HIGH-LUMINOSITY HYDROGEN JET TARGET DEVELOPMENT

F. Sperisen and J. Doskow
Indiana University Cyclotron Facility, Bloomington, Indiana 47408

Since the startup of the Cooler a few years ago the internal target most in demand has been the hydrogen gas jet.[1] It is expected that it will continue to play an important role in high-luminosity experiments, such as pion production near threshold, or as a meson production target in studies of rare decay modes. The following is a status report on our efforts towards a more localized high-luminosity hydrogen jet target.

A supersonic jet is formed by pushing gas through a converging-diverging (de Laval-type) nozzle which is positioned as close as possible (~ 7 mm) to the Cooler beam so that the latter intercepts the jet where it is dense and narrow (several mm FWHM). The target thickness can easily be controlled via the flow rate (or pushing pressure) and adjusted to the optimum value (around 10^{16} atoms/cm^2) where the luminosity is maximum. For experiments demanding high luminosity this is an important advantage over cluster jet targets which have commonly been used internally in storage rings. There, a stored ion beam interacts with a collimated molecular cluster beam far (~ 20 cm or more) from the nozzle. A maximum target thickness of 3×10^{14} atoms/cm^2 for H_2 cluster jets[2] severely limits achievable luminosities. On the other hand, cluster jets are well localized targets, surrounded by very little background gas. In this respect they compare favorably with our jet target. Here, the fraction of the jet gas not removed directly through a catcher has to be differentially pumped along the Cooler beam line and represents 20–40% of the target thickness, distributed mainly in the first pumping stage, within ± 8 cm of the jet. Obviously, the presence of such background gas can create severe difficulties, depending on the specifics of the experiment. The goal of our current development is to improve the localization of our jet target without sacrificing the capability of reaching optimum thicknesses.

The jet localization can be characterized by the ratio of the thickness of the jet to that of the background gas. To improve this ratio one should seek to minimize the background gas density (1) by minimizing the nozzle flow rate needed to achieve the optimum jet thickness, and (2) by maximizing the catcher efficiency and the pumping speed on the first stage. We are planning to increase the latter by replacing the present turbo pump (Balzers TPH 1500) with a faster one (TPH 2200), which has an H_2 pumping speed twice that of the present pump. In order to minimize the nozzle flow rate (at optimum jet thickness), as well as to improve the catcher efficiency, we have been studying the jet formation, both experimentally and theoretically. Our work was initiated by reports[3] that hydrogen jet flow distributions become more forward peaked with increasing pushing pressure, p_o, or nozzle flow rate, f_o. Considering that p_o is a strong function of the nozzle throat diameter, d_t, one may expect narrower nozzles to produce narrower (and denser) jets, i.e., the optimum thickness may be obtained at smaller f_o. In addition to d_t, there are other parameters of the nozzle geometry, in particular the length and opening angle of the divergent part, that should be optimized. Furthermore, while we know that cooling of the nozzle is important, the detailed temperature dependence of the jet flow needs to be investigated.

Our experimental studies are based on the assumption that the jet molecules originate from a virtual point source near the nozzle exit and expand into vacuum under molecular flow conditions, i.e., there are essentially no collisions among themselves or with the diffuse gas in the chamber. This assumption is justified by mean free path estimates as well as experimental observations as explained below. We have mapped out the jet flow distributions with a setup similar to that used in our previous tests which led to the present Cooler jet target.[1] The fraction of the flow into a cone of half-angle θ around the jet axis, $f(\theta)/f_o$, has been measured with a cone-shaped catcher tube, intercepting the jet some distance from the nozzle. Both the catcher and the main vacuum chamber have been pumped by turbo pumps (Balzers TPU 1500 and TPU 510, respectively). We determined $f(\theta)/f_o$ from the ratio of the flow rates through these pumps via their fore line pressures, which were calibrated in separate measurements. In addition, f_o, p_o, as well as the pressures in the main chamber and catcher, were measured. Corrections have been made for the net flow of diffuse background gas between catcher and main chamber.

We have made nozzles from 1 mm i.d. glass capillaries. The capillaries were heated locally with a torch, under slow rotation about their axis to achieve an even temperature distribution, until the inner diameter narrowed to form a converging-diverging passage. While it is difficult to control the resulting geometry of the individual product, we have ended up with a number of nozzles that cover a sufficiently large range of shapes.

