V.G EDM Experimental Apparatus

Overview

The neutron EDM measurement described in this proposal involves a series of carefully orchestrated interactions and measurements that must be engineered into a complicated apparatus. We briefly describe here the main features of the measurement process that drive the design and then give a detailed description of the experimental apparatus that can achieve the goals of the experiment.

There are many requirements needed for the experiment, and some of these requirements are given in what follows to illustrate the engineering challenge. The sensitivity of EDM experiments depends linearly on the electric field. The separation between the two cells and the horizontal size of the cells is set to achieve the maximum field. The uniformity requirement for the electric and magnetic fields across the measurement cells determine the overall dimensions of the target-region cryostat. The combination of these dimensions and the space occupied by the n+p $\rightarrow$ d+γ experiment place significant constraints on the beam line. A number of systematic effects are suppressed at temperatures below the reach of a ^{3}He refrigerator; hence the selection of a dilution refrigerator (DR). The inevitable depolarization of the ^{3}He requires that a cycling system for removing the ^{3}He and introducing freshly polarized ^{3}He be incorporated into the cryogenics system. The reduction of backgrounds from neutron-capture places constraints on the materials used in construction of the components. The SQUIDs for measuring the ^{3}He precession must be placed close to the measuring cells. The SQUIDs need isolation by a superconducting shield from external magnetic noise. All these requirements lead to a grand compromise in the engineering of the apparatus. While still in development, the description that follows is an example of how the compromise will be reached.

Figure V.G.1 shows the reference 3D-layout of the EDM experiment with the beam entering from the right. The major components are as follows:

- the beam line, including the Bi filter and the beam splitter-polarizer
- the target cells
- the cryostat, including the target cryostat, upper cryostat and DR
- the helium purifier
- the high-voltage (HV) generator
- the polarized ^{3}He source
- and some other elements.

Beam Line

The EDM experiment will be installed on LANSCE flight-path 12 immediately downstream of the n+p→>d+γ experiment (see Section V.A). Gamma rays in the transmitted neutron beam will be removed with a Bi filter that will be installed in the downstream end of the n+p→d+γ cave. In addition, the beam stop will be modified to accept the t_0 chopper and one end of the beam splitter-polarizer. The shielding will be configured such that the radiation level outside of this region will be less than 1 mR/hr. The Bi filter, Fig V.A.6, consists of water-quenched Bi shot in a 150-mm x 150-mm x 200-mm (beam direction) block cooled to ~15 K by a 10-watt (at 20 K) cold-head refrigerator. Thin beryllium foils will serve as windows and cryogenic heat shields for both the bismuth filter and the cryogenic apparatus if backgrounds from the filter pose a problem.

The t_0 chopper will be very closely related to existing devices already in use at LANSCE. Its function was described in section V.A, and it will be placed in the n+p→d+γ beam stop.

Upstream of the EDM experimental apparatus, the neutrons are split into two polarized neutron beams (see Section V.A.) The polarizers are arranged to form two walls 100-mm high x 1700-mm long and are installed in the neutron guide at 1.6º relative to the beam direction. Polarizers also line the walls as discussed in Section V.A. The resulting polarized split neutron beams emerge at 3.2º relative to the beam direction and are allowed to separate until they match the separation of the two downstream target cells. In this way the irradiation of the HV electrode is minimized. Supermirror guides, 75 mm x 100 mm in cross section, transport the neutrons to the cells.

Target Cells

Our design has two cells to minimize the systematic error caused by the pseudo-magnetic field (see section V.H.) The organization of the target region is shown in Fig. V.G.2. The two beams of neutrons irradiate a pair of target cells sandwiched between three hollow electrodes (see Sections V.C and V.E). The two target cells have inside dimensions of 76.2-mm wide x 101.6-mm high x 500-mm along the beam direction and a volume of ~3.8 liters each. The target cell walls are 12-mm acrylic and act as light guides. The entrance and exit windows are made of 6-mm deuterated acrylic. All inner surfaces of the target cells are coated with a deuterated wave shifter. The target-cell light guides are connected to special light guide assemblies that connect to room temperature photo-multiplier tubes.

