Technical University of Denmark

# Investigation of Pellet Acceleration by an Arc Heated Gas Gun. An Interim Report on the Investigations Carried out from 1985.09.01 to 1987.03.31

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Risø National Laboratory, DK-4000 Roskilde, Denmark
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# INVESTIGATION OF PELLET ACCELERATION BY AN ARC HEATED GAS GUN*

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**Abstract.** This report describes work on pellet acceleration by means of an arc heated gas gun. The work is a continuation of the work described in Risø-M-2536. The aim of the work is to obtain velocities well above 2 km/s for 3.2 mm diameter deuterium pellets. By means of a cryogenic arc chamber in which the hydrogen propellant is pre-condensed, extruded deuterium pellets are accelerated up to a maximum velocity of 1.93 km/s. When increasing the energy input to the arc in order to increase the pellet velocity further the heat input to the extrusion/punching pellet loading mechanism was found to be critical: preparation of pellets became difficult and cooling times between shots became inconveniently long. In order to circumvent this problems the concept of a room temperature hydrogen propellant pellet fed arc chamber was proposed. Preliminary results from acceleration of polyurethane pellets with this arc chamber are described as well as the work of developing of feed pellet guns for this chamber. Finally the report describes design consideration for a high pressure propellant pellet fed arc chamber together with preliminary results obtained with a proto-type arc chamber.

* This work was done under Art.-14 contract No. JR4/9006 Extension No 1 between the JET Joint Undertaking and the Fusion Research Unit of the Association Euratom-Risø National Laboratory.

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Risø National Laboratory, DK-4000 Roskilde, Denmark

CONTENTS

## I. INTRODUCTION

This report describes work done under an Art.-14 contract No. JR4/9006 Extension No 1 between the JET Joint Undertaking and the Fusion Research Unit of the Association Euratom-Risø National Laboratory. The report, which covers the the work done in the period from September 1985 to the end of March 1987, should be considered as a direct continuation of the report /1/, which covers the first part of the contract work from the start of June 1984 to the end of August 1985.

Report /1/ describes the background of the work, the experimental set-up in details and the preliminary results obtained from acceleration of deuterium pellets. Most of the work described in /1/ concerned the establishment of the experimental set-up with tests of the cryogenic pellet producing unit and the diagnostic equipment. In these tests deuterium pellets were fired by an ordinary fast valve, room temperature hydrogen propellant gas acceleration and only a few preliminary results were obtained with arc acceleration.

The present report describes the results obtained in the continued work with arc acceleration. The work with acceleration of extruded deuterium pellets by means of a cryogenic arc chamber is described in chapter II. The new concept of a hydrogen pellet fed room temperature arc chamber, and the work with acceleration of polyurethane pellets is described in chapter III. Chapter IV describes the work with a pipe gun for production of large feed pellets for the pellet fed arc chamber and chapter V describes design considerations for high pressure arc chambers to be fed by pellets and high pressure hydrogen gas. Finally chapter VI contains conclusions and plans for continuation of the work.

## II. THE CRYOGENIC ARC CHAMBER

### II.1. Experimental set-up for acceleration of $D_2$-pellets

As the experimental set-up for acceleration of deuterium pellet is described in details in /1/, only a brief summary is given here.

A deuterium pellet could be punch-loaded into a gun barrel (3.2 mm diameter, 950 mm long) by means of a cryogenic extrusion and punching mechanism. A cylindrical arc chamber, fig. II.1.1. (20 mm diameter, 25 mm long) was connected coaxially through a conical nozzle to the breech of the barrel. The arc chamber was placed within the thermal radiation shields of the cryogenic deuterium pellet forming unit and kept at a temperature of about 8-10 K. At this temperature hydrogen gas could be introduced into the arc chamber through a capillary tube, whereby a layer of solid hydrogen condensed at the inner wall of the chamber. By igniting an electrical discharge from a co-axial central electrode in the chamber to the inner wall the condensed hydrogen was evaporated and heated and the deuterium pellet was accelerated down the barrel by the hot hydrogen propellant gas.

The motion of the pellet in the gun barrel was observed by optical detectors coupled to the barrel by means of optical fibers and the pressure development in the barrel was monitored by means of pressure transducers connected to the barrel.

The arc was driven by a power supply consisting of 4 capacitor batteries (each of 80 µF/2.8 kV). The output resistance and inductance for each battery could be varied and the batteries could be fired in a preselected time sequence.

## II.2. Results

The results which are described in the following were obtained with 3.2 mm diameter $D_2$-pellets accelerated in a 950 mm long gun barrel.

The loading and firing procedure was the following. With the arc chamber at cryogenic temperature (around 8 K) a dose of hydrogen gas was introduced into the arc chamber where it condensed on the inner surface of the chamber wall. After this the extrusion/punching mechanism was activated to load a $D_2$-pellet into the gun barrel. Then the arc chamber was heated slightly by an ohmic heater in order to increase the hydrogen pressure to a level suitable for ignition and the electrical discharge was fired.

This procedure was found to give the most reproducible shots. At first a reversed sequence of loading the arc chamber and the gun barrel was tried. However when the deuterium pellet was loaded into the gun barrel before the hydrogen gas was loaded into the arc chamber the pellets were more often found to disintegrate during the shot.

Possibly the pre-loaded deuterium pellet was weakened by the influence of the hydrogen gas being loaded into the arc chamber due to the temperature increase in the cryogenic environment associated with the condensation of the hydrogen gas.

The stability of the deuterium pellets was generally found to be a problem in the experimental work. Each step forward in obtaining higher pellet velocities was associated with improvements in the extrusion/punching pellet loading mechanism rather than with optimization of the arc discharge parameters.

Several parameters for the cryogenic pellet loading system, such as extrusion temperature/pressure and knife edge shape of the punching barrel, were adjusted in order to improve the stability of the produced pellets. As described in /1/ the cryogenic pellet producing system could be tested also with fast valve acceleration of the produced pellets. This was done by means of a connecting plug inserted into the arc chamber through which the fast valve could be fired for test acceleration of the pellets with room temperature hydrogen gas. However, in this way the stability of the pellets could be tested only up to acceleration pressures producing muzzle speeds up to 1100-1200 m/s.

By changing to arc acceleration with unchanged extrusion system, somewhat higher muzzle speeds could then be obtained. If, however, the electrical power input to the arc was increased in order to obtain higher velocities the pellets disintegrated and no improvements were found by shaping the power pulse to produce a more soft propellant pressure increase rate.

The progress in getting higher pellet velocities was obtained mainly by further optimization of the deuterium pellet extrusion/punching system. The quality of the produced pellets was found to depend critically on the temperatures of the different parts of the system, such as the extrusion cylinder containing the solid deuterium being extruded, the extrusion nozzle, the barrel piece with the punching knife edge and the barrel piece against which the punching was done. These temperatures were adjusted partly by changing the thermal couplings between the different parts and the cryostat base and partly by changing the distribution of the ohmic heaters used for dynamic temperature control.

Besides of optimizing the temperature distribution of the extrusion/punching system to get stable pellets also geometrical changes of the system were tried.

Different shapes of the knife edge of the punching barrel piece were tried and most successfully the cross section of the channel in the extrusion nozzle was changed from a circular cylindrical to a rectangular shape. By this change the shape of the punched pellet was changed (flat ended pellet) but also the area reduction ratio of the extrusion nozzle was increased in this way, so that extrusion of a more soft deuterium material could be done at increased temperature without loss of control of the extrusion process.

The best results were obtained by using a stainless steel nozzle with a 3.6 by 5.6 mm rectangular cross section with the 3.6 mm defining the length of the punched pellet. With this nozzle whole pellets could be fired with velocities around 1900 m/s (max. recorded velocity 1934 m/s).

A typical time behavior of the arc current and voltage is shown in Fig.II.2.1. and Fig.II.2.2. respectively (# 209, 10-OCT-85). The arc current reaches a maximum value of about 1.4 kA in about 200 μs and the arc voltage reaches an oscillating level of about 1500 V.

Figure II.2.3. shows the arc voltage oscillations with increased tim resolution and Fig.II.2.4. shows the electrical power input to the arc.

Figure II.2.5. shows the time behavior of the pressure in the arc chamber and Fig.II.2.6. shows the pressure in the barrel at a position 220 mm downstream from the pellet seat. The arc chamber pressure was measured by means of a home made piezo electric quartz transducer the calibration of which was undetermined at cryogenic temperature, so only information of the relative pressure time behavior can be obtained from the trace.

Figure II.2.7. shows how the pellet velocity varies with the charging voltage of the capacitor battery. The pellet velocity was measured by time-of-flight between two optical light barrier detectors placed 215 mm and 315 mm from the muzzle of the gun barrel.

Figure II.2.8. shows a diagram in which results from ordinary fast valve and arc acceleration are compared. The diagram shows the initial pellet velocity as a function of distance in the first part of the barrel together with figures for the acceleration and muzzle speed for arc acceleration and fast valve acceleration. These data indicate the maximum values for velocity and acceleration obtained by the two methods. The results were obtained with a fast valve pressure of 50 bar in the case of valve acceleration, and with a capacitor charging voltage of 2500 V and a hydrogen propellant dose of around 75 bar cm in the case of arc acceleration.

The integrity of the pellets was judged partly by the analog signal from the optical light barrier detector placed 215 mm from the muzzle end of the barrel and partly by 20 ns flash photos of the pellets.

Figure II.2.9. shows a photograph of a 1920 m/s pellet. The picture was obtained by means of a 20 ns light flash at a position of 415 mm from the muzzle of the barrel. The flash was triggered by the signal from an optical detector with a light barrier in the frame of the photo. Only a few photographs of pellets with velocities above 1900 m/s were obtained because of false triggering of the flash due to small precursor fragments passing the trigger detector at a time where the pellet was not within the frame of the photo.

The existence of these fragments accompanying the pellets at velocities around 1900 m/s and the fact that the pellets disintegrated in many of the shots indicated that further improvement in the pellet quality was needed in order to reach higher velocity ranges.

However, in order to increase the velocity of the pellets the electrical power input to the arc was increased in addition to the improvements of the quality of the extruded pellets . With the amount of electrical energy (around 400 Joule) dissipated in the arc chamber to produce a pellet velocity around 1900 m/s the temperature rise in the cryogenic system became disturbing in two ways.

Firstly the heat developed in the arc chamber was conducted to the extrusion/punching mechanism thereby destroying the solid deuterium stored for the following shots. Secondly the cooling time required after a shot to get stable cryogenic temperatures for the extrusion/punching system and the arc chamber became inconveniently long (around 30 min.) .

Due to the inevitable leakage of the extrusion/punching system, cryo-condensed deuterium or hydrogen on the electrical high voltage connections to the arc chamber often caused problems with flash-over.

In order to circumvent these problems a new arc chamber concept was developed as described in the following chapter.

## III. THE PELLET FED ARC CHAMBER

### III.1. Working principle

In order to circumvent the problems encountered with the cryogenic arc chamber but maintaining the idea of producing a fast rising pressure pulse of hot hydrogen gas from arc evaporation and heating of cryo-condensed hydrogen the concept of a pellet-fed arc chamber was proposed.

In this concept a feed pellet of cryo-condensed hydrogen should be injected into a room temperature arc chamber and, after closing the injection channel, the hydrogen is vaporized and heated by the electrical energy of an arc.

A schematic diagram of the new arc chamber is shown in Fig. III.1.1. The general features are the same as for the old one: a cylindrical chamber with a central electrode placed in an isolator block opposite the conical outlet nozzle. The new feature of this chamber is that a pellet of cryo-condensed hydrogen may be introduced through an inlet tube into the chamber. By means of valve (1) the inlet tube is closed about 10 ms after the pellet is introduced and the arc can be ignited.

In this way an arc with the same gas heating efficiency as that of the cryogenic arc chamber can now be produced in an arc chamber maintained at room temperature.

The propellant pellet must be injected into the arc chamber in such a way that it enters and stays in the chamber with a small evaporation rate until the inlet valve is closed and the arc can be fired. This is accomplished by injecting the pellet at a low velocity (about 50 m/s) tangentially through a channel in the insulator block, whereby the injected pellet is brought into a circulating motion along the inner surface of the chamber.

**III.2. Set-up for acceleration of polyurethane pellets.**

The pellet-fed arc chamber has so far been used only for acceleration of polyurethane foam pellets having a mass density of about 300 $kg/m^3$ as compared to 200 $kg/m^3$ for deuterium. These preliminary experiments were made with the small interim power supply to investigate the initial phase of pressure build-up and acceleration.

Figure III.2.1. shows a diagram of the experimental set-up used for testing the pellet-fed arc chamber by acceleration of projectile pellets made of polyurethane.
The propellant pellet is produced by in-situ condensation (pipe gun principle) in a 3.2 mm barrel tube in a He bath cryostat. With valve (1) and valve (2) open the pellet is injected through the guide tube into the arc chamber.

The arrival of the pellet is detected by an optical pellet detector, which triggers the closure of the gate valve (1). The detector also triggers the arc after a time delay corresponding to the closing time of the valve.

Valve (2) is closed during the formation of the propellant pellet and valve (3) is a fast valve which may be used for injection of hydrogen gas for accelerating the propellant pellet.

A more detailed description of the work with the development of the feed pellet injector is given in chapter IV.

### III.3. Results with the pellet fed arc chamber.

Pellets of polyurethane (d=3.2 mm, l=4 mm, $\rho$=300 kgm$^{-3}$, M=10 mg) were accelerated in a 150 mm long barrel. The arc chamber was positioned 80 mm from the pellet seat and fed with hydrogen pellets of about 75 bar cm$^3$. The volume of the arc cavity was 1.5 cm$^3$.

Figure III.3.1. shows oscillograms of the time development of some relevant parameters in a particular shot with a battery charging voltage of 2.7 kV and the time delay between each battery unit set to 5 µs. The time scale is 100 µs/div for all traces with the ignition time indicated by the arrows. Trace A shows the arc current (400 A/div) with a peak of 1.9 kA at 150 µs. Trace B shows the arc voltage (200 V/div) reaching about 900 V. Trace C shows the arc chamber pressure (34.6 bar/div) with a peak of about 125 bar at about 250 µs. Trace D shows the barrel breech pressure (21 bar/div) at a position 34 mm upstream from the pellet seat, reaching a peak value of about 100 bar at 250 µs. Trace E shows the barrel pressure (15.6 bar/div) at a position 21 mm downstream from the pellet seat with a peak value of about 75 bar. Trace F shows the signal from the first optical fiber detector at a position 1 mm from the pellet front in its starting position. The first negatively going transient of this curve shows, that the pellet starts its motion 120 µs after ignition. The following positively going signal is caused by light from the discharge. Measurements of an initial acceleration of up to about 6 10$^6$ m/s$^2$ for the 10 mg polyurethane pellets agrees with the measured initial acceleration pressures of about 75 bar.

With no external change in firing conditions, the arc chamber pressure is found to scatter between 100 - 130 bar from shot to shot. From the slope of trace D the breech pressure increase rate is seen to be of the order of 700 bar/ms.

In the present set-up the power input to the arc chamber and hence the arc chamber pressure development is limited by the serial inductance of the magnet coil in the arc circuit. By driving this coil by an independent power supply even larger pressure increase rates may become attainable.

## IV. PIPE GUN FOR PRODUCTION OF SLOW FEED PELLETS

### IV.1. Principle.

The feed pellet for the arc chamber comes from a pipe gun, where the pellet is formed in situ in the gun barrel. This gun type was first suggested by Claudet and his collaborators at CEA in Grenoble and it was first used at TFR in Fontenay-aux-Roses in Paris /2,3/. Pipe guns have later been built also in Oak Ridge National Laboratory /4/.

Actually a device resembling a pipe gun was made in Frascati as early as in 1968 /5/.

