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**A FROZEN SPIN TARGET  
WITH THREE ORTHOGONAL POLARIZATION DIRECTIONS**

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**DEPARTEMENT DE PHYSIQUE DES PARTICULES ELEMENTAIRES**

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**ABSTRACT**

*A frozen spin target has been designed and constructed at CEN-SACLAY for nucleon-nucleon scattering experiments at the synchrotron SATURNE II. In this target, the polarization can be maintained in three directions : vertical, horizontal along the beam, or horizontal perpendicular to the beam. The angle of free access is up to 80° from the forward direction to the left and up to 56° or 43° to the right depending on the magnet configuration; the azimuthal angle is 15°. The magnet system is entirely superconducting. The target of about 70 cm<sup>3</sup> maximum volume is cooled in a vertical dilution refrigerator. A 14 cm<sup>3</sup> target has been used in several experiments with proton and deuteron beams during the 1981-1985 period.*

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## I. INTRODUCTION

The principle of operation of a frozen spin target /1/ is based on the long nuclear spin relaxation time at low temperatures /2/3/. This technique allows freedom in the choice of the magnetic field for polarization holding, when the target temperature is below 50 mK. The holding field does not need to be homogeneous and may be as low as 0.33 T. More generally it could be the field of a spectrometer optimized for large angle of acceptance around the polarized target.

The spin polarization vector always follows the magnetic field vector which may be turned without loss in polarization value. The orientability of the target polarization makes it possible, in a single experiment, to perform complete sets of measurements allowing unique determination of the scattering amplitudes /4/ in two body reactions of particle with spin.

The present polarized target was designed for nucleon-nucleon elastic scattering experiments up to 3 GeV at SATURNE II. Since the cross-sections are large, the target does not need to be very long. For the experiments with incident protons focussed on the target, we use a target of 2 cm diameter in order to minimize the energy loss and multiple scattering of the recoil proton.

For the experiments with the incident neutron beam, which is less intense and cannot be focussed onto a small target, larger transverse dimensions are necessary. The upper limit is given by consideration of the total target volume, limited by the available cooling power in a practical installation. The designed aim was a target volume of about 70 cm<sup>3</sup>.

The solid angle of access is always limited by the geometry of the target refrigerator and of the holding magnets. Vertical geometry for the target refrigerator was chosen due to simplicity in design and good access all around the target in the horizontal scattering plane. An asymmetric configuration with a small coil was preferred for horizontal as well as for vertical holding field, giving maximum angle of access around the target. A low holding field facilitates the detection and analysis of low momentum recoil particles.

In the following we shall describe in detail the target dilution refrigerator, the superconducting magnet system, the NMR equipment for polarization measurement and the microwave apparatus for dynamic polarization. The results are presented and some conclusions are drawn.

## II. DILUTION REFRIGERATOR

### 1. Introduction

Experience has shown that reasonably fast polarization reversal requires a microwave power of 2 to 3 mW per gram of target material at a temperature just below 0.5 K. Thus the refrigerator for a target volume of about 70 cm<sup>3</sup> must have a cooling power of 200 mW. This power requires about 30 mmole/sec He<sup>3</sup> circulation speed for 0.5 K mixing chamber temperature.

The pump system was designed for this 30 mmole/sec maximum mass flow rate. It consists of two Roots blowers of 3000 m<sup>3</sup>/h (ALCATEL MIV 3000) and 350 m<sup>3</sup>/h (ALCATEL MIV 350) nominal speed in series, backed by two rotary blade pumps of 60 m<sup>3</sup>/h speed (ALCATEL 2060H) in parallel.

An important consideration for high-circulation dilution refrigerator is the liquid He<sup>4</sup> consumption. The present refrigerator was designed without a pumped He<sup>4</sup> bath condenser, a technique which had been used earlier with He<sup>3</sup> evaporation refrigerators /5/. This requires 1.0-1.5 bar outlet pressure of He<sup>3</sup> from the 4 K heat exchanger. Allowing some pressure drop in the heat exchangers above 4 K, the primary pumps must be able to exhaust at 1.8 bar pressure. In order to prevent the lip seals on the shaft of the two rotary blade pumps from turning over, the pressure in between the seals is controlled and maintained above the exhaust pressure. For safety reasons, the refrigerator has been designed to permit a 60 mmole/sec He<sup>3</sup> flow rate.

### 2. Description

A cut-away view of the refrigerator is given in fig.1. The flow diagram is shown in the schematic drawing of the refrigerator in fig.2.

The upper inset shows a cut of the 300K-4K exchanger. The exchanger efficiency E is calculated according to :

$$E = 1 - e^{-Ntu}$$

where  $Ntu = us/n'c$  with :-  
- u power rate per unit of surface and per unit of temperature  
- s area of the exchanger  
- n' flow rate (n'(3) & n'(4) for He<sup>3</sup> and He<sup>4</sup> respectively)  
- c specific heat

An estimate of the area of our exchanger leads to a value of  $Ntu = 15$  ( $E \sim 1$ ) for  $n'(3) = n'(4) = 60$  mmole/sec with pressure drops of 30 mtorr in the low pressure He<sup>3</sup> stream,  $\sim 200$  torr in the He<sup>4</sup> stream and  $\sim 100$  torr in the high pressure He<sup>3</sup> stream.

The heat exchanger 1 above 4 K temperature consists of two concentric stainless steel tubes wound into a helix in the He<sup>3</sup> outlet tube. The low pressure He<sup>3</sup> flow is forced to go through the windings of the helix thus improving the heat exchange with the low pressure He<sup>3</sup> vapour. In the concentric tubes He<sup>3</sup> goes in through the annular passage, and He<sup>4</sup> comes out in the inner pipe.

A needle valve in the liquid He<sup>4</sup> inlet allows to lower the end temperature of the 300K-4K exchanger; this speeds up the condensation of He<sup>3</sup> during the initial cooling of the refrigerator. It was planned that in normal running this needle valve should be entirely open. However, the refrigerator was easier to control when using this valve to regulate the He<sup>4</sup> flow.

A He<sup>3</sup> needle valve bypasses all the heat exchangers below 4 K, in order to precool rapidly the mixing chamber by letting in directly 4 K Helium. In normal run this needle valve must be completely shut.

In normal running, the He<sup>3</sup> is expanded in a Joule-Thomson valve after having passed through exchangers 2 and 3. The triple-helix exchanger 2 consists of a tube wound in helix around which is wound and soldered a small spring-shaped wire so to increase the thermal exchange surface with He<sup>3</sup> vapours coming upwards from the still. It can be seen on middle inset of fig.2.

