CERN

Gas Jet Diagnostics for HL-LHC

S. Mazzoni with contributions from the BGC team

LHC Beam Size Measurement Review meeting,

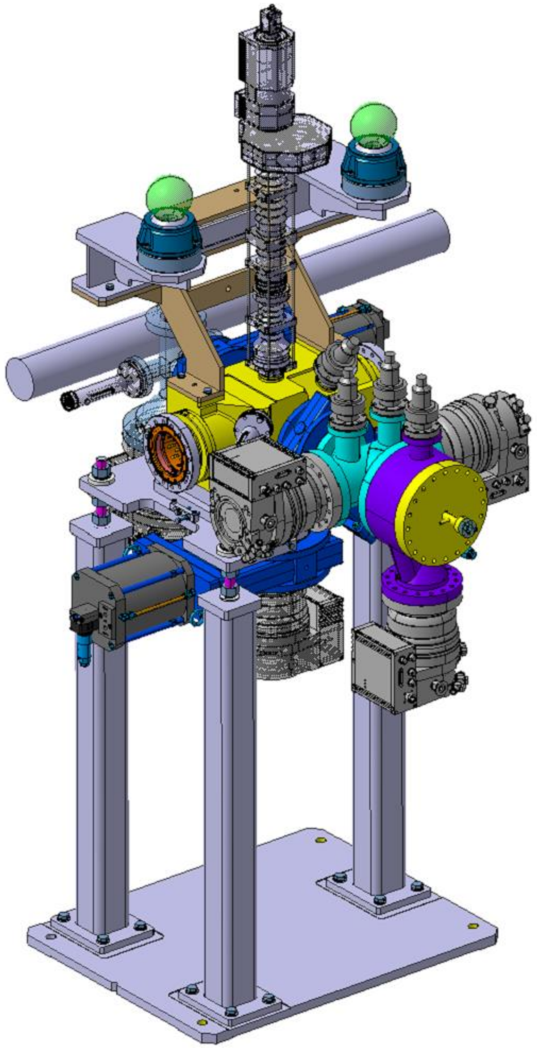
1-2 October 2019

Outline

- Beam Gas Curtain project
- Summary of 2018 LHC measurements
  - Results for Pb+ ions at injection
  - Data for protons at injection
- Potential utilization as beam profile measurement technique

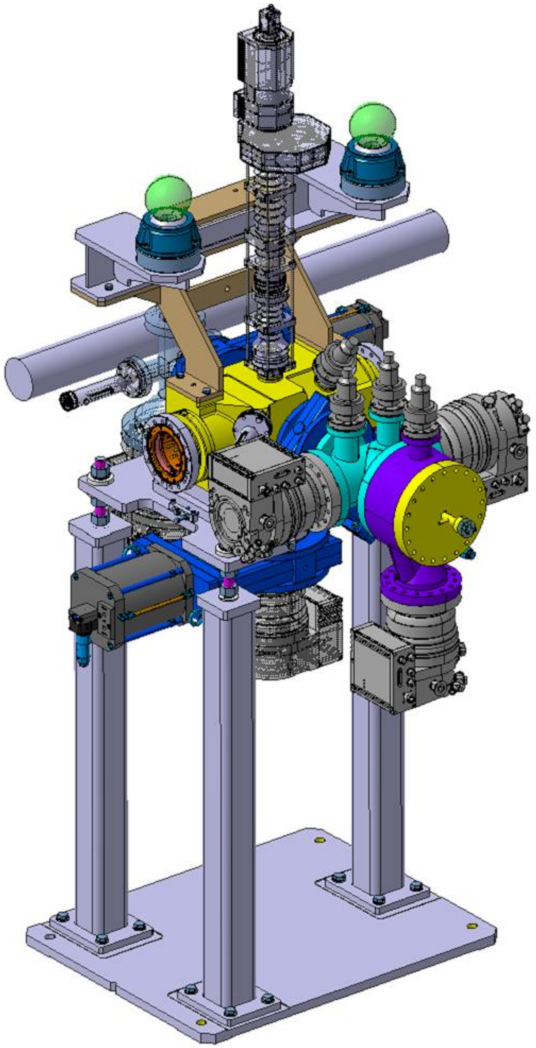
The Beam Gas Curtain in HL-LHC

- BGC: baseline instrument for on-line monitoring of the overlap between proton and electron beams in the hollow e-lens
- BGC is principally funded by HL-LHC in collaboration with Cockcroft Institute and GSI experts
- Prototypes extensively tested with electron gun sources at Cockroft. LHC tests for:
  - Operating scenarios in the LHC synchrotron light background
  - Hadron shower noise background
  - Operations with VSC in the baked LHC vacuum environment



The Beam Gas Curtain in HL-LHC

- If this instrument is to be operational post-LS3, then some preliminary steps need to be taken in LS2 to allow for prototype testing during Run 3
  - This instrument includes a new vacuum sector and significant cabling, long shutdown needed
- BGC prototype installation for HL-LHC is now a stand-alone task (13.2) in HL-LHC WP13
  - The instrument is a deliverable from the Cockcroft Institute



BIF/BGC in the LHC

- **2018:** BIF tests in LHC using Neon with ex BGI injection system (-> no gas jet/curtain)
- **Feb-May 2020**: LHC Vacuum chamber with all-metal gate valves – no injection. Under manufacture
- **Before end LS2**: LHC Vacuum chamber with undirected gas injection to a pressure below $1x10^{-7}$ mbar (recycle LHC BGI/fluorescence test injection, same as BGV), ECR under preparation
- **20XX**: Fully operating BGC. To be developed: Vacuum controls system, full test to prove LHC beam vacuum compatibility.

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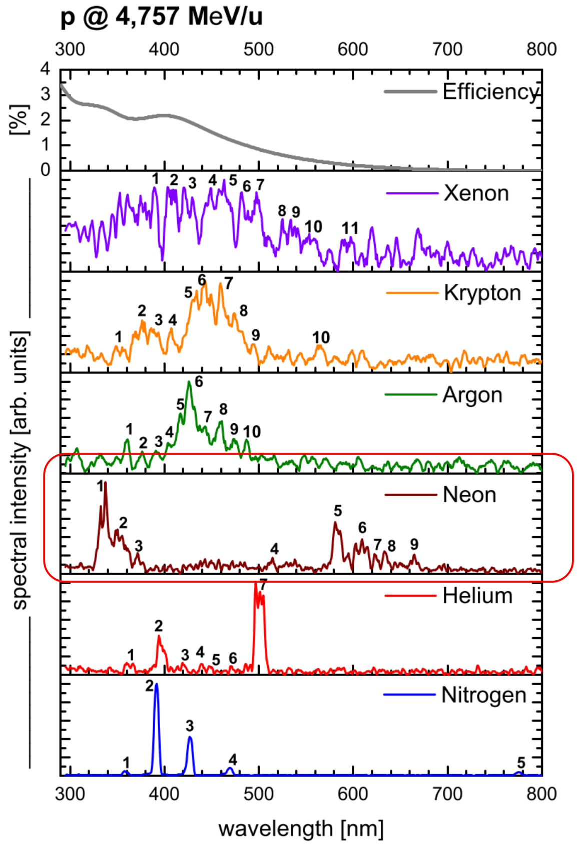
Fluorescence data (Ne)

- Data for Ne is scarce. Emission occurs between 300-400 nm (Ne^+) and 580-700 nm (neutral).
- Strongest (neutral) line 585.4 nm. Fluorescence by direct excitation (negligible cascading, no optical excitation), cross section based on $2p_1$ level excitation (Bretagne et al, J. Phys. D 1986, Puech & Mizzi, J. Phys. D 1991).
- Short life time: approx. 10 ns
- Data for electron impact up to 1 keV & protons up to 1 MeV. Extrapolated for 7 TeV protons



F. Becker (GSI), PhD thesis

$$N_{ph} = N_p \sigma \rho_{Ne} \frac{\Omega}{4\pi} = 0.2 \text{ ph/bunch s cm}$$

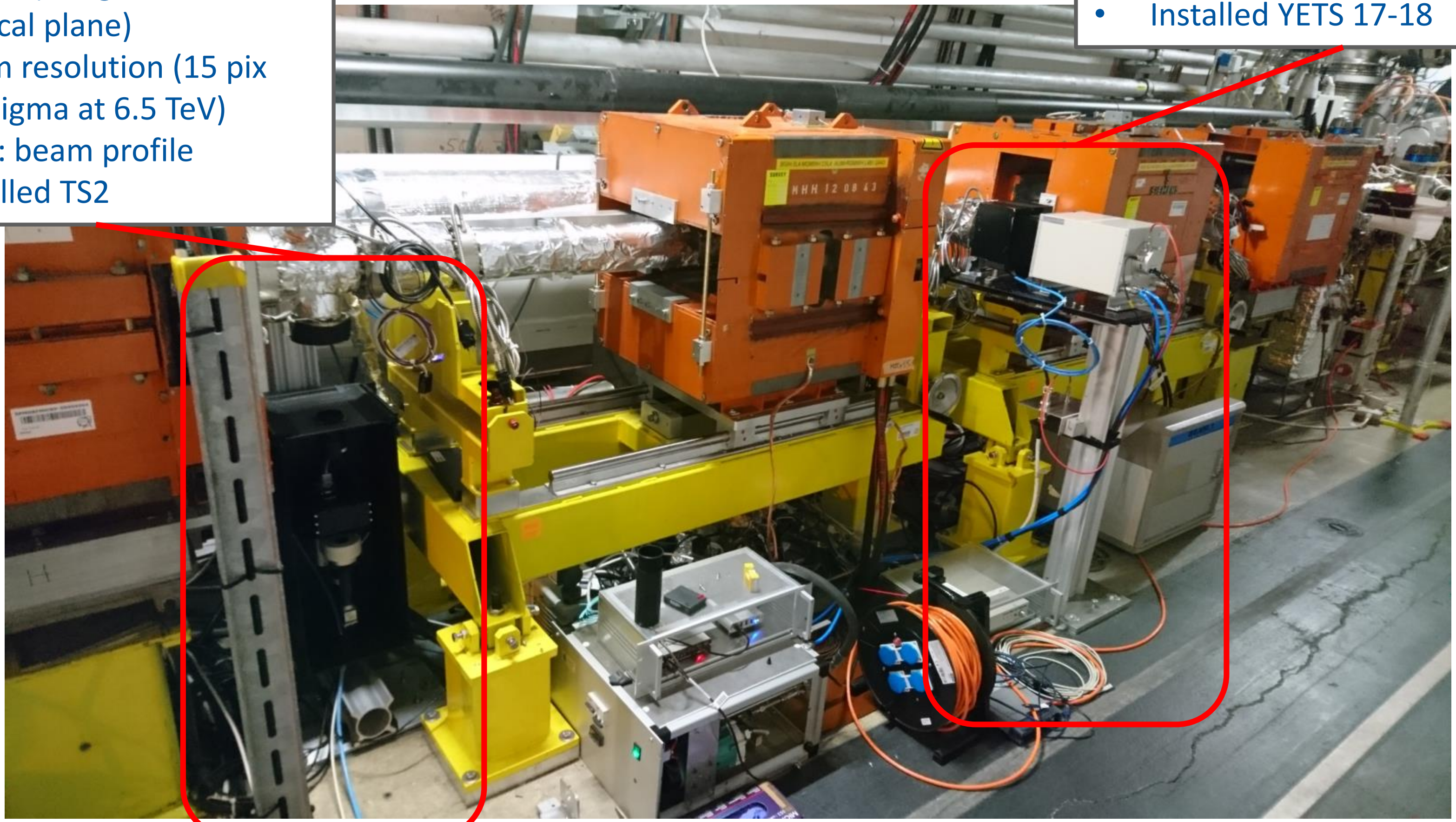
Low light yield!

N_{ph}	photons per unit length & time
N_p	10^{11} x 11400 (1 s int time)
σ	**4.7 x 10^{-22} cm^2**
ρ_{Ne}	7.8 x 10^8 cm^{-3} @ 3x10^{-8} mbar
Ω	7 x 10^{-3} Sr (camera)

LHC BIF test

- Intensified camera
- Image of horizontal beam profile (integrated over vertical plane)
- 20um resolution (15 pix per sigma at 6.5 TeV)
- Goal: beam profile
- Installed TS2

- MCP-PMT photon counting
- Time resolved measurement, 50 ps resolution over full LHC turn
- Goal: measurement of cross section and (exponential) time constant of fluorescence
- Installed YETS 17-18



LHC BIF tests

Date	Fill #	#b	Device	Int. time [s]	comments
25/4	6612	603	PMT	?	First injection. Test
7/5	6650	2556	PMT	?	Again system test
16-17/5	6693	1887	PMT	360	6.5 TeV data plus BG data (no gas, block filter)
27/6	6854	1227	Camera	2.7	First test with camera. GaAsP photocathode.
6/7	6891	1452	Camera	3	6.5 TeV, BG data (no gas)
10/7	6909	2556	Camera	9 (585nm), 3 (340 nm)	6.5 TeV data, 585 and 340 nm.
27/9			Camera	-	System test after TS2. New camera (multialkali photocathode), translation stage
28/9	7232	2556	Camera	133 (585 nm), 200 (BB)	450 GeV data
17/10	7310	2556	Camera	420 (585 nm)	450 GeV data. Also 6.5 TeV data with 340 nm filter (800 s int time)
18/10	7315	2556	Camera	600	450 GeV data, 585 nm filter
19/10	7319	2566	Camera	-	Gas pressure increased to 4×10^{-7} mbar, beam dump
16/11	7448	648	Camera	5	Ion run. 6.3 TeV data, 585 nm filter. BG data (no gas)
20/11	7457	648	Camera	38	Ion run. 6.3 TeV data, 585 nm filter
26/11			Camera		
28/11			Camera		
1/12			Camera		Ion run. Injection energy

