The D_2 cold-neutron source for SINQ

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1. Introduction

This report describes the present state of the design for a D_2 cold neutron source for SINQ. The source is to provide neutrons in the wavelength range 2 to 12 Å for a guide-system[1] and at two beam ports. The basis of the design is an adaptation of the "horizontally" mounted thermosyphon as used for the second cold-source at the ILL, Grenoble[2]. The principal advantages of the thermosyphon are as follows:

- High heat-transfer rates at cryogenic temperatures are easily achieved.
- The system is basically passive and self-regulating.
- Minimization of the cooling power required by allowing, for instance, the condenser/phase-separator system to be removed from the high heating region.

So far, work has been concentrated on the cryogenic part of the source, which is in the region of the bulk shield. The main considerations for the design are outlined in the following section and specific points given in section 3. The layout of the beam-tubes and cold-source plugs is shown in Fig. 6 and details of the present D_2 source layout in Fig. 7.

2. Design considerations

The practical design (dimension specification, services, etc.) comes from a synthesis of requirements (often conflicting) from the following principal areas.

2.1 Neutronics. The aim is to produce the highest "cold" neutron flux, which requires that the source is as close to the thermal flux maximum as is possible, has as large a volume of D_2 as possible, and there is as little as possible material in the path between D_2 and the user. The beam tubes need to view the source at the position that gives the best "cold" flux.

A practicable D_2 source will always be too small to allow complete rethermalization of the neutrons. The thermal neutrons from the D_2O are to be induced to lose about a factor of 10 in energy; but because the scattering is determined by the dynamics of the deuterium molecule, the slowing-down rate is considerably reduced compared to that at "higher" energies, and about 10 collisions are required.

Neutron transport studies have been carried out using Monte Carlo with a scattering kernel derived from differential cross sections calculated using the Young and Koppel model[3]. The calculated total scattering cross sections together with the measured values of Sieffert[4] are shown in Fig. 1; the agreement with the Sieffert results (liquid D_2 at 19 K) is generally good down to about 3 meV. Below this energy, coherent scattering starts to become significant; but as the main effect will be felt only in the long-wavelength (e.g., VCN) region, it has not been included.

We should expect, at best, a spectrum with a mean energy rather higher than the 25 K physical temperature (this is observed with the cold sources at the ILL, Grenoble): this may be seen from the plot of mean-scattered energy as a function of incident energy shown in Fig. 2. An equilibrium will occur at about the energy where the average scattered energy equals the incident, which is 3.8 meV (44 K) for ortho- and 5.0 meV (58 K) for para-deuterium.

The best cold flux will be at a position some distance from the entry point of the neutron into the D_2. The cold neutron intensities for a window 80 mm wide and 120 mm high, at three positions along the cylindrical surface and for various re-entrant windows, are shown in Fig. 3.

The results indicate that a re-entrant hole leaving 10 to 15 cm of D_2 between the two windows and located approximately 15 cm from the target-end of the source cell is about optimum. The neutron intensity gain over a window on the surface could be in the region of 50%. A calculated spectrum of the neutrons leaving the D_2 is shown in Fig. 4.

Flux loss will be caused by materials in the path of the cold-neutron beams. These may be split into two categories:

(i) unavoidable: material that must be present (container walls, safety windows, etc.)
(ii) avoidable: material that may be removed, but with consequences on other aspects of the SINQ design.

The actual losses will come from three effects—direct absorption, scattering of the neutrons to outside the acceptance of the beam tube, and upscattering. A particularly unfortunate material to have in the path of the beam is D_2O, as it is a good upscatterer. The spectra for neutrons transmitted through various thickness D_2O layers (and averaged over all escapes, irrespective of position) has been calculated. The results are presented in Fig. 5 as the ratio of the intensity per unit wavelength in the transmitted spectrum to that in the incident spectrum.

