Experimental Results from Cockcroft 2018/2019

A. Salehilashkajani, H. Zhang, C. Welsch

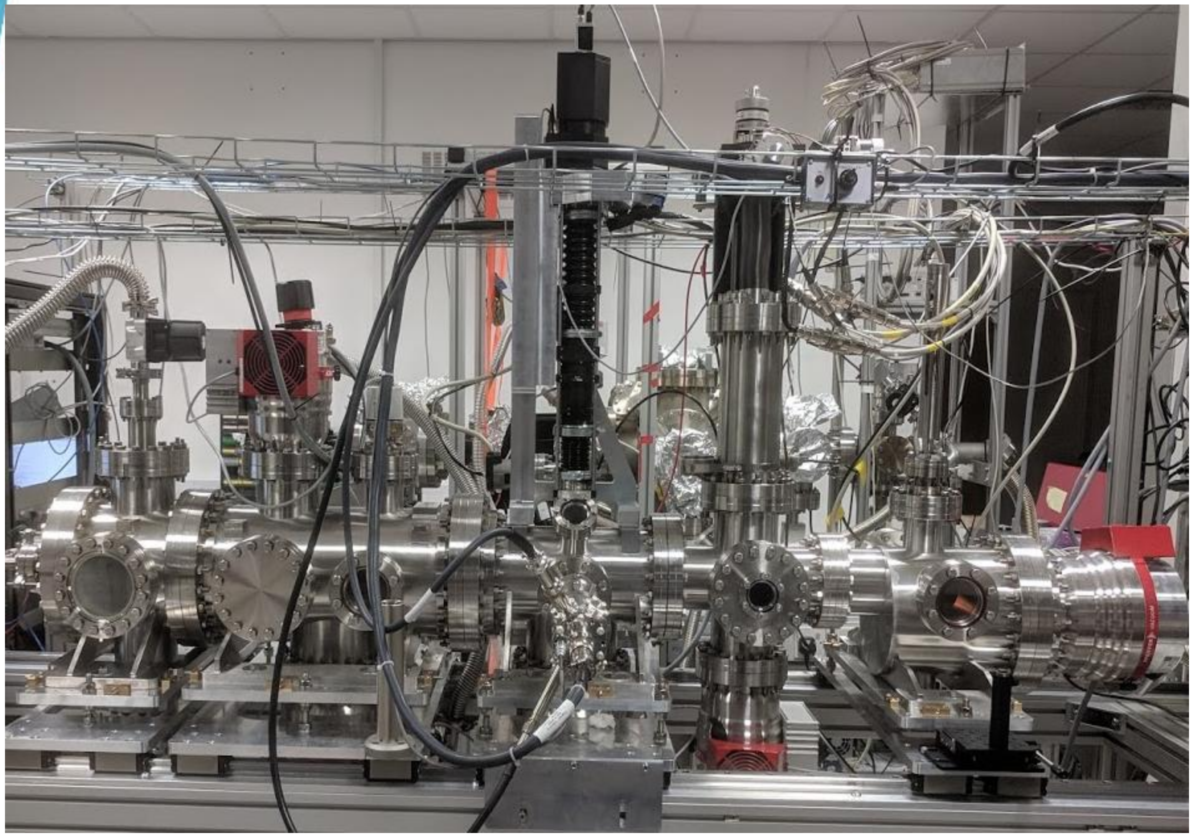
Amir.Salehilashkajani@Cockcroft.ac.uk

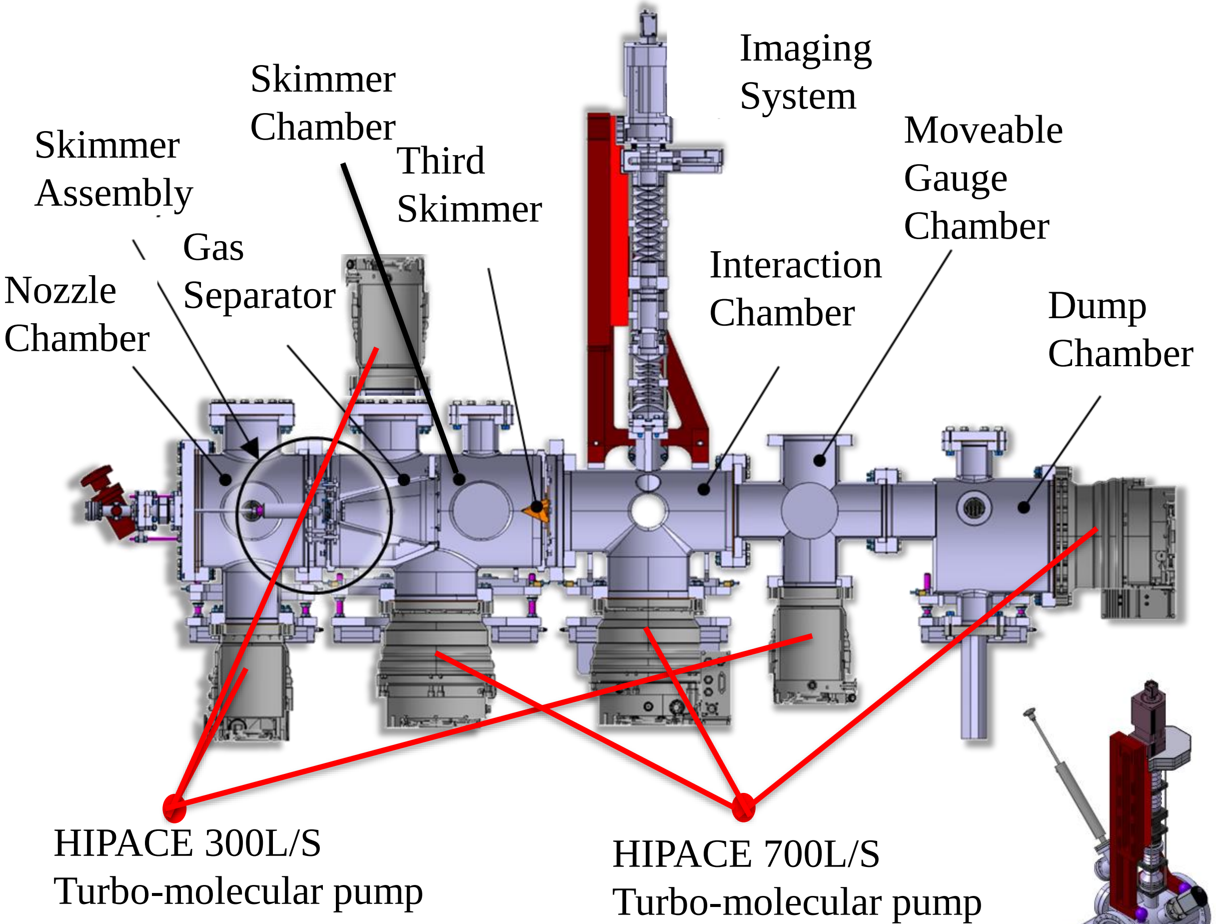
BGC Collaboration Meeting 2019/06/13

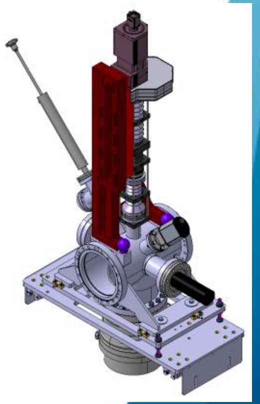
Outline

- System highlights.
- Gas jet signal from Argon, Neon and Nitrogen jets.
- Comparison between the theoretical predictions and the data.
- Optimisations performed.
- Pressure tests in 2019 and pumping modifications.
- Tests with the 50 micron nozzle.

