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Abstract. This report describes a possible design of a fast, high-temperature, arc-driven hydrogen gas source module, to be used in a scheme for multi-stage high-speed pneumatic acceleration of fusion plasma fuel pellets. The potential of this scheme for operating with a moderate driving pressure at long acceleration path lengths is particular attractive for accelerating fragile hydrogen isotope ice pellets. From experiments with an ethanol-based arc unit, design parameters for a propeller module were assessed, and with a barrel-mounted ethanol module staged pneumatic acceleration of a plastic dummy pellet was demonstrated. In experiments with a hydrogen-based, cryogenic arc unit in which 200 joules of electrical energy were dissipated with a power level approaching 5 MW within 30 μs, the velocity of a 23-mg plastic pellet was increased from 1.7 to 2.4 km/s. Results in terms of barrel pressure transients and arc characteristics are described.

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Contents

I. Introduction

High-speed injection of solidified fuel (D_2,T_3) is anticipated as a possible way of fuelling future fusion energy reactors. In current large-scale experiments on magnetic confinement of fusion plasmas (Tokamaks, JET, TFTR), promising results have been obtained by this technique of injecting fuel pellets into the central part of a high-temperature fusion plasma. The production of pellets of a suitable mass and size (about 30 mg, 5mm) is possible by cryogenic condensation of the hydrogen fuel, and the attainment of the required injection speed is possible by applying an accelerating force to the pellet. However, in order to obtain effective injection (deep penetration in the hot fusion plasma) a velocity of 10 km/s or more is anticipated.

At present, single-stage light-gas gun systems for pellet velocities in the 1-2 km/s range are available (1,2), and prototype 2-stage gas guns for pellet speeds approaching 4-5 km/s are being tested (3,4). Apart from the gas dynamic (pneumatic) acceleration principle, other more exotic means for obtaining higher velocities are being examined, such as electromagnetic acceleration (Rail-Gun Accelerator) (5) and ablation reaction acceleration (Electron-Beam Rocket Accelerator) (6). However, so far no experimental results from these efforts competitive with those obtained from the pneumatic gas gun principle have been published. Most experimental development work is at present devoted to extending the velocity capacity of the 2-stage pneumatic high-speed light-gas gun. Here the required high-temperature (high sound velocity) of the propelling gas is attained by feeding the breech of the gas gun barrel from an adiabatic propellant compression stage. Although it is possible by this technique to obtain a high initial propellant temperature, and also to reduce (smooth out) high peak transients of the driving pressure - as required for non-destructive acceleration of fragile fuel ice pellets - velocities approaching 10 km/s will probably be difficult to reach. A pressure smoothing is possible only to a limited extent, and a high propellant temperature is difficult to maintain along a barrel of the required acceleration path length. It has been suggested (7) that further improvements in pneumatic acceleration performance may be possible with light-gas gun systems equipped with multiple downstream electrothermal modules, by means of which energy can be added to the propellant in synchronism with the motion of the pellet in the barrel. A module which may be used in this scheme is described in this report. This module works as a high-pressure and high-temperature hydrogen gas source, with a fast-switching characteristic obtained by electric-arc discharge heating of cryo-condensed hydrogen.

This idea of using arc heating of pre-condensed hydrogen as a way of generating a fast-rising high-pressure pulse of high- temperature propellant for pneumatic acceleration of pellets to high velocities has been investigated experimentally recently (8). In these experiments it was concluded that an important limitation on the efficiency was set by an excessive convective cooling of the propellant in the barrel. However, in this earlier work the traditional scheme for a gas gun with the propellant supplied through the breech of the barrel was used. In the present work the alternative scheme for propellant supply of a gas gun is examined: multiple downstream injection of the propellant from fast-acting pellet-synchronized injection modules distributed along the barrel. With this scheme the energy loss due to propellant/barrel cooling is resolved by requiring the pressure energy of the gas pulse from each injection module to be maintained for only a short barrel length (until the next module takes over). The potential of this scheme for operating with a moderate driving pressure at long acceleration path lengths is of particular significance in connection with high-speed acceleration of fragile hydrogen ice pellets. The diagram of Fig.I.1 illustrates the basic idea of the scheme. It shows a section of a barrel equipped with a number of downstream propellant injection modules. The design and functioning of a module is described in detail in the report. In Section II the details of preliminary experiments on pressure pulse production by electric arc-discharge evaporation and heating of ethanol are presented. Section III describes experiments in which an ethanol- based module is used for staged downstream acceleration of plastic dummy pellets. In Section IV the design and application of a hydrogen-based module is described, and Section V contains a conclusion and suggestions for further development.

II. Ethanol Arc Discharge Experiments

Preliminary experiments on electric arc evaporation of liquid ethanol were performed in order to examine whether pressure levels and time constants adequate for pellet propulsion according to the downstream propellant injection scheme could be produced. In these experiments a dose of liquid ethanol was evaporated by an electric arc in a cavity of variable geometry connected to a tube of fixed length in which the pressure transient could be studied.

Experimental Set-up

A diagram of the experimental set-up is shown in Fig.II.1. It consisted of a stainless steel tube (8 mm i.d., 10 mm o.d., 100 mm long) in which an arc cavity of adjustable length was confined axially in one direction by a vespel plug with a central Ta electrode and in the other direction by a conical vespel nozzle outlet connected to a 4-mm diameter, 120-mm long tube in which the pressure development could be studied. For this purpose two pressure probes were mounted in a block at the end of the pressure tube, one (P1) with its membrane perpendicular to the tube axis and the other (P2) with the membrane parallel to the axis. The mounting block for the pressure probes also contained a channel through which the system could be evacuated. By means of a coil (115 turns of 1.5-mm diameter Cu wire) placed around the SS tube, the effect of a magnetic field on the arc could be studied. The coil could be placed at different positions relative to the arc cavity so that the effect of B-fields of different homogeneity could be studied.

A schematic diagram of the power supply for the arc and the coil is shown in Fig.III.9. The arc current was supplied from an 80 μF/2.5 kV capacitor (with pos. polarity applied to the Ta-electrode relative to the cavity wall) and the coil was driven by a 400 μF/2.5 kV capacitor. In these preliminary experiments, the value of the internal inductance in the arc discharge circuit was set at 15 μH. The arc and coil currents were measured directly by means of current monitors and the arc voltage was measured by means of a current loop containing an 800-ohm resistor. All signals were collected on transient recorders.

Experimental Procedure

With the pressure tube disconnected, a dose of ethanol could be injected by means of a syringe into the arc cavity, and with the pressure tube reconnected a shot was performed by the following steps: 1) the evacuation channel was opened in about 2 seconds in order to decrease the pressure to a level where arc ignition became possible, 2) the coil capacitor was then triggered, and 3) at maximum coil current the arc capacitor was also triggered. Shots were performed with different ethanol doses and with different values of the magnetic field obtained by varying the charging voltage of the coil supply capacitor.

Results

Typical shot recordings are shown in Figs.II.2 and II.3. Figure II.2 shows the arc current and arc voltage as functions of time and II.3 shows the corresponding pressure transients obtained from pressure probes P1 and P2. From the arc characteristics it is seen that a maximum arc current of about 3 kA is obtained about 50 μs after ignition with an arc voltage level close to about 1 kV. From the pressure transient curves, it is seen that an oscillating pressure peak of about 100 bar is measured about 50 μs after arc ignition. A dose of 40 μl ethanol was used in this shot and this amount was found to produce a maximum peak pressure. With larger amounts of ethanol the peak pressure was found to decrease and at the same time the pressure rise time was found to increase corresponding to a broadening of the pressure transient. With smaller amounts of ethanol the peak pressure was also found to decrease; however, in this case the fast pressure rise rate was maintained.

In particular, the effect of the magnetic field on the arc discharge was studied. At first the optimum position of the coil relative to the arc cavity was examined. In a series of shots with otherwise unchanged initial parameters, it was found that a maximum peak pressure was produced when the coil was positioned symmetrically about the cavity, i.e. with the cavity in the centre of the coil. With this geometry the variation of peak pressure and arc characteristic with coil current was examined. In these experiments an ethanol dose of 40 μl was used and the capacitor in the arc discharge circuit was charged to 2.5 kV. By changing the charging voltage of the capacitor in the coil circuit different values of coil peak current and thereby of the magnetic field were produced. In Fig.II.4 the variation of peak pressure with coil current is shown. Due to the pressure oscillations as shown in Fig.II.3, the peak pressure is determined but with a relatively large uncertainty. The effect of the magnetic field is significant, however; the peak pressure is increased by a factor of about 4 when the coil current is increased from zero to about 3 kA. The corresponding change in arc voltage and arc current as a function of coil current is shown in Fig.II.5. In this diagram the points for the arc voltage have been obtained as the mean value of the (oscillating) voltage signal at the time of maximum arc current (cf. Fig.II.2). The data of Fig.II.5 have been used to evaluate the arc power and impedance variation with coil current as shown in Fig.II.6. From this diagram it is seen that the arc impedance is increased with a factor of about 10 when maximum coil current is used as compared to the case of no magnetic field.

From these experiments it is concluded that the maximum available axial magnetic field should be applied to the arc cavity in order to establish an arc discharge in which the energy is effectively coupled into thermal energy of the evaporated ethanol. This result is known from other work on electric arc heating of gas: arc filaments are (Lorentz)forced in a circulating motion to sweep the cavity volume whereby cool gas continuously enters the filament centers. The conversion of electric energy into thermal energy of the gas is thereby augmented by the the magnetic field. If low induction is maintained in the circuit of the arc, a fast energy exchange process corresponding to an explosion can be produced (cf. electrically exploded wire).

III. The Ethanol Arc Module

Construction of Module

Based on the experience of producing a fast-rising pressure pulse by electric arc evaporation of ethanol, a module for demonstrating the concept of staged pneumatic acceleration by downstream propellant injection in a gun barrel was developed. The requirement of a short and unimpeded channel for transmitting propellant from the cavity to the barrel in connection with a requirement of a downstream direction of the momentum of the flow imposes important constrains on the construction. Also, the arrangement for a synchronous triggering of the module is of importance when considering high velocity propulsion. In a first version for a barrel mounted module, the arc cavity-confining elements from the above experimental test equipment were reused. Figure III.1 shows how the cavity tube with the central Ta electrode and coil are mounted at the barrel. By means of a brass manifold (soldered to the barrel) the arc discharge tube is held at a 45°-angle with the barrel. A cylindrical vespel tube with a 6 × 2 mm square bore connects the cavity and barrel. This nozzle channel communicates with the barrel through a 8 × 2 mm slit in the barrel wall. A port for syringe injection of ethanol is located at the bottom of the brass manifold. In Fig.III.1 a pressure transducer is also shown mounted upstream adjacent to the arc module. By means of this a reliable triggering for pellet-synchronized ignition of the arc discharge was obtained.

