HiLumi
HL-LHC PROJECT

Beam Instrumentation: Status and plans

Vancouver, September 2023

Ray Veness on behalf of WP13

Thanks for material from:

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Scope of the talk

Task	Description	Equipment code
WP 13.1	Beam loss monitors	BLM
WP 13.2	Beam-gas curtain monitor	BGC
WP 13.3	Beam position monitors	BPM
WP 13.4	Luminosity monitors	BRANQ
WP 13.5	High-bandwidth BPM in IP4	BPW
WP 13.6	Synchrotron light diagnostics	BSR
WP 13.7	Beam-gas ionisation monitor [new technology baseline]	BGI
WP 13.8	Long-range beam-beam compensator [not covered here]*	BBLR
WP 13.9	Electron beam test stand [moved → WP 5.3.2.9]	-
WP 13.10	Transport and installation [not covered here]	

*Covered in a dedicated WP2/WP13 meeting on Wednesday afternoon

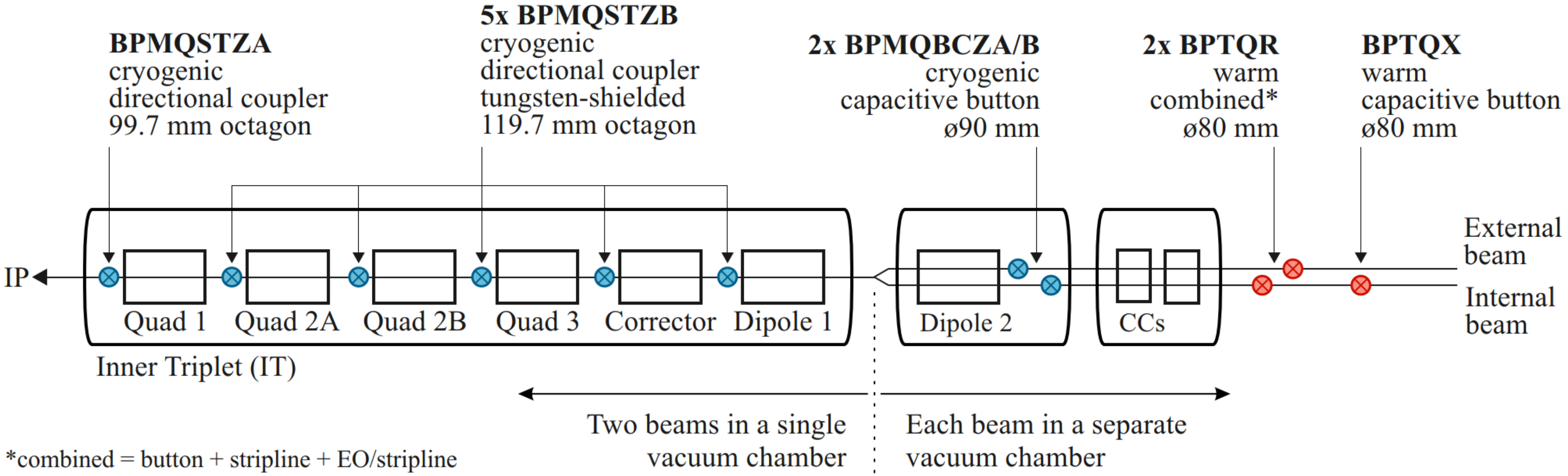
Introduction

- Wide range of instrument types required for HL
  - ‘Workhorse’ operation monitors such as BPMs and BLMs with strict requirements for availability and integration with other systems
  - Diagnostics for beam monitoring and optimisation such as BSRT and BGI with challenging new performance specifications requiring extensive development and beam tests
- ‘External’ factors
  - End of Russian collaborations
    - BPM monitor in-kind production
    - BLM ionization chamber in-kind production
    - Secondary effect of HEL collaboration on BGC and EBTS
  - Availability of accelerators at CERN
    - Prototype testing in the SPS and LHC
    - Unplanned reduction in LHC physics run
- More information from

❑ Papers from IPAC-23, journals and the International Beam Instrumentation Conference (IBIC-23), last week

❑ Parallel session talks at this HL-LHC meeting

Task 13.3 New Beam Position Monitors (BPMs) - Overview

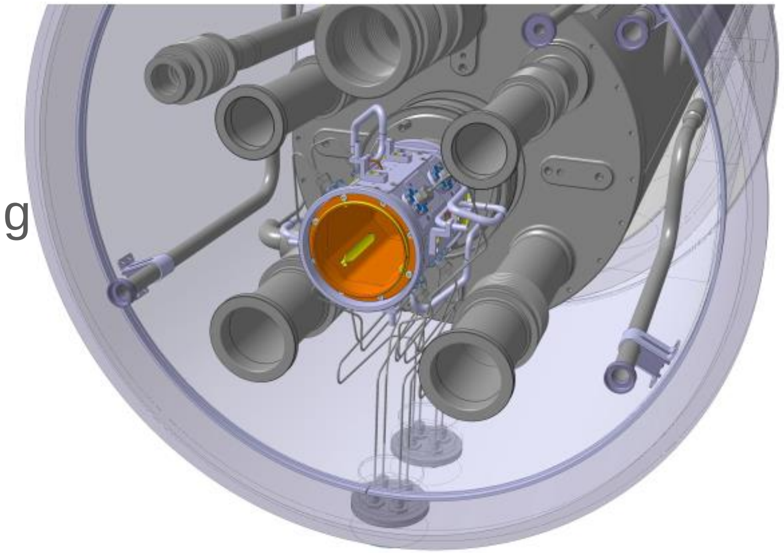


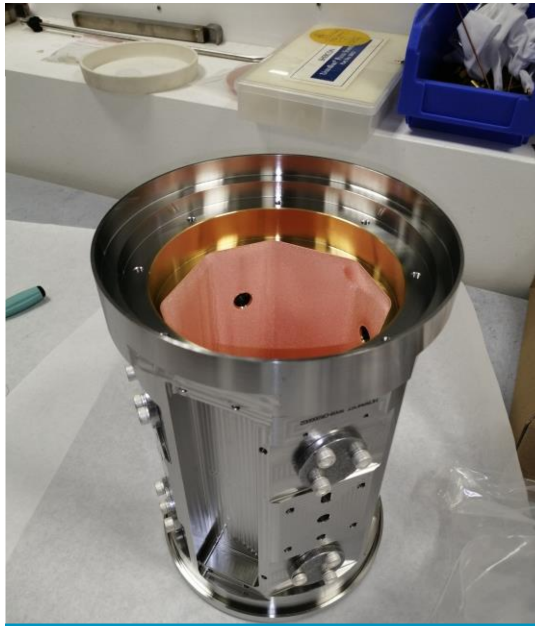
- 44 new BPMs to be built and installed for HL-LHC baseline
  - Cryogenic 'directional' couplers (with 2 variants) in the triplets
    - Stripline pickups sensitive to beam direction for the cryogenic combined beam sections
  - Cryogenic capacitive button BPMs
    - In the dual aperture separation dipole cryostats
  - Room temperature BPMs for crab cavity (CC) diagnostics and experiments
    - Capacitive buttons for phasing with beam and filtering of the antenna signal
    - Stripline antenna for amplitude and noise feedback
    - (Electro-optical) pickups for wideband measurement of beam instabilities from the CC

Crab Cavity Pick-up (M.Krupa, Thursday)

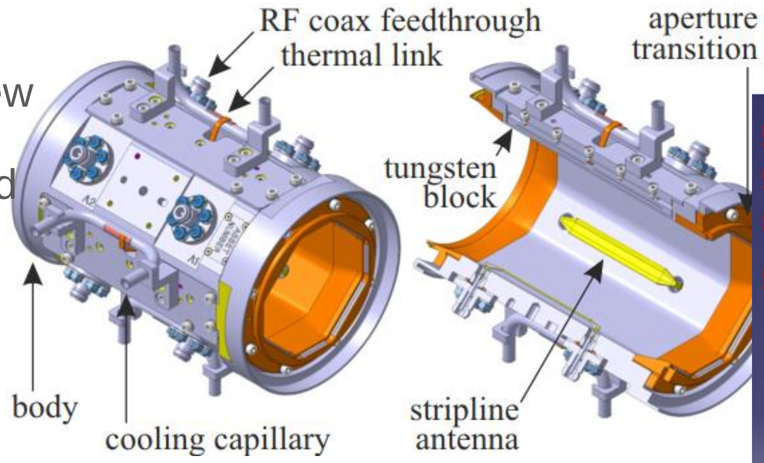
Task 13.3 New BPMs in Q1 to Q5

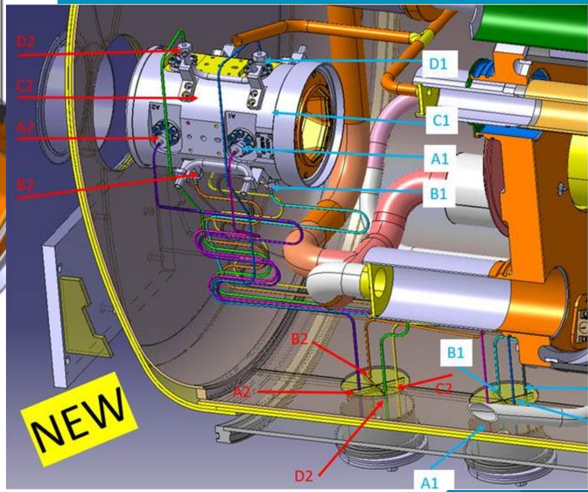
- Design
  - Octagonal body with copper transitions
  - Gold, copper and aCarbon coated
  - Integrated tungsten absorbers with active cooling
  - Memo update released defining responsibilities for integration, including BPM-beamscreen assembly
    - WP3, WP12, WP13, WP15.4
- Status of cryo-BPM body production
  - Production moved in-house (MME/VSC) following termination of Russian collaboration
    - Design frozen following Production Readiness Review in October 2022
    - 5 pre-series bodies have been successfully produced
    - Coatings and cooling tube integration ongoing
    - Series of 33 plus spares in production
    - Cryo-cable integration and installation access in progress
  - Market survey launched for 558 cryogenic SiO2 RF cables (WP13 + WP5.2)





