HiLumi
HL-LHC PROJECT

HL-LHC COLLABORATION MEETING
GENOA, ITALY, 7-10 October 2024

Status of the UK contributions for Beam Instrumentation and Collimation

Stephen Gibson with thanks for material from:

BGC	C.P. Welsch, H. Zhang, D. Butti, R. Veness & BGC collaboration
EO-BPM	M. Bosman, D. Harryman, A. Arteche, T. Levens, T. Lefevre
IR-BPM	P. Burrows, D. Bett, M. Krupa
Collimation	R. Appleby, D. Christie, B. Lindström, C.E. Montanari, R. Bruce, S. Redaelli

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Scope: UK contributions within HL-LHC-UK*

WP13 Beam Instrumentation

- WP13.2 Beam-Gas Curtain monitor [BGC]
  - See talks by: D. Butti and R. Veness
- WP13.3 Interaction Region BPMs [BPM]
  - See talk by M. Krupa
- WP13.5 Electro-Optic High Bandwidth BPM [BPW]
  - See talks by: M. Bosman and T. Lefevre
- *out of scope: earlier UK-CERN student contributions on WP13.6 BSR & WP13.7 BGI
  - See talks by J. Pucek & J. Storey

WP5 Collimation studies

- Collimation MDs and new optics studies
  - See talk by B. Lindström
- Beam Halo studies: diffusion measurement and chaos indicators
  - See talk by C.E. Montanari + Dynamic Aperture studies, D Christie

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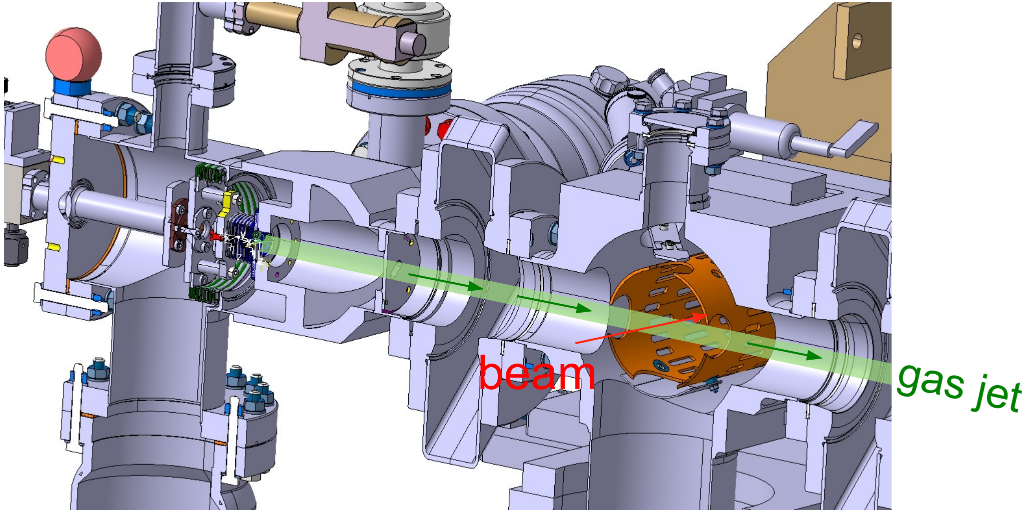
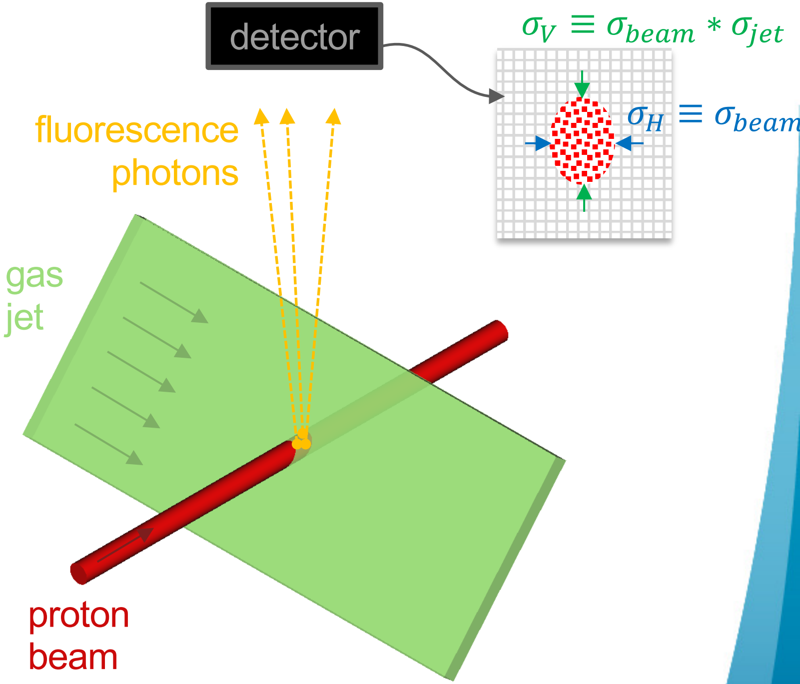
WP13.2: Beam-Gas Curtain monitor principle





- Supersonic gas-jet produced by differential pumping
- Sequence of skimmers shape gas-jet into a thin, curtain that diagonally intersects the proton beam
- Beam-gas interactions generate fluorescence photons, from which the transverse beam size is determined.

Ne gas, fluorescence line at 585nm

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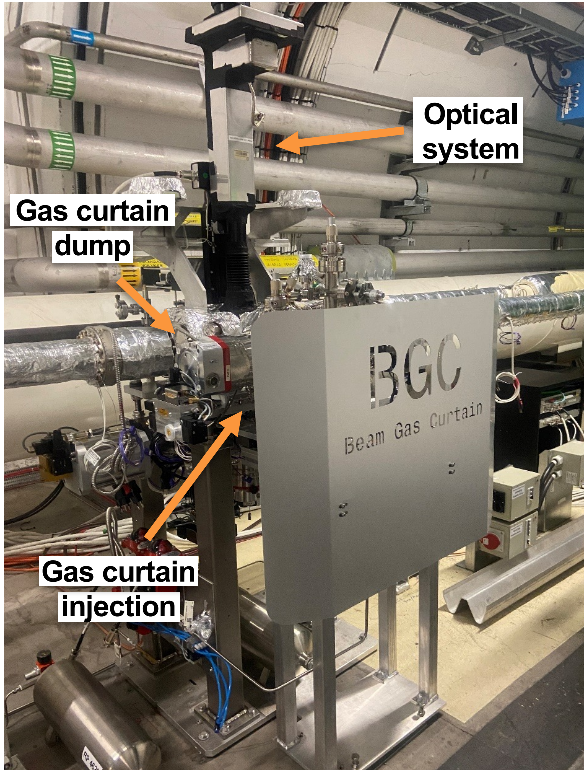
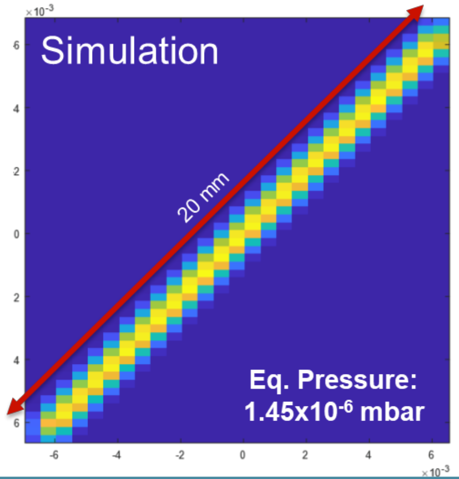
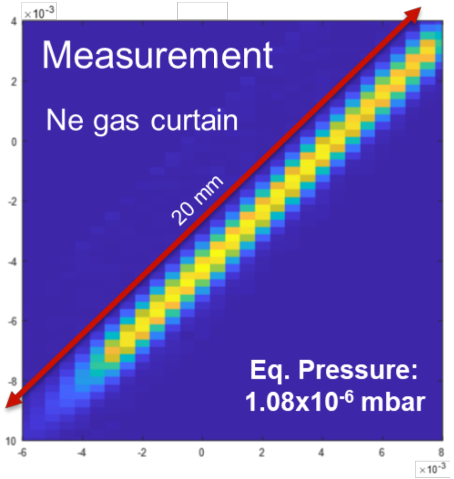
BGC installation in LHC





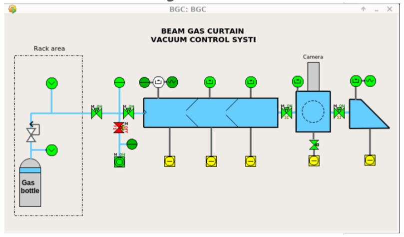
H. Zhang et. al, Vacuum **208**, 111701, 2023.



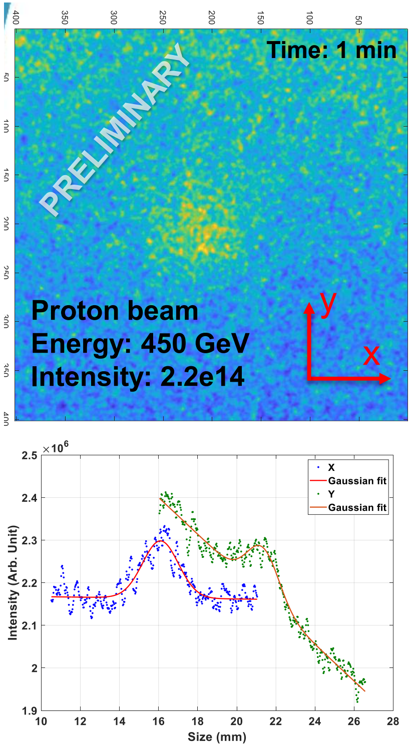
C. Castro Sequeiro, PRAB **27**, 043201, 2024.

