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I. Viniar and S. Sudo

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NEW PELLET PRODUCTION AND ACCELERATION TECHNOLOGIES FOR HIGH SPEED PELLET INJECTION SYSTEM "HIPEL" IN LARGE HELICAL DEVICE

I. Viniar* and S. Sudo

National Institute for Fusion Science, Chikusa, Nagoya 464-01, JAPAN
***) Saint-Petersburg Technical University, Polytechnicheskaya 29,**
St. Petersburg, 195251, RUSSIA

Keywords: **pellet, injector, pellet injection, fueling, pipe gun, two-stage gas gun, repeating pellet injector, HIPEL, Large Helical Device**

* Guest Researcher to National Institute for Fusion Science, Nagoya, Japan

NEW PELLET PRODUCTION AND ACCELERATION TECHNOLOGIES FOR HIGH SPEED PELLET INJECTION SYSTEM "HIPEL" IN LARGE HELICAL DEVICE

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ABSTRACT

New technologies of pellet production and acceleration for fueling and diagnostics purposes in large thermonuclear reactors are proposed. The technologies are intended to apply to the multiple-pellet injection system "HIPEL" for Large Helical Device of NIFS in Japan. The pellet production technology has already been tested in a pipe-gun type pellet injector. It will realize the repeating pellet injection by means of decreasing of the pellet formation time into the pipe-gun barrel. The acceleration technology is based upon a new pump tube operation in two-stage gas gun and also upon a new conception of the allowable pressure acting on a pellet into a barrel. Some preliminary estimations have been made, and principles of a pump tube construction providing for a reliable long term operation in the repeating mode without any troubles from a piston are proposed.

1. INTRODUCTION

One of the main missions of Large Helical Device (LHD) of heliotron/stellarator type with superconducting coils, being created now at National Institute for Fusion Science of Ministry of Education in Japan [1], is to demonstrate a steady state operation of helical system together with investigations of plasma characteristics such as energy and particles transports. Plasma control is one of the key subjects for the LHD successful operation. The powerful technique for plasma density and pressure profiles controlling is a pellet injection. It is also good means for refueling particles in the core area of the plasma and plasma diagnostics. Therefore, a high speed pellet injection system "HIPEL" for LHD has been proposed [2]. Its main parameters are shown in Table 1.

Table 1. "HIPEL" Pellet Injection System Parameters

Pellet species					H_2 , D_2					
Launcher type	single-stage gas gun					two-stage gas gun				
Purpose	refueling				diagn.	refueling				diagn.
Barrels number	2	2	2	2	2	2	2	2	2	2
Pellet diameter	1.5	2.0	3.0	3.8	1-3.0	1.5	2.0	3.0	3.8	1-3.0
Deposited particles number,* 10^{20}	1.6	3.9	13	26	0.5-13					
Penetration depth,* (r/a)			0.53					0.25		
Location of peak density,* (r/a)			0.65					0.35		
Injection interval, s					arbitrary					
Time of pellet renewal into a barrel					> 3 minutes					
Average life-time of a piston into a pump tube			-					500 shots		

* All calculations are carried out for deuterium pellet.

"HIPEL" is most suitable and reliable for LHD among existing and planned pellet injection systems. Its advantages are:

- high reliability, which has been checked by the experience of many pellet injectors exploitation;
- high flexibility in changing of many parameters, such as injection interval, depth penetration, deposited particles number and others;
- possibility to operate in "waiting" mode; it means that the system is able to

stay in stable state with all pellets prepared for shots; it gives possibility to shoot if it is necessary in a very short time, near 1 ms;

- possibility to modernize this system for advanced operation in future.

In spite of the significant successes obtained under testing of main components of "HIPEL", some of its subsystems can be improved.

LHD will operate in a steady state mode, therefore a pellet injection system should be able to operate in such a mode too. However, if the "HIPEL" injects into LHD only 1 pellet per 0.2 s, it will not be able to act on plasma after 4 s during following 3 minutes. All of its barrels will be empty and it takes more than 3 minutes to prepare pellet into a pipe-gun. The situation can be improved by applying a new technology which is proposed in this article.

Another problem is concerned of pump tube operation in a two-stage gas gun. Its duration is limited by life-time of a piston moving inside of tube and is estimated approximately in 300-600 shots with the present technology. It means after 10-20 minutes of operation with frequency 1 shot per 2 s it will be necessary to change piston and most likely the pump tube too. Here is proposed to test a new pump tube construction for "HIPEL". Moreover, the new construction gives a possibility to check a new approach to achievement of pellet velocities above 3 km/s.

Section 2 presents a description of a new pellet production technology, including basic principles, pellet injector construction and experimental results. Description of a new acceleration technology is presented in Sec. 3. Conclusion is given in Sec. 4.

2. PELLET PRODUCTION TECHNOLOGY

2.1. Description of the principle

There are three main pellet production techniques which were developed in 1979-1986 years: a) simple freezing of fuel from liquid phase; b) pellet formation by "in-situ" condensation on pipe-gun; c) extrusion technology.
Such technique as pellet production by means of "Zamboni machine" has not been applied widely.

The simple freezing of fuel from liquid phase was used in the first pellet injectors [3,4]. Its advantage and defect simultaneously is the constant pellet size which can not be varied without replacing some mechanical parts. Besides, it is difficult to apply this technique for repeating pellet injection.

The pellet production technique using "in-situ" condensation has gained the most wide acceptance since its initial demonstration in 1985 [5]. This technology is very simple, reliable, requires no moving units at the cryogenic temperatures and only small amounts of fuel are required for pellet production. But it has one essential defect: a pellet production time is too large (3-5 minutes [5, 6]) for fueling into a steady state or long-pulse operation fusion device.

Extrusion technology is now the most suitable one for a steady state operation of nuclear devices [7]. It allows to produce a solid hydrogen (deuterium) extruded rod with velocity up to 60 mm s and cut off the pellets of any length. This technology is complex mainly because of necessity to use moving mechanical parts at the cryogenic temperatures. Therefore it is applied mainly in repeating pellet injectors for continuous fueling. It is difficult to adjust its operation for diagnostics applications. The recently proposed technique of continuous extrusion [8, 9, 10] is simple, reliable and require a small amount of fuel for pellet production, but it is also aimed to continuous refueling and use a high pressure (100 bar) of fuel gas.

Thus the "in-situ" condensation technology is applied for diagnostics and fueling in short-pulse fusion device, while the extrusion one is used for long term continuous fueling.

The proposed technology [11] integrates the advantages of both ones. The essence of the technology is the pellet production by means of almost "in-situ" technology but using a solid (liquid) fuel instead of gaseous one. Actually the long time of pellet production in the case of "in-situ" technology is caused by slow process of the pellet freezing from gaseous phase, while the cooling time **t** of the solid hydrogen pellet of **d** = 3 mm from 14 K to 9 K is estimated as

$$\mathbf{t} \sim \mathbf{d}^2 / 4\,\mathbf{a} < 1 \text{ s.}$$

where $\mathbf{a} \sim 3 \cdot 10^{-6}\ m^2/s$ is the average thermal diffusivity of solid hydrogen in the range of 9-14 K.

