Beam instrumentation and diagnostics for High Luminosity LHC

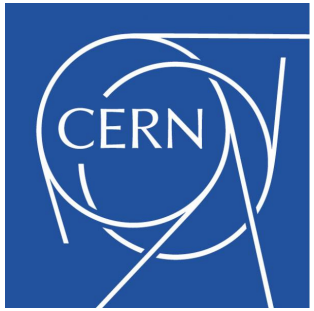
Michal Krupa

For HL-LHC WP13 – Beam Instrumentation

IBIC'19, Malmo, 09/09/2019

Outline

- HL-LHC project context
- Beam position monitoring
- Crab cavity diagnostics
  - Heat-tail (HT) monitor
  - Electro-optic BPM
- Halo diagnostics - coronagraph
- Beam Gas Curtain (BGC) monitor
- Beam Gas Vertex (BGV) monitor
- Luminosity measurements



RWTH AACHEN UNIVERSITY

The Cockcroft Institute of Accelerator Science and Technology

EPFL

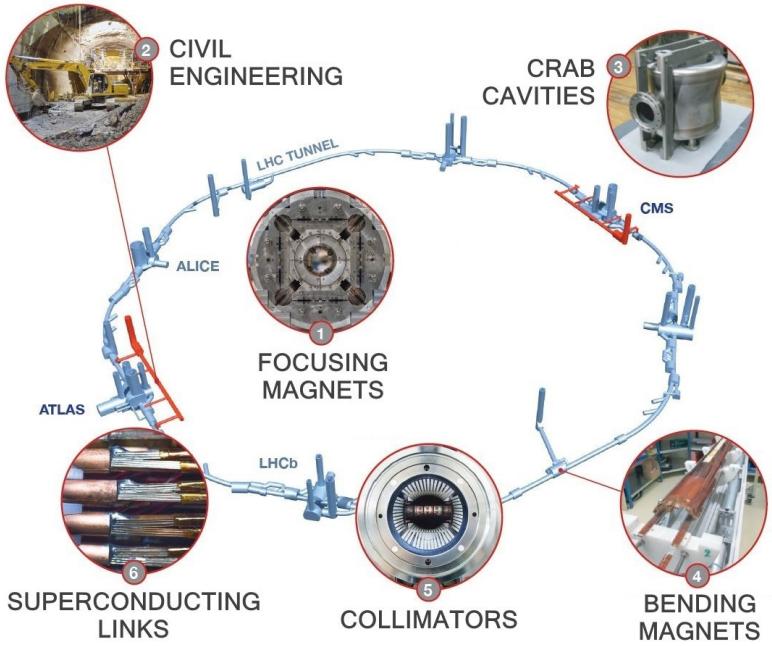
GSI

Wrocław University of Science and Technology

大学共同利用機関法人
高エネルギー加速器研究機構

HL-LHC: High Luminosity LHC upgrade

- LHC foreseen to deliver 300 fb^{-1} by 2023 (190 fb^{-1} so far)
- HL upgrade approved in 2014 with two major goals:
  - Luminosity levelled at $5 \cdot 10^{34}$ $cm^{-2}s^{-1}$ with 130 collisions per bunch crossing (in 2018: $2 \cdot 10^{34}$ $cm^{-2}s^{-1}$ / 40)
  - 3000 fb^{-1} integrated over 12 years
- Main changes:
  - Smaller beams
  - Higher intensity
  - Crab cavities
- Novel / upgraded instruments and diagnostics are needed



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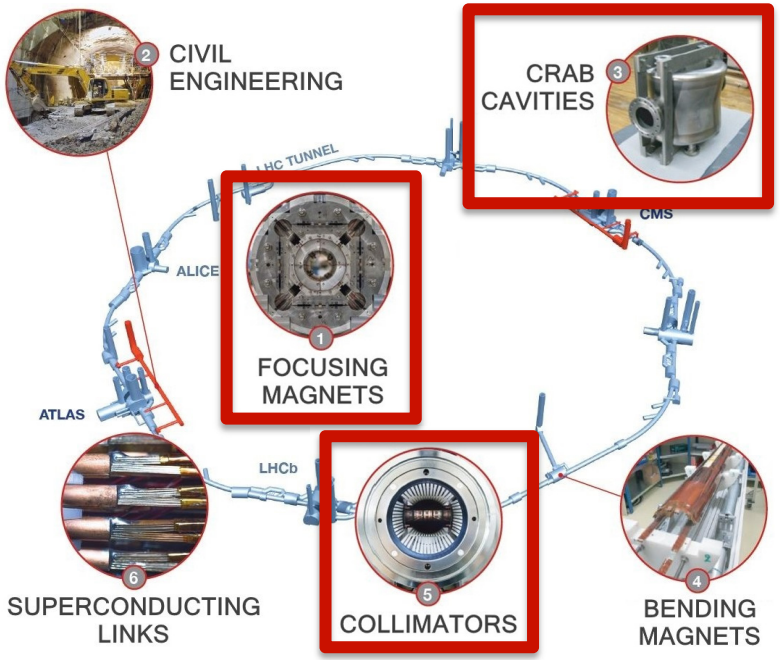
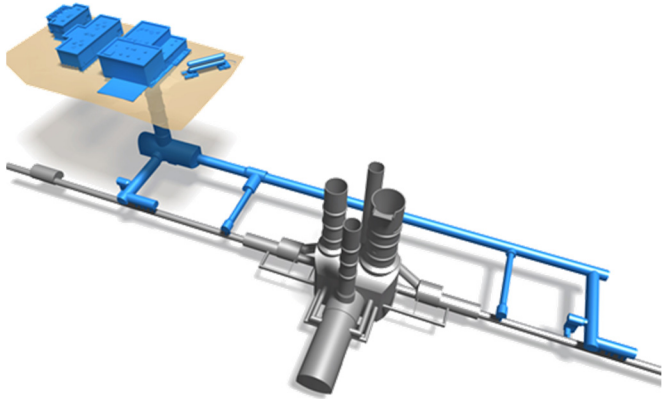
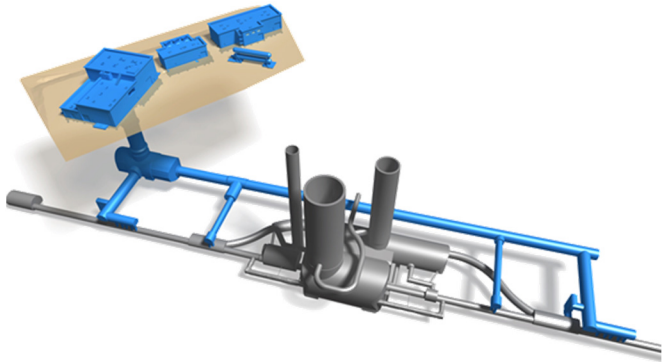