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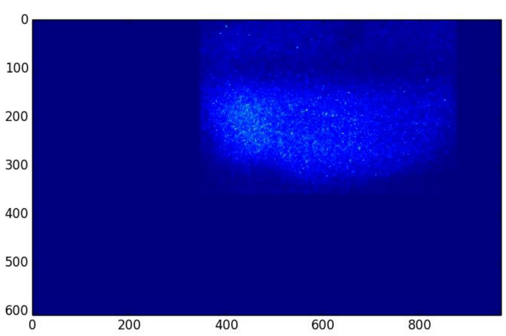
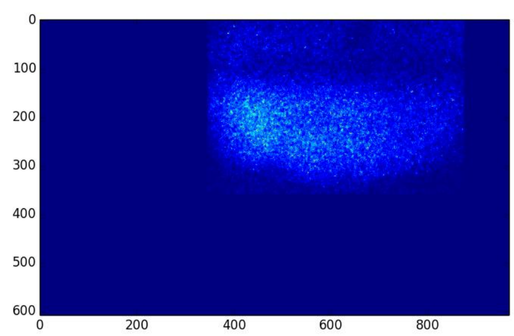
1/12			Camera		Ion run. Injection energy

Data from Pb+ at injection

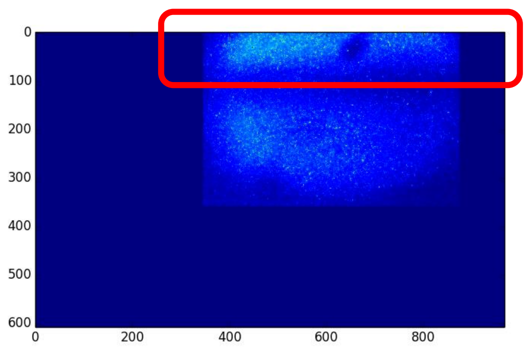
- Fill 7481, 28/11/2018. Acquired data at injection:
  - with / without gas and block filter, beam on
  - with / without gas and 585 nm filter, beam on
- Fill 7487, 30/11/2018. Acquired data at injection:
  - With gas, no beam, 585 nm filter
  - With gas, with beam, 585 nm filter



585 nm, gas **ON**, beam **OFF**
“photon counting” over 577.6 s
(1440 frames, 400 ms exp time)



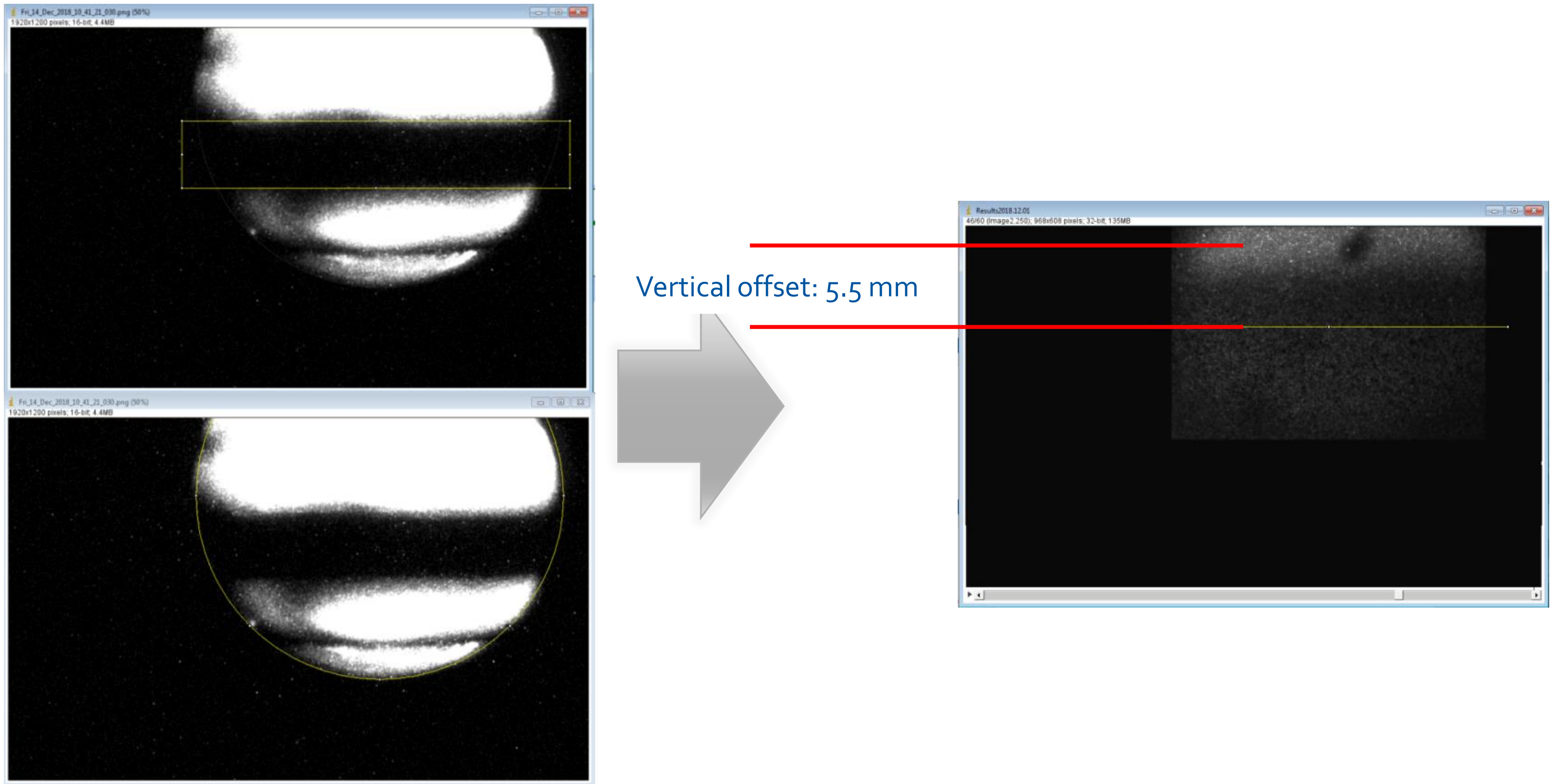
585 nm, gas **OFF**, beam **ON**
“photon counting” over 210.8 s
(527 frames, 400 ms exp time)



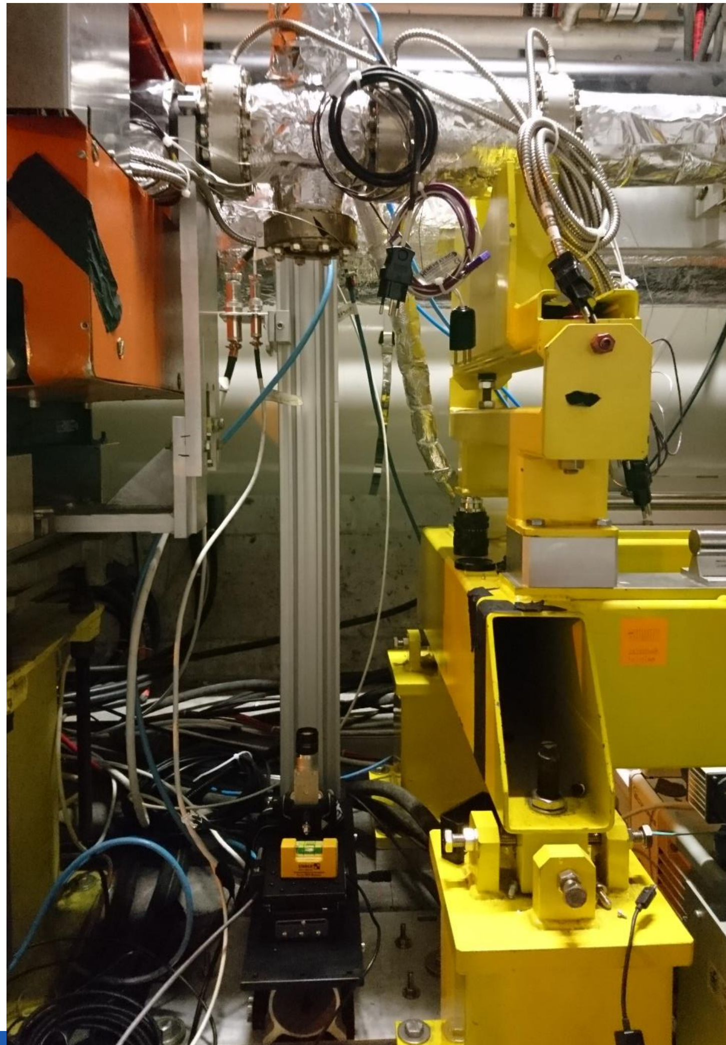
585 nm, gas ON, beam ON
“photon counting” over 1286.4 s
(3216 frames, 400 ms exp time)

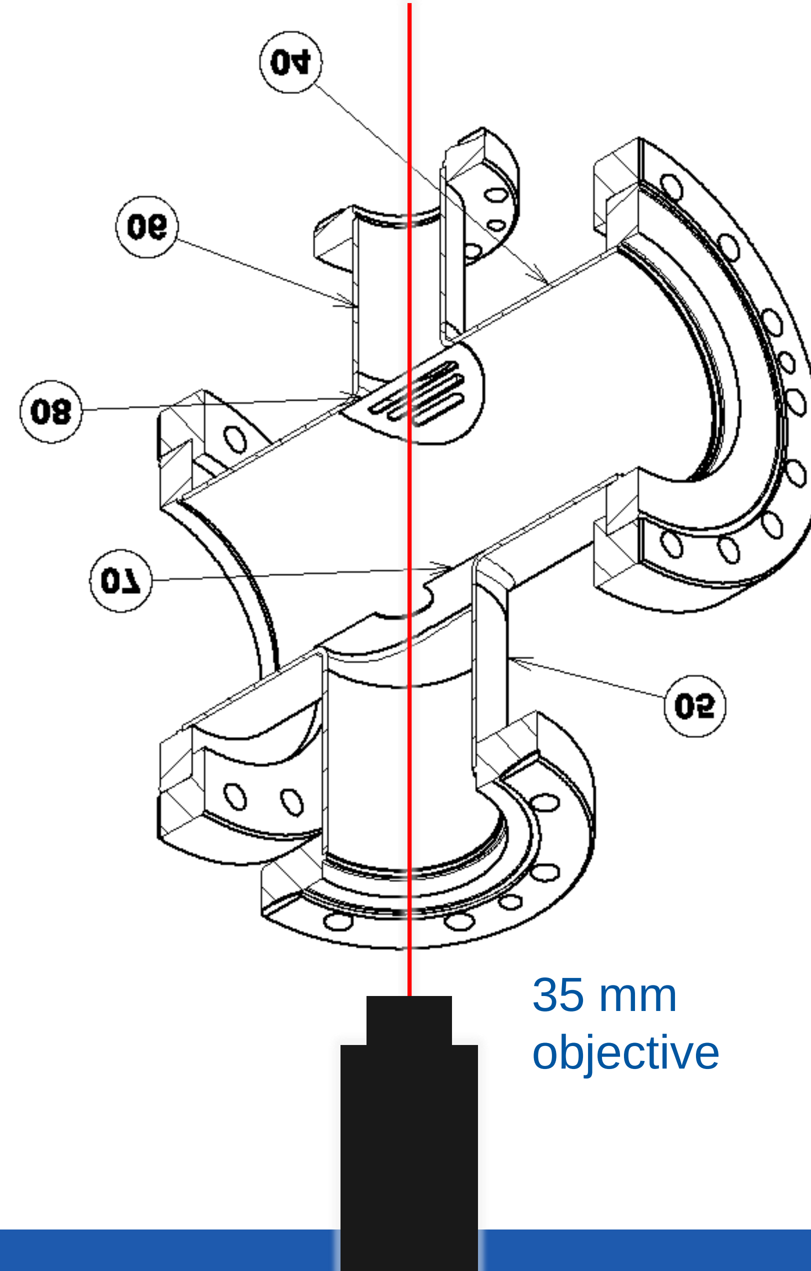
Position

Horizontal position off by 5.5 mm.

