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Supersonic gas jets as internal targets at NIKHEF

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Abstract

We investigated a gas jet issued from a rectangular slit nozzle. Such jets can be made to dynamically converge by interacting with the residual, lower density, gas inside the accelerator vacuum vessel. Densities of up to few times 10^{15} atoms cm^{-2} were achieved. We describe the experimental facility, the diagnostics used and present the result of our data analysis.

1. Introduction

The importance of gaseous internal targets in nuclear and in high energy physics research has been recognized recently. Such targets combine a number of very attractive features when used in a storage ring setting. The current gas jet R&D work at NIKHEF, the Dutch National Institute for Nuclear and High Energy Physics, was launched in order to take advantage of the Amsterdam Pulse Stretcher (AmPS), an addition to the existing electron linac. The AmPS can be operated as an electron storage ring and nuclear physics experiments can benefit from a gaseous internal target with densities of up to 10^{16} atoms cm^{-3} for light nuclei. NIKHEF operates a medium energy electron scattering facility in Amsterdam. Electrons are accelerated in a 200 m long medium energy linac accelerator (MEA) up to energies of 700 MeV, then extracted and delivered to a fixed target experimental area. The duty factor of such a scheme is very small, approximately 0.1% and as a result accurate coincidence experiments were impossible to conduct. To remedy this situation the Amsterdam Pulse Stretcher (AmPS), a 212 m long ring, was recently built at the extraction point of the MEA. Electron pulses from the linac are injected into the AmPS, their time structure changed (“stretched”) resulting in a continuous beam of electrons which can then be slowly extracted and delivered to the fixed target area, with a duty factor close to 100%.

The AmPS can be operated also in a storage ring mode: multiple electron pulses from the linac can be extracted and stored for relatively long times in the stretcher ring. Electron currents of up to 150 mA with beam lifetimes of up to 20 min have been measured. Stored beam energy is usually 550–600 MeV with an option to be extended up to 900 MeV with RF ramping. Such an intense electron beam interacting with an internal target of 10^{16} cm^{-2} , it yields a luminosity $\mathcal{L} \approx 10^{34}$ $\text{cm}^{-2} \text{ s}^{-1}$. In order to take advantage of the storage ring operating mode of the AmPS, a dedicated experimental area, the Internal Target Hall (ITH), was incorporated in the ring proper, as seen in Fig. 1.

Experiments with unpolarized and polarized nuclei as internal targets have been planned for the ITH facility. As an unpolarized target of choice we decided to develop a self-focusing supersonic gas jet. Gaseous internal targets are extremely thin as compared to conventional foil targets: for light nuclei and densities of 10^{16} cm^{-2} the target thickness corresponds to less than $0.1 \mu\text{g cm}^{-2}$. With care an internal gas target can be made to minimally disturb the stored beam, to result in a good beam lifetime and to provide an excellent luminosity while keeping the residual gas pressure in the accelerator vacuum vessel at tolerable levels. By focusing the gas jet one can achieve a well localized interaction volume and a very good reaction vertex; this is a very important property for discriminating signal from background. With minimal hardware modification, gases of different atomic and mass number can be used as targets, transforming the gas jet nozzle into a versatile “target wheel”.

A typical nuclear physics experiment which can benefit from such a self-focusing, intense, supersonic gas jet target, is the coherent π^0 electroproduction off the ^4He nucleus, i.e. the $^4\text{He}(e, e'\pi^0)^4\text{He}$ reaction. Comparing this

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reaction to the electroproduction off pure hydrogen, one can identify the behavior of the nucleon as is modified when in a nuclear matter bath. Such an experiment is notoriously difficult since one must detect the two energetic photons, from the $\pi^0 \rightarrow \gamma\gamma$ decay, in the forward

direction, in an environment “contaminated” by beam halo and secondaries from the stored electron beam. An alternative technique requires the detection of the slowly moving recoiled ^4He nucleus. A self-focusing gas jet target provides enough luminosity for this μb level reaction

Fig. 1. The Amsterdam Pulse Stretcher Ring. The MEA electron beam (top right) is fed clockwise into the AmPS. Beam from the ring can be either extracted towards the fixed target area (EMIN) or kept stored for use by the Internal Target Hall (ITH) facility.

Fig. 2. Transverse cut of an underexpanded supersonic gas jet. P_n = high pressure reservoir, P_a = ambient pressure in the expansion chamber.