Prototype in the Cockcroft Institute



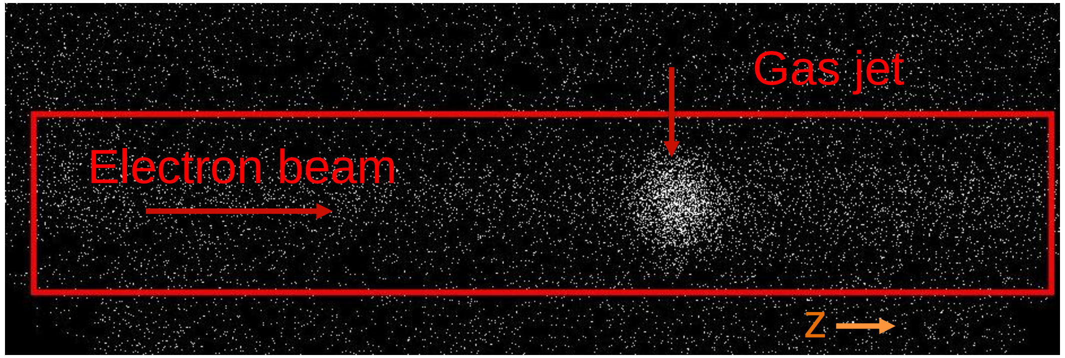


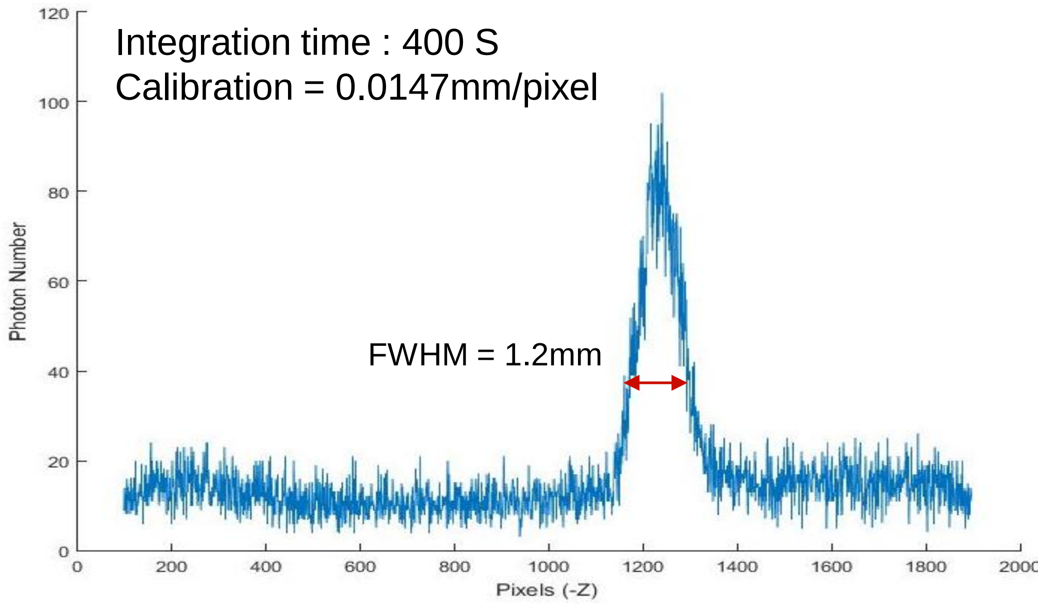


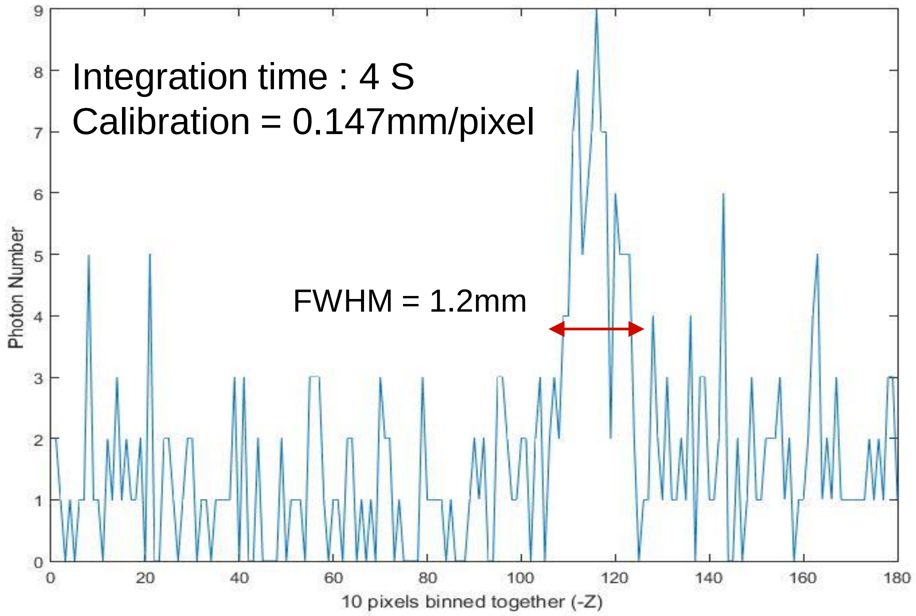
Experimental conditions for the three gases

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

Nitrogen



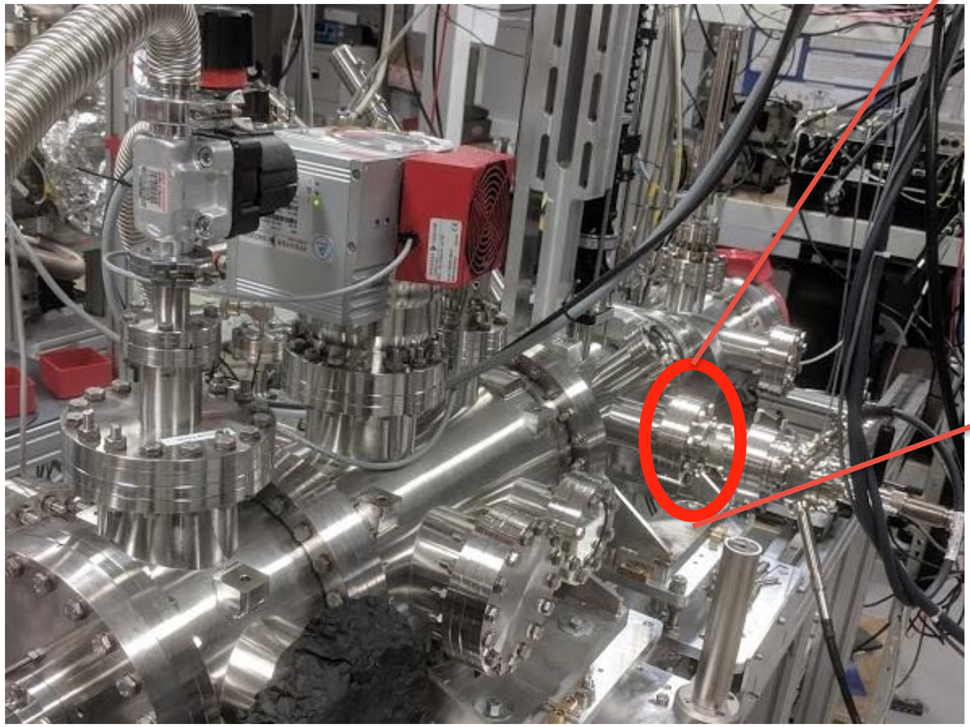


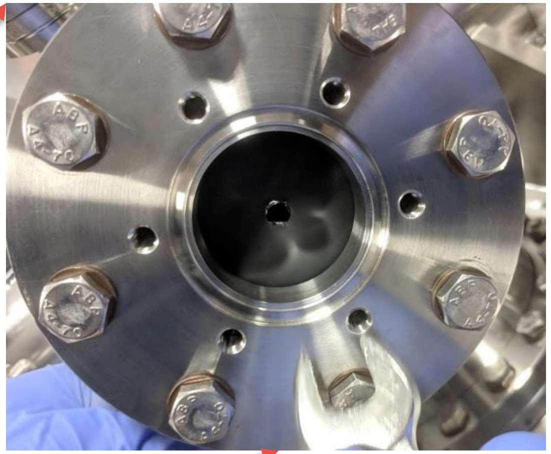


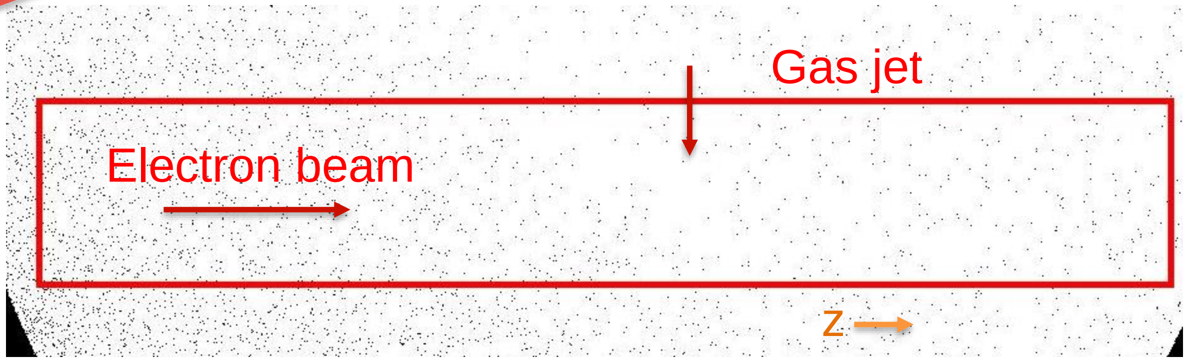
Filter used for Nitrogen : 391 +/- 3nm, HW : 10 +/- 2nm
Number of photons per second from the jet: ~ 17
Electron beam signal is visible in just 4seconds via binning.

Neon

- The background was found to be too strong. An aperture was placed in front of the electron gun.

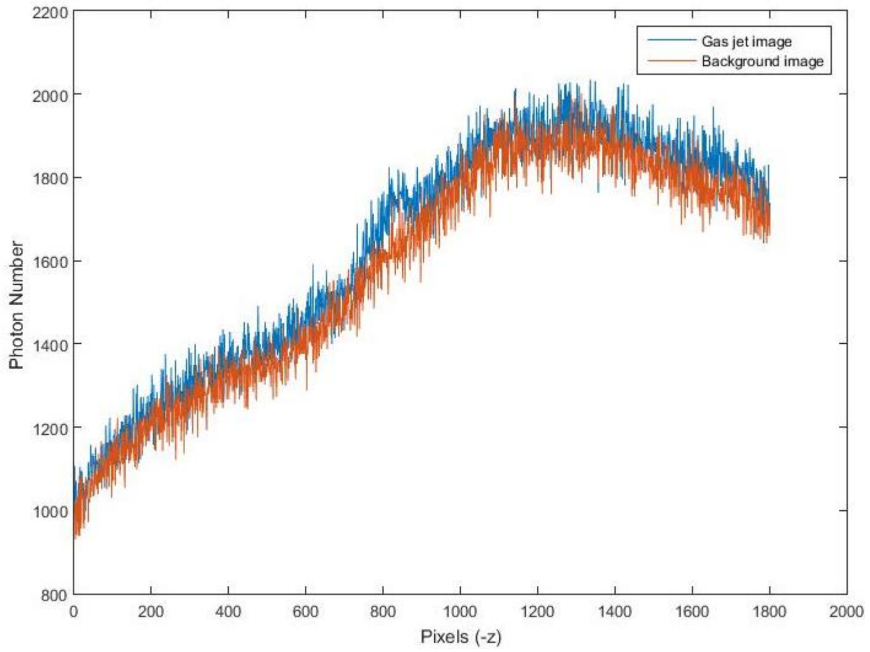






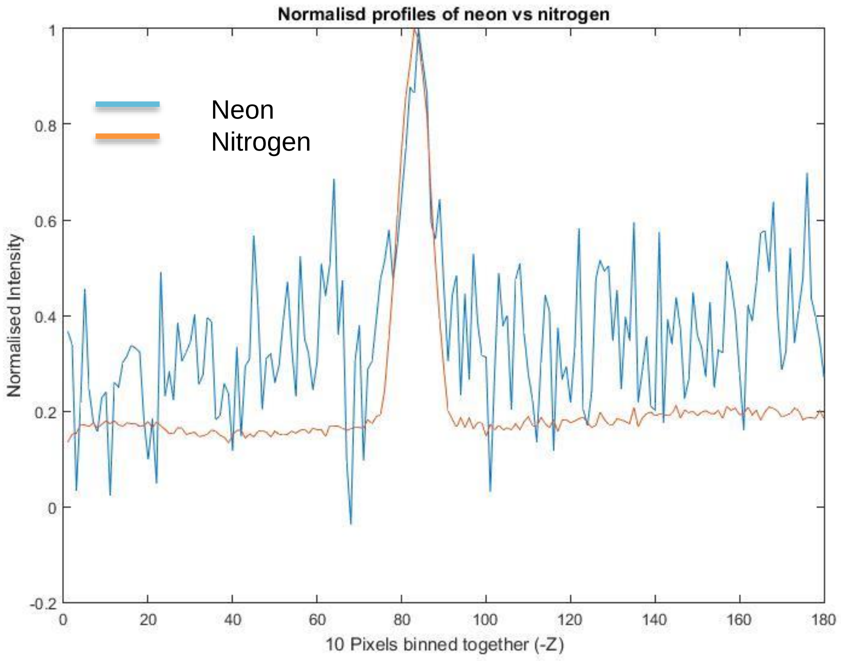
Filter used for Neon : 585.4 +/- 2nm, HW : 10 +/- 2nm
Integration time of the picture above : 4000s