- BGC integrated into vacuum control system

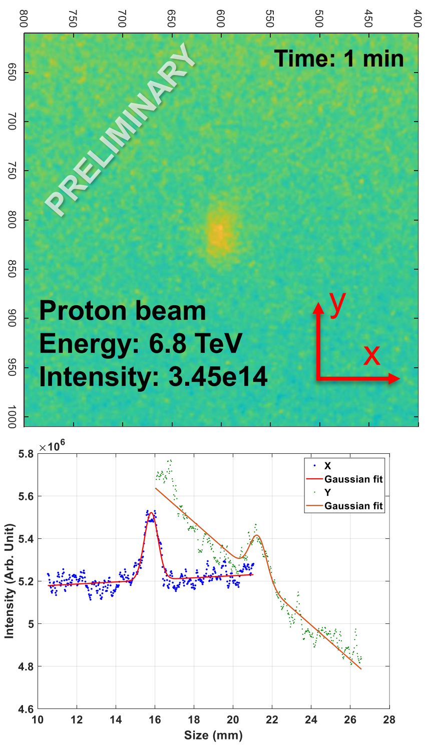
Interaction chamber (VGP.4a.5L4.BGC)	Pressure [mbar]
Ne gas Jet OFF	2.0e-10
Ne gas Jet ON	4.00e-8



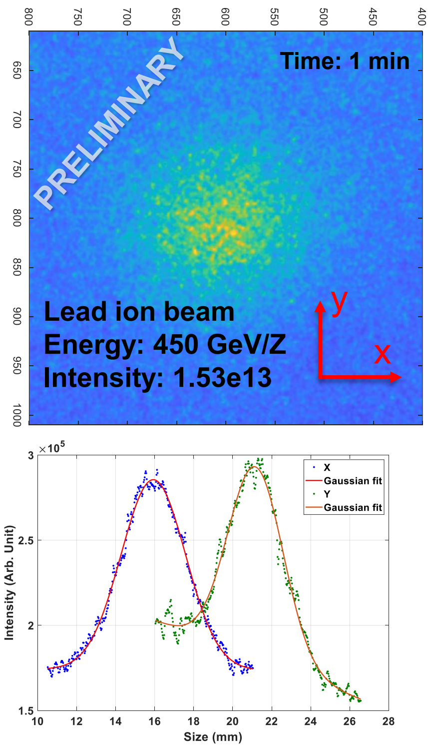
Typical measurements



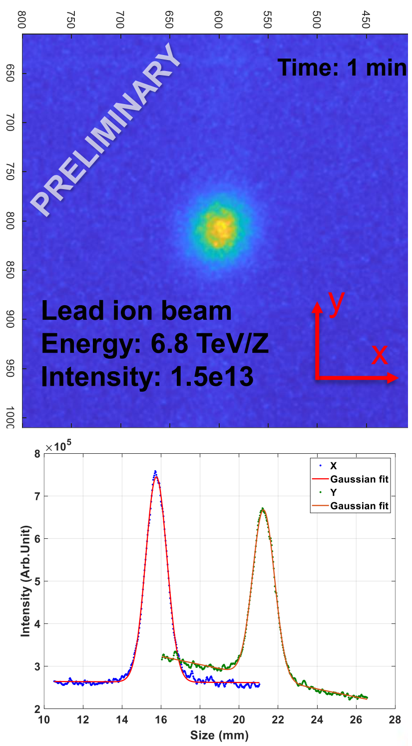
σ_x =0.917mm σ_y =0.817 mm



σ_x =0.308 mm σ_y =0.432 mm



σ_x =1.653 mm σ_y =1.418 mm.



σ_x =0.543 mm σ_y =0.589 mm

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LHC Operation summary

- **2023**
  - ~10 h gas injection for 2023 proton beams – Validation
  - >70 h gas injection for 2023 lead ion beams – Validation & systematic study
- **2024**
  - Gas injection for 2024 proton beams – Validation & systematic study & fluorescence cross-section study.
  - Currently gas injection for 2024 lead ion beams – fluorescence cross-section study.

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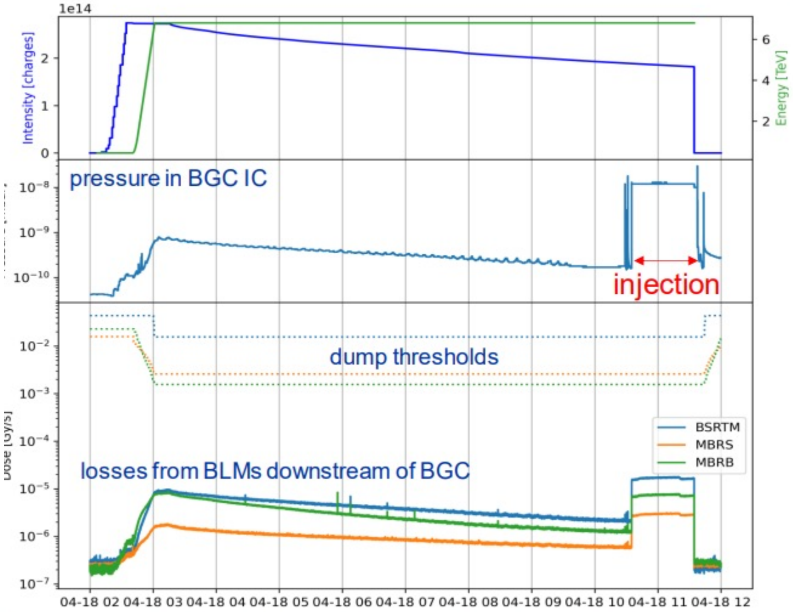
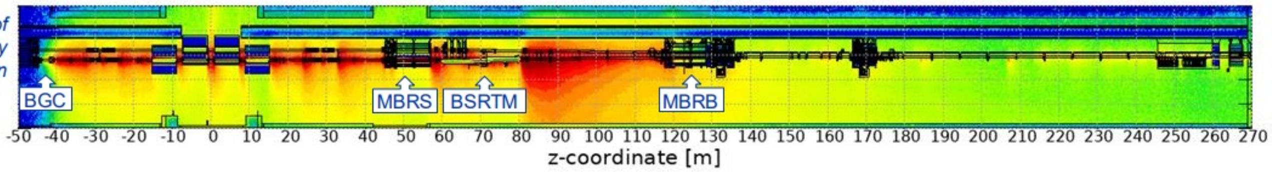
Beam loss due to BGC

- Injection – no losses above noise in CCC Fixed display
- Stable Beams – local increase by 7.5e-20 Gy/s/p in P4 (~2-3x above noise), <1% of dump losses
- Far from dump thresholds, but BGC effect clearly distinguishable on BLMs (8 x baseline)



FLUKA simulation of BGC induced dose by D. Prelipcean



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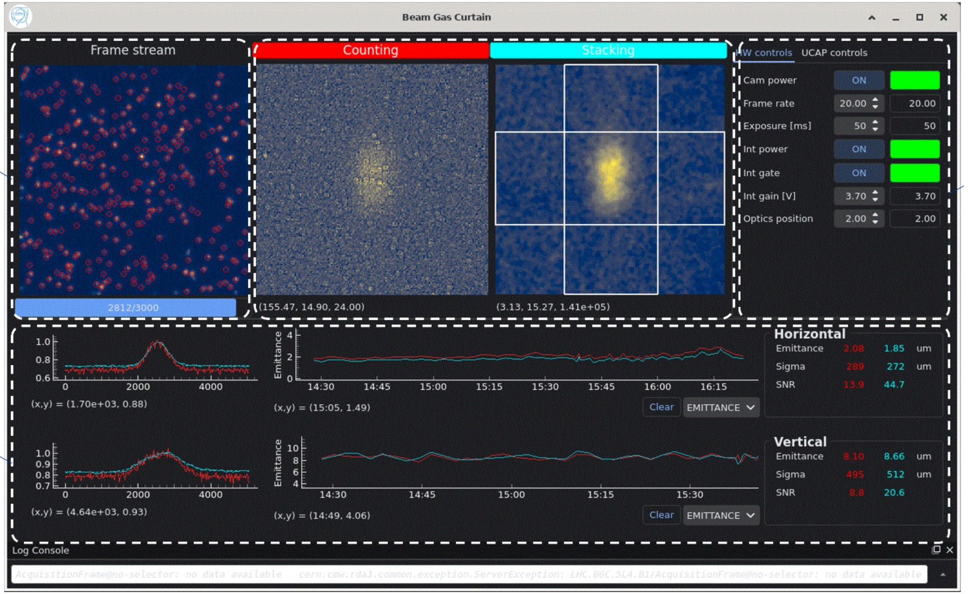
Real-time display of BGC images

Integrated images

Single frames with photon detection

Profiles and fit results



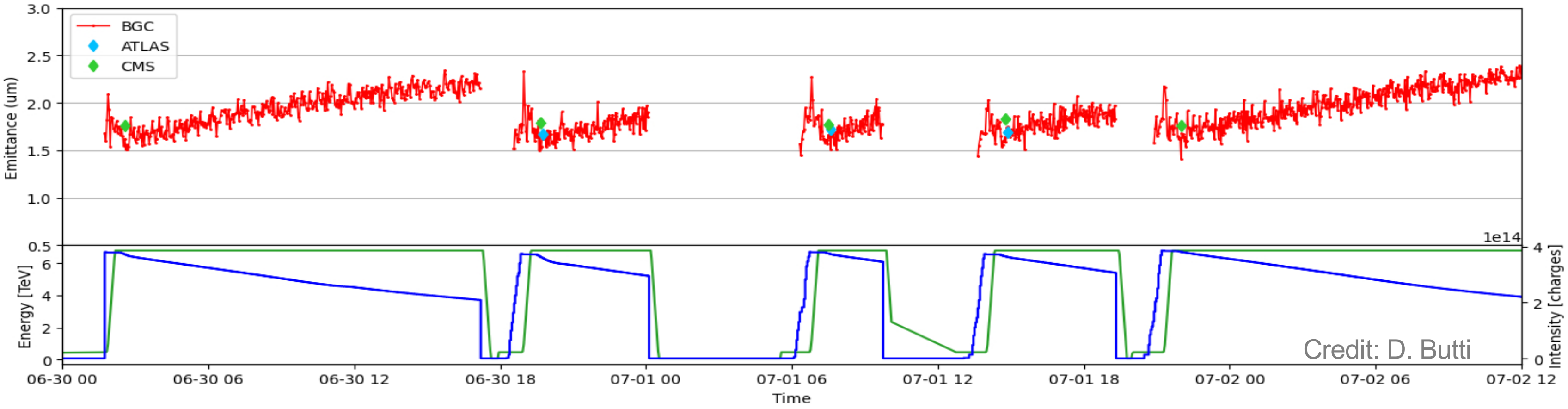
Credit: D. Butti

- 20 Hz processing @ 400x400 pixel ROI.
- Both photon counting and intensity stacking strategies available for direct comparison.
- Machine variables (optics, energy…) automatically imported from CERN control system.

Comparison with ATLAS and CMS

Horizontal emittance over some fills

- quantitatively ok and comparable with emittance scans.
- growth resolvable for stable beams.
- shows residual spikes in ramp. Investigations are needed to check if instrumental artefact or actual data.