The principle is illustrated schematically in Fig.IV.1.1. Three rings are placed on a tube and are cooled to liquid helium temperatures, while the two ends of the tube are at room temperature. Strong temperature gradients will thus exist in the tube just at the rings, and when gas is let in from both sides the gas will condense in the freezing cell inside the ring system to form a pellet. The pellet may hereafter be blown out by means of a fast valve in the normal manner.

In Grenoble and Oak Ridge the cooling is made with a flow of liquid helium through cooling channels on ring 2. The freezing cell is made from copper having good heat conductivity; it is insulated from the gun barrel which may be heated with electrical heaters at the positions of the rings 1 and 3 in order to improve the temperature gradients.

### IV.2. Pipe gun no 1.

At Risø a pipe gun with a nominal pellet diameter of 3.2 mm has been used since January 1986 for injection of hydrogen feed pellets into the arc chamber. The pellets should be injected with low velocities in order that the pressure increase in the arc chamber does not occur too fast. The demands to the gun are thus different from the two above mentioned ones.

The pipe gun, actually the one shown in Fig.IV.1.1. is placed below the base of a liquid helium bath cryostat, Oxford Instruments MD4A, and is cooled through thermal couplings between the three rings and the cryostat base. The three rings may again be heated with electrical heaters. The three ring blocks are made from copper. The gun barrel and the connections between the ring blocks are made from thin-walled stainless steel tubes having low heat conductivity. By using a strong thermal coupling to ring 2 and weak couplings to rings 1 and 3 it was possible to obtain thermal gradients strong enough to allow formation of a pellet inside only ring-block 2. By using strong couplings to rings 1 and 3 also it was possible to form a long pellet extending out into ring-blocks 1 and 3. In the latter case it is possible to form a pellet only inside ring 2 by using electrical heating at rings 1 and 3, however, with increased consumption of liquid helium.

The gun was used normally with formation of pellet only inside ring-block 2. The gas was obtained from a 2 liters-reservoir held at a pressure of around 800 mbar and it was let in through a needle valve, NV. During the formation of the pellet the temperature could thus be regulated by means of the pressure and the setting of the NV. The temperature at ring 2 was normally observed during the formation of the pellet, and it shoved up that it started to decrease when a certain amount of gas had condensed, i.e., the condensation of gas ceased and the pellet no longer increased. The formation of the pellet actually saturated. On photographs of pellets conical holes were seen in the ends and pellets made with less gas than needed for saturation were tubular. The pellet length was around 1.5 times the length of the ring block.

To blow the pellet out with a fast valve and a propeller gas pressures of some bar gave no problems. It was more difficult to blow the pellet out with a low velocity. Solid hydrogen sticks well to metal and the pellet should therefore be loosened from the barrel before being blown out. This is done by heating the barrel 60 to 75 seconds so that the outer layer of the pellet is softened or even vaporized.

When the set up was heated in this manner the pellet mostly came out with low velocity, around 40 m/s, before the fast valve was fired; i.e., the pellet was self propelled. During the heating pellet material evaporates; the cold gas moves backwards into the warmer region and expands here. We believe that this expansion may be forceful enough to force the pellet out and also that this way of forcing the pellet out gives a more gentle start for the pellet than does the fast valve. It is possible also to fire this gun with fast valve and low propellant pressure if the firing is made just before the gun would be self fired; the timing should, however, be rather precise and we therefore preferred to operate the gun self propelled when slow pellets were needed.

During operation of the gun electrical heaters and electromagnetic valves should be activated as was also the case for the extruder gun; the operation is made automatically by means of a PLC.

An extruder gun may fire as frequent as once every 3 minutes. For a pipe gun the time interval will be larger, since the time between start and firing now also includes the time needed to form a pellet by condensation.

It is believed, that the long time needed to prepare firing of the gun was partly caused by the use of stainless steel tubes between the ring-blocks. Stainless steel is a rather bad heat conductor at liquid helium temperatures; actually the heat conductivities of stainless steel and normal solid hydrogen are rather close together.

## IV.3. Pipe gun no 2.

In the second pipe gun this inconvenience was avoided by making the whole gun from one piece of brass, which is around 10 times better heat conducting than stainless steel. The outer part of the rings was still made from annealed copper. The actual barrel of 4.5 mm inner diameter was made as short as possible to keep the velocity low. Between the brass barrel and the valve, where the outer guide tube starts, the pellet is transported in a 5 mm stainless steel tube. The length of the center ring is 5 mm, the distances to the outer rings are 7 mm, while the lengths of the outer rings both were 5 mm.

There is an electrical heater on ring 2, the central one, while another heater is shared between rings 1 and 3. A third heater is split up in 4 parts and placed on the barrel outside the rings and between the rings. For the two first heaters we may use low current to adjust the temperature during formation of a pellet and high current during heating just before firing.
A standard gas flow diagram, shown in Fig.IV.3.1., is used. The hydrogen gas used for the pellet and the hydrogen gas used as propellent were taken from two reservoirs each of 2 liters. The pressures in the reservoirs were measured and controlled with piezoelectric meters. The pellet is fired out through a VAT gate valve, V16, it thereafter enters a guide tube of 6 mm inner diameter through which it is transported to a $\Delta P$ vacuum chamber.

The propellent gas may be pumped at the entrance to the guide tube. The diagnostics, two optical detectors for velocity measurement and a set up for photographing the pellet are placed just before the ΔP chamber.

The PLC program is divided in 7 successive blocks each of adjustable duration. The block diagram is shown in table 1.

**Table 1: The PLC block diagram**

| Action | ...1.. | ...2.. | ...3.. | ...4.. | ...5.. | ...6.. | ...7.. |
|---|---|---|---|---|---|---|---|
| Pump V4 | | | ----- | | | ----- | |
| H2 inlet V7 | ----- | | | | | | |
| Isolate V9 | ----- | ----- | ----- | | | | |
| H2 prop. V10 | | | | ----- | ----- | | |
| Cut off V14 | | | | ----- | ----- | | |
| Fast Va. V15 | | | | | ----- | | |
| Out Va. V16 | | | | ----- | ----- | | |
| Heater 1 | ----- | ----- | ----- | ----- | ----- | | |
| Heater 2, low | ----- | | | | | | |
| Heater 3, low | ----- | | | | | | |
| Heater 2, hi | | | | ----- | ----- | | |
| Heater 3, hi | | | | ----- | ----- | | |
| Seconds: | 200 | 40 | 5 | 0.5 | 0.2 | 5 | 225 |

In block 1 gas is let in and the pellet is formed.
In block 2 the pipe gun cools after the formations of the pellet; in block 3 the cooling continues and gas is pumped out from the gun barrel.
In block 4 the gun is heated before firing and in block 5 the gun is fired.
In block 6 the gun cools after firing and we pump on the gun barrel, in block 7 the cooling continues.

The temperature at which the pellet is formed depends on the gas inflow rate and the input to the electrical heaters. It may further be changed from one run to another by altering the thermal couplings to the cryostat base.

The temperature changes during the formation because it takes several seconds before the temperature becomes stabilized. To form a pellet at a constant temperature one should use a low gas inlet rate to reduce heating from condensation of gas.

The pellet quality (or temperature) may finally also be affected through the duration of the cooling periods in block 2.

The gas inlet may be made from a constant pressure in the gas reservoir or from a decreasing pressure. In the latter case the pressure changes from one value to another giving a direct indication of the pellet size.

The pellet size, or actual the pellet length may be estimated from the signals from the optical pellet detectors. These are used with analog output signals and the length of such a signal corresponds to the time the pellet uses to pass the light barrier of the detector. Such length measurement gave good agreement with length measurement from photos.

Pellets were made at various temperatures ranging from 7 K up to the triple point 13.96K. Pellets made at low temperatures appeared to be brittle when fired with the fast valve. The ones made at high temperatures had poor looking surfaces when photographed; they were also accompanied by fragments that in some cases could arrive several milliseconds before the actual pellet.

It was possible to establish conditions so that pellets with lengths from 8 mm to 18 mm could be made from decreasing reservoir pressure by varying starting pressure and filling time. The ends of the longest pellets were poor looking, like a well chewed cigar, because they were formed at too high temperatures.

The saturation effect seen for the first pipe gun could not be observed by means of the thermometers. It does, however, still exist, and if gas is let in for a too long time the pellet will be of bad quality because of continuing heating from the gas inlet.

In the first runs only the smaller pellets of around 100 bar.cm$^3$ were made. The gun should only be heated for 10 to 20 seconds with moderate power before firing. The pellet could be self fired or fast valve fired depending on the manner in which it was formed and the manner in which firing was prepared. A large fraction, up to 30%, of the pellet material might evaporate during the preparation phase, and it was seen that a burst of gas would reach the $\Delta P$ chamber ahead of the pellet.

Fast valve firing could be made with propeller gas pressures down to around 150 mbar giving velocities down to around 60 m/s. For a given set of firing conditions the scatter in results, velocity and size would be reasonably small, i.e. below $\pm 10\%$. The firing delay, i.e., the time between the firing pulse and the start of movement of the pellet, would for good firing conditions vary from 30 ms at 150 mbar to 10 ms at 500 mbar propellent gas pressure.

Self firing would occur if the fast valve was not fired in time. However, it would normally be easier to choose between the two firing modes than for pipe gun 1. The velocity obtained with self firing would depend on working conditions and might vary from 150 m/s for warm pellets to 30 m/s for colder pellets.

To reduce evaporation losses from the pellet the duration of heating in block 4 was reduced while the heater currents were increased. The losses then fell drastically and when the heating period was below 2 seconds the losses were below 2%. It is still possible to choose between fast valve firing and self firing. However, if the pellet is formed at a high temperature self firing may occur very fast, i.e., after 0.2 seconds.

The results given so far are for pellets made from a constant reservoir pressure. Pellets were also be made from an unregulated reservoir pressure and with this technique pellets up to 250 bar.$cm^3$ were made. Velocities down to 65 m/s were obtained for fast valve firing. The longer pellets were somewhat vulnerable and would sometimes break in two. The two pieces would normally pass the pellet detectors with time intervals below 1 ms.

It is often seen that the behavior of the gun changes after some operation time. The firing delays become longer and the pellets often break. This is probably caused by contamination of the inner surface of the freezing cell since the guide tube system and the gun barrel is only pumped with a rotary pump. The problem with gradual contamination only existed in the beginning when pumping through V4 took place place during the last two blocks of the operating program. The program was then changed so that pumping only took place during a short period during block 6 and the contamination ceased.

In this second pipe-gun pellets have been formed at temperatures ranging from around 7 K up to the triple point temperature 13.96 K. Pellets made at the lowest temperatures appeared to be brittle while the ones made at the higher temperatures had bad looking surfaces. The best pellets are probably made around 8-9 K.

The pipe gun is attached to the base of the cryostat, both mechanically and thermally, and the connection from the pipe gun to outer barrel system should be made inside the vacuum system after the cryostat has been placed on the vacuum chamber.

## IV.4. Pipe gun no 3.

This inconvenience is avoided in the next pipe gun, no 3. In Fig.IV.4.1. is seen how the gun is placed below the cryostat base and supported at the flange on which the cryostat is placed. The set-up is now an integrated unit.

Pipe gun no 3 is further simplified by making pipe gun and barrel from one piece of brass tube going from the bend on the tube for the propeller gas to the VAT valve. The wall thickness of the brass tube is reduced to 0.2 mm between the rings and 5 rings are used as shown in Fig.IV.4.1. The rings are again made from annealed electrolytic copper. One heater was placed on ring 3, one heater was shared between rings 2 and 4 and one heater was shared between rings 1 and 5.

The temperature of ring 3 was around 6 K and the temperature at rings 2 and 4 was around 10 K when the pipe gun was not used. During gas inlet the temperature of ring 3 would increase to 8 to 14 K depending on the inlet rate while the temperature of rings 2 and 4 would increase to around 18 to 22 K.

In the first runs freezing was only made inside the central ring and pellets could be made up to around 350 bar $cm^3$. On photos of pellets two dark areas were seen with 10 mm distance, i.e., at the ends of the rings.

For this gun a saturation was seen during pellet formation. After inlet of around 280 bar $cm^3$ hydrogen gas the temperature at ring 3 started to decrease because of saturation. The temperature would again start to increase at around 340 bar $cm^3$, and further filling will now ruin the pellet. The ends will first be of bad quality as for the very longest pellets in gun 2 and with further filling the whole pellet will become too warm and soft.

Pellets were made from decreasing reservoir pressure at temperatures around 8 K. Pellets of size 300 bar $cm^3$ could be self-fired with 0.5 second heating time just before, while they broke when fired with the fast valve with propeller gas pressure of 400 mbar after 0.4 second. The velocities for the self-fired pellets was around 35 m/s with a scatter of around $\pm 6\%$.

The operating program was as shown in table 1 with times spent in the blocks close to the ones given in the figure.

Smaller pellets could be fired with the fast valve without breaking. In table 2 results are shown for groups of pellets with identical conditions.

Table 2: Results for groups of pellets. The cooling time is the time spent with cooling in block 2.

| Shots No. of | Size bar cm3 | Cool. time sec. | Prop. press mbar | v m/s | Firing |
|---|---|---|---|---|---|
| 3 | 250 | 50 | 700 | 34 | self. |
| 3 | 250 | 80 | 700 | 102 | f. v. |
| 6 | 200 | 80 | 700 | 83 | f. v. |
| 3 | 230 | 80 | 700 | 94 | f. v. |
| 2 | 210 | 80 | 1000 | 111 | f. v. |
| 2 | 210 | 80 | 1400 | 120 | f. v. |
| 2 | 210 | 80 | 1900 | 140 | f. v. |

The spread in velocity was only a few per cent for each group. The smaller pellets were not fully developed. Photographs showed that they were tubular. The firing delay, i.e., the time between the firing pulse and the start of movement for the pellet was around 6-8 ms for all the pellets.

In a following run pellets were formed at a higher temperature, close to 9 K by using higher gas inlet rate and shorter filling time. Pellets were formed up to sizes of 350 bar cm$^3$ and these large pellets were self-fired with velocities of around 36 m/s after 0.6 seconds heating. These pellets could also be fast valve fired with propellent gas pressure of 400 mbar and velocities of 60 m/s after 0.5 sec heating.

Smaller pellets, 225 bar cm$^3$, could be fast valve fired after 0.5 sec with propellent gas pressure of 700 mbar and velocities around 80 m/s. The firing delay was again around 6-8 ms.

In other cases, larger pellets fired with higher propellent gas pressures were broken in two pieces upon arrival at the pellet detectors. By using times of passage for the two fragments at the two detectors we could go backwards and determine where the pellets had broken. This was done for 12 pellets and for 10 of these the breaking had occurred between 0.45 to 0.9 m before the arrival to the first detector. i.e., the pellets broke inside the guide tube.

The gun barrel pointed upward as shown in Fig.IV.4.1. while the guide tube was horizontal when passing through the detectors. The guide tube was thus s-shaped and the breaking of the pellets actually occurred where the curvature of the guide tube changed sign, i.e., where the pellet might have to jump from one innerside to another. In two cases it was possible to make pellets survive by changing the shape of the guide tube.

In principle a guide tube should always be made so that the curvature is unidirectional to avoid that pellets should jump from one wall-side to another. If this rule is followed it is credible that larger and faster pellets can be transferred without problems.

Pipe gun number 3 is very simple in construction and easily made. The pellet length may be varied between 1.6 and 2 times the length of ring 3 while the size may be varied a factor of 1.4. We have not investigated the possibility of making longer pellet by cooling rings 2 and 4. We now believe that it is simpler just to make a new pipe gun with a longer freezing cell.

We do not know how long pellets we can make and handle. Long pellets do break easily and we have seen on photographs that long pellets in some cases are made with a hole in the middle.

