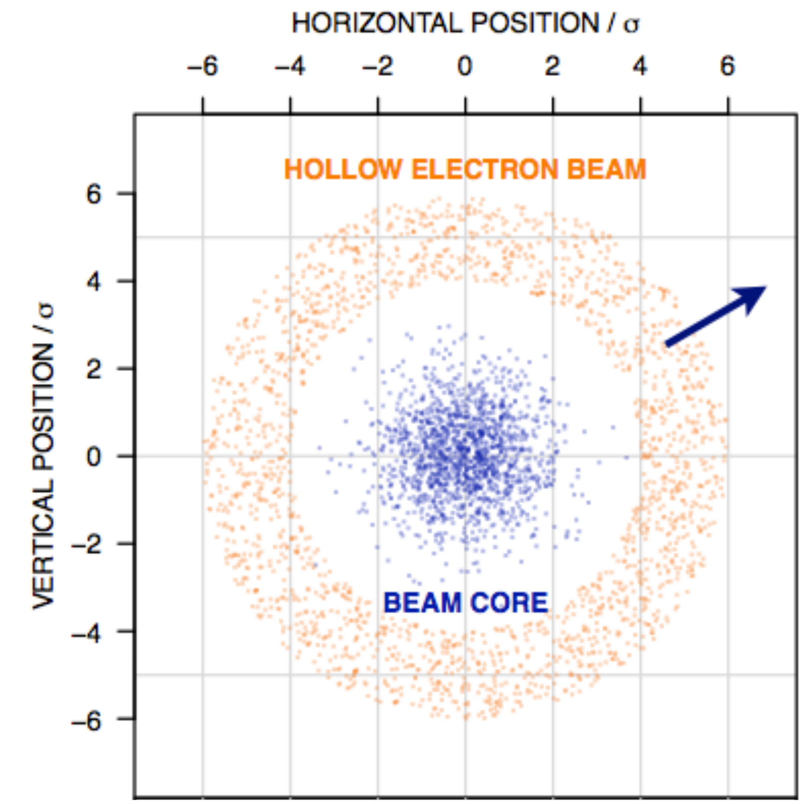
Well-defined *colli*
protection collima

Machine aperture

Critical beam-bas

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.
- it allows distributing losses over a desired time interval.
- it controls tail populations close to collimator jaws (deplete tails).

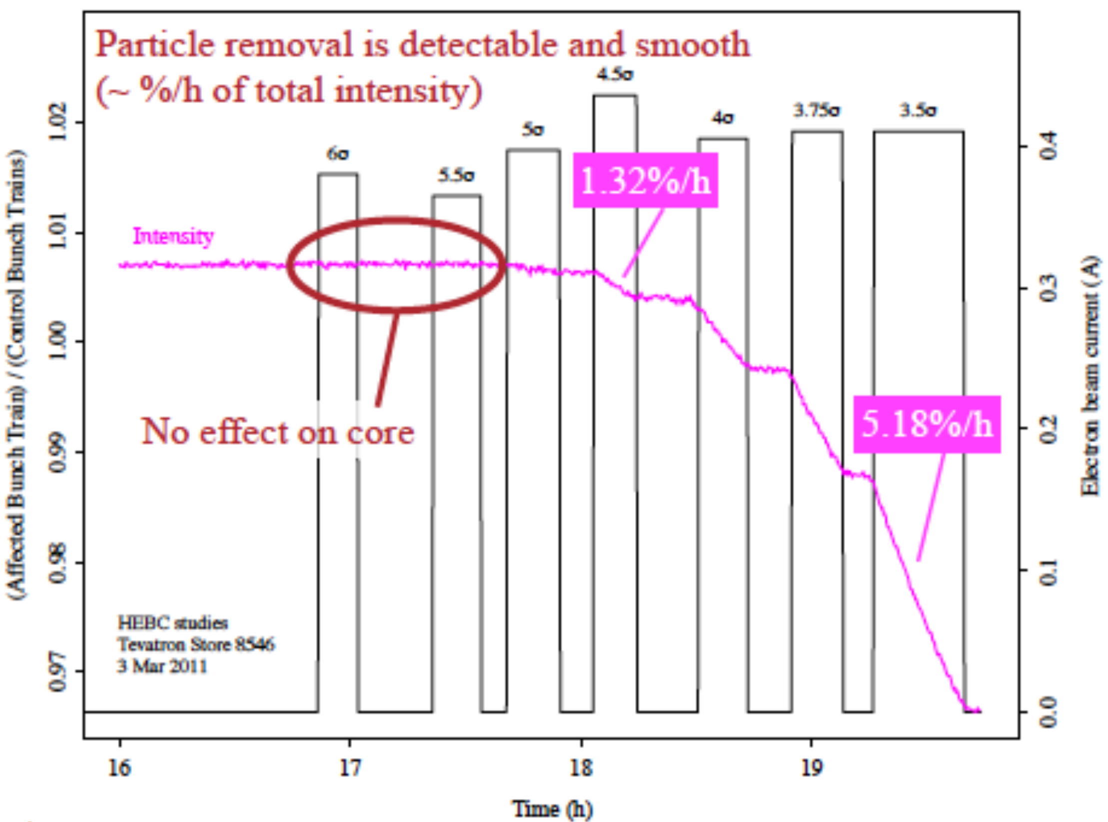
Hollow electron lenses:

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

Can be installed in other points than IR7

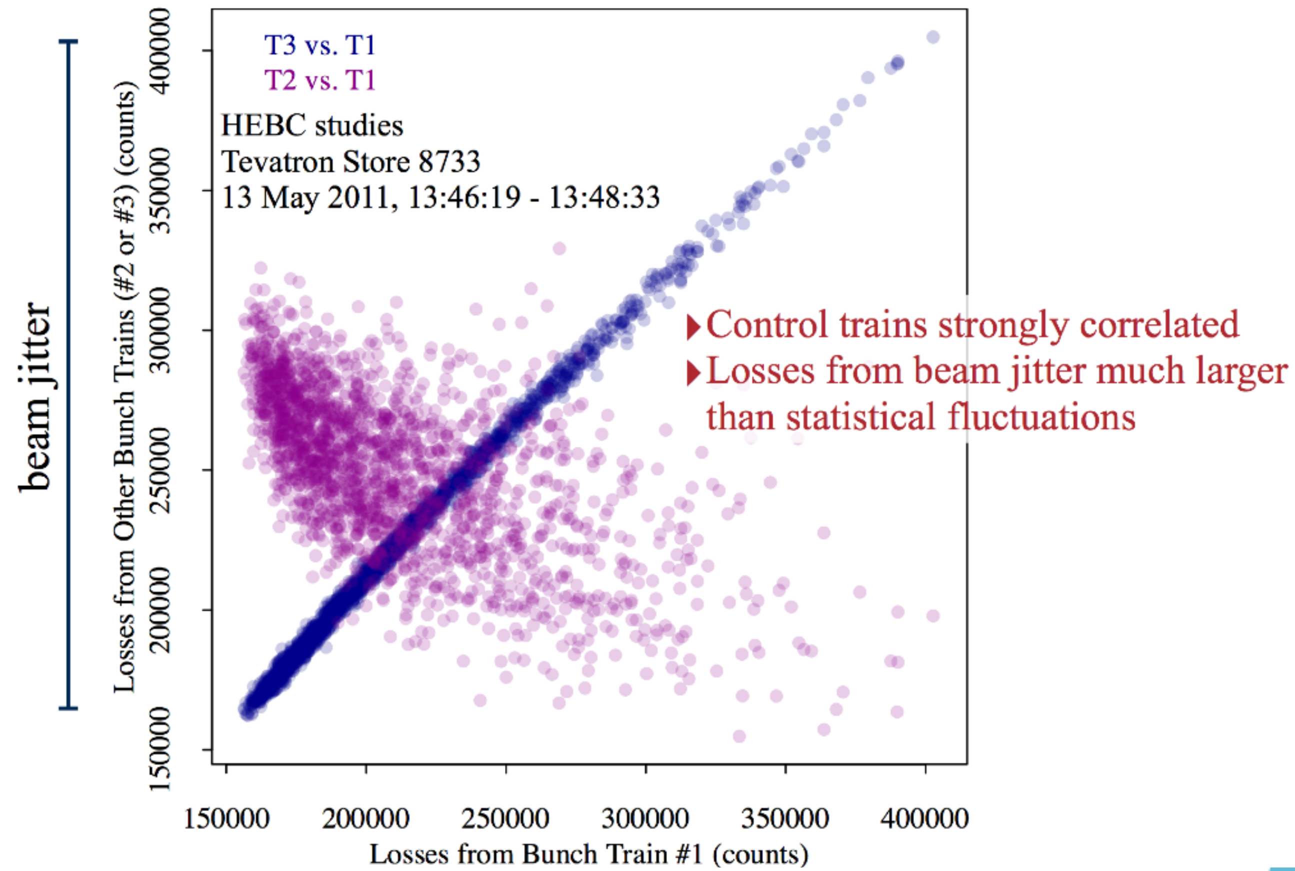
Experience from the Tevatron

Depletion with no effect on beam core



G. Stancari et al.

Removes correlation of losses to orbit jitter

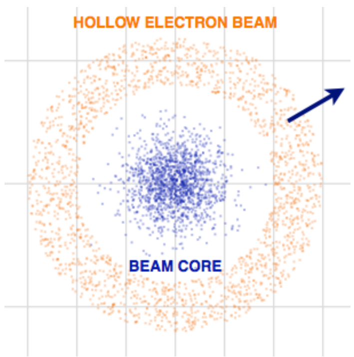


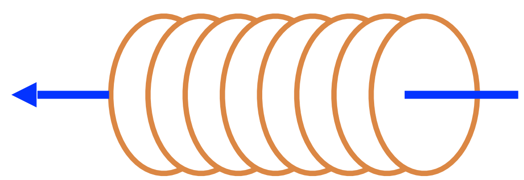
Very convincing results from beam tests at the Tevatron!

