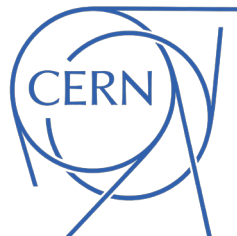


Full-cycle, non invasive emittance monitoring with the Beam Gas Curtain monitor at the LHC

D. Butti, T. Lefevre, E.J. McElroy, C. Pasquino, G. Schneider, R. Veness, CERN

R. Gupta, M. Patel, C.P. Welsch, H.D. Zhang, University of Liverpool and Cockcroft Institute

P. Forck, S. Udrea, GSI



Outline

MOTIVATION

1

Transverse diagnostics at the LHC and the case for beam-induced fluorescence

THE BEAM GAS CURTAIN

2

Instrument on Beam 1, gas-jet curtain and measurement principle

PROTON AND ION BEAM RESULTS WITH NEON

3

Neon as working gas, curtain optimization and full-cycle emittance monitoring

TESTS WITH NITROGEN

4

Nitrogen curtain tests and simulation campaign

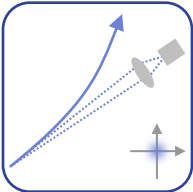
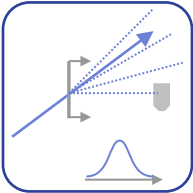
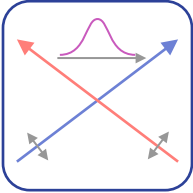
SYNERGY AND OUTLOOK

5

Role among LHC diagnostics, the Beam 2 upgrade and conclusions

Transverse beam diagnostics at the LHC

Transverse beam sizes directly impact the luminosity, **complete diagnostics are essential** $\mathcal{L} = \frac{1}{\sigma_p} \frac{dN_p}{dt} \sim \frac{1}{\sigma_x \sigma_y}$

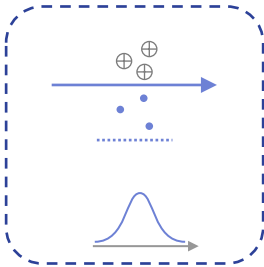
		Non invasive	Absolute	Time resolved
Synchrotron radiation telescopes		✓		✓
Wire scanners			✓	✓
Luminosity scans			✓	✓
		✓	✓	✓

CURRENT STATUS

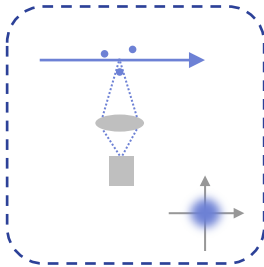
Telescopes calibrated with wire scanners in dedicated fills and used in high-intensity operation. Lumi scans for sanity checks of colliding beams.

OBJECTIVE

Fill diagnostics gap with beam-gas monitors



Ionization
profile monitor



Beam-induced
fluorescence monitor

Beam Induced Fluorescence at the LHC

BUILT ON YEARS OF JOINT R&D

Today's monitor is the latest of several development stages, with GSI, University of Liverpool and CERN.