During the experiments with the ethanol arc module a second version was developed, where in particular the mounting of the module at the barrel was changed. Figure III.2 shows details of this version. Here the arc tube is mounted perpendicular to the barrel, and the arc cavity communicates with the barrel through a (6 × 2 mm square) channel with a 45°-bend in a vespel nozzle element that also forms the upper base of a clamping system by means of which the module is fixed to the barrel. With this mounting the module is clamped to the barrel by 4 bolts (not shown in Fig.II.2) and the whole module can thus easily be removed from the barrel for inspection, etc. This geometry was used in the experiments described below.

Experimental Set-up for Pellet Acceleration

The performance of a single ethanol arc module was tested experimentally in a set-up designed to accelerate plastic dummy pellets. In this experiment the pellets could be pre-accelerated in a barrel by means of pressurized He gas and the effect of the module on the pressure transients in the barrel and on the terminal pellet velocity could be examined.

Figure III.3 shows a schematic diagram of the experimental set- up. A 690-mm long stainless steel tube (4.18 mm i.d., 5 mm o.d.) was used as barrel with the arc module mounted 320 mm from the breech. Plastic pellets could be loaded manually into the breech of the barrel and pre-accelerated by a pulse of He gas obtained from a pressure chamber connected to the breech with an interposed rupture disc (0.5-mm Al). The rupture disc could be broken and firing of the pellet thus accomplished by injecting He gas into the pressure chamber from a 150-bar reservoir via a fast valve. The pressure transient in the chamber was recorded by means of a pressure probe connected to the chamber. A reproducible opening of rupture discs was ensured by punching a central cross mark in the discs.

Four pressure probes (P1 to P4) for measuring barrel pressure transients were located at 21, 264, 354, and 475 mm, respectively, from the breech, and two light barriers for time- of-flight measurements of the terminal pellet velocity were located 1350 and 1537 mm from the breech in a pellet-catching vacuum vessel connected to the muzzle of the barrel (not shown in Fig.III.3).

Figure III.9 shows a diagram of the electrical circuit for power supply to the arc and the coil. The circuit corresponds to that used for the preliminary tests on ethanol arc discharges where pressure transients in a closed volume were studied. With the present set-up for pellet acceleration, the 400 μF/2.5 kV capacitor for coil current supply is triggered by the signal from pressure probe P1 in connection with a time delay which is adjusted so that the maximum coil current is obtained at the time when the pellet passes the arc module. The 80 μF/2.5 kV capacitor for arc current supply is triggered by the signal from pressure probe P2 in connection with a time delay which is adjusted to obtain an optimum synchronization of arc firing in terms of maximum terminal pellet velocity.

Experimental Procedure

With the experimental set-up shown in Fig.III.3, shots were prepared through the following steps: By disconnecting the barrel from the pressure chamber a rupture disc could be installed and a pellet could be loaded into the breech of the barrel. The pressure chamber was evacuated (chamber pump line not shown at Fig.III.3) with the barrel reconnected to it. A dose of ethanol was loaded through the injection port into the cavity of the arc module with atmospheric pressure in the barrel. A shot could now be released by activating the fast valve to allow pressurized He gas to be introduced into the rupture disc pressure chamber. In order to make arc ignition possible, the arc cavity was evacuated through the barrel immediately before firing (barrel muzzle pump line not shown in Fig.III.3). A pumping time of about 2 seconds before the shot was released was found to produce a reliable arc ignition condition. In a separate test it was controlled that no significant amount of ethanol could be evaporated from the cavity during this pumping phase.

When a shot was released by the burst of the rupture disc, the rest of the timing was obtained from the motion of the pellet in the barrel as follows: with the pellet passing the pressure probe P1, a signal for the triggering of the coil current supply and the data collection transient recorders was obtained and with the passing of the pellet by pressure probe P2, a signal for triggering the arc circuit was obtained.

Results

The effect of the arc module on the pressure transients in the barrel is illustrated in Fig.III.4. The pressure transients obtained from pressure probes P1 to P4 in a shot where the arc was not ignited are shown in the upper part (A) of Fig.III.4 and the corresponding curves for a shot where the arc was fired are shown in the lower part (B). It is seen that the driving pressure is increased significantly in a barrel section downstream from the arc module when the arc is fired. At P3, 34 mm from the module, the driving pressure is increased from about 20 to 100 bar and at P4, 155 mm from the module, the pressure is increased from about 18 to 70 bar by activation of the module. In addition, an upstream pressure wave is seen from the signals of P1 and P2. In these shots plastic pellets of 38 mg and ethanol doses of 40 μl were used. The rupture discs were adjusted to burst at a pressure of about 90 bar. This level could be changed by varying the depth of the central cross mark which was punched in the discs. A pressure curve indicating the breaking event of the rupture disc is shown in Fig.III.5 which illustrates the pressure transient in the rupture disc pressure chamber. The volume of this chamber was about 150 cm^3 and its diameter was 70 mm. The change in terminal pellet velocity produced by the module- enhanced driving pressure is illustrated in Fig.III.6, which shows the combined signals from the two time-of-flight detectors for the above shots. It is seen that the velocity is increased from 1270 to 1670 m/s when the arc module is activated ($\delta x = 187$ mm).

Figure III.7 shows the time evolution of the arc current relative to the coil current and indicates the level of the corresponding arc voltage. The timing of the coil current was chosen so that the peak current coincided roughly with the instant the pellet passed the module (trigger delay 50 μs). It was checked that no significant effects were produced if the arc was ignited on a sloping edge of the coil current, which means that a constant magnetic field could have been used. A high-frequency noise was found to exist on the smoothed reproduction of the arc voltage shown in Fig.III.7.

The choice of inductance in the arc circuit was found to influence the propelling effect of the module, e.g. in terms of the terminal pellet velocity. An optimum was found to be about 20 μH for the internal inductor in the supply (Fig.III.9). If this inductance was reduced to zero a reduction in velocity (and module pressure) was observed. This requirement of impedance matching can possibly be related to the detailed development of arc voltage as shown in Fig.III.7. With the delay in the rising slope of the voltage as measured, a delay of the current peak, i.e. a matching induction, should be applied. This delayed onset of a rising arc voltage accounts for an important limitation when propulsion to ultra-high velocities is considered. From the data in Fig.III.7 the time development of the arc power and energy can be calculated as shown in Fig.III.8. It is seen that a peak power of 3.5 MW is produced within about 60 μs from ignition, and a total of about 225 joules are dissipated within about 130 μs in the discharge.

With the above figures for the velocity increase and energy dissipation and with a pellet mass of 38 mg, a figure for the module efficiency (increase of pellet kinetic energy/electrical energy) of about 10% is obtained.

It was found - in agreement with the results of the initial closed tube pressure pulse experiments (Section II) - that an ethanol dose of about 40 μl produced an optimum velocity increase with the present module geometry and power supply.

The above experimental results demonstrate that it is technically possible to induce a staged pneumatic acceleration in a gas gun by a synchronized firing of an arc module for downstream injection of propellant along the barrel of the gun. Ethanol was used as the propellant medium in this preliminary set of proof-of-principle tests in order to obtain simple experimental conditions. However, in order to obtain maximum pellet velocities a low-molecular mass propellant has to be used. Hydrogen then becomes the optimum choice of driver gas. The construction and test of an arc module in which hydrogen is used as propellant is described below.

IV. The Hydrogen Arc Module

Design of the Module

A single hydrogen arc module was built and tested. A cryogenic version in which solidified hydrogen could be loaded was designed. Figure IV.1 shows details of its construction. A CrCu tube, of which the upper part is cooled by liquid helium and the lower part forms the wall of a cylindrical arc chamber, constitutes the central element of the module. The CrCu tube is bolted to the upper flange of a high-pressure enclosure (SS tube), which is attached to the barrel by a vespel clamping part. This part contains a nozzle channel with a 45° bend, through which the arc cavity is connected to the barrel. The channel has a square opening of 2 × 6 mm at the cavity and connects to the barrel through a 2 × 8 mm slit. An axial brass rod makes the electrical connection to a Mo electrode, which protrudes into the arc cavity through a vespel insulator. The brass rod is sealed in a vespel insulator mounting at the top of the CrCu element and cooled through a sapphire tube in the center of this element. A coil (75 turns of 1.5-mm diameter Cu wire) is placed coaxially around the arc cavity. By means of this coil it is possible to apply a pulsed axial magnetic field to the cavity during the arc discharge. To allow the field to penetrate the cavity, four axial slits are made in the lower part of the CrCu tube. The total length of the module is 90 mm and the arc chamber cavity has a length of 10 mm and diameter of 8 mm.

In operation, the CrCu element could be cooled by liquid helium to about 7 K and a dose of hydrogen gas could then be condensed at the inner wall of the cavity. With the magnet coil energized, the condensed hydrogen could now be evaporated and heated by striking an electrical arc between the central Mo electrode and cavity wall. In this way, a pulse of high-pressure and high-temperature hydrogen gas could be injected into the barrel.

Set-up for Pellet Acceleration

The performance of a single hydrogen arc module with respect to pellet acceleration was tested experimentally in a set-up similar to that used for testing the ethanol module. Figure IV.2 shows a schematic diagram of the new hydrogen module set-up. A 965-mm long SS tube (4.18 mm i.d., 5 mm o.d.) was used as barrel with the arc module mounted 500 mm from the breech in a vacuum enclosure that provided thermal insulation. Plastic pellets could be loaded manually into the breech of the barrel and pre- accelerated by a pulse of He gas obtained from the same pressure chamber/rupture disc system as used in the ethanol module experiment. Four pressure probes (P1 to P4) for measuring barrel pressure transients were located at 80, 440, 550, and 665 mm, respectively, from the breach, and a set of light barriers was again used for time-of-flight measurements of the terminal pellet velocity.

The power supply system of Fig.III.9 was used again with the arc- discharge current obtained from the 80 μF/2.5 kV capacitor battery triggered by the signal from pressure probe P2 via an adjustable time delay (t_1), and with the coil current obtained from the 400 μF/2.5 kV capacitor battery triggered by the signal from pressure probe P1 via another adjustable time delay.

Shot Preparation and Procedure

With the CrCu element of the module cooled to about 7 K by a flow of liquid helium, a pellet and rupture disc could be inserted by disengaging the breech coupling between the barrel and the rupture disc pressure chamber; a flow of room temperature helium, introduced through the muzzle, was used to flush the barrel at this operation. After evacuating the system, a dose of hydrogen was introduced through the barrel muzzle, and with the dose cryo- condensed in the cavity of the arc module, the system was then ready for firing. As for the ethanol module experiment, a shot was initiated by activating the fast valve for introducing pressurized He gas into the rupture disc chamber, and with the pellet released by the burst of the rupture disc, triggering of the electrical circuits for producing magnet and arc currents as well as triggering of the data recording equipment was synchronized to the propagation of the driving pressure behind the pellet along the barrel by the transient signals from the pressure probes (P1 to P4).