## IV.5. Conclusion.

In the two last pipe guns described pellets may be formed at temperatures up to that of the triple point at 13.96 K. The best pellets are formed at around 8-9 K. The pellet will be ready for firing 200 to 250 seconds after start and a cooling time of 200 t0 250 seconds is needed after firing. Pellets may be self fired with a timing precision of 0.1 second or they may be fast valve fired with a firing delay of around 6-8 ms.

Pellet sizes ranging from 100 bar $cm^3$ to 350 bar $cm^3$ have been obtained with velocities from 35 m/s to 200 m/s.

## V. DEVELOPMENT OF HIGH PRESSURE ARC CHAMBER

### V.1. Design considerations.

Due to the pressure drop in the barrel during the acceleration of the pellet and the propeller gas itself a desired base pressure of fx. 70 bar can be maintained behind the pellet only if the pressure in the arc chamber can be raised to a several times higher level, depending essentially on the obtained gas temperature.

In order to meet this requirement of a high ultimate chamber pressure a new arc chamber is being developed. A pressure of 1 kbar has been chosen as the upper limit for the new design.

With the larger wall thickness required for this higher pressure a design was proposed by JET in which the coil for the magnetic field was placed inside the chamber in order to keep the dimension and thereby the induction as small as possible.

Also in the design of the arc chamber it should be taken into account that *four different propellant injection schemes* should be possible.

*The first scheme* involves injection of slow pellets of cryo-condensed hydrogen propellant, as for the small, preliminary arc chamber used so far. For this purpose a fast acting gate valve must be used to close off the injection inlet tube after the pellet has entered the chamber and before the arc is ignited. In order to minimize the dead-volume of the injection line (the volume between the gate valve and the arc chamber cavity) the gate valve has to be build-in to the chamber body construction.

*The second scheme* involves injection of fast pellets into the arc chamber. This scheme is wanted in order to examine the arc efficiency in the case where the pellet is crushed by its impact in the chamber.

In comparison with the first scheme, where the whole pellet is softly guided into a circulating motion on the inner cylindrical surface of the chamber cavity, the possibility of a more efficient coupling between the arc and pellet fragments is present with this second scheme. Here a gate valve can not be used; the fast pellet injector system will be attached closely to the arc chamber in order to minimize the injection volume. The main problems will be in the design of the fast feed pellet injector, which will have to stand the high pressure developed in the arc chamber.

*The third scheme* involves injection of a high pressure room temperature hydrogen gas into the arc chamber. The hydrogen is injected from a 300 bar fast valve, which is mounted in close connection to the arc chamber. With this scheme the arc chamber is merely used as a temperature booster as the 300 bar valve reservoir will limit the arc chamber output pressure.

*The fourth scheme* involves injection of hydrogen gas from a piston compressor devise, by means of which the inlet pressure may be programmed to increase during the acceleration process.

In Fig.V.1.1 is shown a sketch of a high pressure arc chamber design which allow the three above mentioned injection schemes to be employed. The chamber body is made from a block of stainless steel (140x160x130mm). A 60 mm diameter, 80 mm long cylindrical hole in the block makes room for the internal elements: the outlet nozzle, the magnet coil and the central electrode. The chamber is closed by means of a 30 mm thick rear flange, which is bolted to the chamber body.

The electrical connections to the central electrode and the coil are fed through this flange. The insulator for the central electrode is made by vespel combined with a ceramic material facing the arc cavity. All the internal elements can be reached by dismounting the rear flange.

At the front of the chamber a coupling element for connection of the arc chamber to the projectile pellet forming cryostat with the acceleration barrel can be mounted . A 3.2 mm diameter channel from the nozzle element through this coupling element serves as propellant gas outlet from the chamber.

At the top of the chamber an interface for the three different inlet systems is provided. A 6 mm diameter channel through the chamber wall serves as hydrogen gas or pellet inlet channel to the arc cavity.

In the scheme with injection of slow feed pellets a plastic pellet guide tube from a slow feed pellet launcher is connected to this inlet channel. In the scheme of fast feed pellet or 300 bar gas injection a common interface at the top of the chamber is used for connecting the outlet of either a fast pellet launcher cryostat or a 300 bar fast valve to the chamber inlet channel.

A hole crossing the 6 mm inlet channel in the chamber wall makes room for different plug-in valve units to be used with the different injection schemes.

A fast acting electromagnetically actuated sliding valve unit will be used in the case of slow feed pellet injection, for closing off the chamber to the large volume of the pellet guide tube. Due to the requirement of fast action the sealing of this valve is not made completely leak proof in order to reduce sealing friction. However, even with some leak, only a small amount of propellant gas will be lost through the valve during the short effective pressure pulse time (about 1 ms).

A slow acting pneumatically actuated rotating valve unit will be used in the case of fast feed pellet injection, for separation of hydrogen gas and deuterium gas during formation of the hydrogen feed pellet and the deuterium projectile pellet. The valve for this purpose does not need to be fast but must be leak proof.

Finally a pressure transducer will be mounted in the arc chamber for monitoring of the pressure transient (not shown in Fig.V.1.1). For this purpose an acceleration-compensated miniature quartz pressure transducer has been chosen (PCB Model M113A03, 1 kbar, 500 kHz). The transducer will be mounted for monitoring the pressure at the outlet channel of the chamber between the nozzle and the coupling element for the projectile pellet cryostat (breech pressure).

### V.2 Proto-type arc chamber experiments.

A proto-type arc chamber corresponding to the design sketched above has been build and tested preliminary with injection of slow feed pellets. This experimental work is described in the following.

The feed pellets were produced by the pipe gun described in chap.IV and injected into the arc chamber through a plastic guide tube. The pellet were injected through a nozzle element with a grove for guiding the pellets into an arc cavity of 6 $cm^3$ volume. The diameter of the feed pellets was 5 mm and the total gas amount per pellet was about 200 bar $cm^3$ (STP).

By means of two optical detectors attached to the translucent guide tube the velocity of the feed pellet was measured by time-of-flight. A velocity of about 50 m/s was found to be adequate.

The signal from the optical detector which was placed close to the entrance of the arc chamber was used for triggering of the gate valve. An adjustable time delay between the detector signal and the valve triggering was used to synchronize the arrival of the pellet in the chamber and the closure of the valve. The closure time of the gate valve was about 5 ms. A piezo electric chock detector which was activated when the valve reached its closed position was used to produce a triggering signal for the power supplies for the arc and the magnet coil. By means of an adjustable time delay the power supply for the coil could be triggered before the arc power supply.

The arc was powered by the JET-design power supply consisting of 120 capacitor batteries (800 V/500 μF) to be fired in a pre-programmed sequence and a pulse transformer (1:4). In series with the arc was placed a 20 μH induction.

The coil was driven by the Risø-design power supply consisting of 4 capacitor batteries (2800 V/80 μF).

A first problem in the experiments was to get the arc ignited. From experiments with the chamber filled with a stationary pressure of hydrogen it was found that ignition with the maximum available voltage (about 3 kV) could be obtained only for hydrogen pressures below about 0.5 bar.

Ignition with pellet injection was found not to be reproducible, indicating that the initial pressure could vary and often be above 0.5 bar, and thereby preventing ignition.

In order to ensure a reproducible ignition, an additional ignition electrode was used. This electrode, consisting of a 0.8 mm tantalum wire, was introduced axially through the center electrode, insulated by means of a 2 mm o.d. alumina tube. The alumina tube ends at the tip of the graphite electrode and the Ta-wire extrudes about 2 mm from the tube end into the arc chamber cavity. Outside the chamber the Ta-wire is connected through 25 Ω to ground.

In this way a current limited pre-discharge can be ignited in the small gap (about 1 mm) between the Ta-wire and the graphite electrode at high initial pressures and for pressures up to about 5 bar this pre-discharge switches the main discharge in less than a hundred micro seconds. This time lag decreases with decreasing initial pressure. With pellet injection it is generally less than 100 μs.

A second problem in the experiments was the high frequency (about 5 MHz) and high level electrical noise, which is produced by the arc during ignition. The presence of this noise did not disturb the work described in chapter III, in which the small preliminary arc chamber was used in connection with the small 4 battery ignitron switched power supply. However, when the same arc chamber was tested in connection with the larger 120 battery thyristor switched power supply delivered by JET, the ignition noise became troublesome. A serious damage was generated in the control circuits of the power supply when it was tested the first time with the arc load. After some improvements in the isolation levels of some of the internal control circuits and in the mains connection to prevent high frequency ground loop couplings the firing control of the power supply was improved. Only occasionally the ignition noise causes all batteries to fire simultaneously at ignition. This problem is believed to be cured when a new series of thyristor ignition transformers of improved isolation are installed.

So far only measurements of the pressure transient in the closed high pressure proto-type chamber has been done. Figure V.2.1. shows results for a shot with a feed pellet of 200 bar $cm^3$, the arc driven by 16 batteries of the JET-power supply charged to 770 volt and fired within 400 µs, and the coil driven by all 4 batteries of the Risø power supply charged to 2.7 kV. The arc was ignited 150 µs after the coil.

It is seen that the main discharge ignites about 80 µs after the ignition of the pre-discharge. The arc current reaches a peak value of about 2.8 kA and the arc voltage reaches an oscillating peak level of about 1.6 kV corresponding to a peak power of about 4.5 MW reached in about 200 µs. The chamber pressure shows a relatively slow initial rising up to about 25 bar and thereafter a fast rising (about 1 bar/µs) up to about 175 bar. With all the energy being confined in the closed chamber we did not try to increase the energy input further, but it is believed that the fast pressure rise rate can be extended by applying more batteries of the power supply. The slow initial pressure foot should not be serious as a break-away pressure of about 20-25 bar can be expected for the ø3.2x4 mm $D_2$ pellet to be used as projectile pellet.

For comparison Fig V.1.2. shows results obtained with the power supplies interchanged: the arc driven by the Risø power supply (still with the 20 µH in series) and the coil driven by the JET power supply. In this case a somewhat faster current (and power) rise is observed, probably due to the lacking transformer induction in the arc circuit. However, apart from the foot the main pressure rise rate is not very different in the two cases.

### V.3. Arc pipe gun for production of fast feed pellets.

As mentioned i chapter V.1., a scheme for injection of fast feed pellets is planned in order to examine the arc efficiency in the case, where the feed pellet is crushed by its impact in the arc chamber.

For this purpose a new feed pellet injector is being developed. The requirements for this injector are: pellet size up to about 1 bar liter (STP), pellet velocities above 500 m/s, pressure capacity up to about 1 kbar and as short as possible barrel length.

The barrel of the injector will be connected directly to the inlet channel of the arc chamber and has to be as short as possible with respect to the cryogenic requirements of the freezing cell in order to minimize the total dead-volume of the combined arc chamber/injector system. Also because no gate-valve will be used between the injector and the chamber cavity the pressure capacity of the injector will have to match that of the arc chamber.

Figure V.3.1. shows a schematic drawing of an arc driven pipe gun type fast feed pellet injector, which has been constructed and preliminary performance tested in a stand-alone set-up.

The device consist of a freezing cell of CrCu (i.d. 5.5 mm) in which a pellet can be condensed by single-ended inlet of hydrogen gas through the barrel. The freezing cell is closed at the one end by a vespel/ceramic insulator through which a central W-wire electrode protrudes into the cell, forming a spark-gap. A coil (70 turns of ø0.8 mm Cu-wire) is placed coaxially around the spark-gap end of the cell. The cell is cooled by heat conduction to the base of a LHe bath cryostat through Cu-wires, which are soldered to the CrCu tube through holes in the stainless steel pressure tube. In the preliminary test device this tube only covered half of the CrCu tube. When used in connection with the arc chamber the pressure capacity of the device is increased by extending the SS-tube to cover the full length of the CrCu-tube and to form the barrel connection to the arc chamber.

In the preliminary tests hydrogen pellets up to about 600 bar $cm^3$ was condensed in the cell and fired by igniting an arc in the spark-gap of the cell. The arc was driven by a capacitor bank of 80 μF/2 kV with the coil (0.16 Ω, 100 μH) and a 0.5 Ω resistor in series with the arc. Signals from optical time-of-flight pellet detectors placed outside the barrel (length ≈ 20 cm) indicated velocities from 800 to 1500 m/s depending on pellet size. No photographs were taken of the pellet at the first tests, so the state of integrity of the pellet when leaving the barrel is yet unknown. However, if the pellet is broken by the acceleration it will only help in reaching the desired fragmented state when injected directly in to the arc chamber.

A special device for obtaining ignition of the propelling arc in the spark-gap of the freezing cell was required when using the available 2 kV power supply. This consisted in applying constantly during the condensation of the pellet a low power discharge (50 μA/1 kV) at the arc gap. By this the gap region is kept clear from condensed hydrogen, which otherwise was found to block ignition. With this preparation, ignition was easily obtained if a slight ohmic heating was applied to the gap region of the cell for pressure conditioning immediately before switching on the discharge voltage.

## V.4. Additional results with pellet fed arc chamber.

Preliminary experiments were done with the high pressure proto-type arc chamber, corresponding to the schematic drawing in Fig.V.1.1., and with the original low pressure version as shown in Fig.III.1.1., where the feed pellets are injected through a channel in the electrode insulator. In these experiments the smaller feed pellets of 3.2 mm diameter, containing about 75 bar $cm^3$ of hydrogen were used.

The effect of the external magnetic field, produced by the coil around the arc cavity, was examined in these experiments. This was done by using the small interim power supply for driving the coil, while the arc was driven by the JET-power supply. In this way the amplitude and the ignition time of the coil current could be adjusted independently of the arc current.

Figure V.4.1. shows the time behavior of the arc voltage and the arc current for 4 shots with different magnitudes of the coil current (#24,#25,#26,#27, 12/3/87). The time base is 100 μs/div for all four shots. Trace A shows the arc voltage (320 V/div), trace B shows the arc current (500 A/div), and trace C shows the coil current (500 A/div).

These results were obtained by means of the proto-type arc chamber by injection of the 3.2 mm diameter feed pellets at a velocity of about 50 m/s. The coil (N = 85 turn, 230 mΩ) was driven by the interim power supply consisting of 320 μF discharged simultaneously with the firing of the arc. The charging of the interim power supply was: 2800 V (#24), 1500 V (#25), 800 V (#26), 0 V (#27). The arc was driven by 8 capacitors of the JET power supply, fired within 40 μs, and charged to 740 V with a voltage step-up of 4:1 by the pulse transformer. In series with the arc was placed a 20 μH induction.

It is seen from Fig.V.4.1., that the arc voltage increases with increasing coil current. With no magnetic field the arc impedance stays low and and the arc power is low even with a high arc current level.
In Fig.V.4.2. the peak value of the arc chamber pressure is plotted as a function of the peak value of the coil current. From this is seen that the presence of the magnetic field produced by the coil is essential.

The effect of shifting the phase of the coil current relatively to the arc current was also examined. Figure V.4.3. through V.4.5. show traces of the arc voltage (A, 320 V/div), the arc current (B, 500 A/div), chamber pressure (D, 10 bar/div) and the coil current (C, 500 A/div). These results were obtained by injecting the 3.2 mm diameter feed pellets in the proto-type arc chamber. The coil was driven by the interim power supply (320 µF/2.6kV) and the arc was driven (in series with the 20 µH induction) by the JET power supply (8 capacitor units, 740 V, , fired within 100 µs, pulse transformer 4:1).

In Fig.V.4.3. the coil current was triggered 200 µs prior to the arc discharge, in Fig.V.4.4. and Fig.V.4.5. the corresponding pre-trigger time was 100 µs and 0 µs. From comparison of the voltage traces of Fig.V.4.3. and Fig.V.4.5. it is seen that the initial voltage rise is increased when the magnetic field is present at the time of break down.

