A QUANTUM GAS JET FOR NON-INVASIVE BEAM PROFILE MEASUREMENT

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Abstract

A novel instrument for accelerator beam diagnostics is being developed by using De Broglie-wave focusing to create an ultra-thin neutral gas jet. Scanning the gas jet across a particle beam while measuring the interaction products, the beam profile can be measured. Such a jet scanner will provide an invaluable diagnostic tool in beams which are too intense for the use of wire scanners, such as the proposed CLIC Drive Beam.

In order to create a sufficiently thin jet, a focusing element working on the de Broglie wavelength of the Helium atom has been designed. Following the principles of the Photon Sieve, we have constructed an Atomic Sieve consisting of 5230 nano-holes etched into a thin film of silicon nitride. When a quasi-monochromatic Helium jet is incident on the sieve, an interference pattern with a single central maximum is created. The stream of Helium atoms passing through this central maximum is much narrower than a conventional gas jet. The first experiences with this device are presented here, along with plans for further tests.

INTRODUCTION

The Compact Linear Collider (CLIC) will use a novel two-beam acceleration scheme to collide electrons and positrons at up to 3TeV [1]. Energy is extracted from a very intense, lower energy Drive Beam (DB) using specially designed RF structures, and transferred to the less intense, high energy colliding beams.

Table 1: Relevant Parameters for the CLIC Drive Beam

Beam Energy	to 2.4 GeV
Beam Current	4.2 A
Pulse Length	140 µs
Bunch Length	13 ps
Bunch Separation	2 ns
Repetition Frequency	50 Hz
Normalised Emittance	150 mm mrad

High intensity beams pose a challenge for beam diagnostics, since all instruments must be non-interceptive. In addition, the short bunch length and separation envisaged for the CLIC DB will generate substantial high-frequency wake fields which can interfere with beam measurements. A number of solutions are being explored, including synchrotron radiation for the high-energy part of the DB. The gas jet monitor described here is a promising option for the lower energy section of the DB accelerator, as well as for other planned high-intensity accelerators.

BEAM GAS IONISATION

Residual gas ionisation is used as a diagnostic tool in many accelerators [2][3]. A charged particle beam ionises a fraction of the residual gas present in the beam pipe. If an electric field is applied across the beam pipe, the ions and the liberated electrons are accelerated away from the beam in opposite directions. A position sensitive detector is used to image either the ions or the electrons, and thus measure the beam profile. Throughout the discussion below we refer for clarity to ion collection; however the conclusions remain valid if the electrons are collected instead.

In order for this technique to be accurate, the position at which the ions are generated must be mapped onto the detector, that is, the ions should fly in a straight line. In reality, however, this is not quite true. Firstly, the ions are created with a certain initial momentum. Secondly, the electromagnetic field of the beam will influence their trajectory. Thus, the profile of ions arriving at the detector will not exactly match the beam profile.

In order to reduce this effect, a magnetic field may be added parallel to the electric field. In this case, the ions follow a helical path which, if the gyroradius is sufficiently small, may be taken to approximate a straight line. In the case of a very intense beam, however, the space charge field may be so strong that a small gyroradius cannot be guaranteed. Numerical methods can be used to correct for this effect [4] but the resolution of the profile is in consequence reduced.

GAS JET MONITOR

Gas jet monitors have been developed at NIRS and J-Parc [5] in order to decrease the measurement time and allow 2-d profile measurements at a single point. A planar gas jet or 'gas curtain' crosses the beam pipe. The curtain is tilted at 45° and acts like a screen when combined with an electric field for ion extraction. The pressure of the gas jet is locally much higher than the residual gas pressure, so that sufficient ions for beam profile measurement with a given accuracy are collected in a shorter time. The jet passes through the beam pipe into a collection chamber, so that the beam vacuum is not substantially affected.

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The gas jet is generated by allowing high-pressure gas to expand through a small-aperture nozzle and then pass through a series of skimmers. The small skimmers separate the jet generator into a number of chambers, and each chamber is separately pumped so that the pressure drops by several orders of magnitude in each successive chamber. After the second skimmer, the jet operates in the molecular regime, where the mean free path of the gas molecules is much longer than the chamber dimensions. In this regime, each gas molecule can be regarded as a projectile, which flies in a straight line until it hits the chamber surface. A final shaped aperture is used to make the planar jet.

