Bringing Helium Microscopy into the Lab - Meeting Key Challenges of Light and Detection Technologies

Liverpool team to develop advanced quantum technology microscope for non-destructive testing

As part of the national strategy to commercialise quantum technologies researchers from the University of Liverpool's QUASAR group based in the Cockcroft Institute, together with UK spin-out company D-Beam, are being funded to develop an advanced microscope for non-destructive testing.

Professor Carsten Welsch, Head of the Department of Physics at the University of Liverpool and a senior academic at the Cockcroft Institute, told International Labmate some more about the challenges and aims of the Quantum Gas Jet-based Helium Atom Microscope (qHAM) project, which builds on ground-breaking work by the team on beam diagnostics.

The Industrial Strategy highlighted quantum technologies as being strategically important to the UK. The funding for technologies in this area comes through Innovate UK which is to invest up to £1 million in a range of projects that are part of the Commercialising Quantum Technologies programme. The quantum gas jet-based helium atom microscope (qHAM) is based on two quantum phenomena: wave-matter duality and matter wave interference and so pushes the knowledge frontier in these areas.

There is now also a second project, QuantumJet, funded with £110k by STFC through the Innovation Partnership Scheme (Follow-on Funding), which also uses the quantum jet technology, but to develop a novel type of beam monitor for beams with very small cross sections as found e.g. in linear colliders. This project is linked to qHAM in the sense that both will allow us to investigate into highly focused beams using quantum effects.

Scanning helium microscopy (SHeM) offers many benefits over the use of x-rays or charged electrons, which can destroy fabrics, biological samples and organic films and present difficulties when using magnetic fields. Neutral helium beams provide a chemical, electrical and magnetically inert surface probe that delivers no charge to the sample. This creates the opportunity to image fragile structures without damaging them.

SHeM takes helium gas, pumps it to high pressure and allows it to expand through a tiny hole into a vacuum. The helium atoms are back scattered from the sample, giving a higher resolution than optical microscope, and the range of scattering pathways creates contrast within the image.

What are the main differences between this and other helium microscopes and the type of benefits this will offer?

There have been other scanning helium microscopes, but these have been limited by the use of simple atom optics and existing detector technologies. Neither a focussed beam of sufficient energy or detectors that are capable of capturing the scattering mechanisms behind the image contrast have yet been developed. A key challenge is maximising the intensity of the imaging beam to overcome noise, while minimising its width, which provides the resolution. This is achieved by creating a supersonic expansion of gas in a vacuum that accelerates the helium atoms to high velocities.

Using quantum technologies will allow us to increase the contrast and the sensitivity of the detectors increasing the resolution. One central element will be the creation of a strongly focused gas jet after an atom sieve – this shall pave the way for mm-resolution.

Microscopes are of two general classes – those that illuminate the sample with a beam, and those that use a probing wave to scan the surface. The resolution achieved by scanning has a number of physical limitations depending on the nature of the particles used for the beam. To overcome the diffraction limit, the probe requires a smaller wavelength. As matter waves have a much shorter wavelength than visible light they can be used to study features of the order of and maybe even below 1µm.

The de Broglie wavelength is determined by the kinetic energy and the particle mass, but increasing the energy can destroy a delicate sample, so electron beams for example would not be suitable. Their charge would also make the analysis of samples with electric conductivity challenging.

Helium atoms provide a greater mass with an energy level similar to thermal energy, enabling a probe length scale down to an atomic level with a lower energy and provide surface scattering without penetrating the sample.

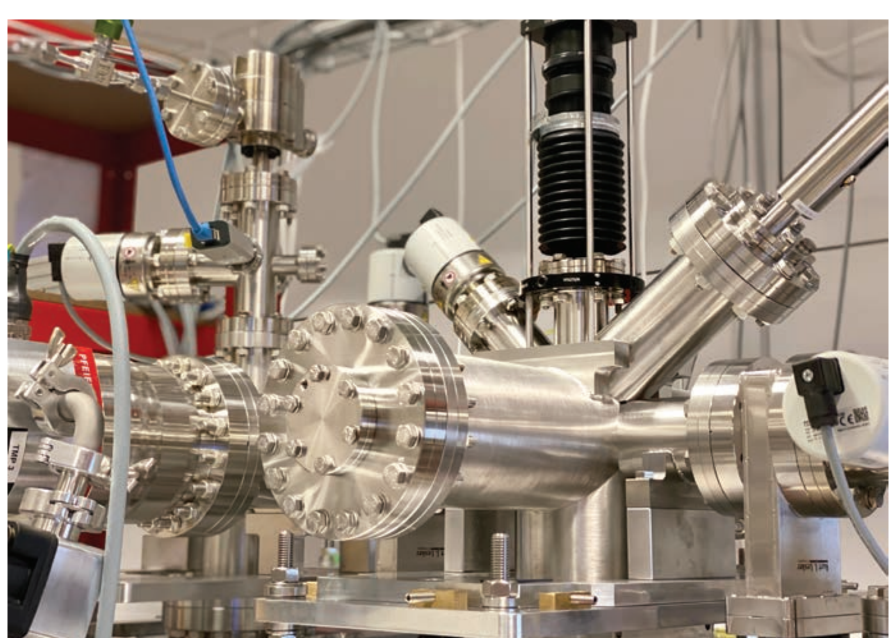
One of the many challenges comes from finding an efficient way to focus the matter beam and detecting the scatter pattern. qHAM is designed to address this challenge.