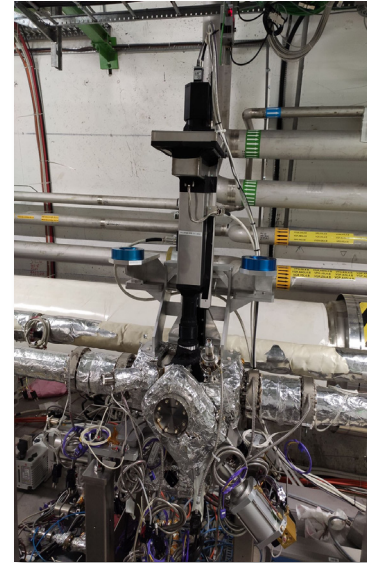
Year-End Stop 2017–18

Cooled MCP-PMT for
photon counting



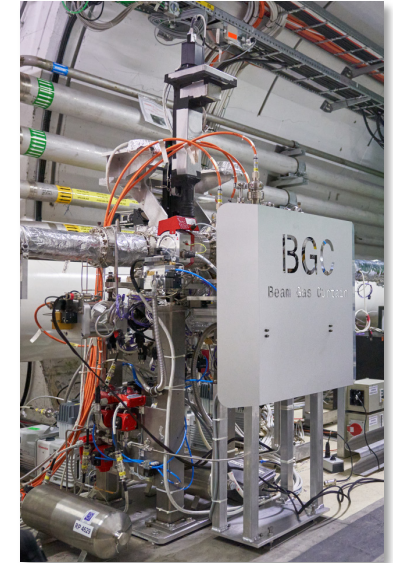
Technical Stop 2018

Intensified camera, diffused gas
injection for beam profiles



Long Shutdown 2020

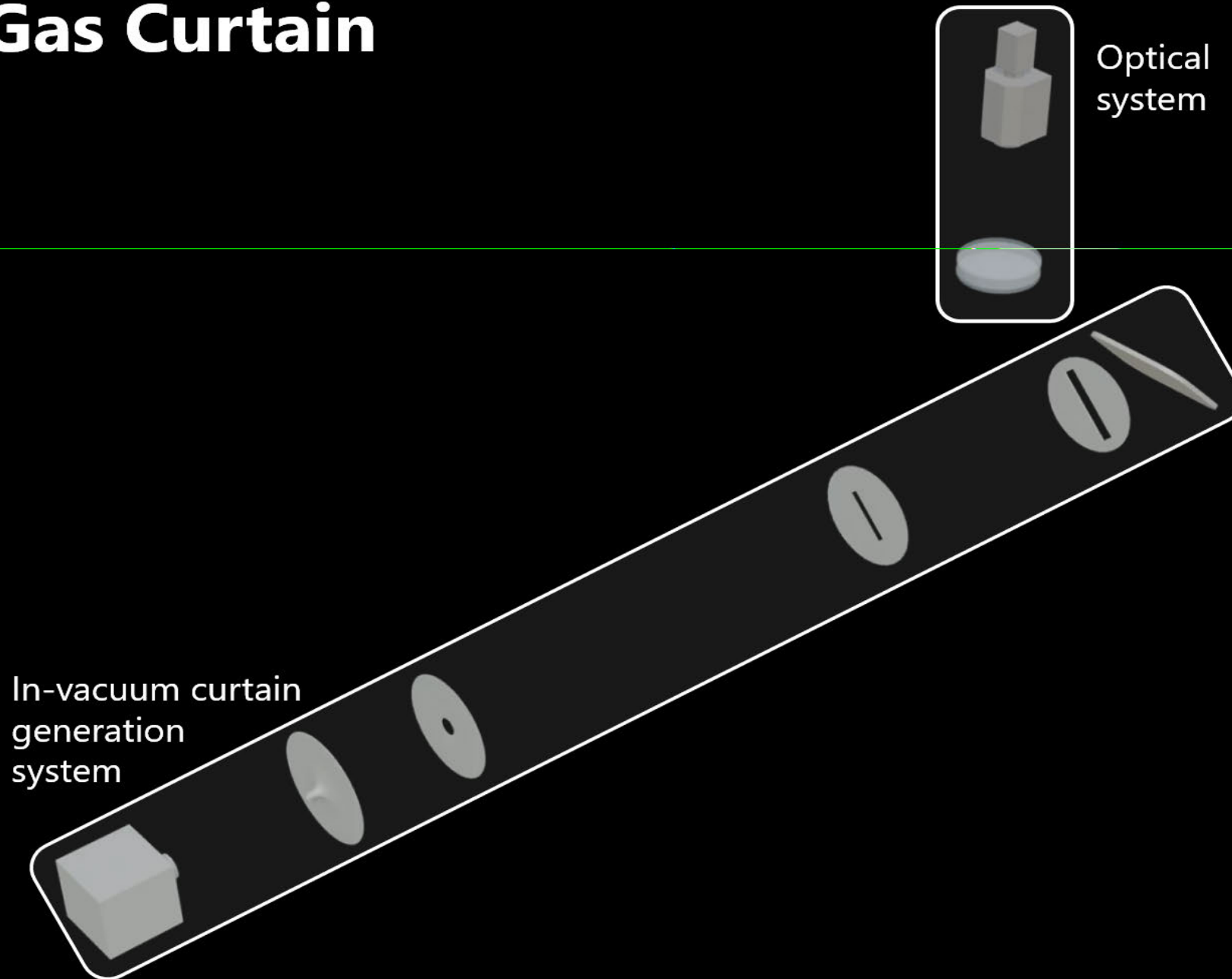
Complete optical line
with diffused gas



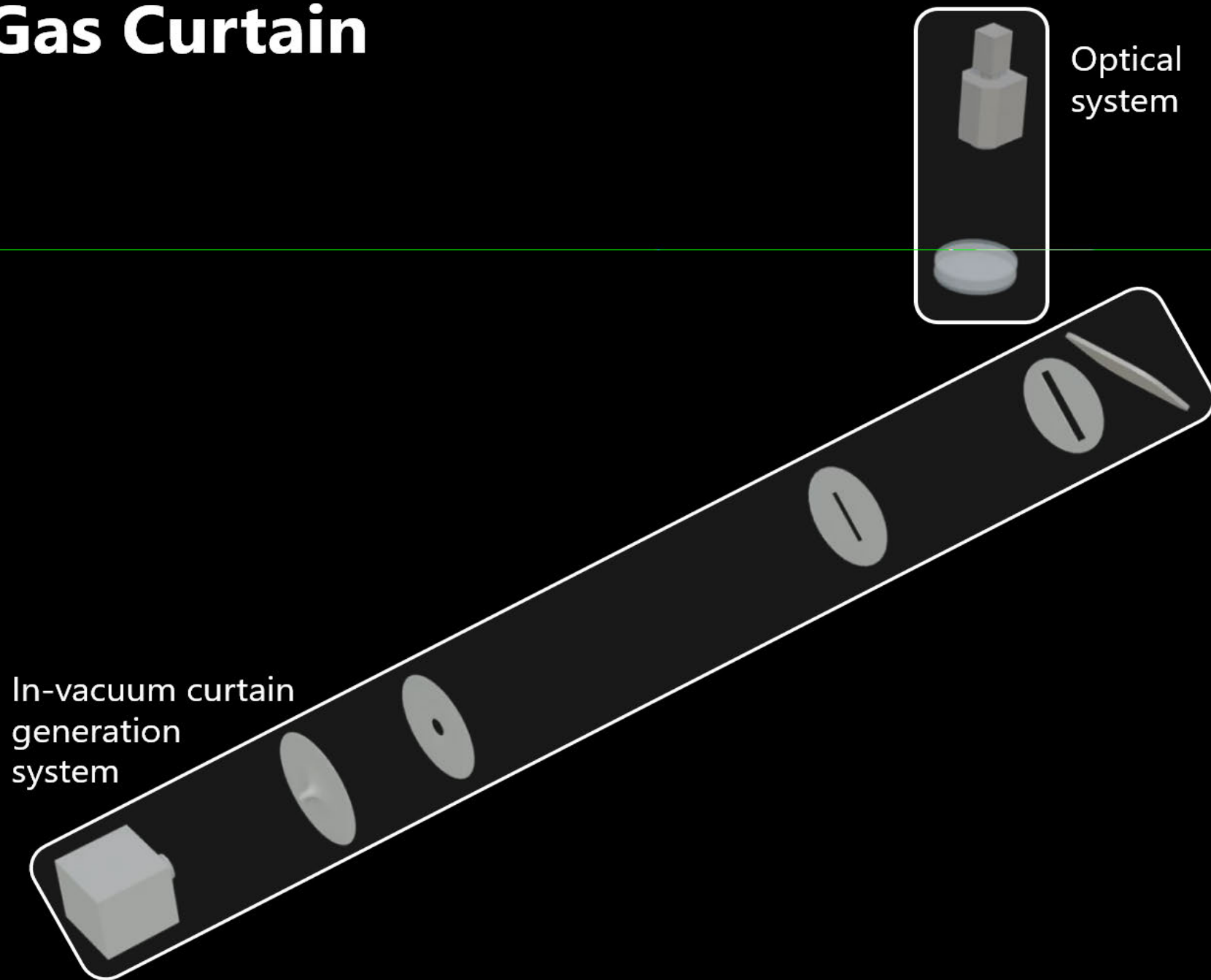
Year-End Stop 2022–23

Final instrument with
gas curtain

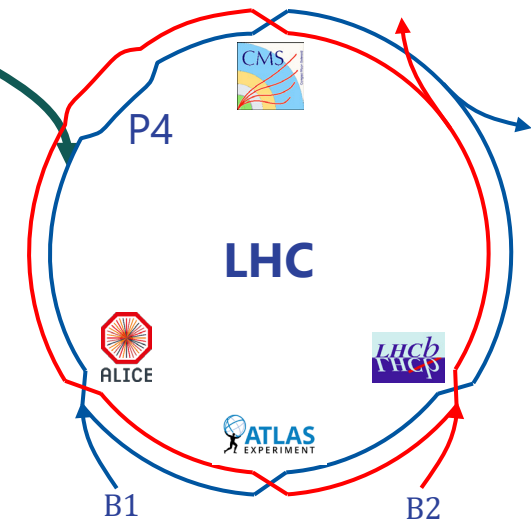
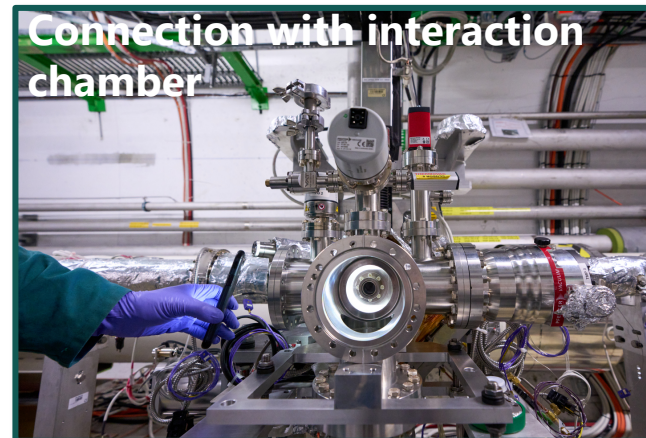
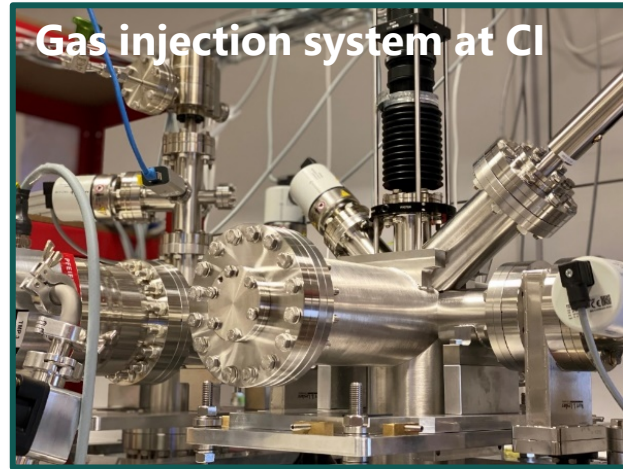
Beam Gas Curtain



