Design and Performance of a Ionization Beam Profile Monitor Based on a Gas-jet Curtain for Applications on Low Energy Accelerator Systems*.

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Abstract

Growing interest in the development of low energy projectiles, in particular heavy ions and antiprotons, calls for new beam instrumentation to be developed to match the strict requirements on ultra-high vacuum and low beam perturbation. When it comes to transverse profile monitoring, a convenient solution for simultaneous determination of both transverse profiles is found in a neutral supersonic gas-jet target shaped into a thin curtain and the two-dimensional imaging of the gas ions created by impacting projectiles. The resolution and vacuum efficiency of this monitor is directly linked to the characteristics of the gas-jet curtain.

In this contribution we describe the overall principle of operation of the monitor, including details of its expected performance and the design of a nozzle-skimmer system to be used for the creation of the jet curtain in the first prototype of such monitor. We also include a discussion on the geometry, shape of the extraction field and the experimental chamber that will house the experiment. Using numerical fluid dynamics simulations, we present the effects resulting directly from changes in the geometry of the nozzle-skimmer system on the characteristics of the jet curtain.

INTRODUCTION

Low-energy physics and storage rings are recently attracting growing interest in the scientific community, as remarkable characteristics of quantum systems are most conveniently studied at low projectiles energies in the keV range [1,2].

Development of low-energy storage rings must be accompanied by developments in beam diagnostic technologies . In particular preservation of the beam lifetime causes perturbing profile monitoring (e.g. interceptive foils) to be ruled out [3]. Furthermore, existing non-perturbing techniques such as residual gas monitors can require about 100 ms [4] to make meaningful measurements, due to the low residual gas pressure, at the expected operating pressure of around 10^{-11} mbar.

A possible solution around these limitations is to use a neutral supersonic gas-jet target shaped into a thin curtain together with bi-dimensional imaging of the gas ions created by impact with the projectile beam. Such a monitor, as compared to those based on residual gas, allows injection of additional gas, in order to increase the ionization rate. The required vacuum level elsewhere in the storage ring is maintained due to the high directionality of the supersonic jet [5]. Furthermore, the method allows simultaneous determination of both transversal profiles and beam imaging. Crucial to such a monitor is the control of the gas-jet in terms of achieved density and directionality.

In this paper, we describe in detail the working principle of the monitor. We then derive the fundamental equation governing its sensitivity and precision. Results of numerical simulations, which show that the geometry of the nozzle-skimmer system has a dramatic impact on the final result, and hence plays a central role in the optimization process, are presented. We then describe the nozzle skimmer system, the chamber that has been designed to house the experimental set-up, the extraction field for the curtain monitor, and finally draw some conclusions.

OPERATION PRINCIPLE

The proposed beam profile monitor relies on a neutral gas-jet, shaped into a thin curtain that intersects the target beam. In its simplest configuration, shown in Fig.1, the velocity vector of the atoms in the gas curtain is perpendicular to the propagation axis of the projectile beam, and the gas curtain plane forms with the same axis an angle of 45 degrees. When the projectile beam crosses the gas-jet, ionisation interactions occur and gas ions are created in the region of the curtain. These ions are accelerated by a 1 kV/m extraction field towards a Position Sensitive Detector (PSD) comprised of an amplification stage of Micro Channel Plates (MCP), a phosphor screen and a CCD camera. The magnitude of the extraction field is large enough to project the ions onto the PSD making the contributions of initial velocity spread negligible.

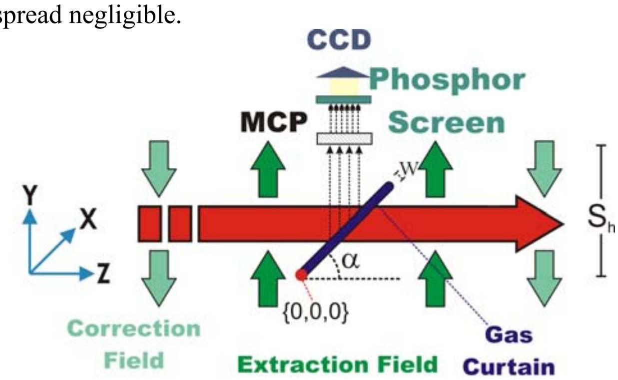

Figure 1: Sketch of the gas curtain ionization profile monitor working principle. The gas curtain, shown in purple, is crosse by the projectiles (red arrow), and the produced ions extracted by suitable electric fields (green arrows.

