Gas Jet Monitor for Medical Accelerator Applications

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UNIVERSITY OF LIVERPOOL

JetDose

Overview

JetDose

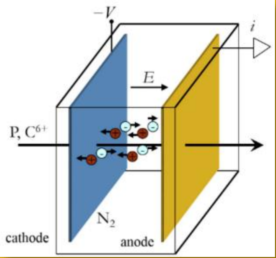
Gas Jet Monitor

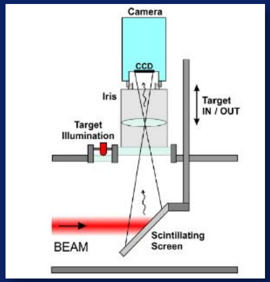
Background and R&D

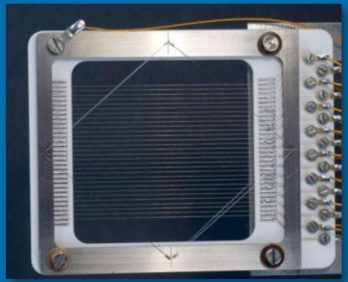
Updates/Work in progress

Existing Diagnostics

+ High resolution
+ Reliability
+ Validity
- Interceptive
- Regular calibration needed
- Beam perturbation
- Limited lifespan
- Prone to radiation damage
- Limited live feedback







B. Walasek-Höhne, GSI and G. Kube, DESY
S. Giordanengo & M. Donetti, arXiv:1803.00893

JetDose- Novel diagnostics solution

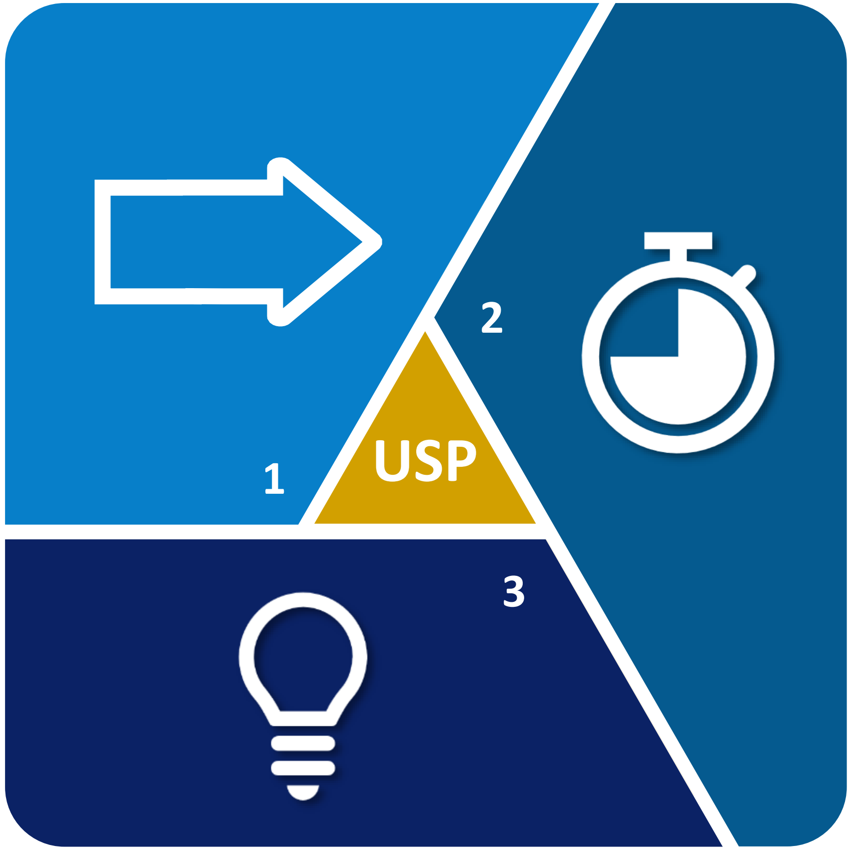
JetDose

1 Minimally invasive

- ✓ No beam perturbation
- ✓ Online monitoring
- ✓ Superior error detection

3 Novel treatments and improved operation

- ✓ Enabling technology for FLASH, LhARA and Mini-Beam treatments
- ✓ Active machine regulation based on live feedback becomes feasible



2 Significantly reduced calibration time

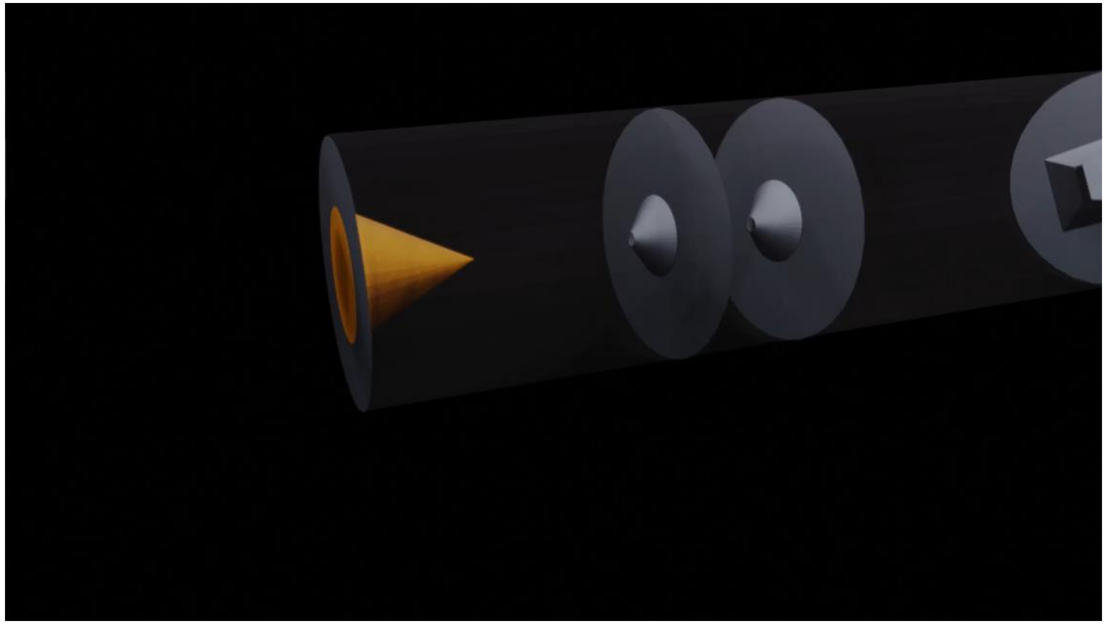
- ✓ No mechanical parts interact with the beam
- ✓ All key parameters monitored remotely
- ✓ Significantly reduced maintenance

N. Kumar, C.P. Welsch, et. al, Physica Medica 73, p 173-178 (2020).

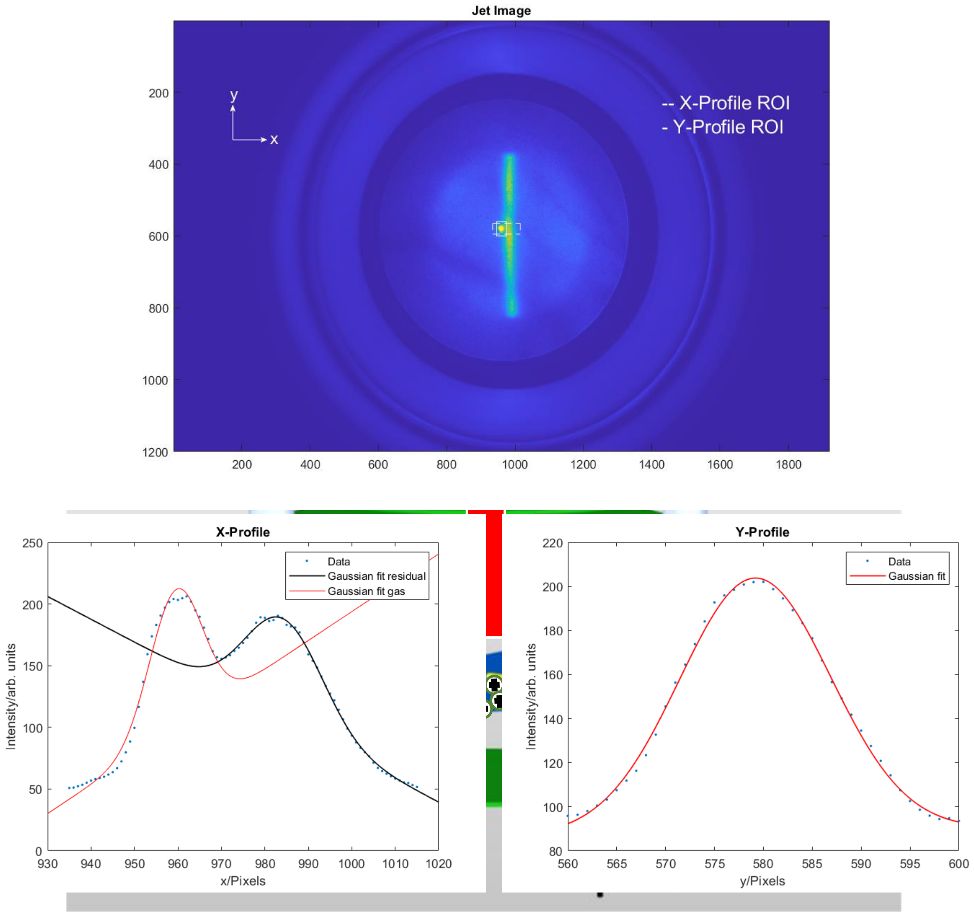
S. Jolly, C.P. Welsch, et al., *"Technical challenges for FLASH proton therapy"*, Phys Med 2020 – **Galileo Galilei Award, best paper in 2020**