In a first series of measurements a nozzle (d_t=68 μm, length of divergent part: ~5 mm) at room temperature was mounted on a push-pull vacuum feedthrough, so that its distance to the catcher, and thus the angle θ, was easily adjustable. As an example, Fig. 1a shows $f(\theta)/f_o$ measured with three catchers of different opening diameters. There seems to be no systematic dependence on the catcher diameter, which validates the assumption mentioned above that the jet molecules emerge from a virtual point source in straight flight paths. The curve represents a one-parameter model fit. It is based on the assumption that the jet flow distribution can be described in terms of a Maxwellian velocity distribution, given by the jet temperature T (fitted) at the nozzle exit, and the jet velocity, $v_j(T)$. The latter is calculated assuming isentropic expansion of the gas through the nozzle, while cooling from T_o=300 K to T. Fig. 1b shows transverse jet density profiles, deduced from such fits to $f(\theta)/f_o$, measured at four flow rates f_o between 0.34 and 2.75 Torr·l/s (p_o between 500 and 2000 Torr). The fitted temperatures T range from 203 K (for the smallest f_o) to 156 K. These values are much higher than one would expect under the assumption that the gas expands isentropically until the mean free path is no longer much shorter than the nozzle diameter. Then, T would range roughly from 50 to 5 °K, respectively. Neglected viscous and heat transfer effects may be responsible for the discrepancy. In any case, these problems have to be kept in mind when interpreting the density profiles resulting from the fits. The density is inversely proportional to v_j, and it would be lower by 50% (for the smallest f_o) to 40% if v_j would be determined effectively from cooling to the lower temperatures. Nevertheless, the results of Fig. 1b indicate that the jet flow does become more forward peaked with increasing f_o, as expected, but not very dramatically (the jet width decreases by 17%, and the more relevant jet thickness per unit flow rate increases by only 12%, both roughly linearly over the measured range of f_o). Likewise, from measurements with three nozzles of different throat diameter (d_t=45, 68, 119 μm)

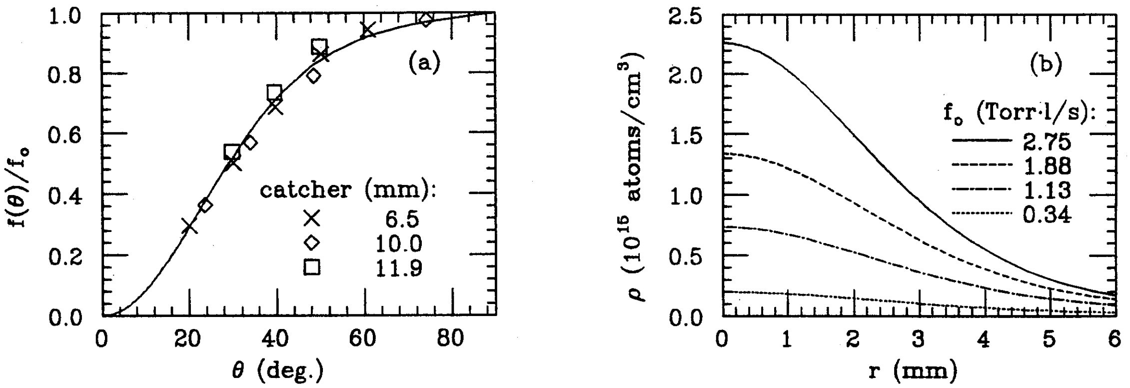

Figure 1. (a) Fractional H_2 jet flow rates into a cone of half-angle θ, measured with a room temperature nozzle (T_o=300 °K, d_t=68 μm, f_o=1.88 Torr·l/s) and three catchers of different opening diameter. The curve is a one-parameter fit assuming isentropic gas expansion through the nozzle and a Maxwellian velocity distribution. (b) Transverse density profiles, at 7 mm from the nozzle exit, deduced from such fits to $f(\theta)/f_o$ data measured at four different f_o (other parameters as in (a)).

at T_o=300 °K, we find that the jet formation depends rather weakly on d_t. Comparison with jet widths reported in ref. 3 (obtained with a 100-μm nozzle) shows good agreement at low pushing pressures (few hundred Torr), while at higher p_o our widths do not narrow as much.

