International Review on the e-lens concept readiness for integration into the HL-LHC baseline

Proposed Beam Instrumentation for the Hollow Electron Lens

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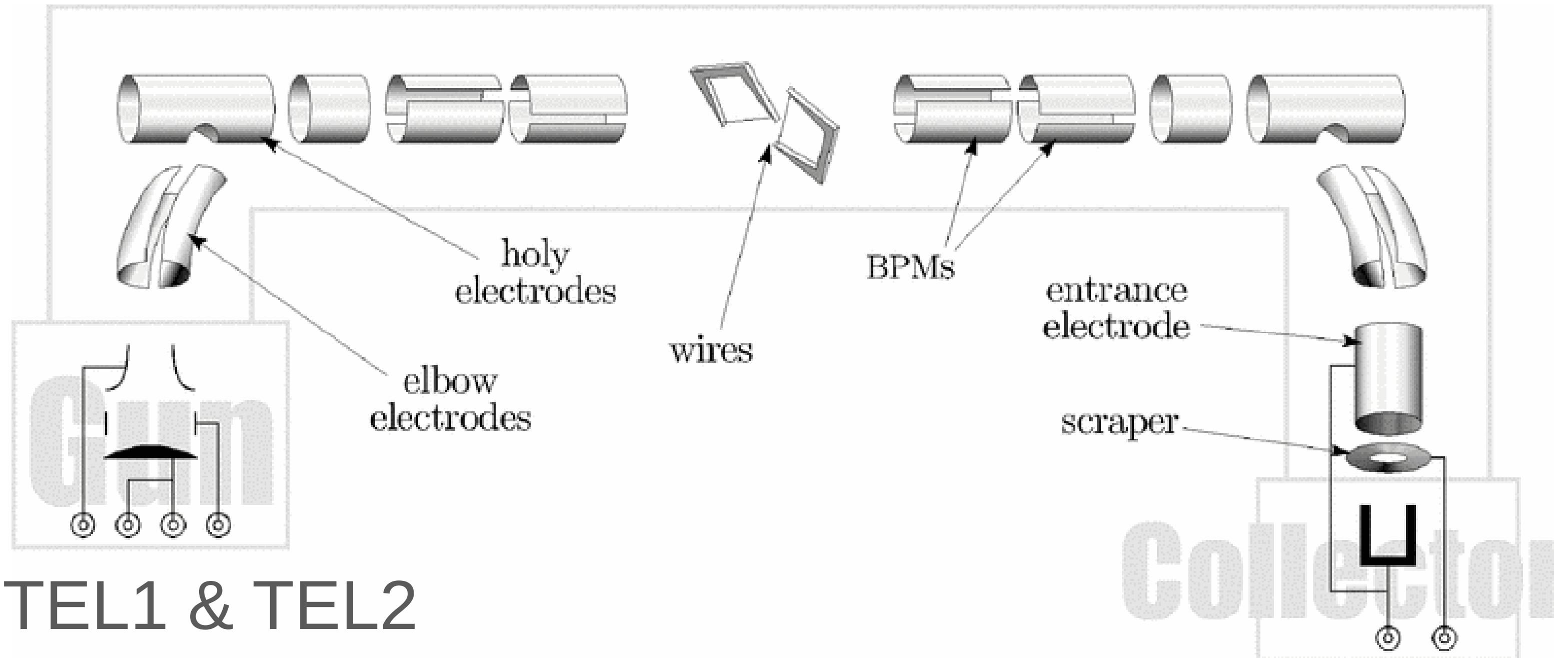
Introduction

- Beam instrumentation concepts based on experience from similar installations in FNAL and BNL
  - With much gratefully received input from G. Stancari & M. Minty
- Hollow e-lens beam instrumentation requirements
  - Alignment of proton and electron beams - the main challenge
    - Inner radius (3σ) at e-beam location 0.9mm / 1mm (Beam 1 / Beam 2)
    - Align to better than 0.2σ over 3m e-beam interaction length
      - Relative proton to electron beam position error < 60μm
  - Electron beam profile measurement
  - Electron beam current measurement
  - Beam loss monitoring for solenoid quench protection
- Other beam instrumentation requirements
  - Halo measurement
    - Ability to measure the beam halo from 3 - 6 σ
  - Beam loss monitoring at primary collimators
    - For diffusion rate studies