"Non-Invasive Gas Jet In-Vivo Dosimetry for Particle Beam Therapy", contributed talk at IPAC21

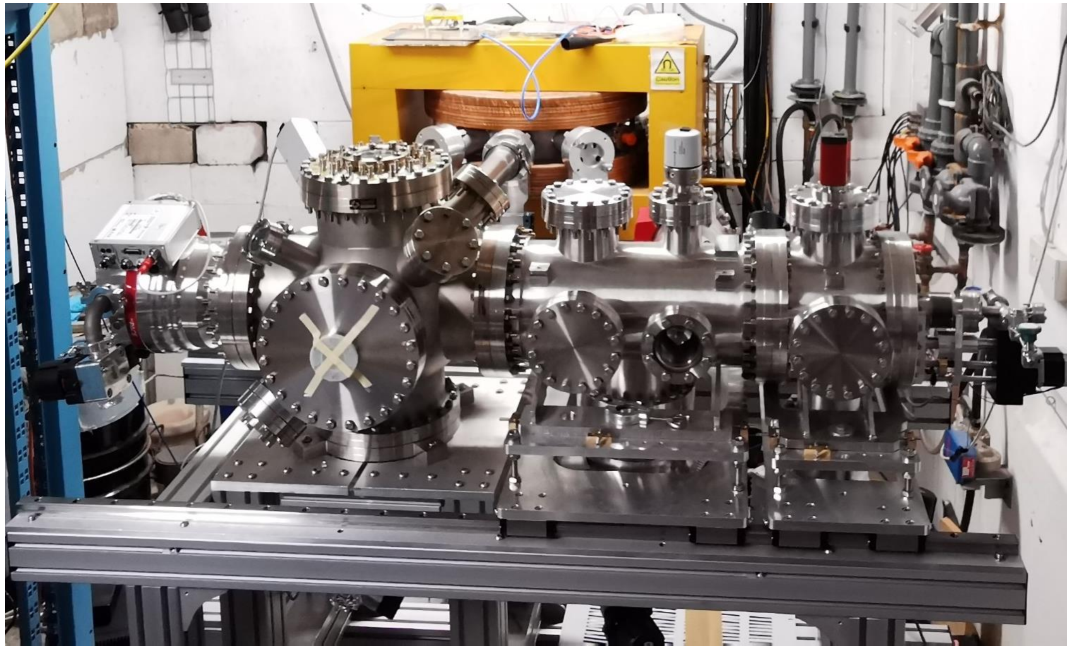
Building up on previous developments

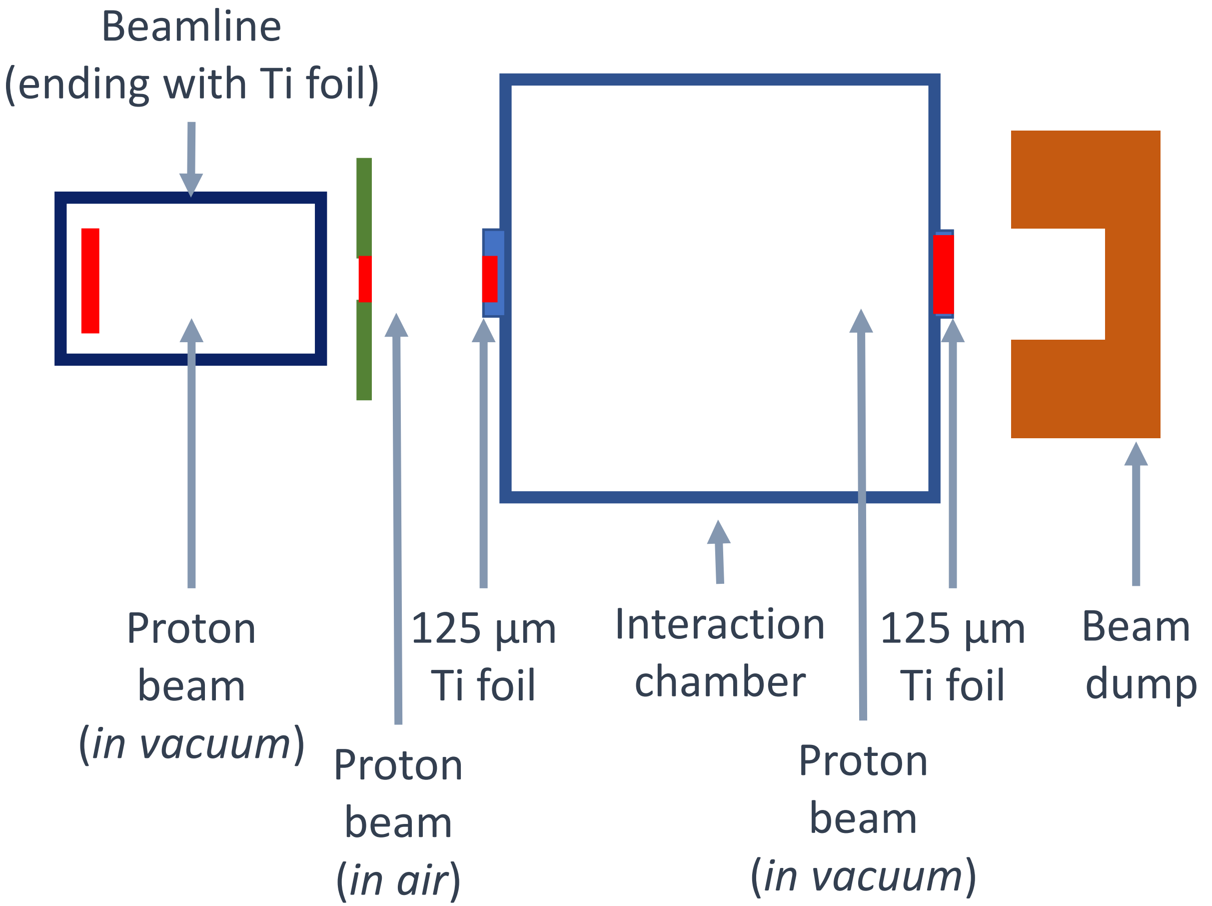


Gas jet shaping



Measurements with protons at UoB MC40 cyclotron

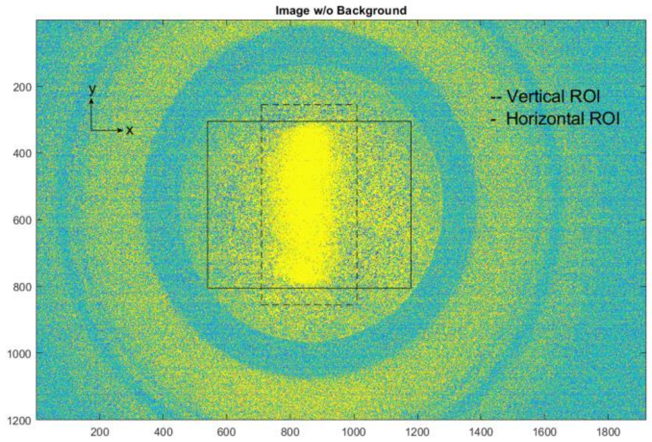


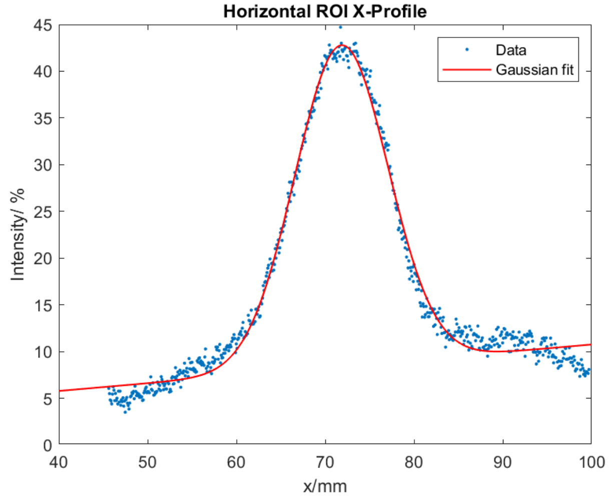


Beam Parameters

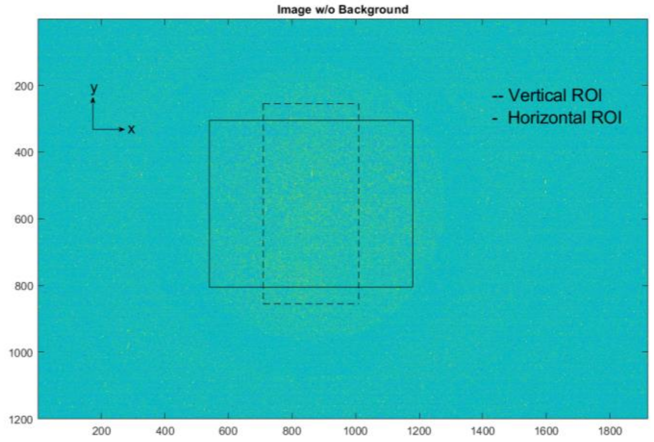
Beam Species:	***Protons***
Beam Energy:	***28 MeV***
Beam Current:	***150-750 nA (on FC1)***
Beam Collimator Area:	***4-100 mm²***