With a high solid hydrogen load of the module, special precautions were required to obtain reliable ignition of the arc. In shots with high loading, ignition was obtained only if a low power stationary arc discharge was maintained in the cavity during the process of hydrogen condensation. The current for this ignition conditioning arc was obtained from a non-destructive insulation tester; with this device activated until immediately before a shot (within ~ 1 s), ignition up to a maximum dose was reliably obtained.

Results

The performance of the hydrogen arc module was examined by comparing the terminal pellet velocities and the corresponding barrel pressure transients obtained in shots with and without the arc module activated. Figure IV.3. illustrates in this way the effect on the barrel pressure transients by activation of the module. The upper part of the figure (A) shows the signals from the four barrel pressure probes (P1 to P4) in a shot where the module was un-activated, and the lower part (B) shows the pressure signals from a shot where the module was activated. It is seen that the driving pressure 165 mm downstream from the module (at P4) increases from below 10 to about 90 bar by activating the module. A corresponding increase in pellet terminal velocity from 1680 m/s (no arc ignition) to 2450 m/s (arc ignition) was observed.

Figure IV.4. shows the time behaviour of arc voltage and arc current. A peak arc current of 3.7 kA was obtained with an arc voltage level of about 1.5 kV corresponding to a peak power of about 5 MW reached within about 30 μs after ignition. About 200 joules of electrical energy were dissipated within 75 μs by the arc discharge. With a pellet mass of 23 mg for the results above, a figure of about 17% for the efficiency (kinetic energy gain/electrical energy) is obtained. These results were found at a hydrogen dose of 100 bar cm^3 (at 300 K), a time delay $t_1 = 20$ μs, and with a coil current of 2.3 kA. The terminal pellet velocity was found to increase with increasing hydrogen dose, but ignition with the applied 2.5 kV became difficult above 100 bar cm^3 and reliable ignition was possible for doses up to this level only with the above-mentioned low-power pre-conditioning arc activated during the hydrogen condensation process. By using a discharge circuit with a higher ignition voltage, a further increase in hydrogen dose may be possible.

By comparing the arc characteristics obtained in the ethanol and hydrogen experiments (Figs.III.7. and IV.4, respectively) it is seen that the initial time development of the arc voltage differs in the two cases: a more prompt voltage rise is produced in the hydrogen case than in the ethanol case. The delay in the onset of a rising voltage as observed in the ethanol case (Fig.III.7) is not present in the hydrogen case (Fig.IV.4). In agreement with this change in initial arc impedance development, an improved energy transfer from the arc circuit to the propellant gas was obtained by lowering the internal induction in the arc circuit. In the hydrogen experiment the maximum pellet velocity was produced when the variable inductance in the circuit was reduced to zero, and only the cable inductance remained. This indicates that a further improvement in response performance of the energy exchange process is possible. The ultra-fast energy-switching time required when synchronous propelling of hyper-velocity pellets is considered could probably be obtained by the use of a proper low-induction discharge circuit design. As in the ethanol case, the triggering of the magnet coil current was adjusted so that the current maximum coincided roughly with the ignition time of the arc. Also, in this experiment with hydrogen propellant it was checked that no significant effects were produced if the arc was ignited on a sloping edge of the coil current pulse, which again confirms that a constant magnetic field could have been used.

V. Conclusion and Suggestions

The objective of the work described in this report was to investigate the concept of producing a staged pneumatic acceleration of a pellet by downstream injection of arc-heated propellant along the barrel of a gas gun. The requirements for this concept of a fast-acting injection device and a reliable synchronizing method have been examined experimentally.

Firstly, it was verified that pressure transients of an adequate amplitude and time constant could be produced by electric arc discharge-heated evaporation of liquid ethanol in a closed volume. From these experiments a geometry for a propellant injection module to be used in conjunction with a gas gun barrel was defined.

Secondly, it was verified that it was possible to synchronize the firing of a barrel-mounted module to the passage of a pellet in the barrel. In these experiments it was also shown that a significant pellet propulsion effect was produced by the module with ethanol as propellant medium.

Finally, it was verified that this concept of modular-staged pneumatic propulsion could also be applied with hydrogen rather than ethanol as propellant. By means of a cryogenic module in which a load of hydrogen could be cryo-condensed, it was shown that an effective transfer of electrical energy from the arc to the hydrogen propellant and thus to pellet kinetic energy could be produced.

From the results obtained so far with a single module of preliminary design and with plastic pellets passing the module at a velocity of about 1500 m/s, it seems worthwhile to investigate experimentally the ultimate velocity range attainable in a multiple module configuration already with this design. The potential of this scheme for operating with a moderate driving pressure at long acceleration path lengths is of particular interest when acceleration of fragile ice pellets of hydrogen isotopes is considered. The introduction of slits in the barrel as required by this design could possibly cause additional mechanical wear of ice pellets. However, different means for stabilizing the pellet motion in the barrel could be examined. For example, by using a slightly curved barrel with the slits arranged at the inner curvature along the barrel, the induced centrifugal force would reduce the interaction of the pellet with the slits. Although the centrifugal force may result in an increased unsymmetrical perimeter erosion of the pellet, this lateral force would also contribute to stabilizing the pellet against a tumbling motion in the barrel, and thus provides a potential means of reducing the disintegration of the pellet due to tumbling.

The ultimate performance of the technique in terms of energy coupling efficiency and response time was unexplored, as the mechanical strength of the present module construction and the remanent induction in the available arc circuitry defined the practical experimental limitations. However, with the hydrogen module, an promising initial arc impedance time development for the required ultra-fast energy switching was observed.

The requirement of a strong magnetic field (B) applied to the arc current density (J) - in order to create conditions for an augmented energy exchange by J × B Lorentz force »stirring« of the arc cavity volume - impose severe restrictions on the optimal close staging geometry. In order to minimize the propellant pressure »ripples« produced by the modular staging of the propellant gas supply, a »continuum« approaching distribution of modules should be developed, i.e. ideally infinitesimally small module units continuously distributed along the barrel. This geometry would minimize the pellet disintegrating effects of a »rippled« acceleration pressure. In this development the cryogenic design of the arc electrode configuration could address the possibility of establishing a partial propellant re-cycling process in order to minimize propellant pollution of the target plasma. This would require an optimal design of the thermodynamic properties of the combined electrode and cryo-panel surface of the barrel. The volumetric requirements of coil windings for electromagnetic production of the implied magnetic field and the observation that only a constant field is required, suggest that permanent magnetic material electrodes could be considered in the design. If a magnetic field of the required intensity and orientation could be implemented in this way, an approach to a continuum-type configuration could be sought.

Only the question of achieving the high pellet velocities necessary for fusion plasma fuelling has been addressed by the present experimental development. The question of obtaining the required repetition rate has not been considered. It is difficult to imagine how the combined electrode/cryo-pump geometry could be configured to produce a discharge/re-condensing recycling process, that is fast enough to fulfill this requirement (about 1 Hz). However, if a reasonable repetition rate could be obtained, this problem could be solved by using a multiple barrel supply scheme.

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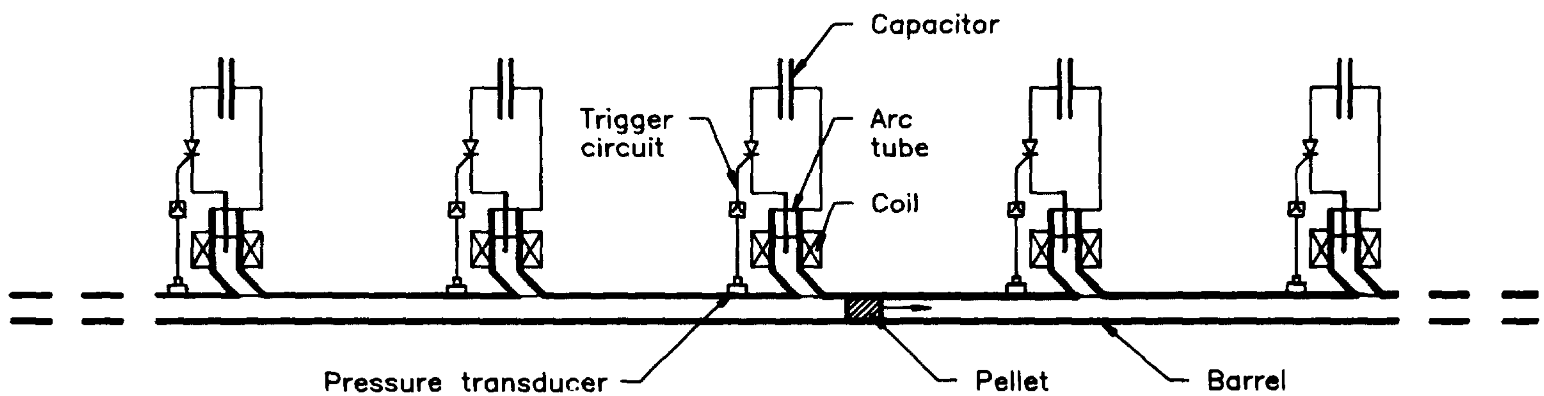

Fig. I.1. Schematic diagram of multi-stage pneumatic acceleration.

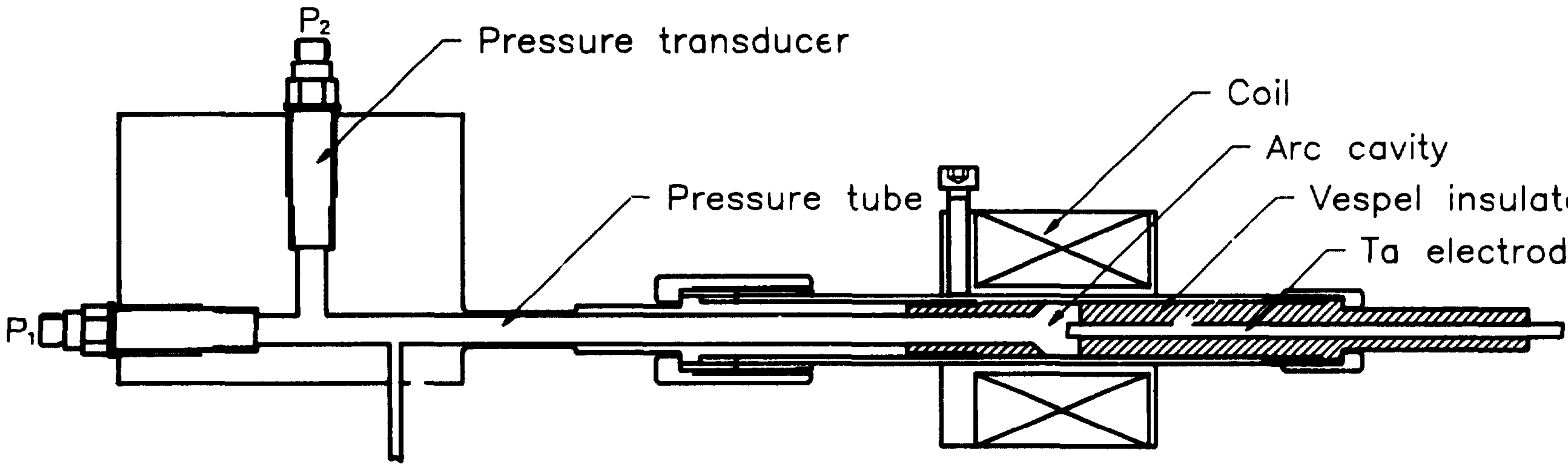

Fig. II.1. Diagram of ethanol arc discharge tube.