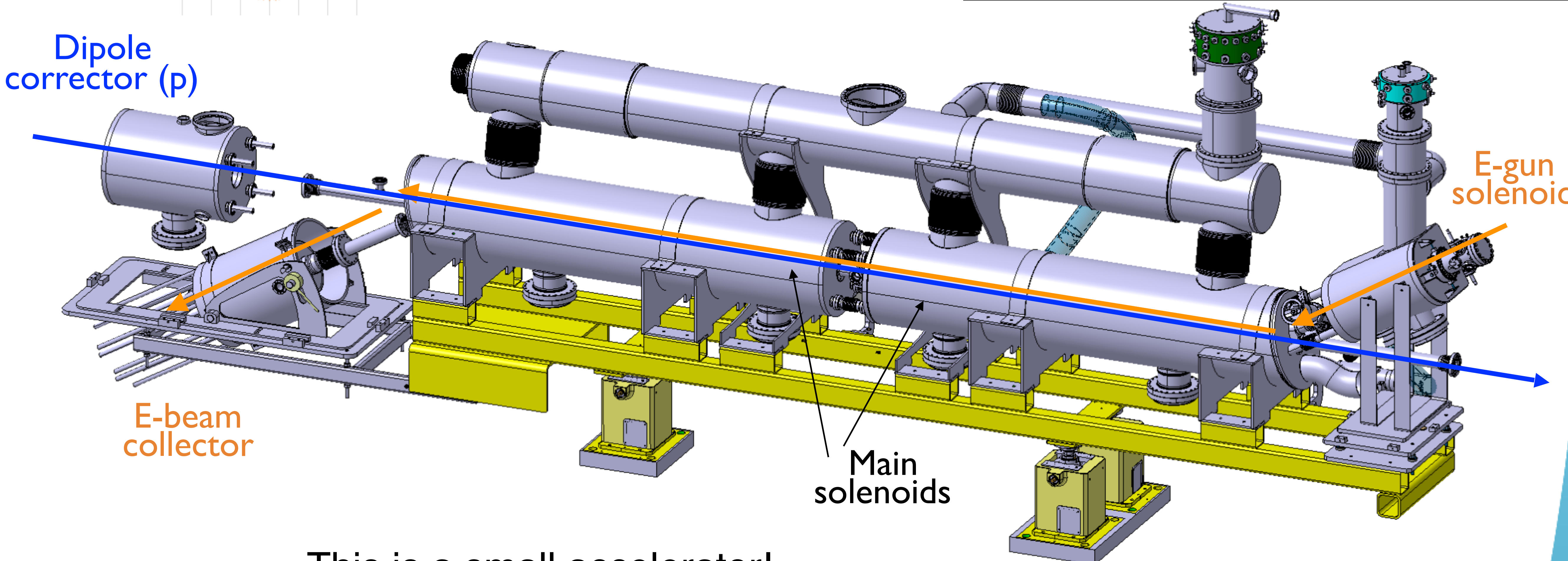
Table of content

The HL-LHC HEL design

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





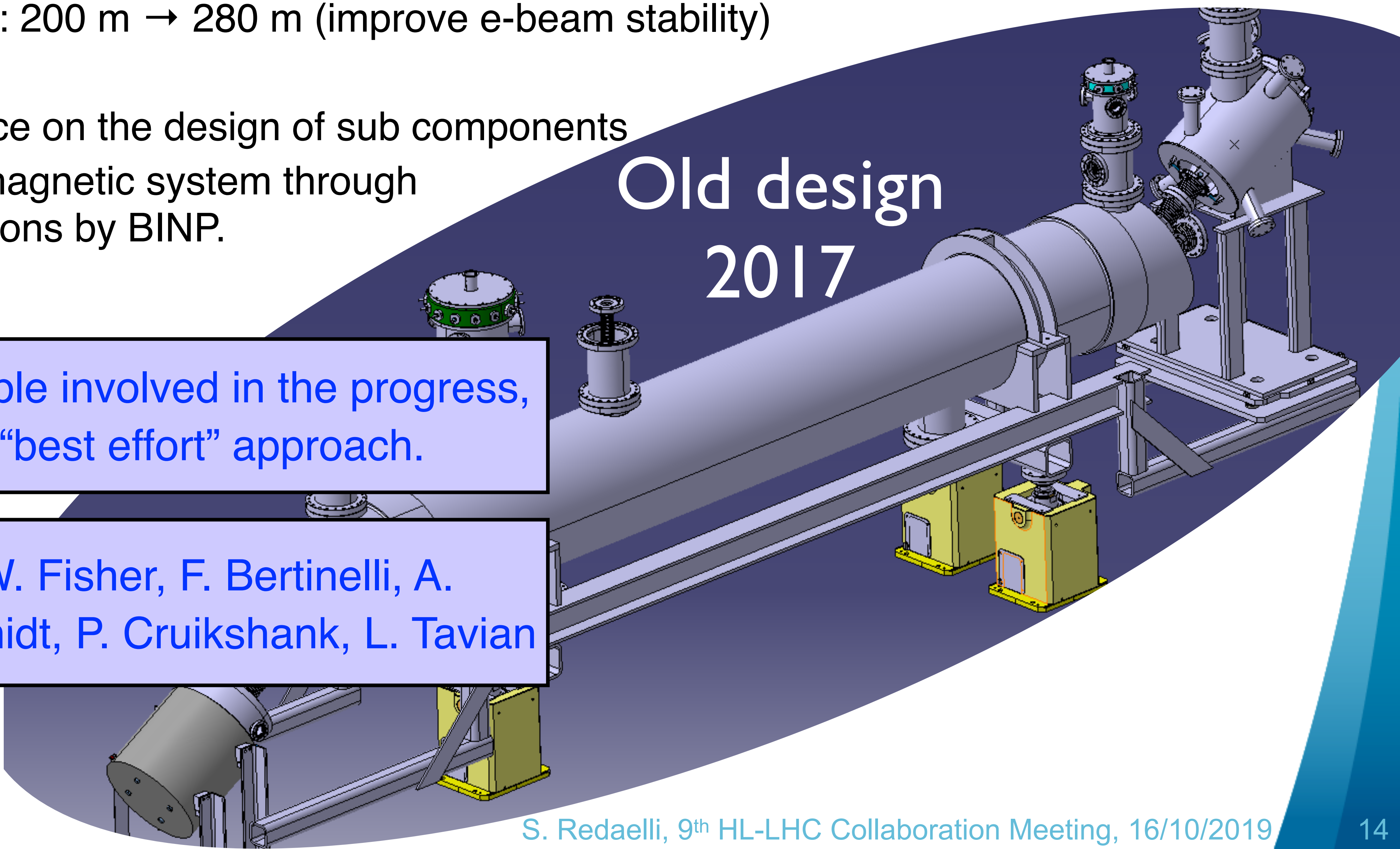


This is a small accelerator!

- Cryogenics and magnetic system;
- Electron gun and collector;
- Electron and proton beam diagnostics; ← Talk yesterday by WP13
- Vacuum system;
- Support and alignment systems.

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 β: 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.



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

Review panel: W. Fisher, F. Bertinelli, A. Yamamoto, R. Schmidt, P. Cruikshank, L. Tavian

Present parameters

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

See talk
D. Mirarchi et al.

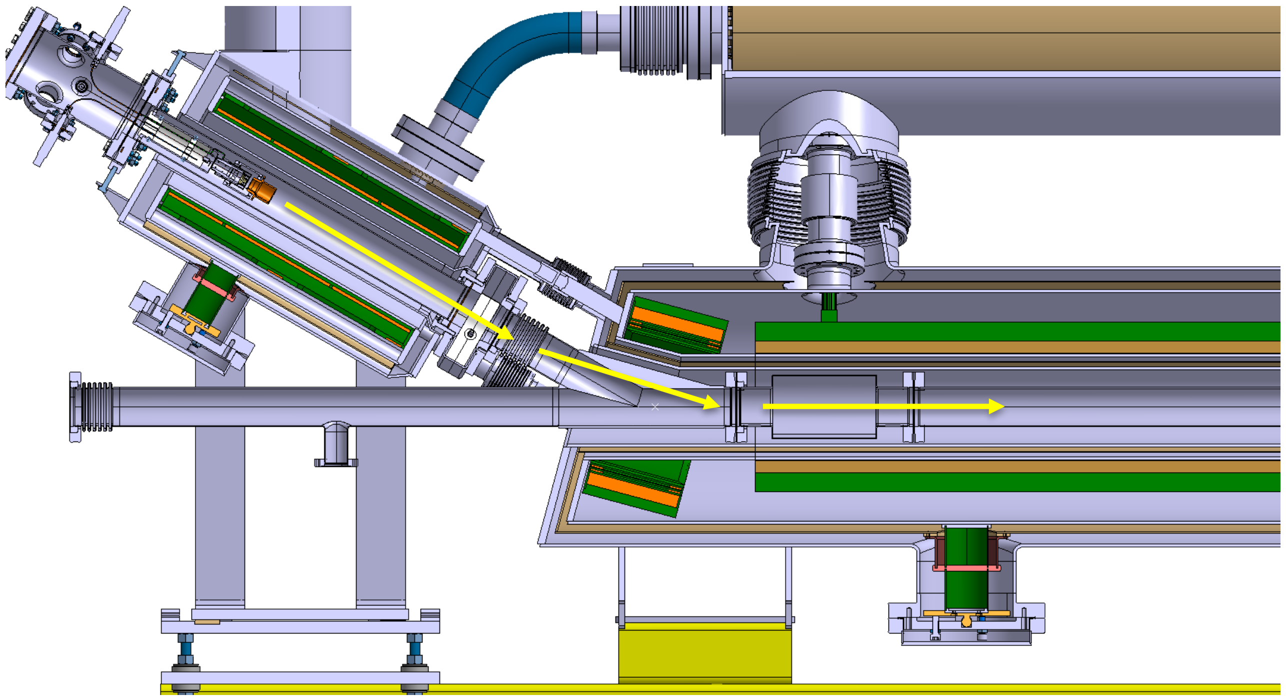
Present parameters

Parameter	Value or range
Proton beam optics at HEL, β [m]	280
Length of interaction, L [m]	3
Desired transverse scraping (> 3.5 σ), r [mm]	1.1 – 2.2 @ 7TeV
Maximum electron beam current, I [A]	5
Cathode diameter, inner/outer [mm]	8 / 16
Gun extraction and modulation voltage [kV]	10
Cathode-ground voltage [kV]	15
Collector bias (decelerating) voltage [kV]	in study
Modulator rise time [ns]	200
Modulator repetition rate [kHz]	35
Magnetic field at gun [T]	
Magnetic field at bend [T]	
Magnetic field at main [T]	

— 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.

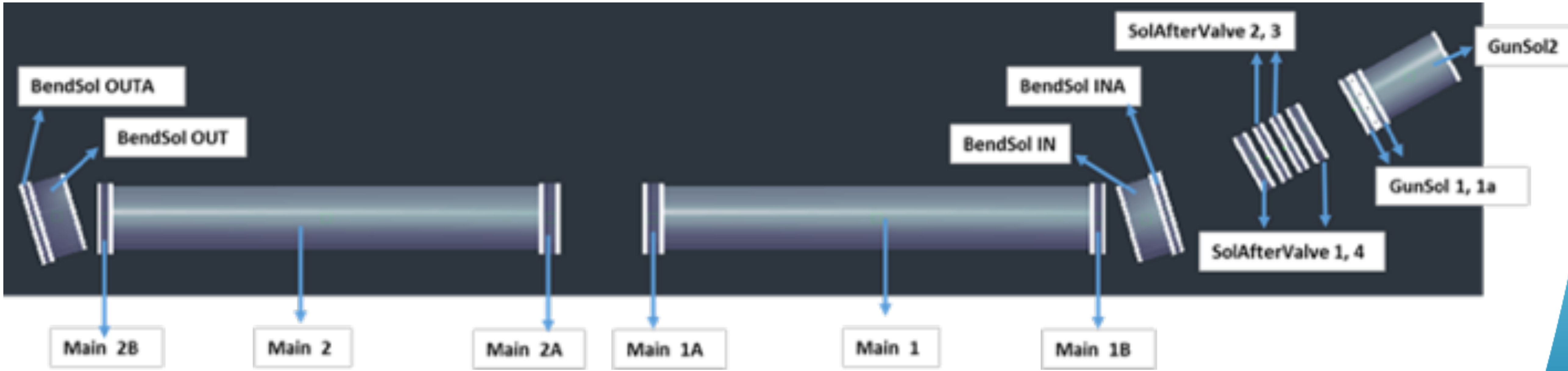
See talk D. Mirarchi et al.

Component design: magnetic system



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

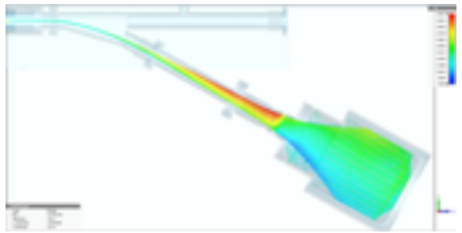
On-going optimisation of the e-beam correctors based on simulations at BINP. Planned an internal technical review at the end of Nov. (visit by Giulio at CERN).

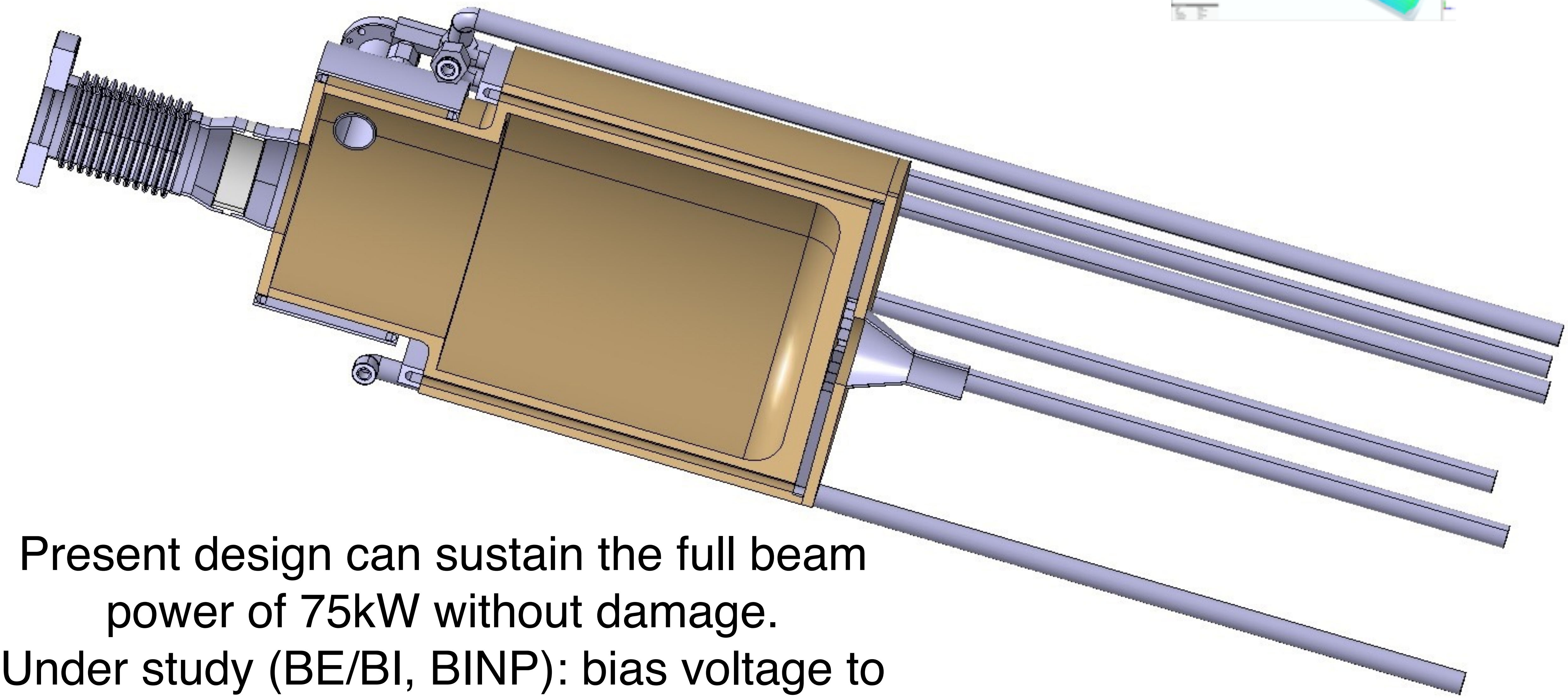


Thanks: G. Kirby et al.

