Pellet Production Methods for Fueling Fusion Devices

Review

W. Riedmüller[+]

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Abstract

A review is given of the methods developed for producing and positioning hydrogen isotope pellets which are used for filling magnetic confinement machines.

Composite pellets used in inertial confinement (i. e. laser fusion) experiments are not considered in this review.

Introduction

A review is given of the methods proposed and used for producing and positioning hydrogen pellets of interest for hot filling (with lasers) of magnetic bottles and for cold refuelling of fusion plasmas. Pellets for laser fusion, which usually are composed of layers of different materials, are not considered.

A (somewhat arbitrary) distinction can be made between three different ways of producing pellets from pure hydrogen isotopes:
In punch-type sources just as much hydrogen is condensed as is required for a pellet; the latter is shaped to form a cylinder and then punched from the condensation vessel with a needle.
In extruder sources a larger quantity of hydrogen than needed is condensed, then compressed and extruded through a nozzle. During or after extrusion single pieces are mechanically or thermally separated from the string to provide pellets.
Whereas these two methods allow the pellets to be produced in vacuum, droplet sources use hydrogen in the liquid phase so that in this case the pressure has to be at least approximately equal to the triple-point pressure (for H_2 54 torr, for D_2 133 torr). Single droplets can now be formed in various ways. These have to be introduced into the vacuum. In the process a small part of the droplet evaporates so that heat is lost and the droplet freezes.

The majority of pellet sources have hitherto been built in connection with the production of laser plasmas for filling magnetic field configurations. Summaries of some early work on pellets for this purpose are to be found in Witkowski /1/ (1971) and Friedman et al. /2/ (1974). Here pellets made of materials other than hydrogen are also treated, but we shall confine attention to those made of pure H_2 and D_2.

With laser pellets it is essential to position them with great accuracy at the laser focus. This has been achieved in two ways: by reducing the scatter of the trajectories of the pellets and/or developing suitable methods of guiding the pellet or laser focus.

For pellets for cold refuelling the two properties mentioned (pure hydrogens and exact positioning) are also of interest. In addition, it is required in this case that the repetition rate be high (up to several

hundred Hz for refuelling tokamaks of the next generation), and that the pellets be larger ($\sim$ 1 mm^3) than those needed hitherto for laser experiments.

1. Punch-type sources

It is interesting to note that the first pellet source ever built already accelerated the pellets to the considerable velocity of 200 - 300 m/s. (The "Hot Ice" Experiment: Ascoli-Bartoli et al. /3/ (1965), Decchini et al. /4/ (1969)). Deuterium was condensed in a He-cooled capillary tube and compressed between a detachable stopper at the bottom end and a needle inserted from above. Pushing the resulting pellets from the tube was a problem: At first this was done by igniting above the capillary tube a spark discharge - supplied from a 15 nF capacitor charged to 13 kV - to produce a fast pressure rise. This unintentionally gave rise to the first light gas gun for D_2 pellets, but owing to the high pellet velocity it was useless for the laser experiments concerned. It was therefore decided to punch the pellet out with a needle; as the pellet then adhered to the needle, it was detached by heating the needle either by irradiation with an intense light source or by means of a high-frequency coil. This yielded cylindrical D_2 pellets with a diameter of 0.25 mm, a length of approx. 0.25 mm, an initial velocity of a few m/s, a scattering angle of 1.5 x 10^{-2} rad and a repetition rate of approx. 1/min.

This method was further perfected in Japan (Hirosawa /5/ (1969), Tanimoto et al. /6/ (1972), Kitsunezaki et al. /7/ (1975)) by introducing an exact control of the temperature and temperature profile of the needle. It was thus possible to evaporate an exactly defined part of the pellet at the tip of the needle so that the rest of the pellet could drop with much less scatter ($\sim$ 2 x 10^{-3} rad) provided the evaporation process was sufficiently slow. The pellet dimensions were either 0.1 ø x 0.2 or 0.4 ø x 0.6 mm.

