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OPTIMIZATION STUDIES OF PLANAR SUPERSONIC GAS-JETS FOR BEAM PROFILE MONITOR APPLICATIONS

M. Putignano, C.P. Welsch, Cockcroft Institute and University of Liverpool, UK

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Abstract

Supersonic gas-jets have attracted much interest as experimental targets in several fields of science since they combine low internal temperatures with high directionality. Axisymmetric jets have found widespread application, triggering a wealth of studies on their properties, while only a limited number of detailed studies have been done on planar jets.

In this paper, the design of a beam profile monitor based on a planar supersonic gas-jet for use in the Ultra-low energy Storage Ring (USR) at the Facility for Antiproton and Ion Research (FAIR) in Germany is described. Optimization of the monitor requires investigation into different characteristic jet parameters. For that purpose extensive simulation work with the Gas Dynamics Tool (GDT) was done. The results of these studies are presented together with a description of a novel nozzle-skimmer configuration and an experimental test stand to benchmark the numerical results.

INTRODUCTION

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

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 [2]. Furthermore, existing non-perturbing techniques such as residual gas monitors can take up to about 100 ms 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 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. Keeping the curtain at a 45° angle from the impinging direction of the projectiles, and extracting the ions 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 [3], as shown in Fig. 1.

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), within the FAIR facility planned at GSI in Darmstadt, Germany.

Crucial to such monitor is the generation and control of the gas-jet in terms of achieved density and directionality.

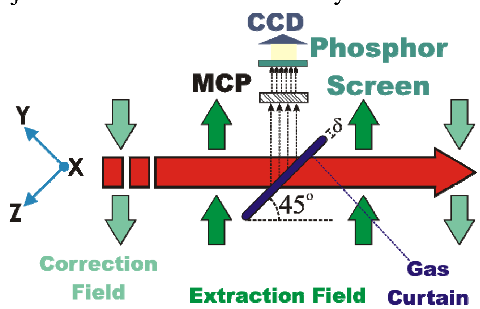

Figure 1: Jet-curtain profile monitor operation principle: the large horizontal arrow shows the projectiles path.

Delving into the study of the gas-jet generation involves the analysis of a large set of both geometric and thermodynamic variables. Such large collection of variables makes a full experimental study unfeasible, and requires hence the use of numerical analysis to narrow down the cases worth exploring experimentally.

In this contribution, we will introduce the numerical simulation package that we used, describe the set of variables and observables that we monitored and finally present the findings of our analysis, which lead to the proposal of a novel nozzle-skimmer configuration to optimize jet performance in beam diagnostic applications.

NUMERICAL SIMULATIONS

The software used for our simulations is 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. Since the initial expansion stages of a typical beam diagnostics gas-jet apparatus 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, the mean-free path at room temperature lies in the sub-millimeter range, hence is still compatible with the continuum description of the flow (Knudsen number < 0.2), allowing the use of the Navier-Stokes equations. In turn, these reduce to the Euler equations as it has been shown that the gas-jet expansion is a quasi-isentropic process [4], and viscosity effects can be neglected. Hence, the GDT continuum flow solver, based on the Euler equations, was used in this study.

In addition, the GDT code was complemented with purpose-written C^{++} analysis modules, which automate variables modification and simulation runs, import data

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†corresponding author: massimiliano.putignano@quasar-group.org

from GDT, compute the observables of interest, and organize them in suitable plots and tables.

Variables and Observables Description

To show the importance of the geometry of the nozzle-skimmer system for the curtain characteristics, 5 geometric variables were varied, as shown in Fig. 2: the skimmer aperture angles (α and β); the width of the skimmer slit (S_W); the depth of the skimmer structure (S_D) and the nozzle-skimmer distance (d_{ns}).

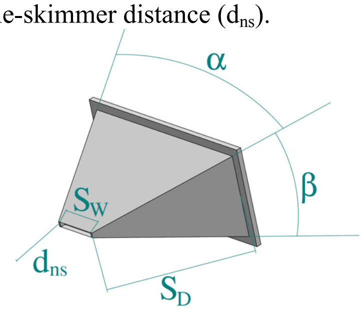

Figure 2: Geometric variables of the skimmer.

In addition, the pressure and temperature in the high pressure gas reservoir from which the jet expands was monitored.

For application to beam diagnostics there are three different characteristics of interest in the curtain: the geometry, which affects the monitor resolution; the density homogeneity, which limits the accuracy; and the confinement, useful for efficient pumping. Due to page number restrictions, we will only analyze the first two in this contribution.