EDMS 2036694

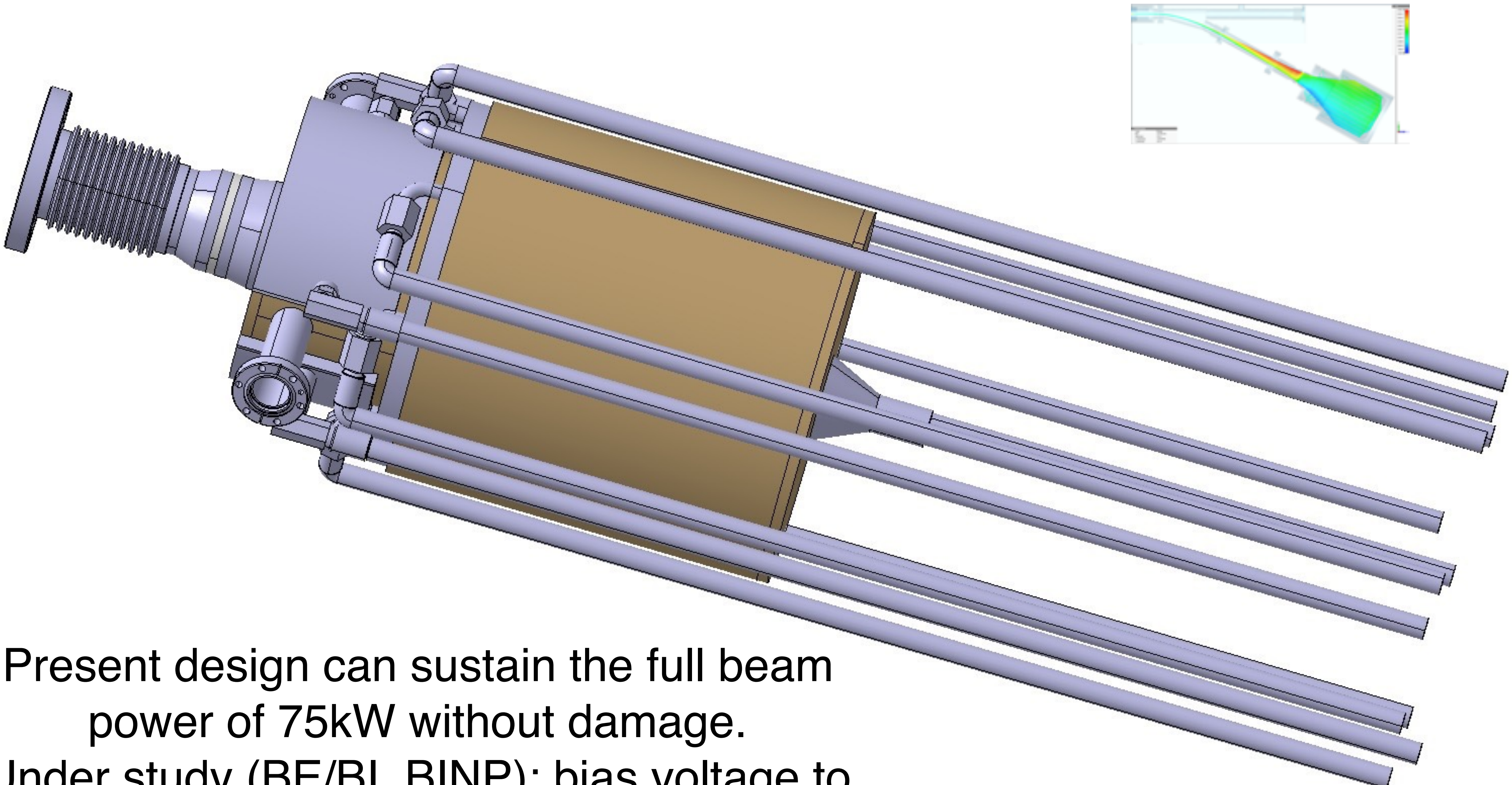
Component design: electron collector





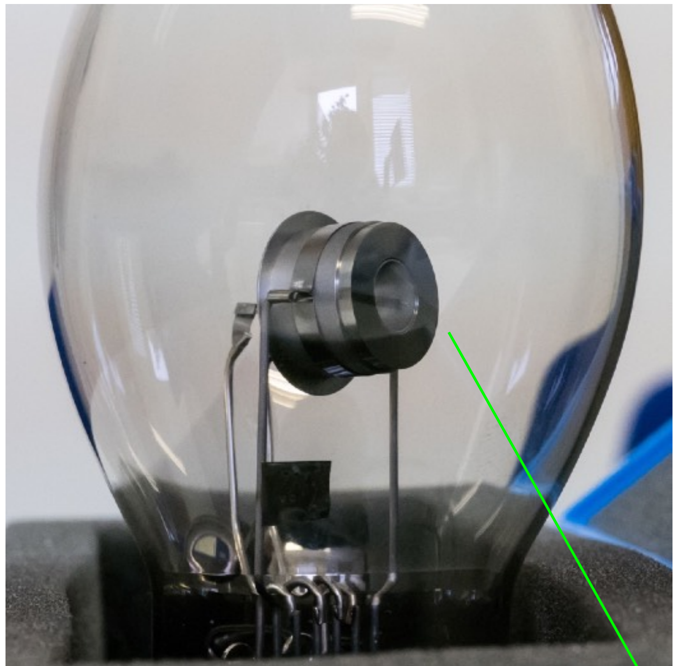
Present design can sustain the full beam power of 75kW without damage.
Under study (BE/BI, BINP): bias voltage to reduce loads, for a possible simplification.

Component design: electron collector



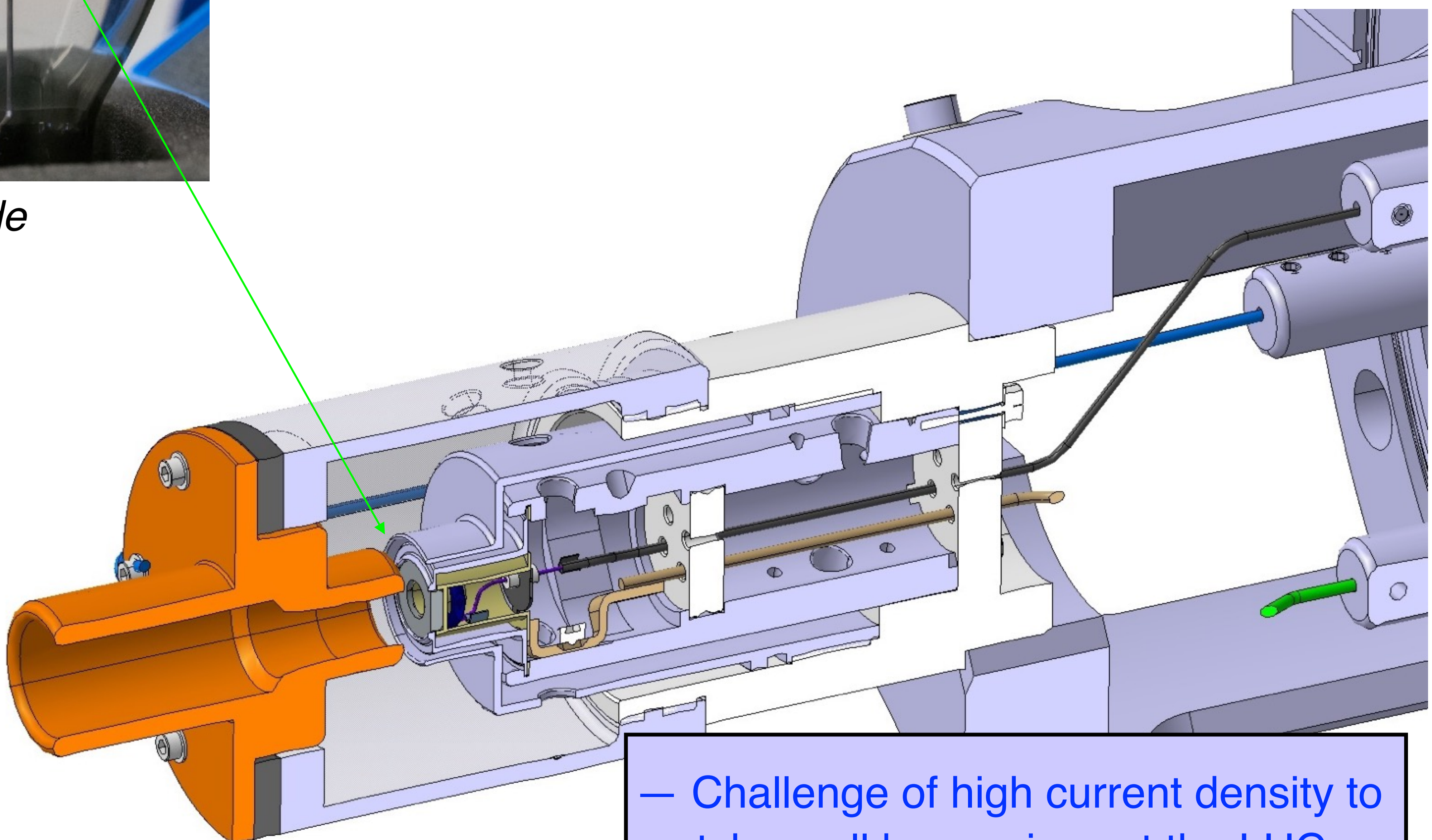
Present design can sustain the full beam power of 75kW without damage.
Under study (BE/BI, BINP): bias voltage to reduce loads, for a possible simplification.

Component design: gun and cathode



Cathode

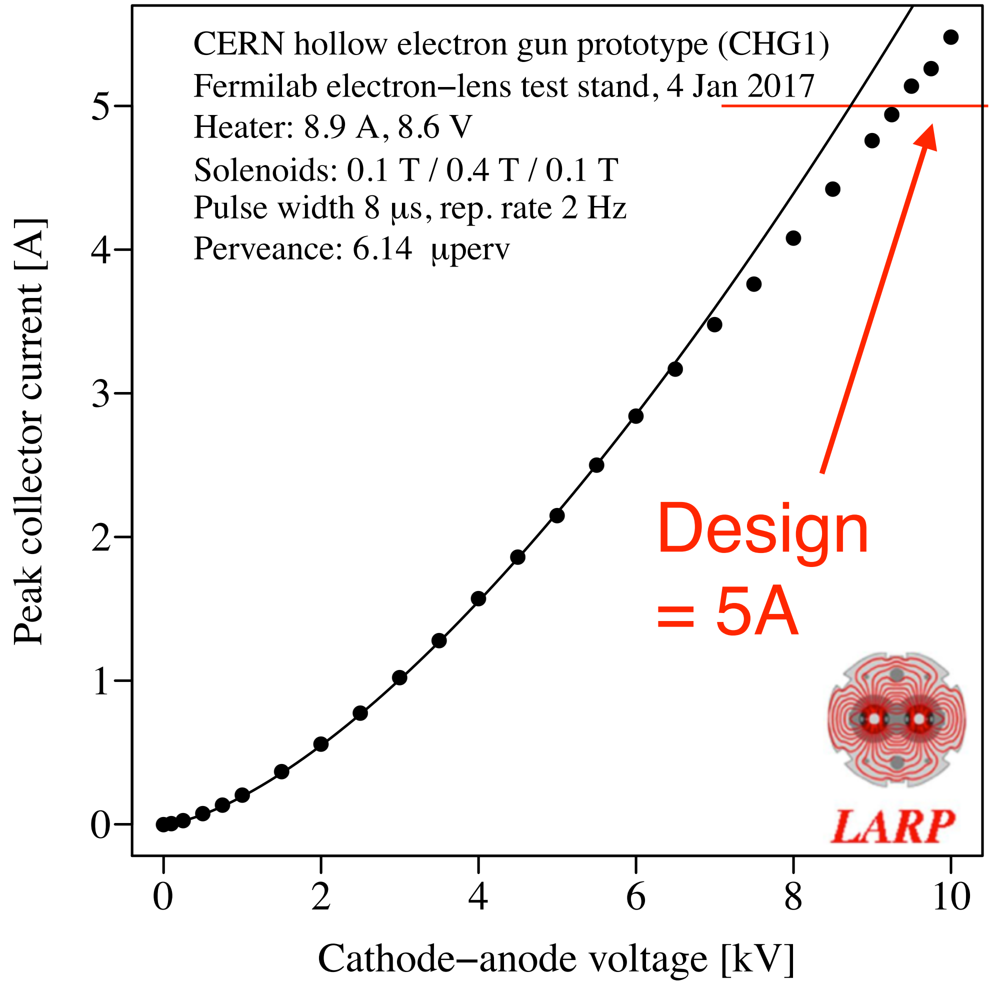
Rich program in the last 5 years, in collaboration with FNAL (e-beam test facility), and China → new, high-current cathode with inner radius of 8 mm.

