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Report

THE PHOENIX II INJECTOR AND BURIAL LINE COMMISSIONING

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THE PHOENIX II INJECTOR AND BURIAL LINE COMMISSIONING

by

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ABSTRACT

The main requirements for the neutral particle injection system of PHOENIX II are that a low divergence, high intensity beam of neutral particles of appropriate energy be produced, and that the accompanying flow of cold gas into the plasma trapping region be reduced to the minimum.

The injector and burial line components are described, and the quantities of gas evolved from various parts of the line are discussed.

Measurements have been made of the speed of the various pumping units, and an estimate is made of the contribution of each source of gas to the centre chamber pressure.

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1. INTRODUCTION

The PHOENIX II experiment has been designed to enable study of the containment of plasma in a magnetic well formed by the combination of a mirror field with a quadrupole cusp provided by four external coils$^{(1)}$.

The plasma is formed by injection of fast neutral atoms, which are produced by external pre-acceleration and are then ionized by Lorentz forces in the strong magnetic field of the well. The central field is designed to be 20 kG and the injection energy is selected to be 20 keV giving a proton Larmor radius of 1 cm.

The injector is required to provide a high intensity, low emittance beam of neutral particles of appropriate energy. It is of prime importance that the qnautity of cold gas entering the trapping region along with the fast neutral beam be reduced to a minimum, since a major cause of loss of plasma can be charge exchange of the trapped ions with background gas. Also, the gas released by the untrapped beam colliding with the vacuum wall after passage through the trapping region must be prevented from diffusing back into the plasma.

2. DESCRIPTION OF THE INJECTOR

The PHOENIX II injector shown in Fig.1 has been designed to accept the beam from a duo-plasmatron ion source$^{(2)}$, operating at 40 kV extraction voltage, with the source optimised for H_2^+ yield. A magnetic focusing coil is used to focus the beam through a 4.6 cm diameter aperture 300 cm from the source exit and 70 cm upstream of the trapping region. The half-angle of convergence of the beam is 0.01 radians, and injector line is collimated by a number of apertures to accept the beam profile. At 40 kV, a beam of 50 mA of H_2^+ is produced, measured on a calorimeter situated about 8½ metres from the ion source (the burial calorimeter).

The source also can be adjusted to give H_1^+ beam, as shown in the performance curves of Fig.2. These show the focused current of H_1^+ and H_1^+ as a function of extraction voltage. The beam currents were measured on a calorimeter placed just beyond the final 4.6 cm aperture of the injector line, with full collimation of the beam line as described above. The maximum total H.T. power supply currents were 800 mA and 200 mA respectively. The beam may be used either continuously or pulsed for periods of the order of a second, as required.

When the injector is in use on PHOENIX, an estimate of the background gas pressure existing in the plasma may be obtained by switching off the input beam and observing the time constant of plasma decay. The pulse length of the magnetic field is several seconds, and it is sometimes desirable to interrupt the beam several times during the pulse. In order to do this, a fast acting pneumatically operated switch is installed in the ion source supplies and is used to short circuit the anode of the duoplasmatron to the intermediate electrode. Under these conditions, no plasma can penetrate through the anode aperture into the extraction region, and so the beam is cut off. A discharge still runs between filament and intermediate electrode, and when the switch is opened, the arc is restored to its original condition and the beam is switched on. The re-striking of the arc is found to be very reliable using this method of switching. The switch is made with sliding silver/tungsten alloy contacts to eliminate contact bounce and to reduce wear.

Oil diffusion pumps are installed at the source, giving a measured pumping speed for hydrogen of 4,000 litres $\sec^{-1}$. The measured operating pressure in the source pumping chamber is 4×10^{-5} Torr.

The beam may be neutralized by passage through a vapour cell, containing either water vapour or perfluoro-dimethylcyclohexane, (C_8F_{16}), giving a resultant neutral beam of 20 keV H_0 particles. The vapour used in a neutralizer cell should have a low vapour pressure at liquid nitrogen temperature, and also should have a high molecular weight. This is so that the vapour molecules have a low thermal speed which ensures that a mechanical velocity filter, working at a practicable speed, may be used to eliminate slow vapour molecules which tend to stream along the beam line. C_8F_{16} is particularly suitable for this purpose, having vapour pressure of $< 10^{-8}$ Torr at -196°C and a molecular weight of 400.