Beam Gas Curtain

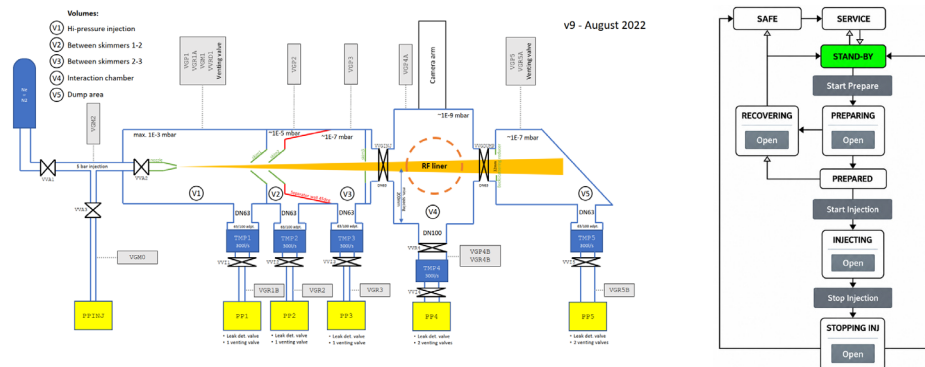


The Beam Gas Curtain monitor for LHC Beam 1



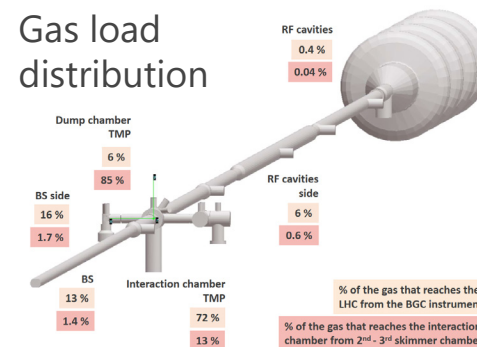
Validation of BGC operation at the LHC

PRESSURE MONITORING AND SAFE CONTROL



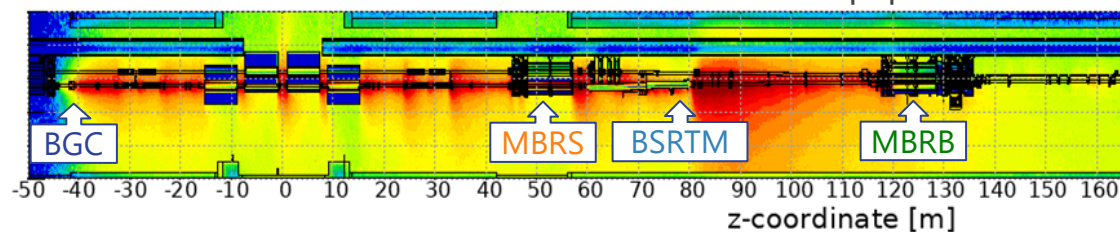
VACUUM COMPATIBILITY STUDIES

Gas load distribution

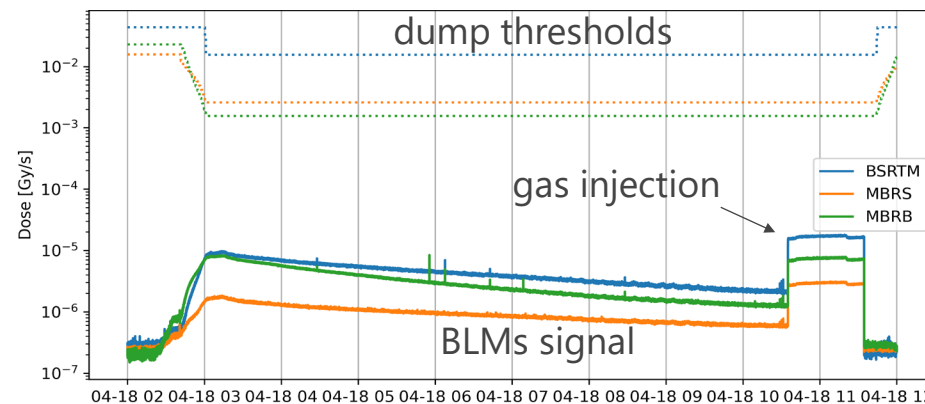


SIMULATIONS OF INDUCED RADIATION

FLUKA simulation of radiation on downstream equipment



BEAM LOSS MONITORING

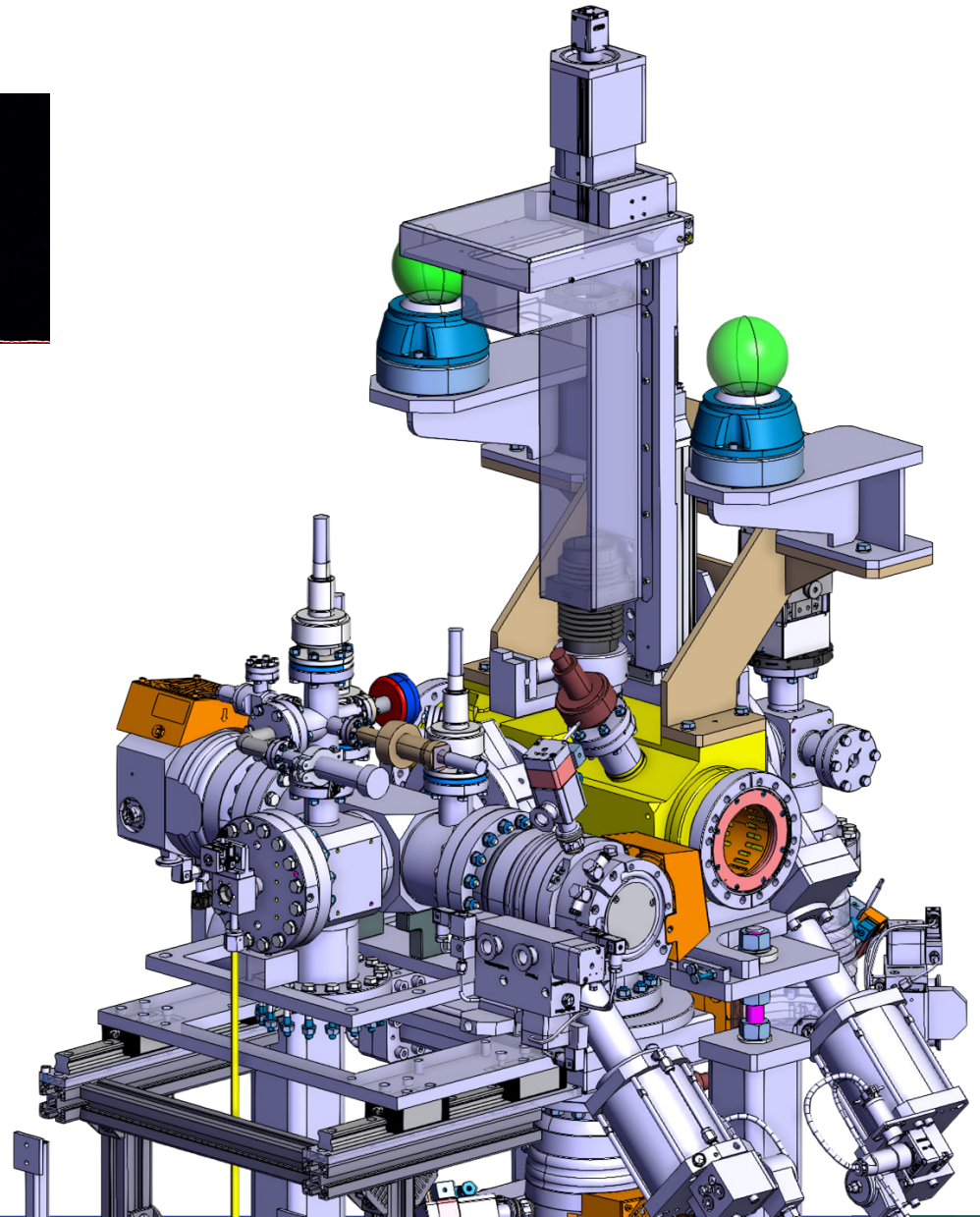
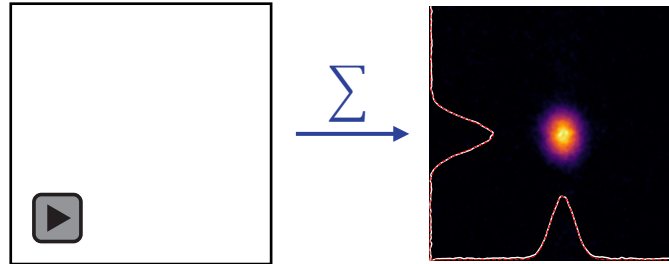


Gas injections are detectable, but minimally invasive to machine operation under all tested conditions

Measurement principle

IMAGE FORMATION

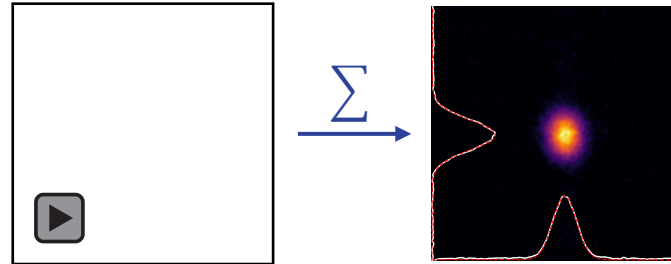
beam image formed by **stacking**
several **single-photon frames**



Measurement principle

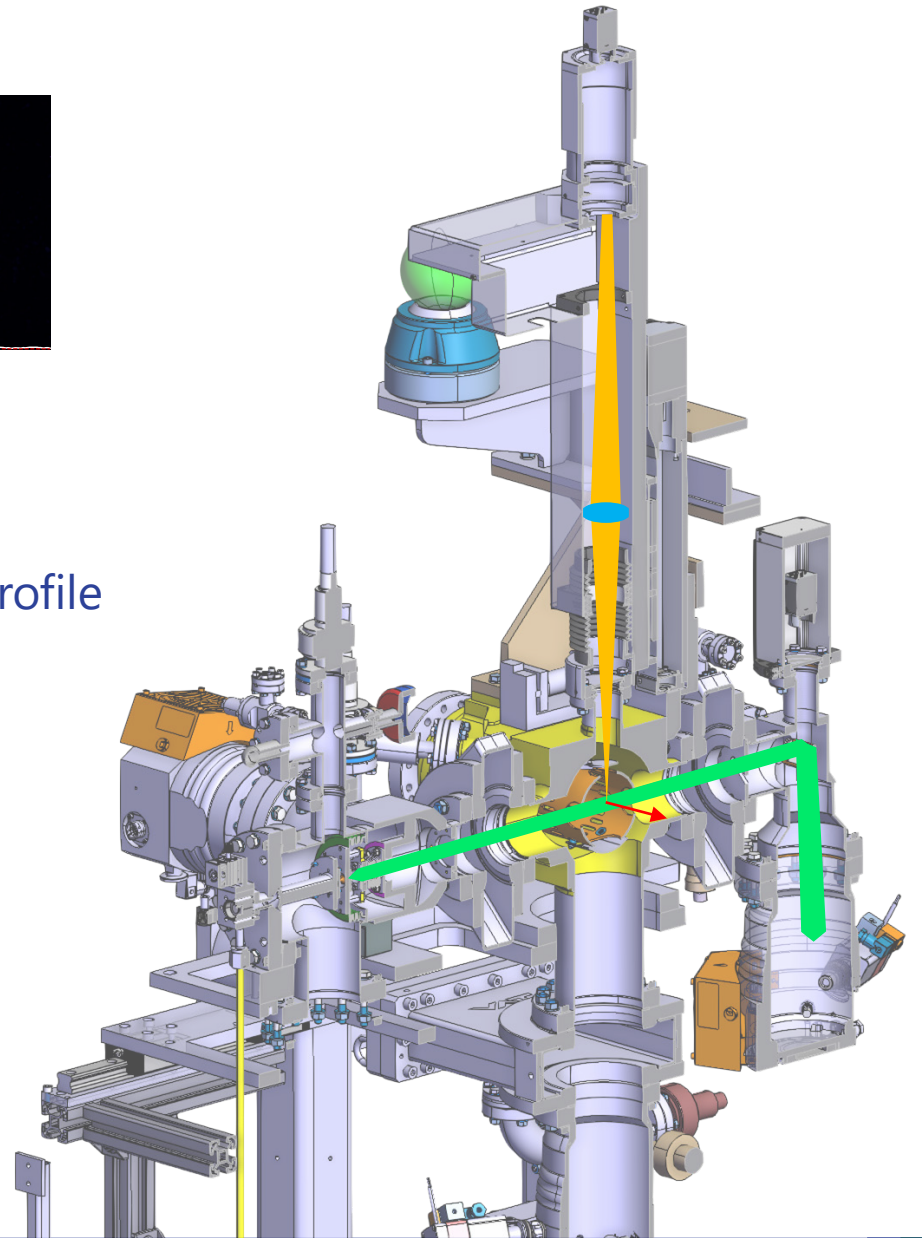
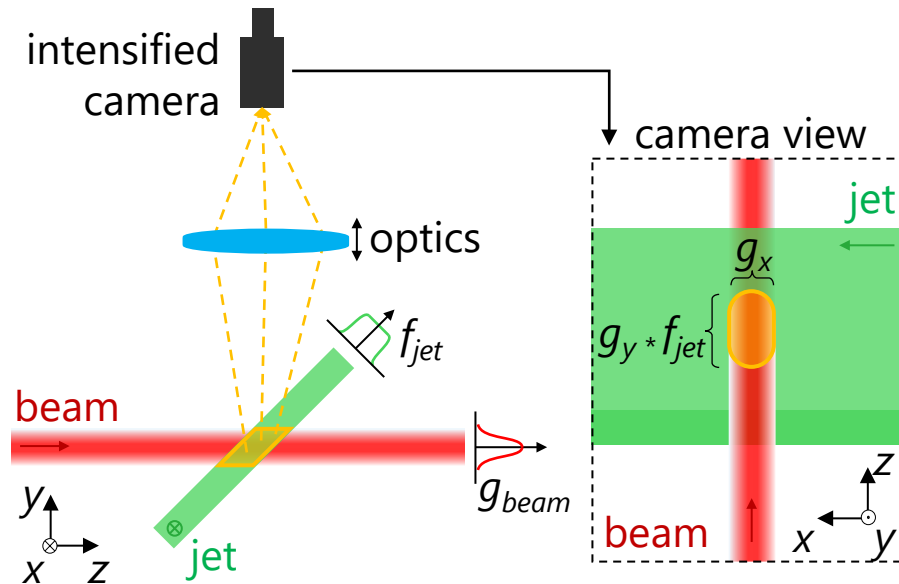
IMAGE FORMATION

beam image formed by **stacking** several **single-photon frames**



BEAM PROFILE RETRIEVAL

- **horizontal** image profile maps directly onto the **beam profile**
- **vertical** profile is recovered by **deconvolving the jet density** profile



Choice of neon as working gas

SELECTION CRITERIA

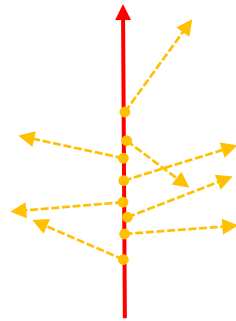
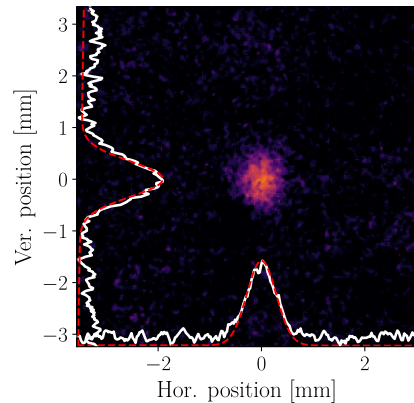
Balance **vacuum compatibility**, fluorescence **yield** and spatial **resolution**.