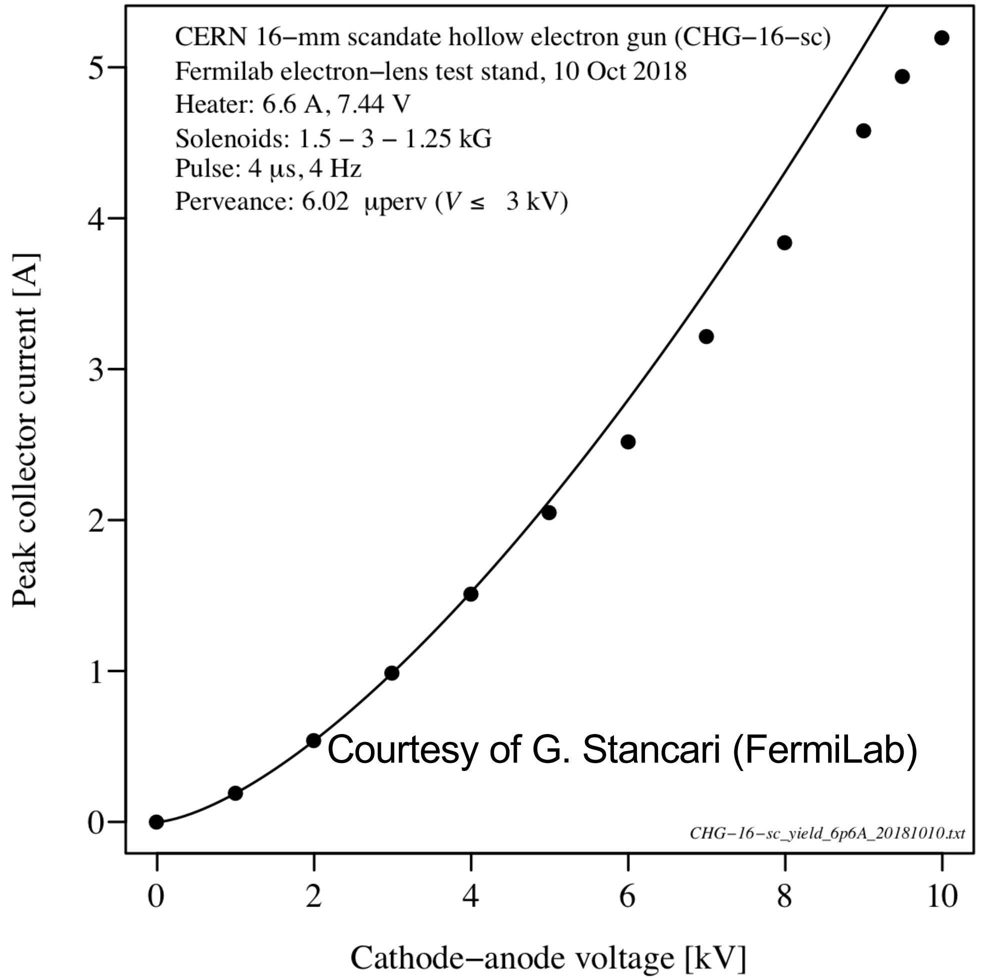


— Challenge of high current density to match small beam sizes at the LHC.

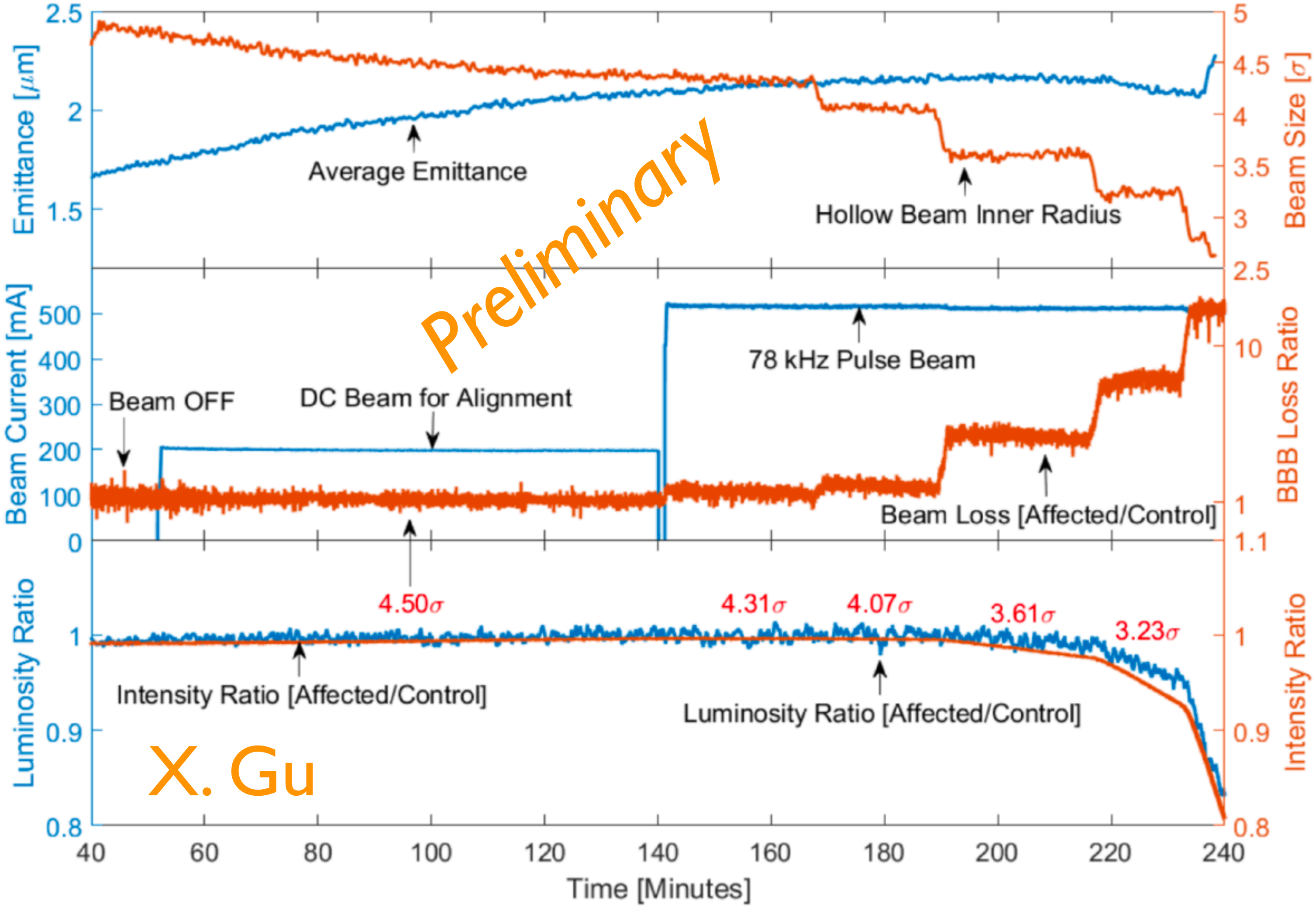
Results of gun/cathode development

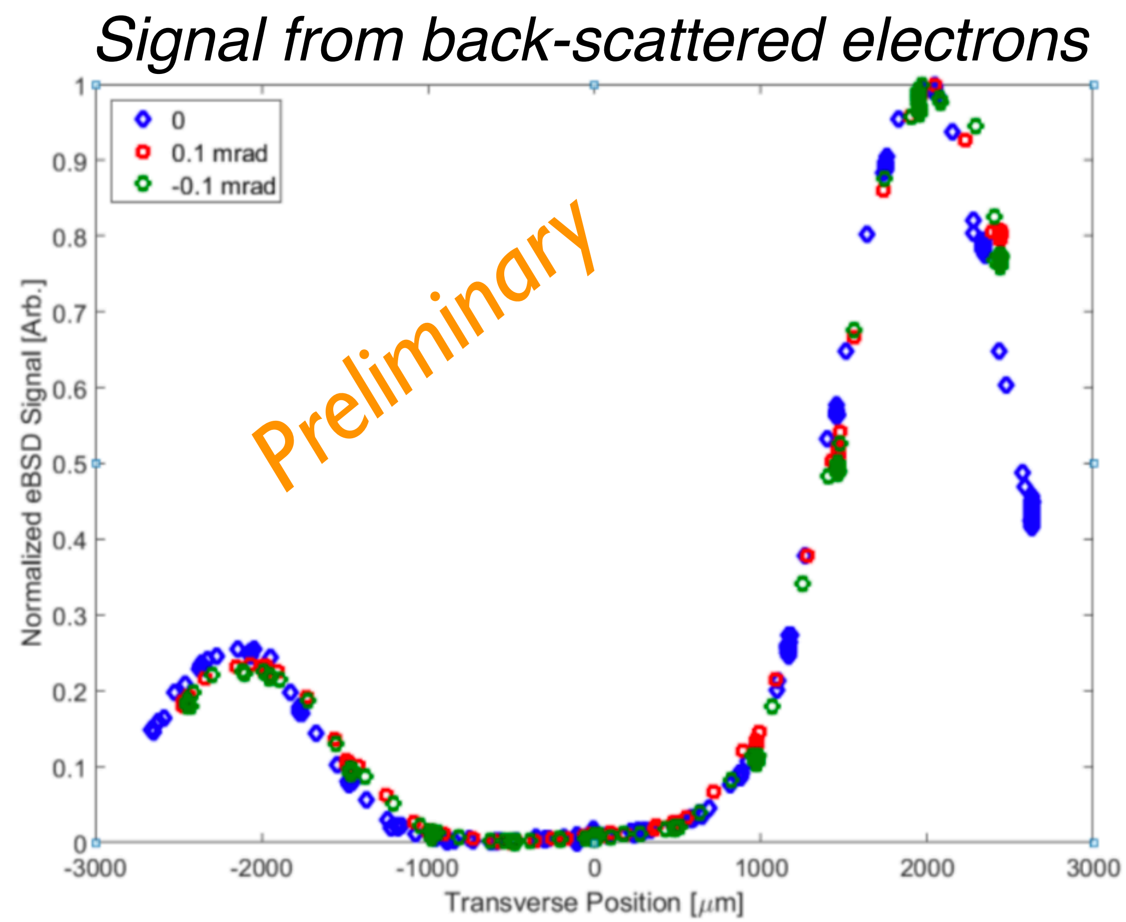
<u>2015-2016</u>
— CERN acquiring know-how on LHC cathode/gun design from FNAL (1" cathode used in Tevatron)
— Record current >5A with first CERN-built gun
<u>2016-17</u>
— New LHC design with smaller, high-current cathode (collaboration with China)
<u>Oct. 2018</u>
— >5 A with first small cathode and old, bigger gun
<u>2019 (final design)</u>: Smaller gun optimised for new cathode
— Presently under test at FNAL and CERN.
Issue of short being investigated.





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.