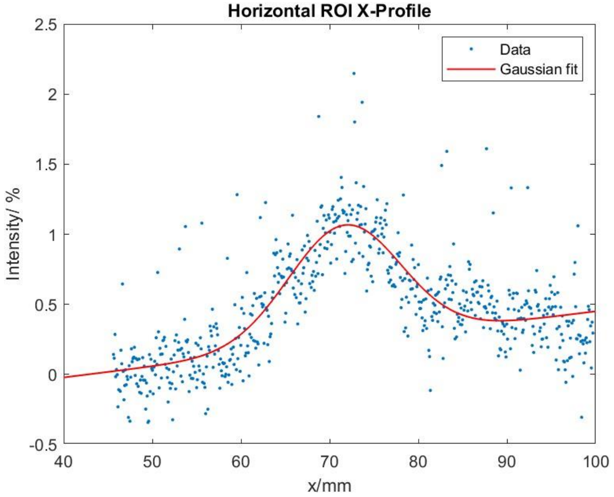
Measurements with protons at UoB MC40 cyclotron





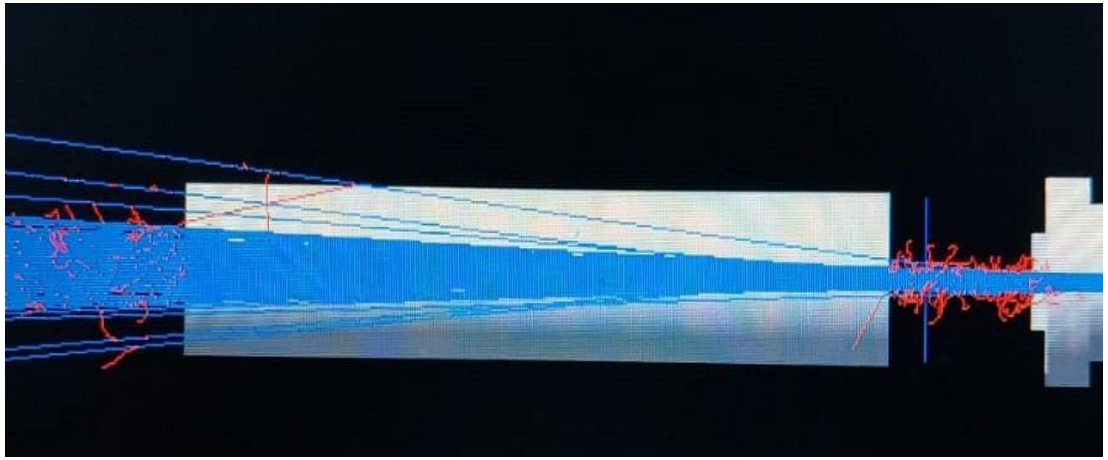
Beam collimator Area= 100 mm^2
Integration time = 1second
Gas Pressure in Interaction chamber
= 1.2 ×10^{-5} mbar
σ = 5.4mm
Beam current at FC1= 150nA



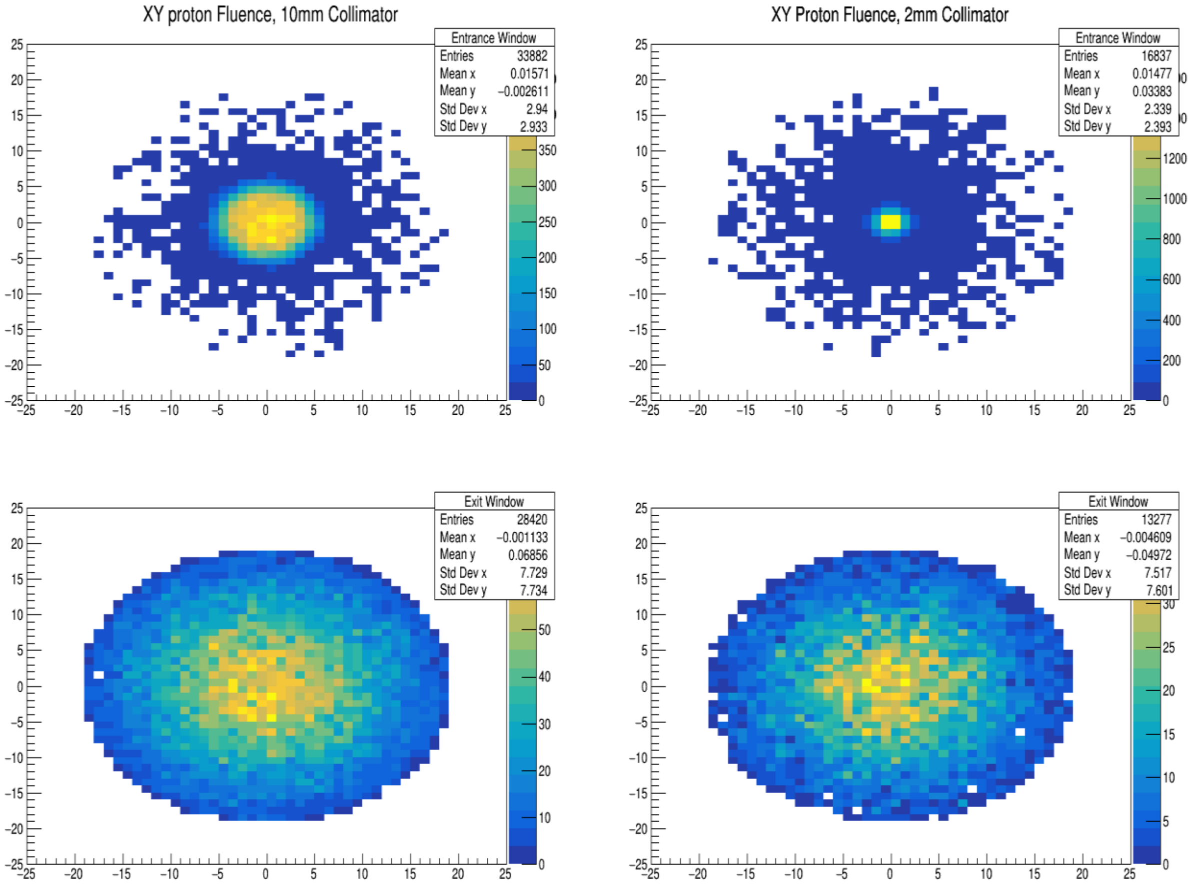


Beam collimator Area= 4 mm^2
Integration time = 20seconds
Gas Pressure in Interaction chamber =
1.2 ×10^{-5} mbar
σ = 6.4mm
Beam current at FC1= 150nA

Simulation Results



GEANT4 simulations



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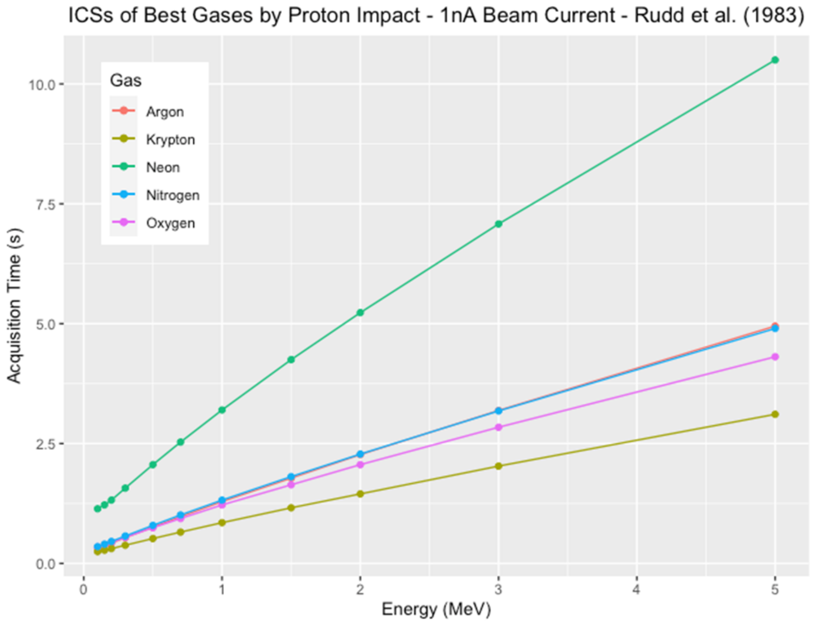
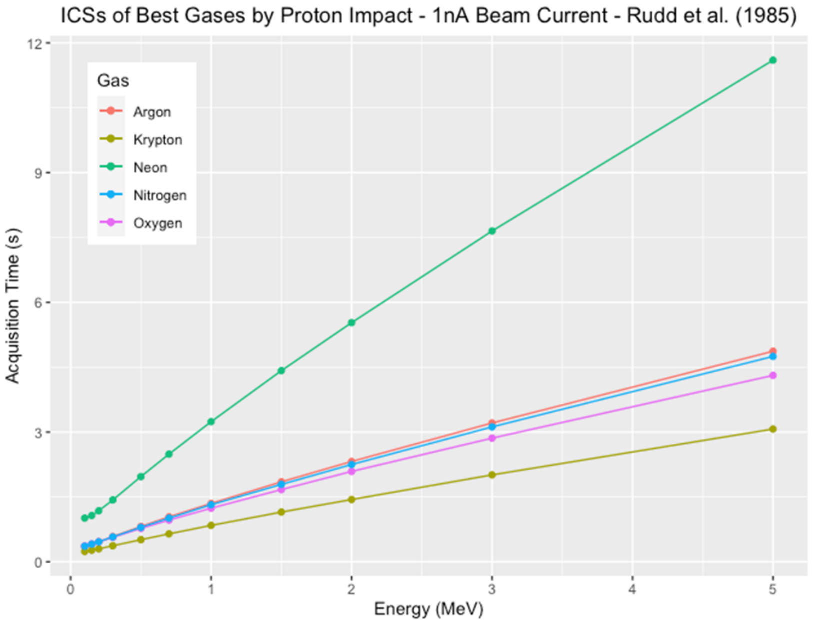
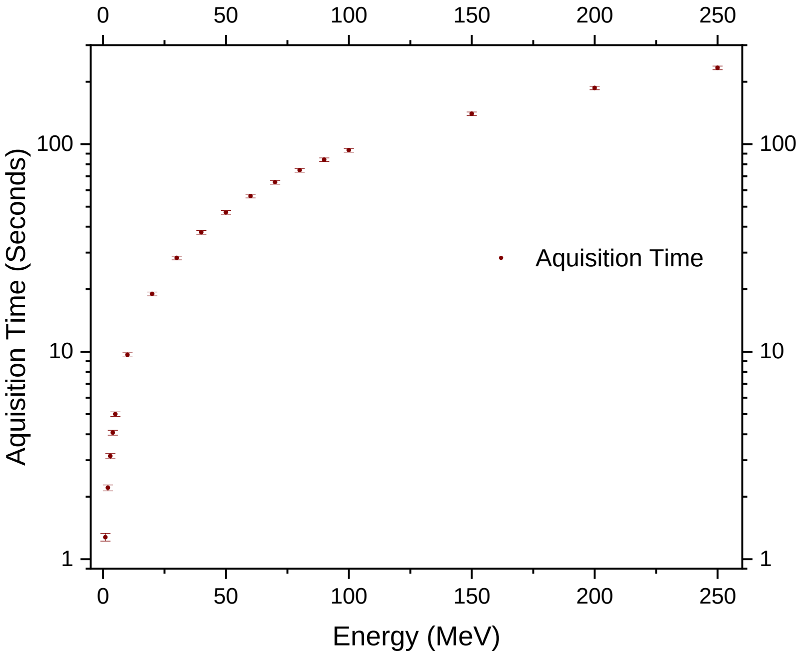
Ionization Cross Section by Proton Impact