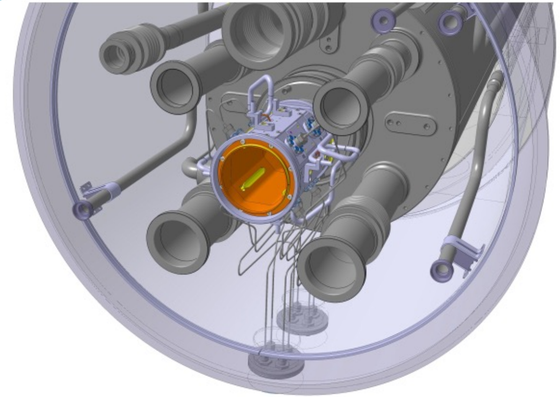


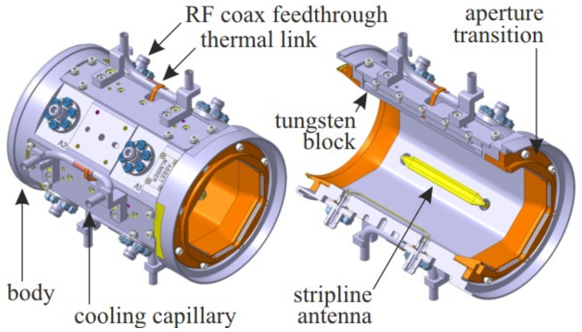
WP13.2: BGC monitor highlights & status

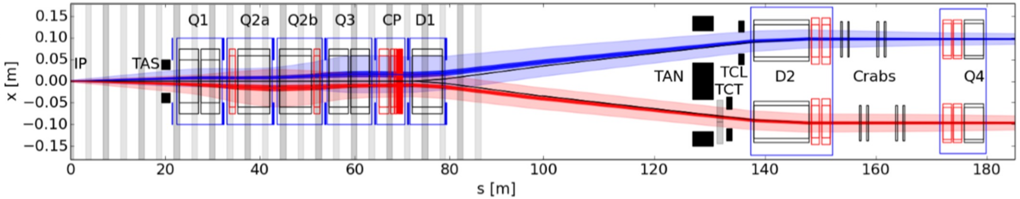
- **BGC monitor** successfully **installed** and **commissioned** on the **LHC.**
- **2D beam profile** of **proton** and **lead ion** beams in 2023 for **injection**, **energy ramp** and **stable beams.**
- Comparison for the horizontal size coincide within the expected uncertainty.
- Developing the BGC monitor as a **standard LHC operational instrument.**
- 2024 run allowed for **systematic studies** with protons and comparison with other devices.

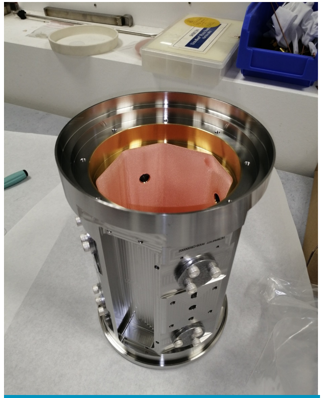
- **Procurement** started for installation of another BGC for Beam 2 during LS3.
- Significant visibility through **talks** at IPAC'24 and IBIC 2024.
- A **new PhD student** starting in October 2024.
- Activities based on BGC have grown further, particularly in medical applications (halo monitor).

WP13.3: Interaction Region BPMs



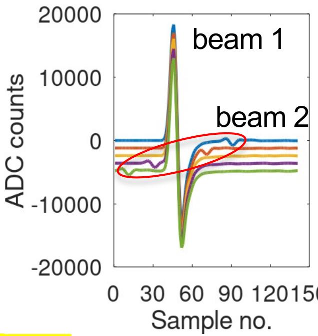


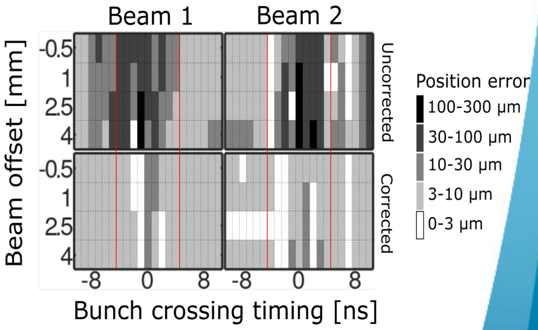




Coated pre-series body at CERN

- Stripline pickups sensitive to beam direction for the cryogenic combined beam sections
- New electronics on state-of-the-art RFSoC chip
- Counter beam compensation algorithm applied to two-beam waveforms:





See Weds talk by M. Krupa

Details in IPAC23: THPL089 & THPL119 + IBIC20 WEPP12 and IBIC21 MOPP24:

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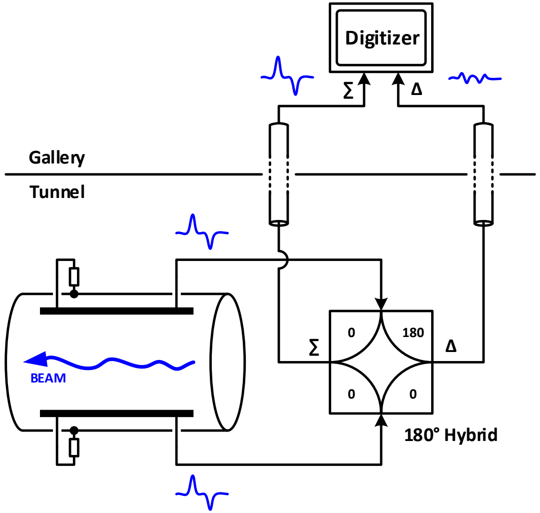
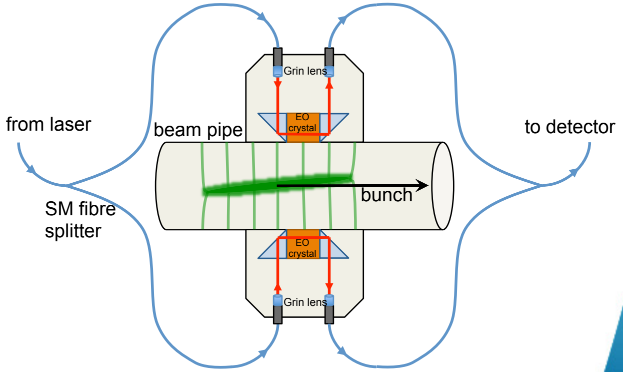
D. Bett, P. Burrows et al

WP13.5: Electro-Optic High Bandwidth BPM

- Existing high-bandwidth "Head-Tail" monitors
  - Measurement of transverse instabilities
  - Measurement of crab-cavities
- Limited in bandwidth & resolution by imperfections of pick-up, hybrid & cables
  - Difficult to achieve significant improvements
- Electro-Optical (EO) BPMs are being studied by WP13, in collaboration with RHUL, as a potential upgrade for higher bandwidth
  - Using birefringent crystals to modulate a laser signal in response to the bunch EM field
  - Fiber coupled interferometer utilises the coherence of light to suppress common mode signal
  - Difference signal measured directly at photodetector

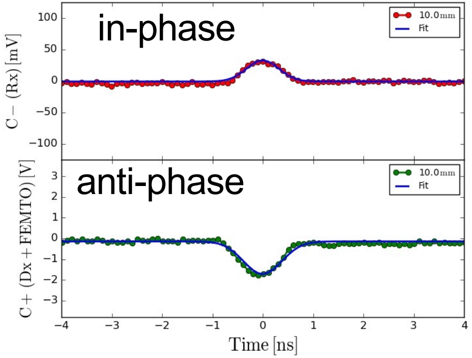




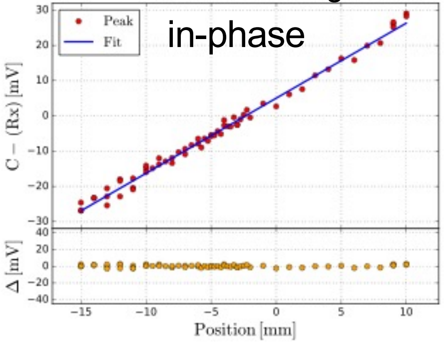
In-air EO-BPM tests at HiRadMat & Clear

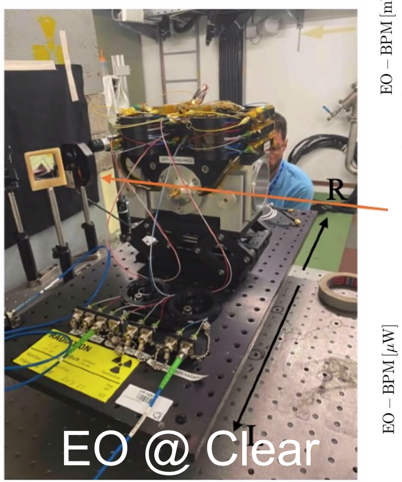
- **2021 HiRadMat: first EO-BPM single-shot measurements:**
  - **Bunch by bunch position measured as EO-BPM translated.**
- **2022 Clear:** measured fast **train of 5 *electron bunches***
- High bandwidth photodetector shows **time resolution** of EO pick-up is well **within the < *50 ps* specification** required for 1ns HL-LHC bunches

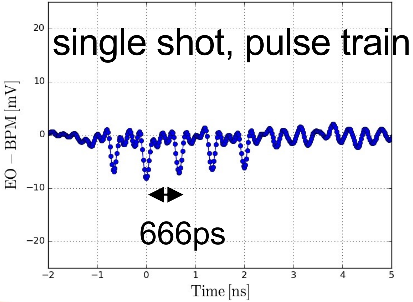
Typical single-shot signals:

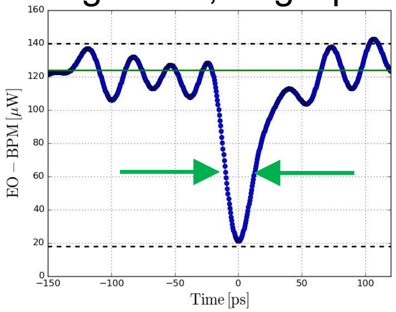


Beam position scan by moving EO-BPM on stage



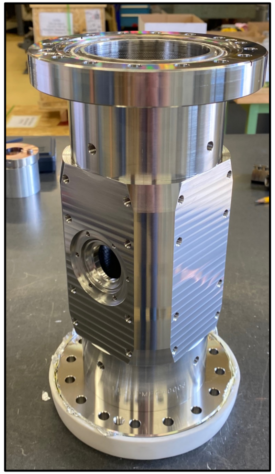




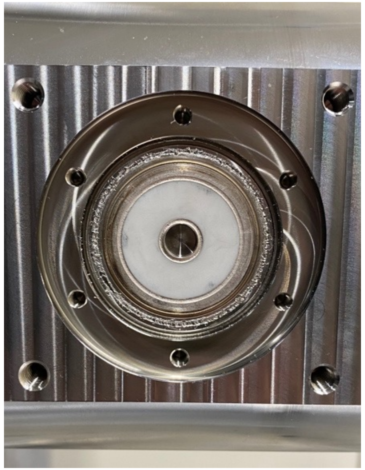


Vacuum compatible EO-BPM

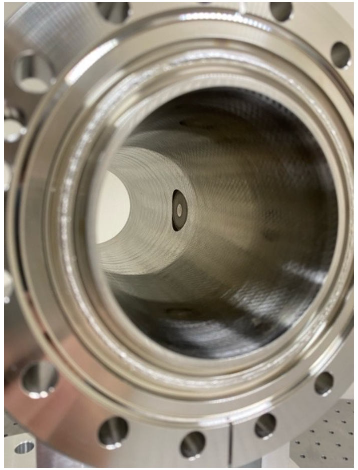
- EO-pick-up incorporated into in-vacuum design for beam tests at the SPS (ideally with crabbed bunches).
- A ceramic washer separates the EO-pickup from SPS vacuum
- 2022: the ceramic washer cracked during brazing, preventing installation in YETS22/23.
- 2023: ceramic washer **successfully brazed and welded** to the body with an airtight seal to be installed in beampipe.



