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ABSTRACT

This report describes a vacuum chamber, used for the computer aided automatic measurement of the thickness of up to 44 thin films, using the energy loss method.

1 – Introduction

Thin films, whose thickness ($\leq 100\mu g/cm^2$) must be known with the highest possible accuracy, are often used in experimental physics.

The thickness of thin films produced by means of vacuum deposition (thermal, electron gun, etc.) can be measured "on–line" by means of a quartz monitor and with higher precision after deposition, by weighing. In both cases, a mean thickness is obtained.

In some instances, when a greater accuracy is required than can be obtained by weighing the sample (for instance, in the in case of frames much heavier than the film) or when it is necessary to know the uniformity of the film, other procedures must be used.

A widely used method consists of using α–emitters and measuring the energy lost by α–particles passing through the film thus deducing within a few percent error the local thickness by exploiting the known energy–loss relations.

The great advantage of this method, beside its precision, is the possibility of measuring the thickness of the film in differents points, thus also obtaining information about its uniformity.

Sometimes it happens that a large number of films need to be measured (up to hundreds), as in the case of stripping foils for accelerators or catcher foils in recoil range measurements[1]. The time needed to reach the desired accuracy (up to about fifteen minutes per film, using standard intensity sources), can therefore be considerable.

In order to avoid the need for the continuous presence of an operator and to eliminate any possible error which could be made through inattention, we have designed, built and tested a Computer Aided System for Thickness Measurements of up to 44 thin films (CASTM), controlled by an IBM PS/2 Model 30 personal computer and a smart card, the servo–motor controller GALIL DMC 220[2].

2 – Design Scheme

The CASTM set–up consists of:

(a) a measuring chamber, with its own vacuum system, having internal moving parts driven by motors,

(b) the motors with the associated electronic hardware, including the servo–motor controller Galil DMC 220,

(c) an α–source,

(d) a surface barrier silicon detector with its associated electronics (pre–amplifier, amplifier, power supplies),

(e) a multichannel analyzer (MCA) to collect the α–energy spectra,

(f) a personal computer providing the automatic operation of the system, and the storing and manipulation of the α spectra.

The vacuum chamber contains a movable disk, rotating around its center (θ movement) and an arm, moving along a radial direction, positioning the α–source–detector system.

Through the combined movement of the disk and the arm, the α–source and the detector may reach any position upon the disk.

An important characteristic is the precision required for the position of each moving part. An accuracy of less than $100\mu m$ for the radial movement and less than 0.02 deg ($\approx 1'$) for θ–movement is enough for our aims, considering the source spot dimensions ($\phi \leq 3\,mm, \leq 2$ % of the film area)

The disk and the arm are driven by motors, which assure the required precision by means of two encoders, one controlling directly the rotation of the disk and the other controlling the translation of the arm through a high precision worm. The movements are directed by a computer which sends commands to the motors, for positioning the α–source and the detector at the measuring points and gives the co–ordinates of each location.

The automation of the measuring process is provided by a personal computer with many roles; it controls the motors, the MCA, the pressure in the chamber, the bias of the detector and allows the operator, at the beginning, to design the map giving the location of those positions to be measured on the disk. It also stores and manipulates the α–particle spectra to determine the energy loss and thus the corresponding thickness of each film and the uncertainty affecting the measurement. The software is organized to have maximum flexibility and expandibility. At the beginning the control code displays a "menu" allowing two different choices:

1) Mapping,

2) Analysis.

The first option allows one to create and store the locations of the different positions to be measured, to modify, to check or eventually to "kill" a map.

By choosing the second option, the analysis of the set of films starts. The α–source and the detector are positioned in the selected locations, and the spectrum of the α–particles penetrating each film are measured and stored on the MCA. The α spectra are subsequently transferred to the PC, where they are analyzed to extract the peak centroid position and its uncertainty, from which the thickness of the film and its error are calculated. At the end of each measurement the results are printed out, together with the film identification word.

3 – Description of the apparatus

A photographic reproduction of CASTM is given in fig. 1. Fig. 2 shows the block diagram of the system and fig. 3 the flow chart of the control code. Finally, fig. 4 shows the mechanical details of the chamber.