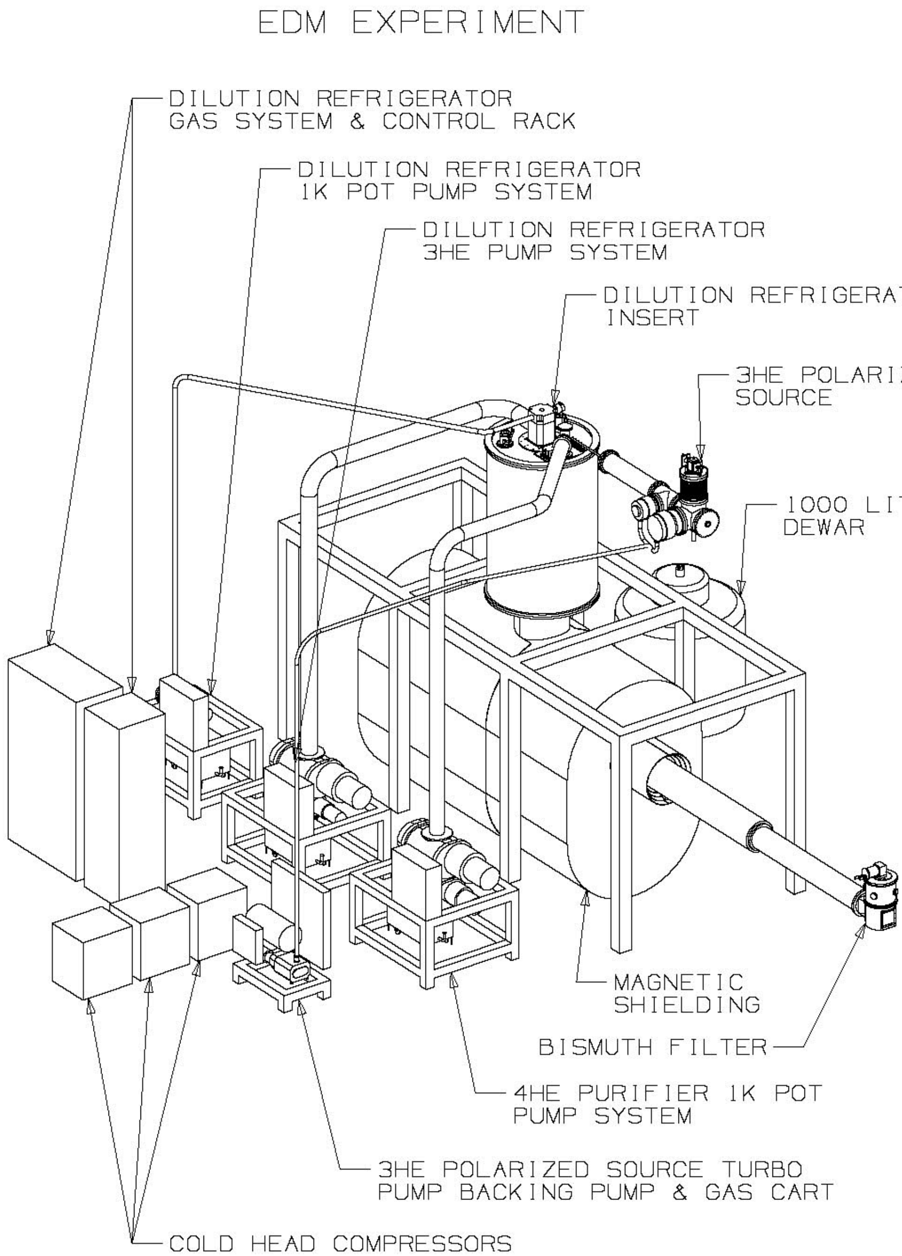

Figure V.G.1. Overall layout of the EDM experiment. The main structure is 2.5 m wide, 5 m high, and ~ 6 m long. The neutron beam guide is 1.4 m above the floor.

Inside the cryostat, the beams are collimated with a structure that is thermally anchored to the heat shields. The choice of materials for the beam collimators is important to minimize activation of the target region.

Each target cell sits between and is embedded in a ground electrode and the high voltage electrode as shown in Fig. V.G.3. The dimensions of the electrodes were set by the field uniformity requirements as set forth in Section V.E. The ground electrode is an acrylic shell 250-mm wide, 38-mm thick, and 715-mm along the beam direction. The side facing the HV electrode has a 25-mm radius on the outer edges and a pocket at the center to accept the target cell. A second pocket is located on the opposite side of the ground electrodes in order to accept the SQUID sensor array (see Section V.F). The pockets bring the SQUID sensor coils as close as possible to the n-^{3}He cell. The outer surfaces of the acrylic ground electrode are polished and coated with a thin layer of copper to serve as the ground plane. This copper coating also serves as a shield for the SQUID sensor array.

The HV electrode is an acrylic shell with pockets on opposite sides for the two target cells. This electrode is 300-mm wide, 101.6-mm thick and 765-mm along the beam direction. The outer edges have a 50-mm radius. The outer surfaces of this electrode are polished and coated with a thin layer of copper. The ground electrodes have a mechanical connection to the target enclosure can. An insulating structure provides support for the HV electrode.

Cryostat

The cryostat (Fig. V.G.4) is divided into two parts. The lower target-region cryostat is pictured in Fig. V.G.2, while the upper cryostat is shown in Fig. V.G.5.

Target-Region Cryostat

The upper part of the target cryostat contains the cylindrical magnetic enclosure that houses the two target cells, the light guides, the electrodes, the cosθ-magnet coils, and the RF-π/2 rotation coils. This volume is filled with approximately 1300 liters of superfluid liquid helium. The lower part of the target enclosure is the can holding the variable capacitor for the HV system and another 200 liters of liquid helium. Also below the target enclosure are the two target-sample transfer bellows. The overall target enclosure is a large T shaped copper can with stainless steel wire seal flanges brazed onto the ends.

The gasket for these flanges is copper wire. The target enclosure also provides space to route the HV connection between the target-cell HV electrode and the HV generator.

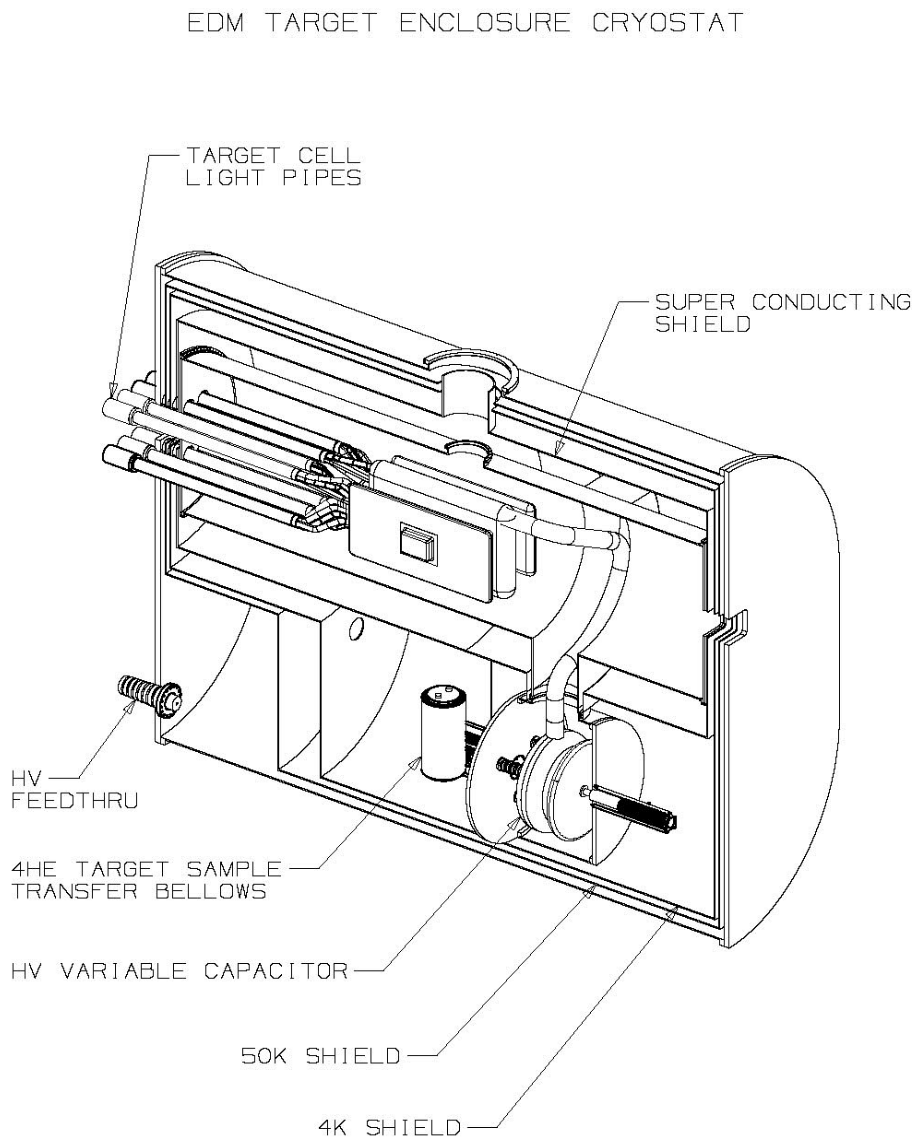

Figure V.G.2. The target-region cryostat is seen in as a cut away. The neutron beam comes in from the right. The target cell light pipes connect to photo-multiplier tubes at room temperature at the left. This volume is 1.5-m wide by 2.3-m high and has a length of 3 m.