The voltage spike, which is seen in Fig.V.4.3. but not in Fig.V.4.4. and Fig.V.4.5. is not due to the different delay between the coil current and arc current for these shots but is believed to be produced by a random effect in the interaction between the feed pellet and the arc during the discharge. This behavior is also illustrated in Fig.V.4.6., the traces of which were obtained under the same shot conditions as that of Fig.V.4.5. (no delay between coil and arc currents). In Fig.V.4.6. is seen a voltage spike, which is not present in Fig.V.4.5.

Another result which indicates a lack of control of the feed pellet/arc interaction is illustrated by the data in Fig.V.4.7. This figure show traces of the arc voltage (A, 320 V/div), the arc current (B, 500 A/div) and the chamber pressure (C, 10 bar/div). This data were obtained by means of the original low pressure arc chamber (Fig.III.1.1), where the 3.2 mm diameter feed pellet was injected through a guiding channel in the central electrode insulator.

The behavior of the arc voltage and the arc current is similar to what is found by using the high pressure proto type arc chamber with the 3.2 mm diameter feed pellets. However, the pressure trace shows a peculiar double humped behavior, which indicates that the feed pellet is not completely dissolved during the electric arc power pulse. The second maximum of the pressure transient could possibly come from undissolved pellet material, which evaporates by contact with heated electrode surfaces of the arc cavity. This behavior was not observed in the experiments with the proto type arc chamber, in which the feed pellet is introduced through a guiding channel in the nozzle element instead of in the central electrode insulator.

## VI. CONCLUSIONS AND PLANS

The results obtained so far with arc chambers based on electrical discharge in cryo-condensed hydrogen indicate that such an arc chamber may be a convenient source of propellant gas with an adequate initial pressure development. The cryogenic arc chamber with pre-condensed hydrogen propellant has been abandoned due to the impractical long cooling times involved, whereas the pellet injected arc chamber has revealed results that approves its further development. A patent on this scheme is being applied.

However, it still has to be shown that the pressure pulse can be extended and shaped in time to maintain a constant pellet base pressure of about 70 bar during the acceleration phase and that a deuterium pellet can stand the acceleration pressure for a sufficiently long time.

As mentioned in chapter V four different schemes for injection of hydrogen propellant into the arc chamber are planned. These schemes are planned to be tested with acceleration of 3.2 mm deuterium pellets. The cryostat unit for production of these projectile pellets is build by CEN-Grenoble and is due to be delivered to Risø in June 1987.

## VII. ACKNOWLEDGEMENT

Ideas and comments to the work from the JET Project Monitor, Dr. P. Kupschus and Dr. K. Sonnenberg are acknowledged with thanks.

## REFERENCES

/1/ S.A.Andersen, J.Bundgaard, V.O.Jensen, A.Nordskiv, B.Sass, H.Sørensen, K.V. Weisberg: "Investigation of Pellet Acceleration by an Arc heated Gas Gun", An Interim Report on the Investigations carried out to 31 August 1985, Risø-M-2536.

/2/ J.Lafferenderie, presented at the International Pellet Fueling Workshop, La Jolla, California, 30 October-3 November 1985.

/3/ O.Lazare, These, Université de Paris-Sud Centre D'Orsay, 1985.

/4/ S.K.Combs, S.L.Milora, and C.R.Foust, Rev. Sci. Instr. 57,2636-2637 (1986).

/5/ A.Cecchini, A. de Angelis, R. Gratton and F.Parlange, J.of Physics E, 1, 1040 (1968).

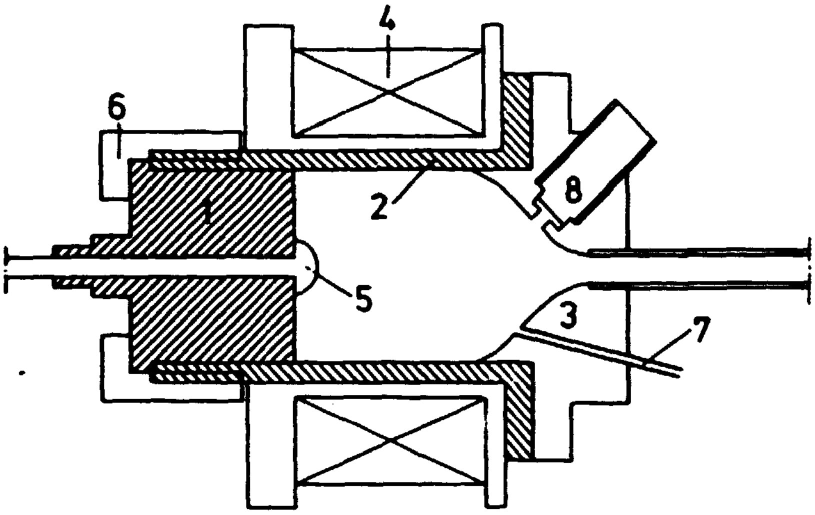


**Fig.II.1.1.**: Schematic drawing of cryogenic arc chamber.
1) Vespel insulator. 2) Stainless steel cylinder. 3) Outlet nozzle flange. 4) Magnet coil. 5) Central electrode. 6) Coupling nut. 7) Capillary tube for hydrogen inlet. 8) Pressure transducer.

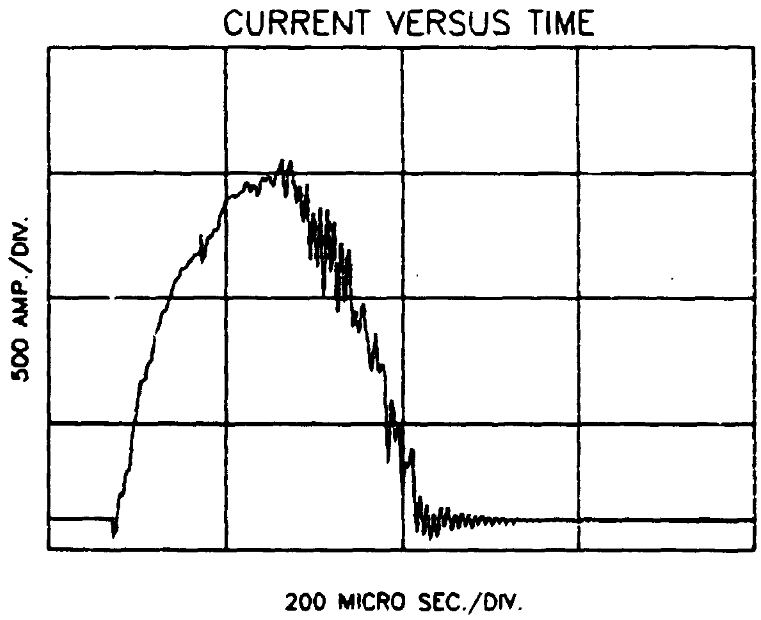


**Fig.II.2.1.**: Arc current versus time. Shot #002 209 10-OCT-85. Hydrogen dose: 98 bar $cm^3$. Charging voltage 2.7 kV. Muzzle speed 1934 m/s.