Another way of producing pellets was used by Krause et al. /8/ (1970) in their punch-type source. In the bore of a cooled plate which at first was separated from the vacuum by a detachable bell, they condensed H_2 in liquid form; by further cooling the hydrogen was frozen and pushed

from the bore by means of a needle. Here, again, the main problem was detaching the pellet from the needle. A slightly heated guide tube placed beneath the bore did reduce the scatter but could not suppress it altogether. The pellet trajectories were located on a hollow cylinder (aperture angle 2,5 x 10^{-2} rad) whose tip was placed at the bottom end of the guide tube. The pellet dimensions could be varied by setting the filling pressure between 0,08 ø x 0,16 mm and 0,05 ø x 0,05 mm.

In a similar manner Milora et al. /9/ (1978) filled the bore in the pellet holder of their gas gun with pellet material: first in liquid from, which was then solidified by further cooling.

As hydrogen undergoes appreciable volume contraction on transition from the liqiud to the solid state (12 % between 14 K and 4.2 K), it is difficult with this method to fill the space for the pellet completely with compact material. This complication is avoided in extruder sources.

2. Extruder sources

Solid hydrogen is a rather soft material. According to measurements of D.N. Bol'shatkin /10/ (1970) et al.: the mechanical strength of D_2 has a flat maximum at 4.2 K. Above this temperature hydrogen is more plastic, while below it tends to be more brittle. It should be noted, however, that the grain size of the sample investigated was relatively large (1-2 mm) and the forzen hydrogen can be present in different crystal forms (A.F. Schuch et al. /11/ (1966)).

Hydrogen has been used on various occasions as pressure transmitting medium for high-pressure investigations at low temperatures (Hatton /12/ (1955 and 1956)).Steward /13/ (1954) has measured the pressures needed to extrude solidified hydrogen through a small hole, to obtain a qualitative estimate of its shear strength. The absolute values of the extrusion pressures observed - these being defined as those at which relatively rapid flow through the hole took place, namely 24 bar for H_2 and 29 bar for D_2, in each case at 4.2 K - have little absolute significance. They depend upon on a number of other parameters, such as sample length, aperture angle of nozzle, viscosity, and the ratio of the sample diameter d_1 to the nozzle diameter d_2 in the form

$\ln (d_1/d_2)^2$ (see for instance Wyatt and Sho-Hughes /14/), presumably on the degree of purity as well and on the ortho-para composition. Similar measurements were made by Towle (1963) at higher pressures. Towle observed the extrusion of hydrogen from one pressure chamber into another with somewhat lower pressure. Unlike other solidified gases, solid hydrogen tends to unstable extrusion which often leads to abrupt loss of the entire sample. Stewart assumed that extruding hydrogen through the ring-shaped slit between the piston and cylinder generates so much heat that all of the hydrogen melts. This was later prevented by a kind of piston ring made of metallic potassium. Despite this precaution Towle reports an almost "explosive" flow of hydrogen from the one pressure chamber to the other as soon as the hydrogen gets completely into motion for the first time. The cause of this is not yet clear.

For laser experiments a number of extruders with circular and rectangular nozzle cross-sections ranging from 0.3 to 2 mm in diameter have been built, no diffifulty in extruding hydrogen having been reported: Saunders et al. /16/ (1967), Bobin et al. /17/ (1969), Krause /18/ (1972/73).

Friedman et al. /2/ (1974) were the first to notice the strong dependence of the extrusion process on the temperature of the ice. The extrusion appears to depend more critically on the temperature than the mechanical strength measurements of Bol'shutkin et al. /10/ (1970) would lead one to believe. Friedman did not extrude by shifting the piston but by fixing it and raising the temperature instead.