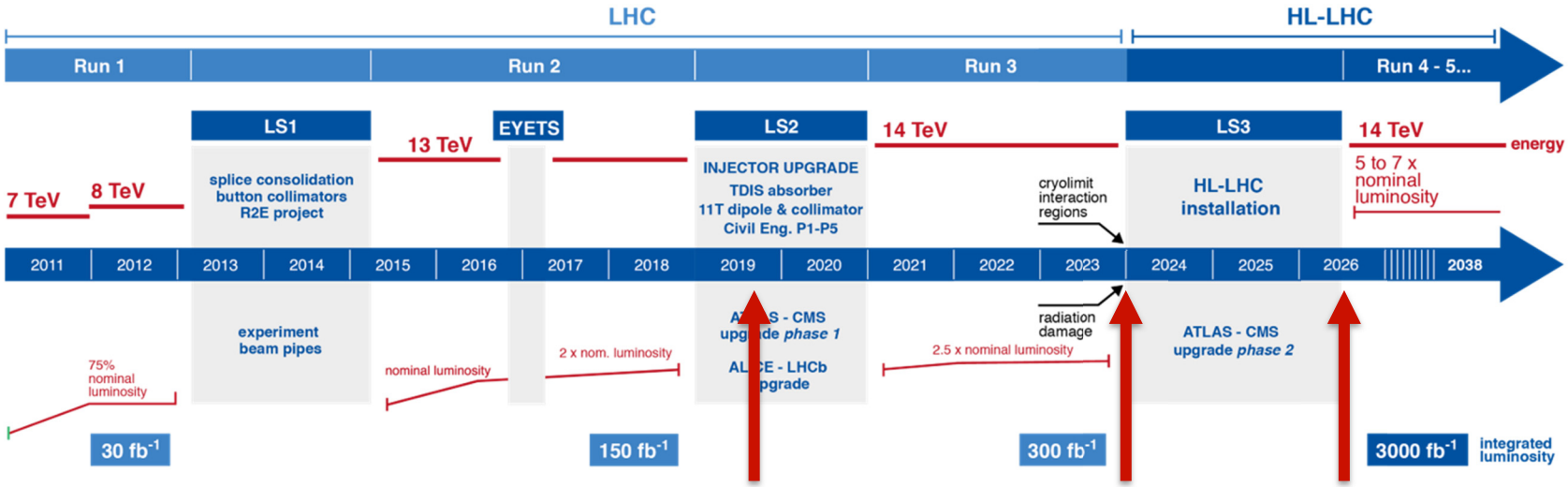
HL-LHC construction





From LHC to HL-LHC

- HL-LHC beam commissioning planned in 7 years

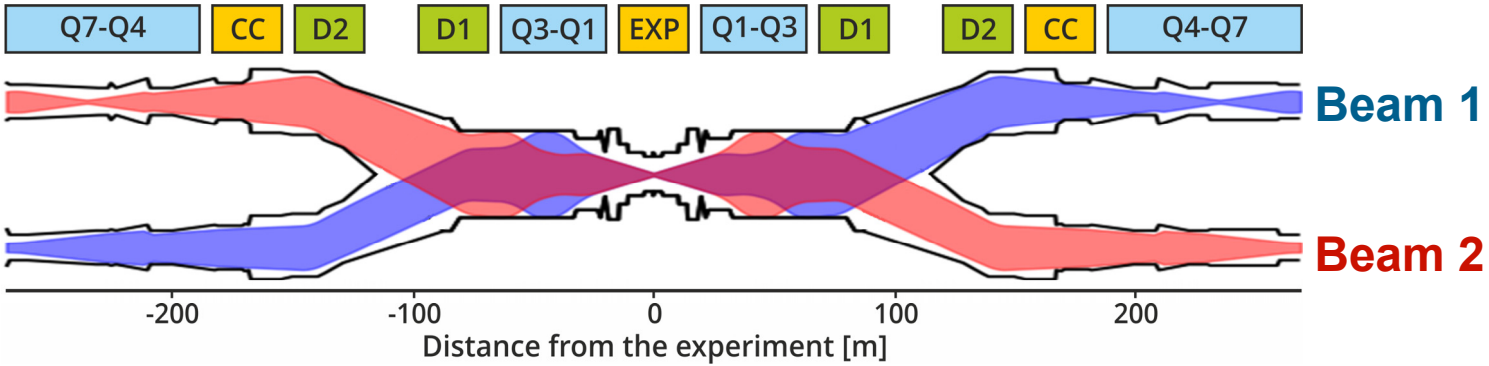


2019: today
Design and construction

2024
Installation

mid 2026
Commissioning

BPMs for Interaction Regions



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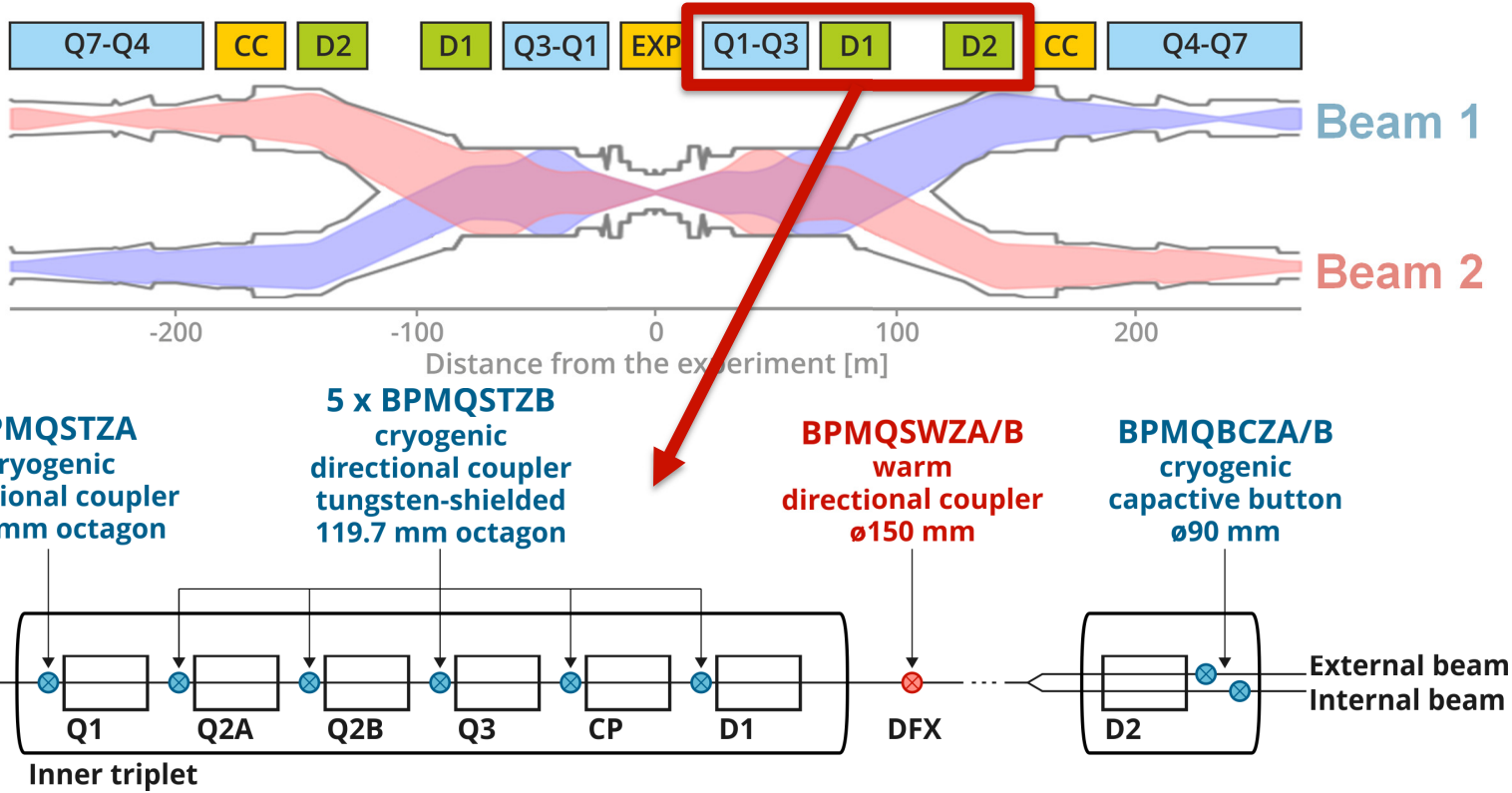
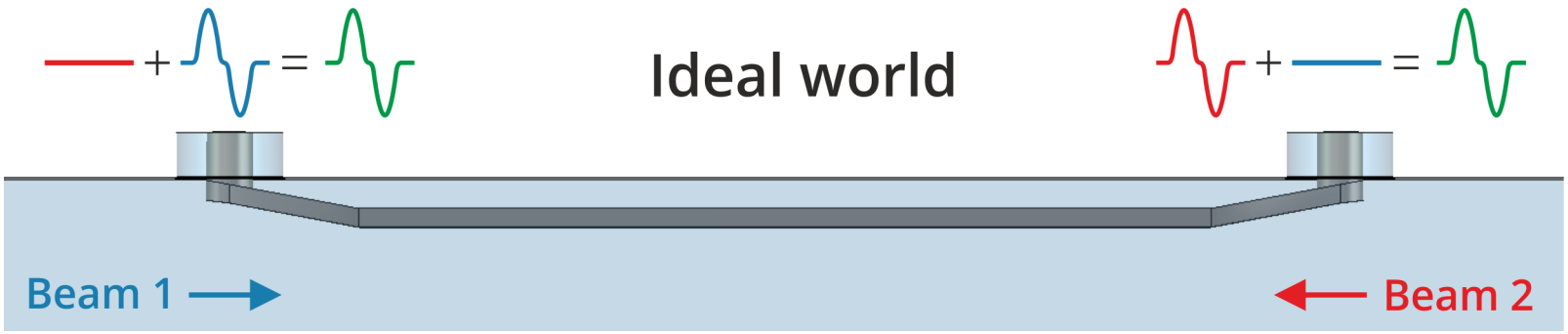


Directional couplers



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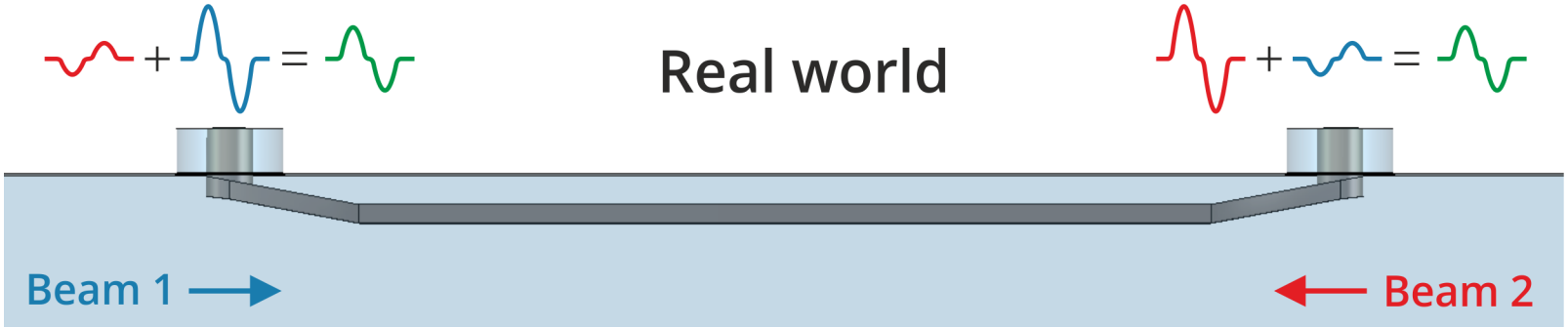

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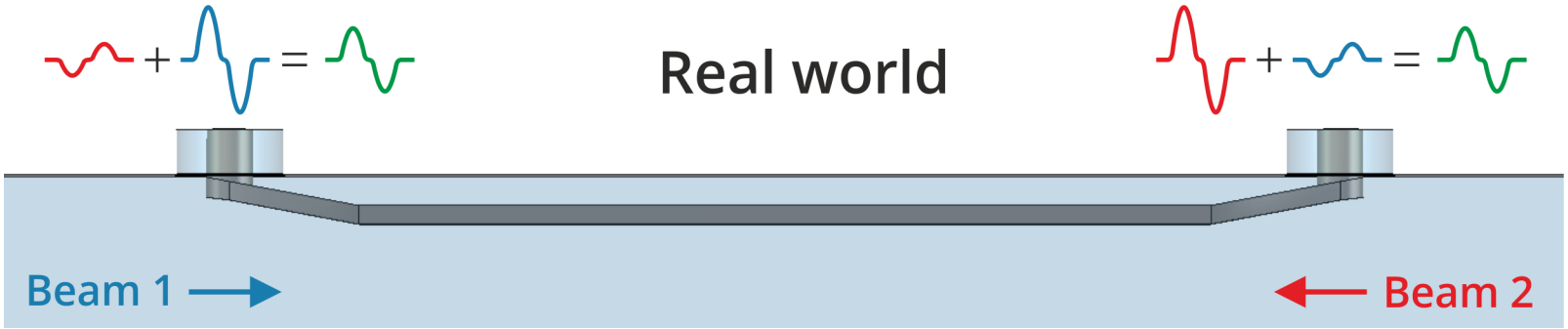