Could you describe in more detail your work on the super-sonic gas jet beam monitoring technology for the High Luminosity upgrade at LHC – and how this approach can effectively be scaled to fit a microscopy instrument that can be used by researchers and industrial users?

The Large Hadron Collider is currently being upgraded to increase its luminosity (rate of collisions) by a factor of ten to increase the number of rare particles it is able to generate. Funding of £26 million for the High Luminosity (HL-LHC) upgrade has just been announced for a range of projects aimed at developing the technologies needed to achieve this ambition. This includes super conducting magnets for improved beam control, new types of cavities for beam rotation, and improved diagnostics for monitoring and controlling the beams. Many of these are being delivered by UK universities and will require high-tech components commissioned from industry.

One of the HL-LHC projects is led by researchers from the University of Liverpool's Quantum Systems and Accelerator Research (QUASAR) Group. With increased luminosity the beams become too powerful and beam instrumentation currently used would no longer work. This requires entirely new approaches to fully characterise the beams. The QUASAR Group is targeting this challenge with the development of a supersonic gas jet beam profiler.

The gas jet profiler creates a thin screen of electrically neutral particles. This jet then crosses the primary beam in the HL-LHC, resulting in excitation of the particles in the jet and the emission of light. This light can then be detected and used for two-dimensional imaging of the beam.



The non-interceptive gas jet beam profiler is flexible and scalable, enabling its use across a range of accelerators, and is not restricted to high-energy storage rings such as the HL-LHC. It can measure the detailed properties of essentially any beam of charged particles in just a few seconds.

The equipment developed in this process will overcome the limitations of existing technologies.

Currently beam-monitoring techniques rely on sensing the electromagnetic fields induced by the beam. Low-intensity beams present a considerable challenge due to the weak signals available to the diagnostic pickups, while, at the same time, the environment found in a particle accelerator usually generates high levels of electromagnetic interference, which further complicates precise measurements.

The supersonic gas jet-based beam profile monitor offers a range of interesting possibilities. As the interaction uses excitation or ionisation, which are well understood and usable with most projectile types, it offers intrinsic flexibility. However, for this technology to be used as part of a microscope, all dimensions have to be reduced, a new way of focusing the gas jet has to be introduced and a 3D movement system needs to be included in the design. All three are significant challenges which will be addressed in the qHAM and QuantumJet projects.

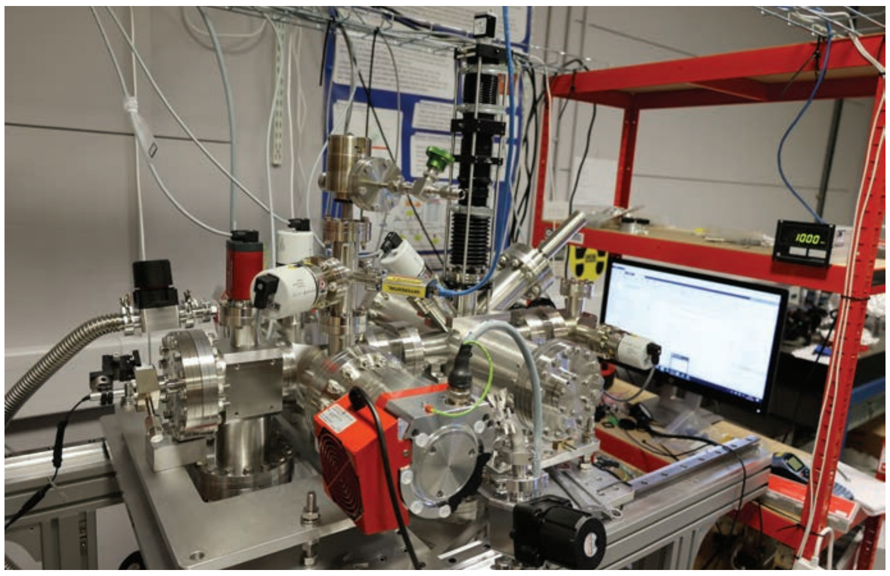
The QUASAR Group in collaboration with our partners at CERN and GSI has already developed a super-sonic gas jet beam monitoring technology for the High Luminosity upgrade of the Large Hadron Collider, and we will be building on this knowledge to develop the quantum microscope.

Will the quantum microscope be installed mainly at larger facilities such as the Cockcroft Institute? Or will this technology ultimately be aimed at large, medium, and smaller business users?

The Cockcroft Institute offers state-of-the-art laboratory infrastructure, most notably DITAlab, a laboratory dedicated to the development of cutting-edge beam instrumentation. Currently, the QUASAR Group has three different gas jet setups in operation in this laboratory and this will form the basis for the new studies into the microscope.