Baumhacker et al. /19/ (1976) extruded in a similar mannner, but they applied to the piston an additional, constant force which at the piston diameter of 4 mm used was equivalent to a pressure of several hundred bar; nevertheless it was not possible to extrude the hydrogen at temperatures of up to approx. 7 K. The extrusion rate then quickly increased with rising temperature and was again immediately stopped by reducing the temperature to below 7 K. When the temperature rose above 11 K the entire hydrogen was lost. This may possibly be due to the unstable extrusion already mentioned, but perhaps it is merely caused by the isolation vacuum of the croystat being destroyed as a result of the high vapour pressure of hydrogen at these high temperatures, so that the croystat heats up, thus melting the hydrogen.

Pellet production with extruders

In Cluham (Francis /20/ (1967), Taylor /21/ (1969)) first a flat strip of solid hydrogen was produced with an extruder and then single pellets were punched from it with a needle. The observed scattering angle of the pellets was relatively large (3×10^{-2} rad), but it was possible to raise the repetition rate to 1 pellet every 15 s. This system seems to be capable of improvement for much higher frequencies.

The Culham pellet source was used later for injecting 0.25 x 0.25 mm pellets at a velocity of $\sim$ 10 m/s into the Puffatron discharge in Risø (Jørgensen /22/ (1974)). In the Garching pellet source (Baumhacker et al. /19/ (1976) and Riedmüller et al. /23/ (1976) the bottom end of a cylindrically extruded deuterium ice stick is cut off by irradiating it with two parallel heated wires normal to the stick axis until so much stick material is evaporated that the pellet is just hanging by a thin D_2 thread. With a sufficiently long cutting time ($\sim$ 10 s), a suitable temperature ($\sim$ 10 K) of the cryostat and careful adjustment of the cutting wires the oscillation of the pellet suspended by the wire is damped until it breaks off and can drop with an extremely small scattering angle (2×10^{-4} rad).

This method of pellet production was also adopted by Spaling /24/ (1978) and Greig /25/ (1978) for producing laser plasmas, and by Amenda et al. /25/ for injecting free-falling pellets into the tokamak Pulsator, and is being used at present in Garching to supply a centrifugal acceleration device with single pellets (Lang /26/ (1978)).

In principle, however, this method only allows production of single pellets with a low repetition rate (1/min, possibly up to 10/min if the scattering angle of the pellet is not important).

Foster and Milora (1977) have porposed that the pellets for the Oak Ridge centrifuge also be produced by means of an extruder: During extrusion one or more rotating blades (either coupled direct with the centrifuge or mounted on a separate disc) continuously cut off single pieces from an ice stick just below the nozzle. In both cases the extrusion rate has to be matched exactly to the frequency of the blade(s) (in the design 60/s) and kept constant to maintain a certain pellet length. So far no results have been published. The possibility of using this method for

the desired higher repetition rates of 100 - 500 /s as well will depend on whether the necessary extrusion rates of 0.1 - 0.5 m/s can be achieved and the above mentioned difficulties in extruding hydrogen can be avoided.

It is perhaps simler to modify Foster and Milora's proposal by prefabricating an ice stick, then advancing it in a controlled manner and cutting it up in pieces.

The light gas guns at Garching and Risø were also developed on the basis of extruders: A piece of extruded deuterium is taken by a rotating plug and aligned in front of the gun barrel, which is placed perpendicular to the extrusion direction (Riedmüller /28/ (1978)). At Risø /29/ a pellet is punched from the extruded material with a hollow cylinder and moved coaxially in front of the gun barrel.