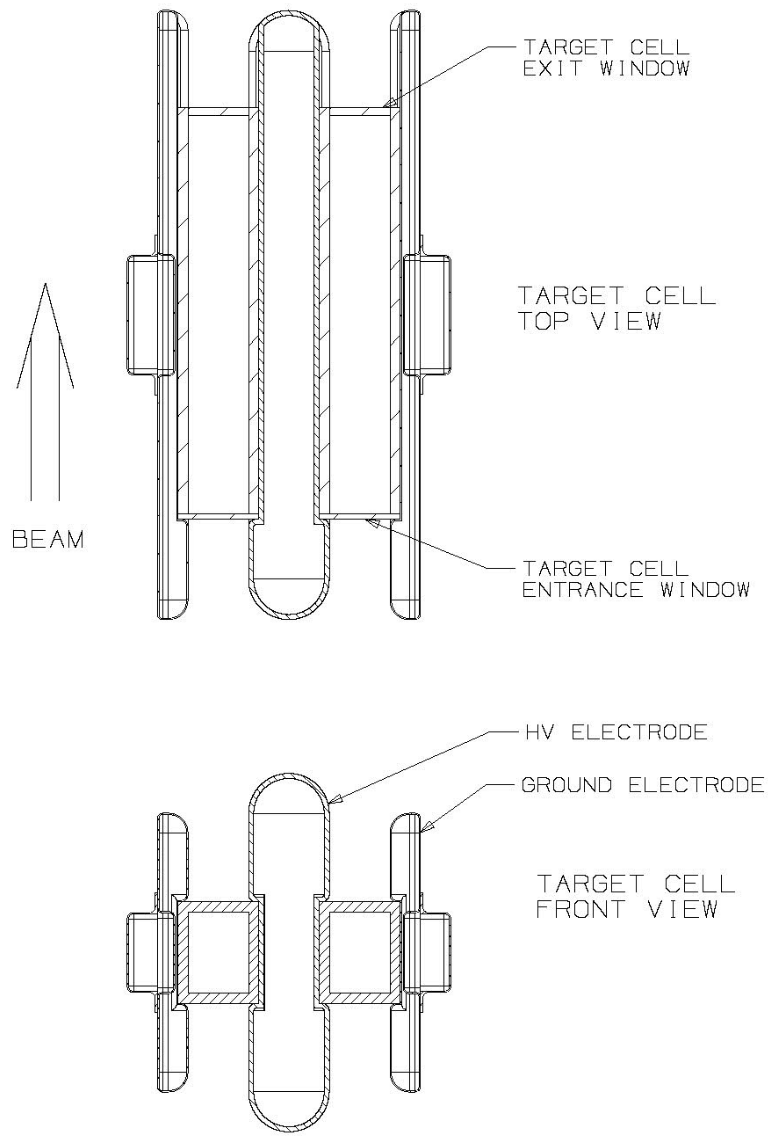

Figure V.G.3. Neutron target cells sandwiched between three hollow electrodes. The two cells are ~50 cm long. The SQUID detectors are embedded in the two ground (outside) electrodes.

Upper Cryostat

The design of the upper cryostat is shown in Fig. V.G.5. It has two major, interconnected components, the DR and the He purifier, that are discussed below. A schematic of the organization of the cryogenics is given in Fig. V.G.6.

Dilution Refrigerator

The central feature of the EDM upper cryostat (Fig. V.G.5) is the DRS 3000 DR insert from Leiden Cryogenics. The DR is rated at 3000 μW at 120 mK. The functions of the DR are to cool the target enclosure to ~0.3 K and to cool the new target sample output from the ^{4}He purifier. The DR ^{3}He pump system consists of a 4000-m^3/hr Roots blower backed by a 500-m^3/hr Roots blower backed by an 80-m^3/hr sealed dry pump. The DR's 1-K pot (^{4}He reservoir) pump system consists of a 500-m^3/hr Roots blower backed by an 80-m^3/hr sealed dry pump. The DR is vertically inserted into an internal, 100-l liquid helium Dewar with a 330-mm diameter neck.

The bottom tube of the Dewar serves as the main support for the target enclosure and consists of three sections so that connections to the DR still and the DR mixer can be made using OFHC copper braid. The connections to the DR still and mixer are made when the DR insert is in place.

During data taking operation, heaters on the DR still and mixer are modulated to keep the DR operation in thermal equilibrium. The upper-cryostat top flange is independently supported from the upper-cryostat bottom flange, which is in turn supported by an external framework. The outer vacuum enclosure of the upper cryostat can be removed to facilitate upper cryostat assembly and maintenance.

The internal liquid-helium Dewar is serviced by two or three Sumitomo RDK-415D (1.5 W at 4K/45 W at 50 K) two-stage cold heads and a transfer line to an external 1000-l Dewar. The cold head second stages are used to condense return ^{4}He from the 1-K pot pump-systems (DR and Purifier). The first stages of the cold head cool the 50-K heat shields, the internal Dewar neck, and the return-^{4}He gas. The refrigeration power of the cold head is matched to the liquid-helium needs of the EDM experiment during normal operation. The external Dewar is necessary during the initial cool down and filling of the cryostat.