Liquid nitrogen cooled traps are used on either side of the neutralizer to pump the exchange vapour. The pressure in the cell is of the order of 10^{-2} Torr, and is adjusted for maximum neutral yield.

It is noticed when using the injector that the measured yield of fast neutral atoms from the neutralizer is less than that which would be expected from the amount of charged beam injected and the known cross-sections for neutral production. This loss amounts to about 20% of the theoretical amount when using water vapour and about 30% when using C_8F_{16}, and is thought to be due to multiple scattering in the exchange cell.

The distance from the neutralizer to the centre chamber of the machine is kept as short as possible, (2 metres), and consequently loss of excited neutral atoms by radiative decay is small.

The charged residue of the beam, about 50 mA of H^+ equivalent, is magnetically deflected into the injector dump, a water cooled copper plate, giving a release of hydrogen of 4.6×10^{-3} litre Torr sec^{-1} on the assumption of a molecule released per two incident protons.

The fast neutral beam then passes through a rotating vane velocity filter (the chopper), which is used to reduce the amount of exchange vapour streaming directly into the centre chamber. The chopper vanes are about 80% transparent to the fast neutral beam, but are opaque to vapour molecules with thermal velocities below a critical value dependent on rotor speed. The chopper rotor has 75 vanes, 7.5 cm long. For $C_8 F_{16}$ vapour, molecular weight 400, the mean molecular velocity is 1.25×10^4 cm sec^{-1}, at ambient temperature. Over 95% of the molecules will have velocities below 2.5×10^4 cm sec^{-1}, and the critical rotor speed for this velocity is 45 revs/sec.

The chopper box is used as a major pumping unit, with both diffusion and getter pumps, having measured speeds for hydrogen of 600 litres sec^{-1} and 10,000 litres sec^{-1} respectively. The conductance of the injector line between the source pumping chamber and the chopper box is calculated to be 25 litres sec^{-1}, so that the pressure in the chopper box, when gettered, with source gas on, is calculated to be 1×10^{-7} Torr. This is in good agreement with the pressure observed.

A final defining aperture of 4.6 cm diameter and an inlet conical trap, cooled with liquid nitrogen, are located between the chopper and the centre chamber. The inlet system has a measured conductance of 50 litre sec^{-1} for hydrogen.

On the far side of the centre chamber is the burial line, Fig.3, which is an ultra high vacuum system for differentially pumping the gas released from the final calorimeter, 5 metres from the centre chamber. Although the half angle of convergence of the neutral beam is 0.01 radians, after the 4.6 cm stop some beam atoms may diverge with a half angle of 0.35 radians, due to spherical aberration in the magnetic focusing lens. This is the maximum possible angle allowed by the injector collimation. The components of the burial line are designed to accept this divergence, and all the untrapped beam, after passage through the centre chamber, is dumped on the burial calorimeter. In order to reduce the thermal time constant of the calorimeter (to simplify beam measurements) it has been constructed from aluminium alloy.

A large titanium getter pump with a liquid nitrogen cooled liner is installed between the centre chamber and the calorimeter to provide differential pumping of the gas released from the calorimeter. The speed of this getter pump has been measured as 10^5 litres sec^{-1}

for hydrogen. The conductance of the flight tube between the pump and the centre chamber has been measured as 600 litres sec^{-1}.

3. SOURCES OF GAS

Gas can enter the centre chamber as

(i) Hydrogen diffusing from the ion source, charged beam dump and burial line.
(ii) A directed stream of hydrogen from the injector line.
(iii) Vapour diffusing or streaming from the neutralizer.