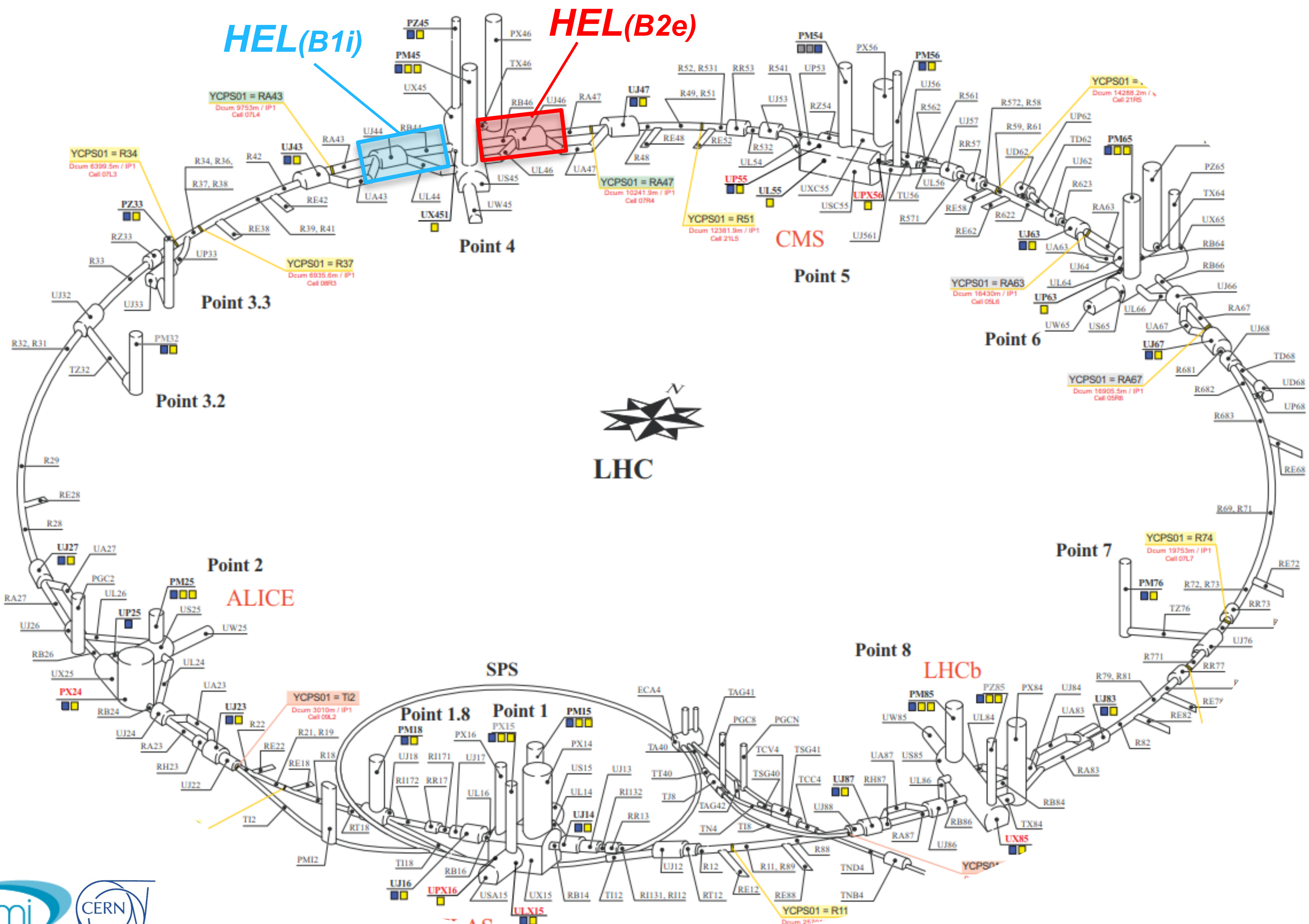
— First set of measurements with various excitation types.

— Analysis ongoing for an upcoming publication.

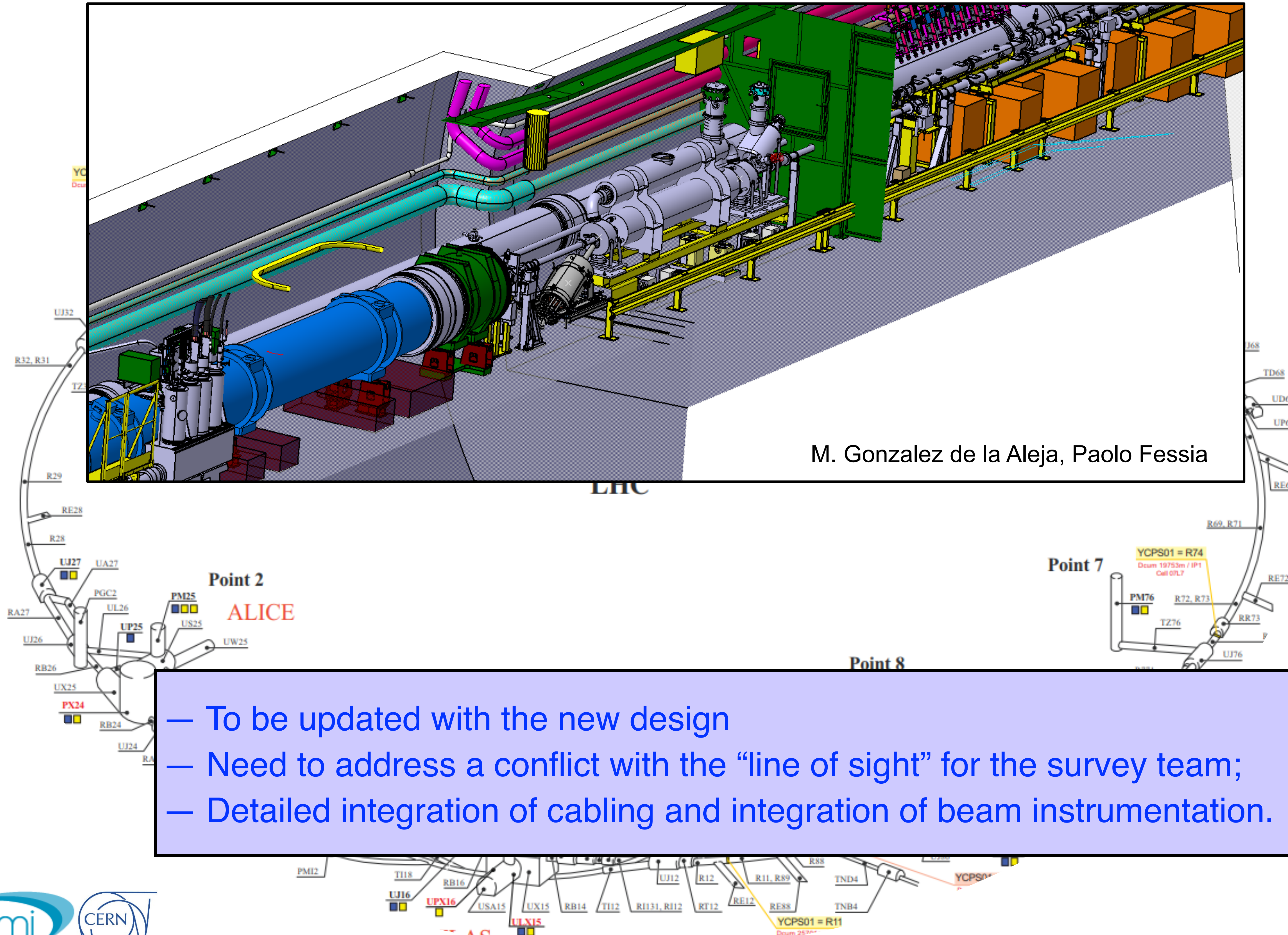
A big thank to Wolfram and Xiaofeng who made this possible!

Visits from CERN team: <u>excellent opportunity</u> for cross-fertilisation and to get experience!

Integration in the HL-LHC



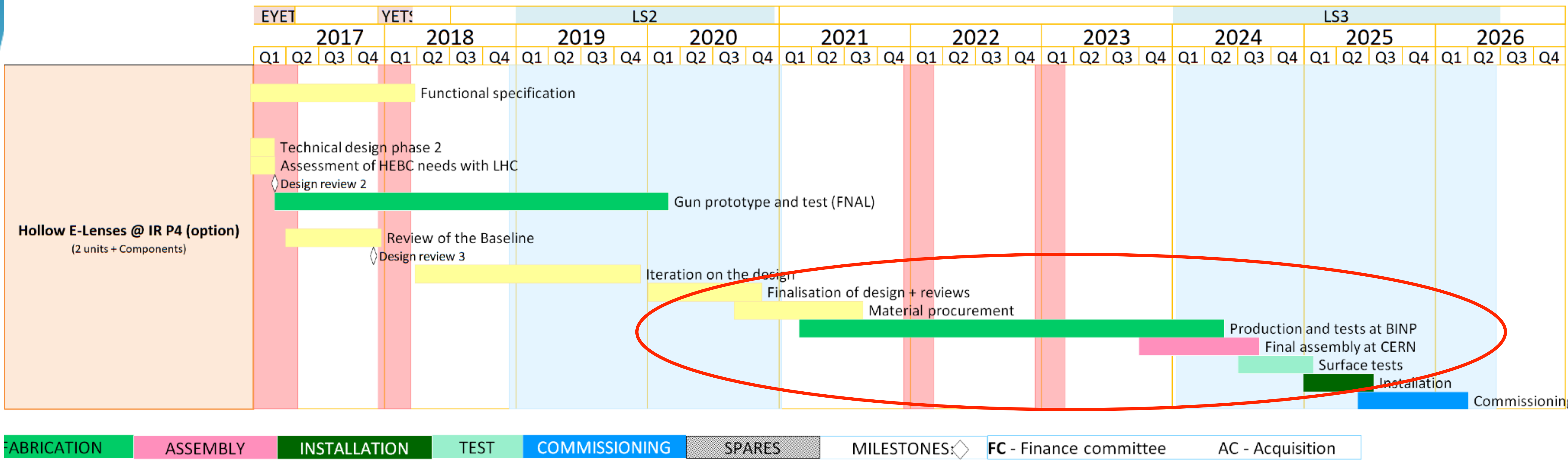
Integration in the HL-LHC



M. Gonzalez de la Aleja, Paolo Fessia

- 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.

Schedule



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”

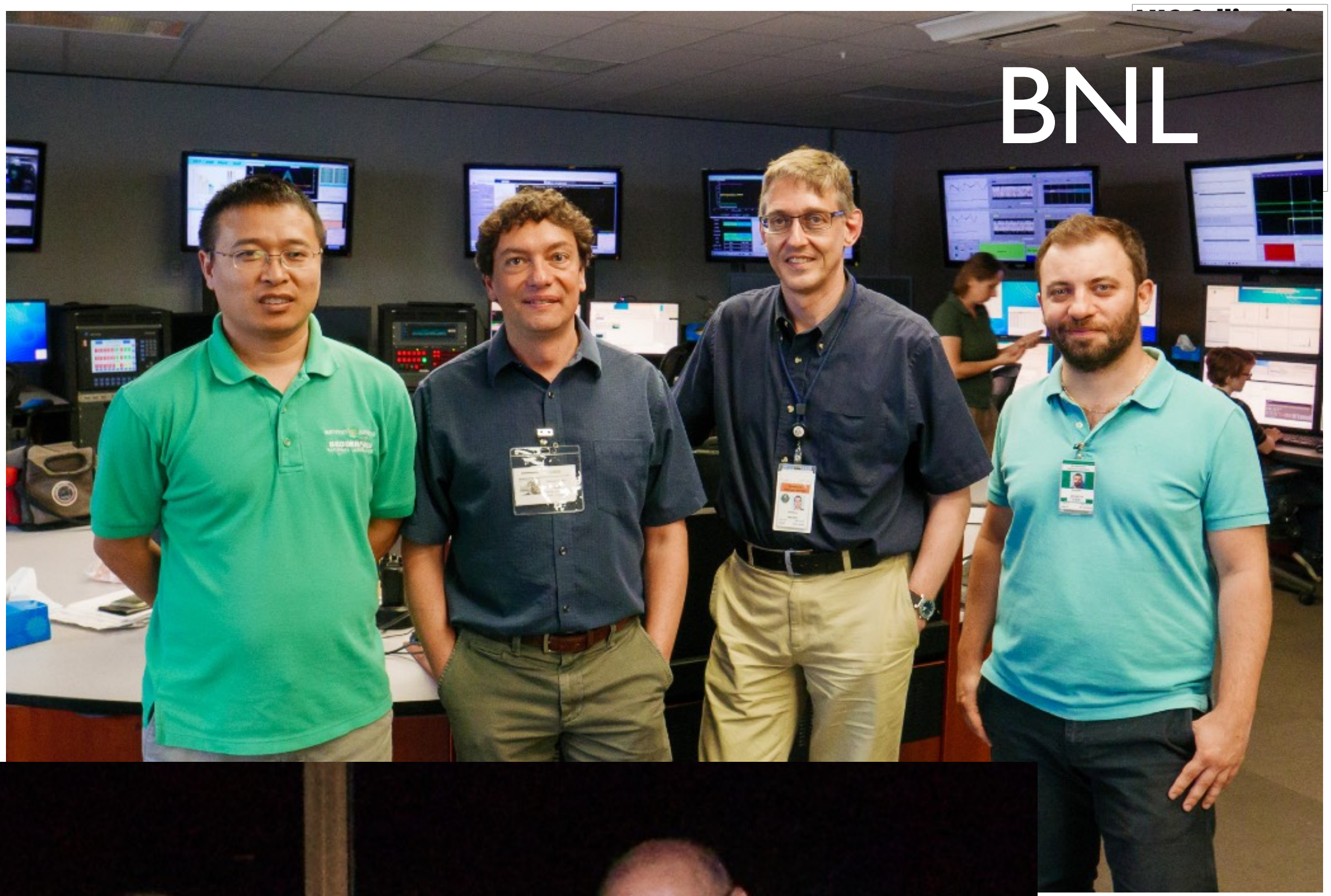
- Some delays accumulated: people leaving + time to pass the design to BINP.