As shown in fig. 2, the motors are driven and controlled by the servo motor Galil DMC 220 card. This card is able to drive two motors, each one supplied with an encoder, to give the right position of the disk or the arm, and of a brake, to lock the motor in the measuring position. It also controls the vacuum within the chamber, and the bias of the detectors.

The x–axis motor has also two limit switches, to control the path of the arm.

The personal computer is an IBM PS/2 Model 30 and is connected through two RS232 ports to the MCA and the Galil DMC 220 card. The α–energy is measured with a surface barrier silicon detector with its associated electronics which allows an energy resolution of 15 keV FWHM for ^{241}Am α–particles.

Measuring chamber

The measuring chamber shown in figs. 1 and 4 is a 3 cm thick stainless steel cylinder, with a diameter of 60 cm and a height of 20 cm. Rotary ($40\,m^3/h$) and cryogenic ($900\,l/s$) pumps form the vacuum system which in 40 minutes reaches a final pressure of $\approx 8 \cdot 10^{-7}\,hPa$.

At the bottom of the chamber, a rotary transmission, with a leak rate less than $10^{-7} hPa\,l\,s^{-1}$ transmits the rotary motion of the motor to the disk under vacuum.

A cross, connected to a lateral flange, allows the connection to the chamber of the pumping system and of the linear x–motion which is obtained through a rotary transmission connected to a high precision worm.

Hardware

The fully programmable servo motor controller Galil DMC 220 is able to control two DC motors, with incremental encoder feedback, and an arc resolution of 1/128 deg. The modes of motion include positioning, jogging or homing. The motion profile for each motor may be specified separately or through a sequence of coordinates vectors.

Moreover a section with two servo amplifiers is designated to transform the signals from the DMC 220 in current ramps, using the pulse width modulation technique, at a frequency of 20 kHz. The controller contains an extensive instructions set for executing complex motion programs. In fact, two different kinds of commands can be sent to the DMC 220:

a) simple commands

b) interrogatories.

The motion commands are of the first category: the location of the disk or the arm given as encoder counts, the speed of rotation given in encoder counts/s, the acceleration (counts/s^2), the motion start or stop commands, the home command – to find the zero position of the encoders etc.

The second set of commands includes either the system set–up commands (system gain, integration factor for the ramp, maximum torque value, acceleration correction term, antifriction term etc.) or the system working mode commands (position of x and θ axes, communication line status etc.) or the card programming (editing, reset, etc.).

The instructions can be sent to the DMC 220 card via Multibus or a daisy chainable RS232 port (the solution adopted). A set of instructions may be stored in a buffer prior to execution.

Instructions can also be stored in the DMC 220 non–volatile memory. The DMC 220 card contains also a digital filter with an integral gain term for eliminating position errors at stop. The filter coefficients can be changed anytime in order to achieve the optimum dynamic performance.

The set of devices connected to the DMC 220 controller is the following: the host computer and two motors, each with its power amplifier, encoder and brake. The power amplifier is needed to amplify the DMC 220 command signals to the current value, necessary for driving the motor and the load. The DMC 220 performs quadrature decoding of the encoder signals, resulting in a resolution of quadrature counts (four time the encoder cycle number).

The brakes are used to lock the motion (x and θ) in the measuring position. In fact, during α–spectra collection, the 20 kHz frequency signal is reduced to a minimum value to decrease the electronic noise. Under these conditions, the motors are not electromagnetically locked and the necessity arises of locking them with mechanical brakes.

To ensure the required precision in linear motion, an encoder of 1000 counts/revolution, connected to a high precision worm with axial pitch of 2 mm/revolution, was used. Because of the large disk radius (26.5 cm), an encoder of 5000 counts/revolution is used for the θ motion. Using the quadrature decoding a maximum intrinsic error of ± 5 encoder counts for θ–axis ($1.57 \cdot 10^{-3} rad$) and of ± 0 encoder counts for x–axis ($< 5 \cdot 10^{-4} mm$) was achieved.