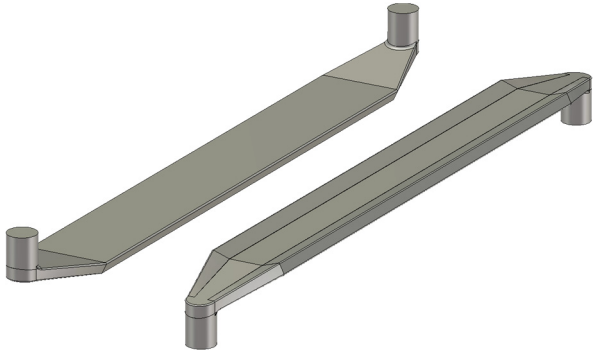

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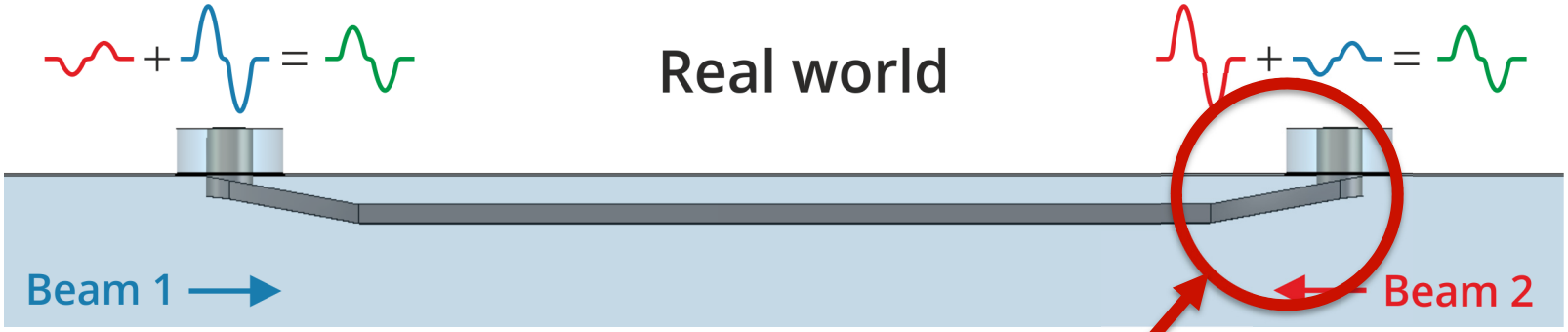
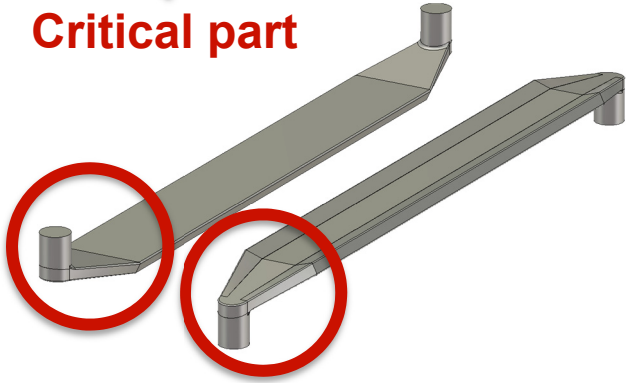
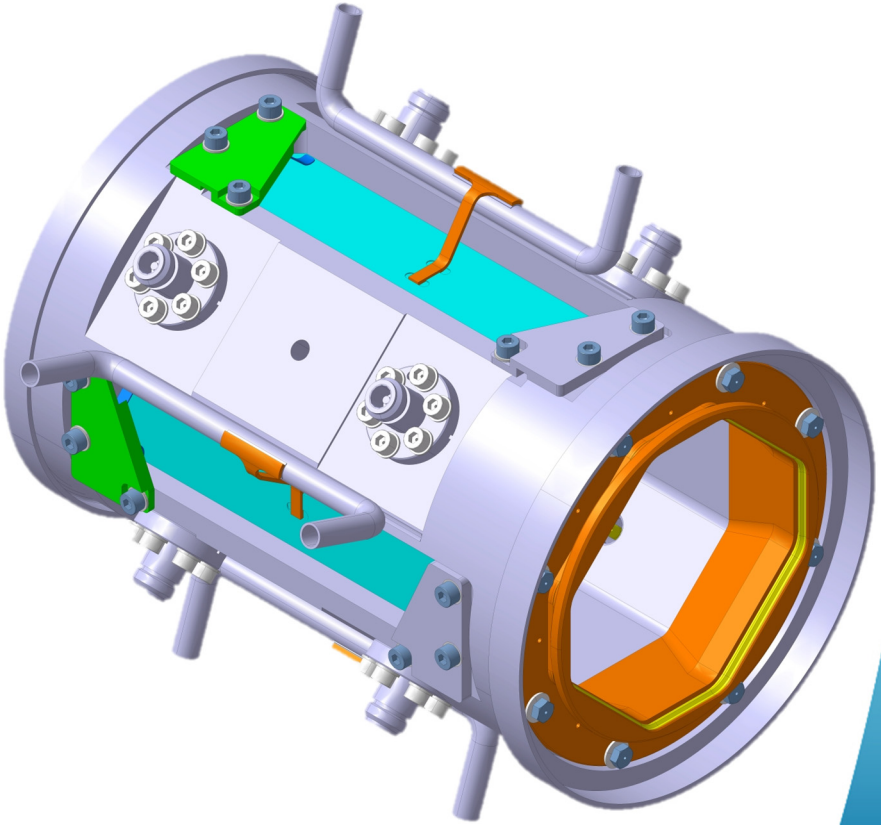


Critical part



HL-LHC cryogenic directional coupler

- Tungsten shielding:
  15% lower TID on Q2B magnet
- Amorphous carbon coating:
  Electron cloud effects decreased by a factor of 40
- Active cooling with liquid He:
  Need to evacuate up to 6 W of head load
- Complicated integration:
  BPMs installed in incredibly busy regions of the machine



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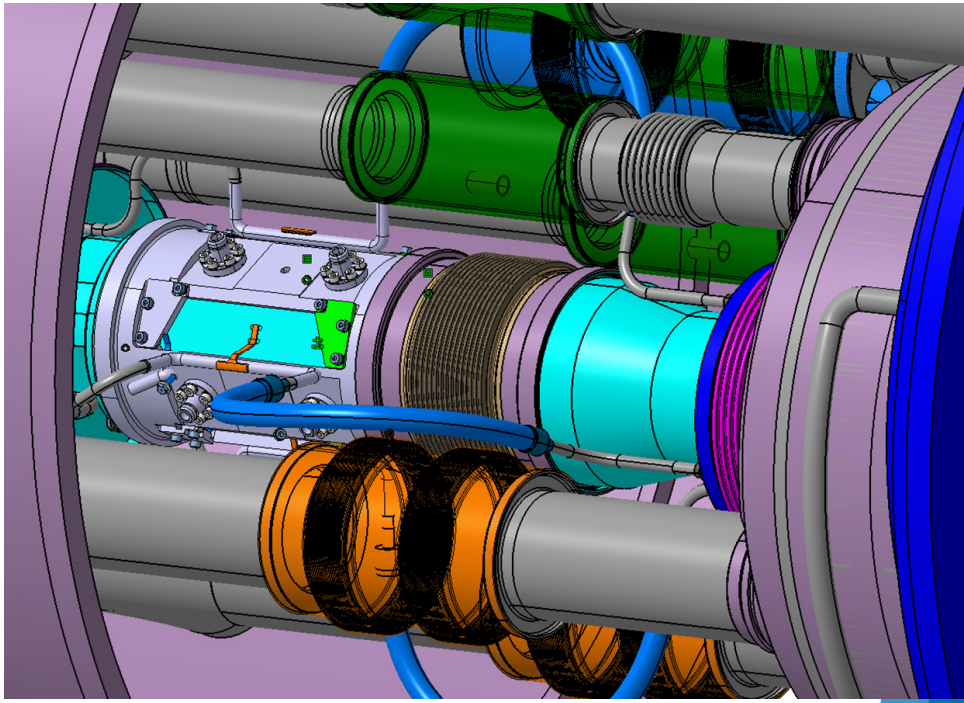
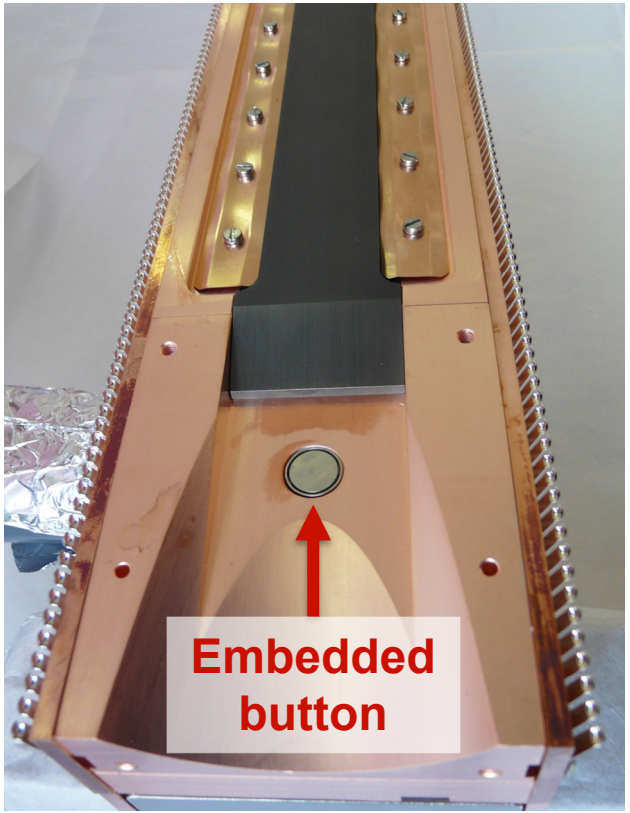