2.2 Cryogenics. We have a cold box that can give about 2.4 kW cooling power at 15 K, but which must also provide cooling for an H_2 source (it is possible that a higher temperature for the helium gas will be used with consequent gain of cooling power). Preliminary estimates for the heating of the inner parts of the D_2 source (cooled by liquid deuterium) is 1.5 to 2 kW/mA. The actual heating will be a function of the final design (wall thickness, actual position of the source cell in the moderator tank, etc.)

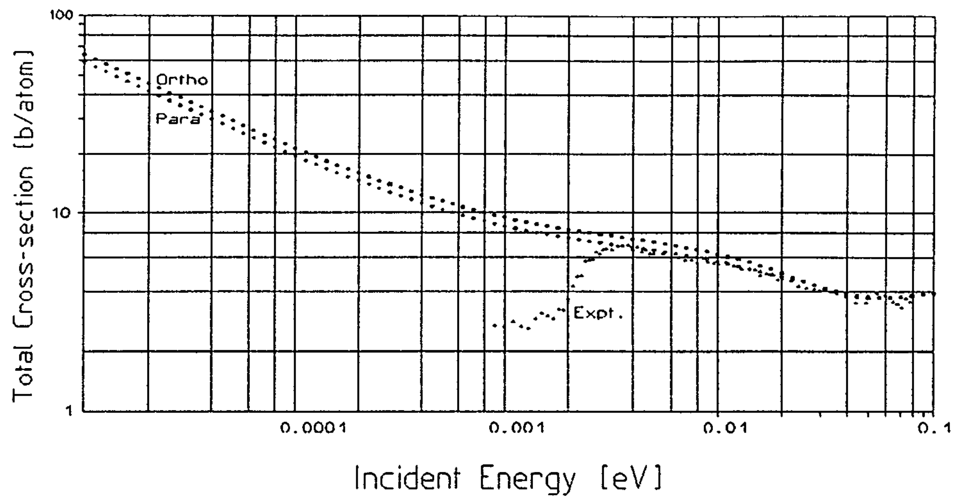

Fig. 1 The calculated total cross section for scattering of neutrons from deuterium molecules at 25 K. The measured results are from W.D. Sieffert[4] and are for liquid D_2 at 19 K.

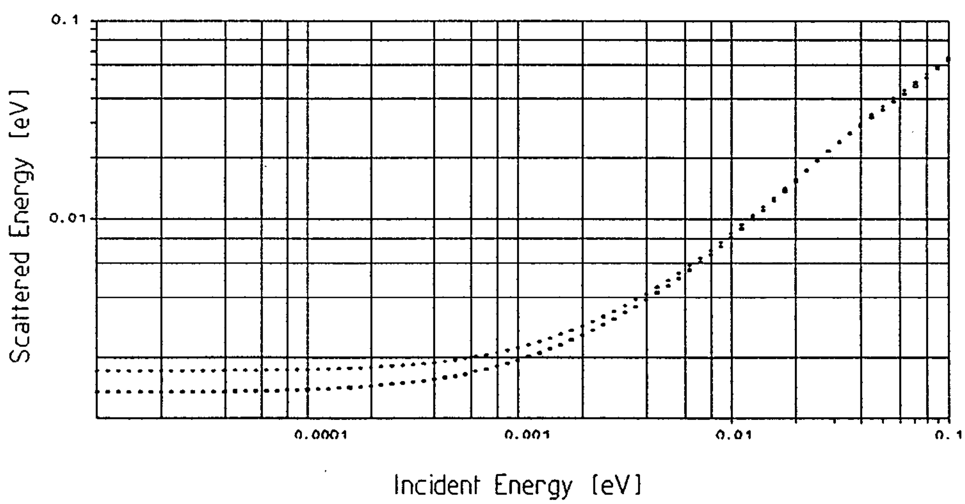

Fig. 2 The average energy of neutrons scattered by deuterium molecules at 25 K as a function of incident neutron's energy.