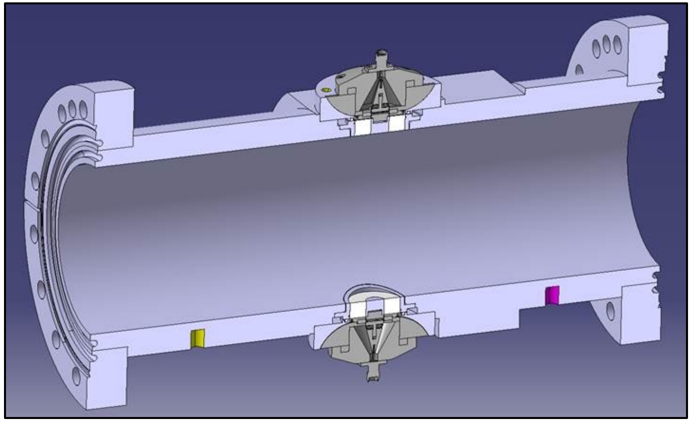
EO body

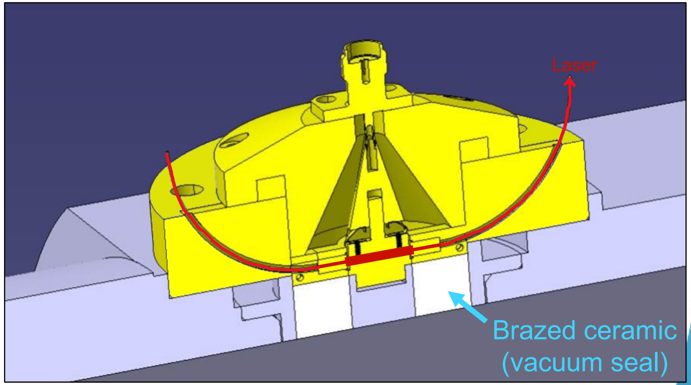


Brazed button



Internal view





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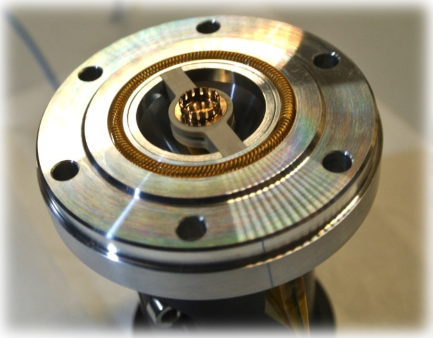
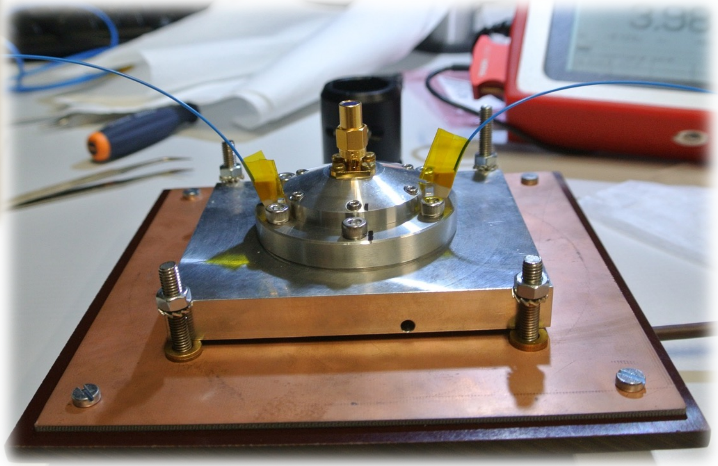
Delivery to CERN of EO-BPM for beam tests at SPS

- EO waveguide pickups built, tested and installed onto brazed-button EOBPM for CERN SPS tests.

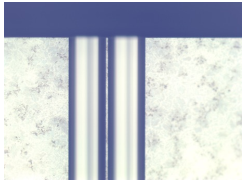
EO waveguide built into pickup

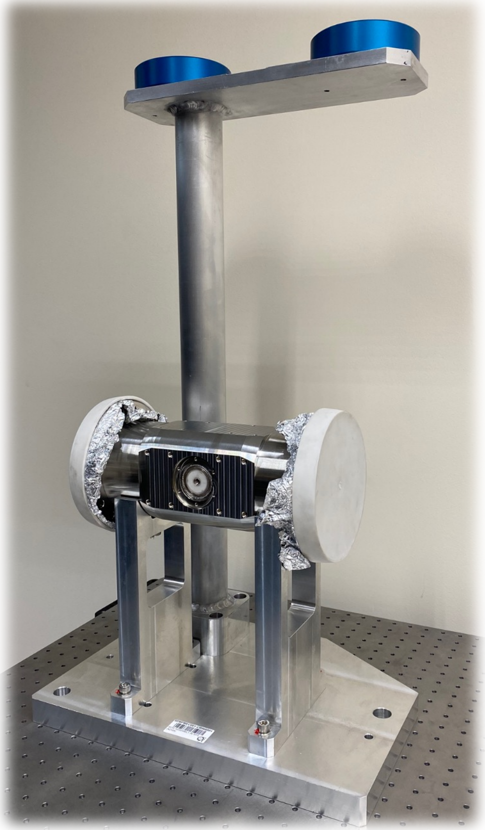


EO pickup test prior to BPM assembly



Optical inspection of waveguide in RHUL clean room





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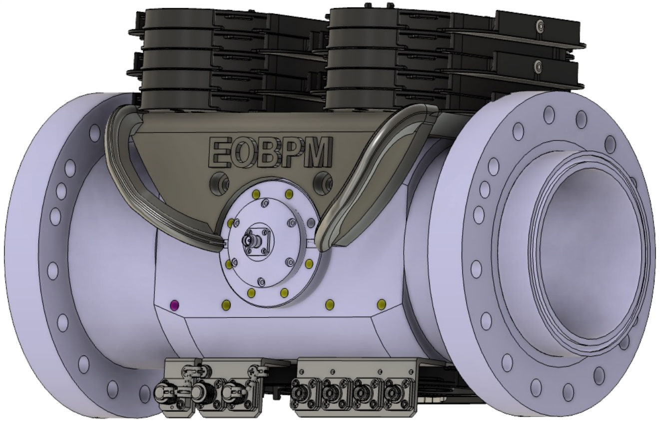
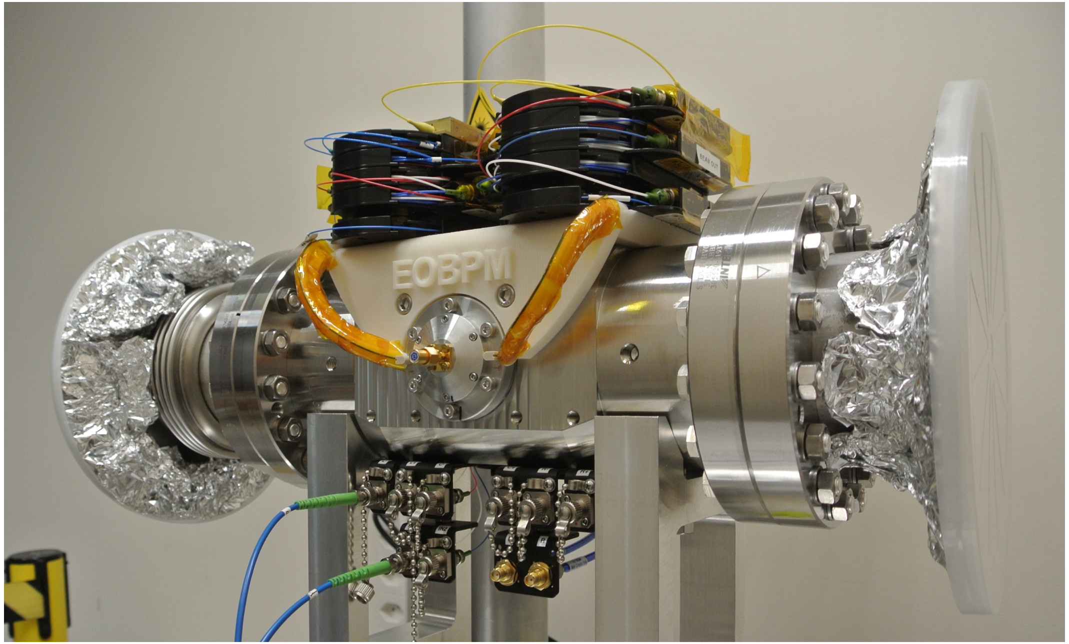
Complete, Dec 2023

Delivery to CERN of EO-BPM for beam tests at SPS

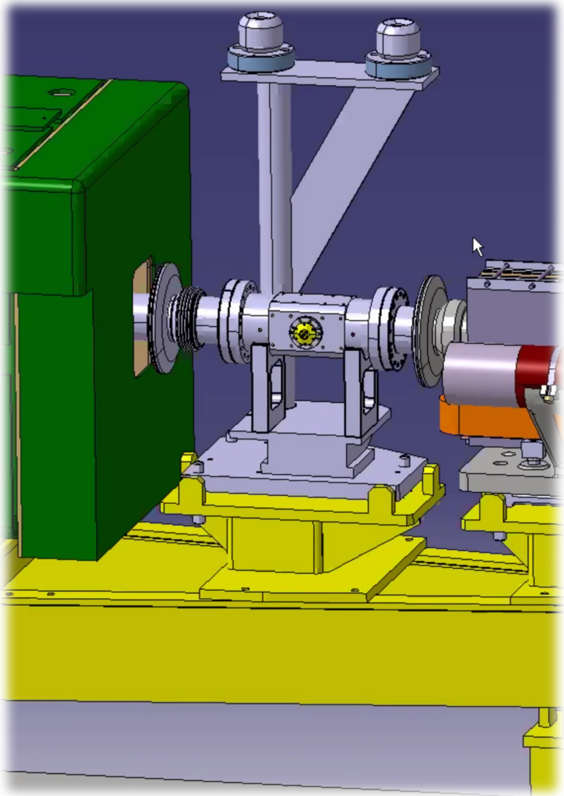
- **EO-BPM demonstrator** assembled and ready for installation in **SPS** for operation in Run 3