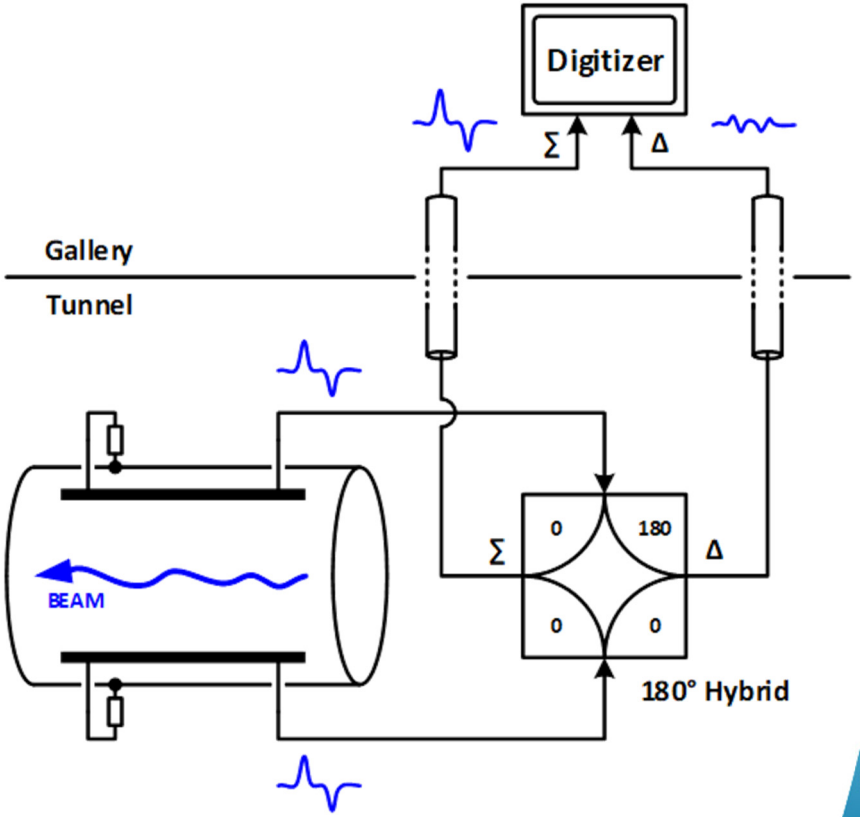
BPMs embedded in collimators

- Buttons embedded in collimator jaws to speed up set up since 2013
- Uses high-precision DOROS acquisition system
- Collimator jaw position now interlocked on BPM readings
- Challenging integration and component procurement: SiO_2 cables
- All HL-LHC collimators will be equipped with BPMs



CC diagnostics - Head-Tail (HT) monitor

- Wideband BPM measuring intra-bunch beam position
- 180º RF hybrid + high-speed oscilloscope



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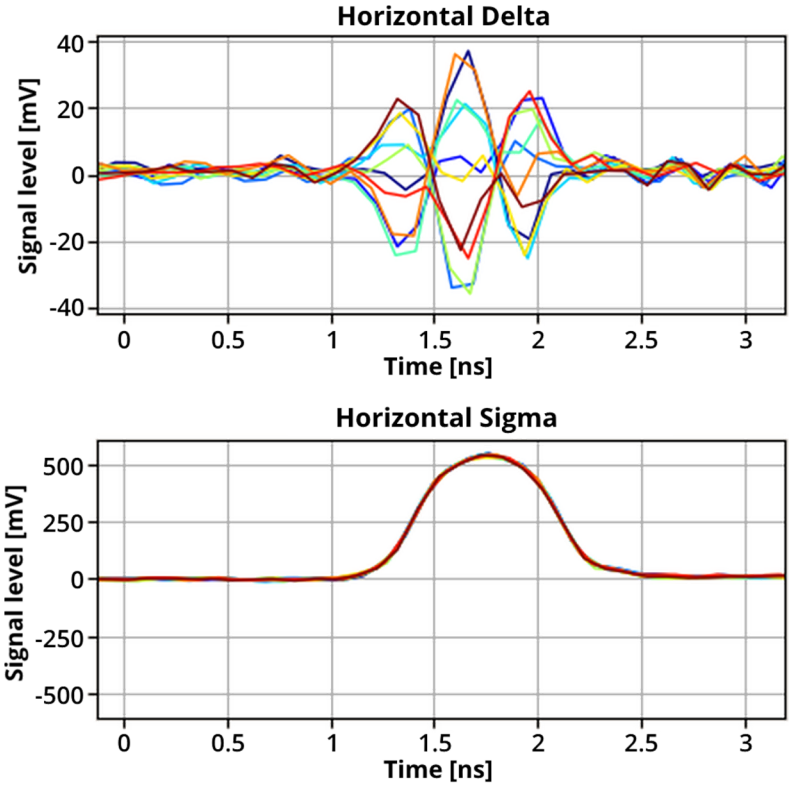

CC diagnostics - Head-Tail (HT) monitor

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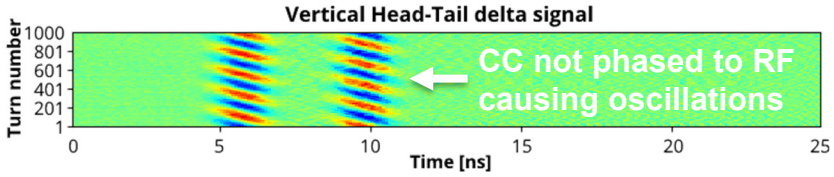
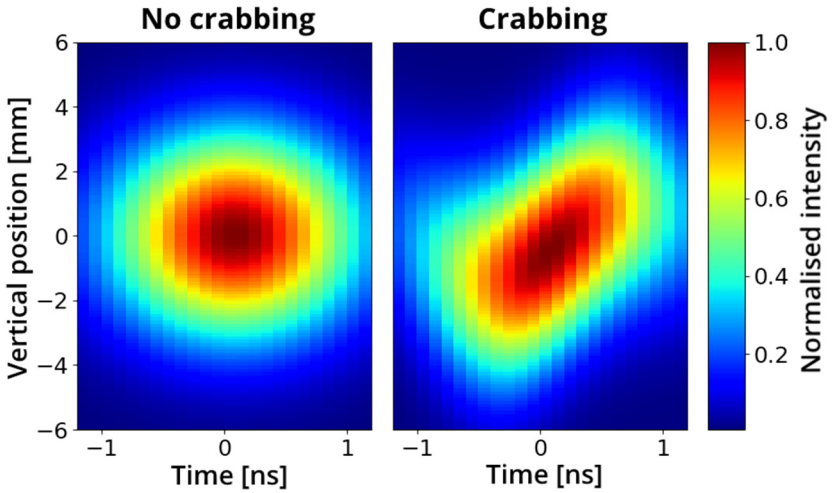
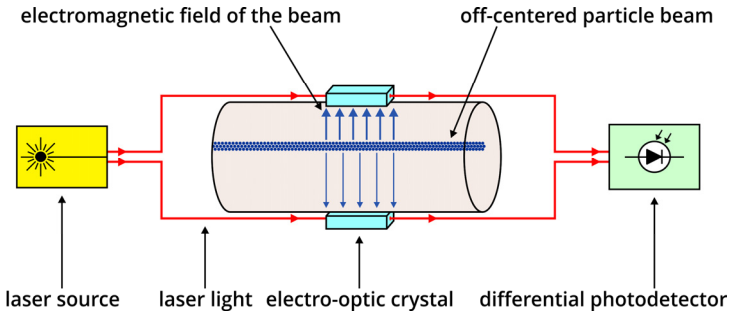
- 180º RF hybrid + high-speed oscilloscope
- Used primarily for instability diagnostics
- SPS HT monitor used in 2018 for crab cavity diagnostics
- Requires ±90º phase advance and large beta functions
- For HL-LHC: limited resolution and bandwidth

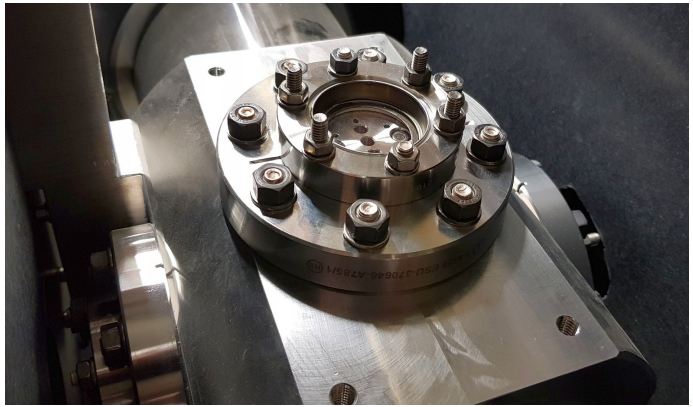




CC diagnostics - Electro-optic BPM

- Birefringent crystals encoding electric field of the beam onto a laser light (polarisation rotation)
- Ultrafast crystals used by telecoms, components commercially available
- Fully in-vacuum prototype installed in the SPS in 2016, modified 2017-2018