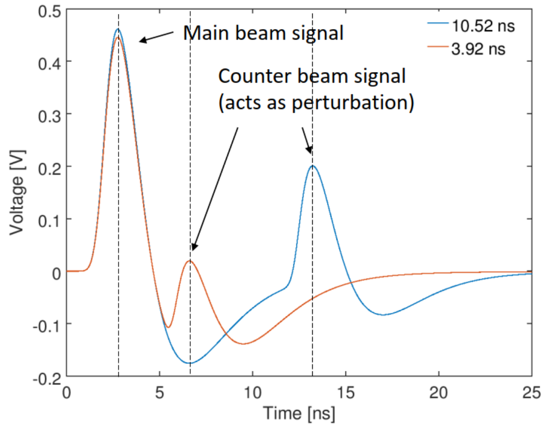
Coated pre-series body at CERN

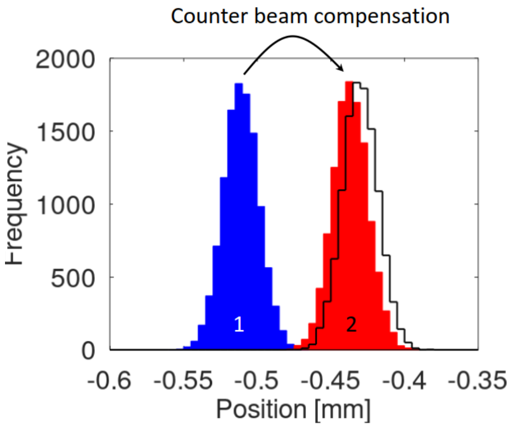


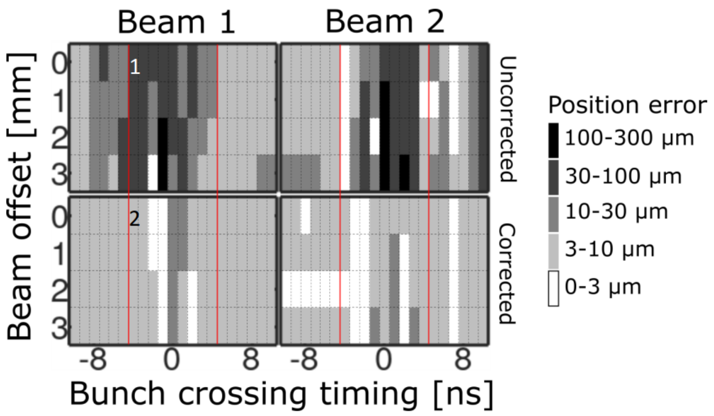


Task 13.3: New BPM acquisition electronics in Q1 to Q5

- Good progress with development of proof-of-principle data acquisition system
  - Based on a commercial evaluation board with a state-of-the-art RFSoC chip
  - Integration into CERN controls infrastructure (Linux, FESA, timing etc.) has been demonstrated
  - CTTB decisions on SoC strategy at CERN are key to the project timeline
  - In-contact with potential vendors with the CERN procurement team
- Testing in CERN accelerators in-progress
  - Large amount of beam data acquired during a dedicated MD in 2022; fully analyzed with main results published at IPAC
  - Electronics recently installed in SPS to develop integration with timing and controls infrastructure
- Custom analogue and digital front-end extension boards under design



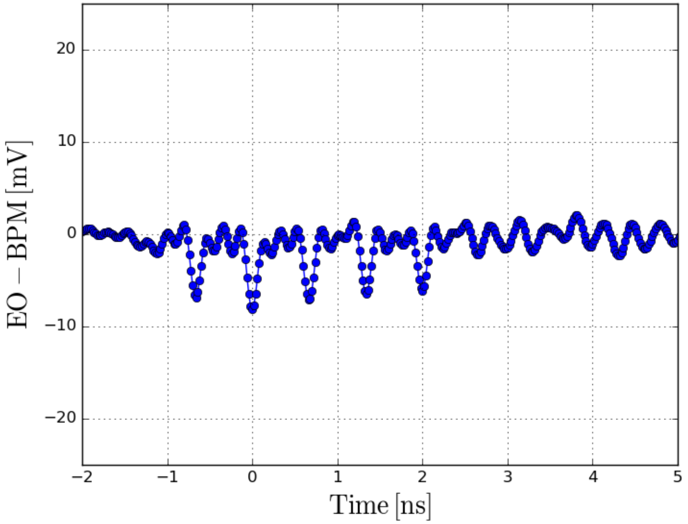




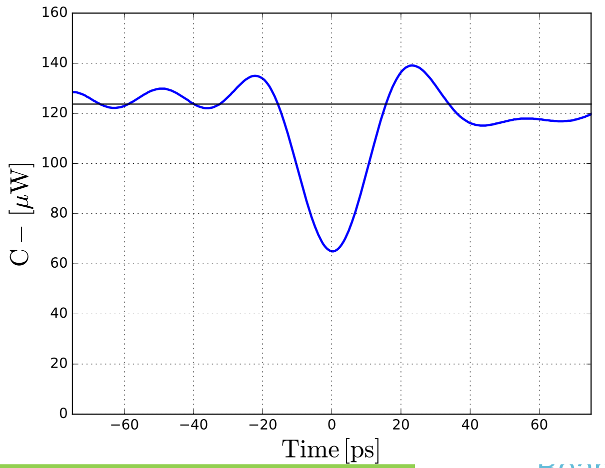
https://www.ipac23.org/preproc/doi/jacow-ipac2023-thpl089/index.html
https://www.ipac23.org/preproc/doi/jacow-ipac2023-thpl119/index.html

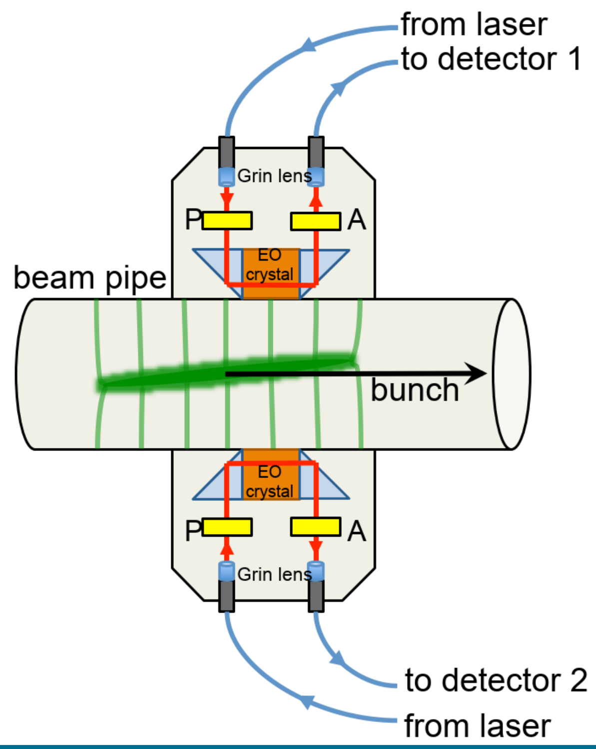
Task 13.5: Electro-Optical BPM

- Upgrade to existing head-tail directional pickup
  - Higher bandwidth (>6 GHz) for transverse resolution along a crabbed HL-LHC bunch
  - Developed with Royal Holloway University of London as part of HL-UK
- Status and plans
  - SPS tests 2016-2018 followed by new device development
  - HiRadMat tests in 2021 for single shot bunch resolution
    - 171 mV/mm gradient measured
  - Bandwidth tests in CLEAR 2022
    - Time resolution well within the <50 ps required for HL-LHC
  - New SPS device being constructed
    - Planned installation in SPS YETS 23-4
    - Some pickup brazing issues recently found