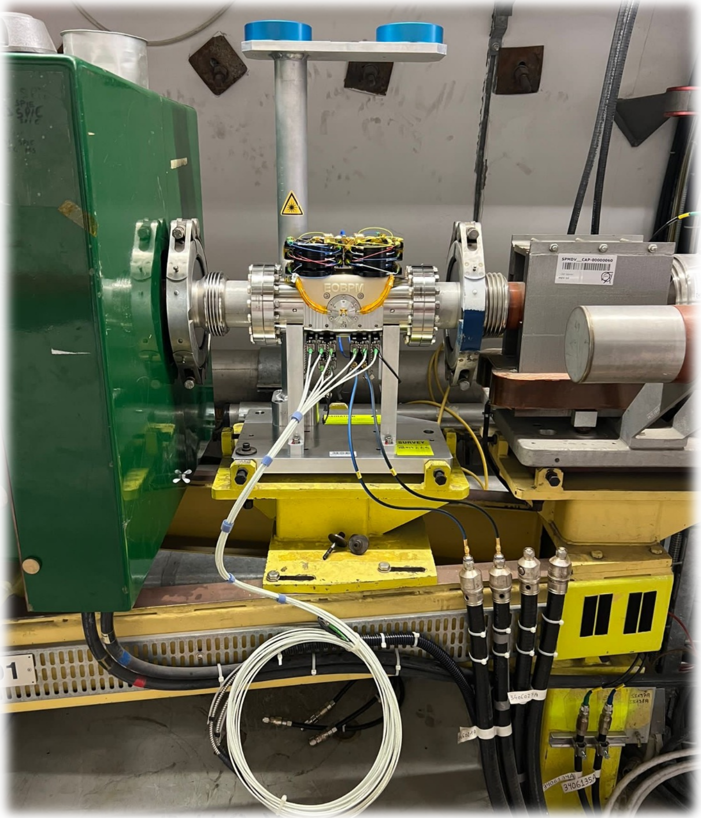




Complete, Jan 2024

EO-BPM demonstrator installed & ready for beam





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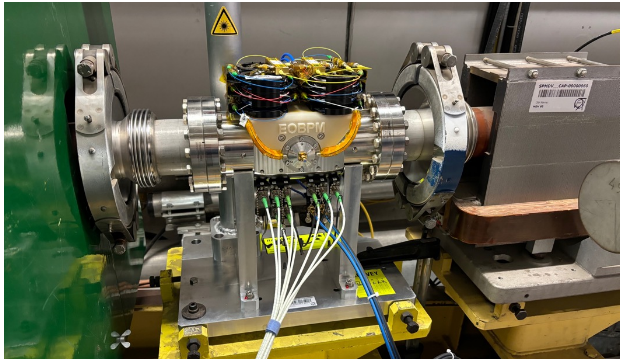
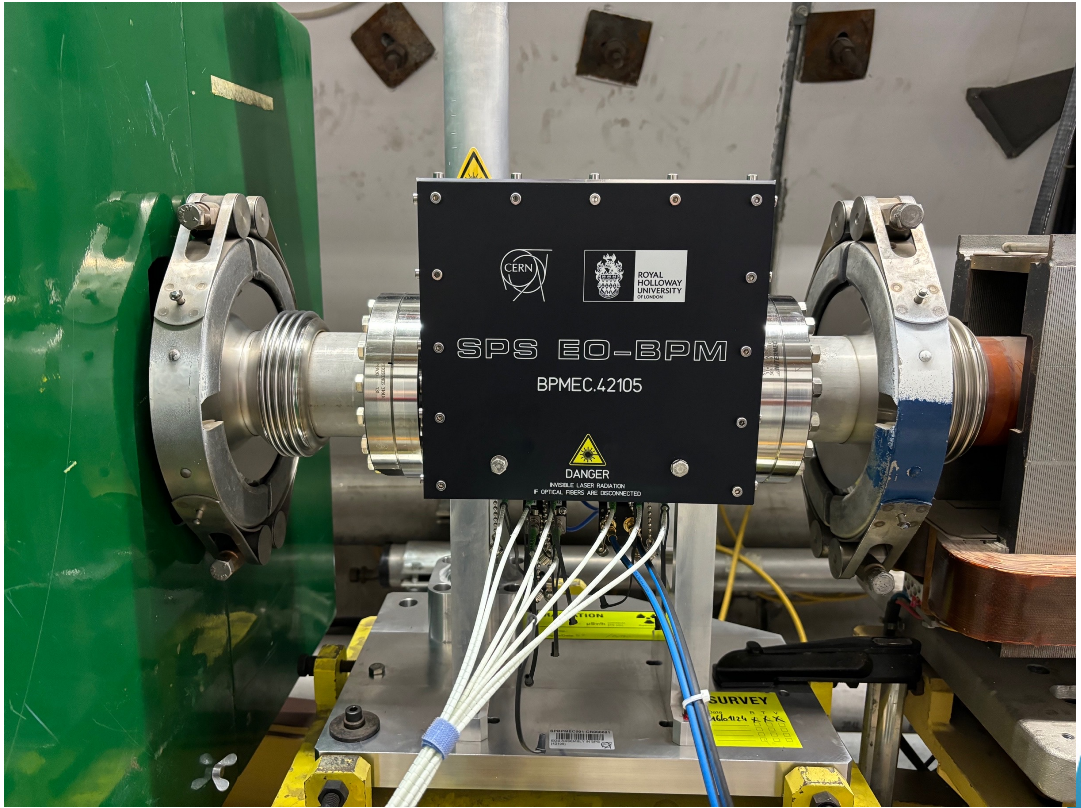
EO-BPM demonstrator installed & ready for beam





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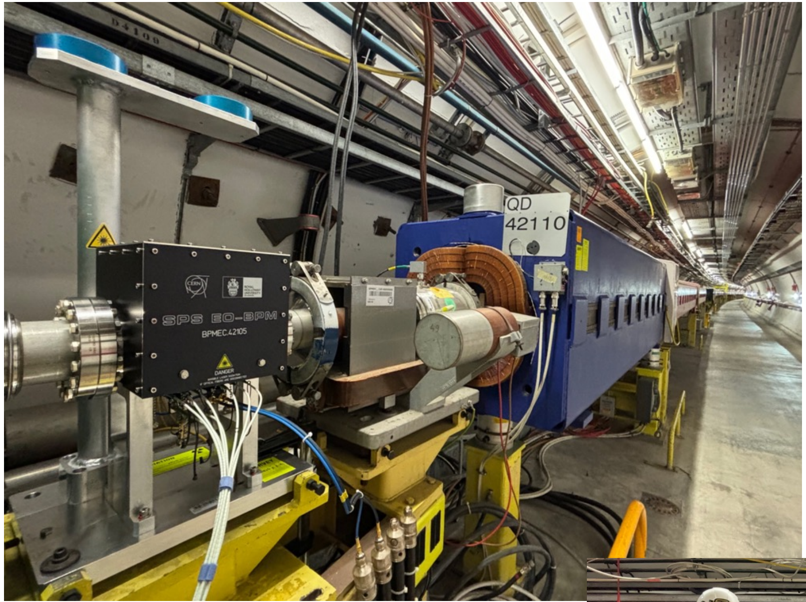
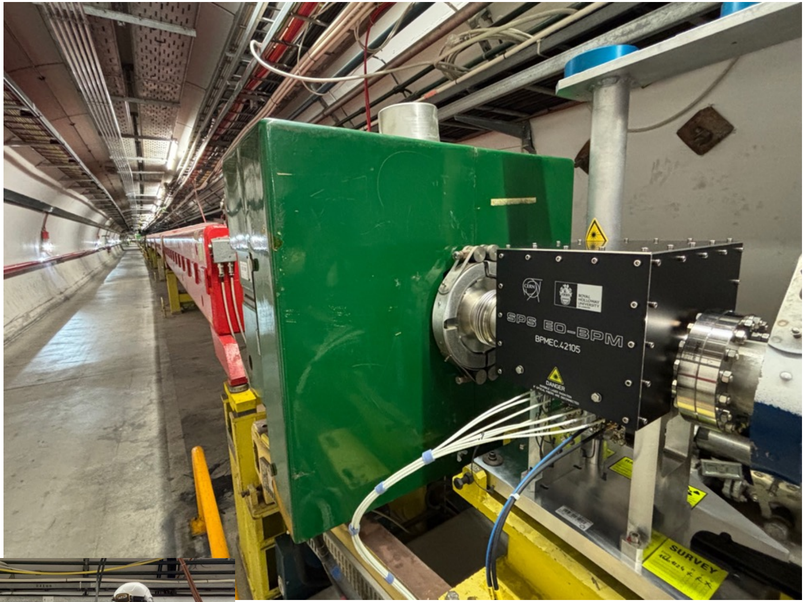
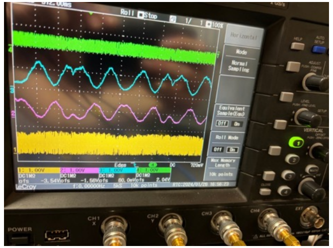
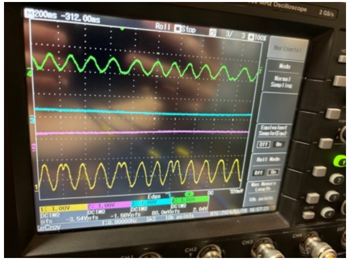
EO-BPM demonstrator installed & ready for beam