Rudd, M.E. et al. (1983). Physical Review A, 28(6), pp. 3244-3257.



Rudd, M.E. et al. (1985), Reviews of Modern Physics, 57(4), pp. 965-994.



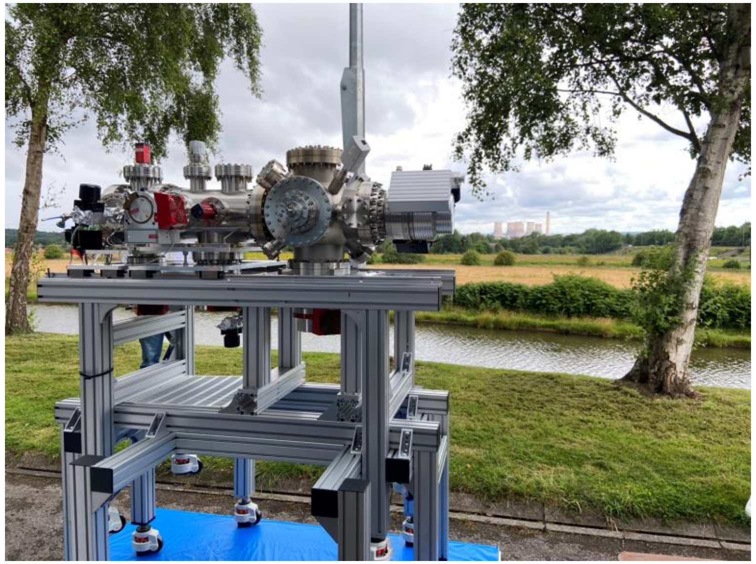
Estimated Acquisition time using Nitrogen gas Jet

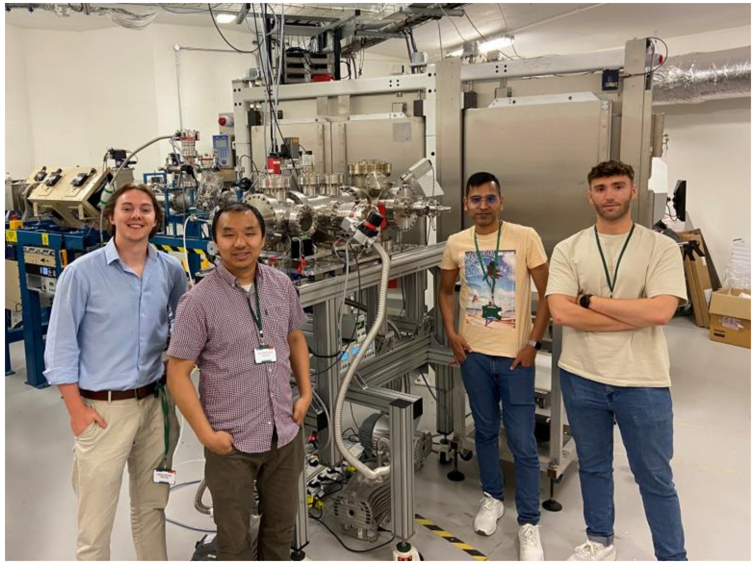
Measurements with Proton and Carbon beam at DCF

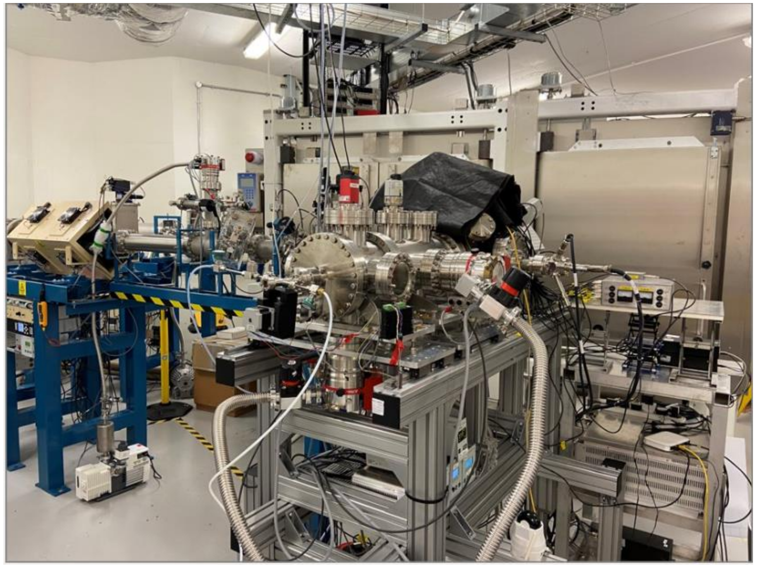
JetDose

Beam Parameters

Beam Species:	***Protons, Carbon***
Beam Energy:	***4-8 MeV, 12-24 MeV***
Beam Current:	***1-100nA, continuous beam***
Beam Size:	***Variable sizes in the range of a few mm’s***







Measurements at DCF, Whitehaven

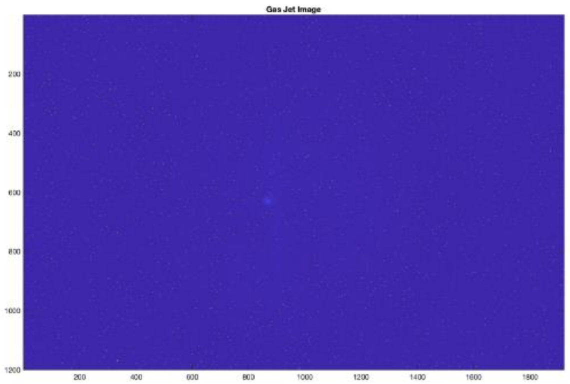
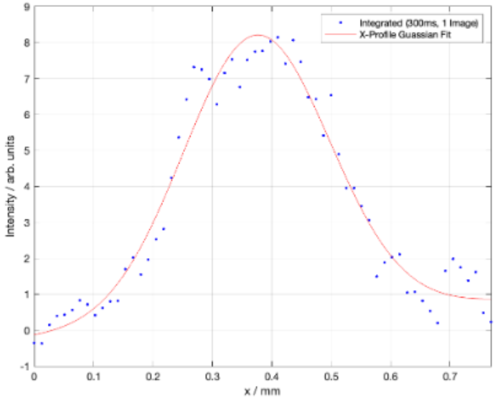


Image of normalised gas jet signal from a 4 MeV, 100nA proton beam (with background removed). X- and Y-axis are X- and Y-position (pixels) respectively. Integration time: 300 mSec.