A further development from the same group is the focusing of the neutral gas jet using a non-linear magnetic field [6]. Oxygen is used due to the larger magnetic moment of the O_2 molecule. A highly non-linear field is applied using short-period multi-pole magnets. This magnetic focusing allowed an increase, by a factor of 2, of the gas density in the plane of the curtain, and a small reduction in the gas jet thickness. However, such non-linear effects are inherently small, and an extremely large magnetic field gradient would be necessary to achieve stronger focusing.

COCKCROFT INSTITUTE TEST STAND

A gas jet test stand has been set up at the Cockcroft Institute, U.K., in order to demonstrate and optimise the gas jet generation [7]. The gas jet is generated using the nozzle and skimmer method described above, and the nozzle is moveable, so that the effect of changing the nozzle-skimmer distance can be investigated. The test stand was designed as a demonstration monitor for an Ultra-low energy Storage Ring [8], where a non-interceptive monitor is required and must operate in extremely high vacuum in order to preserve the beam lifetime.

The gas jet is generated by a circular orifice of 30 μm diameter, and two conical skimmers with open diameters of 180 μm and 400 μm. The orifice can be supplied with either Nitrogen or Helium at a variable pressure up to 12 bar. Finally a rectangular skimmer is used to shape the curtain jet before it enters the interaction chamber. The interaction chamber (located where the beam pipe would be if the jet monitor were installed at an accelerator) contains a series of circular electrodes which are used to generate a homogeneous vertical electric field. An electron gun with an energy of up to 5 keV is used to ionise the gas. Ions are then extracted by the electric field onto two Multi-Channel Plate photomultipliers (MCPs), arranged in chevron configuration to provide a gain of up to 10^6. The electrons released by the MCPs are then accelerated onto a phosphor screen, which is imaged using a CCD camera. The whole setup is illustrated in Fig. 1.

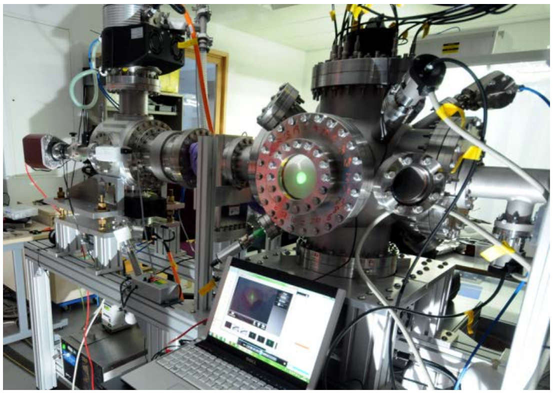

Figure 1: The gas jet test stand at the Cockcroft Institute. The jet generator is on the left, the interaction chamber on the right. The electron beam is seen on the side phosphor screen, while the MCP / Phosphor assembly for imaging of the extracted ions is at the top.

The differential pumping scheme of the gas jet is shown in Fig. 2 and is described in greater detail in [9]. It can be seen that a reduction in pressure by 12 orders of magnitude is achieved between the gas inlet and the interaction chamber.

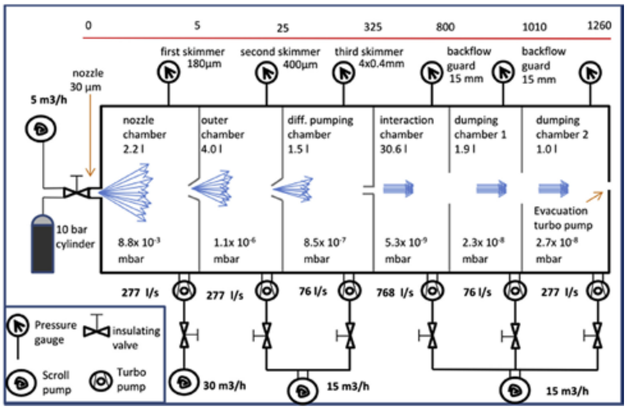

Figure 2: Differential pumping scheme and chamber pressures in the gas jet test stand.

Generation of the gas jet was recently demonstrated [10]. A typical image of the MCP / phosphor screen is shown in Fig. 3. Two separate lines are clearly visible. The line on the left is due to ionisation of the residual gas. As the electron beam passes through the chamber, residual gas ions are generated and then move vertically due to the extraction field. There is some spreading due to the initial thermal motion of the gas, so the line is broader than the true width of the electron beam. The line on the right is due to ionisation of the gas jet. The gas jet is traveling with a speed of around 500 ms^{-1} for Nitrogen or 1000 ms^{-1} for Helium. This horizontal motion continues as the ion is accelerated vertically, resulting in a parabolic path, and a separation of the two lines. The gas jet line is considerably brighter, due to the higher density of the gas jet, and thinner due to the relatively small velocity spread in the gas jet.

