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Profile monitors using gas ionisation or fluorescence have been used at a number of accelerators. Typically, extra gas must be injected at the monitor and the rise in pressure spreads for some distance down the beam pipe. In contrast, a gas jet can be fired across the beam into a receiving chamber, with little gas escaping into the rest of the beam pipe. In addition, a gas jet shaped into a thin plane can be used like a screen on which the beam cross section is imaged.
In this paper we present some arrangements for the generation of such a jet. In addition to jet shaping using nozzles and skimmers, we propose a new scheme to use matter-wave interference with a Fresnel Zone Plate to bring an atomic jet to a narrow focus.

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A GAS-JET PROFILE MONITOR FOR THE CLIC DRIVE BEAM

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The Compact Linear Collider (CLIC) will use a novel acceleration scheme in which energy extracted from a very intense beam of relatively low-energy electrons (the Drive Beam) is used to accelerate a lower intensity Main Beam to very high energy. The high intensity of the Drive Beam, with pulses of more than 10^{15} electrons, poses a challenge for conventional profile measurements such as wire scanners. Thus, new non-invasive profile measurements are being investigated.

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INTRODUCTION

The CLIC Drive Beam (DB) accelerator is designed to produce a high-intensity electron beam at 2.4 GeV. The high beam current of 4.2 A means that all diagnostics must be non-invasive. The beam-gas monitors discussed here will be most interesting at medium energies up to 300 MeV. Some key parameters of the CLIC DB are shown in table I.

Table 1: Relevant Parameters for the CLIC Drive Beam Accelerator [1]

Bunch population	5 x 10^{10} e^-
Transverse Emittance	100 nm rad
Bunch length / spacing	13 ps / 2 ns
Pulse length	140 µs
Pulse Population	3 x 10^{15} e^-
Repetition Frequency	50 Hz

By measuring the locations at which particles interact with gas in the beam pipe, the transverse profile of the beam can be deduced. Several kinds of interactions can occur, notably scattering, ionization, excitation and bremsstrahlung. All but the first produce effects which can be measured to deduce the beam's transverse profile. Since the number of interacting particles is small, such a monitor can be considered as non-invasive.

While some residual gas is always present in the beam pipe, measuring the beam profile within a reasonable integration time usually requires the injection of additional gas. If this gas is injected in the form of a well-collimated jet, an extraction chamber on the opposite side of the beam pipe can receive the jet, with very little gas escaping into the beam pipe. Such a jet can be formed by allowing high-pressure gas to escape through a very narrow nozzle, and using one or more skimmers to select the central part of the resulting supersonic expansion [2].

Since the effect on the beam (losses, emittance blow-up) depends on the total amount of gas present, confining the gas within a thin jet means that a higher pressure can be accepted.

CROSS-SECTIONS

The expected event rate for any beam-gas interaction is given by

$$R = \sigma \frac{I_{beam}}{e} n_{gas} \, l$$

where σ is the cross-section for the interaction of interest, I_{beam} is the beam current, e the electron charge, n_{gas} the gas number density and l the target length. The electron-impact ionisation cross-sections for various gases are shown in Fig. 1 below. The cross-sections are calculated following the Binary-Encounter-Bethe (BEB) model [3] using data from the U.S. National Institute of Standards and Technology (NIST) database [4].

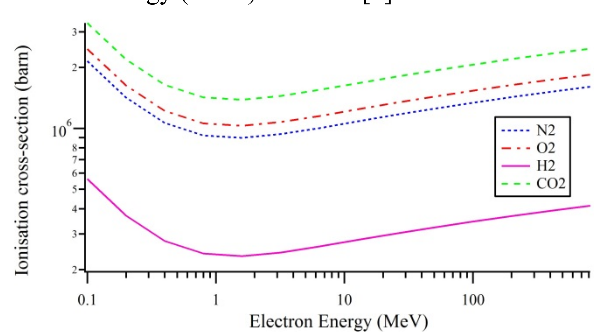

Figure 1: Electron-impact ionisation cross-sections for various gases, calculated using the BEB model.

