BEAM INSTRUMENTATION AND DIAGNOSTICS FOR HIGH LUMINOSITY LHC

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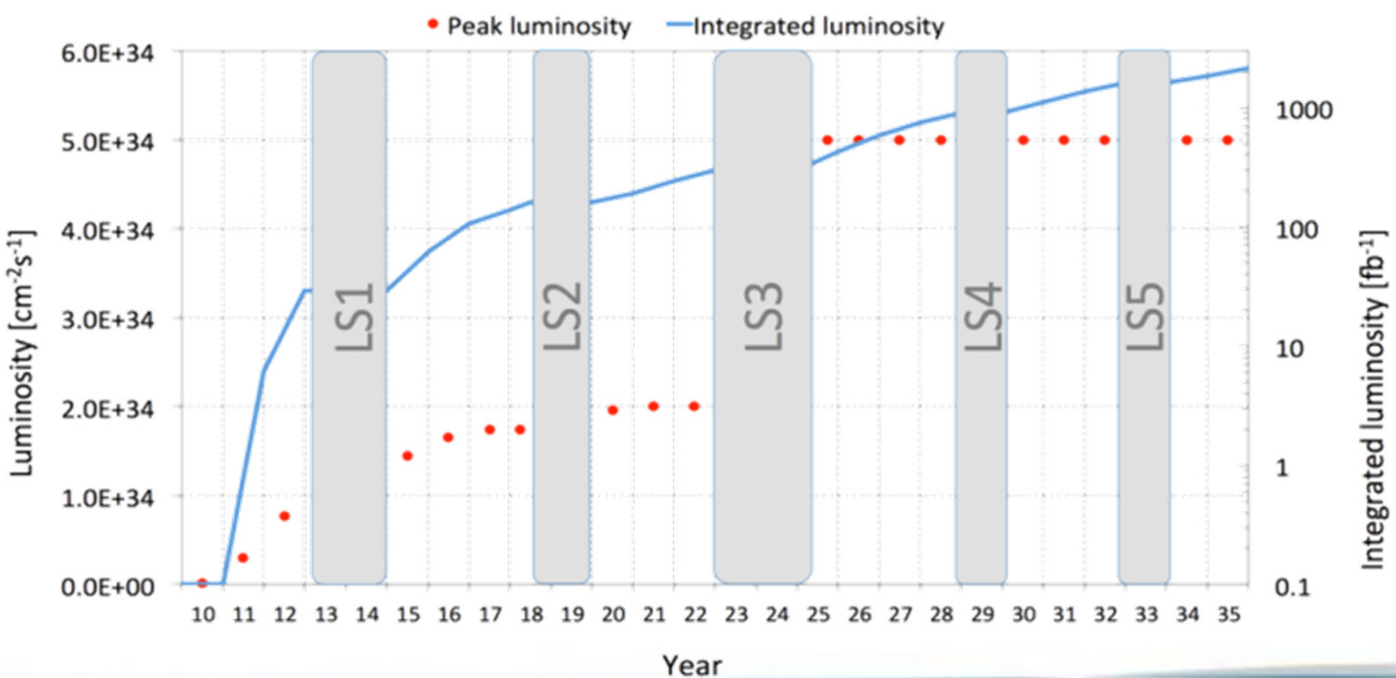
IPAC15

Outline

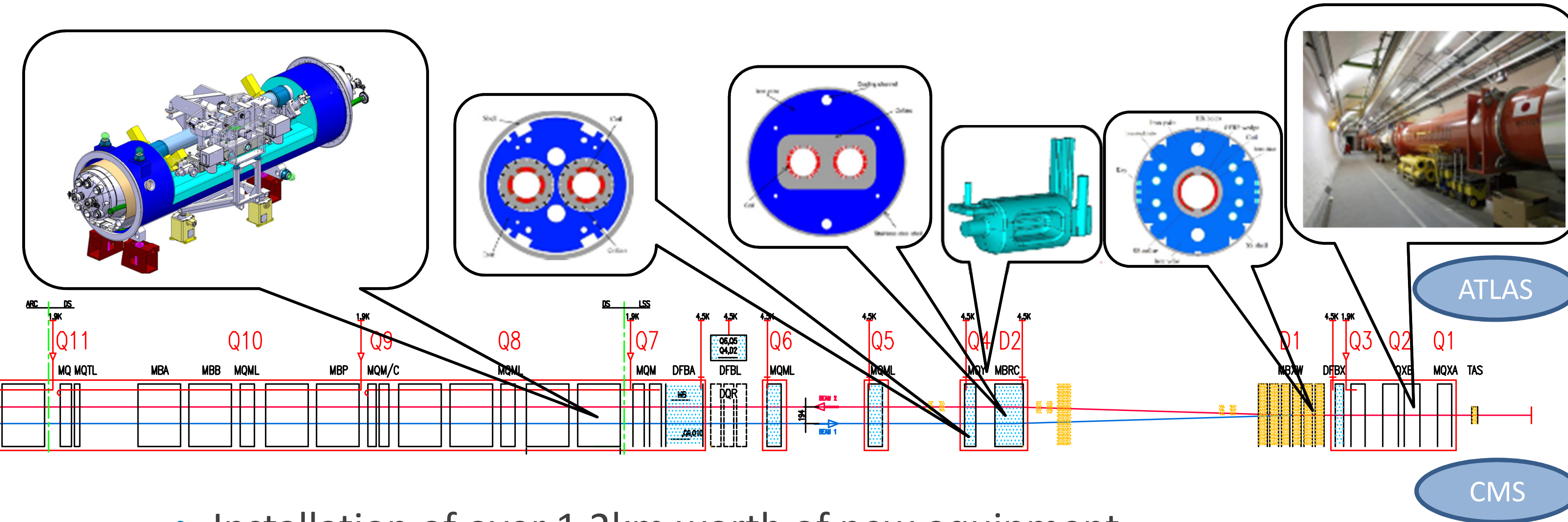
- Goal of the High Luminosity LHC Project
  - Main upgrades required
- Beam Instrumentation Challenges for the HL Upgrade
  - Beam loss monitoring
  - Beam position monitoring
  - Beam size measurement
  - Halo diagnostics
  - Intra-bunch diagnostics
- Summary

Goal of High Luminosity LHC

- Prepare LHC for operation beyond 2025
- Achieve a total integrated luminosity of 3000 fb^{-1} by 2035
  - Ten times luminosity reach of first 10 years of LHC operation
  - Integrated luminosity of 250 fb^{-1} per year (Levelled luminosity of 5×10^{34} cm^{-2} s^{-1})
- Parameters compared to nominal LHC
  - 2 × current (bunch & total) ; 3 × smaller β^* ; 2/3 of emittance



Critical zones around ATLAS & CMS



- Installation of over 1.2km worth of new equipment
  - New triplets using Nb_3Sn technology
  - Addition of Crab Cavities & new D1, D2, Q4 & correctors
  - 11 T Nb_3Sn dipole to allow extra collimator in dispersion suppressor
- Elimination of technical bottlenecks
  - Cryogenic system upgrades
  - Relocation of power converters – high temperature superconducting links
- Need for new beam instrumentation to further optimise the machine

