NUMERICAL STUDIES OF CURTAIN GAS JET GENERATION FOR BEAM PROFILE MONITORING APPLICATIONS IN THE ULTRA LOW ENERGY STORAGE RING*

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Abstract

For beam profile monitoring applications where low beam perturbation together with bi-dimensional imaging is required, ionization monitors based on neutral gas-jet targets shaped into a thin curtain are an interesting option. When integrated in ultra-high vacuum systems, such as in the Ultra-low energy Storage Ring (USR), where local vacuum preservation is of primary concern, such systems present severe difficulties linked to the creation and proper shaping of a high quality gas-jet curtain. In this contribution, investigations into the generation and evolution of the jet with the Gas Dynamics Tool (GDT) software and purpose-written C++ analysis modules are presented. By means of extensive numerical analysis the advantages of a novel nozzle-skimmer system in terms of curtain quality are summarized when compared to traditional axisymmetric gas-jet creation and curtain shaping by means of scrapers. It is also shown that variable nozzle-skimmer geometries allow for modifying the gas-jet characteristics in a wide range, including jet splitting and local density modulation. Finally, the layout of a test stand that will be used for an experimental benchmark of these studies is shown.

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. If the curtain is kept at a 45^{o} angle from the impinging direction of the projectiles, and the ions extracted perpendicularly to this direction on a position sensitive detector, an image of the projectile beam transverse section is formed on the detector, much like a mirror reflection [5], as shown in Fig. 1.

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 [6]; furthermore, it allows simultaneous determination of both transversal profiles and beam imaging. At the same time, it is possible to use it also as a current and beam position monitor.

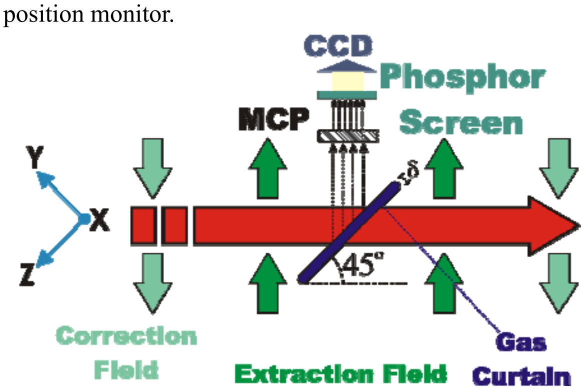

Figure 1: Jet-curtain profile monitor operation principle: the large horizontal arrow shows the projectiles path.

This monitor becomes hence the monitor of choice for multi-pass, low-energy, ultra-high vacuum storage rings such as the Ultra-Low Energy Storage Ring (USR), to be installed at the Facility for Low Energy Antiproton and Ion Research (FLAIR), in the FAIR facility planned to be built at GSI, Darmstadt, Germany.

Crucial to such monitor is the generation and control of the gas-jet in terms of achieved density and directionality. In order to prove that optimization of the jet performance can be obtained through suitable engineering of the nozzle-skimmer system for the jet generation, we have run a detailed numerical study of the fluid dynamic system.

NUMERICAL SIMULATIONS

Software Description

The software used for our simulations was a well-established commercial code, the Gas Dynamic Tool, GDT, developed by the CFD group of A. Medvedev in Tula, Russia. The code has been widely benchmarked against known flows, proving very reliable in dealing with high compressibility effects such as shock waves.

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Indeed, most of our benchmarking cases dealt with very rarefied gases at supersonic velocities.

In order to select the optimum set of equations for the solver, we considered that the initial expansion stages of a typical beam diagnostics gas-jet apparatus are housed in vacuum vessels which are kept at relatively high pressures of $10^{-2}÷10^{-4}$ mbar, while the jet itself has a typical pressure of 1÷0.1 mbar. At room temperature, this equates to mean free paths in the sub-millimeter range, hence still compatible with the continuum description of the flow (Knudsen number < 0.2), allowing the use of the Navier-Stokes equations as opposed to a full molecular description of the gas behavior. In turn, these reduce to the Euler equations as it has been shown that the gas-jet expansion is a quasi-isentropic process [7], and viscosity effects can be neglected. Hence, we have used the GDT continuum flow solver based on the Euler equations.

The boundary conditions have proved to be a crucial point in the simulations. Differently from a standard approach to supersonic flows, the boundary conditions have been set to constant pressure in the regions less exposed to supersonic flow, in order to stabilize the results; whilst only in the regions where supersonic flow is not negligible, mainly downstream the expansion, standard floating value boundary conditions have been kept, to avoid reflection of artifact shock waves formed at the interface between the flow and the constant pressure boundary. In fig. 2-3 it is shown how this choice of boundary conditions leads to a much more stable solution as compared to indiscriminately assigning floating boundary conditions on all sides.

