Experimental Results from Cockcroft 2019/2020

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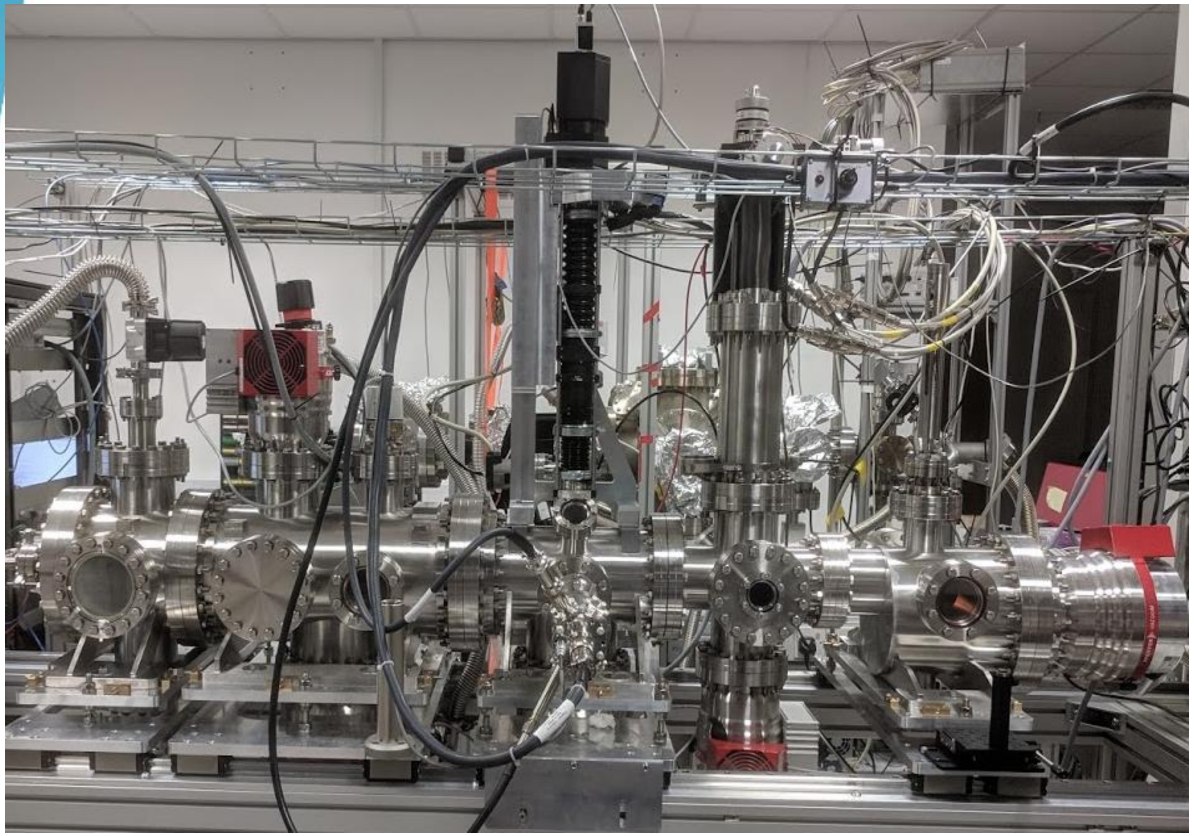
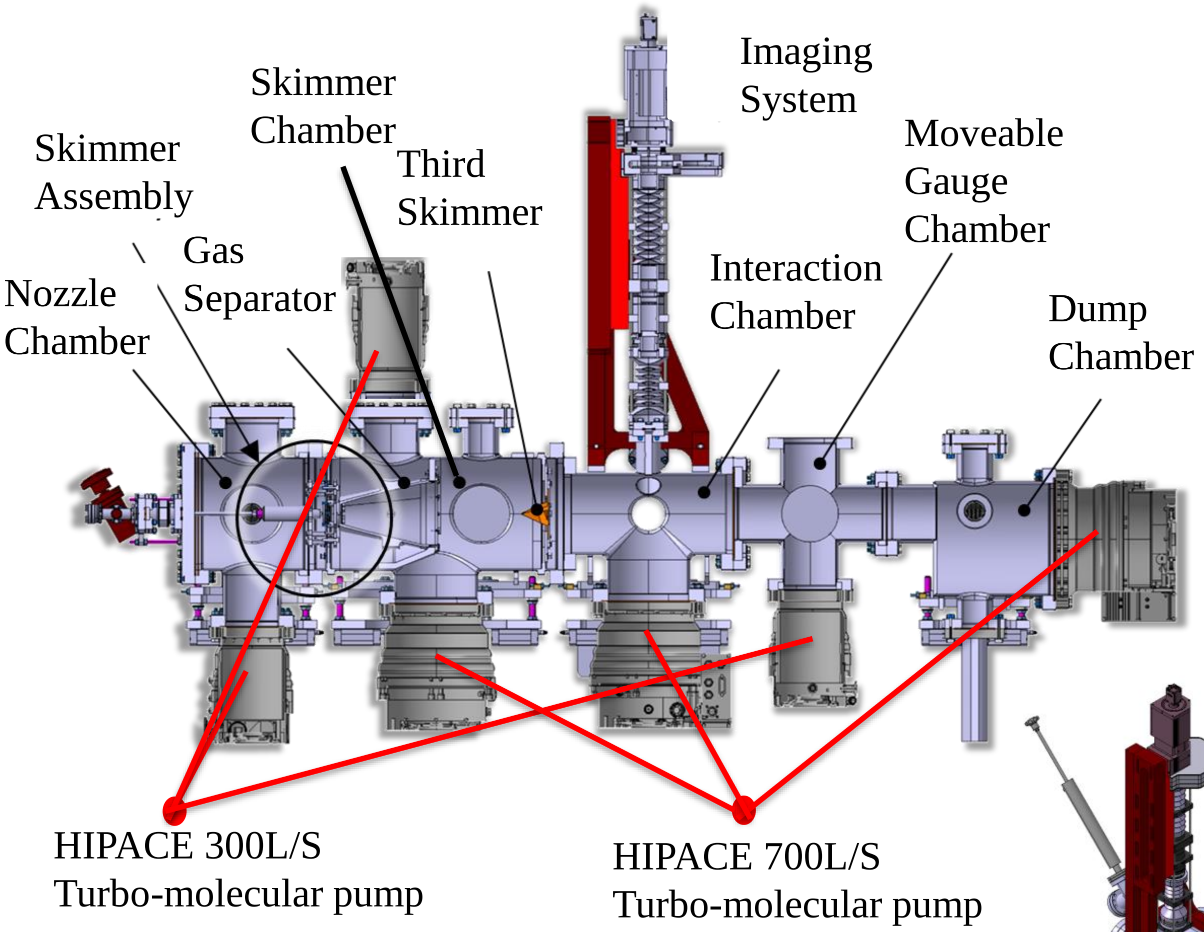
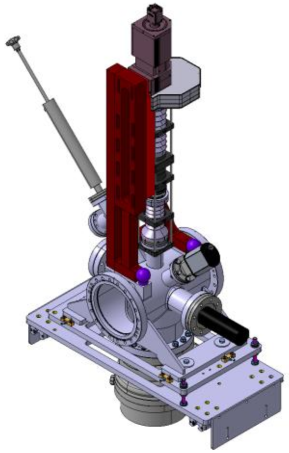
Outline

- System highlights.
- Nozzle and jet formation
- Skimmer geometry and gas jet propagation
- What we know for signal and S/N ratio
- 2020 Experimental Program
- Design and procurement of BGC V3

Prototype at the Cockcroft Institute







Experimental conditions for experiments involving electron gun.

- Gas type: Nitrogen.
- Electron beam current : 0.65 mA.
- Electron beam energy : 5 KeV.
- Gas jet species : Nitrogen, Neon and Argon.
- Camera exposure time : 1 s.
- Inlet pressure 5 bar.
- Nozzle size : 30 micron.
- Nozzle to first skimmer distance : 3.76 mm (The optimum distance).

(Unless stated otherwise)

Nozzle and jet formation

- Jet density when changing nozzle-skimmer distance
- Effect of Nozzle chamber pressure
- Flow rate measurement
- Tests with different nozzle geometry or type
- Laser interferometry

Gas-jet formation

- Few observations that were reported and confirmed experimentally during the last meeting:
  1. There is an optimum nozzle to first skimmer distance for the 30 micron nozzle and the 50 micron nozzle.
  2. The optimum nozzle to first skimmer distance for the 50 micron nozzle is almost twice the distance for the 30 micron nozzle.
  3. The optimum distance is larger for increased inlet pressures.

- A literature review was conducted to find an explanation for this maxima.

Gas-jet formation

- In the following example, the density at the collimator can be given as :

$$n_c \approx \frac{n_0 \mathscr{M}^2 a^2 \gamma / 8d^2}{[1 + (\gamma - 1)\mathscr{M}^2/2]^{1/(\gamma-1)} + [\pi\sigma^2 a n_0/(2)^{1/2}][1 - (\gamma/2\pi)^{1/2}(\mathscr{M} a/2d)]} .$$

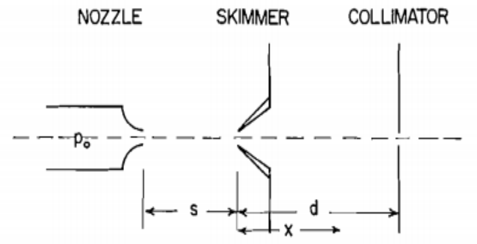


FIG. 1. Schematic diagram of beam-forming apparatus.

- In this model :
  - M= Mach Number, decided by the geometry and is determined by distance s, and the size of the nozzle
  - n_c = density at the collimator.
  - n_0 = stagnation density.
  - a = diameter of the skimmer.
  - sigma = The collision coefficient of the molecules between the skimmer and the collimator.

- The full derivation can be seen at : https://www.nrcresearchpress.com/doi/pdfplus/10.1139/v65-002
  - A cylindrical region based on the skimmer aperture and stretching a distance d to the collimator has been considered.
  - A collision free density was calculated based on purely geometrical considerations.
  - This collision free density was then corrected based on two factors
    1. Diffusive losses: the natural trajectories of most of the molecules carry them across the boundary of the cylinder
    2. Collisional losses: Most collisions between the molecules throw them out of the cylindrical region

Gas-jet formation

$$n_c \approx \frac{n_0 \mathcal{M}^2 a^2 \gamma / 8d^2}{[1 + (\gamma - 1)\mathcal{M}^2/2]^{1/(\gamma-1)} + \underbrace{[\pi\sigma^2 a n_0/(2)^{1/2}][1 - (\gamma/2\pi)^{1/2}(\mathcal{M}a/2d)]}_{\text{Collisional term}}}.$$

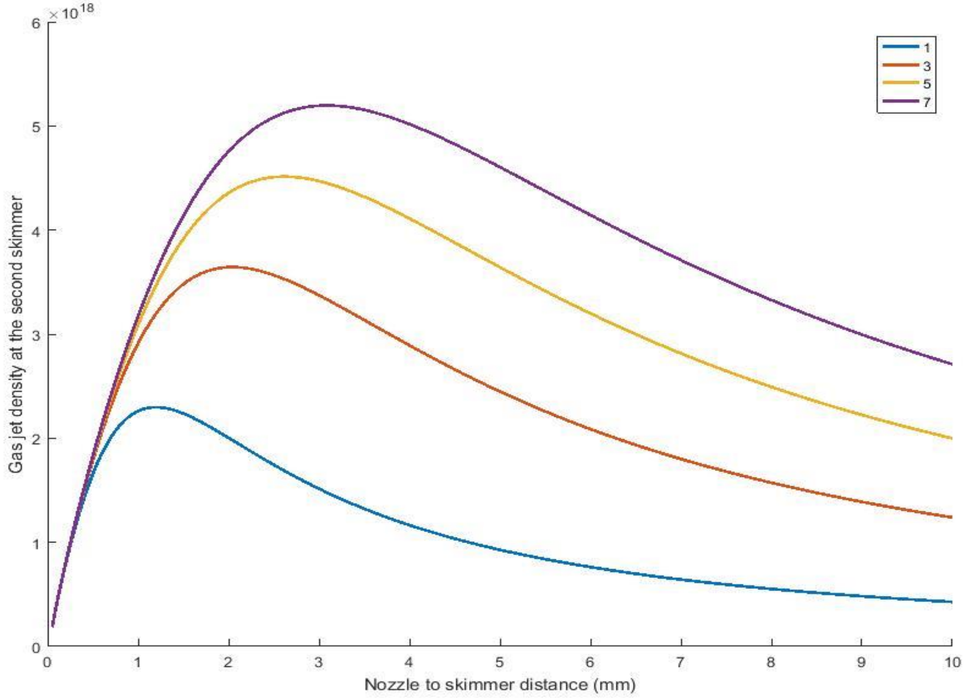
- Mach number increases as we go further away from the nozzle.
- At low nozzle to skimmer distances, the collisional term will dominate, so the intensity of the beam will increase as we increase the distance.
- At high nozzle to skimmer distances, the collisional term is small, and the intensity will fall off as we increase the distance.

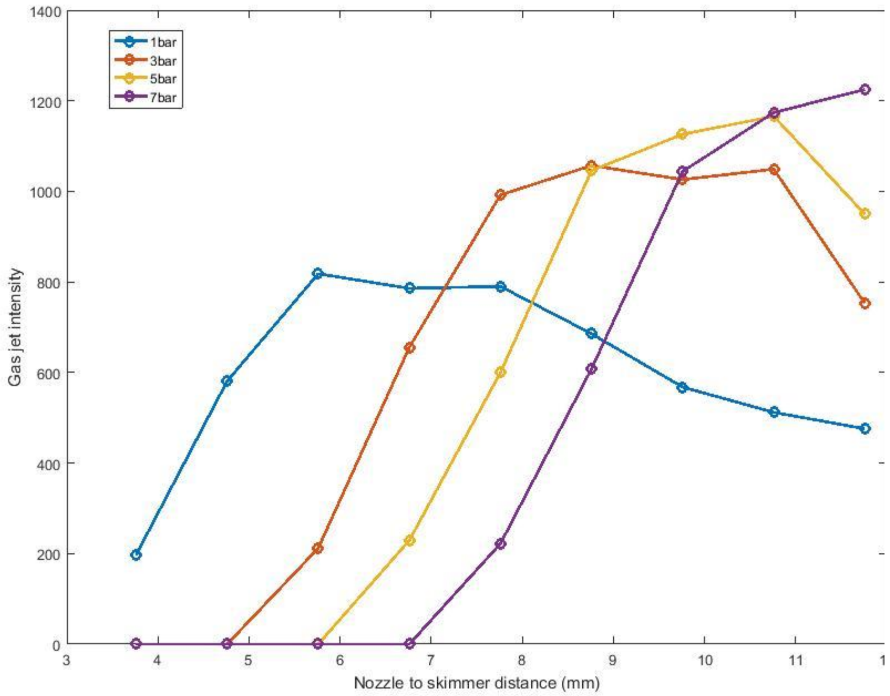
Factors not considered:

  - There are some collisions that knock molecules into the beam - these collisions are ignored;
  - Diffusive problem treated as if all molecules entered at the centre of the skimmer;
  - No backscattering from the skimmer surface is considered.

Gas-jet formation

- Predicted gas jet density at the second skimmer (left) vs the measured gas jet intensity by the electron gun (right). Measurements were taken at various inlet pressures and nozzle to skimmer distances.

