Hollow Electron-Lens Assisted Collimation and Plans for the LHC

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Outline

I. LHC Collimation and HEL for HL-LHC?

II. Fermilab experience

III. Brookhaven experience

IV. LHC plans

V. Conclusions

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I. **LHC Collimation and HEL for HL-LHC?**

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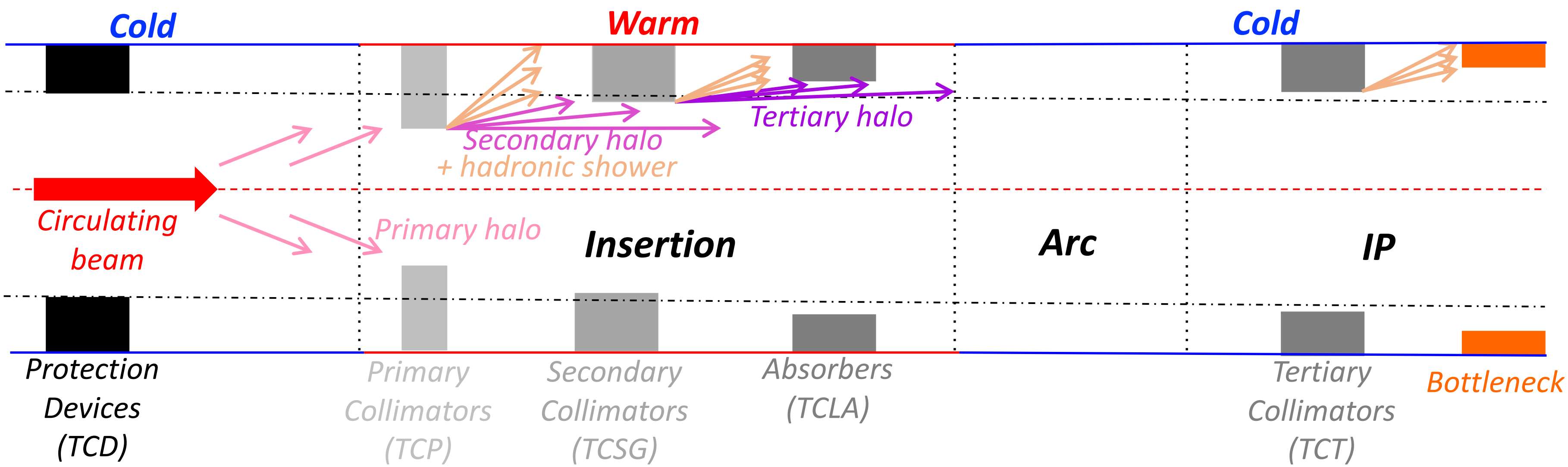
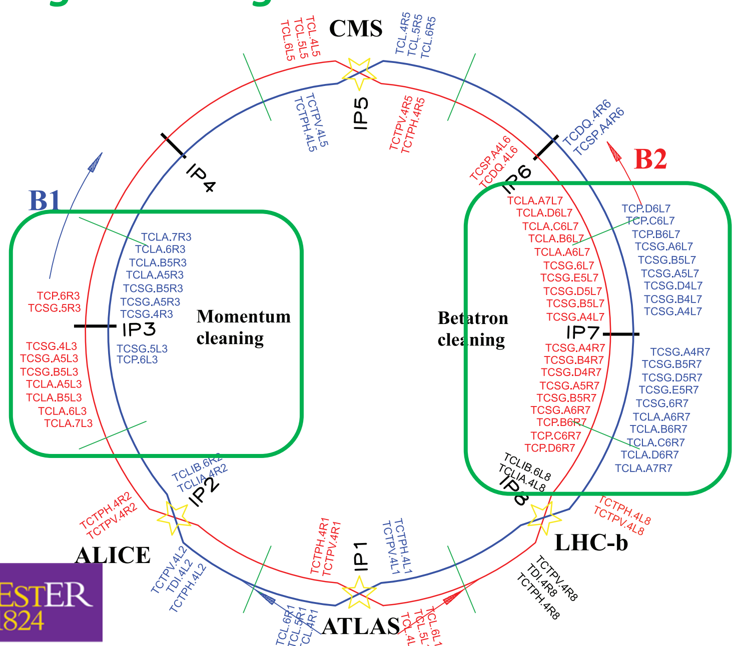
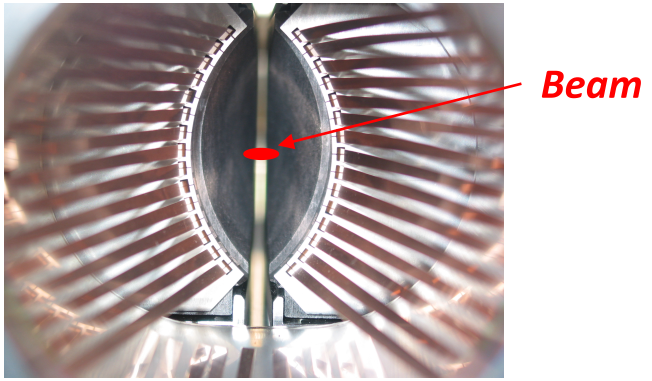
LHC collimation system



Multi-stage cleaning with about 50 collimators per beam, two dedicated insertions



Movable collimators:
ensure required performance along the entire cycle



At 6.5 TeV: ~2 mm gap with 5 μm resolution!