The quality of the geometry can be assessed by the ratio G_R between the long and the short dimensions of the curtain. Both of them shall be defined as the region outside of which the density value never rises to more than a certain percentage of the maximum density. The analysis which leads to the choice of these values lies beyond the scope of this paper, it shall only be mentioned that they need to be different as the two dimensions have a different impact on the performance of the monitor. Suitable values can be shown to be 5% for the short dimension, so that that any contribution external to the curtain can be considered negligible, and 90% for the long dimension, so as to enhance density homogeneity across the curtain. It is expected that this procedure gives a more meaningful system description as compared to a standard FWHM approach.

The region enclosed by these dimensions will henceforth be referred to as *the curtain*. Given the scaling properties of every fluid-dynamic system, it is always possible to scale the physical dimensions of the nozzle-skimmer system to consequently adjust the jet curtain dimensions. Therefore, having obtained the ratio G_R, the actual resolution can be obtained normalizing the long dimension of the curtain to the required curtain width (C_W). Being h the long dimension of the curtain, d the short, and R the resolution, the following results:

$$G_R = {}^{h}\!/_{d} \rightarrow R = \frac{C_W}{G_R}$$

The density homogeneity H_ρ is best expressed as the standard deviation of the density profile in the curtain region. Normalizing the density distribution to its average value makes the standard deviation H_ρ a direct percentage indicator of the accuracy.

RESULTS

Initially a small set of simulations was run, comparing perpendicular and parallel skimmer and nozzle slits. Counter-intuitively, it was found that if the nozzle slit is perpendicular, rather than parallel, to the skimmer slit, the system performs sensibly better. Therefore, all following simulations use the perpendicular configuration.

Due to the C++ automation of GDT it was possible to run almost 10,000 simulations over 3 months, exploring 4 different values for each of the 5 geometric variables and 3 different values for stagnation pressure and temperature.

To show the results, we have plotted in Fig. 3÷5, the values of R and H_ρ for $2^7{*}3=384$ chosen simulations, corresponding to all possible combinations of 2 indicative values for each of the variables but the nozzle skimmer distance, for which we have included 3 indicative values.

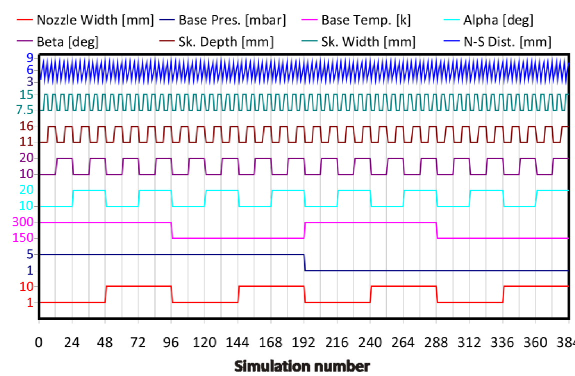

Figure 3. Each of the 384 simulations, shown on the x axis, is run with a different set of the 7 variables analyzed.

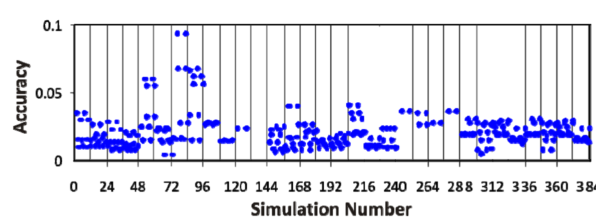

Figure 4: Plot of the simulated accuracy.

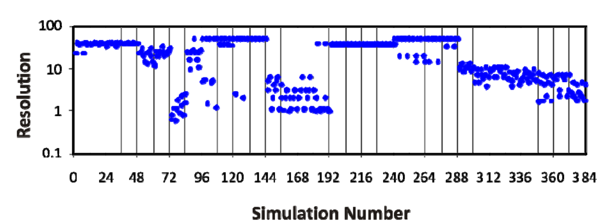

Figure 5: Plot of the simulated resolution, in millimetres.

The missing points in the plots correspond to those variable combinations for which the expansion is not developed enough to create a curtain clearly bounded by shock waves, and the flow results in very low densities, below 300% of the base density.

In the first plot, each line corresponds to a variable, and shows which of the two values it is taking in a particular simulation run, whose number is shown on the x-axis.

Since the accuracy can be corrected by proper calibration, the most important parameter is the resolution, which depends directly on the geometry of the created curtain.

The plot in Fig.4 shows that millimeter to sub-millimeter resolution can be achieved in 3 regions, corresponding to 3 sets of simulations: #73-84 (set 1), #145-192 (set 2), and #373-384 (set 3).