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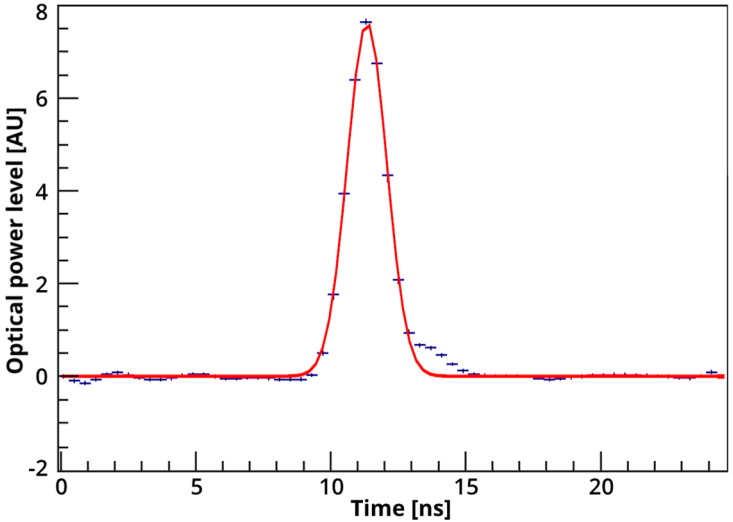
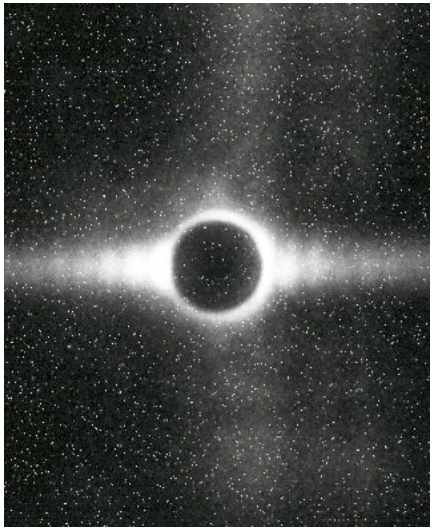
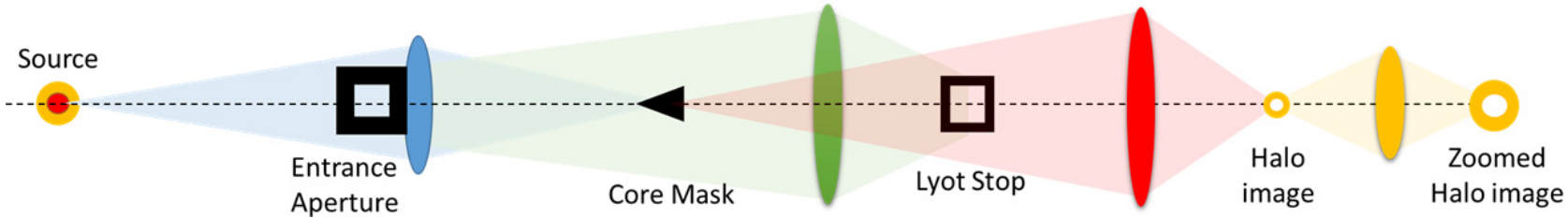
- Ultrafast crystals used by telecoms, components commercially available
- Fully in-vacuum prototype installed in the SPS in 2016, modified 2017-2018
- First electro-optic measurements of a proton bunch
- Design on-going for an HL-LHC out-of-vacuum electro-optic BPM
- Talk by A. Arteche Wednesday morning



Halo monitoring - coronagraph

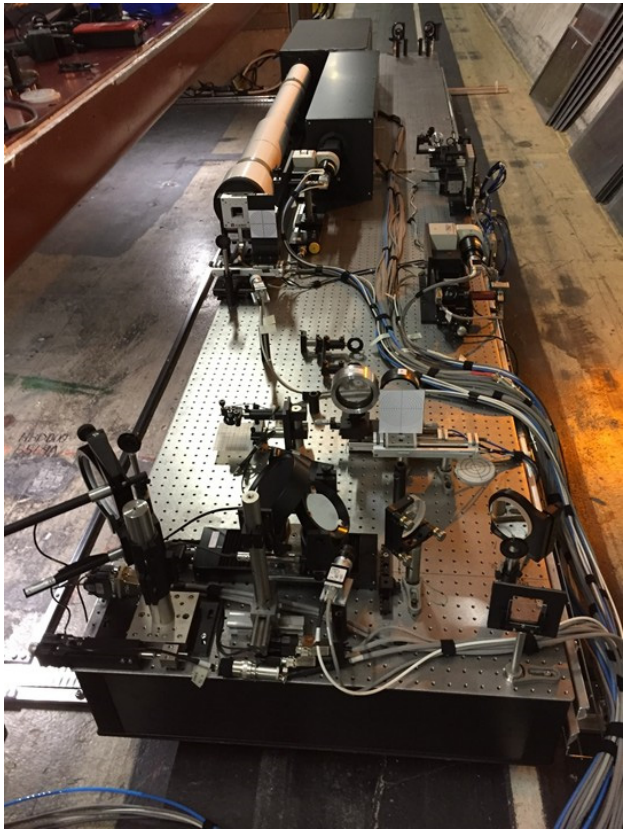
- Beam halo monitoring crucial for adequately adapting the HL-LHC machine protection systems
- Coronagraphs used to view the Sun's corona
- Real image is created by an objective lens
- A mask blocks the bright core
- To deal with light diffracted from the limited entrance aperture, a field lens together with a well-dimensioned stop are used
- Final performance defined by contrast





LHC coronagraph

- Prototype based on KEK photon factory optics installed together with other synchrotron light diagnostics



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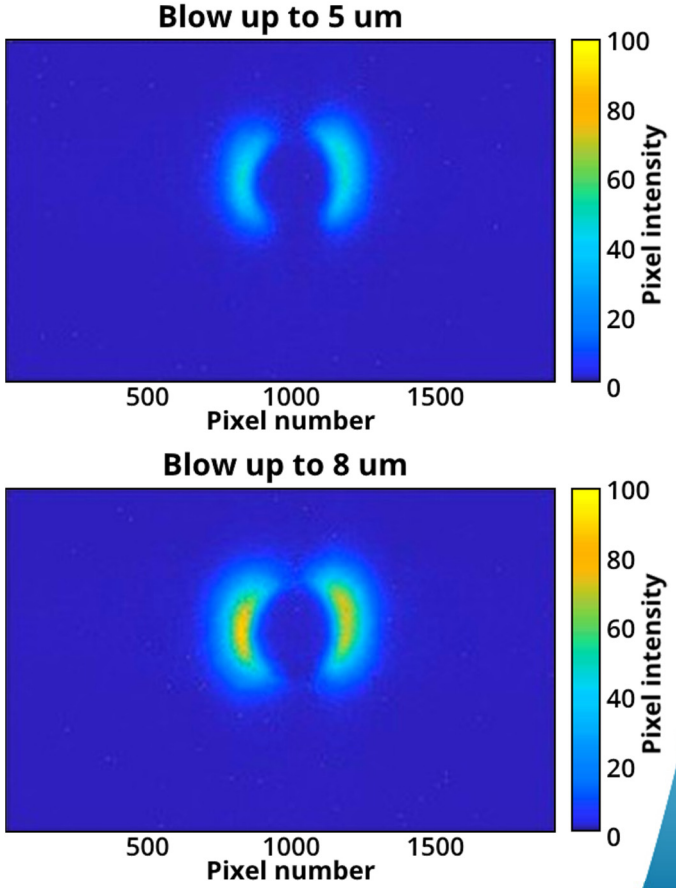
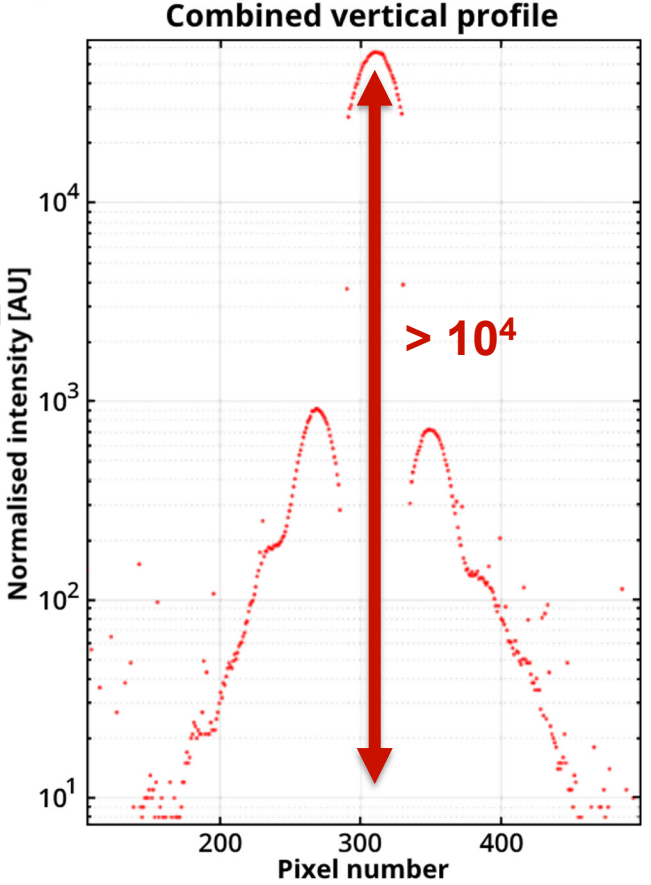