X-Profile obtained from single Image

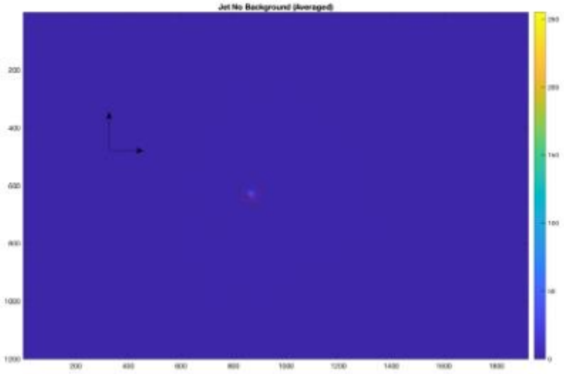
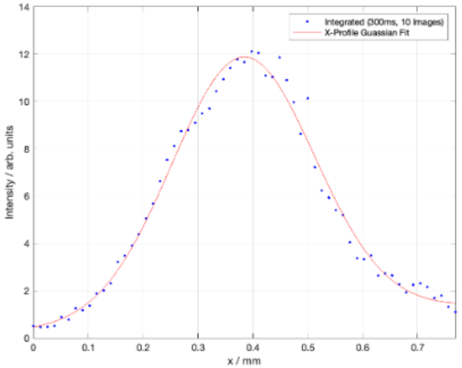


Image of normalised gas jet signal from a 4 MeV, 100nA proton beam (with background removed). X- and Y-axis are X- and Y-position (pixels) respectively. Integration time: 3 Sec.



X-Profile obtained by averaging 10 Images

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Conclusions/Plans

- Successful application for Faculty Impact Fund (UoL) to perform PoC measurements at DCF, Whitehaven with proton and carbon beams. Experiments were carried out in July 2023.
- Detailed analysis of the data is in progress.
- Plan to publish the results in early 2024 (may be 2 publications for 2 beams).
- Experimental studies for quantification of gas jet invasiveness to the primary beam.
- **New PHD project:** within EuPRAXIA-DN, new PHD student is hired to work on the diagnostic challenges directly related to LhARA.

Quantum Helium Atom Microscope (qHAM)

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D-Beam

qHAM

Overview

Literature & Motivation

Key Features & Results

qHAM- A Novel Imaging Solution

Literature & Motivation

- Neutral helium microscopy
- Mostly suitable for imaging fragile and/or insulating structures as well as structures with large aspect ratios.
- Achievable resolution depends upon the nozzle-pinhole assembly and their dimensions.
- Achievable contrast depends upon the intensity of the gas stream produced using the above system.
- Possibility of improving the resolution and contrast limit by focusing the neutral gas atoms.
- Neutral helium atoms are focused as matter waves.
- Lack of charge or spin is helpful for imaging samples with good electrical conductivity and/or magnetic properties.

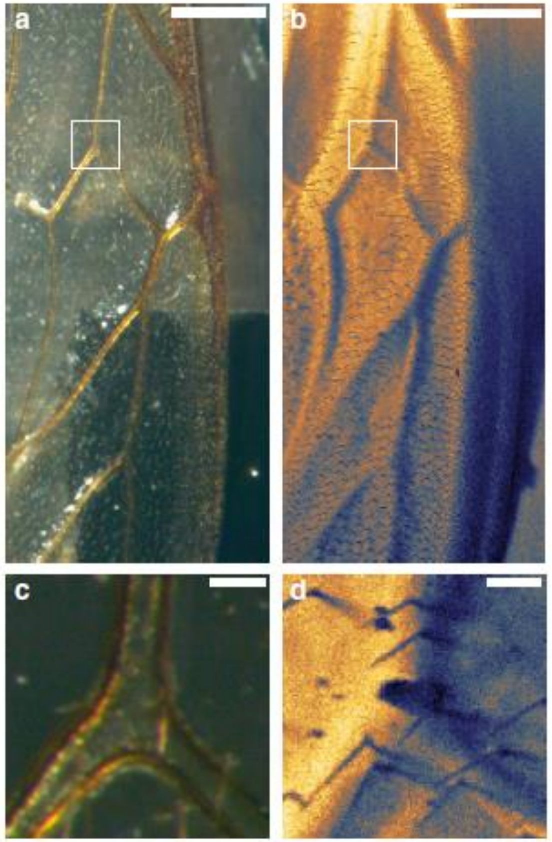


Figure 1 | Topological contrast in SHeM. Comparison of reflection optical (Leica M205 C) (**a**,**c**) and SHeM (**b**,**d**) micrographs of a honey bee wing (*Apis mellifera*) as an example of topological contrast. Bottom images taken from the square region are indicated in **a**. Scale bars, 500 and 50 μm, respectively.

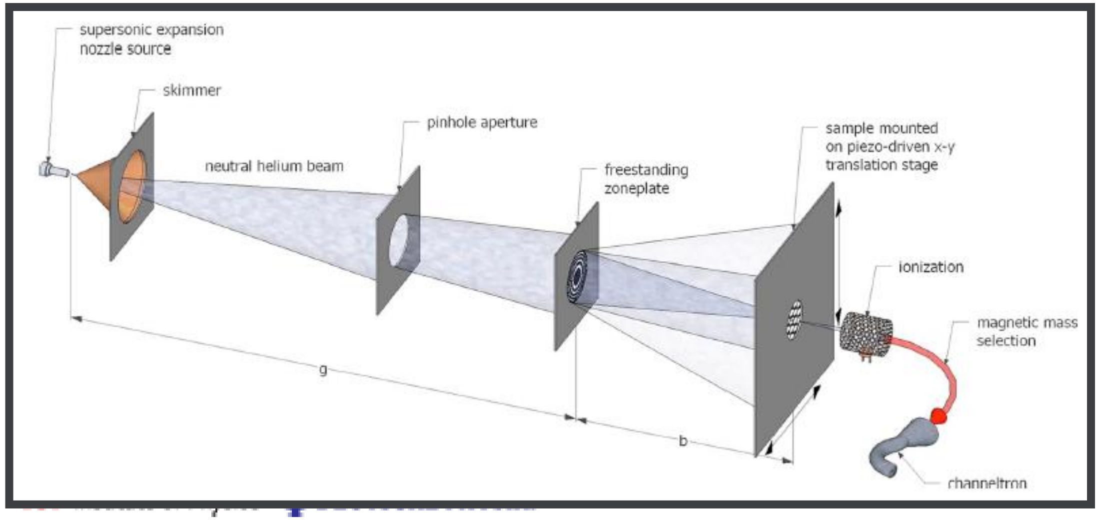
**M. Barr et al., Nature Comm. 7:10189, 2015.*

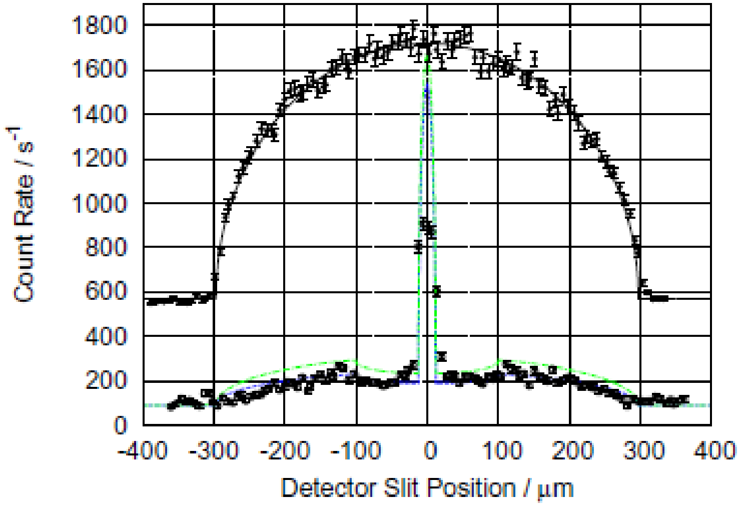
LITERATURE & MOTIVATION

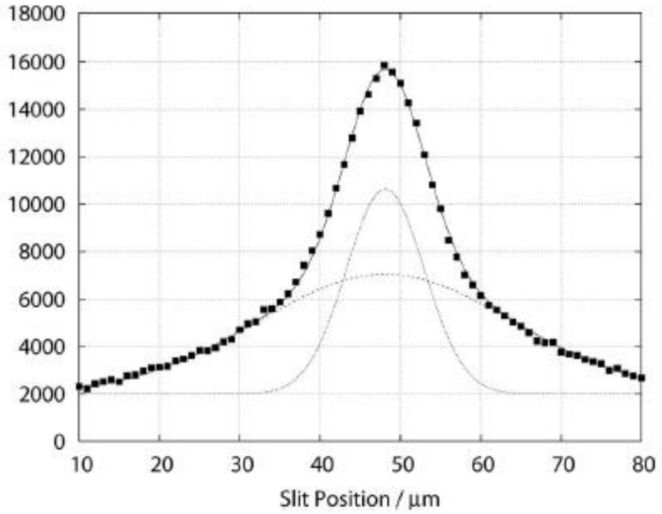
- Research on focusing of gas molecules is based on generating sub-mm supersonic gas jet with high intensities.

- Supersonic D_2 beam focused down to 15.2±0.5 μm.

