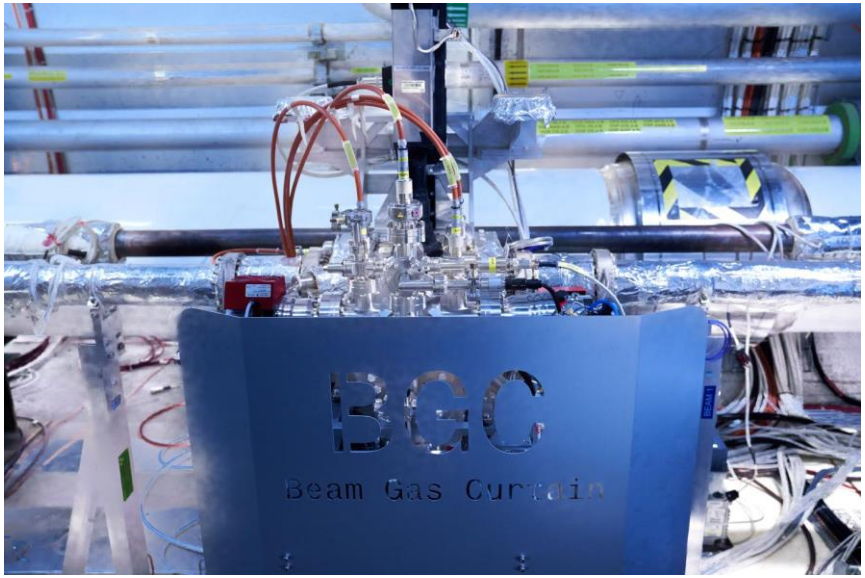


Beam Gas Curtain monitor at LHC

1st year at LHC

Ondrej Sedlacek

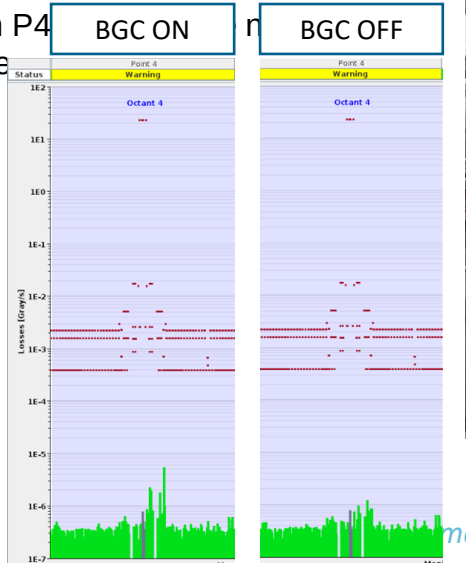
Working conditions

P4: 5L4
Beam 1

- BGC operated and validated on standard full intensity (Injection->Ramp->Stable Beams) for proton and ion beam

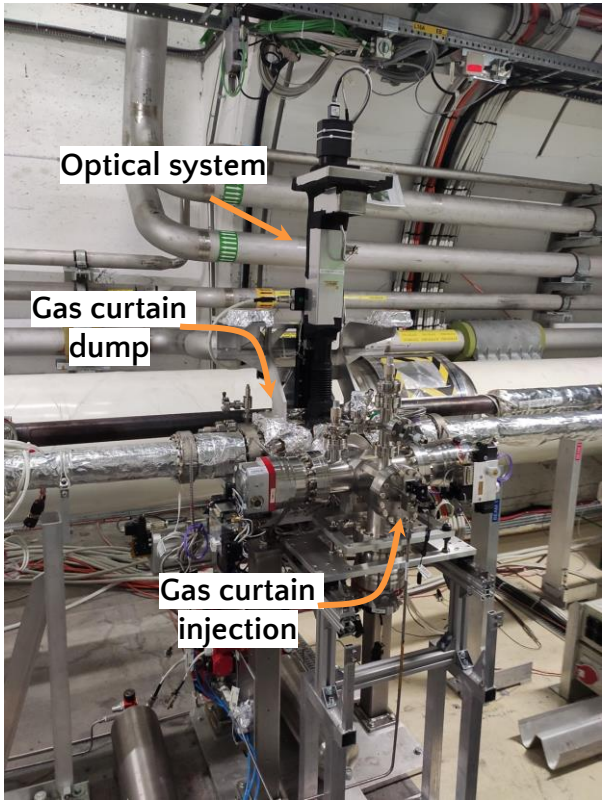
Interaction chamber (VGP.4a.5L4.BGC)	Pressure [mbar]
Ne gas Jet OFF	2.0e-10
Ne gas Jet On	4.00e-8

- Beam losses
  - Beam Injection - no losses above noise in Fixed display
  - Stable beams - local increase in P4 [illegible] n
  - No observed effect on emittance



- BGC in 2023 on LHC p-beam ~10h
  - Validation - ok
  - Systematic studies needed

- BGC in 2023 on LHC Pb-beam >70h
  - Validation - ok
  - Systematic studies done
    - Being analysed



Datasets taken

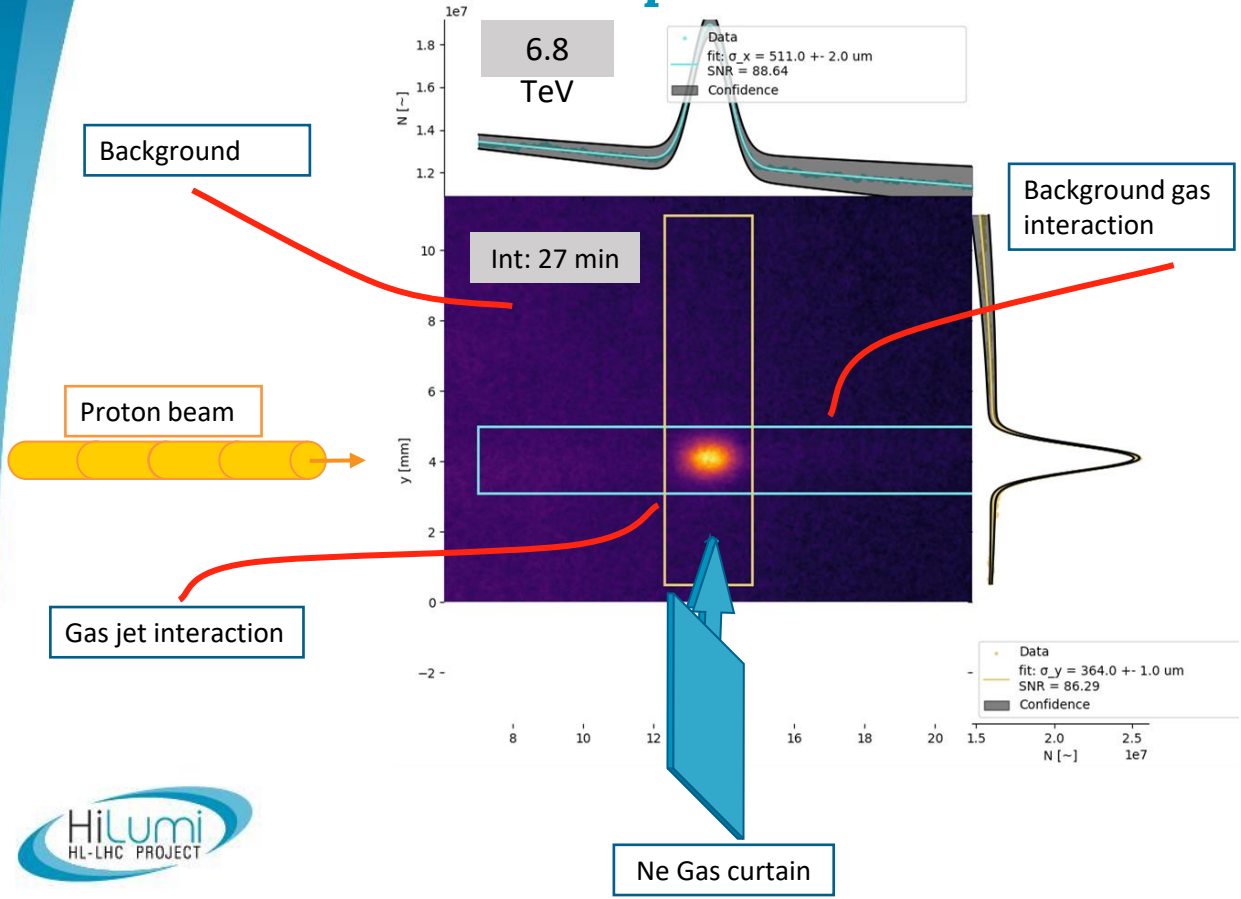
Protons ~ 10h	Energy [TeV/Z]	Comments
1x	6.8	Measurements with full proton beam at Flat Top energy
1x	0.45	Measurements with full proton beam at Injection energy
1x	6.8	Varying the optical system vertical position - focus
1x	0.45-6.8	Losses evolution (without gas injection)

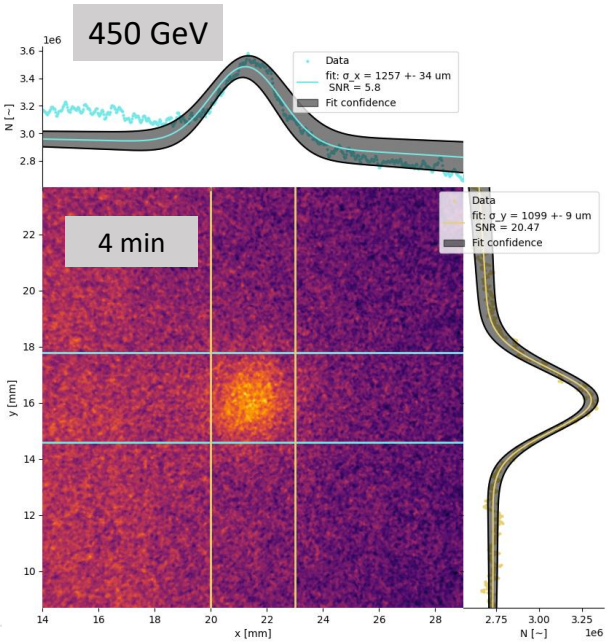
Ion > 70h	Energy [TeV/Z]	Comments
3x	0.45-6.8	Proton run settings
1x	6.8	Varying amplifier gain
1x	6.8	Varying integration time
1x	0.45, 6.8	Varying Averaging time
4x	6.8	Varying the optical system vertical position - focus
04.10.	0.45,6.8	Background study (SR, Beam Losses, Photocathode-Dark Counts)
Inj 6x; FT 4x	0.45-6.8	Different beam intensities
Now: 6x	0.45-6.8	Different beam fills
Now: 3x	6.8	Comparison to emittance scans
Now: 10x	0.45-6.8	Emittance evolution (Injection->Ramp-Flat Top)
1x	6.8	Dedicated local horizontal position bump
1x	6.8	Vibration studies (moving the opt. System up and down)

Proton measurements

First BGC measurements LHC proton beam

Averaging images





Protons - Precision studies

- Systematic error studies to be done
- 6.8 TeV acq. times

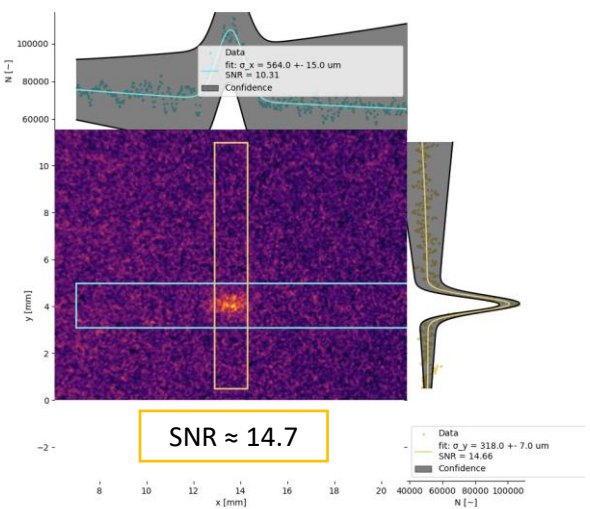
Centroid measurements

Profile measurements

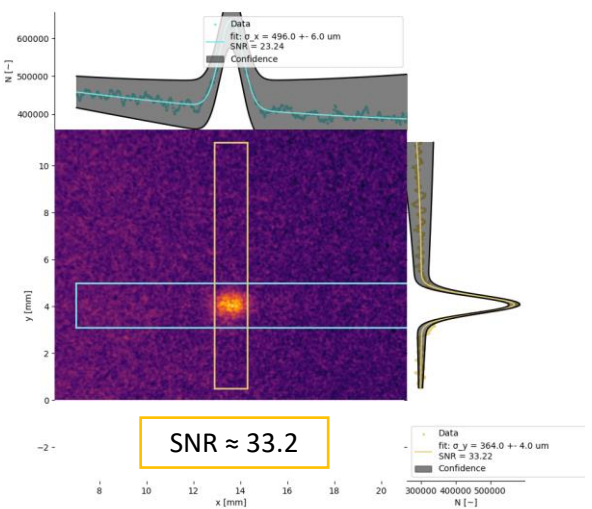
10s

1min

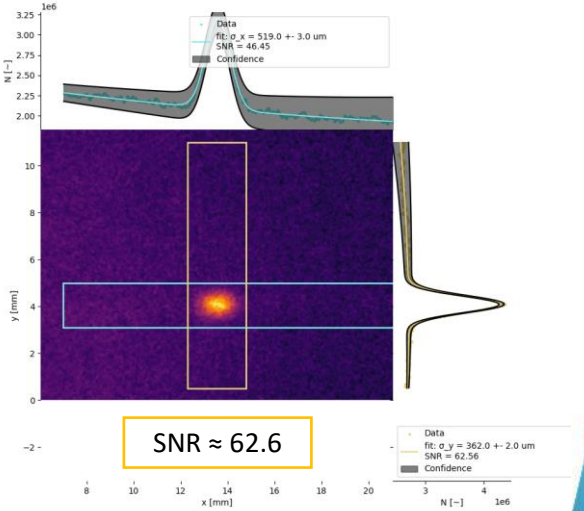
5min



SNR ≈ 14.7

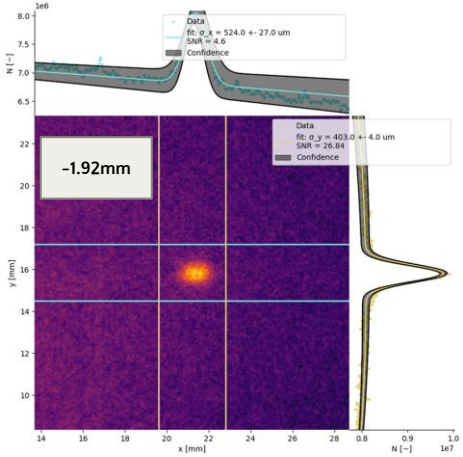


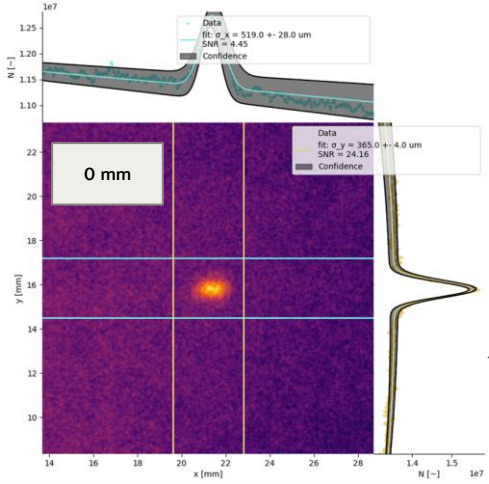
SNR ≈ 33.2

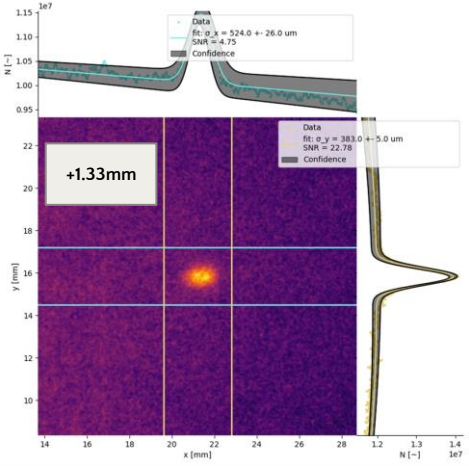


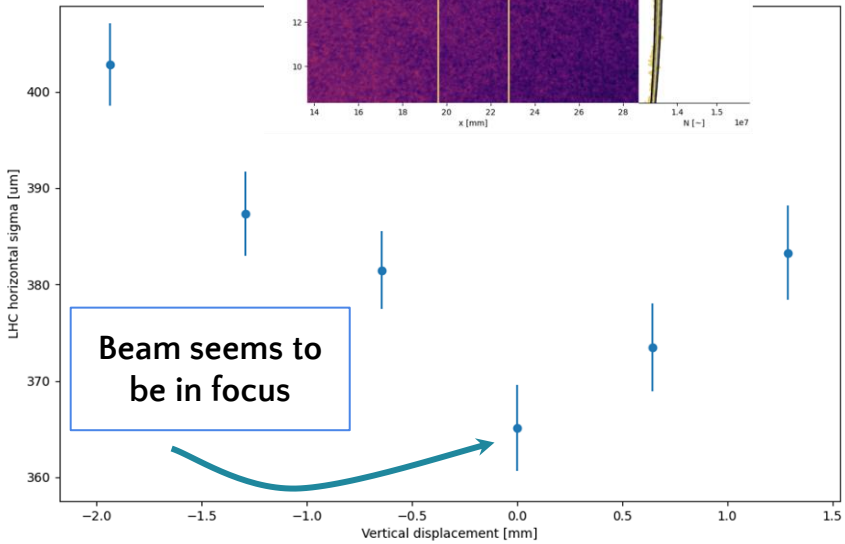
SNR ≈ 62.6

Protons - vertical scan



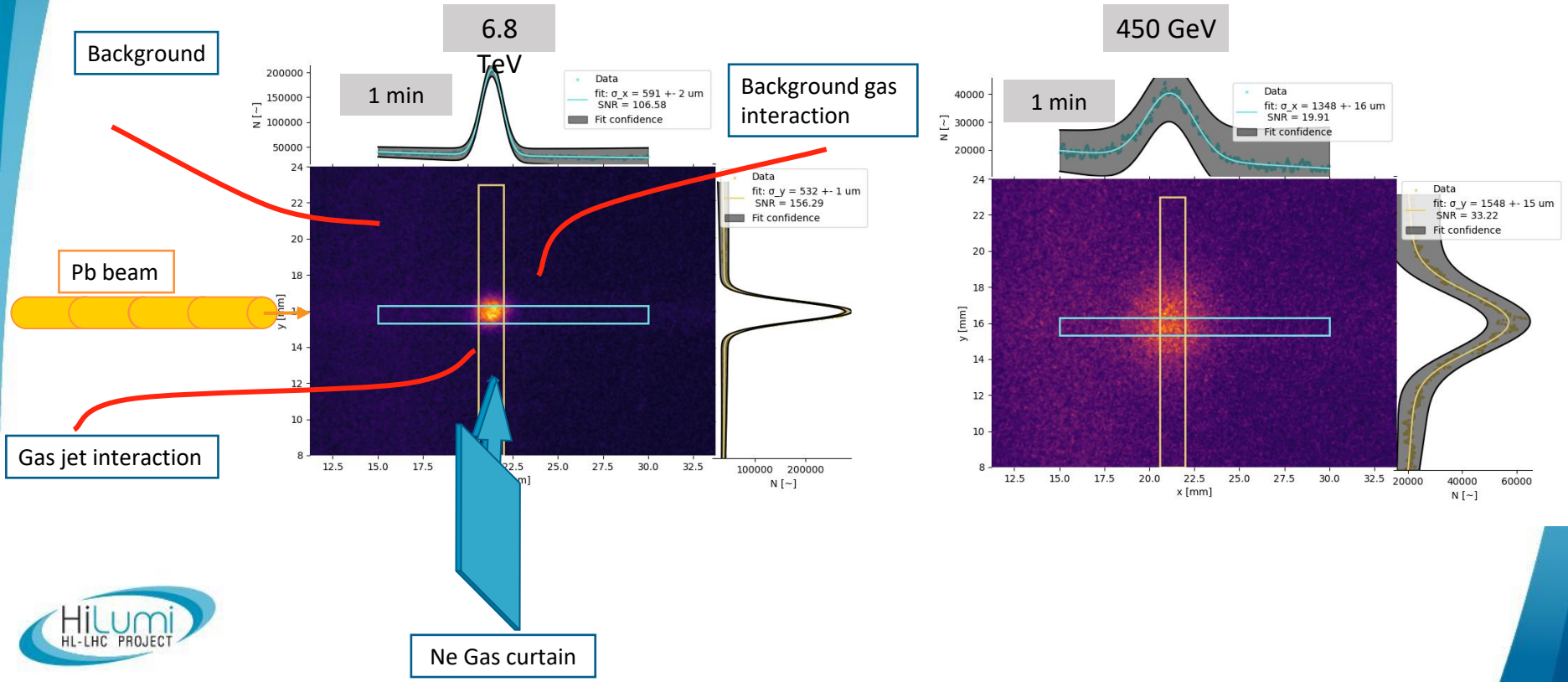






Ion measurements

First BGC measurements LHC Ion beam



Ion measurements - background

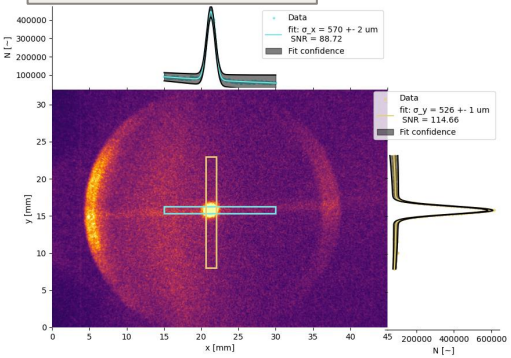
DC + Losses + Gas jet losses + SR + DC + fluorescence