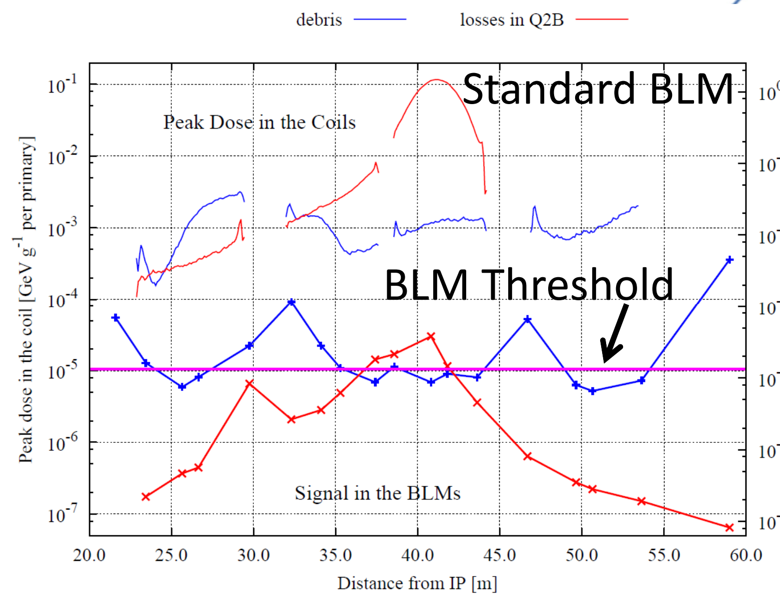
Beam Loss Monitoring for HL-LHC

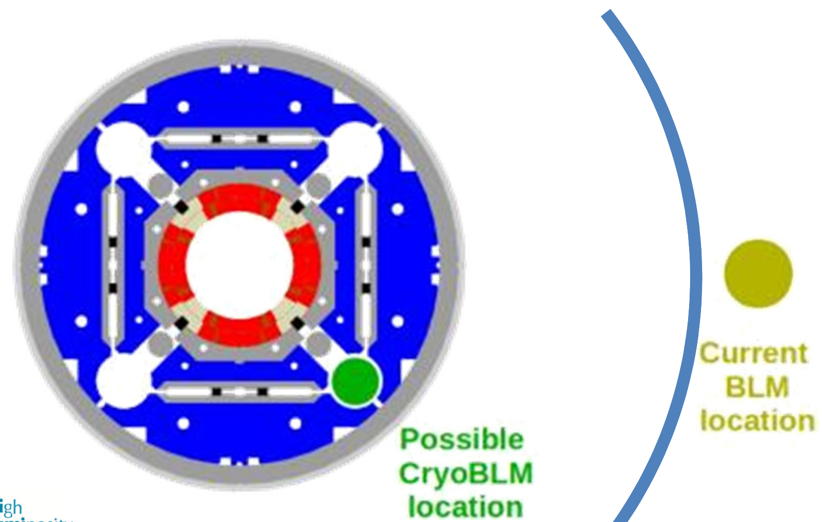
- Essential for safe & reliable operation of LHC
  - Prevents damage to accelerator components
  - Avoids quenches & associated time-consuming cryo recovery

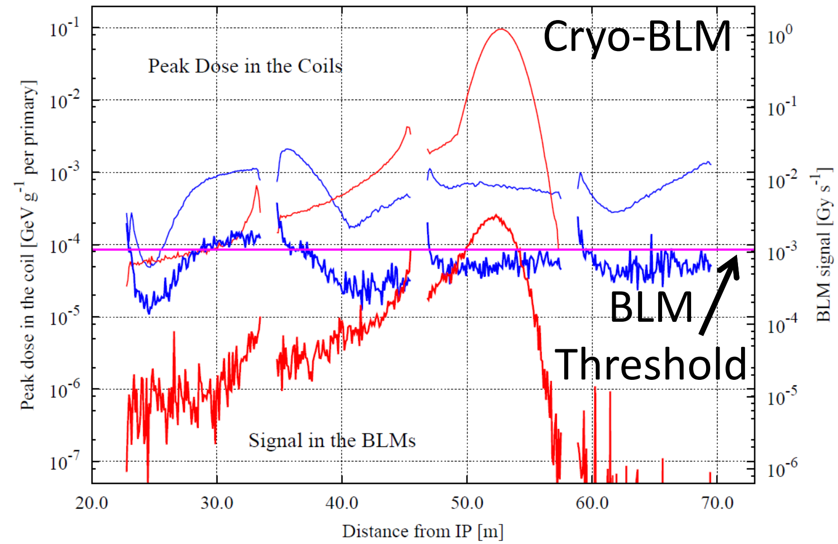
- Existing system
  - Meets needs of the HL-LHC in arc regions
    - ~3000 ionisation chambers
    - Radiation tolerant front-end electronics
- New requirements for high luminosity interaction points
  - Cryogenic beam loss monitors for triplet magnets
  - Radiation Hard front-end electronics

Cryogenic Beam Loss Monitors

- HL-LHC triplets running close to quench limit due to luminosity
- Current BLM thresholds factor 3 below quench level
  - Not possible for HL-LHC triplet
  - Need more precise measurement
- CryoBLMs give 2-3 times better separation of debris & loss