The Helium Purification Cycle

The polarization lifetime of the ^{3}He may be only 100h, so that the polarization will drop below 97% during a measuring cycle. Thus, we want to be able to remove all the ^{3}He from the 8 liters of the target cells every measurement cycle, as short as 20 min. The ^{4}He is purified by utilizing the heat flush technique developed by McClintock.[1] The heat flush technique works above 1 K, where the phonon coupling is substantial. This coupling varies as T^7, and at the operational temperature of the target cell, the ^3He is unaffected. Therefore, the He must be warmed from ~0.2 K to 1.2 K for spent ^3He removal and cooled again after purification for the next cycle. The He recycling system consists of target cell drains, compression bellows to move the He to the top of the purifier, the purifier, and a staging volume for the addition of highly polarized ^3He into ultra pure ^4He.

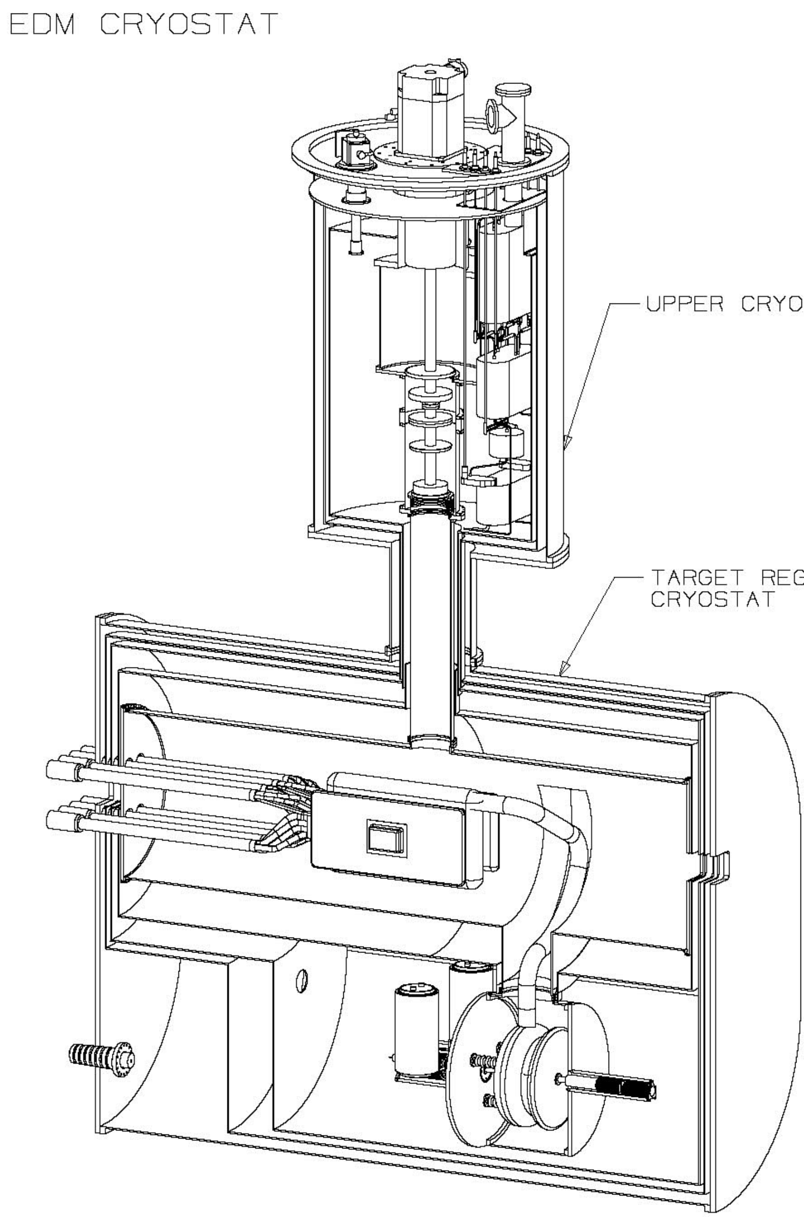

Figure V.G.4. Target region and upper cryostats. The neutron beam enters from the right.