Neon: a noble gas with limited impact on the NEG coating, offering two complementary emission ranges

VISIBLE yellow line at 585 nm, neutral Ne*

- Lower light yield → longer integration times
- Better spatial resolution

Best for accurate absolute measurements

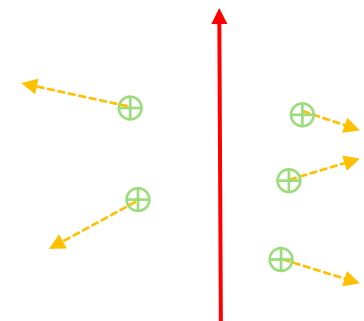
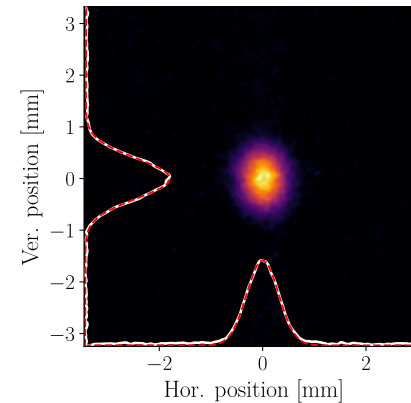


$\sigma_{RES,VIS} = 65 \mu\text{m}$, **constant and driven by optics**

ULTRAVIOLET multiplet at 340 nm, ionic Ne⁺

- Higher light yield → shorter integration times
- Coarser spatial resolution

Best for precise relative measurements



$\sigma_{RES,UV} \simeq 160 \mu\text{m}$, **variable and driven by space-charge**

Continuous monitoring on the UV lines, with periodic switches to the visible line for cross-reference

Full-cycle measurement of proton beams with neon

INJECTION

BGC and SR telescopes compatible within 5%

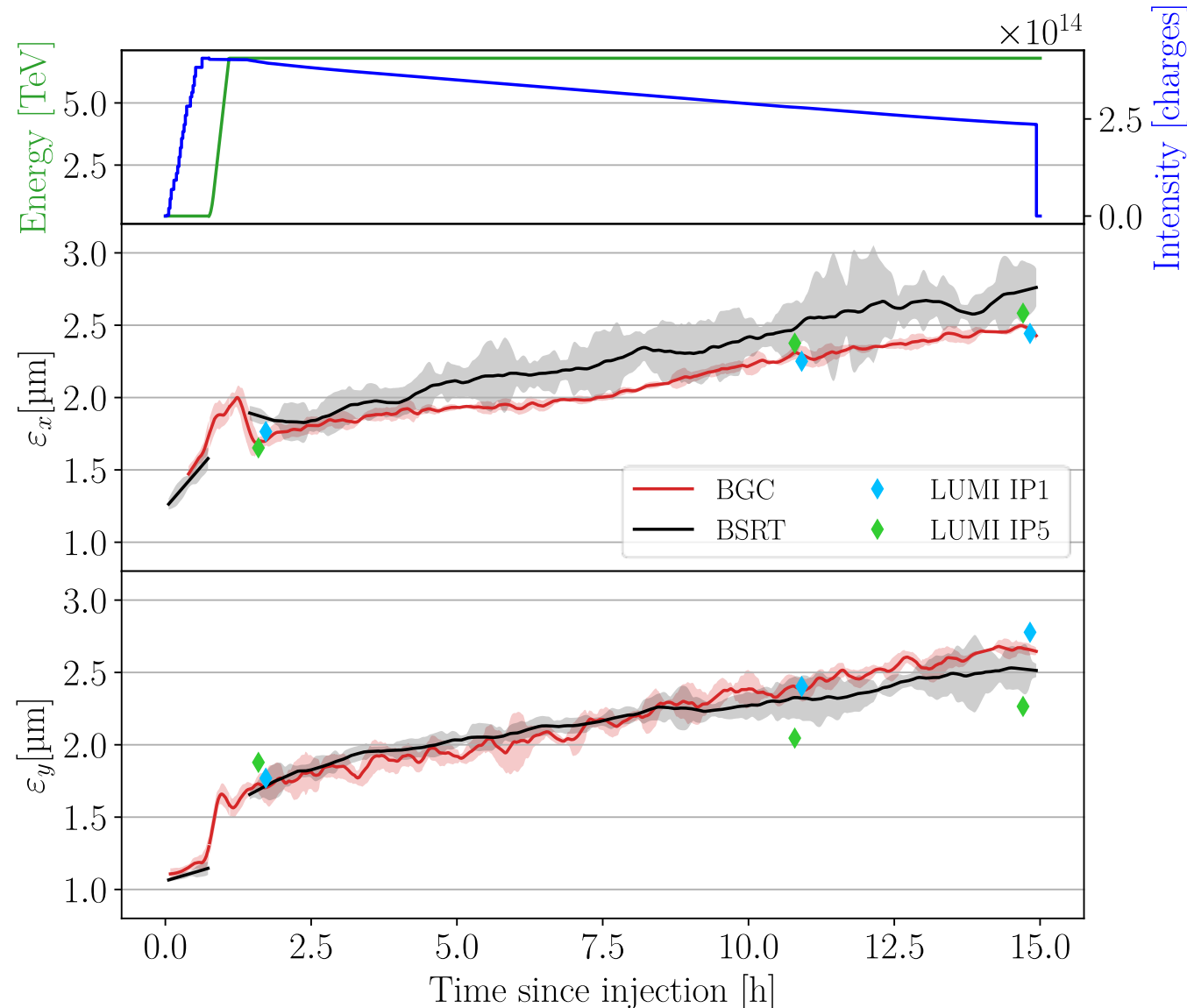
ENERGY RAMP

No cross-reference available, BGC measures realistic trend

FLAT-TOP

Agreement with SR telescopes (diffraction limited) within 10%, and 5% with luminosity scans

BGC measurements compatible with available references from other diagnostics



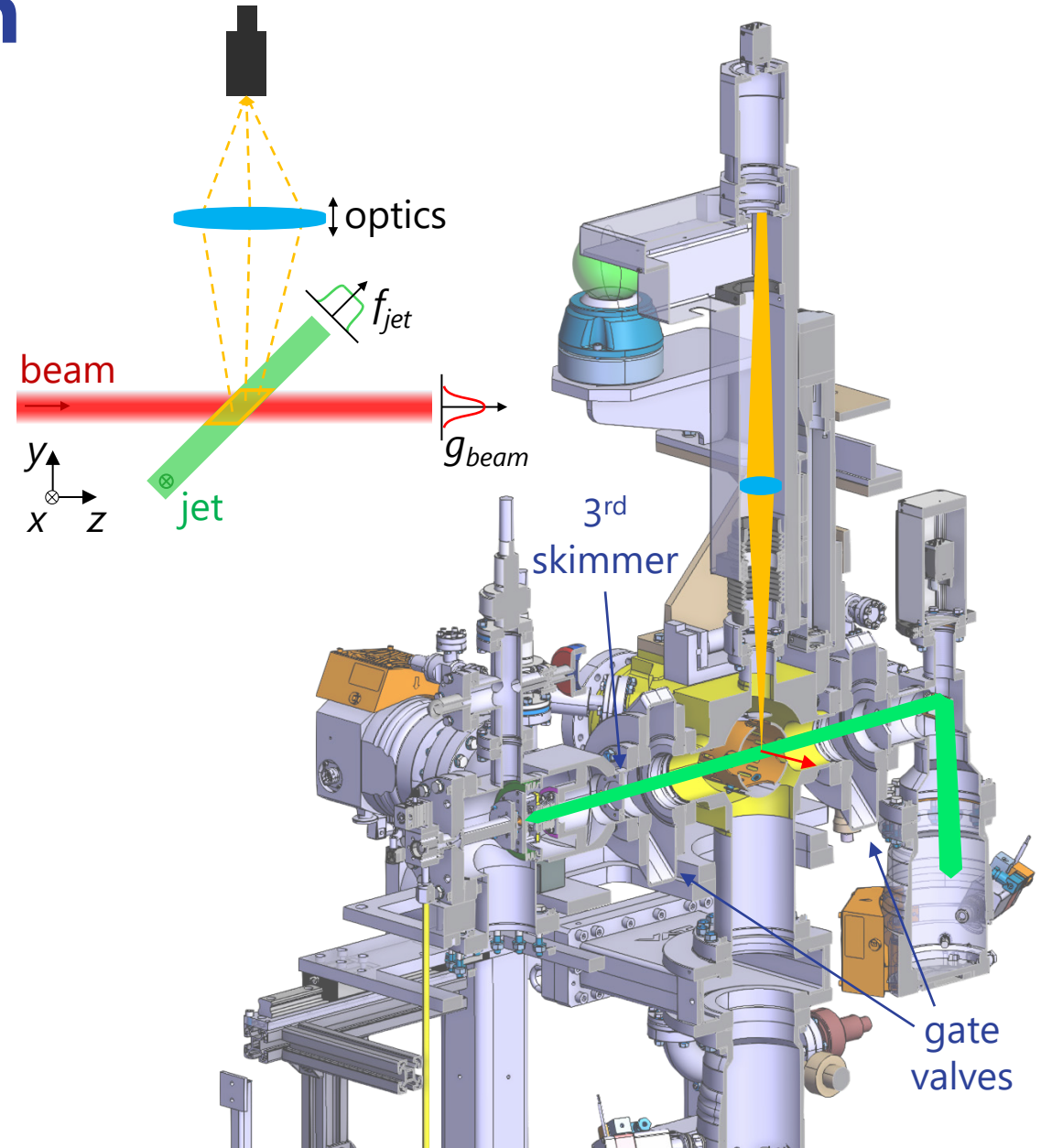
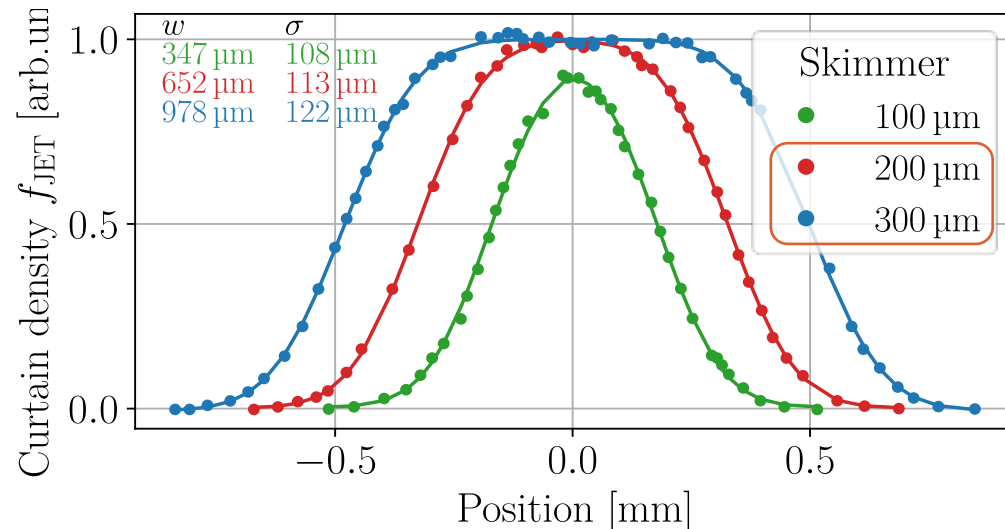
Curtain width optimization

