# IPP-Report

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## Content

# 1. Introduction

In the past years pellets of solid Deuterium have been injected into several tokamaks, stellarators and reversed field pinches to refuel or to diagnose the plasma [1]. The diameters of the applied pellets are in the order of one millimeter. The velocities range from hundred m/s to more than two thousends m/s. The pellets were accelerated by gas pressure, by centrifugal forces or by friction in gas flows. After acceleration the pellet path is straight, thus the injector has to be in line of sight of the plasma. However the access to the plasma device is very limited by technical reasons. This led to the idea to transfer cryogenic pellets of temperatures near liquid Helium temperature through guide tubes of room temperature. Also injection of pellets from the inner side of the torus into the plasma demands the usage of a guide tube. The pellets stay just for a short time in the tube and therefore they are able to survive the "hot" surrounding. In a first experiment was shown that pellets with velocities up to 700 m/s could be launched successfully through a straight glass tube of 2 m length into the stellarator W7A [2]. A guide tube is also mentioned early at the Risø tokamak Dante [3]. This new technique is described in several publications [4 - 12].

In this report we describe investigations of the transfer of pellets of speeds up to more than 1 km/s through straight and curved guide tubes of different lengths and diameters. The loss of pellet mass and velocity as well as the increase of the stray angle will be investigated. The limitations of guiding as a result of the strength of solid Deuterium will be discussed. Undesired flow of propellant from gas guns to the plasma can be effectively suppressed by guide tubes. Also we will discuss two models for the transfer of pellets through tubes of different diameters.

The experiments described in this report are done in the years 1982 to 1986. In 1998 new experiments concerning guiding of pellets in curved guide tubes are made by A.Lorenz and Coworkers in IPP Garching [15].

# 2. Experiments

## 2.1 Experimemtal Arrangement

The experimental setup consists of a pneumatic pellet gun, the guide tube to be investigated, and a test chamber [fig.1]. The Deuterium pellets were produced in a liquid Helium cooled extrusion cryostat [10] and was accelerated by Hydrogen gas of room temperature as a propellant. Applying gas pressures of 0.5 - 4 MPa (5 -40 bar) the pellets reach velocities of 400 to 1600 m/s. At the exit of the gun barrel the trajectories of the pellets have stray angles of about 0.25 degree. The temperature of the pellets is about 4 K. The pellets are photographed with a flash light and their velocities are measured using light barriers. The pressure jump caused by the propellant in the vacuum chamber between barrel and guide tube is measured with a fast pressure gauge. Together with the pellet a dense cloud of gas and small particles presumably of solid Hydrogen leaves the barrel [fig.2].



Fig.2 Pellet leaving the barrel of the gas gun (right)
Left: Entrance of the guide tube

But this material spreads out very fast and is stripped from the pellet at the entrance of the guide tube. The guide tube is not cooled to cryogenic temperatures, but is at room temperature. Guide tubes of different diameters, lengths, and curvatures were investigated including tubes with additional openings for pumping. In a first series of experiments tubes of teflon, glass, copper, and stainless steel with different roughnesses of the inner surface were compared, however no essential difference was observed. Therefore all following measurements were carried out with stainless steel tubes. The inner surfaces of the tubes are cleaned simply with a paper plug, but no chemical cleaning or polishing was applied. When the pellet leaves the guide tube it will be detected by several methods. The velocity is measured by ligth barriers. The pellets are photographed with a flash light of 100 ns duration. The angle of the pellet path was recorded with a target of paper, which was punched by the pellet. The increase of gas pressure in the test volume caused by the evaporating pellet and the propellent flowing through the guide tube was observed with pressure gauges as well as with a mass spectrometer to distinguish between the Deuterium of the pellet and the Hydrogen of the propellant gas.
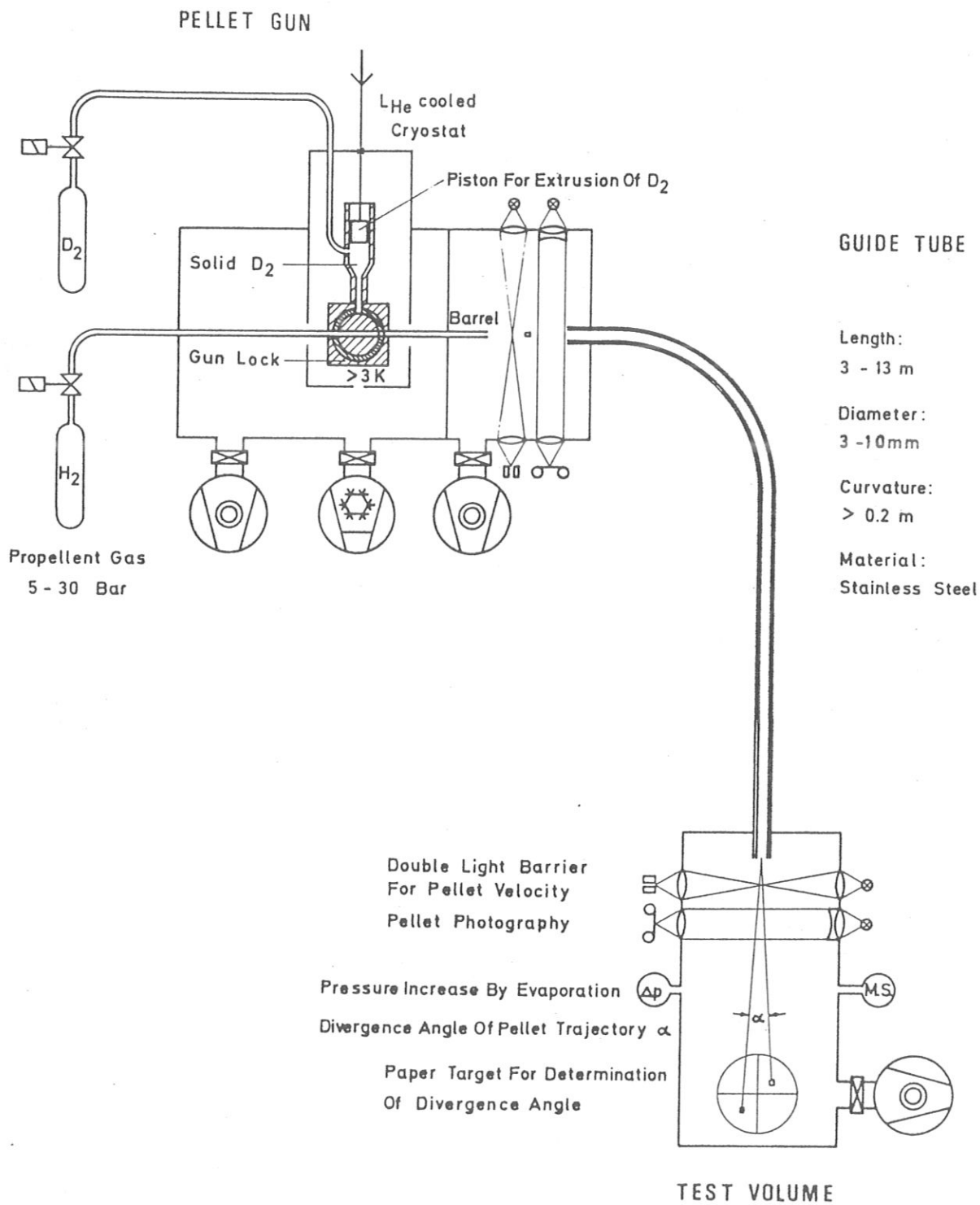
Fig.1 Experiment to investigate curved and straight
guide tubes