DC + Losses + Gas jet losses; No “real photons”

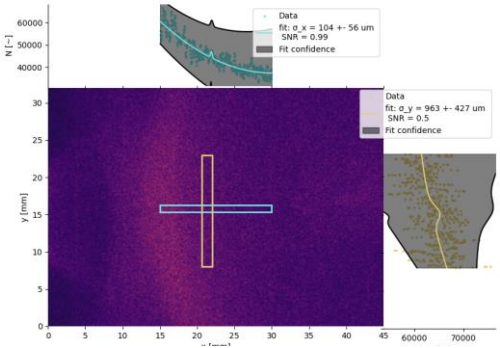
DC + Losses + SR + Ambient; No Gas jet related light

Ion Background – 6.8 TeV

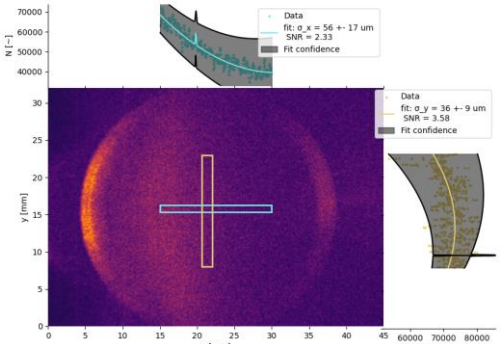
585nm, Beam, GasJet



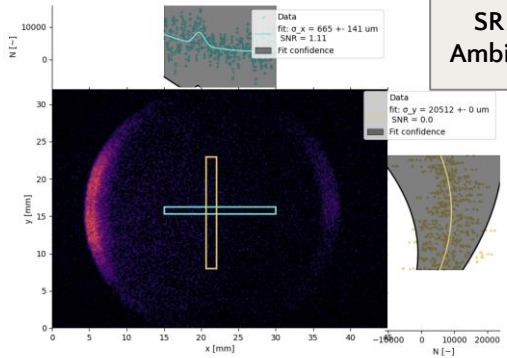
Block, Beam, Gas Jet



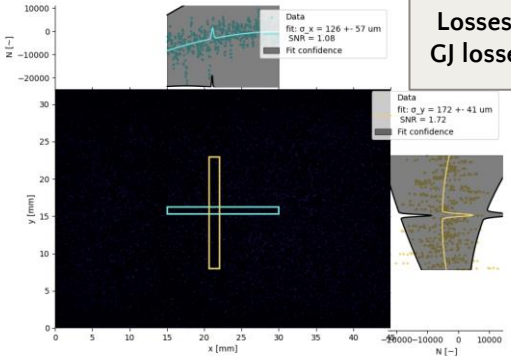
585nm, Beam, No Gas Jet



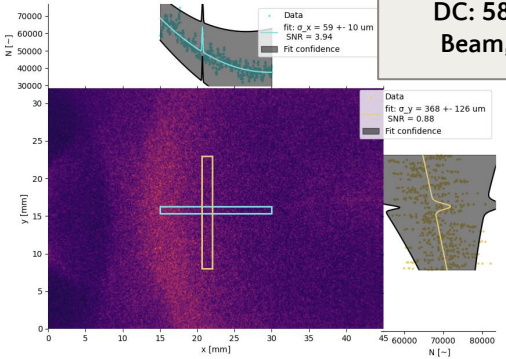
SR + Ambient



Losses + GJ losses:



DC: 585nm, no Beam, Gas Jet



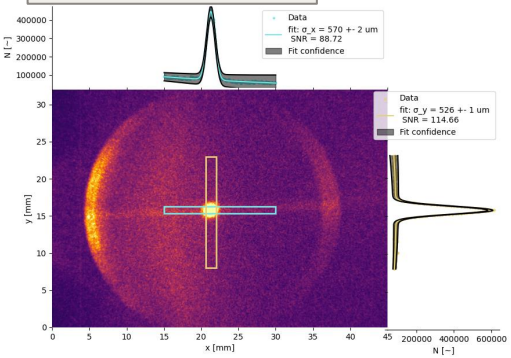
DC + Losses + Gas jet losses + SR + DC + fluorescence

DC + Losses + Gas jet losses; No “real photons”

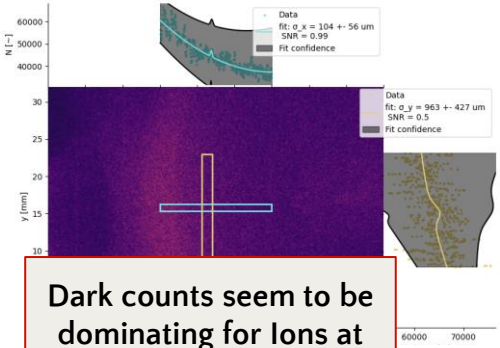
DC + Losses + SR + Ambient; No Gas jet related light

Ion Background – 6.8 TeV

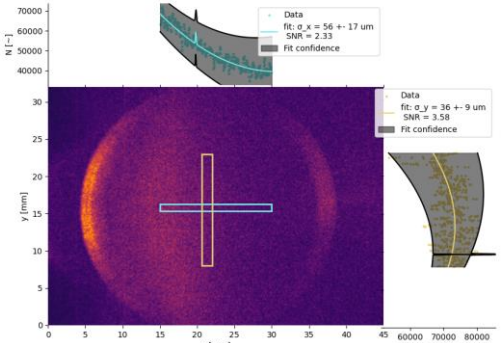
585nm, Beam, GasJet



Block, Beam, Gas Jet

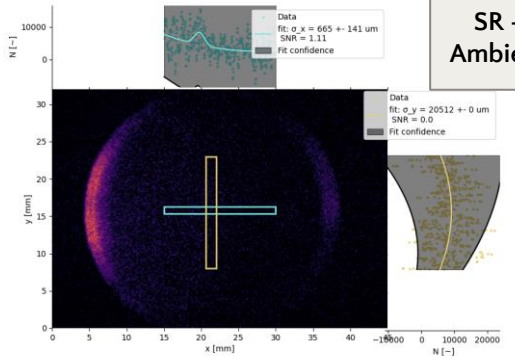


585nm, Beam, No Gas Jet

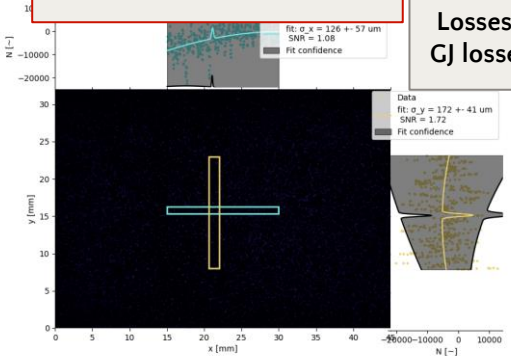


Dark counts seem to be dominating for Ions at 6.8 TeV

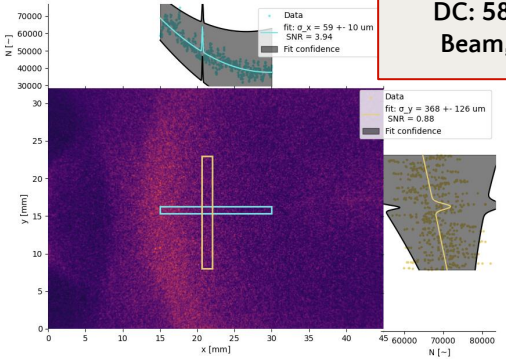
SR + Ambient



Losses + GJ losses:

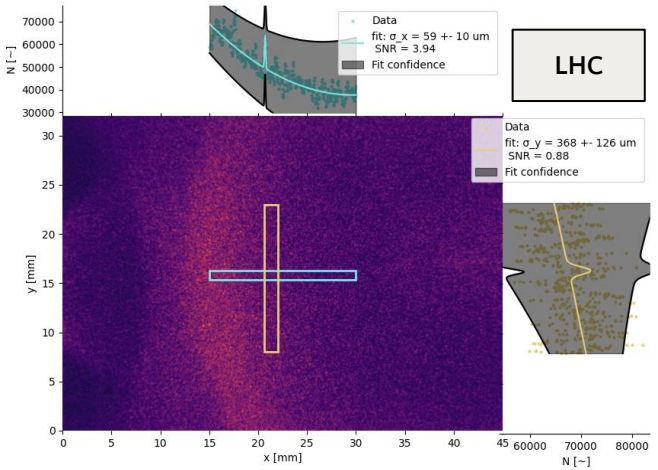


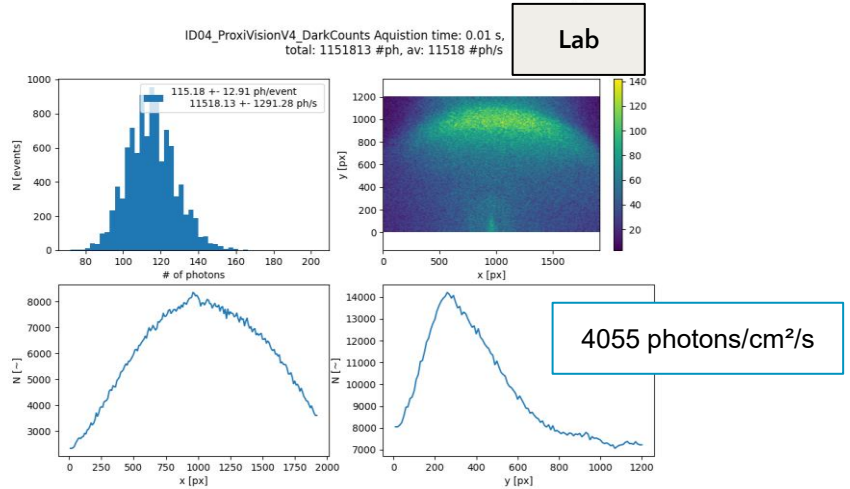
DC: 585nm, no Beam, Gas Jet



Dark counts

- Photocathode nonhomogeneous
- Higher dark count than expected
- Might benefit from a replacement of intensifier





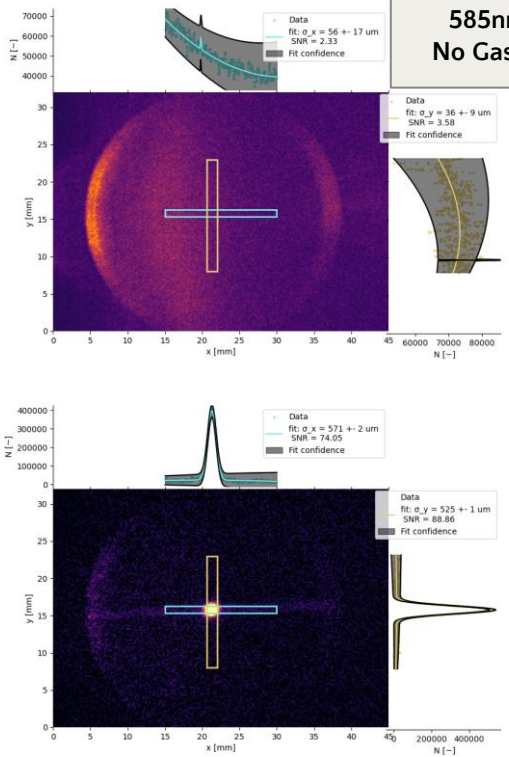
DC + SR + Losses + Ambient;
No Gas jet related light

DC + Losses + Gas jet losses;
No “real photons”

Ion Background sub. - 6.8 TeV

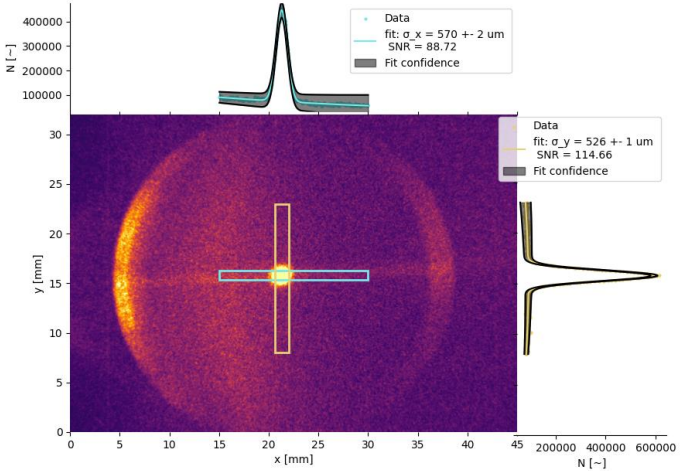
Parameters	Pb
Beam Energy [GeV/Z]	6800
Beam intensity [e]	1.1e13
Gas jet	Ne
Integration time [s]	60
Measurement method	Average

585nm,
No Gas Jet

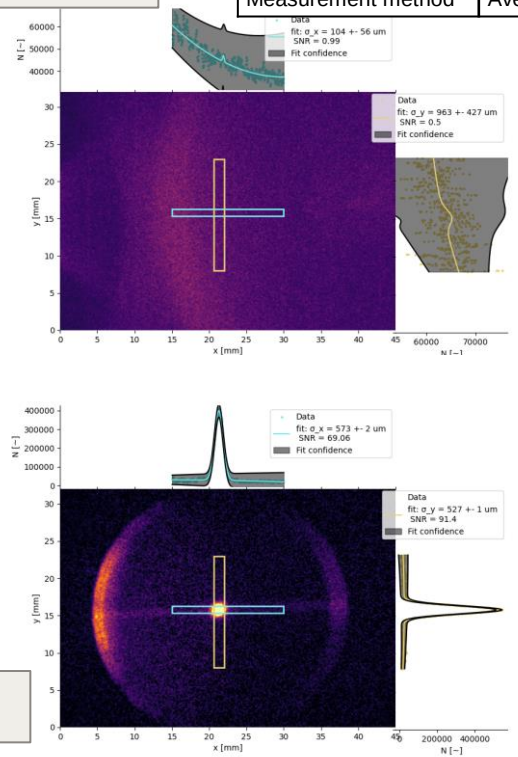


Sub

Original



Block,
Gas Jet

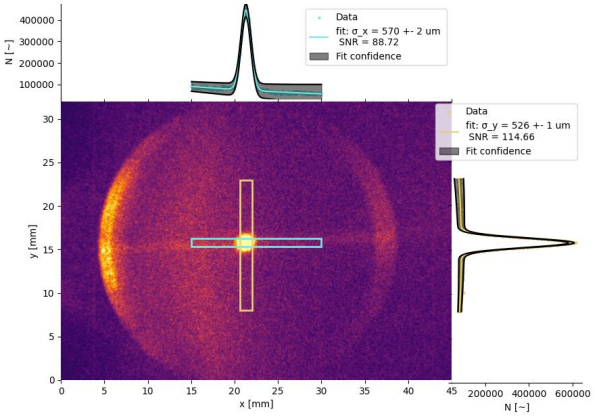


Sub

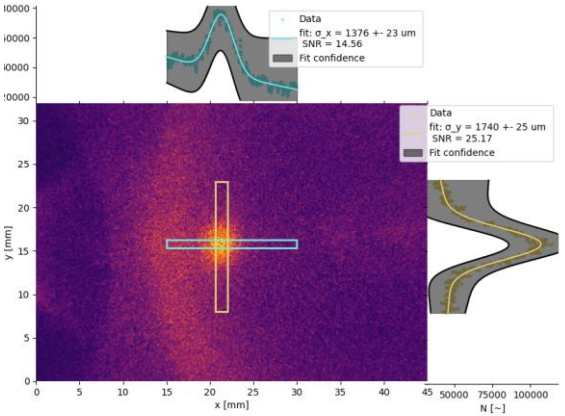
Ion Background sub. - 450 GeV

Parameters	Pb
Beam Energy [GeV/Z]	450
Beam intensity [e]	1.1e13
Gas jet	Ne
Integration time [s]	60
Measurement method	Average

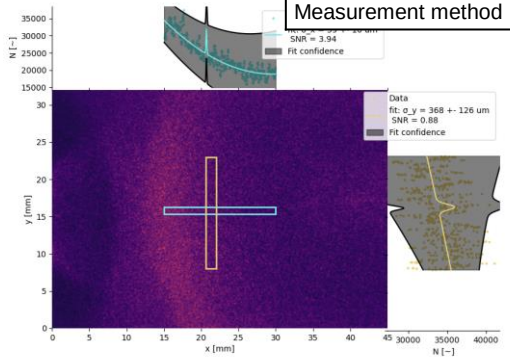
6.8 TeV



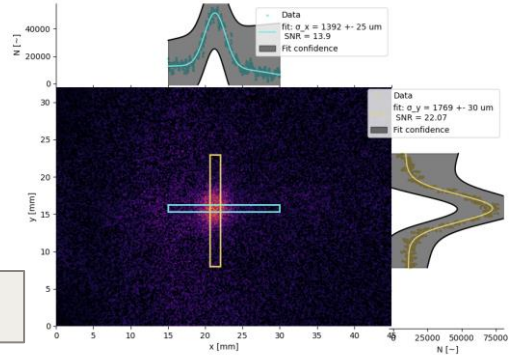
450 GeV



No beam



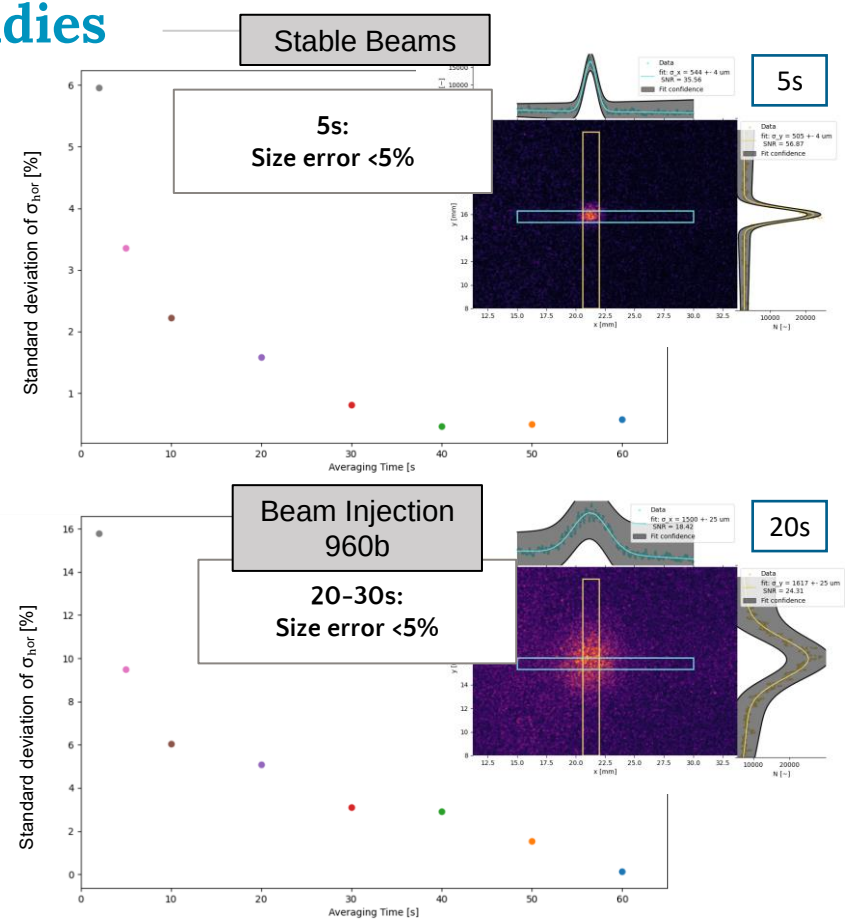
Sub



Ion measurements - systematic studies

Ions - Precision studies

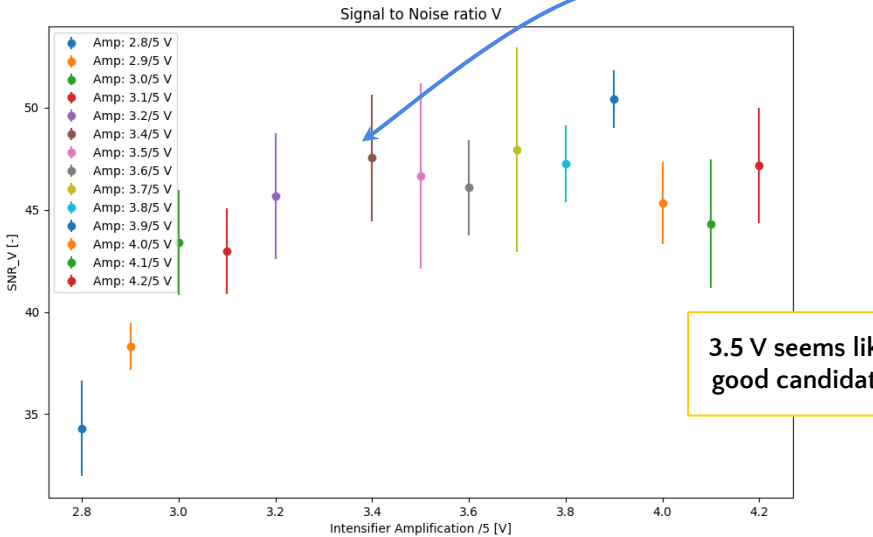
- Time needed for measurement
  - Precision required
  - Beam intensity
  - Beam size
  - Beam losses (only for protons)
- Error studies (for size error <5%):
  - 5s - Flat top ~1.e13 charges
  - 20-30s - injection 960b
  - 30s - injection 640b
  - 5-10m - injection 40b