Neon



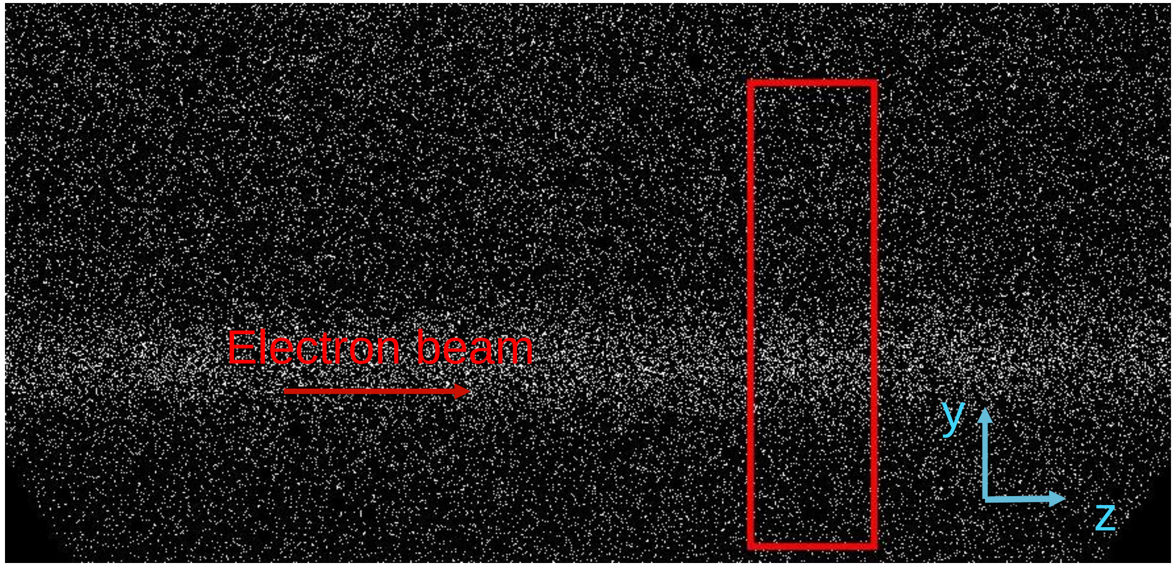
- Integration time : 4000s (+4000s for the background image).
- Background image : Gas-jet off , E-beam on.
- Gas jet image : Gas-jet on, E-beam on.

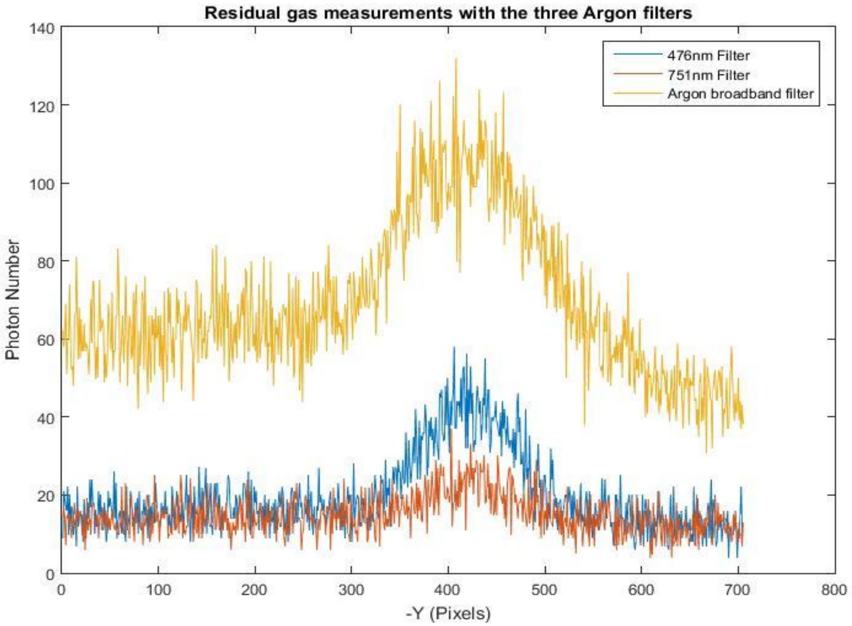
- Good agreement between the normalised profiles of neon and nitrogen.
- Number of photons per second from the neon jet : 1.6.



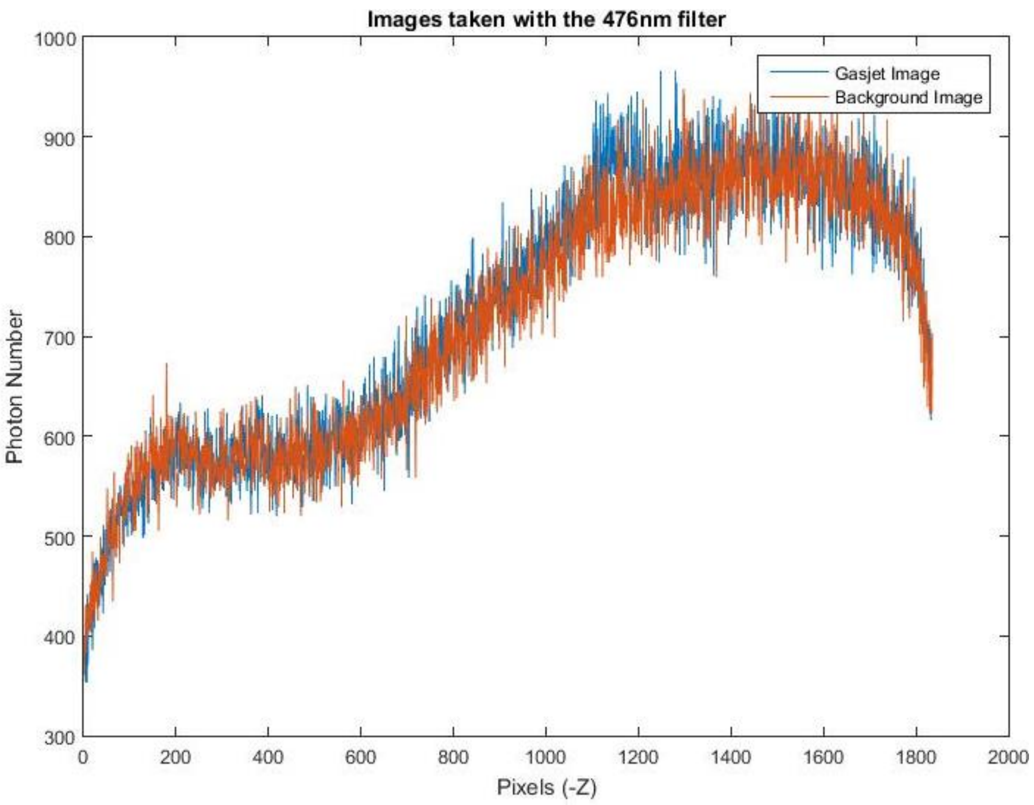
Argon

- Three argon filters available :
  1. 476 +/- 2nm, HW : 10 +/- 2nm
  2. 751 +/- 2nm, HW : 10 +/- 2nm
  3. Broadband filter centred at 443.2 , HW : 150 nm (The Ar+ cross section can be significantly increased by integrating over 400 < λ < 500 nm.
- Residual gas measurements were taken to test the filters.
  - Integration time : 50s
  - Exposure time : 0.5s
  - Interaction chamber pressure : 8.6e-7mbar

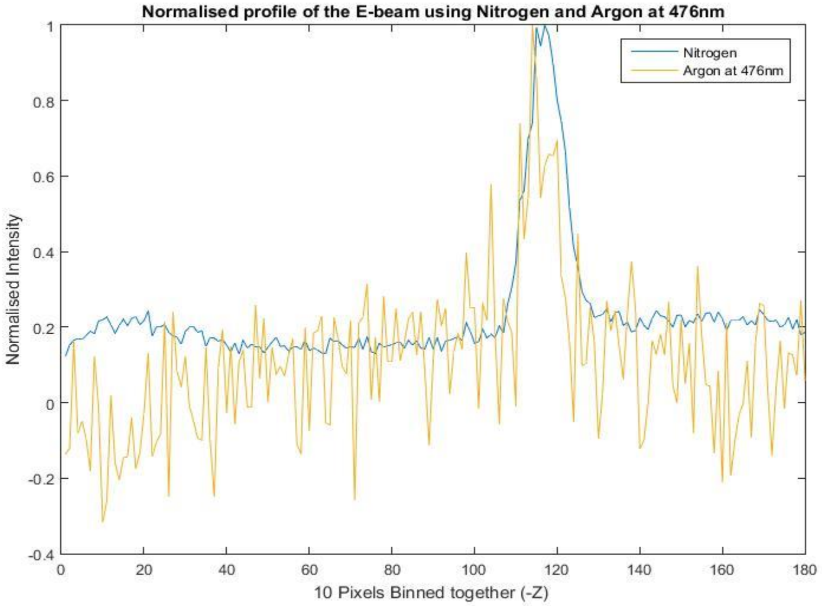




Argon gas-jet with the 476nm filter

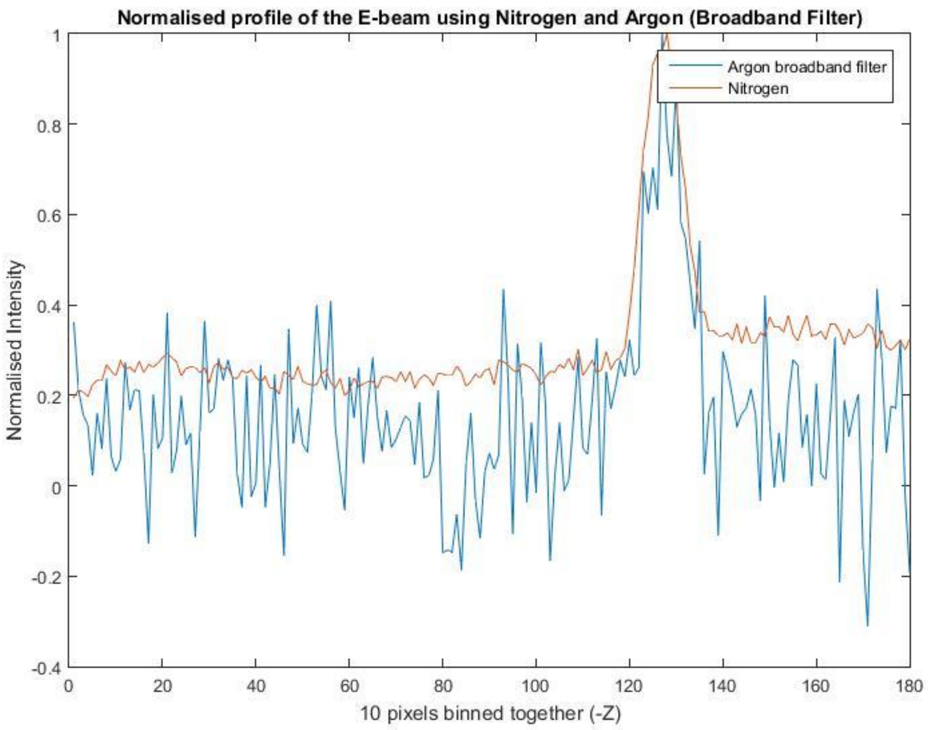


- Integration time : 4000s (+4000s for the background image).
- Background image : Gas-jet off , E-beam on.
- Gas jet image : Gas-jet on, E-beam on.
- The background was subtracted from the gas jet image and this process was repeated for the three filters.