## 2.2 Experimental Results

### 2.2.1 Pellet Velocity

The velocity of the pellet will be changed due its interaction with the wall of the guide tube. The velocity is measured before and after passing the guide tube by double slit light barriers [fig.1]. The pellet is imaged onto the slits. The accuracy of the determined velocity is given by the errors of the magnification of the pellet image, the distance and size of the fiber slits, and the error of the time measurement. Further errors arise by the rotation of the pellet, and an oblique trajectory. The statistical error of the measured velocities is 5%. Both light barriers show a systematic difference of 9% arising from the mentioned errors measured by free flying pellets. This difference was corrected in the plots, because the absolute velocities are not important in our investigations. We are interested in relative changes due the guide tubes. The measured pellet velocities range from 400 m/s to 1600 m/s. The velocity of the pellet after leaving the guide tube is plottet versus its velocity before entering the guide tube [fig.3]. In this plot guide tubes with different curvatures, diameters, lengths of
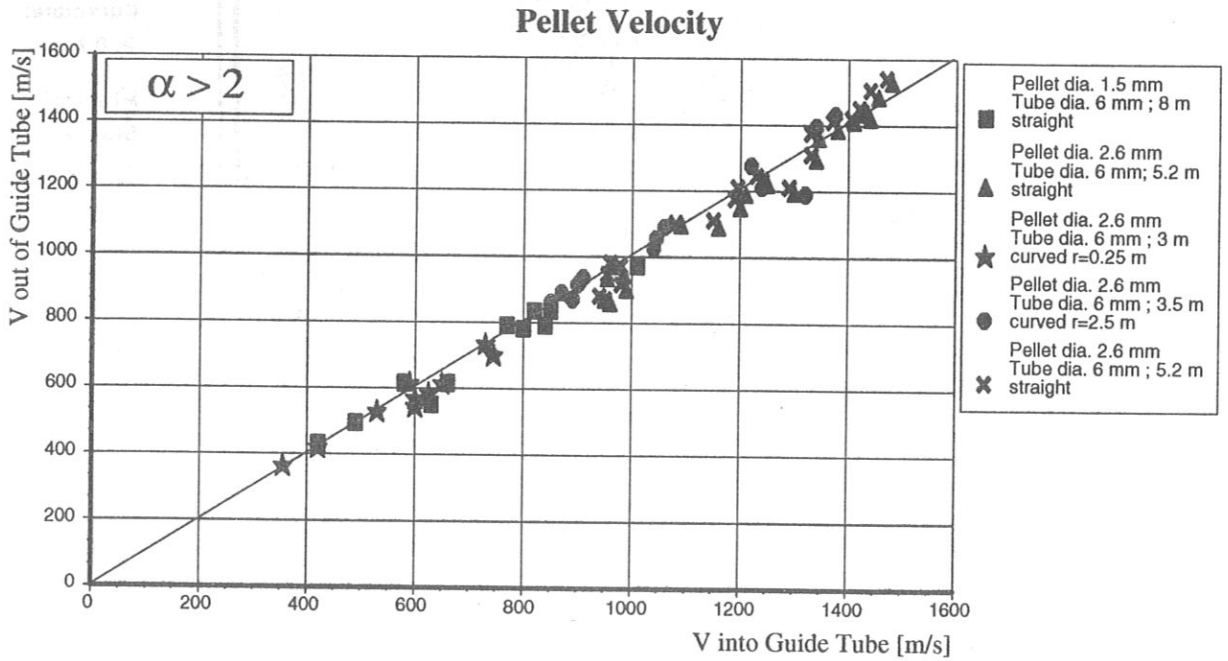
**Pellet Velocity**

Fig.3 Change of pellet velocity in wide and curved guide tubes

the guide tube and pellets with different sizes are included. The parameters are given in Table 1.

The behavior of a pellet with diameter $d_{pel}$ in a guide tube with diameter $d_{tube}$ is determined by the ratio

$$\alpha = \{ \, d_{tube} / d_{pel} \, \} \, .$$

For pellets, which are "small" compared to the tube diameter ( $\alpha > 2$ ) the velocity loss is zero within the error of 5% [fig.3]. This is independent of the parameters of the pellet and the guide tubes. A reduction of the pellet velocity of about 10% is observed in "narrow" tubes ( $\alpha \approx 1$ ) [fig.4]. Photos of these pellets show damage due the interaction with the wall.
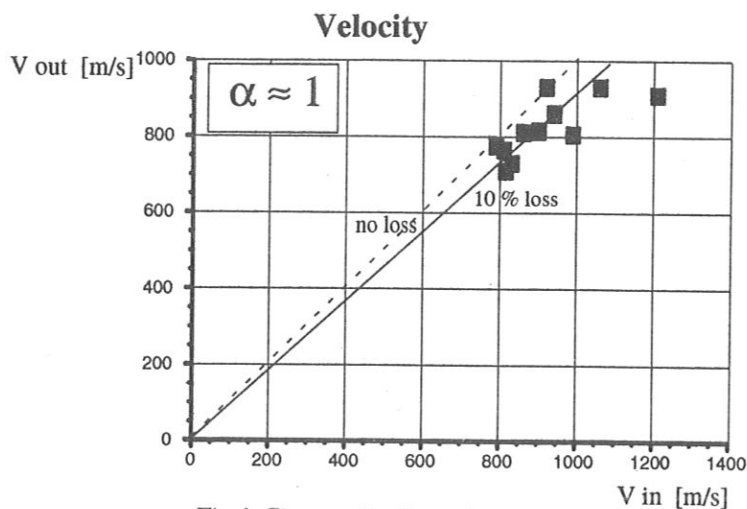
**Velocity**



Fig.4 Change of pellet velocity in narrow tubes

Similar results but for smaller and slower pellets were obtained by P.B.Jensen and V.Andersen [2]. They investigated pellets of 0.6 mm diameter and 2.3 mm length travelling with speeds of 100 m/s to 200 m/s through guide tubes of 4 mm diameter and 4 m length. The reduction of the velocity was less than 10%, too.

# TABLE 1

| Pellet Ø;length | straight / curved | Guide tube Ø | Tube length |
|---|---|---|---|
| mm | - | mm | m |
| 2.6 | straight | 6 | 5.2 |
| 2.6 | curved 2.5 m | 6 | 3.5 |
| 2.6 | curved 0.25 m | 6 | 3 |
| 1.5 | straight | 6 | 8 |
| 1.5 | straight | 4.6 | 4 |
| 2.6 | straight | 3 | 3.5 |

## 2.2.2 Pellet Mass

Several methods are used to determine the mass loss of pellets in guide tubes.

The mass of the original pellet can be calculated from the known extrusion into the gun lock and the density of solid Deuterium. However during acceleration in the barrel the pellet looses already material due friction at the barrel wall and due the interaction with the room temperature propellant.