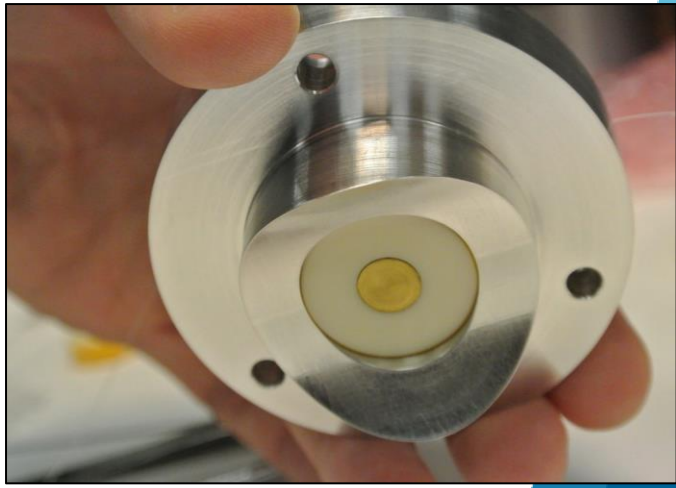


Measurements in CLEAR: Train of 5 bunches spaced by 666ps (above) and Single bunch (2ps bunch length) measurement (below)





Electro-optical BPM principle (above) and new e-o pickup (below)

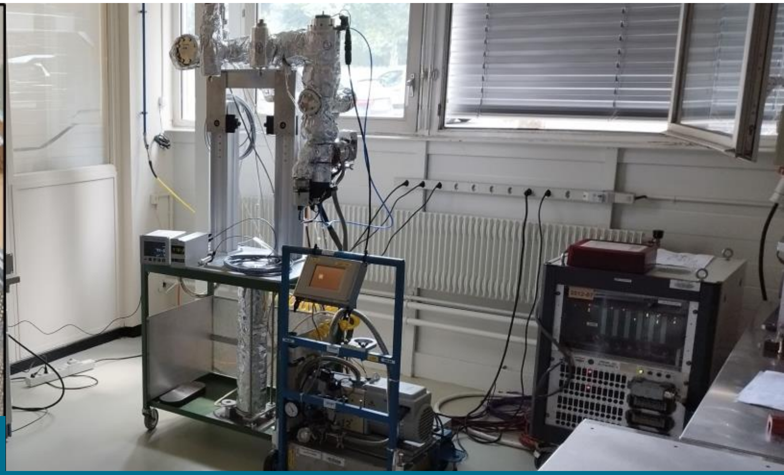


❑ EO BPM studies & PU for CC diagnostics (T.Levens)

Task 13.1: Beam Loss Monitor (BLM) New Ionisation Chamber (IC) Production

- HL-LHC requires extension of existing BLM coverage with many new ICs
- Large-scale IC production following end of Russian Collaboration
  - 1000 to produce for LS3, of which 200 for HL-LHC.
  - Reverse engineering of design and production process with much help from EN-MME and TE-VSC
  - Accelerated production of protoypes in 2022-3 along with the assembly stand needed for bakeout and gas filling
- Recent successful preliminary tests in HiRadMat
  - Two CERN-produced prototypes installed next to beam dump
  - Comparison of beam loss signals for the three different production lots (2008, 2016, 2023) show acceptable dispersion
  - Dedicated beam time planned for 2024
- Strategy and resources being assembled for series production
  - In-house vs. outsource, but materials and production quality are critical to ensure performance in this key instrument

BLM electrical resistance test stand

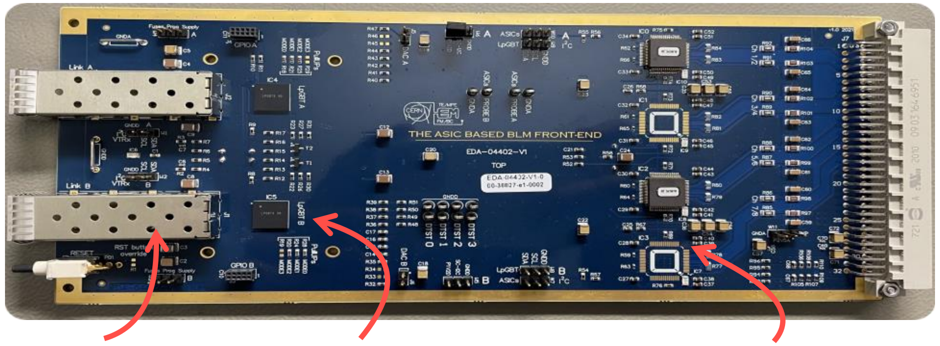


BLM filling and bakeout stand

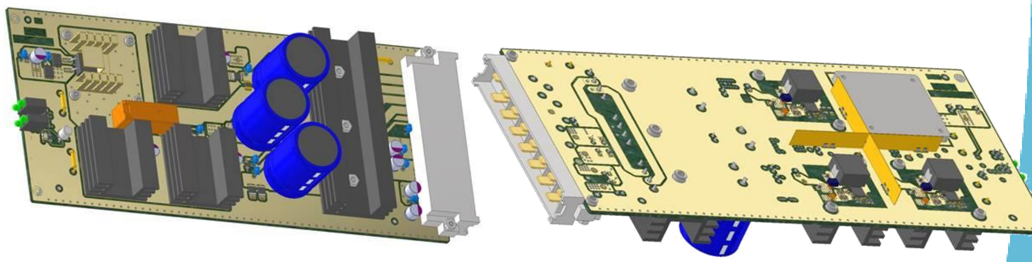
4x42 high intensity bunches on a BLM cluster in HiRadMat (August 2023)

Task 13.1: BLM electronics

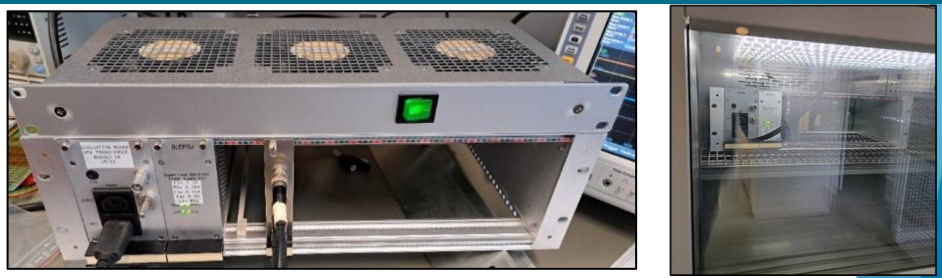
- New Rad-Hard card (BLEIC) to allow reduced cable lengths and improve S/N ratio
  - First deployment at strategic locations during LS3 to complete and validate development in parallel to the current electronics
  - Full electronics deployment during LS4 as part of the Consolidation project,
- New rad-hard power supplies (BLEPSU)
  - Necessary for radiation resistance and replacing obsolete systems
  - Developed in common for BLMs and BPMs, in collaboration with EP-ESE and BE-CEM with likely CERN-wide usage
  - v3 based on bPOL (rad-hard ASIC)
  - Recent v4 prototype validation completed*, optimised for tunnel environment
  - All tests and validations completed, e.g.
    - CHARM (reached ~ 1500 Gy accumulated)
    - Climatic chamber (150h stress-test up to 100°C)