SIGNAL VS RESOLUTION TRADE OFF

curtain width critical parameters to balance signal strength and vertical resolution

THIRD SKIMMER OPTIMIZATION

- curtain width determined by **third skimmer**
- BGC vacuum sectorization allows **skimmer change** without opening machine vacuum



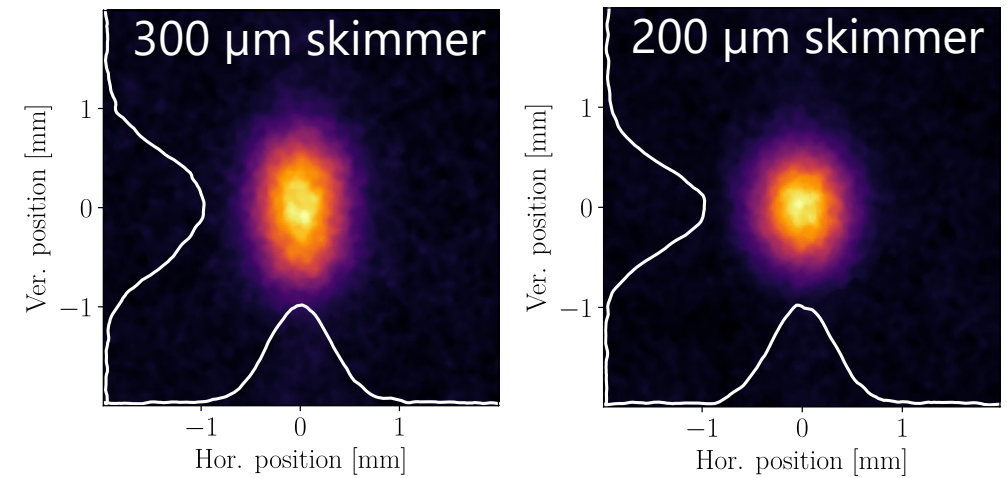
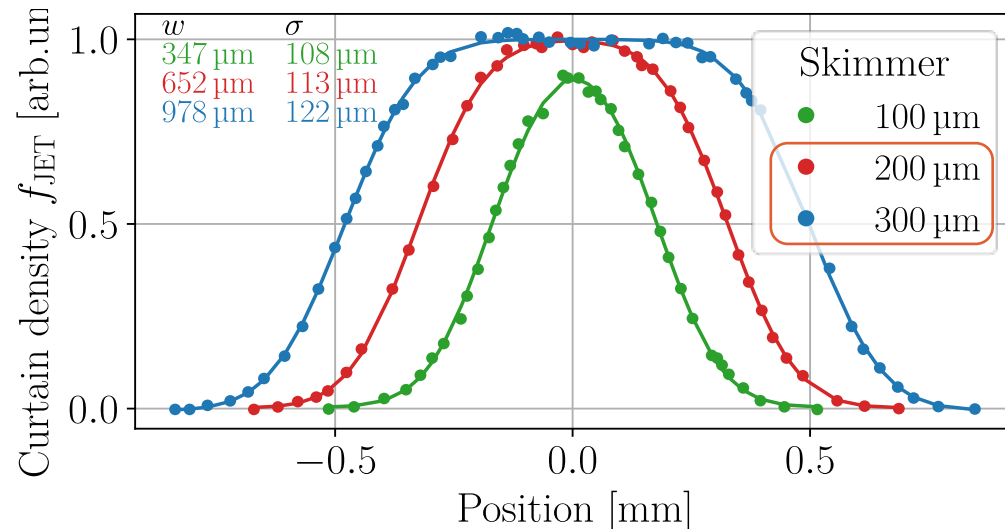
Curtain width optimization

SIGNAL VS RESOLUTION TRADE OFF

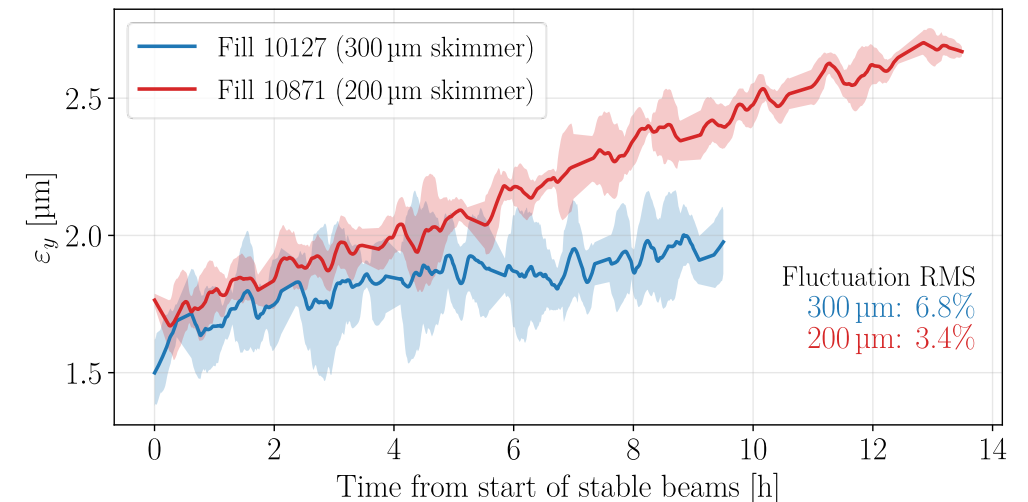
curtain width critical parameters to balance signal strength and vertical resolution

THIRD SKIMMER OPTIMIZATION

- curtain width determined by **third skimmer**
- BGC vacuum sectorization allows **skimmer change** without opening machine vacuum



Best compromise between signal and vertical resolution found with 200 μm



Measuring lead ion beams

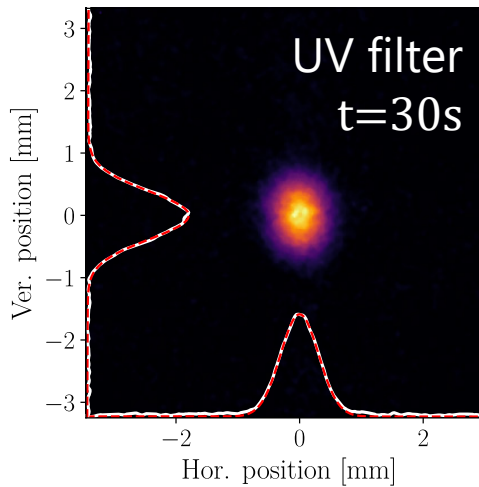
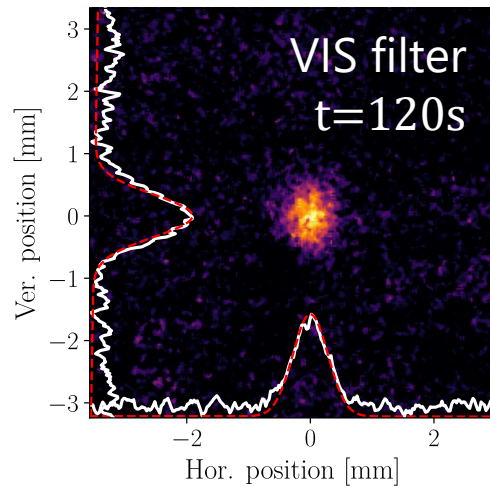
FLUORESCENCE CROSS-SECTION SCALES AS Z^2

- Lead beams are profiled with visible fluorescence alone
- No correction for space-charge broadening is required