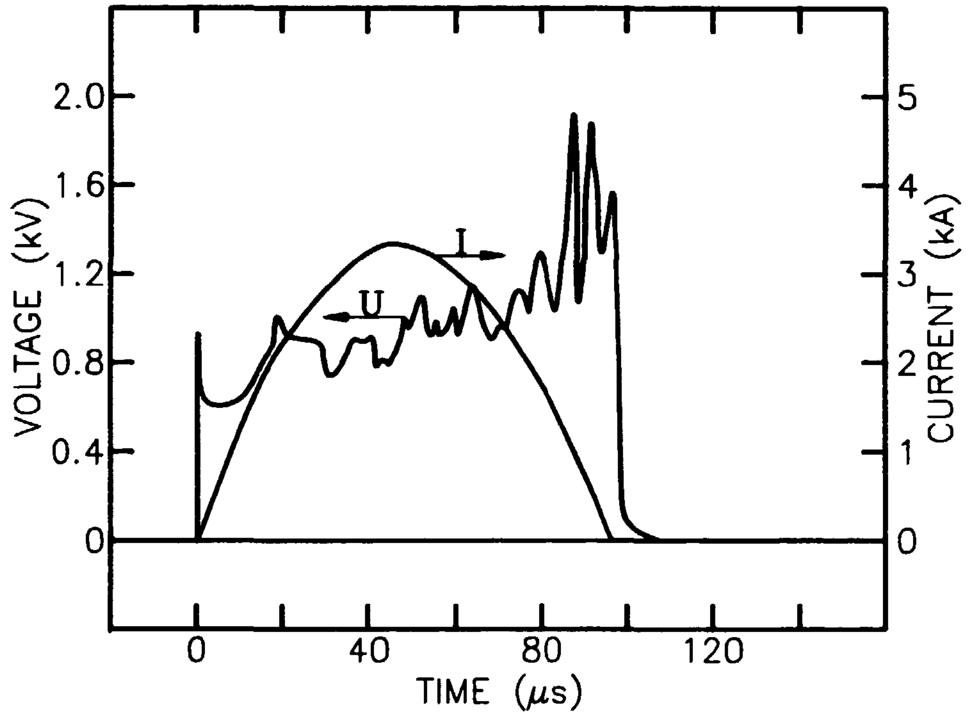

Fig. II.2. Ethanol arc discharge characteristic. Arc voltage (U) and arc current (I) versus time. Ethanol dose: 40 μl. Coil current: 2.5 kA.

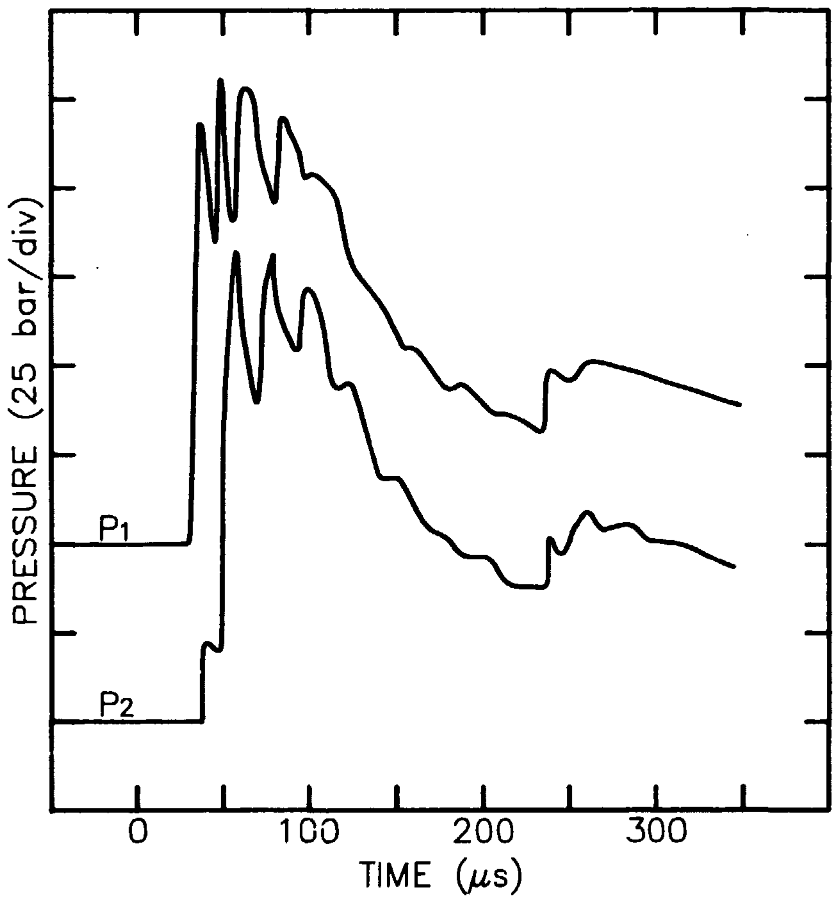

Fig. II.3. Ethanol vapor pressure transients. Signals from pressure probes P1 and P2, Fig. II.1. Same conditions as for Fig. II.2.

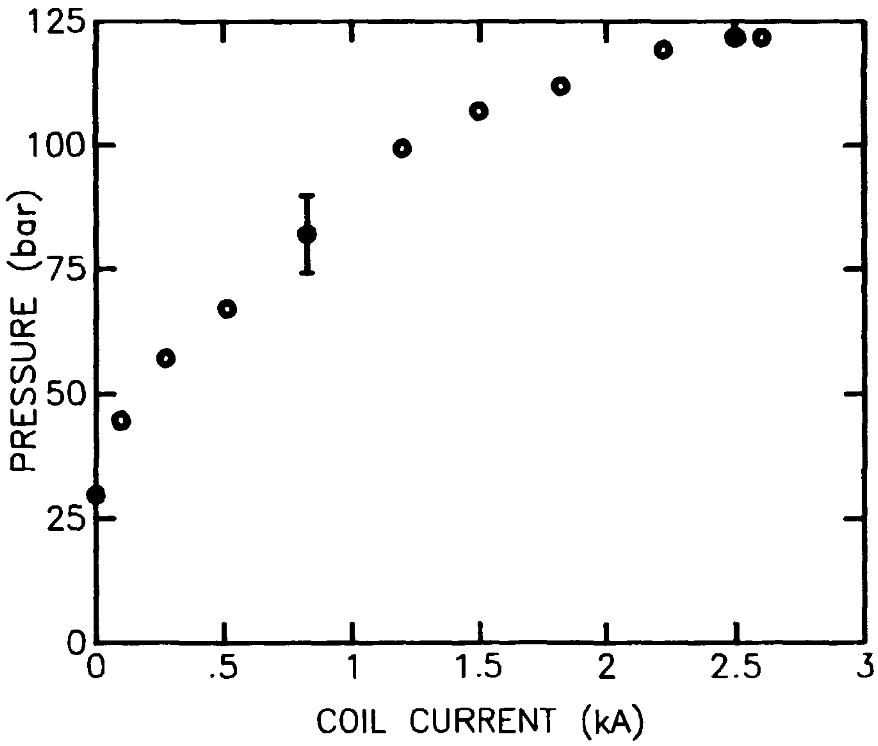

Fig. II.4. Ethanol peak pressure as function of coil current. Points obtained with 40 μl ethanol dose and 2.5 kV charging voltage for the arc discharge capacitor.

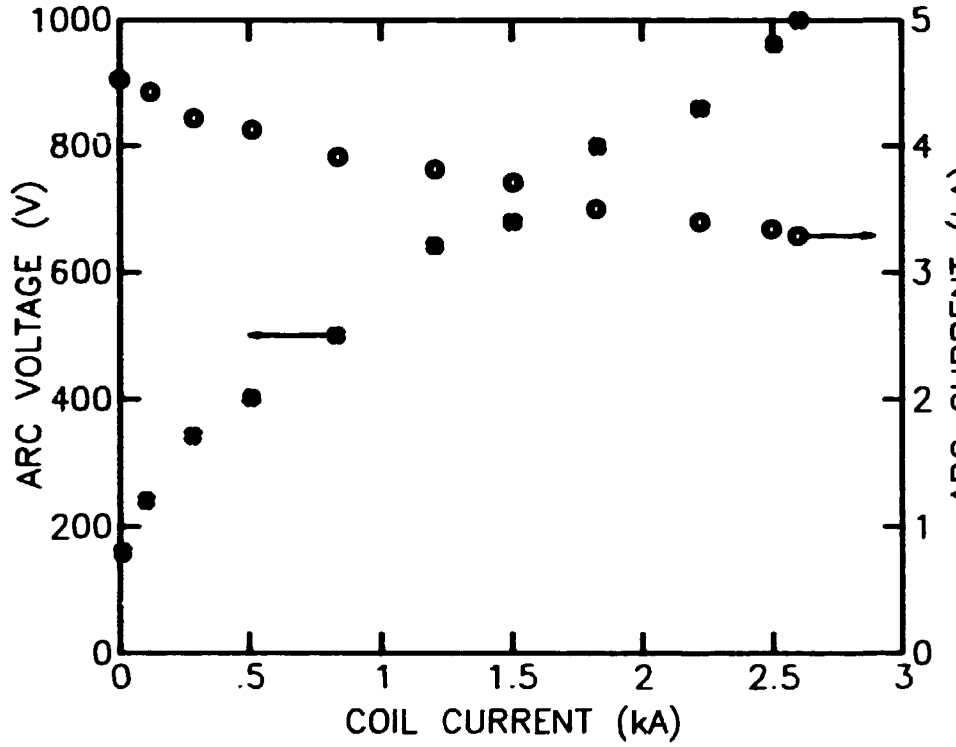

Fig. II.5. Arc voltage at maximum arc current and arc current as a function of coil current (40 µl ethanol, 2.5 kV charging voltage).