The exchangers 3 and 4 consist of loosely wound cupronickel tubes of 0.8/1.0 mm and 1.0/1.2 mm diameter and of 520 cm and 115 cm length respectively. The exchanger 5 in the dilute inlet to the still is wound in such a manner that it reduces the convection of the heavier dilute solution from the still to the heat exchanger.

The exchanger 5, shown in detail in the lower inset of fig.2 consists of two shaped strips of cupronickel foil coated with sintered copper powder of 18 micron effective grain size; the strips are Argon arc welded together after having been bent in helical shape. The helix occupies the annular volume in between the inner vacuum plug and the outer vacuum envelope. A plastic rod closed at both ends has been wound between the turns of the helix to lower the thermal short-circuit between the mixing chamber and the still, thus improving the efficiency of the exchanger.

The mixing chamber is the remaining volume at the end of the inner vacuum plug and outer vacuum envelope. Two thermal screens surround the mixing chamber, the first of which is cooled by the He<sup>4</sup> flow and the second by the boiling fluid in the still. The screens are made of high purity copper in the upper part, and of thin aluminium around the mixing chamber.

A 4 mm circular wave guide and three semi-rigid coaxial cables enter the mixing chamber through the inner vacuum. Instrumentation leads for resistor thermometers and for a heater go as well through the vacuum plug in a thin tube.

The temperature is measured by means of three resistors, one calibrated Germanium resistor (LAKE SHORE CRYOTRONICS INC.) and two carbon resistors packaged in a way to avoid scale drifting /6/. The Germanium resistor and one of the carbon resistors are placed above the target, and the other carbon resistor is placed just below the target in the outlet stream of the mixing chamber.

A mechanical device enables the whole refrigerator to be moved 3 cm above the beam axis in order to introduce a dummy target into the beam, in the position normally occupied by the polarized target.

### 3. Performances

The cooling power of the dilution refrigerator as a function of the mixing chamber temperature is shown in fig.3, the zero power temperature being of 35 mK, with a corresponding circulation speed of 4.5 mmole/sec. The temperature is measured at two points, above and below the target. The corresponding optimum flow rates are given in fig.4. Extrapolation of the power curve by a theoretical  $T^{\wedge}$  line /7/ from the 10 mW point towards lower power values shows that the residual heat leak can be estimated to be less than 50 microwatts.

The target consists of a perforated PTFCE (Polytrifluoride chloride ethylene) cartridge loaded with small glassy beads. After the cartridge is mounted in position, the refrigerator is cooled in a liquid nitrogen bath up to the contact of screen 1. Then the outer vacuum envelope is raised, air is evacuated and cooling by  $He^{\wedge}$  is started. Precooling down to condensation temperature takes one hour and condensation of the  $He^{\wedge}$  / $He^{\wedge}$  mixture another hour. Dilution starts by itself when 3/4 of the mixture is condensed. Cooldown from 0.5 K to 35 mK lasts three minutes.

The dilution refrigerator requires 3 l/h liquid Helium with screen cooling at minimum temperature and 5 l/h at full speed.

The operating conditions of the refrigerator are very stable. In a recent run, the target was at low temperature continuously for 40 days. The problems encountered previously were due to impurities in the  $He^{\wedge}$  gas used for the initial flushing of the installation. This trouble had been cured after having added a nitrogen cooled trap.

### III. MAGNET SYSTEM

#### 1. Description

The magnet system /8/ is shown schematically in fig.5a and 5b for separated vertical and horizontal holding positions. In horizontal position the beam may enter the target either parallel or perpendicular to the axis of the holding coil.

The superconducting polarizing solenoid (fig.6) has a main winding and two correction windings in order to provide 2.5 T with  $10^{-4}$  uniformity in the full 70 cm<sup>3</sup> volume of the target. The air bore of the vacuum vessel is 129 mm, and inner diameter of winding is 182 mm.

The superconducting vertical holding coil is placed with its magnetic center 180 mm above the center of the target in order to have 15° azimuthal angle of access, as one normally has with iron magnets. The field at the target is 0.5 T, when the central field is 1.05 T; this value had been chosen according to CERN predictions about relaxation times in 1976 /1/.

For horizontal polarization perpendicular to the beam direction, the horizontal holding coil permits 36° free angle on the coil side, determined by the requested 0.5 T field at the target. The field at the centre of the coil is 2.3 T and the maximum field at the conductor is 6.1 T.

#### 2. Operating procedure

The shifting from polarizing to holding field is done by lowering the current in the polarizing solenoid to a value corresponding to a 0.5 T field and then gradually rising the holding coil current to nominal value while reducing the polarizing solenoid current simultaneously to zero /9/. The total field is always about 0.5 T during this last operation, which means that in the case of horizontal holding field, the polarization, as it follows the field direction, goes through a 90° rotation to reach its final direction. When the value of the polarizing solenoid field is zero, the solenoid is moved vertically down to provide full access around the target.

For longitudinal target polarization, parallel or antiparallel to the beam direction, it is possible to reverse the sign of the polarization by rotating the magnetic field through 180°. The polarizing solenoid is used to always maintain a non zero field component as the relaxation time drops rapidly towards low holding fields ( $t_0 = 8$  mn at 0.05 T for pentanol doped with EHBA-CrV /10/fig.7). After a 90° rotation, the field component of the holding coil is zero and is 0.5 T for the polarizing solenoid. At this point the power leads on the holding magnet power supply are reversed and the rotation is resumed until the holding field provides a longitudinal polarization with a sign opposite to the initial one. The reversal of the target polarization by this

method lasts 30 minutes instead of three hours for repolarizing with the opposite sign. It causes no depolarization of the target. The difference in the magnetic deflection of the particles for the two target polarization states is acceptable for certain configurations. Total cross section measurements using axial symmetric detectors, performed with target sign reversal by repolarization or by rotation of the holding field gave both the same results /11/. This method has also been tried in elastic scattering experiments where particles scattered at large angles are studied in coincidence in two detector arms in the horizontal plane. After reconstruction and analysis of the events it turns out that the change of sign of the magnetic field does not introduce systematic errors. This is due to the low value of the field integral seen by the scattered particles.

For similar measurements using a vertical target polarization, on the contrary, the magnetic field has such a strong effect on particle trajectories that the method of field reversal would be unacceptable.

### 3. Cryogenics

A stationary 1000 litre dewar supplies liquid He<sup>4</sup> to the holding magnet. The same dewar feeds a 100 litre dewar which moves with the polarizing solenoid. Helium to the dilution refrigerator is taken from the holding coil. Magnet screens as well as transfer line screens are cooled by Helium vapour /12/.

The Helium consumption of the polarizing solenoid is 2.3 l/h without current and 3 l/h at nominal field. The corresponding values for the horizontal coil are 2.2 l/h and 3 l/h and for the vertical coil 2 l/h and 2.7 l/h respectively.