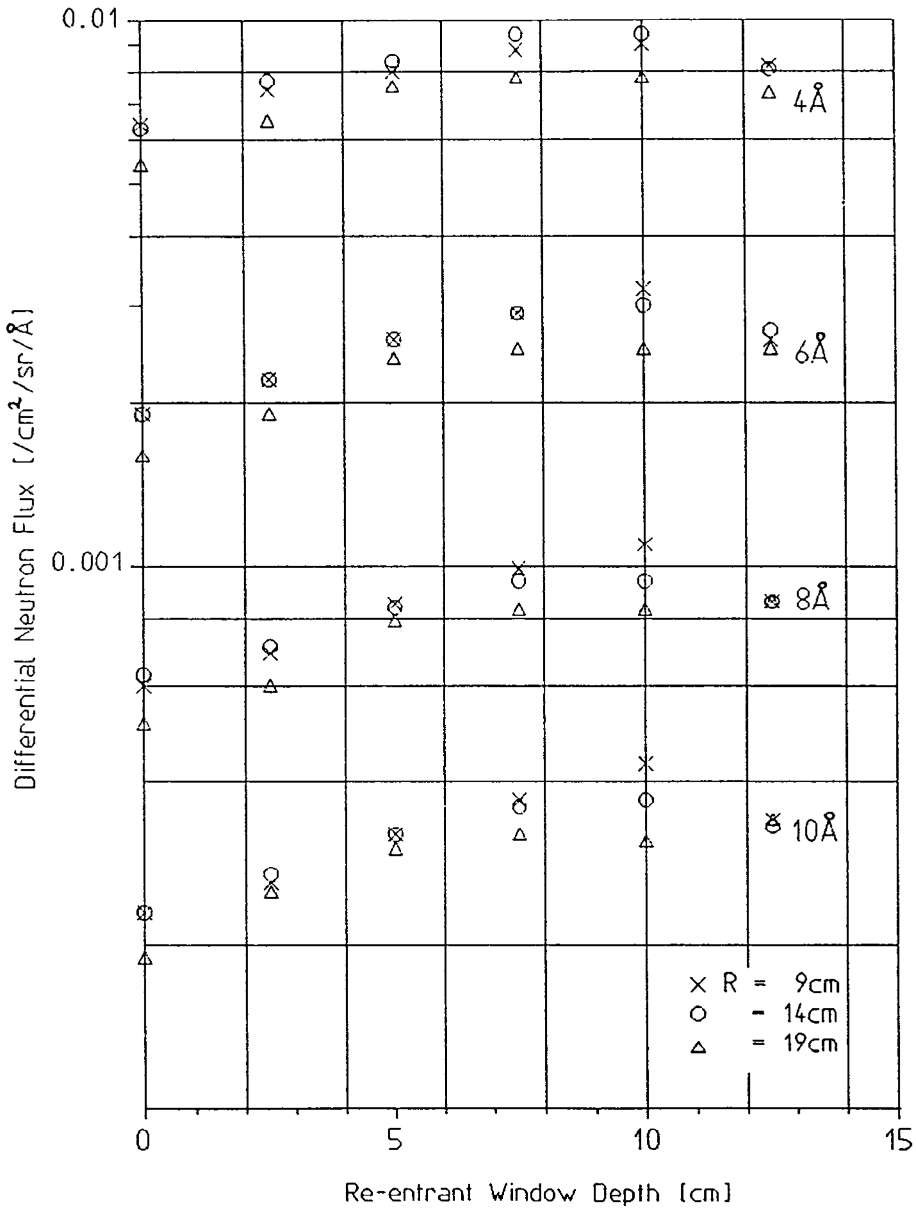

Fig. 3 The variation of cold neutron intensity at given wavelengths as a function of beam window position and depth of re-entrant window. The intensities are normalised to unit thermal flux at the position of the flat surface of the cylinder nearest to the target.