Liquid-solid extrusion

A completely different type of extrusion was applied by Jarboe and Baker /30/ (1973) which has a certain affinity with the liqiud sources of the following section: A liquid jet emerges from a nozzle into a region with a pressure below the triple point of the liquid. If the pressures, temperature and mass-rate are properly chosen, the jet already freezes in the nozzle. In this way Jarboe et al. succeeded in producing a 50 μm thick deuterium thread at a velocity of 4 mm/s. The nozzle diameter was 70 μm, the pressure above the nozzle a few hundred torr, while the pressure below the nozzle could be reduced to 10^{-4} torr. By means of a 25 μm tungsten wire moved perpendicularly across the deuterium thread by a 250 Hz loudspeaker coil they cut it into 50 μm long pellets. It took many cuts to cut right through the thread. Comparing the extrusion rate and the length of the pellets produced with the given production rate of 10 pellets per sec, it is found that almost ten times as much material is evaporated on cutting as is contained in a pellet. The pellets were collimated with a funnel and guided with a tube in the direction desired. About 60 pellets were required to hit the desired location once (the laser focus 10 cm below the guide tube).

Turnbull et al. /31/ (1977) took the extrusion possibility found by Jarboe and investigated it in an extended parameter range. Whereas

Jarboe needed a strongly converging nozzle shape, Turnbull appears to use elongated glass nozzles such that the jet diameter is equal to the thread diameter is equal to the nozzle diameter. Turnbull, too, obtained stable extrusion of a frozen hydrogen thread at nozzle diameters of 51 and 33 µm but not at 70 and 90 µm. As with Jarboe, the input pressure had to exceed the equilibrium pressure of the liquid (a few hundred torr, depending on the temperature) to avoid two-phase flow (liquid and gaseous); the pressure in the extrusion chamber, on the other hand, could only be reduced slightly below the equilibrium value (43 torr for the 51 µm nozzle and 30 torr for the 33 µm nozzle, in both bases at 13.9 K, the equilibrium pressure here being 54 torr) without the nozzle freezing up completely and blocking further extrusion. This difference can possibly be accounted for by the use of different nozzle shapes and/or nozzle materials of different thermal conductivity. The question arises whether this method can be extended to jet diameters of about 1 mm, i.e. by a factor of 20. This involves a number of complications: Besides the technical problem of handling such large mass flows being pumped and of controlling them with the necessary accuracy, the surface, and hence the extracted evaporation heat per unit length of the jet, just increases as the square of the radius. The speed of the jet, however, is largely governed by the pressures required above and below the jet. In addition, the region of presumably turbulent flow is quickly reached as the radius increases. At a nozzle diameter of 33 µm already Turnbull gives a Reynolds number of 4000, which is typical of the transition region. With Jarboe the extrusion appears to be much more complex than would be expected from freezing a free liquid jet. This is already obvious from the fact that the velocity of 4 mm/s actually observed is more than two orders of magnitude smaller than that of a free (non-viscous) liquid jet. It remains to be seen whether it will be possible under these circumstances to extrude an ice stick approx. 1 mm in diameter at a controlled rate of up to 0.5 m/s in order to achieve the high pellet frequencies required.

Droplet source

The physics of droplets has a history of more than 150 years. There are numerous application possibilities covering such different fields as the investigation of atmospheric phenomena, fuel injection, ink printers, spinning of synthetic fibres, space propulsion systems, electrical spraying

and fusion fueling systems, whether for hot filling (with lasers) of magnetic field configurations or for cold refuelling of plasmas in fusion research. The result of this has been that a number of generators have been developed which provide droplets with excellent reproducibility, shape, size, separation,and different frequencies. Pellets for fusion research, of course, involve the additional difficulty that the droplets have still to be introduced into the vacuum.

The large majority of droplet sources (Dabora /32/ (1967) gives a list of those described up to that time) are based on controlled division of a liquid jet into single droplets. There are, however, a number of other methods of producing droplets:

Powell /33/ et al. (1968) condensed liquid hydrogen on the surface of a body connected with a crystal driven at its resonance frequency of 125 kHz. This causes the liquid at the lower end of the body to disperse as a fine mist. The formation of the mist droplets is attributed to break-up of large-amplitude surface tension waves, in which case the droplet size should vary as $(\text{frequency})^{-2/3}$. In this special case the diameter was 15 μm. It is not clear whether and how these droplets can be introduced into the vacuum and whether much larger droplets can also be produced.