The choice of gas depends not only on the cross-section but also on the ease of removing the escaped gas. For example, CO and CO_2 are interesting options because they are efficiently captured by Non-Evaporable Getter (NEG) coatings. However, heavy molecules are to be avoided due to the risk of ion trapping [5], in which

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positive ions are held in the centre of the beam pipe by the field of the negatively charged beam. While ion trapping would not occur in the profile monitor itself because of the applied electric field, it would increase the effect of any gas which escapes from the monitor.

Taking the minimum cross-section around 1 MeV beam energy, in order to produce 1000 ionisation events per bunch in 1 mm of N_2, the gas pressure should be around 10^{-5} mbar. However, it is doubtful that the ion detector could perform at the required frequency for bunch-by-bunch operation of the monitor. To produce instead 1000 events for each train of 121 bunches, the required pressure would be $7x10^{-8}$ mbar.

During ionisation, some momentum is transferred to both the ejected electron and the ion. This leads to a spreading out of the ionisation products and therefore affects the resolution of the monitor. A simple simulation was carried out using the Livermore low-energy physics model in Geant4 [6] in order to quantify this initial momentum spread. The production threshold was set at 0.1 eV. The average kinetic energy for the ejected electron is 69 eV while for the ion it is 61 eV. Fig. 2 gives the recoil momentum distribution for ions and electrons.

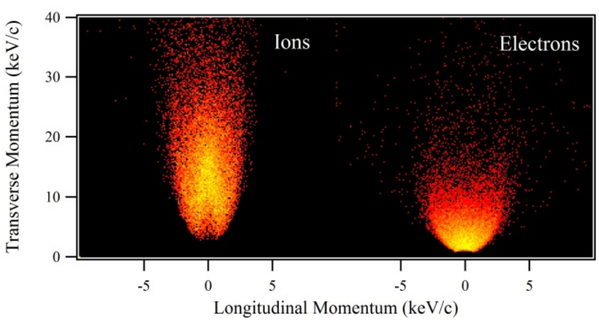

Figure 2: Recoil momenta of ions and electrons generated by impact of 100 MeV electrons on N_2 gas.

PLANAR JET

In a supersonic gas jet at low pressure, there are almost no collisions between gas molecules. Conventional fluid flow is replaced by a model in which molecules behave as projectiles. If a skimmer is used to select part of the jet, the skimmer shape is preserved.

One interesting option is to shape the jet into a plane inclined at 45 degrees to the beam. If an electric field perpendicular to the beam is then used to extract the ionisation products, the beam cross-section can be imaged, as on an inserted screen. This arrangement thus has a significant advantage over conventional residual gas monitors, in which only the beam profile is measured and which therefore require two monitors to measure the horizontal and vertical profiles.

The disadvantage, however, is that the resolution is dependent on the gas jet thickness (though only in one plane). In addition, the gas density must be constant across the plane or the measured profile will be distorted. Substantial efforts have gone into making the gas jet as thin as possible. One option is to focus the jet using a non-linear magnetic field acting on the magnetic moment of the neutral gas molecules. A gas-jet monitor based on this principle has been tested at the HIMAC synchrotron and achieved a jet thickness of 1.3 mm with excellent homogeneity across the jet [7]. Another approach is to use a series of skimmers to select only the part of the jet which has the required characteristics. In this case the skimmers must be aligned to very tight tolerances [8].

SPACE CHARGE

As in conventional residual gas monitors, the ions and electrons produced in the gas jet feel not only the applied extraction fields but also the space charge field of the main beam. Ions/electrons produced in different transverse positions and/or at different times within the bunch train will feel different space charge fields, and will therefore not follow parallel paths to the detector. In a high intensity accelerator such as the CLIC DB this would be a significant effect and would limit the monitor resolution.

In order to overcome this limitation a magnetic field must be applied parallel to the extraction electric field. The space-charge effect on the resolution is then limited to the gyroradius of the particles, given by:

$$r = \frac{mv_\perp}{qB}$$

where m is the particle mass, $v_\perp$ is the component of velocity perpendicular to the magnetic field, q is the charge and B is the magnetic field strength. Magnetic fields of opposite direction and half the integrated field strength must be applied before and after the monitor in order to cancel the effect on the main beam.