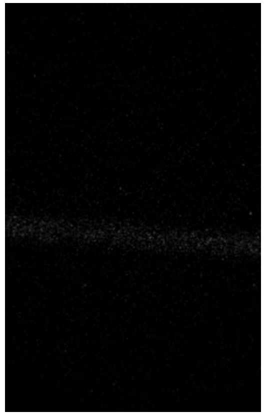
Argon

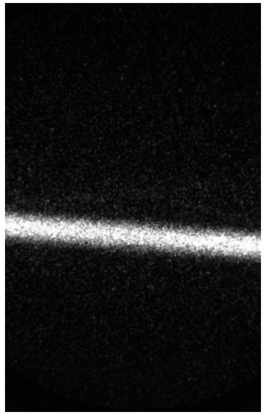
- 476nm filter :
  1. Exposure time : 1s
  2. Integration time 4000s (+4000s background)
  3. Good agreement between the profiles obtained from nitrogen and Argon at 476nm
  4. Number of photons per second : 1.3
- 751nm filter :
  1. Exposure time : 1s.
  2. Integration time 4000s (also tried 8000s) .
  3. No gas jet observed
- Broadband filter :
  1. Exposure time: 0.5s
  2. Integration time: 4000s (+4000s background)
  3. Good agreement between profiles obtained from nitrogen and argon (using the broadband filter.)
  4. Number of photons per second: 4



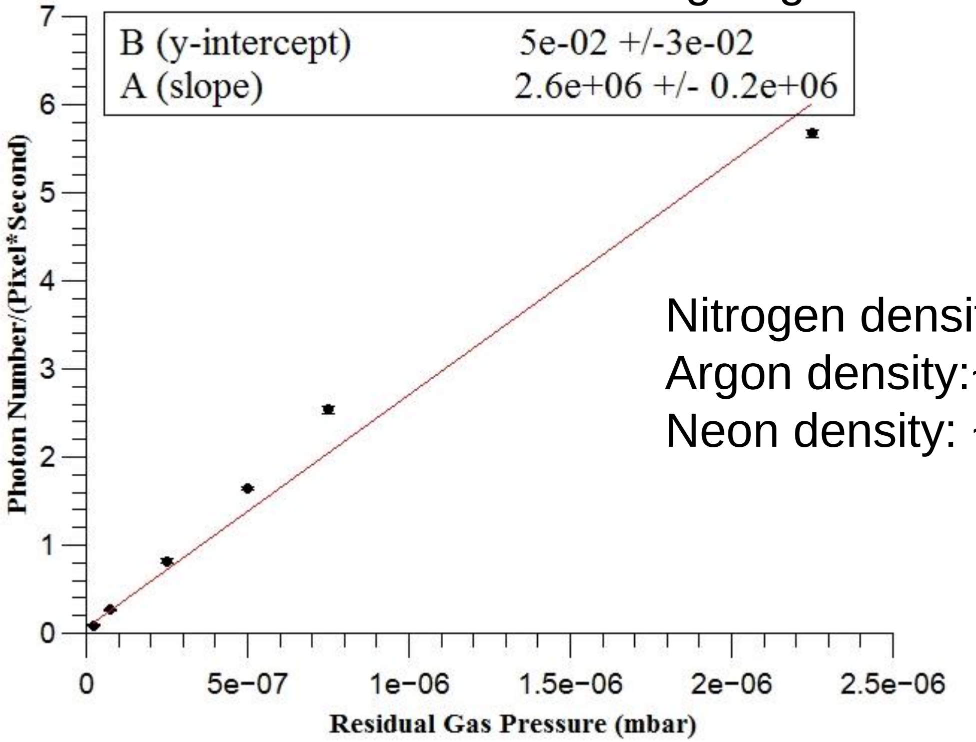
Density Measurements (Photon Gauge)

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





Linear calibration of the Nitrogen gas

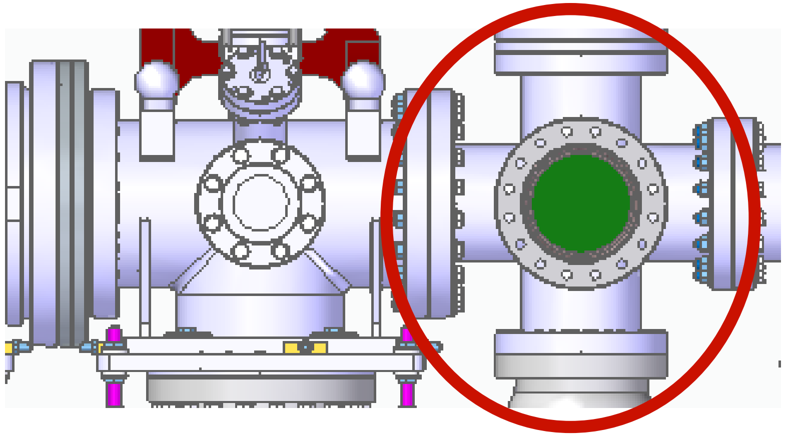


Nitrogen density : ~1E15/m^3
Argon density:~2E15/m^3
Neon density: ~2 to 3E15/m^3

- The pressure in the interaction chamber is increased using a leaking valve.
- A series of residual gas measurements are taken to find a calibration between number of photons and pressure.
- This linear plot is then used to measure the equivalent pressure for the jet

Density Measurements (Moveable Gauge)

- Moveable gauge density measurements using a slit opening was presented during the last collaboration meeting.



- Density was measured in the diagnostic chamber.
- Slit-opening scan:
  1. Horizontal slit opening : 10mm*0.5mm
  2. Gas-jet and the gauge are set to pulse mode.
  3. A full scan of the jet took around 15 hours

- Pin-hole opening details :
  1. Pin-hole size : 0.5mm.
  2. Gas-jet and gauge continuously on.
  3. A full scan of the jet takes 3-4 hours.

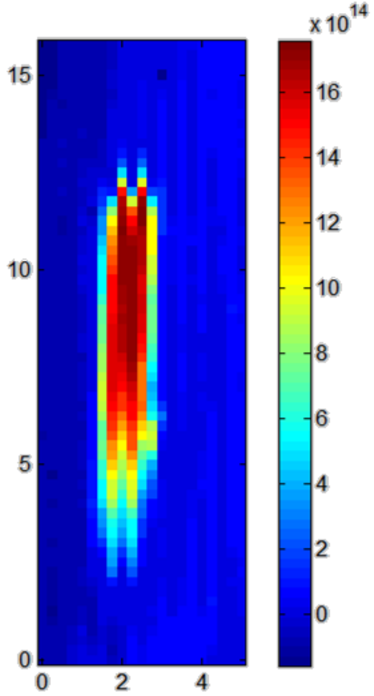
Density measurements with the pin-hole gauge

- A scan was taken using the pin-hole opening for nitrogen, neon and argon under similar experimental conditions. (30 micron nozzle at the optimum nozzle-skimmer distance and the third skimmer set vertically).

- Density measured by :

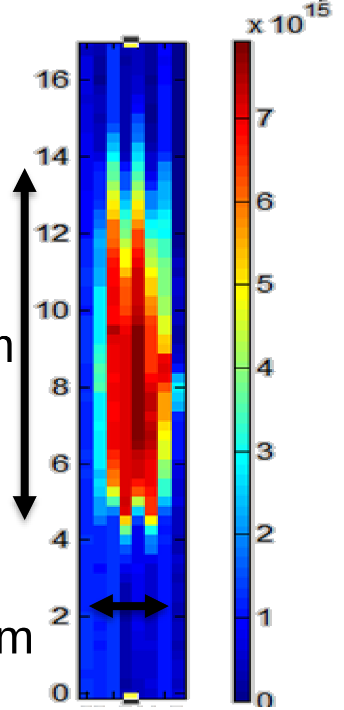
$$\rho = \frac{\frac{I_{ion}}{I_e} * S* < v >}{4Q * k_B * T * v_{jet}}$$

Nitrogen

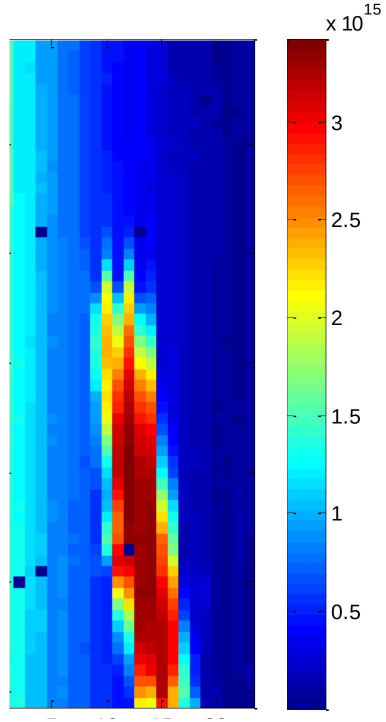


Neon 9.1mm

1mm



Argon



Comparing the gases

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

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_γ [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

Theoretical Photon Numbers vs Experimental Ones

Emitter	Photon Number/s (LHC conditions)	Expected Photon Number/s (Lab conditions)	Experimental Photon Number per second
N2+	3.4E6	2.4E1	17
Ne	2.5E4	1.76	1.6
Ar (750 & 751.5)	2.9E4	1.17	-
Ar+ (476)	2.3E4	1	1.3
Ar+ (Broadband)	N/A	N/A	4

LHC Conditions :

- Cross sections calculated at 10KeV
- Gas jet density assumed to be 2.5E16
- Current assumed to be 5A

Lab Conditions :

- Cross sections calculated at 5KeV (Assuming Linearity)
- Gas jet density :
  1. Nitrogen: 7E14/m^3
  2. Argon: 4E15/m^3
  3. Neon: 6.5e15/m^3
- Current assumed to be 0.65mA

Integration Times For Profile Measurement

- "BIF based beam diagnostics performed at GSI showed that a few hundred of photons are usually enough for obtaining well defined profiles. " (Milestone 1.1)
- In the case of Nitrogen 100photons is enough but due to the strong background from Neon, one needs higher number of photons (around 5000).