The temperature of the propellant gas decreases during the acceleration. This estimation gives an upper limit of the pellet mass at the entrance of the guide tube. A better determination of pellet volume and mass before the guide tube was made from pellet photos [fig.5]. This assumes rotational

symmetry for the pellet and a parallel pellet axis to the image plane, which is given in a short dis-
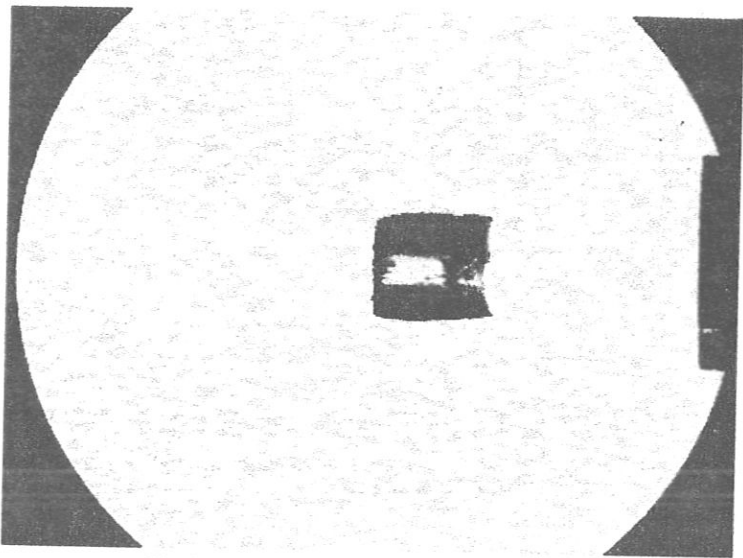


Fig.5 Pellet in flight leaving the barrel (left)

tance behind the barrel. This method delivers a pellet mass with an accuracy of about 20%.

Behind the guide tube the determination of the pellet mass from photography could be done only in a few shots. In most cases the assumption of rotational symmetry was not fulfilled, because the pellet interacts with the wall. Also the pellet axis was not always in the object plane of the photo. The error was about 20%. The method to punch a paper target has the same disadvantages and gives an error of more than 30%.

Another method is the evaporation of the pellet in a known test volume with an error of 20%. The accuracy of the determination of the pellet mass gets better, if the evaporation time of the pellet gets longer, and the pumping of the propellant gas by the test chamber walls gets larger. However these effects are estimated to be small. The pressure of Deuterium jumpes up in less than one second. But the Hydrogen pressure of the propellant rises slowly in several ten seconds.
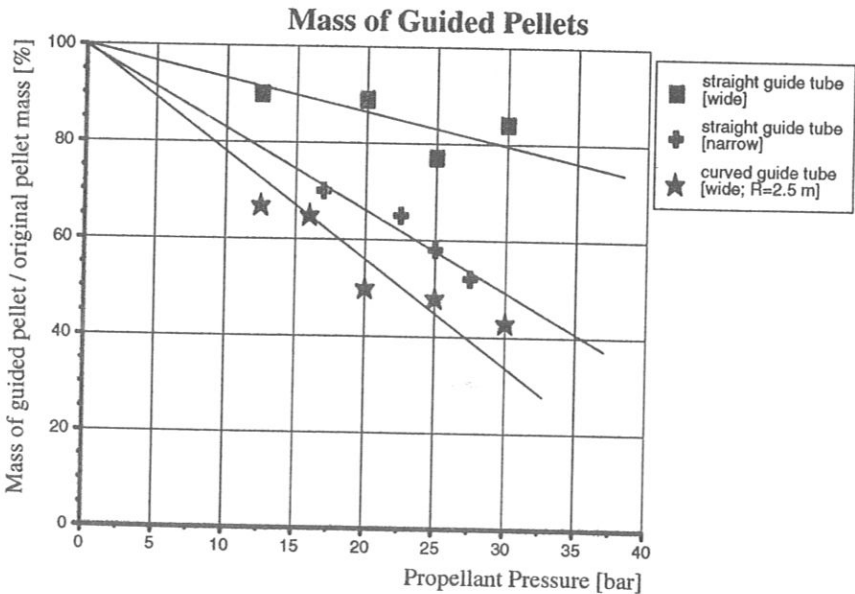


Fig.6 Mass loss of guided pellets in straight and curved tubes

The dependence of the mass loss from the parameters of the guide tubes could not be determined due the large errors. However approximate losses can be given. For wide guide tubes ( $\alpha > 2$ ) the mass loss is less than 20%, if the pellet is not destroyed. For narrow guide tubes ( $\alpha \approx 1$ ) the pellet diameter is clearly decreased behind the guide tube. A mass loss of 40% is estimated.

The pressure of the propellant influences the mass loss of cryogenic pellets in guide tubes. This is shown for cylindrical pellets of 2.6 mm diameter and 2.6 mm length travelling through different guide tubes [fig.6]. The mass loss is determined by the evaporation method. The mass at the exit of the tube is normalized to the original mass in the gun lock. For straight wide tubes ( $\alpha > 2$ ) the mass loss is in the order of 10% and increases just slightly with the propellant pressure. The erosion of the pellet at the wall of the tube is small. For narrow tubes ( $\alpha \approx 1$ ) a stronger interaction is observed. Also a large mass loss is observed for curved guide tubes, when the friction is increased by the centrifugal force.

### 2.2.3 Stray Angle of Pellets

The averaged stray angle of pellets is determined from the statistics of many pellet shots. It is defined as the cone angle from the mean trajectory, which contains 90% of the pellet paths. The pellet trajectories were measured by punching a paper target by the pellets. The distance of the target from the exit of the guide tube was 1.06 m. The curved guide tubes were straight for 1 m from the end of the bended part. The stray angle of 0.25 ° after leaving the barrel was measured by the same

method. With the same angle the pellet enters the guide tube.

The dependence of the stray angle from the parameters of pellets and guide tubes is investigated to obtain information on the interaction of the pellets with the wall and also on the applicability of pellet injection into fusion devices. For wide guide tubes ( $\alpha > 2$ ) the stray angle depends linearly on the length of the tubes [fig.7].
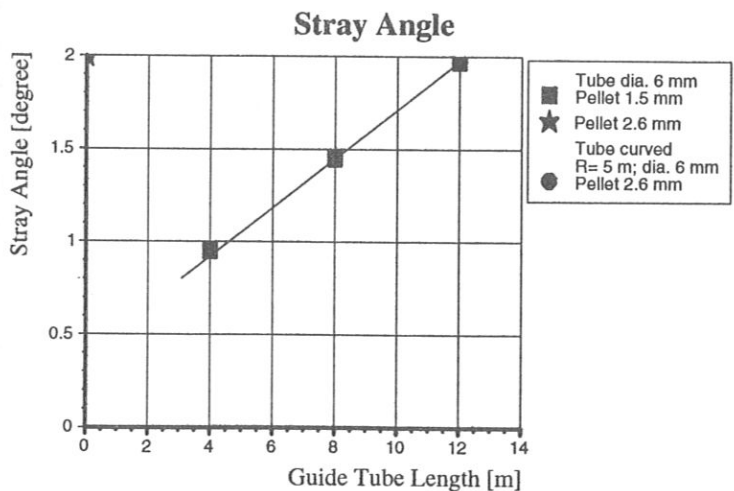


Fig.7 Dependence of stray angle from guide tube length

A model of seperated collisions with the wall will be able to explain this dependence. Also the passage of pellets of different diameters through the same straight tube is investigated. The stray angle decreases with increasing pellet mass or diameter [fig.8]. The stray angle is a function of the tube diameter, too [fig.9]. We observe a maximum at about 2 - 3 pellet diameters. For larger tube diameters the number of collisions decreases with increasing diameter of the tube, if the pellets fly on straight lines between two impacts. For tube diameters smaller than the maximum the assumption

of free flight between two collisions becomes invalid. With decreasing tube diameter the case of narrow tubes will be approached. Thet points of 0.25° at 1.5 mm and 2.6 mm represents the barrel, when the barrel diameter equals the pellet diameter ( $\alpha = 1$ ).