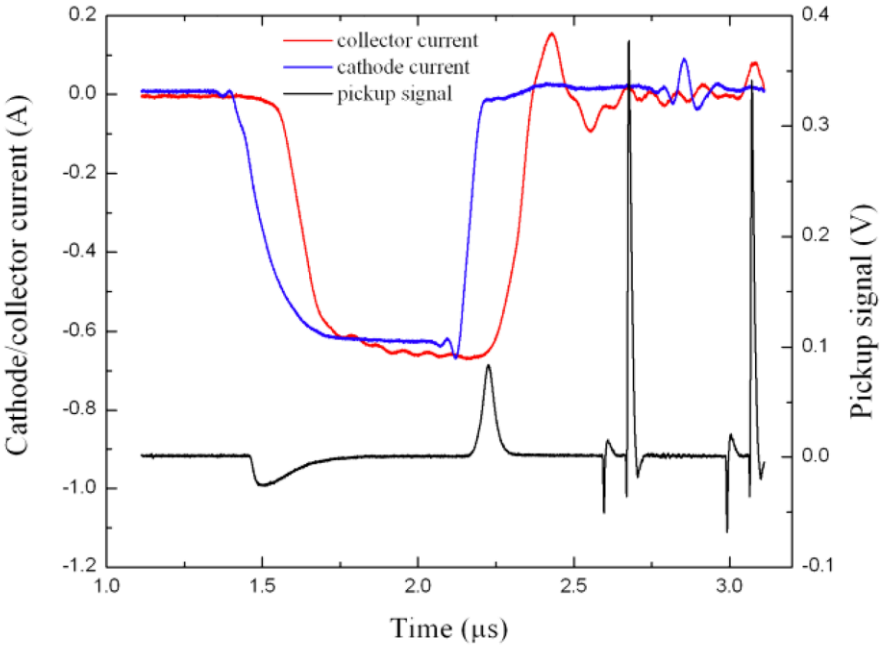
Beam Instrumentation at FNAL



- TEL1 & TEL2
  - Beam position monitors
    - Ring electrodes for losses in the elbow
    - Strip electrodes as a beam position pick-up
  - Beam profile (TEL1 only)
    - Wire scanners (broke early on) & scraper
  - Beam current
    - Via cathode & collector current measurements

Position Measurement at FNAL

- Beam Position Measurement
  - Strip-line BPMs giving signals for both e-beam and circulating beams
  - For protons were calibrated with orbit & electrostatic separator bumps
  - For electrons calibrated with the correctors in the main solenoid



V. Kamerdzhiev et al,
COMMISSIONING OF THE SECOND TEVATRON ELECTRON LENS AND BEAM STUDY RESULTS, PAC07, 2007

Challenge for HL-LHC

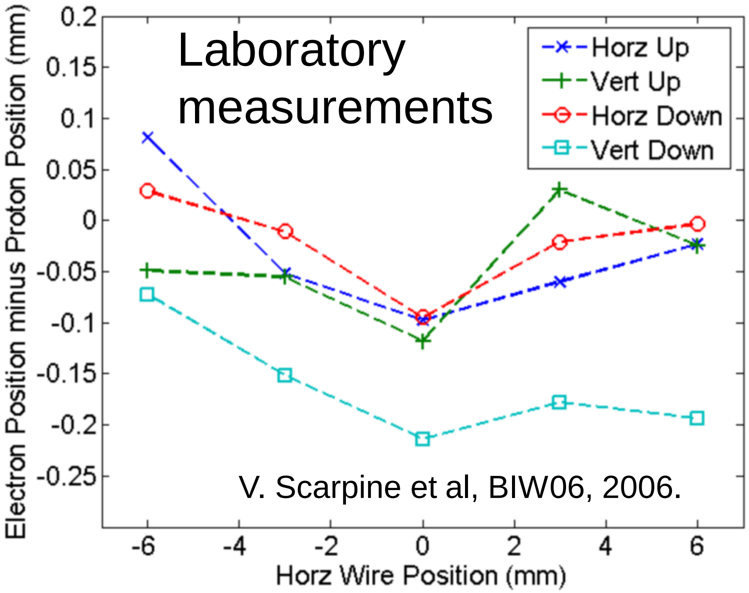
- Measuring electron beam in presence of intense peak currents from proton beam
- Gating may be necessary to measure switch-on/off of e-beam pulse in abort gap
- Will investigate if AM modulation in MHz range can be produced and tolerated on the e-beam current

Position Measurement at FNAL

- Beam Position Measurement Accuracy
  - Alignment reproducible from store to store
  - Initial BPM calibration and set-up was manual and time consuming
  - Measured offsets (in V plane) confirmed stretched wire measurements
    - Globally < 100μm over range of interest

Beam measurements	Horizontal		Vertical	
	gun	coll.	gun	coll.
Offset $(e-p)$ (mm)	-0.28 ± 0.38	-0.34 ± 0.38	$+0.01\pm0.14$	-0.05 ± 0.14