### 4. Present configuration of the three magnets

Measurements of the relaxation time of the polarization /10/ done with the configuration as described above has shown that it was possible to use a lower holding field, between 0.3 and 0.4 T. This allowed us to install the horizontal coil 7 cm farther from the target, in order to have both the vertical and the horizontal holding magnet in position and at low temperature (fig.8). A switch system connects the power supply to either one of the two magnets. We have thus the possibility to change from vertical to horizontal holding field and vice-versa in 30 minutes instead of several days. The polarizing solenoid is used in the same way as for polarization sign reversal to provide a field when the current is zero in the holding coils.

In the new configuration, the horizontal holding magnet supplies liquid He<sup>4</sup> to the vertical holding magnet which itself feeds the dilution refrigerator. For a horizontal holding field perpendicular to the beam direction the unobstructed region extends now to 43° instead of 36° previously.



#### IV. POLARIZATION MEASUREMENT

The polarization is measured in three coil loops. Two loops are placed around each end of the target and are actually supporting the cartridge. The third coil loop has a diameter larger than the target, it is placed around the middle of the cartridge and gives an average measure of the polarization. The calibration of the Q-meter signal is done by measuring the signal area arising from the sample in thermal equilibrium with Helium at 1 K.

The NMR Q-meter was designed with a view of using it with deuterated targets as well. A main oscillator produces a 106.3-106.8 Mhz sweep for proton NMR measurement at 2.5 T. This signal is converted down by mixing it with a fixed 90.15 MHz quartz oscillator, to produce a 16.5-16.65 MHz sweep for the deuteron resonance measurement at 2.5 T. The frequency of the main oscillator is stabilized by reading out the frequency from a meter (SCHLUMBERGER FH 2521) by means of a CAMAC processor (MAC68K built from a MOTOROLA 68000 /13/), which calculates the feedback value to keep the oscillator frequency stable. The sweep is also controlled by the processor.

Up to now the target has been operating with undeuterated material. The 16.35 MHz signal is used only to check the value of the proton polarization in a field of 0.383 T in the polarizing solenoid, while reversing the sign of the polarization by reversal of the horizontal holding field or while going from horizontal to vertical holding field (and vice-versa) without repolarizing the target.

In the following, however, we shall describe the two-frequency operation for simultaneous measurements of proton and deuteron polarization. Accurate calibration of deuteron polarization requires the measurement of both proton and deuteron signals in the same coil. A coaxial rf-relay is used to connect the cable from the coil either to a 106 MHz Q-meter or to a 16 MHz Q-meter. The cables to each Q-meter are adjusted to an integer half-wave length at their working frequency.

Fig.9 shows the block diagram of the polarization measurement electronics. Two coils are needed for a large target; two additional relays are provided for switching the oscillators to one or the other coil. We have even added a third coil which can be connected by hand to replace one of the two others. An analog multiplexer chooses the amplitude-detected signal which is digitized with a fast 12-bit ADC. The ADC is read by the MAC68K processor.

The MAC68K processor in a CAMAC crate is connected to a MITRA 125 of SATURNE II. The processor is used to calculate the value of the polarization and the dispersion correction of the Q-meter signal. Data logging of Helium levels, magnets and refrigerator vacuum pressures, magnets currents etc... are also performed through the CAMAC crate. A DVM (SCHLUMBERGER A210/214, 0.001 mV accuracy) is provided for accurate DC measurements of transducer signals. Printout is provided by a line printer (Logabax LX 113) and graphics by two displays.

## V. MICROWAVE SYSTEM

The microwave source is a carcinotron (THOMSON CSF F4076 CO 40B) located at a distance of about 7 m from the target; in order to minimize power losses the line is made of oversized 8 mm rectangular wave guide. The source is insulated from the line by a ferrite insulator followed by a variable attenuator and by a directional switch for frequency measurement with a cavity wavemeter. One of the thermometers in the mixing chamber is used as a microwave power monitor and, since it detects the power transmitted by the target, it can also be used when searching the correct field-frequency relation during magnetic field scan.

## VI. RESULTS AND CONCLUSIONS

### 1. Polarization

Except for the initial tests in 1980, performed with propanediol-CrV /14/, we have been using butanol or pentanol chemically doped with EHBA-CrV /15/ in 1.5 mm diameter glassy beads loaded into the 20 mm diameter PTFCE cartridge of 44 mm length. The concentration of paramagnetic spins is about  $5 \cdot 10^{19}$  spins/ml.

Dynamic polarization with a microwave power of about 2 to 3 mW per gram corresponds about to 30 to 45 mW absorbed in the target material. During dynamic polarization, the Helium temperature is between 150 and 200 mK. The optimum microwave frequencies corresponding to 106.5 MHz proton NMR frequency, are  $f_+ = 69.33$  GHz  $f_- = 69.54$  GHz for propanediol and  $f_+ = 69.17$  GHz  $f_- = 69.58$  GHz for pentanol.

Careful optimization of the critical parameters allows to reach in a reproducible way the polarization values listed in Table I. In some way the absolute calibration is estimated to be of the order of 3%.

The experiments carried out with this target (see section IV.3) include separate determinations of the beam- and the target-analysing powers. These quantities are equal in p-p elastic scattering. The former result is essentially inverse by proportional to the beam polarization whereas the latter is inverse by proportional to the target polarization. The comparison was made at two energies /16/. In both cases the results for the two analysing powers agree within the experimental errors, showing that the ratio of beam- to target-polarization is correct within 2.5%. The beam polarization is known with a relative precision of about one percent.

Table I

```

*****
*                               *                               *
*   Sample                      * Paramagnetic spin          * Polarization          *
*                               * concentration (1019 spins/ml) *   +   :   -          *
*                               *                               *   :   :   :          *
*                               *                               *   :   :   :          *
*                               *                               *   :   :   :          *
*                               *                               *   :   :   :          *
*                               *                               *   :   :   :          *
*                               *                               *   :   :   :          *
* Propanediol                   *      5.8                *   93   :   96          *
* CrV-5%H2O                     *                               *   :   :   :          *
*                               *                               *   :   :   :          *
* Butanol                       *      5                   *   86   :   93          *
* EHBA-CrV                      *                               *   :   :   :          *
* 5%H2O                         *                               *   :   :   :          *
*                               *                               *   :   :   :          *
* Pentanol                      *      5                   *   87   :   93          *
* EHBA-CrV                      *                               *   :   :   :          *
* 5%H2O                         *                               *   :   :   :          *
*                               *                               *   :   :   :          *
*****

```

2. Relaxation time

Because of the running time schedules, proton spin-lattice relaxation time could be measured only during physics data acquisition. Previous data for butanol and pentanol at 55 mK and 45 mK showed little influence of beam rate at  $10^7$  to  $10^8$  protons per burst, every 1.5 second (fig.7). More recent measurements with pentanol at 36 mK show no sizable influence ( $t_0 = 50$  days) of beam intensity up to about  $10^8$  protons per burst, the energy being higher than 1.2 GeV. The relaxation time decreases significantly when the beam energy is  $< 1.2$  GeV as beam rate increases; it varies with the particle distribution during one spill and with the accelerator cycling speed. At  $2 \cdot 10^8$  protons per burst however, the proton spin-lattice relaxation time drops to  $t_0 = 11$  days and the temperature rises to about 50 mK. At both temperatures we observe relaxation times considerably larger than those predicted in 1976 /1/ for propanediol.