Simulations were carried out using CST Particle Studio [9] to determine the effect of space charge for different values of magnetic field. The results are shown in Fig 3. The CLIC DB was taken to have a Gaussian cross section with σ=0.25 mm in both planes and an energy of 150 MeV. The beam current and longitudinal distribution as shown in table 1. An electric field of 10 kV/m is applied. Electrons and ions are generated on a plane so the gas jet thickness is not taken into account. The simulation tracked the electrons and ions created by the first bunch in the train, which is the worst case for space charge effects. Electrons and ions from the last few bunches in the train will undergo less spreading as they see the field of fewer following bunches.

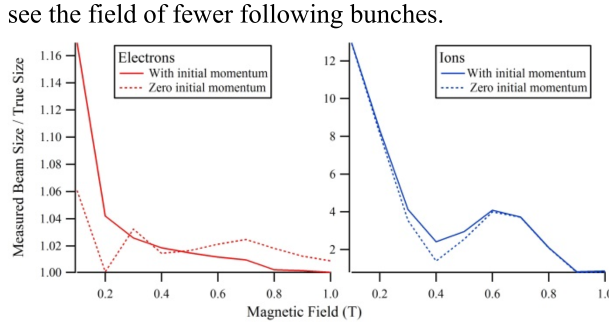

Figure 3: Growth of the measured beam size, as simulated with CST Particle Studio, as a function of magnetic field strength and initial particle momentum.

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It can be seen that extracted electrons are much less affected by the beam's space charge. This is because electrons are quickly accelerated out of the high field region. Ions are extracted much more slowly and therefore feel the field of many following bunches.

For electrons a magnetic field of 0.2 T is sufficient to keep the profile broadening to below 5%. Such a field is easily achievable and the bump in the main beam trajectory would be of the order of a few mm.

PENCIL JET

One way of avoiding the space charge issue is to replace the plane jet with a thin pencil jet. The jet could be scanned slowly across the beam or, to avoid problems with loss of alignment, the beam could be steered to produce a scan through the jet. The profile resolution then depends only on the jet thickness. In this configuration, however, two jets are required, for horizontal and vertical profile measurement.

The measurement of the beam intensity at each jet position could be done by collecting the ions or electrons (but recording only the total charge produced, not the position) or by measuring beam losses or bremsstrahlung photons. The latter options have the advantage of avoiding the need for any extraction fields.

The success of this technique depends on being able to produce a sufficiently thin pencil jet. In addition, the jet divergence must be sufficiently small to maintain the diameter constant over a distance greater than the width of the beam. For a resolution acceptable in the CLIC DB case, the jet diameter should be less than 100 µm. This is very challenging to achieve due to the mechanical constraints of nozzle / skimmer systems.

One intriguing possibility is the use of matter-wave interference to produce a very tightly focused jet. Focusing using the wave nature of molecules has been demonstrated [10] and can produce focal spots as small as 2 µm. The focusing element is a binary Fresnel Zone Plate (FZP) in which alternate zones block the molecules or allow them to pass.

The DeBroglie wavelength λ of a particle is related to its momentum p by $\lambda = h/p$ where h is Planck's constant. Thus, a lighter molecule is desirable in order to make the wavelength as large as possible. For a Helium atom moving with thermal velocity at room temperature, the most probable DeBroglie wavelength is 0.9 Å.

An FZP achieves a focus at the point where the path difference between molecules travelling via adjacent zones is equal to one wavelength. From this condition it can be derived that the radius r_n of the nth zone must be

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

assuming that the FZP is small compared to the focal length f. Clear zones are located at increments of n=2. The width of each zone becomes smaller further from the centre, while the area of each zone is the same. Thus, the amount of gas transmitted increases linearly with the number of zones, while the size of the focal spot decreases, since the resolution of an FZP is roughly equal to the width of its narrowest zone. The number of zones is limited by the smallest structure that can be reliably machined.

FZPs are commonly used to focus X-rays of similar wavelength. However, X-ray zone plates are usually built by depositing rings of X-ray absorbing material onto an X-ray transparent substrate. For an atom-focusing zone plate no substrate can be used since the clear zones must allow gas to pass freely. An alternative technique is necessary in which clear zones are removed from a thin film [11]. Narrow struts must be left in place to support the inner zones.