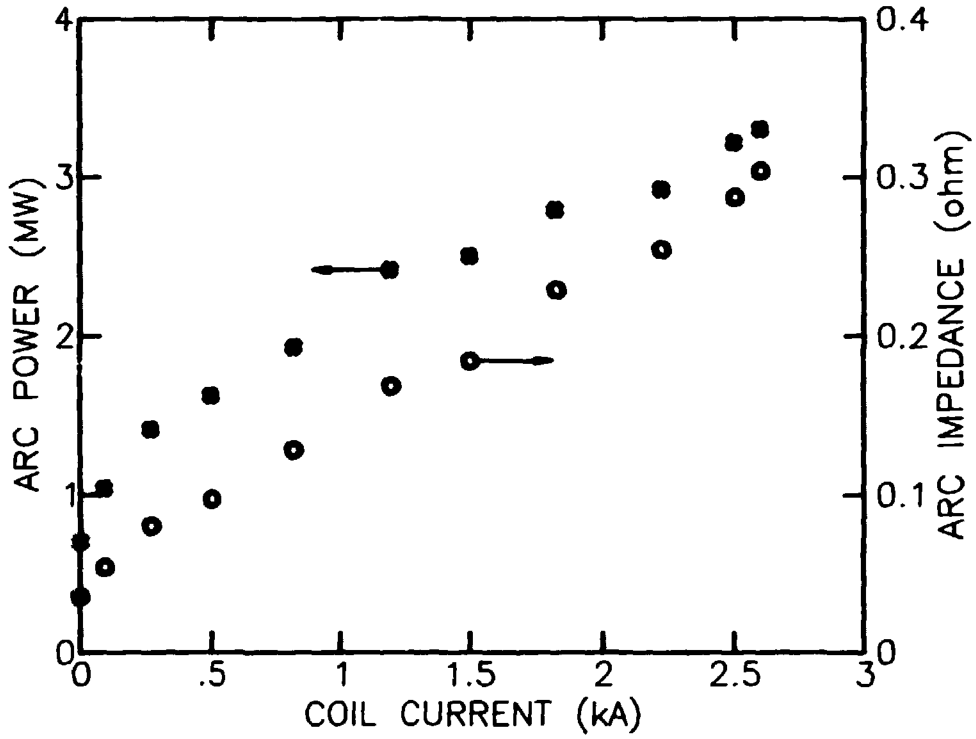

Fig. II.6. Arc power and arc impedance as a function of coil current. Points calculated from data in Fig. II.5.

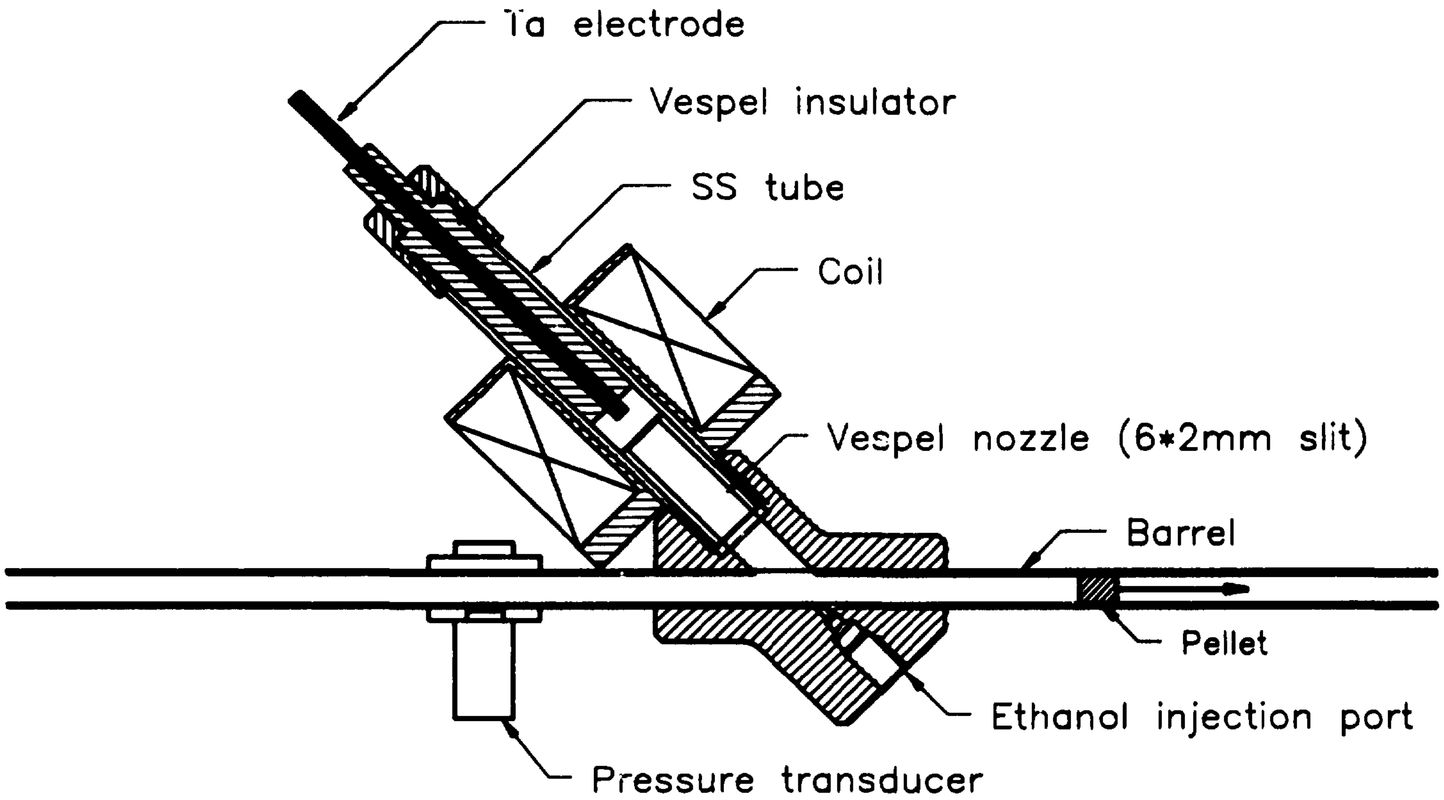

Fig. III.1. Diagram of ethanol-based arc module with oblique fixed barrel mounting.

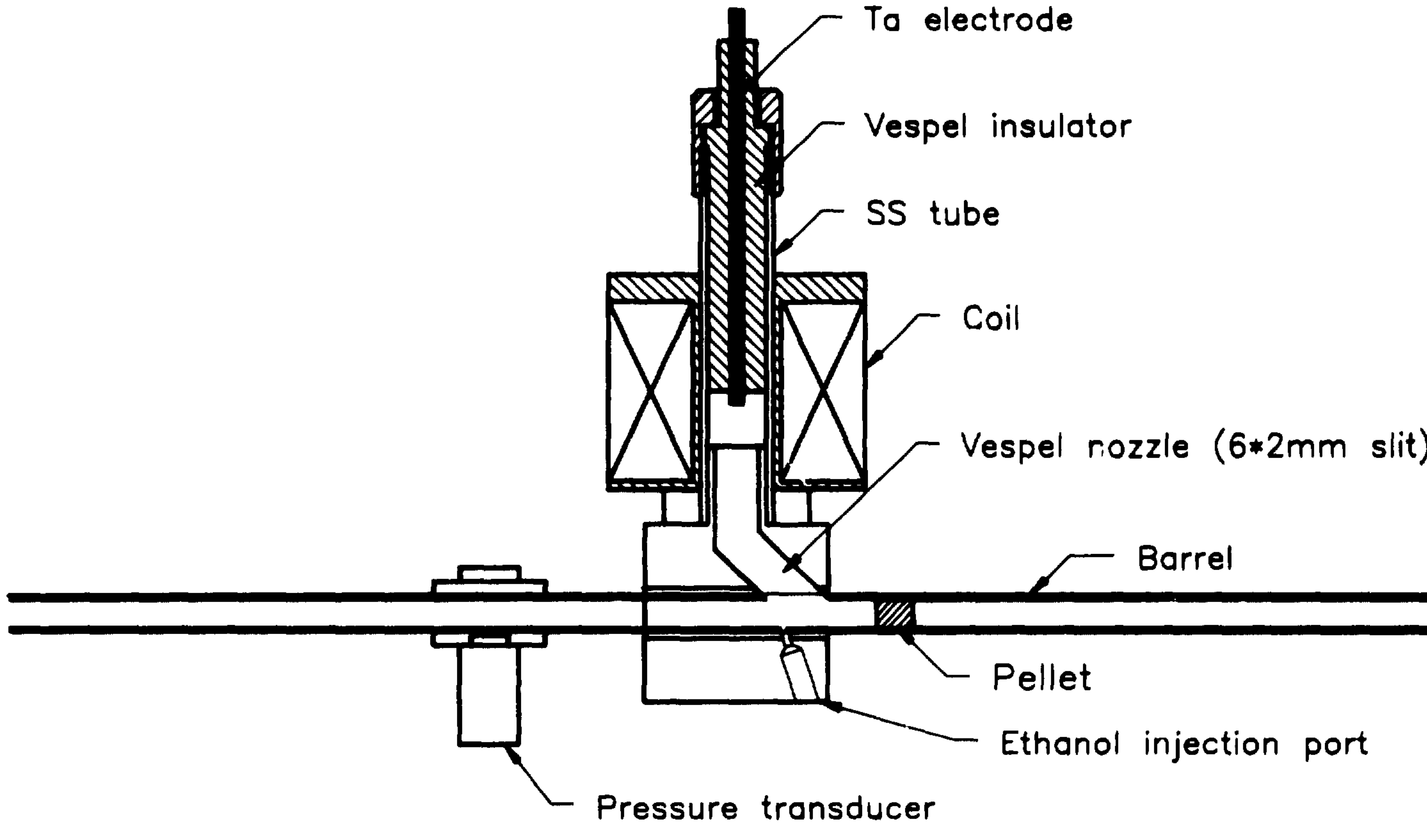

Fig. III.2. Diagram of ethanol-based arc module with perpendicular clamped barrel mounting.