Thus, if one takes a solid hydrogen at the temperature near to the melting point and inserts it into a pipe gun, it will be possible to prepare a pellet for a time less than 1 s. The store of solid hydrogen can be replenished continuously by any usual technology of fuel freezing. Thus, the procedures of pellet production by means of new technology are:

- to prepare a small store of solid fuel by usual technique outside of pipe-gun barrel and replenish it continuously;
- to heat the solid fuel up to the melting point;
- to admit the portion of solid (liquid) fuel into a pipe gun;
- to cool the pellet up to 8-10 K.

In order to admit the portion of solid (liquid) fuel into a pipe gun it is proposed, for example, to apply a porous material as it is shown in Fig. 1. The solid hydrogen at the temperatures near to the melting point (12.5-13.8 K) is very fluid and can penetrate through porous materials as a liquid because of pressure differences between two opposite surfaces of solid fuel inside of a porous unit (Fig. 1).

The operation principle of the pellet injector using the new technology is differed a little from the one of a pipe gun. Hydrogen gas is continuously supplied into the area upper of porous unit (Fig. 1) and freezes inside it. Before a (or simultaneously) shot an impulse heater increases the temperature of porous unit and hydrogen. The latter penetrates into a pipe gun barrel and freezes there. This state is stable and pellet can wait for an injection moment.

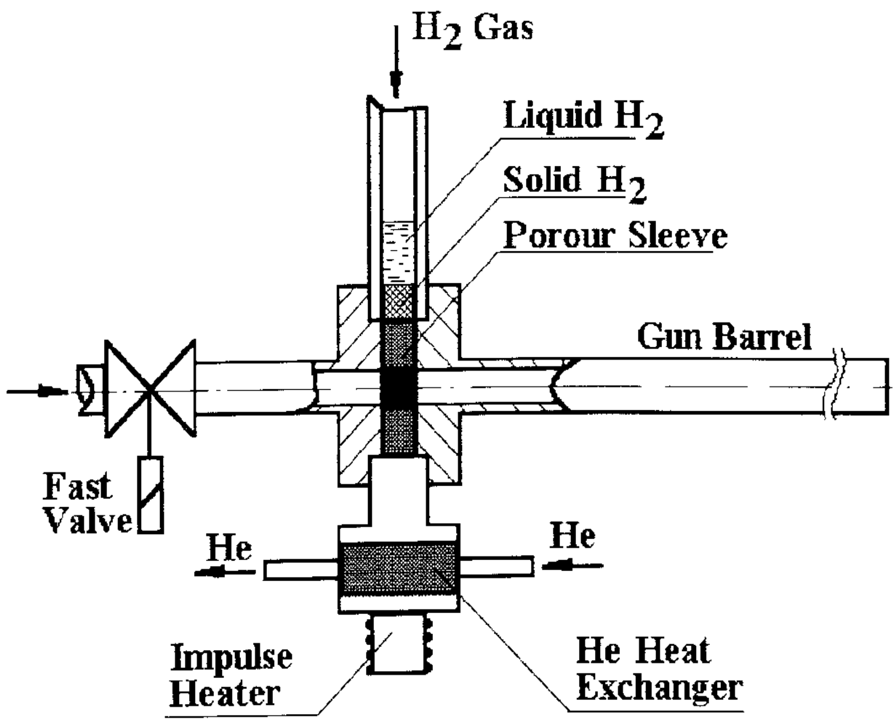

Fig. 1. Schematic of the repeating pipe-gun.

A fast valve admits a propellant gas into the barrel and the pellet is accelerated. The propellant gas heats the porous unit for a 10 ms and promotes the new portion of solid fuel to penetrate into the barrel. The cycle can be repeated in any time. Its minimum duration depends on fuel species, pellet size and is estimated of 1-10 s. It is also possible to apply liquid fuel instead of solid but in this case the pellet production duration is estimated approximately of 10-20 s.

2.2. Pellet injector construction

In order to test the proposed technology a simple one barrel pellet injector has been developed. A schematic drawing of the injector is shown in Fig. 2. There are two vacuum chambers separated of each other: the main (D=200 mm, H=400 mm) where a pipe gun is housed and the diagnostic chamber (D=100 mm, L=200 mm). The barrel (d=3 mm, l=370 mm, t= 0.5 mm) is connected