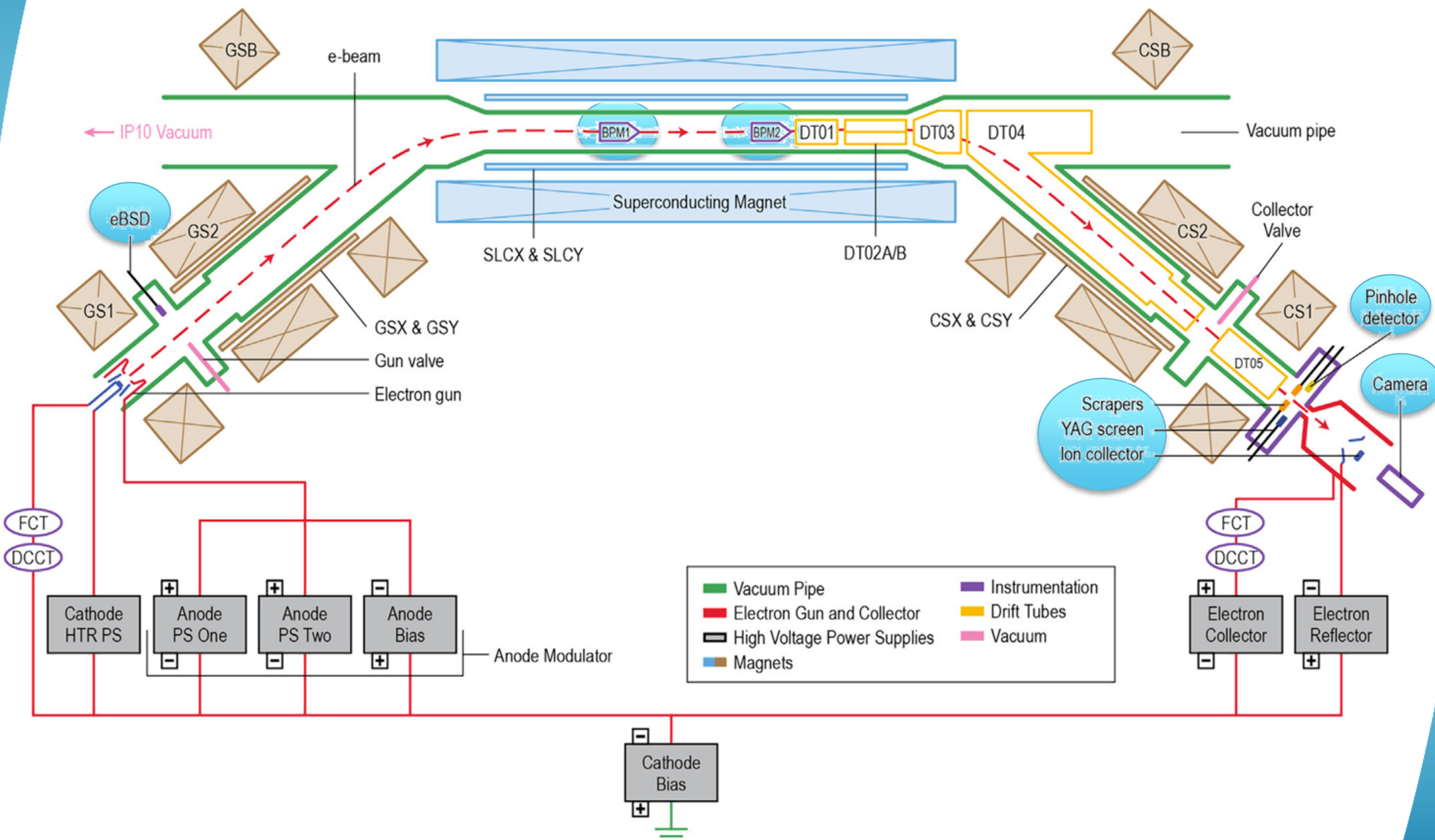
A. Romanov et al, Fermilab note Beams-doc-3542-v2 Feb. 2010.



Challenge for HL-LHC

- Reducing systematics further to reach offsets < 60μm
  - Variation with intensity
  - Variation with e- & p+ beam position
- Ensuring fill-to-fill reproducibility at this level
  - Currently achieving ~30μm with special electronics at LHC IR BPMs

Beam Instrumentation at BNL



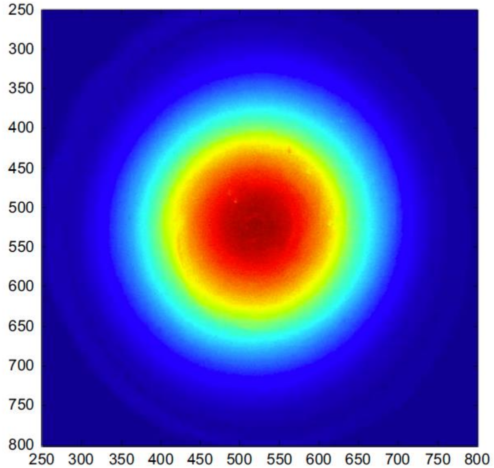
The BNL Profile Monitors

- YAG screen in front of collector to measure beam profile with low repetition rate
  - Main profile measurement device
  - Tested to near destruction with an 80μs long pulse with up to 660mA of electron beam at 1Hz
    - “At this point the crystal was heating so much that it began to bow between shots”
- Pinhole and collector assembly
  - Operated up to 1A with 12μs long pulses with 1-10 Hz rate
  - 80 x 80 scan takes >10 mins

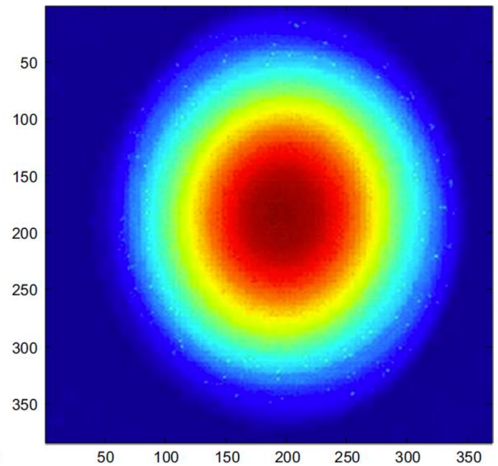
The BNL Profile Monitors

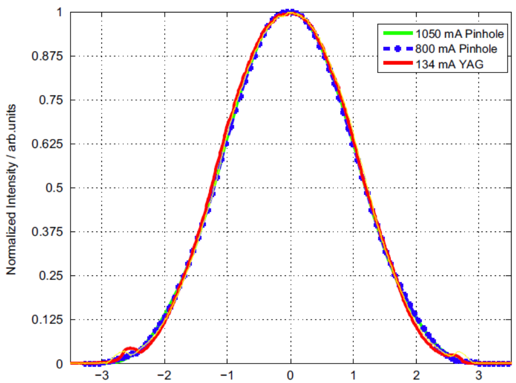
- Extensively used to study transverse profile evolution of the electron beam for different currents to confirm simulations of space charge effects