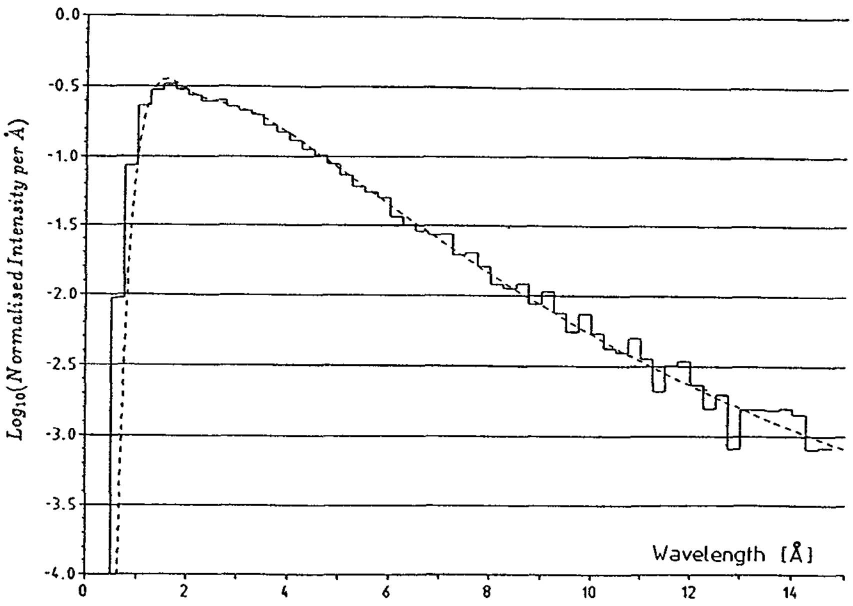

Fig. 4 The calculated neutron escape spectrum from the D_2 cold-source (histogram) for a 80-mm-wide beam window centered 90 mm from the end of the source nearest the target and re-entrant to a depth of 25 mm, together with the result of a two-component Maxwellian fit to the data in the region 1.25 to 9.75 Å.

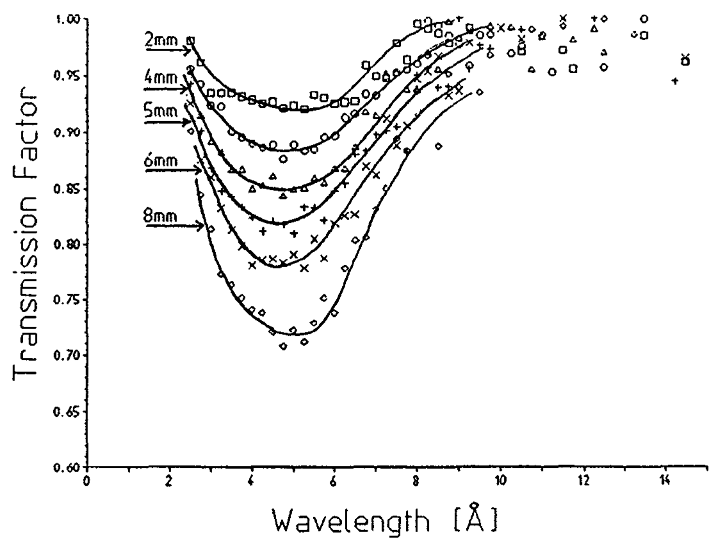

Fig. 5 The ratio of the transmitted to incident intensity per unit wavelength as a function of wavelength for various thickness layers of D_2O.

The liquid part of the system (at about 25 K) requires a vacuum insulation layer with a pressure ≈ 10^{-5} Torr.

2.3 Thermohydraulics. The main parameter to be fixed is the hydrostatic head for the thermosyphon circuit. The aim should be to have as short and smooth a path as possible between cell and condenser but against this are the following:

(i) chicanes in the transfer line to limit streaming paths in the shielding;
(ii) putting enough distance so that connections and components are in low heating and low activation regions; and
(iii) making things accessible for maintenance.