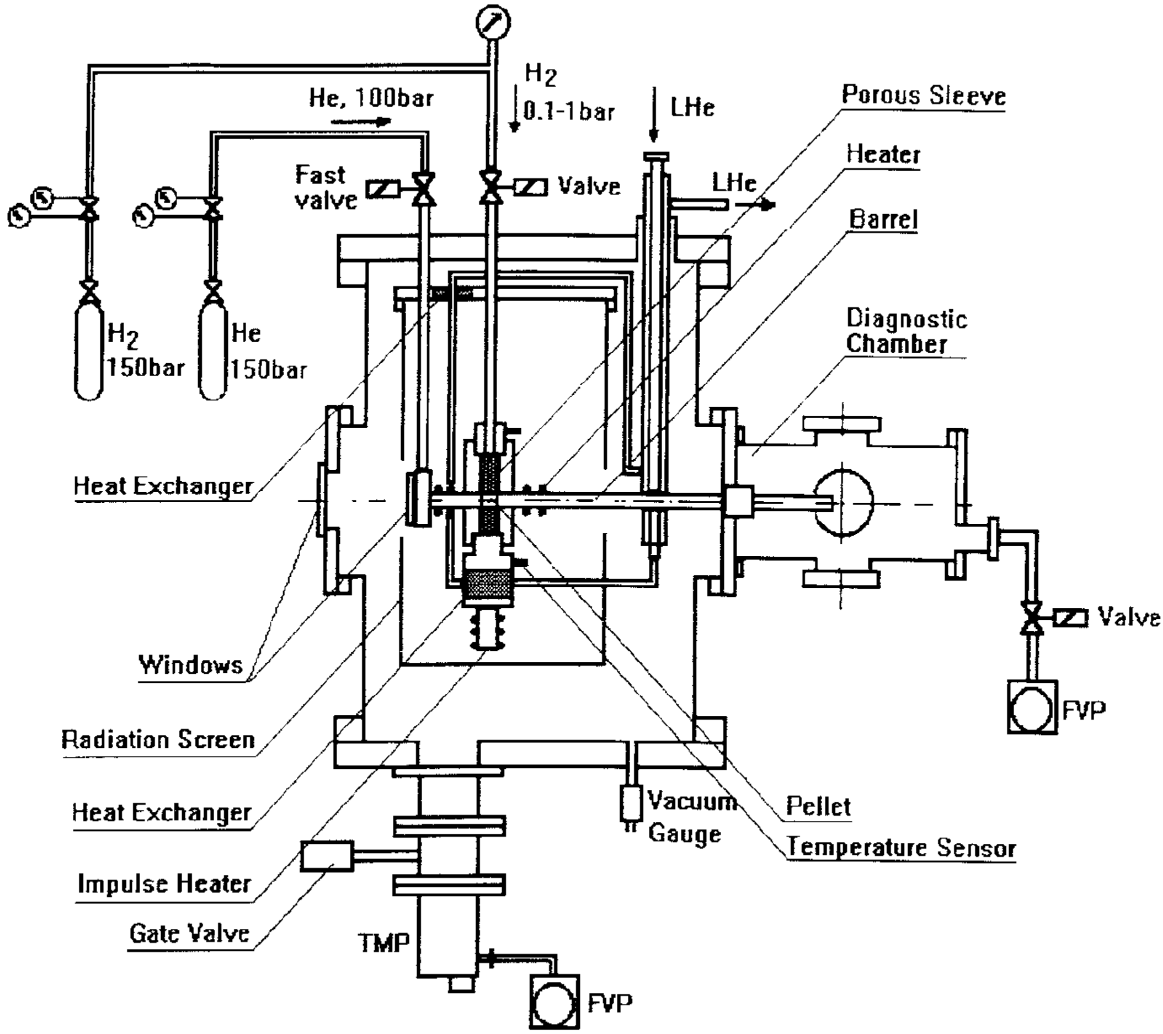

Fig. 2. Schematic of the repeating pipe-gun pellet injector.

with cryogenic unit produced of OFC copper. Two temperature sensors DT-470SD is installed on the upper and lower parts of the unit. There is a helium heat exchanger (d=10 mm, l=18 mm) in the lower part of cryogenic unit. The impulse heater of 50 W power is also attached from below of it. Some different samples of porous sleeves produced of usual copper could be housed inside of cryogenic unit along the axis of pipe gun barrel. The tube of fuel gas (d=3 mm, t=0.15 mm) is conducted through upper flange of main chamber and radiation shield (D=80 mm, H=180 mm) to the cryogenic unit and porous sleeve. This tube is equipped with a standard magnetic valve and a manometer and is connected with a fuel gas cylinder (150 bar) and reducer. The propellant gas (helium) is introduced from cylinder (150 bar) with reducer and fast valve (opening time is ~ 1 ms) through the upper flange as it is shown in Fig. 2. It is not optimal position of the fast valve layout, but for the visual observation it is acceptable. Two small heaters (20 ohm) produced of 0.2 mm diameter manganine wire are wound on the propellant gas tube and the barrel from the both sides of cryogenic unit. The vapor of liquid helium is admitted from 250 l dewier vessel through a long tube (d=15 mm, t=0.3 mm) into the heat exchanger and then into another miniature heat exchanger (d=10 mm, l=3 mm) brazing into upper flange of radiation shield. Then the vapor is gone out through the tube (d=20 mm, t=0.5 mm) surrounding the vapor inlet tube. It makes for decreasing of liquid helium consumption. To stabilize the helium vapor flow an original helium pressure stabilizer is installed on the one of the outlet holes of helium dewier. A vacuum gauge and a high vacuum pumping system (turbomolecular pump TG 200CA) are connected to the bottom of the main chamber. There are four windows (d=55 mm) in the center of diagnostic chamber in order to measure the pellet velocity and follow for pellet shape using CCD-camera. The propellant gas after a pellet acceleration is evacuated through the diagnostic chamber by a fore vacuum pump.

At first, in order to study new technology, the cryogenic unit of the injector has been assembled with diagnostic visual chamber without a barrel as it is shown in Fig. 3. The main chamber has two flanges with windows (d = 35 mm)

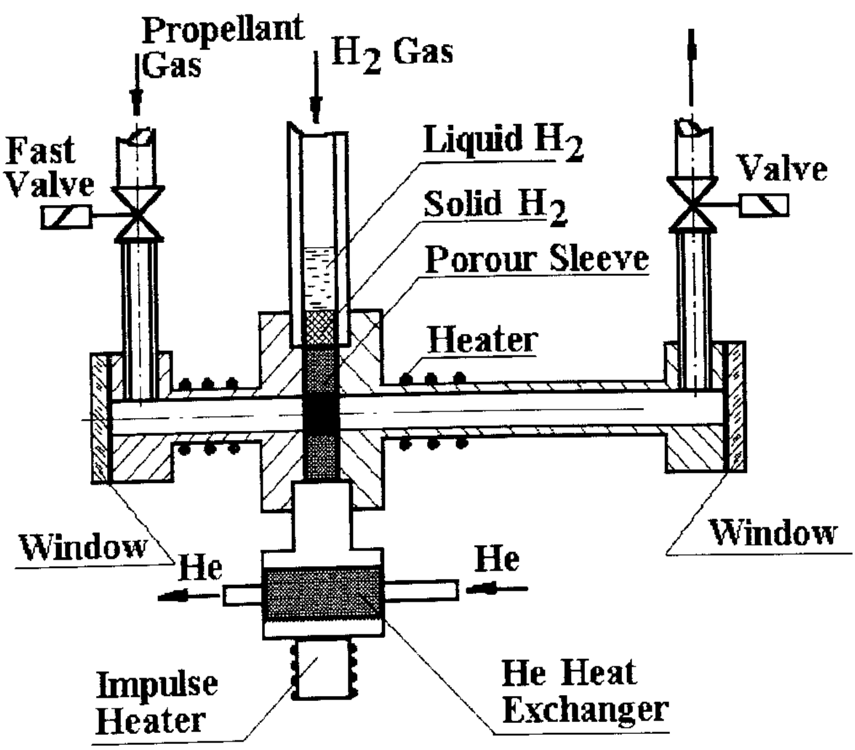

Fig. 3. Schematic of the repeating pipe-gun test rig.

placed on the opposite sides of the chamber along of a one axis to observe the pellet formation. It was possible to observe pellet formation through these windows. Afterwards the barrel has been connected instead of the visual chamber to the cryogenic unit.

The general view of the repeating pipe-gun pellet injector prototype is shown in Fig. 4.