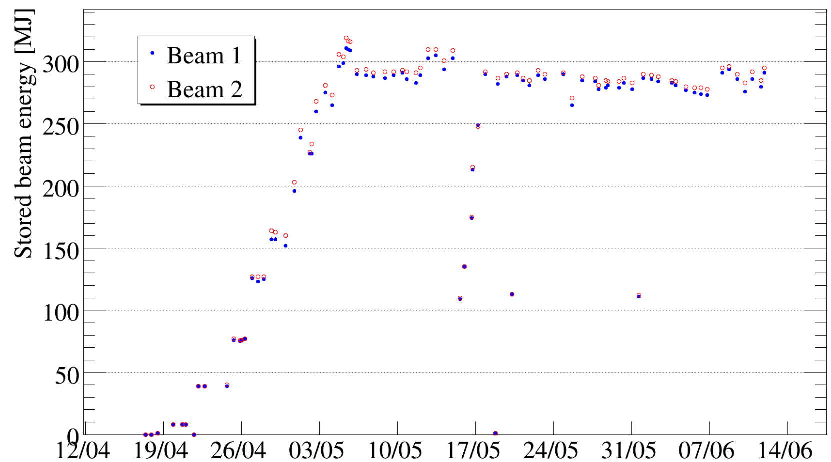
LHC collimation performance

LHC Collimation Project

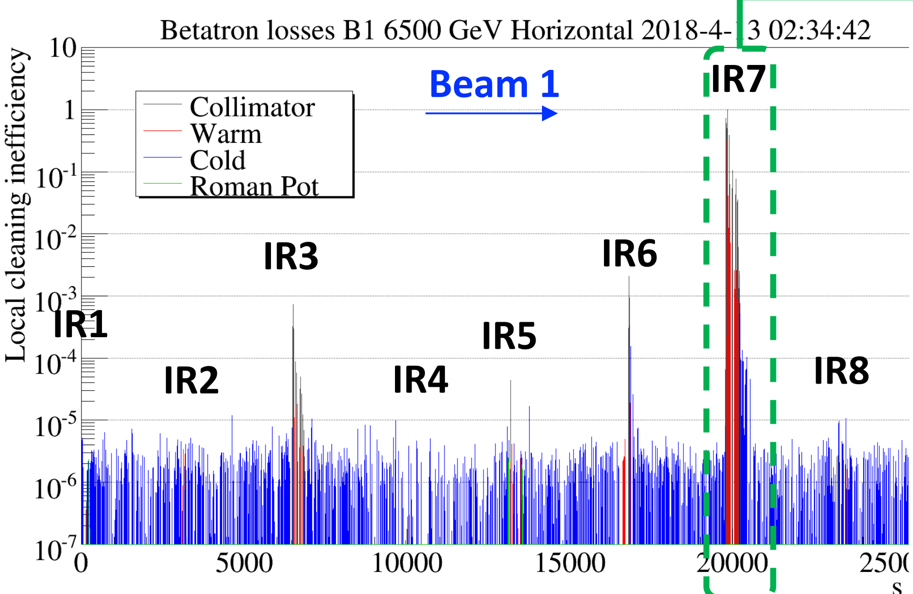
Excellent performance *of the present collimation system with stored beam energies up to* ***300 MJ at 6.5 TeV***

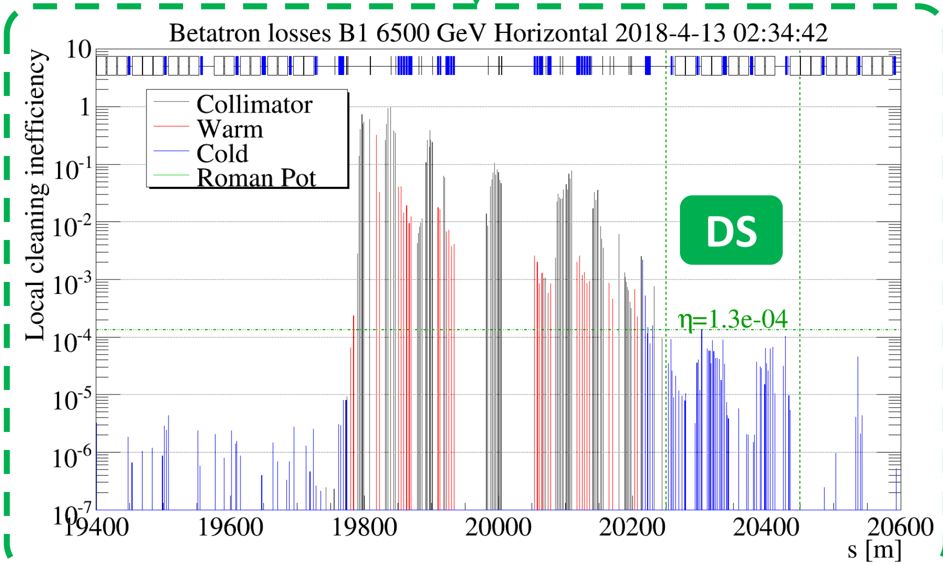
Never experience magnet quench due to collimation losses

Stored energy in 2018 physics fill



- ***Cleaning performance:*** $\eta_i = \frac{BLM_i}{BLM_{TCP}}$





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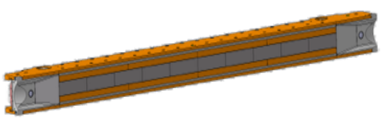
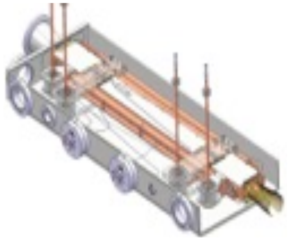
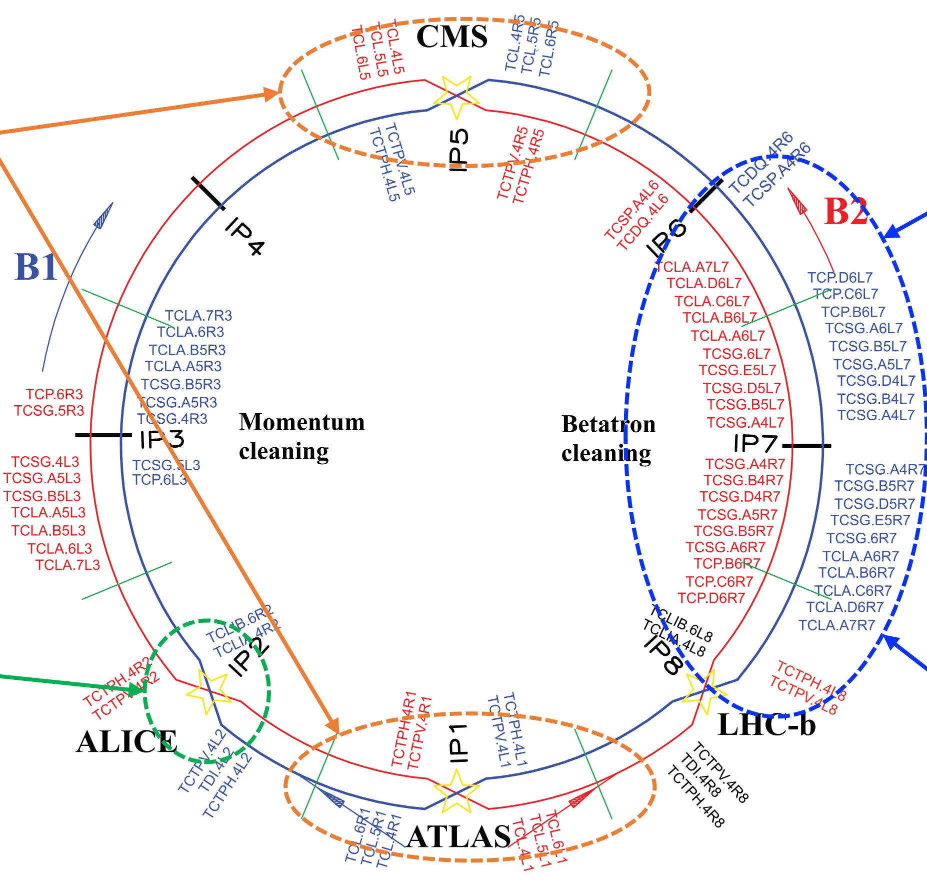
HL-LHC collimation upgrade baseline