New BLEIC card with application-specific IC (ASIC) so fewer componants



3-D models of BLEPSU v4

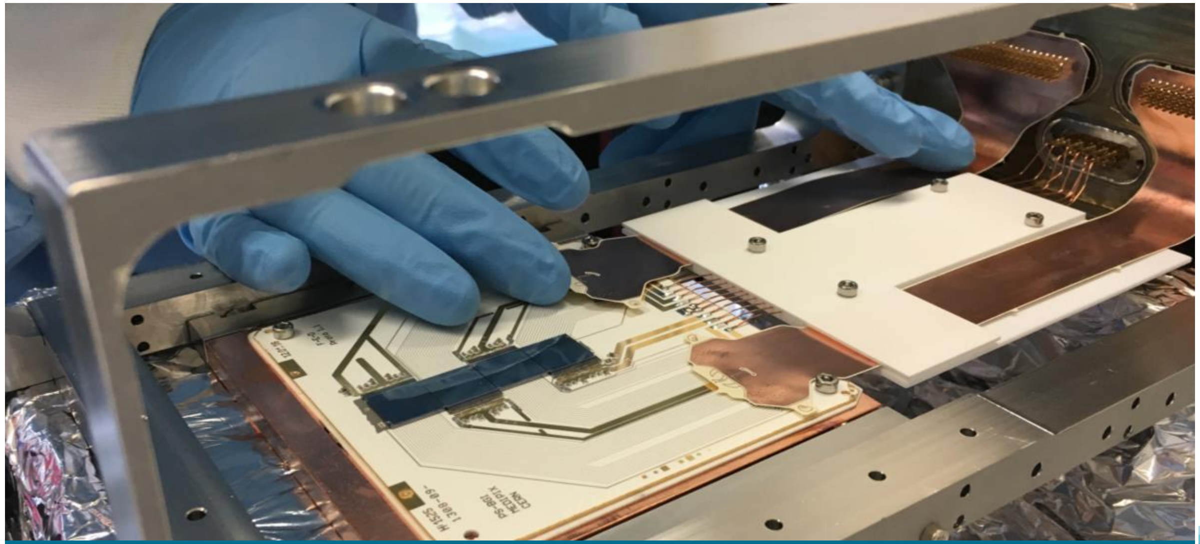


Set-up for CHARM and climatic test-chamber

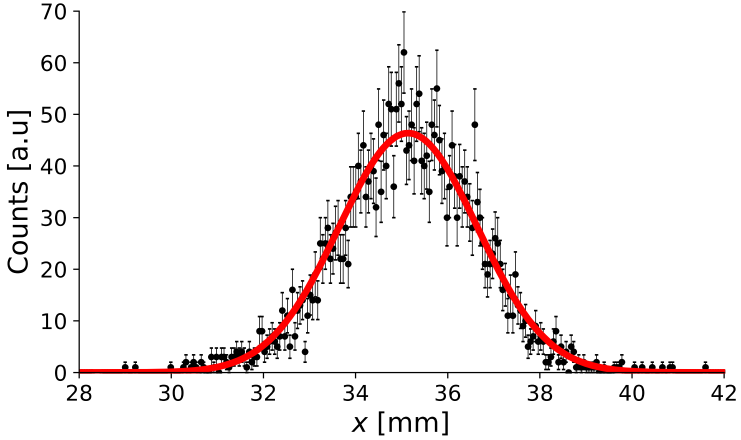
*https://edms.cern.ch/item/EDA-03919-V4-0/0

Task 13.7: Beam gas ionisation (BGI) monitor

- Non-destructive transverse beam profiles with continuous bunch-by-bunch measurements throughout the accleration cycle.
  - Following the BGV/BGI review in Oct. ’22 the BGI became the HL-LHC baseline
  - HL-LHC device is developing from the instrument built for LIU-PS, installed in LS2 and the SPS-CONS instrument in production for YETS23-4
- BGI detects ionization electrons produced by beam-gas interactions
  - **Individual ionisation electrons** detected with Timepix3 Hybrid Pixel Detectors (HPD’s) installed directly in the beam pipe.



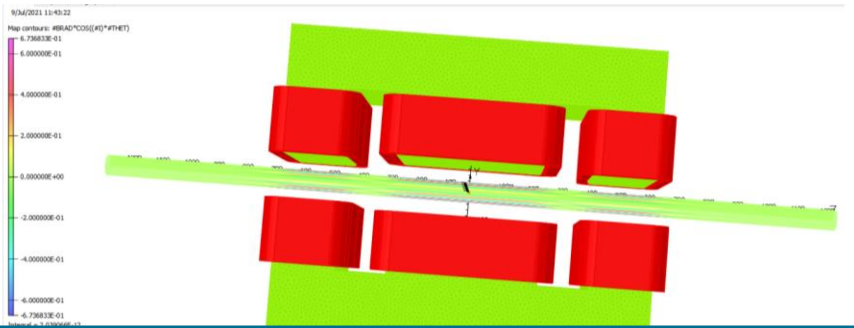
Timepix3 boards assembled onto the detector structure



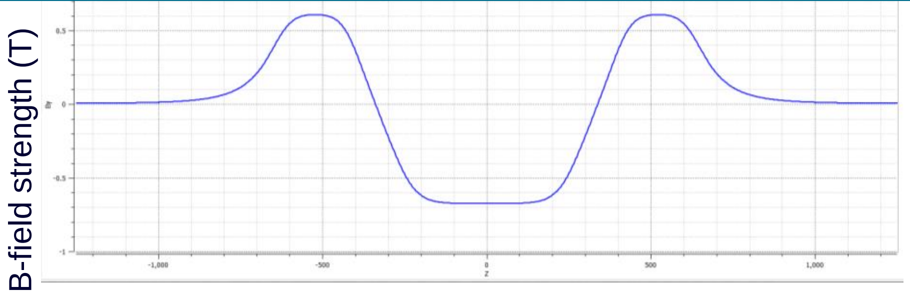
Beam profile is measured by counting the number of detector ionisation electrons.

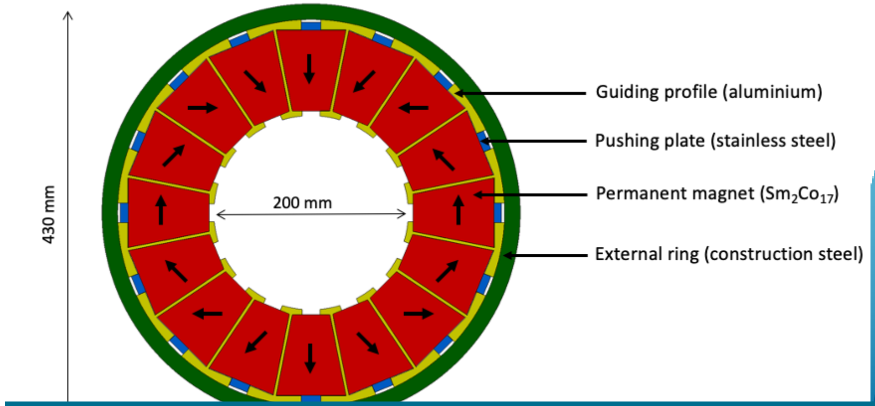
Task 13.7: BGI Magnet

- BGI requires a dipole magnet to guide ionization electrons to the detector plane
  - Equipment Integration Note released for IR4*
- Two options for BGI magnet
  - Baseline from the 2022 review is a 0.6 T electro-magnet, using conventional technology
  - Reviewers also recommended investigating permanent magnet designs
  - TE-MSC investigating **permanent magnet concepts** based on ‘**Halbach**’ or ‘**C**’ shaped designs.



Preliminary electromagnet design - 0.6T self-compensating dipole magnet [D.Bodart (MSC)]



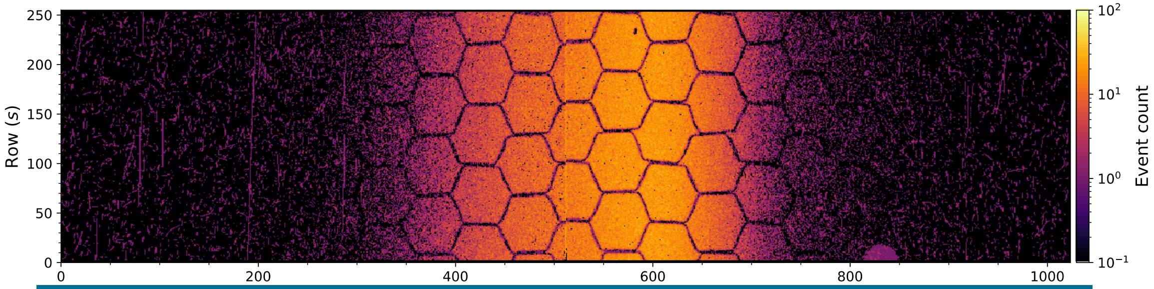


‘Halbach’ permanent magnet concept [P-A. Thonet (MSC)]

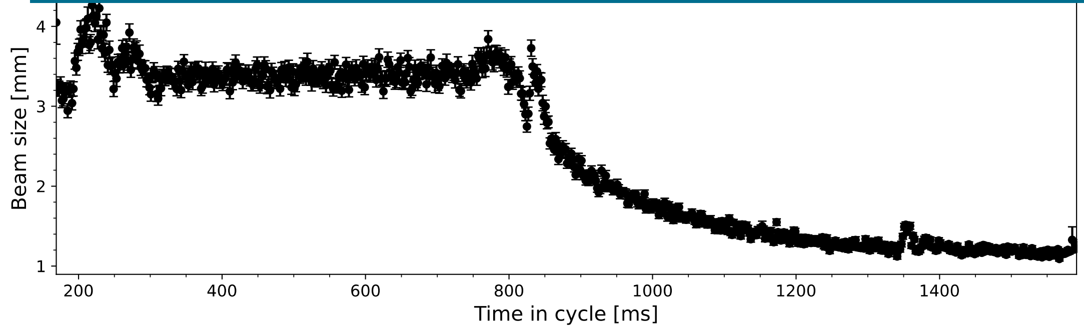
*https://edms.cern.ch/document/2932261/0.1 (M. Navarro Baeza, J. Oliveria)

