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Numerical investigations of the WASA pellet target operation and proposal of a new technique for the PANDA pellet target

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ABSTRACT

The conventional nozzle vibration technique of the hydrogen micro-droplet generation that is supposed to be used for internal pellet target production for the future PANDA experiment at the international FAIR facility in Darmstadtfor is described. The operation of this technique has been investigated by means of detailed computer simulations. Results of calculations for the geometry and operation conditions of the WASA pellet generator are presented and discussed. We have found that for every given pellet size, there is a set of operation parameters where the efficiency of the WASA hydrogen pellet target operation is considerably increased. Moreover, the results of presented computer simulations clearly show that the future PANDA pellet target setup can be realized with the use of much smaller (and cheaper) vacuum pumps than those used at present in the WASA hydrogen pellet target.

To qualitatively improve the PANDA hydrogen pellet target performance we have proposed the use of a novel flow focusing method of Gañán-Calvo and Barreto (1997,1999) [28,30] combined with the use of conventional vacuum injection capillary. Possibilities of this approach for the PANDA pellet target production have been also explored by means of computer simulations. The results of these simulations show that the use of this new approach looks very promising and in particular, there is no need here to use of expensive ultra-pure hydrogen to prevent nozzle clogging or freezing up due to impurities and it will allow simple, fast, smooth and a wide range of change of pellet sizes in accordance with requirements of different experiments at the PANDA detector.

In this article we also propose and describe the idea of a new technique to break up a liquid microjet into microdroplets using a process of liquid jet evaporation under pulsed laser beam irradiation. This technique should be experimentally checked before it may be used in the design of the future PANDA pellet target setup.

1. Introduction

A high thickness internal hydrogen target is required for strong interaction studies in the PANDA (Antiproton Annihilation at Darmstadt) experiment (see e.g. Refs. [1,2]) that will be installed at the High Energy Storage Ring (HESR) [3] for antiprotons that is under construction at the international FAIR facility [4]. To achieve in the PANDA experiment the design luminosity of $2\times10^{32}\,cm^{-2}\,s^{-1}$, an effective internal target thickness of 4×10^{15} atoms/cm^2 is required. The following two types of internal hydrogen beam-targets are under development. They are a cluster-jet target and a pellet target. The cluster-jet target consists of hydrogen clusters (nano-sized particles composed of 10^3–10^5 weakly bounded hydrogen molecules), which are produced under a supersonic gas expansion into vacuum through a nozzle having a long narrow diverging supersonic part, when gas stagnation conditions are near those of condensation. Operation and design of this type of internal targets are described in detail elsewhere (e.g. see Refs. [5–8]) and they are out of the scope of the present article.

The pellet target will consist of a chain of frozen hydrogen micro-spheres, which pass in vacuum through the circulating beam of antiprotons in HESR ring and are then evacuated by pumping downstream.

Let us describe in short a process of pellets production as realized nowadays in the existing installations [9–16]. A thin liquid hydrogen jet is produced by pressing cooled liquid hydrogen through a miniature converging nozzle into so called droplet formation chamber (DFC) filled with a buffer gas (helium or hydrogen) at low pressure. This liquid jet is broken up into uniformly sized and spaced micro-droplets by means of acoustic vibration at ~10–150 kHz applied to the nozzle with the use of a piezo-electric transducer. Then the liquid hydrogen droplets, whose diameter is about twice as much as the jet diameter, are extracted into vacuum by passing them through a long thin vacuum injection capillary (VIC) [9,13] via the

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buffer gas flow. Behind the capillary exit the buffer gas expands into vacuum as a supersonic gas jet; the gas temperature, pressure and density in this gas jet drastically decrease and as a result of liquid droplet surface evaporation they transform to frozen micro-spheres (called pellets). The pellet size is less than the original droplet size due to the evaporation and the hydrogen density change from liquid to solid. For example, it is expected [11] that for a pellet with a diameter of 33 μm the corresponding droplet diameter will be about 39 μm. Downstream of the VIC a skimmer [11] (or 2nd sluice [13]) is installed on the gas-jet axis. It serves as a pellet-beam collimator and allows for the use of differential pumping meeting vacuum requirements in the storage ring.

To get a maximal stored antiprotons use and to have smoother counting rate distributions at the PANDA experiment the size of pellets and a mean distance between pellets at the interaction point should be minimized.

2. Numerical investigation of the WASA pellet target operation

2.1. General description

At present three hydrogen pellet-target systems exist in the world and only one of them—the WASA pellet target system developed at the Svedberg Laboratory (TSL) in Uppsala, Sweden—has been used for taking data in storage ring experiments. This pellet target, which is described in detail elsewhere [9–12,15,16], is presently installed in the COSY-ring at Jülich, Germany. The second pellet-beam generator called Uppsala Pellet Test Station (UPTS) is a copy of the WASA pellet target and it has been constructed also at TSL as a testing facility. The third pellet target setup [13,14] called "Moscow- Jülich pellet target" has been built at the IKP of FZJ at Jülich in collaboration with ITEP and MPEI institutes from Moscow. The main characteristics of the WASA hydrogen pellet target are listed in Table 1 (Ref. [16]).