The stray angle of pellets passing curved guide tubes [fig.10] reflects with increasing radius of curvature the transition from continuous riding on the wall on a gaseous cushion to seperated collisions. The sliding along the curved surface is caused by the centrifugal force. It should be notified that the measurements were done at different pellet velocities, because at small radii of curvature the pellet strength does not allow high velocities. In the experiments was found, that in the range of pellet velocities from 400 m/s to 1600 m/s the stray angle does not depend on the pellet velocity.
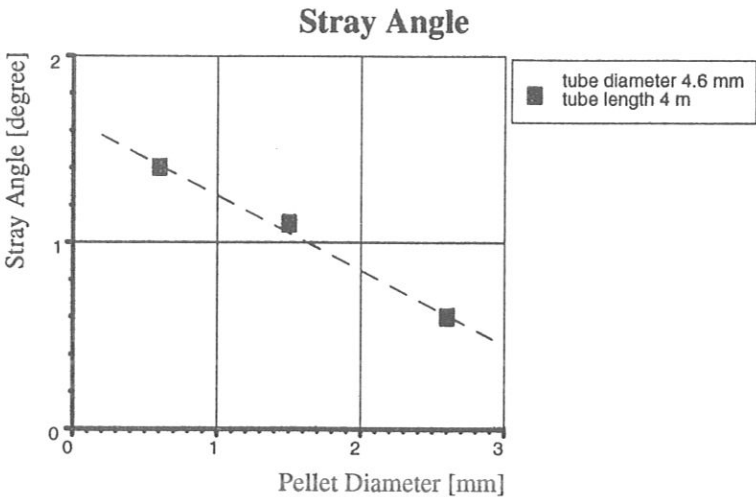
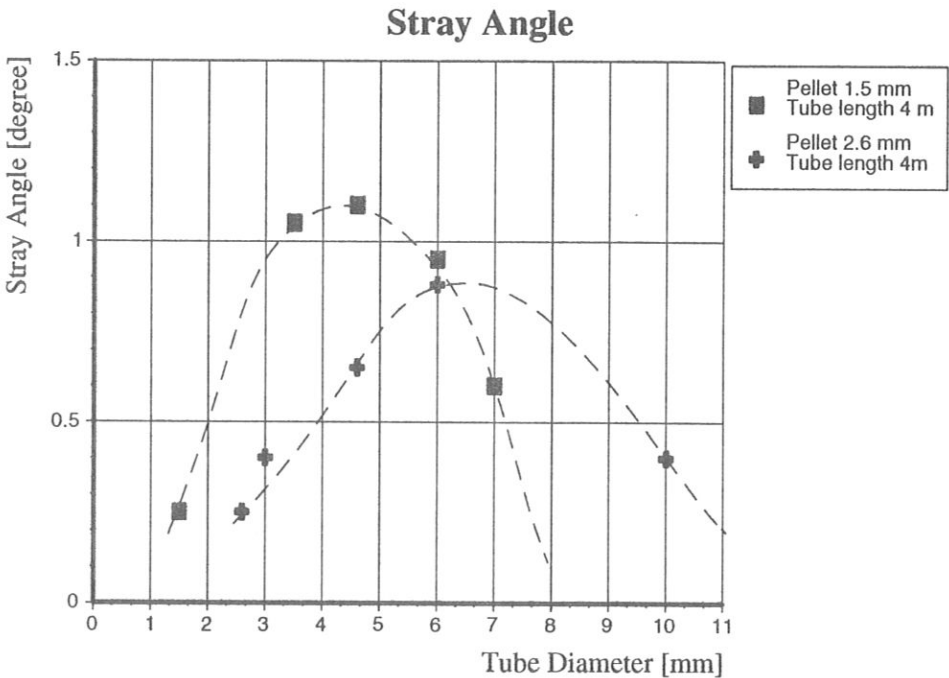Fig.8 Dependence of stray angle from pellet diameter

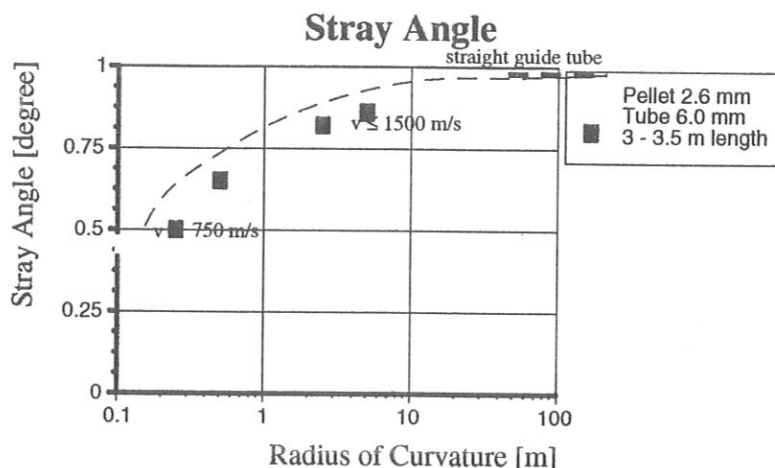Fig.9 Dependence of stray angle from tube diameter

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**Stray Angle**

Fig.10  Dependence of stray angle from radius of curvature

## 2.2.4  Pellet Strength

The tensile strength of solid Hydrogen and Deuterium ( ≈0.5 MPa) is more than a factor of 100 smaller than that of metals for example. This restricts strongly the applicability of tubes for guiding of pellets. Two forces contribute to the disintegration of the pellet : the impact force and the centrifugal force. The damage of pellets in straight and slightly bended tubes is generally caused by the impact force during the collision with the surface. In bended tubes with small radii of curvature the centrifugal force plays an important role.

The damage of pellets is simply detected by photographing them in front and behind the guide tube. Also this enables us to recognize when a pellet hits the front edge of the guide tube due incorrect adjustment. Two or more fragments instead of an intact pellet leave the guide tube, if the force to the pellet in the tube exceeds at any time its strength.

The destruction experiments are summarized in fig.11 as function of the curvature of the guide tubes. The plotted transition curve separates the regions of undamaged from fragmented pellets. The individuell points of the experiments are not shown. For straight tubes (radius of curvature => ∞ ) never  damage of pellets was observed  in the investigated velocity range. With decreasing radius of curvature the pellets are destroyed at lower velocities. When the mechanical properties of solid Hydrogen and Deuteriun pellets  change due to the production process then the curve of transition  will shift. Therefore the validity of the shown transition curve [fig.11] is limited to the applied pellet production. However it is a good estimation for the general applicability of guide tubes for guiding of pellets in refueling experiments in fusion devices.