Software

The code controlling the CASTM operation consists of two main sections: mapping and analysis.

The **mapping** operation is subdivided in two blocks: (a) sector definition, (b) sector checking.

In the first case, it is possible to create a new map (N), to list the existing ones (L) or to kill a map (K). While L and K options are simply structured, the creation of a new map needs a more complicated set of instructions.

The rotating disk is subdivided in four sectors, each one with up to 11 holes, upon which the frames of the thin films, which may have different shape or area, are positioned. For each measurement a map must be given for each sector. Each map, characterized by an identification word, gives the co–ordinates of the measuring locations.

The co–ordinates may be those of the center of the films or, in case of film–uniformity testing, those of different points on the film area (five for small size and seven to nine for large size films).

Three standard maps (circles of 20 or 30 mm diameter on frames $50 \times 50 \, mm^2$ – 11 per sector – for the most used catcher shapes, or circles of 60 mm diameter on

$90 \times 90\,mm^2$ frames – 3 per sector –) are stored in a proper file and used as default option.

The new–map option works differently for, respectively, standard and non–standard maps. In the first case only the identification word is asked. In the second one the position of each center (or point) is given in orthogonal Cartesian co–ordinates, as if the sector would be in the fourth quadrant. Automatically the code tranforms the Cartesian coordinates to polar: ρ giving the translation of the arm and θ the rotation of the disk.

The correctness of positioning may be tested with the **sector checking option.** In this case the code allows one to reach each measuring position without measuring the α spectra. Using frames with calibrated openings – in the sample position – and calibrated cylinders – in the detector–source position – it is possible to check the accuracy of positioning.

The **analysis** option represents the working mode of the CASTM. The operator is necessary only at the beginning for specifying the sequence of sectors, the calibration constants for the detector chain and few other control data. The general flow chart of the analysis option is shown in fig. 4.

After receiving the input data the DMC 220 card is reset, the pressure in the chamber and the bias of the detector are checked and the MCA initialized. Moreover the code verifies if a reference measurement (empty–hole) has to be made to check the electronics. In this case the hole position is located and the test measurement performed; otherwise the position specified by the map is reached and the α spectrum measured and stored on MCA. Afterwards the α spectrum is transferred from the MCA to the PC via a RS232 port (9600 bauds), where it is analysed to find the centroid with its error and to deduce, by comparison with a reference α spectrum measured trough an empty hole, the α energy loss. Finally, using the stored range–energy data the film thickness and its corresponding uncertainty is given in $\mu g/cm^2$.

To check the stability of the electronics, an empty hole measurement is made at the beginning, periodically throughout the operation and at the end. All the α spectra and the results of the analysis are stored on a hard disk and the measured thickness of each film printed out.

4 – Testing and performances

The vacuum conditions were tested with a helium leak detector and it was found that the leak rate is less than $10^{-7} hPa\,l\,s^{-1}$.

The parallelism of the disk and the arm, during their motion was measured with a Galaxy II machine[3] and it was found that the angle between the arm and the disk is always less than 0.5 degrees during a rotation of the disk (360°) and a complete translation of the arm (25 cm.).

Special care was spent in optimizing the parameters to be stored into the non–volatile memory of the DMC220 to ensure the best operating conditions of the motors. These include:

1) the gain of motor servoamplifiers,
2) the "KI" value (gain correction factor),
3) the speed value,
4) the acceleration value,
5) the accuracy in positioning.

The choice of the stability coefficients is critical due to the large momentum of inertia of the disk and the high precision in positioning ensured by the encoders: in fact, if the gain of the motor servoamplifier is too high, the θ motor, trying to position the disk with high precision, oscillates around the final position at high frequency, overheating and producing mechanical damage.

The same care must be used to choose the speed and acceleration value. While a high speed is permitted for the translational motion, (20·000 *pulse/sec = 1 cm/sec*), a very low speed (only 500 *pulse/sec = 09'00"/sec*) is required for θ rotation, to avoid damage of thin films during the measure .