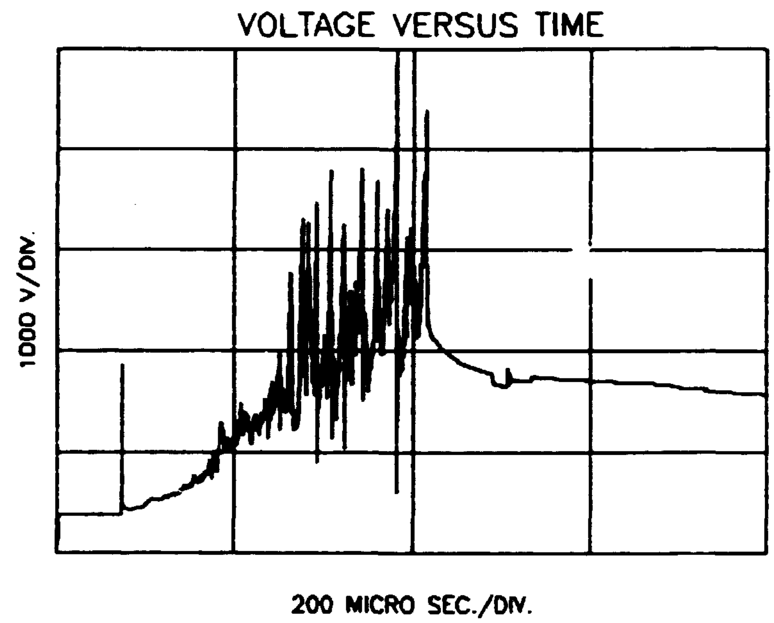


**Fig.II.2.2.:** Arc voltage versus time. Shot #002209 10-OCT-85.

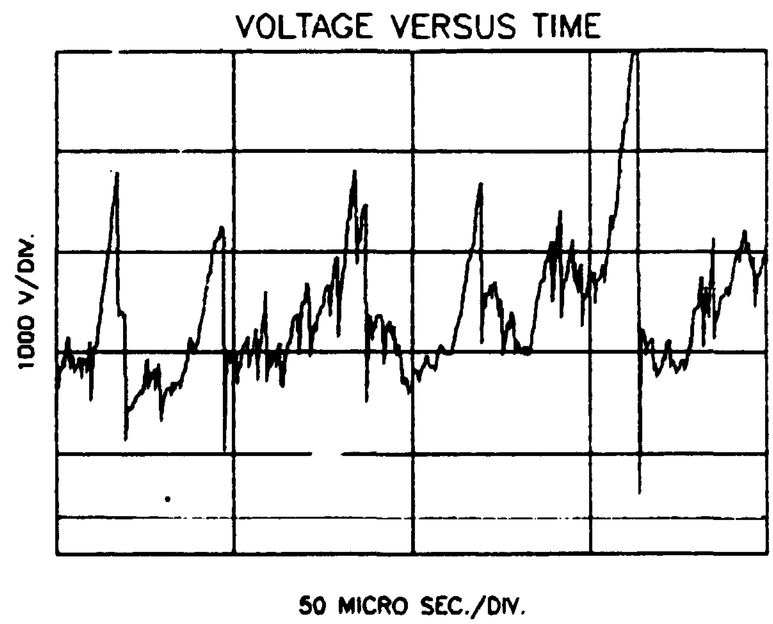


**Fig.II.2.3.** Arc voltage versus time. Expanded time scale. Shot #002209 10-OCT-85.

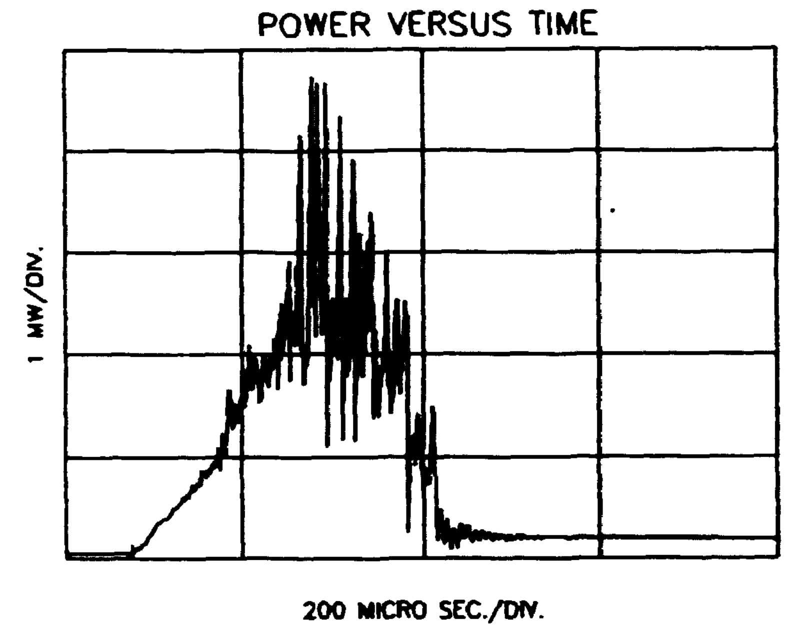


**Fig.II.2.4.:** Electrical power versus time. Shot #002209 10-OCT-85.

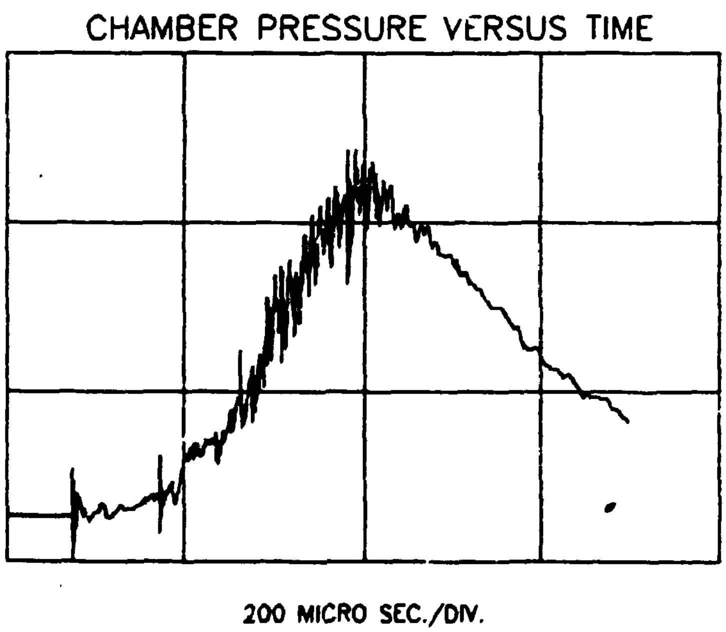


**Fig.II.2.5.:** Chamber pressure versus time. (Pressure transducer not calibrated). Shot #002209 10-OCT-85.

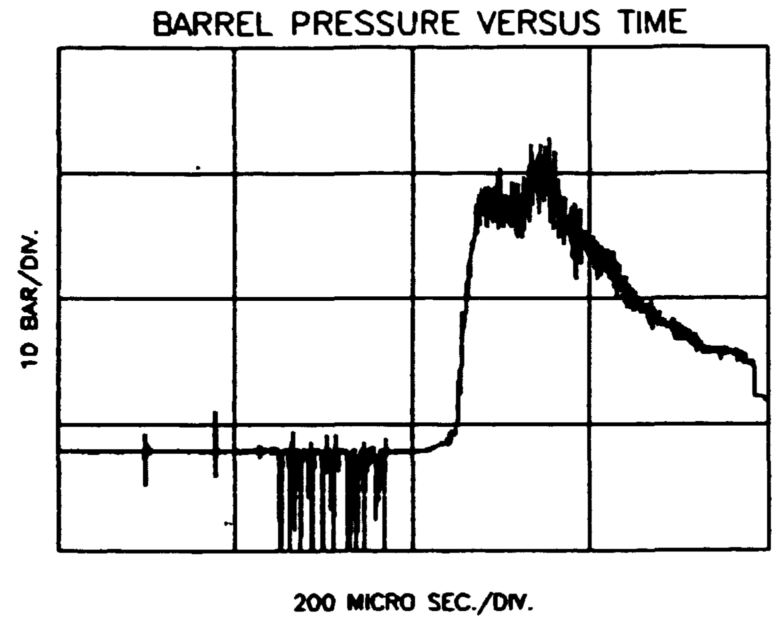


**Fig.II.2.6.: Barrel pressure versus time. X = 220 mm. Shot #002209 10-OCT-85.**

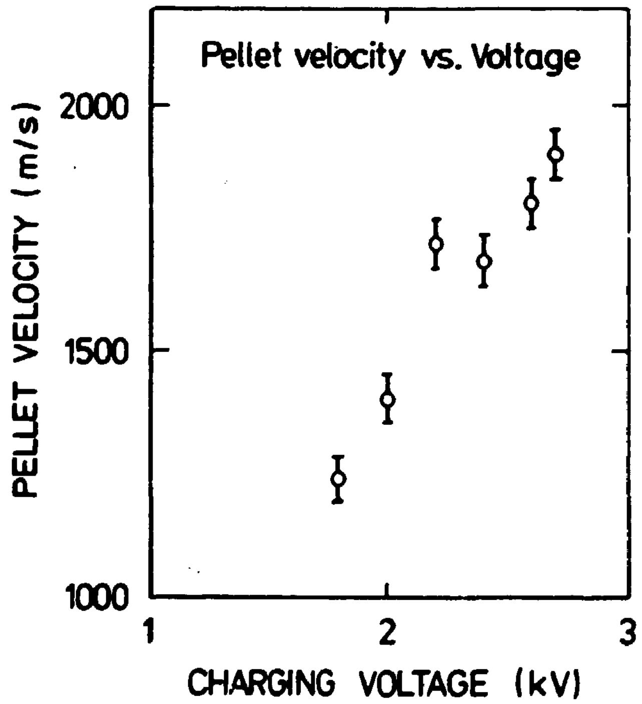


**Fig.II.2.7.: Pellet velocity versus charging voltage.**

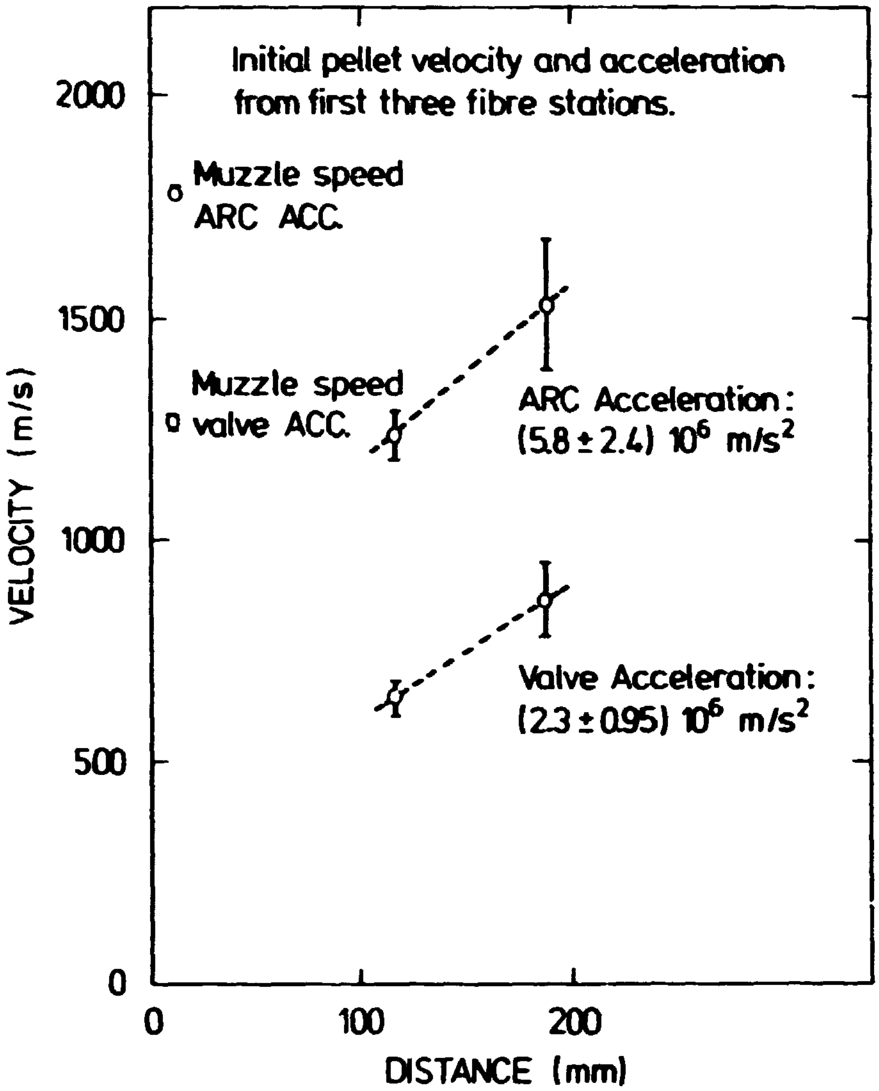


**Fig.II.2.8.:** Initial pellet velocity versus distance in barrel as measured from first three optical fiber stations. Figures for initial accelerations and muzzle velocities for arc acceleration and fast valve acceleration are indicated in the figure.

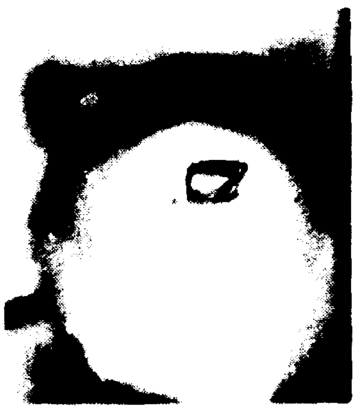

**Fig.II.2.9.:** 20 ns flash photo of 1922 m/s pellet. Shot #002210 10-OCT-85.

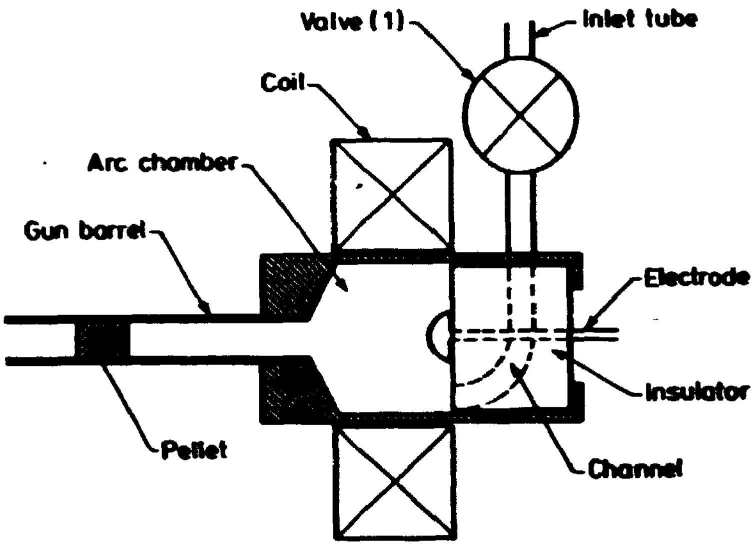


**Fig.III.1.1.: Schematic drawing of pellet-fed arc chamber. Arc cavity: diameter = 14 mm, volume = 1.5 cm$^3$.**

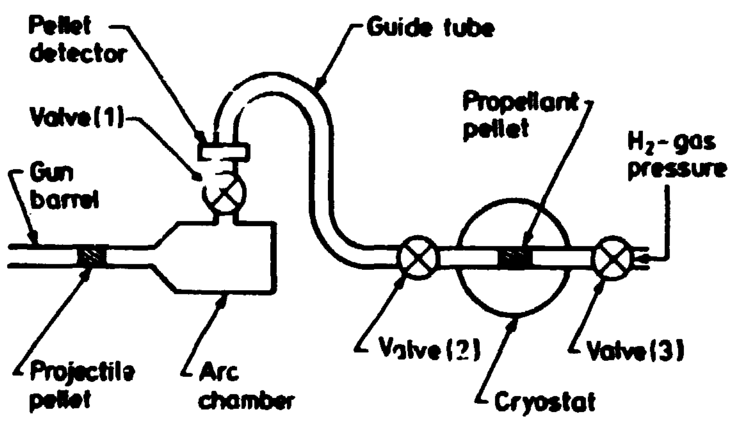


**Fig.III.2.1.: Schematic diagram of set-up used with the pellet-fed arc chamber.**

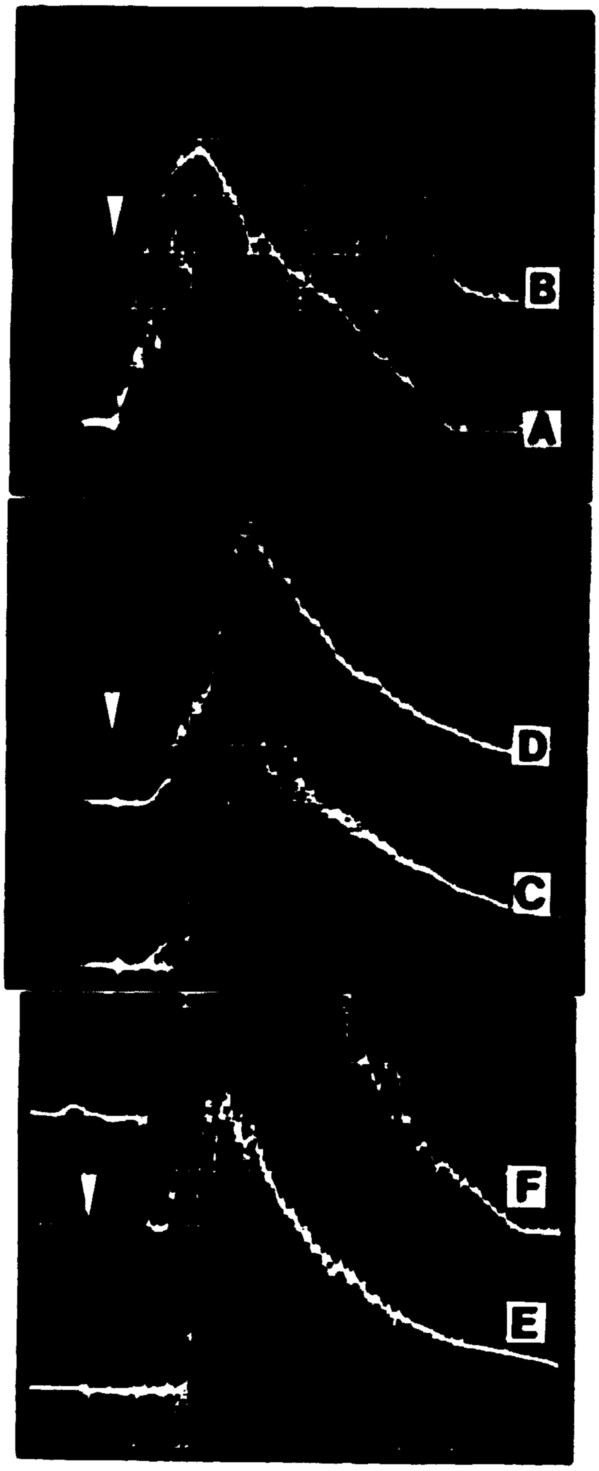


Fig.III.3.1.: Oscillograms for shot with pellet-fed arc chamber.
Time base 100 μs/div.
A: Arc current, 400 A/div.
B: Arc voltage, 200 V/div.
C: Chamber pressure, 34.6 bar/div.
D: Breech pressure, 21 bar/div.
E: Barrel pressure, 15.6 bar/div.
F: Signal from optical fibers.