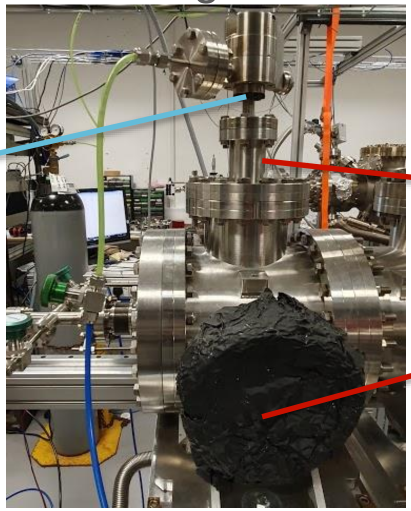




Pressure in the nozzle chamber

- It has been confirmed that the gas jet density is directly affected by the pressure in the nozzle chamber.
- Normal pumping conditions for the nozzle chamber :
  - A 700 l/s turbo-pump connected through a DN160 to DN100 converter.
  - A nXDS15i from EDWARDS roughing pump
- Two sets of tests were conducted to investigate this dependency.
  1. Installing a leak valve at the nozzle chamber to see how gradually increasing the pressure affects the gas jet density;
  2. Installing two extra turbo pumps to investigate how decreasing the pressure in the nozzle chamber affects the gas jet density.

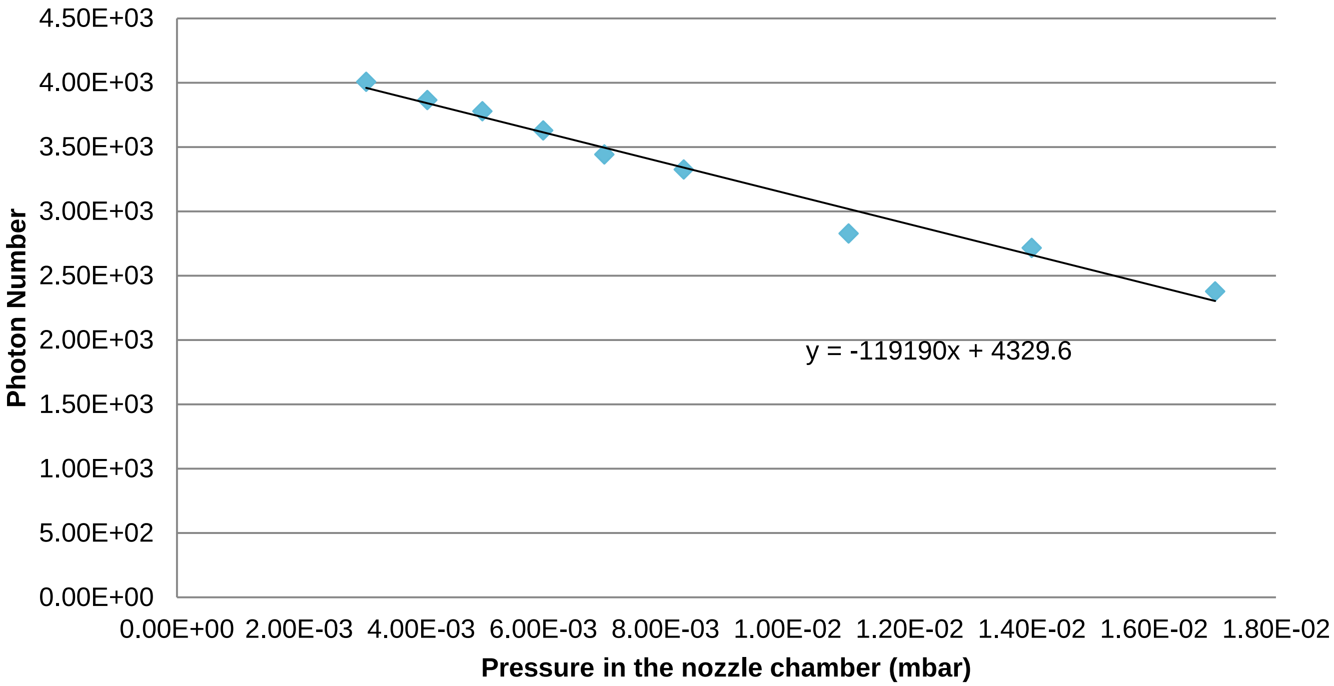
1. Leaking valve installed



2. Two extra turbo-pumps installed on these windows.

Pressure in the nozzle chamber

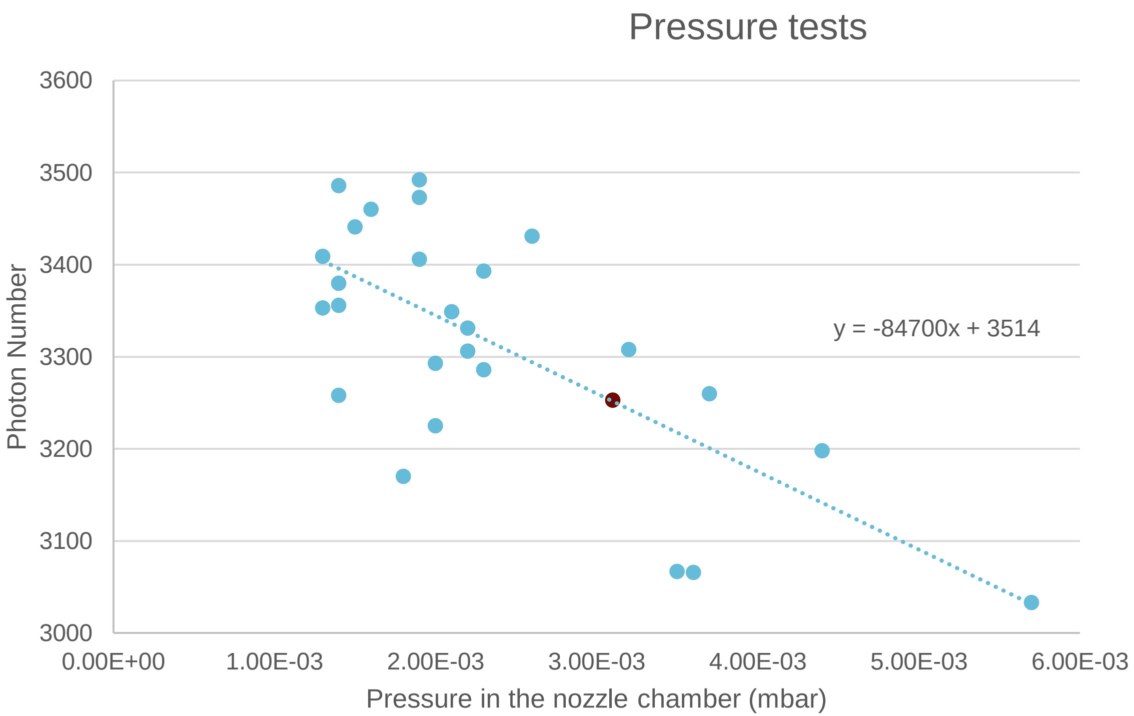
- The pressure in the nozzle chamber was gradually increased from 2.3e-3 mbar to 1.7e-2 mbar
- A series of measurements were taken with the electron gun with an integration time of 400 s.
- Number of photons was plotted against the pressure.



- At a pressure of 1.7e-2 mbar, the gas jet density is almost half of its nominal value at 3e-3 mbar.
- Pressure cut-off point is between 1.7e-2 mbar and 1.5e-1 mbar. Assuming linearity, it lies somewhere between 4 to 5e-2 mbar.

Pressure in the nozzle chamber

- Three turbo-pumps were added to the nozzle chamber, each with a dedicated backing pump.
- A series of tests were taken at different pumping conditions (ON, OFF, STANDBY)
  - 180 l/s 2. 300 l/s 3. 700l/s



- Approximately a 10% increase in the jet density was found after adding 2 extra turbos with dedicated backing pumps.
- Pressure cut-off point is around 3e-2 mbar

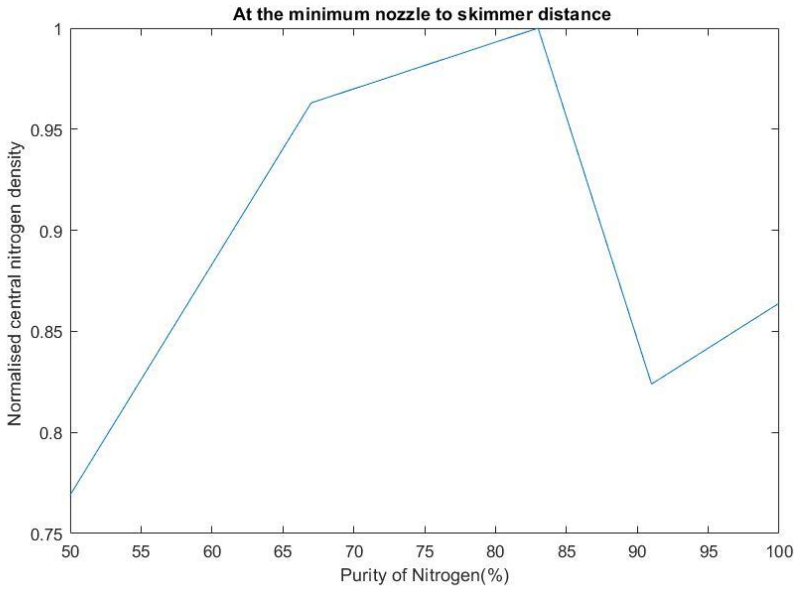
Pressure in the nozzle chamber	300L/s	180L/s	700L/s
1.90E-03	OFF	ON	ON
2.30E-03	OFF	STANDBY	STANDBY
2.00E-03	OFF	ON	STANDBY
2.20E-03	OFF	STANDBY	ON
3.20E-03	OFF	OFF	ON
3.50E-03	OFF	OFF	STANDBY
1.90E-03	ON	OFF	STANDBY
2.20E-03	STANDBY	OFF	STANDBY
2.00E-03	STANDBY	OFF	ON
1.80E-03	ON	OFF	ON
3.60E-03	ON	OFF	OFF
4.40E-03	STANDBY	OFF	OFF
2.60E-03	STANDBY	STANDBY	OFF
2.10E-03	STANDBY	ON	OFF
2.30E-03	ON	STANDBY	OFF
1.90E-03	ON	ON	OFF
5.70E-03	OFF	STANDBY	OFF
3.70E-03	OFF	ON	OFF
1.30E-03	ON	ON	ON
1.40E-03	STANDBY	ON	ON
1.40E-03	STANDBY	ON	STANDBY
1.60E-03	STANDBY	STANDBY	STANDBY
1.40E-03	ON	STANDBY	STANDBY
1.50E-03	STANDBY	STANDBY	ON
1.40E-03	ON	STANDBY	ON
1.30E-03	ON	ON	STANDBY

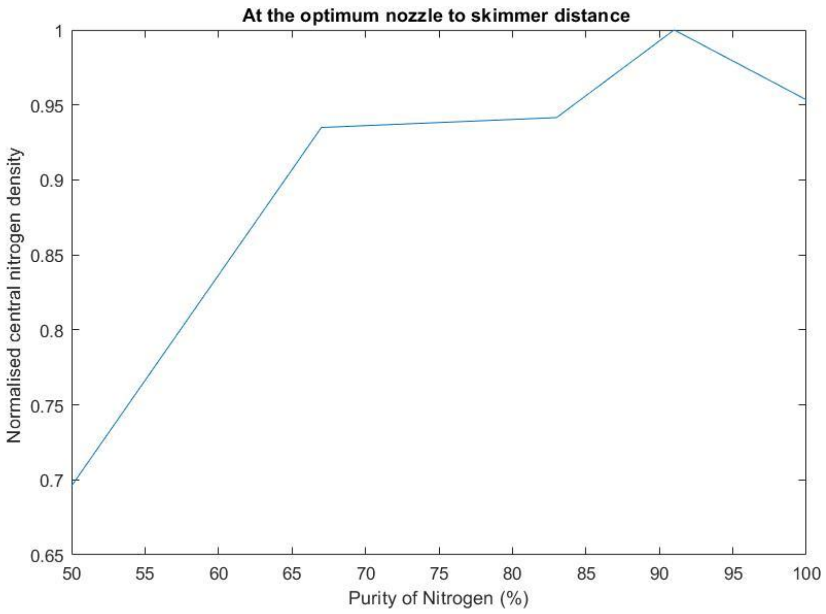
Gas mixing

- If a beam is formed from a mixture of a light and a heavy gas, a large concentration enrichment of the heavy gas is to be expected.
- Some preliminary data was taken mixing Nitrogen and Helium, using a simple setup.
- The gases were mixed at various concentrations, the electron gun was then used to measure the nitrogen portion of the gas jet signal.
- Nitrogen intensity in the gas curtain was then plotted against the nitrogen concentration.

Gas mixing

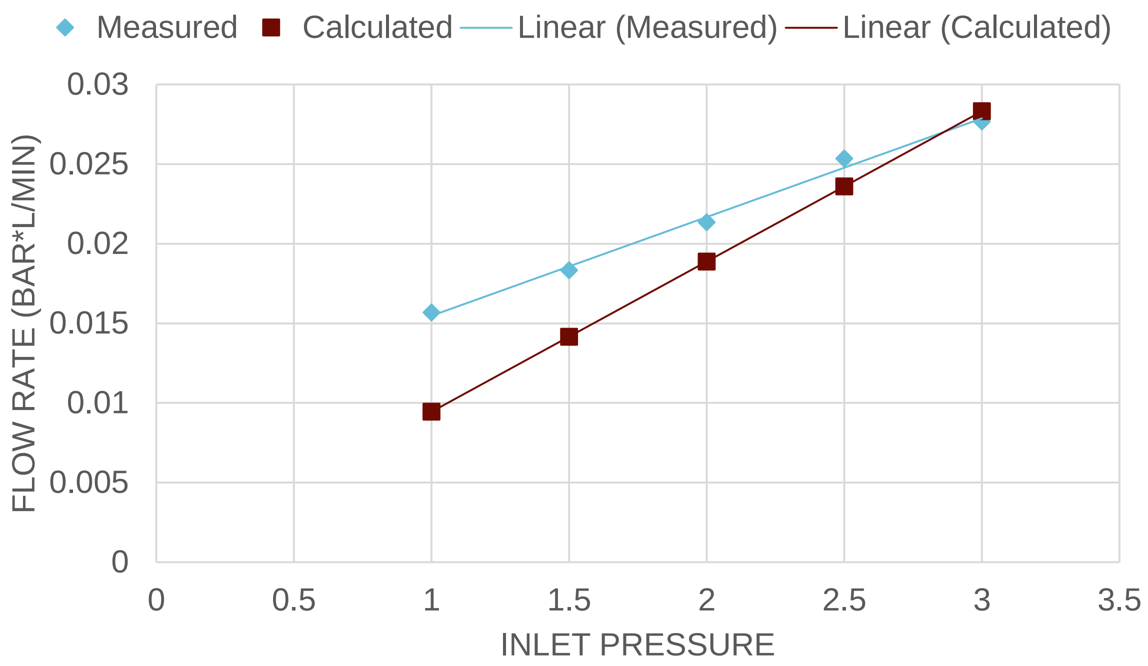
- Literature suggested that mixing heavy and light gases has a more predominant effect at low nozzle to skimmer distances.
- Various Nitrogen and Helium mixtures were tested at the minimum distance.
- Inlet pressure was set to 2 bar and was kept constant for all the measurements.





Flow rate

- One of the recent additions to the system was a flow rate meter to measure the flow through the nozzle. (Model = PFMV505, installed before the inlet).
- The flow meter can support inlet pressures of up to 3 bar. A theoretical estimate of the flow rate is plotted below against the experimental flow rate for various inlet pressures (up to 3 bar).



There is only a small discrepancy between the two measurements.

This can be explained by small leaks through the injector pipe or an inaccurate reading of the inlet pressure.