- Helium beam focused to diameter less than 1 μm







*T. Reisinger et al. J. Vac. Sci. Technol. B 26(6), 2008, 2374-2379

**S. D. Eder et al. New J. Phys. 14 (2012), 073014

QUANTUM HELIUM ATOM MICROSCOPE

- Key Features
  - Atom sieve used in similar fashion as FZP are used for X-rays
  - Non-invasive and non-destructive as He atoms impact least energy to the samples
  - Interacts with uppermost surface of the sample
  - Scattered *He* atoms are collected to construct the surface image of the sample
  - Spatial Resolution depends upon the FWHM of quantum gas jet

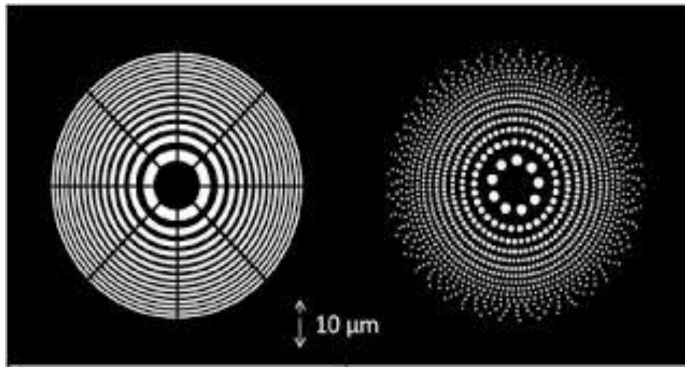
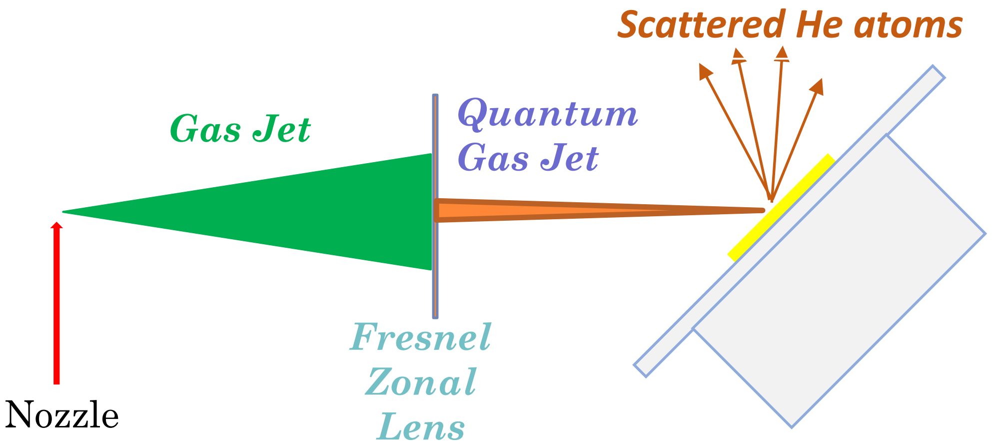
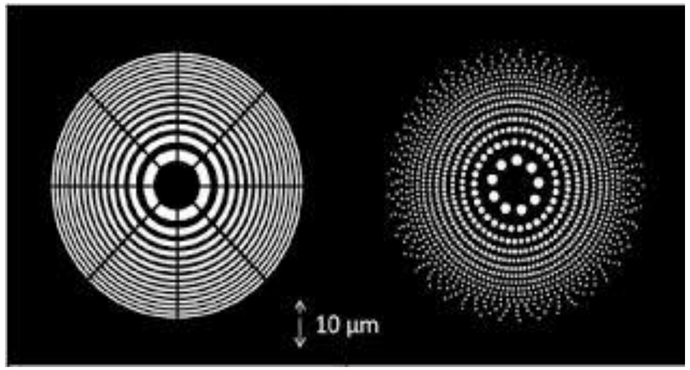


Illustration of Fresnel Zone Plate used for the generation of focused quantum gas jet



Quantum Helium Atom Microscope

- Key Features
  - Acquisition time will depend on the total scan area and contrast required for the image
  - The ultimate resolution is determined by the width of the outermost zone.
  - Low-energy beam (typically less than 0.1 eV),with a very high resolution, potentially smaller than 10 nm.
  - Lack of net charge or spin and short de Broglie wavelength of 0.1 nm



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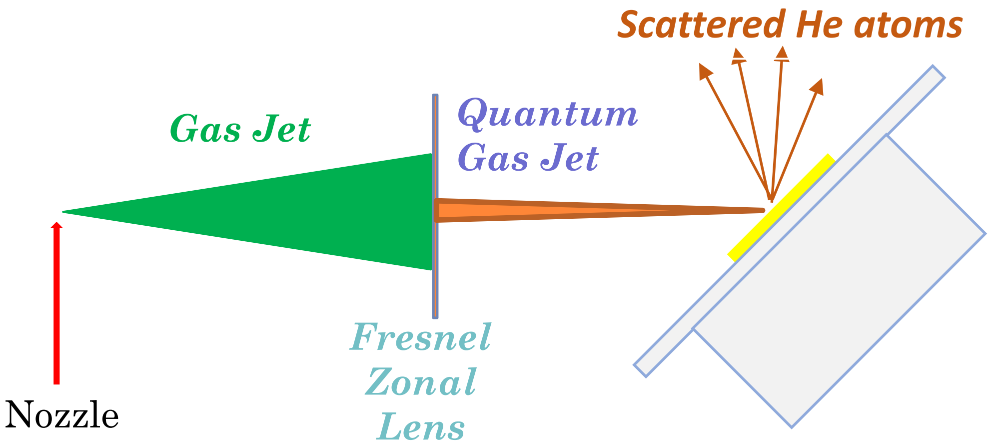
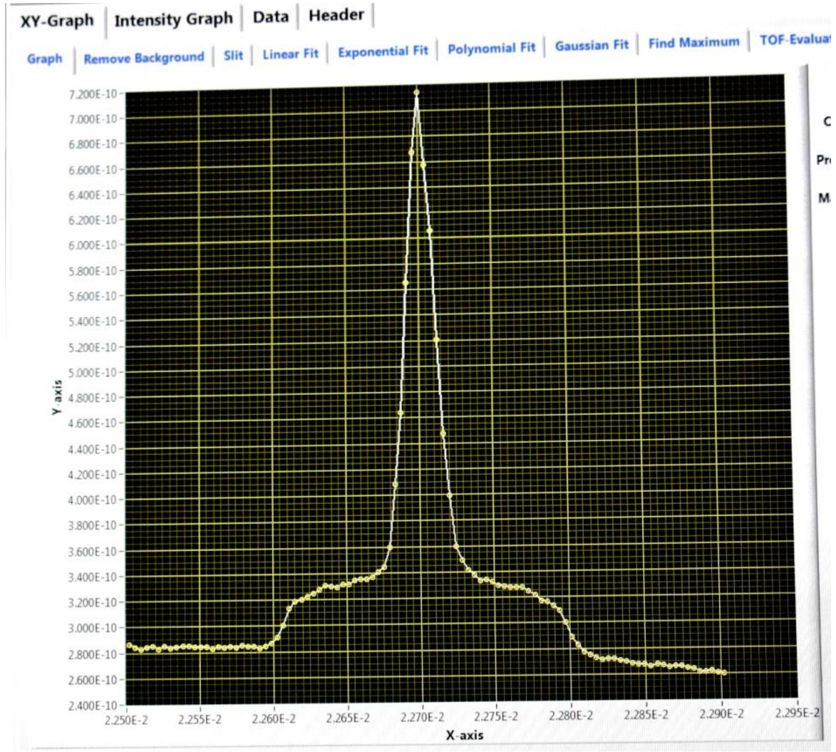
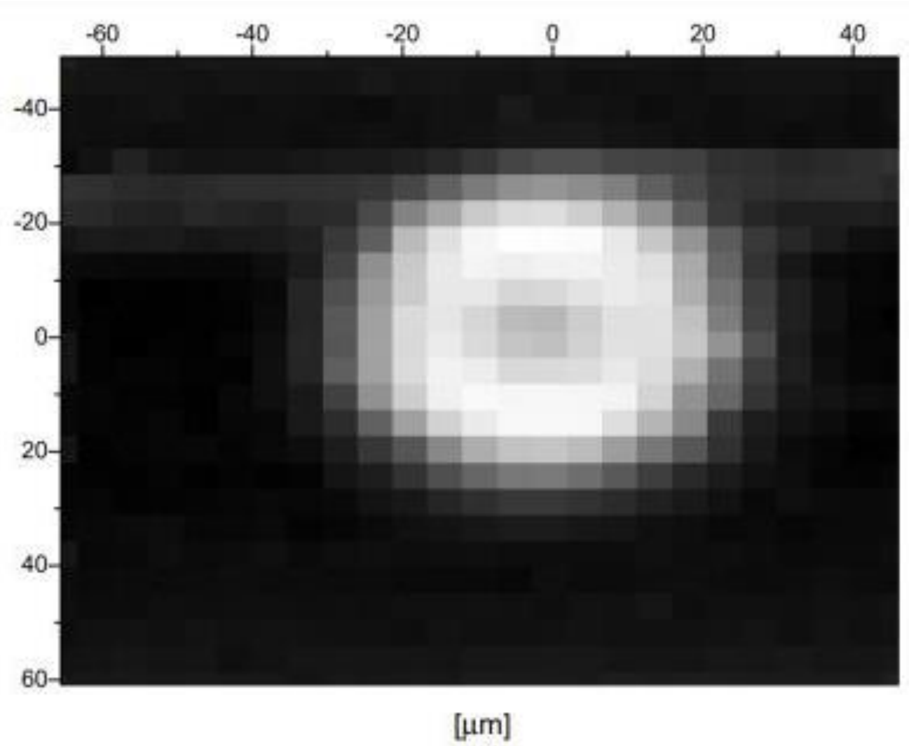