Beam	Emitter	Estimated photon number per second	Corrected photon number per second	Estimated Integration Time
Electron	Nitrogen	3.4e6	9.52e4	0.001s
Proton	Nitrogen	2.8e4	7.84e2	0.1s
Electron	Neon	2.5e4	6.5e3	1s
Proton	Neon	1.7e2	4.42e1	100s
Electron	Ar (476)	4e4	6.4e3	1s
Proton	Ar (476	1.4e3	2.24e2	25s
Electron	Ar (Broadband	N/A	2.6e4	0.2s
Proton	Ar (Broadband)	N/A	8.9e2	7s

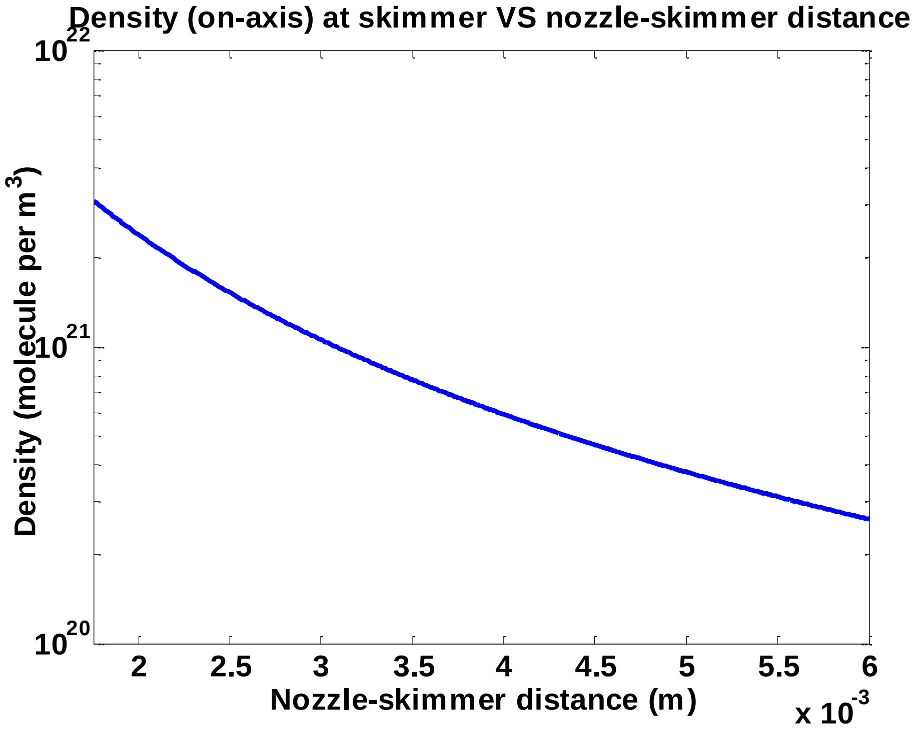
Gas-jet behaviour from theory

- The density of the jet is expected to be increase with the square root of the nozzle size.
- Assuming a free expansion:

M is Mach number, $M = A\left(\frac{x-x_0}{d}\right)^{\gamma-1} - \frac{\frac{1}{2}\left(\frac{\gamma+1}{\gamma-1}\right)}{A\left(\frac{x-x_0}{d}\right)^{\gamma-1}}$

Calculating the density after the first skimmer :

$$\rho = \frac{P_0}{k_B T_0}\left(1+\frac{\gamma-1}{2}M^2\right)^{-\frac{1}{\gamma-1}}\left(1+\frac{x * v_{mean}}{r_{nozzle} * v_{jet}}\right)^{-2}$$



Further optimisations to increase the jet density

1. The second skimmer was removed completely.

   Reason: If there is a large misalignment between 1st and 2nd skimmer, there will be a photon number increase after removing the 2nd skimmer.

   Result: Pressure increase in the skimmer chamber and interaction chamber but no change in the gas-jet density/photon number.

2. The skimmer assembly was removed and the system was realigned with nozzle placed at the optimum location.

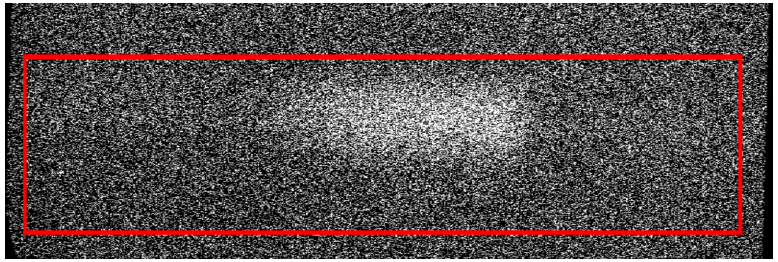
   Result: No change in the gas jet density/photon number.

Further optimisation to increase the jet density [2]

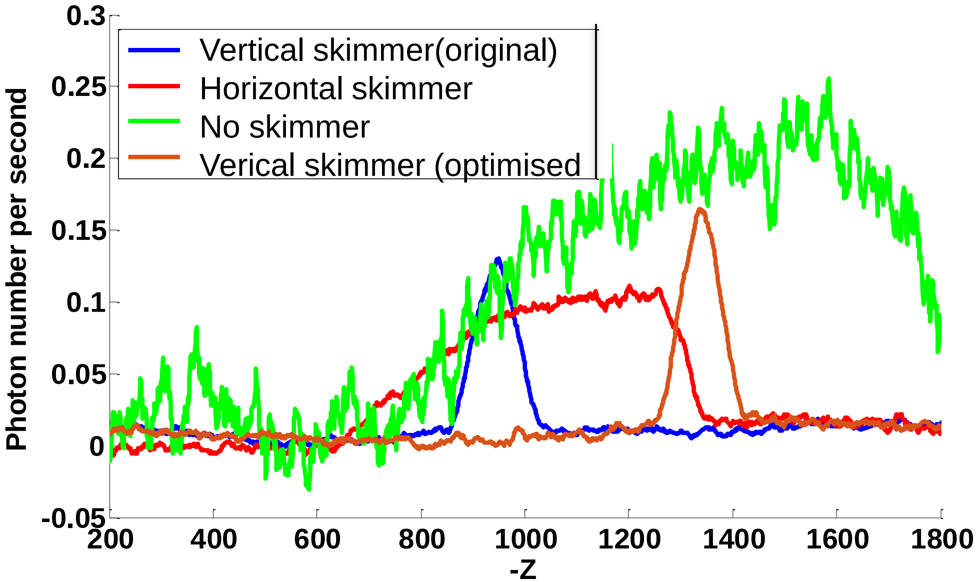
3. Optimising the location of the third skimmer using the new set of slit-opening third skimmers.

Result: 10% Increase in the density of the jet.

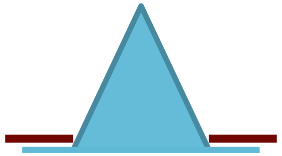
- The third skimmer was first set horizontally and then completely removed to find the best horizontal position for the skimmer.



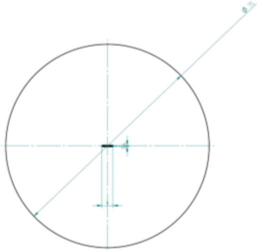
Horizontal profile of the jet.



- New slit opening third skimmer were ordered and placed at the optimum position.