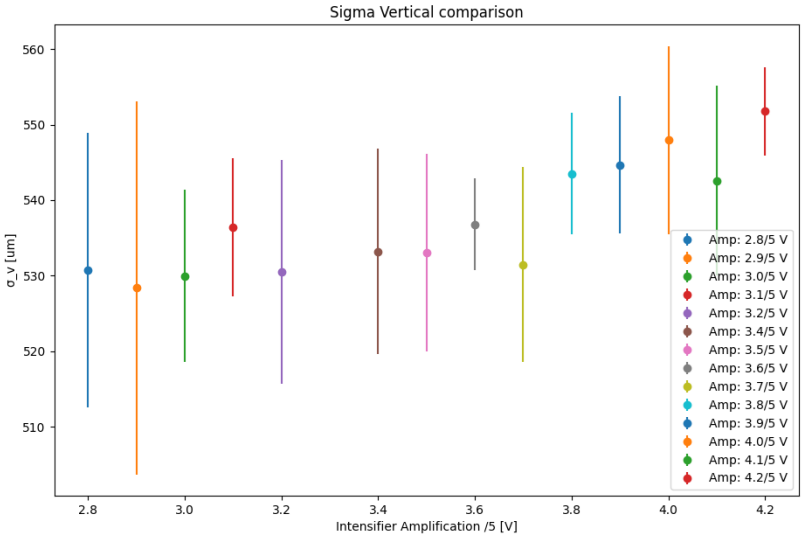
Intensifier amplification

Parameters	Pb
Beam Energy [GeV/Z]	6800
Beam intensity [e]	1.12e13
Gas jet	Ne
Integration time [s]	6x30
Measurement method	Average

Seems to plato after ~3.4 V



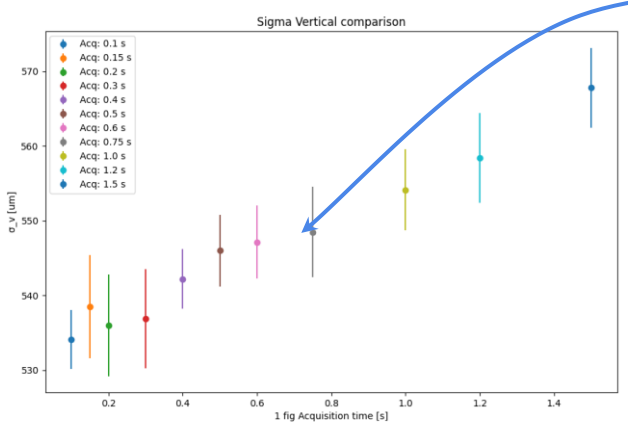
3.5 V seems like good candidate

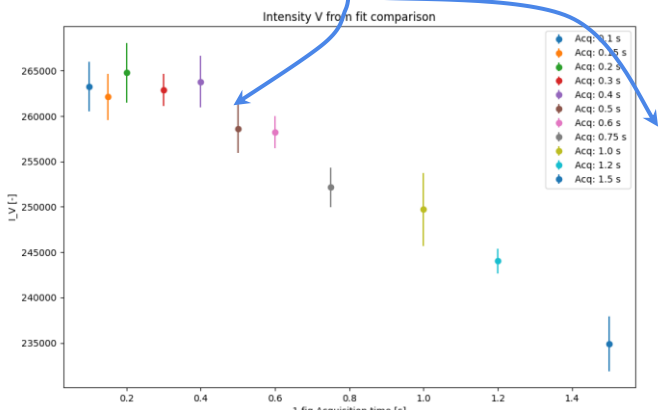


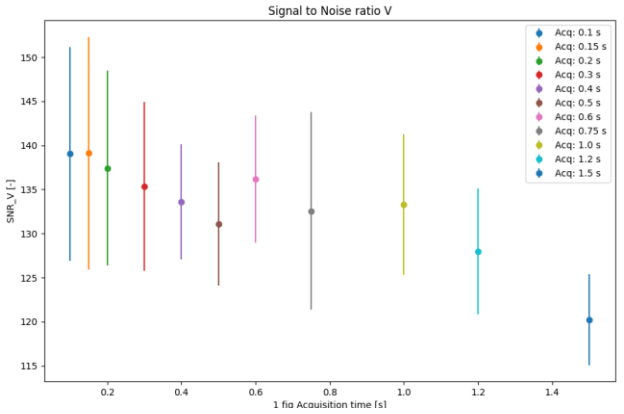
Acq. time; Cam gain - max

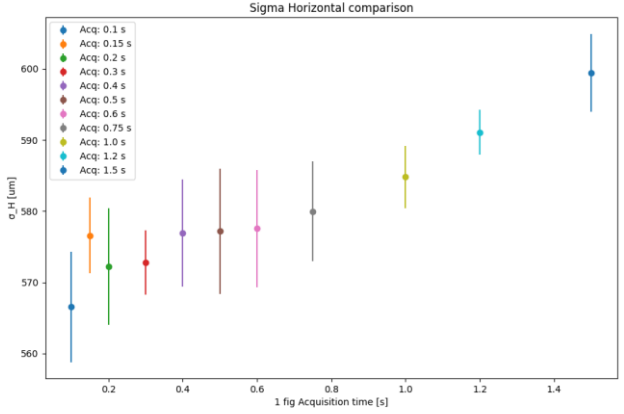
>0.3s seems to be worse (size increase, Intensity decrease, SNR slight decrease

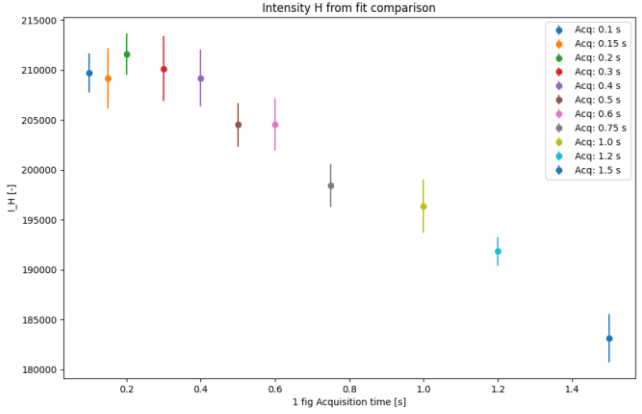
Parameters	Pb
Beam Energy [GeV/Z]	6800
Beam intensity [e]	1.12e13
Gas jet	Ne
Integration time [s]	6x20

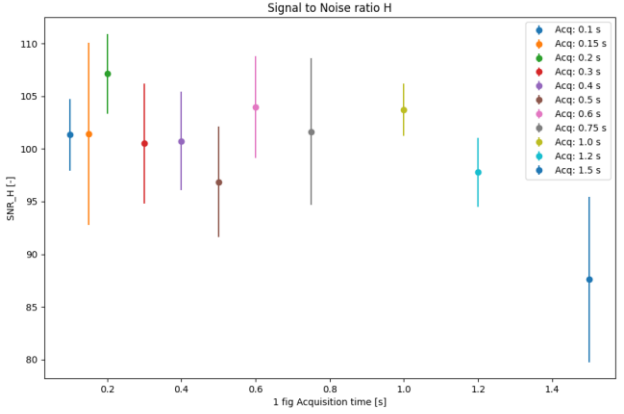








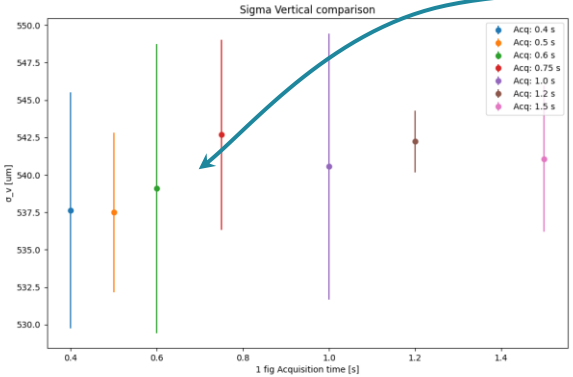


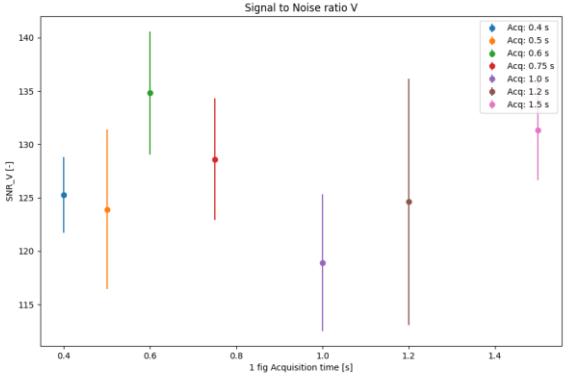


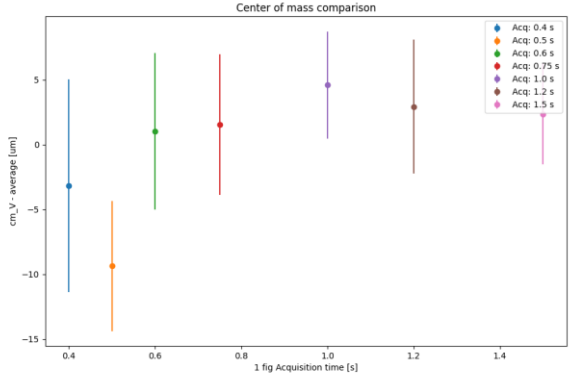
Acq. time varied

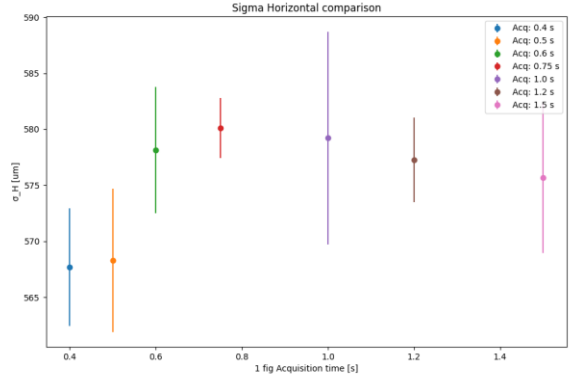
Camera gain varied to avoid saturation

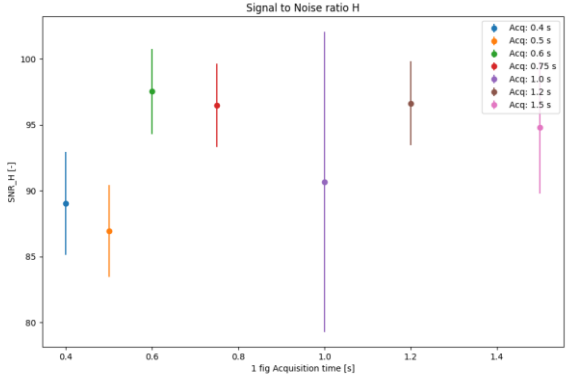
Parameters	Pb
Beam Energy [GeV/Z]	6800
Beam intensity [e]	1.12e13
Gas jet	Ne
Integration time [s]	6x30

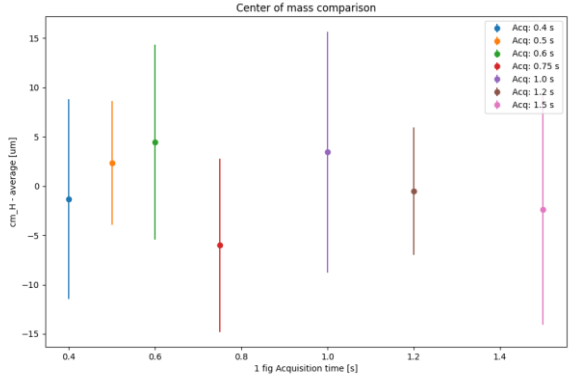




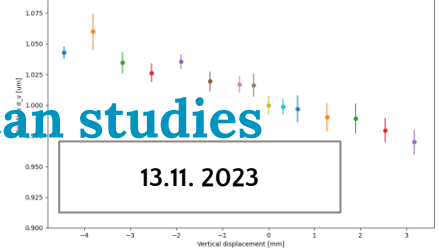






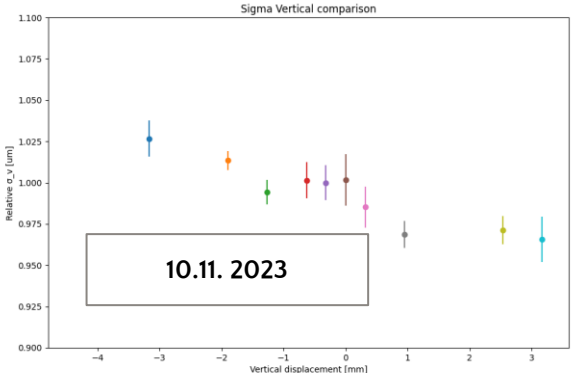


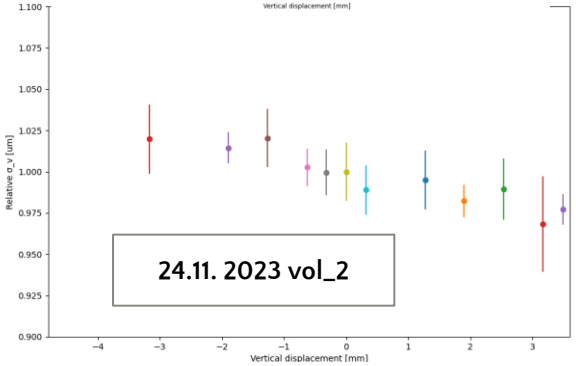
Ions - Vertical scan studies

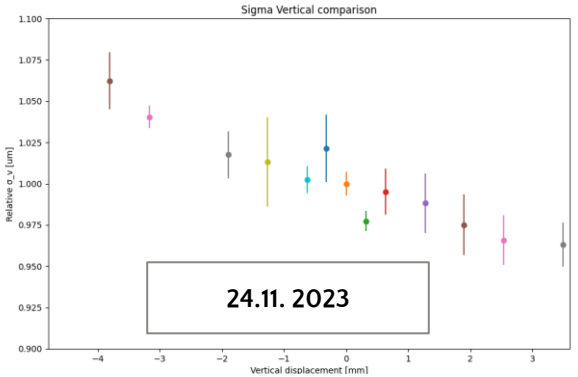


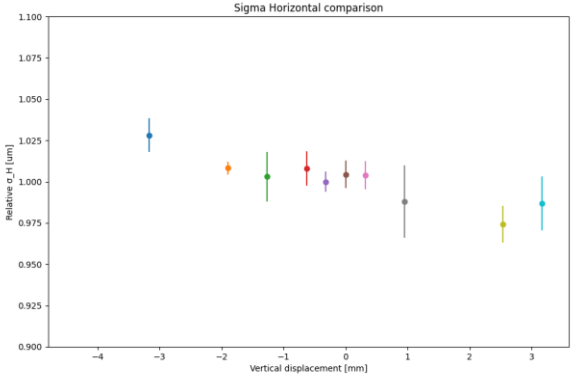
Visible decrease, <5%

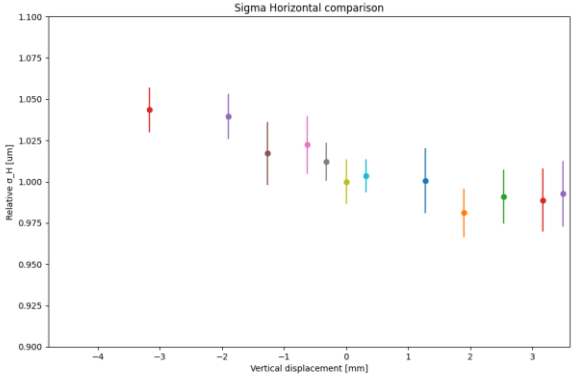
Visible decreasing trend without minimum

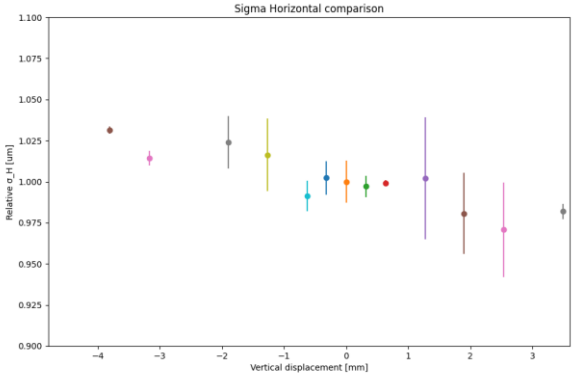












Ion measurements - Emittance

Emittance calculations

$$\epsilon = \frac{\sigma^2}{\beta}\gamma$$

- Emittance calculated
- Beta function provided by CERN
  - Beta-beating around 10%
  - Upper limit on, can be made more precise upon request

	Pb beam
β horizontal [m]	290.4
β vertical [m]	219.6

Emittance calculations

- Emittance scans convolute both beams
  - Comparable only with assumption of similar beams
  - Wire scans at injection: B1H1 & B2H1 within 10%
  - All scans shown are at the end of the fill -> highest probability of similar beams

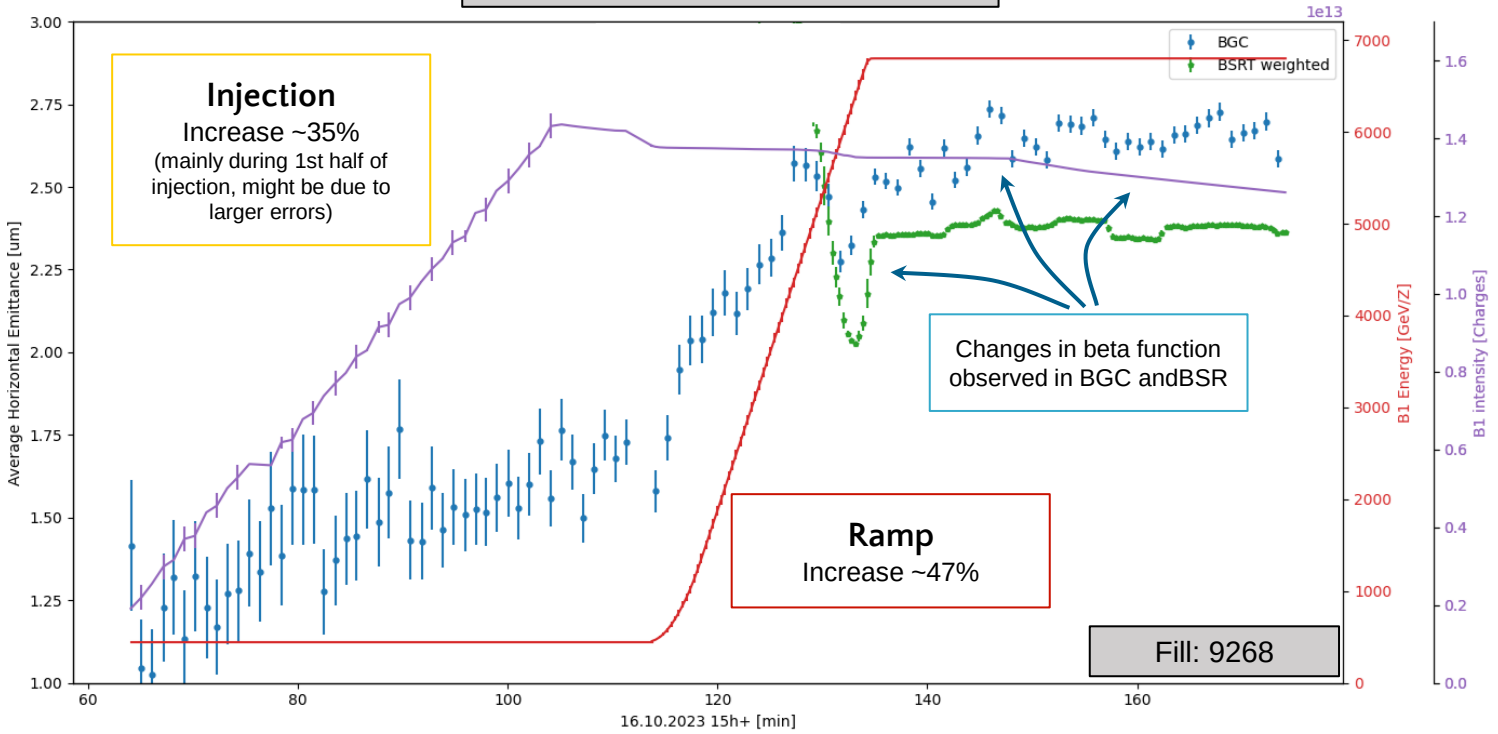
- Measurements agree within 10%
- BGC consistently higher by ~8%

	BGC $emitt_h$ [um]	IP1 $emitt_h$ [um]
27.9. (227b)	2.7 ∓ 0.3	2.5 ∓ 0.2
13.10.	2.7 ∓ 0.3	2.5 ∓ 0.3
17.10.	2.6 ∓ 0.3	2.4 ∓ 0.2