At  $6 \cdot 10^8$  particles per burst (E=350 MeV) the relaxation time drops to a value of one day.

3. Use of the target in physics experiments

The target system has been used since 1981 in physics experiments at Saturne II in a beam line with polarized protons and deuterons in the energy range from 400 to 2800 MeV beam kinetic energy. Most of these experiments are part of the "Nucleon-Nucleon" program aiming at the model independent determination of the p-p and n-p elastic scattering amplitudes by

performing "complete sets" of measurements at several energies and at C. M. angles from  $20^\circ$  to  $90^\circ$ . Such sets of experiments comprise measurements of single spin parameters (beam- and target-analysing powers) /17/, of spin correlation parameters with both initial nucleons in definite spin states /16/17/18/, and of measurements requiring rescattering of the recoil proton in a carbon analyser. The total cross section differences  $\Delta\sigma_T$  and  $\Delta\sigma_L$  measured with this target /11/19/ represent about 40% of all existing results.

The list of the quantities measured up to August 1985 is given in ref. /20/. These experiments have considerably increased the data base for phase shift analyses /21/ and for amplitude reconstructions of p-p elastic scattering in the energy range of SATURNE.

The same system, but with a larger target volume of  $> 70 \text{ cm}^3$ , will be used in a series of n-p elastic scattering experiments starting in 1986 with a narrow-band polarized neutron beam obtained by break-up of polarized deuterons.

In addition to the Nucleon-Nucleon experiments, the polarized beam- polarized target-facility has been used also for two other experiments:

- (1) Measurement of beam- and target-spin correlation parameters at  $\theta_{CM} = 90^\circ$  in  $p-p \rightarrow d-\pi^+$  around 350 MeV and 500 MeV.
- (2) Study of d-p elastic scattering at 1600 MeV with rescattering of the proton in a carbon analyser.

The above experiments carried out since 1981 represent all together about 6500 hours of data taking with polarized target.

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**FIGURE CAPTIONS**

- (1) : Cut of the refrigerator
- (2) :  $\text{He}^3$   $\text{He}^4$  Flow diagram
- (3) : Cooling power vs. mixing chamber temperature
- (4) : Optimum flow rates vs. temperature
- (5) : Magnet system (old configuration)
  - a) Vertical holding position
  - b) Horizontal holding position
- (6) : Polarizing solenoid
- (7) : Proton spin-lattice relaxation time vs. holding field
- (8) : Magnet system (present configuration)
- (9) : Electronics block diagram