Hydrogen diffusing from the ion source charged beam dump and burial line

A diagrammatic representation of the overall pumping system for diffusing hydrogen is shown in Fig.4. It is assumed in this diagram that gas released by the beam striking surfaces is entirely hydrogen and that an equilibrium ratio of one molecule released for two incident fast atoms is immediately achieved. The pumping speeds quoted are as measured by admission of known quantities of hydrogen; the conductances and pressures are either calculated or measured as shown. The gas flows are calculated from these values of pressure and conductance.

It will be seen that the chopper pressure when operating is calculated to be 6×10^{-7} Torr, of which a component of 1×10^{-7} Torr is due to ion source gas, a similar amount is released from the chopper blades due to interception of 20% of the beam, and the rest is due to gas coming from the injector beam dump. This value for the pressure in the chopper is in good agreement with that observed during machine operation.

The resulting flow of hydrogen diffusing into the centre chamber from the injector line is estimated as 3×10^{-5} Torr litre sec^{-1}.

The neutral beam of 30 mA on the calorimeter is assumed to represent an equivalent gas flow of 3×10^{-3} Torr litre sec^{-1}. The amount which will diffuse back into the centre chamber is calculated to be 2×10^{-5} Torr litre sec^{-1}.

Fig.5 shows the response of a mass spectrometer head situated in the burial line, between the getter pump and the centre chamber, firstly to a calibrated source of 1.08×10^{-3} Torr litre sec^{-1} of hydrogen and secondly to a beam of 23 mA of H_o particles being dumped on the burial calorimeter. It will be seen that the time to reach an equilibrium value of gas released corresponding to 1 molecule of hydrogen evolved for 2 incident atoms is of the order of 20 seconds. This effect can be used to improve the efficiency of the burial line by operating the beam in bursts of a few seconds duration.

Directed hydrogen from the injector line

The hydrogen released in the charged beam dump will be pumped most through a collimating aperture with a calculated conductance for hydrogen of about 1100 litres sec^{-1} into the chopper box. There should be a pressure in front of this aperture therefore of about 6×10^{-6} Torr, which would result in some streaming of hydrogen directly into the centre chamber. (The streaming hydrogen from the ion source will be randomized in direction by collisions with vapour molecules in the neutralizer). The pressure due to the stream at the centre of the centre chamber 150 cms away is estimated to be 5×10^{-10} Torr.

Diffusing and directed vapour

The vapour diffusing from the neutralizer is pumped by cylindrical liquid nitrogen traps on either side of the vapour cell. The pressure rise in the chopper box due to C_8F_{16} vapour is 1.5×10^{-8} Torr, measured on an Alpert gauge calibrated for air. The input conductance to the centre chamber for C_8F_{16} is almost 4 litres sec^{-1} so that the amount of vapour diffusing into the centre chamber cannot be more than 5×10^{-8} Torr litre sec^{-1} which is 3 orders of magnitude less than the hydrogen flow.

The effect of directed vapour may be deduced from Fig.6. This data was taken using an Alpert gauge, (calibrated for air), with directional collimation as shown. It was mounted in the centre of the centre chamber and pointed towards the injector line. If a nude gauge is exposed to a stream of molecules of F Torr litre sec^{-1} per sq/cm it will register a pressure P_1 proportional to $\frac{F}{V}$, where v is the thermal velocity of the molecules. If, however, the gauge is shrouded as indicated with an inlet tube of area A and conductance C, the gauge will register a pressure P_2 proportional to $\frac{FA}{C}$. A shrouded gauge thus acts to a directed flow as a pressure amplifier of gain $\frac{vA}{C}$.

The gauge used to obtain the graph of Fig.6 had an inlet tube as shown, with a conductance estimated as 0.6 litres sec^{-1} for C_8F_{16} and had a gain of 14.5. With the chopper stationary, the gauge reading of 1.8×10^{-6} Torr represents a centre chamber pressure of 1.2×10^{-7} due to the stream of C_8F_{16} molecules. This figure shows a reduction in pressure of at least 100 times when the chopper is run above 3000 r.p.m.