An alternative focusing element is the photon sieve (or in this case 'atom sieve') in which holes are located at the same radii as clear zones on an FZP. This type of plate should be easier to manufacture since no supporting struts are required. Furthermore, the holes can be larger than the zones of an equivalent FZP while maintaining the same focal length and resolution [12]. However, less gas is transmitted since the fraction of clear space is smaller.

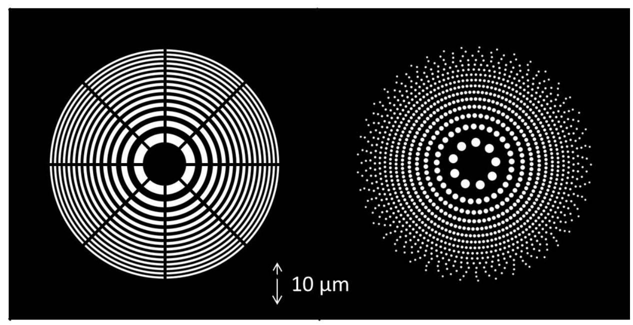

Figure 4: Fresnel Zone Plate (left) and 'Atom Sieve' (right) for diffractive focusing of a gas jet. The scale shown would give a focal length of 0.3 m for a jet of thermal-velocity He atoms.

The size of the focal spot is limited by the spread in focal length due to the thermal velocity distribution. However, if the gas is passed through a nozzle and then undergoes a supersonic expansion, the resulting jet has a much narrower velocity distribution, and is thus close to a monochromatic beam.

The matter-wave concept is only valid when the gas pressure is sufficiently low for molecules to have a negligible probability of colliding with each other. This sets an upper limit to the intensity of a jet produced by this method. On the length scale of the profile monitor this 'decoherence' limit lies around 10^{-6} mbar, which is more than enough for the profile monitor.

CHERENKOV RADIATION

If the gas jet is sufficiently dense, the beam may emit Cherenkov radiation [13]. Since the radiation is emitted in a hollow cone, the light could be collected by a ring-shaped mirror placed some distance downstream and imaged on a camera. The best gas jet arrangement for this application would be a plane jet perpendicular to the

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beam. There are a number of advantages: the gas jet thickness does not affect the resolution; no extraction fields need to be applied; and since Cherenkov emission is instantaneous longitudinal diagnostics could also be included.

Cherenkov radiation is emitted if charged particles are travelling faster than the local speed of light, i.e. if $\beta > 1/n$ where n is the refractive index of the medium. The refractive index of nitrogen at 1 bar is only 1.0003, for CO_2 it is 1.00045. Heavier gases such as Xenon (n=1.0007) provide some improvement but are much harder to pump. Further, the refractive index depends on the gas pressure P. For an ideal gas $(n-1) \propto P$. The emission angle and the light yield both increase with βn as shown in figures 5 and 6. If the gas pressure is too low, either the Cherenkov condition will not be met or the emission angle will be so small that the extraction mirror would have to be placed very far downstream.

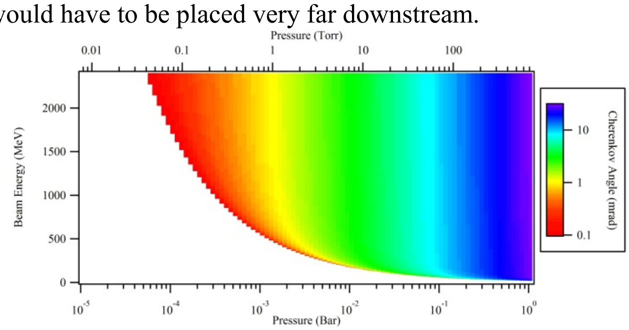

Figure 5: Cherenkov emission angle for an electron beam crossing a CO_2 gas jet.