The D_2 mass-flow to transfer the heat is about 7 g/s (1.5 mA operation), that is about 2.2 litres/s of gas flowing to the condenser and 50 cm^3 of liquid D_2 in the return path. The hydraulic losses will be compensated by the liquid-D_2 head to the condenser, but estimation of the required height is complicated by:

- A variable degree of two-phase flow in the return line (i.e., the actual D_2 mass-flow will be higher due to a liquid/vapor mix being present).
- The needs to include bends (a) to turn the transfer lines into the vertical and (b) to minimize the length of direct streaming paths through the shielding.
- Pressure loss through the D_2-cell itself.

2.4 Shielding and induced activation. The axis of the source is in direct line with the target and, hence, looks directly at the high-energy neutron source. The shield design has two main aims:

(i) to reduce activation in the region of the change from horizontal to vertical so that "hands on" maintenance can be used (see Section 3.1); and
(ii) to reduce the dose rate at the outer surface of the assembly to ≤ 0.5 mrem/hour, but to do this within the geometrical limits of the bulk-shield to avoid loss of operating space for instruments on the adjacent beam ports (see Fig. 6).

The transfer-line connections in the plug assembly include chicanes to limit the length of direct streaming paths, and a final large homogeneous shielding plug can be inserted behind.

The inner parts of the cold-source system will become highly activated during operation and a shielded container to extract the source into and for its transport to a suitable place for repair will be required. Where possible, materials that give the lowest possible post-irradiation dose are to be selected.

2.5 Radiation damage. Radiation damage will change material properties during the lifetime of the source and needs to be taken into account in the engineering design of the source-cell and auxiliary containers (items in the highest radiation field). The choice of "auxiliary" materials (for seals, etc.) will also be made with due regard for the radiation field where they are to be located, so as not to have the operational life of the source limited by such auxiliary materials.

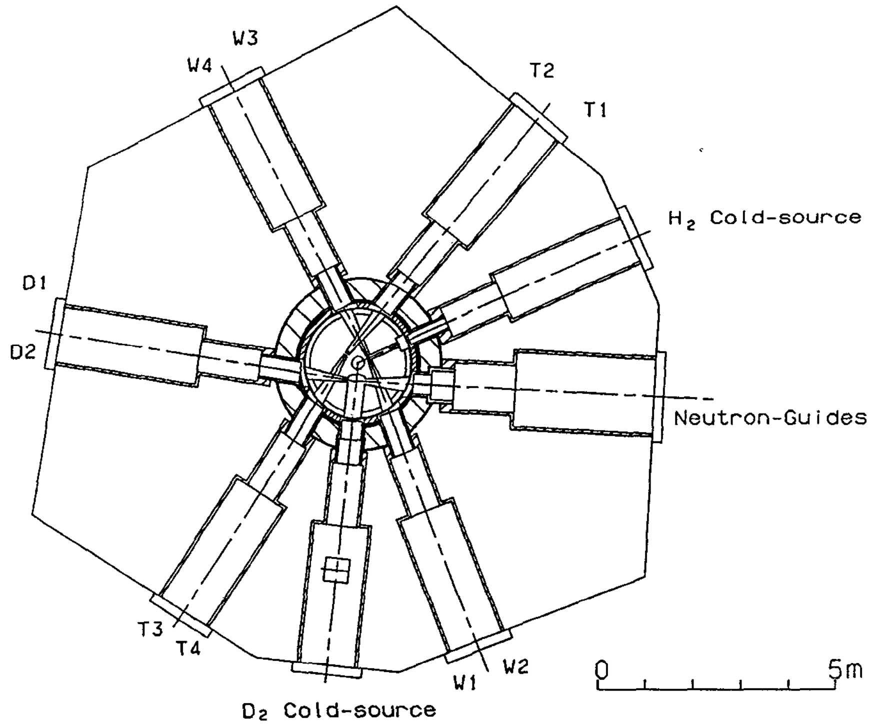

Fig. 6 Layout of the beam tubes and plugs for the cold sources.

2.6 Safety. The three major concerns are (i) deuterium explosion or fire, (ii) overpressure, and (iii) radiation. The principal safety measures planned are as follows:

(a) A minimum of three walls between liquid deuterium and any source of oxygen (or uncontrolled atmosphere). The two outer regions will contain a controlled inert atmosphere. For the (warm) gaseous deuterium parts of the system, we plan to use one less wall.
(b) The use of high-purity deuterium and stringent operational procedures so that this purity is maintained.