Due to the fact that the centre chamber is pumped almost entirly by titanium getter pumps, a lower limit to the pressure is set by the partial pressure of argon from microscopic air leaks, as it does not getter. This background pressure is monitored with a mass spectrometer head in the burial line, and is normally of the order of 3×10^{-10} Torr.

As the injector is normally used for short beam bursts, the hydrogen diffusing from the chopper box is the prime source of hydrogen in the centre chamber. Fig.7 shows the relationship between hydrogen pressure rise in the chopper box to pressure rise in the centre chamber with the latter gettered. The centre chamber pressure was measured with a nude Alpert gauge, mounted on a probe, located 15 cm from the centre of the centre chamber.

4. FUTURE DEVELOPMENTS

In order to reduce the gas diffusing into the centre chamber from the injector line and to reduce the argon content, an inlet cone cooled to about $3^{o}K$ with pumped liquid helium is to be fitted to the centre chamber.

A revised charged beam dump is also to be installed. This will give a further stage of differential pumping for the dumped beam, and will also reduce the amount of hydrogen streaming into the centre chamber.

5. ACKNOWLEDGEMENTS

The engineering design of the components of the injector and burial system was undertaken by a team led by Mr. S. Skellett of the Culham Engineering Division. Mr. J. Coupland has developed techniques for performing vacuum measurements, and carried out much of the experimental work described in this paper. Messrs. K. Hall, P. Lovell and J. Mepham have been responsible for machine operation.

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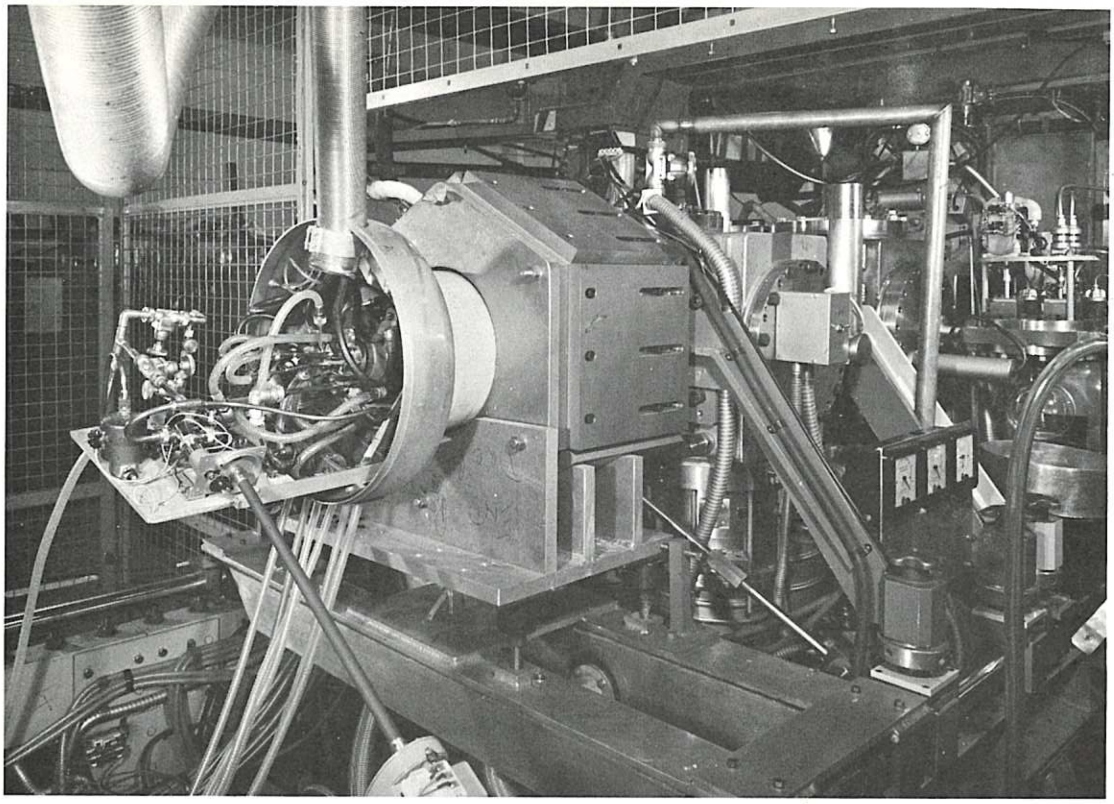
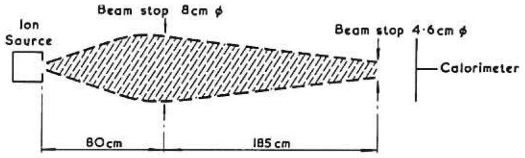