Flow rate

- Most of our experiments are measured with an inlet pressure of 5 bar.
  1. Theoretical estimation for the flowrate at 5 bar = 0.04 bar l/min = 0.67 mbar l/s.
  2. Experimental extrapolation for the flow rate at 5 bar = 0.047 bar l/min = 0.78 mbar l/s
- The effective pumping speed can be approximated since we know the pressure in the nozzle chamber and the flow rate through the nozzle.

Theoretical estimation of the pumping speed required

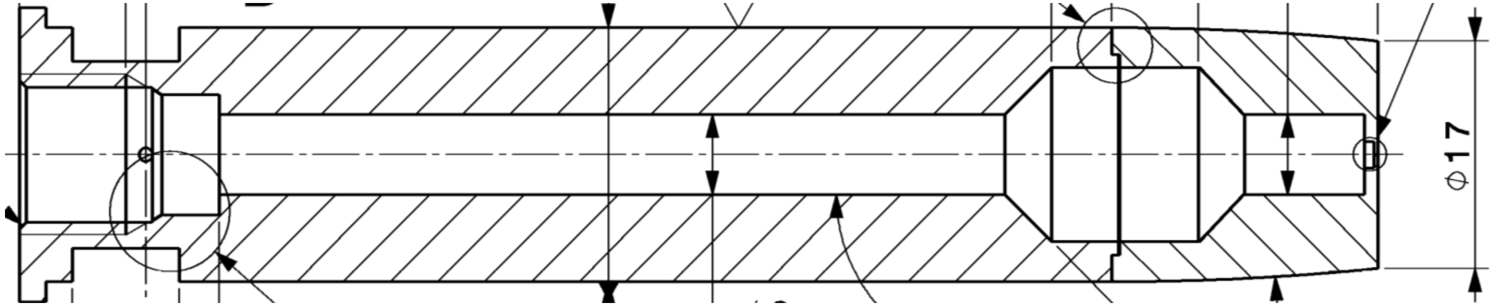
Nozzle chamber pressure (mbar)	Pumping speed needed (l/s)
5e-3	133~157
4e-3	166~195
3e-3	222~261
2e-3	333~391
1e-3	666~783
1e-4	6,666~7,833

Experimental pressures and effective pumping speeds

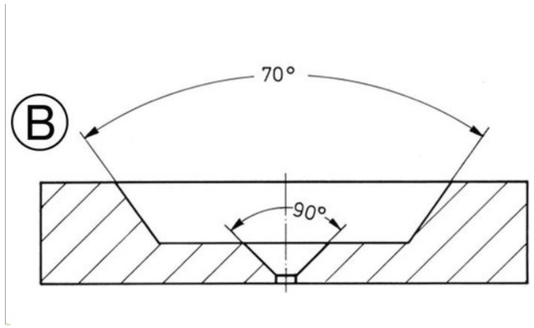
Nozzle chamber pressure (mbar)	Effective pumping speed (l/s)
Real case (3.6e-3)	185~217 (Only 300 l/s on)
Real case (3.8e-3)	175~206 (Only 180 l/s on)
Real case (1.9e-3)	350~412 (300 l/s and 180 l/s on)

Tests with CI nozzles

- A 30 micron nozzle with a neck length of 100microns, designed by CERN is usually used for the experiments.



- To test how the nozzle type and the nozzle diameter affect the gas flow, a new series of nozzles were designed, as shown below. (Capillary length of the aperture is 15microns).



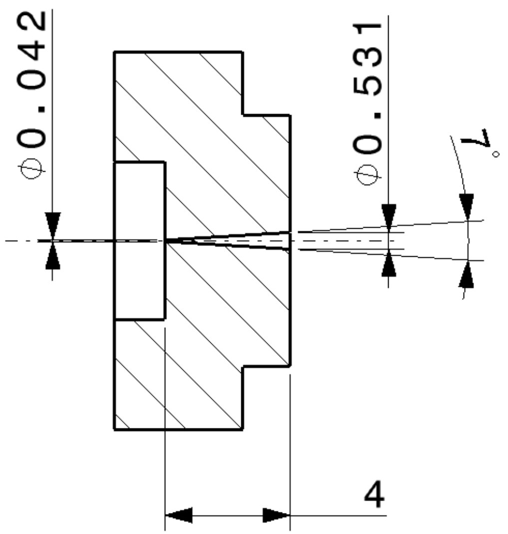
Tests with CI nozzles

- Three apertures were bought with the following diameters:
  - 20 microns
  - 30 microns
  - 50 microns.
- The system was aligned with each one and a series of measurements were taken to assess the intensity of the jet with each nozzle.
- Number of photons per second (Signal strength) :
  - 20 micron : ~4
  - 30 micron : ~3
  - 50 micron : ~2.5
  - CERN 30 micron nozzle : ~15 to 20
- The signal from the 15 micron neck nozzle is consistently weaker compared to the 100 micron neck on piece nozzle.
- There is not much difference between different nozzle apertures if we use the optimum nozzle to skimmer distance.

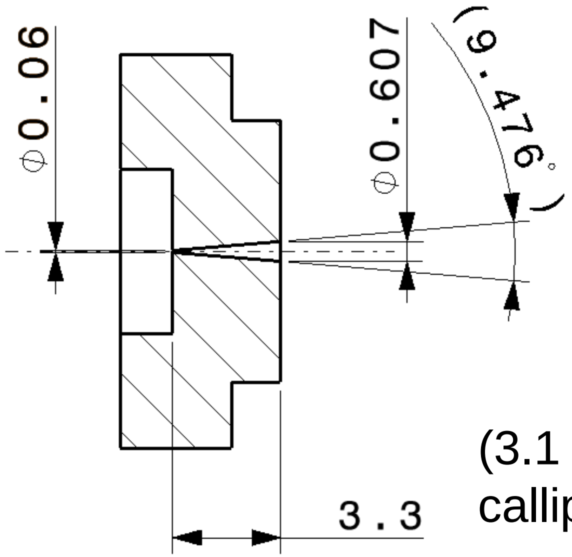
Flat divergent nozzle

- A flat divergent nozzle with an opening of 60microns was also received from CERN.

Drawing



Measurement



(3.1 with callipers)

Presented by Johanna – 19th of July

- Pressure in the nozzle chamber for the original 30 microns nozzle (CERN Design) – 5 bar inlet pressure = 3.5e-3 mbar
- Pressure in the nozzle chamber for the flat divergent nozzle with a neck of 60 microns – 5 bar Inlet pressure = 1.9e-2 mbar
- Flow rate was measured for the flat divergent nozzle. The rate of flow of the nozzle is 10 times higher compared to the 30 microns CERN nozzle.

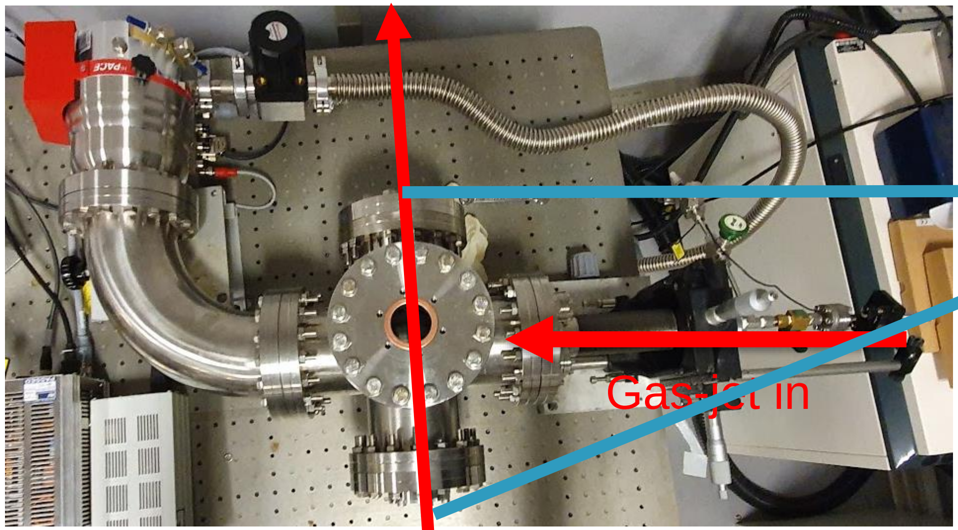
Flat divergent nozzle

- Due to the large nozzle diameter and high pressure in the nozzle chamber, at an inlet pressure of 5 bar, no gas jet was observed.
- A series of measurements were taken at various pressures and various nozzle to skimmer distances.
- Optimum conditions :
  - Nozzle to first skimmer distance : 7 mm
  - Inlet pressure 0.5 bar

- The flat divergent nozzle gives a gas jet that is 3 times lower density than the original CERN 30 micron nozzle with these conditions.

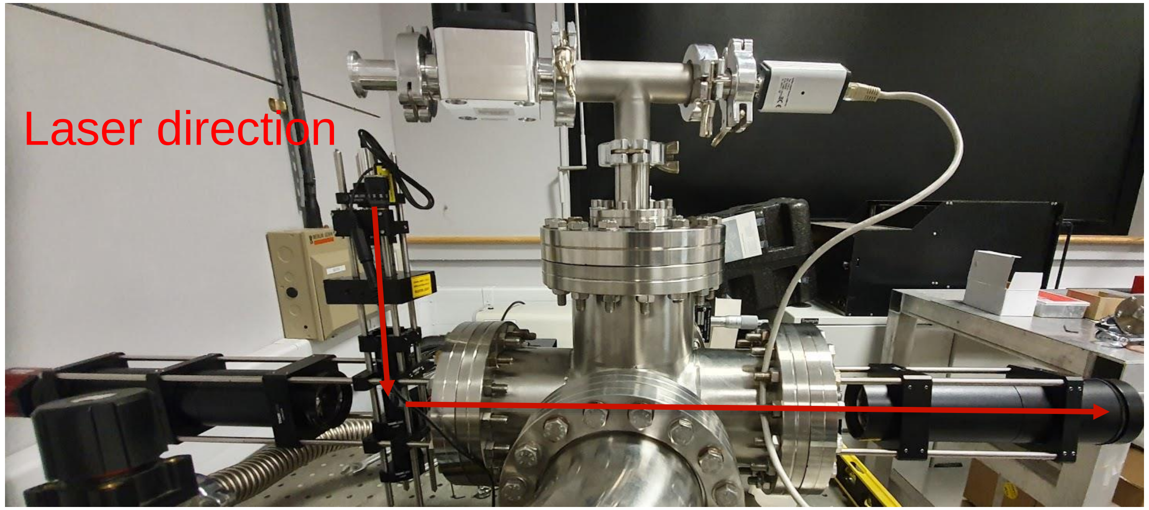
Laser Interferometry

- A stand-alone laser interferometry was assembled, using the 30 micron nozzle from the first setup. This nozzle is connected to a 2D translation stage.
- EDWARDS nXDS15i scroll pump is used in conjunction with a 300 l/s turbo pump to pump a small vacuum chamber.



Pressure inside the chamber with no gas-jet = 1e-3 mbar
Pressure inside the chamber with a 5 bar inlet = 7e-3 mbar

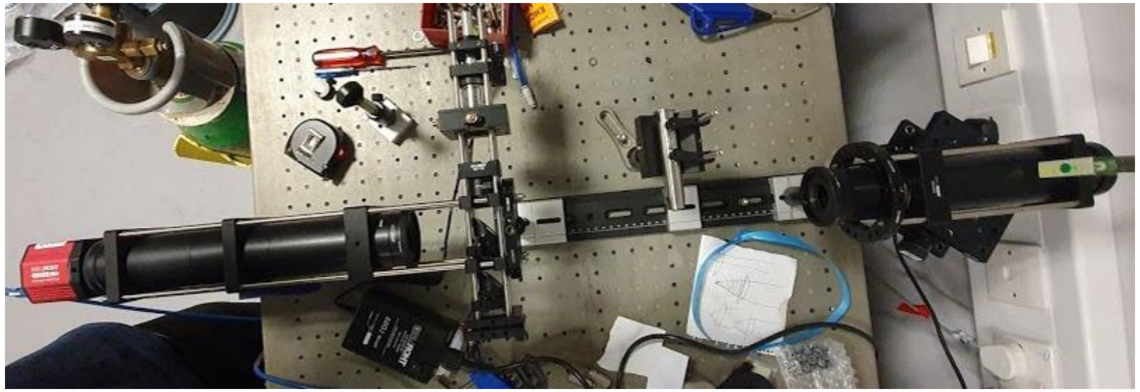
DN40 **UVFS Windows**

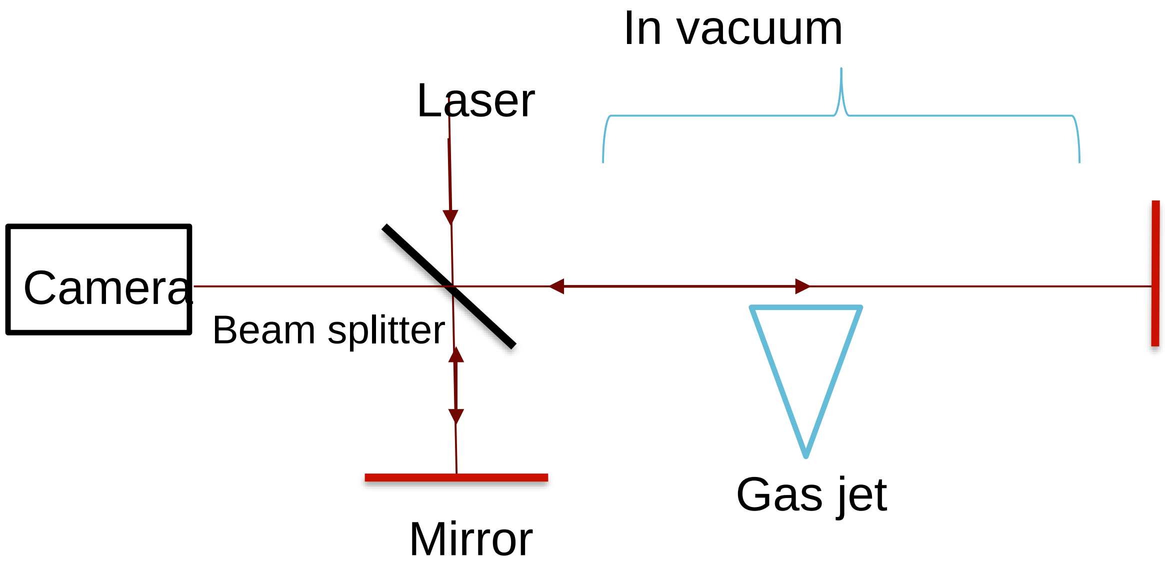


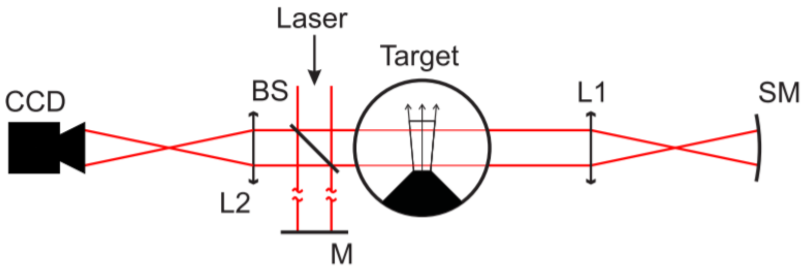
Laser direction

Laser Interferometry

- Two different versions of the optics, one using flat mirrors and one using a spherical mirror.