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!

CERN

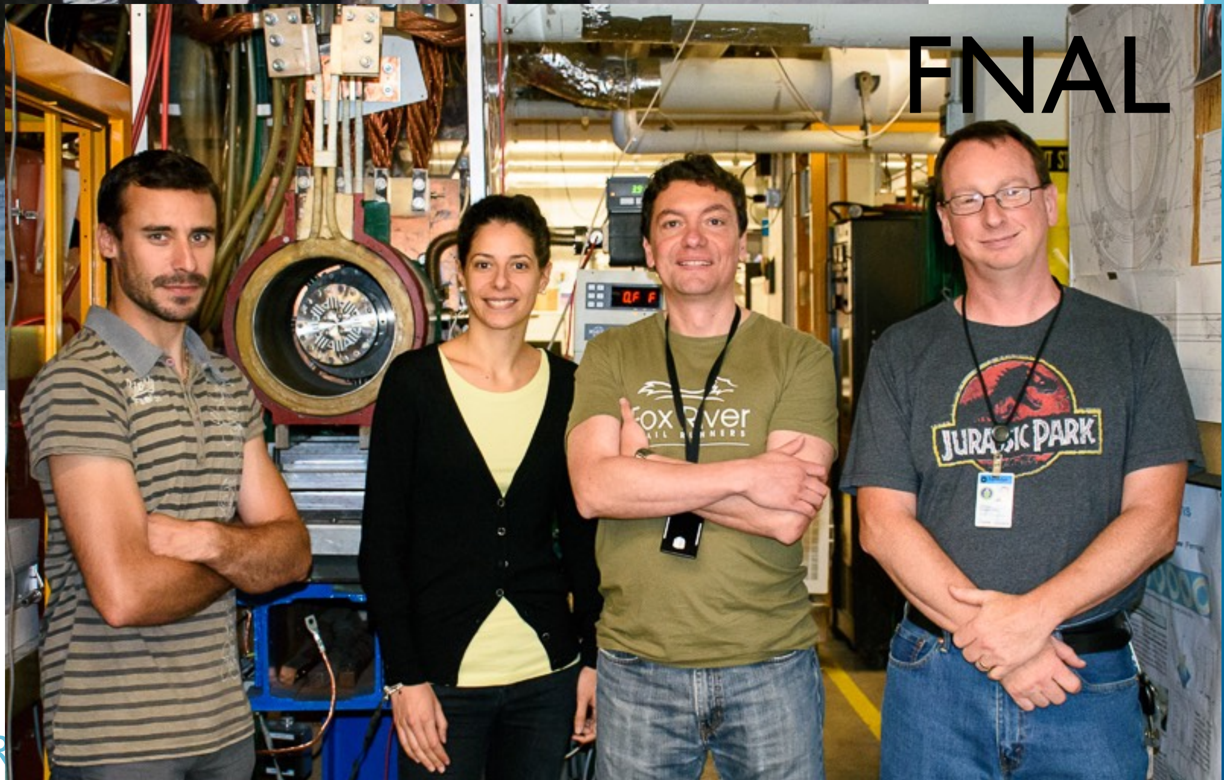
BNL



Chicago

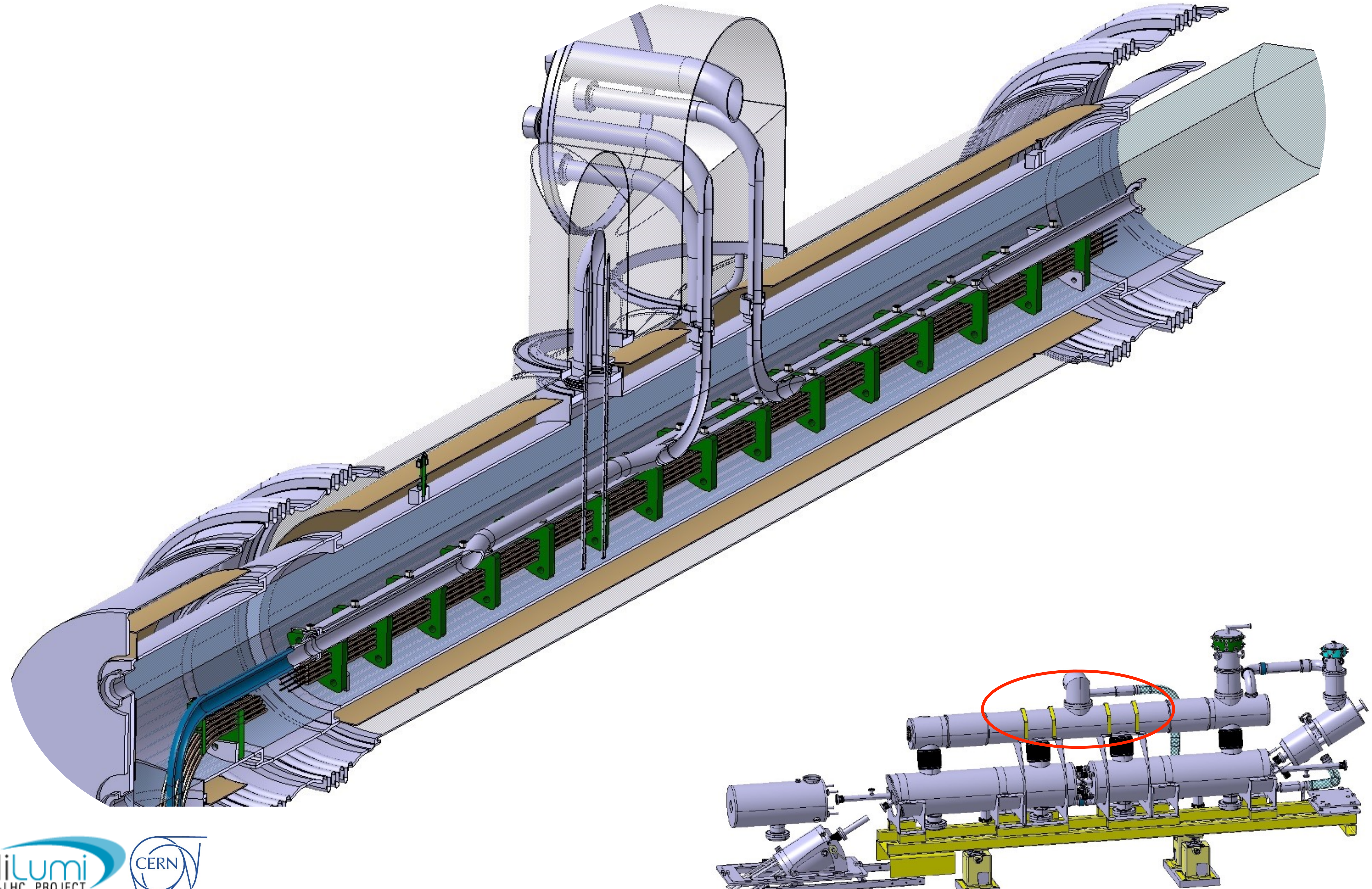
CERN

FNAL

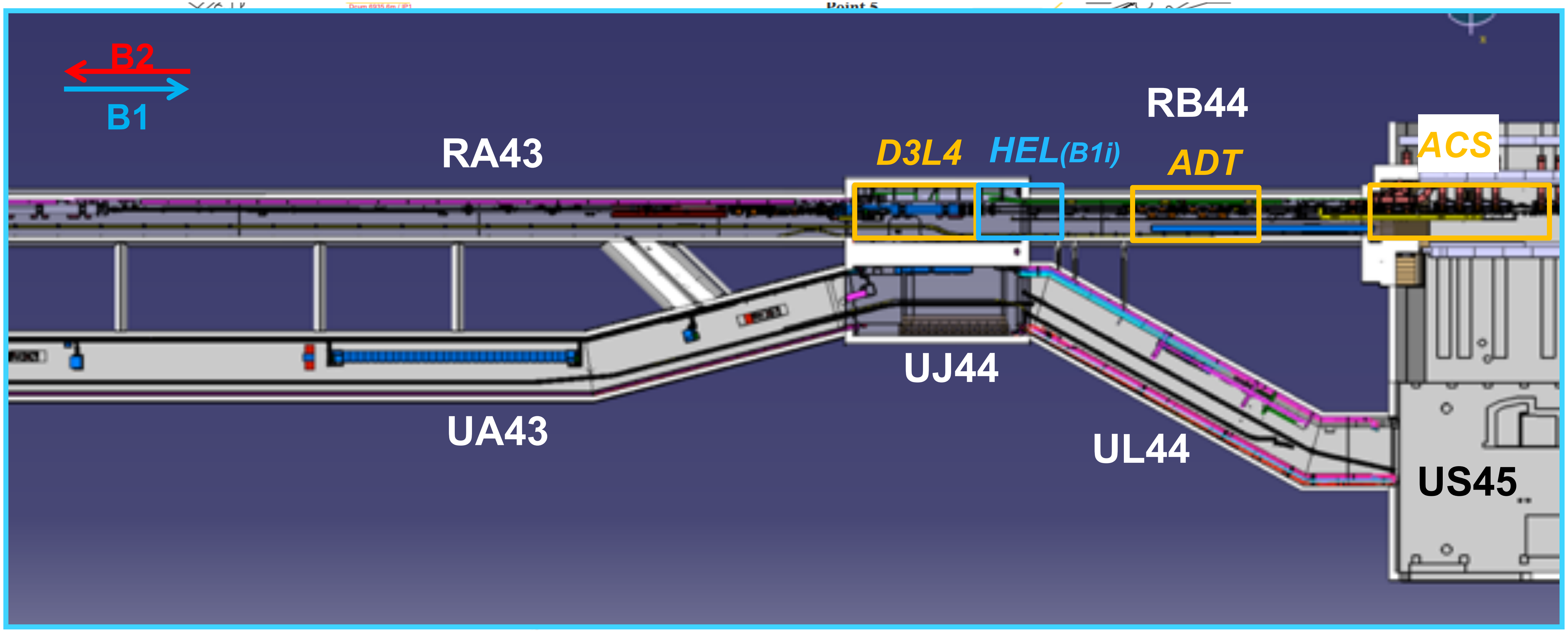


Reserve slides

Component design: cryogenics



HEL location around the ring

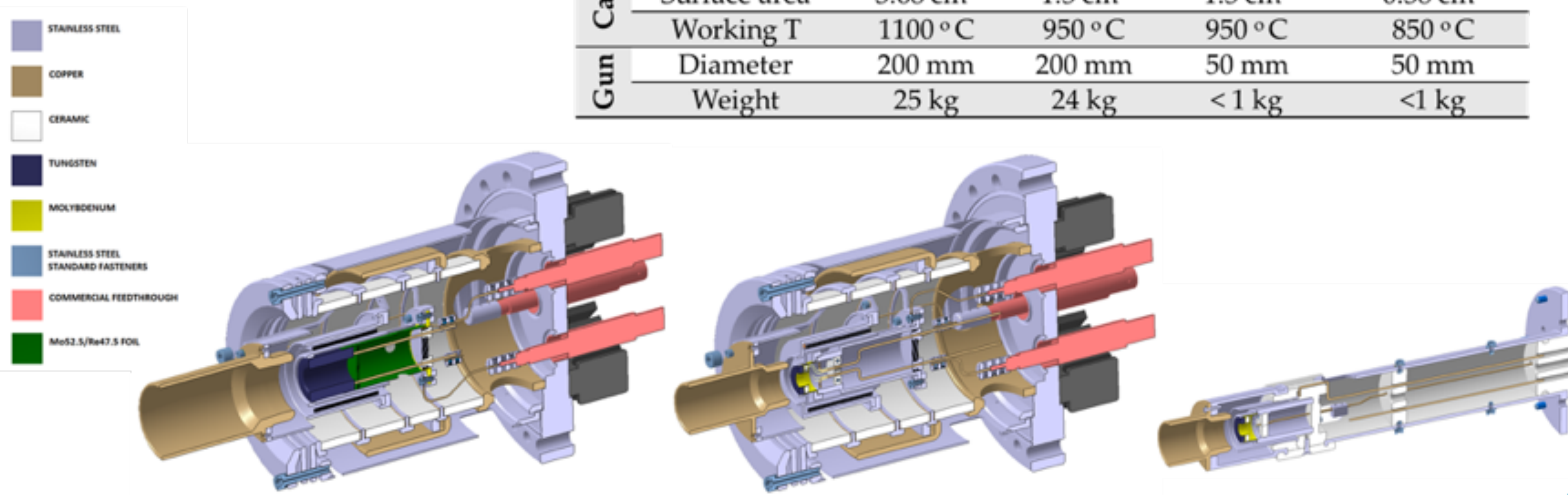


M. Gonzalez de la Aleja, Paolo Fessia

HL-LHC cathodes — i

Aim
→ cathode that provides high emission, working at temperature as low as possible