Fig. 1 View of the injector (CLM-R59)



Profile of beam line collimation

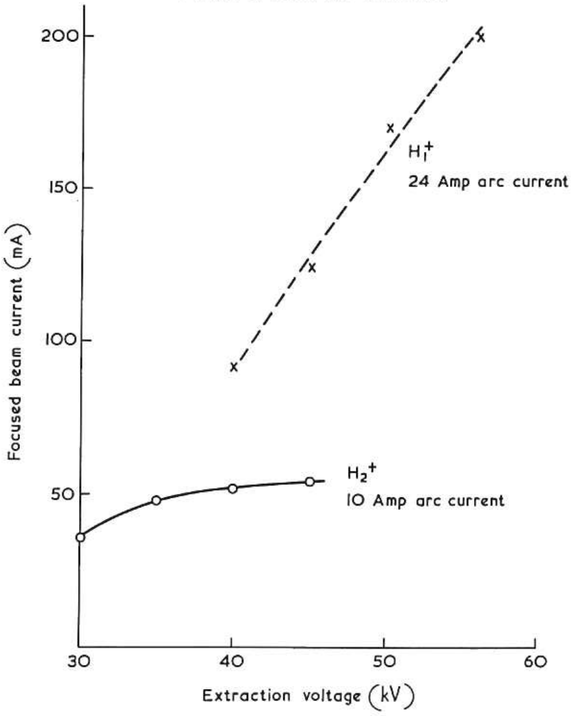


Fig. 2 Source perfomance curves (CLM-R59)