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To counterbalance the effects of the extraction field on the main beam, two additional correction fields are added, as shown in Fig.1. Even at the lowest beam energies, this results in a net displacement of the beam from its main orbit of only 1mm at the interaction point, and both the displacement and the transverse momentum introduced by the extraction field are fully counterbalanced.

After the gas-jet crosses the beam in the interaction chamber, it flows into the dumping chamber, where an appropriate vacuum system captures the jet preventing it from affecting the vacuum in the rest of the ring.

The gas-jet consists of a high-density curtain-shaped region where densities in the range of 10^{10} to 10^{13} particles/cm^3 can be obtained by varying the stagnation pressure of the gas-jet reservoir. Preliminary measurements show that the jet does not appreciably affect the vacuum in a 10^{-11} mbar chamber; this is dues to its high directionality. If a 1 cm wide gas curtain (including also the lower pressure region around the main curtain) is made with Argon atoms, for whose ionization by slow antiproton impact cross section is in the order of 10^{-20} m^2 [6], then a probability of 10^{-6} to 10^{-3} interactions per particle per turn is predicted. Even in the worst case, allowing a hundred collisions before a particle falls out of acceptance, beam lifetimes of 1s are still possible in machines such as the USR (approx. 20 μs revolution time).

For beams of 10^7 particles, these probabilities would in turn lead to a reaction rate in the order of 10^5 to 10^8 events per second, compatible with ms to μs imaging and consequent single 1 μs bunch measurement.

This profile measurement method allows the actual bi-dimensional imaging of the transverse beam density distribution, hence providing the measured function ρ(x,y). From ρ(x,y), both transverse profiles $\rho_{tot}(x)$ and $\rho_{tot}(y)$ can be computed by direct integration of the measured densities:

$$\rho_{tot}(x) = \int_{-\infty}^{\infty} \rho(x,y)dy\ ;$$

$$\rho_{tot}(y) = \int_{-\infty}^{\infty} \rho(x,y)dx$$

This, together with the method's compatibility with an ultra high vacuum environment, gives it advantages over the ionisation residual gas monitors, which provide only a measure of a single, already integrated transverse profile (either $\rho_{tot}(x)$ or $\rho_{tot}(y)$); hence two residual gas monitors are needed to measure both profiles, and the combined function ρ(x,y) is not measurable.

SENSITIVITY AND PRECISION

To compute the sensitivity and resolution intrinsic to the monitor itself (i.e. without taking into account the extraction fields and the detection system) we analyze the monitor in its simplest configuration, referring again to Fig.1. A particle travelling along in the +x direction, and starting at the point {x,y,0} can ionize a gas atom anywhere in the segment

$$\left\{\left(x;y;\frac{y}{tan(\alpha)}\right);\left(x;y;\frac{y}{tan(\alpha)}+\frac{w}{sin(\alpha)}\right)\right\}$$

which would in turn result in a projection on the position sensitive detector in the segment

$$\left\{\left(x;S_h;\frac{y}{tan(\alpha)}\right);\left(x;S_h;\frac{y}{tan(\alpha)}+\frac{w}{sin(\alpha)}\right)\right\}.$$

An effective width of the curtain can then be defined as the distance travelled by a projectile through the gas in a straight line, i.e. w/sin(α).

Using a subscript *s* to refer to the the coordinates of the image on the sensor and with the subscript *i* to the initial coordinates of the ionizing particle, the sensitivities of the profile monitor for each direction become:

$$S_x = \frac{dx_s}{dx_i} = 1 = M_x;$$

$$S_y = \frac{dz_s}{dy_i} = tan(\alpha)^{-1} = M_y;$$

which also represent the magnification M_x and M_y of the beam profile's image on the position sensitive detector.