Notice that the pellet rate in Table 1 is the number of pellets per second crossing the interaction point. The total transmission efficiency of the pellet beam through the VIC and the skimmer is about 11% for the WASA pellet target (see e.g. Refs. [1,11]): about 50% of droplets produced in the DFC do not pass through the VIC and then about 79% of the pellets passed through the VIC are skimmed off because of too large angular spread of the pellet beam.

The effective pellet target thickness t_{eff} can be defined as

$$t_{eff} = \frac{\rho_p \Omega_p}{x_p w} = \frac{\pi \rho_p d_p^3}{6 x_p w} \quad (1)$$

where ρ_p=87 kg/m^3 is solid-hydrogen density, Ω_p and d_p are the pellet volume and diameter, respectively, x_p is the average distance between pellets, which can be determined as the ratio of the pellet velocity to the pellet rate and w is the full width of the pellet beam at the interaction point (it is determined by the VIC–skimmer system geometry and the distance from the skimmer to the interaction point). Substituting the values from Table 1 in formula (1) one obtains that $t_{eff}=4.1\times10^{15}$ atoms/cm^2. This value of the effective target thickness suits the PANDA experiment, but due to the large granularity (the large pellet diameter d_p and the large average inter-pellet distance x_p) this pellet target does not satisfy the requirements for the PANDA detector operation.

Table 1
Performance of the WASA hydrogen pellet target [16]

Pellet diameter	30 μm
Pellets rate	10,000 s^{-1}
Pellet beam divergence	1 mrad
Pellet beam diameter	2 mm
Pellet velocity	90 m/s
Average distance between pellets	9 mm

Unfortunately there are no published data on the t_{eff}, x_p and pellet rate values at the interaction point (or at about 2.3 m distance from the nozzle) for the Moscow–Jülich pellet target, so we cannot compare its performance with that for the WASA pellet target.

Various factors (e.g. the VIC geometry and its distance from the nozzle, the liquid jet velocity and the droplet diameter, the buffer gas pressure, temperature and velocity flow fields in the DFC and in the region behind the VIC exit) strongly affect the performance of the pellet target. But it is not possible to measure in detail the droplet trajectories in the DFC and inside the long narrow VIC and it is very difficult to find an optimum set of design parameters and operation conditions for the pellet target setup only by an experimental approach. This is why detailed computer simulations of the pellet target operation for various VIC geometries, liquid jet velocities and buffer gas conditions are very important.

We explored the operation of WASA pellet generator by means of computer experiments. For this purpose detailed gas dynamic simulations of buffer gas flow have been performed using our VARJET code. This code is based on the solution of a full system of time-dependent Navier–Stokes equations for multicomponent gas mixtures and it is described in detail in Ref. [17]. It has been carefully checked and we have successfully used it for development of radioactive ion beam buffer gas cooling techniques [18–22], supersonic internal gas-jet targets production [23,24] and for development of a focused ion beam source of a new type for micro- and nanoelectronics technologies [25], as well.

Results of the gas dynamic calculations (flow fields of the buffer gas density, temperature and velocity) have been used for detailed droplet trajectory simulations. At operation conditions of the WASA pellet generator the hydrogen droplet sizes are much larger than the mean free pass values of the buffer gas molecules. Therefore, the droplet dynamics in the buffer gas flow can be described in the framework of continuum theory, where droplets move in the buffer gas under the action of a viscous drag force. In the region downstream of the VIC exit, where buffer gas density drastically decreases due to the supersonic gas jet expansion, the continuum theory is corrected by a rarefaction factor (see Eq. (3) below).

In trajectory simulations we used the following expression for the drag force $\vec{F}_D$ on a spherical particle (in our case it is a droplet) of diameter d_d in the gas [26]

$$\vec{F}_D = -\frac{1}{8}\pi d_d^2 \rho_{gas} |\vec{V}_{rel}| \vec{V}_{rel} \frac{C_D}{C_c} \quad (2)$$

where $V_{rel}=V_d-V_{gas}$ is the relative velocity between the droplet velocity V_d and the buffer gas velocity V_{gas}, ρ_{gas} is the buffer gas density, C_D is the drag factor, whose expression depends on the local Reynolds number of the particle in the buffer gas flow (see for details Ref. [26]), and C_C is the Cunningham rarefaction correction, which can be written as [26]

$$C_c = 1 + \frac{2\lambda_{gas}}{d_d}\left[1.257 + 0.4\exp(-0.55 d_d/\lambda_{gas})\right] \quad (3)$$

where λ_{gas} is the mean free pass of the buffer gas molecules.

Inside the VIC the buffer gas velocity distribution across the capillary has a parabolic shape with a maximum value on the axis (a classical Poiseuille flow). It means that the buffer gas velocity value on the side of the droplet towards the axis is higher than that one towards the capillary wall. So, due to Bernoulli's law there is a force F_B that compels the droplets to move to the axis:

$$F_B = \frac{1}{4}\pi d_d^2 \rho_{gas} |V_{rel}| \Delta V_{gas} \quad (4)$$

This Bernoulli's force is proportional to the buffer gas density, the droplet cross-section, the relative velocity V_{rel} and the