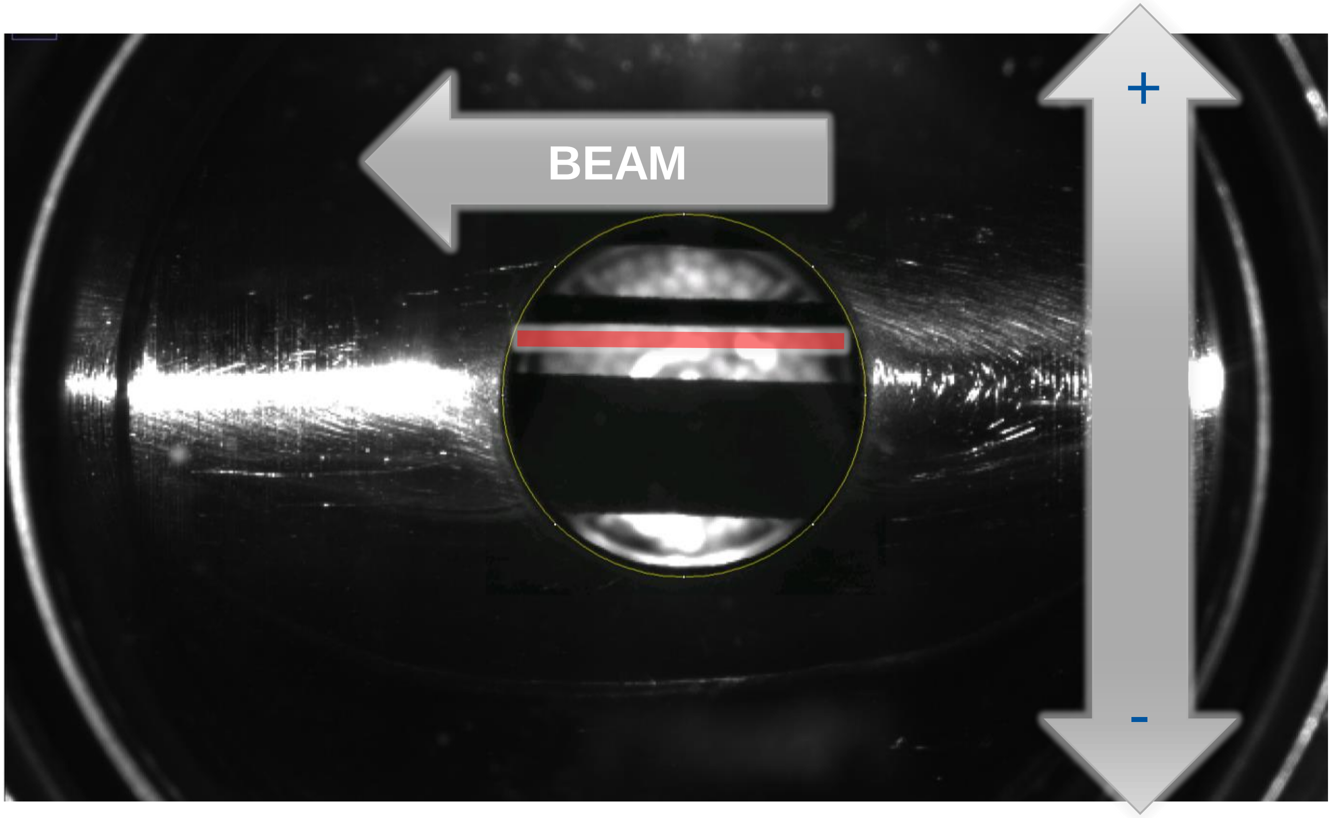


Position





Position



- When compared to the centre of the viewport and beam screen, the beam appears to be approx. + 1.5 mm off
- Closest BPM reads -0.5 mm

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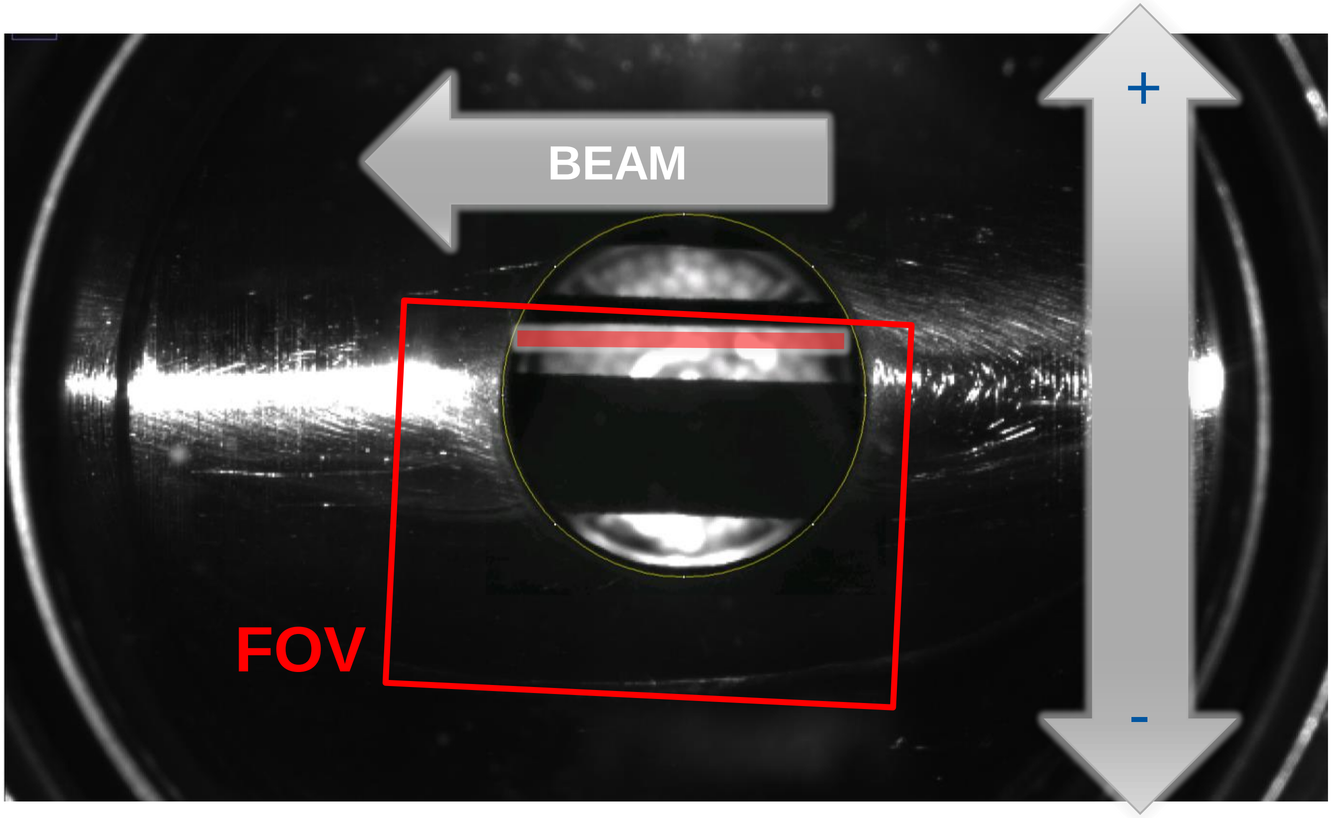

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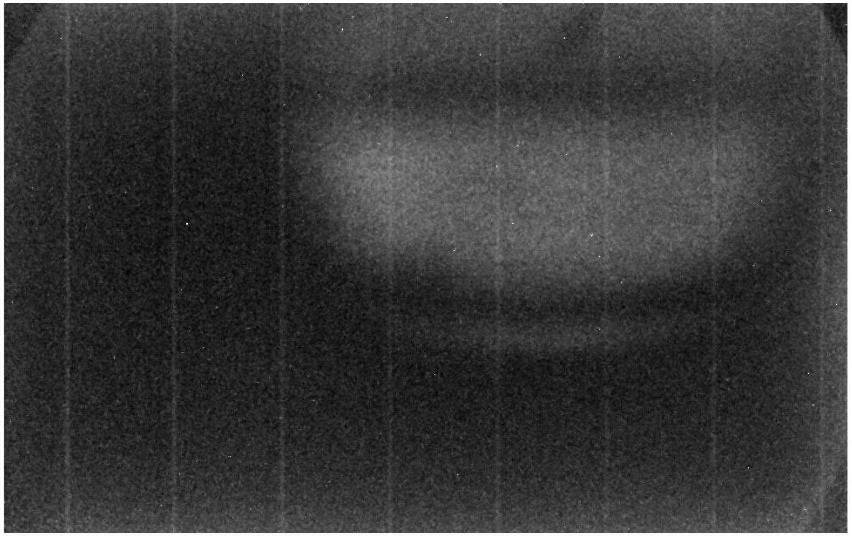
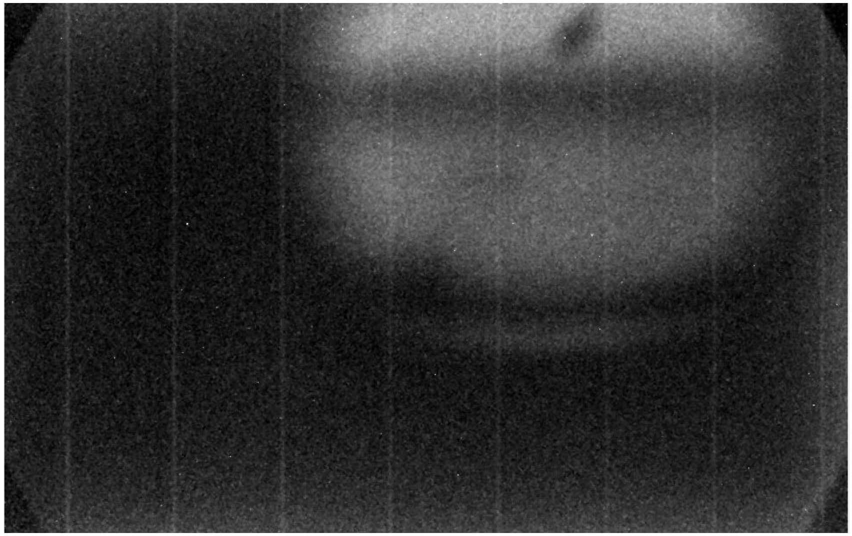
Profile from Ions



585 nm, gas **ON**, beam **OFF**
Integration over 577.6 s
(1440 frames, 400 ms exp time)



585 nm, gas ON, beam ON
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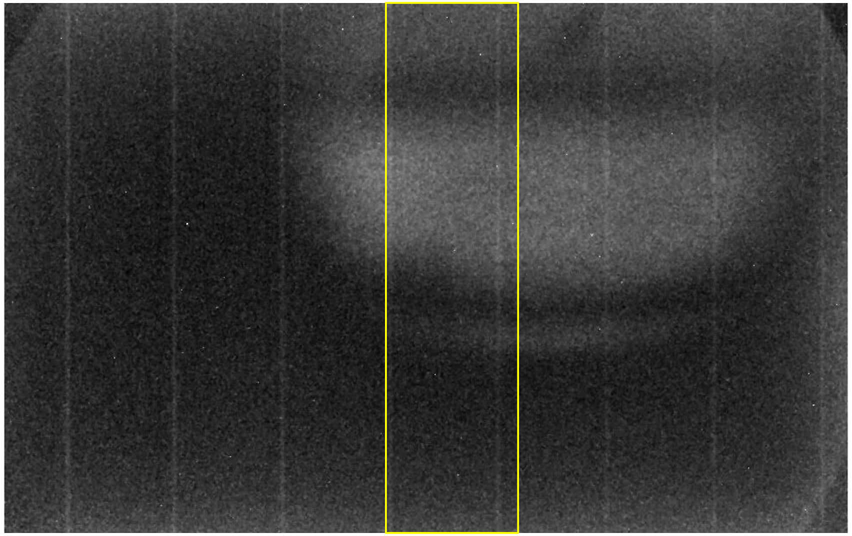
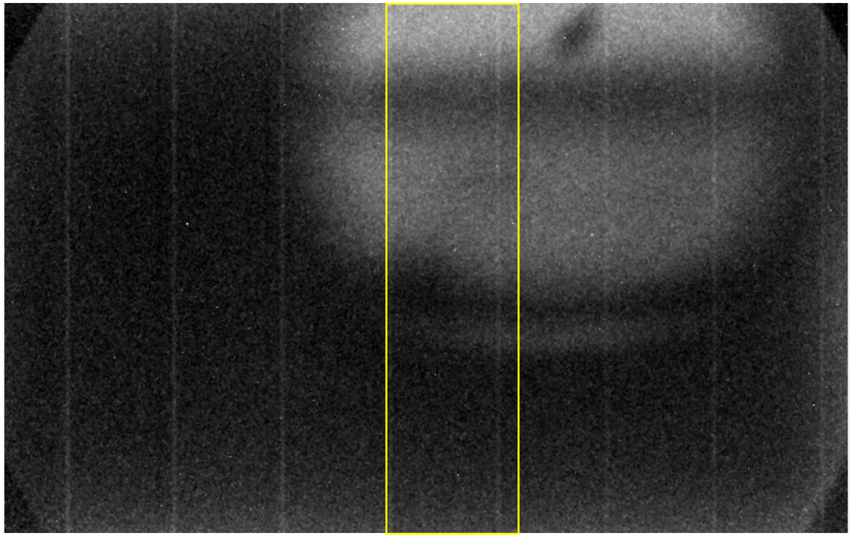


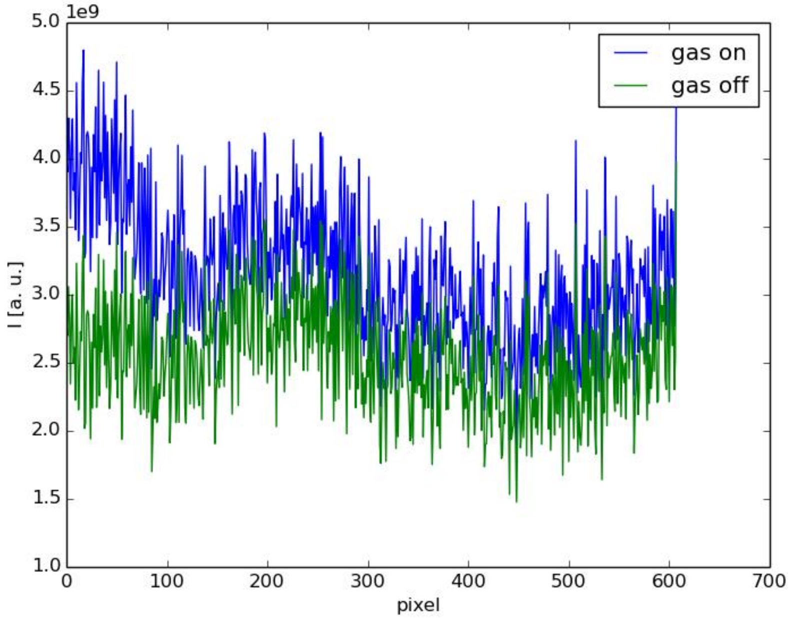
585 nm, gas **ON**, beam **OFF**
Integration over 577.6 s
(1440 frames, 400 ms exp time)

