HYDROGEN PELLET TARGET DEVELOPMENT FOR CELSIUS

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Abstract

Development work is presently underway with the purpose to experimentally show that a high speed stream of solid micro-spheres from pure hydrogen, having diameters ~ 20 μm, is possible to aim into a millimeter-sized volume at a stored ion beam intersection. A successful outcome will make close to a full solid angle detection geometry with luminosities $\geq 10^{32}$ cm^{-2}s^{-1} feasible for light meson rare decay studies at the CELSIUS cooler storage ring facility. Design features and the present status of the project are presented.

Introduction

Background

The studies of light meson rare decays and search for exotic propagators using the WASA experimental station [1] (Fig. 1) at CELSIUS will demand a solid detecting angle as close to 4π as possible in order to facilitate a high total detection efficiency and complete reconstruction of events. In addition, a high event rate is also required when doing physics at the pico-barn level. Hydrogen is the most attractive target element when considering production cross sections and target interference with secondaries. The solid hydrogen micro-sphere target facility now under development, is the only internal target concept known today that can meet these requirements.

The research on the refueling of fusion tokamak reactors by injection of hydrogen isotopes has spawned several types of hydrogen pellet generators. One of these, developed at the University of Illinois at Urbana-Champaign (UI) [2], has a promising potential of being adaptable as an internal hydrogen target generator for cooler storage rings. Based on this concept, work is now in progress in Uppsala with the aim to demonstrate the feasibility of continuous vacuum injection of a narrow hydrogen pellet stream by using differential pumping.

The continuous vacuum injection and employment of modern cryogenic technology like cold head refrigeration and silicon diode thermometry has required a quite substantial alteration of the UI pellet generator design and, furthermore, a unique vacuum injector has been added.

Conceptual Target Facility Description

A pure liquid hydrogen jet, emerging through a ≈ 15 μm inner diameter glass nozzle at near triple point conditions (14 K, 7.2 kPa), is broken up into uniformly sized and spaced droplets by means of acoustical excitation of the nozzle. The velocity of the jet is ≈ 10 m/s and the production rate about 200 kHz for obtaining droplets having diameters ≈ 20 μm. By keeping the pressure in the droplet formation region slightly below the triple point value, a frozen shell is allowed to develop on the droplets prior to the vacuum injection through a differentially pumped,

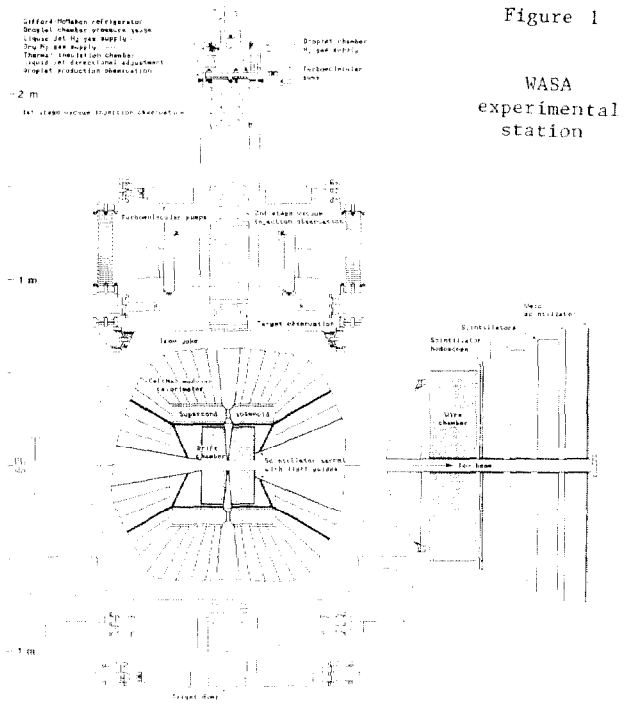

Figure 1

WASA experimental station

two-stage section, where a velocity increase to about 100 m/s is expected due to gas drag acceleration [3].

By charging the droplets, electric fields can be used to deflect a fraction of the pellets into a dump volume, thereby reducing the frequency of targets crossing the beam to about 35 kHz, i.e. just one target at the time will be present in a 3 mm wide beam. With 10^{10} stored protons in CELSIUS an experimental luminosity of 10^{32} cm$^{-2}\cdot$s^{-1} will be achieved.

When entering the proton beam, some ten milli-seconds after their creation, the targets have cooled to temperatures ≈ 6 K and lost about 20 % of their original mass due to evaporation [4]. When passing through the beam, they are tracked by means of optical techniques, and since their frequency of appearance has been matched to the beam size, the reaction vertex can be assigned to the known pellet position when the appropriate triggers are alerted.

The pellets are heated to about 9 K when passing through the proton beam, giving a gas load rate of a few times 10^{-4} Pa$\cdot$m$^3\cdot$s^{-1} and a vacuum of $\leq 10^{-3}$ Pa in the interaction area [4]. The pellets are finally dumped in a differentially pumped, two-stage collector.