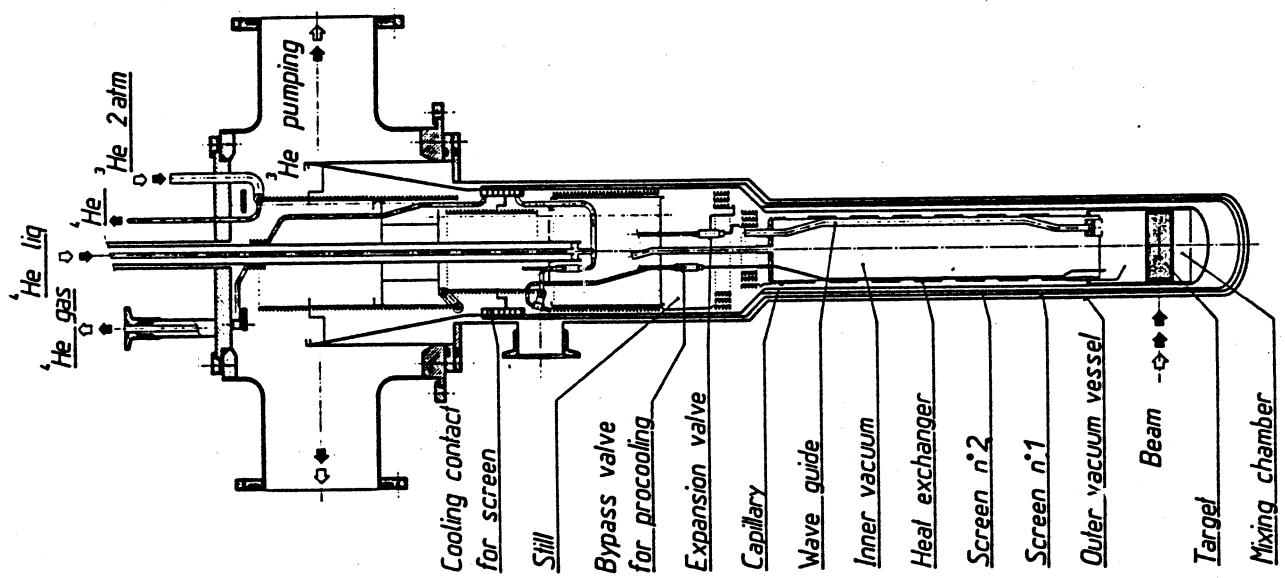


FIG. 1

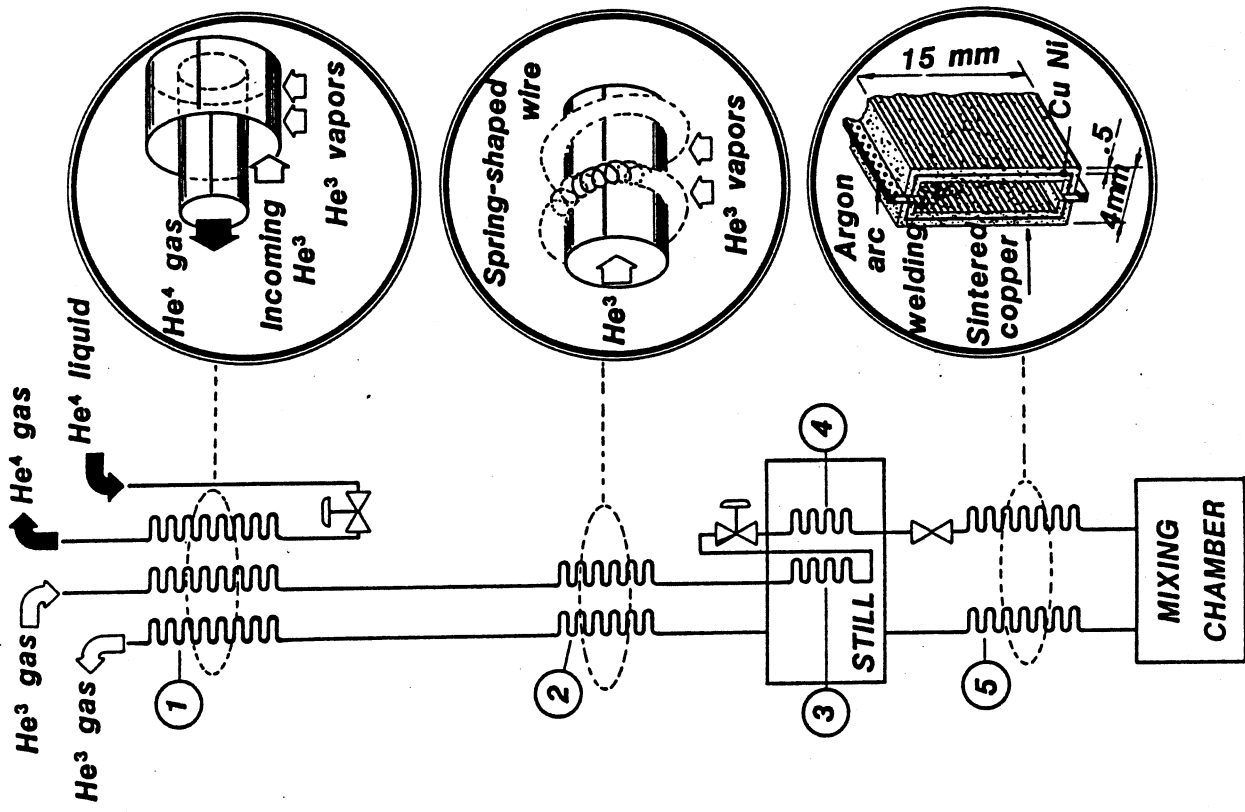


FIG. 2



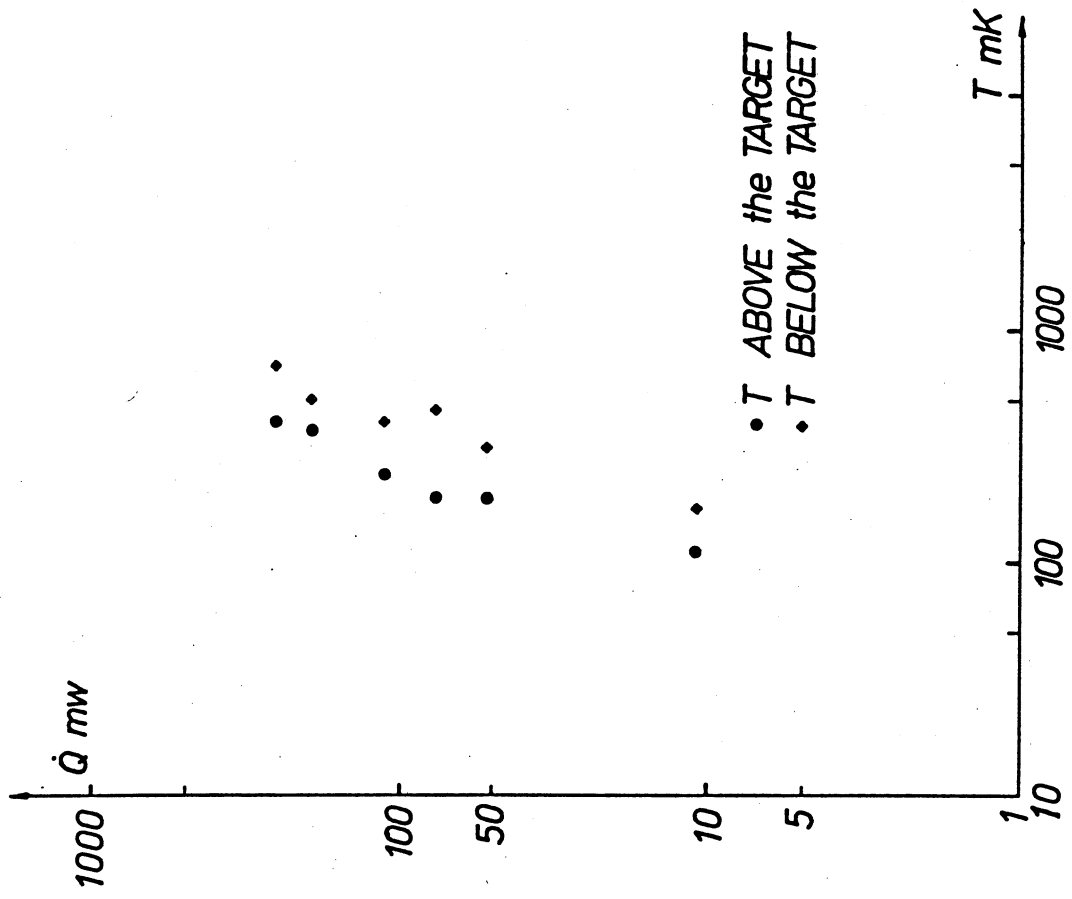