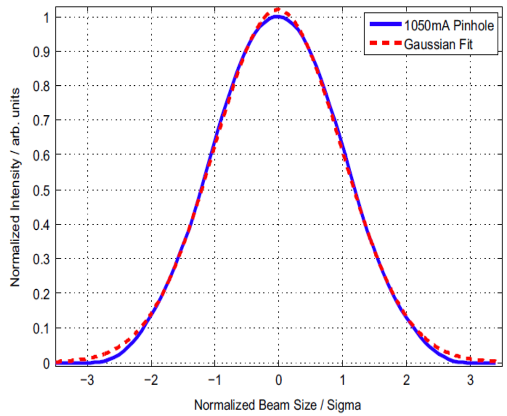
YAG Screen



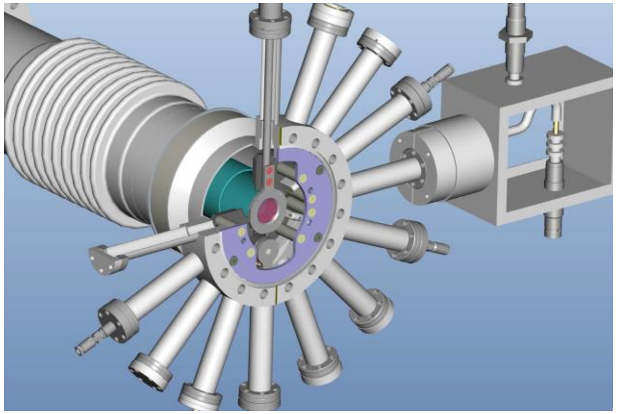
80 x 80 pinhole

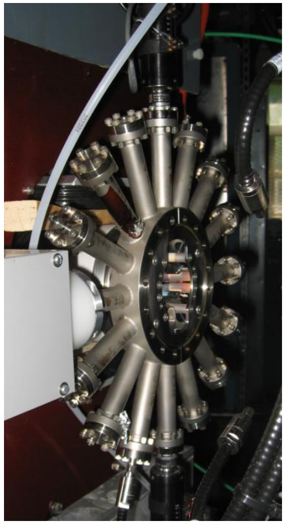






X. Gu et al, Nucl. Instr. Meth. Phys. Res. A 798 (2015) 36–43



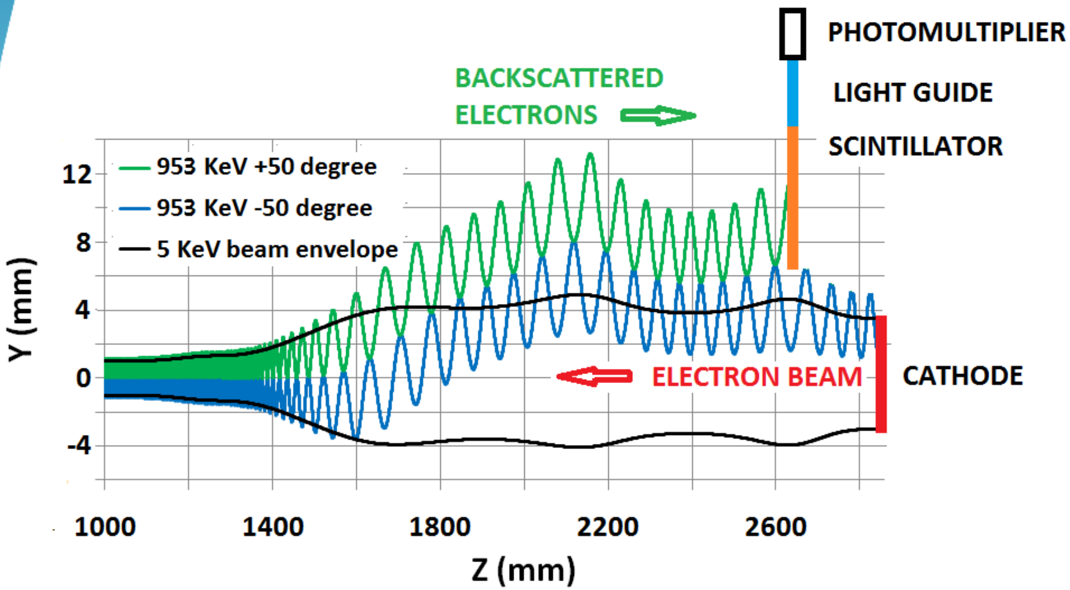


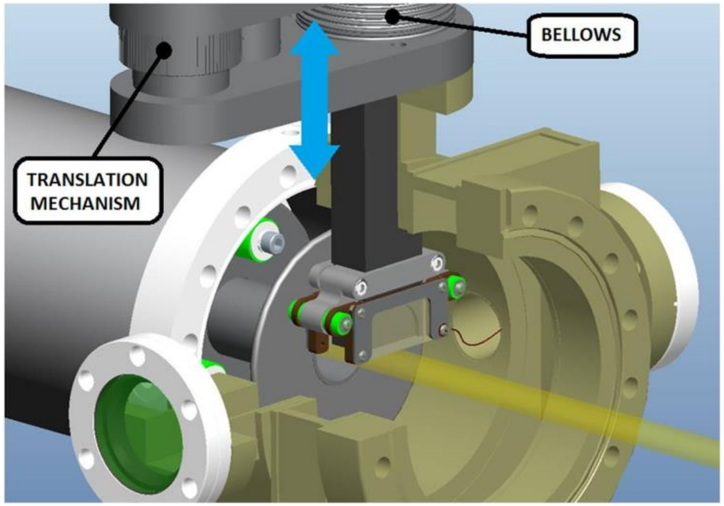
RHIC instrument holder containing
- YAG Screen
- Pinhole
- Halo detector