Cryogenic system

Hydrogen Micro-Sphere Production

A closed cycle He gas two-stage refrigeration system, operating according to the Gifford-McMahon method, is used for cooling down the hydrogen gas to cryogenic temperatures. Since vibrations from such a refrigera-

tor increases with the cooling power it delivers, a unit with a rather low cooling capacity at the second stage, ≈ 3 W at 14 K, has been chosen in order to avoid unnecessary mechanical disturbances on the droplet production. Thermal contact with the hydrogen is ensured by means of a copper heat exchanger attached to each cooling stage. The hydrogen flows through the heat exchangers in channels filled with a sintered copper bead structure.

The liquid H_2 jet nozzle unit is vacuum-tight connected to the second heat exchanger by a copper flange. A copper tubing, with a ≈ 15 μm inner diameter glass nozzle glued into it and a hollow cylinder piezo-electric transducer attached to the outside, is soldered onto this flange. The jet is broken up into ≈ 20 μm diameter droplets by exciting the piezo-electric transducer using a ≈ 200 kHz AC source. The production frequency refers to the one giving optimum growth rate of the acoustical disturbance of the jet, i.e. resulting in the shortest possible jet at a given excitation amplitude [5]. Studies of the liquid jet break-up into droplets is possible through observation windows in the outer vacuum chamber for thermal insulation of the cryogenic system (Fig. 1).

In order to freeze a solid shell on the droplets prior to the vacuum injection but still avoid freezing of the jet, the pressure in the droplet formation region, enclosed by an inner observation chamber attached to the nozzle unit, is adjusted to slightly below the triple point pressure of hydrogen, 7.2 kPa. Purely liquid droplets would otherwise, due to the very low surface tension of hydrogen, shatter under the gas flow conditions which are at hand in the first vacuum injection nozzle [6,7].

Temperature Measurement and Control

The temperature sensors are of silicon diode type and mounted in threaded adapters specifically designed for cryogenic applications. The sensors intended for monitoring the nozzle unit temperature are individually calibrated with an absolute accuracy in the 1.4 to 40 K range of ± 12-15 mK whereas the first stage temperature monitoring sensor has an accuracy of ± 1 K. A second stage temperature stability of about ± 0.05 K is expected.

A total heat load of ≈ 1.2 W on the second cooling stage is expected, where the cryogenic hydrogen production accounts for about 1/3. In order to attain a working temperature of 14 K, a resistive heating power of ≈ 1.8 W is added. Under this conditions the first stage operates at a temperature of ≈ 70 K. The resistive heating is carried out using a ≈ 20 Ω resistor, fitted as a cap directly on the second cooling stage flange and powered with ≈ 0.3 A by the temperature controller.

Pressure Measurement and Control

Two pressures in the cryogenic system require active feed-back control, the liquid jet driving pressure and the droplet formation region pressure. This is done by means of solenoid operated valves and a capacitance gauges working on the room temperature H_2 gas supply lines. The liquid jet driving pressure, which determines the jet velocity, is kept at ≈ 10^5 Pa for having a jet velocity of ≈ 10 m/s. The droplet formation region pressure, kept slightly below the triple point pressure of normal hydrogen, is maintained by continuously replacing the hydrogen gas lost to the vacuum injection system. Since gas temperatures > 30 K would involve fatal heat transfers to the droplets [3], the admitted gas is cooled to ≈ 14 K in a second channel system in the heat exchangers. Condensation in the second heat exchanger is avoided by a very slight adjustment of the temperature.

The volumes probed by the pressure control systems are, for practical reasons, at room temperature and separated from the actual cryogenic volumes of interest by the copper bead filled heat exchanger channels, where pressure drops occur. The capacitance gauges are accurate to below 1 %, an accuracy needed, at least for measuring the droplet formation region pressure. In order to avoid ambiguities this pressure is therefore measured separately, by-passing the heat exchanger channels, but, for the purpose of ensuring stable operating conditions, the pressure control system remains operating on the room temperature volume.

The cryogenic system is presently being assembled in Uppsala and hydrogen micro-sphere production studies are about to start.

Vacuum Injector Test Set-Up

General

The continuous injection of partially frozen hydrogen micro-spheres into vacuum is the first important problem to be studied. This is a crucial study with respect to the angular spread imposed on the pellet stream by the gas flow conditions in the vacuum injection nozzles.

The main strategy behind the design of the vacuum injection system has been to accept continuum gas flow conditions only in the first vacuum injection nozzle, where it is under any circumstances unavoidable, since close to the triple point pressure has to be maintained in the droplet formation region in order to avoid freezing of the liquid jet. This means, that the effects of the gas flow conditions on the micro-sphere trajectories are critical at just one location under well controlled initial conditions.

Vacuum System

The test set-up for vacuum injection studies (upper part in Fig.1) is a two-stage differentially pumped injector where the second stage also serves as a hydrogen pellet dump. In order to allow as large variety of vacuum injection nozzles as possible to be tested, the vacuum system is designed to permit quite large gas load rates in the high pressure end of the molecular flow region. For this purpose, anything but turbomolecular pumps are ruled out. Each differentially stage is thus equipped with two such pumps with total nominal pumping speed for hydrogen of 5.6 m^3/s. These pumps are backed with a 1000 m^3/h Roots blower together with a 120 m^3/h single stage rotary vane pump.