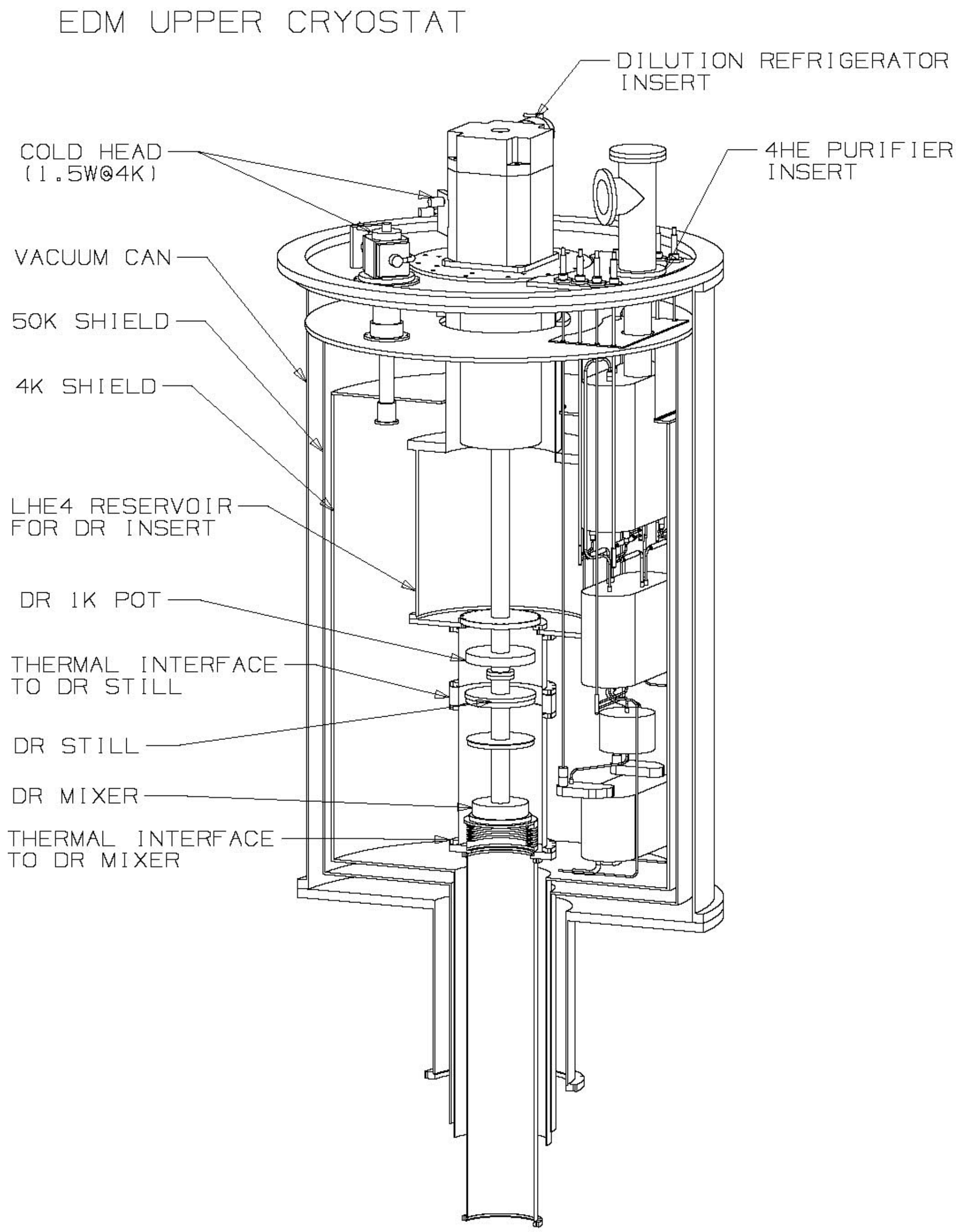

Figure V.G.5. Upper cryostat that encloses the DR, the ^{4}He purifier apparatus, and the target-preparation reservoir, V3. This cylinder has a height of 2 m and a diameter of 1.2 m.

The upper cryostat houses a large-capacity, continuous-cycle helium purifier. (Fig. V.G.7). The purifier insert consists of three volumes that are separated vertically and thermally isolated from each other. Gravity is used to move the helium through the purifier and to the target cells. Volume 1 (V1) is a copper can that receives the spent liquid helium target samples when the transfer bellows are compressed. V1 resides inside a can that is a high-capacity, continuous-cycle ^{4}He refrigerator.

The phonon wind, initiated by heaters, pushes the ^{3}He impurities back toward V1. Helium from V1 flows through a set of four helium purifiers heat flush tubes, see Fig V.G.7. Each purifier consists of a metering valve and a horizontal 100-mm length of 10-mm diameter tube with a ¼-watt heater at the downstream end. The heater raises the local temperature of the liquid helium to ~1.2 K. The 1-K pot removes the 1 watt of heat generated by the purifier heaters. The 1-K pot is serviced by a large sealed Roots-blower system consisting of a 4000-m^3/hr Roots pump backed by a 1200-m^3/hr Roots blower backed by a sealed 80-m^3/hr dry pump.

The purified ^{4}He flows into a second ^{4}He volume, V2, which is thermally isolated from the purifiers by long capillary tubes. Thermal links made of OFHC copper braid connect V2 to the DR still that is at ~0.6 K. A heat exchanger in V2 helps to cool this volume when the spent target samples are moved from the transfer bellows to V1. The purifier is initially filled with ultra-pure helium that has been generated using the same heat flush technique in a separate apparatus. This apparatus is currently being modified from an existing device built at the Hahn-Meitner Institut. It serves as a development prototype for the upper-cryostat purifier. The purifier insert can then supply the experimental needs for pure liquid ^{4}He for approximately 6 months, until the build up of ^{3}He in V1 becomes a problem.

After V2, the purified liquid helium flows through a metering valve and into a heat exchanger with thermal contact to the DR mixer (see Figs. V.G.6 and V.G.7). The liquid helium then continues into the target preparation volume (V3). The size of V3 is carefully matched to the volume of the two target cells. In V3, polarized ^{3}He atoms are introduced until a fractional density of ~10^{-10} is achieved. The inner walls of V3 must be coated to preserve the ^{3}He spin. A magnetic holding field, carefully matched to the main field, is used to keep the target samples polarized. The liquid helium in V3 is kept at the nominal target operating temperature. At the end of the EDM-measurement cycle, valves below the target cells are opened to drain the spent target samples. At the end of this operation the valves are closed. A prototype valve to fill and empty the target cells has been developed for other applications.[2] The valve needs some modifications to prevent it from absorbing neutrons, and it must be tested for reliability over thousands of cycles. The newly prepared target material in V3 now flows through a valve into the target cells.