Measurements At University Of Bergen

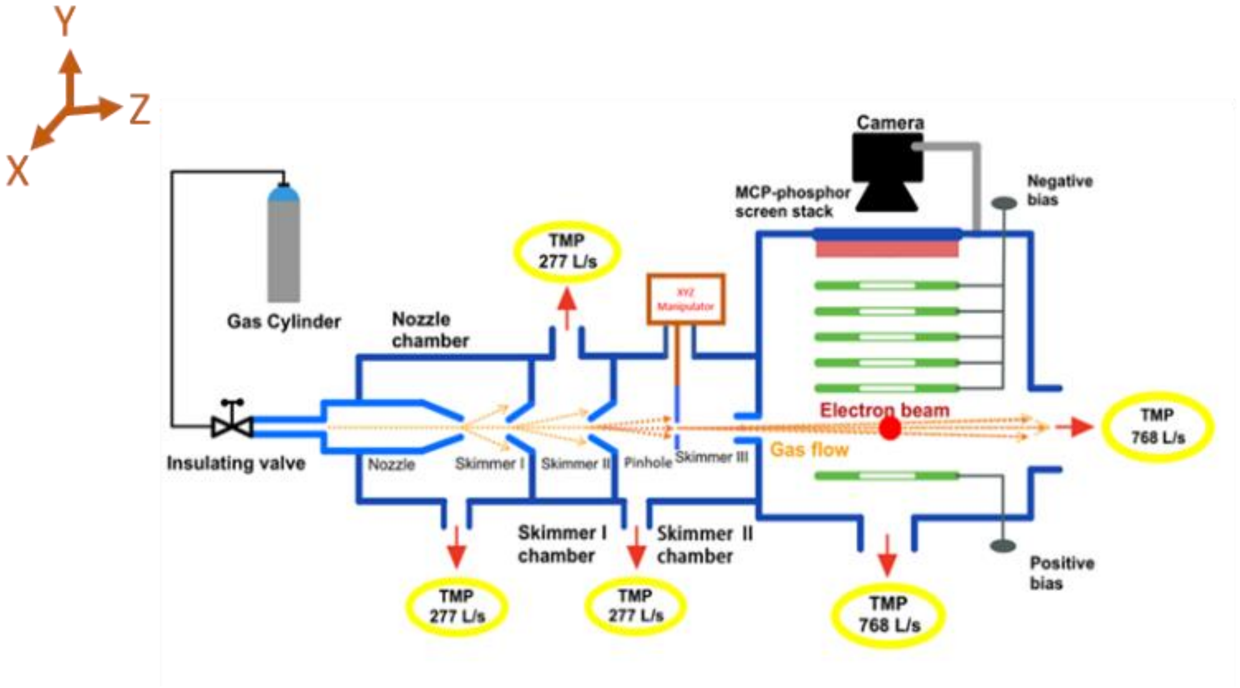


Snap-shot of Intensity vs. x position showing x profile of the quantum gas jet

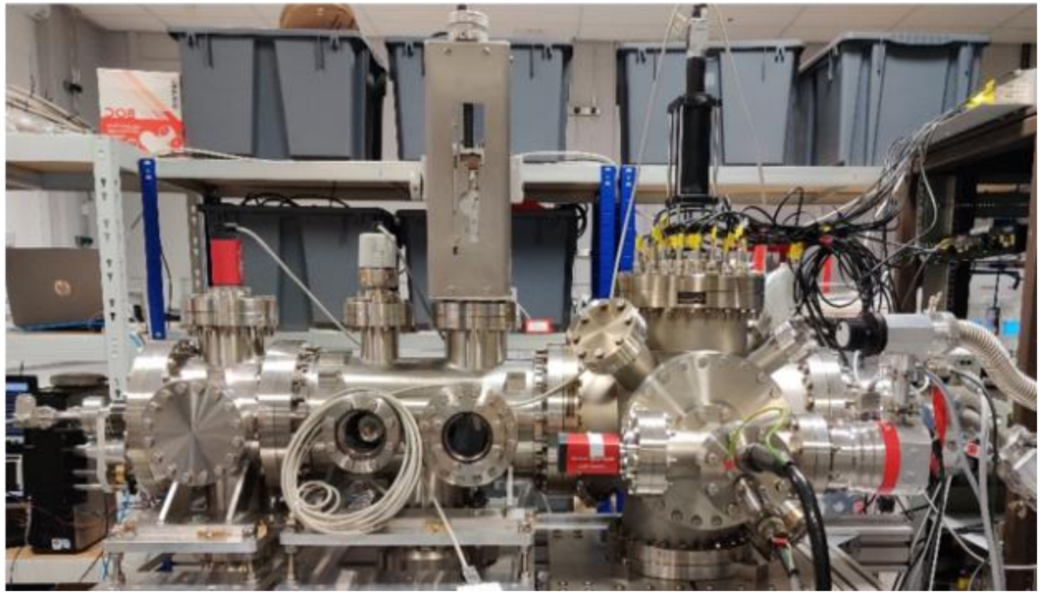


Measurements showing the 35 µm (FWHM) spot size for our FZL design

Measurements At The Cockcroft Institute

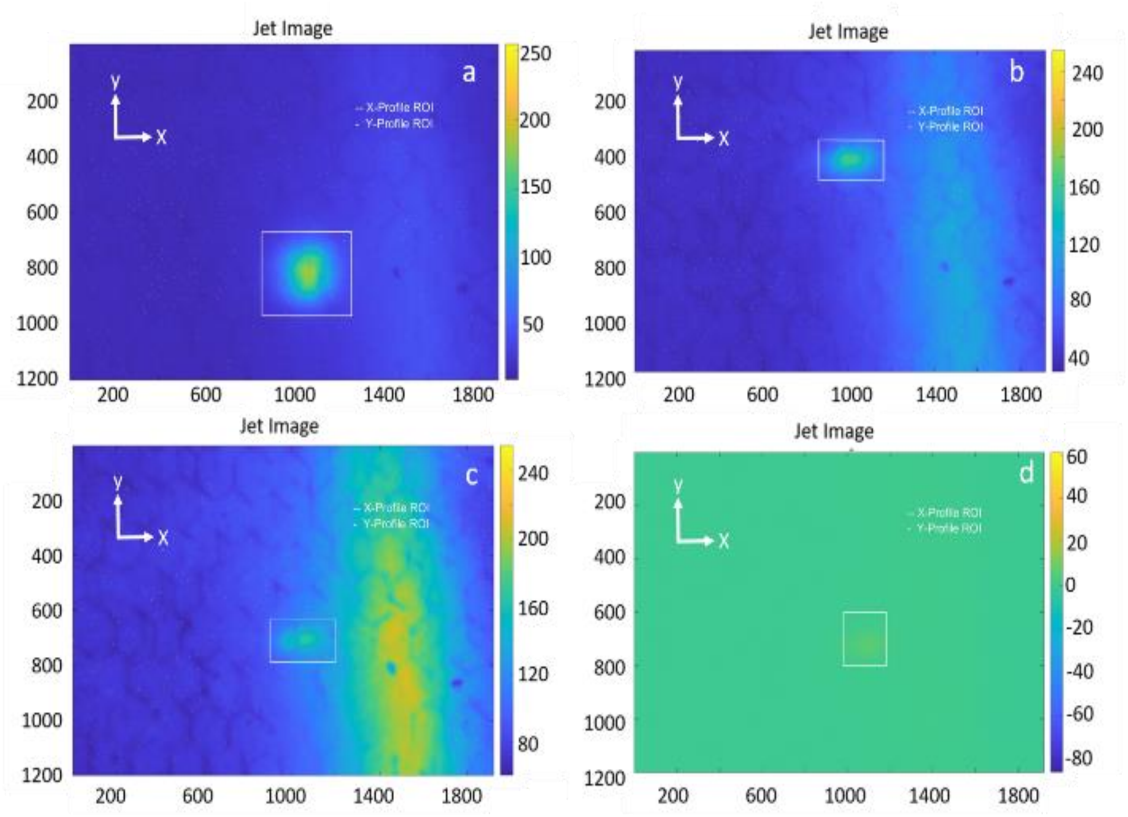


Schematic of the gas jet setup at the Cockcroft Institute

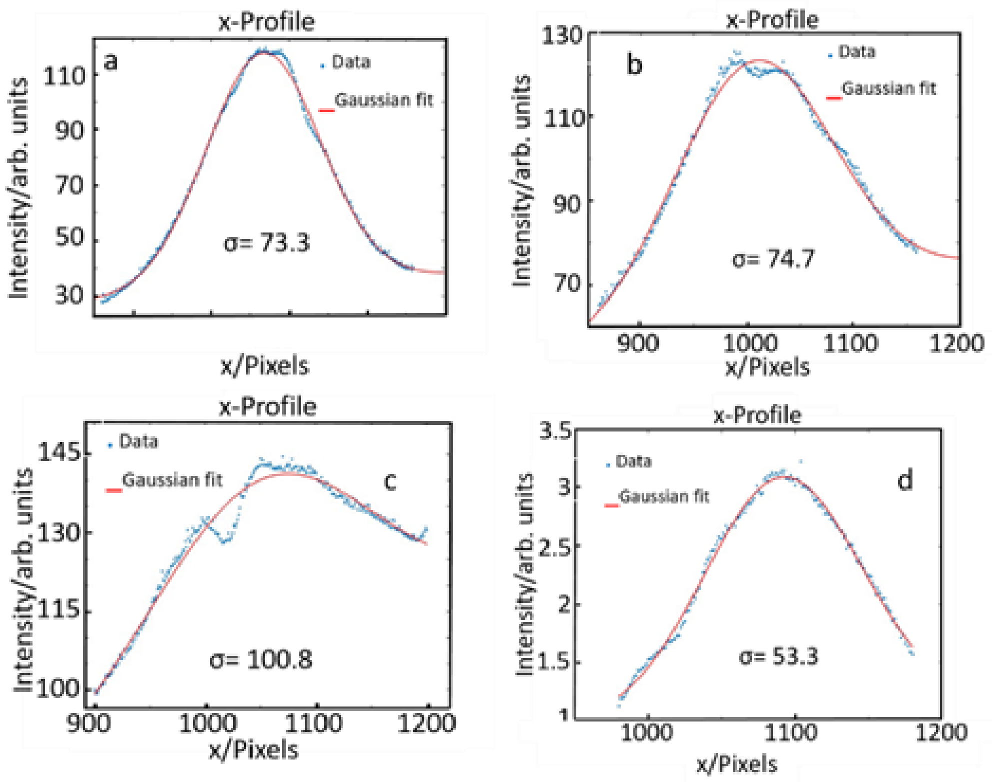


Modified gas jet monitor for the Quantum gas jet measurements

Measurements At The Cockcroft Institute

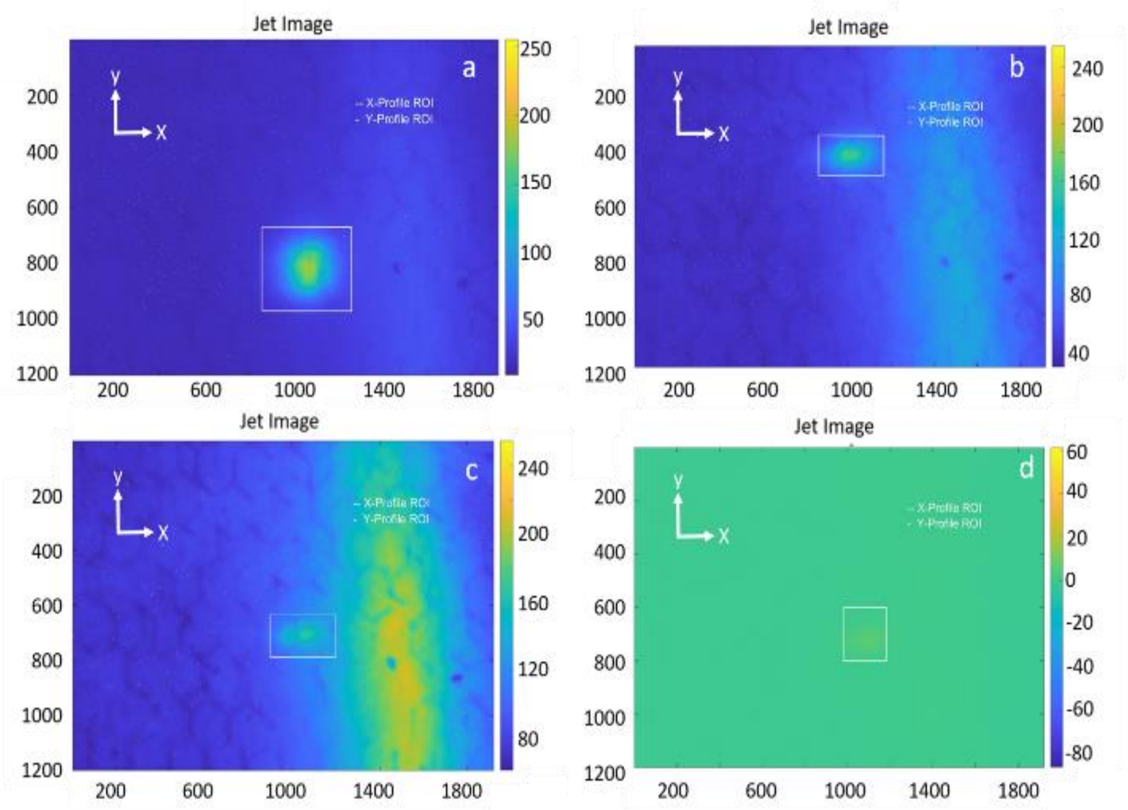


Beam profile images obtained for various pinholes diameters: (a) 500µm, (b) 200µm, (c) 100µm and (d) 50µm. The integration time for each image is 6, 9, 30 and 300 seconds respectively



X beam profile obtained for various pinholes diameters: (a) 500µm, (b) 200µm, (c) 100µm and (d) 50µm

MEASUREMENTS AT THE COCKCROFT INSTITUTE



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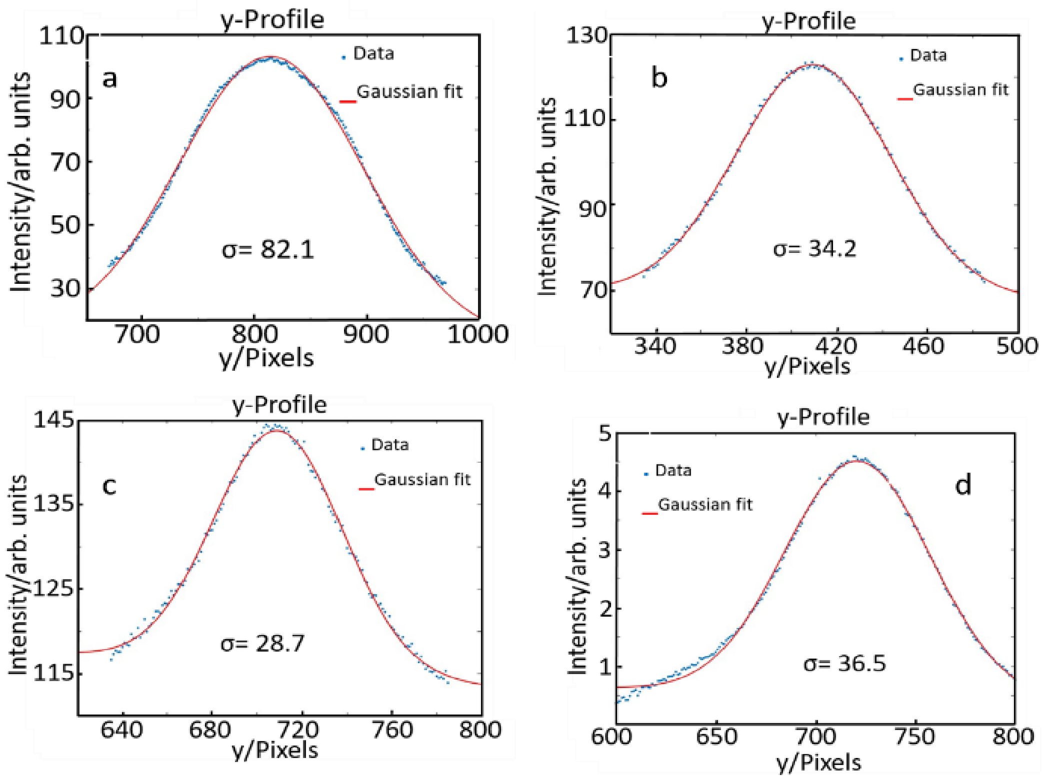


Y beam profile obtained for various pinholes diameters: (a) 500µm, (b) 200µm, (c) 100µm and (d) 50µm

Novel Imaging Solution

1 Minimally destructive

- ✓ Negligible energy imparted to the sample
- ✓ Interaction with only uppermost layer of the sample

3 Novel Imaging and improved operation

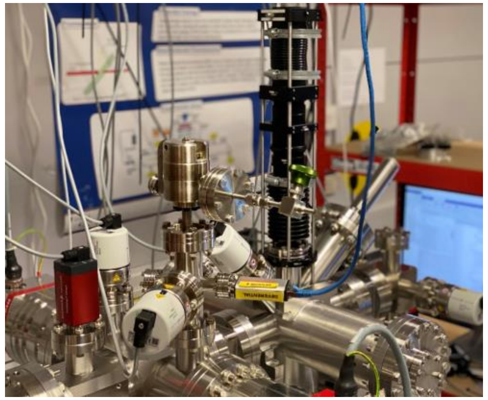