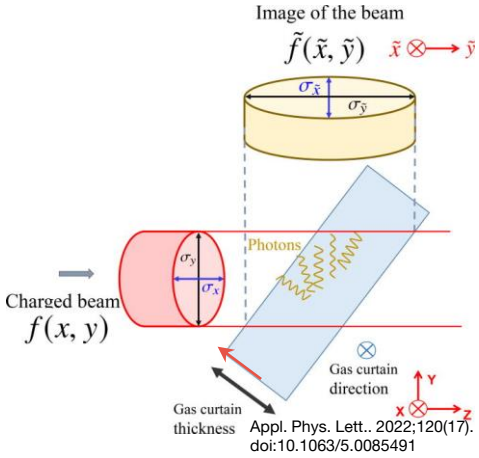
Pb Beam 1: 16.10.2023

Average Horizontal emittance
BGC: absolute measurements

BSRT not calibrated –
a relative measurements



Vertical measurements

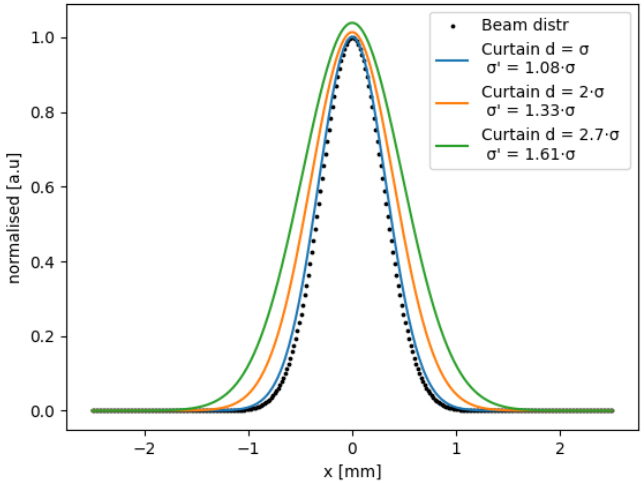


$$\widetilde{f_x} = f_x$$

$$\widetilde{f_y} = \int_{-d/2}^{d/2} \rho(\xi) \cdot f_y\left(\xi \cdot 2/\sqrt{2} - y\right) d\xi$$

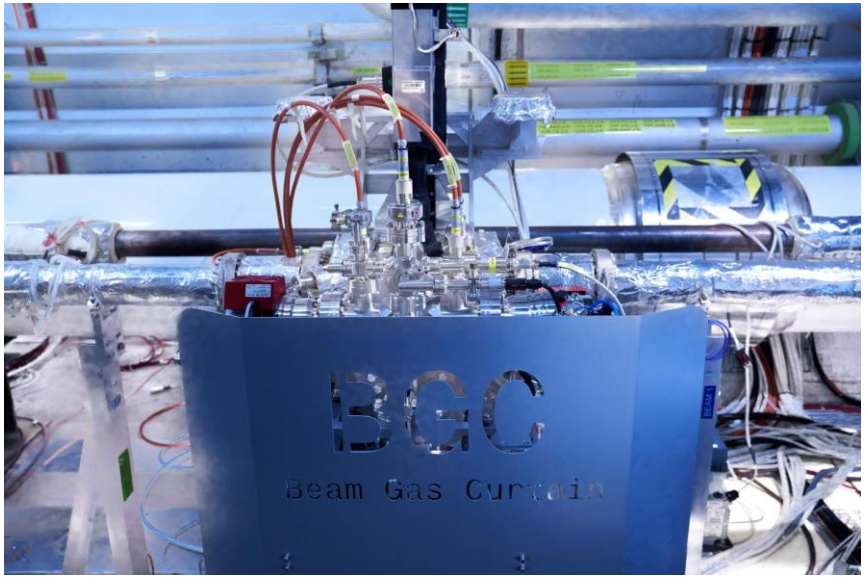
- Geometrical factor depends on
  - Beam size/curtain thickness ratio
  - Gas curtain density distribution
- From simulations the uniformity

Uniform gas curtain
Gaussian beam



Summary

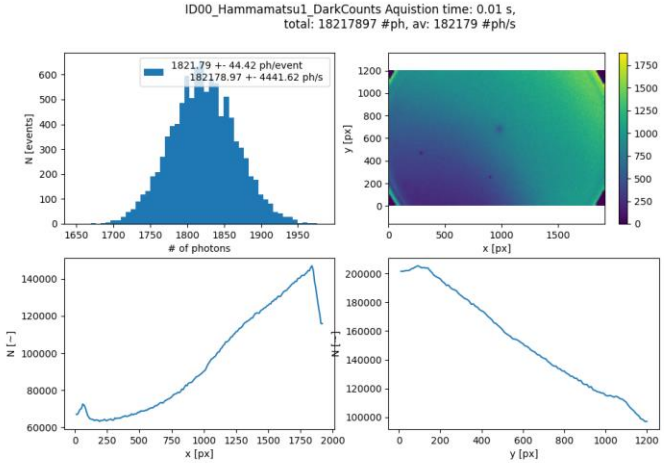
- BGC successfully operated at LHC during 2023
- Validated both with p & Pb beams from beam injection through energy ramp, up to 6.8 TeV
- Proton dataset - limited -> systematic studies needed
- Ion studies very successful!
  - Systematic studies carried out
  - Background dominated by photocathode dark counts
  - The only measurements of emittance at Injection Energy!
  - Horizontal emittance within 10% to independent measurements at IP1
- Potential to be operational instrument during 2024

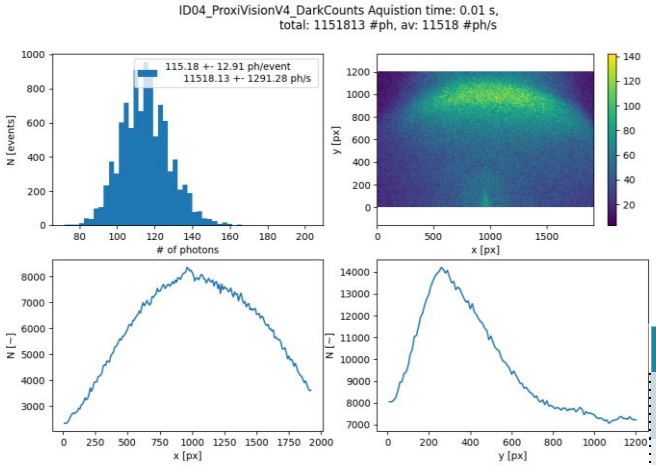


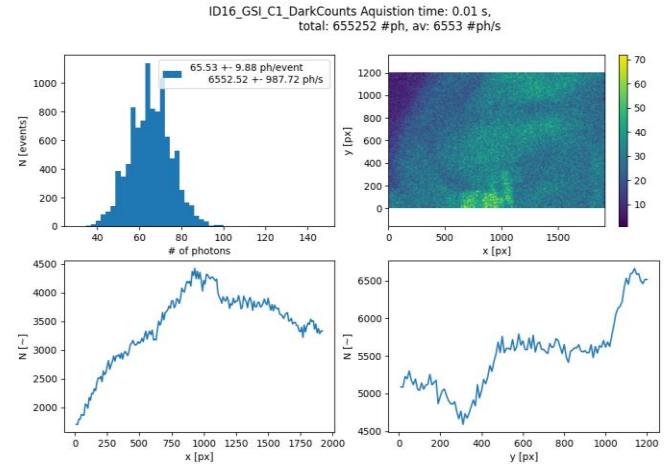
Thank you for the great experience here!

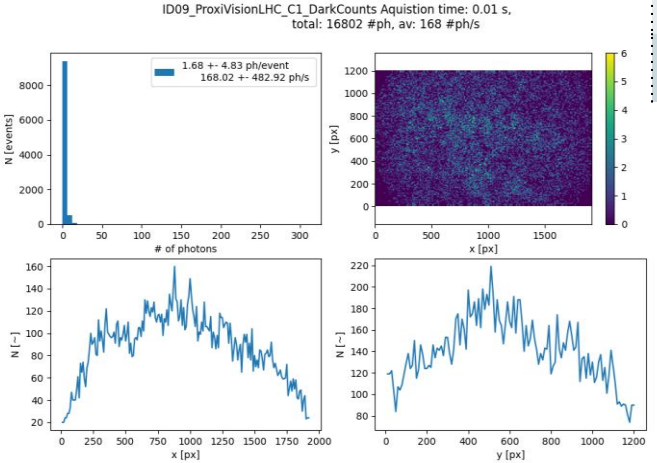
If you need to contact me

ondrej.sedlacek@cern.ch



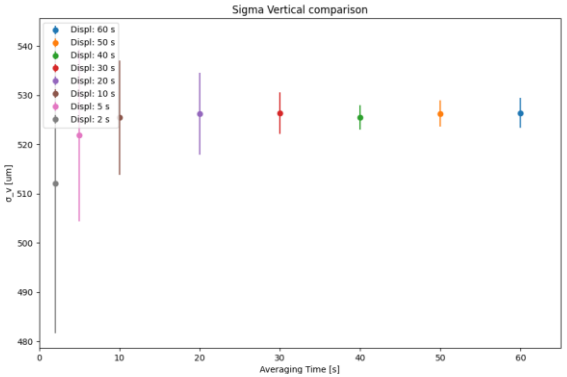


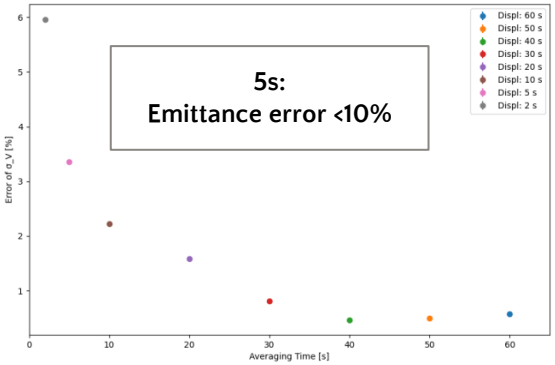




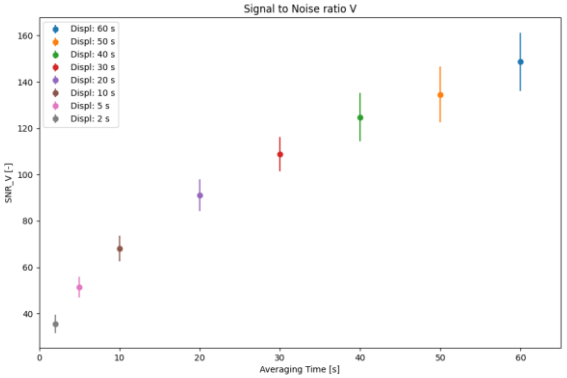
Camera	ph/cm^2/s
Hamamatsu (Multialkali)	44 897
ProxiVision - LHC 2022	41
ProxiVision - V4 LHC 2023	4 055

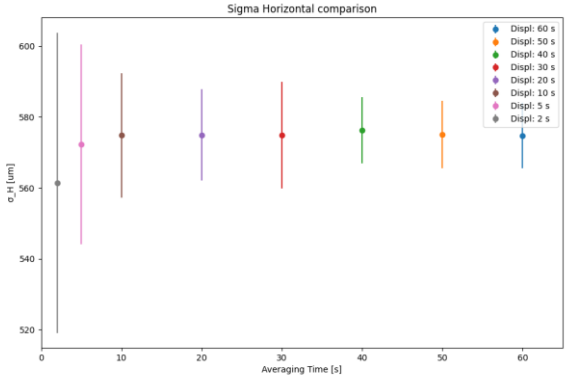
Ions - Averaging times 6.8TeV

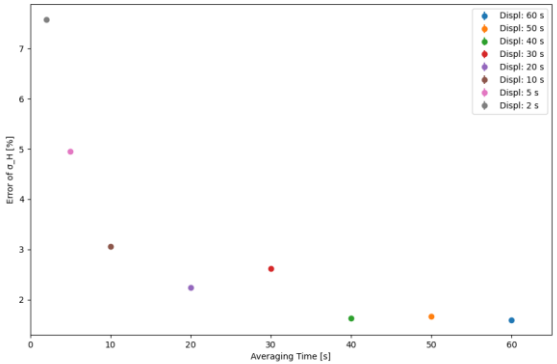


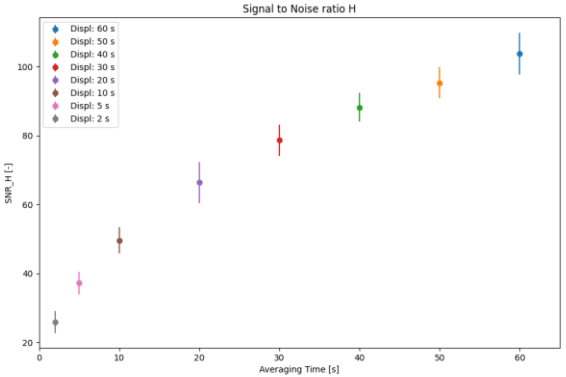


5s:
Emittance error <10%

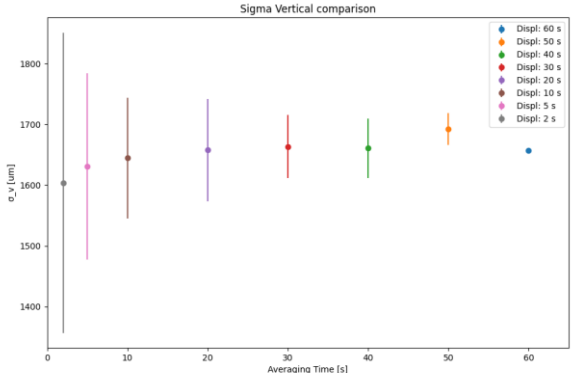


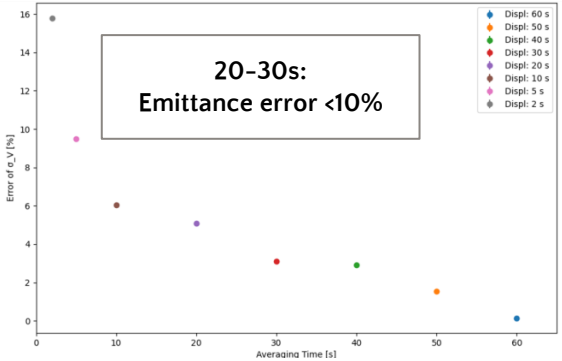




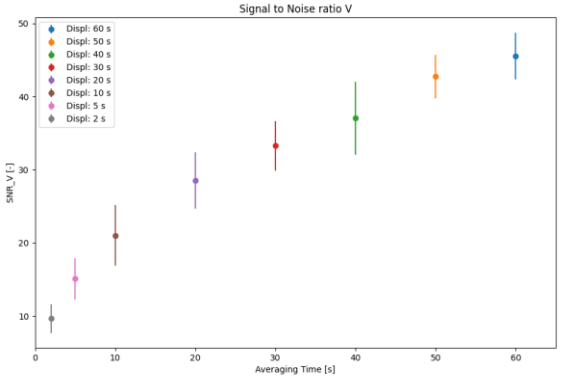


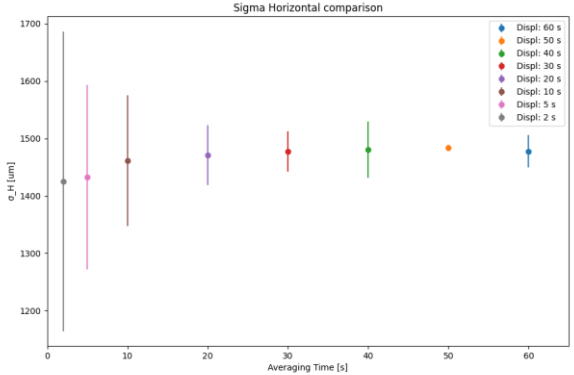
Ions - Averaging times 450 GeV 960b

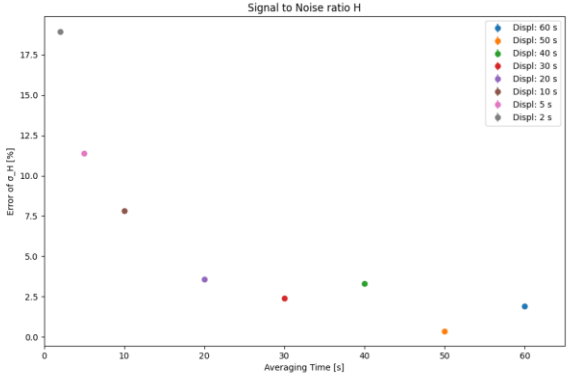


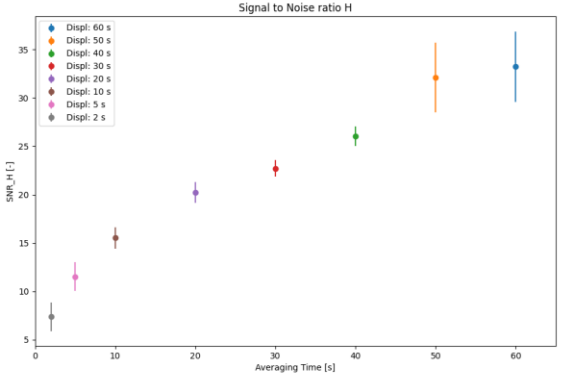


20-30s:
Emittance error <10%

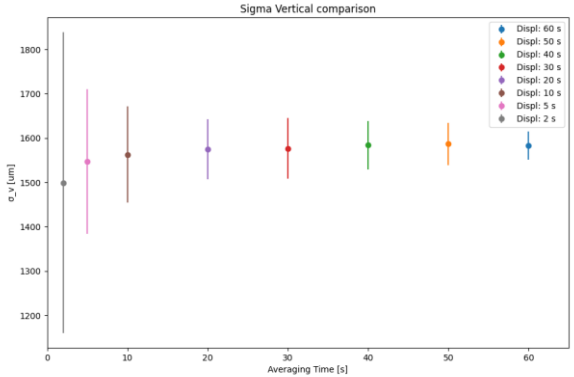


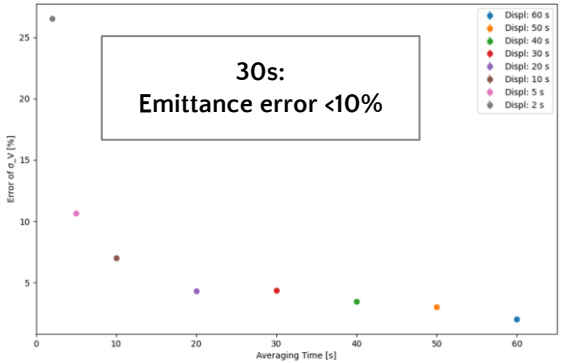




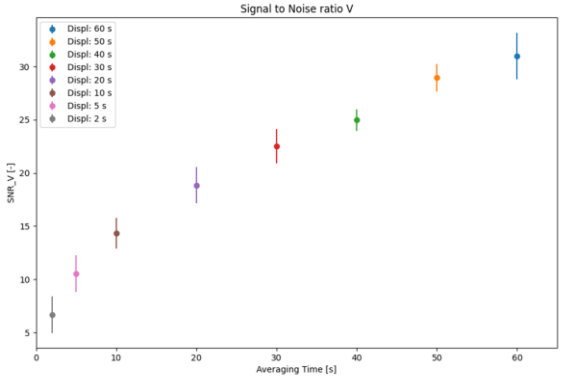


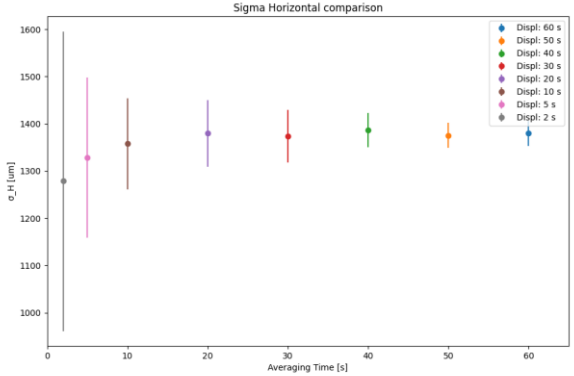
Ions - Averaging times 450 GeV 640b

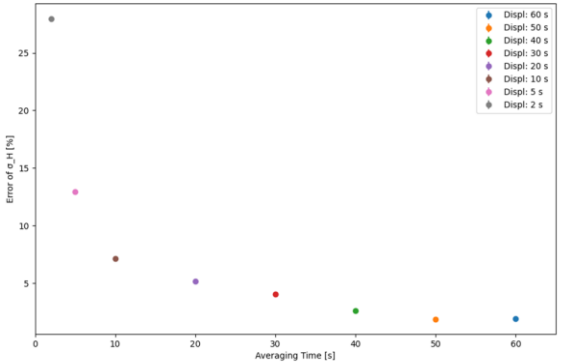


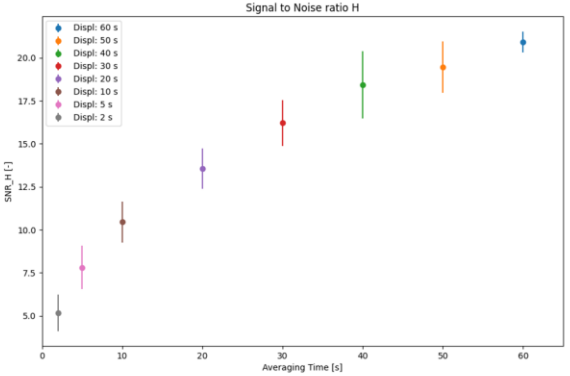


30s:
Emittance error <10%

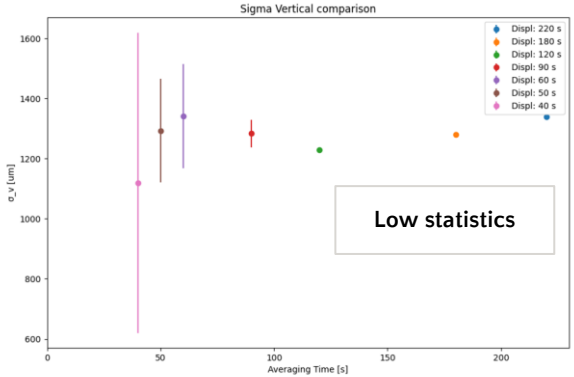


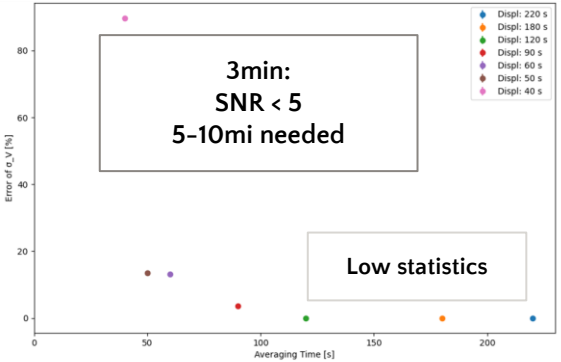


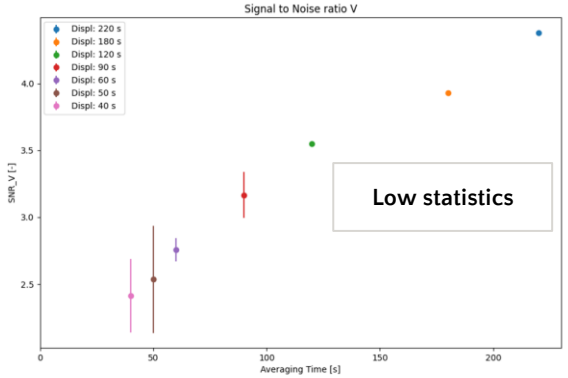


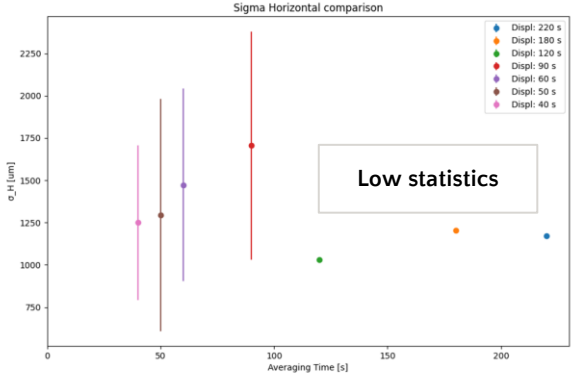


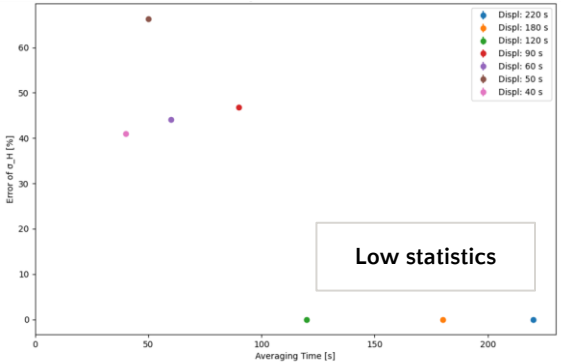
Ions - Averaging times 450 GeV 40b (1 train)