Fig. 3. The slit nozzle: the whole assembly and detailed views of the end of the nozzle along the two vertical planes of its symmetry.

while being transparent to the recoil [1]. Another very interesting and promising application of such a target is in the hadron production of B-mesons for CP violation studies. Here a well defined interaction vertex is required in order for the trigger to differentiate between the copiously produced minimum bias events, which are directly traced to the vertex, and the B-mesons decay products which are produced centimeters downstream [2].

2. Experimental setup

A standard method for obtaining a gas jet with a high localized density is to trigger partial condensation in an expanding gas jet and produce a cluster beam [3]. Existing cluster gas jet setups and unfocused gas jet targets achieved densities up to 10^{16} cm^{-3} at the interaction point. In order to create target densities higher than these, without having to increase the pumping capacity dramatically, we decided

Fig. 4. The NIKHEF gas jet test setup. The expansion chamber is located in the center of the drawing. Gas enters to the test chamber from the top; the coiled pipe can provide cooling. The electron gun assembly is on the center right.

to investigate a supersonic gas jet produced by a rectangular slit nozzle.

Such a nozzle gives a strong focusing of the gas jet in the direction of the long axis of the slit and a mild defocusing in the direction perpendicular to that. Slit nozzles have been studied by Beylich [4], Teshima [5,6], and Dupeyrat [7]. These studies have been carried out with minimum nozzle widths of 0.24 mm. They covered a wide range both in pressure ratios ($50 < P_n/P_a < 10^4$) and in aspect ratios ($2 < L/D < 960$) of the orifices, where P_n = high pressure reservoir, P_a = ambient pressure in the expansion chamber (see Fig. 2).

We constructed a rectangular slit nozzle $50 \mu\text{m} \times 2500 \mu\text{m}$ (Fig. 3) and estimated that a pressure ratio of up to 10^5 was needed in order to meet our design goal [8]. A vacuum chamber was built around the slit nozzle head (Fig. 4). This central chamber served as the expansion volume for the gas jet. Typical input pressure at the top of the gas jet nozzle was a few bar while the residual pressure in the expansion chamber was 10^{-4} times lower. To achieve such a background pressure while operating the gas jet a series of conventional and turbo pumps were connected to the expansion chamber walls. Our diagnostic studies concentrated on measuring the absolute density profile of the expanding gas jet and determining the position of the focusing loci. To facilitate a 3-dimensional visualization of the gas jet density distribution, the nozzle head assembly could be rotated over 90° . For safety and convenience we used molecular nitrogen throughout our experimentations.

3. Gas jet diagnostics

The technique of choice must provide an accurate measurement of the density profile of the expanding gas jet, while keeping the interference of the measuring device with the jet itself to a minimum. Light should have been an ideal probe if it were not for the low densities in our setup. The anticipated densities of up to 10^{16} cm^{-3} are too small, by at least two orders of magnitude, for any visible light techniques (schlieren, interferometry) to be useful. We opted instead for constant temperature anemometry and for low energy electron scattering. By scanning with a constant temperature hot-wire anemometer in a direction perpendicular to the expansion of the jet one can obtain the local gas flux. Probing the gas jet with a 10 keV electron beam one can measure resulting ionization current or collect the light from de-excitation.

3.1. Measurements with an electron beam

The probe electron beam was provided by an off-the-shelf television electron gun of the same type as the one incorporated in Philips M32EBJ/L flat monochrome dis-

Fig. 5. A photograph of a supersonic gas jet Mach disk. The electron beam enters from the right. The slit nozzle is located at the center of the photograph and above the topmost electron beam trace. The distance from the nozzle to the visible node is 5 cm.

play tubes, used in high resolution computer monitors. The electron gun was mounted on a computer controlled table. The gun was aimed on the axis of the gas jet and could be moved vertically and horizontally ($3.5 \text{ cm} \times 3.5 \text{ cm}$) in steps of 0.12 mm. The gun was connected to a HV power supply, achieving accelerating voltages up to 10 keV. By regulating the heating of the gun filament currents up to 200 μA were obtained. The current of the electron beam was monitored by a Faraday cup, located at the diametric opposite side of the test chamber. A set of eight small coils located at the exit of the gun were used for fine tuning the position of the beam.