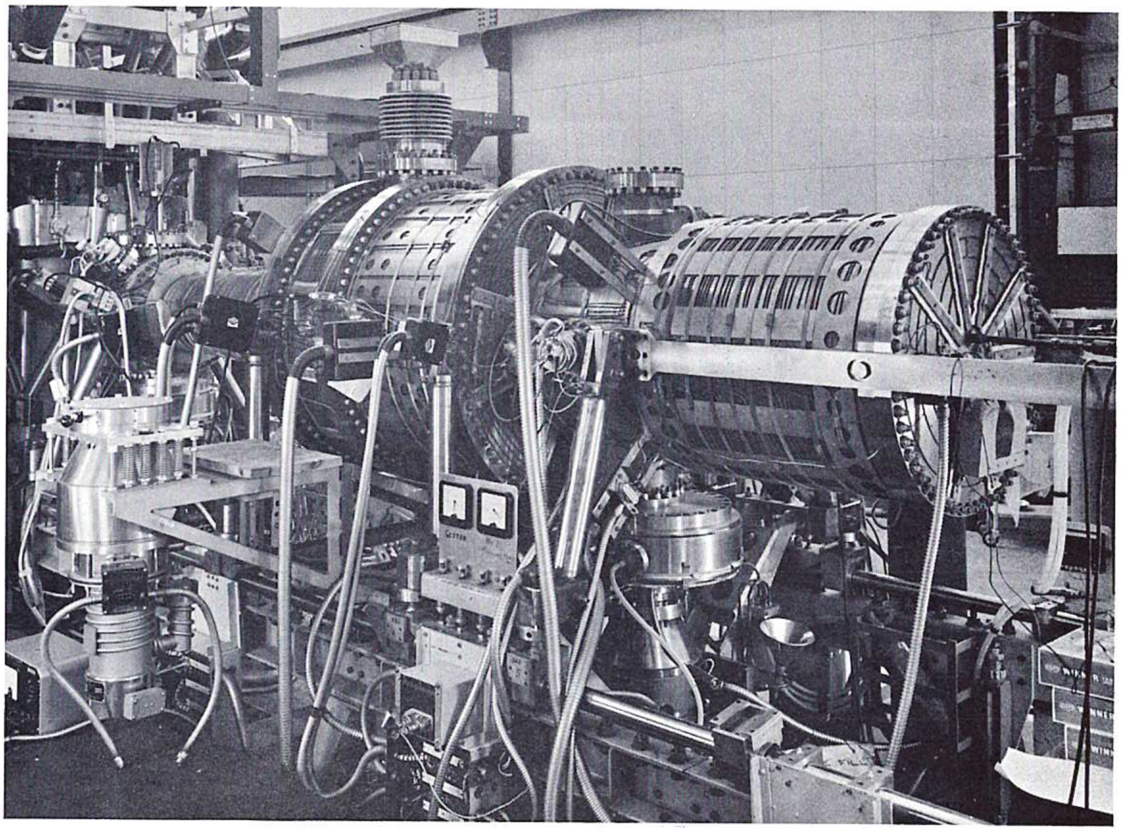


Fig. 3 View of the burial line (CLM - R 59)

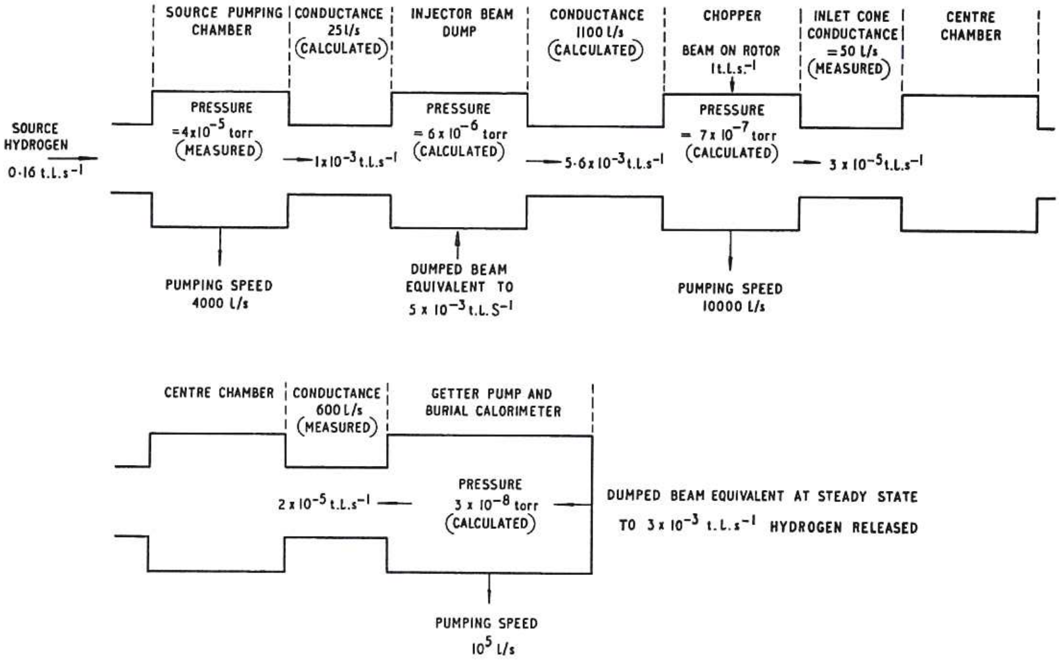


Fig. 4 Diagram of gas flows (CLM - R 59)