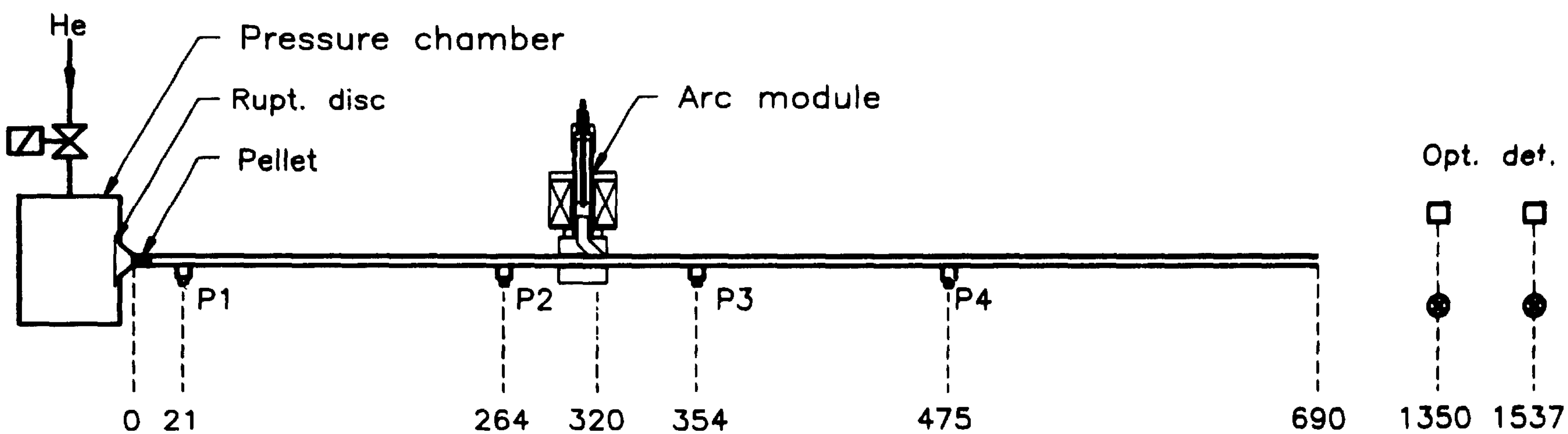

Fig. III.3. Diagram of experimental set-up for acceleration of plastic dummy pellets with the ethanol arc module.

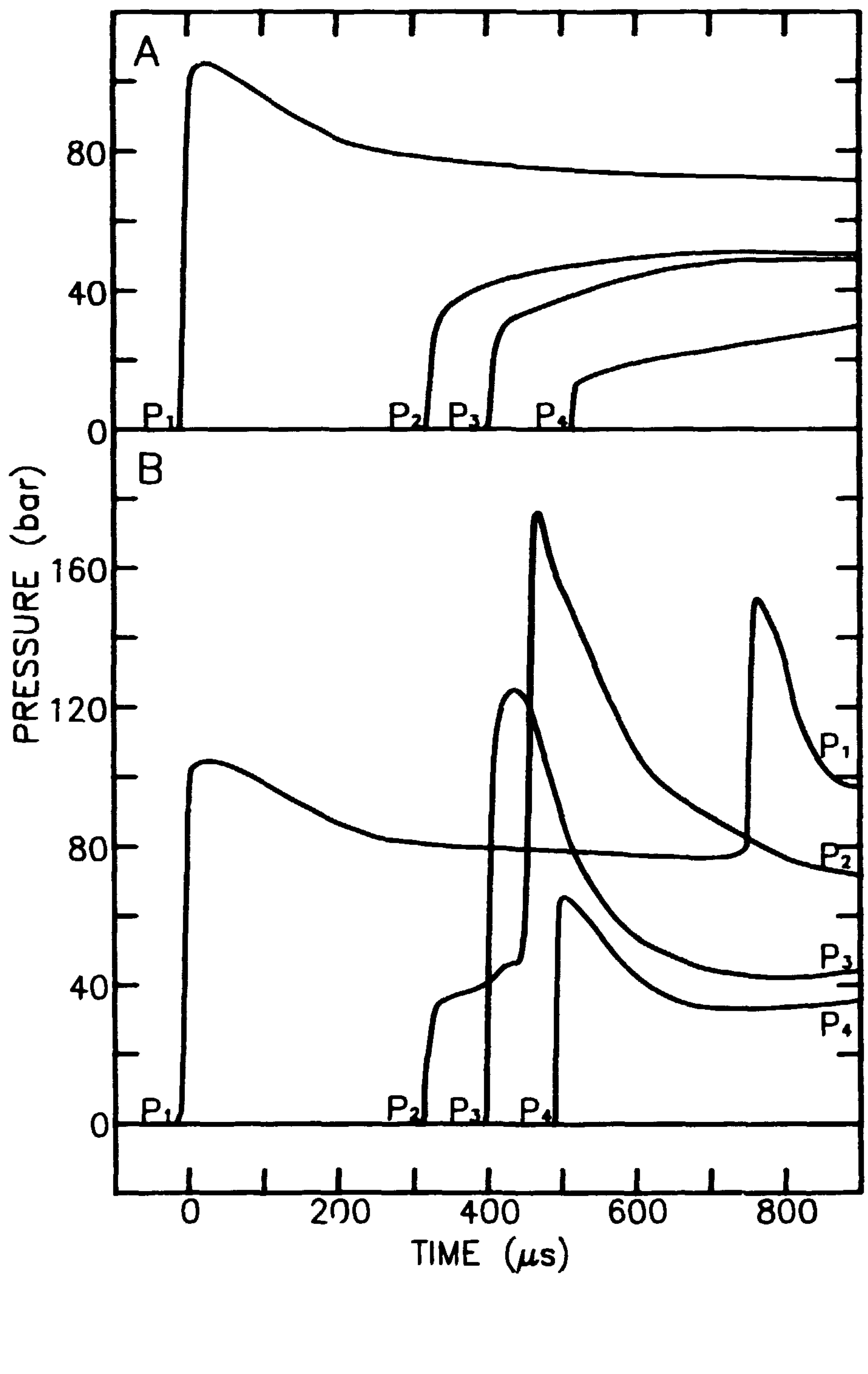

Fig. III.4. Barrel pressure transients. Signals from pressure probes P1 to P4, Fig. III.3. Upper part (A) from shot without ignition, lower part (B) from shot with ignition of the ethanol arc module. Ethanol dose: 40 μl, discharge capacitor voltage: 2.5 kV and coil current: 2.5 kA.

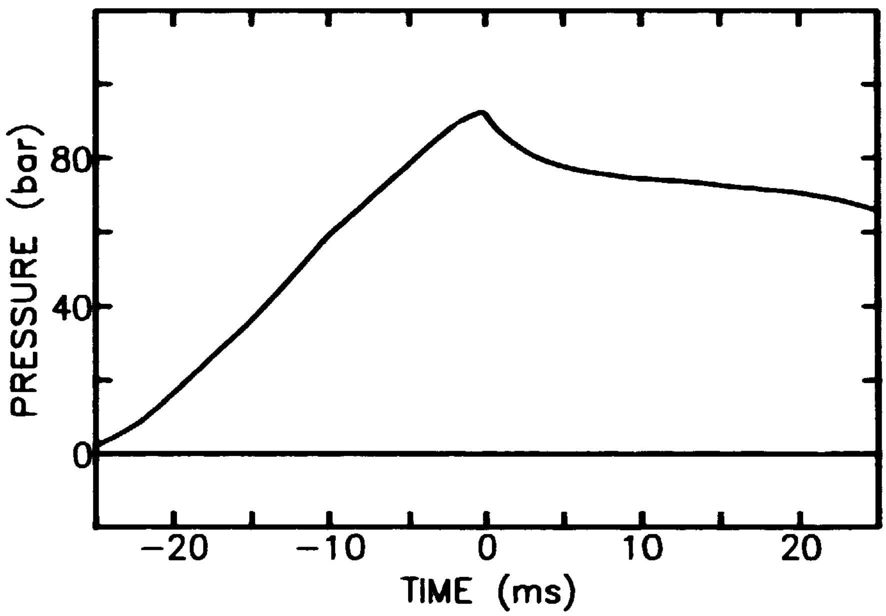

Fig. III.5. Pressure transient in the rupture disc pressure chamber of Fig. III.3.

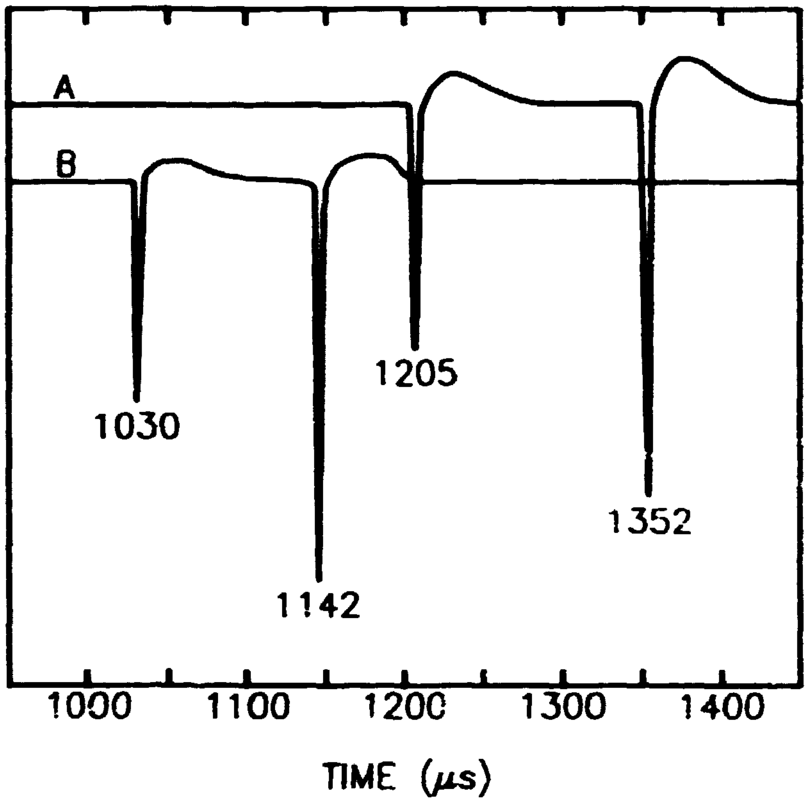

Fig. III.6. Time-of-flight signals from optical detector. Trace A: without firing of arc module; trace B: with the arc module fired.

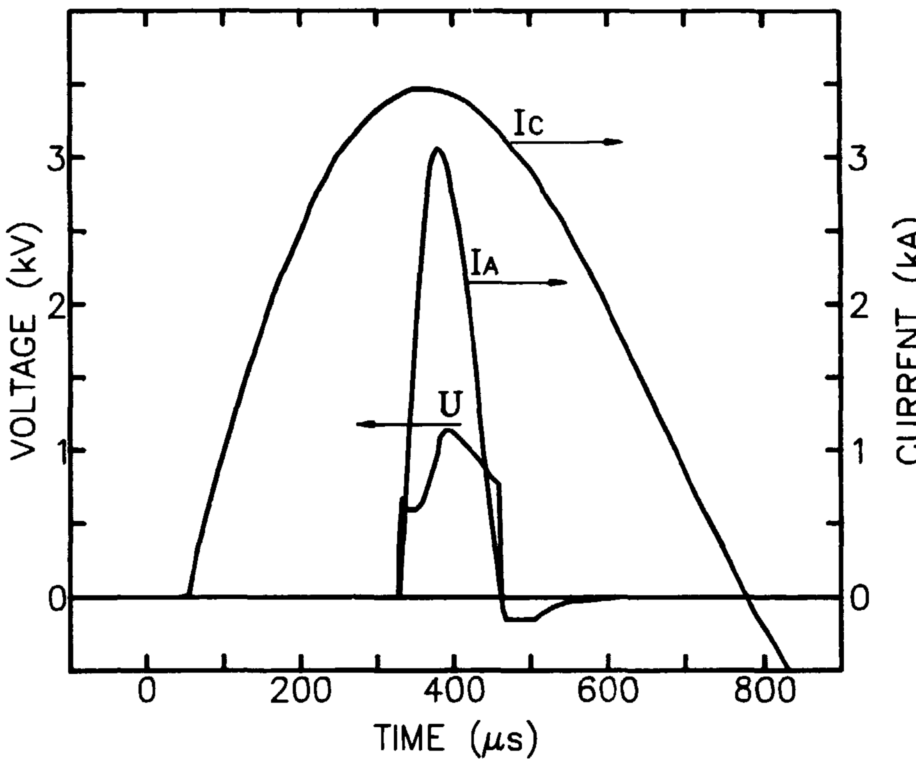

Fig. III.7. Arc discharge characteristics for the ethanol module. Arc voltage (U), arc current (I_A) and coil current (I_C) versus time.