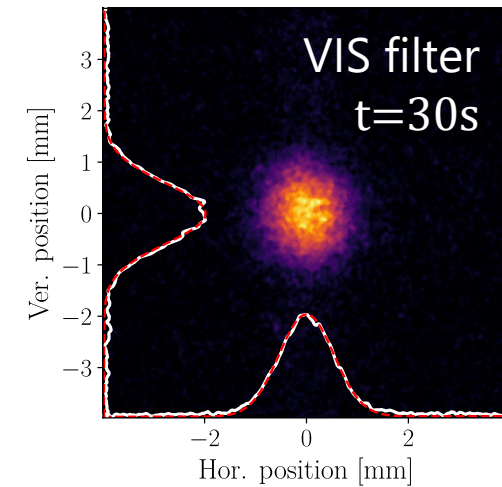
ION BEAMS ARE LARGER

- Better resolution, especially in the jet-thickness-limited vertical direction

Proton beams 6.8 TeV



Lead beams 6.8 ZTeV



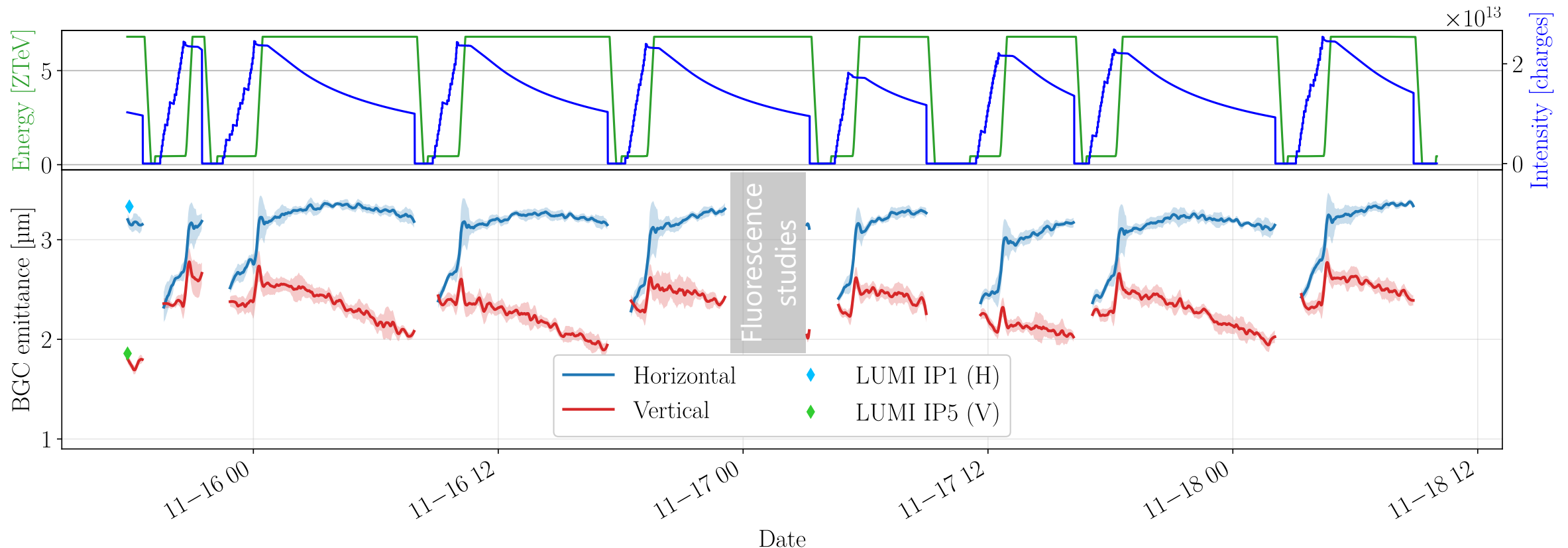
Full-cycle measurement of ion beams with neon

THE LIMITATION WITH IONS

BSRT: no light at injection, coarse flat-top calibration
LUMI SCANS: rarely performed with ions

WHAT THE BGC ADDS

Fills diagnostics gap in conditions more favorable for beam-gas diagnostics.



Tests with nitrogen curtain

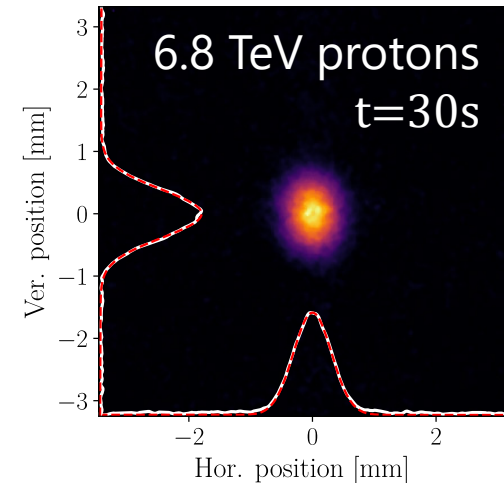
CASE FOR NITROGEN

Strong fluorescence line at 391 nm,
Standard gas for BIF monitors.

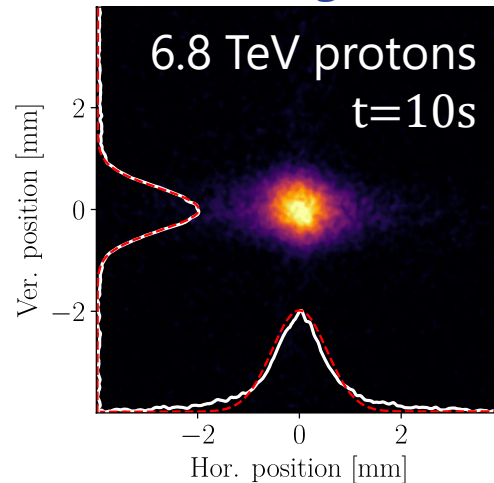
DOWNSIDE OF NITROGEN

Ionic line, with ~ 60 ns lifetime, large space-charge broadening.
N₂ saturates NEG coatings fast.

Neon



Nitrogen



front view

top (camera) view

side view



Measurements of proton beams with nitrogen

INJECTION

Space-charge correction smaller than beam size,
no significant precision degradation

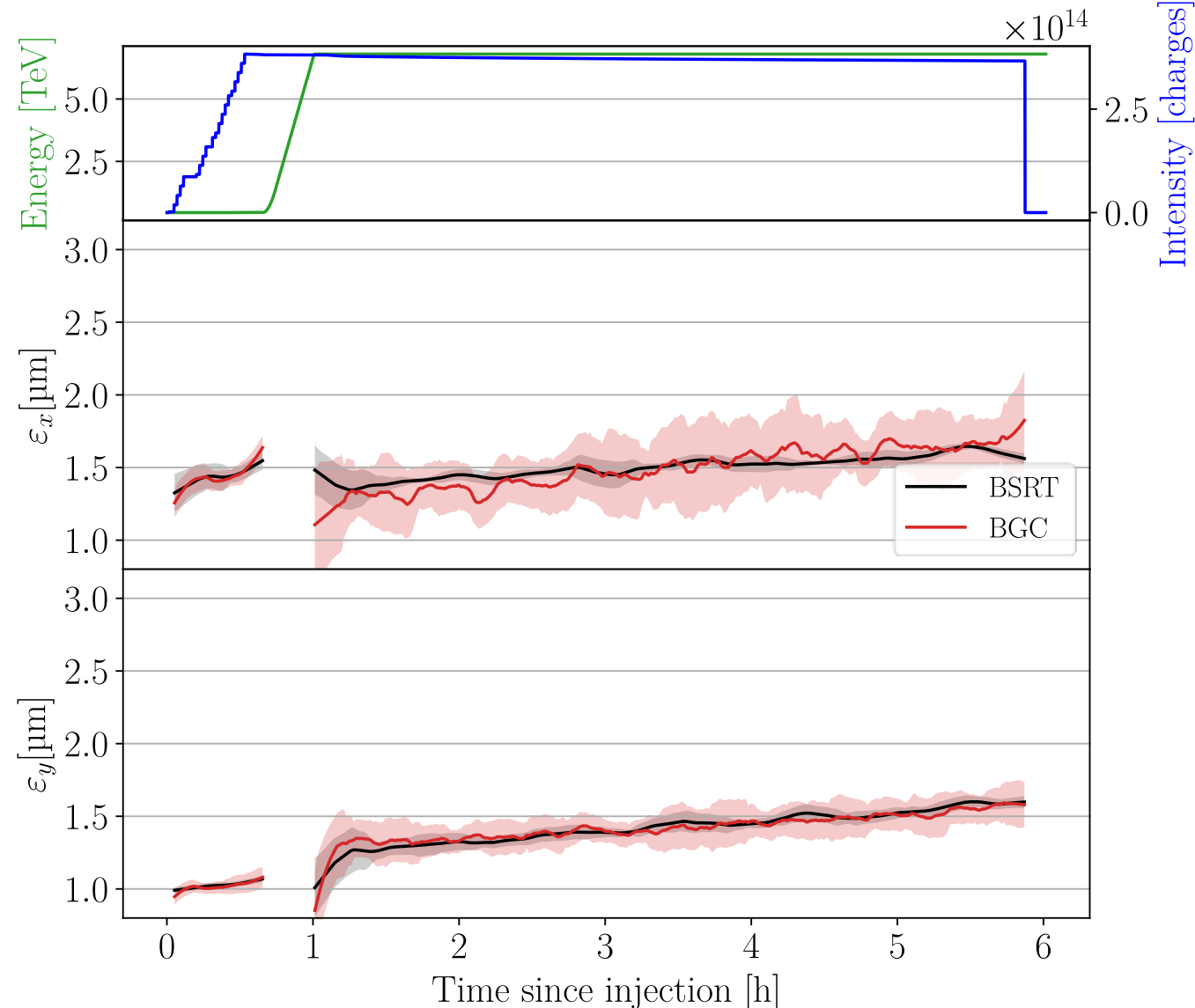
ENERGY RAMP

No cross-reference available, no effective
correction for BGC measurements

FLAT-TOP

Space-charge correction larger than beam size,
degraded precision especially in horizontal plane