We investigated also S-shaped tubes. For all velocities used in the experiments (>400 m/s) the pellets are damaged in the guide tube. This result is consistent with the assumption of seperated collisions in the tube.  Pellets do not survive a critical velocity of 50 m/s [14] if they shot perpendicular to a surface. In an S-shaped tube the collision angles with the wall get for geometrical reasons so large, that already for 400 m/s the perpendicular velocity exceeds the critical value. The experiments with S-shaped tubes are not included in fig.11 .
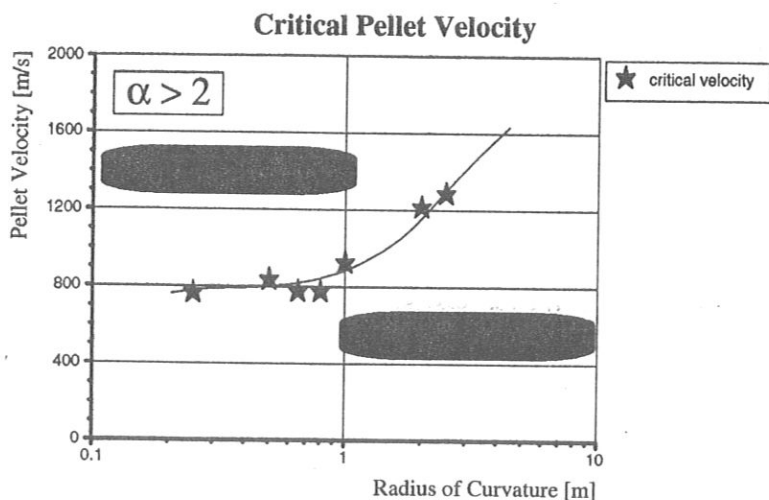
**Critical Pellet Velocity**

Fig.11 Critical pellet velocity for damage in curved guide tubes

Also experiments with narrow guide tubes ( $\alpha \approx 1$ ) are not taken into consideration in fig.11 . In these cases the pellets do not undergo seperated collisions but they ride on a surrounding gaseous cushion and have continuous contact with the wall. This causes strong ablation and a decrease in mass by a factor of about 2. These pellets have a larger mass loss than pellets in wide tubes ( $\alpha > 2$) however they break in pieces at higher velocities.

## 2.2.5  Flow of Propellent Gas

The flow of propellant is connected with the injection of pellets by pneumatic guns. Uncontrolled flow of gas into the plasma device should be avoided. A guide tube with its low flow conductivity is a good tool to reduce the unavoidable gas input of the propellant. Therefore in the experiments the increase of gas pressure in the vacuum chambers in front and behind the guide tube was measured by several pressure gauges. In the vacuum volume between barrel and guide tube a piezoresistive probe with a frequency response of 30 kHz was used. In the test chamber at the exit of the guide tube the pressure was measured by ionization, thermal conductive and membran manometers. A mass spectrometer was installed to investigate the relation of Deuterium from pellet evaporation to Hydrogen from the propellant.

The accumulated gas flow through the tube was for more than one second smaller by one to two orders of magnitude than the flow by the evaporating pellet. Thus a fast gas valve is able to avoid the influx of propellant, for example.

Although the gas flow through the guide tube is small, it can be reduced further by pumping stations in the tube. A curved guide tube (radius of curvature =1 m ) was slitted at the inside of the arc [fig.12a]. The pellets are transfered in the same way as in an unslitted tube, however the flow of propellent gas could be strongly reduced. The same observations were made for a straight guide tube with a ring-shaped slit [fig.12b]. The propellant gas flow was strongly reduced too. All pellets passed the slit in the tube without any damage. This is a strong argument for the model of seperate collisions. The probability that an impact of the pellet with the wall just at the position of the interruption occurs is small.
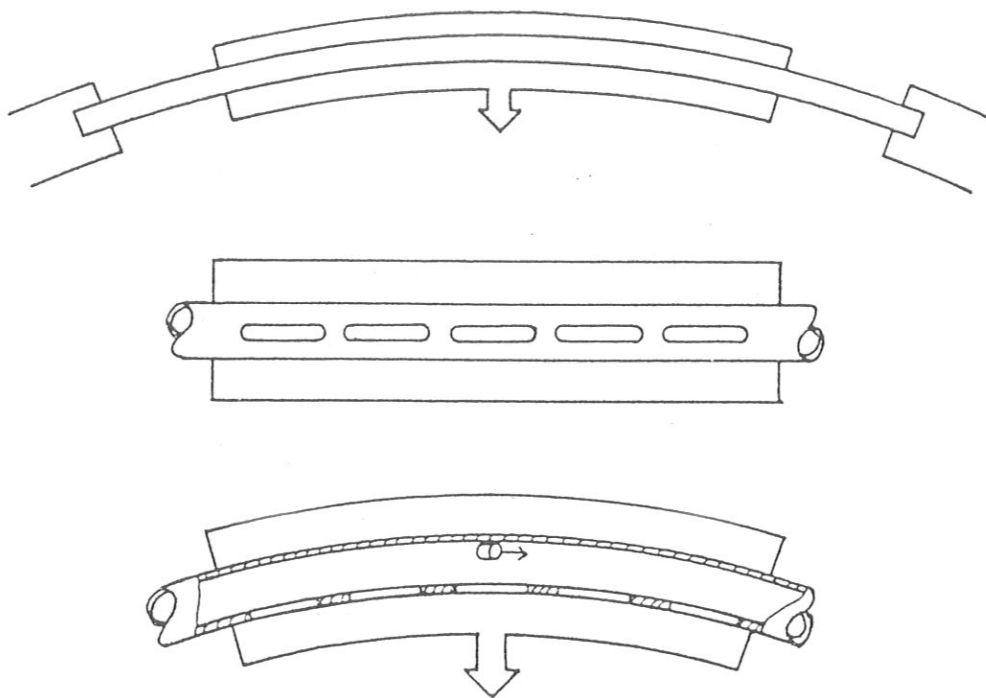
11

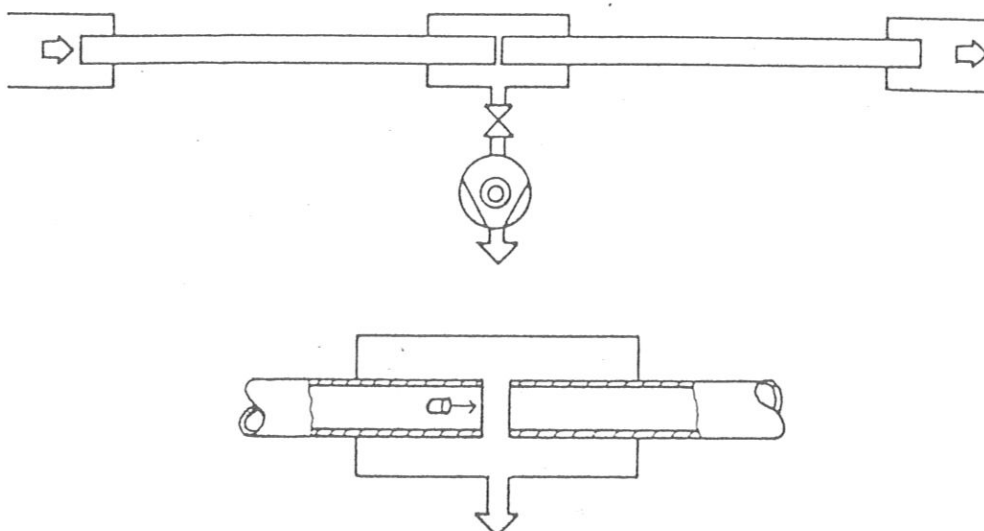Fig.12a Curved guide tube with pump slits at the inner side of the arc