The BNL Overlap Monitor

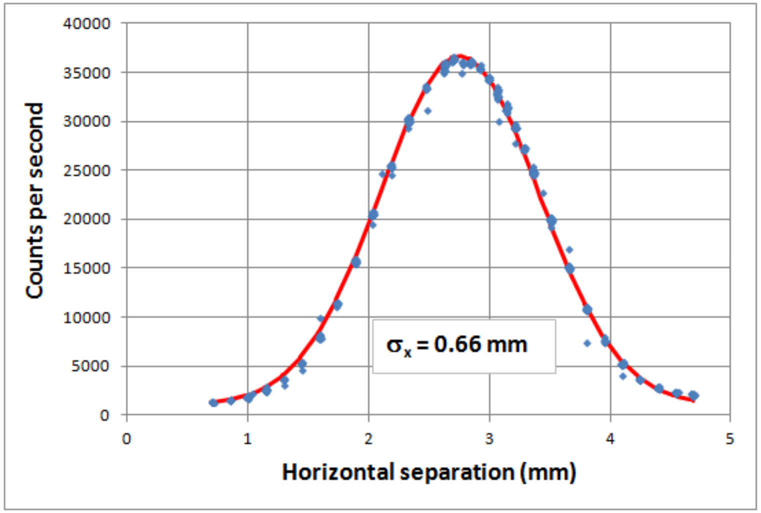
- BNL beam overlap requirement was ~100μm
- Initially used BPMs
  - BPMs located to detect both ion & electron beams
  - Severe problems to obtain reliable measurements for the different ion bunch and electron beam lengths
  - Disparity between ion & electron beam very large
    - 1mm or so even once optimum overlap was established
- Electron Backscattering Detector (eBSD)
  - Once commissioned was far superior to BPMs
  - Determines optimum overlap by maximising backscattering detection rate

The Electron Backscattering Detector (eBSD)





- eBSD system provides the sensitivity and precision necessary to achieve the stringent BNL eLens beam alignment requirements



HiLumi HL-LHC PROJECT

CERN

P. Thieberger et al, Proceedings of NAPAC2016, Chicago, IL, USA

Proposed Beam Instrumentation for HL-LHC hollow electron beam

HL-LHC Hollow e-Lens Beam Instrumentation

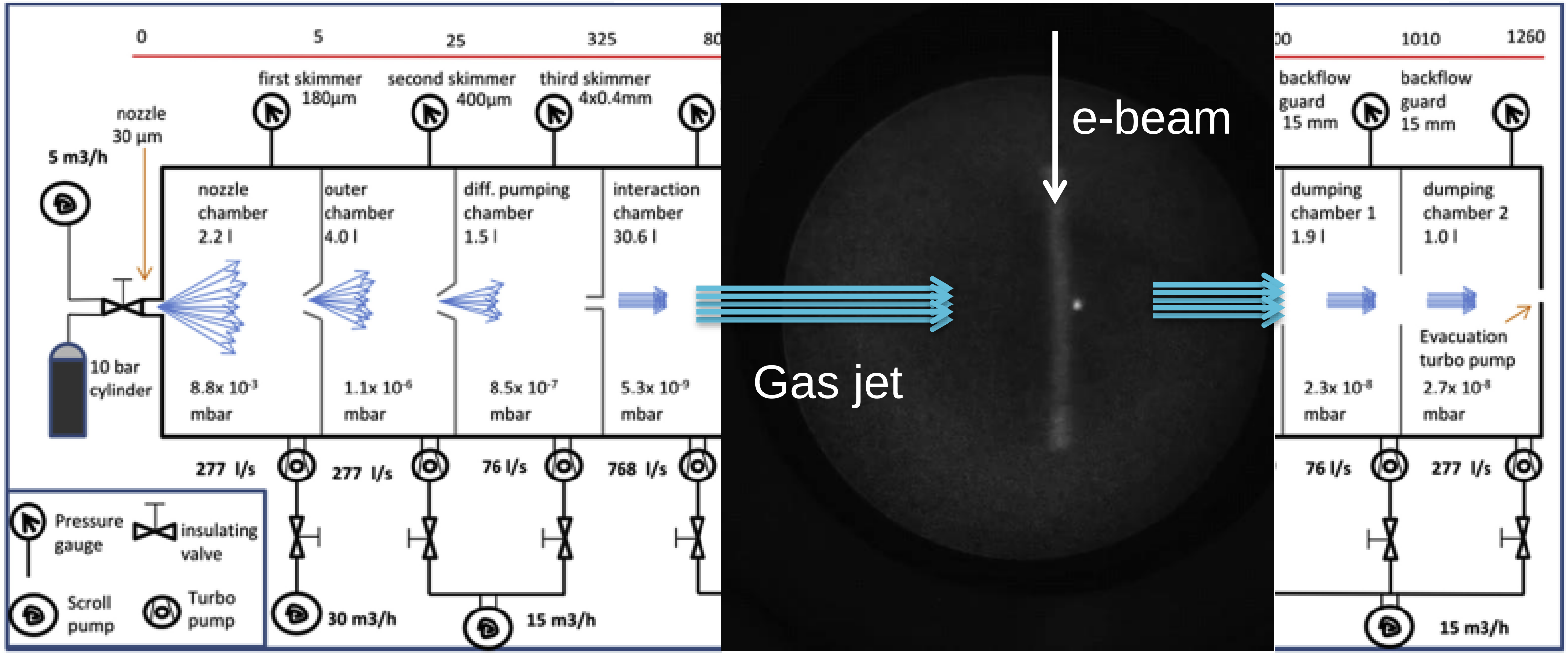
- Beam position monitors for general alignment
  - BPMs at input and output (no e-beam) for proton position measurement
  - BPMs at start & end of solenoid for e-beam position measurement
  - Dedicated electronics for measurement of each beam type
    - e-beam measurement for 200ns rise time in presence of intense proton bunches will be a challenge
      - Factor ~1000 less BPM amplitude with respect to short proton bunches
    - Possibility to use AM modulated e-beam to be studied
- Beam Loss Monitors
  - Addition of ~4 BLMs around eLens for solenoid protection
    - Exact number & layout to be determined
  - Use of existing BLMs in the collimation region for determining depletion rates and, if necessary, for verification of alignment
    - Ionisation chambers and diamond detectors