- ✓ Enabling technology for In-situ sample imaging while growth/deposition process
- ✓ Online imaging of samples become feasible based on live feedback system using Machine Learning

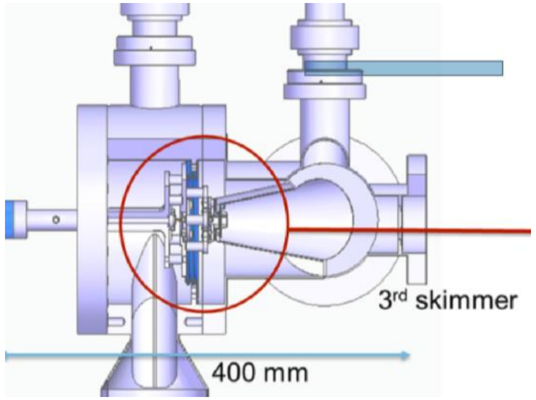
2 Significantly reduced time

- ✓ All key parameters monitored remotely
- ✓ Significantly reduced maintenance and calibration
- ✓ Imaging for all sort of samples can be done using single system

*N. Kumar, C.P. Welsch, et. al, Physica Medica 73, p 173-178 (2020).

Work Programme





Deliverables

- Prototype of quantum gas jet-based microscope, tested with standard samples
- Design report of the optimized system
- Software for monitor control and image analysis

SUMMARY

- *qHAM* will apply cutting edge STFC Gas Jet technology to a key surface imaging challenge;
- Identified beneficiaries from this microscope- with an possibility for using the system for almost every vacuum compatible samples and during sample growth process;
- Project will be realized by consortium with collaborative links with Institutes having experience in their respective relevant areas;
- Exceptional international network for collaboration.

Thank you for your attention

Special thanks to

W. Butcher, M. Patel, I. Maltusch, O. Stringer, J. Wolfenden, H. Zhang, T. Price, C.P. Welsch

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D-Beam

HAM