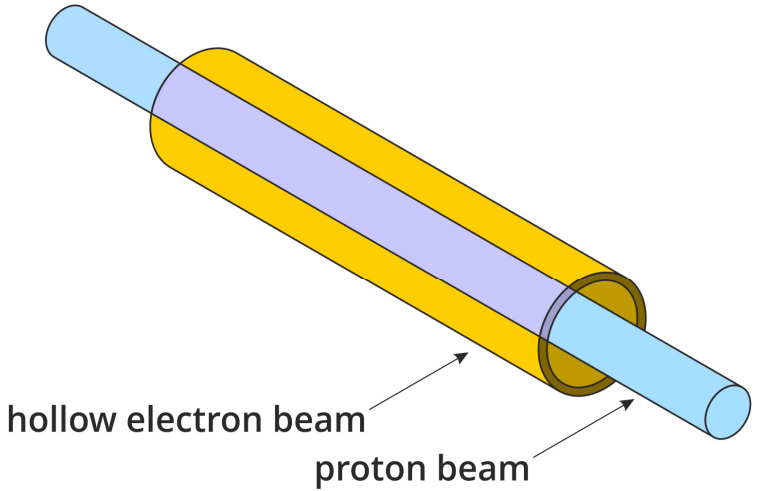
LHC coronagraph

- Prototype based on KEK photon factory optics installed together with other synchrotron light diagnostics
- First successful beam halo observation in 2016 using undulator-produced SR
- Demonstrated contrast ~10^{-4}
- Plans to replace the existing coronagraph with a new prototype
- Final installation on a dedicated synchrotron radiation optical line



Beam Gas Curtain monitor - BGC

- Hollow Electron Lens (HEL) to collimate beam halo – both beams must be concentric



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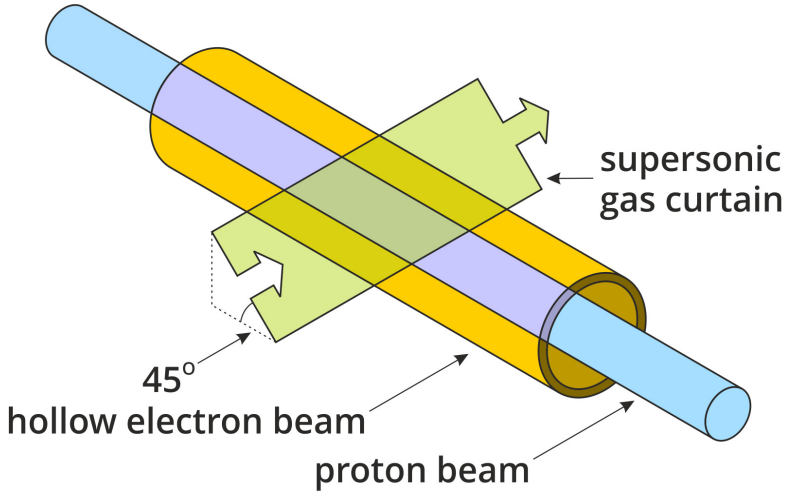

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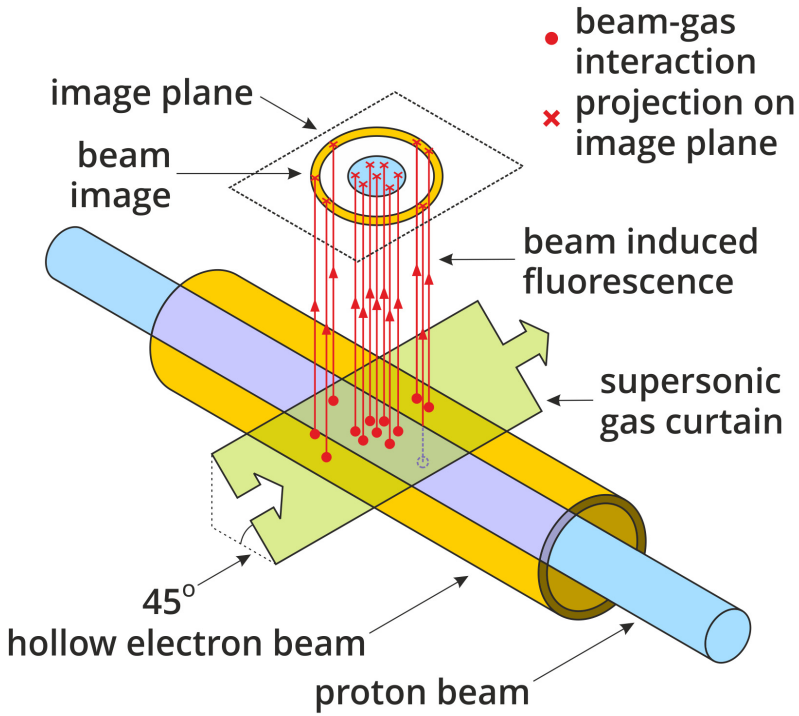

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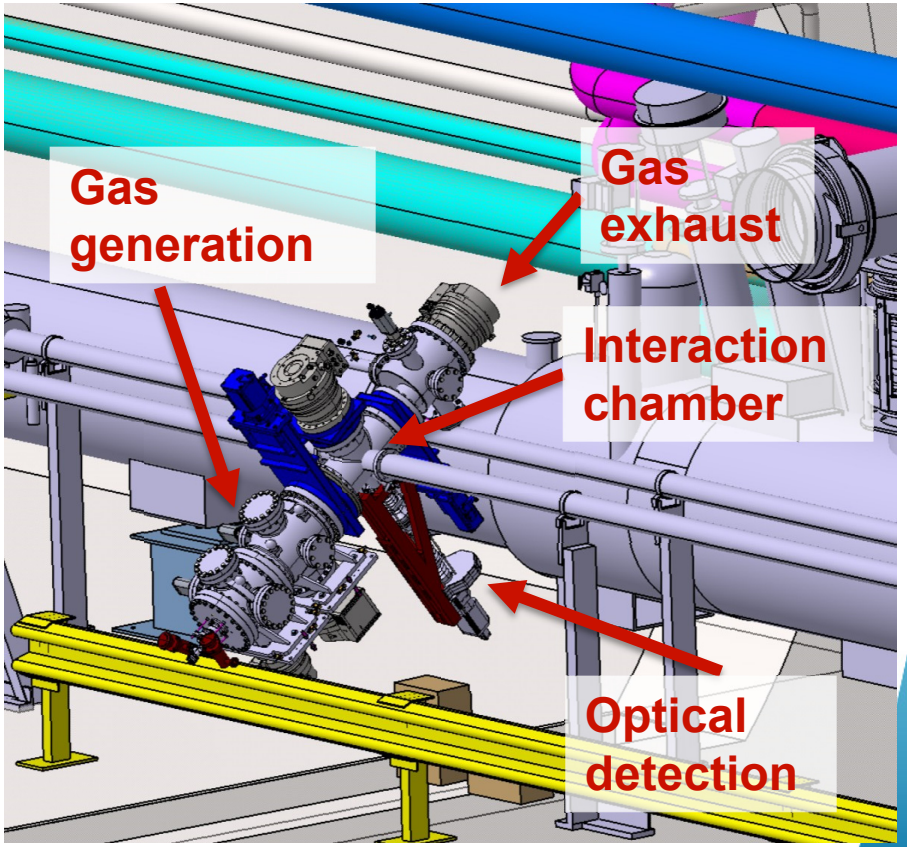
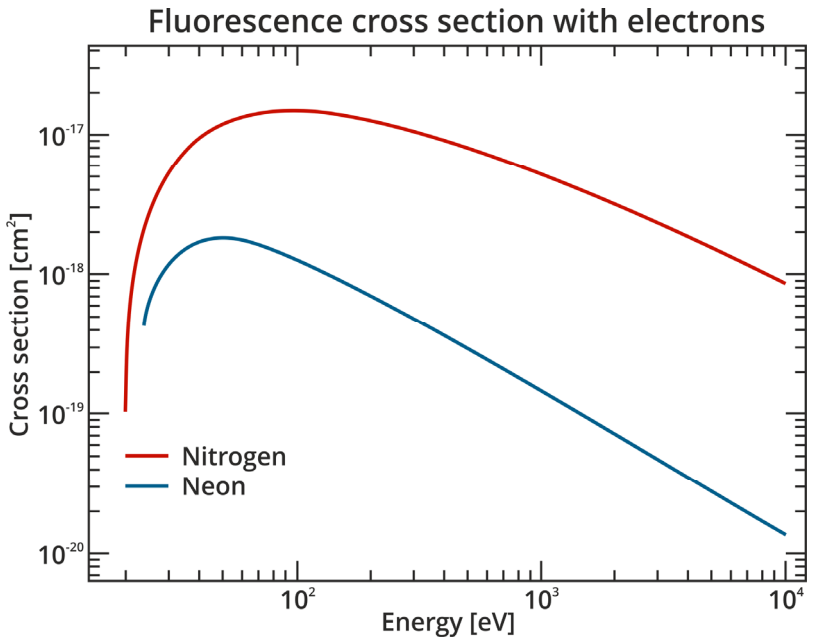


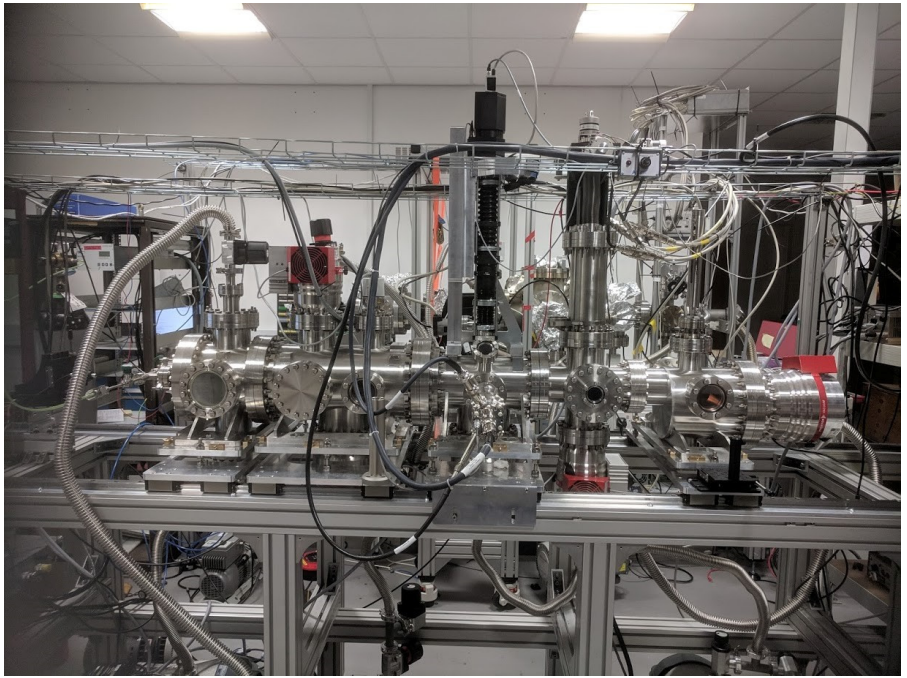
Beam Gas Curtain monitor - BGC

- Hollow Electron Lens (HEL) to collimate beam halo – both beams must be concentric
- 2D image of both beams on supersonic gas “screen”
- Beam Induced Fluorescence: minimally invasive and unaffected by strong solenoid field
- Compatible with both low and high energy beams
- Gases under study: N_2, Ne, Ar