These measures are to prevent (i) oxygen and deuterium coming into contact, (ii) blockage of the thermosyphon system by frozen contaminants, and (iii) containment for tritium.

Pressure transients that result from reasonable operational equipment failures will be limited by provision of bursting discs and by including in the choice of sizes for transfer lines (cryogenic, gas line to the buffer volume, vacuum, etc.) the need for a suitably high gas conductance.

During operation there will be production of about 150 Ci/year tritium by neutron capture in the D_2. This requires that the complete D_2 system be surrounded by a controlled atmosphere with tritium monitoring, and that all pump exhausts, emergency D_2 dumping arrangements, pressure relief systems, etc., have appropriate venting arrangements.

3. Source layout

3.1 Bulk shield insert. The D_2 cold-source is to be inserted into a gas-tight box built into the bulk shield between beam-tube pairs T3/4 and W1/2 (see Fig. 7). The box has a vacuum liner that extends into the beam-tube assembly in the moderator tank and gives the vacuum insulation for the cryogenic parts of the source. It will be cooled over the first meter or so and is also the second wall for the containment; the third wall is provided by the inner helium containment system for SINQ. The insert itself has the source cell (a cylindrical flask of about 300 mm diameter and 300 mm length), an auxiliary D_2O tank mounted behind the source cell to reduce flux depression and the shielding plug with the transfer lines. The inner parts of the shielding block will require forced cooling. The overall shielding is complete by a large mobile block.

The region about 4200 mm from the target center line has the changeover to the vertically mounted section. This has a system of flanges to allow source insertion and extraction. The details of this region may be seen in Fig. 8, which shows the principal operations of a plug change.

3.2 Vertical insert. This consists of the vertical part of the transfer lines and the condenser/phase-separator system. These are mounted in a chimney through the fixed part of the bulk shield with a continuation of the vacuum system and a cover gas system (possibly nitrogen), which is independent from the helium of the horizontal part. Access to these parts will be from above (the upper part of the bulk shield consists of "loose" blocks). The transfer lines (deuterium-gas, vacuum, cold-helium, etc.) will cross to a plant area located just off the bulk shield with the cold-box, vacuum pumps, etc.