FIG. 3

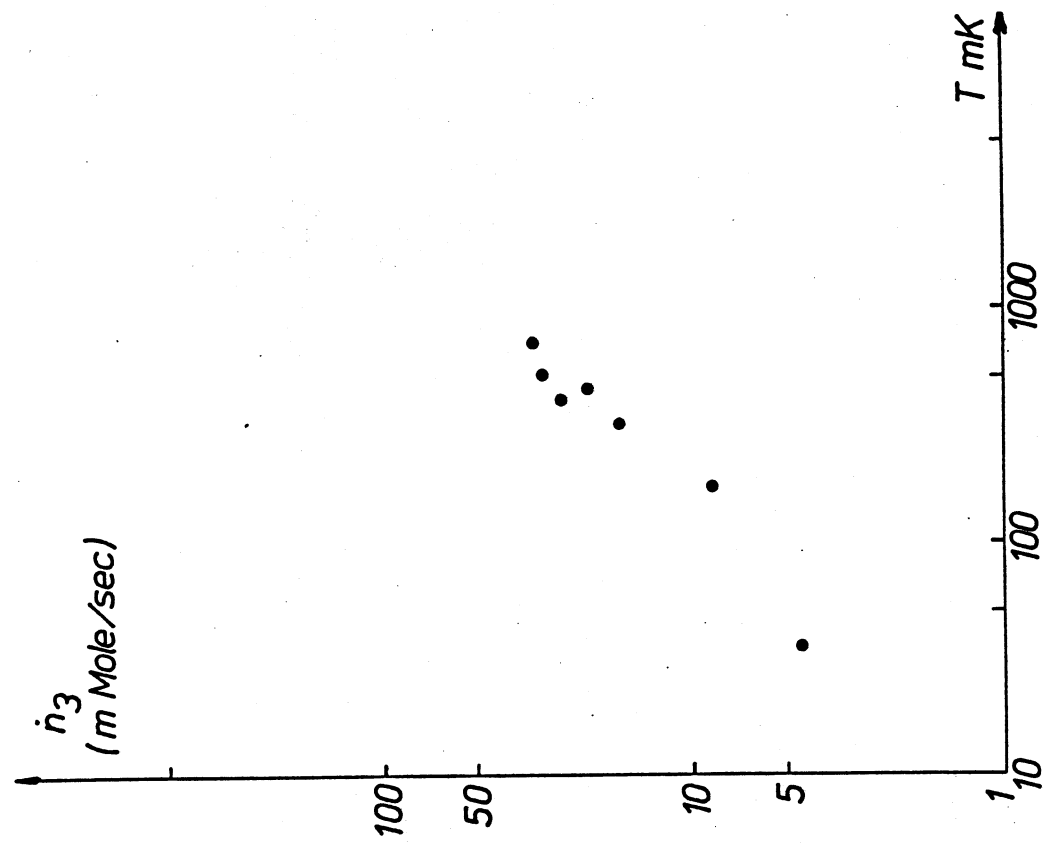


FIG. 4

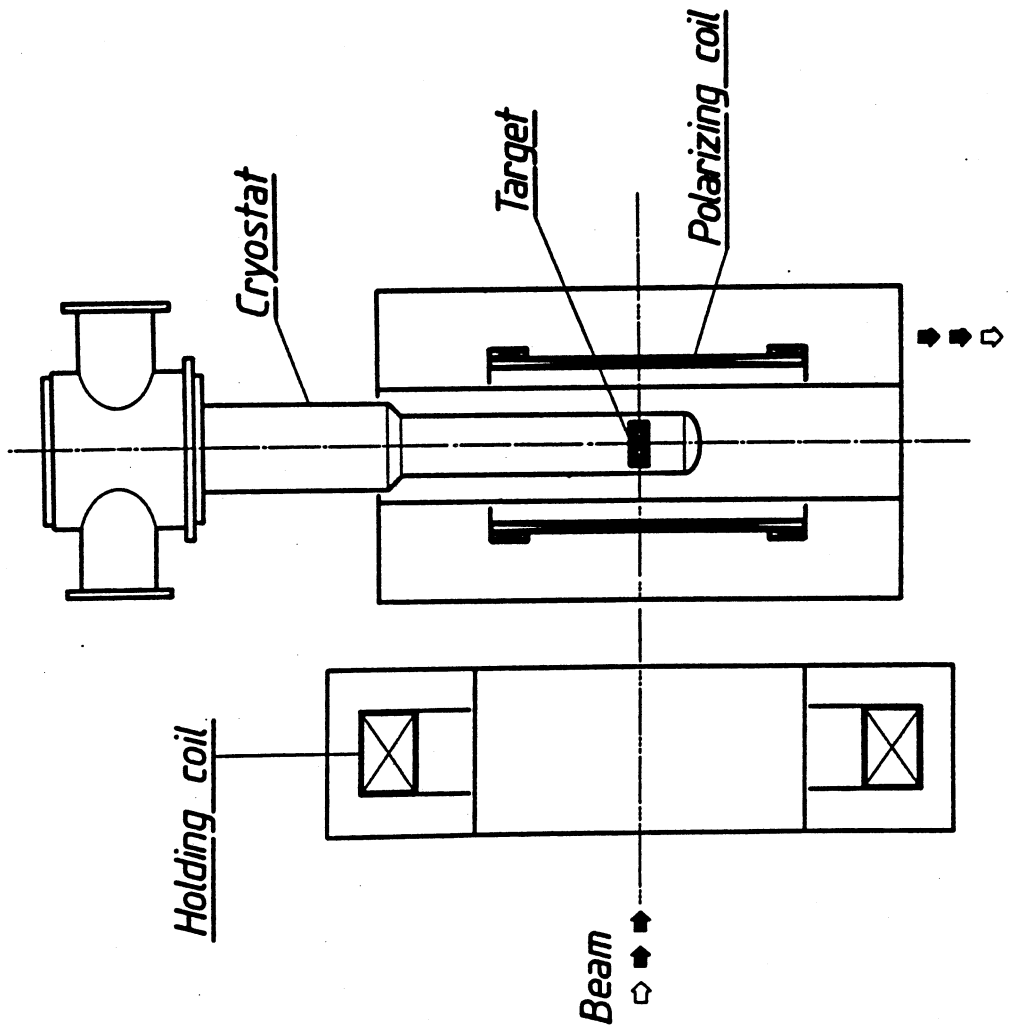


FIG. 5a

