DESIGN OF A NOZZLE-SKIMMER SYSTEM FOR A LOW PERTURBATION IONIZATION BEAM PROFILE MONITOR*

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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 design of a nozzle-skimmer system to be used for the creation of the jet curtain in the first prototype of such monitor, together with the geometry and extraction field shape of the experimental chamber which 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 causes widespread beam diagnostic technologies to become obsolete. In particular preservation of the beam lifetime causes perturbing profile monitoring, like e.g. interceptive foils, to be ruled out [3]. Furthermore, existing non-perturbing techniques such as residual gas monitors can take up to 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 constituted by a neutral supersonic gas jet target shaped into a thin curtain and bi-dimensional imaging of the gas ions created by impact with the projectiles. Such monitor, as compared to those based on residual gas, allows injection of additional gas, in order to increase the ionization rate, together with efficient evacuation to keep the required vacuum level elsewhere in the storage ring, due to the high directionality of the supersonic jet [5]; furthermore, it allows simultaneous determination of both transversal profiles and even beam imaging.

Crucial to such monitor is the control of the gas-jet in terms of achieved density and directionality. In the following section we present the 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. We then describe the nozzle skimmer system, the chamber which has been designed to house the experimental validation, the extraction field for the curtain probing experiment, and finally draw our conclusions.

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 [6]. Nevertheless, this approach results in several difficulties, amongst which the need of a large setup, which is needed for 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 already 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 run several set of simulations, varying 5 geometric parameters, which we will refer from now on as variables, 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 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].

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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. In this paper, we will rather 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.

A trend is intended 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. This way, we are able to draw a table, shown in Fig.1, 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 even 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 a qualitatively different behaviour as compared to the first two cases, where the shape of the trend does not depend on the remaining variables, while still 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%.

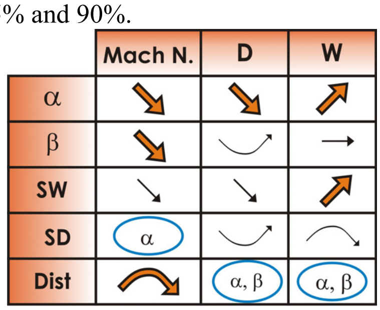

Figure 1: Table of simulated trends.

This table gives an indication of how sensitive the gas jet is 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 skimmers' holding system, shown in Fig.2, has been designed to grant maximum flexibility. It can accommodate up to two skimmers, which can be fine aligned both angularly (with a 5 degrees range) and longitudinally (within 20 mm). The longitudinal adjustability 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 to keep the two skimmers very close to each other and still perform differential pumping between them.

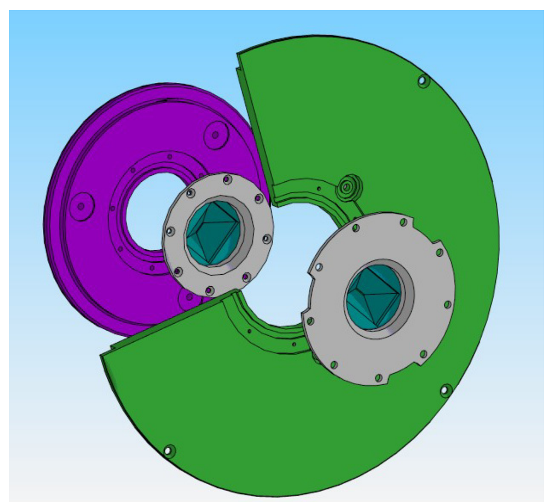

Figure 2: Skimmers holding system, exploded view.

The skimmer system is furthermore designed to allow removing both skimmer holders, detaching the skimmers, and glueing differently shaped skimmers back in place without demounting the whole chamber, hence also preserving its alignment.

An additional structural problem arises with the skimmers, as in order to preserve quasi-laminar flow downstream the expansion fan and hence allow the establishment of a stable supersonic jet, they need to be manufactured with walls thinner than 100 μm. Therefore, due to the large pressure difference across their walls caused by differential pumping, care must be taken to prevent them collapsing towards the low pressure region. Therefore, we chose not to design a variable geometry mechanism, rather manufacturing several skimmers of different geometries, spanning over 18 models 3 different values 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 keV/m electric field and guided to an MCP stack for amplification, finally hitting a phosphor screen, whose emitted photons will be detected by a CCD camera. The current signal on the second MCP will then give a measure of the number of collected ions, while the CCD camera will show the spatial extension 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 is attached to the electron gun, so as to increase the spatial range provided by electrical deflection of the electron beam. The experimental chamber designed to this purpose is shown in Fig.3.

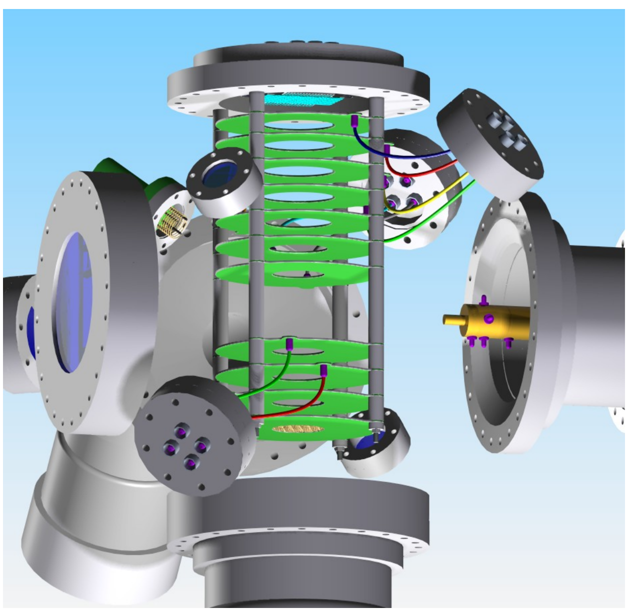

Figure 3: Experimental chamber and extraction system for the density mapping of the supersonic-jet curtain.

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 stable 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. 4. 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.

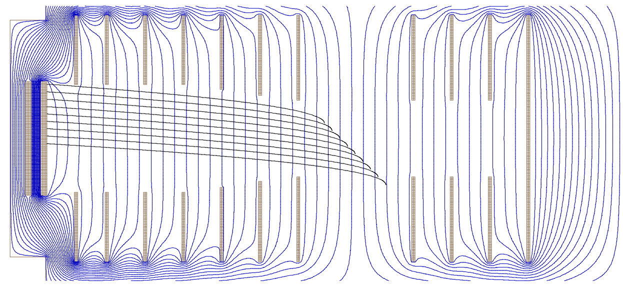

Figure 4: SIMION 8.0 simulated extraction field and tracking of the ions created on the curtain.

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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