The precision can alternatively be calculated considering the influence of the uncertainty due to the curtain width on the position of ionization. This influences only the vertical (y axis) profile, introducing a flat error distribution with a full width of w/sin(α). This in turn results in an intrinsic final resolution in the y direction poorer than in the x direction; this has also been reported in the work of Hashimoto [7], where much effort has been devoted to decreasing the curtain width.

It should be noted that a more correct indication of the precision would take into account the magnification of the beam profile image on the detector. We can introduce the modified error distribution full width W_{Err} scaled with the value of magnification:

$$W_{Err,y} = \frac{(w/sin(\alpha))}{S_y} = \frac{w}{cos(\alpha)}$$

Whilst it is in principle possible to minimize W_{Err} by decreasing the value of α, hence effectively improving the resolution, the equation above shows, however, that it is possible to gain only a factor 2\√2 as compared to the 45 degree case. We have chosen the value of α make the magnification equal in the x and y direction, leading to a non-deformed image, and thus avoiding the need of image post-processing. As the x-axis magnification is equal to unity and independent from the value of α, the y-axis magnification is also chosen to be unity, corresponding to α=45 degrees.

It is now clear how the extent of the vertical resolution degradation depends only on the width of the curtain, which becomes a factor of primary concern in the design of the nozzle-skimmer system used for the creation of the gas-jet.

NUMERICAL SIMULATIONS

The most common technique for the creation of a supersonic curtain-shaped gas jet involves the creation of an axis-symmetric jet of great intensity and the subsequent reshaping via collimators, after supersonic speed is attained [7]. Nevertheless, this approach results in several difficulties, amongst which the need of a large setup, to enable the gas jet to expand to the desired dimension; the use of large focusing magnetic fields to be coupled to the magnetic moment of the gas molecules, generally O_2; and the use of large quantities of gas, since most gas is collimated out, which results in large stagnation pressure needed at the source. We performed preliminary simulations, showing that it is possible to achieve a curtain-shaped jet by means of a suitable nozzle-skimmer system, at the gas source, if a rectangular slit nozzle and a skimmer shaped as a hollow trapezoidal prism is used in a suitable geometry, instead of the circular nozzle used in common applications.

To show the importance of the geometry of the nozzle-skimmer system for the curtain characteristics, we ran several sets of simulations, varying 5 geometric parameters, while monitoring 3 relevant observables, as described below.

The variables are: the skimmer aperture angles in the direction parallel (α), and perpendicular (β) to the curtain expansion, the width of the skimmer slit (SW), the depth of the skimmer structure (SD) and the nozzle-skimmer distance (Dist). We observed the Mach Number downstream of the skimmer (M), which gives an indication of the efficiency of the expansion and hence of the directionality of the jet, as well as the geometrical dimensions of the gas curtain: width and depth (W and D respectively), which directly affect the resolution of the monitor [5].

When analysing this system we are confronted with 5 variables, resulting in an exceedingly complex set of results, whose mathematical description needs a detailed treatment. Therefore, in this paper, we will express our results in the form of qualitative behavioural trends of each observable as a function of each variable, obtained by varying that variable alone while leaving the others constant.

For this analysis, a trend is said to be found when the form of the functional relationship between the observable and the variable under investigation is preserved in the simulations regardless of the actual values of the other variables. We are then able to draw a table, shown in Fig.2, which summarises the simulated behaviour of each observable (column entry) when the respective variable is increased (row entry).

We identify linear relationships (straight arrows), parabolic relationships (curved arrows), and more complex relationships (circles), where the form of the functional relationship depends on the value of some secondary variables (indicated inside the circle), and hence, according to our previous definition, a trend is not found. This last is qualitatively different behaviour compared to the first two cases, where the shape of the trend does not depend on the remaining variables; in the last case the details of the trend, such as the gradient for the linear relationships, will depend on the values of the remaining variables.