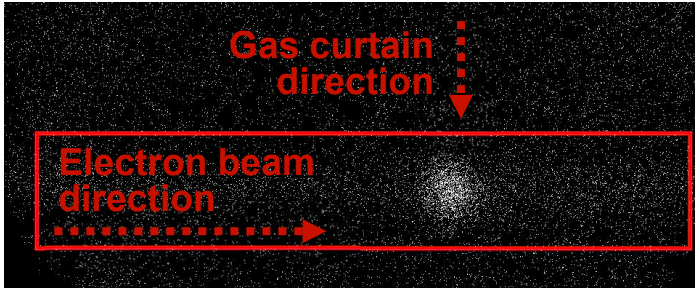
BGC prototype

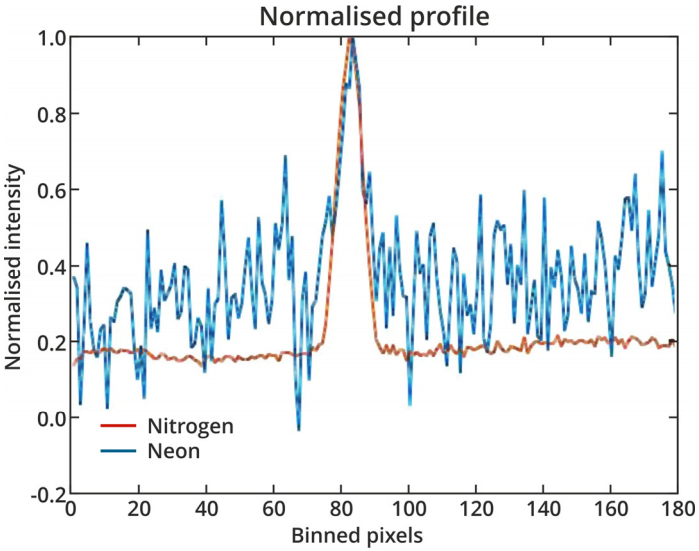
- Prototype BGC built at Cockcroft Institute (UK)
- Three gases tested with 5 keV electron beam at 0.65 mA



BGC prototype

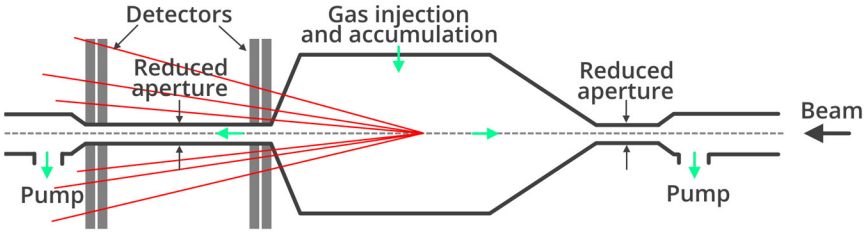
- Prototype BGC built at Cockcroft Institute (UK)
- Three gases tested with 5 keV electron beam at 0.65 mA
- Fluorescence observed with all gases
- HL-LHC HEL electron beam current ~5 A – much higher photos flux
- Extensive simulation and engineering work put into gas curtain generation

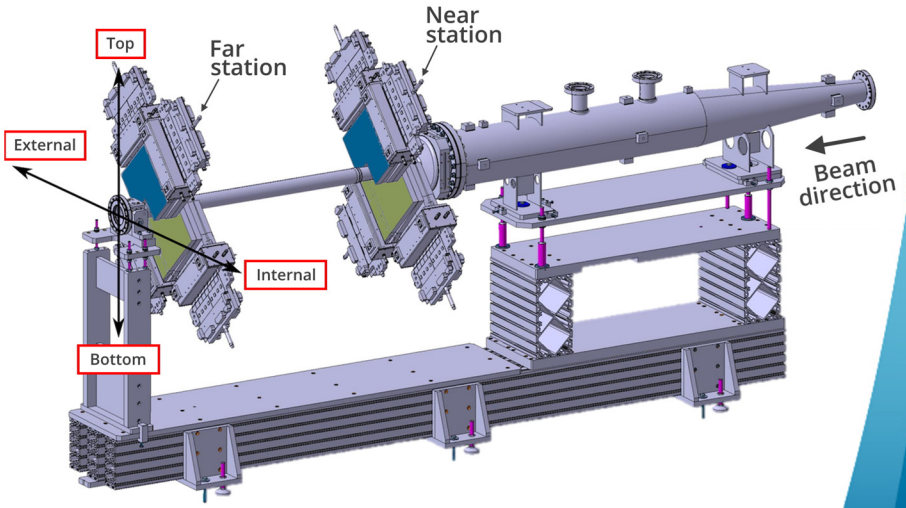




Beam Gas Vertex monitor - BGV

- Currently, no reliable emittance measurements during energy ramp with a full LHC beam
- Beam-gas interaction track reconstruction under study as a non-invasive measurement
- Demonstrator installed in 2014 using neon at $5 \cdot 10^{-8}$ mbar and scintillating fibres from LHCb





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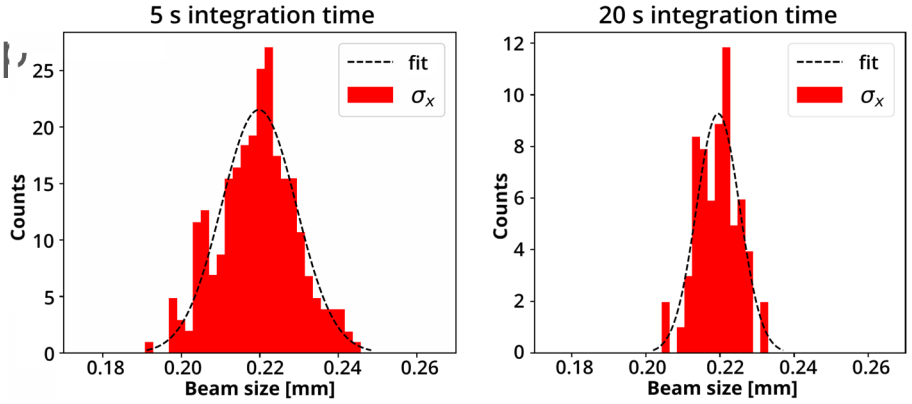
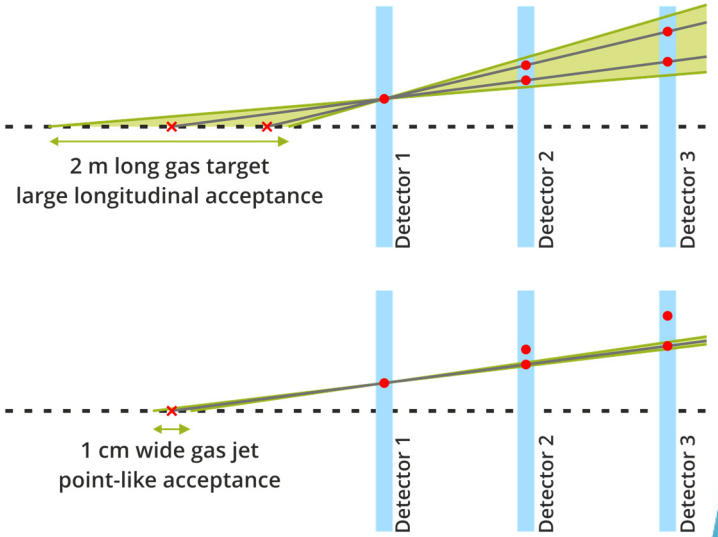
- Beam-gas interaction track reconstruction under study as a non-invasive measurement
- Demonstrator installed in 2014 using neon at $5 \cdot 10^{-8}$ mbar and scintillating fibres from LHCb
- ~20 s integration for 2 % precision at 6.5 TeV
- Demonstrated beam size measurements through the ramp