**Due to space-charge, nitrogen is viable option
only for injection diagnostics (large beams)**



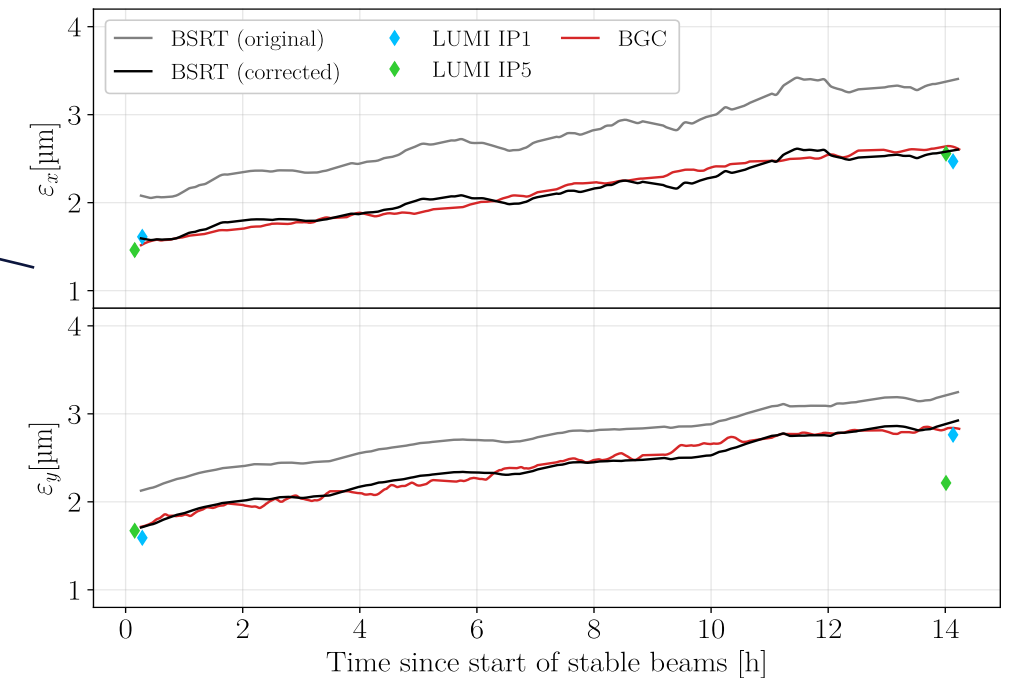
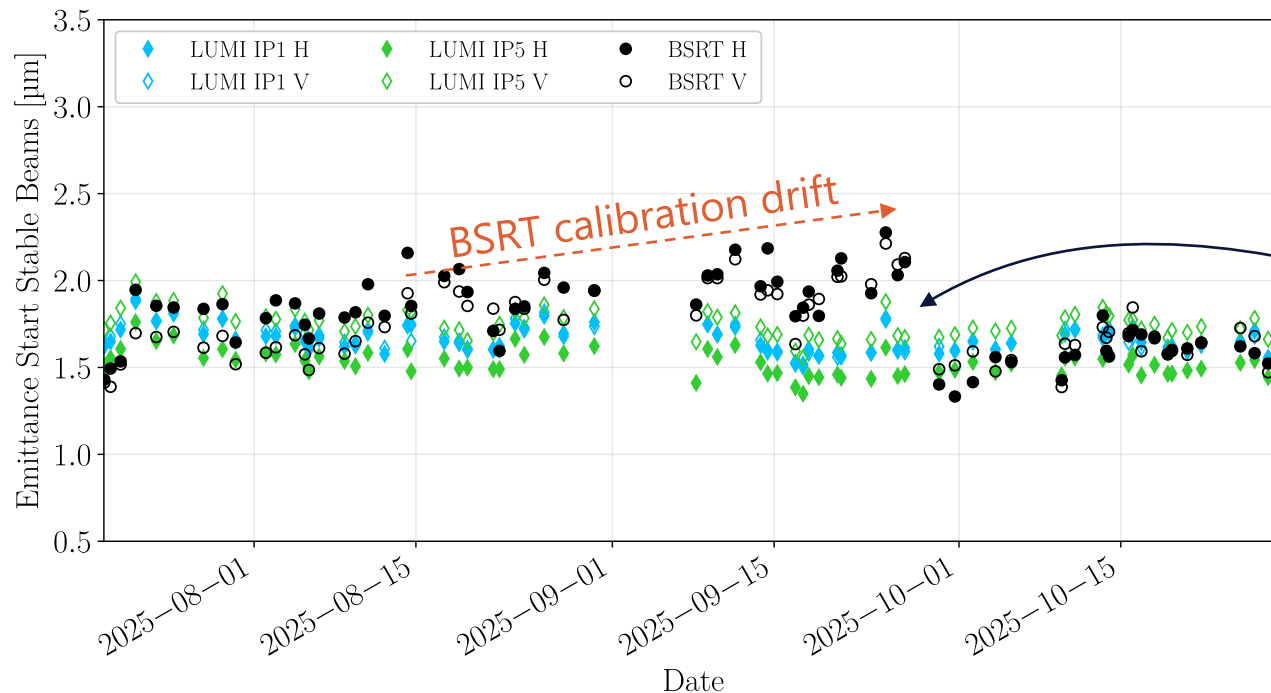
Synergy with current LHC transverse diagnostics

THE LIMITATION TODAY

BSRT calibration drifts over the year. Recalibration requires dedicated fills that interrupt physics.

WHAT THE BGC ADDS

Absolute evolution of average emittance, a reference for BSRT calibration adjustment

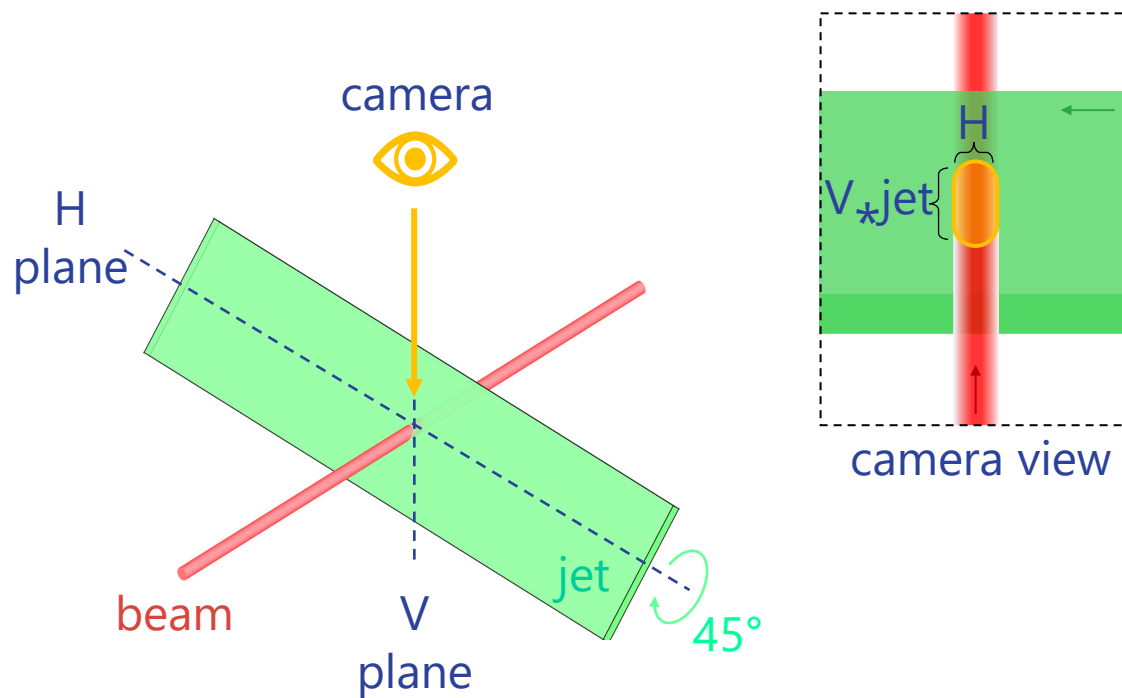


An upgraded instrument for Beam 2

A **second BGC monitor for Beam 2** is approved for the HL-LHC upgrade, concept upgraded.

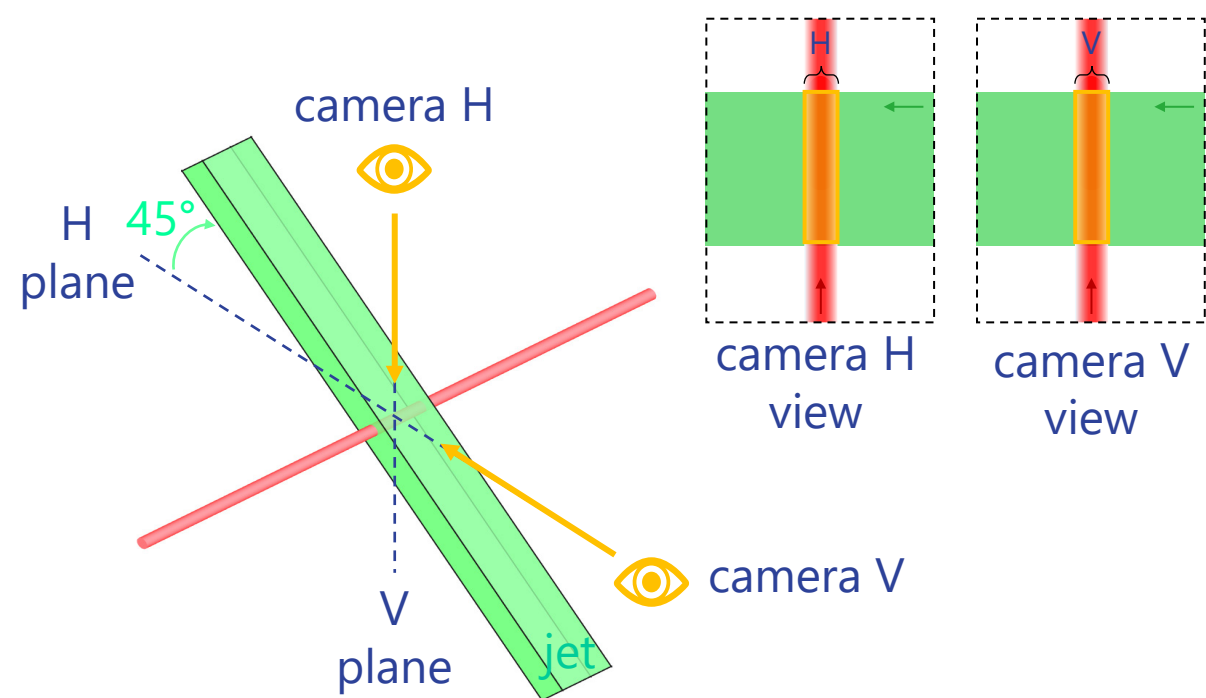
CURRENT DESIGN: GAS "SCREEN"

Thin jet crosses the beam: jet thickness is traded off against signal and vertical resolution.