In the table the bold orange lines represent the very clear trends, defined as those trends where the average over all points of the best fit Pearson value lies above 90%, while the slim, black lines represents less evident trends, where the average best fit Pearson value lies between 75% and 90%.

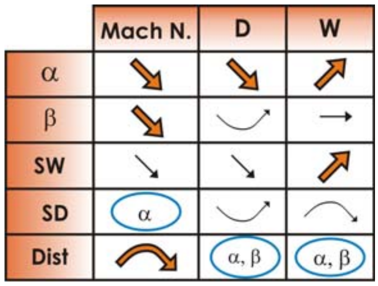

Figure 2: Table of simulated trends.

The table gives an indication of how sensitive the gas jet parameters are to the geometry of the nozzle-skimmer system, hence providing strong evidence in favour of the need of a detailed study for the goal of proper optimization. Furthermore, it also gives an insight as to which variables have a stronger impact on the performance of the jet in termes of directionality (namely α, β and Dist) and curtain width to depth ratio (α and SW).

CHAMBER DESIGN

In order to test the optimization of the jet curtain, it is necessary for the apparatus to fulfil two crucial requirements. First, it should include a nozzle-skimmer system whose geometry can be readily modified and secondly it should include a monitoring system able to deliver the density map of the jet curtain. The density of the curtain is indeed the crucial parameter for the operation of the profile monitor, as the reaction rate, and hence the sensitivity, will scale with it. In this section we present these two sub-systems.

Nozzle-Skimmer System

The holding system for the skimmer, shown in Fig.3, has been designed to grant maximum flexibility. It can accommodate up to two skimmers, which can be aligned in both angle (with a 5 degrees range) and in the longitudinal dimension (within 20 mm). The longitudinal adjustment is obtained by welding the smallest plate (violet) on the end flange of an inner chamber ending with an adjustable bellow, which sits inside the main chamber, welded in turn to the larger plate (green). Such ‘nested’ chamber design also allows the two skimmers to be placed very close to each other whilst still allowing differential pumping between them.

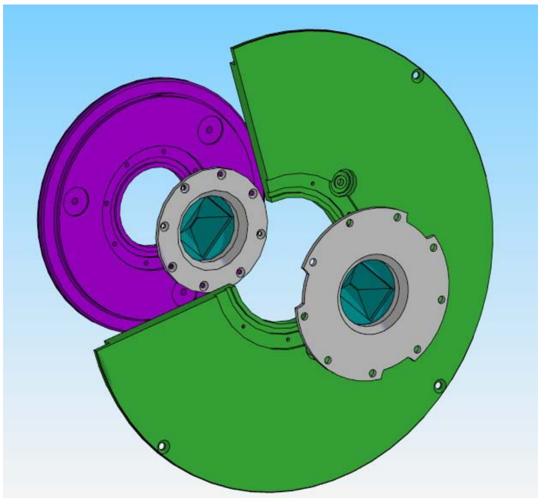

Figure 3: Skimmers holding system, exploded view.

The skimmer system is furthermore designed to allow the removal of both skimmer holders to enable the skimmers to be changed for different shaped ones without demounting the whole chamber, hence also preserving its alignment.

In order to preserve quasi-laminar flow downstream of the expansion fan, and hence allow the establishment of a stable supersonic jet, the skimmers need to be manufactured with walls thinner than 100 μm. Due to the large pressure difference across their walls caused by differential pumping, care must be taken to ensure they do not collapse towards the low pressure region. Therefore, we chose not to design a variable geometry mechanism, but rather had several skimmers of different geometries manufactured, which give over 18 configurations, 3 different values each for α and β, and 2 different values for SW.

Curtain Monitoring

In order to probe the curtain and map its density, our apparatus will rely on electron impact ionization of the gas atoms. The gas ions produced will then be extracted by a 1 kV/m electric field and guided to an MCP stack for amplification, before hitting a phosphor screen, whose emitted photons will be detected by a CCD camera. The current across the second MCP will be measured and will be proportional to the number of collected ions, while the CCD camera will record the spatial distribution of the collected ions, i.e. the depth of the curtain in the point of interaction with the electron beam. Therefore, coupling this information with the measured spot size of the electron beam and the known electron impact ionization cross sections, the density of the curtain can be calculated.