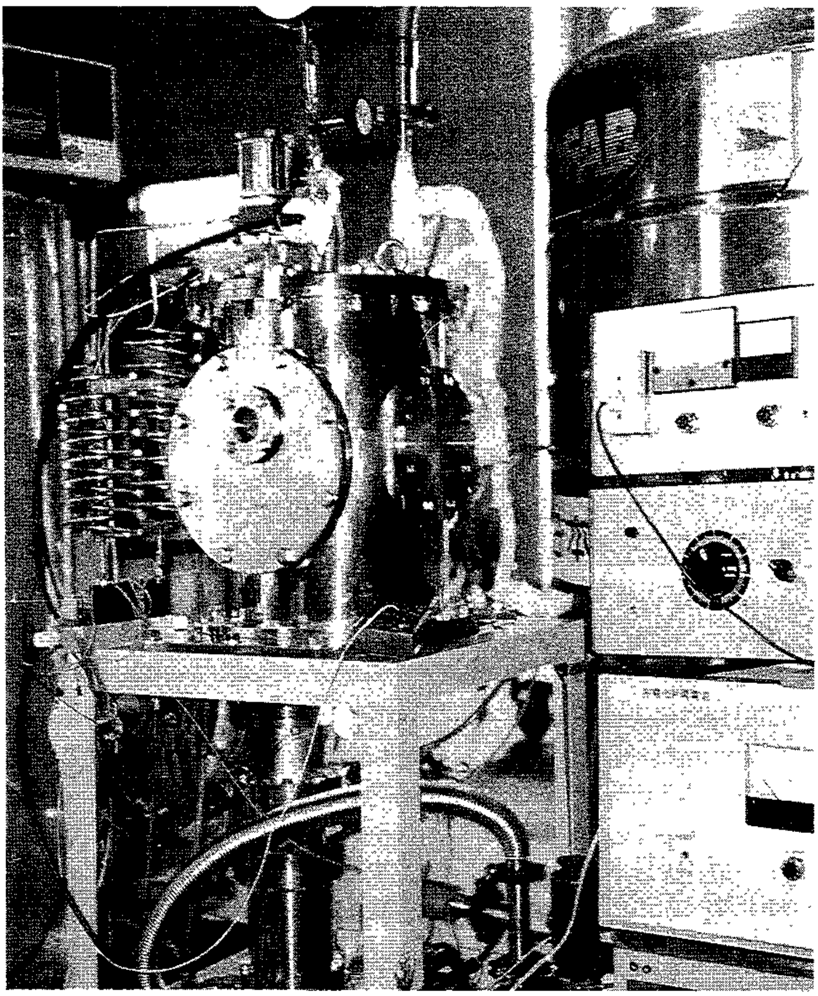

Fig. 4. The general view of the repeating pipe-gun pellet injector.

2.3. Operation procedures and experimental results

The main vacuum chamber is pumped out up to 10^{-4} Pa. Helium vapor cools the cryogenic parts of injector. Its flow pressure is maintained at the stable level by the stabilizer shown in Fig. 5. When the pressure inside the dewier vessel is decreased, the soft bellows shrinks and a microswitch connects

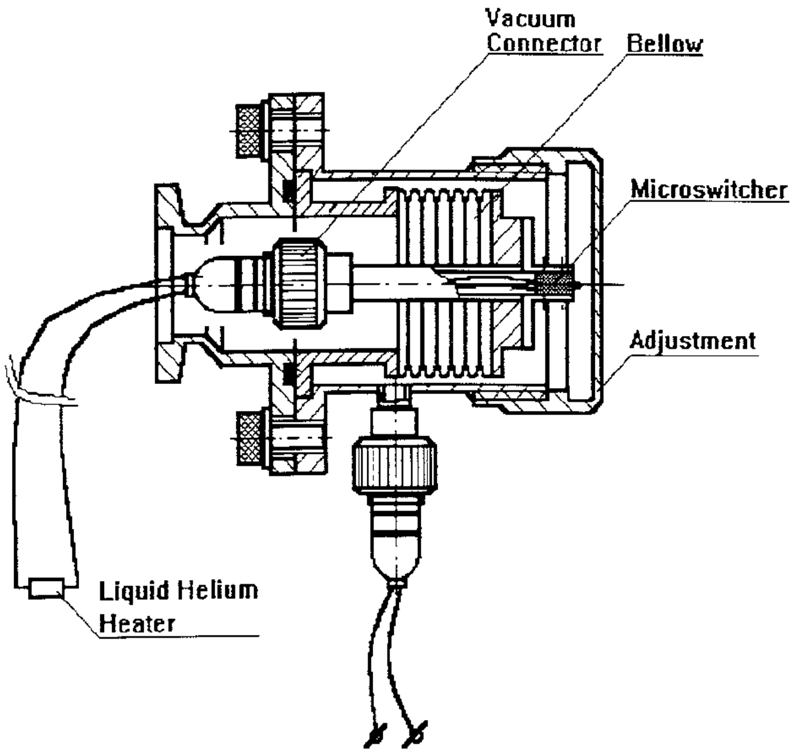

Fig. 5. A stabilizer of helium vapor pressure.

the small ohmic heater on the bottom of the dewier with a power supply. Liquid helium evaporates and pressure is increased up to initial level. The bellows spreads and the microswitch turns off the electrical circuit. The pressure is stable in the range of $(0.1 - 0.7) \pm 0.01$ bar. It is usually enough to maintain the stable temperature of cryogenic units. The temperature of porous sleeve achieves of 9-10 K in a 20-60 minutes in dependence of pressure into the dewier vessel. At the first stage experiments with repeating pipe-gun test rig shown in Fig.3 have been carried out. It was found that solid and liquid hydrogen penetrate through porous sleeve into a barrel under conditions shown in Fig.6. However, the cryogenic unit has been so small that under the shooting its temperature was changed from 8-10 K to 12-24 K only by acting of propellant gas impulse. Therefore, two operation modes have been realized: "liquid" mode and "solid" mode.

2.3.1. "Liquid" mode

In this case much hydrogen penetrate into the barrel just after the shooting because of the residual hydrogen gas (pressure 0.1-0.2 MPa), due to too long time of closing the vacuum valve between the barrel and pumping system which is operated manually.

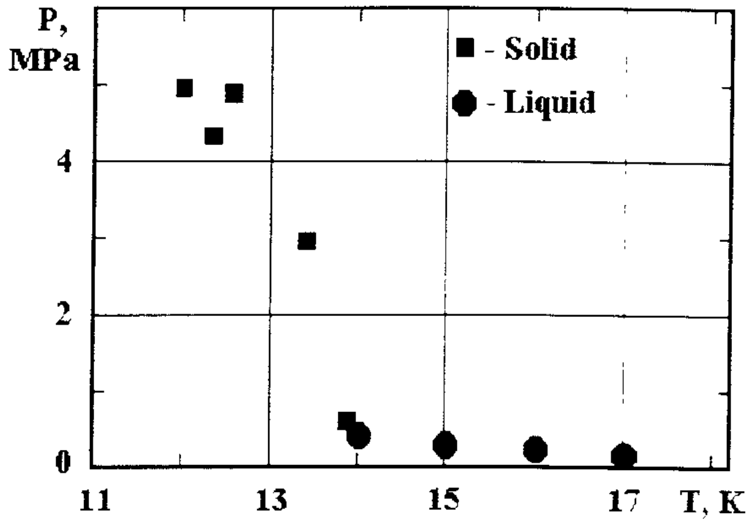

Fig. 6. Minimum pressure values available for penetration of the liquid and solid hydrogen through porous sleeve versus of the temperature.

Therefore, the inlet hydrogen valve was closed and has been opened only for pellet formation period. The typical thermal sensors signals of the process are shown in Fig. 7. After shooting (with delay less than 1 s) the vacuum valve has been closed and simultaneously the hydrogen inlet valve has been opened. During 2-4 s liquid hydrogen fills the barrel. The inlet valve has been closed and hydrogen is frozen for 5-8 s. Then the vacuum valve has been opened and the next shot has been done by a fast valve which admits the helium propellant gas into the barrel and so on. Propellant gas and pellet originated gas are evacuated by fore vacuum pump. The cycle can be repeated. The duration of the whole cycle was registered of 9-15 s and can be decreased by automatic operation and improvement of the cryogenic system. More than 200 pellets with temperature of 11.5-12 K have been formed and shot with frequency 1 shot per 9-15 s continuously in this mode. The pellet formation process and cycle duration have been recorded by a CCD-camera.