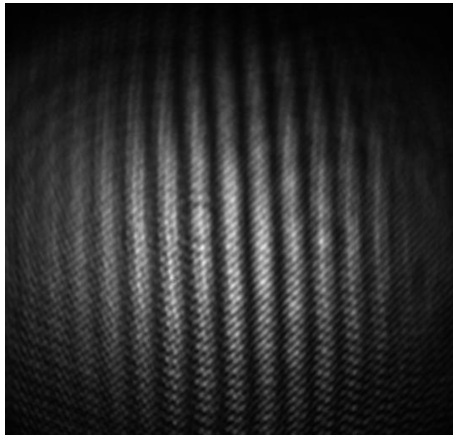




Reference: Imaging Michelson interferometer for a low-density gas jet characterization

Laser Interferometry

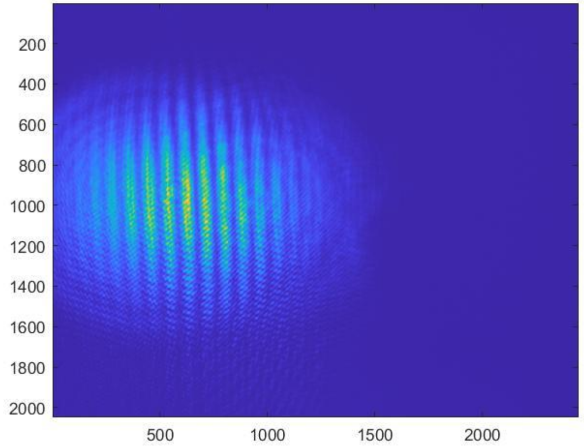
- The system was pumped down and the optical arms were aligned and setup to create fringe patterns with the appropriate width.

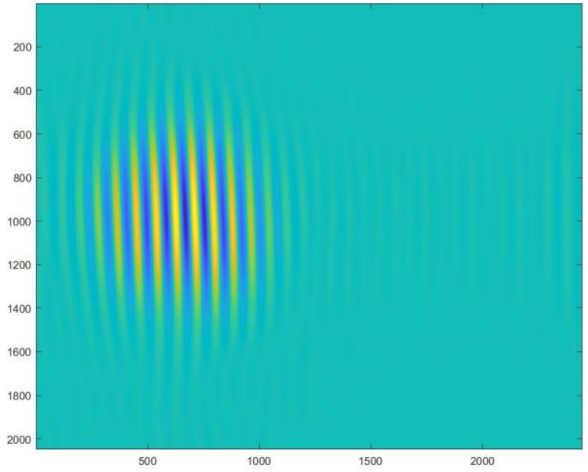


- As well as the dominant vertical fringes, other patterns can also be seen which is caused by reflections from the vacuum windows and beam splitters.
- To retrieve gas jet information the following steps need to be followed :
    1. Retrieve the phase profile.
    2. Unwrap the phase profile.
    3. Retrieve the gas jet density.
- Each step presents algorithmic challenges and there are different methods to do each one.

Laser Interferometry

- The Fourier transform method was used on a series of background images to “clean” the image and reduce the noise. We followed these steps:
  1. The image is transformed via a 2D Fourier transformation and shifted to the centre.
  2. A mask is created in the Fourier plane to set all frequencies but the fringe frequency to zero.
  3. The masked image is then transformed again using a 2D Fourier transformation and the real part of the image is plotted.





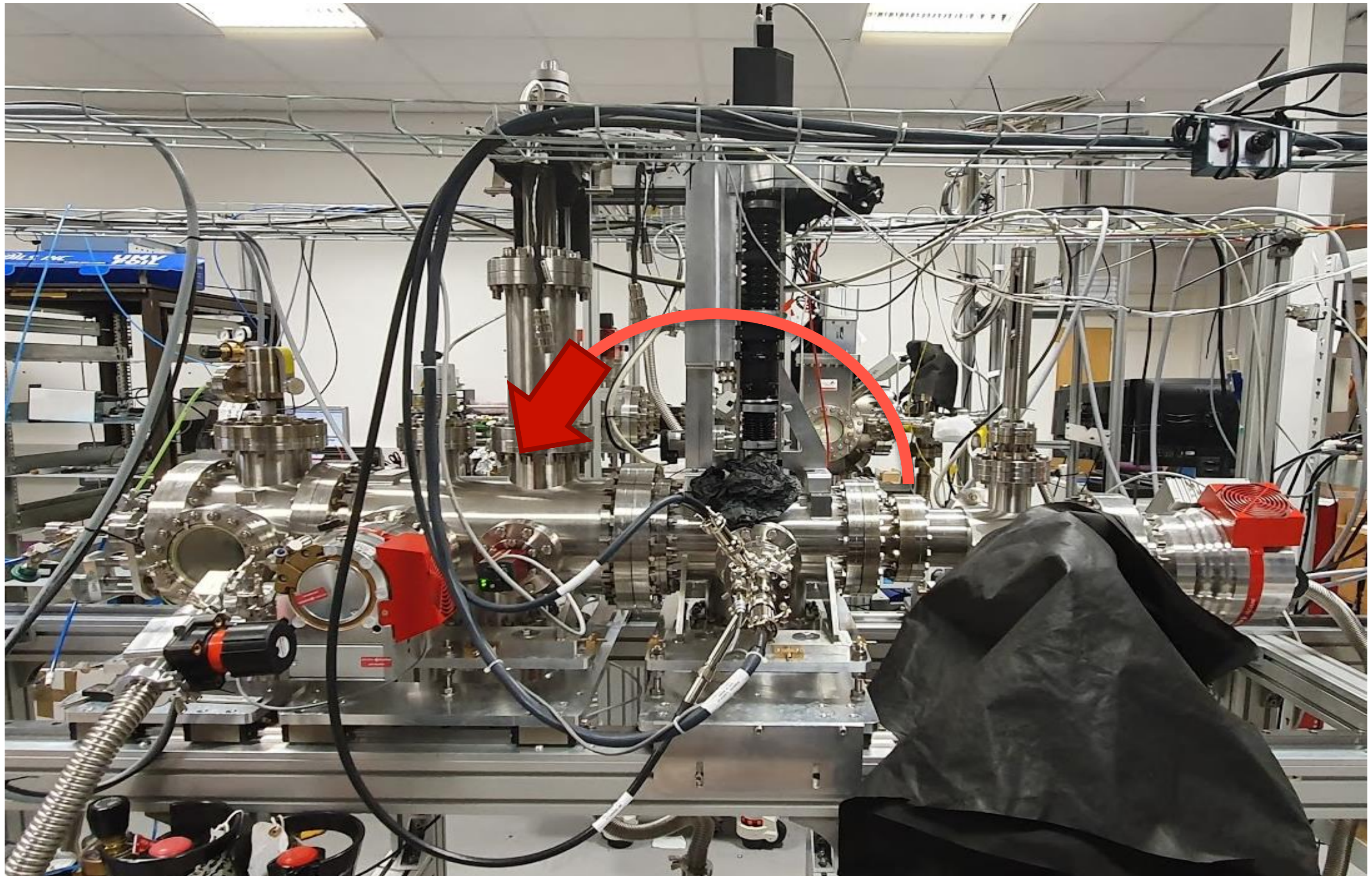
What we know about Skimmer geometry gas jet propagation

- Moveable gauge measurement.
- Density estimation and measurement.
- Jet propagation, divergence and achievable curtain size.

Moveable gauge measurement

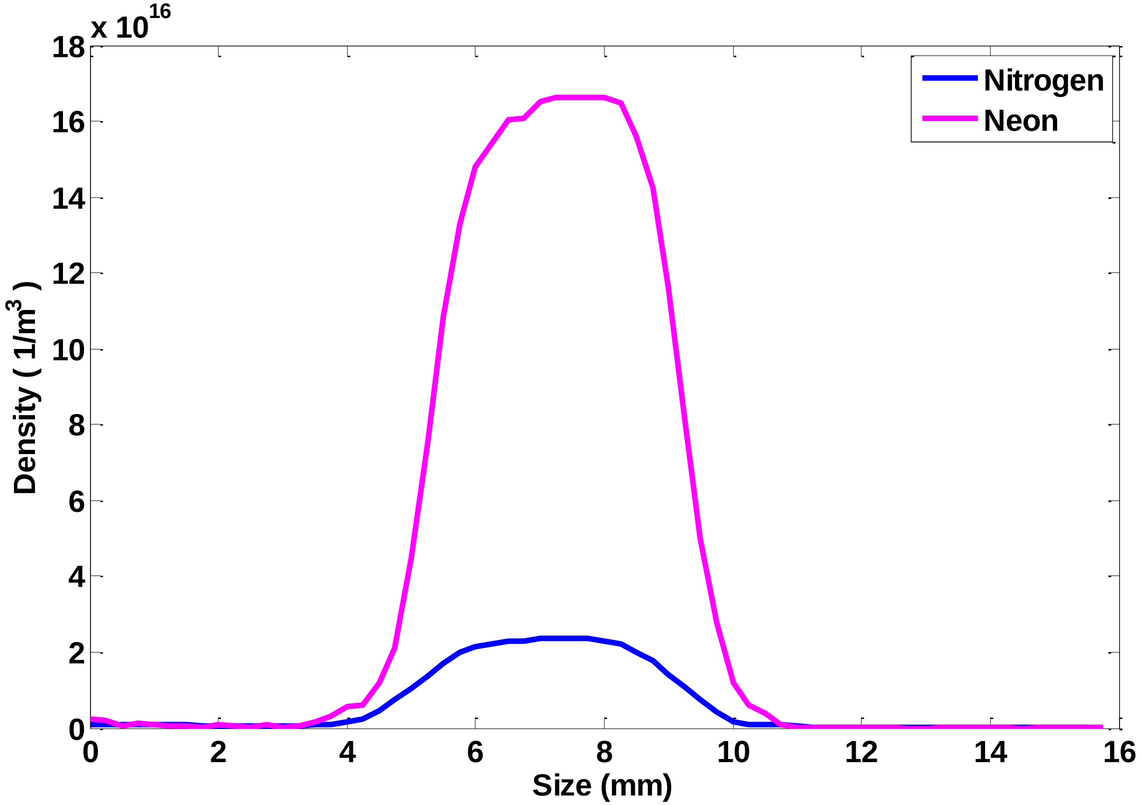
- Goal: Understand how the density of the jet changes as it propagates through the chamber.
- How? The location of the moveable pressure gauge was changed.
- Specifically, it was moved from the diagnostic chamber (after the interaction chamber), to the skimmer chamber (between the second and third skimmer).
- The diagnostic chamber was removed.

Moveable gauge measurements

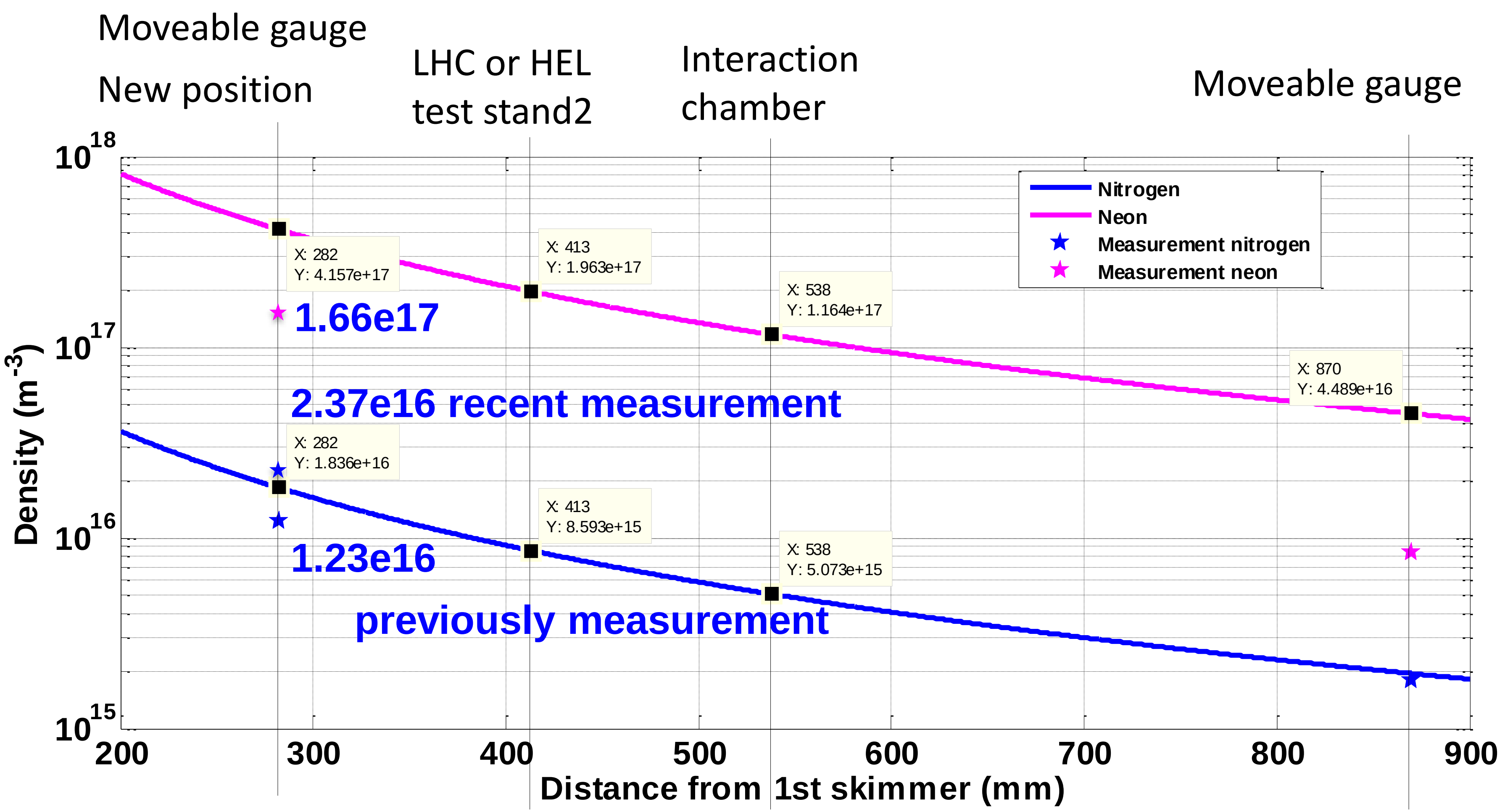


Moveable gauge measurements

- A horizontal scan was performed through the most dense part of the gas-jet for Neon and Nitrogen.