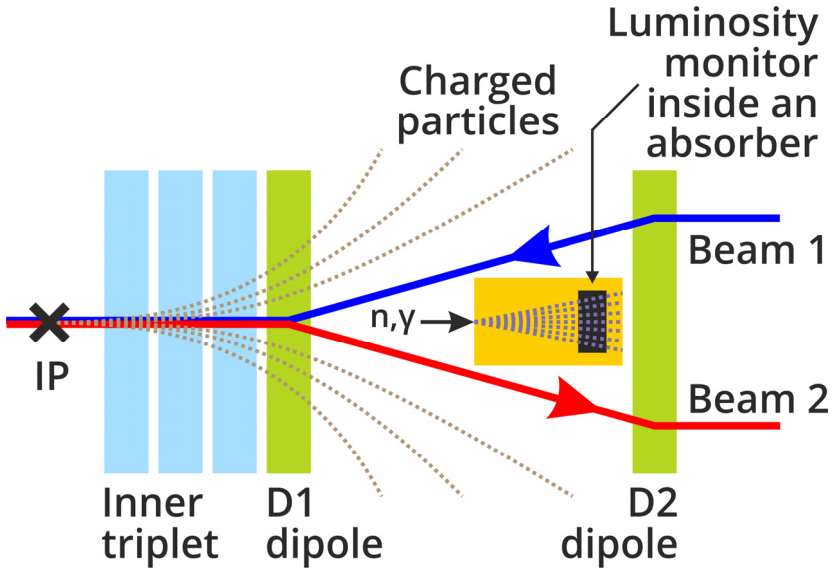
HL-LHC BGV design

- BGV is a candidate instrument for HL-LHC beam size measurements
- Final design proposal by the end of 2020
- Performance target:
  - 5% resolution with a single bunch
  - 2% absolute accuracy with the whole beam
  - < 1 minute integration time
- Various improvements under study:
  - Addition of a third detector plane
  - Other detector technologies (silicon, gaseous)
  - Using a gas jet instead of large gas volume to reduce longitudinal acceptance region
- Optimal location to be identified: symmetric optical functions, large beam size, small aperture



Luminosity monitoring - BRAN

- Luminosity monitoring independent of experiments
- LHC: ionisation chambers measuring the shower created by forward neutral debris



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- HL-LHC: fused silica rods producing Cherenkov radiation under study
- Prototype installed and tested in the LHC

400 x 10 mm

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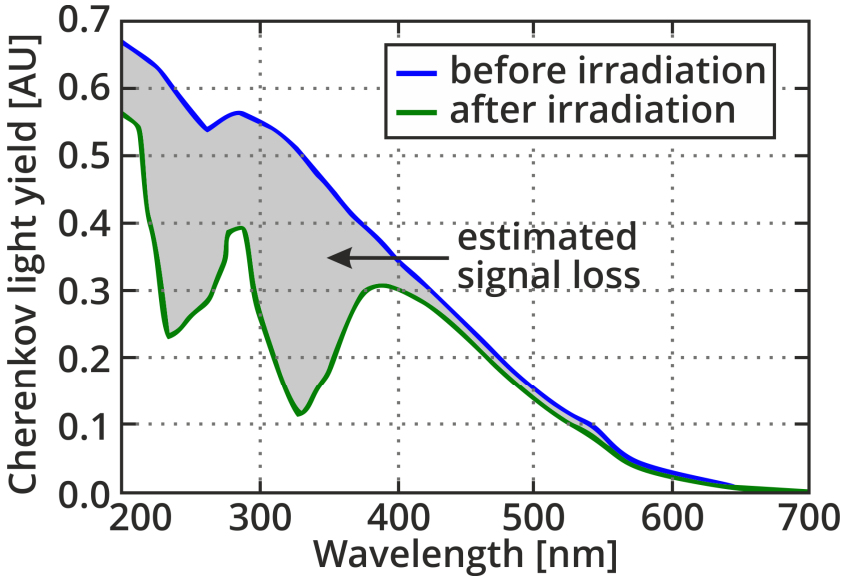
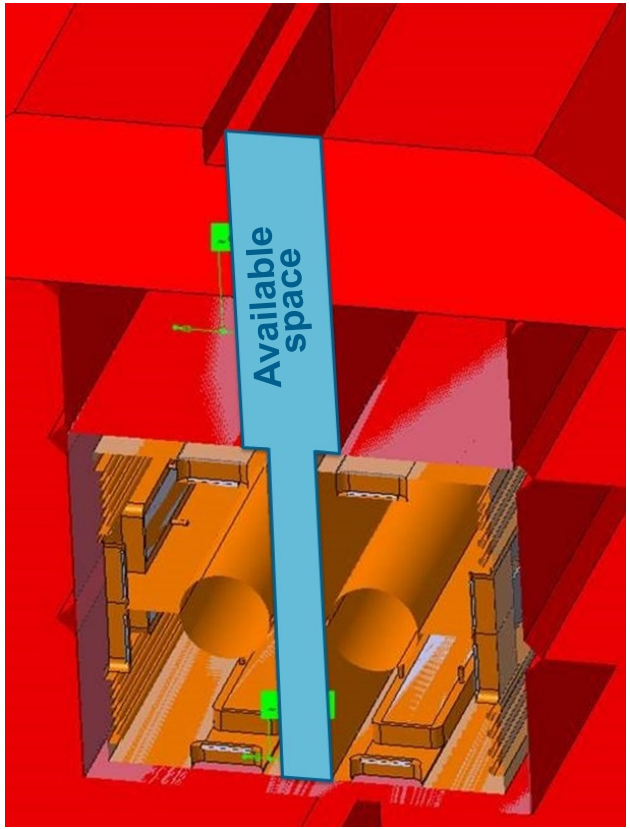
- LHC: ionisation chambers measuring the shower created by forward neutral debris
- HL-LHC: fused silica rods producing Cherenkov radiation under study
- Prototype installed and tested in the LHC
- Rod darkening observed within first 10 fb^{-1}



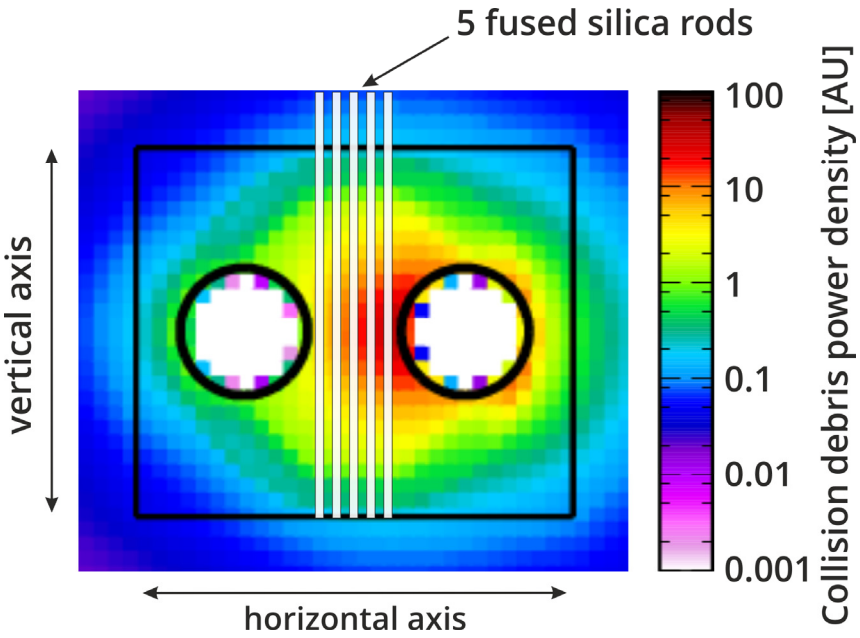
Luminosity monitoring with varying crossing angle

- Beams collided at an angle
- Different crossing planes for ATLAS and CMS experiments
- Luminosity monitor installed in the same orientation for both



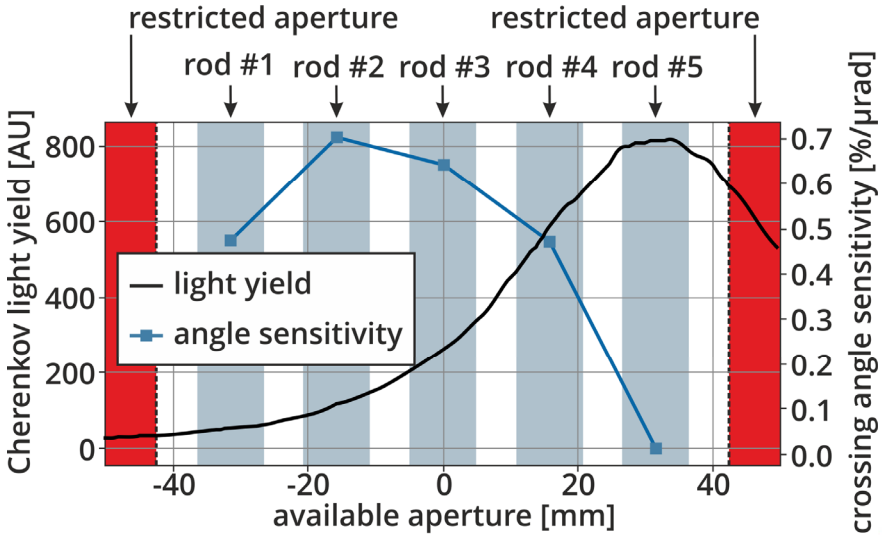
Luminosity monitoring with varying crossing angle

- Beams collided at an angle
- Different crossing planes for ATLAS and CMS experiments
- Luminosity monitor installed in the same orientation for both
- Not all rods irradiated with the same power



Luminosity monitoring with varying crossing angle

- Beams collided at an angle
- Different crossing planes for ATLAS and CMS experiments
- Luminosity monitor installed in the same orientation for both
- Not all rods irradiated with the same power
- Sensitivity to the crossing angle ~10% for a 15 µrad change



Summary

- HL-LHC requires new and upgraded instrumentation
- Currently – peak of R&D
- Design of **new BPMs** for the interaction regions is well advanced
- **Electro-optic BPM** prototype tested in the SPS
- **Coronagraph** demonstrated 10^{-4} contrast in the LHC
- **Beam Gas Vertex monitor** demonstrator shown to continually measure beam size during energy ramp
- Fused silica rods a promising candidate for upgrading the **LHC luminosity monitors**
- **Beam Gas Curtain monitor** prototype successfully demonstrated beam size measurement using beam induced fluorescence at Cockcroft Institute
- Consolidation of many other existing instrumentation systems foreseen (BLM and BPM read-out, wirescanners, synchrotron light monitor, …)
- Beam commissioning foreseen in 7 years

Thank you for your attention

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