The first important result is that all 3 regions correspond to the slit nozzle configuration, while the analogue regions with circular nozzle configuration (respectively #25-36, #97-144 and #325-336) perform much worse yielding in the first case a very weak expansion, resulting in poor accuracy, and in the second a multiple times split curtain. In the third case, instead, the difference in performance is not as dramatic, but the resolution is still better in the slit nozzle case by more than a factor of 2.5. This proves the advantages of using a slit nozzle configuration over a standard, axis-symmetric jet followed by collimators.

To discriminate between the three sets, the most important factor proves to be the density profile shape of the created curtains. A *curtain splitting* phenomenon is clearly seen in the second set, in which the curtain density drops abruptly by more than one order of magnitude in the center. Curtain splitting, whilst making the curtain unsuitable for profile measurement, could be used for beam halo scraping in systems, like storage rings, where multi-pass operation is available or allow for limiting the profile monitoring to the tail regions of the beam.

Furthermore, as can be seen from Fig.3, when operating in the regime of simulations #73-84, it only takes a temperature variation to bring the system in the regime of simulations #169-180, where curtain splitting occurs. This shows another advantage of the system proposed here, namely the flexibility of changing the operation mode by adjusting the temperature of the gas reservoir, without having to modify any mechanical feature.

The third set of simulations, #373-384 presents a splitting behavior that depends strongly on the value of the nozzle-skimmer distance and, less severely, on the skimmer width. This chaotic behavior is unsuitable for practical operation, as the nozzle-skimmer distance is controlled mechanically only with difficulty, and depends on temperature and aging effects.

Therefore, the best operating mode identified by these simulations is the one resulting from simulations #72-84. This corresponds to a slit nozzle configuration, moderate pressure differential, room temperature, large angle α and small angle β. Furthermore, it can be seen that the skimmer depth has no noticeable impact on resolution and accuracy. On the other hand, whilst a larger skimmer width stabilizes the dependence of the resolution on the distance, it also negatively affects the accuracy. Therefore, the optimized configuration is obtained when the skimmer width is about 1.5 times as large as the nozzle width. In addition, the nozzle-skimmer distance is kept short to optimize the resolution; down to about 1/3 of the skimmer width. With these parameters, the accuracy can be kept at a 2% level. This could be further improved by calibration of the system.

OUTLOOK AND CONCLUSION

In this contribution it was shown by means of numerical analysis how an optimized geometry, relying on a slit nozzle and rectangular skimmer, oriented perpendicular to each other, performs better than a traditional setup made of a circular orifice, followed by a conical skimmer and collimators. The geometric and thermodynamic settings to optimize the jet operation were also listed. Furthermore, it was shown how the proposed system can be adjusted to two different modes of operations: plain curtain for beam profile measurements and split curtain for beam halo scraping/imaging, solely by varying the temperature of the gas reservoir, i.e. without any mechanical modification.

An experimental apparatus to benchmark all results, shown in Fig. 6, is presently under construction, and experiments will be carried out before the end of this year.

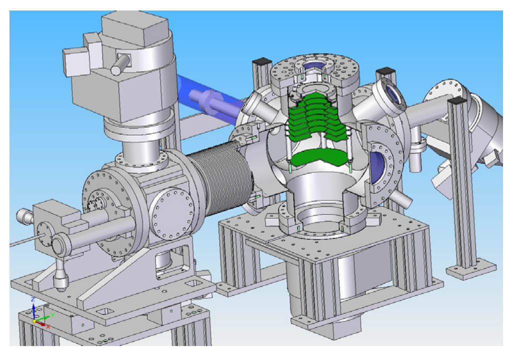

Figure 6: Illustration of the experimental setup.

REFERENCES

[1] C.P. Welsch, et al.,"Exploring Sub-Femtosecond Correlated Dynamics with an Ultra-low Energy Electrostatic Storage Ring", AIP Conf. Proc. 796 (2005) p. 266-271

[2] J. Harasimowicz *et al*, "Beam instrumentation for the future ultra-low energy electrostatic storage ring at FLAIR", Hyperfine Interact (2009) 194:177-181.

[3] M. Putignano *et al*, "A Fast, Low Perturbation Ionization Beam Profile Monitor Based on a Gas-jet Curtain for the Ultra Low Energy Storage Ring.", Hyperfine Interact (2009) 194:189-193.

[4] M. Jugroot *et al*, "Numerical Investigation of interface region flows in mass spectrometers: neutral gas transport.", J. Phys. D: Appl. Phys. (2004) 37:1289-1300.