Given the output of GDT in the form of a value matrix, shown on screen by the GDT Visualizer Package, we then completed the code with our own C++ purpose-written analysis modules which import the data from the GDT output matrix, compute the variables of interest and organize them in suitable plots and tables.

Description of the Quality Factors

Differently from most other applications, which aim to low temperature jets, for application to beam diagnostics, there are different characteristics of interest in the curtain by which it is possible to assess its performance.

Firstly, the Mach Number reached downstream the skimmer at the designed point of interaction with the projectile beam (M), which gives an indication of the efficiency of the expansion: it is linked to the efficiency of transferring thermal energy into kinetic directional motion and hence directly relates to the directionality of the jet. Secondly, the geometrical dimensions of the gas curtain: width and depth (W and D respectively), which affect the resolution of the monitor [6].

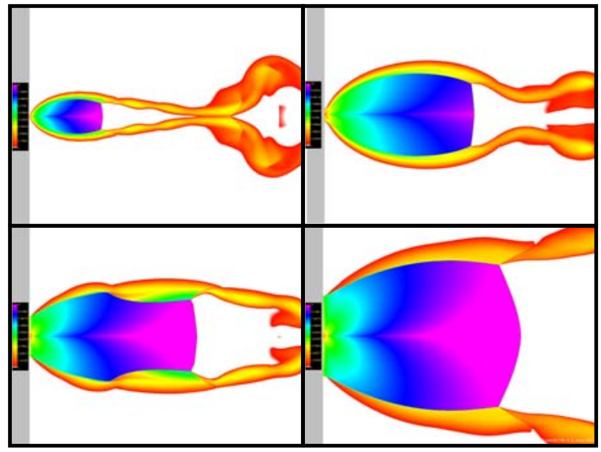

Figure 2: subsequent stages (top line 0.5 ms; 1 ms; bottom line 1.5 ms; 3 ms) of the free expansion of an axissymmetric gas jet computed by GDT using open boundary conditions on all boundaries. Time instability of the equilibrium pattern is shown. The flow reaches a first condition of equilibrium (top left); then expands further and reaches a second position of equilibrium (top right); only to show some instabilities (bottom left) and finally blowing up (bottom right) until it eventually exceeds the simulation domain (not shown).

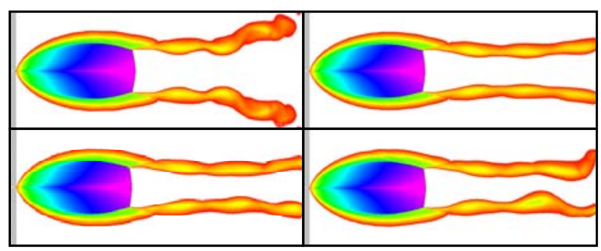

Figure 3: subsequent stages (5 ms, 10 ms, 300 ms, 650 ms) of the free expansion of an axissymmetric gas jet computed by GDT using the optimized boundary conditions discussed in the text. An equilibrium pattern is visible in the region of interest upstream the main Mach Disk shock wave .

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.

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), as shown in Fig.4.

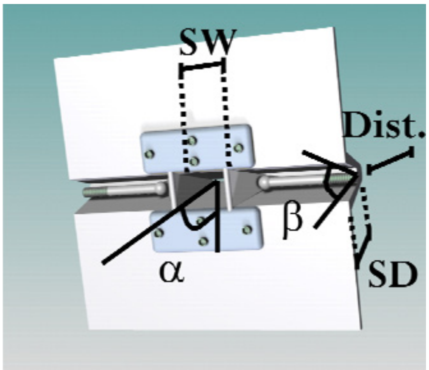

Figure 4: Geometric variables of the skimmer.

Results

We have run about 5000 simulations using different geometrical parameters for the nozzle-skimmer system, automating the numerical investigation through our own purpose written c++ code, which also took care of the computation of the three quality factors.

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 which goes beyond the scope of this paper. Our results are hence best expressed 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.5, 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 one 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%.

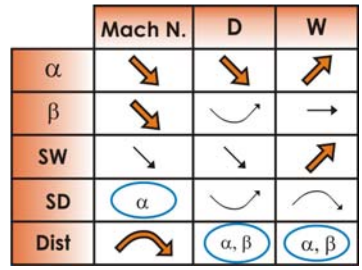

Figure 5: Table of simulated trends.

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 favor 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 terms of directionality (namely α, β and Dist) and curtain width to depth ratio (α and SW).