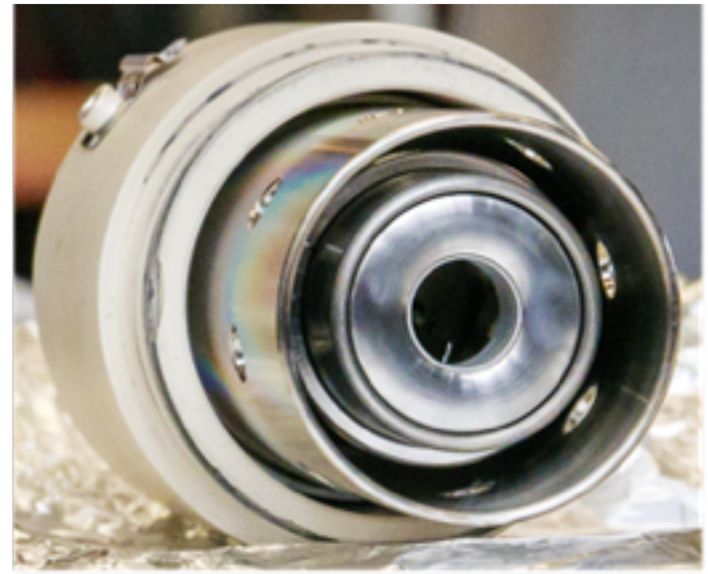
		Phase 1	Phase 2	Phase 3	Phase 4
Cathode type →		Ba-W impregnated	Impregnated scandate		Scandia doped dispenser
Cathode	Inner diameter	12.5 mm	8.05 mm	8.05 mm	4 mm
	Outer diameter	25 mm	16.1 mm	16.1 mm	8 mm
	Surface area	3.68 cm^2	1.5 cm^2	1.5 cm^2	0.38 cm^2
	Working T	1100 °C	950 °C	950 °C	850 °C
Gun	Diameter	200 mm	200 mm	50 mm	50 mm
	Weight	25 kg	24 kg	< 1 kg	<1 kg

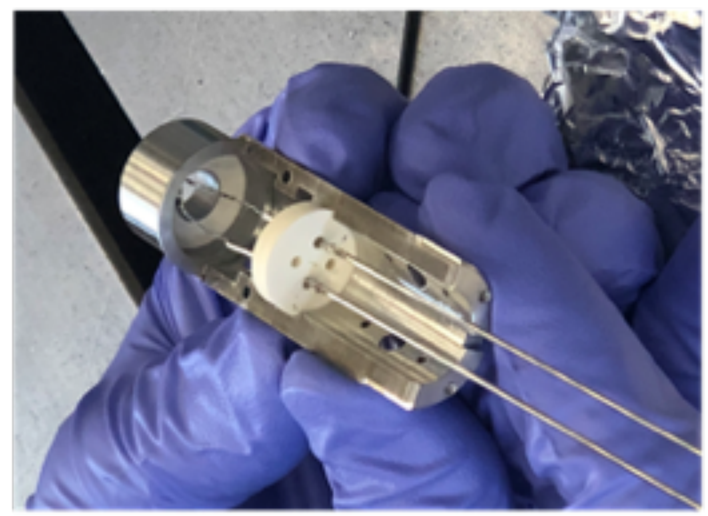


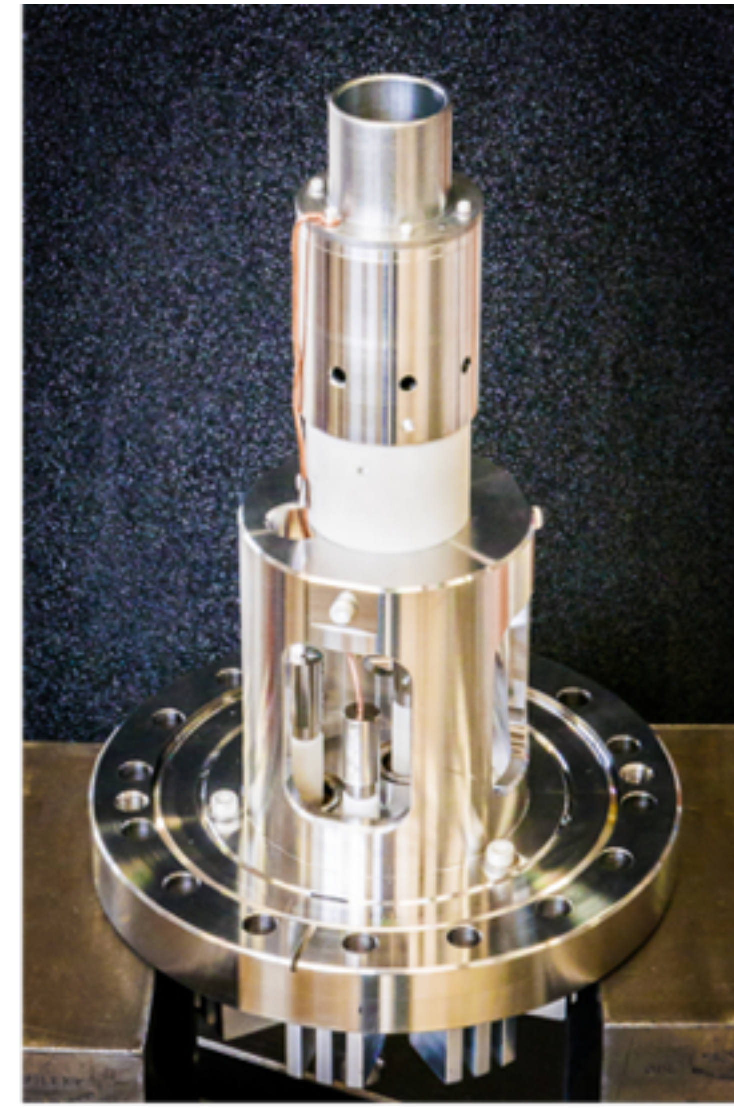
HL-LHC cathodes — ii

HEL cathode nominal dimensions	
Outer diameter	16.1 mm
Inner diameter	8.05 mm
Lifetime	≥ 7000 h

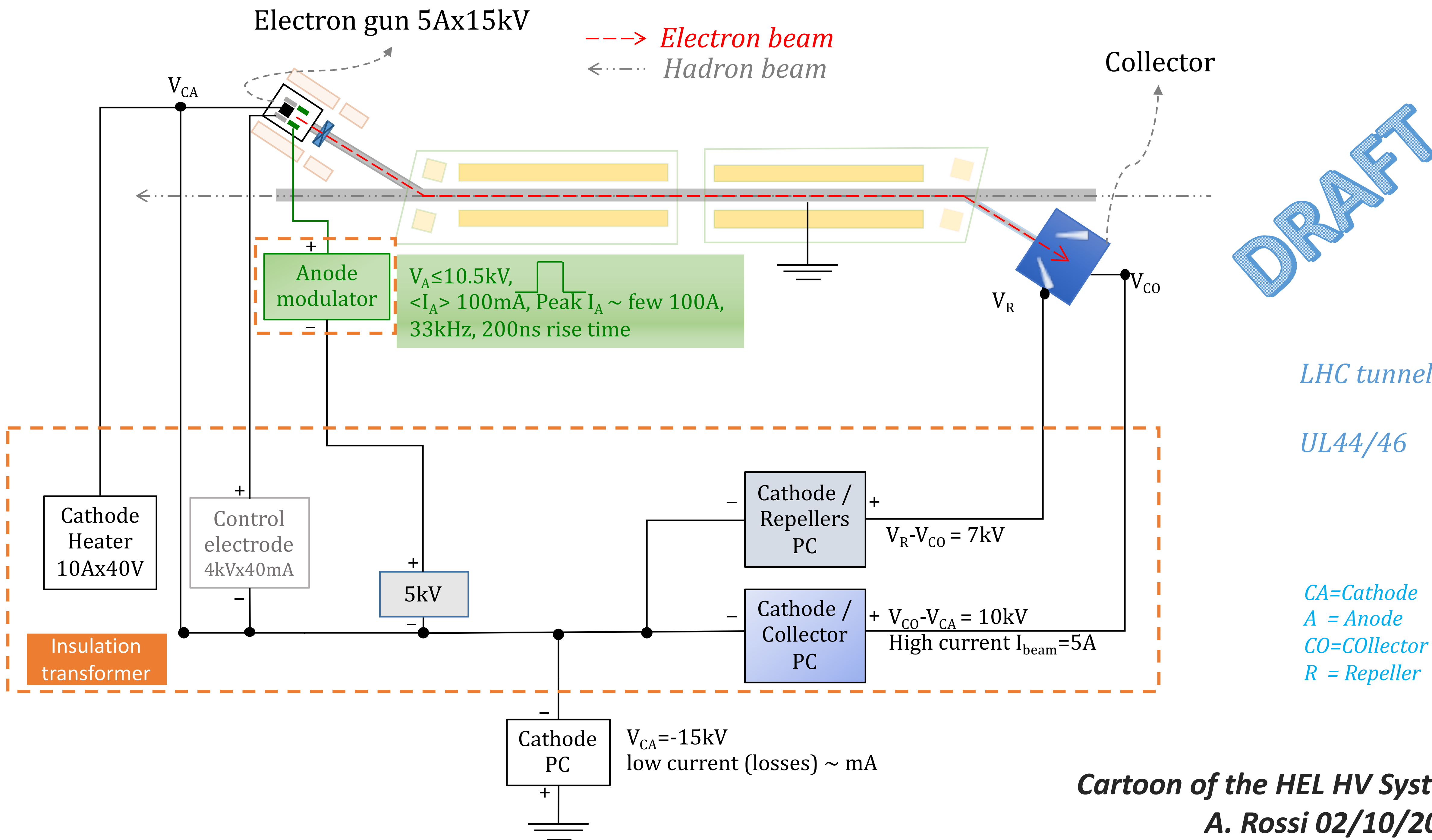
- The cathode and all the electrodes are mounted on a support made in aluminium nitride ceramic Shapal™ → good thermal conductivity
- The electron gun fits in a 60 mm diameter vacuum chamber