Fig.12b Straight guide tube with a ring shaped slit

# 3. Discussion

For the discussion of the guide tube experiments we will differ three cases. In the first chapter (3.1) guiding of pellets in straight wide tubes is discussed. The duration of free flight is long compared to the interaction with the wall. The second chapter (3.2) describes the interaction of pellets with straight narrow tubes. In the third chapter (3.3) the additional acting centrifugal force in curved guide tubes is examined.

Using simple models for the interaction estimations are done which are able to explain the measurements of velocity, mass, stray angle, and strength.

## 3.1 Straight Wide Guide Tubes ( $\alpha > 2$ )

The above described experiments suggest the following model. The Deuterium pellet moves with a velocity $v_\perp$ against the wall of the guide tube. During the elastic deformation of the pellet part of the pellet evaporates. According to the Leidenfrost phenomenon the heat flux to the pellet is strongly reduced. The rapidly developing gas cloud forces the pellet back additional to the elastic force. The collision becomes superelastic changing the reflection angle and following the stray angle at the exit of the tube. The friction in the gas cloud influences the parallel velocity of the pellet $v_=$. After the collision the gas expands fast along the tube. The pellet moves without interaction with the gas to the next collision at the opposite side of the tube.

The collision time $\tau$ can be estimated from calculations of Hertz [13] for the elastic collision of two spheres. We will assume that the mass of the wall $m_{wall}$ is large compared to the pellet $m_{pel}$, also the radius of the pellet $R_{pel}$ is smaller than the radius of the wall $R_{wall}$. Further on the shear modulus of steel $G_{wall}$ is larger than that of deuterium $G_{pel}$.

$$m_{pel} < < m_{wall}$$

$$R_{pel} < < R_{wall}$$

$$G_{pel} < < G_{wall}$$

The collision time $\tau$ is given by

$$\tau = 3.21 \sqrt[5]{\frac{\alpha^3 \, m_{pel}^2}{v_\perp}}$$

with

$$\alpha^3 = 0.141 \frac{1}{R_{pel}} \left( \frac{1-v_{pel}}{G_{pel}} \right)^2$$

$v_\perp$ = velocity of the pellet perpendicular to the wall

$v_{pel}$ = Poisson constant of deuterium

Using a pellet radius of $1.3 \cdot 10^{-3}$ m and a pellet mass of $2.7 \cdot 10^{-6}$ kg a collision time $\tau$ of 30 µs is calculated. This is long compared to the transfer times of elastic waves through the wall and the pellet of about 1 µs. Thus the elastic model of Hertz can be applied. The real contact duration of the pellet with the wall should be shorter, because of the additional force of the gas pressure of the vaporizing pellet material .

A pellet with a velocity of 1000 m/s needs a time of 4 ms to tranfer a 4 m long guide tube . In each collision it contacts the wall less than 30 µs equivalent to 3 cm sliding along the surface of the wall. The stray angle at the exit of the barrel is 0.25 degree. Assuming an alignment error of the same order the perpendicular velocity of the pellet $v_\perp$ is about 10 m/s. From this we get the number of collisions in the guide tube to be about 10 seperated by free flights of 50 cm.

The total time of contact with the wall is 0.3 ms. During this time the friction force by the gas cloud decelerates the pellet. Solving the equation of motion including the friction term

$$m_{pel} \frac{d^2x}{dt^2} + f \frac{dx}{dt} = 0$$

with

$$f = \frac{\eta \cdot A}{\Delta z}$$

$\eta$ = viscosity of deuterium gas

A = surface

$\Delta z$ = thickness of gas cloud

we get the pellet velocity $v_=$

$$v_= = v_{0=} \cdot \exp\left( -f \cdot t / m_{pel} \right)$$

From this we estimate a decrease in $v_=$ of $\leq 0.1$ %, which is in agreement with the measurements.

A mass loss of the pellet can be caused by radiation from the room temperature wall to the cryogenic pellet. This willbe determined the Stefan-Boltzmann-Law. The calculated mass loss is less than 0.01 % of the pellet mass. Thus this effect can be neglected.

During the tranfer of the pellet through the guide tube heat flow to the pellet during the collisions and also by the contact of the pellet with the propellant. In wide tubes the propellent gas expands fast and the heat conduction to the wall should be small. Also the energy content of the propellant

which has after the barrel a temperature between room and cryogenic temperature should be small. However the measurements [fig.6] show that the mass loss rises with increasing propellant pressure also for wide tubes. Therefore we extrapolate to pressure zero, a mass loss of 5 - 10 % is observed. This has to be explained by heat transfer from the wall to the pellet, during the collisions.

During a collision the pellet has contact with the wall (stainless steel). If we assume, that the temperature at the contact surface is fixed due the evaporation, a cooling wave travels into the wall. The parallel movement of the pellet with $v_= =1000$ m/s produces a contact surface of about $6 \cdot 10^{-5}$ m$^2$. The pellet interacts only a short time with a limited area of the wall, about 2 - 3 $\mu$s. During this time the cooling front moves about 5 $\mu$m into the wall [fig.13].
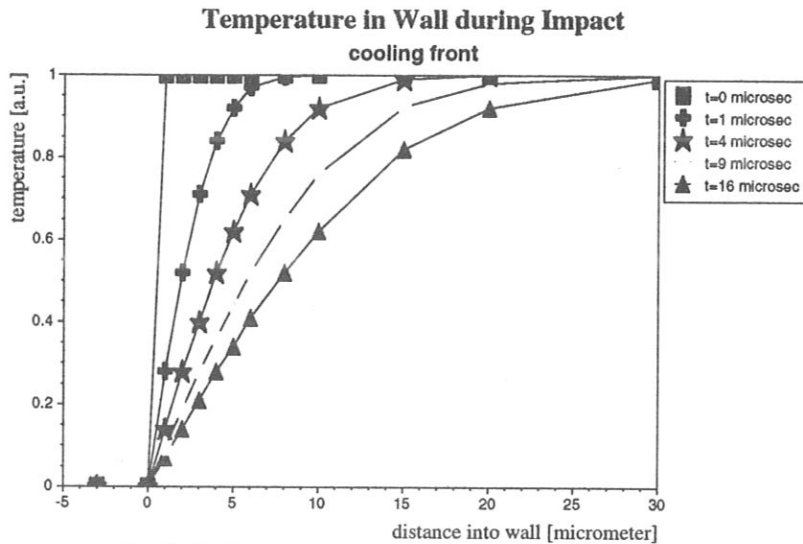