Due to the relatively large area of gas-jet under investigation (4x4 cm), a ± 12.5mm XY manipulator will be attached to the electron gun, so as to increase the spatial range provided by electrical deflection of the electron beam. The experimental chamber designed for this monitor is shown in Fig.4.

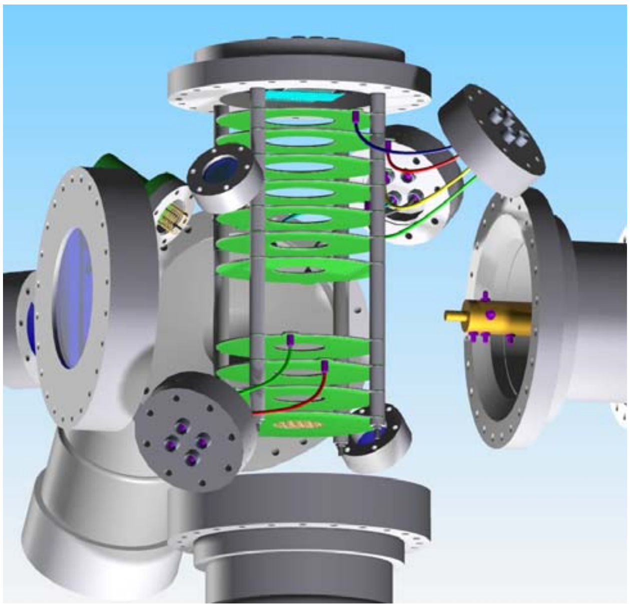

Figure 4: Experimental chamber and extraction system for the density mapping of the supersonic-jet curtain.

The spatial resolution of this mapping scheme depends mainly on the spot size of the scanning electron beam, which can be kept below 2 mm diameter. On the other hand, the accuracy depends on the quality of the extraction field and on the current stability of the electron beam. The electron gun is tested to yield a beam that is stable to within less than 1% of the nominal current when guided with a current feedback loop. The extraction field has been designed after having carried out extensive simulations with the SIMION 8.0 code. The simulations were intended to optimize the field in the central region of interest in the experiments, around the extraction electrodes axis; it is indeed in this region of interest that interaction between accelerated projectiles and the gas jet will take place in the final application for beam profile monitoring. Following the simulations, the voltages and geometry of the extracting field electrodes have been adjusted to yield the field shown in Fig. 5. This field is homogeneous within a 2.5% in the central region of interest of diameter 40 mm, where the curtain density measurements will lie.

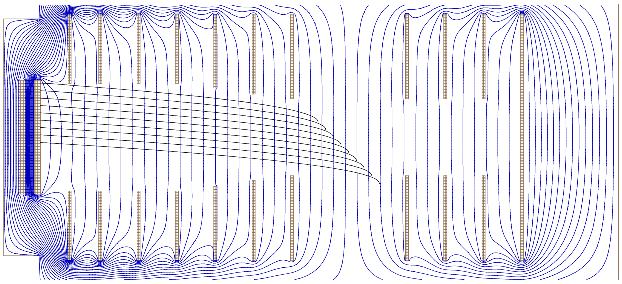

Figure 5: SIMION 8.0 simulated extraction field and tracking of the ions created on the curtain.

CONCLUSIONS

By means of numerical fluid dynamics simulations, it has been possible to highlight the importance of a nozzle-skimmer system geometry for the quality of a curtain-shaped gas-jet for use in a fast, nearly non-perturbing ionization beam profile monitor, suitable for operation at very low energy machines. It was also possible to pinpoint the most relevant observables and predict their behavioural trends when the geometric variables are changed. Finally, an experimental setup was designed to validate the numerical studies and characterize the supersonic gas-jet curtain.

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