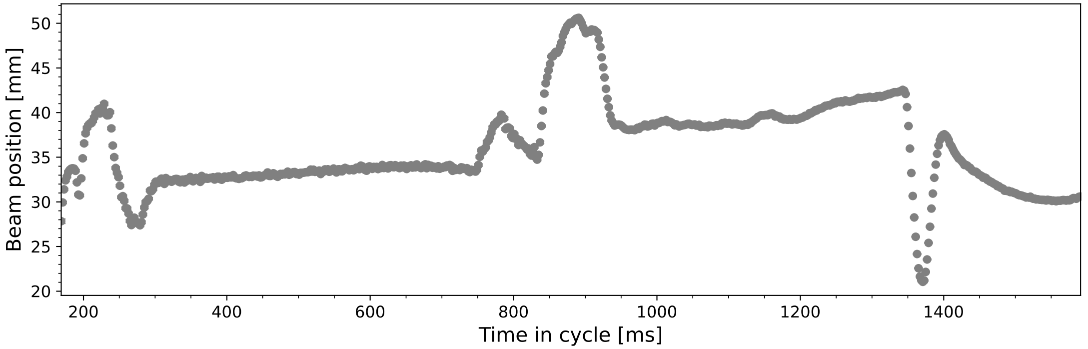
Task 13.7: BGI Tests and Plans

- PS-BGI [LIU-funded project]
  - Installed during LS2 and operating with beam for Run 3
- SPS-BGI [CONS-funded project]
  - Learning from the PS-BGI, in preparation for installation in EYETS23-4 [Critical path construction with EN-MME]
- Plan to install prototype instrument (w/o magnet) in LHC during YETS24-5
  - Learning from both the PS and SPS designs
  - Qualify the instrument for the LHC beampipe environment (vacuum & impedance tests);
  - Verify operation of the Timepix4 HPDs with the LHC electro-magnetic environment
  - Measure backgrounds due to beam loss & syncrotron light;
  - No plans to measure beam profiles as it requires the dipole magnet



(transverse) Image of a single PSB bunch in the PS

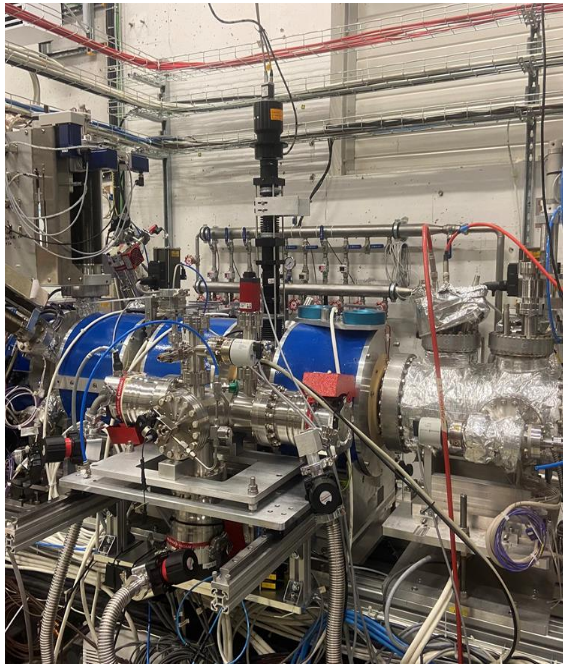




(Time domain) Continuous & non-destructive measurement of beam size and position throughout the PS cycle (1.2s)

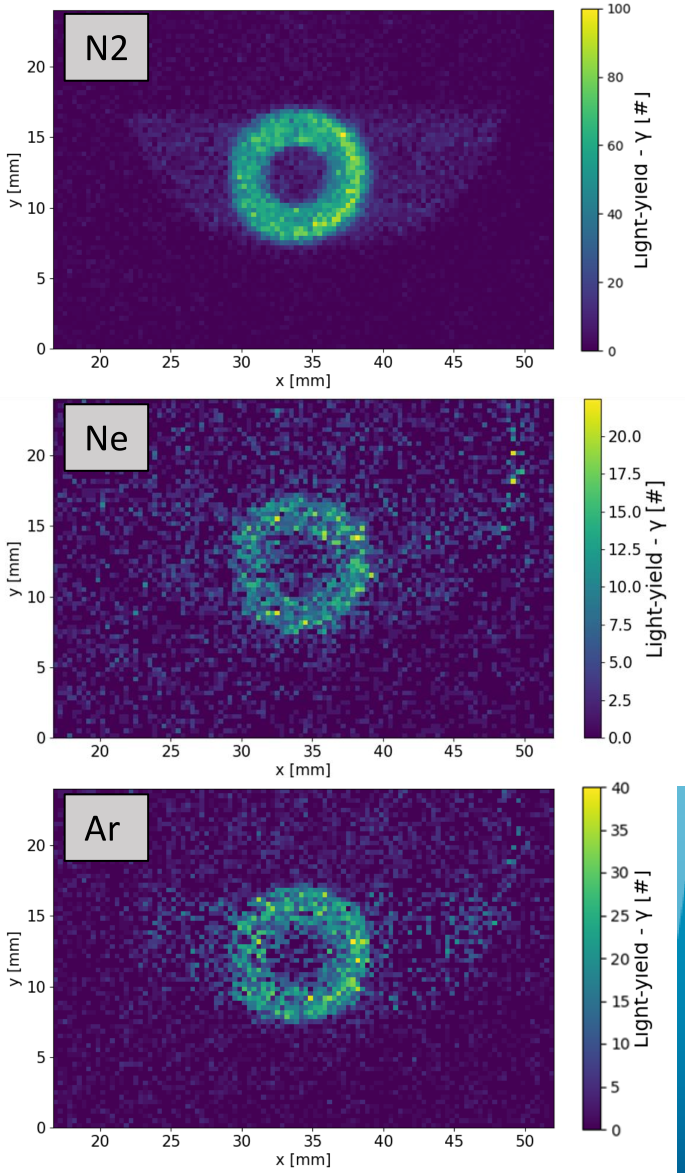
Task 13.2: Beam Gas Curtain (BGC)

- A 2D gas 'screen' generates a direct optical image of the beam via beam-induced fluorescence
  - Non-invasive 'on-line' monitor
  - Sensitive to both electrons and protons
  - Operates in strong magnetic fields
  - Developed as 'overlap' instrument for the HEL
- Full prototype instrument delivered and tested at CERN from HL-UK
  - In-kind contribution from the UK (Cockcroft Institute) with support from GSI
  - Tested with hollow electron beam on the Electron Beam Test Stand (EBTS) in November 2022 (shown right), then installed in the LHC (next slide)



BGC installed on the EBTS (November 2022- above) with non-destructive images of the hollow electron beam taken with different curtain gases (right)

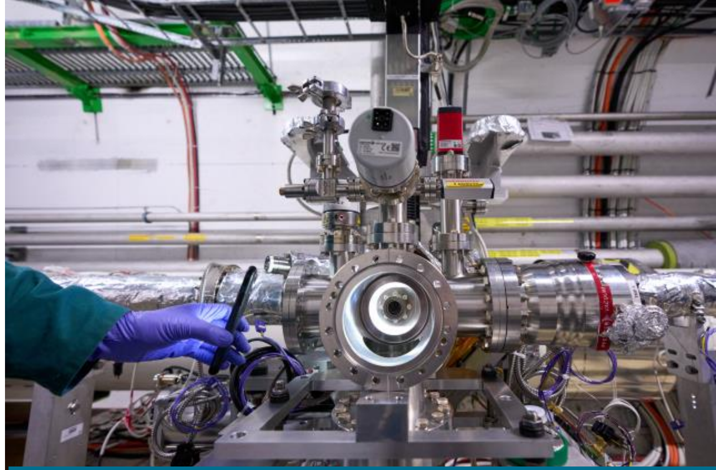
7 keV, 1.1 A
Beam int. time: 2 s



❑ O.Sedlacek et al. Gas Jet based Fluorescence Profile Monitor for Low Energy Electrons and High Energy Protons at LHC [IBIC 2023]

Task 13.2: BGC in the LHC

- Installed in the LHC, p4 during YETS22-3
  - Commissioned, then very successful (but preliminary) non-invasive tests measuring LHC proton beams during run 2023
  - Plans for future tests with ions then protons in 2024