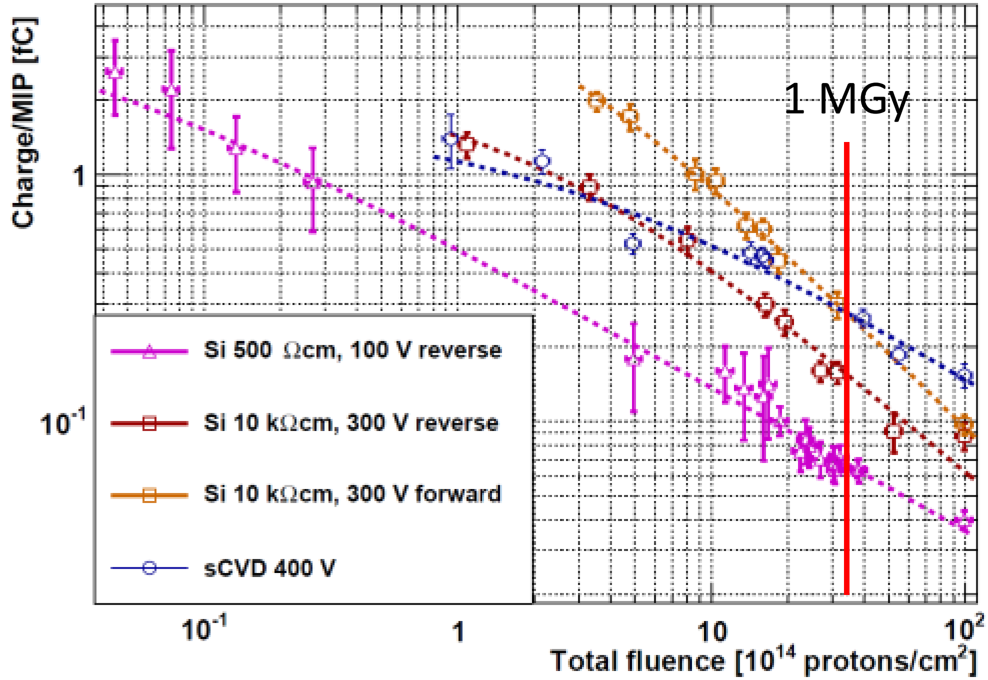






Cryogenic Beam Loss Monitors

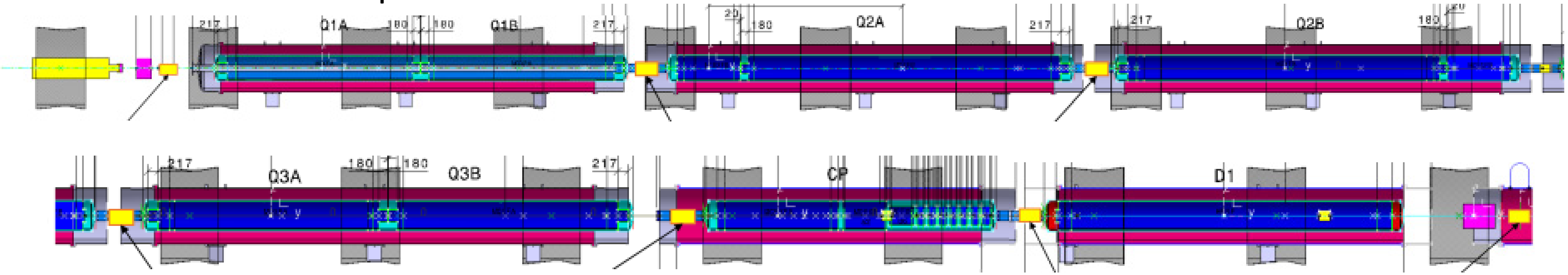
- Two types of detectors tested under irradiation at cold (2K) up to several MGy
  - Single crystal chemical vapour deposition (CVD) diamond
  - p^+-n-n^+ silicon
- Charge collection efficiency degrades by factor 15 in both up to 20 MGy
- Higher leakage current of Si when irradiated at warm disappears when irradiated at cold
- Now testing both detectors in LHC under operational conditions



Beam Position Monitoring for HL-LHC

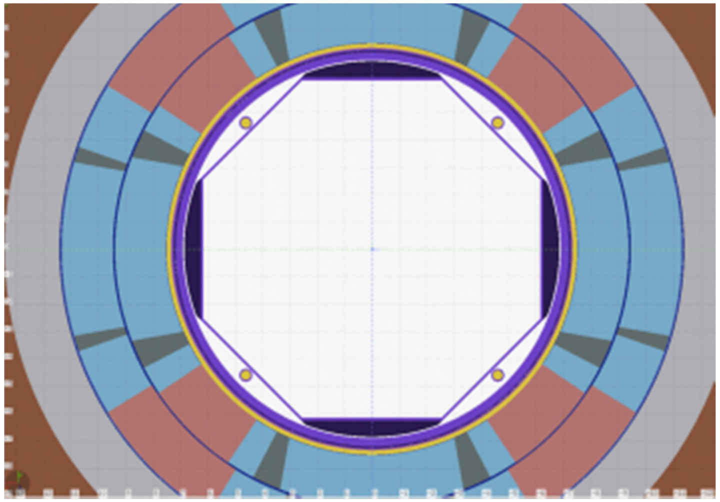
- Beam Position System
  - Over 500 BPMs per beam capable of bunch by bunch acquisition
    - No performance increase required for arc BPMs
    - Renovation of the electronics foreseen for Long Shutdown 3 (2023-2025)
- New BPMs required for HL-LHC insertion regions
    - Directional stripline BPMs
    - Distinguish between both beams (in same vacuum chamber)
    - Limited by signal isolation of one beam on the other
      - Location optimised for time separation
      - Directivity optimised by design

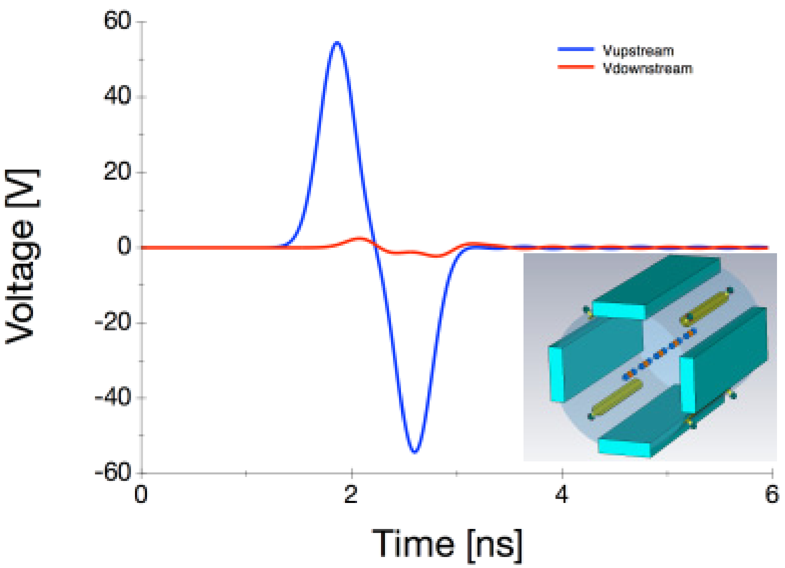
← Towards collision point



Directional Stripline Couplers

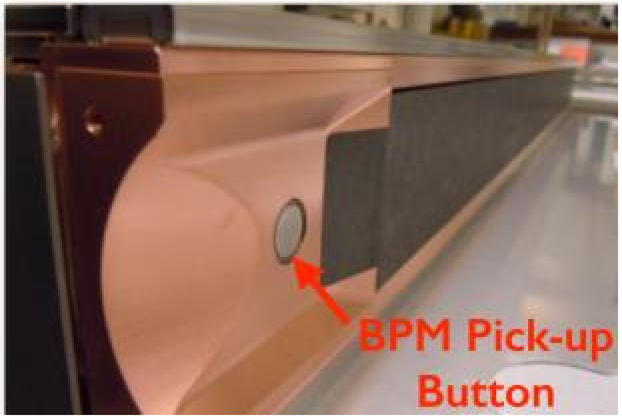
- Current BPMs suffer from limited directivity (~27 dB @ 70MHz)
  - Leads to position error from tens to hundreds of microns
- New designs being pursued to improve this
  - 7-10 dB improvement demonstrated in simulation
  - Next step is to turn this into mechanical design with all the constraints of a cryogenic BPM
- Added constraint
  - Integration of Tungsten shielding
  - Required to maintain uniform cold bore aperture to limit energy deposition in magnet coils