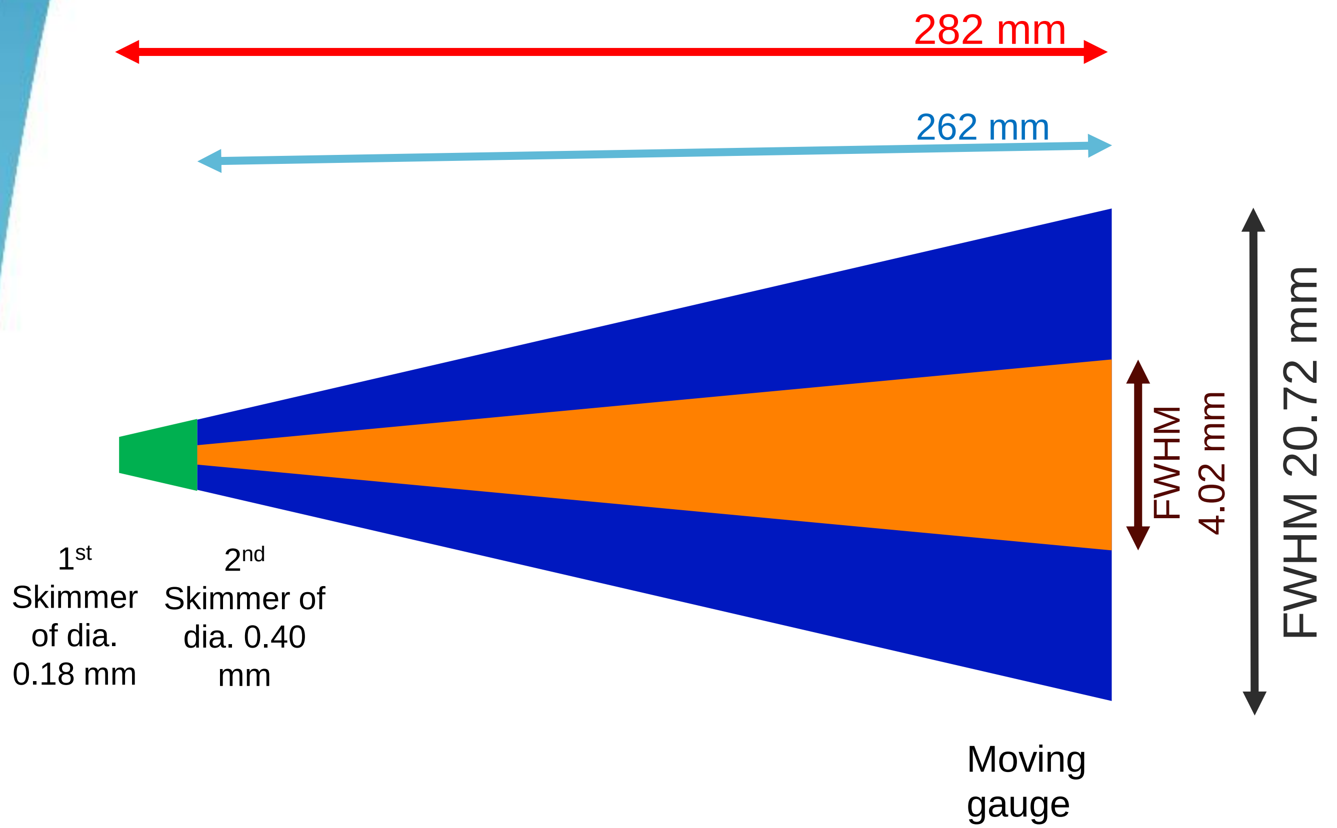


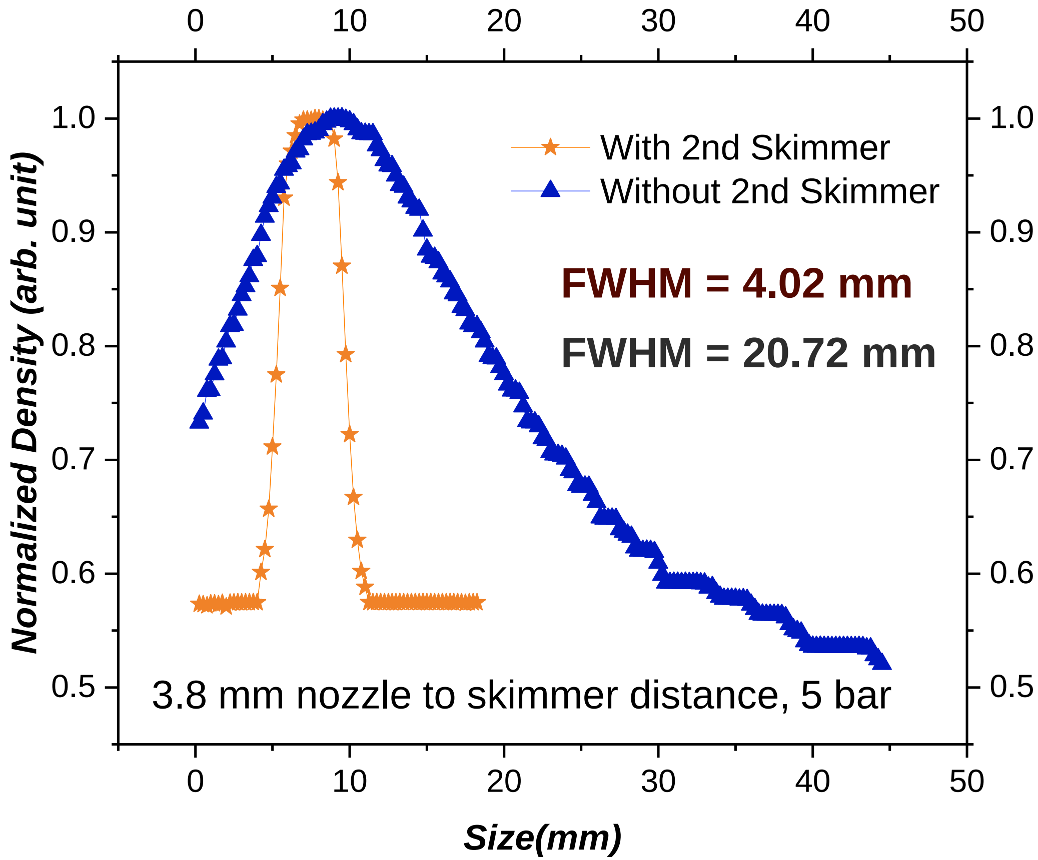
Density estimation and measurement



Experimental Data for gas-jet size

Current Location of Interaction point = 583 mm from 2nd Skimmer (0.4 mm diameter)
New Location of Interaction point= 389.53 mm from 2nd skimmer (0.4 mm diameter)





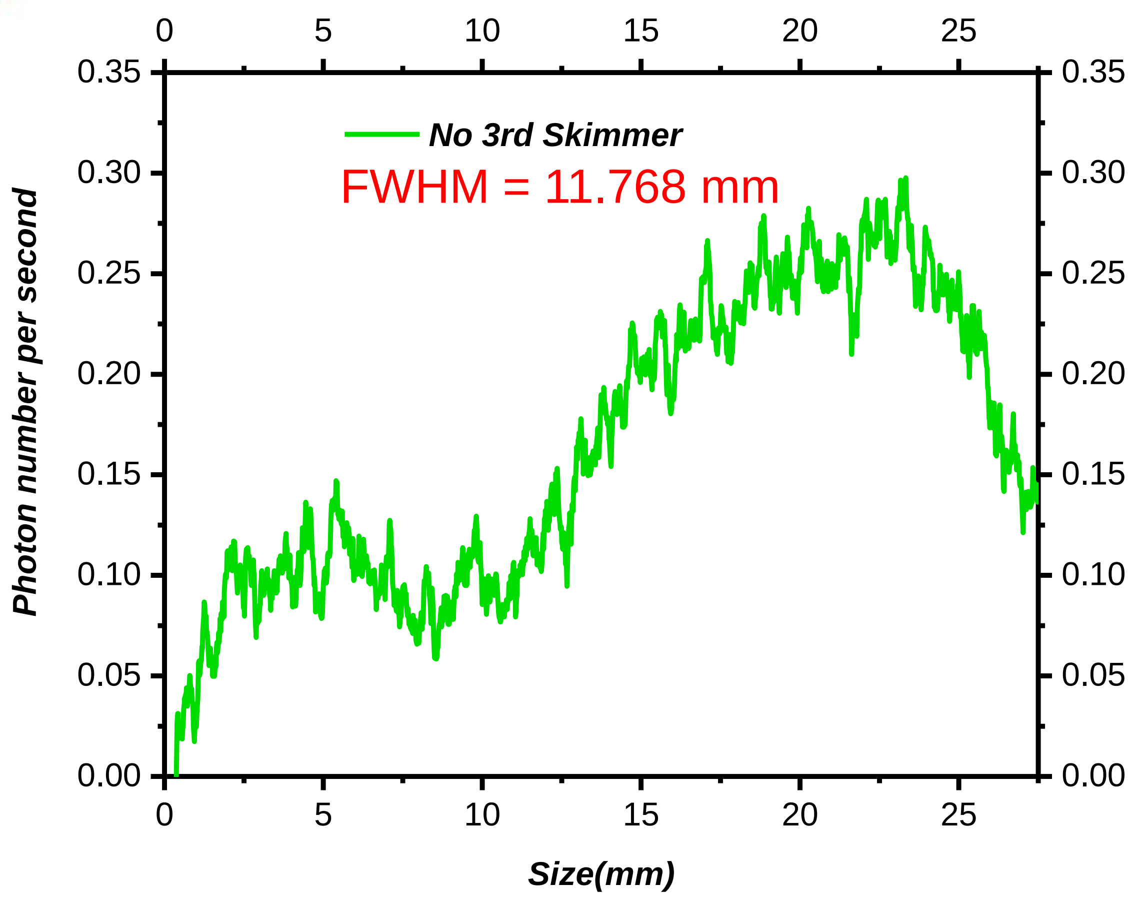
Data from Oct-Nov 2019

Pin Hole Gauge Data located at 262 mm from 2nd Skimmer (0.4 mm Diameter)

HiLumi HL-LHC PROJECT

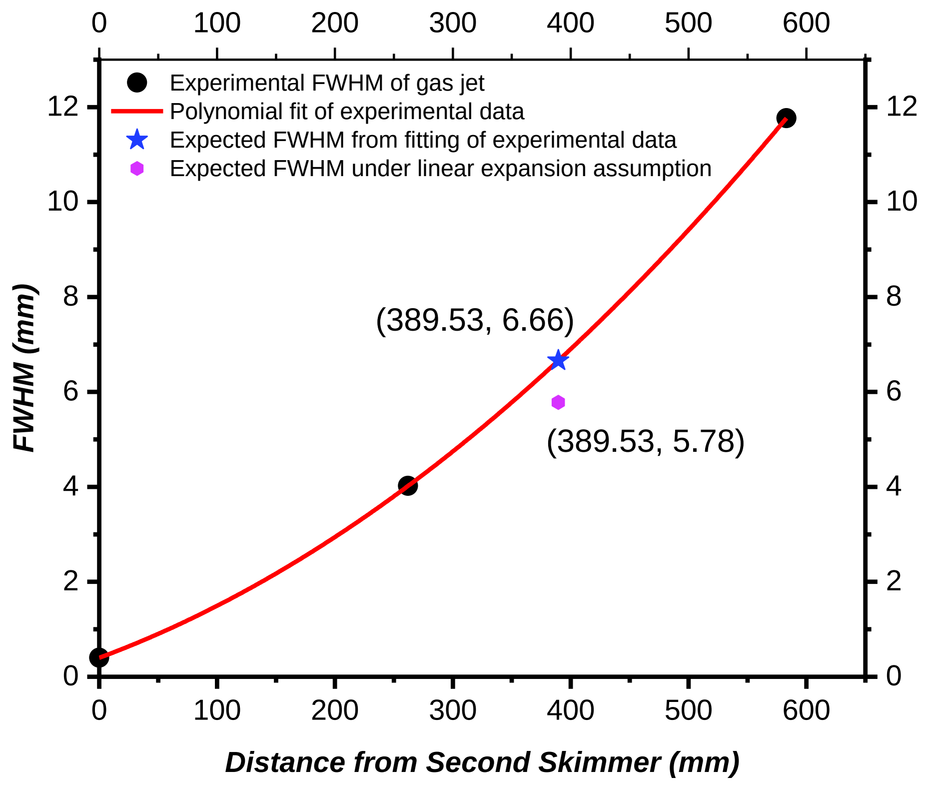
UNIVERSITY OF LIVERPOOL

The Cockcroft Institute of Accelerator Science and Technology



Data for Photon Counts at 583 mm from 2nd Skimmer

Data from Feb. 2019

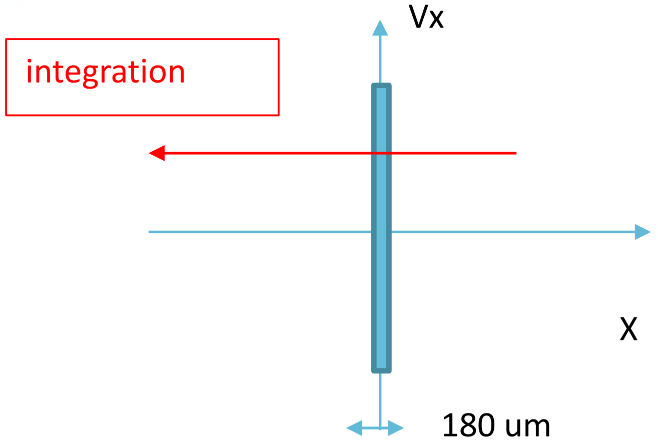


Under the assumption of linear expansion of gas jet after 2nd skimmer

Size of the jet should be (at current interaction point location)= $\left[\frac{4.02-0.4}{262} \times 583\right] + 0.4 = 8.46\ mm$

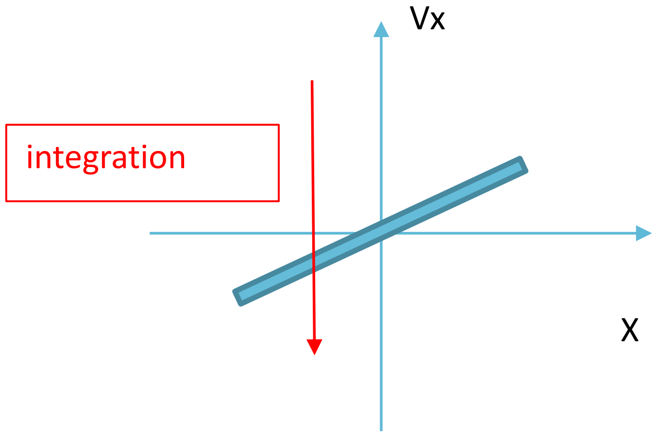
Size of the jet should be (at new location of interaction point) = $\left[\frac{4.02-0.4}{262} \times 389.53\right] + 0.4 = 5.78\ mm$

Gas jet velocity distribution at 1st skimmer



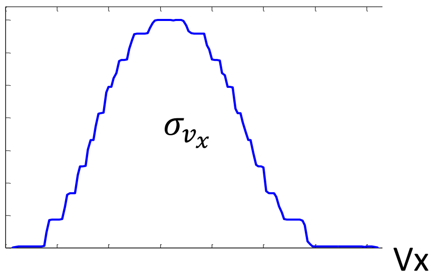
1st skimmer

$$\sigma_x = \frac{282\ mm}{V_{jet}} * \sigma_{v_x}$$

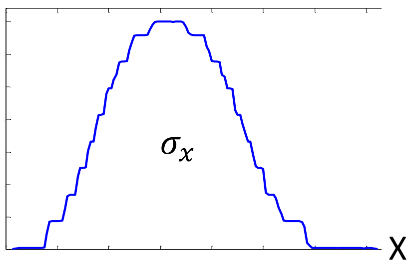


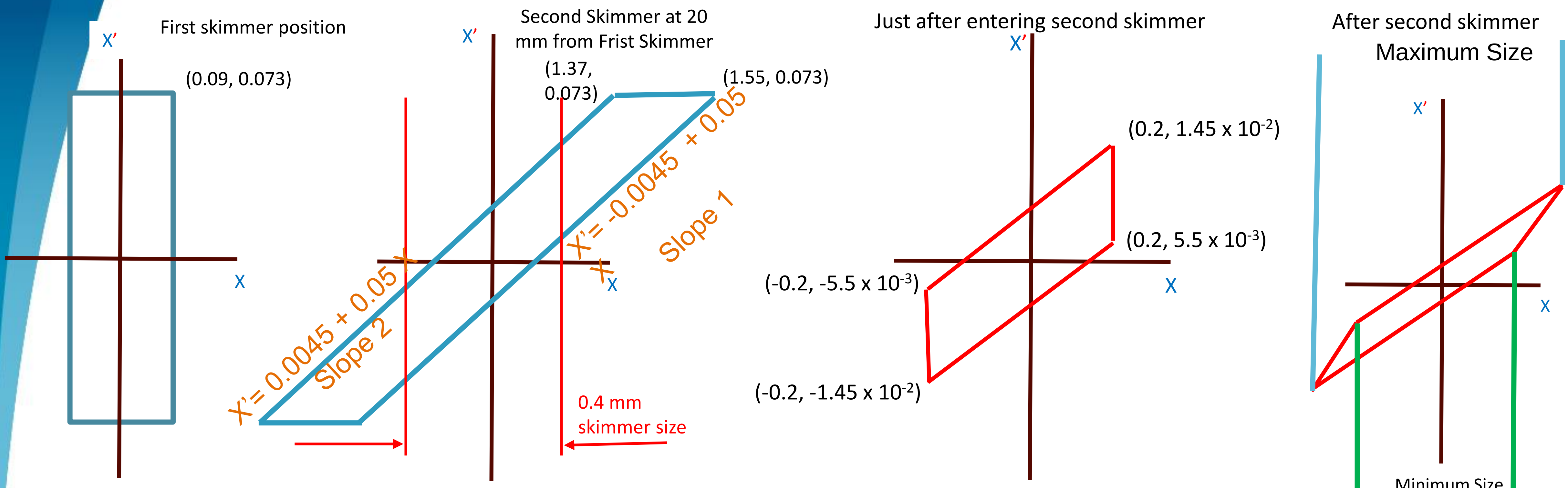
282 mm

Movable gauge



Since the skimmer size is small compare with the propagating distance, what we measured without 2nd skimmer is the velocity distribution.