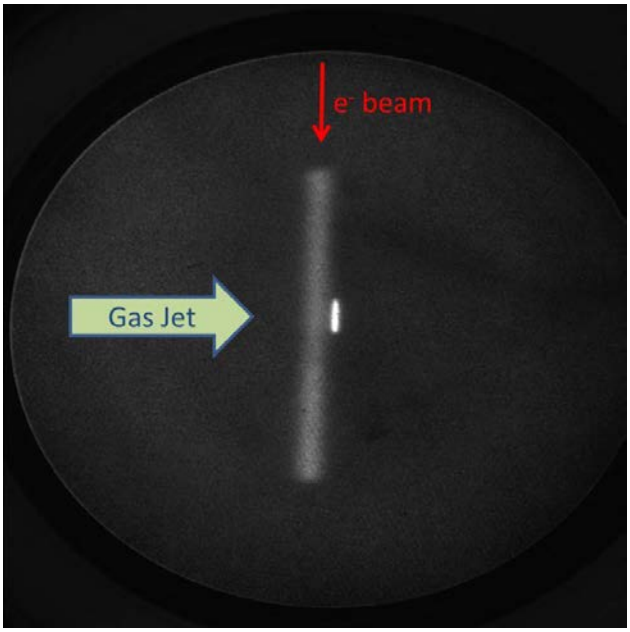

Figure 3: Typical image on the phosphor screen. The longer, fainter line is ions from the residual gas in the chamber; the shorter, brighter line is ions from the gas jet.

The jet acts like a ‘thick’ screen, since ionisation can occur anywhere in the intersection volume of the beam and jet. This affects the resolution of the monitor. Specifically, for a jet of thickness t, the point spread function (PSF) is stretched by a factor $\sqrt{2}t$ along the axis perpendicular to both the beam and the jet; the resolution along the axis parallel to the jet is not affected. The gas jet appears as a streak instead of a circular profile because the gas jet thickness is larger than the beam size.

By scanning the electron beam vertically through the gas jet, a rough cross-section of the gas jet density can be reconstructed, and the average thickness of the jet is estimated to be 2 mm. A more accurate method for measuring the jet density profile is currently being commissioned. This consists of an ionisation vacuum gauge which is inserted into the gas jet on a 3-axis translation stage. The gauge is covered on the side facing the gas jet by an aluminium shield with a thin slit through which the gas jet can pass. By scanning the slit through the gas jet we will be able to measure the density profile.

Each of the chambers is equipped with a vacuum gauge, and the effect of the gas jet on the pressure in each chamber can be examined. As expected, the pressure in the nozzle chamber and the outer jet chamber (i.e. between the nozzle and 1st skimmer, and between the two skimmers) increases linearly with the gas inlet pressure. Thanks to the differential pumping scheme and the efficient collection of the gas jet in the dumping section, however, the pressure in the interaction chamber increases only slightly, as shown in Fig. 4.

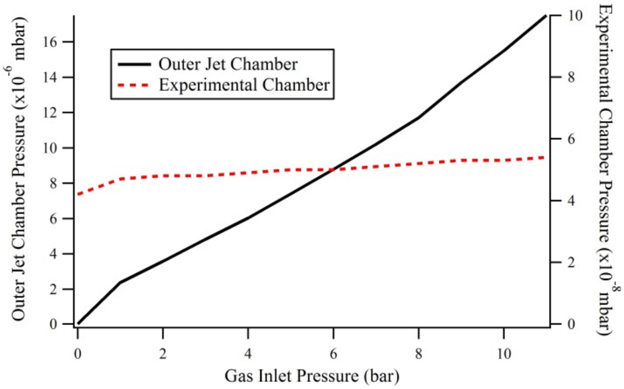

Figure 4: Dependence of the chamber pressure on the gas inlet pressure. Solid black line, left axis: pressure in the outer jet chamber. Dashed red line, right axis: pressure in the experimental chamber.