C+/-
interferometers

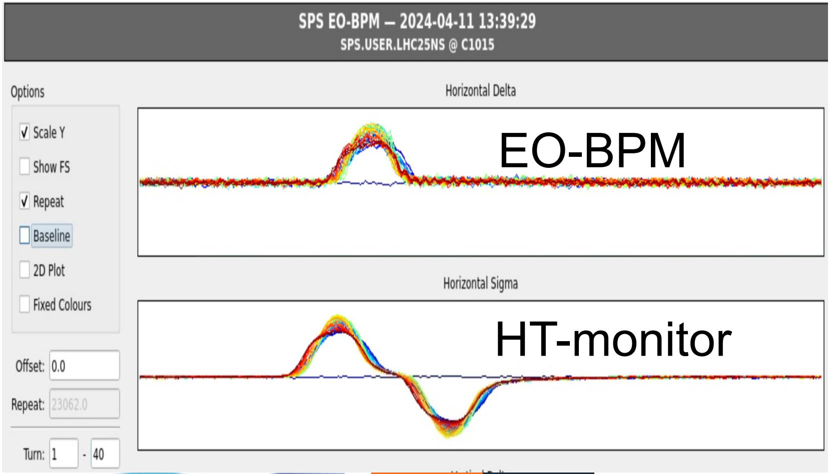


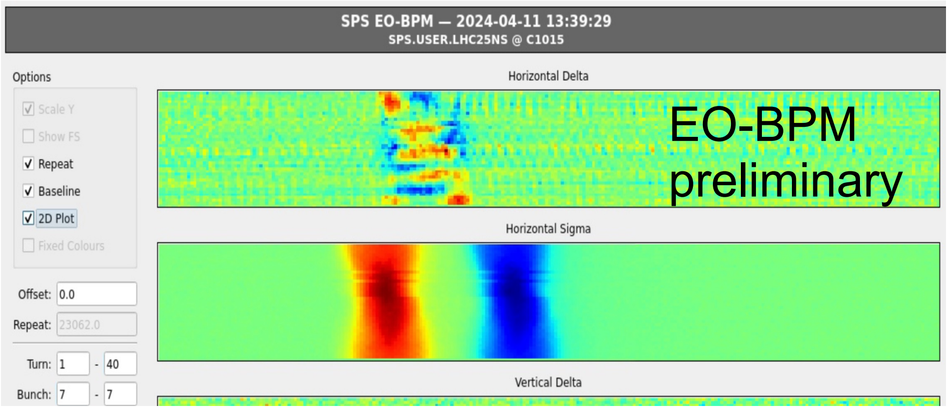


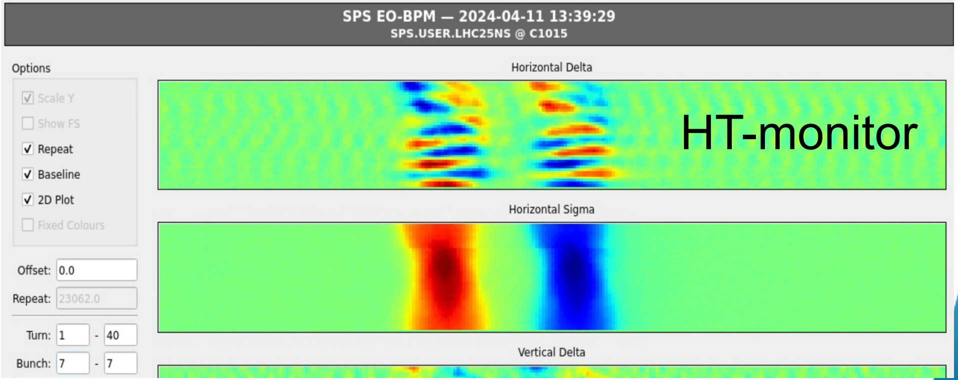
L / R
interferometers

April 2024: SPS results

- First SPS beam data shows good EO-BPM signals allowing first comparison with HT monitor:
- Bunch instability observed with EO-BPM and HT-monitor, measuring same bunch over 40 turns.







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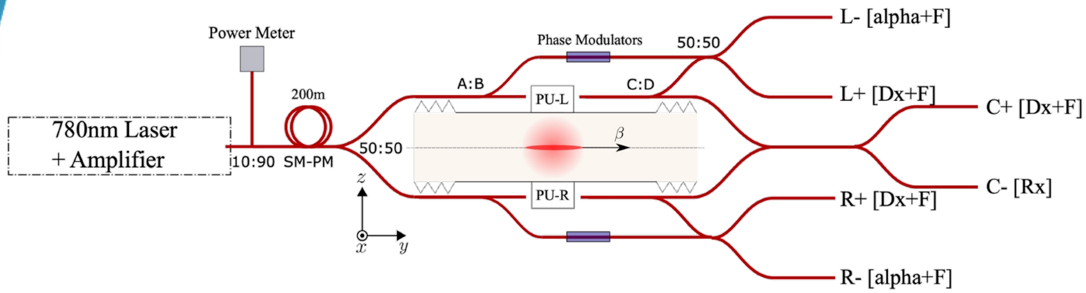
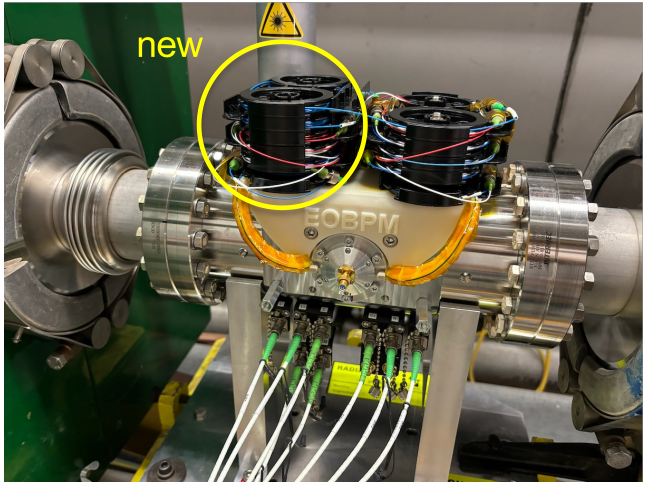
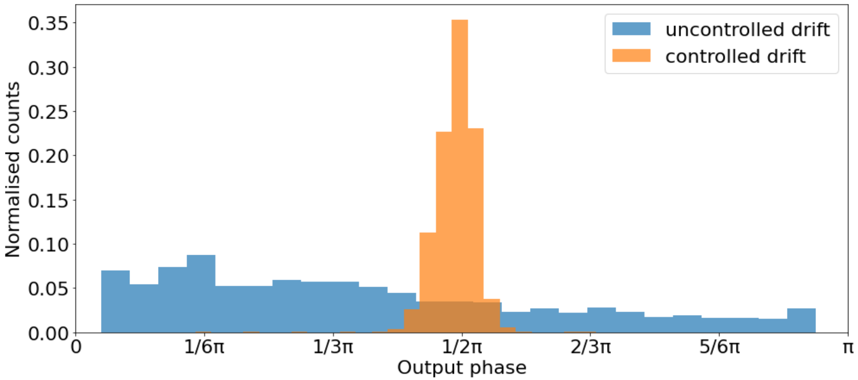
June 2024 TS: upgrade of EO optics



- New optical splitters installed during June 2024 technical stop & phase modulators removed.
- Fibre lengths changed to improve control of left & right interferometers



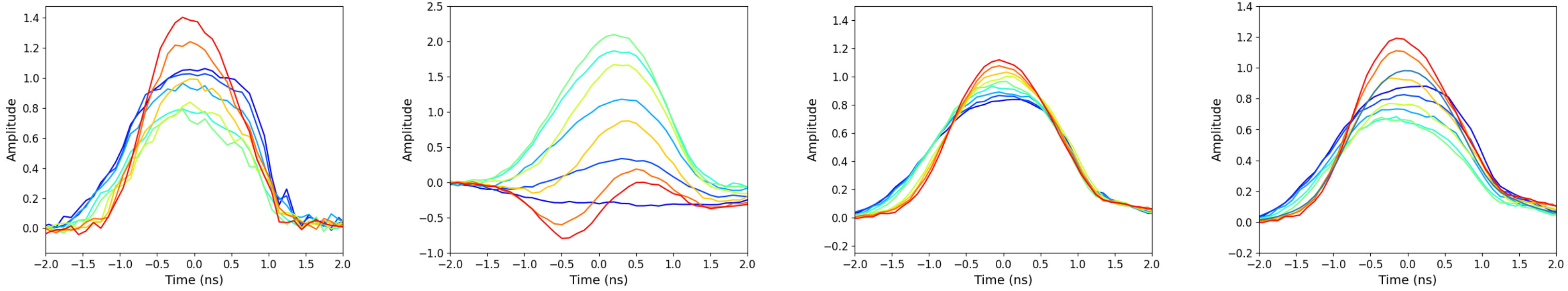
- Active control of working point with laser frequency shown to stabilise of phase drift of the interferometer.



doi:10.18429/JACoW-IBIC2024-TUP46

Sept 24: Turn by turn comparison with HT monitor

IBIC24



(a) EO-BPM (b) HT difference (c) HT sum (d) Combined HT sum & diff.

Figure 6: Turn-by-turn signals from 10 turns of a 2.2E11 proton bunch at injection into the SPS, as measured by the EO-BPM and the Head-Tail Monitor (HT). The signals have been normalised to the peak of the average of all turns. Blue represents the first turn and red represents the last turn.

- EO-BPM **signals follow the fast evolution** of SPS bunch during injection: sensitive to both longitudinal shape and transverse position.
- Known **difference between left and right EO pickups** results in mixture of sum and difference signals in the interferometer difference signal. **Combination of HT sum and difference signals reproduces the EO signal**.
- Modified pick up design required to tune and set the sensitivity of pick-up to beam field signal.

See Weds talk by: M. Bosman

WP13.5: EO-BPM highlights & status

- **Ceramic brazing solved**: vacuum-compatible, waveguide EO-BPM successfully installed in SPS
- **Operational experience gained** with EOBPM during 2024 run has enabled:
  - **Active control** of interferometer working point to stabilise phase drift.
  - **Tests of beam position sensitivity** with beam bumps: observe offset compatible with assembly imperfections between left and right pickups.
  - **Assessment of dynamic range** to bunch charge; depends on **laser power** and **detection** system.
  - EO single-shot measurements are **sensitive at high bandwidths to intra-bunch motion**.
  - Comparison with Head Tail monitor shows how **sum and difference signals combine to give EO signal**, as expected for imbalanced pickups: results presented at IBIC2024.

Future steps:

- Highly sensitive EO pick-up may over-rotate phase signal at high bunch charges. Mitigate by implementing **phase extraction method to improve dynamic range.**
- Improve design with fine-adjustable mechanics to **set the balance** during assembly.
  - Plan to **review high bandwidth technology** for HL-LHC in the coming months

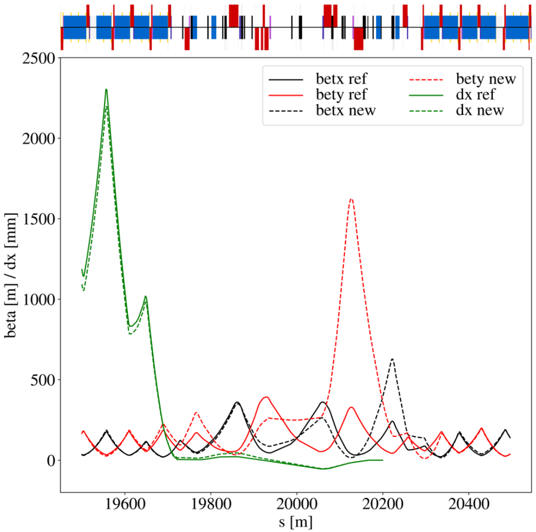
See Weds talk by: M. Bosman

WP5 Collimation Studies

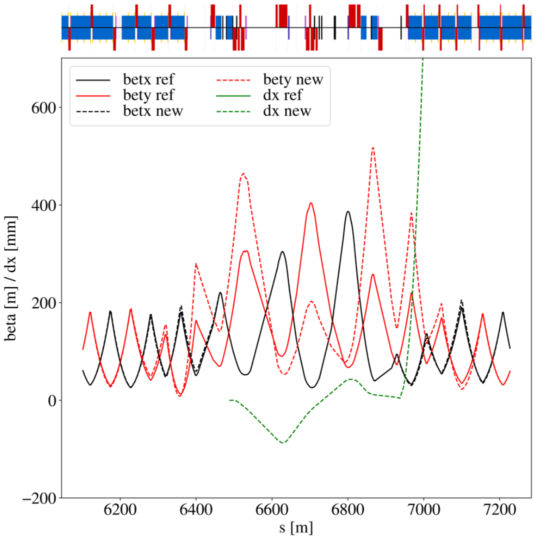
Why new collimation optics?