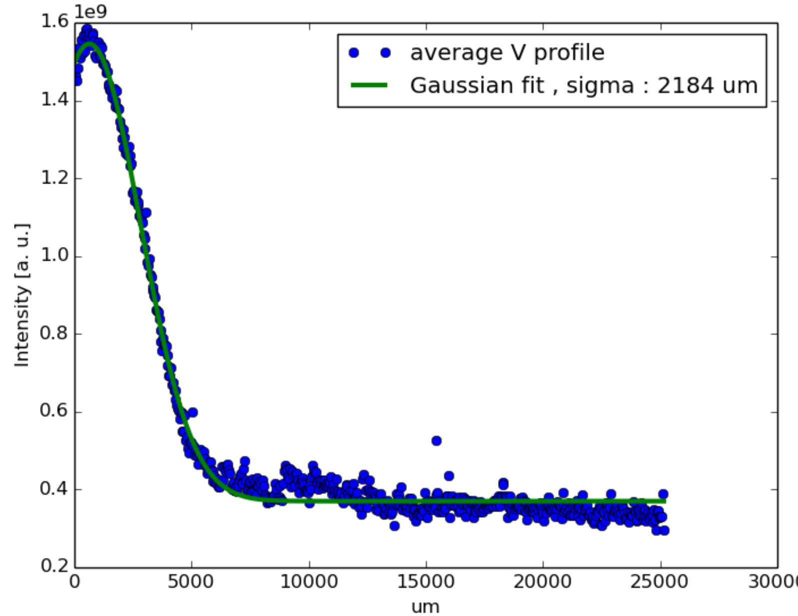


585 nm, gas ON, beam ON
Integration over 1286.4 s
(3216 frames, 400 ms exp time)

Compute vertical profile over ROI

Profile from Ions





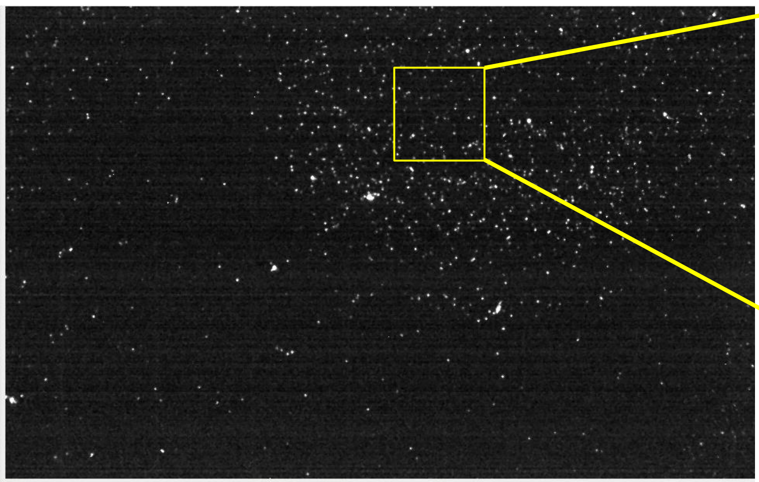
V Profiles from sum of

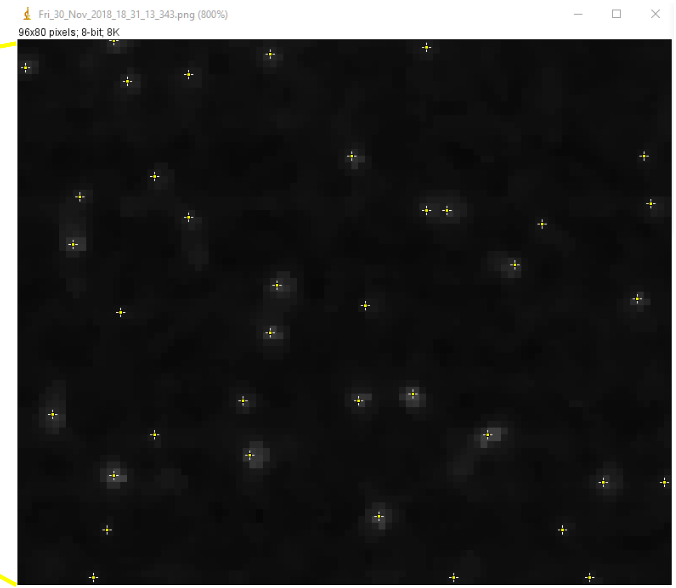
- 3215 images (gas on)=> 1285 s integration time
- 1443 images (gas off)=> 577 s i.t.

Difference corrected for different integration time, no other adjustable parameter.

Sigma 2.2 mm

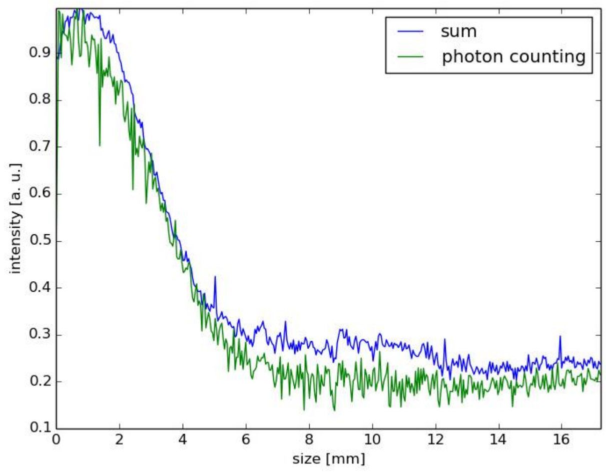
Photon counting

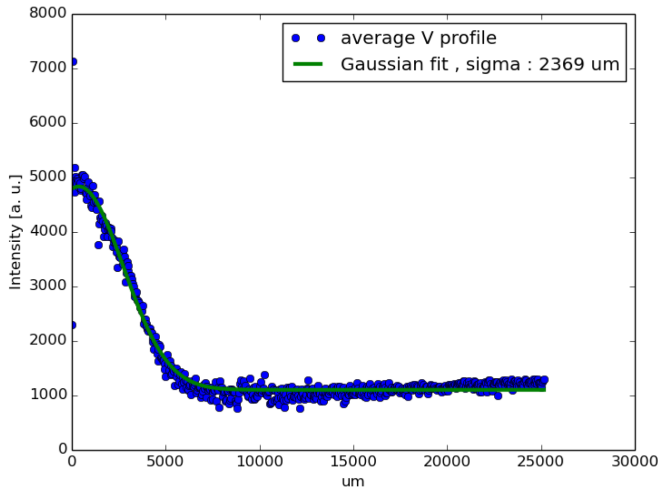




- Due to low light yield, counting individual photons is possible:
- CI algorithm
  1. apply median filter
  2. Run ‘Find maxima’ macro on ImageJ. Threshold adapted to image
- My algorithm:
  1. Create binary map based on upper and lower threshold (= pixel =1 if its value is inside lower-upper threshold, =0 otherwise)
  2. Apply scipy.ndimage.measurements routine to count objects
  3. Discard objects smaller than minimum size
- Both algorithms give comparable results, depend on (arbitrarily set) thresholds

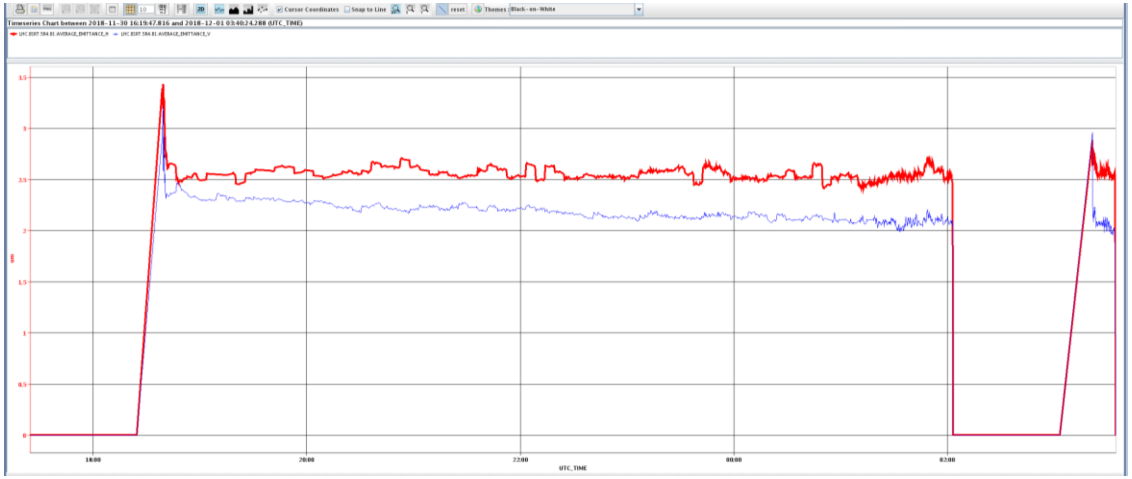
Profile from ions (photon counting)





- Discrepancies arise when calculating profiles using photon counting: 2.4 mm sigma (vs. 2.2 mm)
- Edge effects are observed when counting, however this does not explain discrepancy

Estimation of expected profile



- Fill 7487. No profile data available at injection energy. BSRT measures 2.5 um H emittance at flat top (red curve)
- **Upper limit** estimation for beam size at injection:

$$\sigma_{BIF\_INJ} \leq \sqrt{\frac{\beta\varepsilon^*}{\gamma_{INJ}}} \cong \mathbf{2.1\ mm}$$

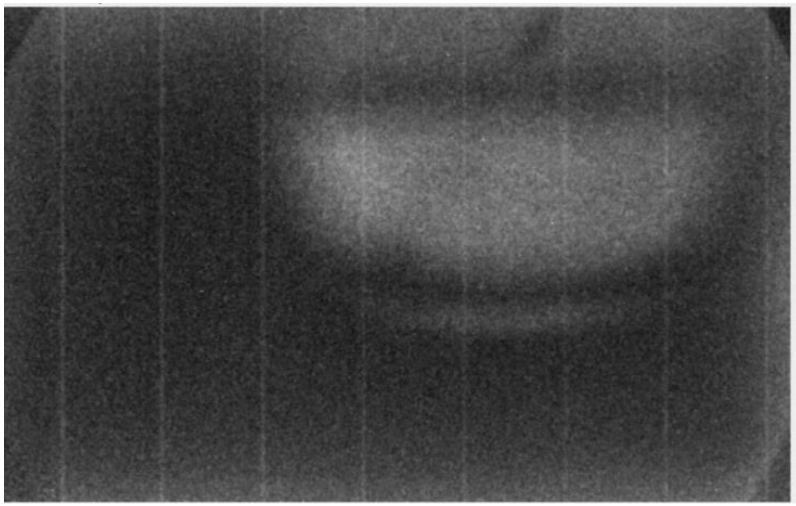
- Observed values (2.2-2.4 um) *compatible* with LHC beam

Photon Counting

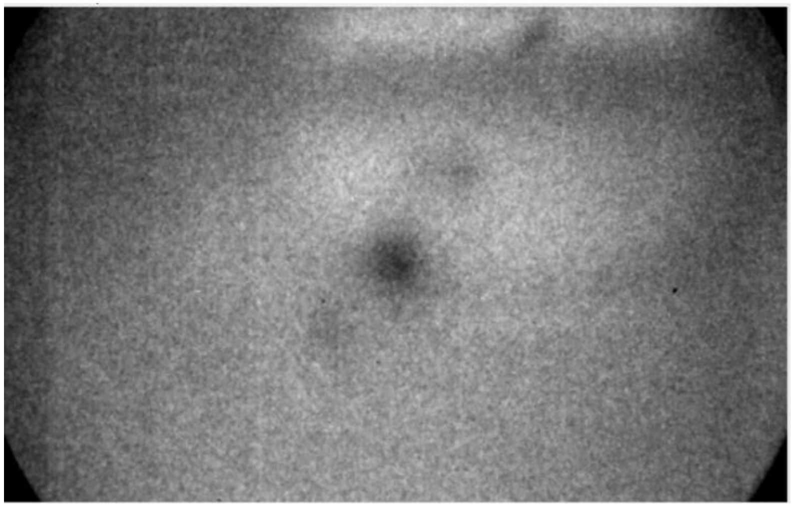
```
ata/BIF/LHC.tests/camera/SubtractedPhotonMap/12.01_3_50_
  SubPhotonMap = np.loadtxt(PhotonMapPath, delimiter =
PB82
Measured n. of photons: 306611
Measured n. of photons from Gaussian fit: 265362
Expected n. of photons: 60446

Cross section [cm2]: 3.16e-18
Number of particles: 8.21e+10
Total exposure time [s]: 1286
Gas density [cm-3]: 7.42e+08
Optical acceptance: 5.50e-04
Quantum efficiency: 0.08

In [69]:
```

- Photon count is approx. *5 times higher* when compared with expected from extrapolation for protons (and scaled for Z^2)
- Very difficult measurement (absolute). Camera is not calibrated as photon counting instrument.
- Tests at CI with other camera: approx. 1.6 lower counts wrt Proxitronic setup at CI

Profile from protons

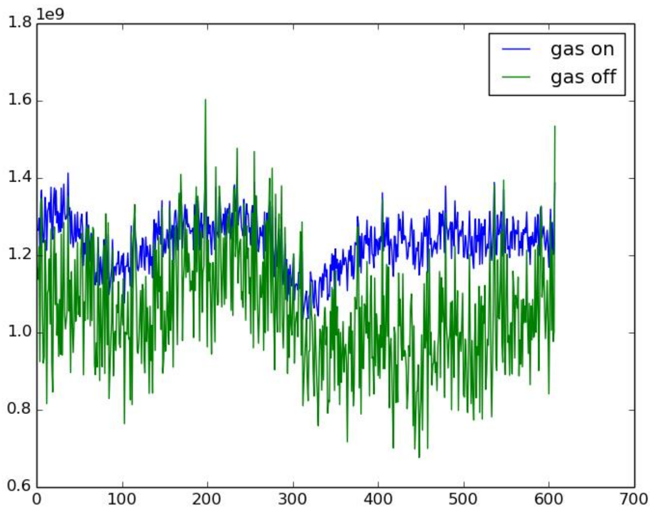


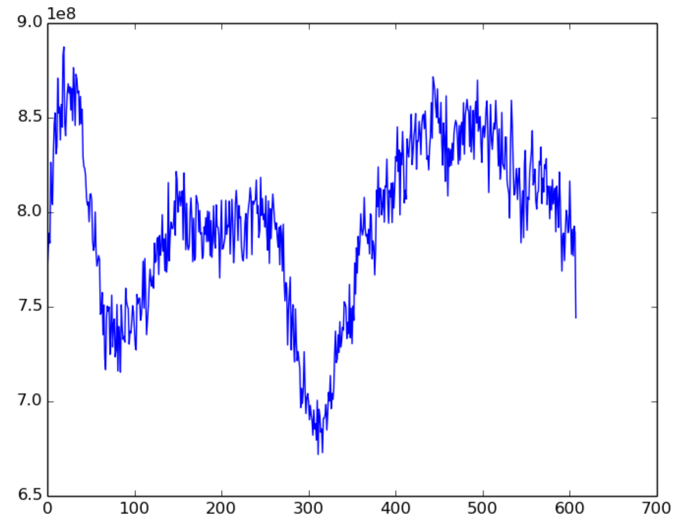
585 nm, gas **OFF**, beam **ON**
Integration over 486 s
(1215 frames, 400 ms exp time)