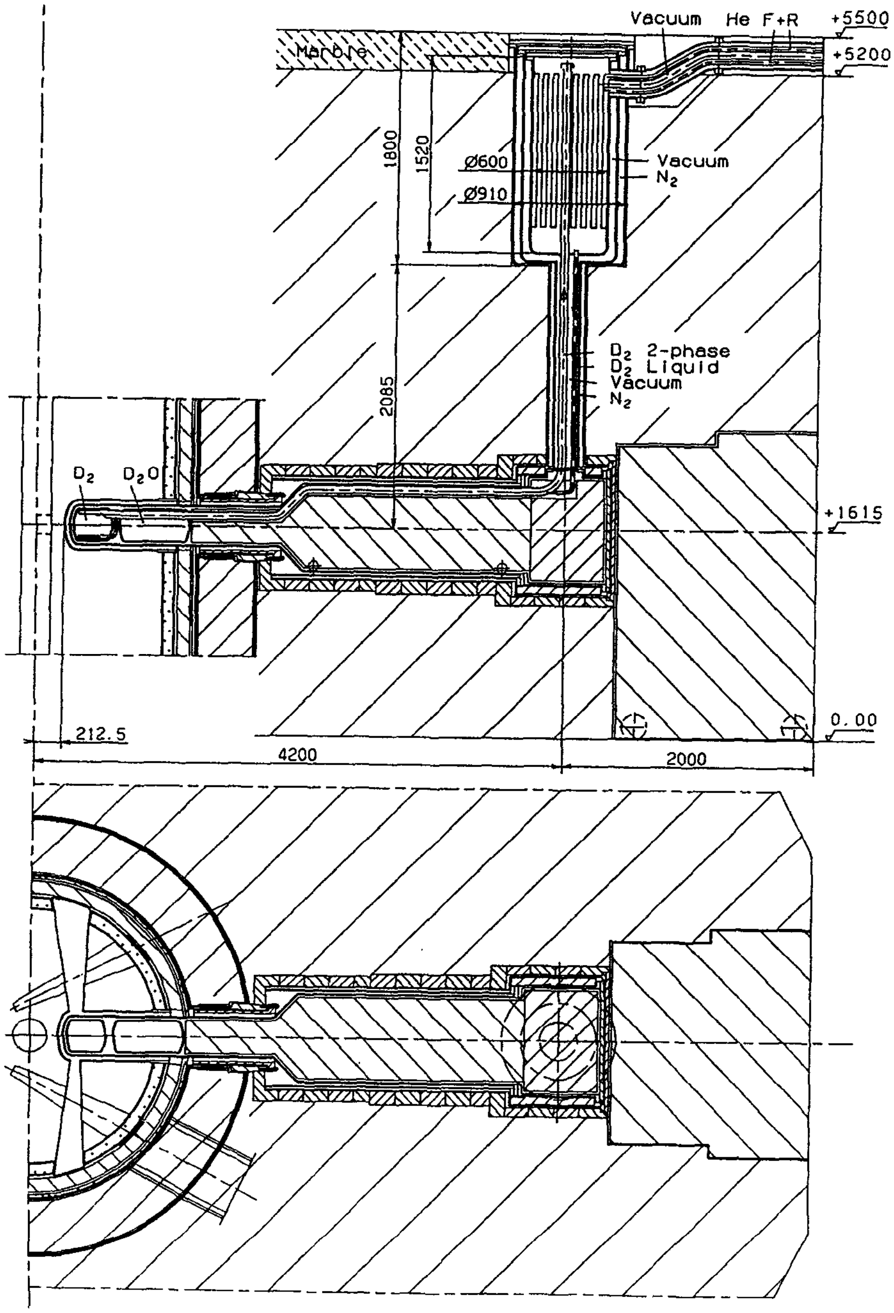

Fig. 7 The layout of the D_2 source in the bulk shield.

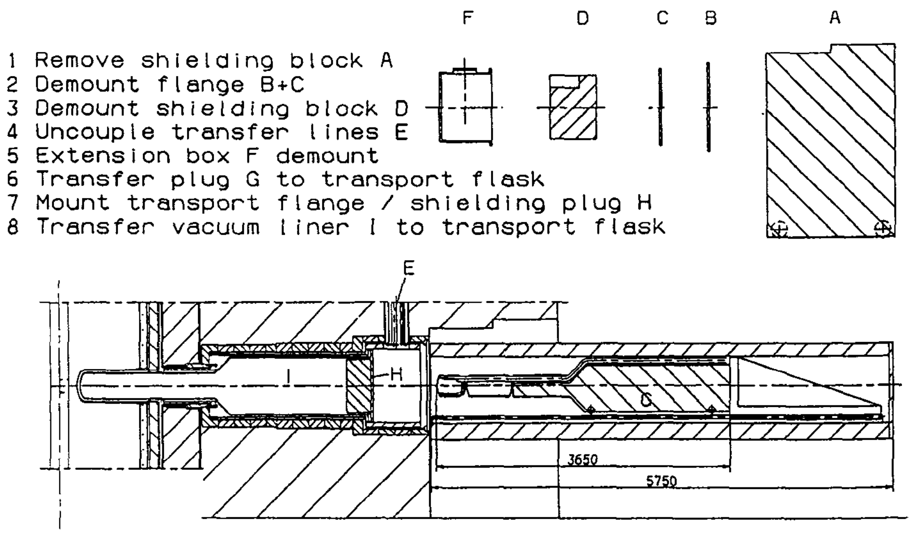

Fig. 8 Details of the plug change operation.

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