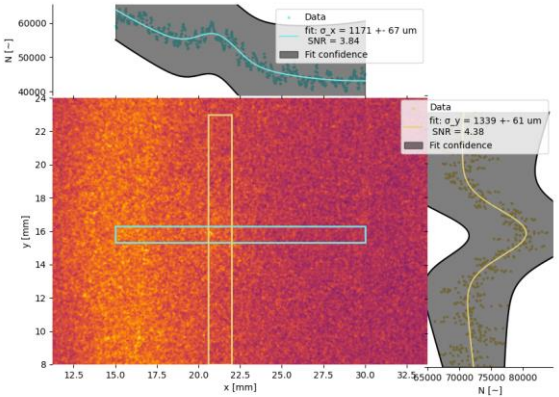




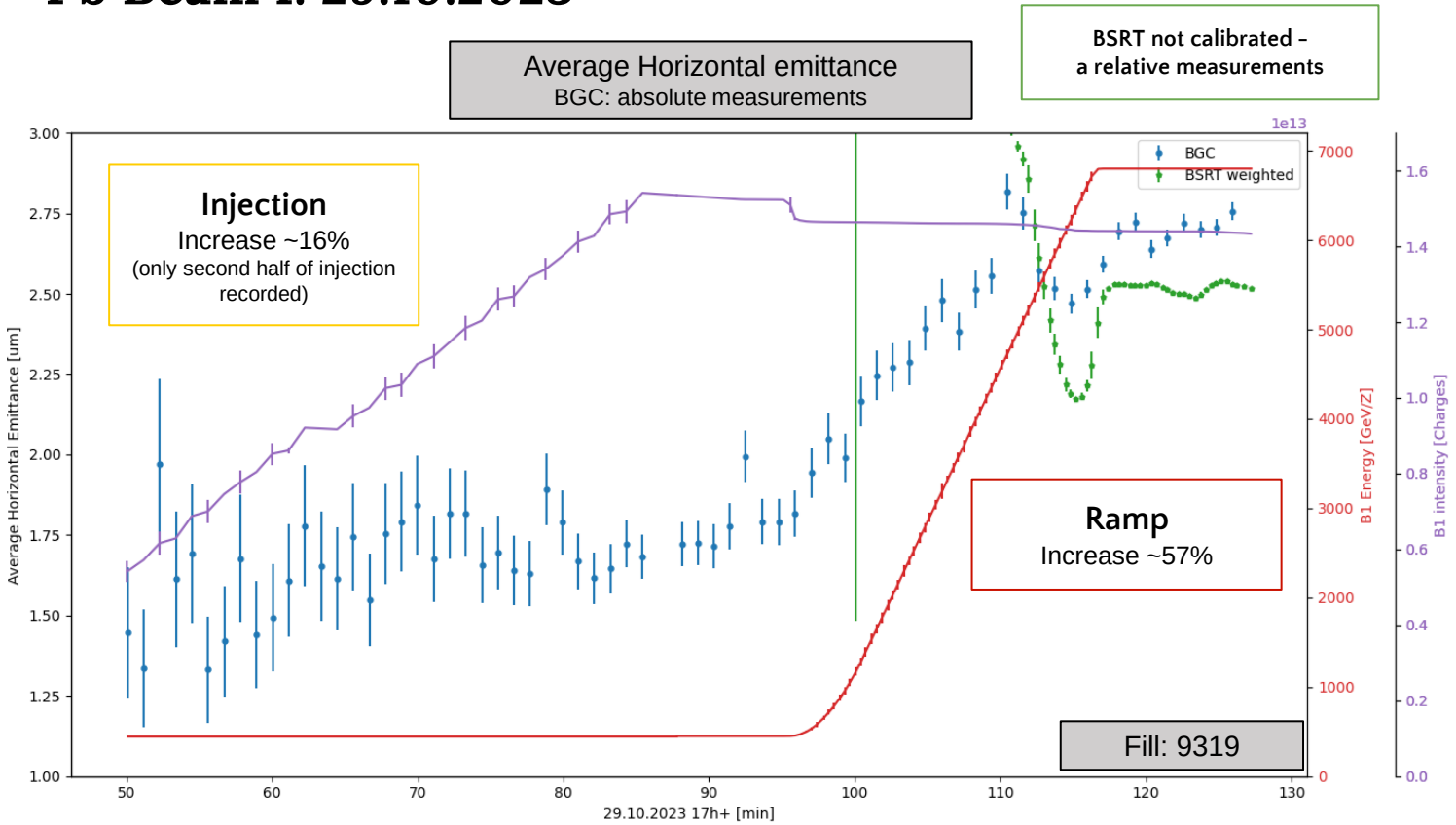




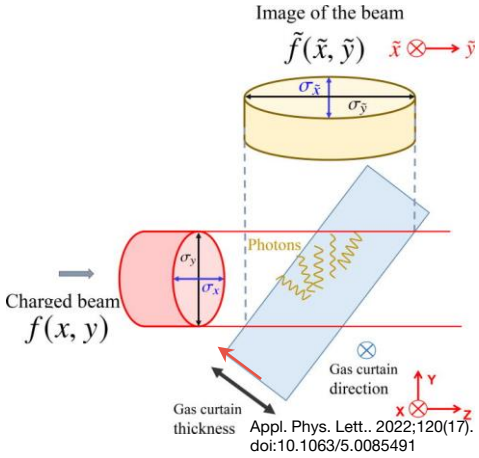




Pb Beam 1: 29.10.2023



Vertical measurements



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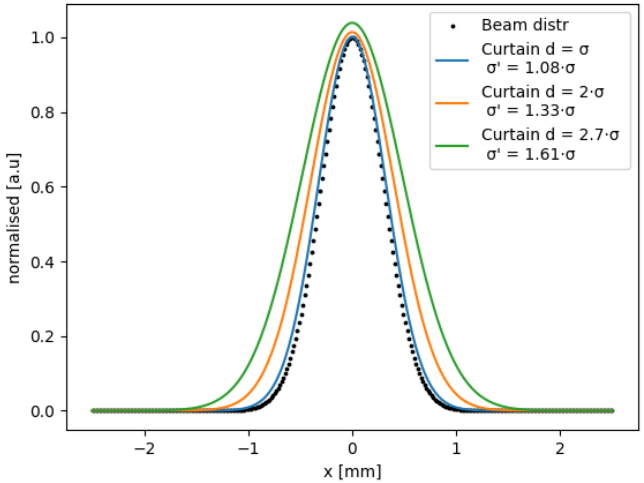
$$\widetilde{f_x} = f_x$$

$$\widetilde{f_y} = \int_{-d/2}^{d/2} \rho(\xi) \cdot f_y\left(\xi \cdot 2/\sqrt{2} - y\right) d\xi$$

- Geometrical factor depends on
  - Beam size/curtain thickness ratio
  - Gas curtain density
- Subject of analysis

Uniform gas curtain
Gaussian beam

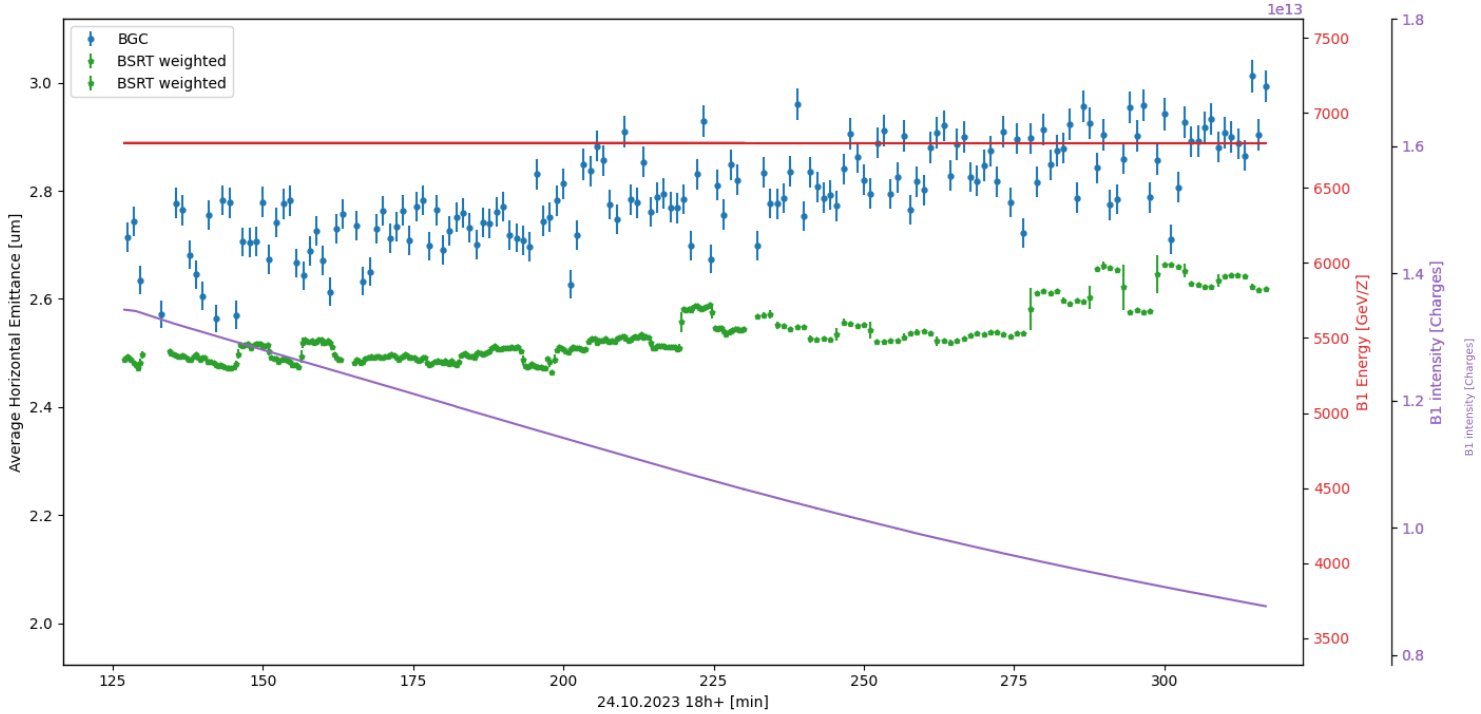


Proton measurements

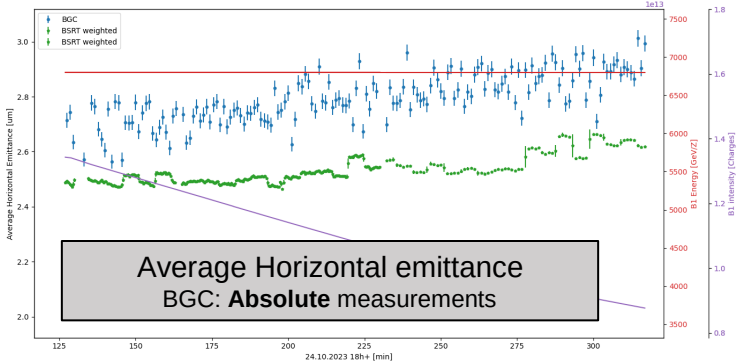
Current state

- Monitor still under development (1st year at LHC)
  - Can become operational instrument during 2024 (injection sequence, software)
  - Started logging on Timber (simple horizontal size and emittance published)
  - Most of the analysis is still done offline, routines are being developed
- Systematics under investigation - narrowing down accuracy
  - Point spread function
  - Beta function variation
- Analysing & mapping correction factor for absolute vertical measurements

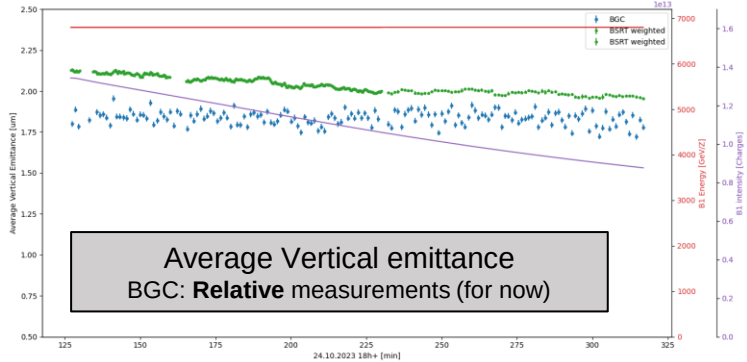
Pl


BGC
BSRT weighted
BSRT weighted
1e13
Average Horizontal Emittance [um]
B1 Energy [GeV/Z]
B1 intensity [Charges]
24.10.2023 18h+ [min]

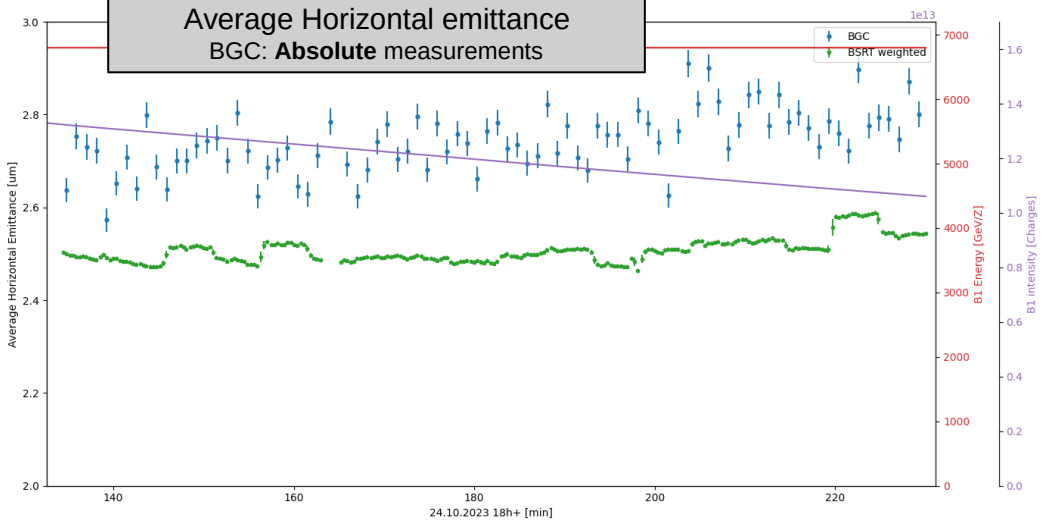
Pb B1: 24.10.2023



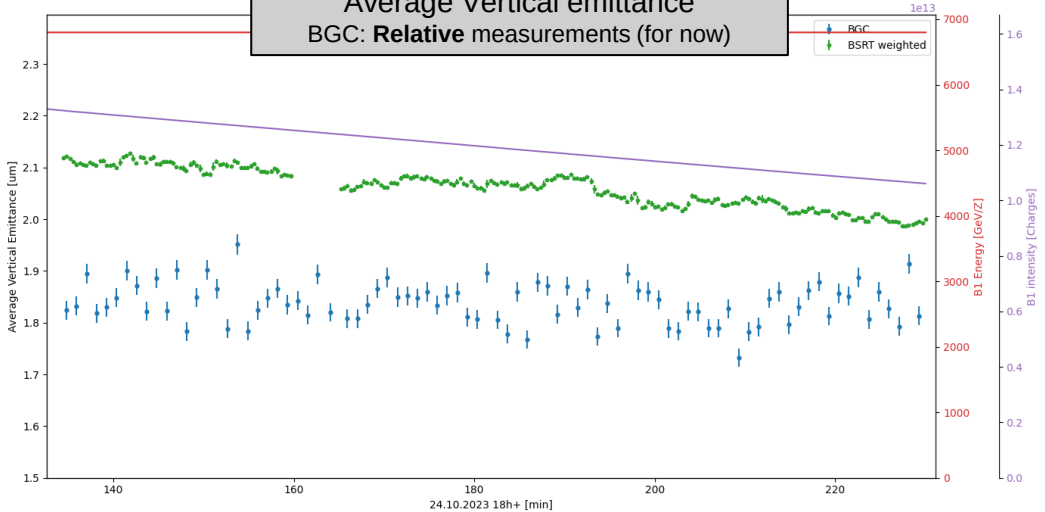
Average Horizontal emittance
BGC: **Absolute** measurements



Average Vertical emittance
BGC: **Relative** measurements (for now)

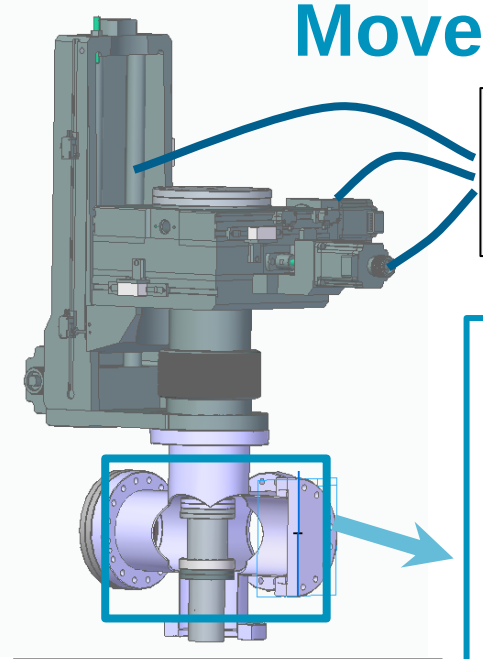


Average Horizontal emittance
BGC: **Absolute** measurements

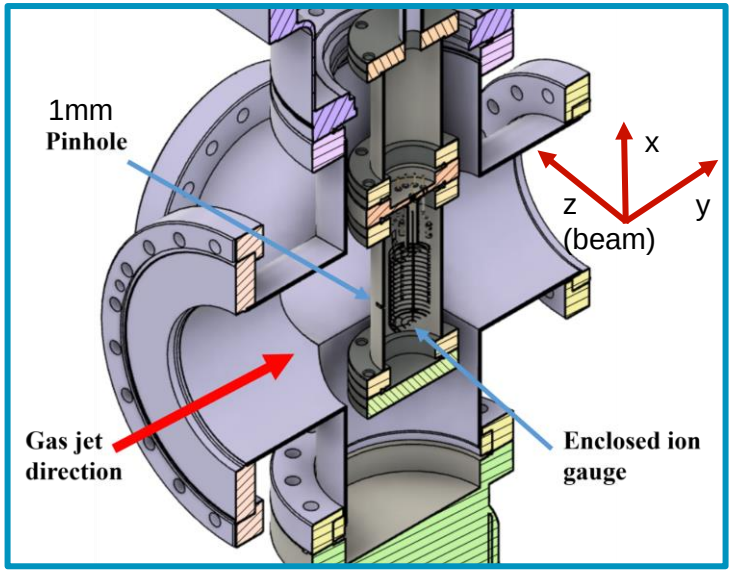


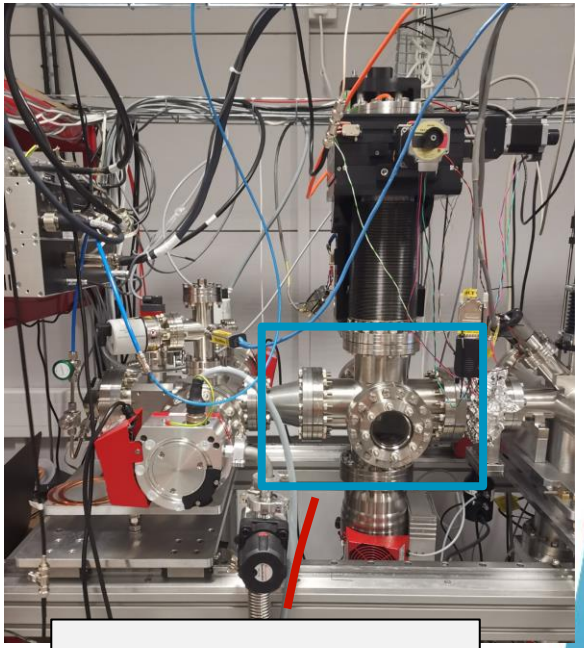
Average Vertical emittance
BGC: **Relative** measurements (for now)