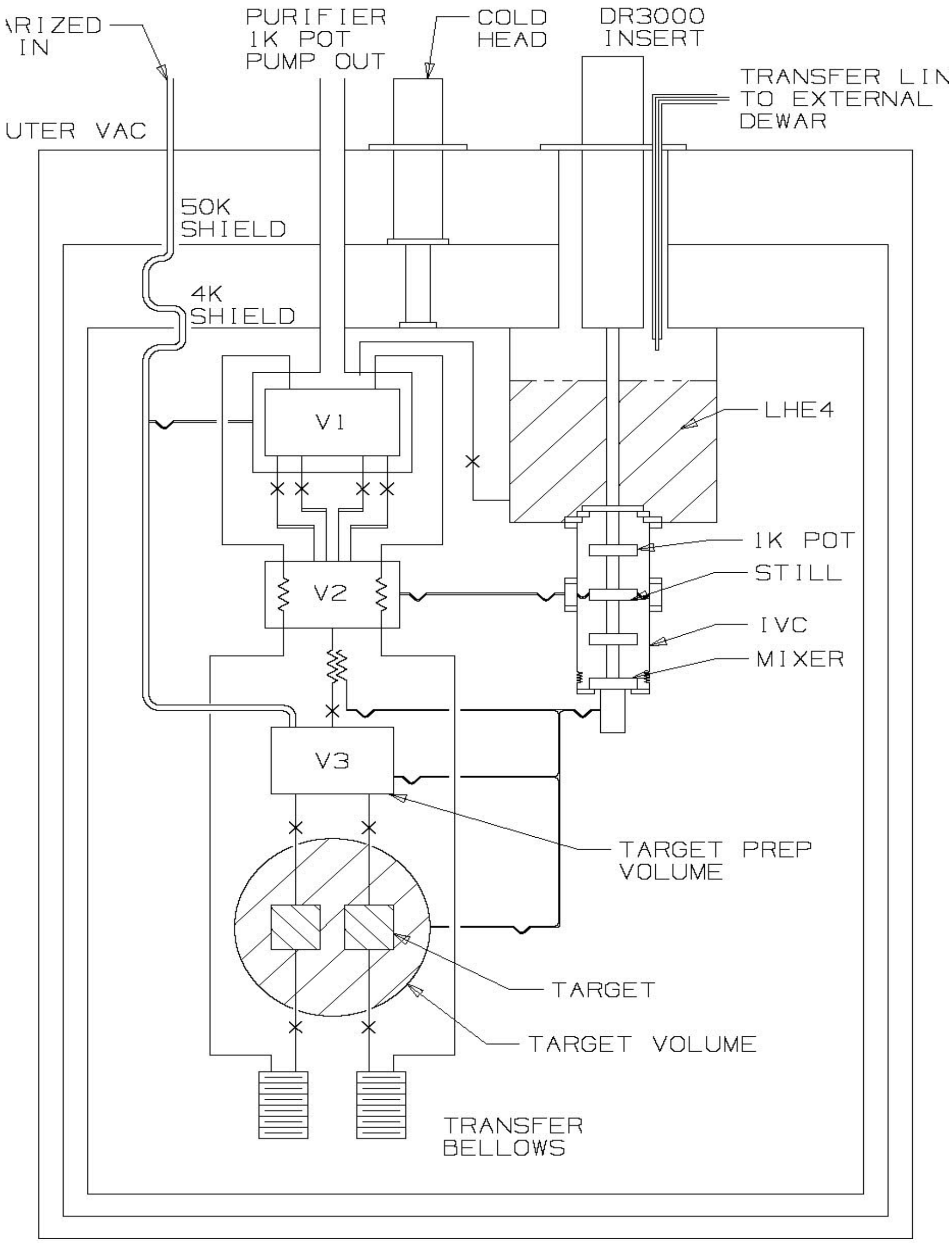

Figure V.G.6. Schematic of the Upper cryostat with the ^{4}He purifier and the dilution refrigerator.

HV Generator

A design requirement of the EDM experiment is a high electric field across the target cells. The field strength assumed for the pre-proposal is 50 kV/cm (section V.H.). The spacing between the ground electrode and the HV electrode is currently 76 mm. The voltage requirement is then 360 kV. It does not appear to be practical to bring the full voltage into the apparatus from an external source. Commercially available ceramic vacuum feed-throughs suitable for our apparatus have a maximum voltage rating of 100 kV. Also, an existing 125-kV power supply is available for use in the experiment.

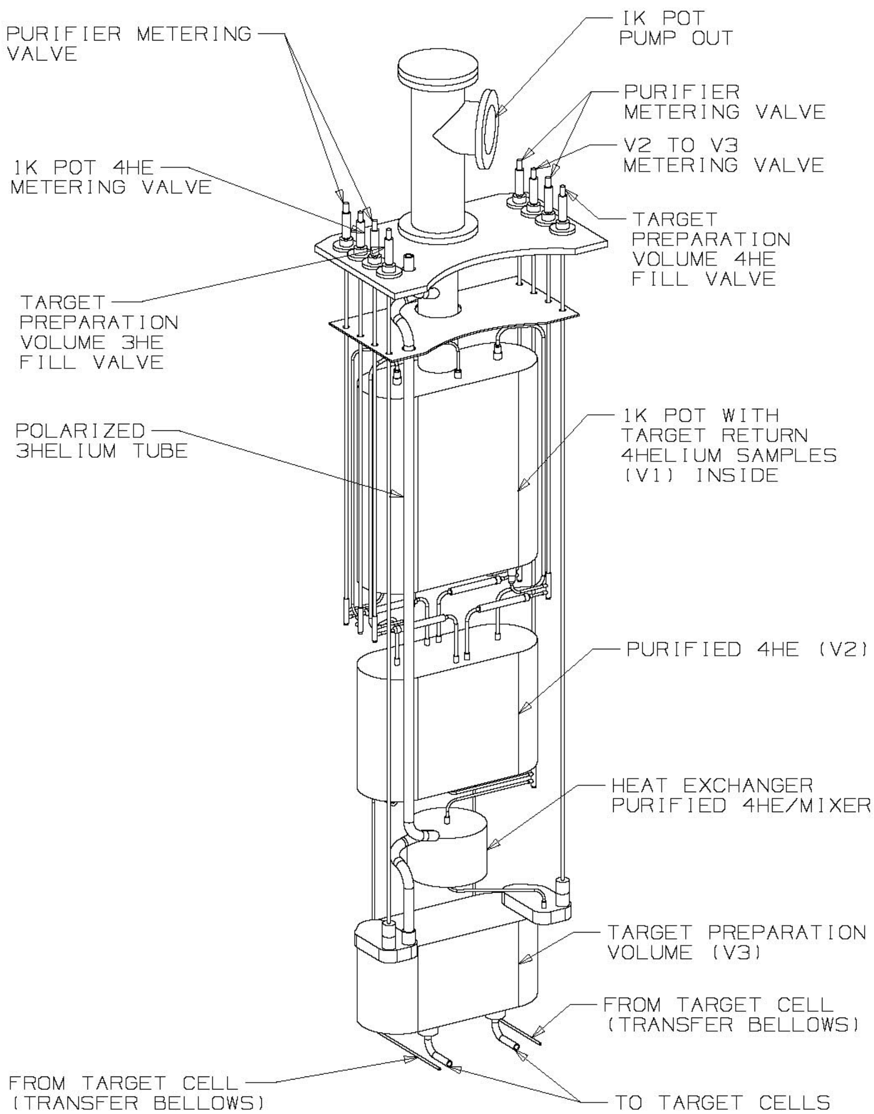

Figure V.G.7 The ^{4}He purification apparatus and the polarized ^{3}He and ^{4}He target preparation reservoir (V3).

The alternative approach being adopted here is shown in Figs. V.G.2 and V.G.8. A variable capacitor is connected in parallel with the two target capacitors formed by the three target-region electrodes. The variable capacitor (and the target capacitors) is initially charged from an external HV source, isolated, and then adjusted to step up the voltage inside the liquid helium volume. The procedure will be to engage the HV plate of the variable capacitor with a rod that carries the applied external voltage; the ground plate is held close to the HV plate to maximize the capacitance. After the charge build up, the HV rod contact is broken, and the ground plate is moved away from the HV plate of the variable capacitor. The movement decreases the capacitance of the variable capacitor; increasing the voltage across both the variable capacitor and the two target capacitors. The net result is that charge is moved from the variable capacitor to the target capacitors, increasing their electric fields.