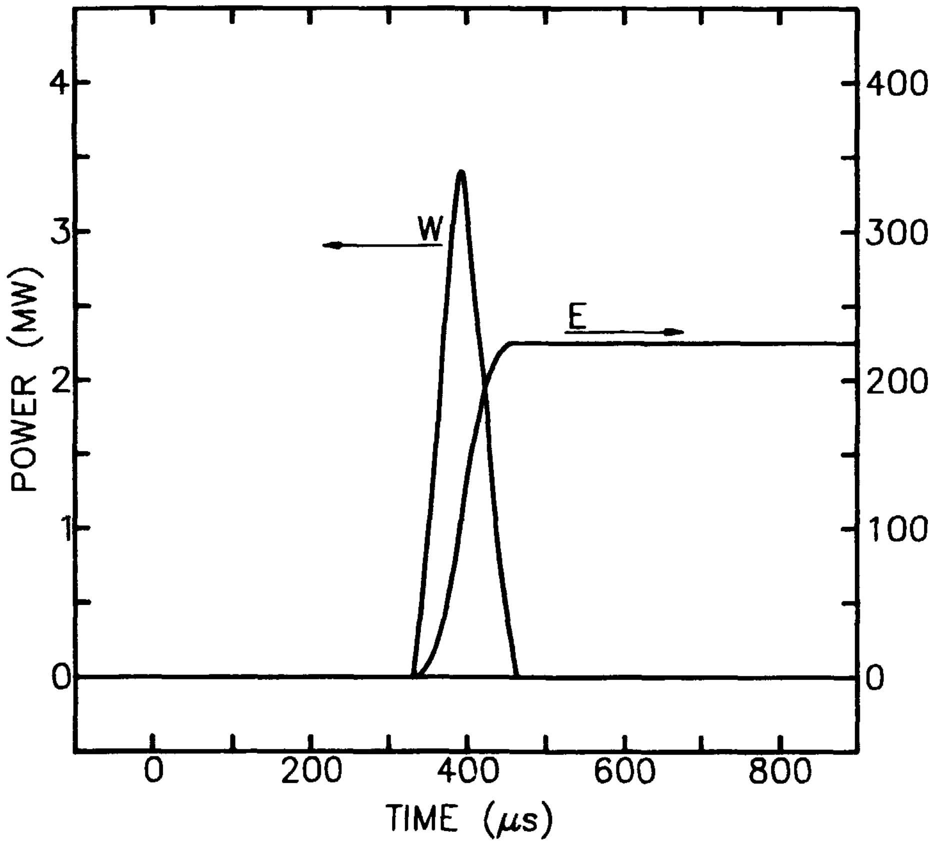

Fig. III.8. Arc power (W) and energy (E) versus time for the ethanol module.

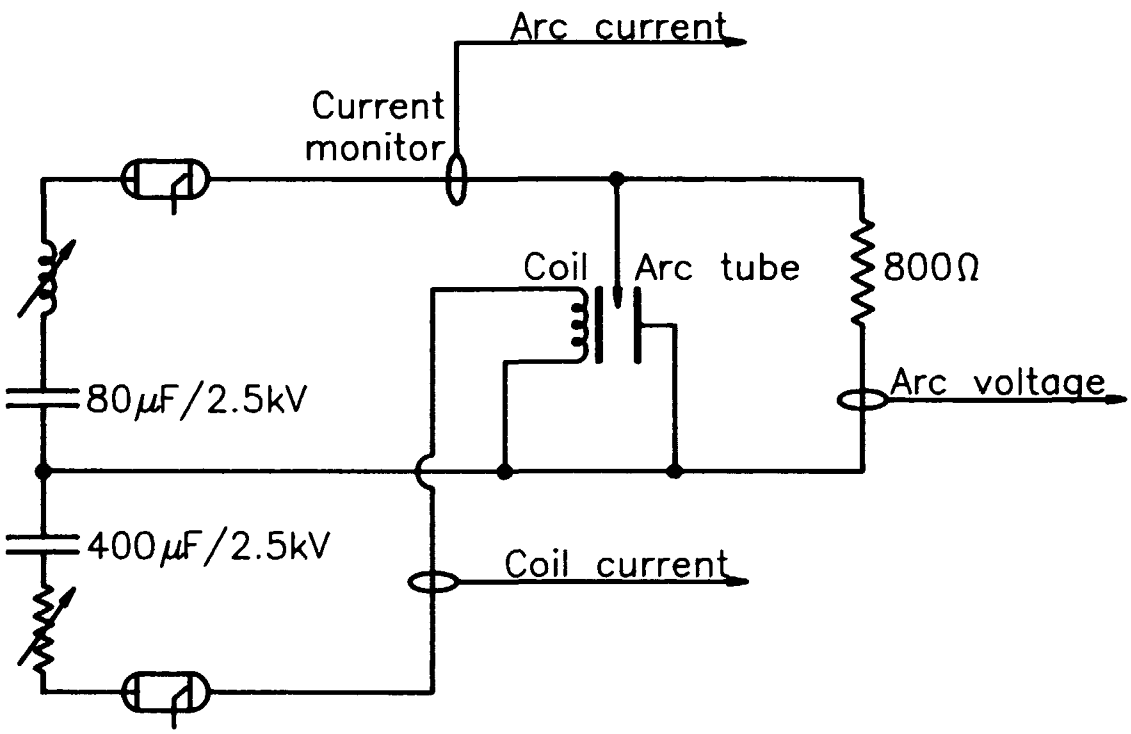

Fig. III.9. Diagram of power supply circuit for the arc tube and the magnet coil.

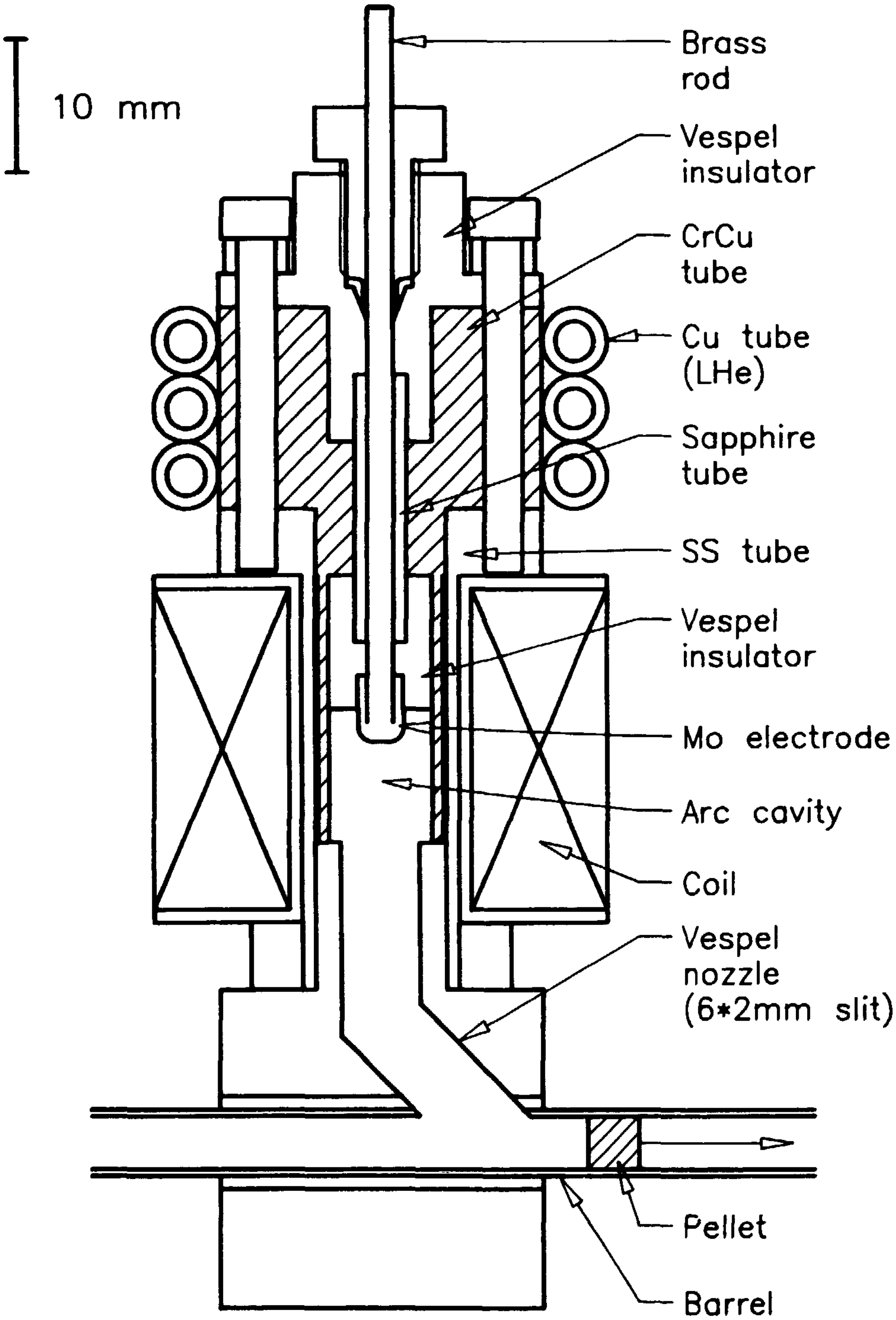

Fig. IV.1. Design details of the cryogenic hydrogen arc module.