New TCTs layout and material (CuCD)

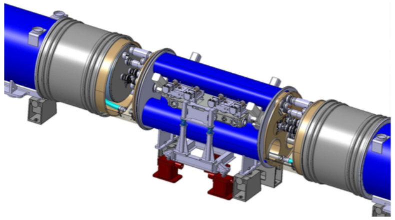


Ion physics debris: DS collimator

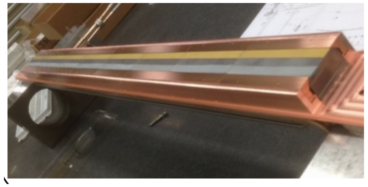




Cleaning perf.: 11 T dipoles + DS coll.



Low impedance high robustness TCSGs (coated MoGr)



Solid baseline to improve the **passive** nature of the **system!**

Any possibility for an active control of overpopulated beam tails?

Possible concerns for HL-LHC

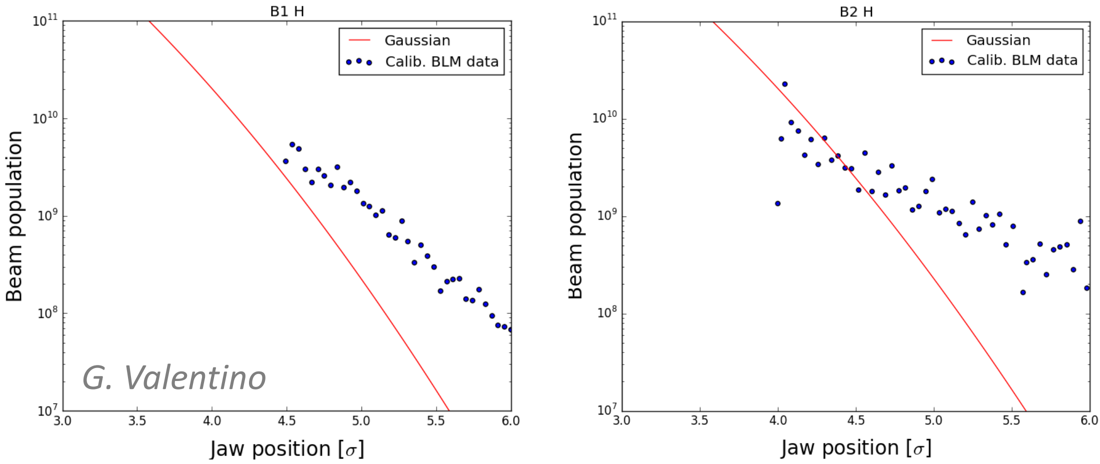
- **Present system** designed to handle up to **360 MJ**, **HL-LHC** design stored energy **~700 MJ**
- **How much** of this energy is **in the tails**?

Halo population probed by means of **collimator scans**

BLM signal calibrated using BCT signal

Around 5% of the beams in the tails (>3.5 σ) while 0.22% if Gaussian

Scaling to HL-LHC parameters: ~33.6 MJ in the tails!



Fast failure scenarios:

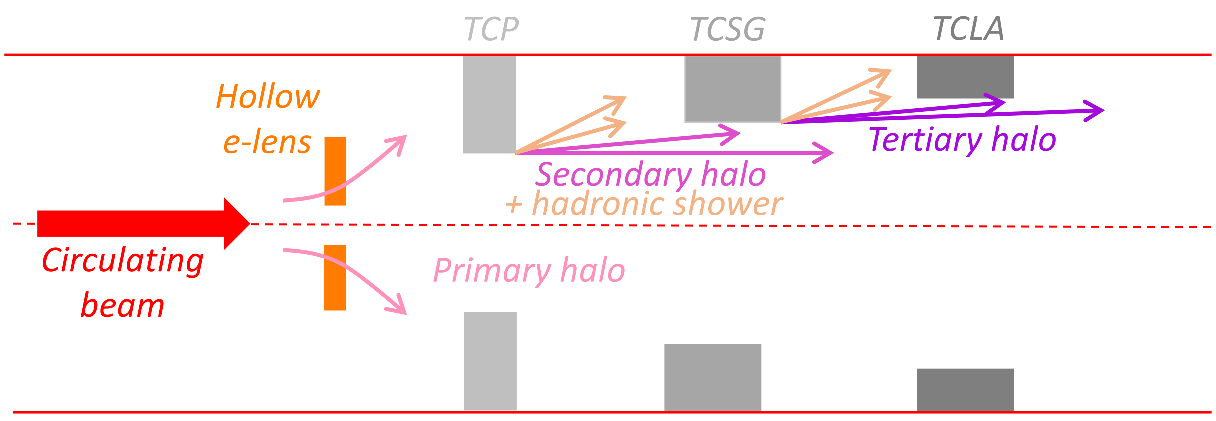
Orbit jitter
Crab cavity phase slip

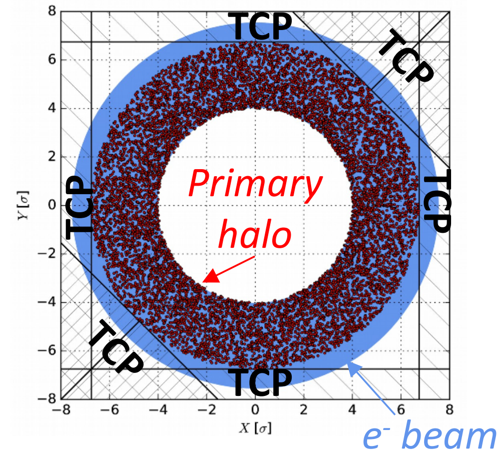
Possible consequences:

Magnet quench
Permanent damage to TCPs

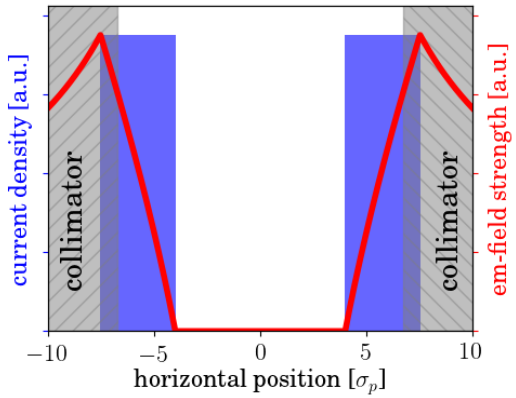
Hollow e-lens assisted collimation

Working principle: **hollow electron beam** surrounding the proton beam as **additional hierarchy layer**

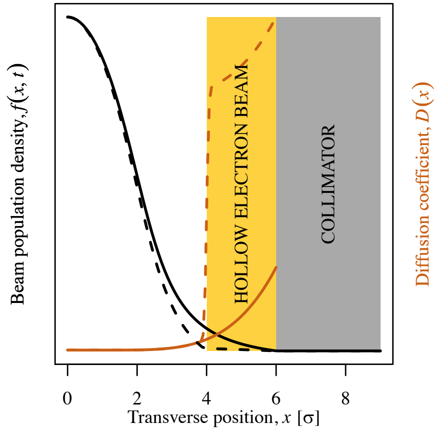




em-field acting only on halo particles



Increased diffusion speed and depleted halo population



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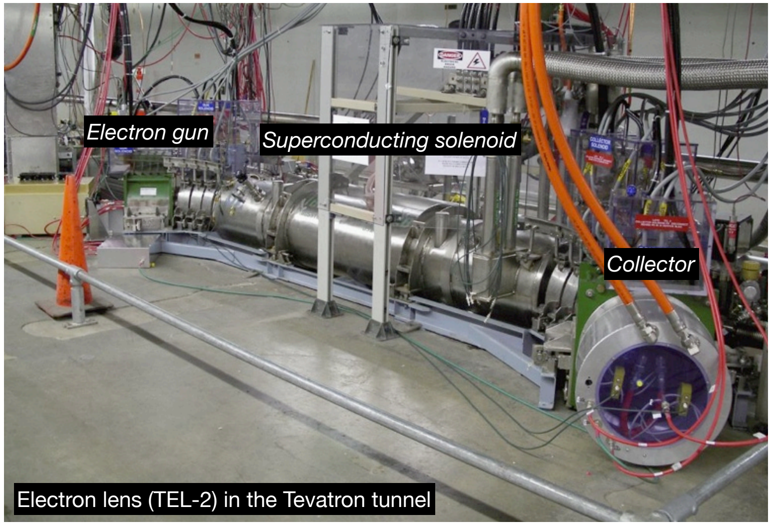
Fermilab experience

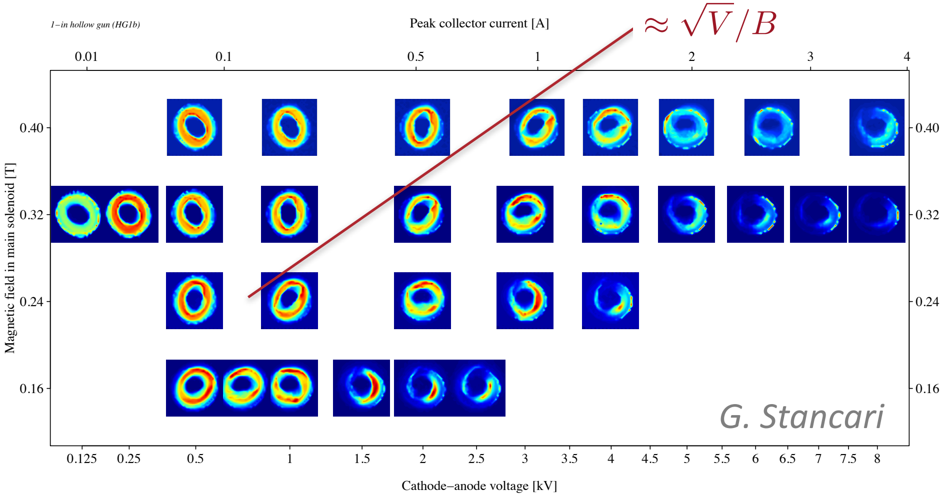
Two e-lenses in the Tevatron collider

Long range beam-beam compensation and abort gap cleaning

First test stand that **demonstrated halo scraping with hollow electron beams!**



- Fundamental requirement to **avoid effects on the core: symmetric hollow e^- beam**



Characterization as a function of magnetic field in the main solenoid and cathode-anode voltage

HL-LHC e-gun prototype under test: operation parameters successfully reached!

Halo scraping tests at Fermilab

Two milestones achieved:

Increased halo loss rate

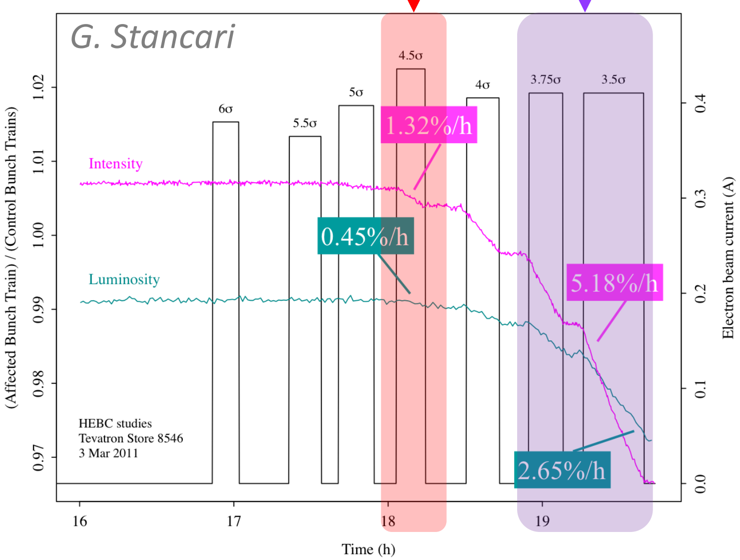
- HEL acting only on one train
- Main observables: $I_N = \frac{I_{HEL}}{I_{cont}}$ $L_N = \frac{L_{HEL}}{L_{cont}}$