After the real barrel had been installed as it is shown in Fig.2, this operation mode has been realized in the cases of hydrogen and deuterium pellets. The pellet temperatures were equal of 9-10 K and 11-12 K respectively. The cycle duration of 11-25 s has been achieved under the manual operation. It has taken

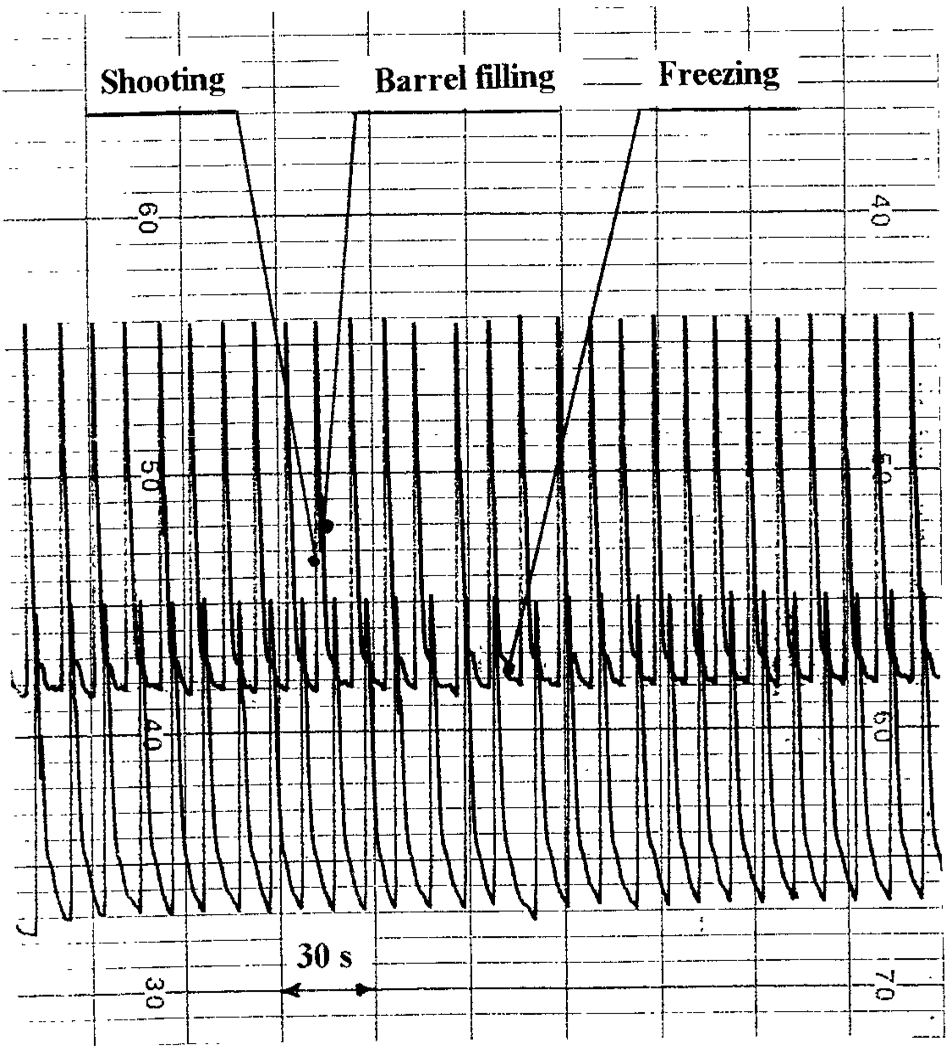

Fig. 7. The typical thermal sensors signals of the pellet formation and shooting process in the "liquid" mode.

3-5 s for filling of the diagnostic chamber by some small liquid droplets before the pellet has been formed inside the barrel. The pellet velocities above 1 km/s have been achieved with the initial helium propellant gas pressure of 40 bar. The typical quality and shapes of the pellets are shown in Fig.8.

In case of large porous cells the propellant gas penetrates inside of porous sleeve and fuel tube and evaporates the whole fuel. Nevertheless a new portion of deuterium gas formed a solid pellet passing through porous sleeve for 30-35 s. More than 60 pellets have been formed and accelerated in this case with frequency of 1 shot per 30 s continuously.

The repeating pipe gun pellet injector can operate unlimited time. The cycle duration will be decreased up to 1 shot per 3-5 s by means of an automatic control, improvement of the cooling system and using of the OFHC copper for the porous sleeve and the cryogenic unit.