585 nm, gas ON, beam ON
Integration over 205 s
(512 frames, 400 ms exp time)

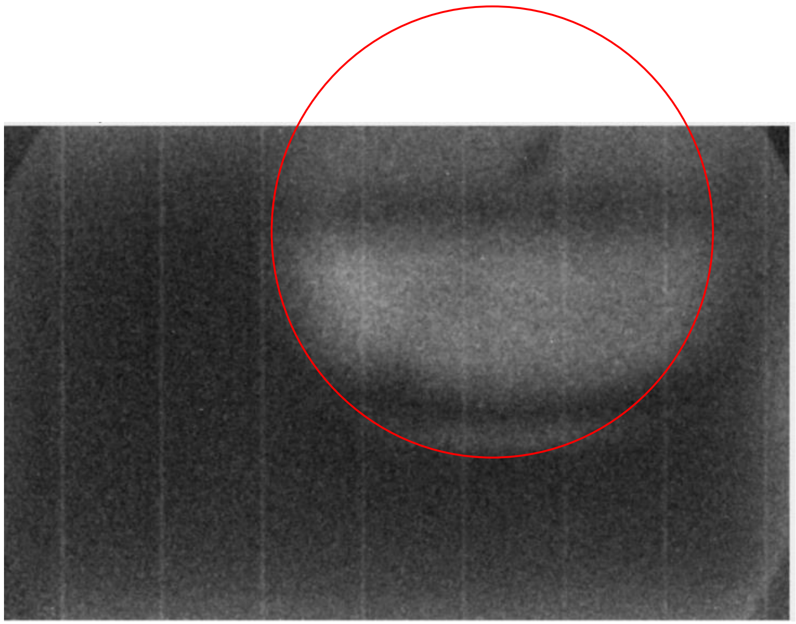
Protons





- Same procedure for protons. Subtracted signal is corrected for different exp time. Int time shorter than Pb run (here 200 s approx. for both gas on/off)
- Dip at 300 pix defect of photocathode
- Background subtraction very poor: not understood!

Profile from protons



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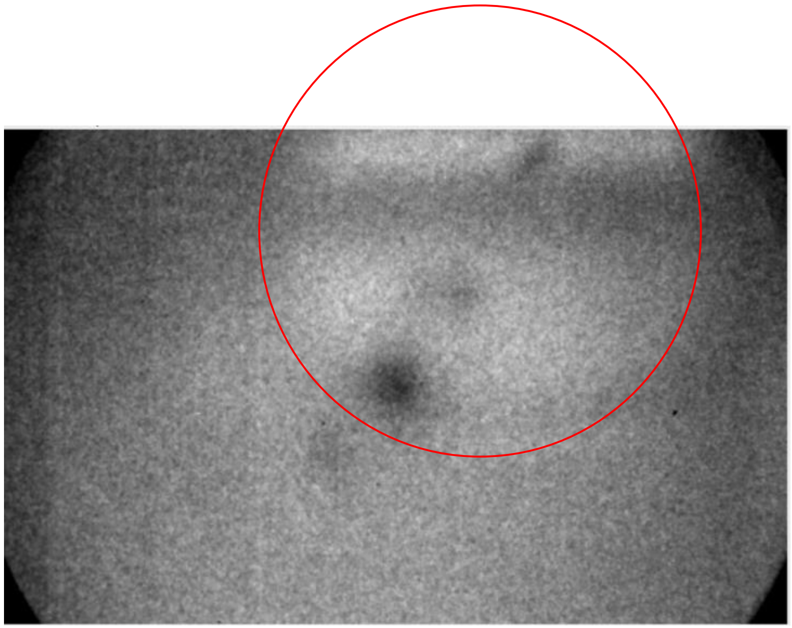

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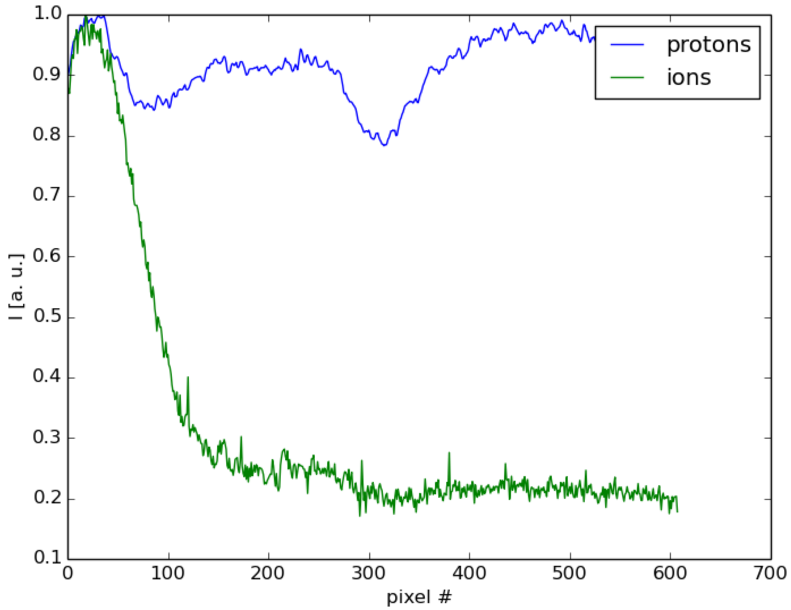
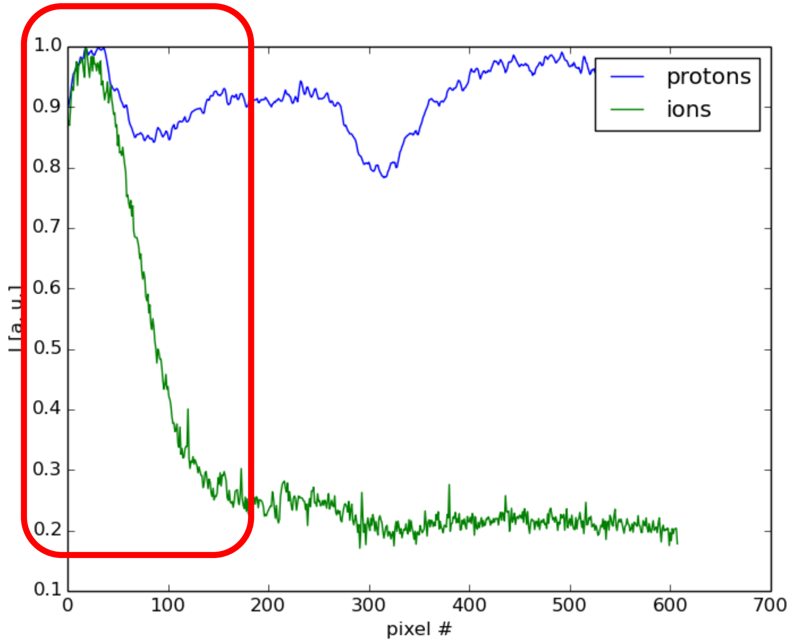
Protons vs ions



- Protons vs Pb ions profiles normalized for peak intensity
- Ion cross section per particle Z2 (82^2 = 6742) times the one for p.
- Considering higher intensity of p beam (2.5E+14 vs 0.7E+11): overall expected light yield for ions is **x2** times protons
- However: losses signal is proportional to intensity => **x 10^{-3} S/N wrt Pb+**

Protons vs ions



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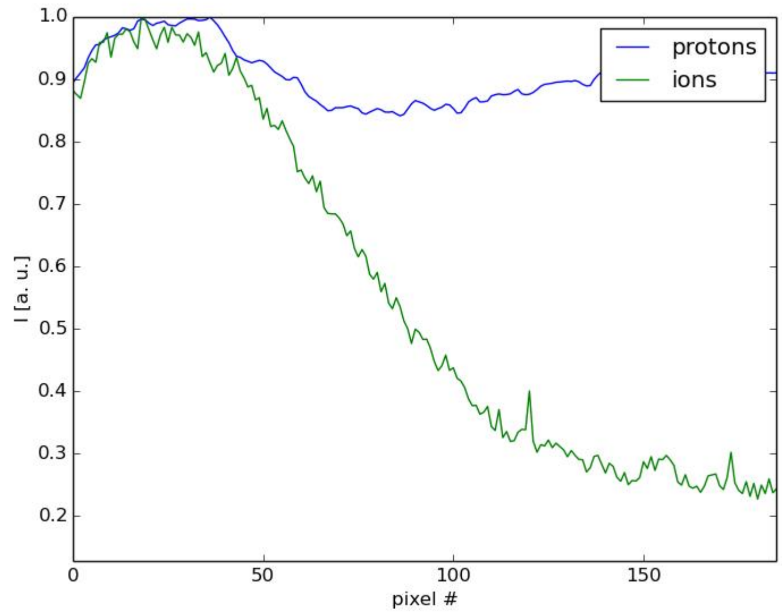

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Final considerations

- Improvement of S/N is *imperative:*
  - **Losses**:
    - gas jet / curtain vs. 10+ m gas volume (based on BGV data) $=>\sim 10^3$
    - Long optical line if needed
  - **SR & reflected light:**
    - NEG on Cu (R = 44.3%) vs. Polyteknik black coating (R = 0.12 % @ 585 nm) => $\sim 3 \times 10^2$ reduction
    - BandPass filter is 585 +/- 40 nm (FWHM). Use a BP filter with a few nm BW => ~ 10 reduction

    } $\sim 10^3$
  - **Gas pressure:**
    - Gas curtain might reach 10^{-6} mbar, LHC tests at $5x10^{-8}$ mbar $=>\sim 10 - 10^2$
- Nitrogen should be tested:
  - Ionic transition and longer emission time ($\tau \cong 70$ ns) => some distortion of profile will occur
  - Larger light yield (x5 wrt Ne) at 391.4 nm

Final considerations

- Fluorescence:
  - PROS. Very simple source: incoherent, isotropic, monochromatic. Detection is simple: imaging
  - CONS. Low light yield, noise sources (SR, losses).
- Potential for a precise average beam size measurement technique for protons, ions at injection. Ramp & high energy require better S/N.
- Test during LHC Run 3 will clarify actual performance of BIF + BGC:
  - Actual S/N improvement
  - Choice of gas (profile distortion with N?)
  - Actual gas curtain properties (pressure, shape,…)

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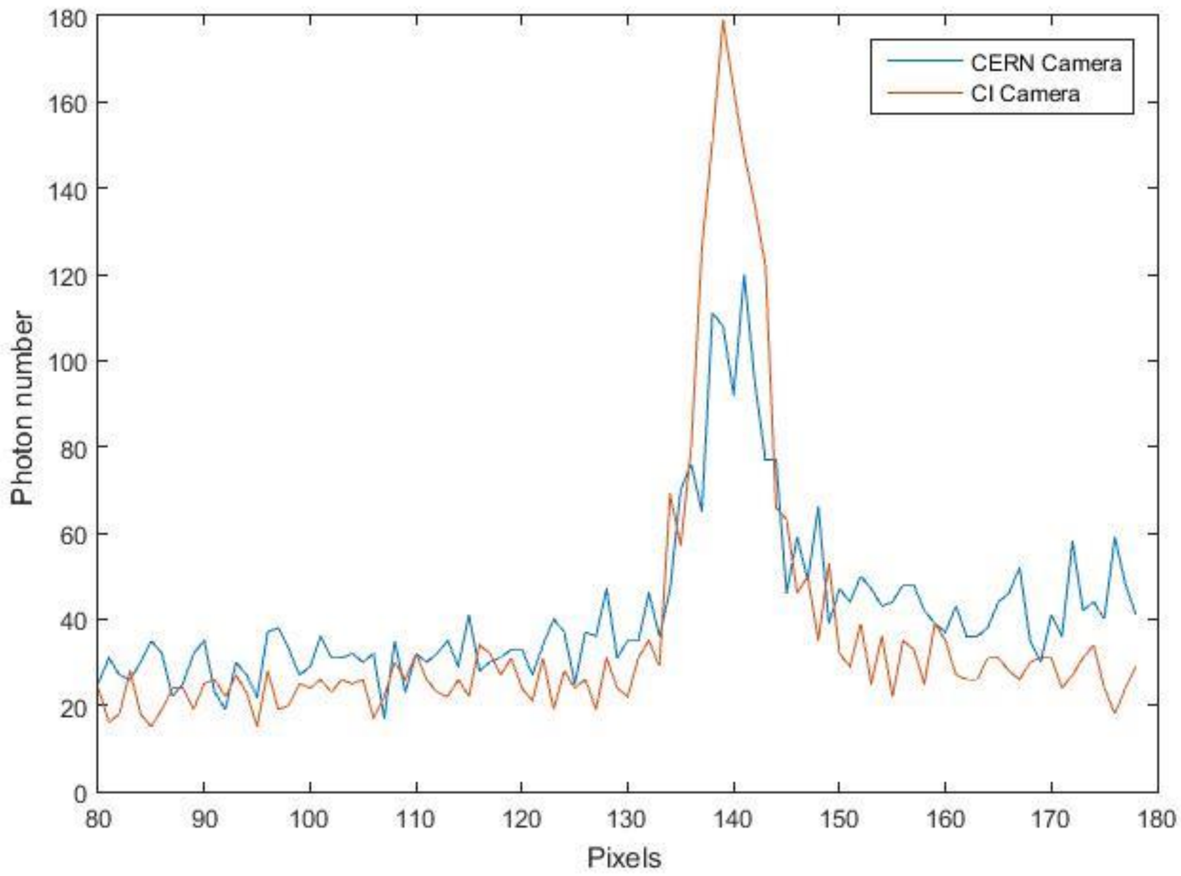
Some extra slides