Halo scraping

If $\frac{dI_N}{dt} < 0$ and $\frac{dL_N}{dt} = 0$

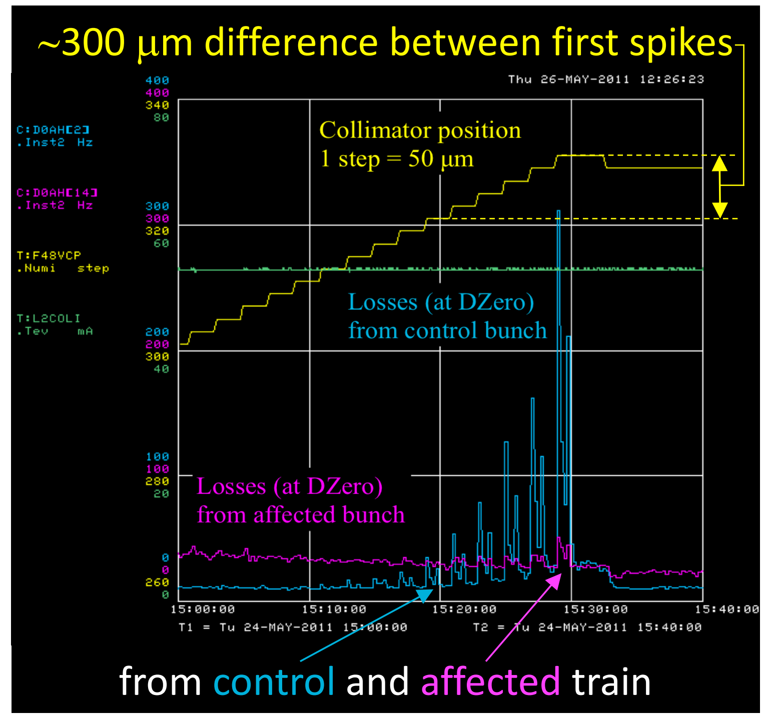
Effects on core

If $\frac{dI_N}{dt} < 0$ and $\frac{dL_N}{dt} < 0$



Halo depletion

- HEL acting only on one train
- Main observables: *Losses at collimators during scraping*



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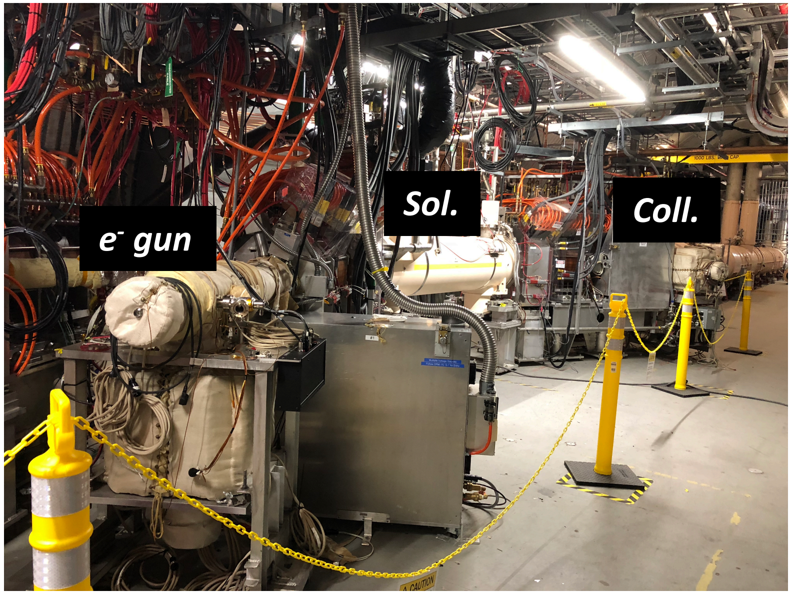
Brookhaven experience

Two e-lenses are installed in the RHIC collider

head-on beam-beam compensation for p-p operations

none of the 112 stores was aborted due to equipment failure



- **sPHENIX detector upgrade on-going**

  only heavy ions are used in operation

  do not require head-on beam-beam compensation

- **Changed the e$^-$ gun** of one e-lens to provide an **hollow electron beam**

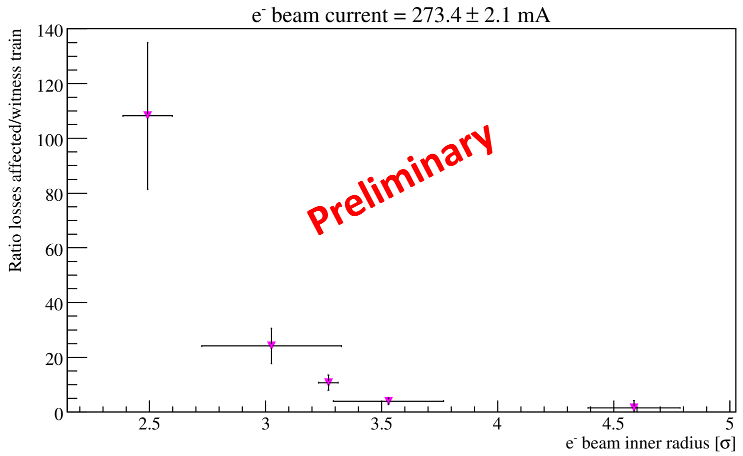
  unique opportunity to explore different operational scenarios