HL-LHC Hollow e-Lens Beam Overlap Monitor(s)

- Beam position monitors
  - From FNAL & BNL experience should not rely only on BPMs for accurate alignment
- Electron Backscattering Detector (eBSD)
  - Simple monitor which should be relatively easy to integrate
  - May not be easy to determine optimum positioning for hollow e-beam
    - Looking for minimum on continuous background – needs study
  - No on-line measurement as for Gaussian e-beam
- Gas jet curtain combined with luminescence
  - Non-invasive, on-line technique
  - R&D already funded by HL-LHC as option for measurement of high current e-beams for long range beam-beam compensation
  - If successful gives possibility of 2D visualisation of both e- & p+ beams
- Proposed baseline
  - Installation of gas jet curtain luminescence monitors at both entrance & exit of e-beam for easy set-up and continuous monitoring
  - Fallback solution
    - Rely on BPM reproducibility once set-up completed using eBSD or BLM alignment techniques

HL-LHC Hollow e-Lens Beam Instrumentation

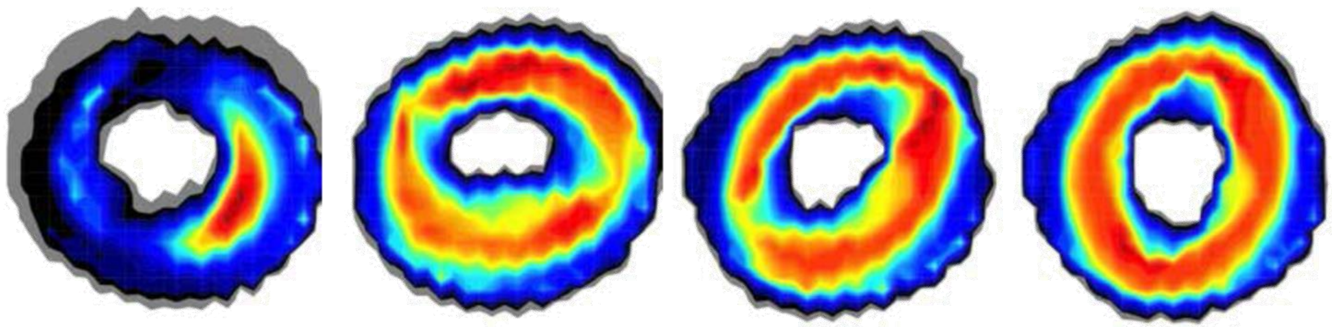
- Gas jet curtain combined with luminescence detection
  - R&D collaboration with University of Liverpool (UK) & GSI
  - Use supersonic gas jet to locally increase gas density creating a “gas screen” while maintaining the surroundings at low pressure
  - Detect the visible photons emitted when gas atoms or molecules excited by the electron or proton beam decay to lower states
  - Non-invasive technique able to give 2D profile
- Separate talk by R. Veness on progress with this development



V. Tzoganis et al, Phys. Rev. Accel. Beams 20, 062801 (2017)

HL-LHC Hollow e-Lens Beam Instrumentation

- Beam profile monitoring
  - Considered essential to study space charge effects, instabilities & non-uniformity with high current beams



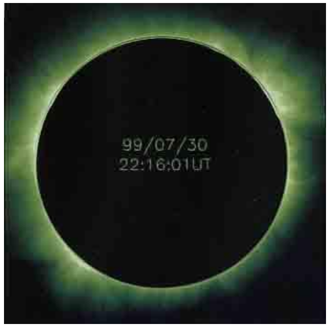
(a) $B_{main}=1.6\ kG$ $V=2\ kV$ (b) $B_{main}=2.4\ kG$ $V=2\ kV$ (c) $B_{main}=3.2\ kG$ $V=2\ kV$ (d) $B_{main}=4\ kG$ $V=2\ kV$