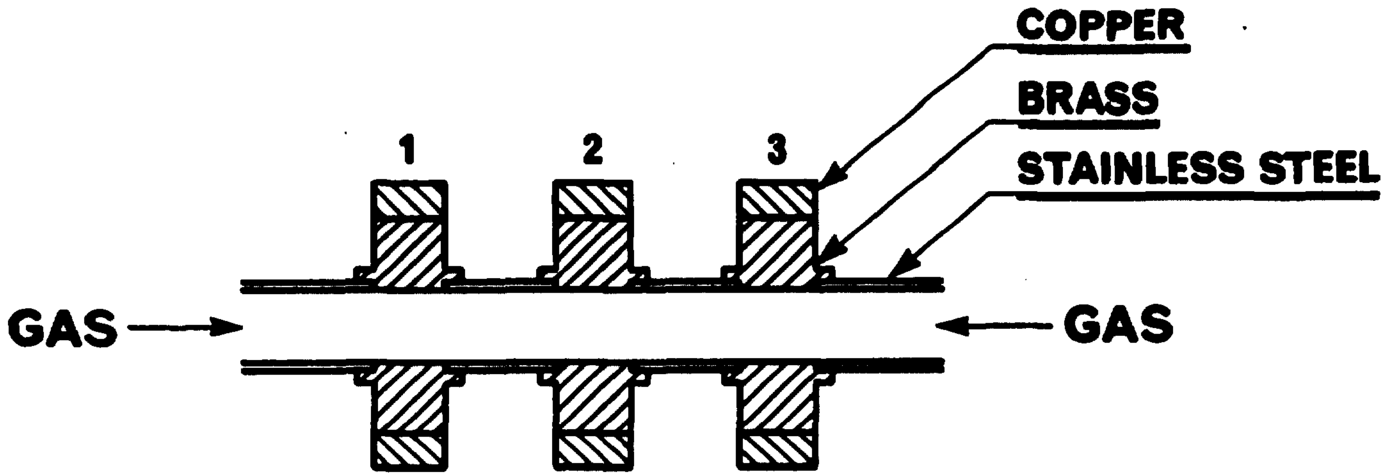


**Fig.IV.1.1.: Schematic drawing of freezing cell in pipe gun**

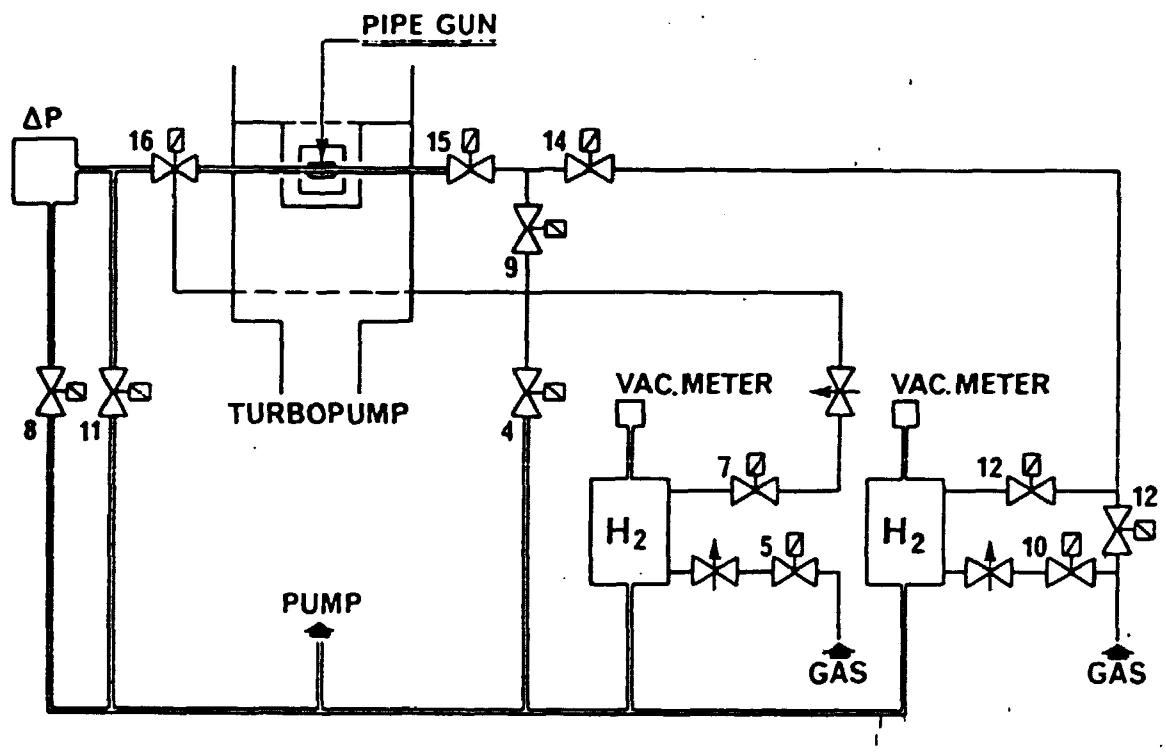


**Fig.IV.3.1: Diagram of gas supply for pipe gun.**

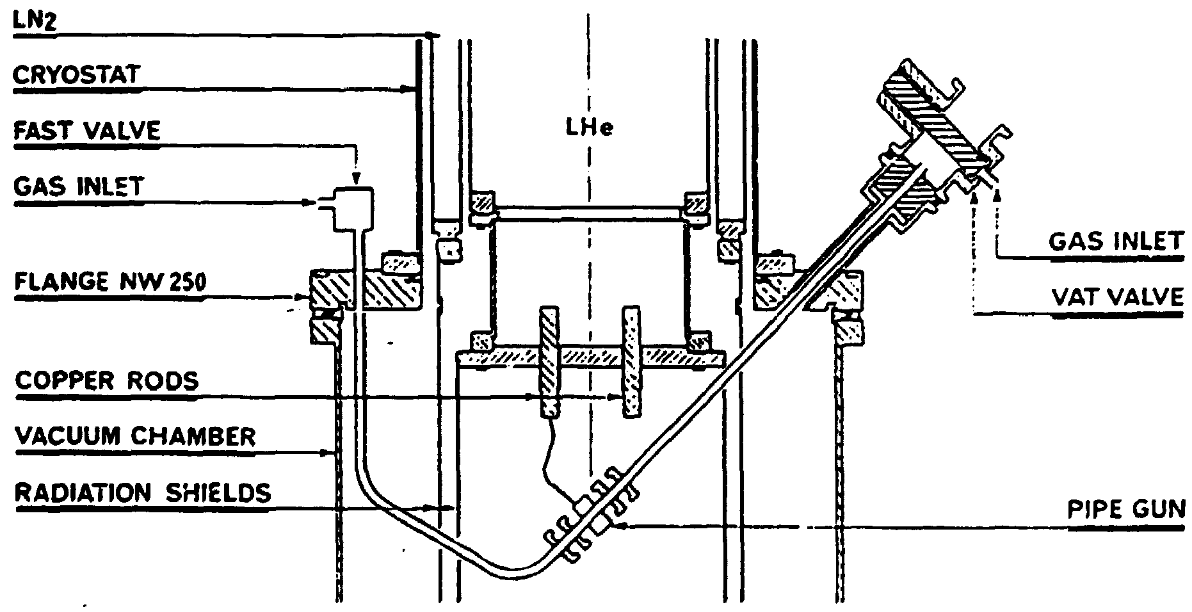


**Fig.IV.4.: Schematic drawing of pipe gun set-up.**

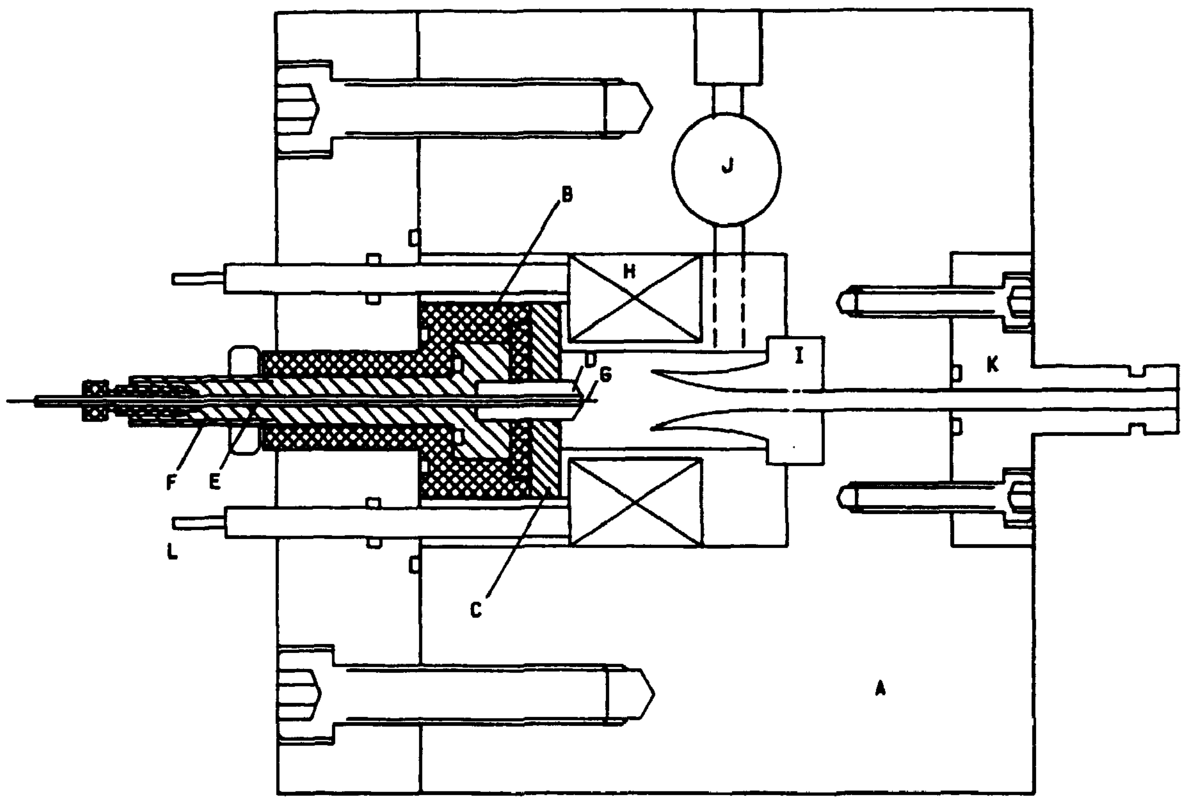


**Fig.V.1.1.**: Schematic drawing of high pressure arc chamber.
A: stainless steel chamber. B: vespel insulator. C: alumina plate. D: central graphite (molybdenum) electrode. E: alumina tube. F: brass rod. G: tungsten wire. H: magnet coil. I: outlet nozzle. J: cylindrical channel for feed pellet inlet gate valve. K: coupling element for connection to deuterium projectile pellet cryostat. L: electrical wire feed-through for magnet coil.

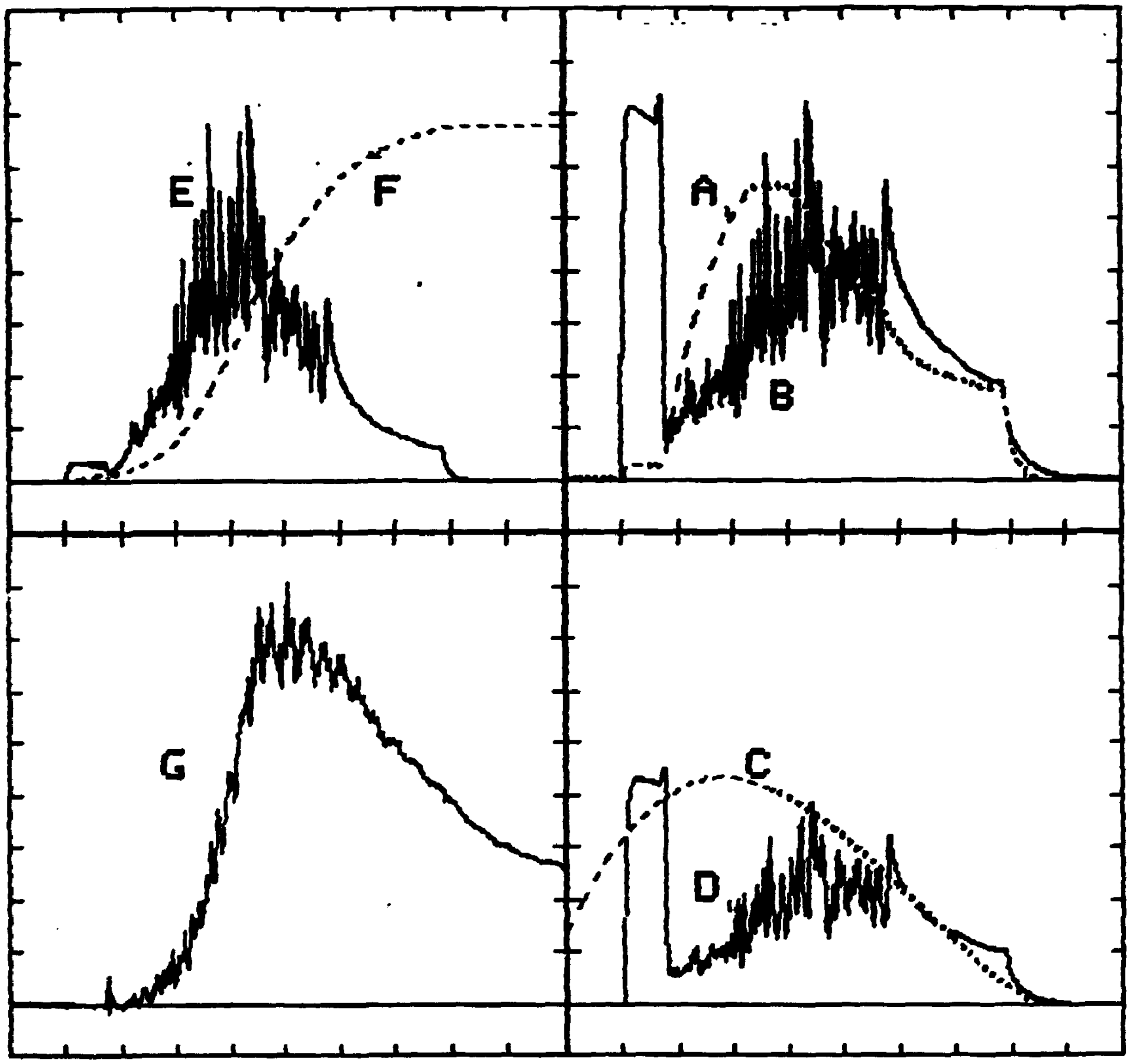


Fig. V2.1.: Data from shot with proto-type high pressure arc chamber. Time base 100 μs/div. A: arc current, 500 A/div. B: arc voltage, 388 V/div. C: coil current, 500 A/div. D: ignition current, 20 A/div. E: arc power, 1 MW/div. F: arc energy, 200 J/div. G: chamber presure, 25 bar/div.

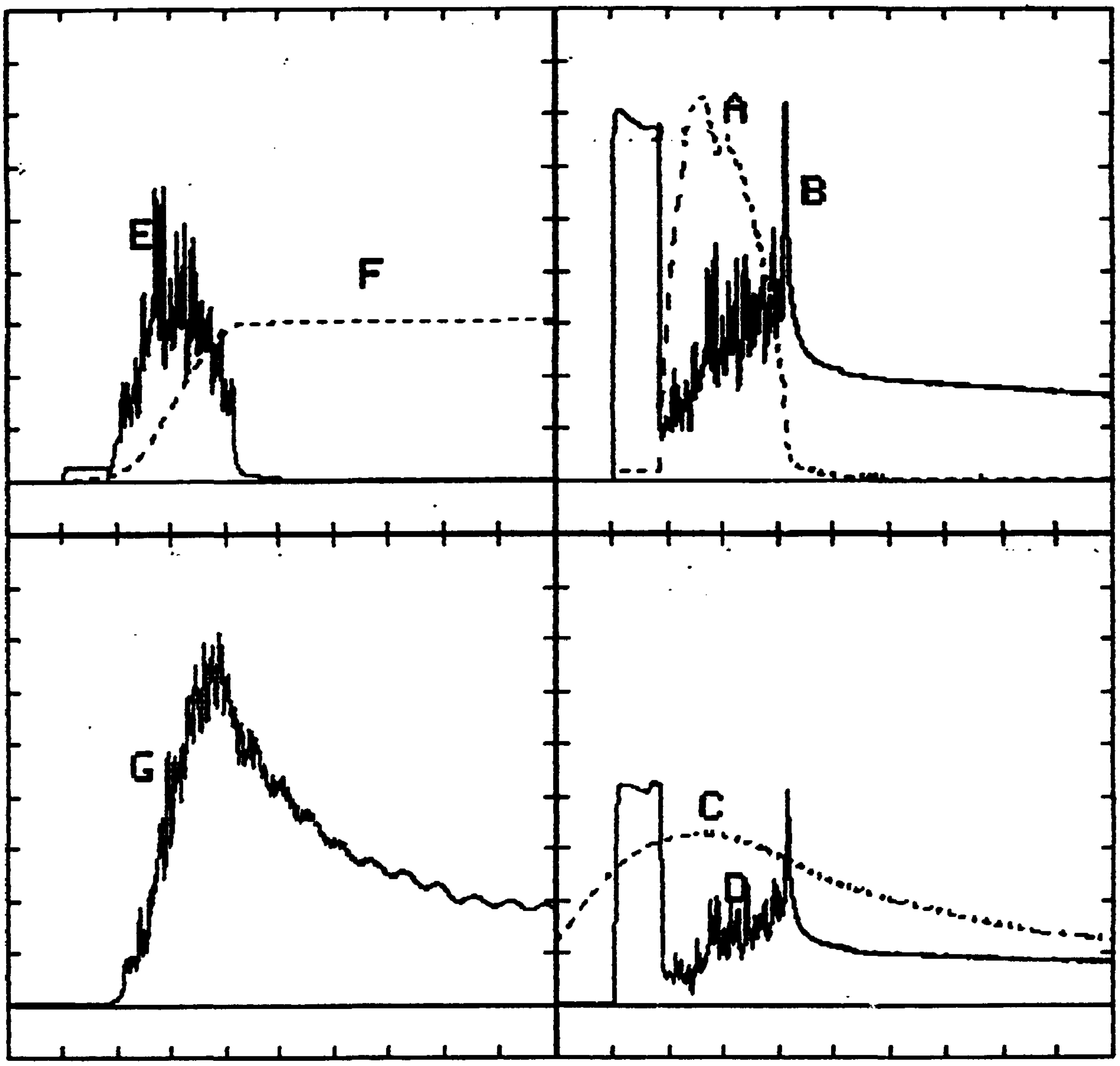


**Fig.V.2.2.:** Data from shot with proto-type high pressurearc chamber with inter-changed power supplies for arc and coil circuit. Units as for Fig. V.2.1.