Fig.13  Cooling wave into the wall without gas shielding

Using the thermal data of stainless steel an energy of 0.1 J is transfered to the pellet and is used to evaporate the pellet and to heat the arising gas cloud. If we assume 100 % tranfer into the evaporation this has to be compared with the energy to vaporize the pellet totally. The total vaporization energy of a pellet of 2.6 mm diameter can be estimated to be 0.85 J. The mass loss is then 12 % of the pellet mass in one collision. In a 4 m long guide tube we get about 8 impacts to the wall, which was estimated from the stray angle of the pellet trajectory. This predicts a total mass loss of 64 %. However this is not observed in wide guide tubes. We have neglected the Leidenfrost phenomenon. The produced gas cloud isolates the pellet from the wall due its very low thermal conductivity. If we do the same estimations as before but using the thermal conductivity of Hydrogen gas at low temperatures we get a cooling front as shown in [fig.14].
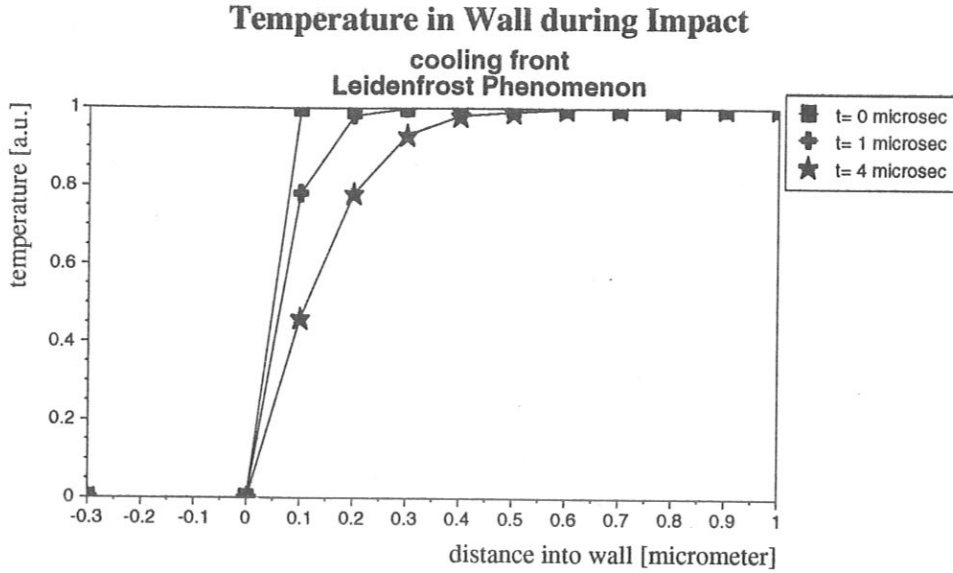
## Temperature in Wall during Impact
### cooling front
### Leidenfrost Phenomenon

Fig.14 Cooling wave into guide tube wall including
Leidenfrost phenomenon

Now the relevant pentration depth is smaller by a factor of 20. The disposable energy for evaporation in one collision is 1.1 % of the total vaporization energy of the pellet. In 8 impacts we get a mass loss of 9 % if the energy is completely used for vaporization and if we assume that half of the energy is going into heating of the gas cloud, we get about 5 % mass loss, which is in reasonable agreement with the measurements. This seems to be a good argument for a Leidenfrost interaction model in wide guide tubes.

This simple model is able to make comprehensible the velocity and mass losses in wide guide tubes. It is also possible to explain the observed variations of the stray angle of the pellet at the exit of the guide tube.

For elastic collisions the stray angle, measured to the surface of the wall, at the exit of the guide tube should not rise with increasing length of the tube, but for inelastic collisions it should even decrease. For superelastic collisions, caused by the pressure of the evaporated gas, the stray angle should increase with the length of the guide tube which is proportional to the number of collisions. This is observed in the experiments [fig.7].

The evaporation of the pellet is proportional to the contact area, that means to $d^2_{pel}$ and the aditional acceleration of the pellet perpendicular to the wall to $1/d_{pel}$ . Thus the reflection angle gets smaller for larger pellet diameters as is measured in figure 8. The range of $\alpha$ is from 7.7 to 1.8.

With increasing guide tube diameters the number of collisions decreases. If the pellet dimensions are not changed, then the stray angle should decrease with increasing $d_{tube}$ . This is observed in figure 9 at the righthand side of the maxima of the curves. The lefthandside belongs to the case $\alpha \approx 1$ and is discussed in section 3.2.

A discussion of the pellet strength will be given in section 3.3, because all pellets in straight wide ($\alpha > 2$) guide tubes survived in the accesssible velocity range.

## 3.2. Straight Narrow Guide Tubes ($\alpha \approx 1$)

In the case of narrow guide tubes, defined by

$$\alpha = d_{tube}/d_{pel} \approx 1$$

the cryogenic pellet moves all the time close to the room temperature wall. A small layer of evaporated gaseous Deuterium surrounds the pellet and determines viscosity and heat conduction of the interaction between pellet and wall.

In wide tubes the gas expands very fast and the pellet moves between collisions in vacuum. In narrow tubes the pellet moves all the time inside the gas cloud. Its speed finally approaches the sound velocity of the gas depending on the gas temperature. This temperature is unknown but one can assume that it is between 20 K and 100 K corresponding to sound velocities of 400 m/s to 1000 m/s. The experimental found pellet velocity of 900 m/s would then indicate a gas temperature of 77 K.

According to figure 6 the mass loss in narrow guide tubes is a factor of 2.5 larger than in wide tubes. But this is due the interaction with the propellant. The extrapolation to vanishing propellant gas pressure shows, that the mass loss due the interaction with the wall is of the same order than in wide tubes. Using the pellet and tube geometry a total energy transfer of 0.045 J is estimated during the flight in a 4 m long guide tube with a velocity of 1000 m/s. If we neglect the heating of the vaporized gas this is equivalent to a mass loss of less than 5 %, which is of the order observed in the experiment.

The experimental measured stray angle at the exit of narrow guide tubes is included in figure 9. The branch of the curves left of the maximum corresponds to narrow guide tubes. For an $\alpha$ very close to 1 the stray angle is about the same as at the exit of the barrel of the pellet gun. With increasing diameter of the guide tube, that means with increasing $\alpha$, the angle gets larger. The stabilizing effect to the trajectory by the produced gas cloud decreases due the larger distances to the wall. This is the transition region to separated collisions at large $\alpha$.

The pellet will be accelerated perpendicular to the wall by the gas pressure of the evaporated Deuterium. It moves to the opposite side of the wall of the tube, will be slowed down and again accelerated towards the tube axis. This motion of the pellet perpendicular to the axis of the tube can be approximately described by the differential equation

$$\frac{M}{A\,p_0}\frac{d^2x}{dt^2} = \frac{2x}{\Delta r^2\left(1-\dfrac{x^2}{\Delta r^2}\right)}$$

if we assume a linear decrease of the gas pressure with increasing distance to the wall.