Once the technology has been successfully demonstrated in proof-of-concept studies, it would be progressed towards a user instrument that could be run anywhere, including smaller businesses. This is a particularly interesting aspect in terms of developing a technology originally developed for the world's largest collider for much wider applications.

In this project, fundamental research by the QUASAR Group will be commercialised by D-Beam, a company co-founded by you fast-track the benefits of scientific breakthroughs to industry.



Could you tell us more about D-beam's involvement, is this largely on the detector development side?

D-Beam was spun out of the University of Liverpool/Cockcroft Institute a few years ago and has since become of choice partner in a number of UK and EU projects, contributing its unique experience in the design, manufacture and optimisation of instrumentation that can be used to characterise beams of particles in great detail.

This expertise will be very important for the Helium atom microscope as well – understanding how the gas jet is formed, focused and then reflected from the sample are all formidable monitoring challenges and the company will help identify solutions.

Have you received other investment and support to carry the company forward? Other than yourself, who are the key people at D-Beam?

I had the pleasure to found D-Beam a few years ago with Dr Alexandra Alexandrova who had just benefitted from a fantastic training experience through the STFC Royal Society of Edinburgh Enterprise Fellowship.

The company was invited into the STFC-CERN Business Incubation centre soon after its foundation and has since been awarded funding with academic partners through EU projects such as ARIES Proof of Concept funding, has benefitted from STFC Impact Acceleration Account support and STFC Innovation Partnership Scheme Follow on Funding. Following Dr Alexandrova's departure, Dr Joseph Wolfenden has joined the company as director and helped promote D-Beam's beam diagnostics solutions.

The company can already look back to a very successful journey: Its optical-fibre beam loss monitor (oBLM) was selected as an ASTeC technology highlight of the year in 2018/2019. Collaborative work with the University of Liverpool's physics department was selected as an STFC Impact Acceleration Account success story in 2020 and its studies into adaptive optics was selected an ARIES 'success story' this year. The company advances prototype monitors that were developed to address specific challenges in fundamental research projects to much wider markets and has excellent growth potential. Given the many areas where particle beams find application, from airport security scanners to novel cancer therapies, and the fact that all of these monitors need to be monitored in great detail, there are many interesting challenges for D-Beam to tackle!

Will new start-up businesses or spin-outs be able to access this technology? Have plans for a supportive business hub development or extension of existing innovation parks using this technology been discussed or possibly considered?

Licensing part of this novel technology to other SMEs is certainly an option that can be considered. The current research is still at a low technology readiness level and therefore it seems a little premature to already look into extending into innovation parks. However, such an extension could happen quickly if we manage to clearly demonstrate its capabilities.

What do you think will be the overall impact of this technology on the local area economy and to the UK as a whole?

The Cockcroft Institute for Accelerator Science and Technology in the North West of England enjoys a strong reputation as a leading centre for accelerator research, and this has stimulated a cluster of medical and industrial organisations that utilise the research output or provide the instrumentation required to build and develop the accelerators.

The world's first proton cancer therapy treatment centre is at Clatterbridge and the UK is now investing strongly into high energy proton beam therapy. Amongst others, CI researchers have been developing new monitors to better characterise a treatment beam and these have the potential to benefit patients around the world. Gas jet-based monitors show excellent potential in this area as well.

The quantum microscope shall capitalise on the University of Liverpool's unique expertise in gas jet formation and shaping, as well as D-Beam's skills in monitoring some of the most demanding beams in great detail. In combination, this shows great promise for a wide range of applications and sectors. The synthetic biology and the organic and polymer electronics industries will be among those to benefit from the technology.

The aim is to create a compact, low-cost table-top microscope with superior imaging qualities that will enable critical proof-of-concept studies, unlocking the potential of this exciting new approach to imaging.

The Cockcroft Institute is an international centre of excellence for accelerator science and technology based at the Daresbury Laboratory, UK. It is a joint venture between the Universities of Lancaster, Liverpool, Manchester and Strathclyde and the Science and Technology Facilities Council (STFC).

Professor Carsten P Welsch (pictured), Head of Physics at Liverpool University and Head of the Liverpool Accelerator Physics Group at the Cockcroft Institute has devised a highly successful concept for training networks and has been leading several pan-European programmes. His research focuses on beam diagnostics and the design of particle accelerators.

Researchers at the Physics Department at Liverpool University lead world-class R&D programmes in fundamental science in particular in accelerator physics, condensed matter physics, nuclear physics and particle physics. They are also known internationally for work in applied fields such as semiconductor sensors, nuclear and renewable energy.

The Quantum Systems and advanced Accelerator Research (QUASAR) Group is focused on the development and experimental exploitation of particle accelerators and light sources.

Accelerator scientists are collaborating with leading institutes and laboratories around the world, including CERN in Geneva, Diamond Light Source and Daresbury Laboratory in the UK, ESRF and GANIL in France, GSI and DESY in Germany and TRIUMF in Canada.

More information online www.cockcroft.ac.uk

Read, Share and Comment on this Article, visit: www.labmate-online.com/article