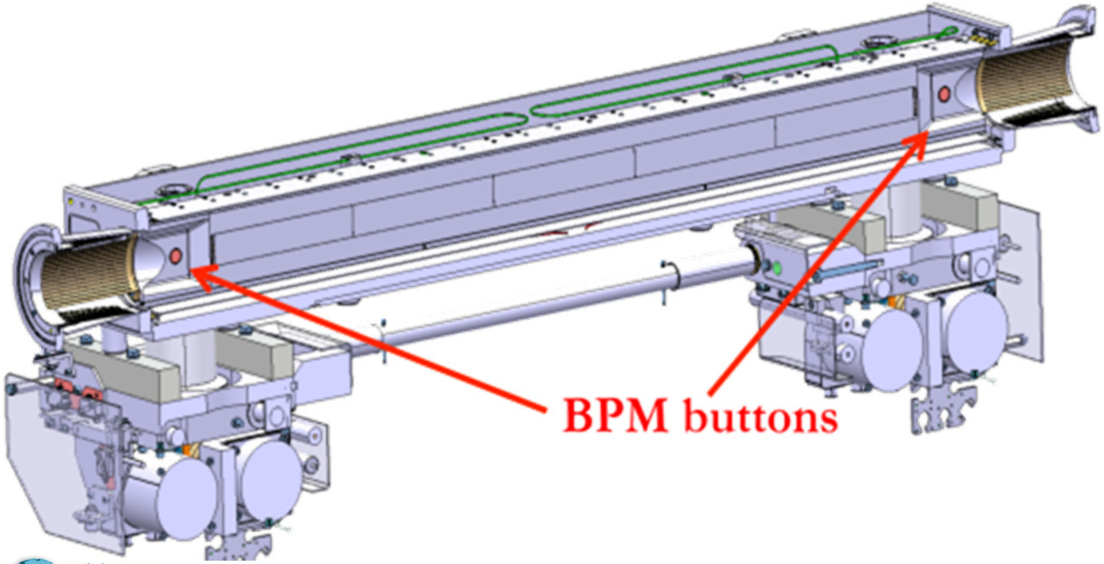


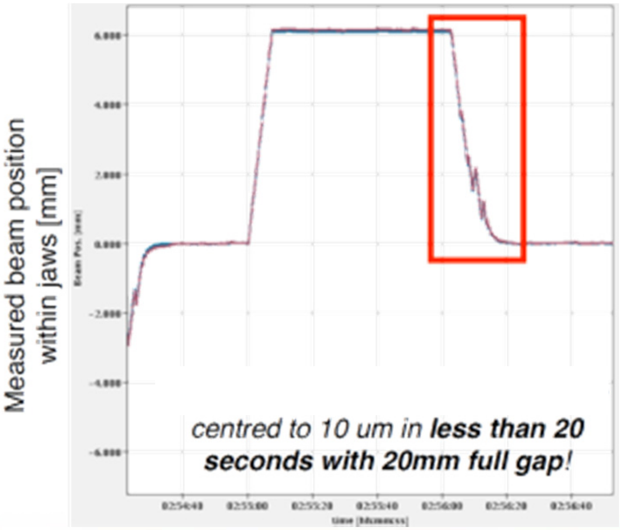


Collimators with Embedded BPMs

- All future collimators to be equipped with BPM buttons
  - 18 such tertiary collimators already installed
- Readout via new Diode Orbit electronics
  - Resolution < 100 nm for centred beams
- Parallel jaw alignment in < 20 seconds
  - 2 orders of magnitude faster than BLM method



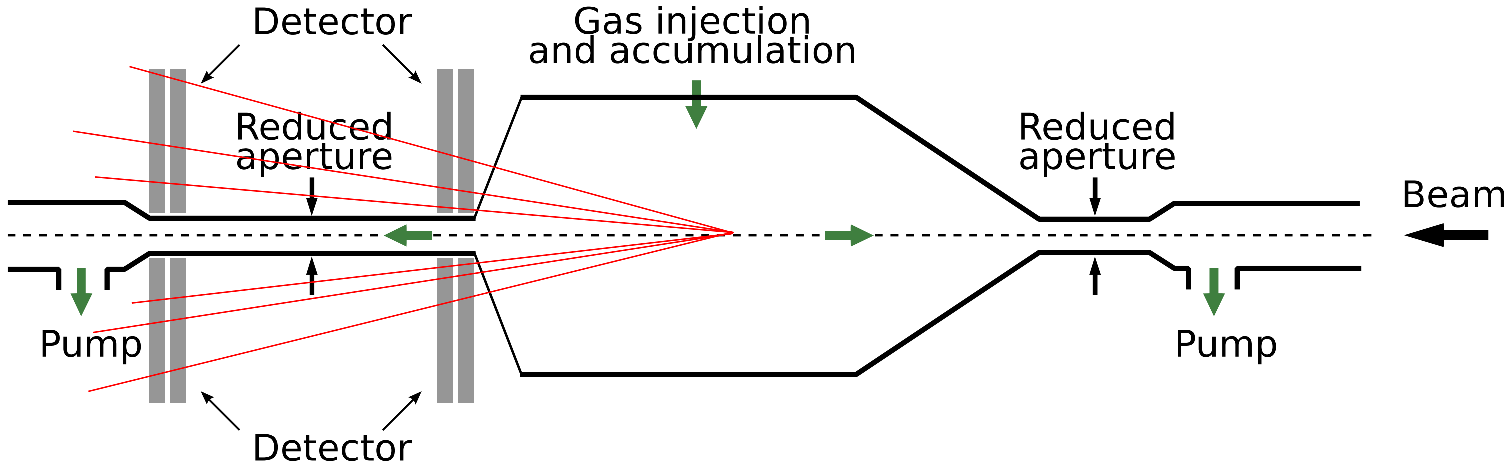




High Luminosity LHC

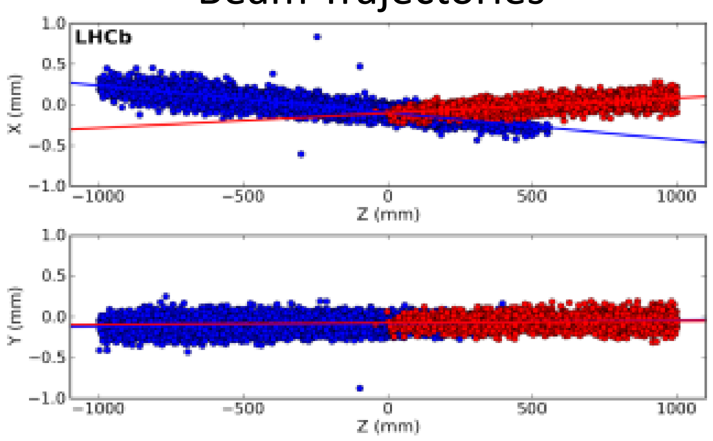
Non-invasive beam size measurement

- The Beam Gas Vertex Detector
  - To overcome limitations of wire scanner & synchrotron light