Two important examples of the plots from which the above table was deduced are shown in Fig.6-7. These two plots express the trade-off needed in choosing the angle α: indeed, while increasing α brings about an improvement in the width/depth ratio, crucial for resolution, it also decreases the efficiency of expansion at the expenses of directionality; furthermore, too high a value of alpha appears to bring instability in the response of the system to slight nozzle-skimmer distance variation. This could potentially become a problem as vibrations in the apparatus, slightly modifying the nozzle-skimmer distance could sensibly change the performance of the monitor.

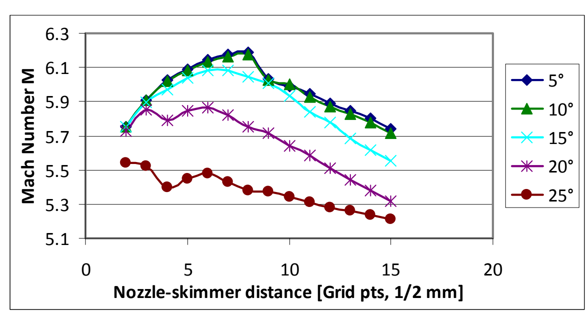

Figure 6: Mach number plotted as a function of nozzle-skimmer distance, with the aperture angle α as parameter. It is seen how increasing α brings about a decrease in Mach number, and hence decreases the expansion efficiency, worsening the directionality of the jet.

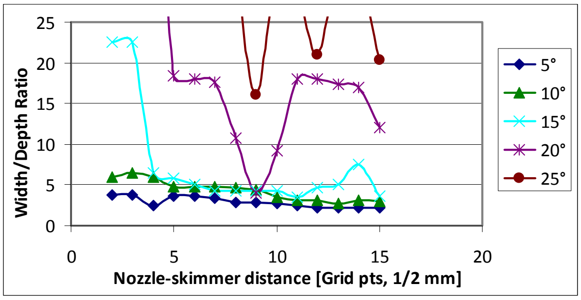

Figure 7: Geometric width/depth ratio plotted as a function of nozzle-skimmer distance, with the aperture angle α as parameter. Increasing values of α improve the width/depth ratio, hence increasing monitor resolution. However, the system becomes more unstable with respect to the nozzle-skimmer distance.

On the other hand, the examples also show how the nozzle-skimmer distance can be used to maximize the Mach Number without negatively affecting the geometric width/depth ratio.

It must be also mentioned that suitable modifications of the nozzle-skimmer geometric parameters, namely large α/β ratios, and small nozzle-skimmer distance, together with high pressure ratios bring about a peculiar "split" behavior in the formed jet curtain, illustrated in Fig.8. Such form of the curtain could be exploited for beam halo monitoring (where its peculiar density distribution could be exploited for decreasing the count rate in the high density core of the beam, avoiding detector saturation effects), or, in storage rings, where multi-pass operation is envisaged, even for halo scraping applications.

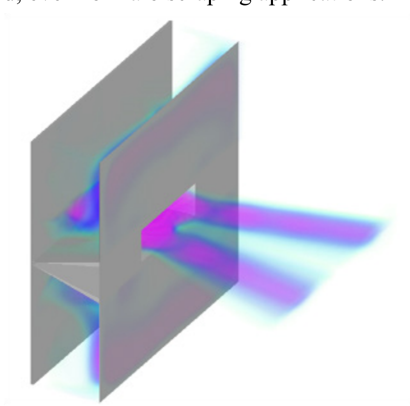

Figure 8: Simulated split curtain operation of the gas jet.

OUTLOOK

Experiments tailored to benchmarking the results described in this contribution are currently in preparation in our laboratories.

The vacuum vessels, the signal acquisition electronics and the detectors needed for the experiments were designed and are in the final stage of manufacturing, while the experimental stand which will hold the system has been already mounted in our laboratory (Fig.9).

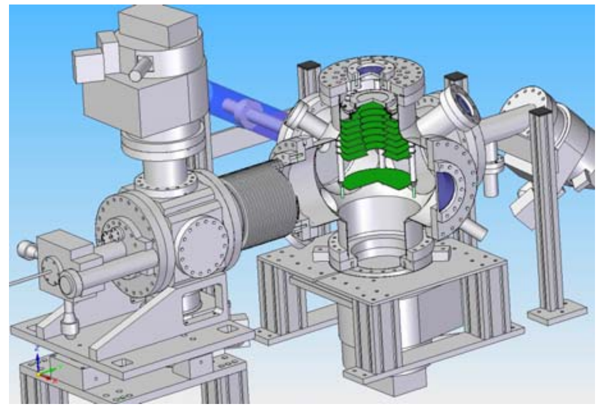

Figure 9: CAD of the experimental setup.

First experimental tests, which will characterize the created Argon and Nitrogen jet curtains density-wise, are expected to be performed before the end of 2010.

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