Recently, we have begun measurements with cooled nozzles. The glass capillary nozzles are mounted on the head of a closed-cycle helium expander refrigerator (Leybold RG1040). The latter is flanged to the vacuum chamber in fixed position; therefore, to adjust θ, the nozzle has to be moved by changing spacers between it and the cold head. The temperature is measured with a sensor sunk into the copper base holding the nozzle. Unfortunately, we found (by comparison with the calculated T_o dependence of $f_o(p_o)$) that the downstream end of the 3-cm long glass capillary, where the jet is formed, was considerably warmer than the sensor reading (~25 °K) indicated: We estimate that T_o was between 50 and 90 °K. Nevertheless, the results so far demonstrate the importance of nozzle cooling. See Fig. 2 for a comparison between a cooled and a room temperature nozzle. The quality of the fit to $f(\theta)/f_o$ for the cooled nozzle is essentially unaffected by the assumed T_o within the estimated range, but the resulting density is roughly proportional to $T_o^{-1/2}$. Furthermore, the dependence of the density profile on d_t appears to be somewhat more pronounced than at T_o=300 °K. We have now improved the nozzle cooling with a copper heat shield covering its full length, and an initial measurement confirms that T_o is consistent with the sensor reading.

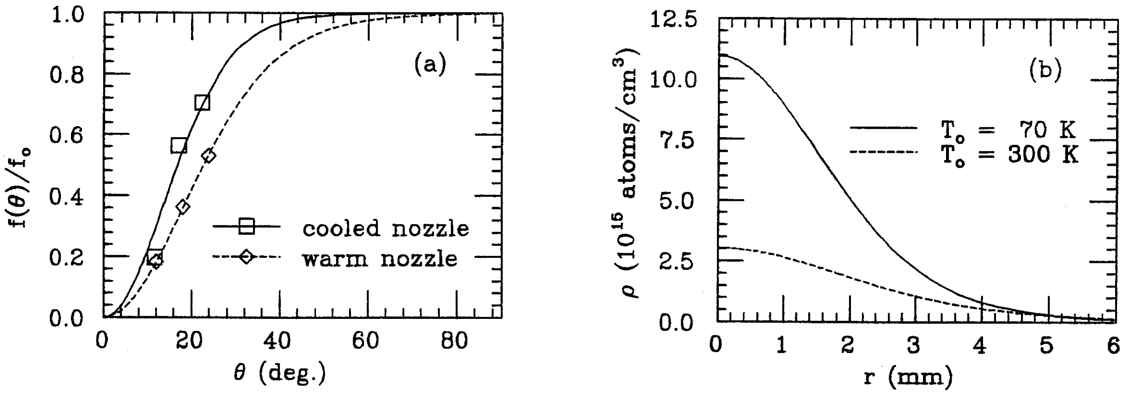

Figure 2. Like Fig. 1 (a) and (b), comparing jets from cooled (T_o=70 ± 20 °K) and room temperature nozzles (d_t=45 μm, f_o=3.05 Torr·l/s).

In conclusion, we have developed a method to study the jet formation by measuring the fractional flow, $f(\theta)/f_o$. Clearly, only *cooled* nozzles are of interest in future optimizations of the nozzle geometry (as well as the temperature itself). So far we have observed only a rather modest improvement of the jet profile from narrower nozzles. However, effects of other parameters, in particular the length of the divergent part of the nozzle, have not yet been investigated. Theoretical guidance from modern Monte Carlo simulations of the jet flow[4] could greatly benefit this optimization. Finally, we have to point out that the fractional flow method described here has its limits and drawbacks. Most important is the uncertainty due to the presence of *diffuse* background gas flow through the catcher, which gets worse for large f_o and both large and small θ. We are therefore planning to study the potential of another method, which is based on scanning the jet with an ionizing electron beam, and which has been used previously with jets of heavier gases.[5]

1. F. Sperisen, *et al.*, IUCF Sci. and Tech. Rep., January 1987–April 1988, p. 194; F. Sperisen *et al.*, IUCF Sci. and Tech. Rep., May 1989–April 1990, p. 117.
2. C. Ekström, CERN Rep. 90-04, 1990, p. 184.
3. D. Gross, P. Mantsch, F. Turkot, FNAL Rep. TM-534 0710.000 (1975); P. Mantsch and F. Turkot, FNAL Rep. TM-582 0710.000 (1975).
4. I.D. Boyd, private communication.
5. J. Wellman, *et al.*, IUCF Sci. and Tech. Rep., May 1990–April 1991, p. 168.