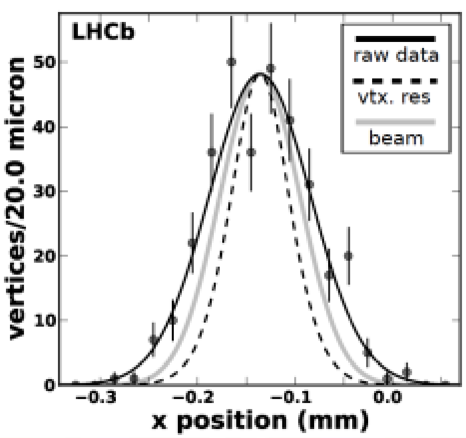


- Concept used by LHCb vertex detector (VELO)
- Collaboration between CERN, EPFL (CH), RWTH (DE)

Beam Trajectories

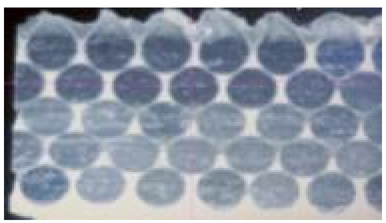


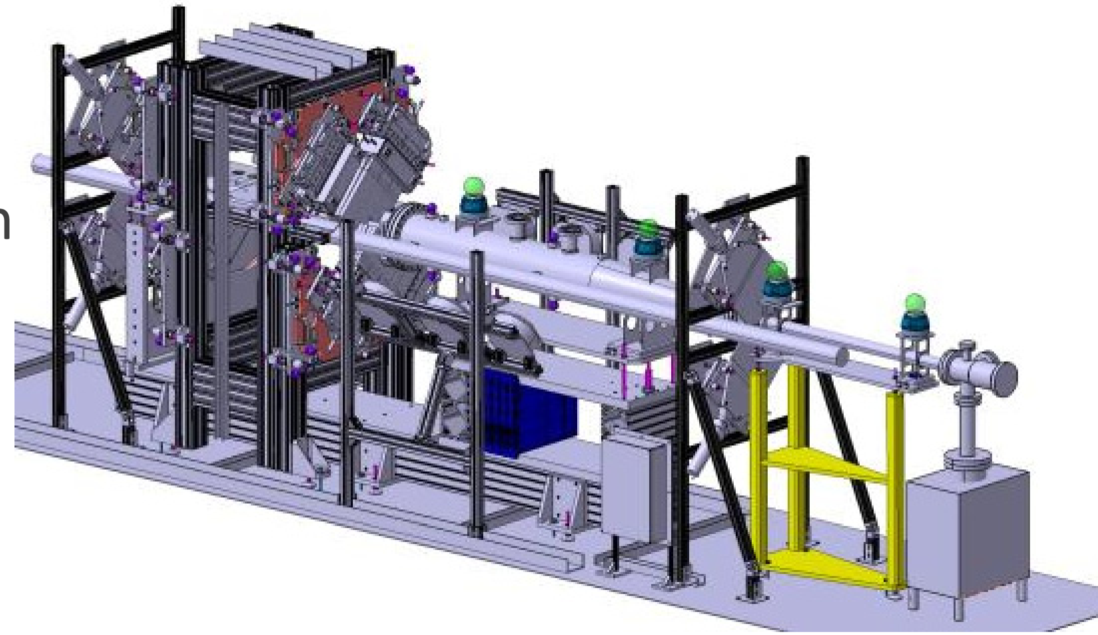
Beam Profile

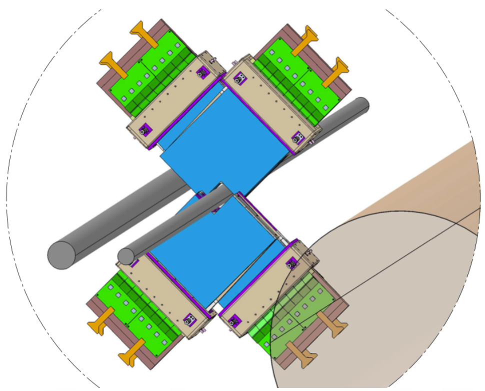


Non-invasive beam size measurement

- Prototype installed on one beam during LS1
  - Detectors based on scintillating fibres
  - Read-out with Silicon Photomultipliers





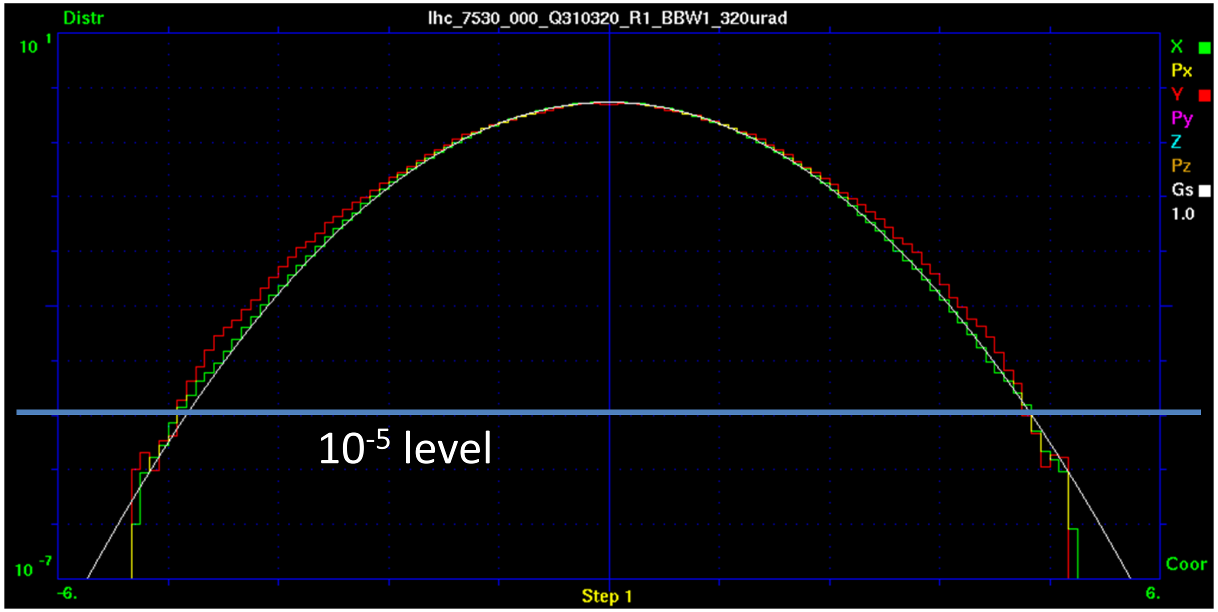


Quantity	Accuracy	Time interval	Key factors
Relative bunch width	5 %	< 1 min	vertex resolution stability
Absolute average beam width	2 %	< 1 min	σ_{beam}, σ_{MS}, σ_{extrap} (σ_{hit})