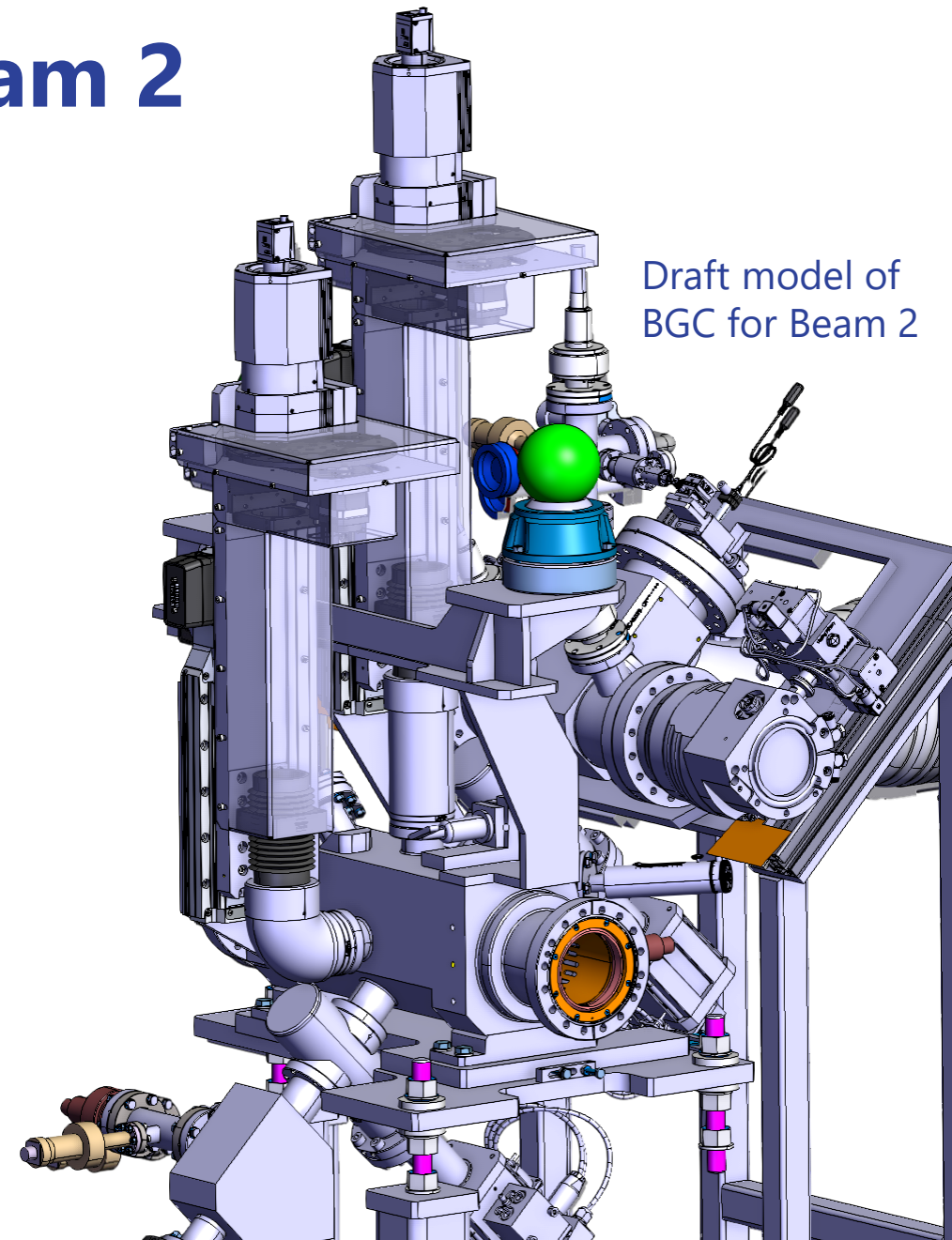


NEW DESIGN: GAS "SEARCHLIGHT"

Jet length is maximised for signal, resolving the H/V transverse profiles with independent optical lines.



An upgraded instrument for Beam 2



An upgraded instrument for Beam 2

GAS INJECTION SYSTEM

In-vacuum system copied from Beam 1 version to avoid LHC compatibility re-assessment, rotated by 45 degree

CURTAIN ASPECT-RATIO

Third skimmer chosen to **maximize beam-curtain overlap**

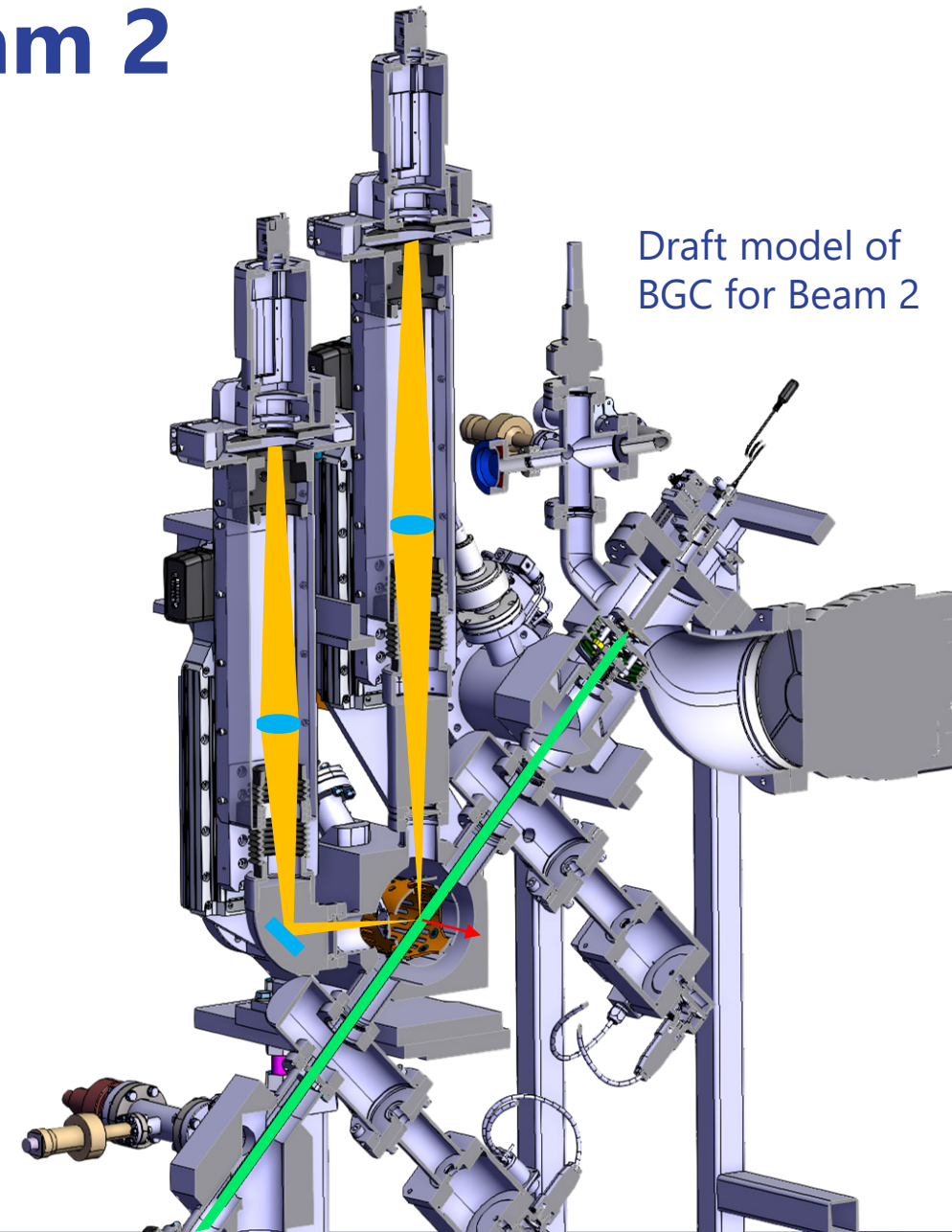
OPTICAL LINES

Flat mirror to **fold the horizontal line**.

Same optical elements and distances for both lines.

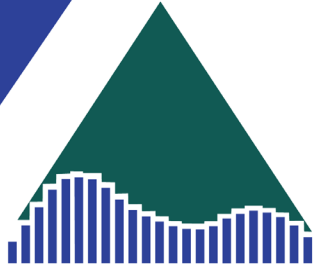
Light **acceptance and transmission further optimized** for Ne wavelength of interest.

Performance optimization preserving proven critical features of the existing instrument



Conclusion

- 1 BEAM GAS CURTAIN CAPABILITIES DEMONSTRATED ON LHC BEAM 1**
Non-invasive gas-curtain monitor installed at Point 4 and fully validated with beam.
- 2 PROTONS AND LEAD IONS MEASURED**
Full-cycle accurate emittance monitoring with neon as working gas.
- 3 PERFORMANCE OPTIMISED**
Skimmer and curtain-width tuning sharpened resolution; nitrogen tested as an alternative gas.
- 4 COMPLEMENTS EXISTING DIAGNOSTICS**
Fills gaps of present monitors, towards upgraded transverse diagnostics for HL-LHC.
- 5 NEXT: UPGRADED MONITOR FOR BEAM 2**
Lessons from Beam 1 instrument feed directly into the second instrument.
- 6 BENCHMARK FOR FLUORESCENCE STUDIES**
Beyond emittance monitoring, a reference for fluorescence at unprecedented LHC energies.



IBIC
2026

15TH INTERNATIONAL
BEAM INSTRUMENTATION
CONFERENCE

**Whistler
Conference
Centre**

August 30th to
September 3rd
Whistler BC, Canada

Thank you for your attention!

The BGC **collaboration thanks** the **CERN teams involved** in the development and deployment of the BGC monitor, in particular TE-VSC, SY-STI-BMP, BE-OP-LHC and SY-BI-BL, as well as **former BGC collaborators** for their contributions over the years.