As an exploratory measurement we attempted to locate the first node of the expanding gas jet. Using an ordinary 35 mm reflex camera with an ISO 100 film, we obtained time exposures of the de-excitation light generated when the electron beam struck the steady state gas jet. A series of 10 s time exposures were taken on a single plate while the electron gun scanned vertically along the center axis of the jet. With this technique we verified that the first high density node appeared at the expected distance from the

slit nozzle (Fig. 5). The convergence point, the so called Mach disk, was found at a distance from the nozzle in general agreement with the empirical formula of Beylich [4]. For most of our scans the first density node appeared 5–10 cm away from the slit nozzle and on the axis of the expanding jet. The photography technique is of limited accuracy and provides only a qualitative description of the density distribution of the gas jet.

By using the same 10 keV electron beam we ionized the gas jet molecules and measured the produced positive ion current. A ring shaped copper electrode was constructed and mounted inside the vacuum vessel on the axis of the expanding jet and exactly opposite of the slit nozzle. The collection electrode was connected to a small bias voltage, about -50 V . The primary electron current was monitored and recorded continuously during an ionization scan.

The ion current, normalized over the electron gun current, is proportional to the integral gas density along the electron beam path. The constant of proportionality is the total ionization cross section; we obtained the numerical

Fig. 6. An integral density profile of the expanding gas jet as measured by the ionization method. Peak density of $1.3 \times 10^{13} \text{ cm}^{-2}$ was measured over a background of two orders of magnitude lower. The slit nozzle is located at $x = 0.0 \text{ mm}$, $z = 55.0 \text{ mm}$.

Fig. 7. A gas jet density profile taken with the CTA. The high density points correspond to densities of few times 10^{15} cm^{-3} at a flux of 10^{17} s^{-1} . The slit nozzle is located at $x = 0.0 \text{ mm}$, $z = 65.0 \text{ mm}$.

value of the ionization cross section from the review Kiefer and Dunn [9]. The ion collection efficiency of our apparatus was calibrated by measurements at different background pressures, without the gas jet running, and comparison with the vacuum gauges. The result of a typical scan is shown in Fig. 6.

3.2. Measurement with the anemometer

Following the pioneering work of Gross and Melissinos [10] we employed a constant temperature anemometer (CTA) as an additional diagnostic technique. The sensitive part of our anemometer consisted of a $25 \mu\text{m}$ thick and 45 mm long, cylindrical cross section, stainless steel wire. Such a thin wire had an electrical resistance of 70Ω at room temperature. The wire was heated to approximately 450 K by applying a small bias voltage. When the gas jet intercepted the wire, it dissipated energy and thus cooled the wire, resulting in a change of its resistance. In the

constant temperature mode of the anemometer, an appropriate feedback circuitry maintained the initial resistance of the hot wire by increasing the bias voltage, and kept the exposed wire at constant temperature. The additional power needed to keep the anemometer at constant temperature is a measure of the power dissipated from the wire to the gas jet stream. The dissipated power is directly related to the local gas flux. Only the sensitive part of our anemometer was mounted on the x - y table inside the vacuum vessel. Appropriate wiring connected it to the feed back circuitry on the outside of the chamber. We followed the calibration procedure of Gross and Melissinos where it is explained how one can extract the gas jet density from the gas flux measurement and refer to their paper for details. The length of the hot wire was sufficiently long to avoid the creation of shock waves by the wire supports. For a gas density of 10^{16} cm^{-3} the mean free path of molecular nitrogen is $\lambda = 0.1 \text{ cm}$, which is much larger than the diameter of the anemometer sense wire. Thus our

Fig. 8. Numerical simulation of a gas jet density profile along the expansion axis. The first Mach disk starts appearing at $x = 0.0 \text{ cm}$, $z = 8.0 \text{ cm}$. The density is indicated in particles per m^3 . Taken from Ref. [11].

anemometer did not perturb in any significant way the expanding gas jet flow.

In Fig. 7 we show a 2-dimensional gas jet density profile. One clearly sees an island of increased density downstream from the nozzle and along the direction of the expansion.

4. Discussion

Parallel to the experimental work we developed a Monte Carlo simulation of our setup [11,12]. The numerical code was essentially 2-dimensional, but the results obtained were in good agreement with the data as seen in Fig. 8. We currently work on the implementation of a true 3-dimensional code. The development of a reliable simulation will guide our experimental effort towards the most promising region of the parameter space.

We built an experimental setup for supersonic self-focusing gas jet studies. We demonstrated such a target and constructed diagnostics to measure its absolute density. Currently we work to optimize our setup: we need to keep the Mach node density at the measured values of 10^{15} cm^{-3} or higher while trying to lower the residual gas pressure in the expansion chamber.

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