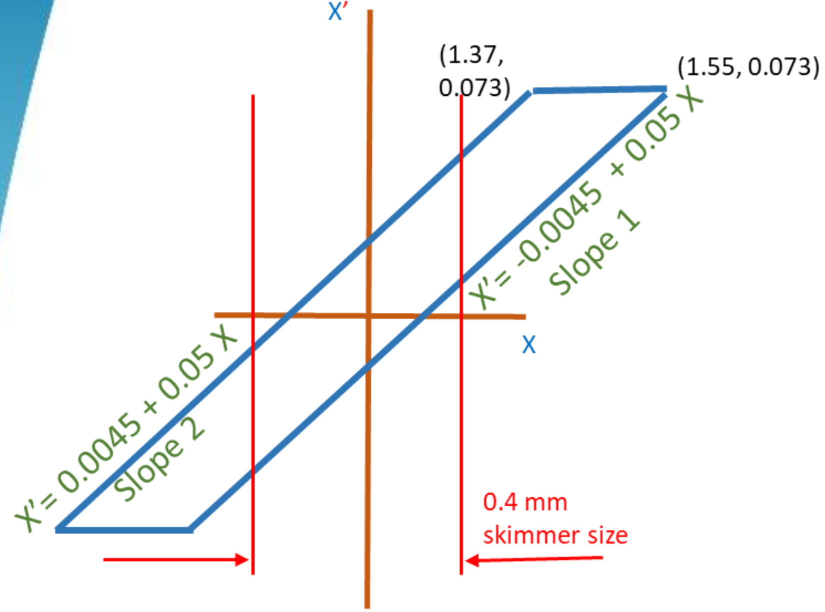
After travelling from second skimmer to movable gauge which is located at 262 mm distance from second skimmer

X = 0.2 + 1.45 X 10^{-2} X 262 = 4.00 mm and X = 0.2 + 5.5 X 10^{-3} X 262 = 1.64 mm Est. Maximum size = 8.00 mm, Est. Minimum size = 3.28 mm
Average is 5.64 mm which is higher to measured FWHM value 4.02 mm (40.3% higher)

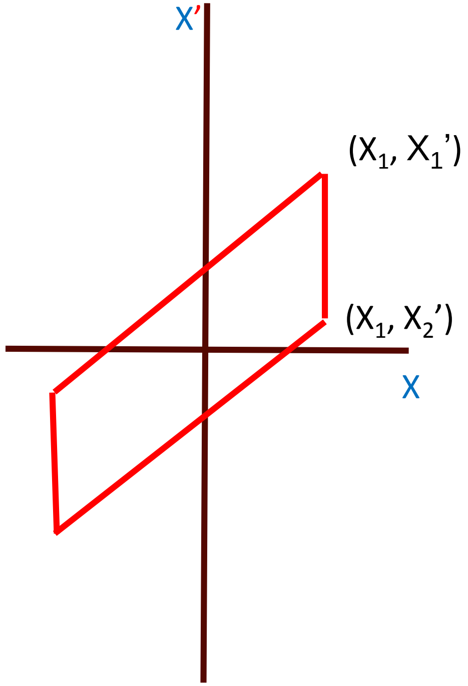
To the location of new interaction point X= 0.2 + 1.45 X 10^{-2} X 389.53 = 5.85 mm Est. Maximum Size = 11.7 mm
X = 0.2 + 5.5 X 10^{-3} X 389.53 = 2.34 mm Est. Minimum size = 4.68 mm From Fitting of experimental data FWHM is 6.66 mm, Average is 8.19 mm which is higher to value obtained from poly. (18.5% higher)

If we have a second skimmer of diameter 3.10 mm (equivalent to no 2nd skimmer) in that case the maximum achievable size of gas jet would be = 2*(1.55+ (389.53 X 0.073)) = ***59.97 mm (expected size would be 50.61 mm)***

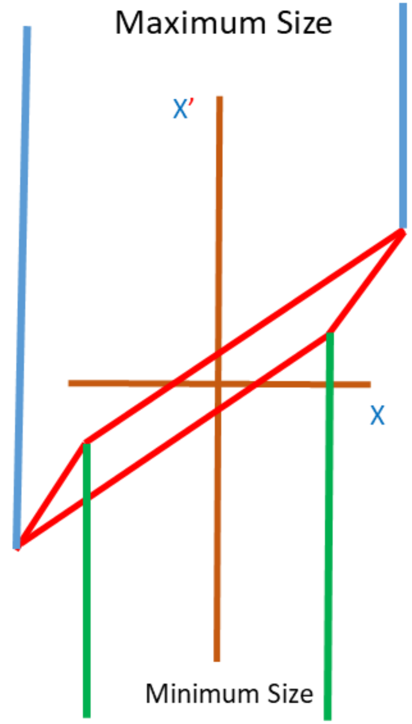
Goal: To Achieve Gas Jet with FWHM 40mm



Second Skimmer at 20 mm from Frist Skimmer



Just after entering second skimmer



After second skimmer

We have to choose a size of second skimmer, Such that FWHM would be 40 mm at interaction point,
The possible solution should also agree with conditions imposed by the gas jet structure and distribution just before the second skimmer, means should satisfy two eqn.'s and considering 18.5% error, we should be aiming for 47.4 mm as Estimated Maximum Size, practically leading to 40 mm FWHM.

X(mm)/ Radius of 2nd Skimmer	X' from slope 1	Estimated Maximum Size (mm) at new IP	Achievable Size (mm)
1.24	0.0575	47.27	39.89
1.25	0.058	47.68	40.23

What we know for signal and S/N ratio

- Photon rate or integration time estimation
- Experimental measurement
- Simulation test for effects from binning, photon number and S/N ratio

Gas performance

- Previously, the estimates on the left hand side were used to approximate the expected photon number.

1. Cross section was calculated at 5 keV instead of 10 keV
2. Density was scaled down for Neon, Argon and Nitrogen.

- These estimates agreed with the experimental values, so they were used again to estimate the number of photons per second for the final setup based on the density at that location.

$$N_\gamma = \sigma \cdot \frac{I \cdot \Delta t}{e} \cdot n \cdot d \cdot \frac{\Omega}{4\pi} \cdot T \cdot T_f \cdot \eta_{pc} \cdot \eta_{MCP}$$

n = 2.5 · 10^{10} cm^{-3} (Still not there!)
d = 5 · 10^{-2} cm
Ω = 40π · 10^{-4} sr (Scheimpflug!?)
T = 85%
T_f = 80%
η_{MCP} = 75%

N_γ = average number of photons detected during time Δt
σ = cross section of the photon generation process
I = electron or proton current (electrical)
e = elementary charge
n = gas density
d = distance traveled through gas (curtain thickness)
Ω = solid angle of the optics
T = transmittance of the optical system
T_f = transmittance of the optical filter
η_{pc} = quatum efficiency of the photocathode
η_{MCP} = detection efficiency of the MCP

Projectile	Emitter	λ [nm]	σ [cm²]	I [A]	η_{pc}	N_γ [s^{-1}]	$1/N_\gamma$ [s]
electron	N_2^+	391.4	$9.1\cdot10^{-19}$	5	0.19	$3.4\cdot10^{6}$	$2.9\cdot10^{-7}$
proton	N_2^+	391.4	$3.7\cdot10^{-20}$	1	0.19	$2.8\cdot10^{4}$	$3.6\cdot10^{-5}$
electron	Ne	585.4	$1.4\cdot10^{-20}$	5	0.09	$2.5\cdot10^{4}$	$4.0\cdot10^{-5}$
proton	Ne	585.4	$4.7\cdot10^{-22}$	1	0.09	$1.7\cdot10^{2}$	$5.9\cdot10^{-3}$
electron	Ar	750.4 & 751.5	$7.4\cdot10^{-20}$	5	0.02	$2.9\cdot10^{4}$	$3.4\cdot10^{-5}$
proton	Ar	750.4 & 751.5	$3.3\cdot10^{-21}$	1	0.02	$2.6\cdot10^{2}$	$3.8\cdot10^{-3}$
electron	Ar^+	454.5 & 476.5	$9.9\cdot10^{-21}$	5	0.20	$4.0\cdot10^{4}$	$2.5\cdot10^{-5}$
proton	Ar^+	454.5 & 476.5	$1.7\cdot10^{-21}$	1	0.20	$1.4\cdot10^{3}$	$7.4\cdot10^{-4}$

S. Udrea, P. Forck, E-Lens Collab. Meeting, Nov. 27th, 2018

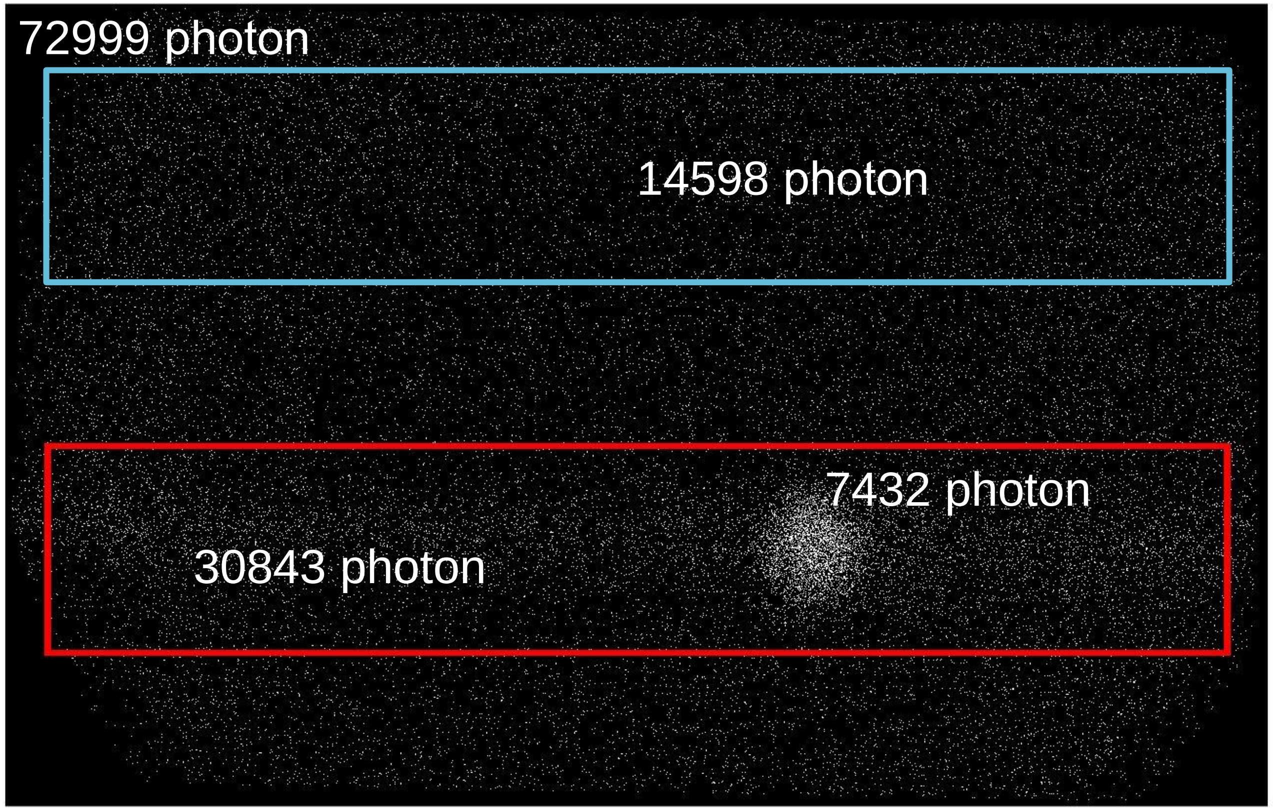
Estimation for LHC or HEL test stand2

single photon average integration times

Projectile	emitter	Cross-section[cm²]	I (A)	$<t_i>_{MCP}$ (s)	N_{photon} (s^{-1})
Electron	N_2^+	9.1e-19	5	8.53e-7	1.17e6
Proton	N_2^+	3.7e-20	1	1.05e-4	9.52e3
Electron	Ne	1.4e-20	5	1.79e-5	5.59e4
Proton	Ne	4.7e-22	1	2.64e-3	3.79e2