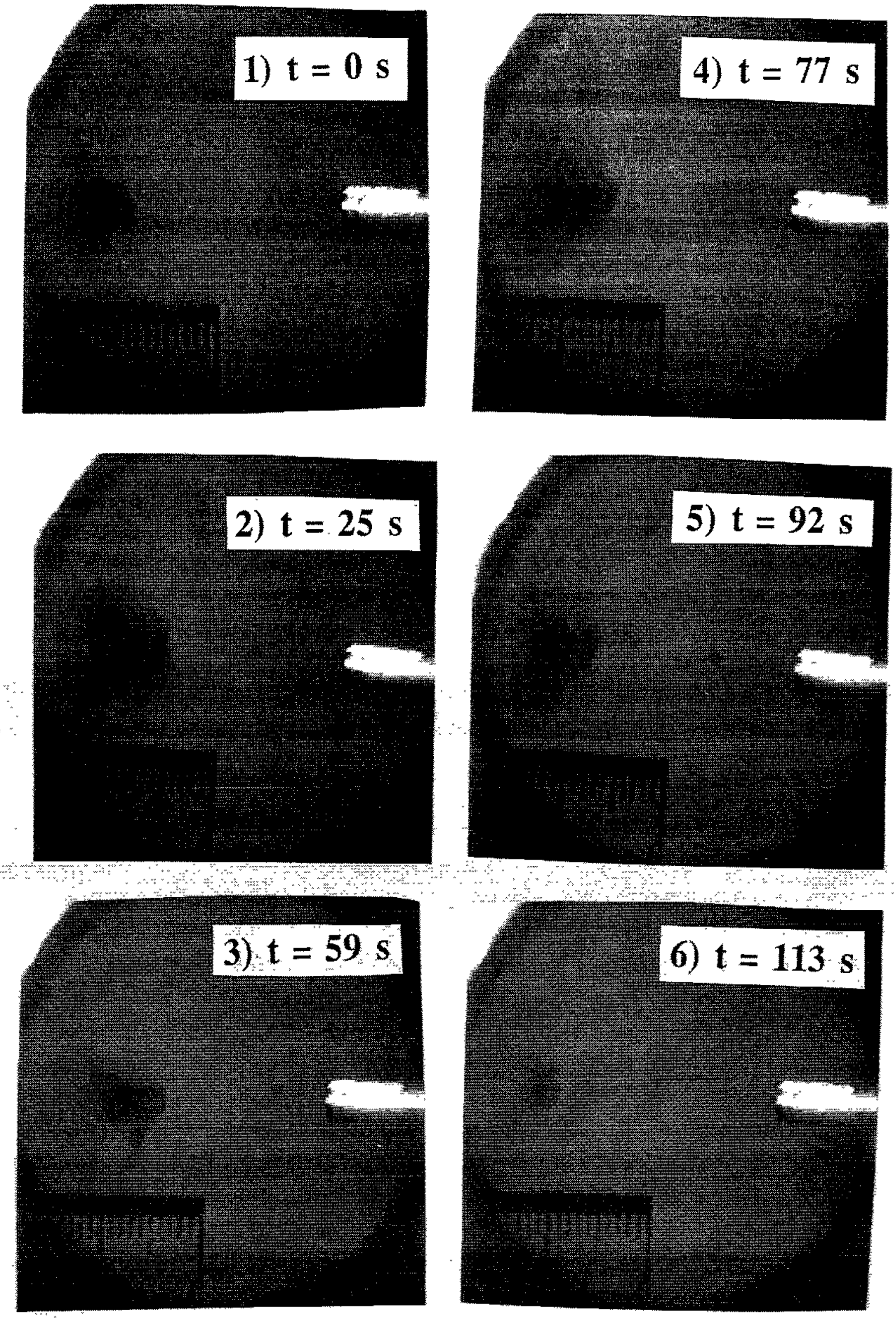

Fig. 8. A series of the hydrogen pellets.

2.3.2. "Solid" mode

In this case solid hydrogen under the pressure of 4.0-4.5 MPa penetrated inside the barrel just after the shooting for less than 1 s. The typical thermal sensors signals are shown in Fig. 9 The hydrogen inlet valve and the vacuum

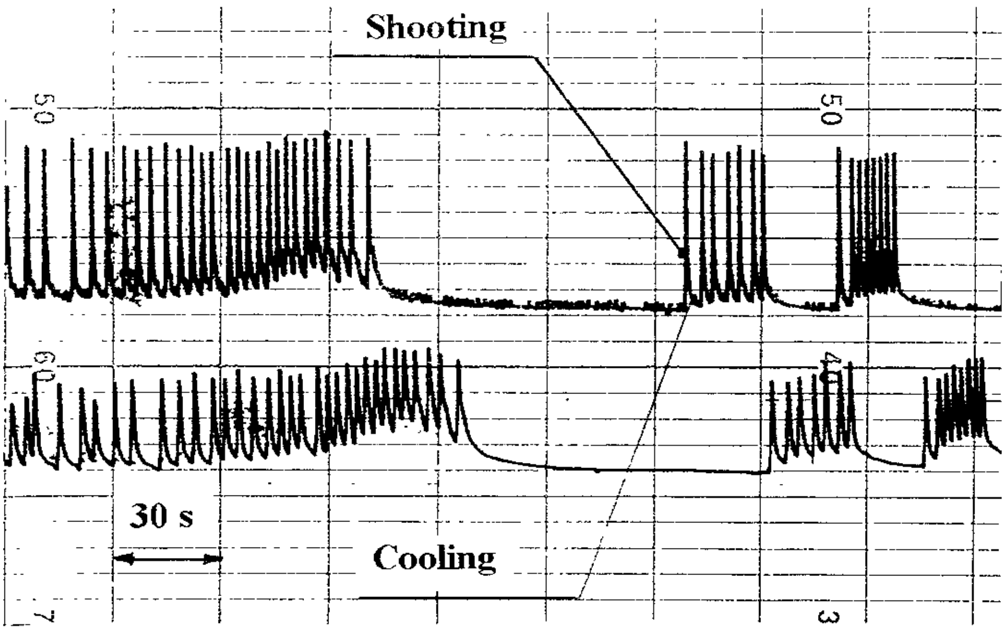

Fig. 9. The typical thermal sensors signals of the pellet formation and shooting process in the "solid" mode.

valve were opened all the time of operation of the test rig as shown in Fig. 3. The stable pellet formation and shooting cycle has been realized with frequency 1 shot per 2-3 s under the pellet temperature 12-12.5 K. There are no delays due to the liquid-solid phase transformation and the duration of the solid pellet cooling is more short than in case of the liquid one. In case of the application of more powerful cryogenic system and OFHC copper the process duration can be decreased up to 0.5-1 s at least.

When the pellet temperature had been reduced up to 10 K , the impulse heater has been switched on for 1-3 s before shooting and switched off just after it. So long time of heating is explained by bad layout of the heater concerning of porous sleeve. The whole cycle time was equal 5-6 s in this case.

The pellet formation process and cycle duration have been also recorded by a CCD-camera. More than 150 pellets have been formed and shot in this mode continuously under the propellant gas pressure of 1.5 MPa. After the real barrel and diagnostic chamber had been installed (Fig.2), the propellant gas heated the porous sleeve up to 20 K. Therefore this mode will be realized after improvement of the cryogenic system.

3. PELLET ACCELERATION TECHNOLOGY

3.1. Introduction

Amongst the existing pellet acceleration technologies, such as pneumatic (light gas gun) [3,6,12-15], mechanical (centrifuge machine) [16-18], electrothermal (arc discharged gun) [4,19,20], electromagnetic (rail gun) [7,21] and others, the pneumatic one has gained the most wide spreading especially for high-speed pellet injection. The most simple technique of pellet acceleration up to several km/s is the application of a two-stage light gas gun. The last results reported are the velocity of 3.4 km/s for a bare deuterium pellet [15] and the velocity of 4.3 km/s for one protected by a sabot [22]. Nevertheless higher pellet velocities are desirable (and are probably necessary) to provide fuel penetration deep for optimal performance. For example, in case of the pellet velocity of 5 km/s it can reach the plasma axis of LHD [2].

Almost all investigations of pellet acceleration are aimed to receive the maximum pressure (acceleration value) against which a pellet is able to sustain during its movement into a gun barrel. Several codes are developed to model the performance of pellet acceleration in a two-stage gas gun [23,24]. They take into account that the strengths of hydrogen and deuterium ice are very small (2-5 bar) and simulate the gas flow inside the barrel and pump tube with pressure peak as low as possible to achieve the maximum velocity. But the above-mentioned values are of tensile strength [25], while a pellet is exposed by a pressing force in the barrel. As well known some materials has different values of tensile and pressing strength limit. Moreover, the experiments show that the H_2 and D_2 pellets are not destroyed under the acceleration value up to 10^7 m/s^2 [4] or $(5\text{-}10)\cdot 10^6$ m/s^2 [7] corresponding to the pressure of 20-40 bar. Therefore, at first it is necessary to measure the pressing strength limit of H_2 (D2, T2).