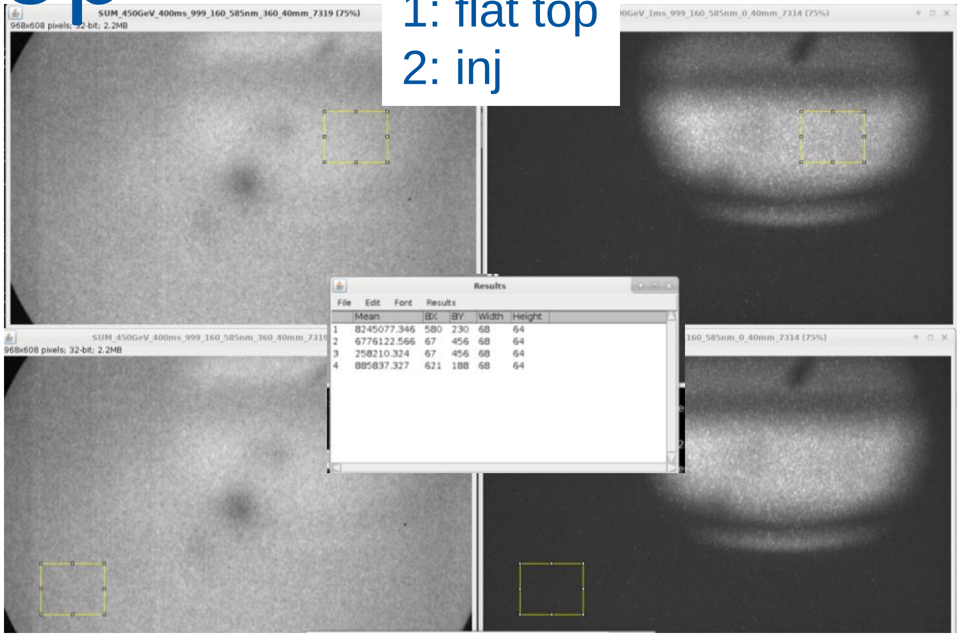
Experimental conditions for both measurements

- Current of the electron gun = 0.65mA
- Energy of the electron gun = 5KeV
- Exposure time per image = 1s
- Total integration time for the measurements = 100 seconds (100 images)
- Inlet gas and pressure = Nitrogen at 5bar
- Nozzle type = 30micron nozzle designed and manufactured at CERN


180
160
140
120
100
80
60
40
20
0
Photon number
80
90
100
110
120
130
140
150
160
170
180
Pixels
CERN Camera
CI Camera

Injection vs Flat top

- Inj: 500 x 400 ms images, gain 360, fill 7315 (18/10)
- Flat Top: 691 x 1 ms images, gain 0 fill 7315 (18/10)
- Lab test: gain 360 = x65.8 factor
- SR: compare reflected light
- LOSSES: compare background

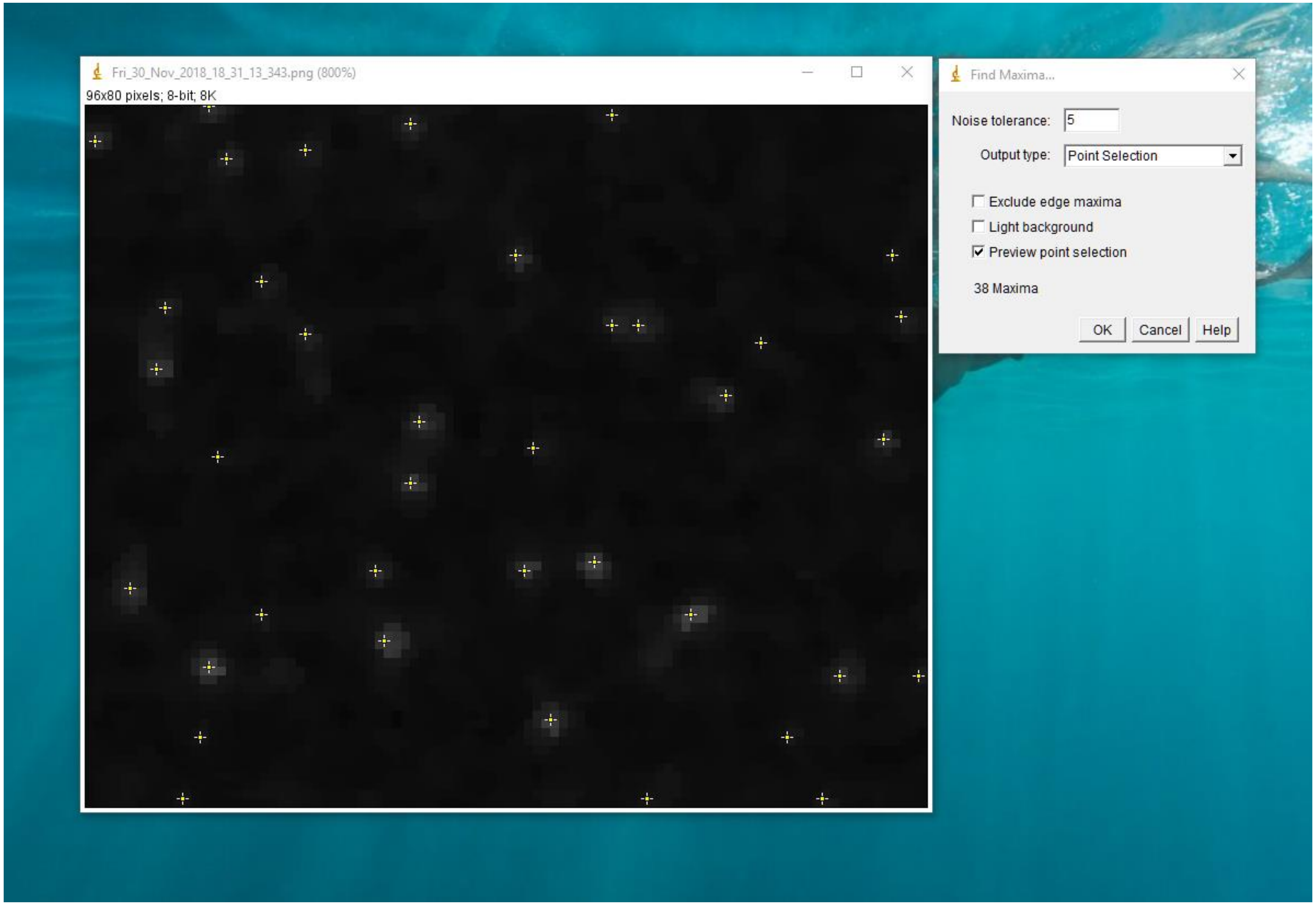


$$\frac{LY_{FT\_LOSS}}{LY_{INJ\_LOSS}} = \frac{258210}{6776122} \times \frac{500\times400}{691} \times 65.8 = 0.04 \times 289 \times 65.8 = 7.6E+02$$

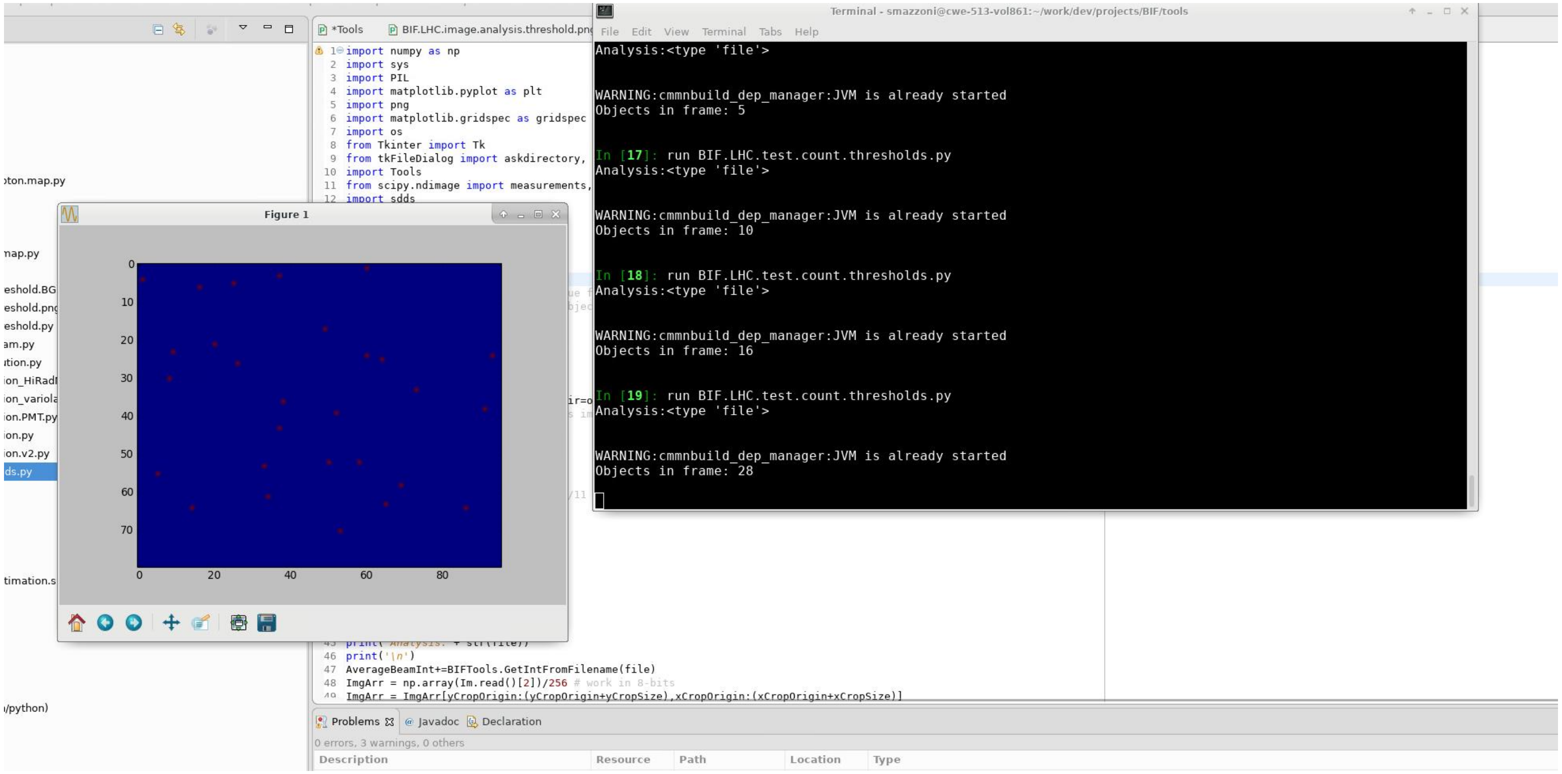
$$\frac{LY_{FT\_SR}}{LY_{INJ\_SR}} = \frac{(885837-258210)}{(8245077-6776122)} \times \frac{500\times400}{691} \times 65.8 = 0.82 \times 289 \times 65.8 = 8.1E+03$$

Scripts summary

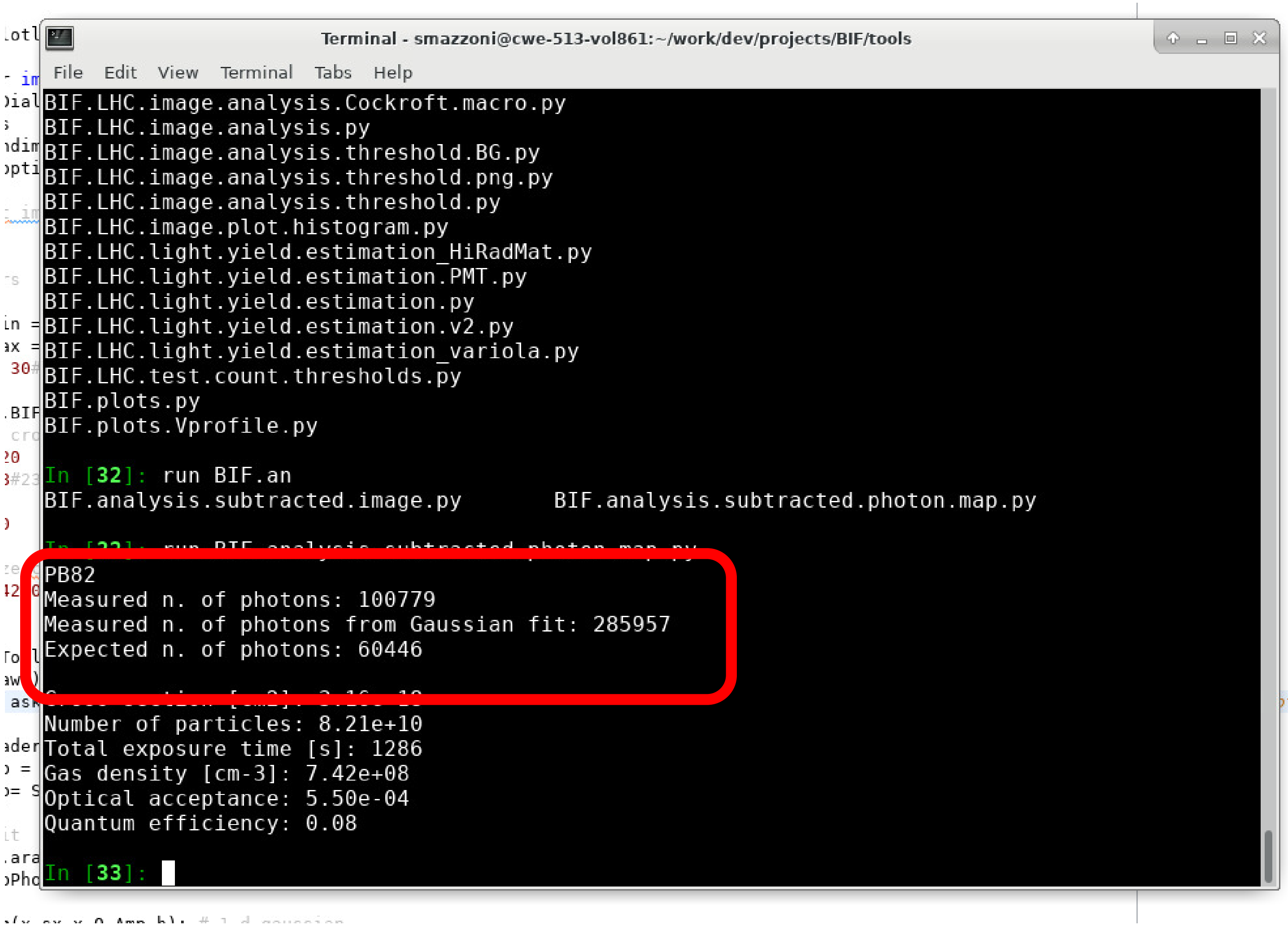
- My scripts:
  1. BIF.LHC.image.analysis.threshold.png. Counts photons from LHC or CI images according to two parameters: threshold and minimum size of clusters. Results are saved in folder 'results_<min size>_<threshold>' as:
     - Individual photon maps (txt files)
     - In folder 'Results': AnalysisSummary.txt, PhotonCountMap.txt, PhotonMap.txt
  2. When photon maps are produced by Serban's ImageJ script, I use BIF.LHC.image.analysis.Cockroft.macro to produce a 'Results' folder that contains AnalysisSummary.txt (for LHC images), PhotonCountMap.txt, PhotonMap.txt
  3. BIF.get.subtracted.photon.map calculates the correct subtracted photon map (es: photon map with gas and beam minus photon map with beam no gas) taking into account number of images that might be different between the two datasets. For LHC data sets takes into account different beam intensities.
  4. BIF.analysis.subtracted.photon.map.py is the macro that counts photons and fits profile with Gaussian