BGC installed in the LHC during YETS22-3

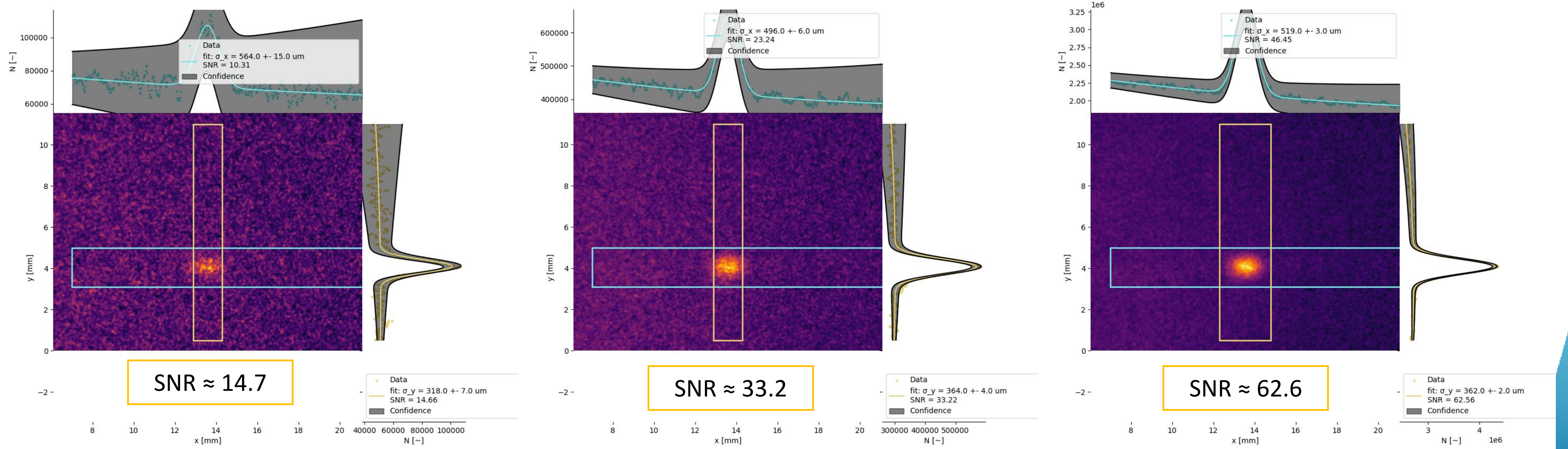
Centroid measurements

Profile measurements

10s

1min

5min

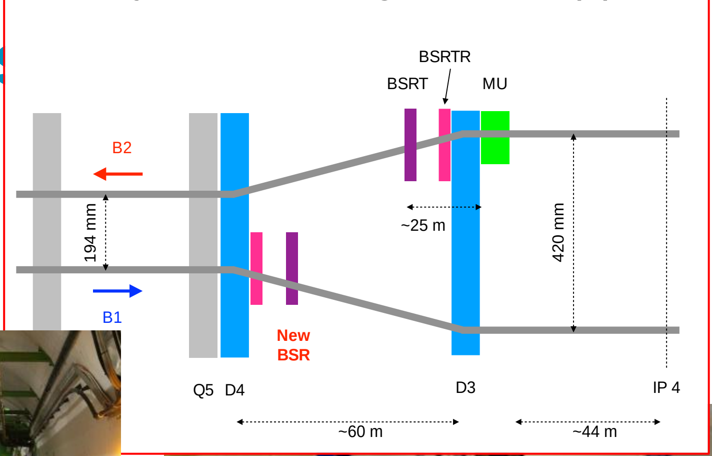


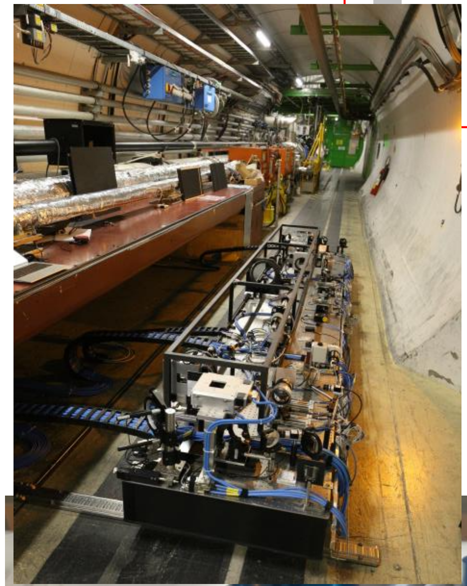
https://videos.cern.ch/record/2297523

HL-LHC PROJECT

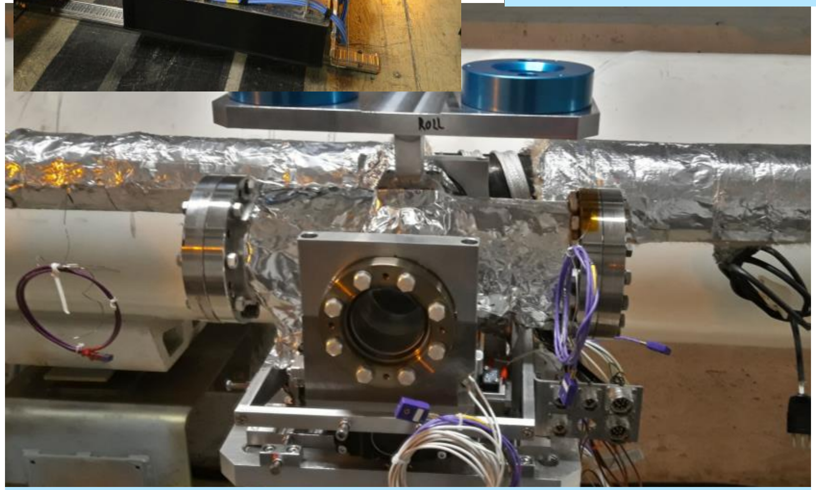
Task 13.6: Synchrotron light diagnostics

- New SR light extraction tank with mirror (BSRTM)
  - Installed in LHC 4L, equipped with new mirror design, proved to be ok w.r.t. to impedance in 2022-2023.
- Beam Halo monitoring with a SR Coronagraph
  - Built in collaboration with KEK and installed on BSR
  - Commissioning and tests were planned during LHC machine development (MD) time in Aug 2023 (now postponed to Oct)
  - Detailed simulations using SRW software show fundamental limitation with source diffraction
    - Suggesting HL specification (10e-5 contrast) not achievable with this instrument, ultimate reach to be confirmed by experiment
- Options for Beam Halo measurement
  - Performing the characterization of Coronagraph with beam asap.
  - Studying feasibility of alternative halo measurement instruments
  - Will review situation as soon as data available, along with an update of the HL-LHC halo measurement needs





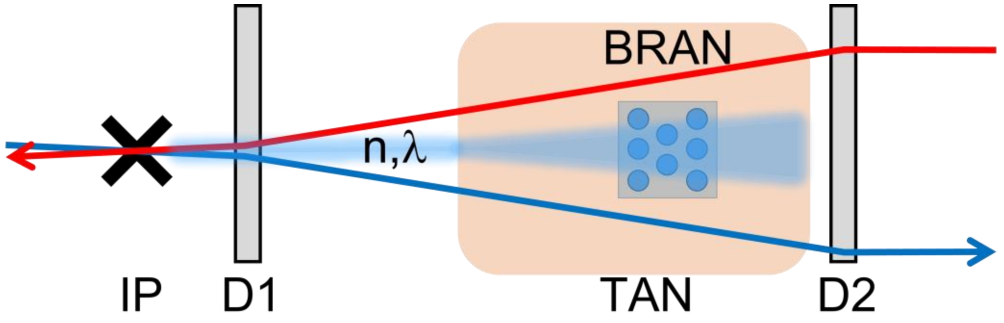
New SR extraction mirror



New extraction tank in IR4L

Task 13.4: Luminosity Monitors (BRANQ)

- Provides a relative luminosity measurement for LHC experiments
  - Used for optimising collision rates and
  - Cross-checking the absolute monitors in each experiment
  - Detects the electro-magnetic showers in the TAXN
- New design for HL
  - Based on Cherenkov radiation produced in fused silica rods
  - Four prototypes installed in IR1/5. New firmware and data acquisition system
  - Recent tests with beam in the LHC confirm wide luminosity range to $2x10^{14}$ µb/Hz and very good resolution
- Future plans for the final HL version
  - Based on the same SiO_2 bars, adapted to the new TAXN absorber and optimised for full HL intensity



Luminosity monitor concept and schematic

BRAN-D 1R, Fill 9072, 16/7/2023, full 2.1e04 lumi range.

Yang et al. 'Optical transmission characterization of fused silica materials irradiated at the CERN Large Hadron Collider', NIM A **1055**, 168523 (2023)