Apart from dividing a jet into droplets, this was the only experiment in which hydrogen was used in liquid form. It is useful here, however, to describe the droplet sources not hitherto operated with hydrogen in order to see whether they are suitable for operation with hydrogen.

The simplest way is to let a liquid drip from a vertical capillary tube (Lane /34/ (1947)). The liquid is at a pressure just above that needed to overcome the surface forces. The droplet breaks off when its weight G is sufficient to overcome the surface tension T. The situation is given approximately by the relation $G = 2\pi r T$, where r is the radius of the horizontal cross-section at the point of contraction, which is a little smaller than the radius of the capillary tube, and T is the surface tension. With, for example, an 80 μm thick capillary tube it thus follows that a D_2 droplet 1 mm in diameter should form. The droplet frequency depends on the mass flux, but is only a few Hz. To attain higher frequencies, it is necessary to apply an additional force. There are several possibilities here:

One kind of device involves blowing water droplets from the needle tip by an intermittent air flow concentric with the tip of the needle capillary (Lane /34/ (1947), Reil et al. /35/ (1969), Samuels /36/ (1973)).

Ink jet printers have been developed (Kamphoefner /37/ (1972)) which propel a single droplet from a nozzle each time that a pressure pulse is applied to an ink reservoir. The droplet size is determined by the nozzle diameter and the energy of the driving pulse. The device could be operated between single pellets and 8 kHz.

Another type of droplet source utilizes electrostatic forces (Hendricks /38/ (1962), Taylor /39/ (1969), Scott et al. /40/ (1968), Melcher et al. /41/ (1970), Kim et al. /42/ (1975) cite a complete reference list). The surface of the dripping liquid is electrically charged - with liquids that are at least slightly electrically conductive this is done simply by induction in an applied electric field or, if the electrical conductivity is not sufficient for the purpose as is probably the case with liquid hydrogen, by field emission from a needle tip placed in the liquid (Woosley et al. /43/ (1976)). If some electric field is applied, the frequency of the droplet emission increases and the droplet becomes smaller in diameter. At higher fields a small jet stabilized by electrostatic forces (Melcher /40/) forms at the lower end of the droplet. At still higher fields the liquid meniscus constricts to a long column, decreasing in diameter until it is small enough to become unstable again, and breaks up into small droplets. The critical value for the jet diameter is $\xi_C = (4\varepsilon_o \, TQ^2/I^2)^{1/3}$, where Q is the volume flow rate and I is the electric current in the jet (Melcher /41/, Kim /42/) and is usually at very low values of below 50 µm. The advantage of this method is that it is possible with a single nozzle to vary the droplet diameter over a wide range (20:1, Raghupathy et al. /44/ (1969)). Apart from the very small droplets which are probably only suitable as laser targets, the repetition rates are rather low. Experiments with hydrogen are planned (Turnbull /31/ (1977)), but no results are yet known.

For the sake of completeness, mention should be made of the droplet source of Wolf /45/ (1961) and later Abbott et al. /46/ (1972): If a wire is pulled rapidly out of a fluid, it pulls a filament of fluid from the surface. When the filament reaches a certain length, it will break off at the ends and contract to form a droplet. The size of the

droplet is determined by the diameter of the wire, the angle between the wire and the fluid surface, and the depth of penetration of the wire into the fluid. In this way, water droplets with radii of 4 to 130 µm and with rates of up to 100/s for the smallest size have been produced. A charge was induced on each droplet by applying an electric field.