Halo Diagnostics for HL-LHC

- No instrumentation currently installed in LHC to measure the beam halo
- Important for HL-LHC
  - Mitigate crab cavity failure by measuring the halo
    - Excessive halo population can be quickly lost on crab failure
  - Essential diagnostic for several options currently considered
    - Hollow electron beam collimation
    - Long range beam-beam compensators

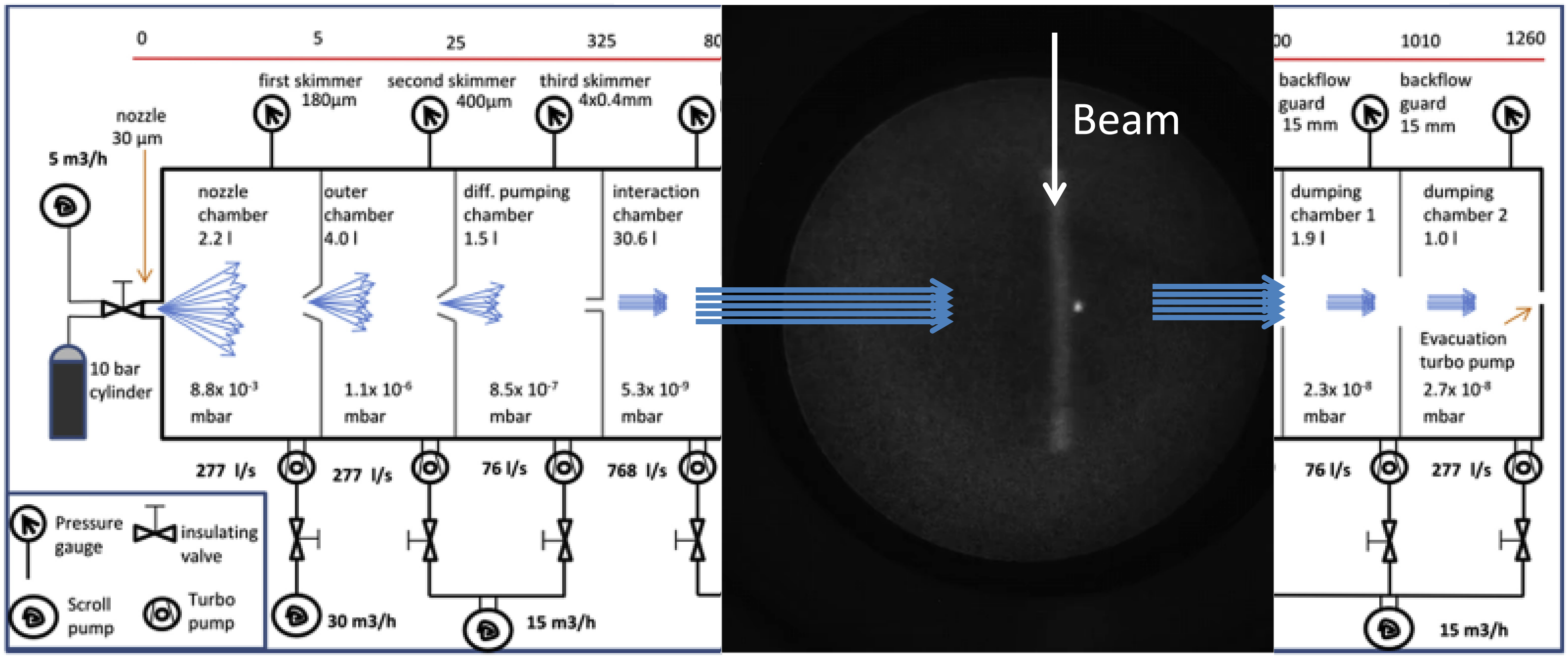
- Non-Invasive techniques being considered
  - Use of gas jets
  - Optical techniques using synchrotron radiation



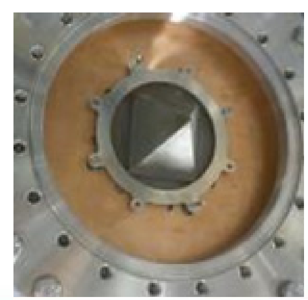
Courtesy of
Alexander Valishev

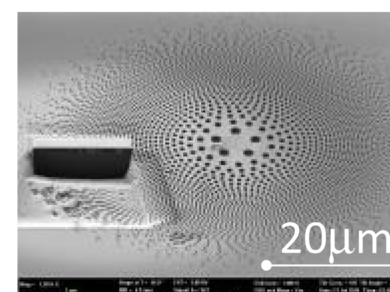
Gas Jet Techniques

- Gas sheet & luminescence (University of Liverpool (UK) & CERN)
  - Being considered for hollow electron lens diagnostics



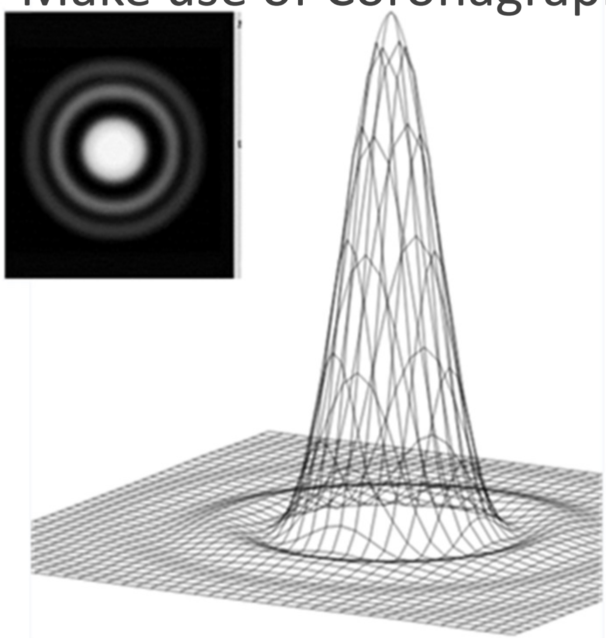
- Gas jet scanner - alternative to wire-scanner
  - Use of atomic sieve to focus neutral gas atoms
    - Quantum interference
  - Scan faster/slower for core/halo