To be more quantitative, all together there are four capacitors to be charged. The HV variable capacitor (1 pF to1000 pF) is in parallel with the 2 x 53-pF capacitance of the two target cell electrodes. In addition, the capacitance due to the HV connection between the variable capacitor and the target cell HV electrode is ~54 pF. During the charging operation, when the ground electrode has been moved to close proximity with the HV electrode (~1 mm), the combined capacitance is ~1150 pF. The moveable HV contact is translated so as to be in contact with the HV electrode. A charging voltage of 50 kV is applied to this configuration. After the charging operation is complete, the moveable HV contact is withdrawn ~100 mm and the high voltage power supply is turned off so that the internal capacitor system is isolated. The ground electrode is then moved out so that the spacing between the ground electrode and the HV electrode is ~100 mm. The net capacitance of this configuration is 165 pF and the voltage gain factor is ~7. Thus the voltage can be increased to the required ~360 kV across the cell.

It is important that the net leakage current in super-fluid helium be small in order to meet the time-stability requirement of the measurement. In order to limit the change of the voltage across the target cell to 1-2%, during a 1000-s measuring period, the net leakage current must be < 1 nA. This specification is also sufficient to eliminate the systematic effect associated with spiral currents.

The variable capacitor and its actuators will be enclosed in a can, Fig. V.G.8, which is tee shaped and made of copper with the flanges brazed on at the ends. The flanges are wire seal flanges made from stainless steel with copper wire gaskets. The ground electrode and its actuator are mounted off of one large diameter flange. The ground electrode includes an actuating rod, which is supported by linear ball bushings that are immersed in a super-fluid helium bath common with the rest of the variable capacitor. A pair of stainless steel bellows allows the ground electrode to move, with external control, through a range of 100 mm without changing the super-fluid helium volume. During actuation, one bellows expands while the other contracts to keep the volume constant.

The HV electrode is mounted from a second flange using custom ceramic HV standoffs. The HV moveable contact has a similar bellows arrangement with the additional requirement that the moveable contact and its linear ball bushings be isolated from ground. The HV feed-through is fixed in position and a spring makes the electrical connection to the HV contact. The requirement of a ceramic HV-insulator feed-through between a super-fluid helium volume and vacuum is a challenging requirement. Discussions with an engineer, who designs ceramic feed-throughs, led us to choose a commercially available feed-through that could be welded to a stainless-steel flange.

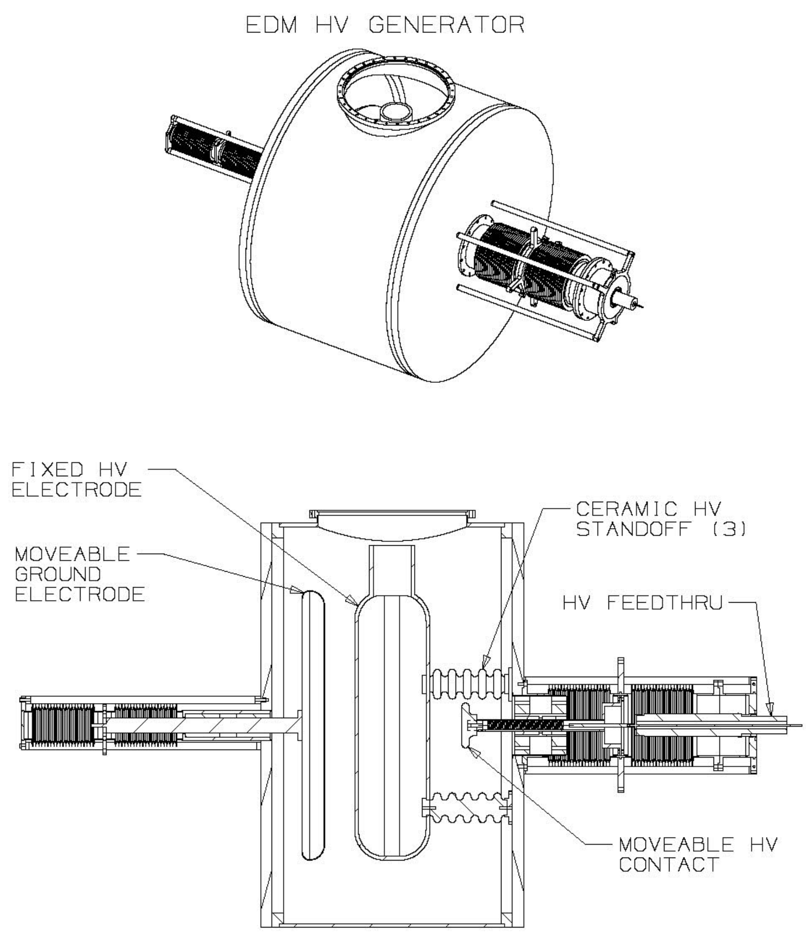

Figure V.G.8. Voltage amplification technique using a variable capacitor and an external HV disconnect. The main volume is filled with superfluid ^{4}He.

The connection between the variable-capacitor HV electrode and the target-cell HV electrode passes through the top flange in Fig. V.G.8. This flange has a 250-mm ID and keeps the spacing between the 100-mm diameter HV connection and ground at 75 mm.

Polarized ^{3}He Source

The design goals for the performance of the polarized ^{3}He source are the following:

- pressure in the cold head region	$< 10^{-5}$ mbar
- pressure in the magnet region	$< 10^{-6}$ mbar
- polarized ^{3}He source output rate	$> 10^{14}$/sec
- ^{3}He polarization	> 97%

The polarized ^{3}He source assembly, discussed in Section V.D, is shown in Fig. V.G.9, with the details of the injection region pictured in Fig. V.G.10. A recirculating flow of ^{3}He gas is cooled to ~0.5 K and ejected from a nozzle pointed at the axis of an array of quadrupole magnets. The nozzle consists of multiple 1-mm diameter x 20-mm long tubes, 0.7-mm inner diameter (ID), filling the ID of a 9-mm ID stainless steel tube. The gas stream is defined by a beam skimmer and a beam collimator; they match the nozzle aperture to the acceptance of the quadrupole-magnet array. The gas atoms that fail to enter the magnet acceptance are pumped away by the Varian V2000 turbo pump (2000 liters/second). The gas atoms that fail to traverse the quadruple array are pumped away by the Varian V1000 turbo pump (1000 liters/second). The turbo pumps are backed by a Pfeiffer Unidry 050 sealed dry pump. This pump is part of the ^{3}He gas system that services the source.