In order to reduce even further the load on the beam vacuum system, the jet can be operated in pulsed mode. A fast solenoid valve is attached to the gas inlet line. If the gas inlet is simply closed, the gas jet continues operating for some time, as the gas pipe slowly empties through the orifice. Instead, a two-way valve is used. When the valve is in the ‘off’ position, the orifice is connected to a vacuum pump, quickly emptying the high-pressure gas. The valve has a switching time of approximately 20 ms and can be operated at up to 20 Hz. As an example, Fig. 5 shows the operation of the gas jet at 1 Hz with a 50% duty cycle. The brightness of the gas jet line on the phosphor screen closely follows the operation of the valve. The gas jet rise time could not be precisely measured since the CCD camera was only capable of 10 fps. The pressure in the differential pumping chamber and the dump chamber are also shown. It can be seen that the pressure rises asymptotically over a few hundred µs, and then falls just as quickly to its original value.

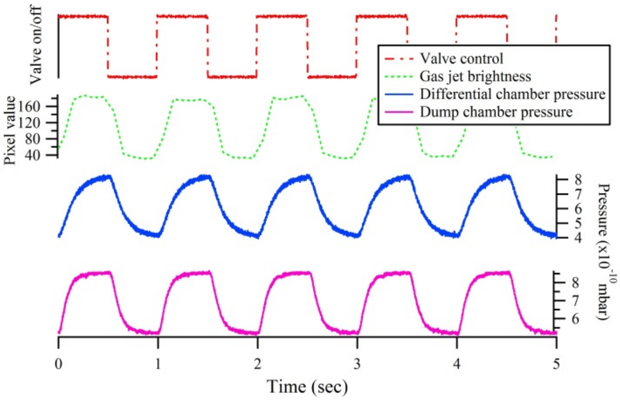

Figure 5: Operation of the jet in pulsed mode. Traces from top to bottom: Valve control, average pixel brightness of the gas jet line, pressure in the differential pumping chamber, pressure in the jet dumping chamber.

QUANTUM GAS JET

Due to the thickness of the gas jet as well as the space charge effects from an intense beam, it is unlikely that a

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monitor based on the curtain gas jet will achieve a sufficiently small resolution to measure sub-mm beams such as the CLIC DB. Instead, we propose to develop a gas jet scanner. A thin pencil beam must be generated and is then moved through the beam to measure the profile. The device would be analogous to a wire scanner, but since it is minimally interceptive it can be scanned much more slowly.

The beam intensity at each position could be derived by extracting and counting ions, as with the current setup. However the trajectory of the ions would not be important, since the position information is provided by the gas jet position, so the profile measurement would not be affected by space charge. Alternatively, reliance on charged particles could be eliminated altogether by recording the beam losses during the gas jet scan or by detecting bremsstrahlung photons.

In order to achieve a thin gas jet with a diameter below 100 µm, a novel focusing method is being developed for the generation of the gas jet. The quantum wavefunction of the neutral gas atoms is used to generate an interference pattern with a single maximum, which acts as an ultra-thin gas jet. A similar technique has been used successfully to create a neutral-Helium matter-wave microscope [11]. A Fresnel Zone Plate (FZP) was used to create a focal spot of 2 µm FWHM.

A Fresnel Zone Plate consists of a series of alternating open (transmitting) and closed (blocking) concentric rings. The width of the rings is chosen such that the path difference of a wave/particle passing through adjacent open rings to reach the focal point is equal to one wavelength. This is achieved if the open rings are centered at radii

$$r_n = \sqrt{nf\lambda}$$

where f is the focal length of the FZP and λ is the wavelength to be focused. Since only the relative path length is important, n may begin at any number, so long as it is incremented by 2 for each successive open ring.

The rings become narrower the further from the center they are, such that the area of each ring is the same. In addition, the resolution of the FZP is approximately equal to the width of the smallest (outermost) zone. Thus, it is desirable to have as many zones as possible, in order to maximize the transmitted power and produce a tight focus. However, for a small wavelength the zones must be extremely small in order to produce an acceptable focal length, so that manufacturing constraints limit the number of zones which can be produced.

The focal length for a given FZP is inversely proportional to the wavelength. Thus, FZPs suffer from large chromatic aberration if the wave to be focused is not monochromatic.

In order to use this particle-wave focusing, a conventional Helium jet will be generated using the current setup. However, the final skimmer will be replaced with the diffractive focusing plate. During the expansion of the jet from the orifice, the gas is adiabatically cooled. Almost all the thermal motion of the gas atoms is converted into forward motion of the gas jet, leaving a very small velocity spread. Thus, the jet can be considered to be almost monochromatic. The average thermal momentum of a gas atom is derived from the Maxwell-Boltzmann distribution:

$$\bar{p} = \sqrt{\frac{8kTm}{\pi}}$$

where k is Boltzmann's constant, T is the gas temperature and m is the molecular mass. The de Broglie wavelength of a particle depends on its momentum,

$$\lambda = {}^{h}\!/_{p} = \sqrt{\frac{h^2\pi}{8kTm}}$$

where h is Planck's constant. It can be seen that in order to make the wavelength as large as possible, a light gas species should be chosen. For Helium at 300K, λ=0.08 nm.