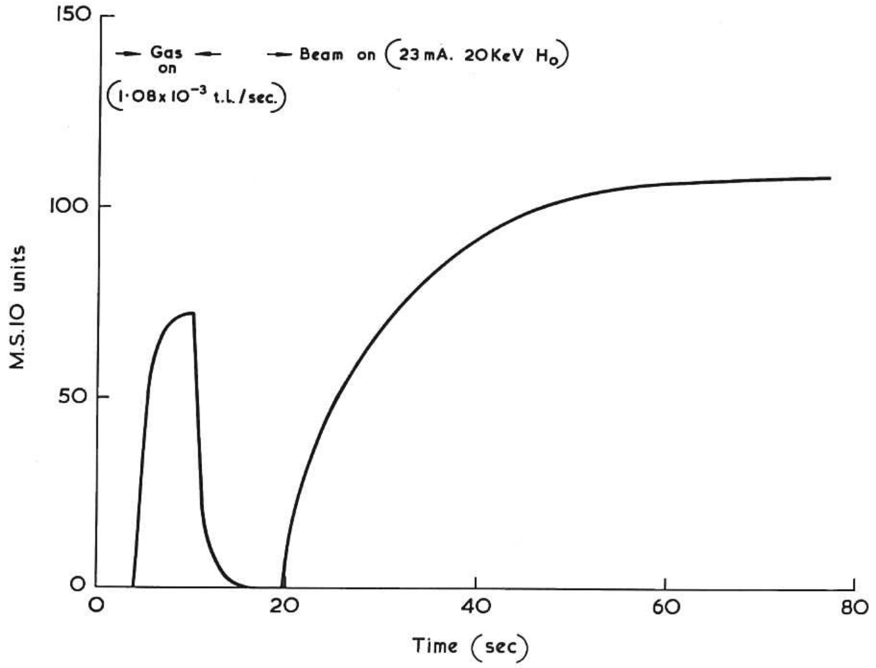


Fig. 5 Burial line pressure/time curve (CLM-R 59)

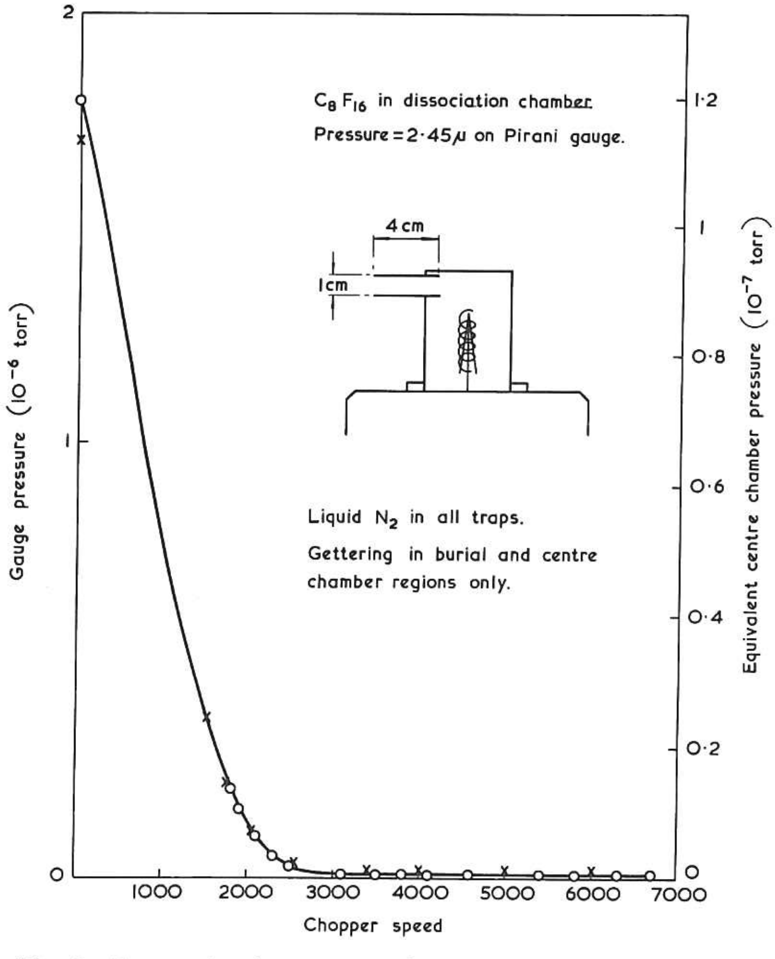


Fig. 6 Centre chamber pressure/chopper speed (CLM-R 59)