Each quadrupole magnet sector is constructed from four neodymium bar magnets that have dimensions of 159 mm x 12.7 mm x 38 mm. The nominal magnetic field is ~0.7 T. Each magnet sector has a central tube that provides support for the magnet bars and has multiple holes for good pumping of the beam volume. The magnet array resides inside of a 200-mm diameter tube with conflate flanges on the ends.

The gas flow and cooling is organized as follows. A Sumitomo RDK-415D cold head is used to cool the ^{3}He gas stream to a design goal of < 0.5 K. The first stage of this cold head is rated for 45 W at 50 K and is used to cool a heat shield and to cool gas streams of both ^{3}He and ^{4}He. The second stage of the cold head is rated for 1.5 W at 4 K and 0.3 W at ~3.2 K. The ^{4}He-gas stream is liquefied by the second stage of the cold head, and the liquid helium continues through a metering valve into a volume that serves as a 1-K pot.

An Edwards XDS10 sealed scroll pump is used to recirculate the ^{4}He gas. The ^{3}He-gas stream is cooled to approximately 4 K by the cold head second stage. Some of the ^{3}He gas continues to a heat exchanger, with its 1-K pot, where it is liquefied. The ^{3}He liquid flows through a metering valve into a pumped liquid bath. A Varian 551 turbo pump backed by the Pfeiffer Unidry 050 sealed dry pump (same pump that backs the big turbo pumps) lowers the temperature of the ^{3}He bath to ~0.3 K. The remaining ^{3}He gas is cooled below 0.5 K in a heat exchanger in contact with the pumped ^{3}He bath. This gas stream continues through a third metering valve to the nozzle that points the gas stream at the quadrupole-magnet array.

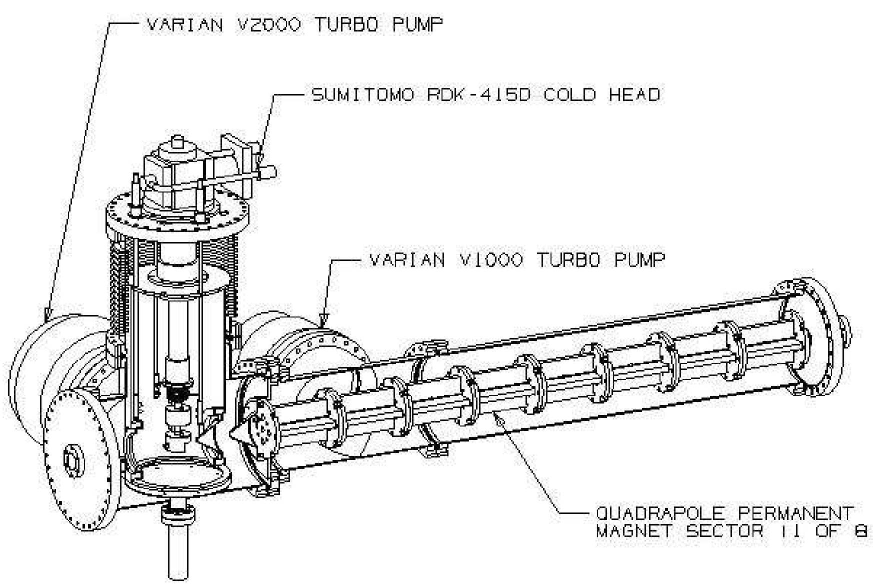

Figure V.G.9. The polarized-^{3}He source with its quadrupole magnet spin filter array.

Other Components

The cosθ magnet, π/2 RF Helmholtz coils, and the outer ferromagnetic-shield have less detailed designs. These constructs are in use in other experiments like the current neutron EDM experiment at the ILL. We will rely heavily on their design. As noted in Appendix A, there is a question of whether the cosθ coil, when in a cryogenic environment, can be wrapped on a ferromagnetic material. The uncertainty should be resolvable with some measurements on a prototype.

The superconducting shield is necessary for noise isolation of the SQUIDs. As a new feature of this measurement, it requires development. The main uncertainty is the nature of trapped fields inside the shield as it is cooled through the superconducting transition. We hope to measure the size of such effects by measuring the fields inside a prototype shield using nuclear magnetic resonance. A cosθ coil wrapped on a ferromagnetic material would mitigate the problem.

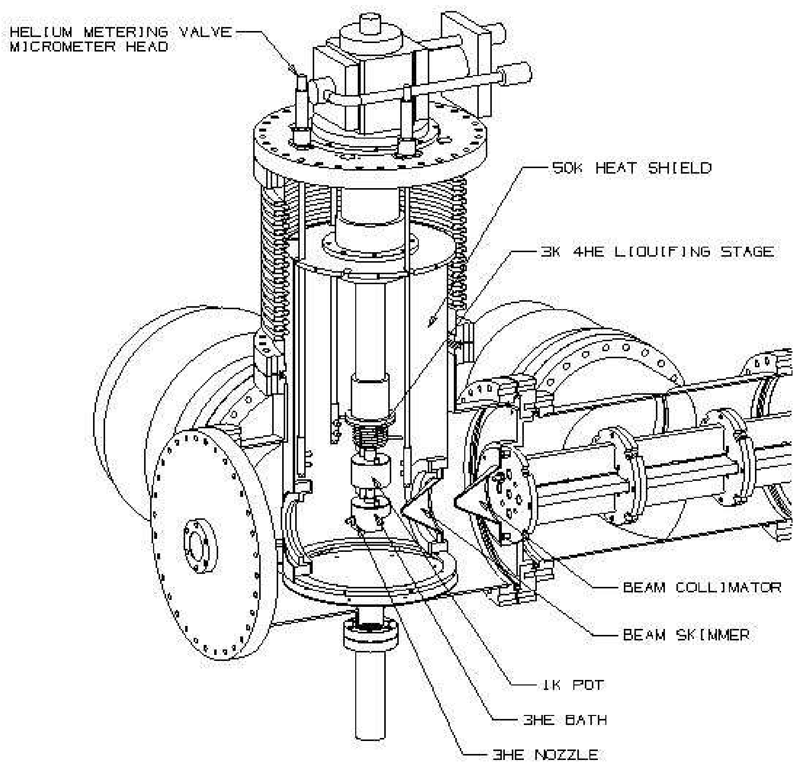

Figure V.G.10. Details of the injection region of the ^{3}He source.

References

1. P. V. E. McClintock., Cryogenics **18**, 201 (1978); P. C. Hendry and P. V. E. McClintock, Cryogenics **27**, 131 (1987).

2. R. Duncan, (private communication).