Collimation tests at Brookhaven

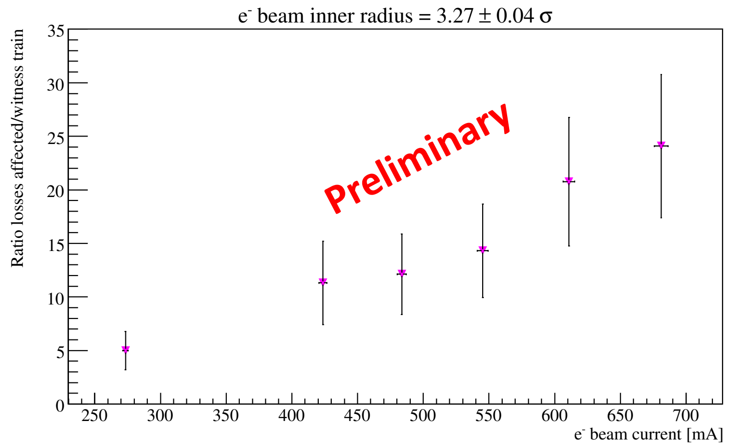
- **Similar test as done at Tevatron** but with **100 Z GeV Ru** and **13.6 Z GeV Au** beams
- Two trains injected in each ring and HEL acting only in one of them (Yellow ring)
- Main observables: normalized bunch-by-bunch losses at collimators

Preliminary results:

e^- beam radius (r) scan



e^- beam current (I) scan



In agreement with expectations: $\theta \approx {}^{I}/_{r}$

Detailed tests and analysis on-going to probe effects on beam core and non linearities

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HEL for HL-LHC

<u>*Main design requirements:*</u>

- Compact design
- Reasonable magnetic fields in the solenoids
- Adjustable inner radius of the electron beam
- technically feasible dimensions and current density of the cathode

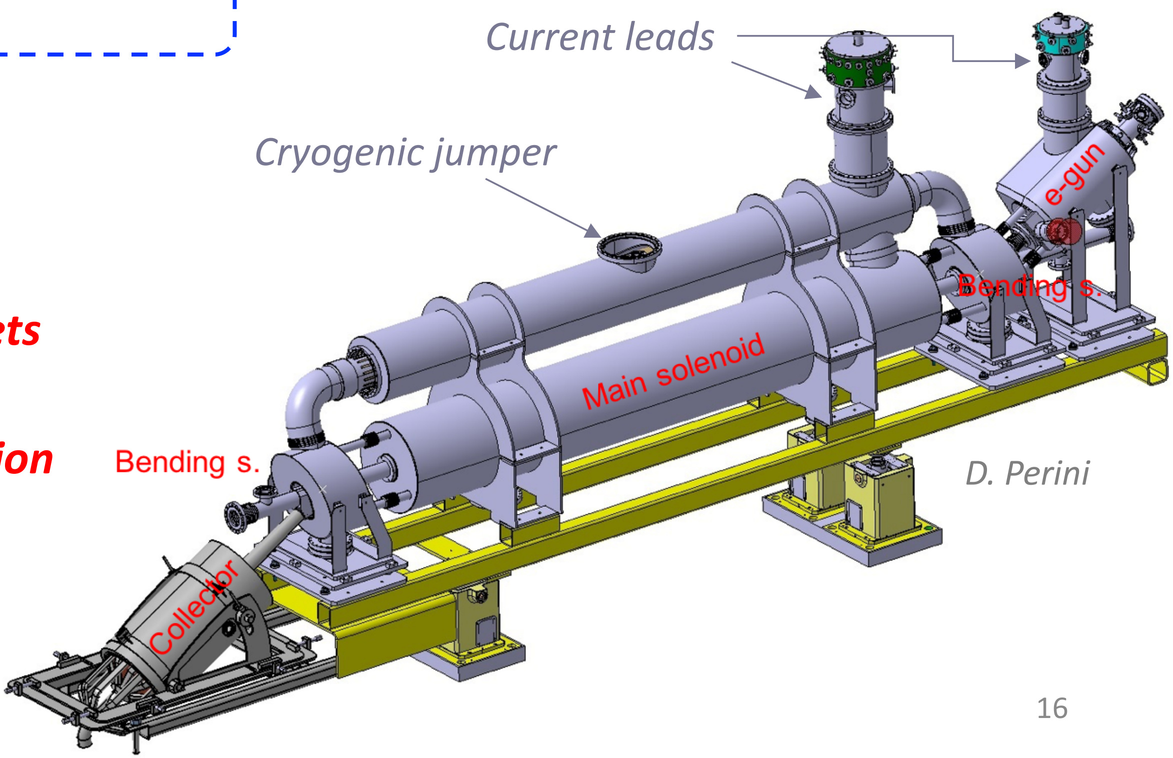
Operational specifications

Parameter	Value or range
Magnetic field main solenoid [T]	5
Magnetic field cathode [T]	0.2 - 2
Inner radius electron beam [mm]	0.9 - 5.67
Outer radius electron beam [mm]	1.8 - 11.34
Inner diameter cathode [mm]	8.05
Outer diameter cathode [mm]	16.10
Nominal current cathode [A]	5

Final design ready!