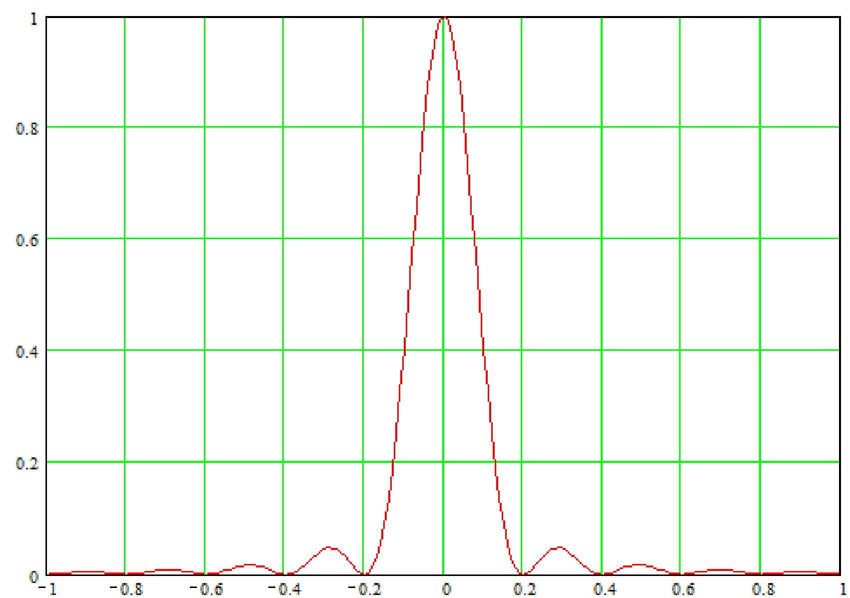




Coronagraph for Halo Diagnostics

- Diffraction creates fringes surrounding central beam image
- Intensity of fringes in range of 10^{-2} to 10^{-3} of peak intensity
- Masks observation of weak halo at 10^{-5}
    - Need a way to reduce effect of diffraction fringes
- Make use of Coronagraph developed for astronomy





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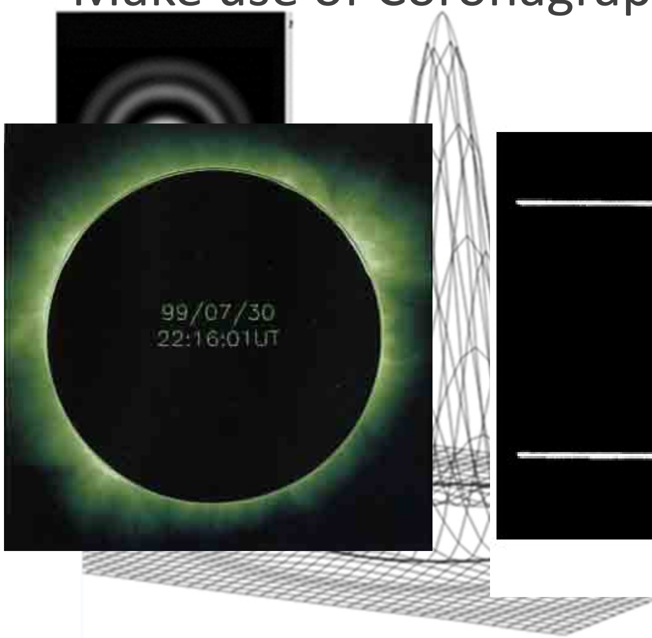
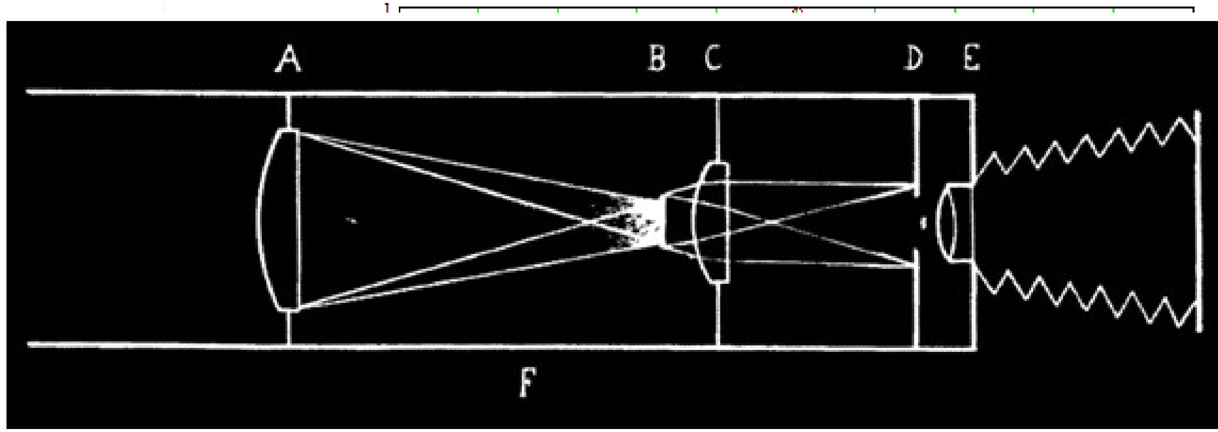
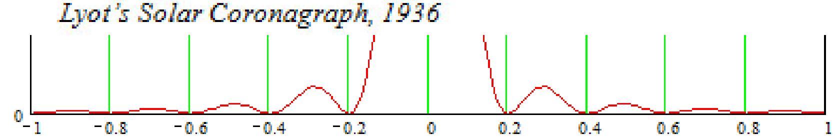


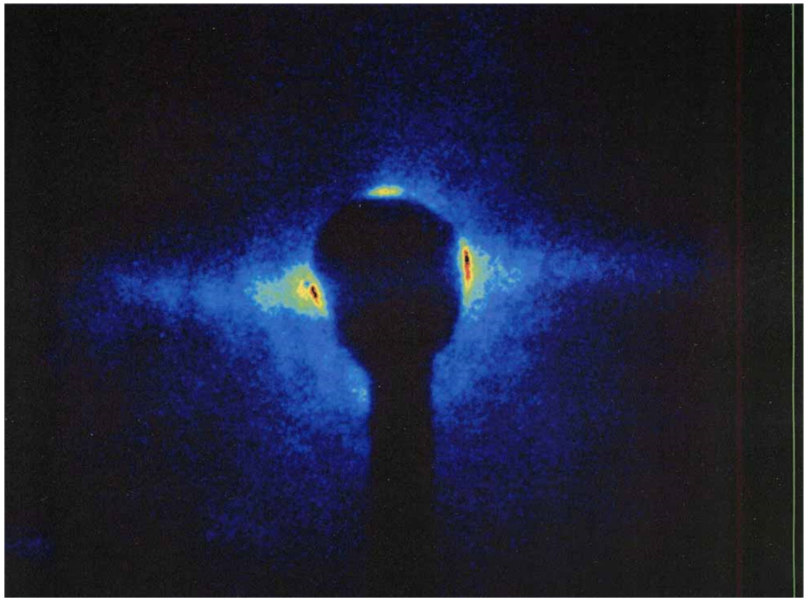


Lyot's Solar Coronagraph, 1936



Coronagraph for Halo Diagnostics

- Demonstrated at KEK Photon Factory
  - Achieved ratio for background to peak intensity of $6x10^{-7}$
  - Spatial resolution of about 50µm
- Main challenge
  - Avoid noise from imperfections or dust on objective lens