Density estimation: 5.60e16 m^{-3}(Neon), 8.59e15 m^{-3} (N2) , see slide 29

S/N ratio from the experimental data

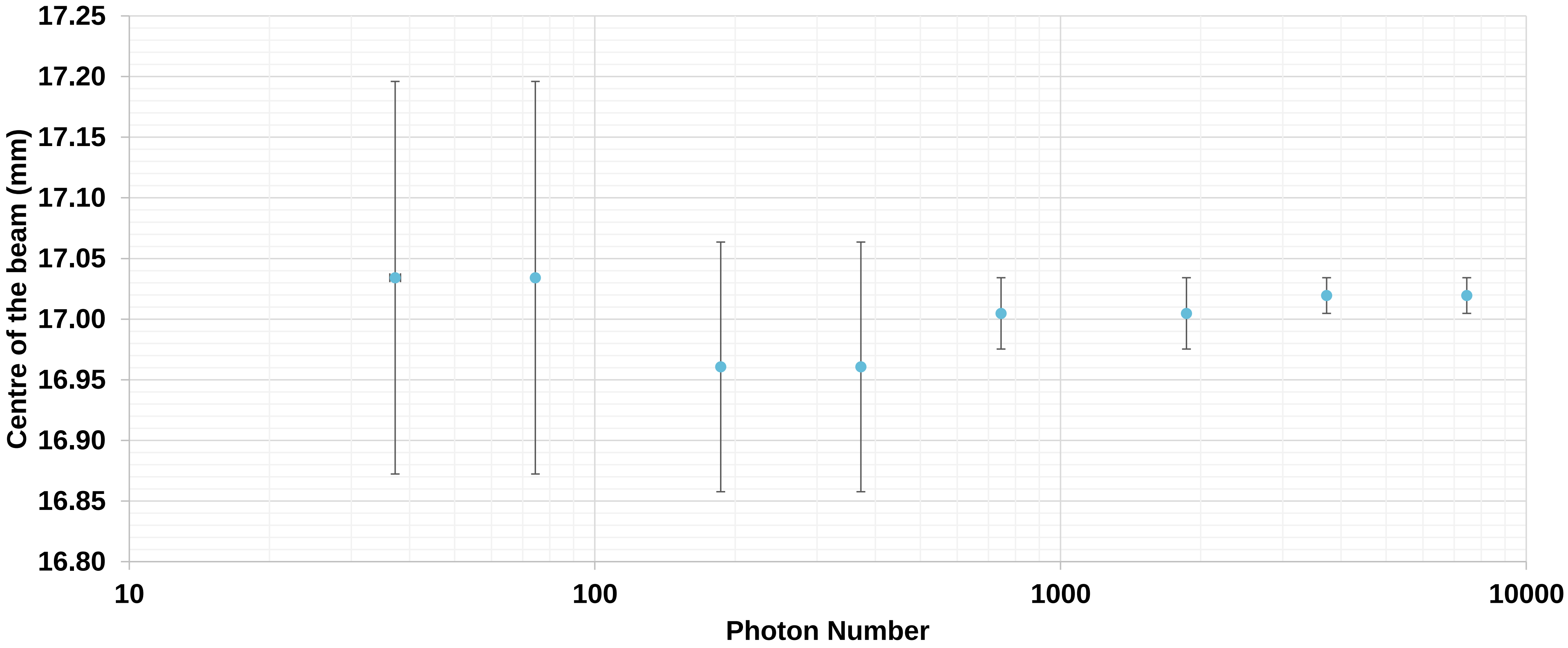


Integration time : 400secs

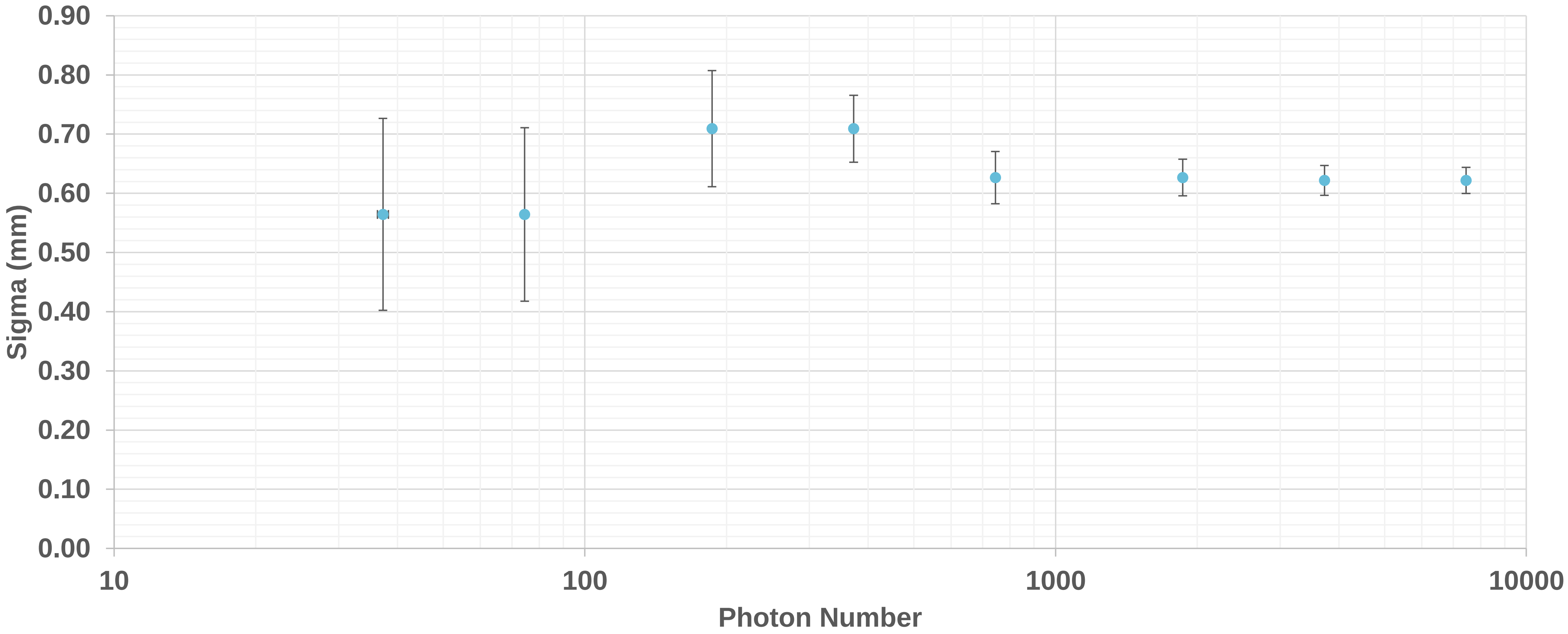
- Total number of photons in the entire image = 72999
- Total number of photons in the blue box (includes only statistical noise) = 14598
- number of photons in the red box (includes residual +statistical noise and jet) : 30843
- Total number of photons from the jet : 7432 +/- 200

- S/N ratio for the image ~7432/72999 ~0.1
- S/N ratio for the ROI ~ 7432/30843 ~ 0.2

Centre of the beam measurements

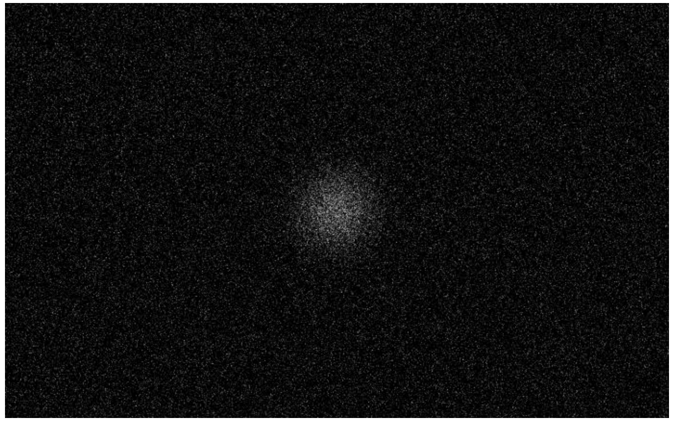


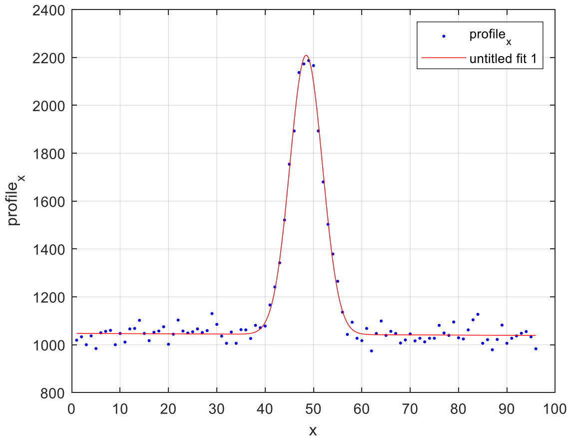
Beam size measurements

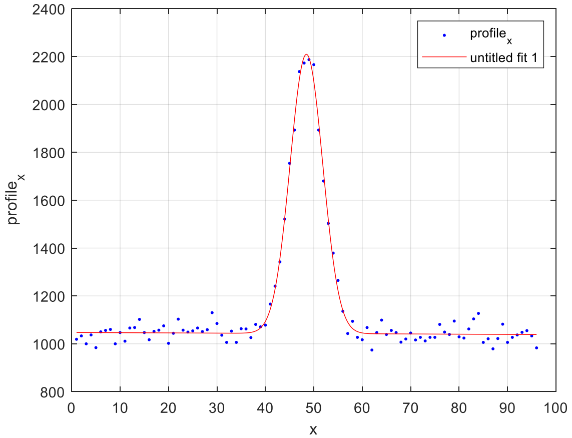


Tests with simulation

- Randomly generated gaussian beam distribution based on photon number.
- 1. Test how the binning number affect the measurements.
- 2. Test how the photon number affect the measurements.
- 3. Test how the noise level (uniformly distributed) affect the measurement.

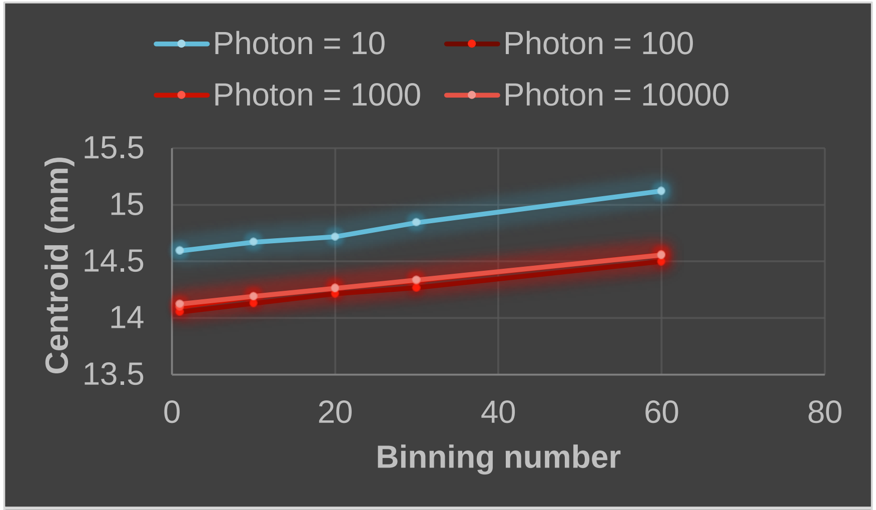


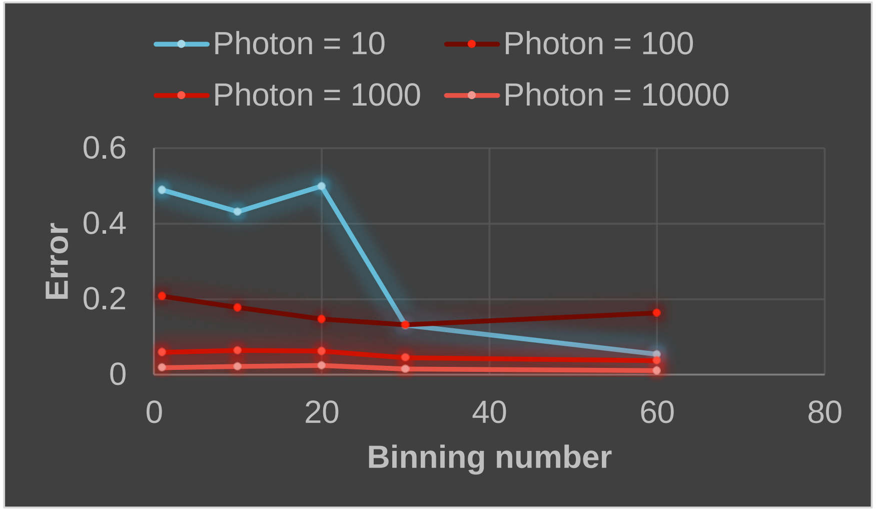


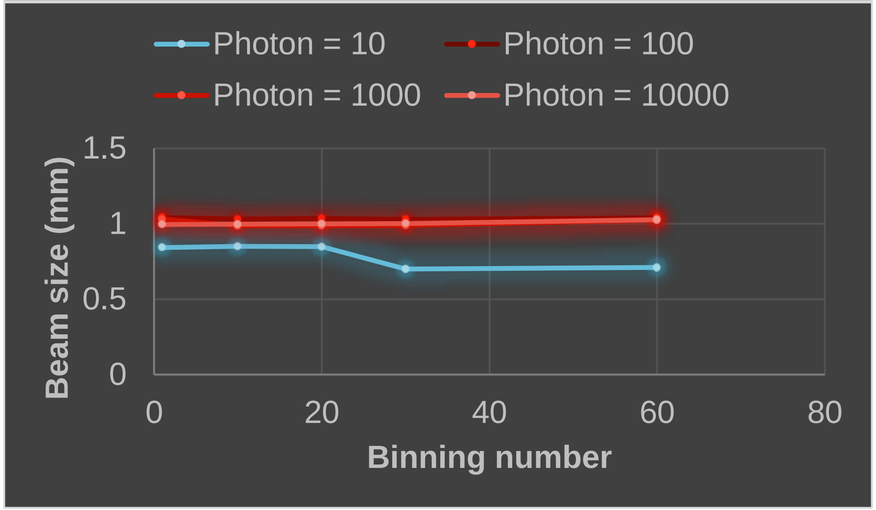


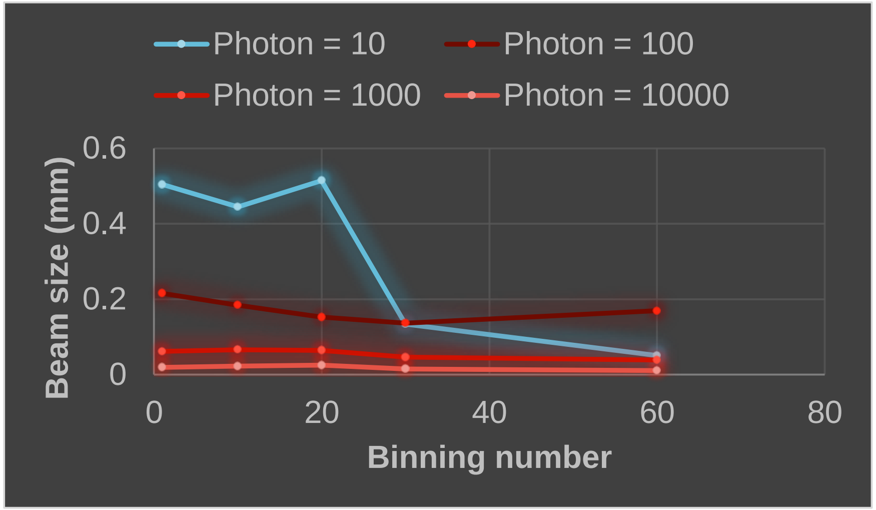
Example: N = 10000, binning number = 20, S/N ratio = 0.1