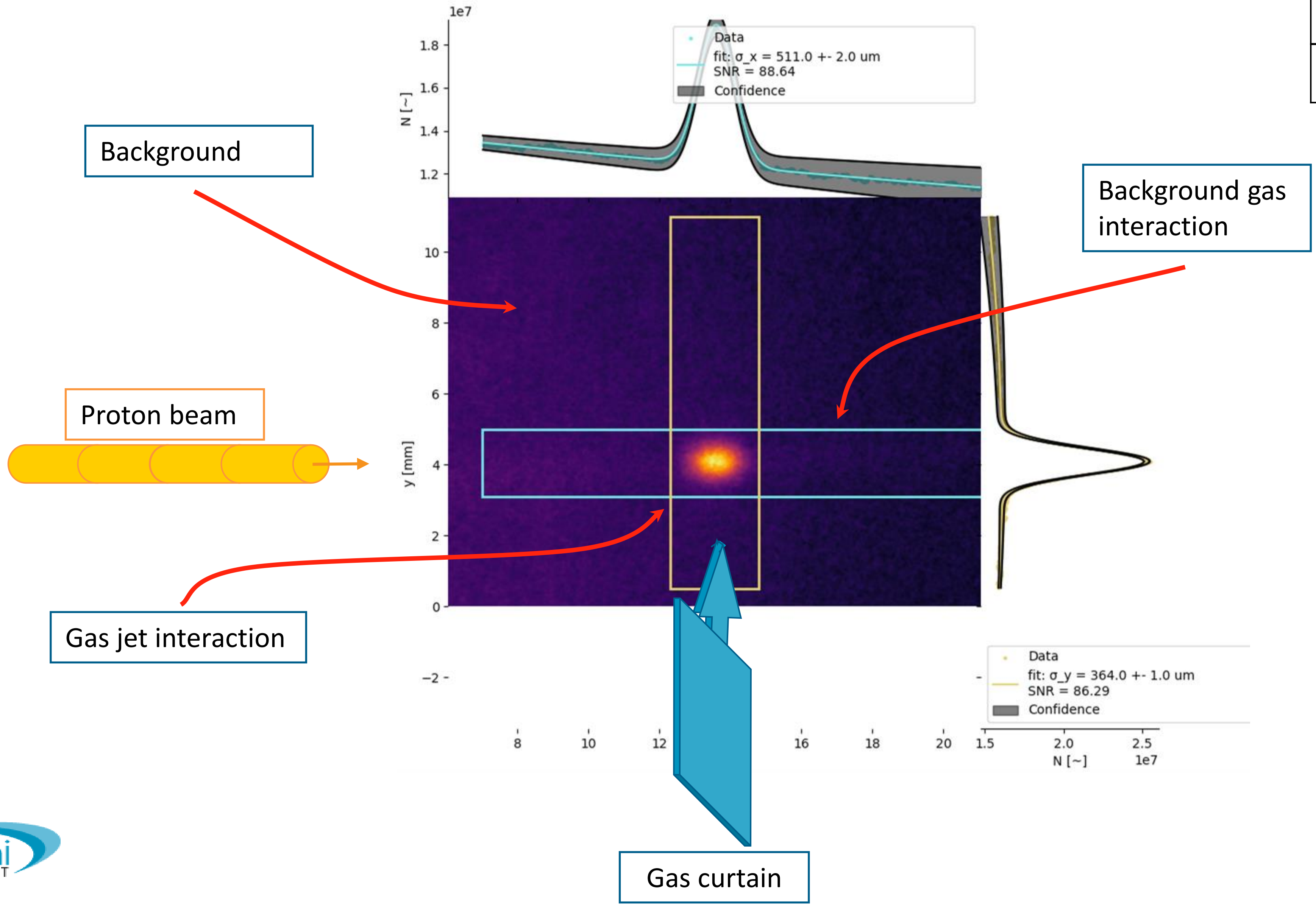
Summary

- Excellent progress made in the development, tests with beams and production for all tasks
  - Critical cold BPM manufacture is back on-schedule despite the end of the Russian in-kind contribution
  - BLM ionization chamber also back under control following urgent reverse-engineering and prototyping
  - Design review on full-cycle transverse beam size measurement resulted in new baseline for BGI instrument
    - Benefitting from convergent development and instrument installations in PS and SPS
  - Early successful tests made with the BGC, both for hollow electron beams and as a profile monitor in the LHC are being continued
- Some decisions to be taken:
  - Beam halo monitoring baseline and requirements
  - Production strategy for series BLM ionization chambers
  - High-bandwidth pickup technology

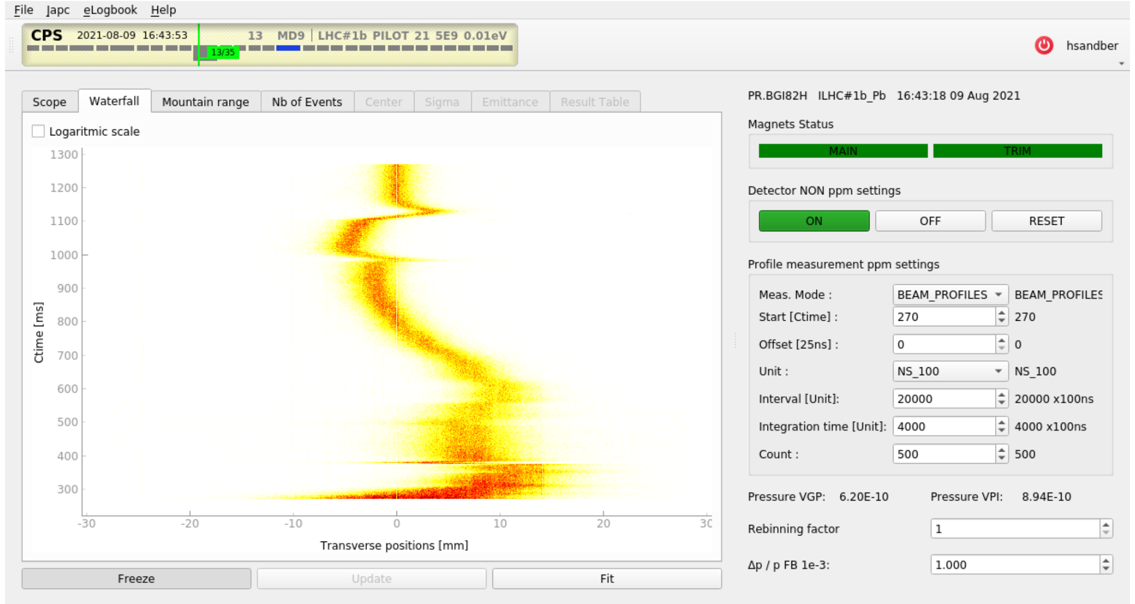
Collaboration partners

First Gas Jet fluorescence measurements at LHC at 6.8 TeV

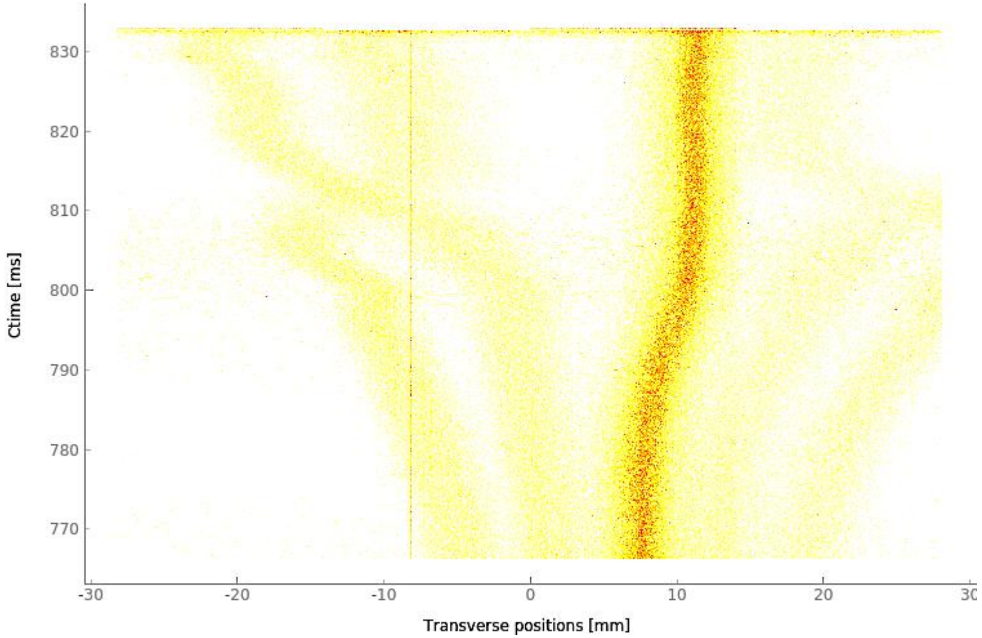
Parameters	
Beam Energy [TeV]	6.8
Beam intensity [p]	2.2e14
Gas jet	Ne
Integration time [s]	1659



PS BGI – Example operational measurement



*Evolution of **Pb54+ beam** from injection to extraction*

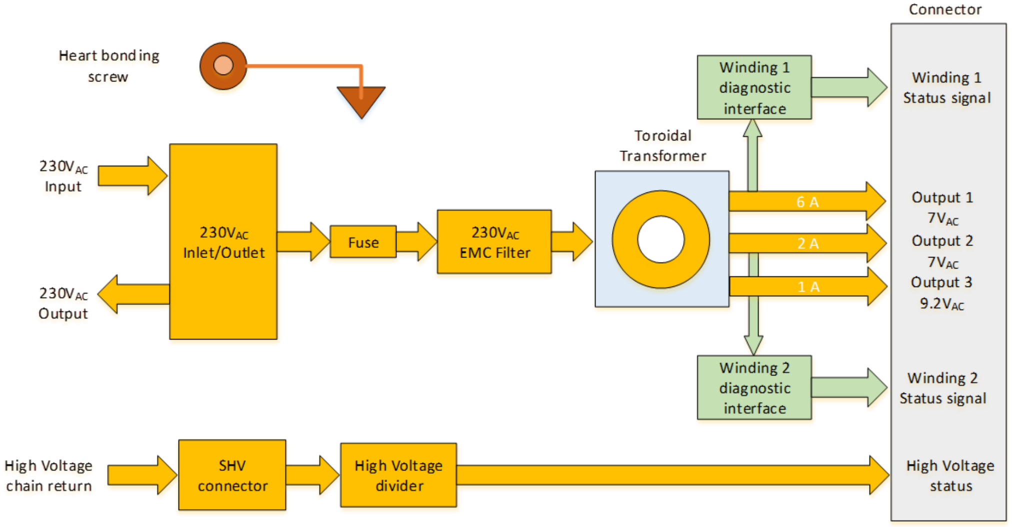


Evolutions of beamlets in Multi-Turn Extraction (MTE) beam (for fixed target experiments)