Old design



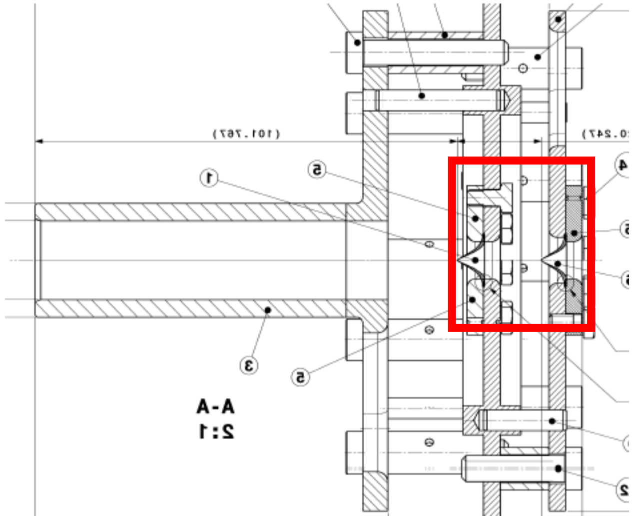
New design

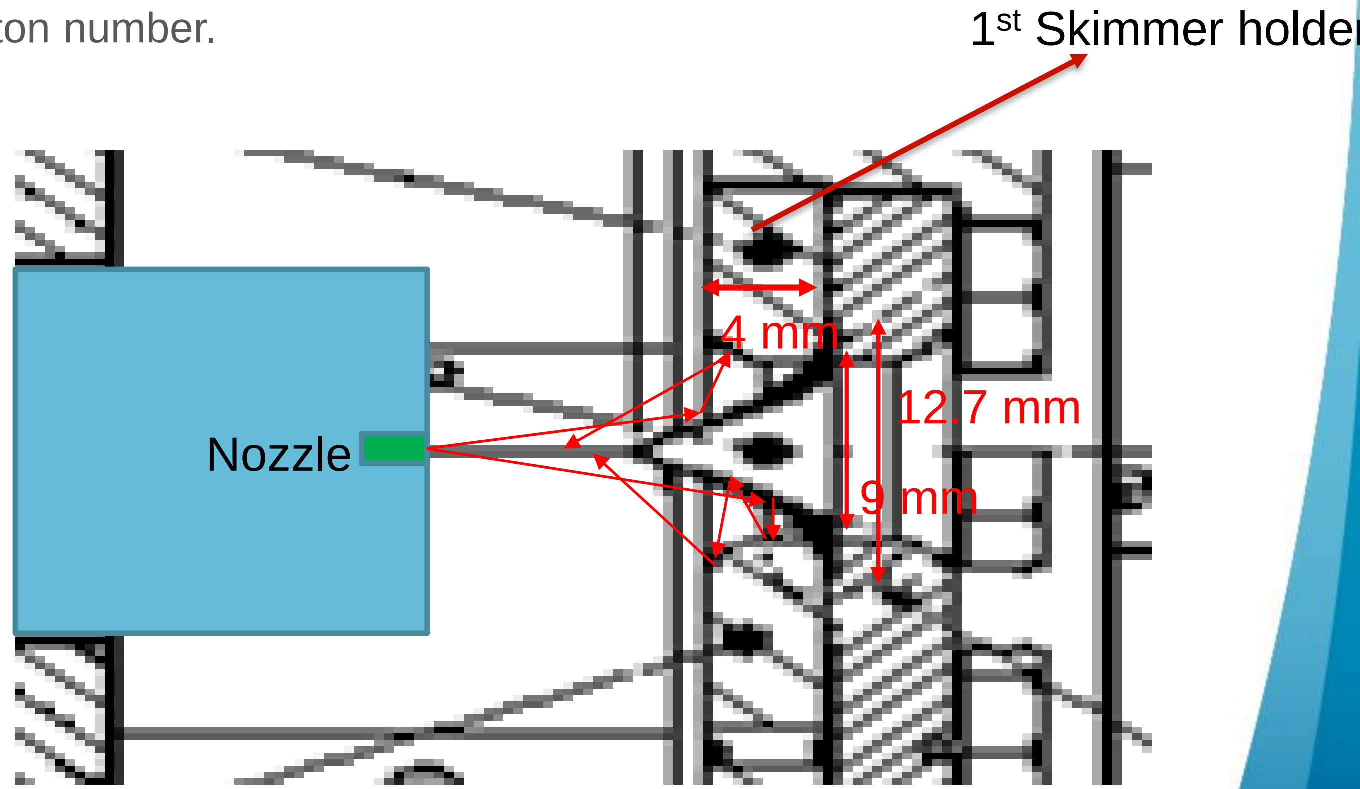
Further optimisation to increase the jet density [3]

4. Another 1st skimmer holder was designed with a thickness of 1mm instead of 4mm. The skimmer assembly was removed and the system was aligned with the new thin skimmer holder.

Reason: Decreasing the distance between the nozzle and the skimmer will increase the chance of off-axis jet reflecting back in to the gas jet.

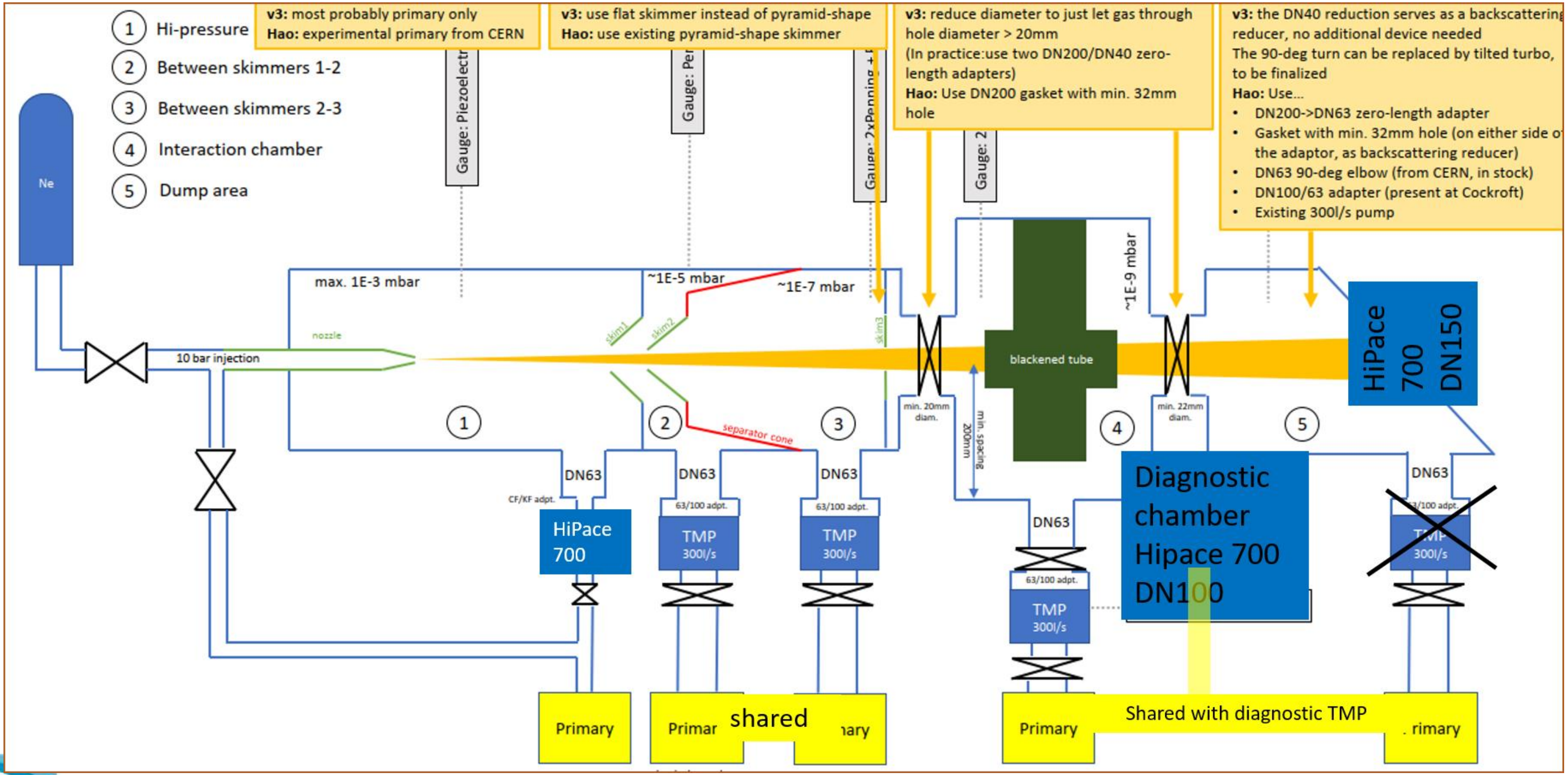
Result: 10-15% increase in the gas jet density/photon number.





Pressure tests (normal operating conditions)

- Eric and Julien from CERN's vacuum group visited Cockcroft Institute on 13-14th of March.
- Normal operating conditions :



Pressure tests (normal operating conditions)

- The first test was taken under normal operations. The following parameters were kept constant throughout all the tests.
- Nozzle to first skimmer distance - Optimised to 3.7mm
- Electron gun conditions - Current : 0.66mA , Energy : 5KeV
- Inlet gas : Nitrogen at 5 bar
- Total integration time: 400 seconds, Exposure time for each photo: 2seconds
- Number of photons detected over 400seconds : 7411

Pressures in each of the chambers (mbar) (5 bar inlet):

Inlet pressure	Nozzle Chamber	Skimmer Chamber (1)	Skimmer Chamber (2)	Interaction Chamber	Dump Chamber
5bar	3.9e-3	8.4e-6	7.3e-7	4e-9	1.4e-9

Technical Details :
Nozzle size : 3E-5mm
Skimmer 1 : Conical _ 1.8e-4mm
Skimmer 2 : Conical _ 4e-4 mm
Skimmer 3 : 4*0.4 mm

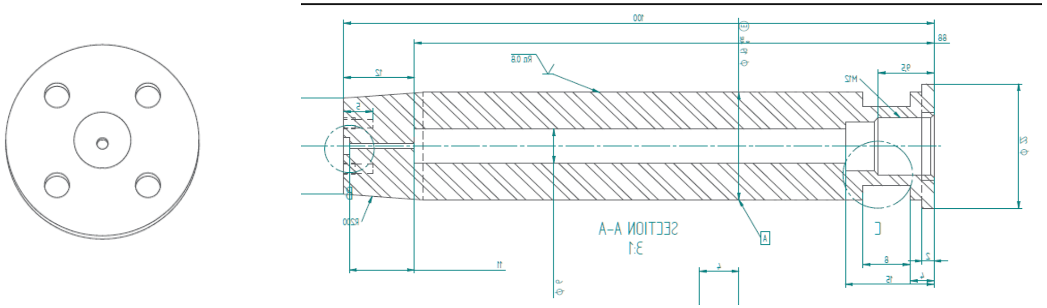
Summary of the pressure tests

Three primary pumps were tested (nXDS15i from EDWARDS, EBARA PDV250 and ACP28) .

1. Using either of these three pumps as the backing pump for the nozzle chamber does not change the vacuum level or the gas jet density.
2. Connecting either of the backing pumps directly to the nozzle chamber and turning off the turbo pump in this chamber results in a pressure of 0.15 mbar and no gas-jet.
3. Operating the turbo-pumps in the nozzle chamber and skimmer chamber in standby speed (reducing the speed to 2/3) will reduce the power consumption by a factor of 2 but does not affect the vacuum levels or the gas jet density.
4. Turning off TMP2 and connecting either of the three pumps directly to the volume 1 of skimmer chamber (volume between the first and second skimmer) will result in 35% reduction in gas-jet density. The pressure in the skimmer chamber will increase by a factor of 10.
5. Using either of the three primary pumps as the backing pump for all 5 of the turbo pumps (except the one in the nozzle chamber) does not affect the vacuum level or the density of the jet.
6. Full report of the vacuum tests and the pressure in each of the chambers during the tests can be found on : https://indico.cern.ch/event/791437/contributions/3374473/attachments/1820469/2977316/Vacuum_groups_visit.pdf