Direct gas curtain profile measurements
Moveable pinhole pressure gauge



Stepmotors in all 3 dimensions

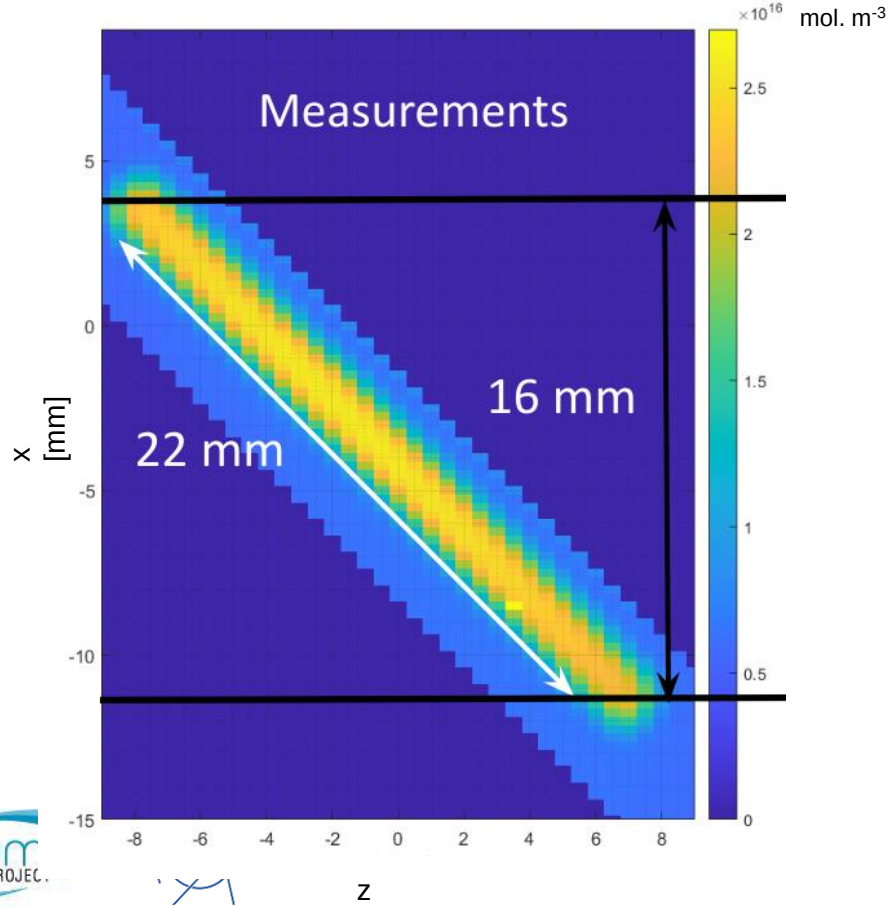




Local gas pressure measurement

Replaces interaction chamber -> **Measuring Gas curtain profile at interaction point**

BGC Version 3 to CERN - Commissioning

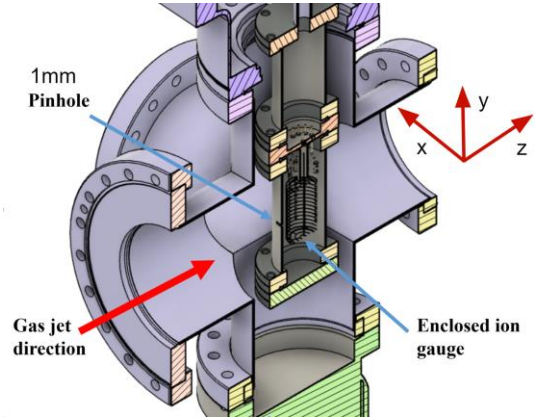


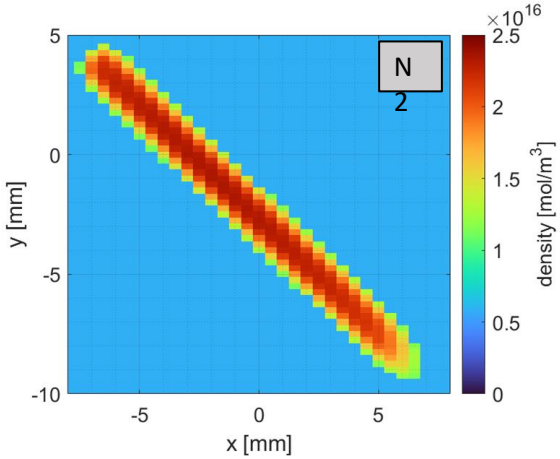
- Full assembly in one week
  - Including vacuum pump down tests - Successful
- Alignment of nozzle-skimmer assembly - Successful
  - Including building alignment setup at CERN
- Moveable pressure gauge installed & Gas curtain profile measured - Successful
  - Great agreement with simulations

Gas jet profile

- Moveable pinhole
  - Jet pressure sampling

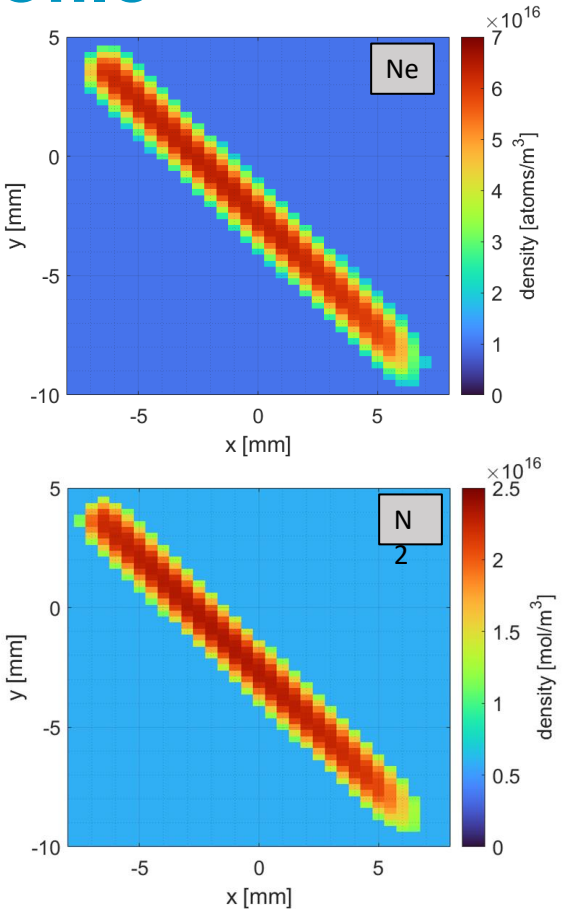
Appl. Phys. Lett.. 2022;120(17).
doi:10.1063/5.0085491





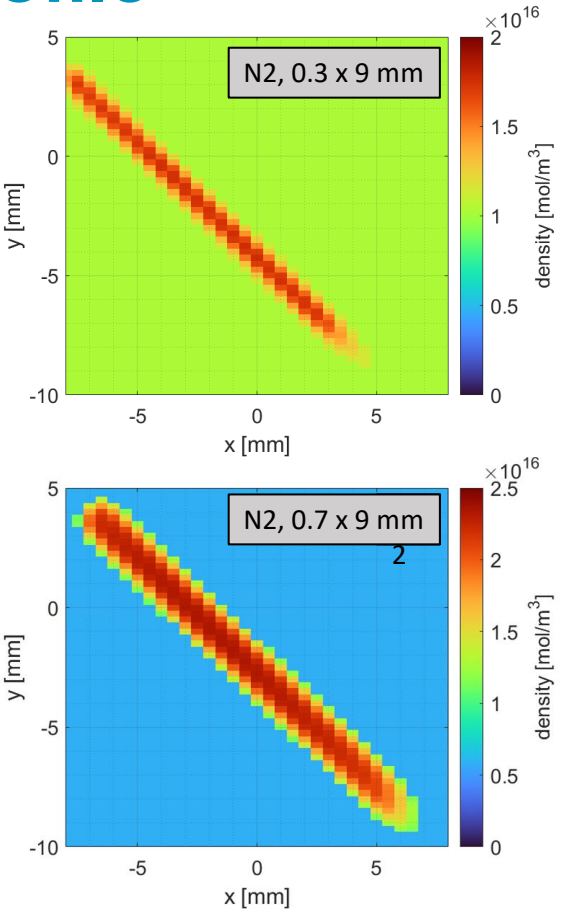
Gas jet profile

- Moveable pinhole
  - Jet pressure sampling
- Gass shape - constant
  - $Ne/N_2 \approx 2.9$



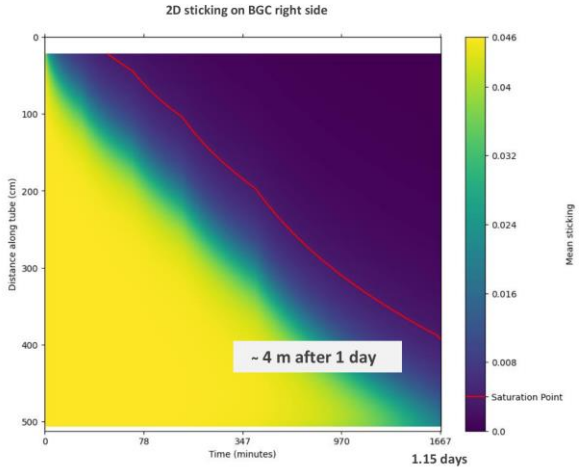
Gas jet profile

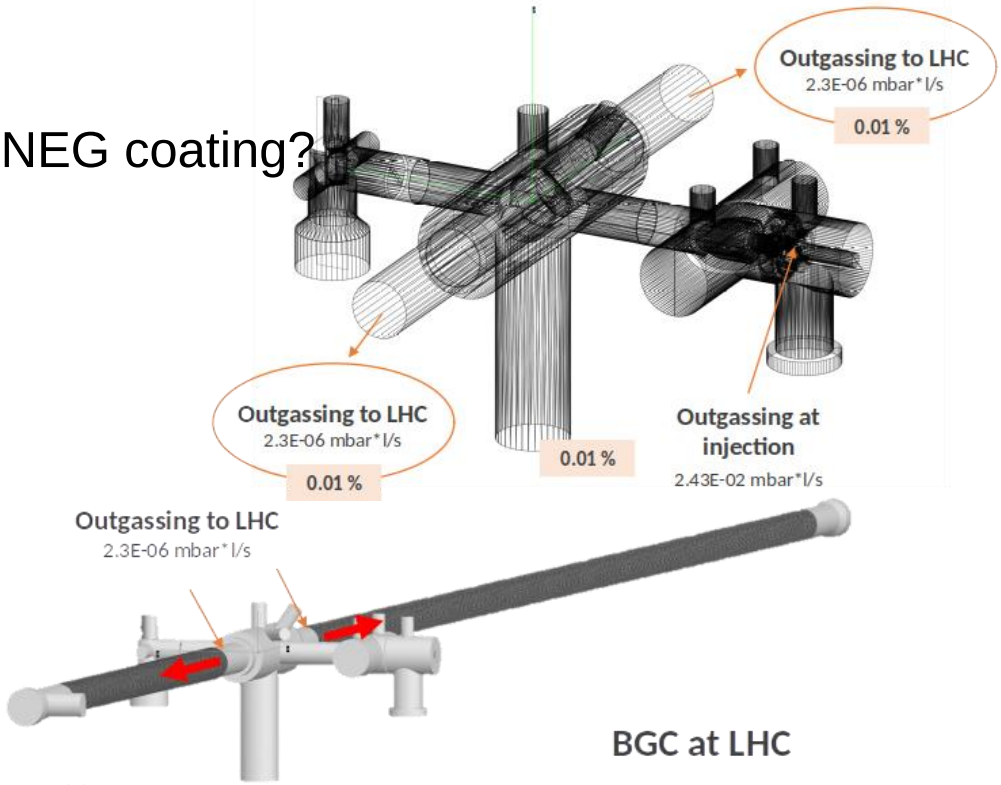
- Moveable pinhole
  - Jet pressure sampling
- Gass shape - constant
  - $Ne/N_2 \approx 2.9$
- 3rd skimmer - thickness, density
  - Signal vs vacuum



LHC Vacuum and LHC NEG coating saturation

- BGC Version 3 - Pump down curves being characterized to simulate effect on LHC vacuum
  - Bakeout needed ?
  - If N_2 jet - saturation of NEG coating?



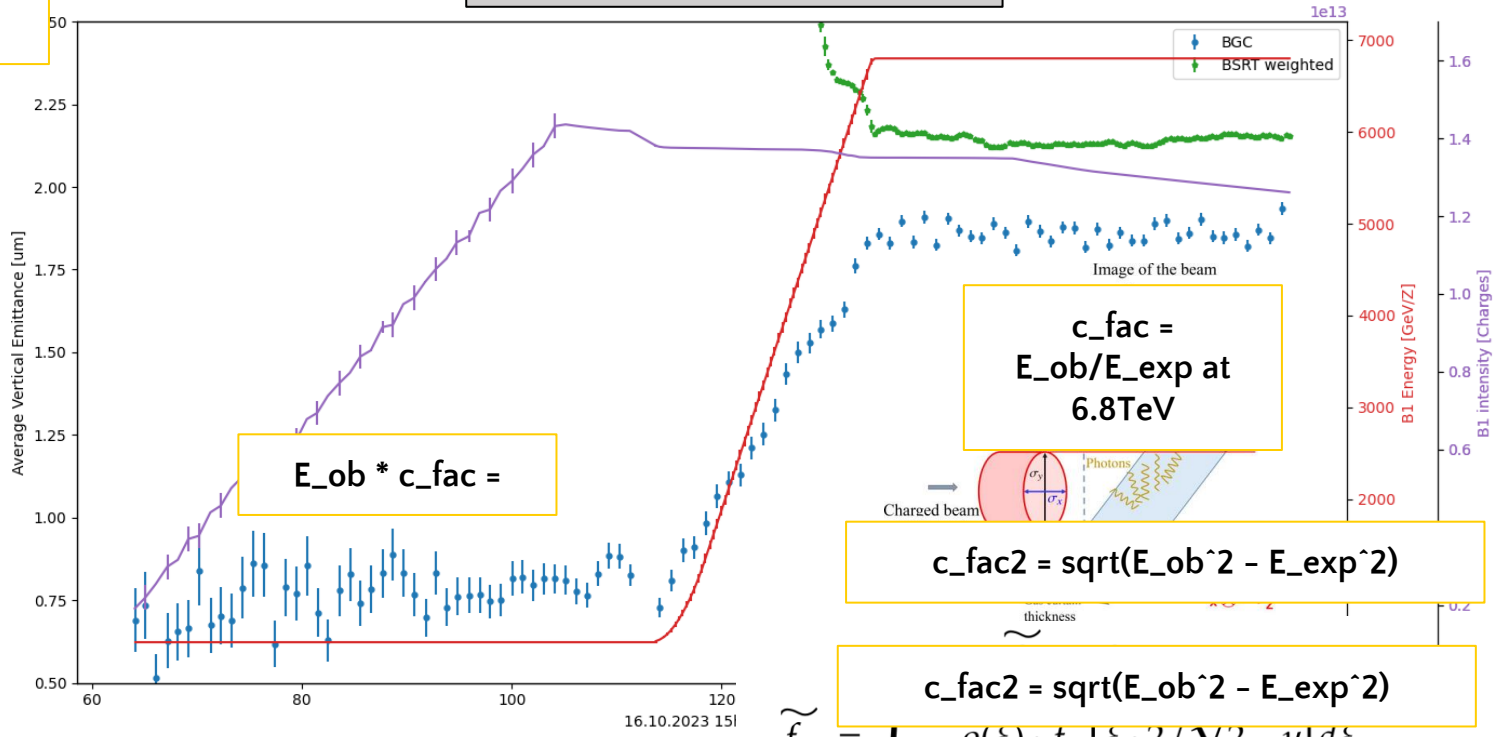


Courtesy of Cristina Castro Sequeiro TE-VSC

Pb B1: 16.10.2023

Injection
Increase ~%

Average Vertical emittance
BGC: **Relative** measurements (currently)



E_ob * c_fac =

c_fac = E_ob/E_exp at 6.8TeV

c_fac2 = sqrt(E_obˆ2 - E_expˆ2)

$$\widetilde{f_y} = \int_{-d/2} \rho(\xi) \cdot f_y(\xi \cdot 2/\sqrt{2-y}) d\xi$$

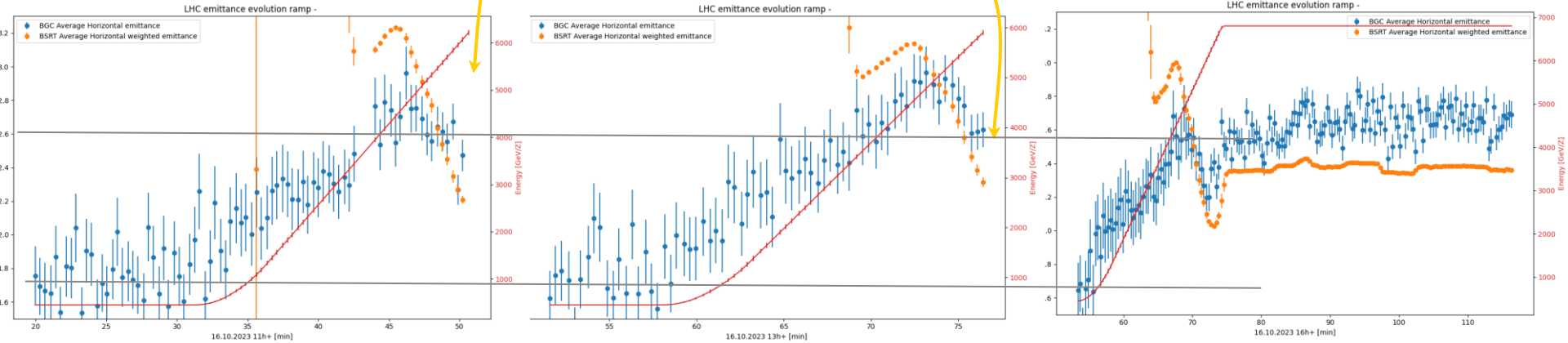
c_fac2 = sqrt(E_obˆ2 - E_expˆ2)

16.10.2023 – Dumps during ramp

Parameters	Pb
Beam Energy [GeV/Z]	450
Beam intensity [e]	1.40e13
Gas jet	Ne
Integration time [s]	30
Measurement method	Average

2 dumps during ramp

3rd fill – fine



Higher emittance

1st & 2nd: 1080b
3rd: 960b
Different fill with 1080b for emittance comp?