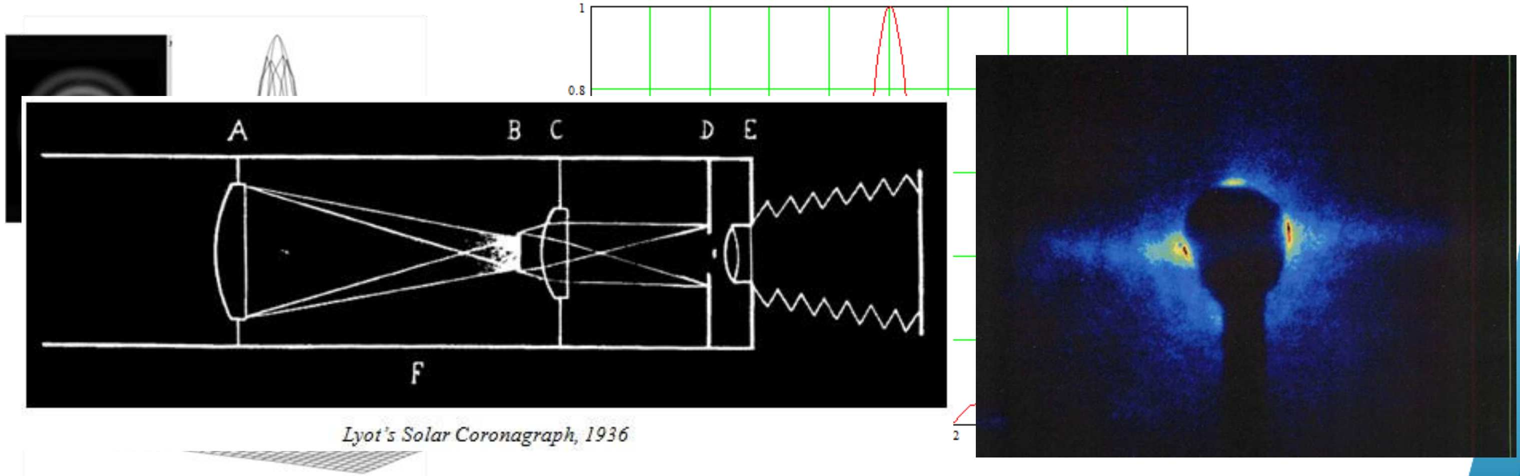
Pinhole results from FNAL
V. Moens
CERN-THESIS-2013-126

  - Baseline - Gas jet curtain combined with luminescence
    - If proven would allow on-line 2D imaging during operation for full intensity electron beam
    - Resolution better than 100μm expected (limited by image intensifier)
  - Following success at BNL could also consider YAG screen in front of collector for low duty cycle studies

HL-LHC Proton Beam Halo Measurement

- Essential for understanding the tail evolution during operation of the hollow e-lens
- Coronagraph (prototype for HL-LHC now installed in LHC)
  - Uses synchrotron radiation (non-invasive)
  - Need to limit diffraction from core
    - Intensity of fringes in range of 10^{-2} to 10^{-3} of peak intensity would mask any halo at 10^{-5} level
  - Reduce effect of diffraction fringes using Coronagraph developed for astronomy
    - KEK Photon Factory achieved 6×10^{-7} background to peak intensity ratio



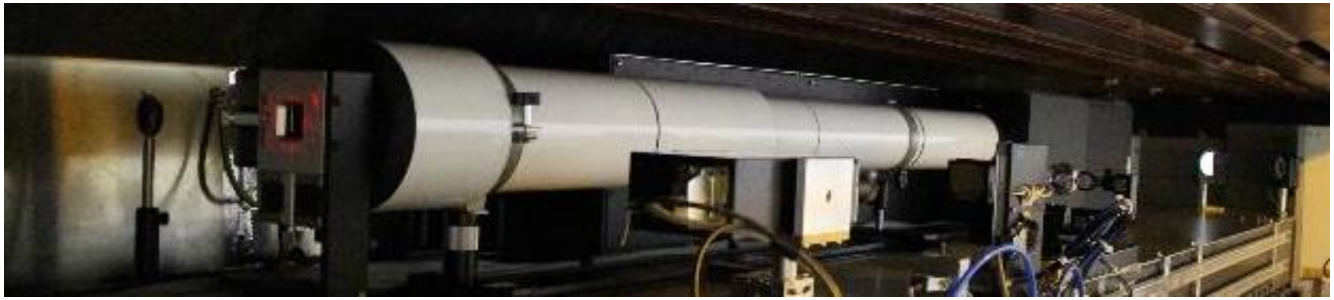


Lyot's Solar Coronagraph, 1936

HL-LHC Coronagraph Status

Status

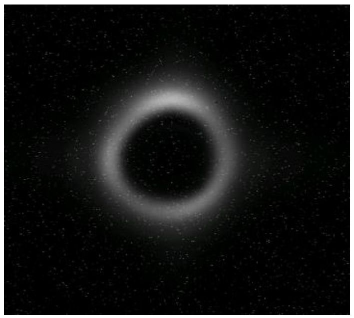
- Prototype coronagraph for halo diagnostics installed in LHC