Courtesy of Toshiyuki Mitsuhashi

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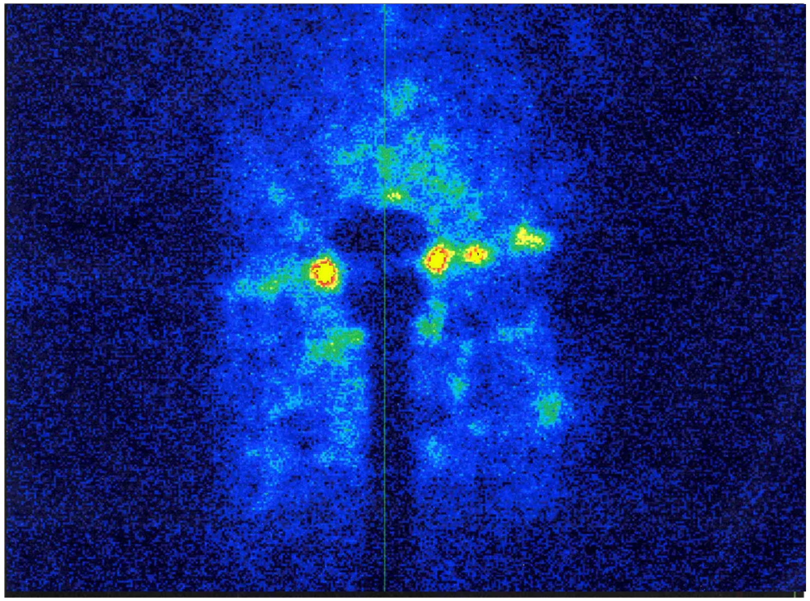
- Demonstrated at KEK Photon Factory
  - Achieved ratio for background to peak intensity of 6×10^{-7}
  - Spatial resolution of about 50μm
- Main challenge
  - Avoid noise from imperfections or dust on objective lens
- Preliminary estimation for HL-LHC
  - Seems possible to reduce background from diffraction to 10^{-6} in region of interest
  - Should be able to image halo to few mm surrounding the beam core with 0.1 - 0.2 mm spatial resolution
- Collaboration with KEK



Courtesy of Toshiyuki Mitsuhashi

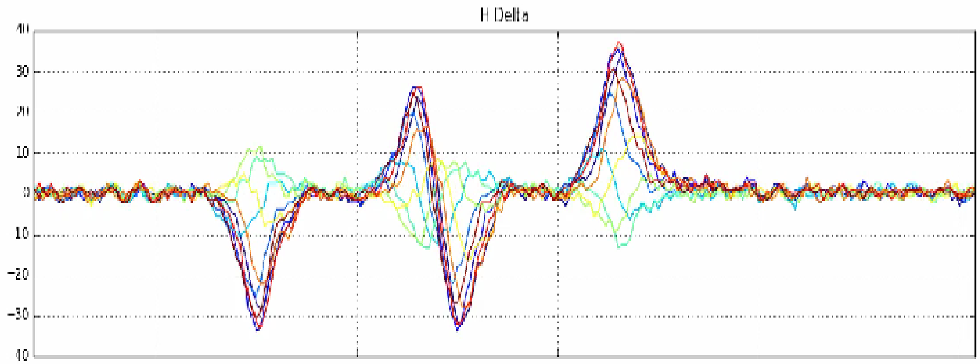
Intra-Bunch Diagnostics

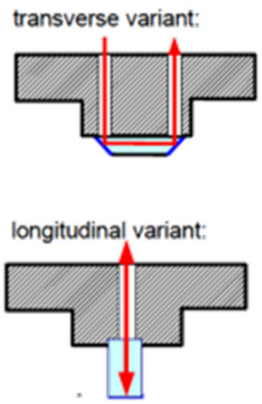
- Already important for understanding instabilities
  - Electron cloud, impedance, beam-beam, ….
- Will also be essential for crab cavity diagnostics
  - Understanding their effect on the beam
- Two methods being investigated
  - Streak cameras looking at synchrotron radiation
    - Will require new light extraction line to be built
    - Light transport to radiation free area
  - High resolution electromagnetic pick-ups

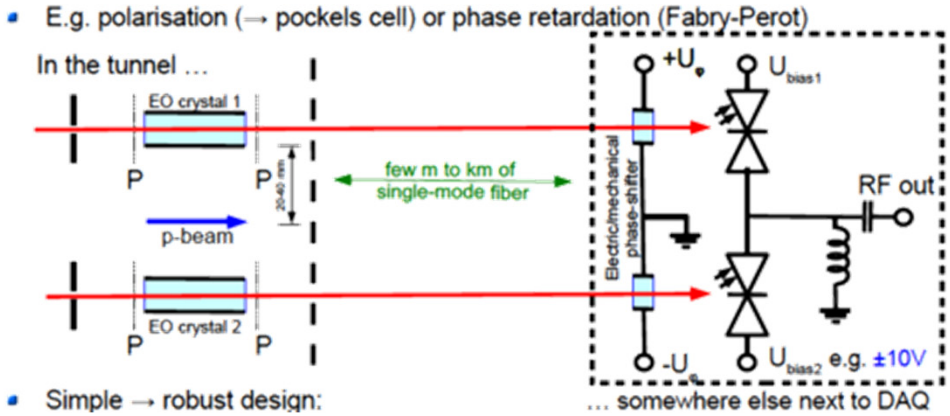
High Luminosity LHC

Intra-Bunch Diagnostics

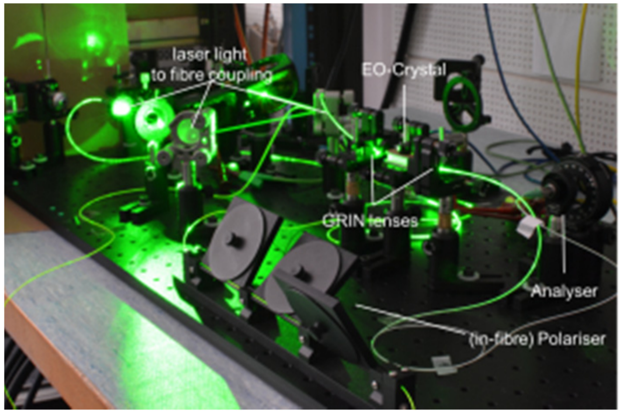
- Electromagnetic monitors already installed in LHC
  - “Head-Tail” monitors provide information on instabilities
    - Bandwidth of some 2 GHz
  - For higher resolution require bandwidth > 10 GHz
    - R&D on pick-ups based on electro-optical crystals







Lithium Niobate	Lithium Tantalate
$LiNbO_3$	$LiTaO_3$



Collaboration with Royal Holloway University of London (UK)

Summary

- LHC constructed with comprehensive suite of beam diagnostic devices
  - These play an important role in its safe & reliable operation
- HL-LHC will push the performance of LHC even further
  - Requires a deep understanding of beam related phenomena
- Can only be delivered through its beam instrumentation
  - Upgrade to many of the existing systems
  - Development of new diagnostics to address specific needs

High Luminosity LHC