- HL-LHC beam intensity and brightness produces significant challenges:
  - Beam losses in IR7 DS could cause quenches
  - Impedance can cause instabilities
- Strategy:
  - **IR7:** Use new optics with improved cleaning and impedance
    - Keep collimator settings in sigma
  - **IR3:** relax collimator settings, or use new optics
    - For impedance, **only if needed**

New IR7 optics[1,2]



1: R. Bruce et al, doi:10.18429/JACoW-IPAC2021-MOPAB006
2: B. Lindström et al, doi:10.18429/JACoW-HB2023-TUC4C2



New IR3 optics

IR3 collimation is mostly horizontal
Idea: reduce problematic vertical beta peak, while keeping horizontal plane unchanged

See talk by: B. Lindström

John Adams Institute for Accelerator Science

Collimator MD studies

- MD7203: New IR7 optics for improved cleaning and impedance
  - Proposed by WP5, 3 years ago as proof of concept
  - Only IR7 changed
  - FT only, real cycle requires combined ramp & desqueeze
  - Scheduled in 2022 and 2023, but suffered from machine availability
  - 2024-05-16 – successfully tested main objectives!

- MD11243: HL-LHC cycle
  - Proposed by WP2
  - New optics whole machine, integrated IR3 and IR7 optics in cycle
  - Feasibility assessment of IR3 / IR7 desqueeze during ramp
  - 2024-06-06 / 2024-06-08 / 2024-06-24 / 2024-09-29

- MD11843: Collimation performance with HL-LHC settings
  - Comparison of 2024 collimator settings and HL-LHC tight and relaxed
  - Comparison of 2024 optics, IR7 squeeze only and complete HL cycle optics
  - 2024-09-29

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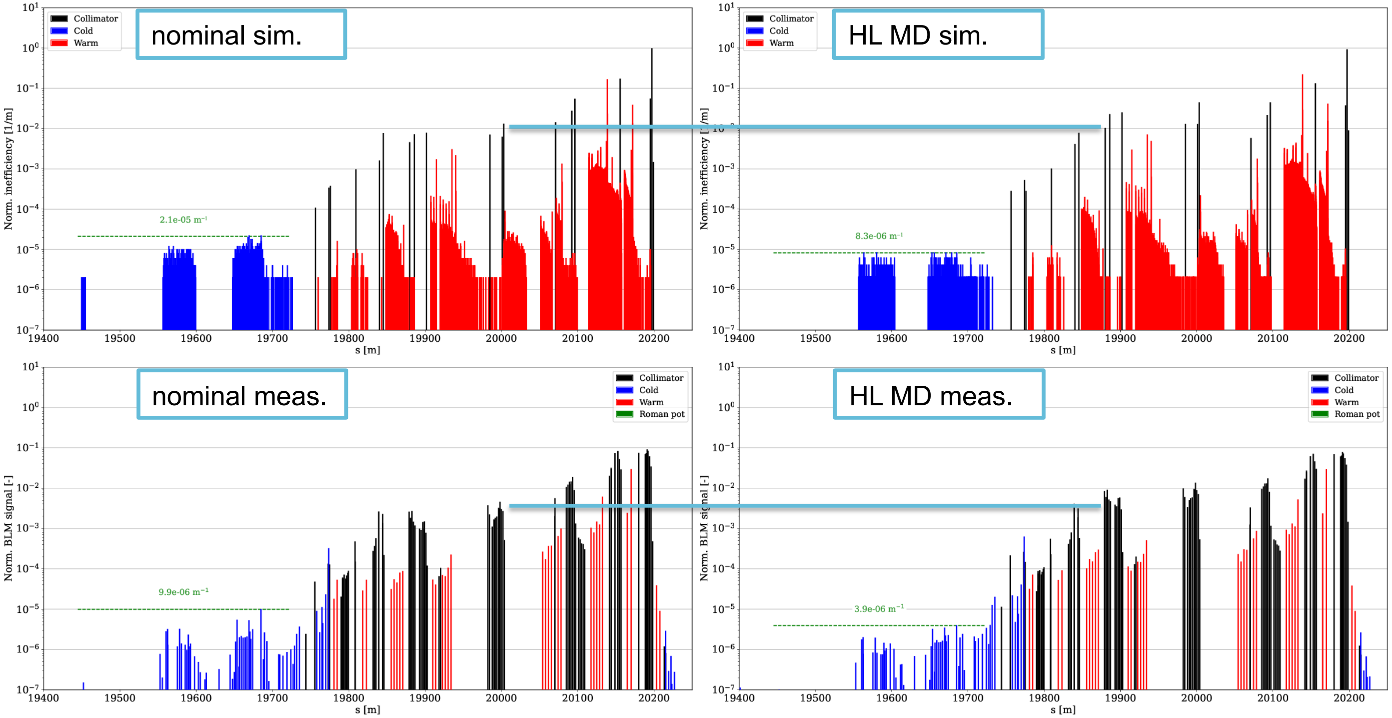
See talk by: B. Lindström

Collimator MD: IR7, B2H losses (FT – HL MD)

- Simulated 61 % improvement – measured 61 % *(σ=7.4 %)*
- Secondary stages catch more losses – less leakage to DS



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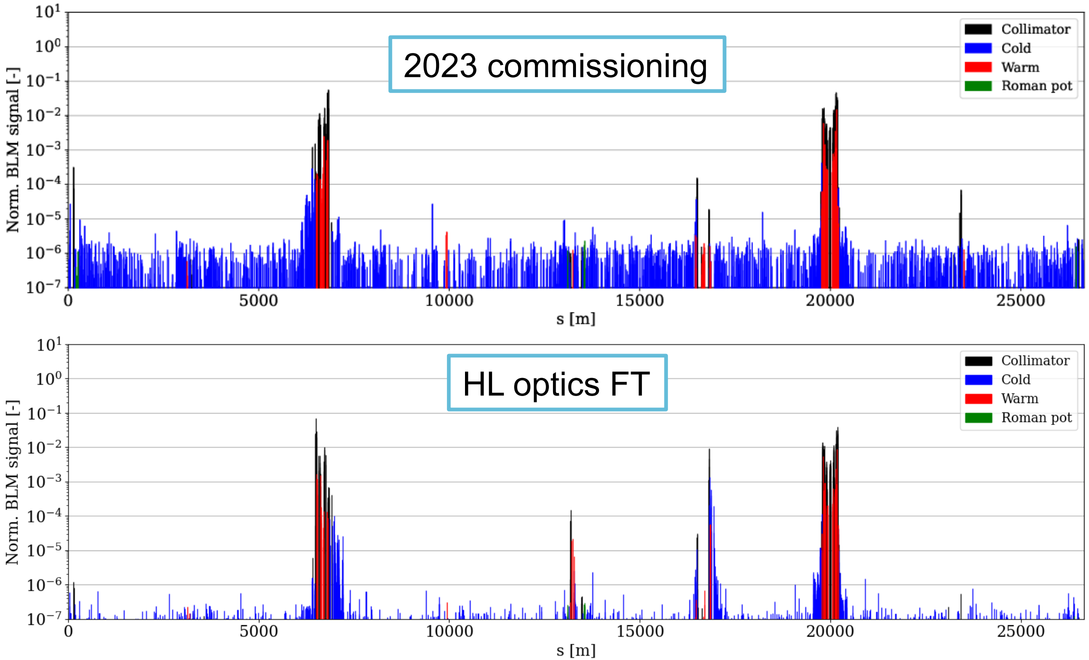
Collimator MD: Off-momentum loss maps

- Could only do negative
- Similar balance IR3 / IR7 and TCT losses
- Large increase in IR6, possibly due to new optics and different TCDQ setting



Conclusions:

- Very promising results on cleaning performance
  - DS leakage cut by 19 - 61 % in all cases
  - Simulations seem to overestimate the improvement in some cases
    - detailed analysis ongoing
  - TCT losses increase but can be mitigated if necessary
    - phase advance constraint already planned for HL optics
  - IR3 / IR7 loss balance shifts – in general larger fraction of losses in IR7
- Significant reduction of impedance by 19 – 33 %
  - B1H could not be measured
- IR7 Aperture > 28 sigma

See talk by: B. Lindström

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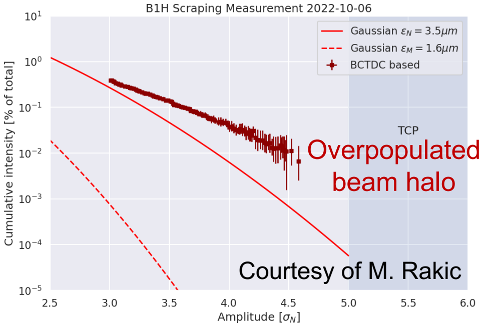
Collimator MD studies

- Tighter settings for smaller beta*
- Proton studies:
  - Halo measurements (population, diffusion, removal)
  - New optics for the collimation insertions
  - B1 quench test with protons
  - Impedance and stability limits / models
  - Crystal characterization and energy ramp
  - Study of Run4 commissioning scenarios
- Ion MDs:
  - Crystal collimation quench test
  - Collimation with different crystal settings

See talk by: B. Lindström

Modelling and measurements of Beam Halo

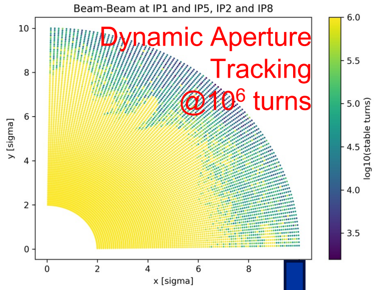
- **Transverse beam halo** (particles >3 σ_N) can be **overpopulated**
  - up to 5% total intensity
  - potential risks for operation
- Absence of mitigation tools demands modelling to understand beam halo formation for HL-LHC target intensities.