All superconducting magnets

Thermal and structural verification performed by means of numerical simulations



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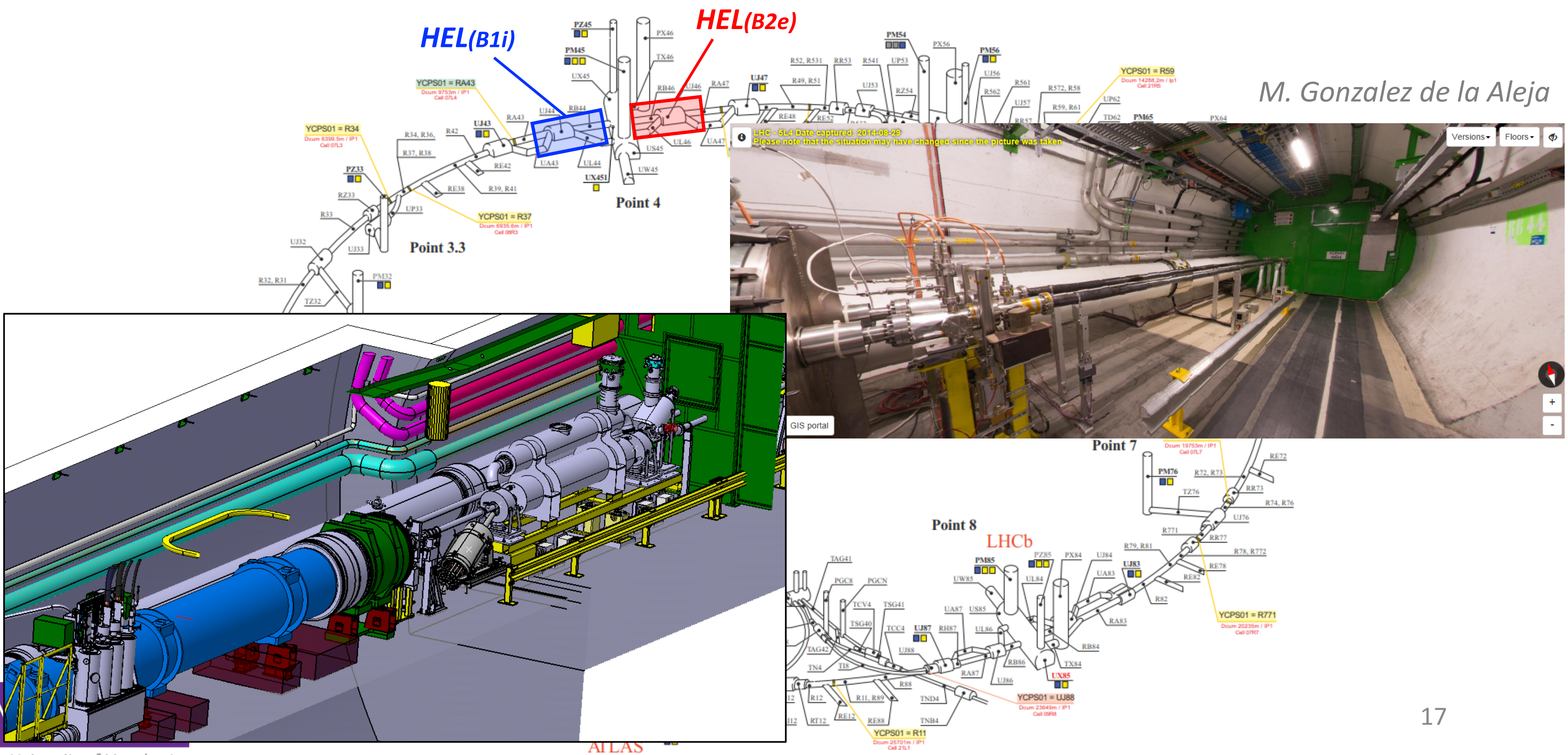
Integration in the LHC tunnel

<u>*Main requirements:*</u>

- Available **space**

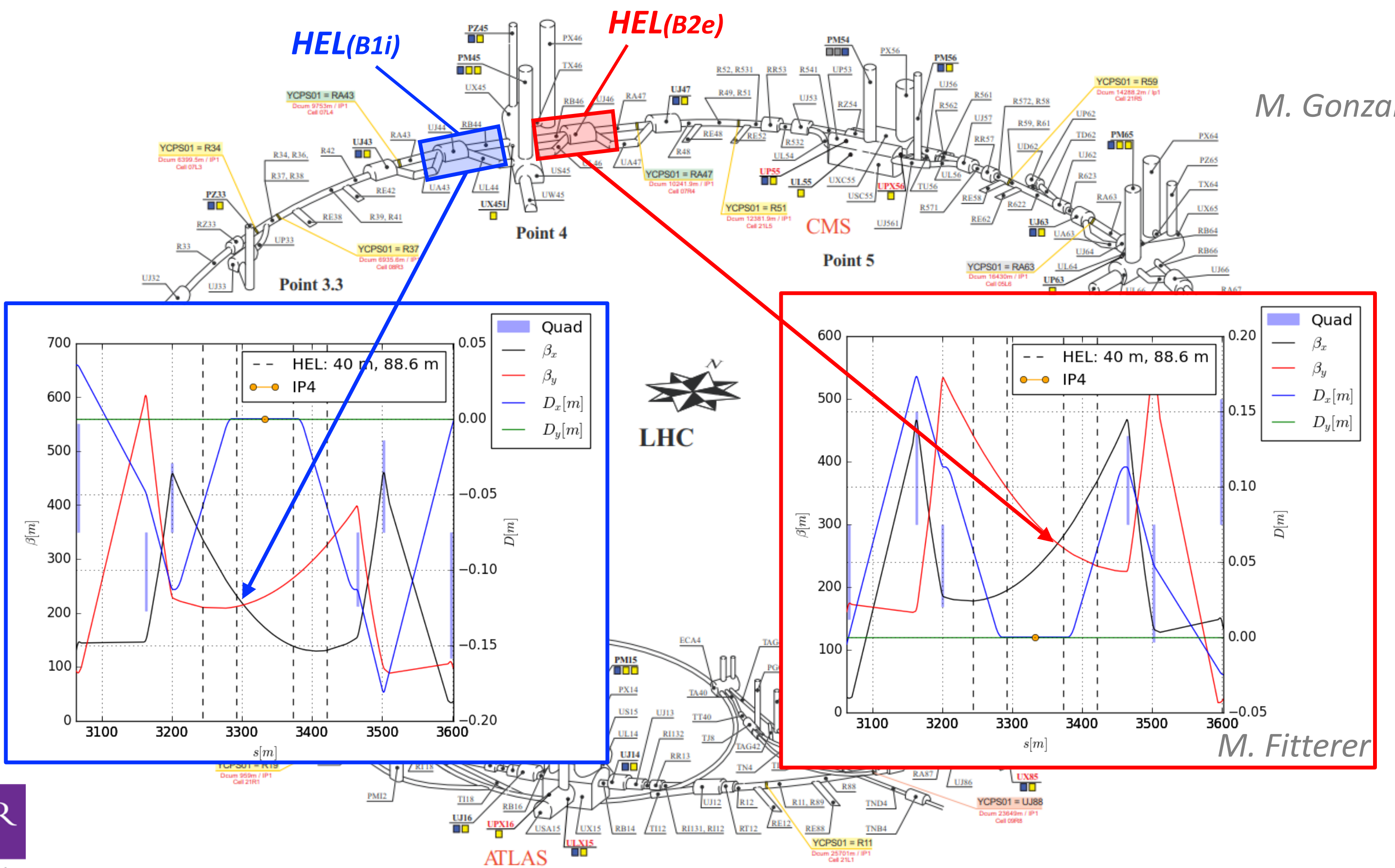
M. Gonzalez de la Aleja



Integration in the LHC tunnel

Main requirements:

- Available **space**
- Favorable **optics** conditions (i.e. round beams)