FZPs are used at similar wavelengths for x-ray focusing. However, x-ray FZPs are usually constructed from metal rings attached to an x-ray transparent substrate. In the case of the gas-focusing FZP, the open zones must allow gas atoms to pass, so no substrate can be used. For the matter-wave microscope, the plates were etched from a thin film of silicon nitride, and struts were added in order to support the inner zones [12].

We propose to simplify the production process by using a different focusing plate based on the photon sieve [13]. In the photon sieve, the concentric rings of the FZP are replaced with a series of small circular holes. Each hole is centered at the radius of an open zone in the equivalent FZP. The two plates are compared in Fig. 6. It can be seen that since there are no completely cut rings in the photon sieve, struts are not necessary.

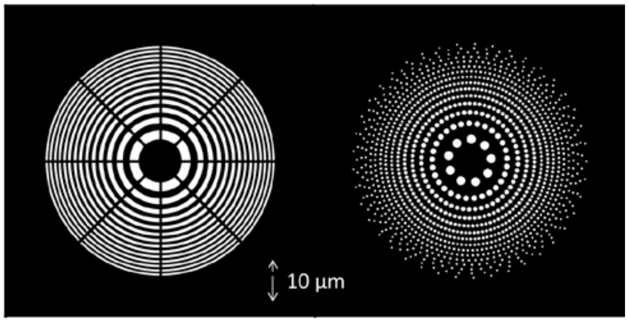

Figure 6: Comparison of an FZP and a photon sieve, both giving a focal length of 0.5m for λ=0.08nm.

It has been shown that a photon sieve with the same number of zones can create a sharper focus than the equivalent FZP. In addition, the sharp cut-off at the edge of the FZP causes higher-order diffraction which leads to side-lobes close to the focal spot. In a photon sieve, the intensity of side-lobes can be reduced if the fraction of each ring that is filled with holes is gradually reduced. The sieve is then said to be apodised [14].

Taking the above considerations into account, an 'atomic sieve' has been designed, applying the principle of the photon sieve to quantum matter-wave focusing.

The atomic sieve consists of 5230 holes, the smallest having a diameter of 80 nm and the largest 1.5 μm. The holes are etched into a 2 μm membrane of silicon nitride. The plates are currently under production, a Focused Ion Beam image of one of the test plates is shown in Fig. 7.

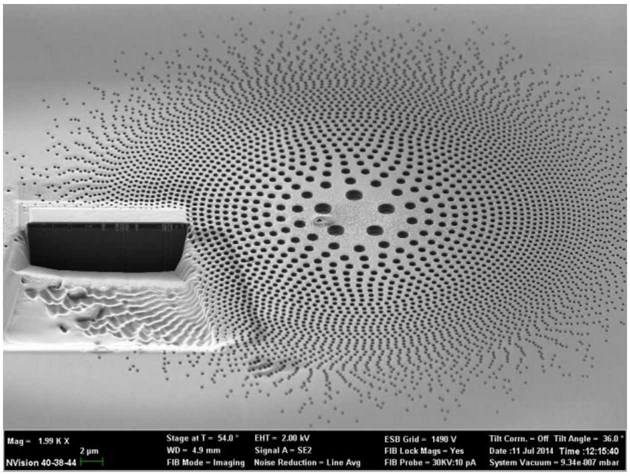

Figure 7: Focused Ion Beam image of the atomic sieve in production. The large hole on the left of the image has been cut into this test plate in order to check that the holes completely penetrate the silicon nitride film.

CONCLUSION

The test setup at the Cockcroft Institute has demonstrated reliable gas jet operation, and can be used for profile measurement in both continuous and pulsed mode. Thanks to efficient dumping of the jet and differential pumping in the jet generator, the effect on the beam vacuum system is small. However, due to the thickness of the jet it is not suitable for measuring beams of less than a millimetre.

For measurement of smaller beams with intense space charge, a new gas jet scanner is proposed. A focusing method based on the de Broglie wavelength of the neutral gas atoms will be used to produce a thin pencil jet. A focusing plate based on an apodised photon sieve has been designed. This ‘atomic sieve’ is under production and will be tested later this year.

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