$\dot{M}$ = pellet mass

A = contact surface with the wall

$\delta$ = distance of pellet to the wall

$p = f(\delta) = p_0 \cdot \delta$ gas pressure acting to the pellet

$$2 \cdot \Delta r = d_{tube} - d_{pel}$$

x = pellet coordinate perpendicular to the guide tube axis

A first approximation of the solution of the differential equation is a sinusoidal oscillation. Near the wall higher orders of sin and cos have to be taken into consideration. The pellet has its maximum velocity at the axis of the tube. If the gas pressure would be known the maximum perpendicular velocity could be calculated getting an estimation of the stray angle. Assuming a gas pressure of the vaporized Deuterium of $5 \cdot 10^5$ N/m$^2$ , which was estimated from the vaporized mass in one collision, a perpendicular velocity $v_\perp = 30$ m/s is calculated. From this a stray angle less than 1.6 ° follows, which is of the order of the observed stray angles. The assumed gas pressure is in the order of the pellet strength corresponding to a velocity of 50 m/s [14] which is in the experiments with straight guide tubes not exceeded.

We conclude that the model of a permanent gas cloud around the cryogenic pellet in narrow guide tubes is able to explain the experimental data.


## 3.3 Curved Guide Tubes


The effect of curvature has to be taken into account when the pellet after the first collision with the wall will further touch the surface at the same side. Its trajectory will therefore follow the surface in close distance due the developing of a gaseous cushion. An estimation for the effect of curvature can be made from the path of the pellet perpendicular to the wall in relation to the gradient of the wall. For pellets of 2.6 mm diameter, a parallel velocity of 1000 m/s, and a perpendicular speed of about the strength limited velocity of 50 m/s curvature plays a role up to a maximum radius of curvature of 2 m. Pellets in slightly curved guide tubes with radii of curvature larger than 2 m behave like in straight tubes depending on $\alpha$ as described above.

The experimental measured loss of velocity does not differ within the errors from the loss in straight tubes and is less than 10% (fig.3). This is in agreement with estimations for deceleration in straight tubes replacing the collision duration of 30 μs by 4 ms. A velocity loss of about 1% is calculated.

The mass loss in a guide tube with a radius of curvature of 2.5 m (fig.6) extrapolated to vanishing propellant pressure is about the same ($\approx$10%) as in straight tubes. But these measurements are made for a curvature larger than the above estimated limit. To estimate the mass loss in tubes with a radius of curvature less than 2 m we use the calculations including the Leidenfrost phenomen but replace the collision duration again by the total flight time of the pellet in the tube. We get a mass loss between 10% and 100%, which agrees with photos of the pellet leaving the guide tube. On these pictures one observes a strong grinding of the pellets at their surfaces.

The experimentally observed stray angle decreases with increasing centrifugal force (fig.10) . This is equivalent to an increase of gas pressure of the evaporated Deuterium or a decrease of $\alpha$ for narrow guide tubes (fig.9). The stray angles are of the same order and depend on the pressure the same way.

Estimations show, that the pressure on the pellet surface due the centrifugal force is of the same order than the strength of solid deuterium. Thus we expect that with increasing radius of curvature the critical velocity for damage increases as it is experimentally shown in figure 11.

The centrifugal force is given by

$$F_{centr} = M_{pel} \cdot \frac{v_0^2}{R}$$

with    R = radius of curvature

   $v_0$ = pellet velocity

   $M_{pel}$ = pellet mass

We replace the centrifugal force by the pellet strength $p_{strength}$ multiplied with the contact area $A_{contact}$ between pellet and wall. The pellet will be destroyed above a critical pellet velocity $v_{0\ crit}$, which depends on the curvature.

$$v_{0crit} = \sqrt{\frac{p_{strength} \cdot A_{contact}}{M_{pel}}} \cdot \sqrt{R}$$

However figure 11 does not show a square root dependence of R. It seems that $v_{0\ crit}$ is independent of R below a certain radius of curvature $R_{limit}$ . We have assumed a constant pellet mass, which is not correct, as is observed in photos of the pellets at the exit of the guide tube. If this mass loss is taken into account in a very simplified assumption

$$M_{pel} = M_0 \cdot \frac{R}{R_{limit}}$$

the critical pellet velocity for damage gets independent of the curvature in rough agreement with the measurements.

$$v_{0crit} = \sqrt{\frac{p_{strength} \cdot A_{contact} \cdot R_{limit}}{M_0}}$$

With the assumptions, that the contact area is 1/5 of the mantle surface of the pellet, the limiting radius is 1 m and the pellet strength is $5 \cdot 10^5$ N/m², we get a good approximation for the critical velocity for damage below a radius of curvature of 1 m of  900 m/s.


## 4.0 Conclusion

The experiments to guide cryogenic pellets through tubes at room temperature have shown that Deuterium pellets can travel through very long tubes without vaporizing or to be damaged. The limitations have be shown. Mass loss, velocity loss, change of stray angle at the exit of the guide tube and damage of the pellets have been determined experimentally depending at several parameters of the guide tubes (diameter, length, radius of curvature) and the pellet (diameter and velocity).

It was found that two experimental regions can be differed : wide and narrow guide tubes compared to the pellet size or as ranges of the relation of the tube diameter to the pellet diameter.

$$\alpha \; = \; d_{tube}/d_{pel} \; \left\{ \begin{array}{l} \approx \; 1 \qquad \text{\textit{narrow guide tubes}} \\ \geq \; 2 \qquad \text{\textit{wide guide tubes}} \end{array} \right.$$

Experiments and estimations have shown that for calculations of the interaction of cryogenic pellets with guide tube walls the evaporated gas cloud and the Leidenfrost phenomenon has to be taken into account.

The case of wide guide tubes ($\alpha > 2$) can be explained by a simple model assuming seperated collisions. The evaporation of deuterium causes superelastic impacts. The duration of one collision is estimated to be 30 μs, which leads to 2 - 3 collisions per meter in the tube. The evaporation is limited by the Leidenfrost effect and produces just small velocity losses ($< 1\%$) and mass losses ($< 10\%$). The stray angle at the end of the guide tube increases with increasing length and increasing pellet diameter. The angle decreases with increasing diameter of the tube, that means it decreases with increasing $\alpha$.

The case of narrow guide tubes ($\alpha \approx 1$) can be explained best if we assume a continuous surrounding gaseous cushion which travels with the pellet along the tube. The path of the pellet will make small oscillations around the tube axis. The heat transfer is still governed by the conductivity of the Deuterium gas layer. This results in a velocity loss of $\Delta v \leq 10\%$ and a mass loss of $\Delta m < 10\%$. The stray angle increases with increasing $\alpha$ from the angle at the entrance of the guide tube to a maximum of about $1°$ at $\alpha \approx 3$.

The centrifugal force has to be taken into account for curved guide tubes. Although the experiments are done in the range $\alpha > 2$, as a result of the centrifugal force a continuous gas layer at the contact side to the wall convoys the pellet. This determines the heat transfer and following the velocity loss to be $\Delta v \approx 1\%$ and the mass loss to be $\Delta m \approx 10\%$ - $100\%$. The stray angle increases with increasing radius of curvature reaching the asymptotic stray angle of wide guide tubes for large radii of curvature.

A simple model is able to explain the limiting pellet velocity for damage. For small radii of curvature the mass loss has to be taken into account. For larger radii of curvature this critical velocity increases with increasing radii.

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