Binning number



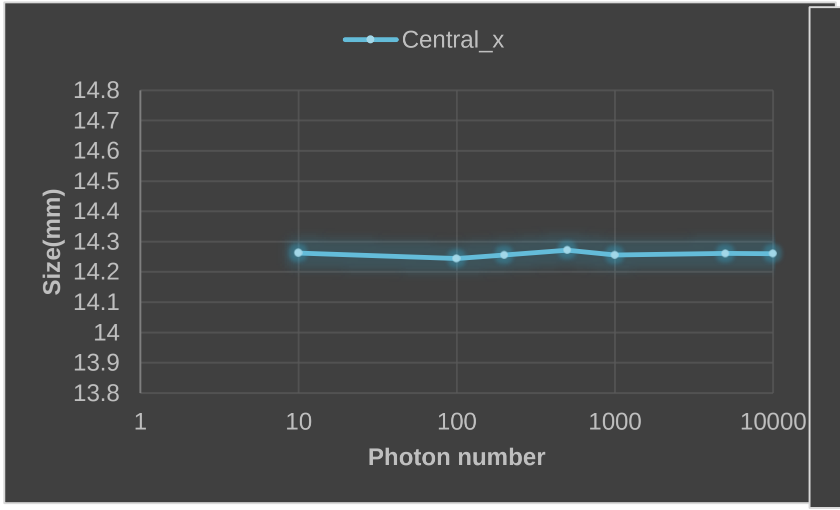


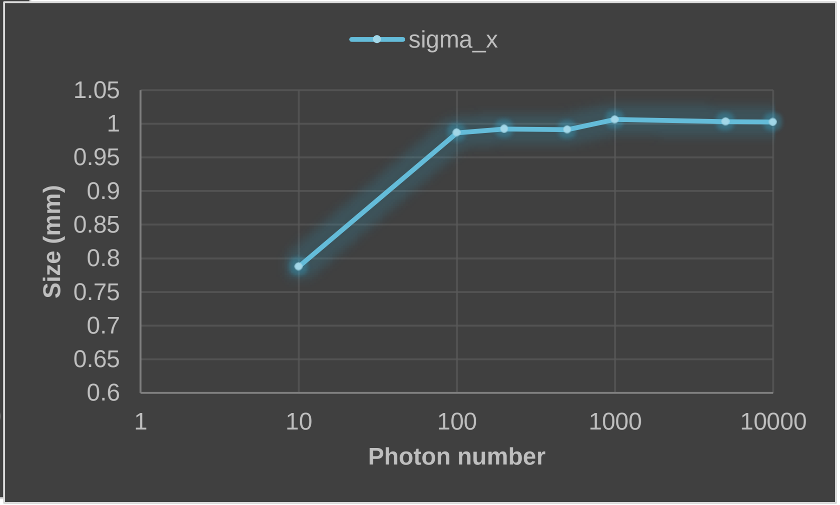


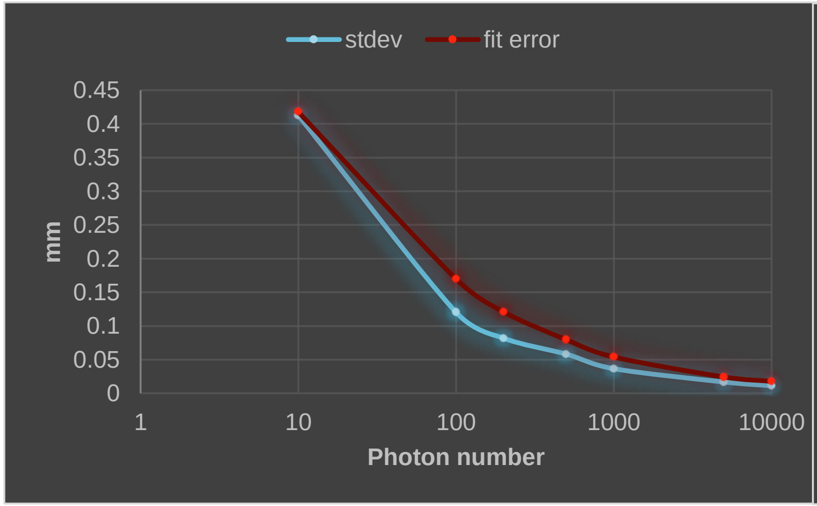


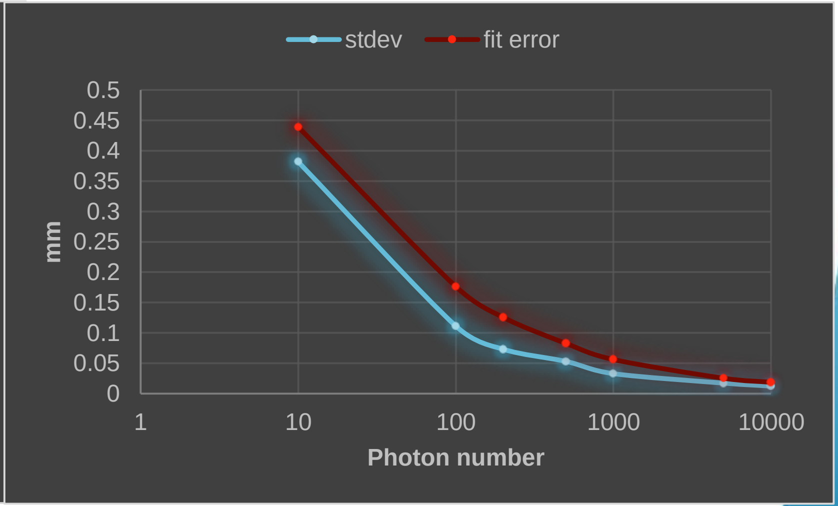
Photon number

- Condition
  - Binning = 20
  - Average over 100 beam profile
  - Stdev based on 100 beam profile
  - Fit error is averaged from 100 fitting each case



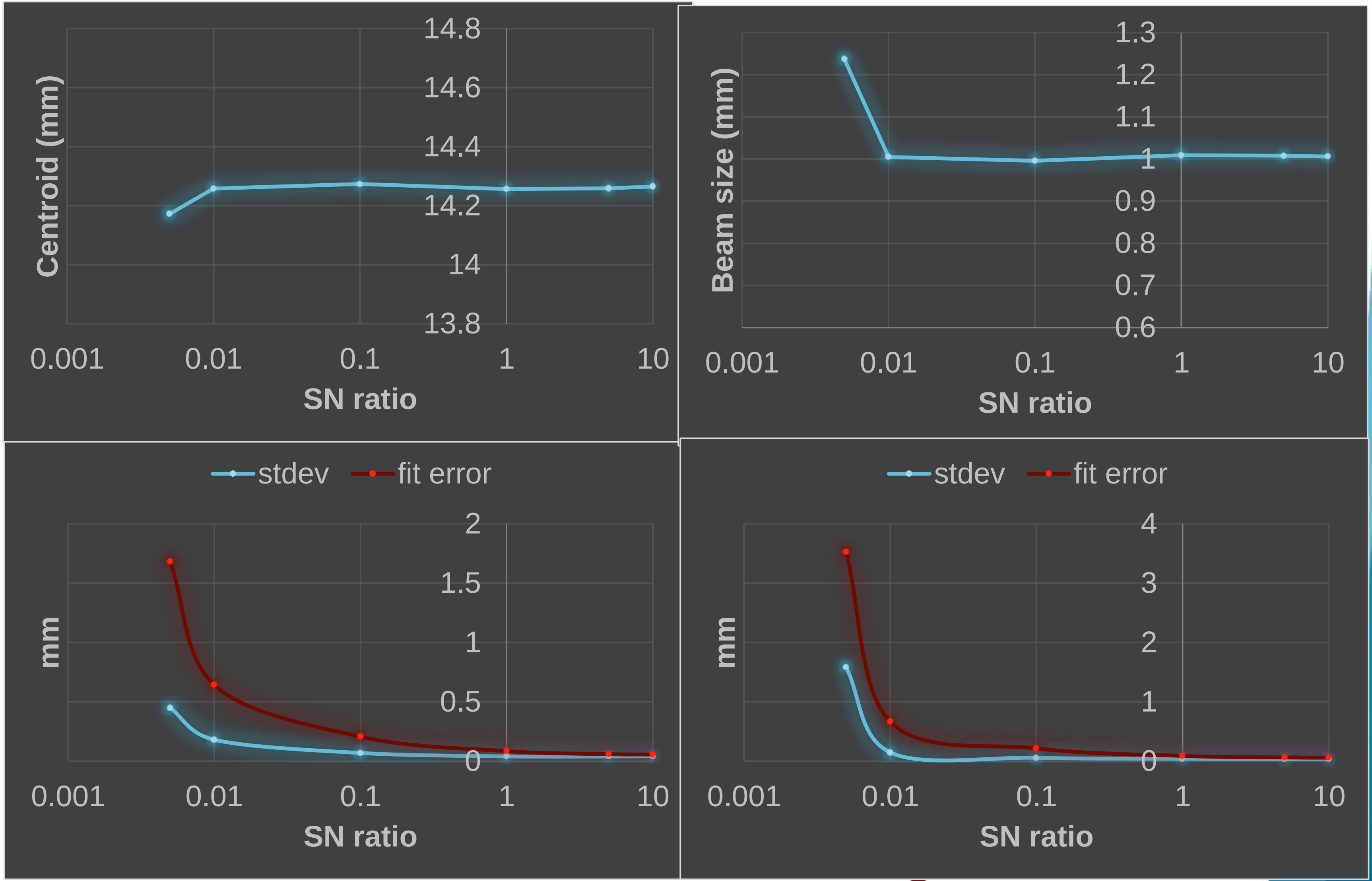






Noise

- Condition
  - Binning = 20
  - Average over 100 beam profile
  - Stdev based on 100 beam profile
  - Fit error is averaged from 100 fitting each case
  - Photon number = 1000



Summary for the simulation tests

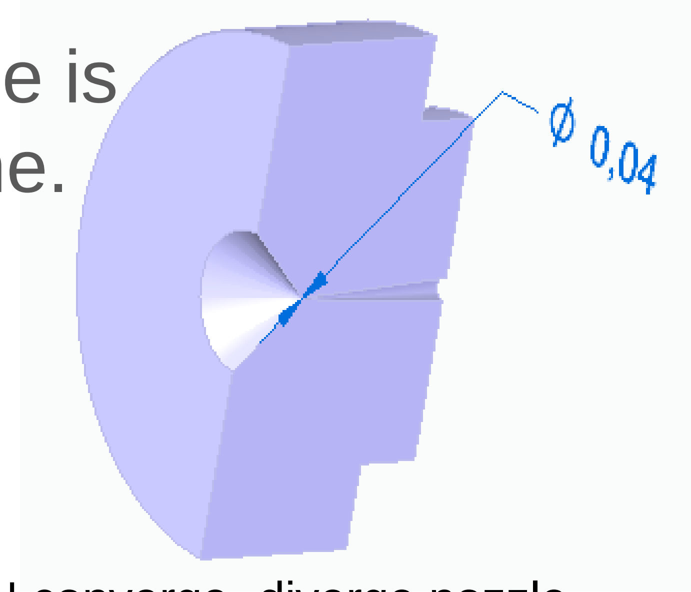
- Binning only work for low signal level.
- Increasing photon number will increase resolution but has a limit.
- Low S/N ratio will increase the error. (did not consider residual gas effect and region of interest).

2020 Experimental Program

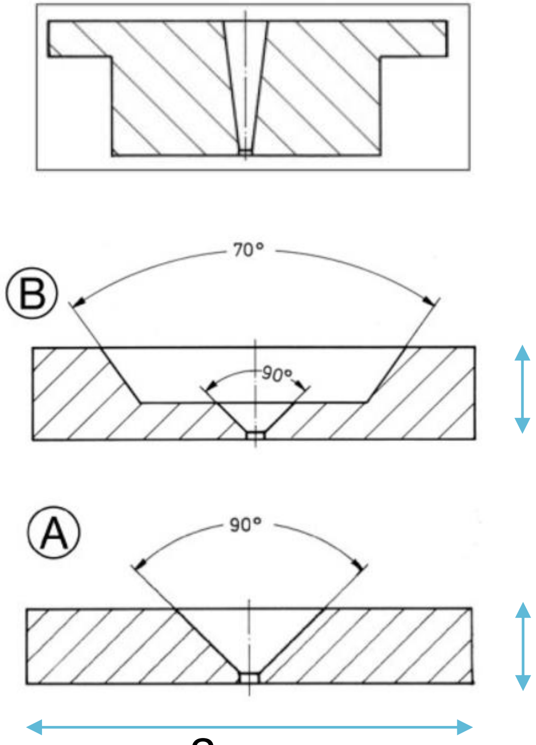
- Laser interferometry
- Test on v1 instrument
  - gas mixing test.
  - FZL lens holder design, manufacturing and installation in V1 setup (IPM).
- Test on v2 instrument
  - Skimmer diameters
    - Order different shape skimmer
    - Spacer length
  - CST simulations for Gaussian profiles to determine the size and density distribution by comparing with experimental data
- V3 instrument
  - Nozzle test
    - (depend on the availability of CERN convergent-divergent nozzle)
    - Alternative design
  - Manufacture the chambers (2 months-3 months)
  - Assemble the instrument (2 weeks)
  - Test the vacuum conditions
    - Ultimate pressure
    - Pressure distribution during gas injection
    - Gate valve mechanism during unwanted events (Leaking, over pressured)

Alternative nozzle

- Depend on the availability of CERN nozzle.
- Independent CI nozzle design in case the nozzle is not delivered before June.



CERN converge- diverge nozzle



0.25 mm

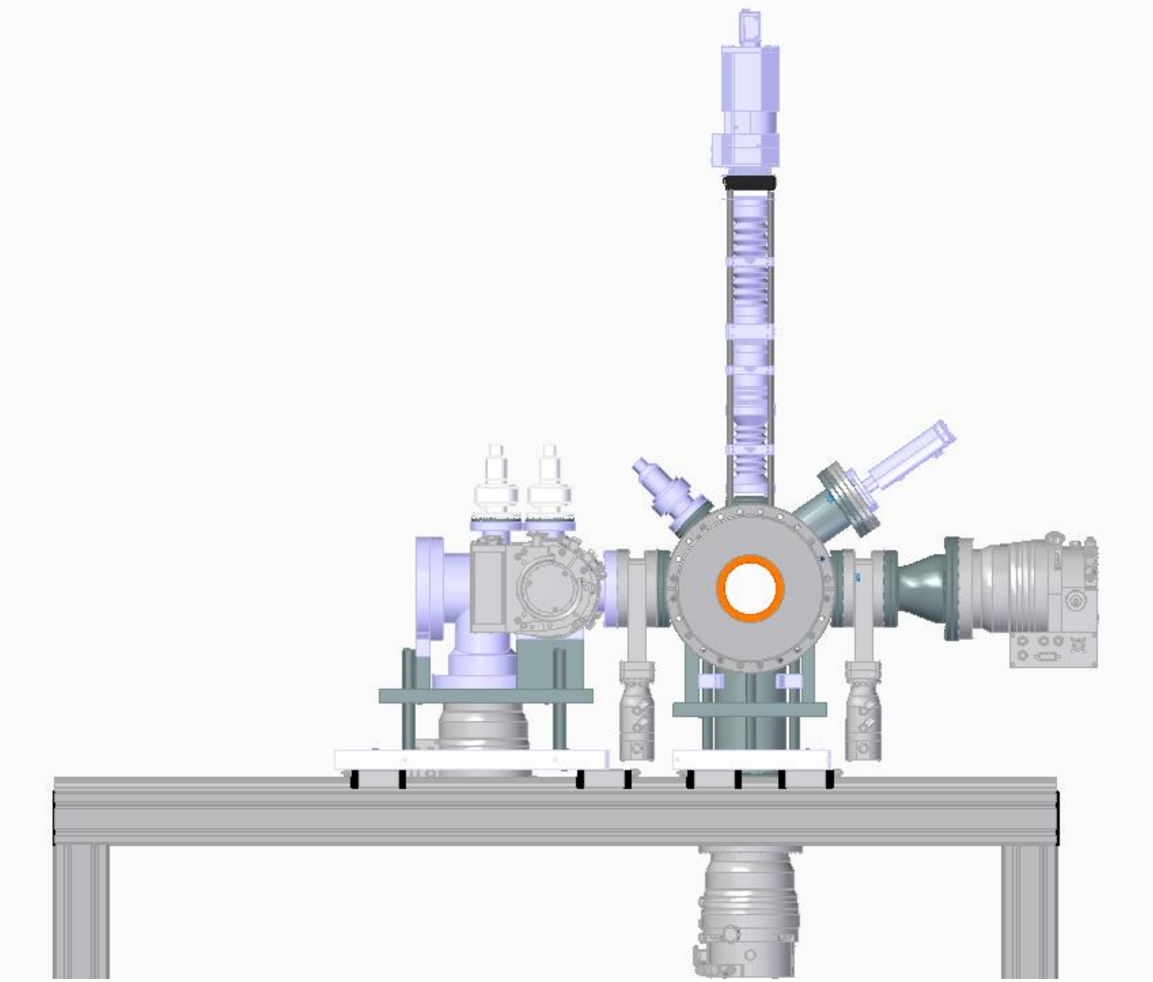
0.1 mm

3 mm

Available hole size: 20 – 100 um
Capillary length: ½ hole diameter

Design and procurement of BGC V3

- Compatible to BGC for LHC
- Flexible for CI test and HEL test stand implementation.
- Working on producing the manufacture drawing.



Procurement for V3 instrument in CI

- Frame ready.
- Optics ready by end of March.
- Gauges ready.
- Target and bellow drive (CERN ordered)
- Pumps ordered (delivered day to be confirmed with CERN).
- Gate valve ready by May.
- Injection chamber sent out for manufacturing
- Interaction chamber is waiting for manufacture drawing.

HiLumi
HL-LHC PROJECT

Thanks !