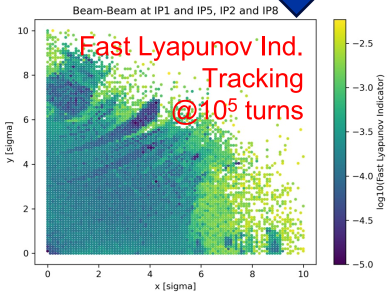


Chaos indicators for enhancing single-particle tracking

- Chaos: sensitivity of a particle orbit to initial perturbations
- Investigating applications of advanced chaos indicators
- Seek connection between chaos presence, diffusive behaviours, and beam halo formation:

Courtesy of C.E. Montanari



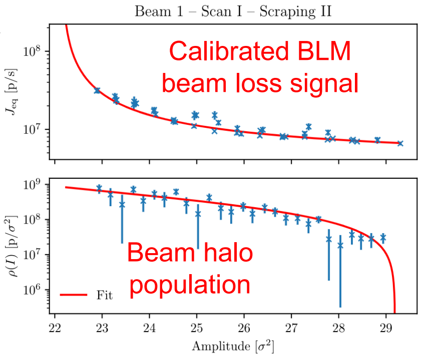


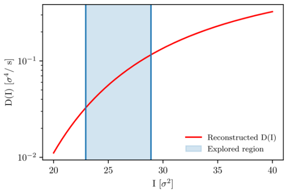
Global diffusion models for beam halo evolution

- Describe beam halo evolution by means of a Fokker-Planck equation
  - Natural extension of established Dynamic Aperture scale laws
  - Link between beam halo population and beam loss signal at different collimator amplitudes
- Promising measurements performed

$$\frac{\partial \rho(I,t)}{\partial t} = \frac{1}{2}\frac{\partial}{\partial I} D(I) \frac{\partial}{\partial I}\rho(I,t)$$

Diffusion reconstruction in LHC





See talk by: C. E. Montanari

Time Dependence of Dynamic Aperture

Background

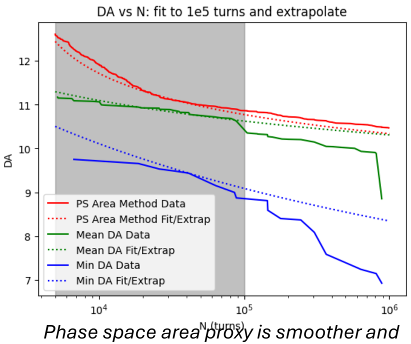
- Particles starting at amplitude *r* will survive *N* turns
- Fitting parameters r_*, κ, N_0 and λ based on simulation data (e.g. <10^5 turns), and inverting, will allow longer-term predictions (e.g. > 10^6 turns…) of DA as a function of N
- Special cases:
  - "Model 2":
  - λ =0;
  - $D(N) = r_* \left[\ln \frac{N}{N_0}\right]^{-\kappa}$
  - Nekhoroshev:
  - $\lambda = \frac{1}{2}, \quad N_0 = \frac{7\sqrt{6}}{48} r_*^{\lambda}$

$$\frac{N}{N_0} = \left(\frac{r}{r_*}\right)^{\lambda} \exp\left[\left(\frac{r_*}{r}\right)^{\frac{1}{\kappa}}\right]$$

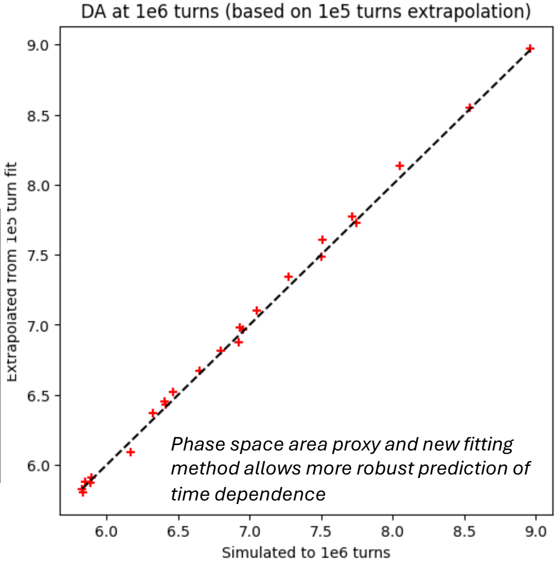
Bazzani et al,
https://doi.org/10.1103/PhysRevAccelBeams.22.104003

Recent Progress

- Developed procedure/formulae for fit parameters r_*, κ, N_0 and λ (based on gradients/reference points in N v r curve)
- Defined a DA proxy based on phase space area, more amenable to fitting than standard min/mean/RMS value of largest connected amplitude
- Tested method on set of octupole/ppb configurations (see scatter plot)



Phase space area proxy is smoother and easier to fit than standard DA



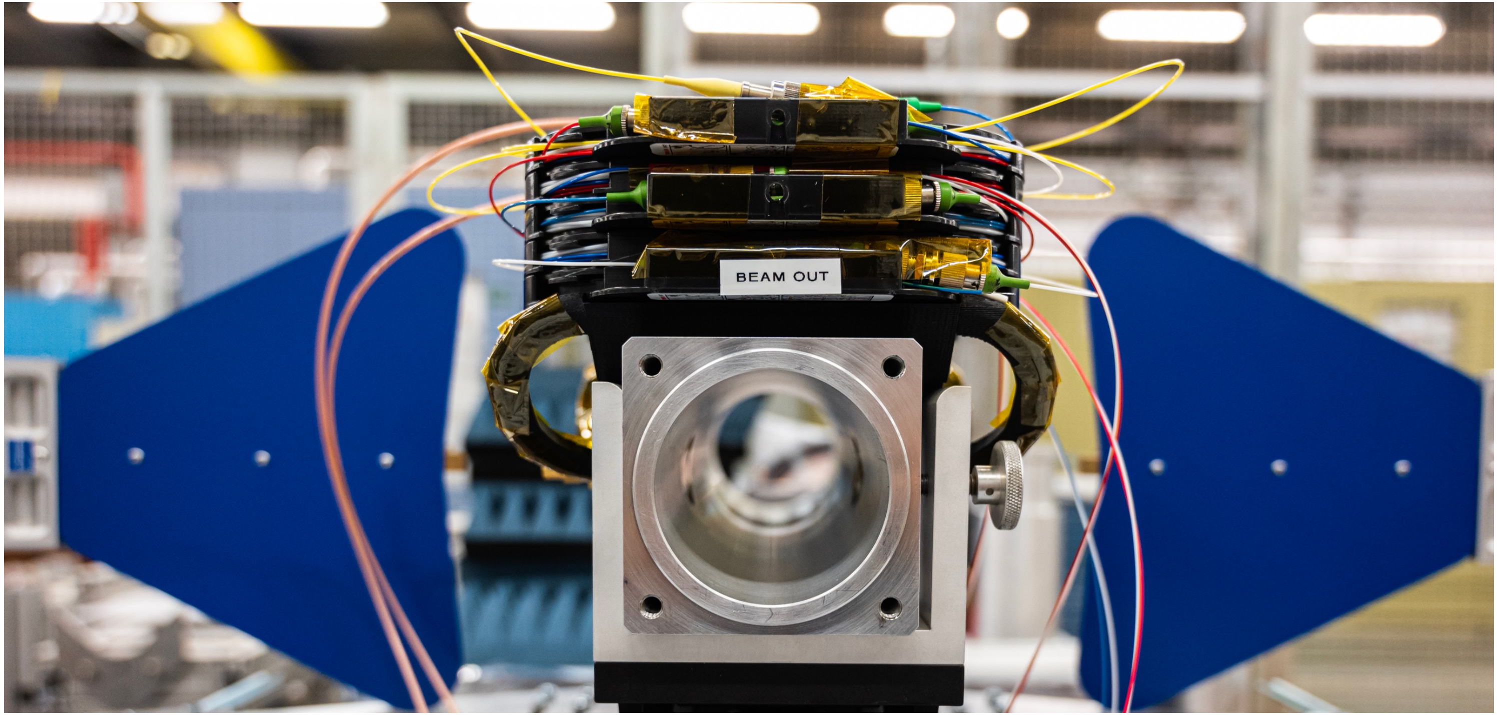
Phase space area proxy and new fitting method allows more robust prediction of time dependence

Next steps: Seeking more simulated datasets to test methodology (please get in touch!)

R. Appleby, D. Christie (Manchester), A. Fornara, C. Montanari, G. Sterbini (CERN)

Summary

- Excellent progress on beam instrumentation deliverables from UK since last HL-LHC annual meeting:
- **Successful installation** and **commissioning** of BGC and EO-BPM in CERN accelerators.
- **BGC monitor developing** as an **LHC operational instrument**, enabling **multiple systematic studies** with protons and ions beams, including emittance.
- **Operational experience gained** with EO-BPM and first comparison with HT monitor shows **sensitivity to fast intra-bunch motion**.
- **BI reviews of technologies planned** in coming months
- **UK team contributing** to collimation studies and models of **beam halo**, **dynamic aperture** and new optics for **collimation insertions**



Thank you!

Back up

BGC: Milestone and deliverables

M3.2.2	Review of gas-jet drawings to launch production	17/01/2023	17/01/2025	
M3.2.3	Orders placed for major gas-jet unit 1 components	30/06/2023	Complete	Recorded in **Change request** in March'23 #0028
M3.2.4	Production gas-jet completed and shipped to CERN	31/03/2025	31/03/2025	
M3.2.5	BGC Unit 1 prototype installed in LHC	31/12/2024	Complete	Completed earlier in March'23. Recorded in **Change request** in June'23 #0036
M3.2.6	BGC Unit 2 specifications agreed	31/12/2024	31/12/2024	Recorded in Change request in June'23 #0036. 31/10/2023 -date changed
D3.2.4	Delivery of gas-jet monitor unit 1, pre-tested at CI, for integration in Hollow Electron Lens and testing, participation in commissioning tests	30/03/2025	30/03/2025	Recorded in **Change request** in March'23 #0028. Recorded in Change request in March'23 #0036
D3.2.5	Delivery of gas-jet monitor unit 2 for integration at CERN, pre-tested at CI	31/03/2025	31/03/2026	

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BGC: Publications

- Referred journal:
  - C. Castro Sequeiro et al., “Beam gas curtain monitor: Vacuum studies for LHC integration and operation”, Phys. Rev. Accel. Beams, 27, 043201, 2024.
- Proceedings
  - W. Butcher, et al, “Experimental study into the invasiveness of a gas jet beam profile monitor for charged particle beams”, Proc. IPAC’24, Minneapolis, USA (2024).
  - O. Stringer, et al, “Gas jet-based beam profile monitor for the electron beam test stand at CERN”, Proc. IPAC’24, Minneapolis, USA (2024).
  - H. Zhang, et al, “BGC monitor: first year of operation at the LHC”, Proceedings of IBIC 2024, Beijing, China, 2024.
- Talks:
  - O. Stringer, “First measurement of the proton beam and lead ion beam in the LHC using beam gas curtain monitor”, invited talk, IPAC 2024, Minneapolis, USA (2024)
  - H. Zhang, “BGC monitor: first year of operation at the LHC” contributed talk, IBIC 2024, Beijing, China, 2024.

EOBPM: Milestone and deliverables

D3.1.3 complete ‘*Delivery to CERN of a complete EO-BPM system suitable for beam tests at the SPS’*

M3.1.2 complete *‘EO-BPM demonstrator installed and ready for beam tests at CERN’*

D3.1.4 complete *‘Report on EO-BPM beam tests at SPS’; see IBIC24 proceedings Sept 2024*

EOBPM: Publications

- Referred journal
  - A. Arteche et al, “First Interferometric Electro-Optic Beam Position Monitoring System for High-Bandwidth Beam Diagnostics”, HiRadMat & CLEAR tests; paper submitted & under review.
- Proceedings
  - S. Gibson et al, “High-bandwidth Electro-Optic BPMs and an optical time-stretch technique”, IPAC23 doi:10.18429/JACoW-IPAC2023-THPL160.
  - M. Bosman et al, “Design and deployment of an in-vacuum Electro-Optic BPM at the CERN SPS”, doi:10.18429/JACoW-IBIC2024-TUP46, Beijing, Sept 2024.
- Conference
  - M. Bosman et al, “Design of a coaxial line as an EO-BPM high-frequency characterisation setup” presented at UK IoP Particle Accelerator & Beams Conference, Strathclyde, June 2023.