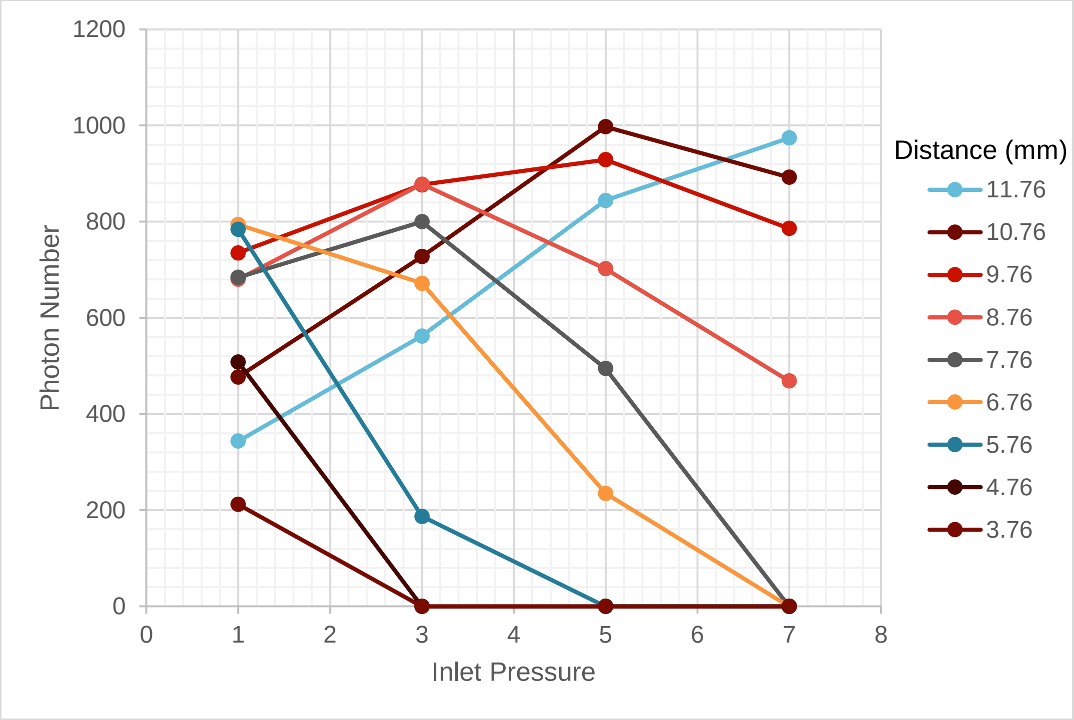
Changing the nozzle diameter

- The 30micron nozzle designed by CERN can be replaced with two nozzles designed at Cockcroft with varying diameters of 50micron and 20micron.



Tests with the 50micron nozzle [1]

- The skimmer assembly was removed and the system was aligned with the 50micron nozzle.
- The position of the third skimmer was optimised with respect to the new alignment.
- A series of measurements were taken at different pressures and different nozzle-skimmer distances using the electron gun.



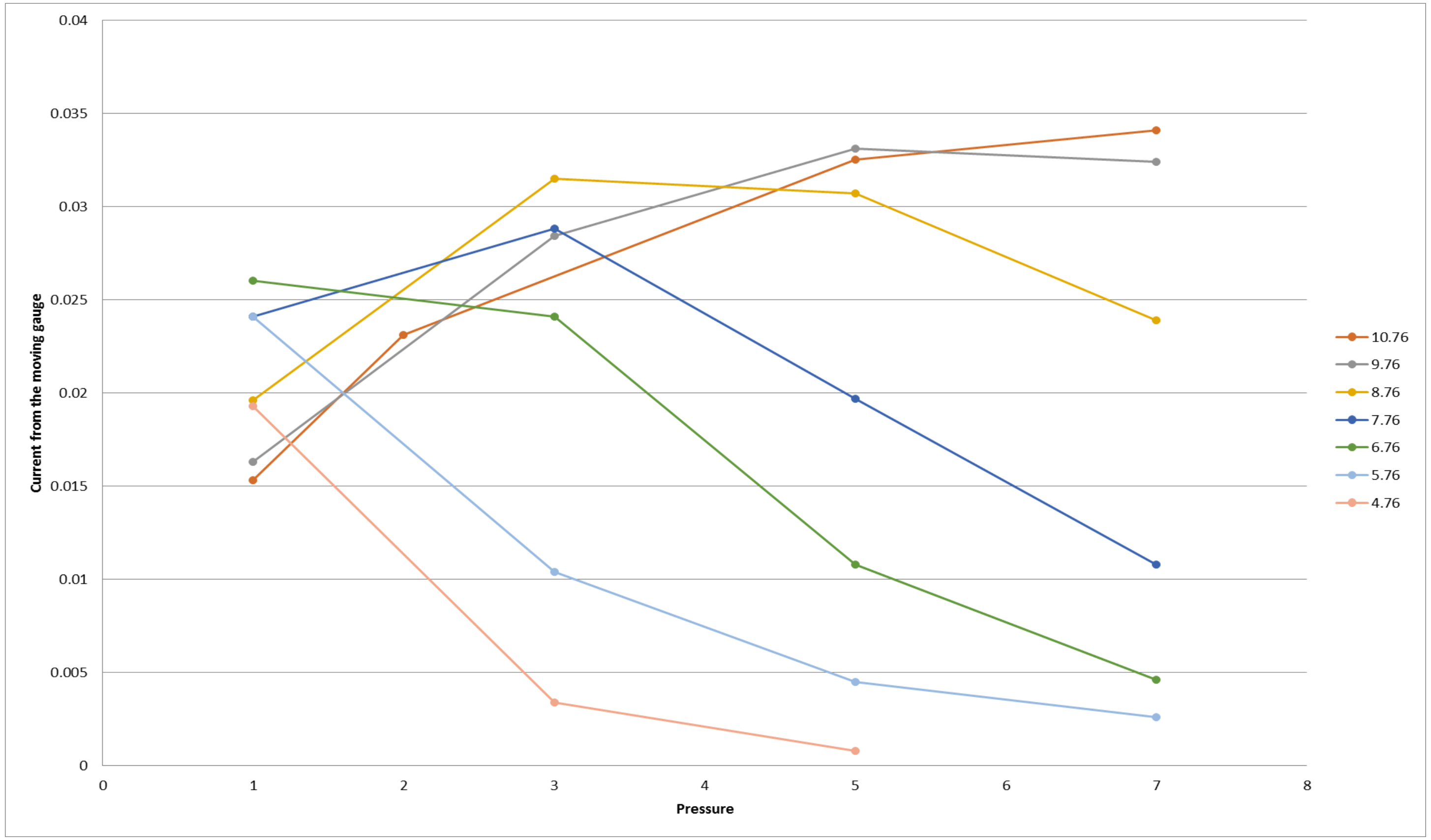
Integration Time : 400s
Electron Beam : 0.65mA , 5KeV
Inlet Gas : Nitrogen

- For an Inlet pressure of 5bar, the optimum nozzle-skimmer distance is 10.7mm (Compared to the 30micron nozzle which was 3.76).
- At distances below 7mm, gas jet density decreases as the Inlet pressure is increased.
- Pressure data for an inlet pressure of 5bar is displayed below.

Nozzle	Nozzle Chamber (mbar)	Skimmer Chamber(1) (mbar)	Skimmer Chamber (2) (mbar)	Interaction Chamber (mbar)	Dump Chamber (mbar)
30 um	3.80E-03	3.90E-06	3.80E-07	7.68E-09	2.21E-09
50 um	8.2E-03	5.2E-05	4.8E-06	1.8E-08	5.25E-09

Tests with the 50micron nozzle [2]

- The density of the jet at the optimum distance for the 50micron nozzle is 6-7 times lower than that of the 30micron nozzle. This was also confirmed with the moving gauge. Pressure data for an Inlet pressure of 5bar is displayed below.

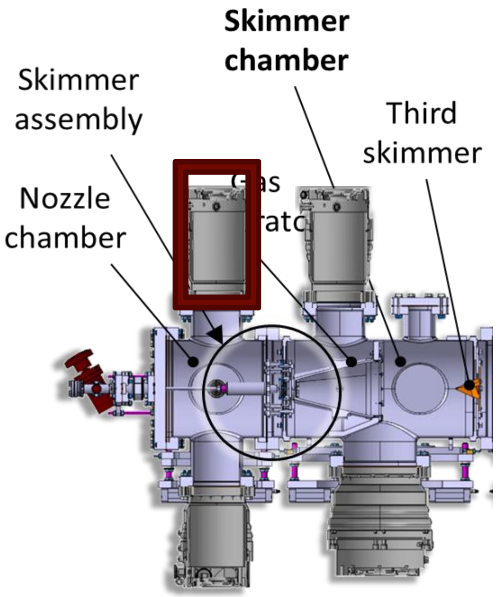


A rough horizontal scan was conducted at the most dense part of the jet using the moving gauge.

The reading from the moving gauge is in agreement with the measurements taken using the electron gun.

Tests with the 50micron nozzle [3]

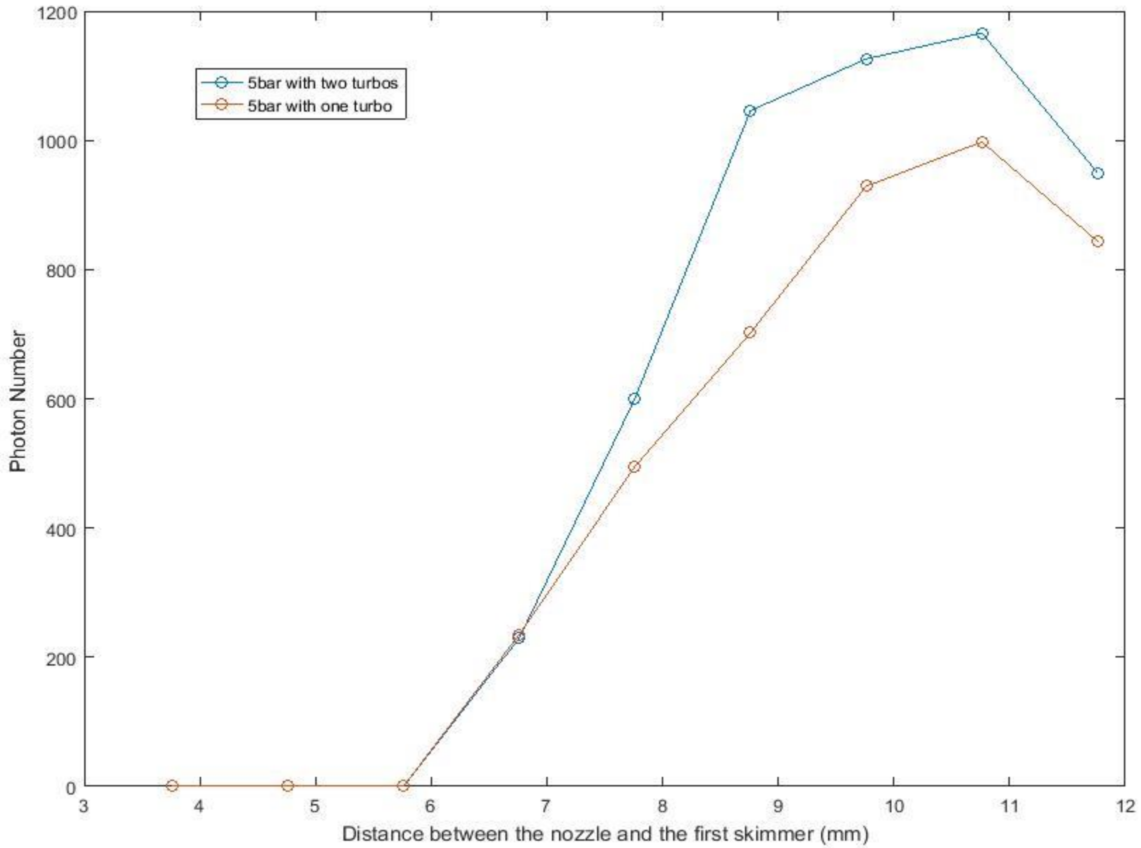
- An extra 180L/S turbo pump with a dedicated primary pump was added to the nozzle chamber.
- Pressure in the nozzle chamber decreased by 30% and the gas jet density increased by 10~15%