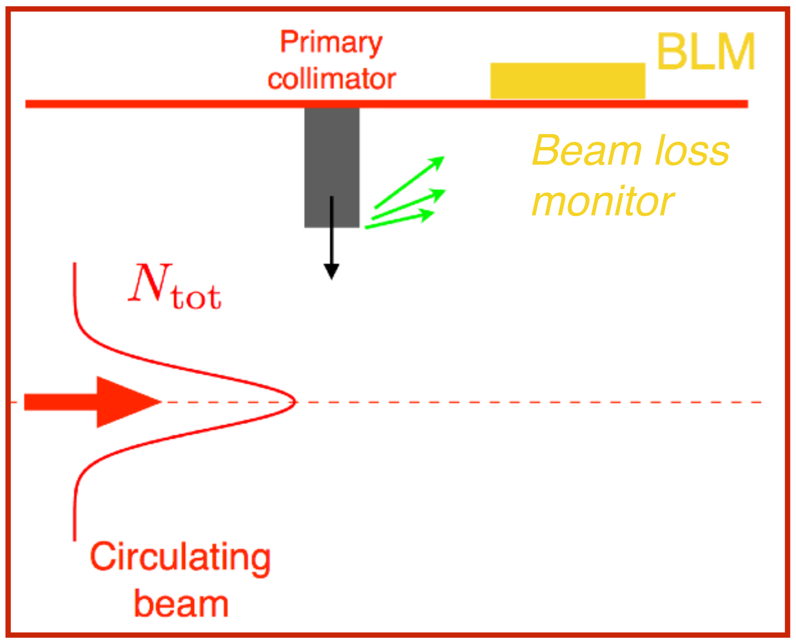
Draft HV schematics



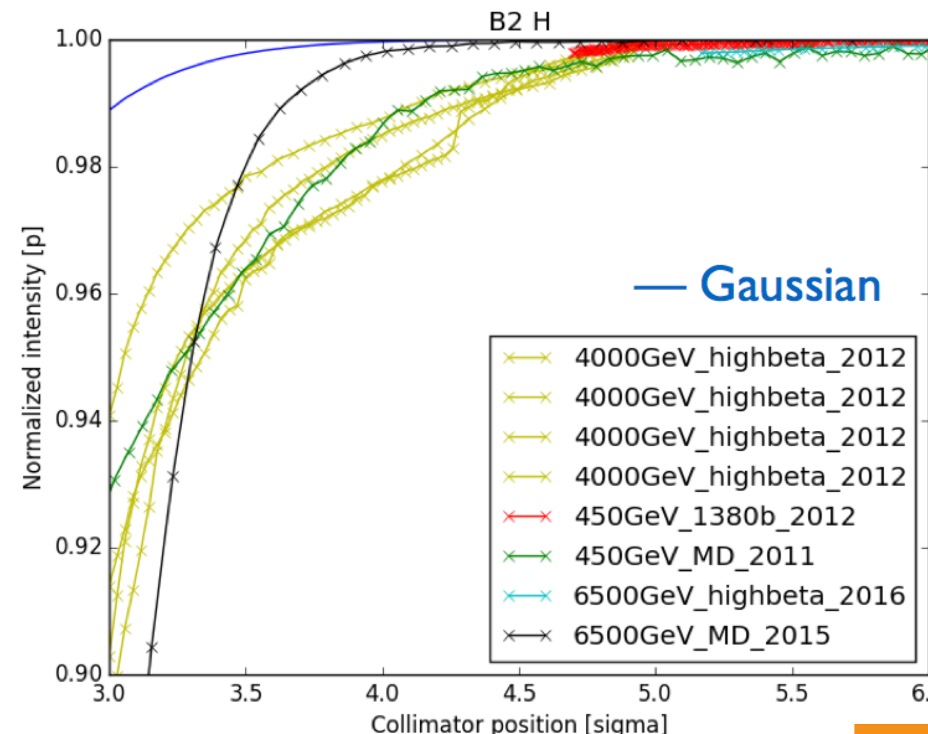
Cartoon of the HEL HV System
A. Rossi 02/10/2019

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.



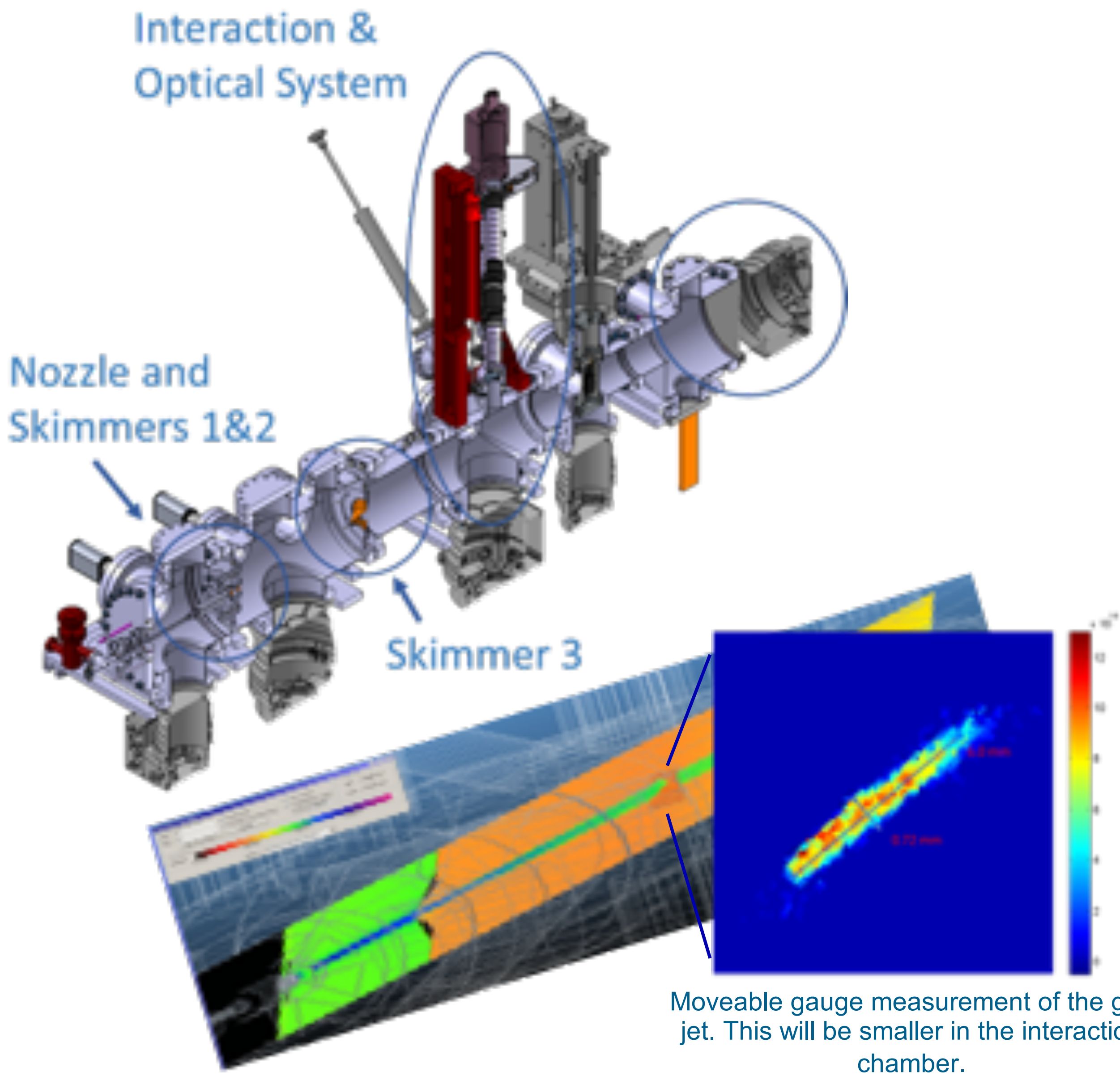
G. Valentino

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

Beam gas curtain monitor

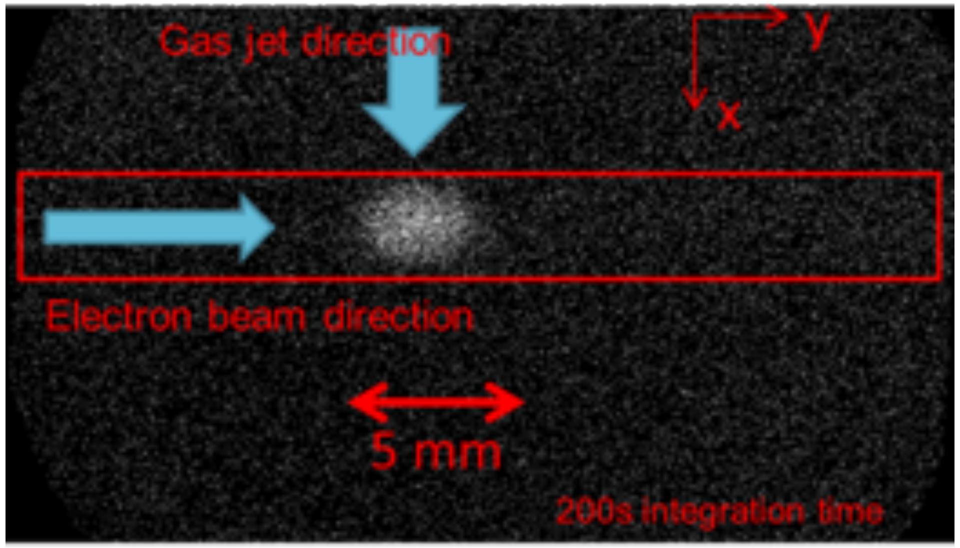


Moveable gauge measurement of the gas jet. This will be smaller in the interaction chamber.

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

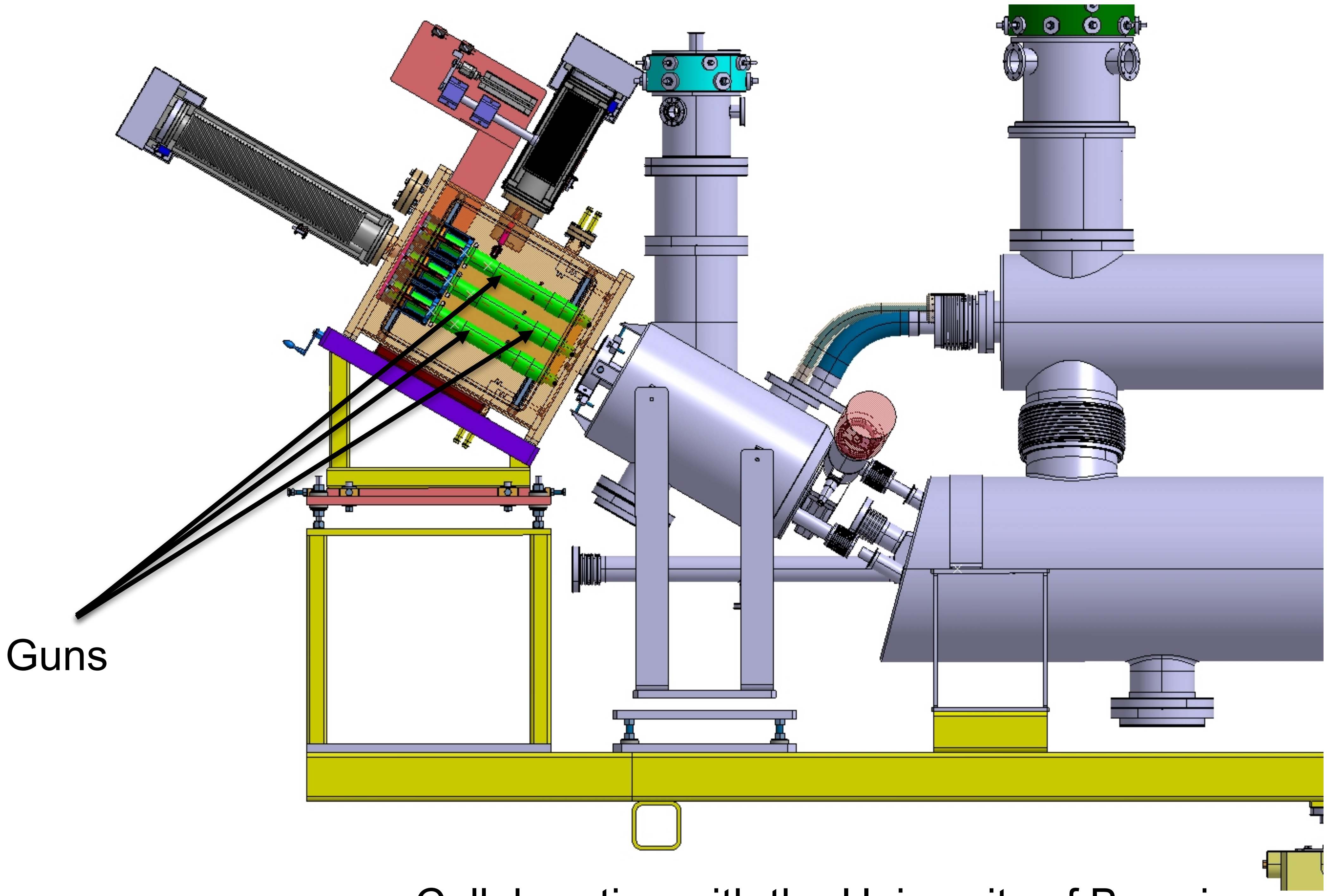
- Beam-Gas Fluorescence on target gas curtain
- Looking at Ne and Ar as gas
- Prototype to be installed in LHC

Nitrogen gas jet test



- Final design scaled to fit

“Crazy” idea of multiple guns



Collaboration with the University of Brescia