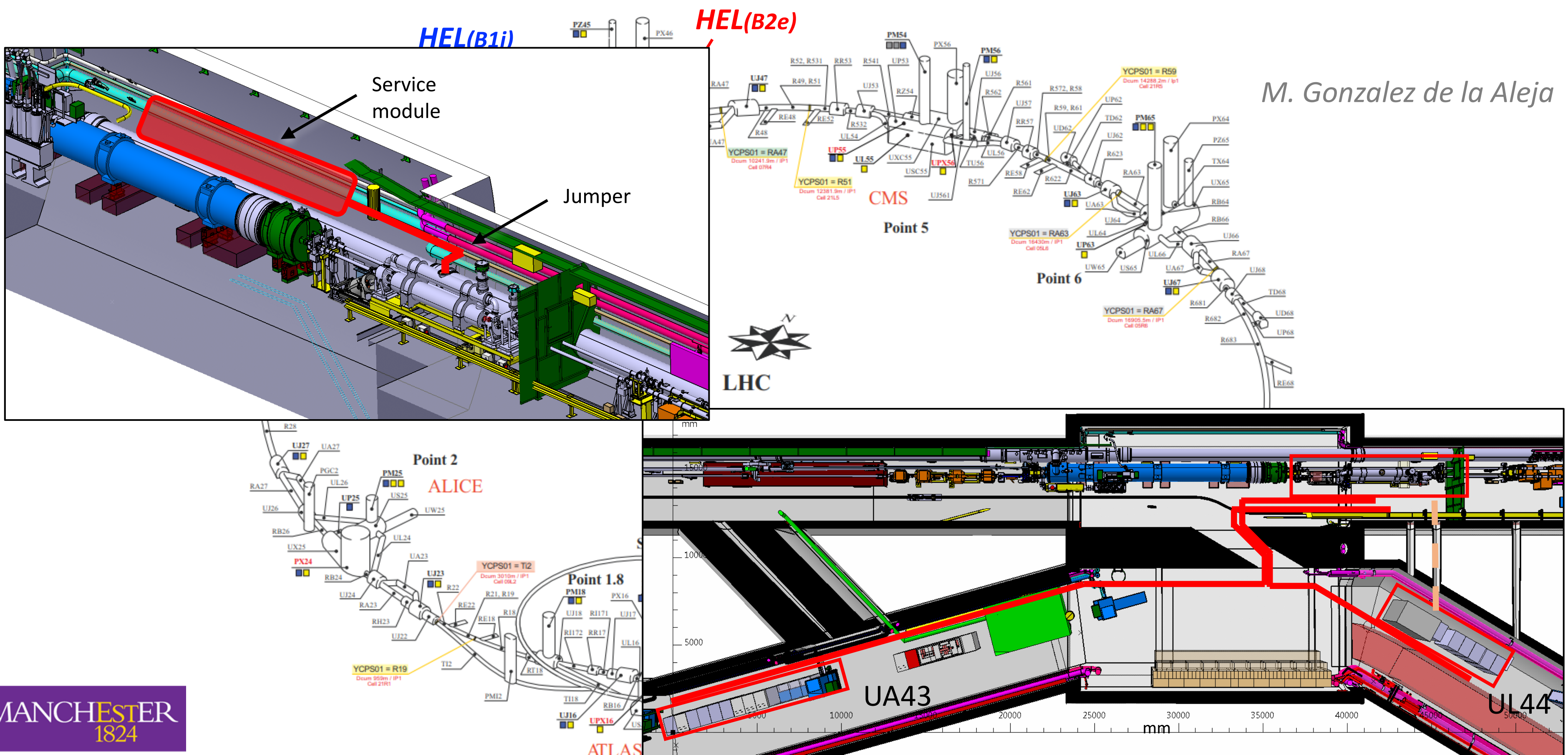
M. Gonzalez de la Aleja

M. Fitterer

Integration in the LHC tunnel

Main requirements:

- Available **space**
- Favorable **optics** conditions (i.e. round beams)
- **Infrastructures** (i.e. cryogenics, space for control electronics)



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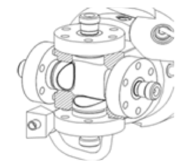
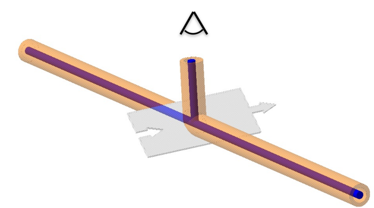
Beam instrumentation

Beam instrumentation concepts based on experience in FNAL and BNL

Requirement	Detector	
Absolute alignment of p and e^- beams	Beam position monitors	 
Characterization of e^- beam and relative alignment w.r.t. p beam	Gas jet curtain monitors	
Beam loss monitoring	Ionization chamber	

Operational aspects

Several aspects studied:

- Avoid issues in terms of **available aperture** for the circulating beam → **Round pipe of 60 mm radius**
- **Linear coupling** due to solenoidal fields → Simulations show a **negligible** effect
- Contribution to the **impedance** budget of the machine → Simulations show a **negligible** impact
- **Missing dipole kick in case of quench** → Proper **interlock** strategy is needed
- **Effects on beam core** from the two **electron beam crossings**
  - → **Self-compensated** thanks to the **"S" shape**
    - → **Dipolar kicks** from bending solenoids **add up**
      - → Dedicated **orbit corrector** is present
- **Effect on beam core due to imperfections** on the bends or electron beam profile
  - → **Negligible in DC mode**
    - → **Studies** on-going to find feasible **pulsing operational mode**

HEL Pro and Cons

Main operational gains:

- **Loss spike free** operation in the case of orbit jitter and bunch rotation due to crab cavities phase slip
- **Increased of impact parameter** on TCPs improving cleaning performance
- Tighter collimator settings to **improve β* reach**

Possible drawback		Possible solution
Loss of Landau damping	⇨	Tuneable radius of e^- beam
Detection of unusual loss rate	⇨	Witness bunch trains

Outline

Conclusions

- **Solid collimation upgrade baseline for the HL-LHC**

  Recent assessment of **large tail populations might require active halo control**

- **HEL identified as most promising solution**, also in light of reliable operations in other machines

  Recommended by different reviews, in the process of adding them to the baseline
  Looking for collaborators interested to contribute and make this possible

- **The design of the HL-LHC lenses is mature** and essentially ready for launching production

- **Detailed operational scenarios** and pulsing strategies **being studied** in simulations and experimentally

Thank you for your attention!