Nozzle (5bar Inlet)	Nozzle Chamber (mbar)	Skimmer Chamber(1) (mbar)	Skimmer Chamber(2) (mbar)	Interaction Chamber (mbar)	Dump Chamber (mbar)
30 um	3.80E-03	3.90E-06	3.80E-07	7.68E-09	2.21E-09
50 um	8.2E-03	5.2E-05	4.8E-06	1.8E-08	5.25E-09
50 um (extra turbo)	5.6e-3	-	3.1e-6	1.29e-8	3.88e-9

Tests with the 50micron nozzle [3]

- The inlet pressure was set to 5bar and a series of measurements were taken at different nozzle to skimmer distances.

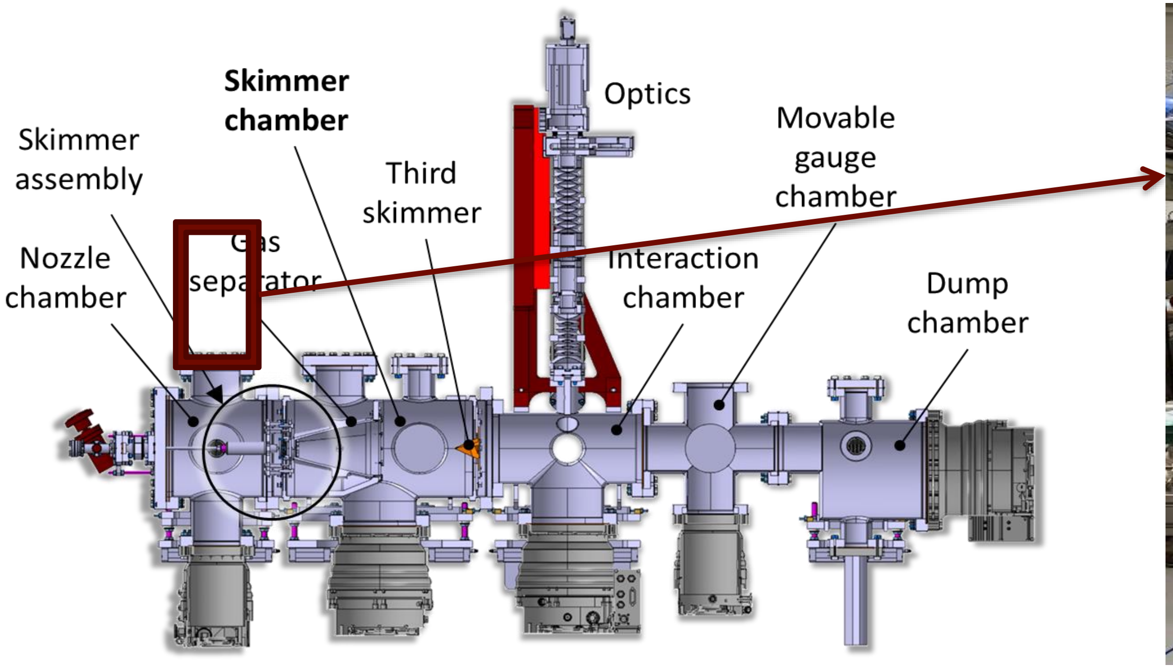


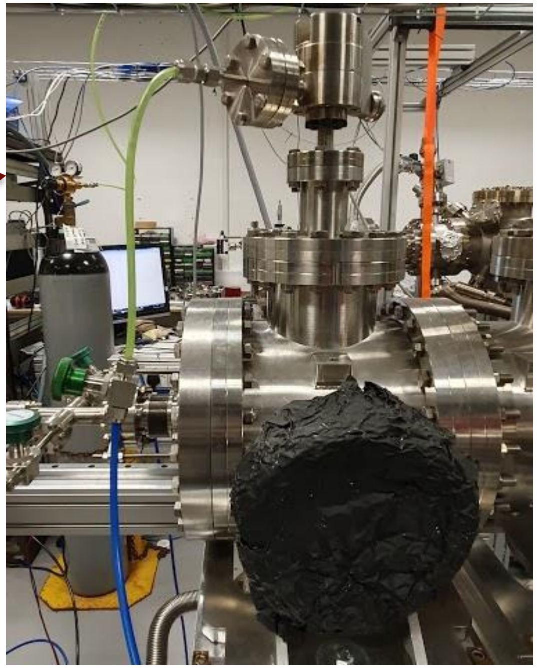
Integration Time : 400s
Electron Beam : 0.65mA , 5KeV
Inlet Gas : Nitrogen

At larger distances, decreasing the pressure in the nozzle chamber Increases the pressure of the jet.

Tests with the 30 micron nozzle

- The skimmer assembly was removed and the gas jet system was aligned with the 30micron nozzle from CERN.
- The 180L/S turbo-pump was replaced with a leaking valve.



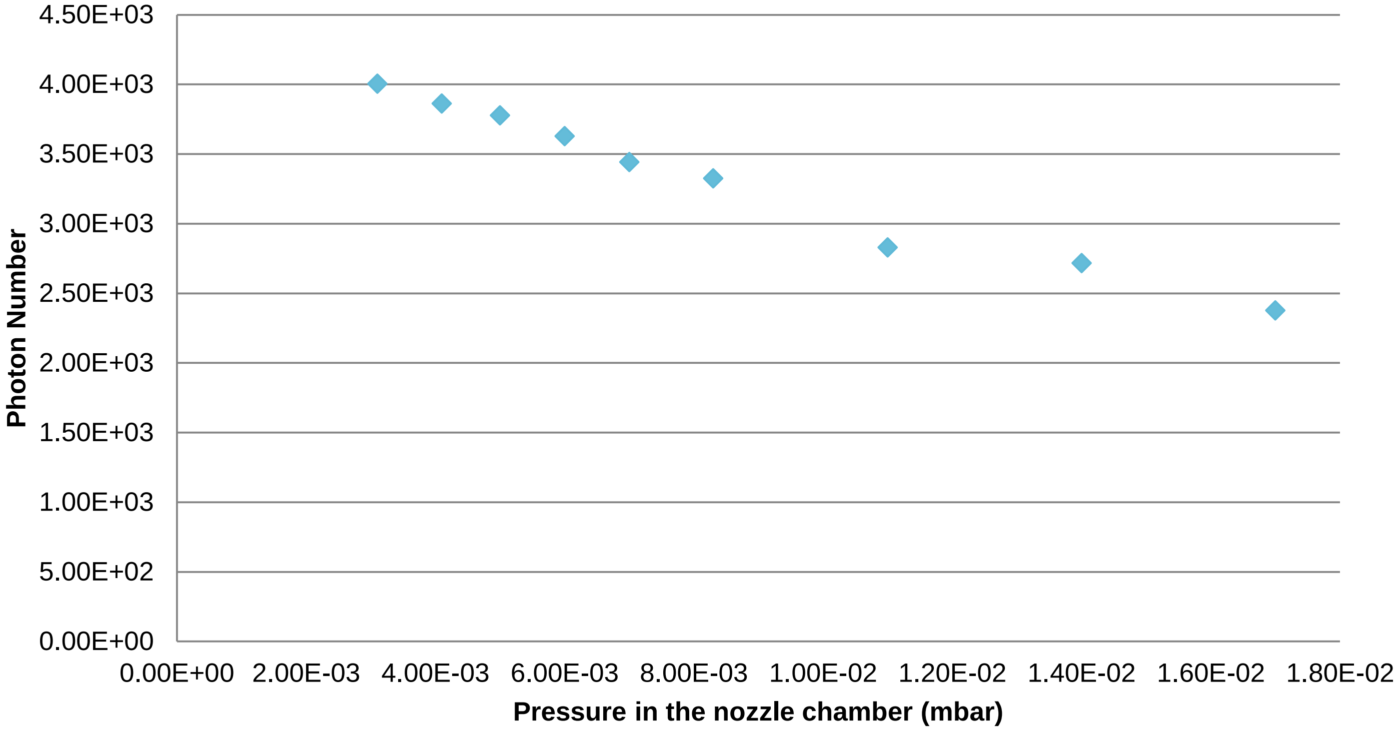


Tests with the 30micron nozzle

- Test conditions :

Integration Time : 400s
Electron Beam : 0.65mA , 5KeV
Inlet Gas : Nitrogen
Nozzle-skimmer distance = 3.76 (optimum distance)

- The pressure in the nozzle chamber was gradually increased from 2.3e-3mbar to 1.7e-2mbar.



- At a pressure of 1.7e-2mbar, gas jet density is almost half of its nominal value at 3e-3mbar.
- Pressure cut-off point is between 1.7e-2mbar and 1.5e-1mbar. Assuming linearity it lies somewhere between 5 to 6e-2mbar.
- The gas jet density with the 30micron nozzle is approximately 4 times higher than the 50 micron nozzle for the same pressure in the nozzle chamber.

Overview

- The gas-jet signal from the Neon, Argon and Nitrogen jets were characterised.
- The expected number of photons per second is in relatively good agreement with the estimated number.
- The gas jet density of Argon, Neon and Nitrogen was characterised using the photon gauge method and the moving pressure gauge.
- The integration times in LHC conditions was estimated.
- The pressure tests concluded that running the turbo-pumps on reduced rotational speed would be a solution to overheating.
- The results from the experiments using the 50micron nozzle, specifically the effect of nozzle to skimmer distance on the jet density was shown.