Controlled breakup of a liquid jet into droplets

Devices for producing streams of uniform drops from liquid jets are based on the experimental observations made by Savart /47/ in 1833 upon breakup of liquid jets and on Rayleigh's /48/ analysis of the instability of capillary jets. It can be shown that whenever the wavelength of a disturbance in the jet is greater than the circumference of the jet the surface decreases, hence the surface tension tends to produce instability. Rayleigh showed that the wavelength λ_m for maximum instability is related to the jet diameter d by

$$\lambda_m = \pi\sqrt{2} \cdot d$$

Introducing the jet velocity v and frequency $f_m = v/\lambda_m$, one gets the optimum frequency of a disturbance

$$f_m = \frac{v}{\pi\sqrt{2} \cdot d}.$$

When the jet is mechanically disturbed at such a frequency, drops of uniform size are formed. According to Schneider and Hendricks /49/ droplets of uniform size can still be produced within a range of such that

$$3.5\ d < \lambda < 7\ d.$$

droplet diameter at the optimum frequency is $D = 1.89 \cdot d$. The velocity of the jet has to be chosen within certain limits. The minimum velocity necessary to form a jet can be found from an energy consideration. According to Windblad and Schneider /52/ (1965) the rate of energy flow into the jet from the capillary tube must be greater than the amount of energy per unit time required to create the jet surface, hence

$$v > 2\left(\frac{T}{d \cdot \varrho}\right)^{1/2},$$

which is 0.3 m/s for the example of a deuterium jet 1 mm in diameter. In order to avoid uncontrolled breakup of the jet, it might be necessary to restrict the Reynold number of laminar flow values:

$$Re = \frac{dv \cdot \varrho}{\eta} < Re_{cr}.$$

Assuming $R_{cr} \approx 3000$, the upper limit for the velocity of a D_2 jet 1 mm in diameter would be as low as 1 m/s.

Another jet breakup regime exists where the boundary is defined by the Weber number (ratio of inertial force of the background gas to jet surface tension force)

$$We = \frac{v^2 d}{T} \lesssim We_{cr} \sim 10$$

beyond which the jet begins to atomize. However, there is experimental evidence /51/ that individual nozzle geometry and jet turbulence can have a stabilizing influence on jet integrity.

Hendricks and his group /52, 53/ were the first to succeed in producing liquid-hydrogen pellets 7o and 210 μm in diameter at a rate of 10^5/s and 2.6 x 10^4/s respectively. The drops were frozen by evaporation at a pressure slightly below the triple-point pressure of hydrogen. A small number of pellets were injected into vacuum by using one or two fast gate valves and accelerated by gas dynamic drag to a velocity of 100 m/s. This pellet generator has been used to perform pellet ablation experiments in the Ormak tokamak at Oak Ridge National Laboratory /54/.

Four major problems have to be solved if a droplet generator is to be considered as the pellet source for refuelling tokamaks of the next generation:

1) Larger pellets, typically 1 mm in diameter, will be necessary.

2) The trajectories of the droplets (which were strongly disturbed during vacuum injection) have to be controlled.

3) Steady or quasi-steady operation of the pellet injection has to be established.

4) The pellet generator must be coupled with some other accelerator since the acceleration by gas dynamic drag utilizing the difference between triple-point pressure and vacuum is very limited.

The feasibility of such a droplet generator has been demonstrated in Livermore /55, 56/, where a complete ammonia pellet generation system for the Baseball II-T laser target plasma experiment has been built.

For large hydrogen pellets the possible operating parameters still have to be found. Generators for hydrogen pellets 600 μm and 500 μm in diameter are now being investigated at IPP Garching /57/ and at the University of Illinois /31/.

A somewhat different method for producing a limited number of ice pellets, called "electric curtain" method, has been proposed by T. Sekiguchi and S. Masuda /58/. This method consists of the following steps:

1) generation of liquid droplets
2) charging of the droplets
3) suspension of the droplets in an electrostatic field
4) freezing of the droplets by evaporation
5) transfer into high vacuum
6) injection into reactor.

The method is being investigated at present by Mitsubishi Atomic Power Ind. Inc. with simulation gases of oxygen and argon.

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