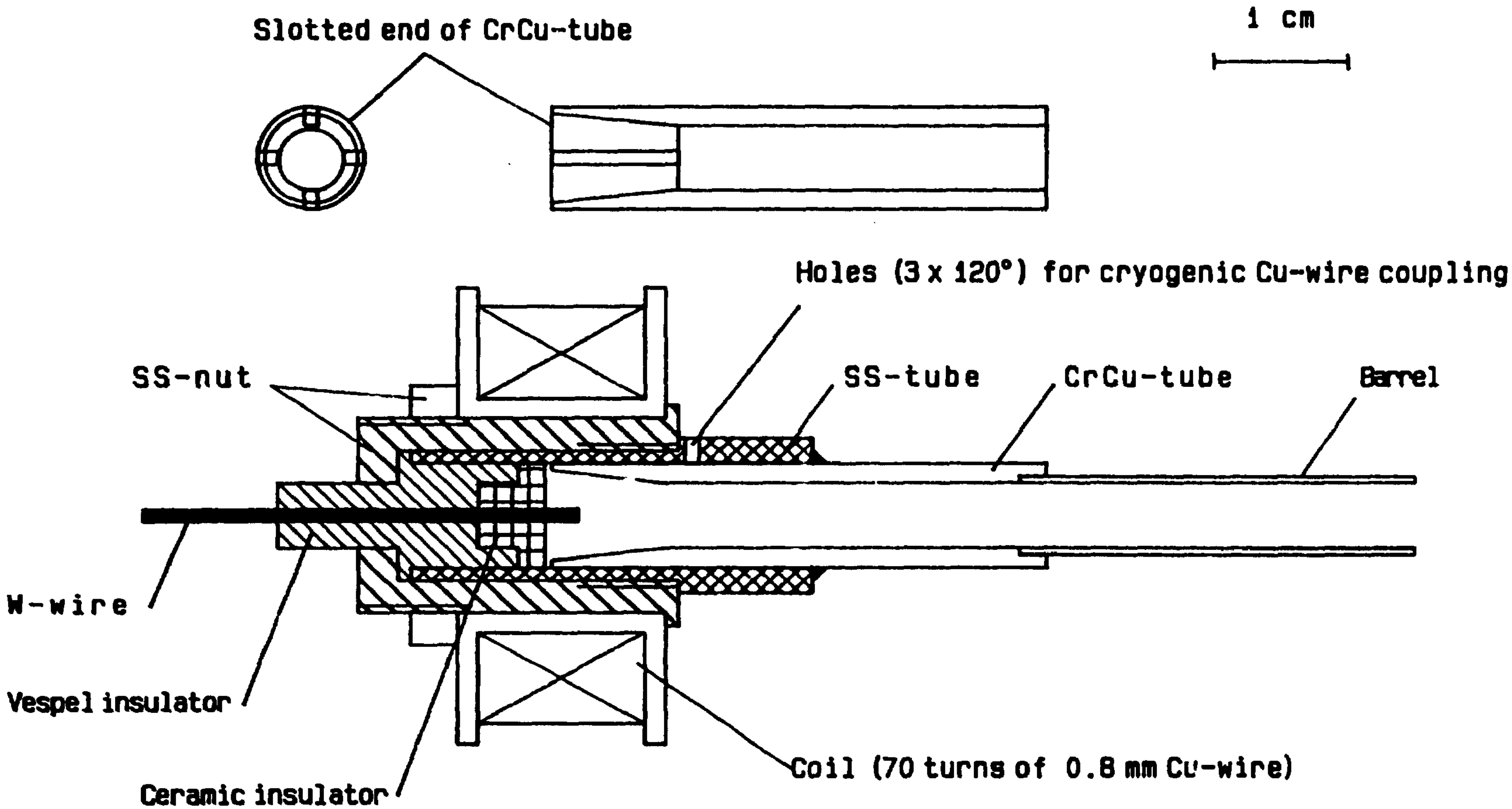


**Fig. V.3.1.: Schematic drawing of arc driven pipe gun for fast feed pellet injection in arc chamber.**

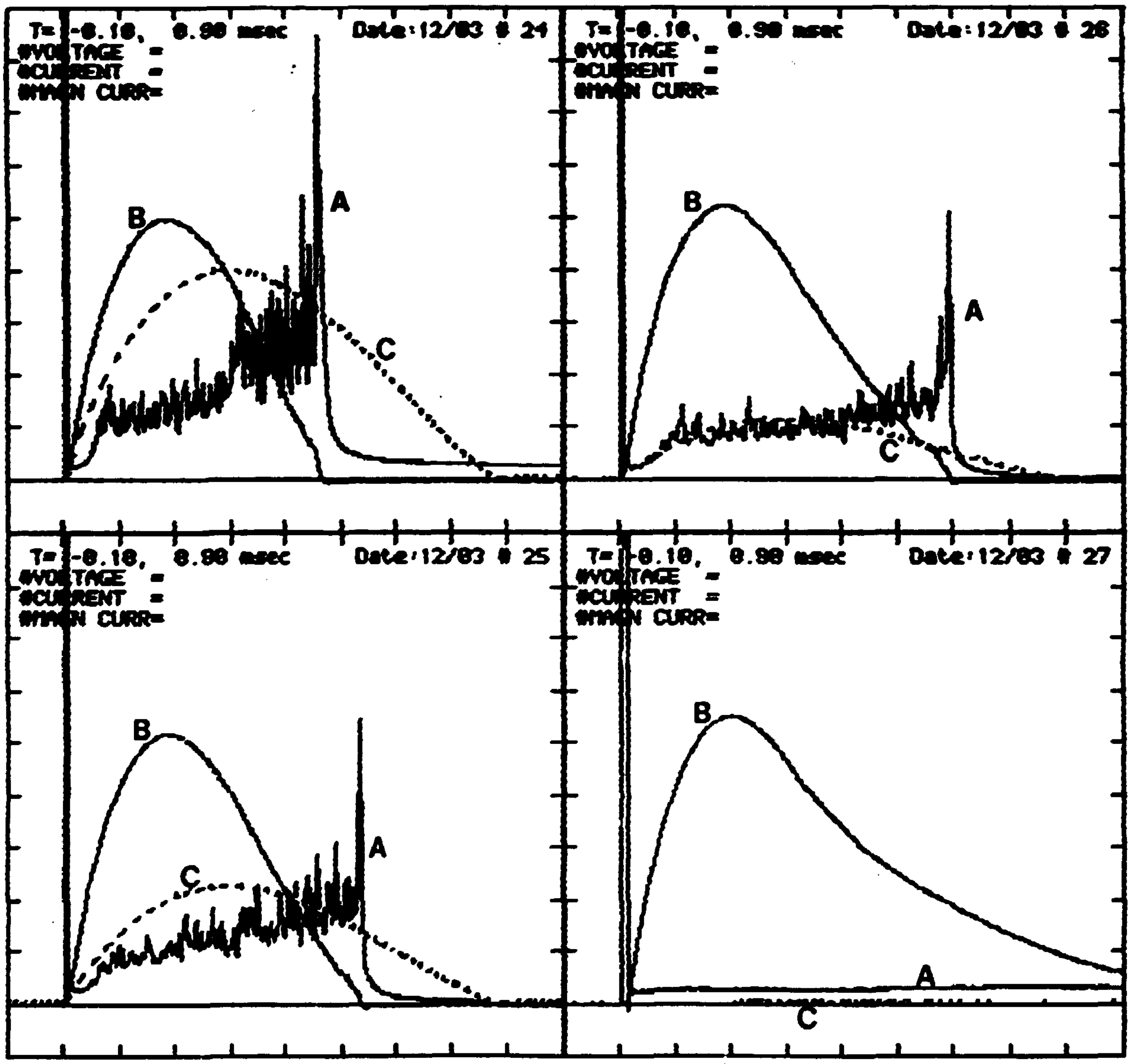


Fig.V.4.1.: Traces of arc voltage, arc current and coil current vs time for different amplitudes of the coil current. Time base 100 s/div. A: arc voltage (320 V/div). B: arc current (500 A/div). C: coil current (500 A/div).

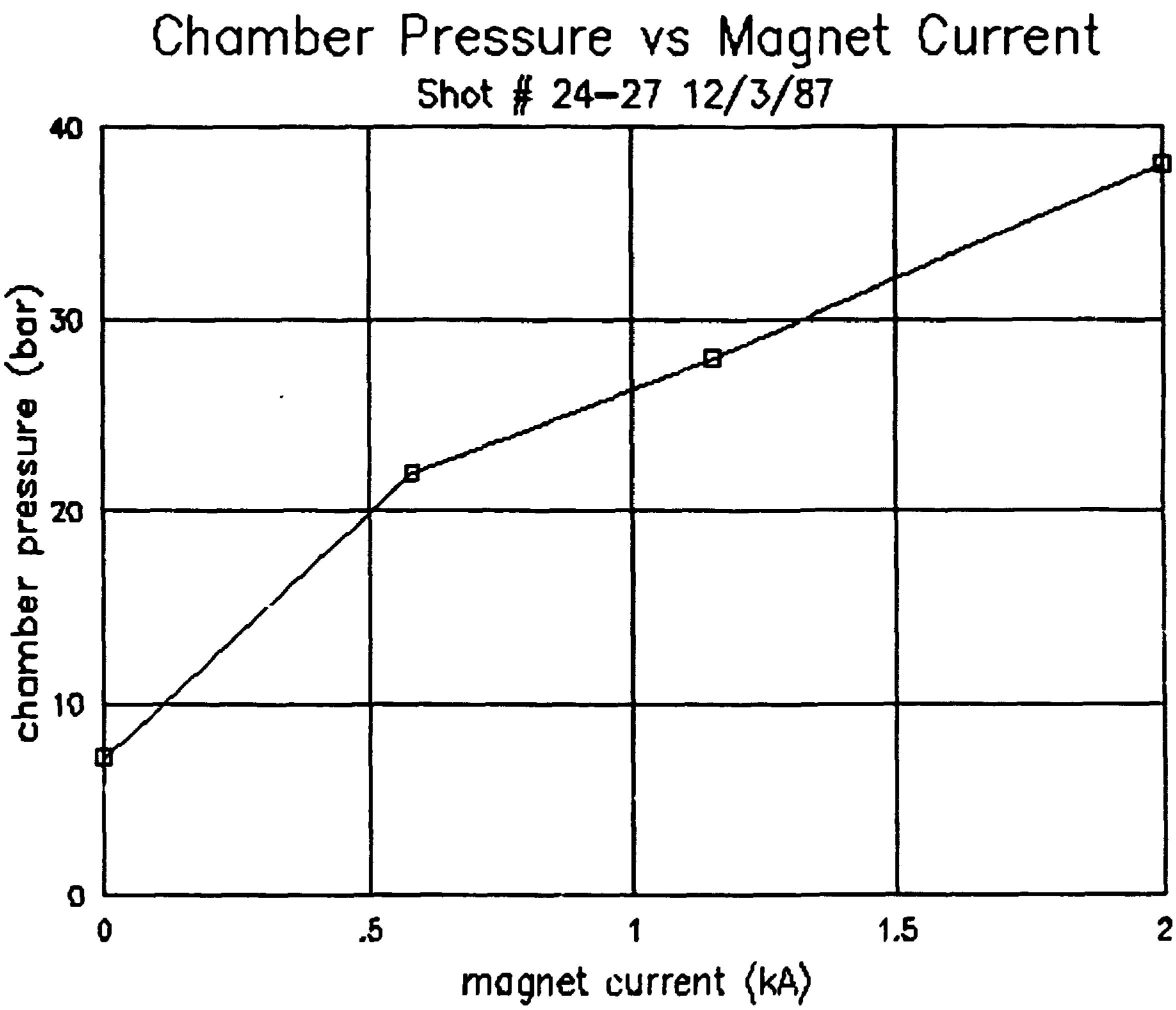


**Fig.V.4.2.:** Arc chamber pressure as a function of coil current.

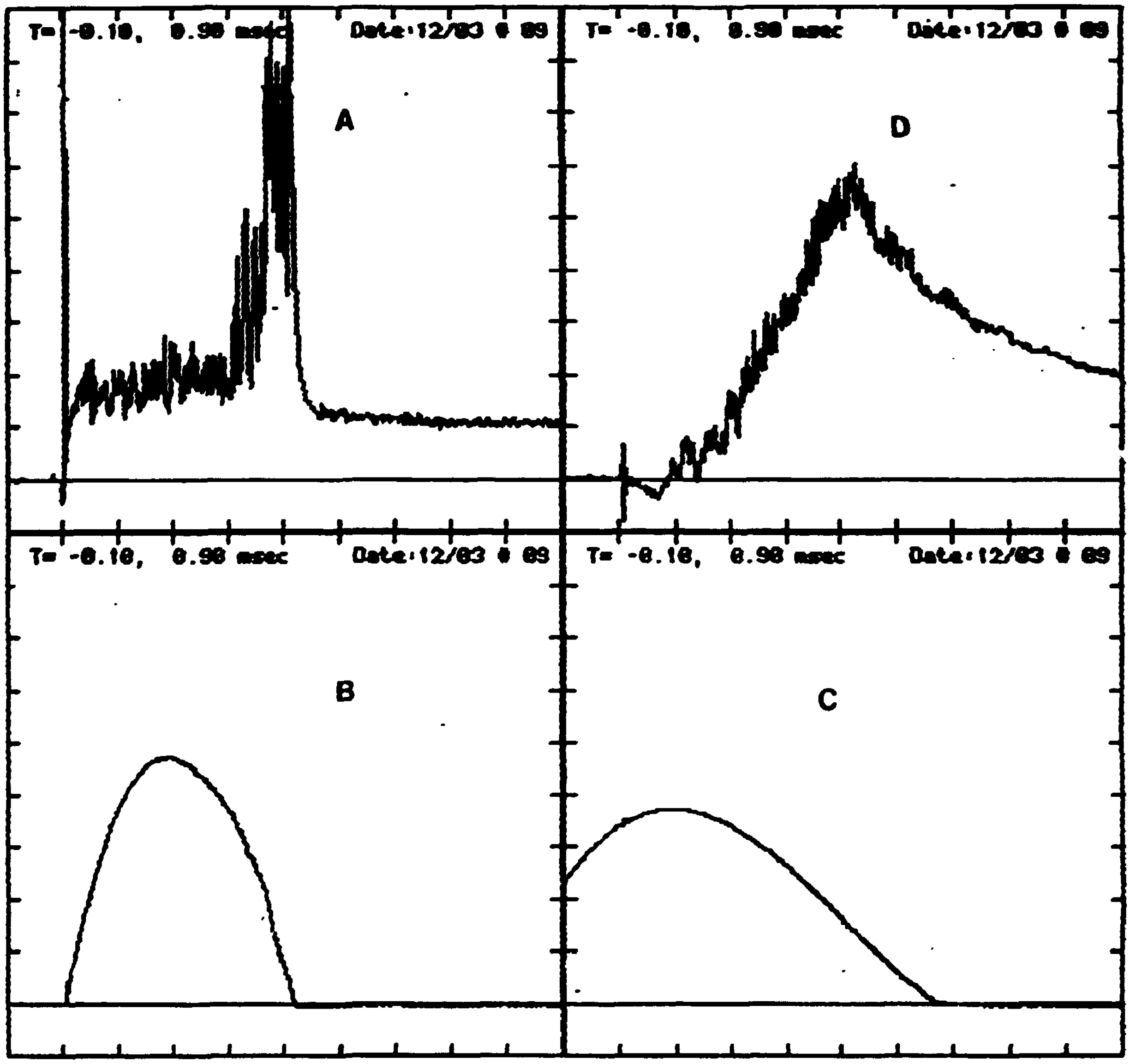


**Fig.V.4.3.:** Traces of arc voltage (A, 320 V/div), arc current (B, 500 A/div), coil current (C, 500 A/div) and chamber pressure (D, 10 bar/div) as function of time (100 µs/div). Pre-trigger of coil current: 200 µs.