The vacuum conditions in the first diffe-

rentially pumped chamber is completely determined by the conductance of the first injection nozzle whereas the second chamber pressure is determined by the dumped pellet mass load rate ≈ 10^{-7} kg/s, giving a vacuum of a few times 10^{-2} Pa, rather insensitive to the exact dimensions of a reasonable sized second vacuum injection nozzle.

For the purpose of alignment, the rigid structure at cryogenic temperatures, including the liquid H_2 jet nozzle, is adjustable in position and angle relative to the first vacuum injection nozzle by a bellows arrangement. Observation of the exit of each vacuum injection nozzle is possible through observation windows in the vacuum chambers at these positions (Fig. 1).

First Injection Nozzle

The design requirements for this nozzle are, from the target injector point of view, that it should introduce as small angular spread as possible on the target trajectories, have reasonable outer dimensions and a continuum flow conductance low enough to allow continuous operation of the first stage turbomolecular pumps at molecular flow conditions.

As a result from a collaboration with the Älvkarleby Laboratory of the Swedish State Power Board, a design is now available for a nozzle with sonic (choked) flow at the outlet [3]. This nozzle has a smooth, 10 mm long, contraction region, with an inner diameter of 8 mm at the inlet, joined to a 50 mm long, straight cylindrical section having an inner diameter of 0.2 mm [3]. The shape of the contraction region has been determined by criteria given in [8].

The conducted hydrogen mass load rate to the first differentially pumped chamber, a few times 10^{-7} kg/s, is determined by the dimensions of the straight cylindrical section. The pressure in the chamber will then be a few times 10^{-1} Pa since the pumping speed of the turbomolecular pumps is reduced due to the poor vacuum.

The vacuum injector test set-up will be assembled summer-90 when the vacuum chamber manufacturing is completed.

Diagnostics Systems

High speed photography

A 0 - 1 MHz sine wave oscillator is used to drive the wide band amplifier, which excites the hollow cylinder piezo-electric transducer attached to the liquid jet nozzle. For droplet production diagnostics the synchronous square-wave, available from this oscillator, is fed into a digital frequency divider, reducing the frequency from ≈ 200 kHz to a time correlated frequency of < 50 Hz with a known, variable delay. These pulses are used to trigger the pulsed high voltage source of a spark gap flash lamp, giving ≈ 10 ns bursts of ≈ 15 mJ light. This method of illumination enables visual inspection of the liquid jet break-up process in a stroboscopic manner, using a microscope optionally equipped with a video camera.

If stroboscopic diagnostics of the micro-sphere vacuum injection is ruled out due to randomization of the micro-sphere appearances after the first vacuum injection nozzle, motorized film exposures will be employed, completely un-correlated to the droplet production, using a standard 36 mm camera attached to the microscope. The target velocities of ≈ 100 m/s will give an image diffuseness of ≈ 1 μm due to the flash duration while the time jitter contribution from the electronics is negligible. Statistics from the exposures will be used to deduce micro-sphere flow intensity profiles.

Laser doppler velocimetry

A more advanced and expensive diagnostics method is foreseen to be introduced later on. This type of diagnostics, Laser Doppler Anemometry (LDA), is based on the relative doppler shift of the scattered light from coherent laser beams, impinging on the micro-spheres at different angles with respect to their velocity vector. It will not only give continuous information on micro-sphere flow intensity profiles, but also on velocity distributions.

Hydrogen micro-sphere vacuum injection studies will start autumn-90.

References

[1] S. Kullander (Spokesman), "Wide Angle Shower Apparatus for CELSIUS," Proposal from the WASA Collaboration, Uppsala, Sweden, 1987

[2] C.A. Foster, K. Kim, R.J. Turnbull and C. D. Hendricks, "Apparatus for Producing Uniform Solid Spheres of Hydrogen," Rev. Sci. Instrum., vol. 48, pp. 625, 1977

[3] H. Tinoco, "Vacuum Injection System for Hydrogen Micro-Spheres in the CELSIUS Storage Ring," Swedish State Power Board, Älvkarleby Laboratory, Sweden, Report UL-90:10, 1990

[4] B. Trostell, "The Thermodynamics of Hydrogen Micro-Spheres as Internal Targets in Ion Storage Rings," in Proc. 1st European Particle Accelerator Conf., 1988, pp. 1424

[5] E.F. Goedde and M.C. Yuen, "Experiments on Liquid Jet Instability," J. Fluid Mech., vol. 40, pp. 495, 1970

[6] A.R. Hanson, E.G. Domich and H.S. Adams, "Shock Tube Investigation of the Break-Up of Drops by an Air Blast," Physics of Fluids, vol. 6, pp. 1070, 1963

[7] E.Y. Harper, G.W. Grube and I.-D. Chang, "The Break-Up of Accelerating Liquid Drops," J. Fluid Mech., vol. 52, pp. 565, 1972

[8] T. Morel, "Comprehensive Design of Axisymmetric Wind Tunnel Contractions," J. Fluids Eng., pp. 225, 1975