16.10.2023 – Dumps during ramp

Parameters	Pb
Beam Energy [GeV/Z]	450
Beam intensity [e]	1.40e13
Gas jet	Ne
Integration time [s]	30
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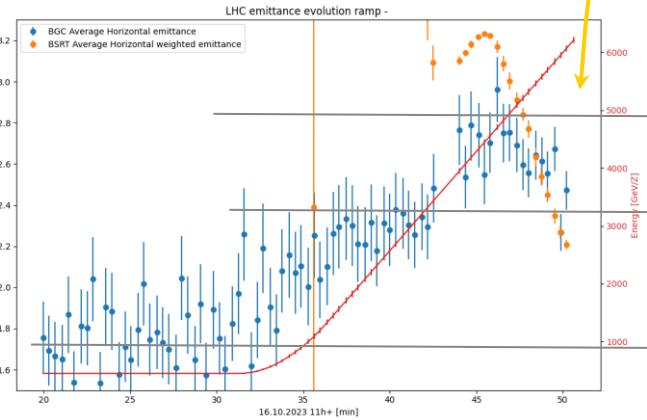
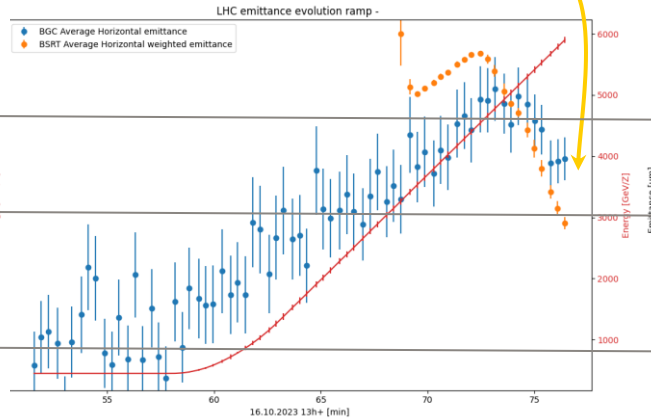
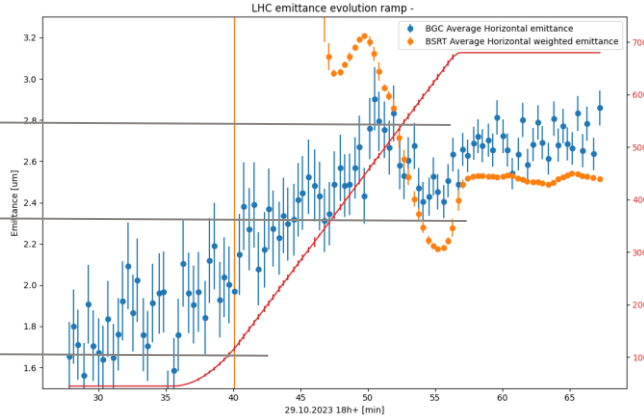


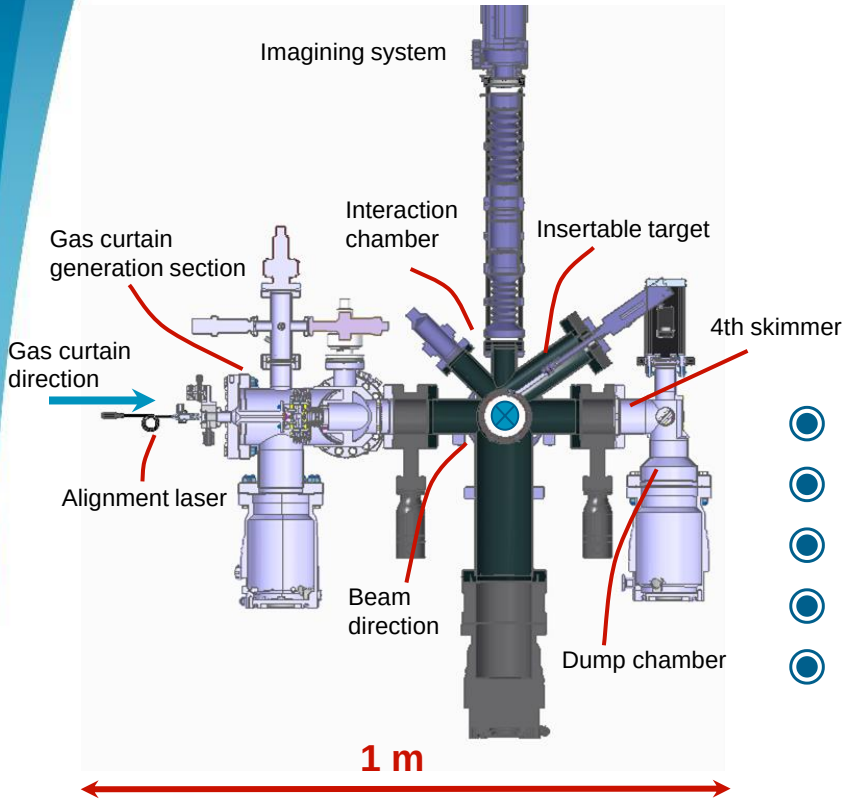


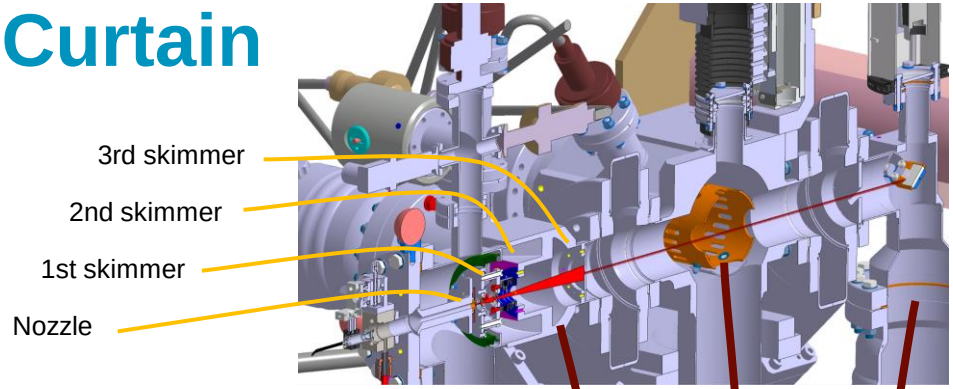


Higher emittance

1st & 2nd: 1080b
3rd: 960b
Different fill with 1080b for emittance comp?

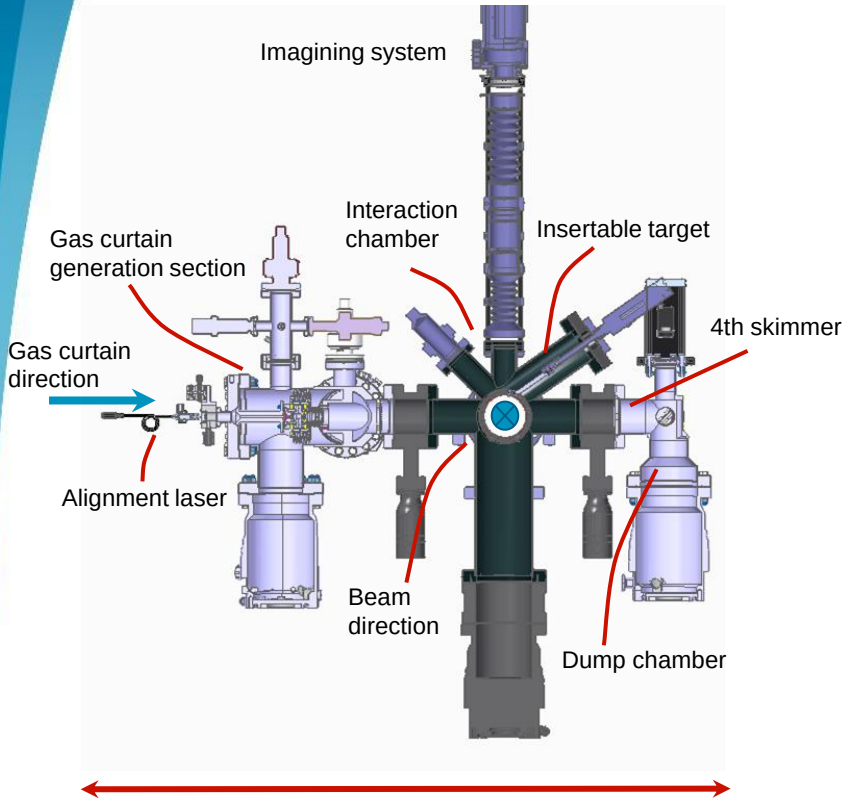
Gas Curtain

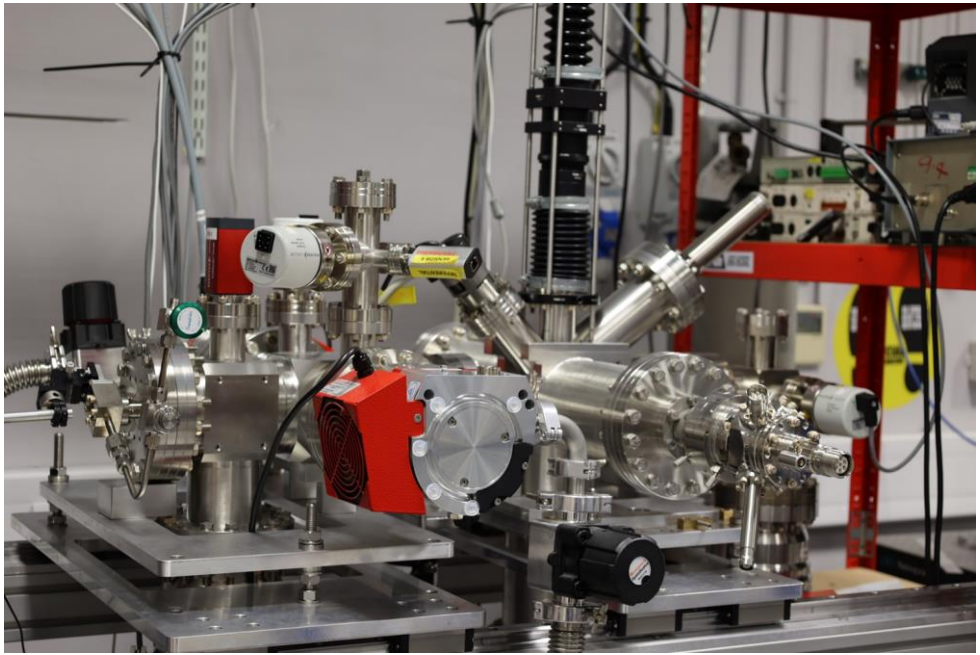




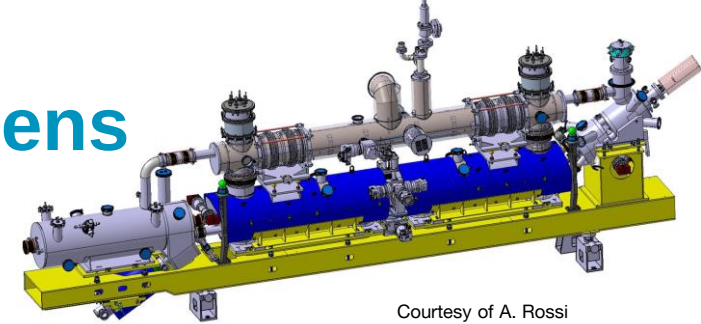
- Gas curtain formed by skimmers
- Passing through beam
- Fluorescence photons
- Pumped out in dump chamber
- Keeping low background pressure

Beam gas curtain monitor at Cockcroft Institute





Hollow Electron Lens

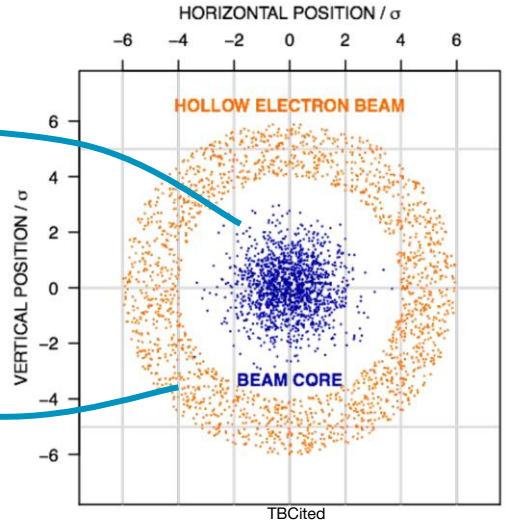


Courtesy of A. Rossi

- Proposed new stage of LHC collimation system
- 10 keV, 5 A hollow electron beam

LHC Beam core - experiences no field

Beam Halo - experiences nonlinear transverse kicks



Working conditions

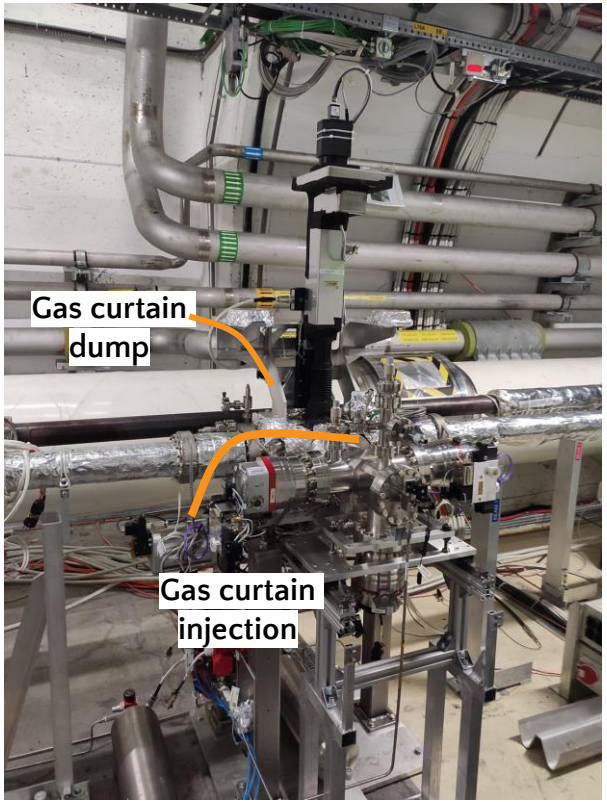
Show the losses at FT Ions and protons

Injection -> below noise on Fixed display

Interaction chamber	Pressure [mbar]
Gas Jet OFF	2.0e-10
Gas Jet On	4.00e-8
Gas jet pressure eq.	≈3.30e-6

- Validated for standard LHC proton and Ion beam

2023



Working gases

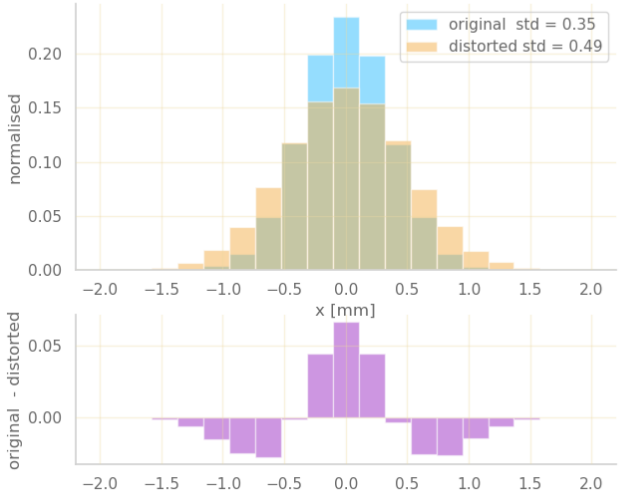
- Neon
  - Same shape as N_2
  - Neutral transition at 585.4 nm
  - Lifetime appr. 16 ns
  - Not affected by beam space-charge

$$Ne + p/e^- \longrightarrow Ne^\star + p/e^- \longrightarrow Ne + \gamma + p/e^-$$

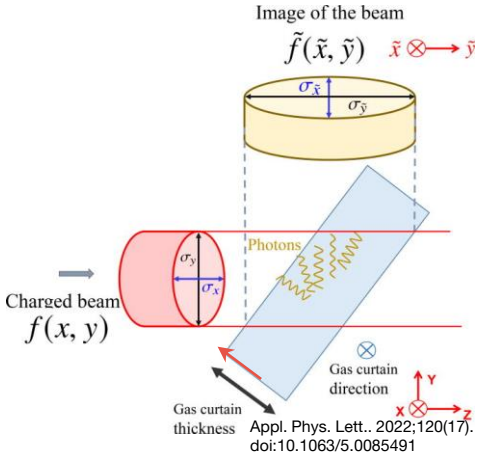
$$N_2 + p/e^- \longrightarrow \left(N_2^+\right)^\star + e^- + p/e^- \longrightarrow N_2^+ + \gamma + e^- + p/e^-$$

- Nitrogen
  - Light-yield N_2/Ne = 15(1)
  - Charged transition at 339.4 nm
  - Lifetime appr. 60 ns
  - Affected by beam space-charge

LHC bunch
Space-charge effect
N_2 curtain



Thickness broadening



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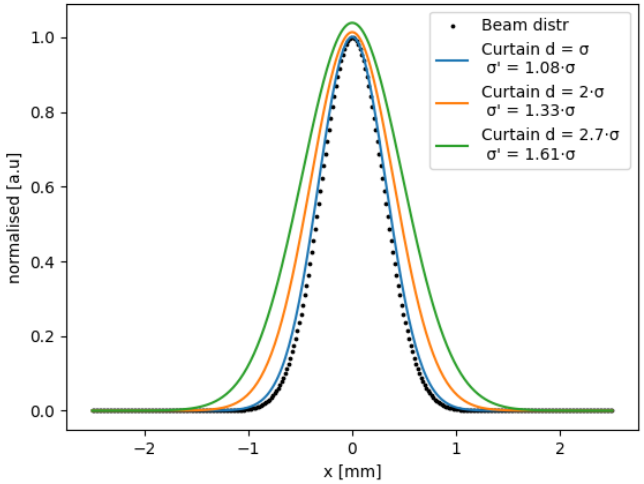
$$\widetilde{f_x} = f_x$$

$$\widetilde{f_y} = \int_{-d/2}^{d/2} \rho(\xi) \cdot f_y\left(\xi \cdot 2/\sqrt{2} - y\right) d\xi$$

- Signal vs Broadening tradeoff
- d = 830(20) μm

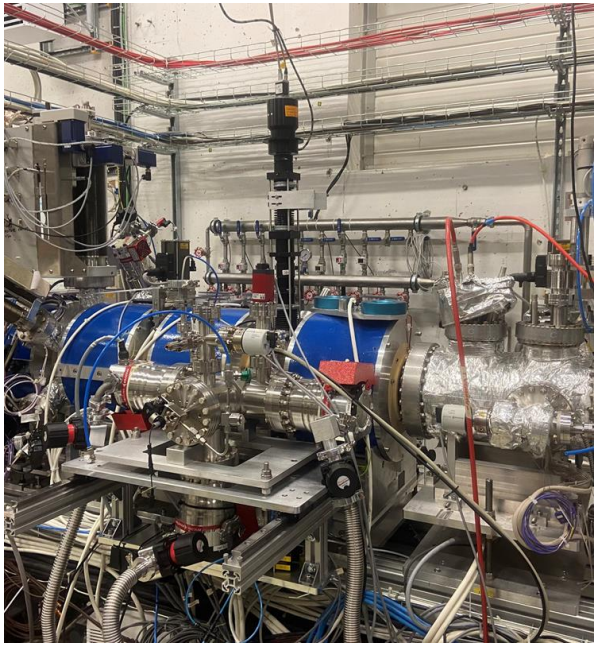
Uniform gas curtain
Gaussian beam



Electron Beam Test Stand (EBTS)

- Development of Hollow electron beam
- Typically: 7 keV, 1.1 A, 25 μs pulse, 10 Hz repetition rate

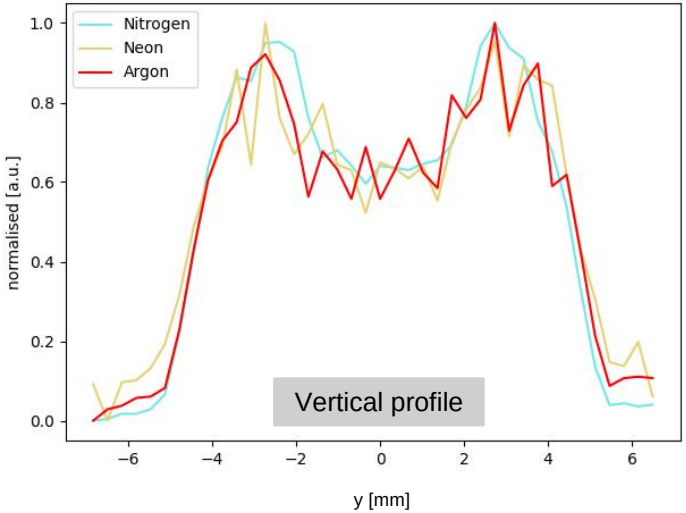
Interaction chamber	Pressure [mbar]
Gas Jet OFF	4.71e-8
0.7 x 9 mm 3rd skimmer	2.04e-7
0.3 x 9 mm 3rd skimmer	8.63e-8

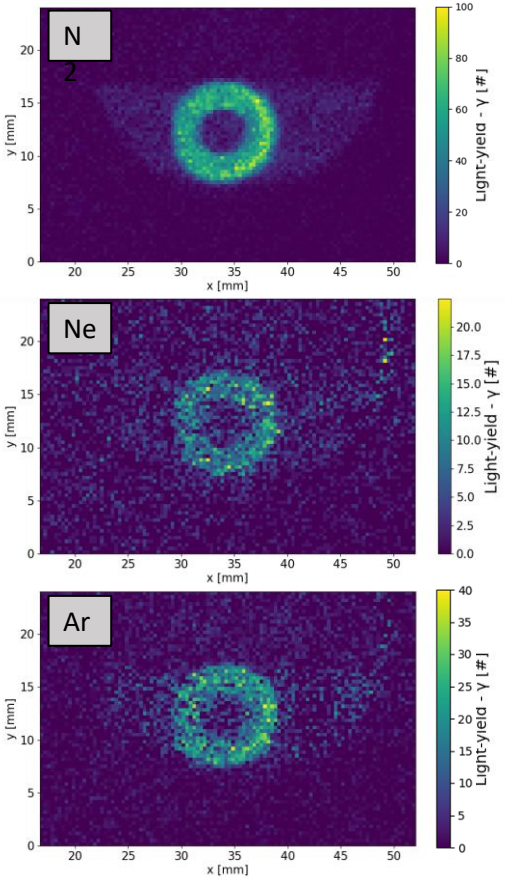


EBTS: Gas variation

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

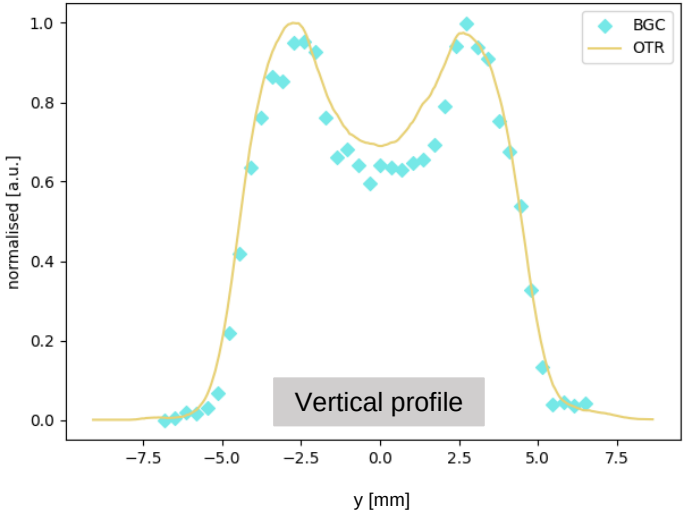
- Distribution shape - Constant
- Centre of Mass - Constant
- N_2 - Best resolution