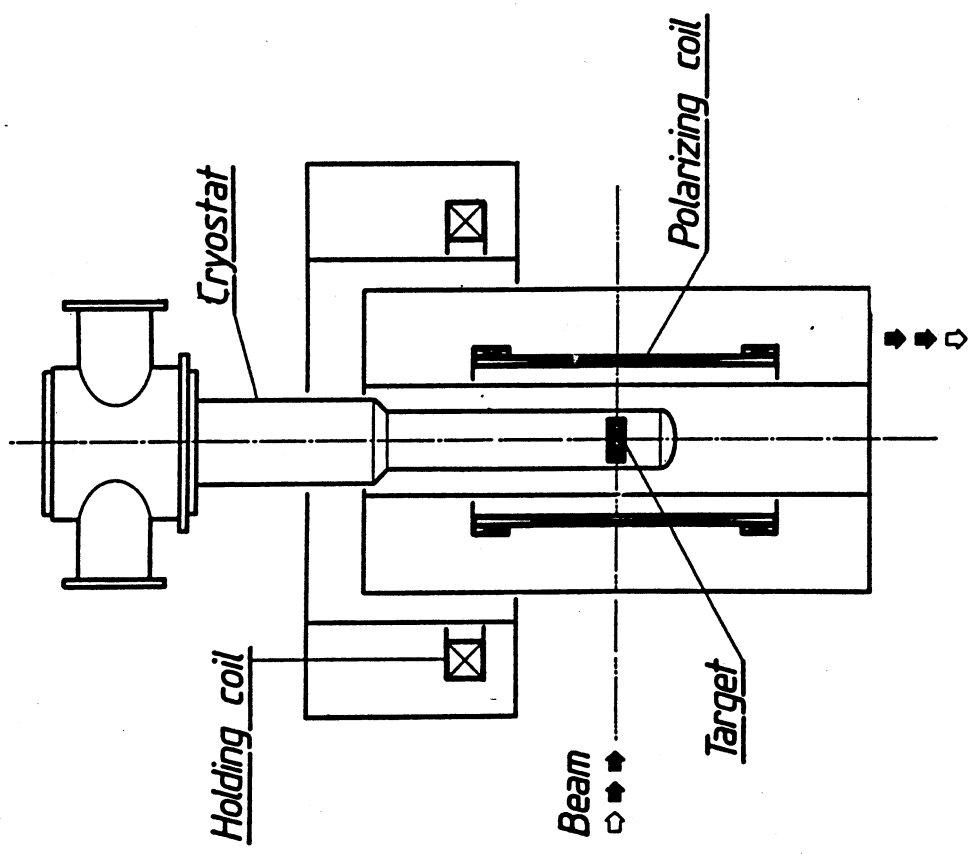


FIG. 5b

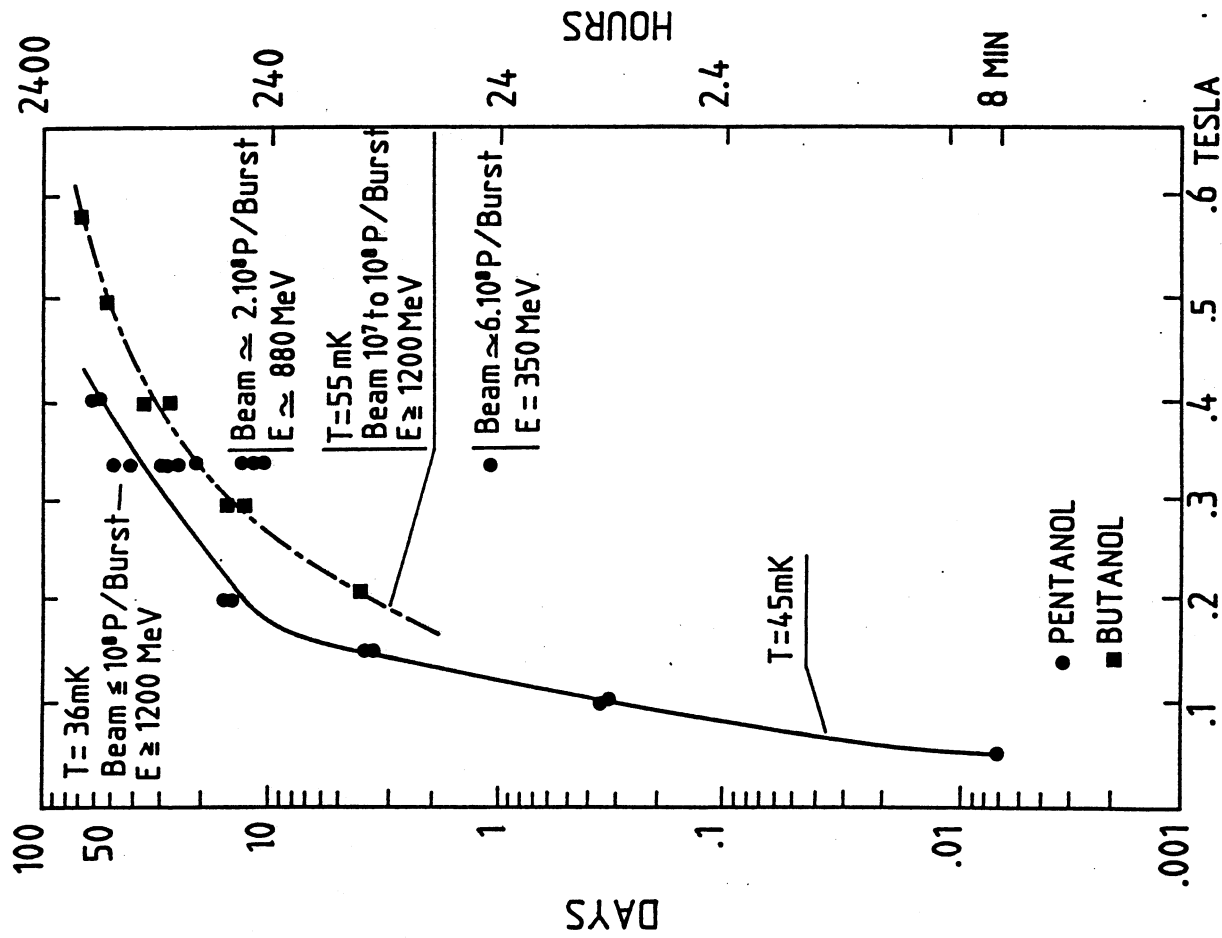


FIG. 7

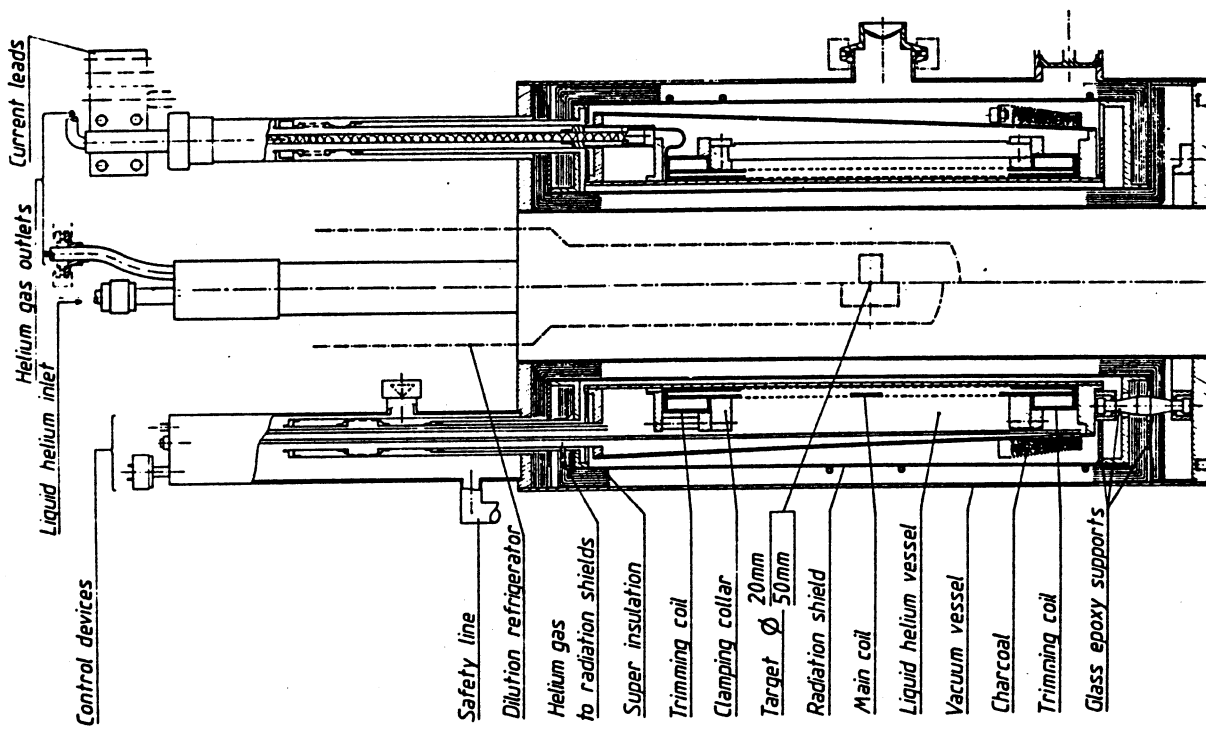