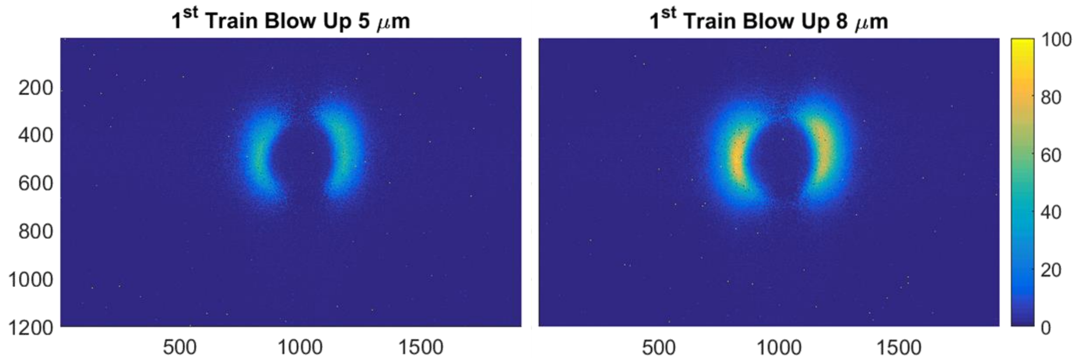


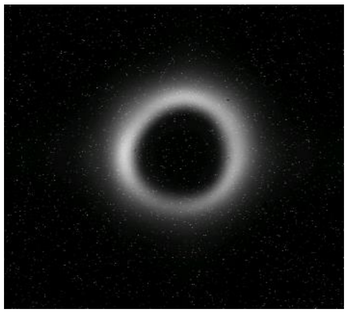
- KEK collaboration providing expert manpower & optical components from Photon Factory
  - First measurements taken during machine development periods
  - Parasitic light at 6.5TeV observed and needs to be understood
  - Contrast of $2x10^{-3}$ already demonstrated with early tests at 450GeV
- Optimised design for HL-LHC underway
  - New prototype foreseen to be installed during LS2
  - Aim to reach contrast of 10^{-5}

Prototyping the Coronagraph in LHC

- Coronagraph images during controlled blow-up





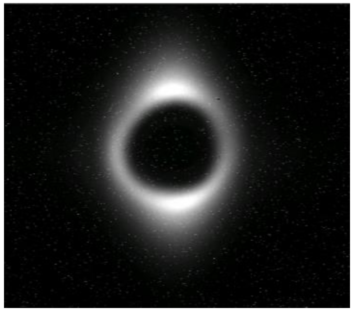


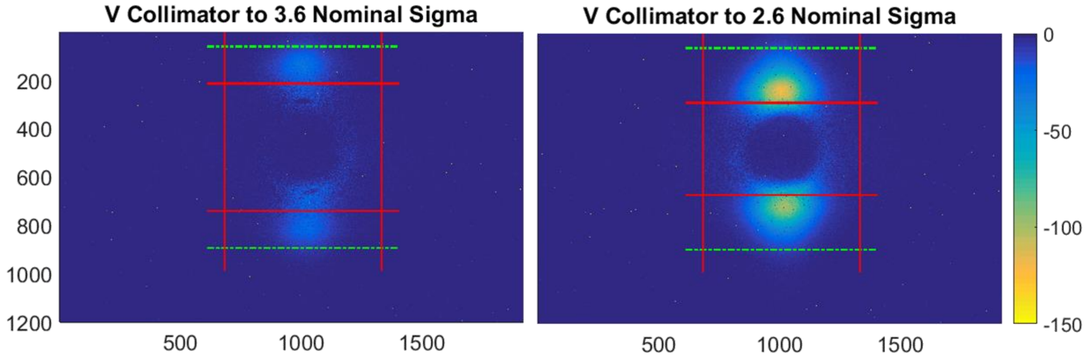
Start

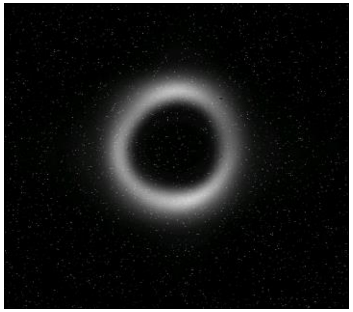
Difference images

End

- Coronagraph images during controlled scraping







Start

Difference images

End

HL-LHC Hollow e-Lens Beam Instrumentation

- Preliminary Budget Estimate

Baseline (per hollow e-lens)		Number	Unit Cost (kCHF)	Total (kCHF)
	Proton BPM	2	30	60
	Electron BPM	2	30	60
	BLM	4	10	40
	Gas Jet Curtain (at entrance & exit)	2	100	200
	TOTAL			**360**

Options (per hollow e-lens)		Number	Unit Cost (kCHF)	Total (kCHF)
	Backscattered electron detector	1	60	60
	YAG Screen	1	60	60
	TOTAL			**120**

Summary

- Experience from FNAL & BNL shows that most challenging aspect is alignment of proton & electron beams
  - Can be done with BPMs but initial commissioning to understand systematics laborious and time consuming
  - On-line detector considered a must for robust & reliable operation
- HL-LHC R&D already funding two essential developments
  - Coronagraph for halo measurement
  - Gas jet curtain luminescence monitor
  - Proof of principle experiments foreseen at start of Run III
- Total cost of proposed hollow e-beam instrumentation
  - Estimated at around 360kCHF baseline (+120kCHF options)