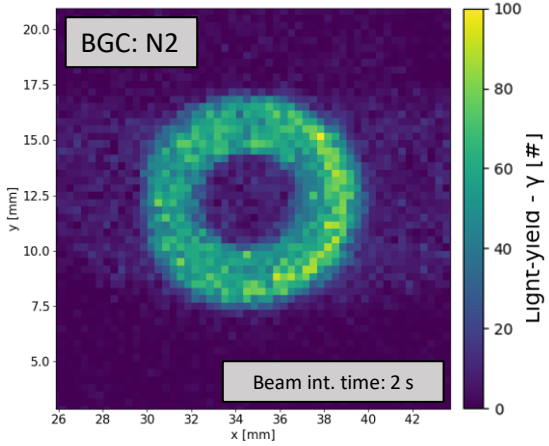


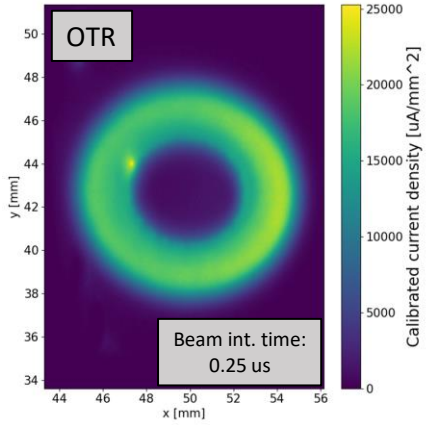
EBTS: OTR comparison

- Distribution shape - Compares
- Outer radii - Agree within 1%
- Inner radii - Agree within 5-10%



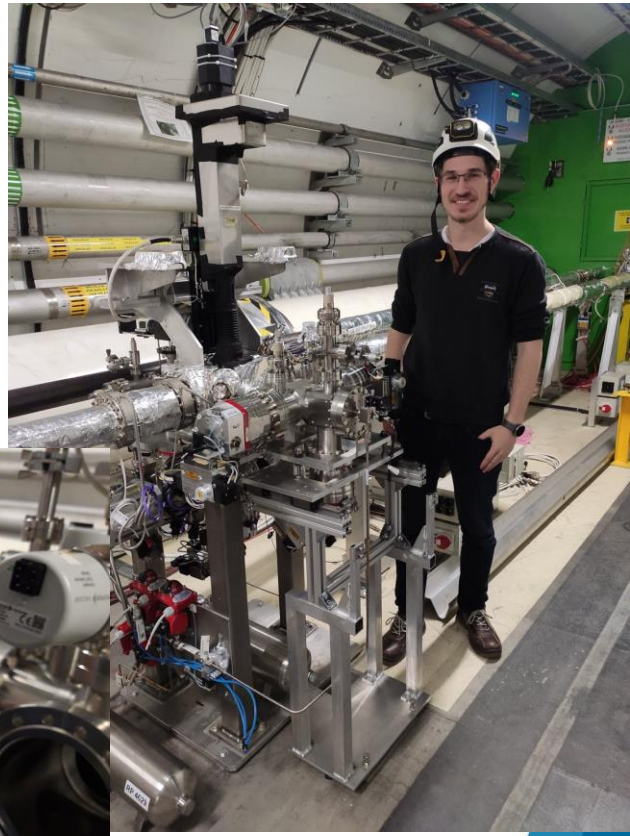
7 keV, 1.1 A

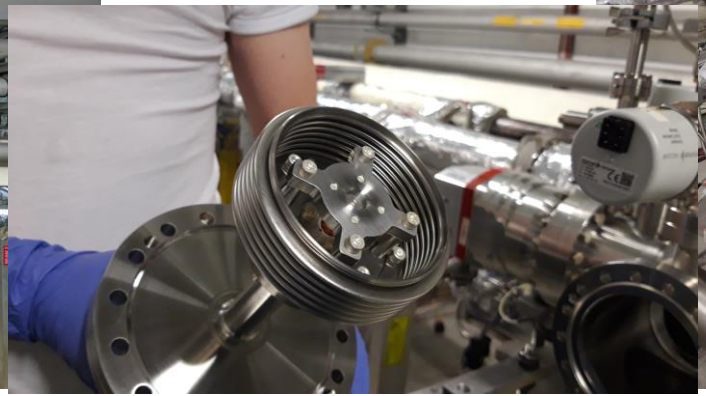




Gas jet installation at LHC

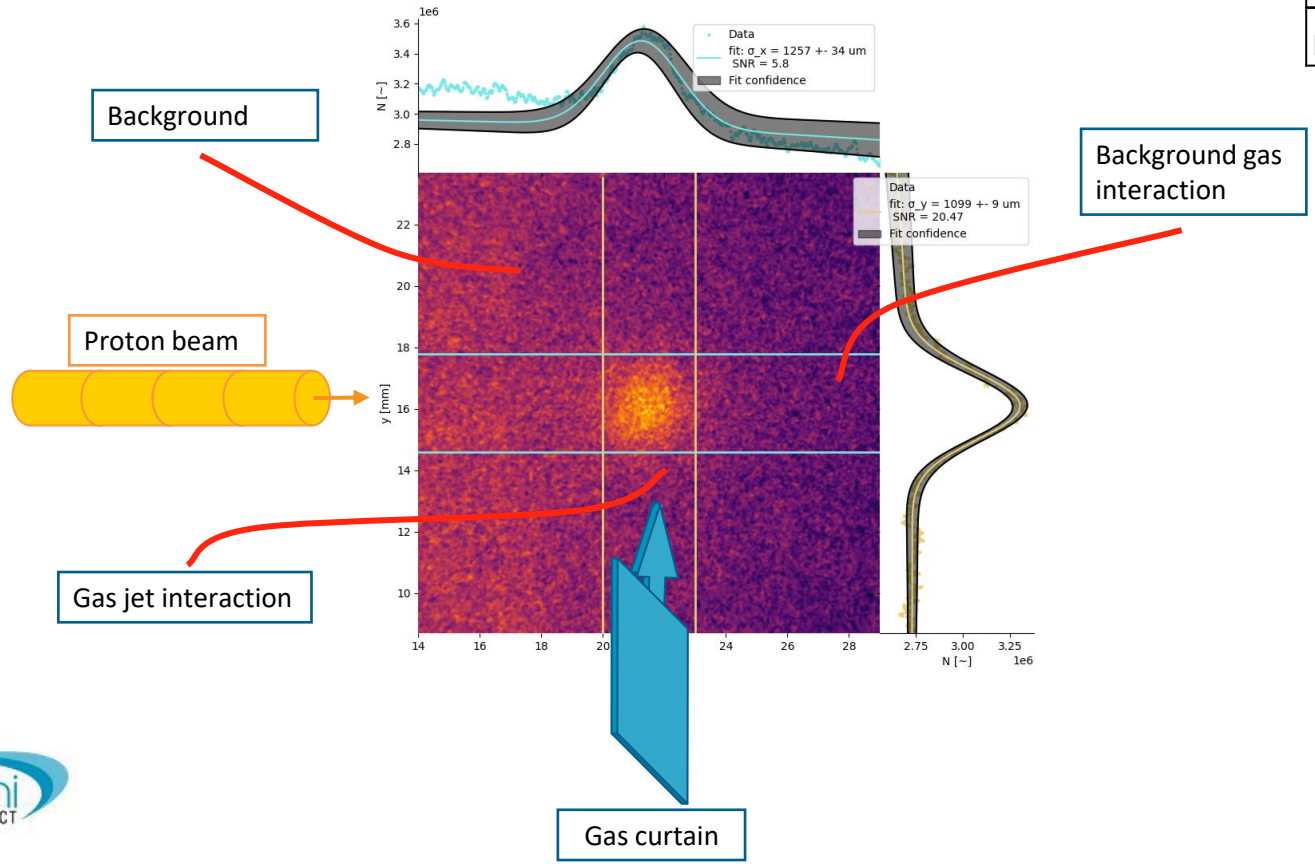
- Gas jet monitor successfully installed at LHC in January of 2023!!
- Huge effort and success for the whole collaboration





First Gas Jet fluorescence measurements at LHC at 450 GeV

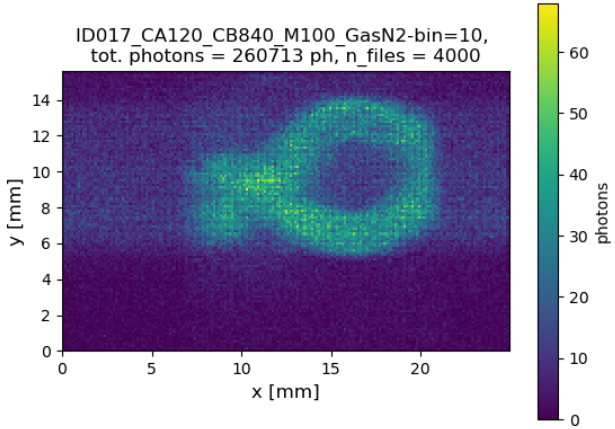
Parameters	
Beam Energy [GeV]	450
Beam intensity [p]	3.7e14
Gas jet	Ne
Integration time [s]	1659



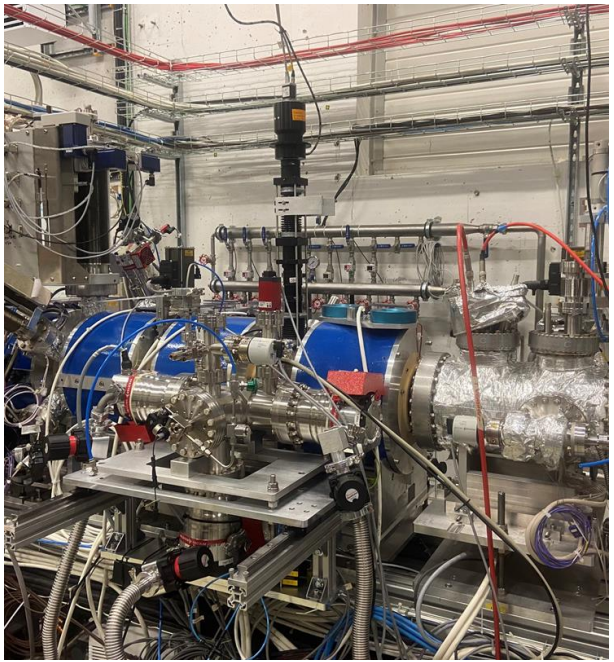
Summary

- Beam Gas Curtain monitor, a 2D profile monitor utilizing fluorescence of supersonic gas jet
- Gas curtain density profile shown good transverse uniformity for Neon and Nitrogen gas
- Varying 3rd skimmer lowers background and resolution significantly
- BGC monitor measured a hollow electron beam on Electron Beam Test Stand
  - Beam profile and centroid using N2, Ne, and Ar gas curtain in agreement
- BGC monitor measured installed and validated at LHC
  - First gas jet measurements of 6.8 TeV proton beam!
  - Further studies will be published in journal paper

EBTS: Fishtail



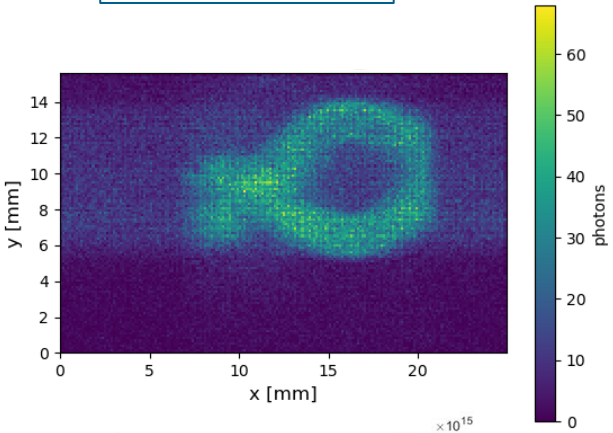
Backscattered photons from the collector
Only thanks to

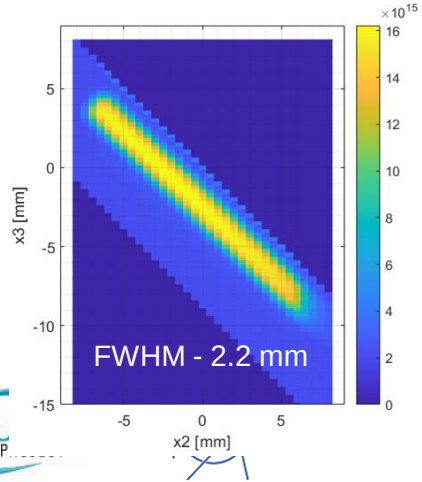


Skimmer: 0.3x9 mm
Beam: 1.5 A
Gas Jet: N2
Beam int. time: 2 s
B: Gun:181 mT Rest:82 mT

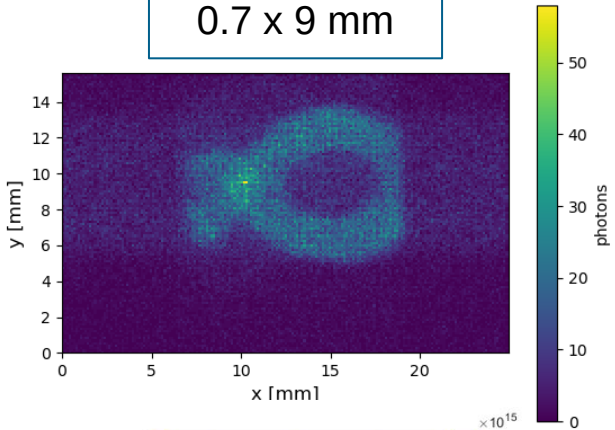
EBTS: Varied 3rd skimmers

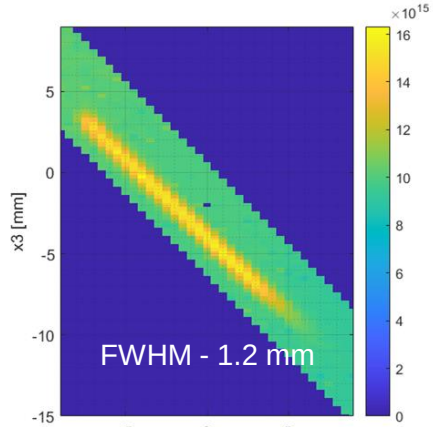
3rd skimmer - 0.3 x 9 mm





3rd skimmer - 0.7 x 9 mm





N_2 Gas curtain measurements at 5 bar

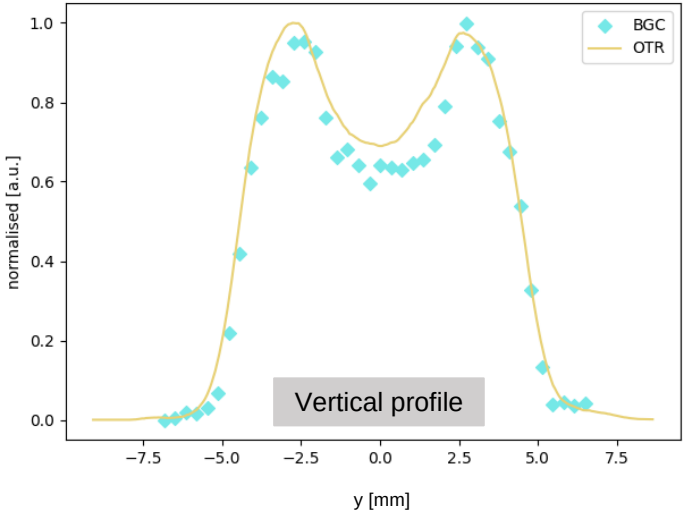
0.3x9 mm vs 0.7x9 mm:
- Signal ~2x
- Shape - same
- 12 mm vs 14 mm

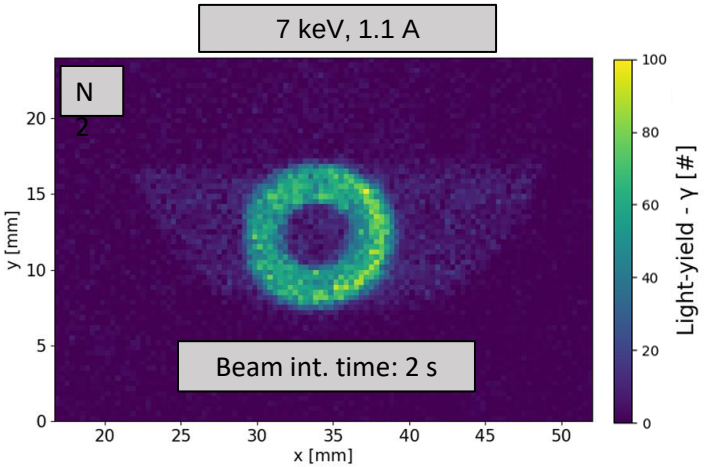
Pressures:

Skimmer: 0.3x9 mm
Beam: 1.5 A
Gas Jet: N2
Beam int. time: 2 s
B: Gun:181 mT Rest:82 mT

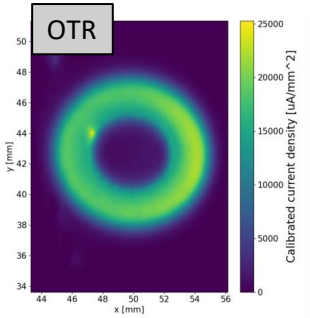
EBTS: OTR comparison

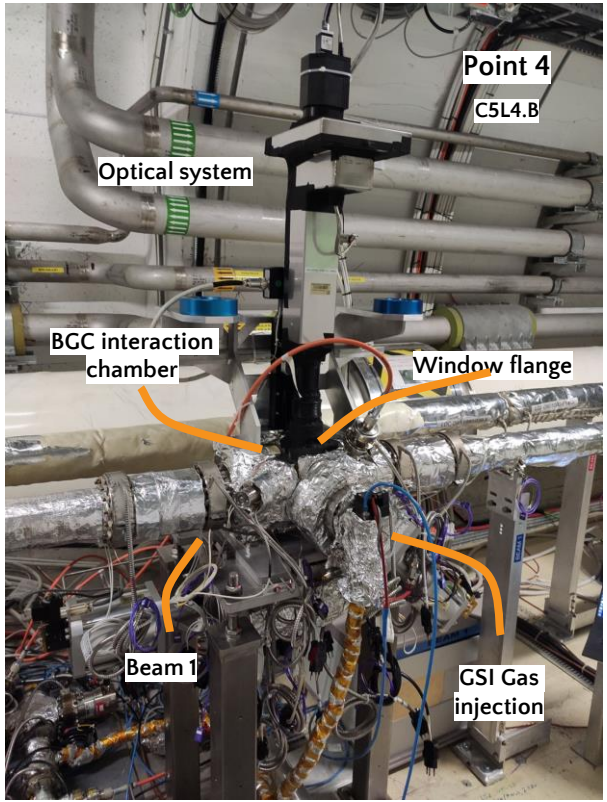
- Distribution shape - Agrees



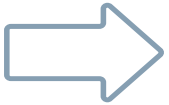


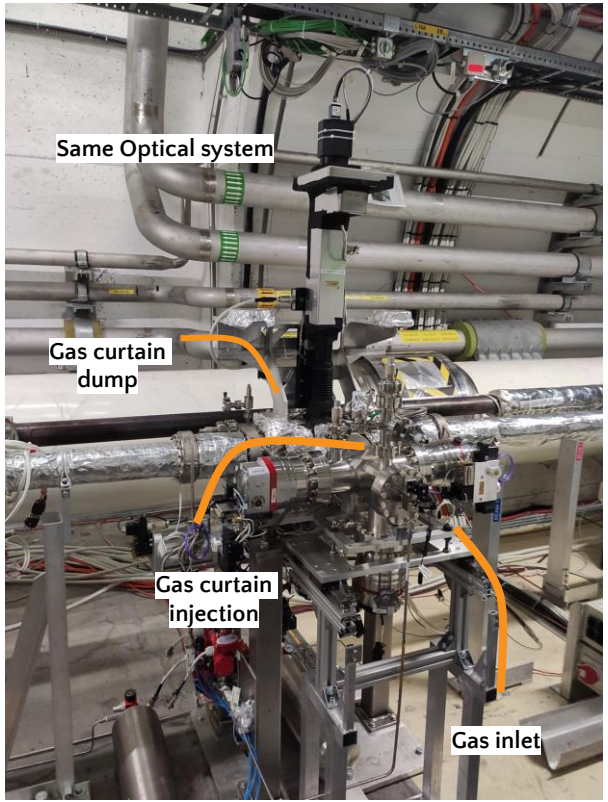
Beam int. time: 0.25 us




Point 4
C5L4.B
Optical system
BGC interaction chamber
Window flange
Beam 1
GSI Gas injection

a)




Same Optical system
Gas curtain dump
Gas curtain injection
Gas inlet

b)

Transport of BGC Version 3 to CERN 17th May 2022