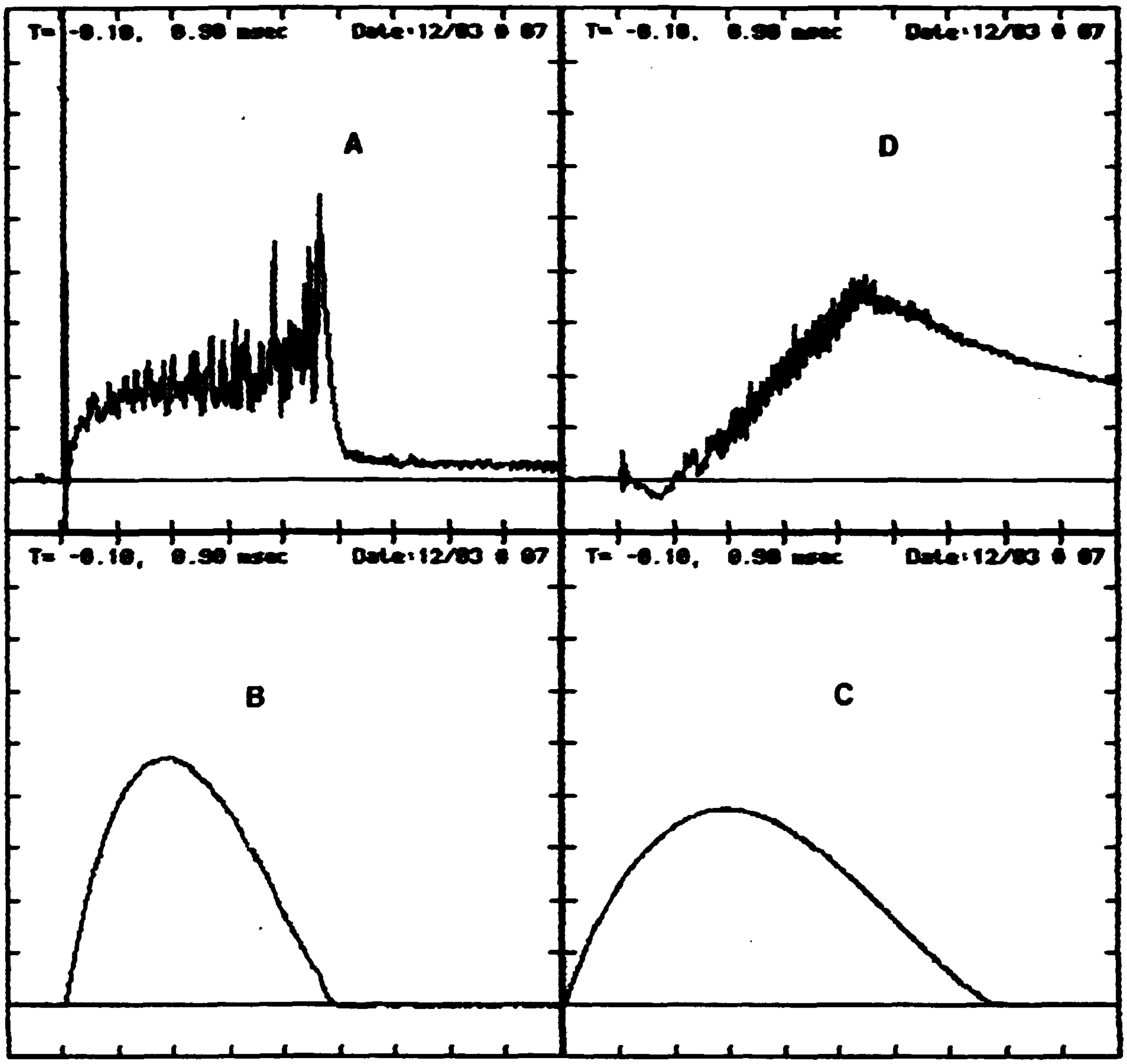


Fig.V.4.4.: Traces of arc voltage (A, 320 V/div), arc current (B, 500 A/div), coil current (C, 500 A/div) and chamber pressure (D, 10 bar/div) as function of time (100 μs/div). Pre-trigger of coil current: 100 μs.

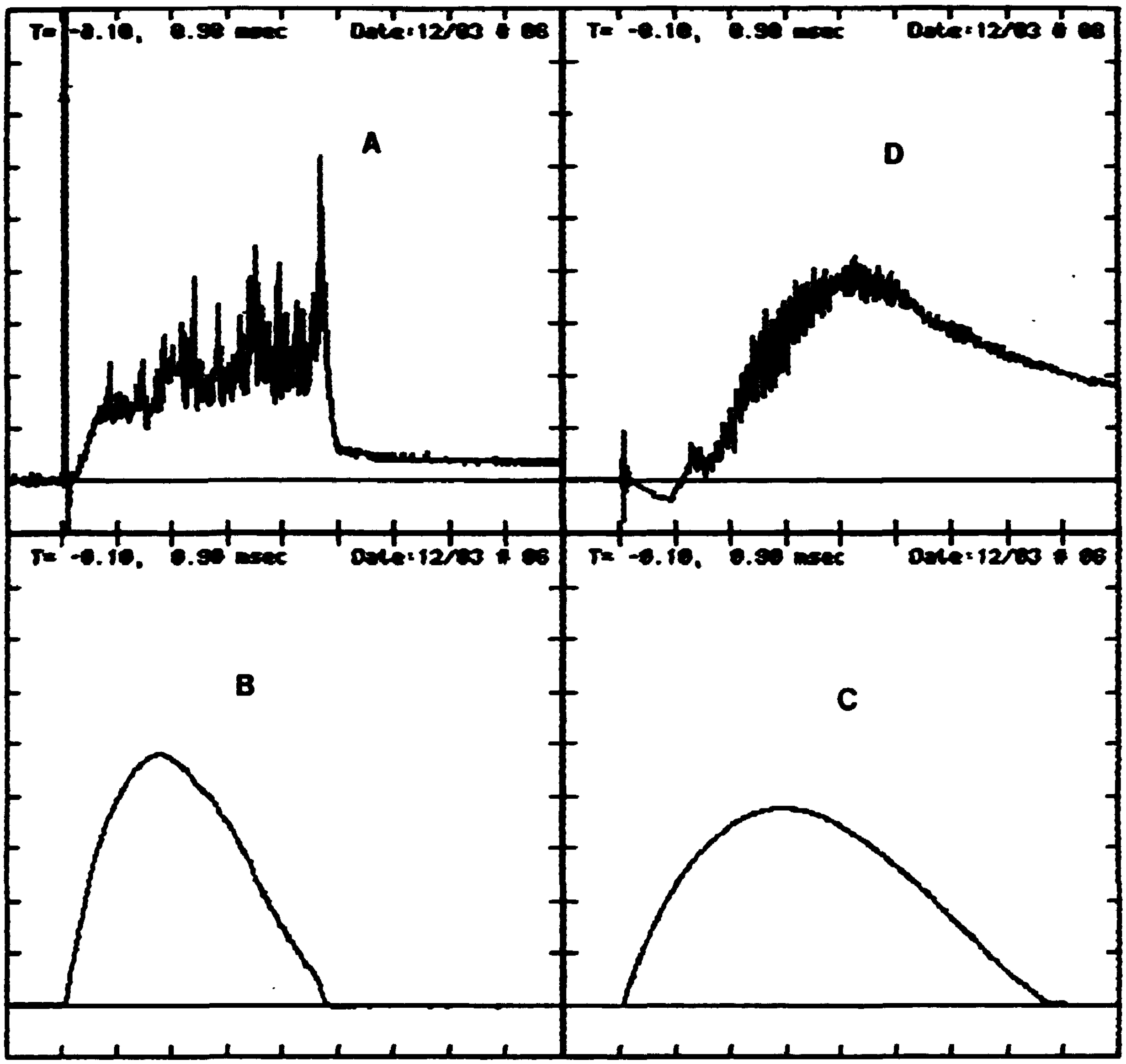


**Fig.V.4.5.:** Traces of arc voltage (A, 320 V/div), arc current (B, 500 A/div), coil current (C, 500 A/div) and chamber pressure (D, 10 bar/div) as function of time (100 µs/div). Pre-trigger of coil current: 0 µs.

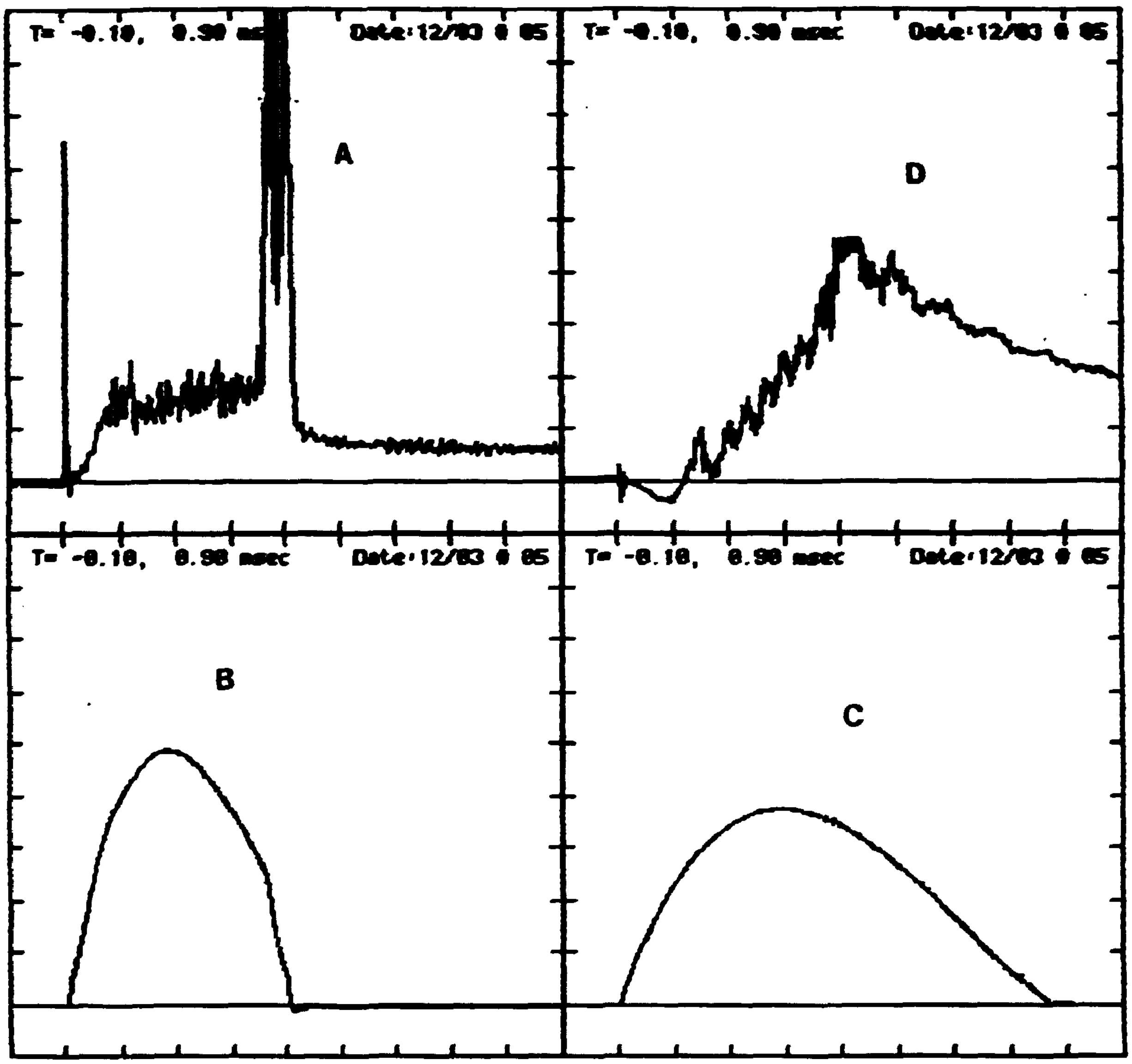


Fig.V.4.6.: Traces of arc voltage (A, 320 V/div), arc current (B, 500 A/div), coil current (C, 500 A/div) and chamber pressure (D, 10 bar/div) as function of time (100 μs/div). Pre-trigger of coil current : 0 μs. Voltage spike.

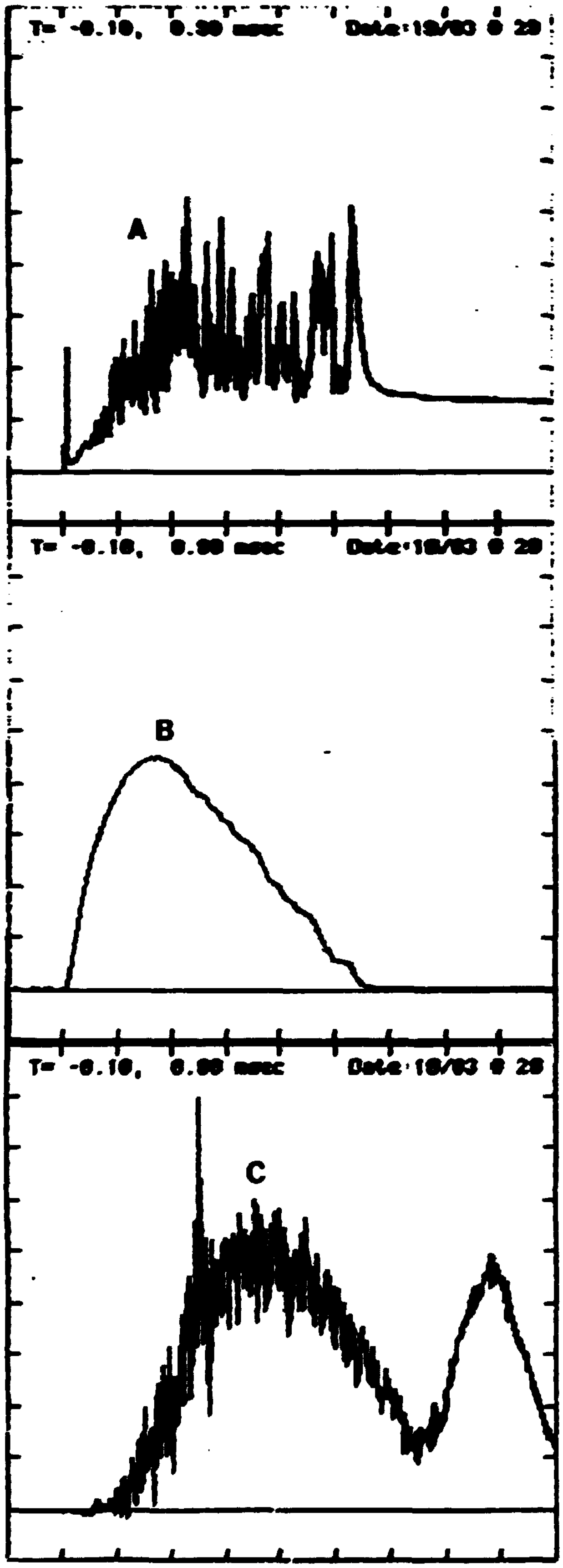


**Fig.V.4.7.: Traces of arc voltage (A, 320 V/div), arc current (B, 500 A/div) and chamber pressure (C, 10 bar/div) as a function of time (100 μs/div). Double hump pressure transient.**

# Risø National Laboratory — Risø - M - 2650

Title and author(s)

**INVESTIGATION OF PELLET ACCELERATION BY AN ARC HEATED GAS GUN***

An Interim Report on the Investigations carried out from 1985.09.01 to 1987.03.31.

P. Andersen, S. A. Andersen, J. Bundgård, L. Bækmark, B. H. Hansen, V. O. Jensen, H. Kossek, P. K. Michelsen, A. Nordskov, B. Sass, H. Sørensen, K. V. Weisberg.

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Abstract (Max. 2000 char.)

This report describes work on pellet acceleration by means of an arc heated gas gun. The work is a continuation of the work described in Risø-M-2536. The aim of the work is to obtain velocities well above 2 km/s for 3.2 mm diameter deuterium pellets. By means of a cryogenic arc chamber in which the hydrogen propellant is pre-condensed, extruded deuterium pellets are accelerated up to a maximum velocity of 1.93 km/s. When increasing the energy input to the arc in order to increase the pellet velocity further the heat input to the extrusion/punching pellet loading mechanism was found to be critical: preparation of pellets became difficult and cooling times between shots became inconveniently long. In order to circumvent this problems the concept of a room temperature hydrogen propellant pellet fed arc chamber was proposed. Preliminary results from acceleration of polyurethane pellets with this arc chamber are described as well as the work of developing of feed pellet guns for this chamber. Finally the report describes design consideration for a high pressure propellant pellet fed arc chamber together with preliminary results obtained with a proto-type arc chamber.

Descriptors - INIS

ACCELERATION; DEUTERIUM; PELLETS INJECTION; PLASMA GUNS; PNEUMATIC TRANSPORT; TOKAMAK DEVICES; VELOCITY

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