Experimental data and simulation results show that the maintaining of pellet constant acceleration in a barrel requires increase of pressure in a pump tube up to of 2000 bar and over [9,23,26]. The main reason of such high pressure is the rarefaction waves coming from a pellet to the pump tube. They strongly reduce the gas pressure and temperature inside the local area affiliated to the pellet inside the barrel and new portions of propellant gas from the pump tube have no time to push up the pellet especially when its velocity close to sound speed. Moreover, the calculations show [23,26] that the gas friction and boundary layer also hinder the propellant gas from the pump tube to accelerate itself and accelerate the pellet. Actually it is easy to estimate that the average pressure acting on pellet during acceleration is equal to only 15 bar. All these factors stimulate the necessity to fill gun barrel by propellant gas from pump tube with high temperature and high pressure for a short time (0.3-0.8 ms) while a pellet is inside the barrel. Unfortunately the pressure peak being created by piston inside the pump tube is too short. The attempts to spread the peak pressure duration lead either to the too long pump tube [6] or to the application of two pistons inside it [26]. The both techniques lead to increasing of piston wear and they are not practical for steady-state operation of nuclear devices. In spite of high pressure inside the pump tube the propellant gas follows the pellet badly.

High pressure and temperature of gas inside the pump tube reduce the lifetime of piston due to its strong wear. The latter also increases the probability of pump tube damage due to gas leakage through split between piston and tube wall. If the maximum piston lifetime is 600 cycles, it means that in steady-state mode it will be a big problem to change pistons every 10 minutes especially for tritium compatible pellet injectors.

All above mentioned reasons impel us to propose a new technology for pellet acceleration into a two-stage gas gun. In our opinion, it may resolve the problems of piston lifetime and increase the pellet velocity. But at first consider the pellet strength problem.

3.2. Pellet destruction model

The key issue of the achievement of pellet high velocity is the elucidation of the maximum pressure admissible for pellet acceleration without destruction.

Let a homogeneous cylindrical solid hydrogen pellet with length **L** in moment **t=0** expose to pressure **P(t)** in the section **x=0** coinciding with the one of the pellet edges. Second edge at **x**=L remains free. The axis **x** is directed along the pellet axis. Let **u(x,t)** is the displacement of pellet section **x** in the moment **t**. Then in elastic area it can be written for **u(x,t)**:

$$\frac{\partial^2 \mathbf{u}}{\partial t^2} = \mathbf{a}^2 \frac{\partial^2 \mathbf{u}}{\partial x^2}, \qquad (1)$$

with the initial and boundary conditions:

$$\mathbf{u}(\mathbf{x},0) = 0,$$
$$\mathbf{u}_t(\mathbf{x},0) = 0,$$
$$\mathbf{u}_x(0,\mathbf{t}) = -\frac{P(t)}{E},$$
$$\mathbf{u}_x(L,\mathbf{t}) = 0,$$

where: $\mathbf{u}_x = \frac{\partial u}{\partial x}, \mathbf{u}_t = \frac{\partial u}{\partial t}, \mathbf{a}^2 = \frac{E}{\rho}$, E - Young module, ρ – solid hydrogen density, **P(t)** - pressure acting on the pellet in the section **x**=0. In general pellet status at **t** > 0 is determined with superposition of pressing-rarefaction waves spreading inside the pellet under the sound speed **a** [27]:

$$u(x,t) = f\left(t - \frac{x}{a}\right) + \sum_{n=1}^{\infty} (-1)^n \left[f\left(t - \frac{x}{a} - 2n\frac{L}{a}\right) - f\left(t + \frac{x}{a} - 2n\frac{L}{a}\right) \right] \qquad (2)$$

Function $f(z)$ is determined from boundary conditions; besides $f(z) = 0$, if $z \le 0$. The equation (2) is infinite sum, but in every moment **t** only finite number of its components differs from zero. It is easy to check that the tension at **x=L** is equal of zero and the maximum tension acting on pellet is in section **x=0**. Along moving pellet the pressing-rarefaction waves spread with period **2L/a** step by step compressing the pellet.

Let, for example, pressure function

$$P(t) = P_0 t, \qquad P_0 = \frac{dP(t)}{dt} = \text{const.}$$

Then the tension σ in the section **x=0** is equal:

$$\sigma(0,t) = -E\frac{\partial u}{\partial x} = P_0 t.$$

A hydrogen pellet under the temperature less than 7 K is brittle and if the tension $\sigma(0,t) > \sigma_s$, where σ_s is the pressing strength of solid hydrogen, then the pellet is destroyed. But under the temperature of 9-9.5 K a hydrogen pellet is plastic and if the tension $\sigma(0,t) > \sigma_p$, where σ_p is the fluidity strength limit of solid hydrogen, the pellet starts to flow, not being destroyed. Under the stationary (or slowly changing) load a pellet will be compressed only. Pellet destruction can arise because of shock waves when they are reflected from the free edge of pellet. If by the moment $t = 2L/a$, when the pressing wave is reflected from the free edge of pellet and comes back to the section **x=0**, the tension $\sigma(0,t)$ does not exceed σ_p, the pellet is compressed and accelerated without shock waves and destruction. This condition can be written as:

$$\frac{dP}{dt} < \frac{\sigma_p a}{2L}. \qquad (3)$$

For solid hydrogen the values $\sigma_p \approx$ 2 bar, $a \approx 2$ km/s, thus 4 mm size pellet can be accelerated under the pressure increasing as

$$\frac{dP}{dt} \approx \mathbf{0.5\ bar/\mu s}. \qquad (4)$$

Thus if the condition (3) is observed, it means that the pressure inside the pellet is increased more slowly than tension relax due to spreading of pressing-rarefaction waves from the one edge of the pellet to the other and back. Certainly pellet can be destroyed if it is very fluid and soft as a liquid at temperatures above 11-12 K due to spreading on the barrel walls. It is more important for acceleration to increase the pressure continuously in accordance with the condition (3) than use the long barrel where the pellet will strongly lose its mass because of friction. The pellet under the condition (4) can be accelerated up to 5 km/s for 0.3 ms in the barrel of 0.6 m length. Gas pressure acting on the pellet by the end of acceleration will be equal of 150 bar and pellet will be plastic deformed but without destruction. Because of the high tension inside the pellet it is necessary to use barrel with very smooth surface of inner walls and ensure the smooth decreasing of pressure before the pellet flies out from the barrel. It should be noted that dynamic strength of materials as a rule exceeds the stationary one therefore the condition (4) can be varied. It is also important to use a pure hydrogen (deuterium) with low amount of impurities [15].

In fact the pellet destruction process is more complex than it is written in equations (1-2). But for zero approximation the condition (3) is also useful.

3.3. Description of principle

Ideas of the new proposal are following [28] (see Fig. 10):

1) piston should be destroyed and produced in every shot as a pellet; it can be produced both of deuterium or more strength material; for example, the krypton and xenon ice has a strength 40 bar (80 K) and 52 bar (100 K) respectively [29];

2) piston is accelerated not only inside a pump tube, but inside a barrel too. Thus two pellets are accelerated and last one destroyed and evaporated during a shot.