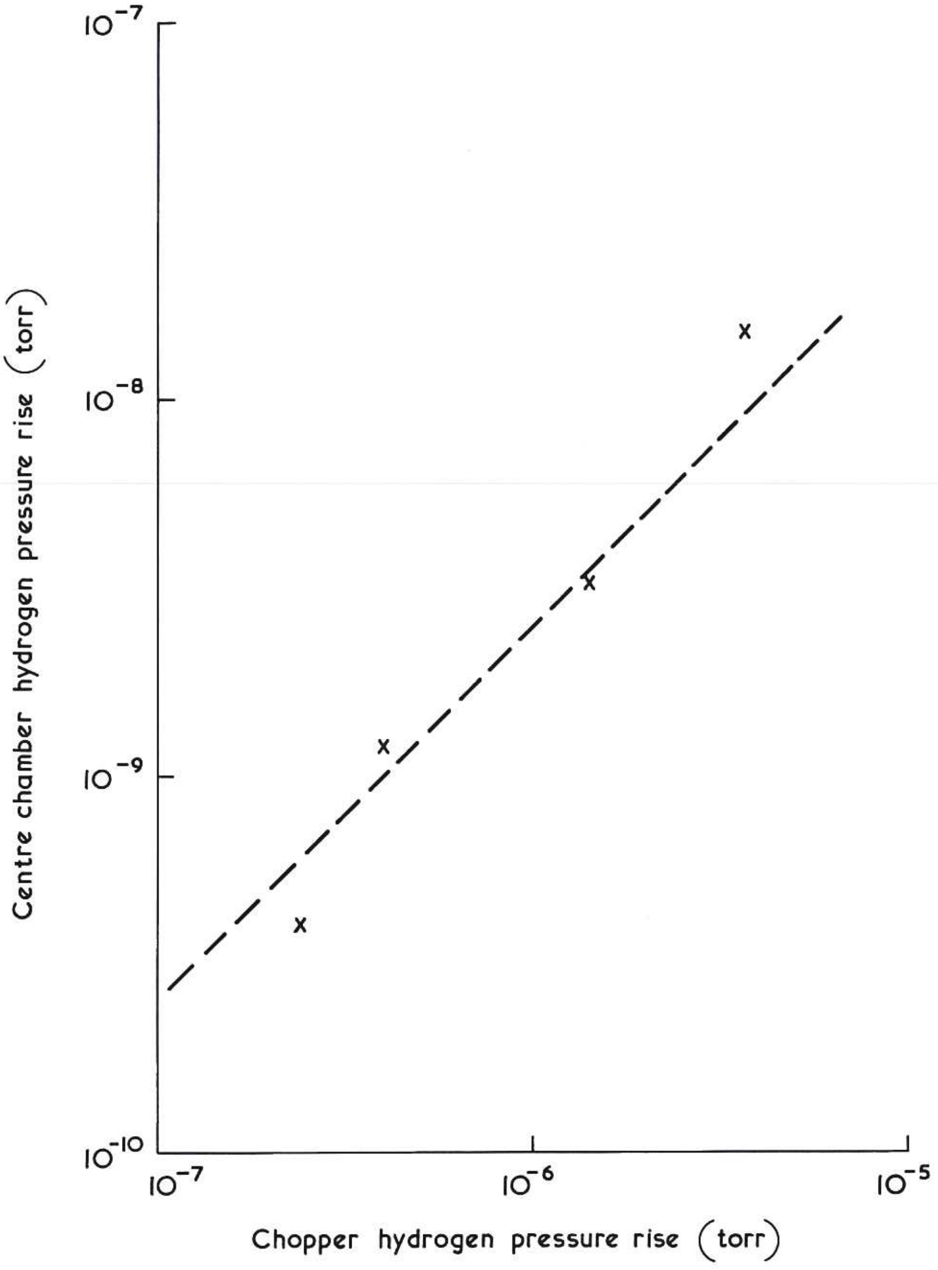


Fig. 7 Centre chamber pressure/chopper pressure (CLM-R 59)

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