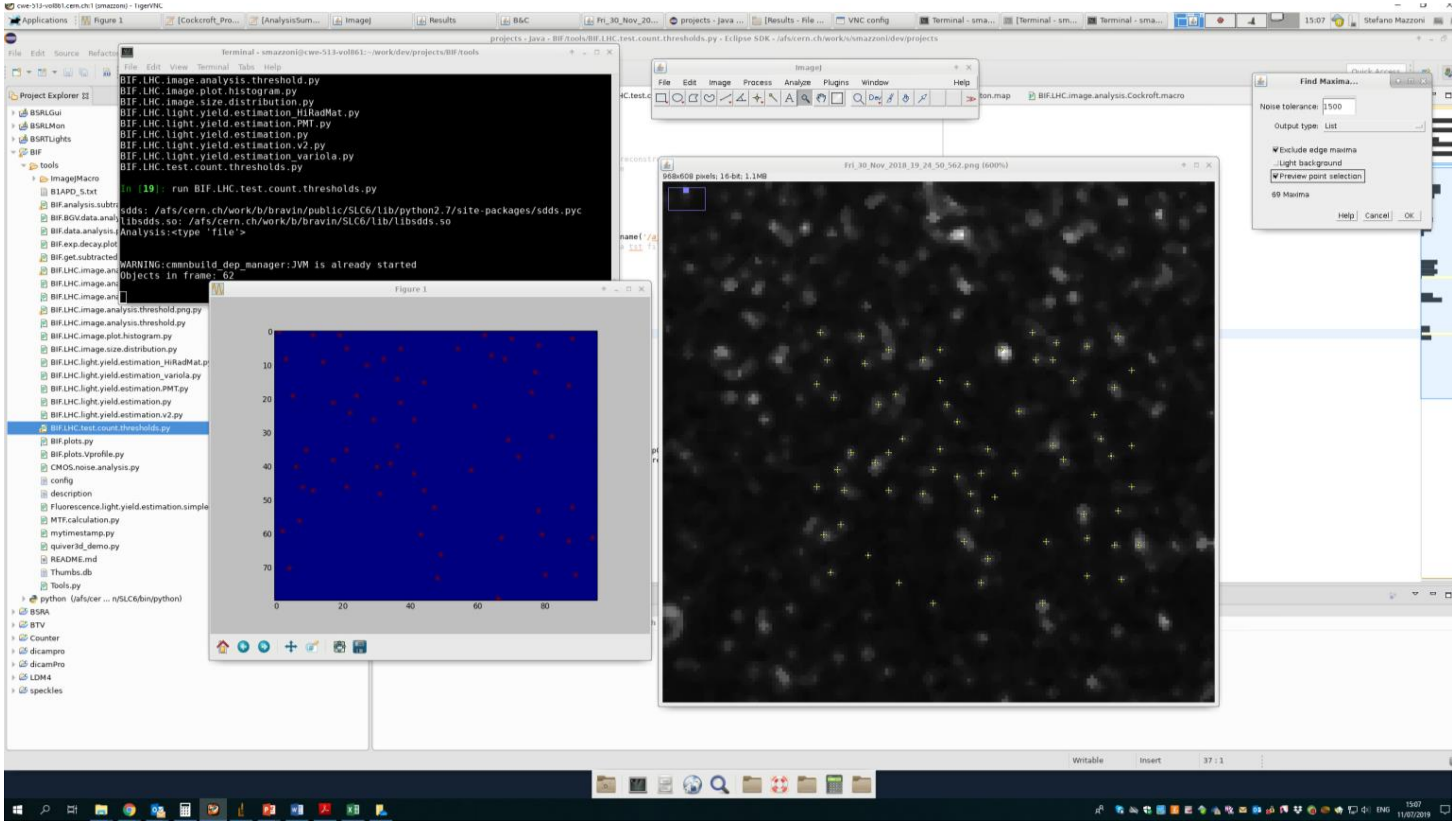
With ImageJ procedure: 2x median filter (1 pix), find maxima with noise tolerance at 5 pixels. This is according to the parameters set by CI team when performing the tests at CI.



With ImageJ procedure: 2x median filter (1 pix), find maxima with noise tolerance at 5 pixels. This is according to the parameters set by CI team when performing the tests at CI.   This corresponds to my python script with 50 levels threshold and 3 pix minimum size limit.

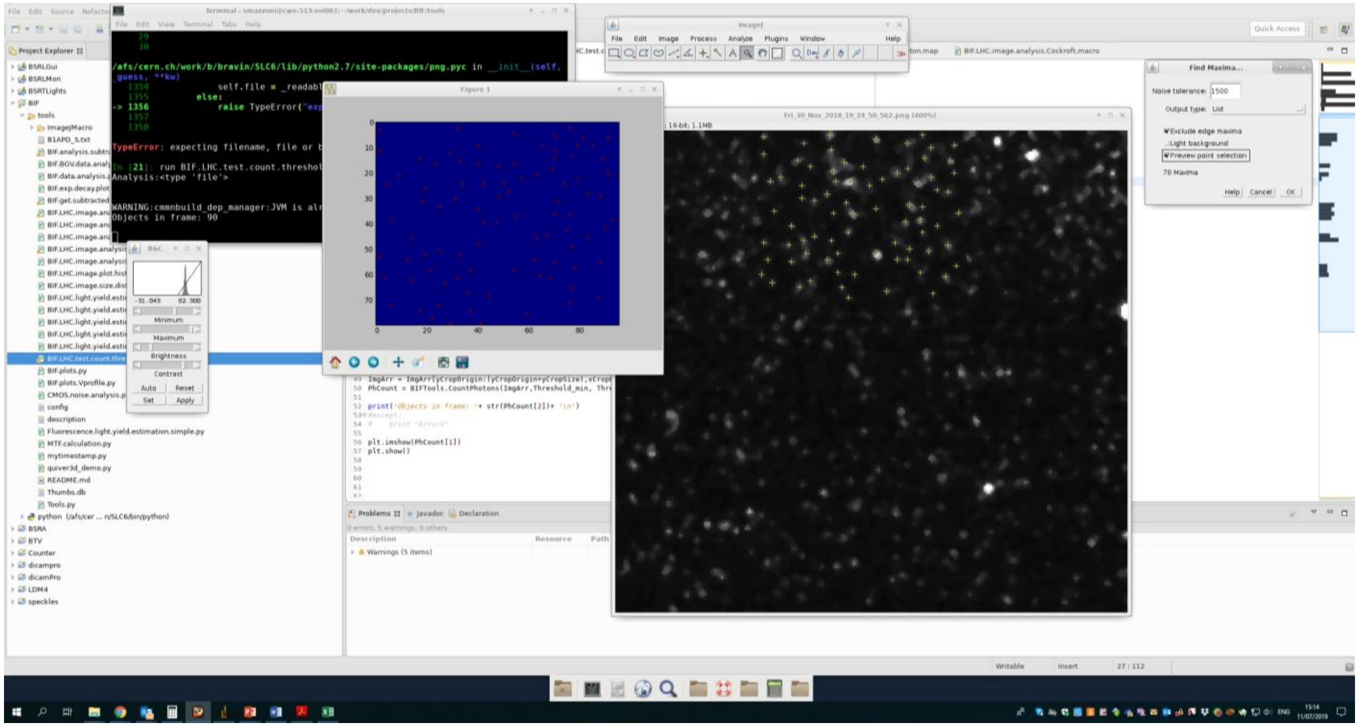


With same parameters (50 levels threshold, 3 pix min size) I get a x1.6 the expected number of photons with the cross section estimated by GSI.



Comparison of mine vs CI routine for photon counting on area xCropOrigin = 450 xCropSize = 96 yCropOrigin = 53 yCropSize = 80 of last image of 12.01 ion run with gas & beam:

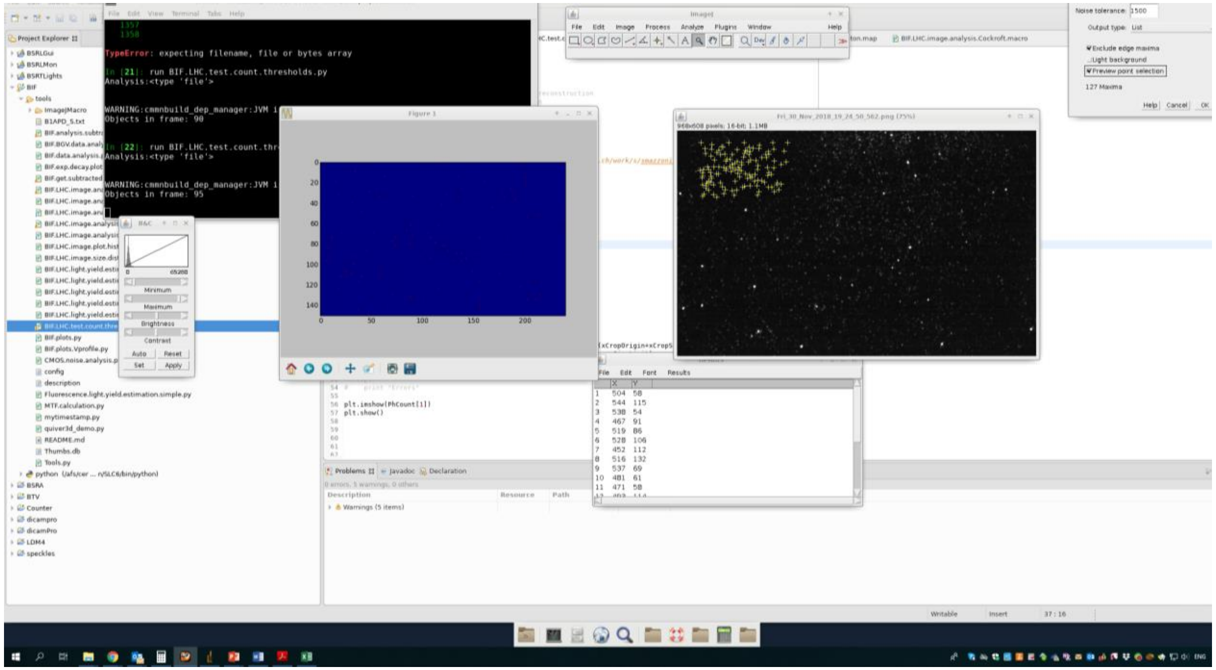
- Mine with 50 min threshold, 3 min size: 62 objects
- CI with 1500: 69
- Ci with 5000: 41
- CI with 10000: 21



Comparison of mine vs CI routine for photon counting on area xCropOrigin = 450 xCropSize = 96 yCropOrigin = 0 yCropSize = 80 of last image of 12.01 ion run with gas & beam:

- Mine with 50 min threshold, 3 min size: 90 objects
- CI with 1500: 78
- Ci with 5000: 45
- CI with 10000: 30

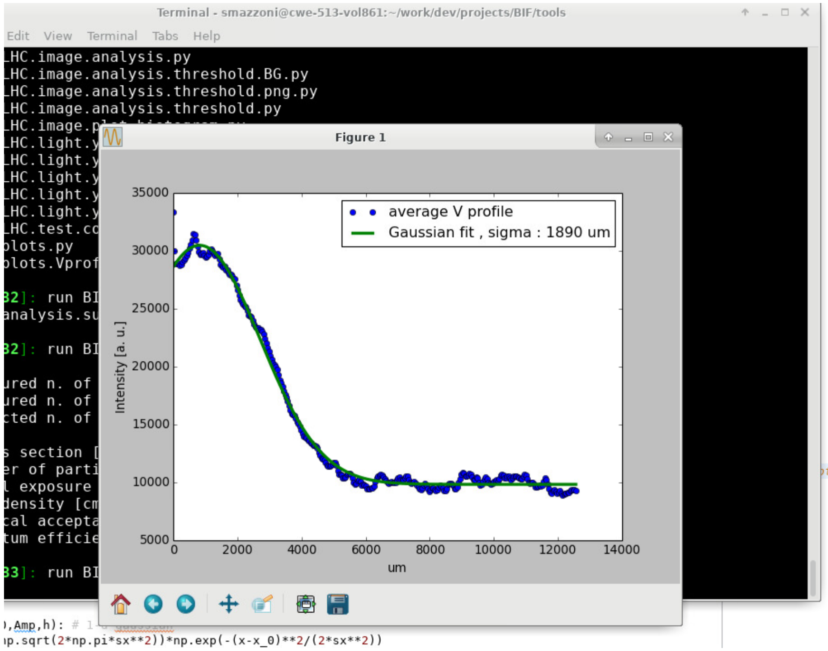
=> When signal is higher looks like my routine sees more counts