The proposed technology consists of some components:

1. A pump tube cylinder must be produced of low heat conductive stainless steel with diameter by 2-3 times larger than a pellet one and have a short cryogenic surface as it is shown in Fig. 10.
2. A piston inside the pump tube must be produced of hardened gases or others materials which are able to be destroyed and evaporated under the high pressure or impact. It is produced of gas or liquid as a pellet (for example, by extrusion technology for 0.5-1s) and used only one time. It is preferable to choose material which is able to be deformed fluidity.
3. A head of the barrel should have a special profile to transform subsonic gas flow to supersonic one.
4. A pellet must be housed right from the beginning of the barrel.

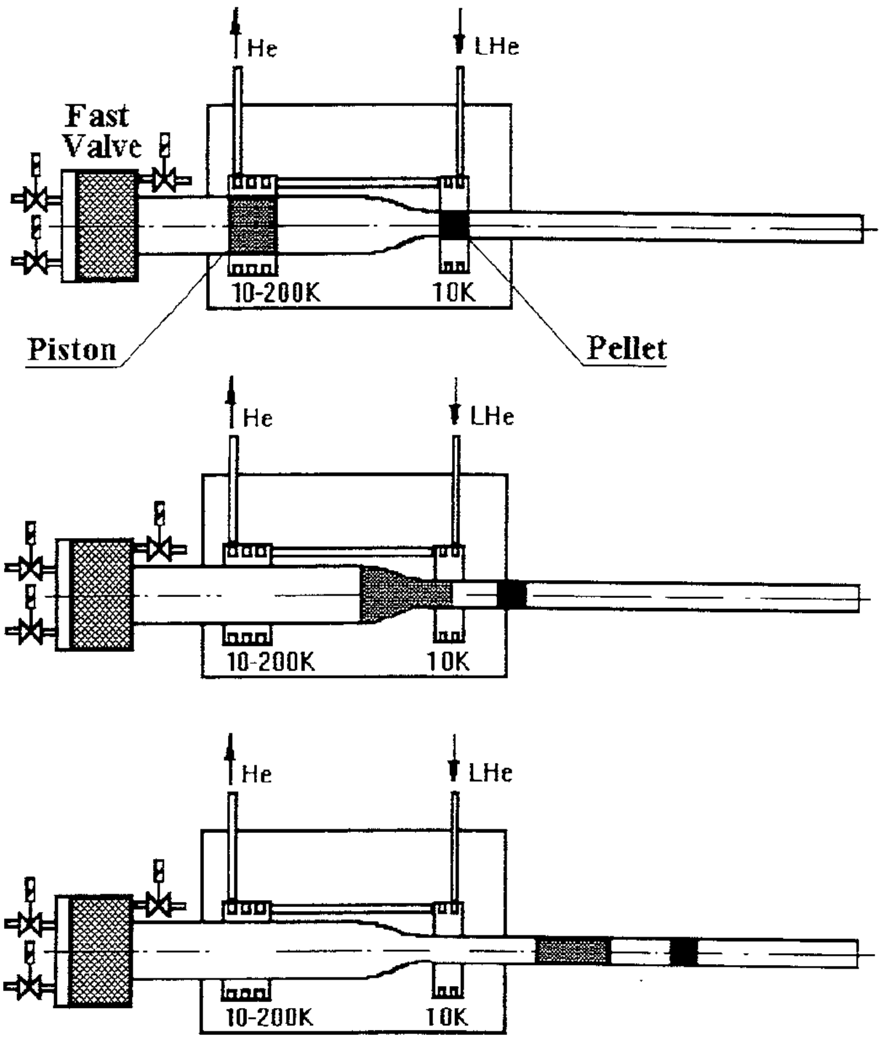

Fig. 10. Schematic of a new operation principle of a two-stage light gas gun.

The principle of operation is as follows (see Fig. 10):
A piston and a pellet are produced simultaneously in the different parts of a two-stage gas gun. A propellant gas at low pressure fills the volume between the piston and pellet. A fast valve admits the gas from reservoir into pump tube behind of the piston. Gas accelerates the latter up to the maximum velocity (in dependence on properties of gases and piston). Piston compresses the propellant gas and pushes out it into the barrel. When the piston comes to the end of the pump tube, it will be deformed (or destroyed) and penetrate into the gun barrel. Its velocity should be as high as possible. During the part of acceleration time, piston will drive the pellet increasing and maintaining the pressure of propellant gas. After the pellet and remained part of piston fly out

from the barrel, the piston will be destroyed and evaporated under the impact about a metallic surface.

Some modifications of this technology can be proposed. It is possible to accelerate instead of a piston a solid hydrogen (deuterium) pellet too. An additional fast valve at the end of pump tube to increase piston velocity may be also useful.

The possibility of realization of proposed "double pellet" technology follows from the following arguments. In the simplest case it can be considered the movement in a tube of constant diameter a pellet with mass equal sum of ones of pellet, piston and gas between them. Such complex pellet can be accelerated up to 1.4 km/s with application of usual fast valve. The initial parameters of gas between piston and pellet should be chosen thus that the gas by the moment of acceleration up to 1.4 km/s was compressed and heated due to piston movement up to 30-40 bar and 1000-2000 K respectively. If in this moment the piston is suddenly stopped the pellet will be accelerated only by this gas expansion else up to of 2 km/s for a 0.4 ms in the barrel of 0.5 m length. Thus the final pellet velocity will be equal of 3-3.5 km/s. In fact the pellet velocity will exceed these values because of the piston will proceed its movement behind of the pellet and decrease the distance between them. The rarefaction waves will be reflected from the piston surface and returned to pellet maintaining the more high level of average propellant gas pressure. Besides, the more high pressure than 30-40 bar can be applied probably for moving pellet. The pressure increasing should not be too fast in accordance to the (3) condition. In this case the pellet velocity will exceed of 5 km/s.

Certainly an accurate model should be developed to simulate movement of gas, piston and pellets and determine parameters of acceleration.

4. CONCLUSION

Two new technologies of continuous pellet production inside of a pipe-gun type pellet injector and acceleration into a two-stage light gas gun have been proposed.

The proof-of-principle of new pellet production technology has been demonstrated in a small pipe gun. The main idea of technology is the production of pellet similar as "in-situ" condensation but by means of heating (melting) of solid fuel. It decreases the pellet formation time and allows to create a continuous repeating pipe-gun type pellet injector. The results are greatly promising both for LHD and for the other steady-state operation fusion devices. The systematic study should be carried out for development of such type of pellet production units for "HIPEL" Pellet Injection System for Large Helical Device.

The principles of the new pellet acceleration technology have been formulated on the basis of analysis of two-stage gas guns operation. It has been proposed to apply a piston, being produced as a pellet, only one time and accelerate piston inside of a barrel behind of the pellet. This "double pellets" technology allows to avoid of problems with piston lifetime and to maintain a pressure acting on the pellet inside the barrel. It looks promising for achieving of the pellet velocity up to 5 km/s. The simulation of the pellet and the piston movement should be carried out to determine the parameters of acceleration process.

Both proposed technologies are promising for continuous and reliable operation of pellet injection systems. They have not any moving details limiting the operation time and require only a small amount of fuel for a pellet production. They also look compatible with tritium technology. The successful development and application of these technologies in "HIPEL" Pellet Injection System allows to improve its parameters and create a prototype of future refueling systems for fusion power stations.

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