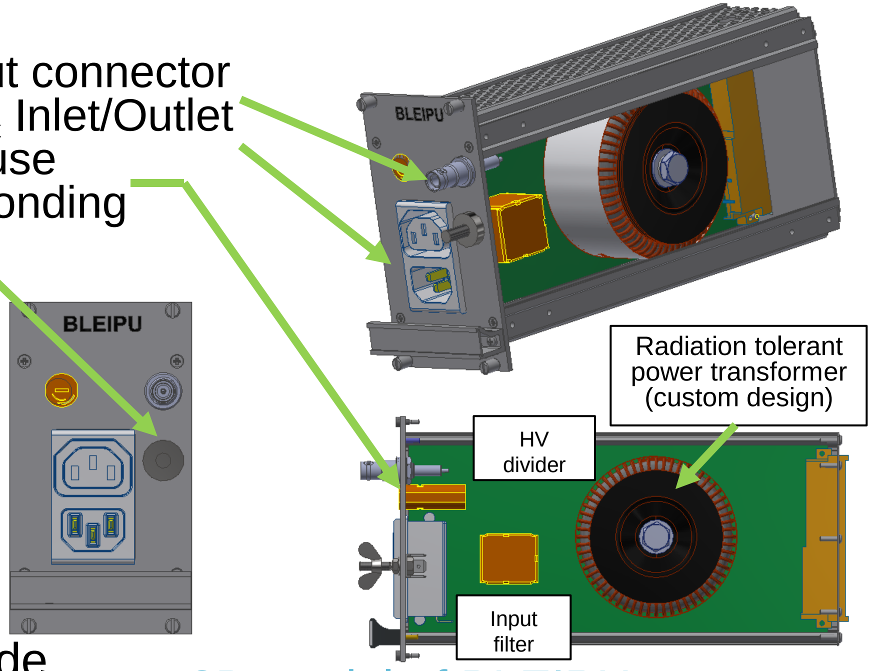
Task 13.1 Radiation hard beam loss monitor electronics

BLEIPU : BLM/BPM Rad-tol Input Power Unit

- The Input Power Unit (BLEIPU) converts the 230 V_{AC} power input in the AC output voltages delivered to the Power Supply Unit
  - EDA-03918
- Provides also
  - transformer diagnostic and
  - the detector bias chain return with voltage conversion

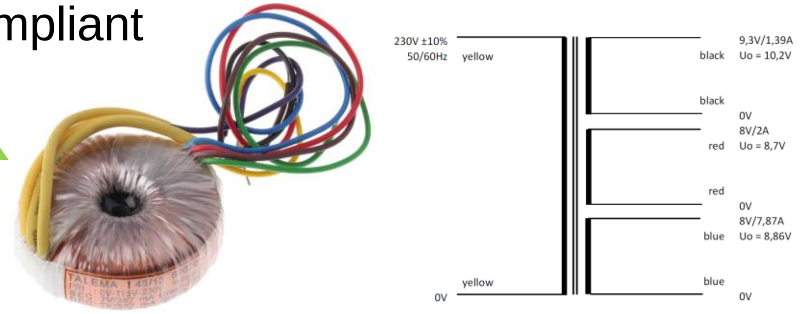


HV input connector
230 V_{AC} Inlet/Outlet
Main Fuse
Earth bonding



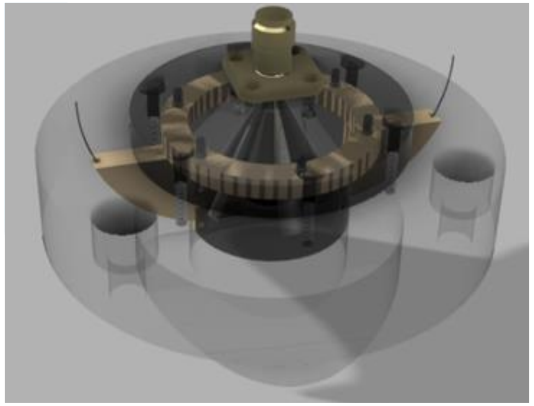
3D model of BLEIPU

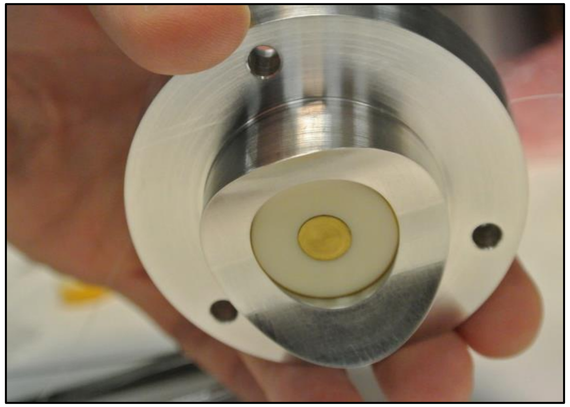
New custom-made toroidal transformer with radiation compliant material

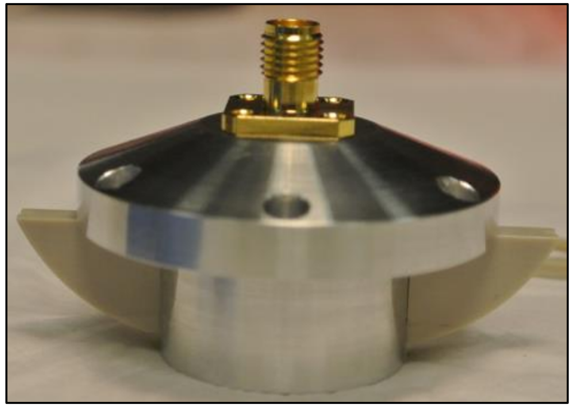


Transformer & output voltages

Task 13.5: Electro-Optical BPM tests at CLEAR

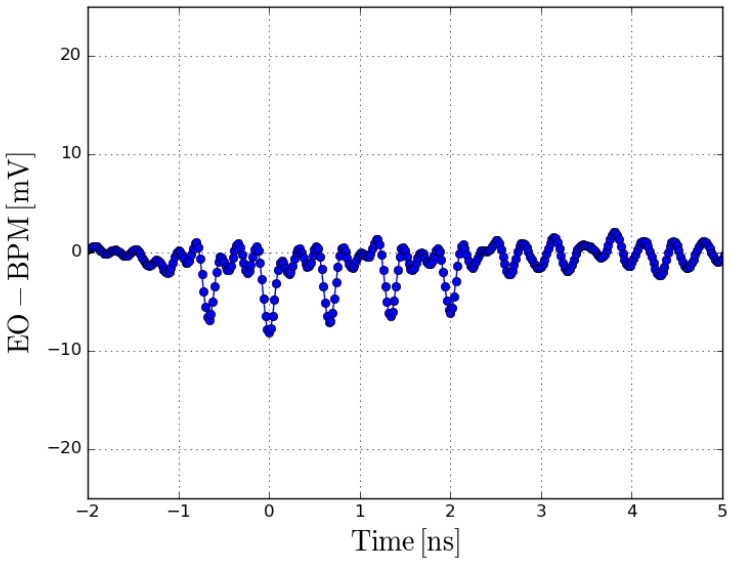




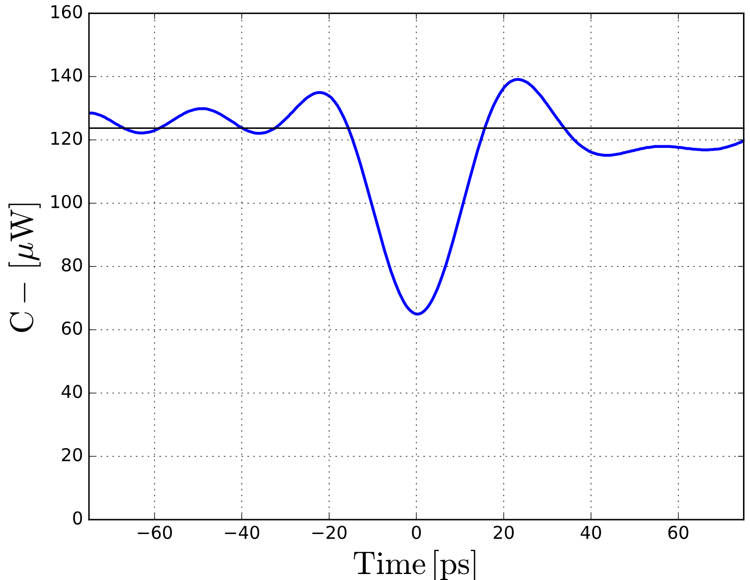


Tested with 200MeV, ps long electron bunch @ CLEAR, measured using 33GHz oscilloscope

Train of 5 bunches spaced by 666ps



Single bunch (*2ps bunch length*) measurement



- Measured time response of the EO BPM ~30ps FWHM
- Well within the expected EO-BPM design and our specifications