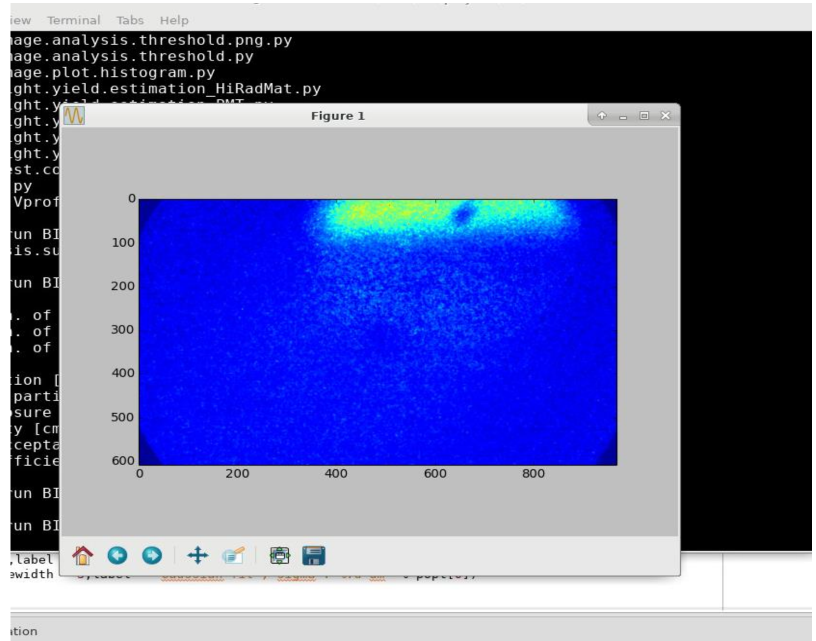


Comparison of mine vs CI routine for photon counting on area xCropOrigin = 60 xCropSize = 240 yCropOrigin = 30 yCropSize = 150 of last image of 12.01 ion run with gas & beam:

- Mine with 50 min threshold, 3 min size: 95 objects
- CI with 1500: 127
- Ci with 5000: 65
- CI with 10000: 24

=>BG: the background is much more enhanced by the CI routine





The profile depends quite heavily on the S/N. Different threshold levels give a different s/n. The cleanest way to calculate the profile for the Pb run is just to calculate it from the subtracted image calculated with ImageJ:
-sum of last 1000 images with beam & gas
-sum of 1000 images without beam
-subtraction of the two resulting images with no adjustable coefficient (this because the BG signal does not depend on the beam)
- Gaussian fit on the results, see above

BIF SW

BIF.image.analysis.threshold.py with 50 threshold, 3 min size is equivalent to the ImageJ routing with 1500 threshold

LHC images

CI images

BIF.image.analysis.threshold.py

Based on threshold and min size

LHC images

CI images

ImageJ macro (Serban)

Based on threshold

Photon maps

Photon map per image.
Whole image, no more BG area.

BIF.get.subtracted.photon.map.py

Produces a 'Results' folder with

- AnalysisSummary.txt
- PhotonCountMap.txt
- PhotonCountMap.png

A BG data set is needed (es. No beam or no gas)

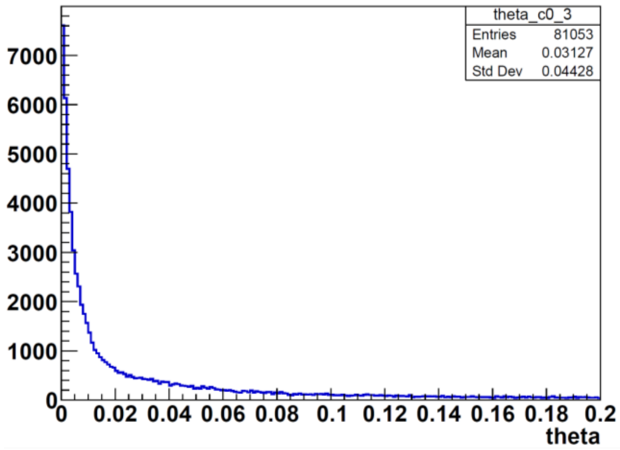
Subtracted Photon map

Final product analysed with

BIF.analysis.subtracted.photon.map

Beam – gas interaction

- Cross section for p-Ne inelastic scattering:
  - 245 mb = 2.45 x 10^{-25} cm^2 @ 450 GeV
  - 297 mb = 2.97 x 10^{-25} cm^2 @ 7 TeV (= 0.5% of the 585.4 nm fluorescence one)
- .DAT files with 3.6 x 10^6 vertices

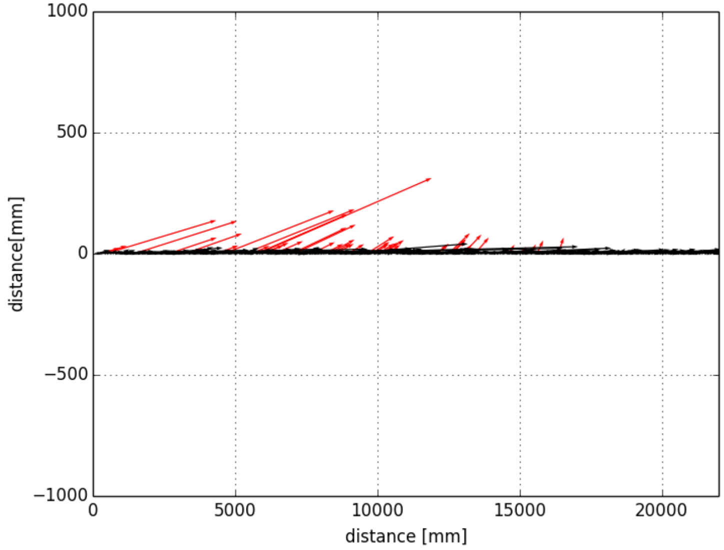


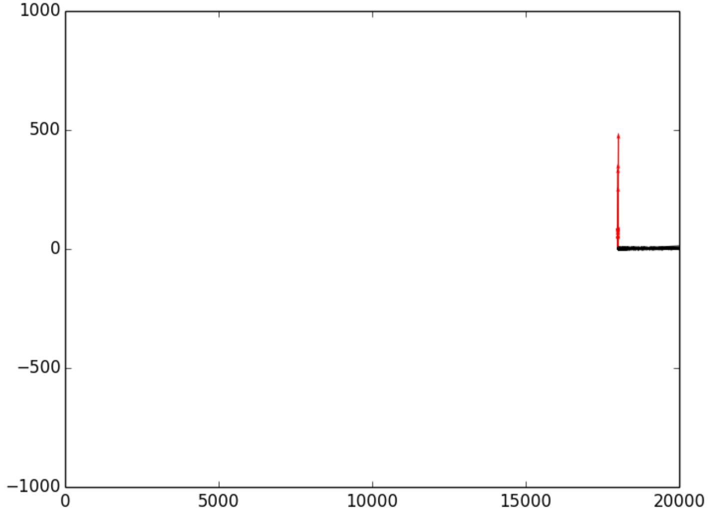
Thanks to BGV team: Benedikt, Robert, Sotiris!

Beam – gas interaction

- Monte carlo simulation with BGV vertex data (3.6×10^6 events):
  - Vertices randomly distributed in 22000 mm long, 80 mm dia tube
  - Sensor is a cube of 25mm side at z= 18000 mm, r = 600 mm
  - Counting vertices that cross the volume area:
- Present case: 1.4×10^{-5} hit probability
- BGC case (18000<z<18001): 5.3×10^{-6} hit probability

0.4 times per particle

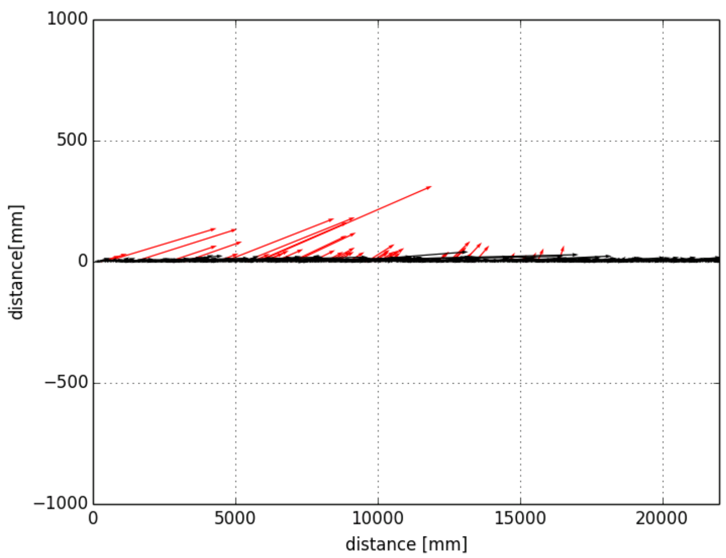


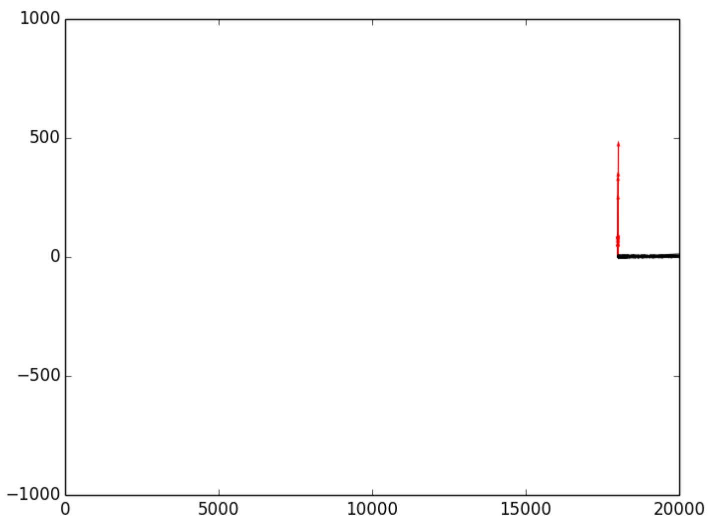


Beam – gas interaction

- Estimation of total number of gas particles for BGC vs present case ongoing
- ROUGH ESTIMATE:
  - Present 10^{-8} mbar over 10000 mm
  - BGC: 10^{-6} mbar over 1 mm

10^{-2} times BGV vs preset case



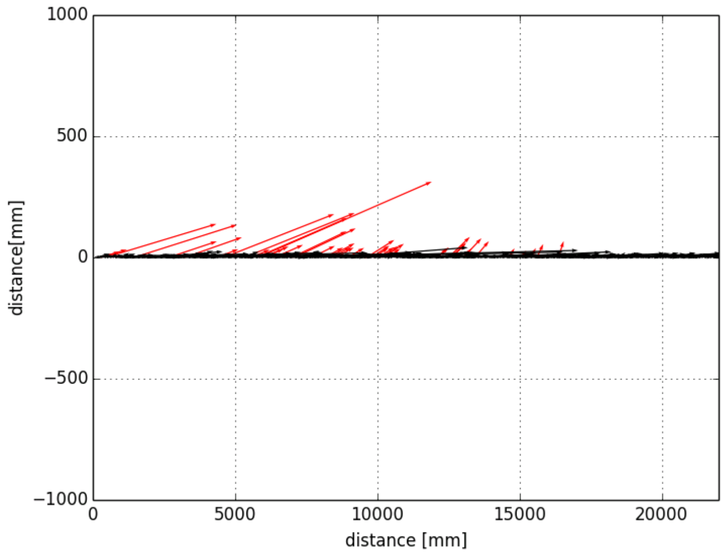


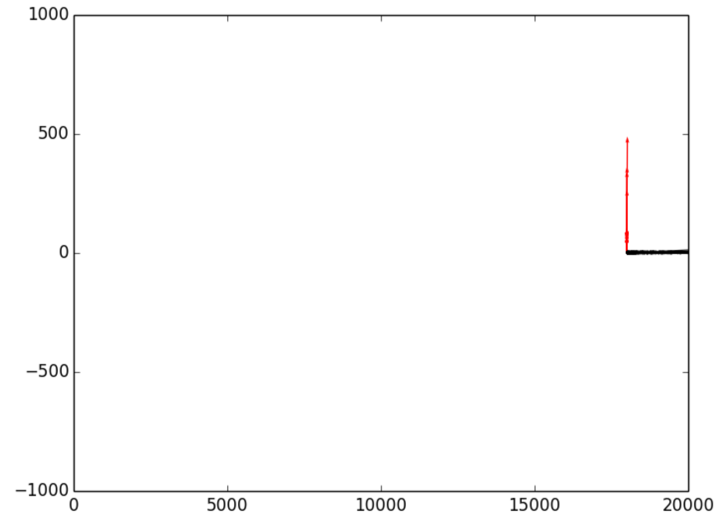
Beam – gas interaction

- Total number of detected losses BGC vs present case:

0.4 per particle x 10^{-2} particles = $4x10^{-3}$ losses

ROUGH ESTIMATE: order of 10-3 detected losses BGC vs present case





notes

- Beta functions
  - Ions:
    - BGIH.5L4.B1: 314 H, 242 V
    - MU.A5R4.B1 (BSRT): 203 H, 317 V
  - Protons
    - MGMWH.C5L4.B1: 323.7 H, 213.3 V (this should be the location)
    - MU.A5R4.B1 (BSRT): 205.1 H, 287 V