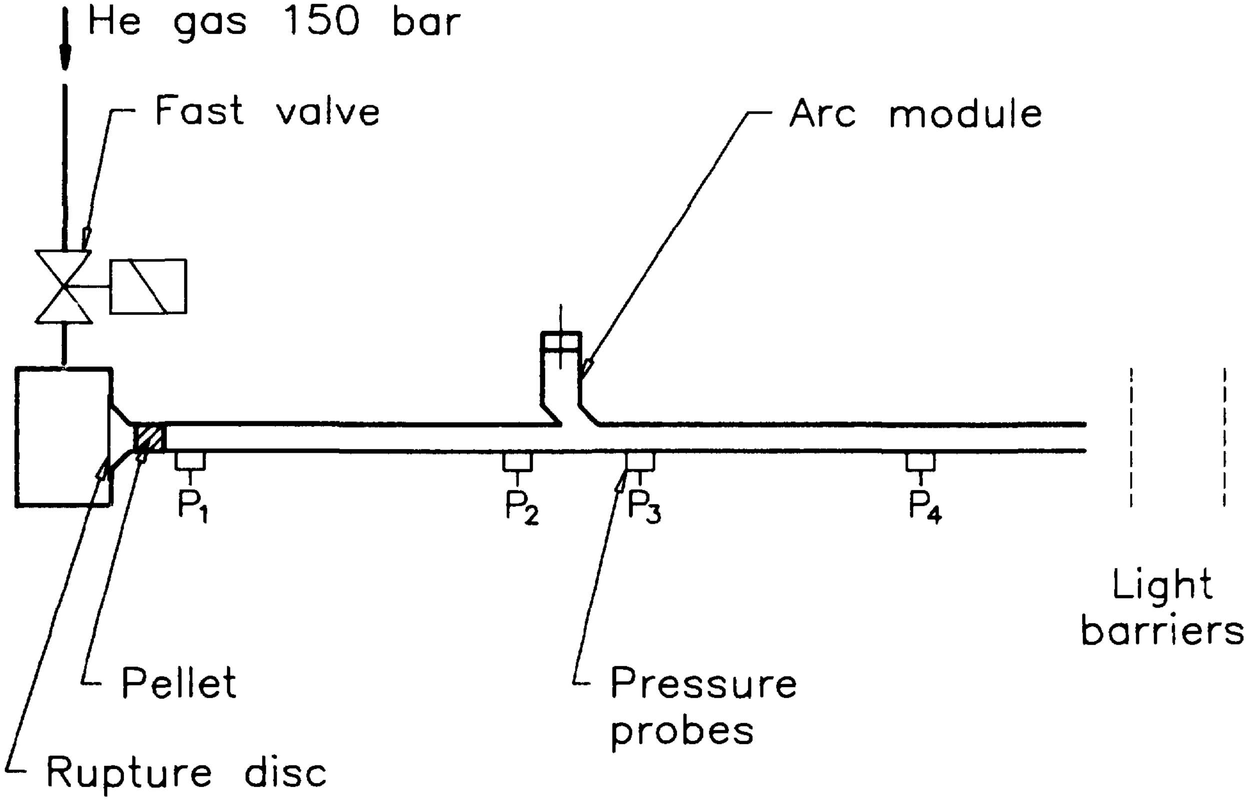

Fig. IV.2. Diagram of experimental set-up for acceleration of plastic pellets with the hydrogen arc module.

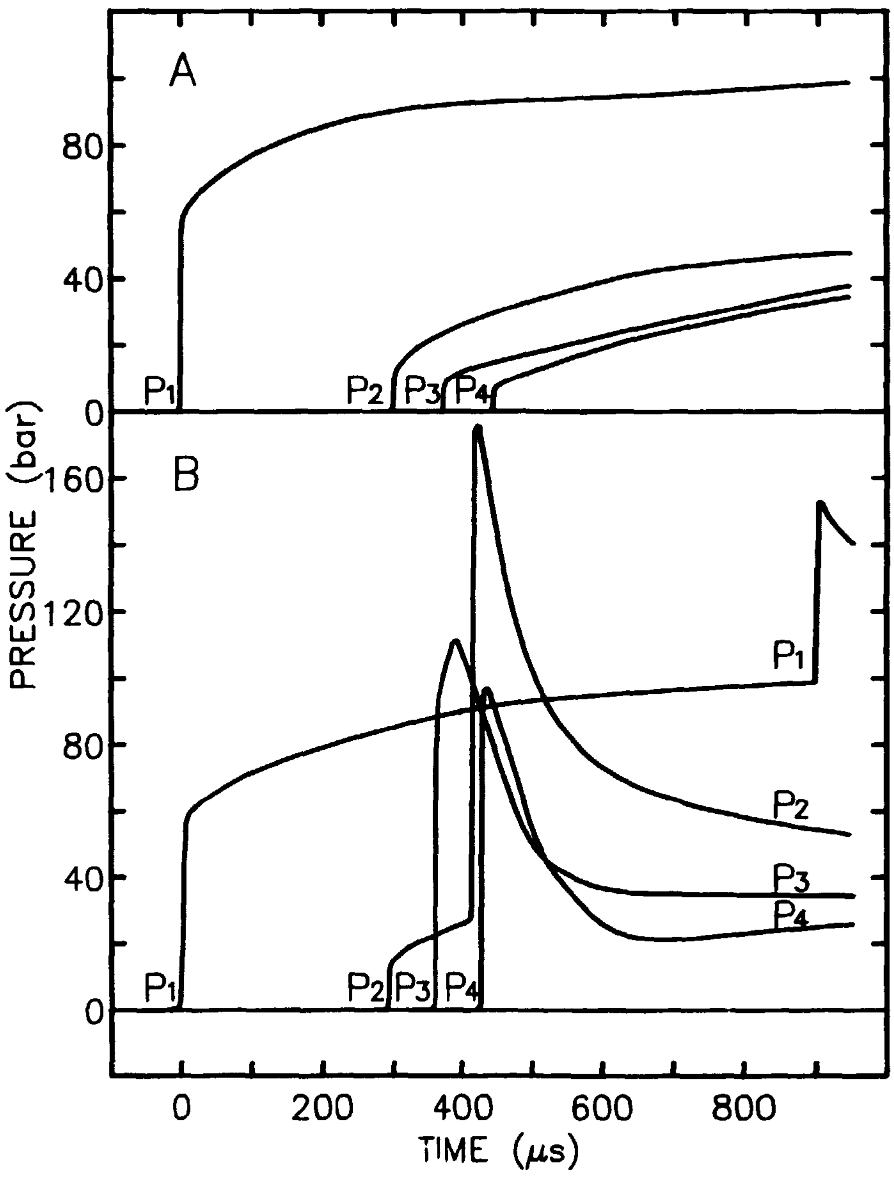

Fig. IV.3. Barrel pressure transient. Signals from pressure probes PI to P4, Fig. IV.2. Upper part (A) from shot without ignition; lower part (B) from shot with synchronized ignition of the hydrogen arc module. Hydrogen dose: 100 bar cm³. Peak arc power: 5 MW. Coil current 2.3 kA.

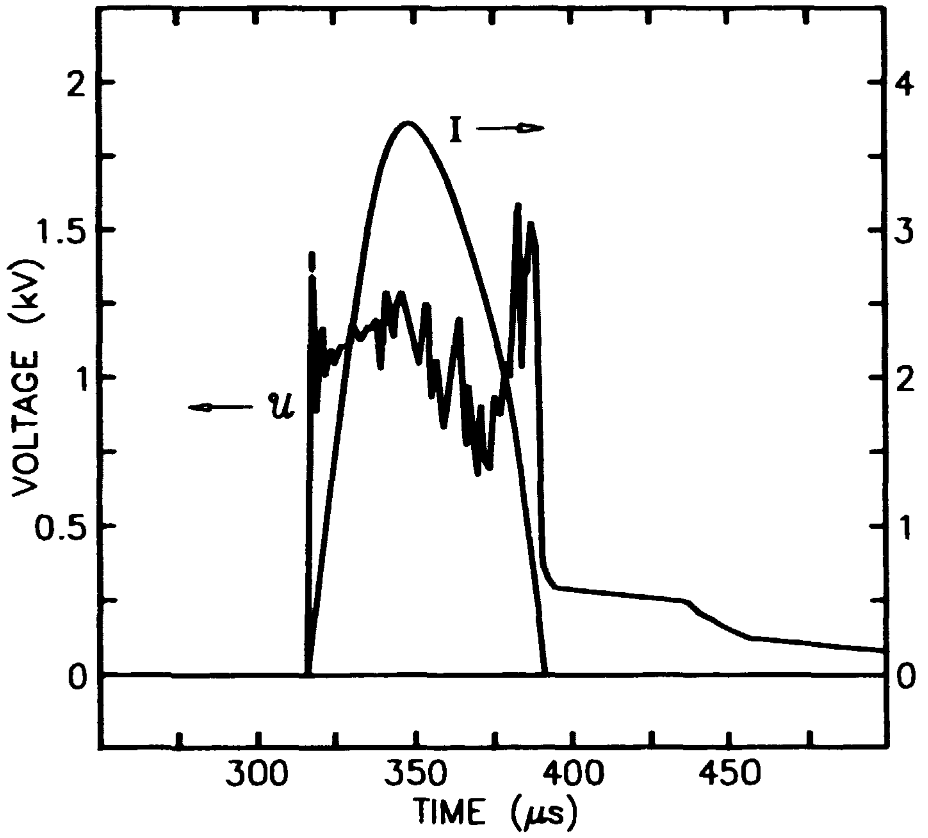

Fig. IV.4. Arc discharge characteristics for the hydrogen module. Arc voltage (U) and arc current (I) versus time. Same conditions as in Fig. IV.3.

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Title and authors

A Fast-Acting Hydrogen Gas Source for Staged Pneumatic High-Speed Acceleration of Fusion Plasma Fuel Pellets

S.A. Andersen and L. Bækmark

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Abstract (Max. 2000 characters)

This report describes a possible design of a fast, high-temperature, arc-driven hydrogen gas source module, to be used in a scheme for multi-stage high-speed pneumatic acceleration of fusion plasma fuel pellets. The potential of this scheme for operating with a moderate driving pressure at long acceleration path lengths is particular attractive for accelerating fragile hydrogen isotope ice pellets. From experiments with an ethanol-based arc unit, design parameters for a propeller module were assessed, and with a barrel-mounted ethanol module staged pneumatic acceleration of a plastic dummy pellet was demonstrated. In experiments with a hydrogen-based, cryogenic arc unit in which 200 joules of electrical energy were dissipated with a power level approaching 5 MW within 30 μs, the velocity of a 23-mg plastic pellet was increased from 1.7 to 2.4 km/s. Results in terms of barrel pressure transients and arc characteristics are described.

Descriptors INIS/EDB

ACCELERATION; CRYOGENIC FLUIDS; DEUTERIUM; ELECTRIC ARCS; ETHANOL; FUEL PELLETS; HYDROGEN; PELLET INJECTION; PLASMA GUNS; PNEUMATIC TRANSPORT; TOKAMAK DEVICES; VELOCITY

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