FIG. 6

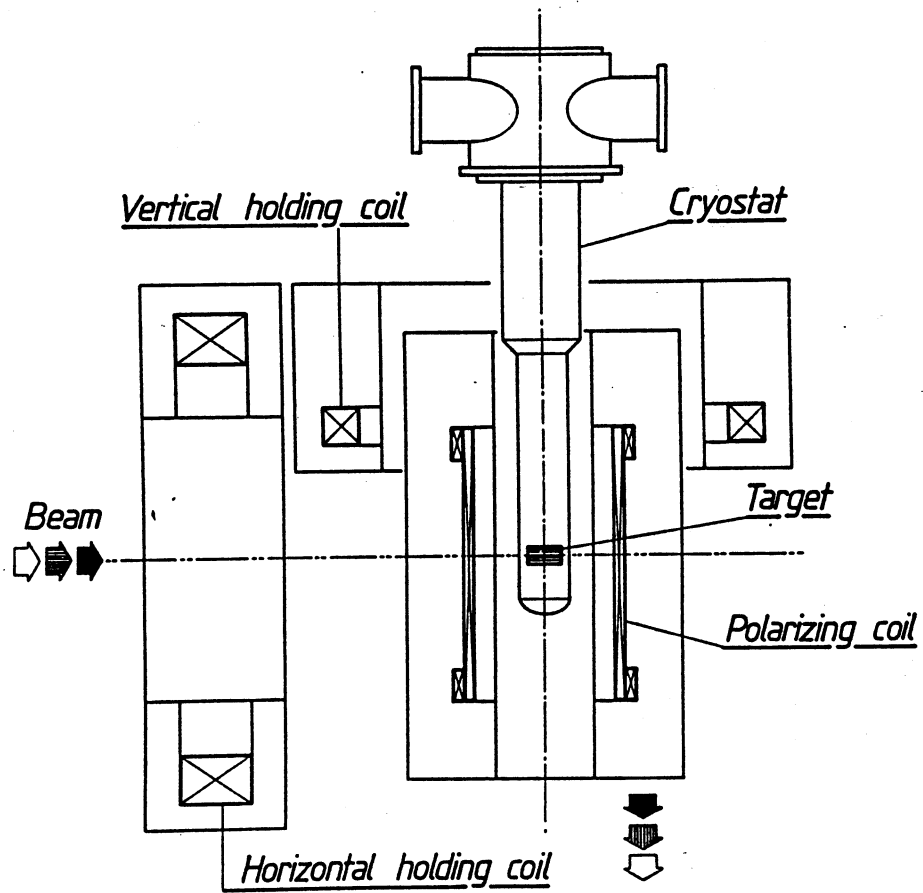


FIG. 8

- 2-COIL 2-FREQUENCY Q-METER -

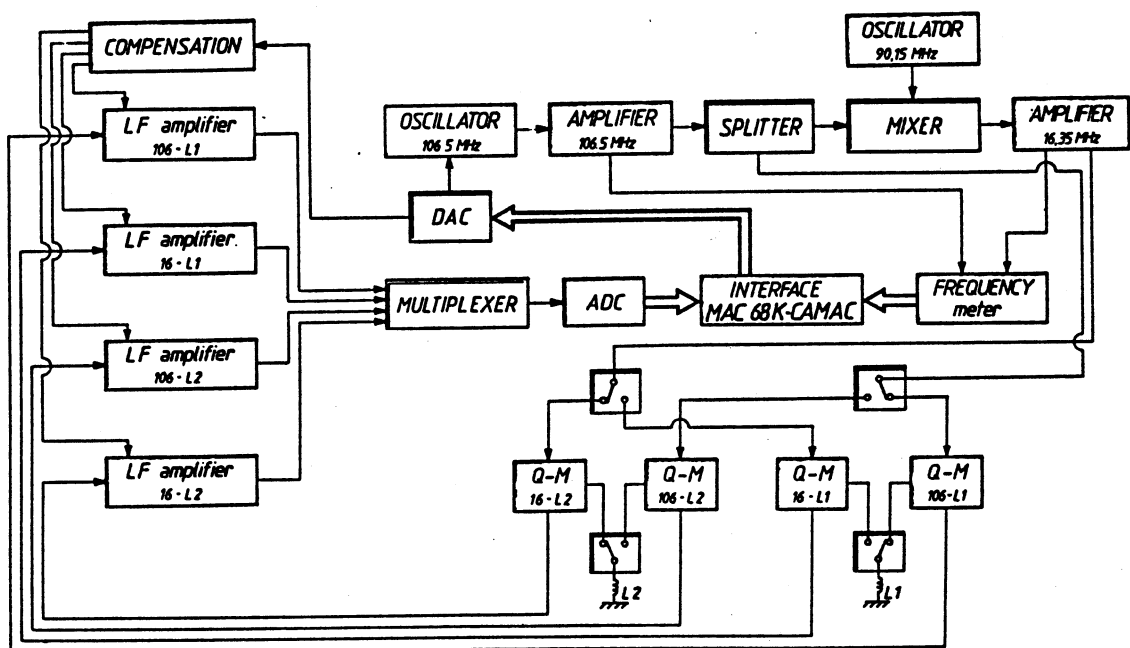


FIG. 9