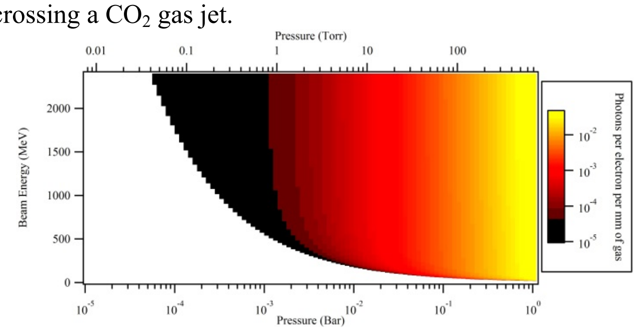

Figure 6: Cherenkov light yield for an electron beam crossing a CO_2 gas jet.

For beam energies above 1 GeV, gas pressure of the order of 1 mbar is needed. For lower energies an even higher pressure would be necessary. Gas jets with such high pressures can be generated using suitably shaped nozzles. However, the quantity of gas escaping into the beam pipe would be very significant. It could perhaps be tolerated if a fast valve were used to inject pulses of gas on-demand for single profile measurements in the manner of a wire scanner.

This gas-jet Cherenkov monitor might be an interesting tool for the dump lines to which the drive beam will be sent after most of its energy has been transferred to the CLIC main beam. Since the beam is about to be dumped the vacuum pressure there is less critical. In addition, as the emission angle depends on β, it would be possible to measure the beam energy spread as well as the profile.

CONCLUSION

We have investigated two different designs for a gas-jet profile monitor for the CLIC Drive Beam. A monitor based on a planar jet can measure both beam profiles on a train-by-train basis. Space charge effects can be overcome using a magnetic field of at least 0.2 T, and the monitor resolution will be dominated by the achievable gas jet thickness. An alternative design based on a thin pencil jet using matter-wave focusing is suggested. Such a jet could be scanned across the beam to produce a profile with micrometer resolution.

A gas-jet test stand is currently installed at the Cockcroft Institute in the UK. It is planned to carry out further tests there for the generation of both planar and pencil jets. If these are successful a full prototype may be constructed at the CTF3 machine at CERN.

REFERENCES

[1] M. Aicheler, et al., "A Multi-TeV linear collider based on CLIC technology: CLIC Conceptual Design Report", Geneva, (2012)

[2] M. Putignano, et al., "'Numerical study on the generation of a planar supersonic gas-jet", Nucl. Instrum. & Meth. A **667** (2012)

[3] W. Hwang, Y.-K. Kim, and M. E. Rudd, "New model for electron-impact ionization cross sections of molecules", J. Chem. Phys. **104**, 8 (1996) p. 2956

[4] "Electron Impact Ionisation Cross-sections", physics.nist.gov/PhysRefData/Ionization/molTable.html

[5] F. Zimmermann, et al., "Experiments on the Fast Beam-Ion Instability at the ALS", International Workshop on Multi-Bunch Instabilities, Tsukuba, (1997)

[6] J. Apostolakis, S. Giani, L. Urban, M. Maire, A. Bagulya, and V. Grichine, "An implementation of ionisation energy loss in very thin absorbers for the GEANT4 simulation package", Nucl. Instrum. & Meth. A **453**, 3 (2000), pp. 597–605

[7] Y. Hashimoto, et al., "Oxygen gas-sheet beam profile monitor for the synchrotron and storage ring", Nucl. Instrum. & Meth. A. **527**, 3 (2004) pp. 289–300

[8] V. Tzoganis, "Alignment of a Nozzle-Skimmer System for a Non Invasive Gas Jet Based Beam Profile Monitor", these proceedings

[9] www.cst.com, "CST Particle Studio"

[10] M. Koch, S. Rehbein, G. Schmahl, T. Reisinger, G. Bracco, W. E. Ernst, and B. Holst, "Imaging with neutral atoms: a new matter-wave microscope", Journal of Microscopy, **229** (2008)

[11] S. Rehbein, R. Doak, and R. Grisenti, "Nanostructuring of zone plates for helium atom beam focusing", Microelectronic Engineering **53** (2000)

[12] L. Kipp, M. Skibowski, R. Johnson, and R. Berndt, "Sharper images by focusing soft X-rays with photon sieves", Nature, **414** (2001)

[13] The LHCb Collaboration, "The LHCb detector at the LHC", JInst **3**, S08005 (2008)

ISBN 978-3-95450-127-4