These speed values are reached in a time depending on the choosen acceleration value; a low value (500–1000 $pulse/sec^2$) allows a gentle motion which lacks in precision when the distance is small (this occurs during the measurement of the uniformity of the samples.). For this reason the recommended acceleration value is also the maximum permitted value (100·000 $pulse/sec^2$).

To perform this optimization, the DMC card was directly connected to the bidirectional auxiliary port of a CIT 224 video terminal[4]. This allowed a full instruction set to be send command by command, testing the obtained result after each command.

In Table I is shown a typical set of intructions to move to a particular position and to check its location.

Finally the operating code was tested with the chamber open at air pressure. Using a calibrated hole and cylinder, as previously described, the precision in positioning was checked and it was found to be the order of $\pm 20\,\mu m$ (the tolerance of the cylinder–hole system).

Ordinarily CASTM is used to measure the thickness and the uniformity of 44 Al foils (diameter 20 mm). Using a 4400 Bq source of ^{241}Am with area of $1\,cm^2$, and a 3 mm diameter collimator between of the source and the detector (SSD $100\mu m$ thick), to improve the resolution (typically 15 keV FWHM), a satisfactory collection time for each spectrum is 1000 s. Including the empty hole measurements, one every ten spectra plus one at the beginning and one at the end (and five measurements for each film to check uniformity), the total number of collected spectra is $(44\times 5)+\frac{44\times 5}{10}+2 =$ 244. So the total time needed is 244·000 s. for collecting the spectra, plus the time for positioning and transferring the data (about 3 days). Typical outputs are shown in Table II which collects the results obtained for the absorbers of two sectors and in Fig. 5 which summarizes the results of an uniformity test.

Considering that during this run the operator is needed only at the beginning, to calibrate the electronics ($\approx \frac{1}{2}hr$) and at the end to collect the paper output from the printer (few minutes), one may conclude that CASTM is a great labor and time saving device for this kind of measurement.

Acknowledgements

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References

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2 – DMC 220 User's Manual, Galil Motion Control Inc., Palo Alto, CA 94303, USA

3 – Galaxy II User's Manual, Poli S.p.A., 13019 Varallo Sesia VC, Italy

4 – CIT 224 Video Display Terminal User's Guide, C.ITOH Electronics Corp., Tokyo 150, Japan

Table I : Set of instructions to move the α source and the detector to a particular position and to check its location. Note that when the DMC 220 is turned *on* the brakes are in *off* state and the servo amplifiers are in *on* state

COMMAND	EXPLANATION
GN 10,2	Chosen X,Y gain values (X=10, Y=2)
KI 1,0	Chosen X,Y gain correction factor
PR 10000,5000	Number of *pulse* to cover in X,Y direction
SP 1000,500	Speed in *pulse/sec* for X,Y motion
AC 100000,100000	X,Y acceleration in $pulse/sec^2$
TP	Tell present X,Y position
BG	Begin motion
AM	After the end of motion execute next steps
SB1	Set X brake *on*
SB2	Set Y brake *on*
SB3	Set X servo preamplifier *off*
SB4	Set Y servo preamplifier *off*
TP	Tell reached X,Y position

Table II : Typical output printed at the end of a set of measurements.

SECTOR NUMBER 1		STANDARD		SECTOR NUMBER 2		STANDARD	
			α–peak centroid channel 3075.4				
Sample	*Thickness* ($\mu g/cm^2$)	$\pm$ ($\mu g/cm^2$)	Δ E (keV)	*Sample*	*Thickness* ($\mu g/cm^2$)	$\pm$ ($\mu g/cm^2$)	Δ E (keV)
1	91.2	2.76	52.0	1	86.4	2.75	49.3
2	83.6	2.63	47.6	2	87.3	2.74	49.8
3	96.6	2.52	55.1	3	91.4	2.59	52.1
4	80.1	2.68	45.7	4	88.1	2.64	50.2
5	94.4	2.63	53.8	5	93.5	2.56	53.3
6	80.9	2.67	46.1	6	79.6	2.69	45.4
7	92.8	2.82	52.9	7	92.2	2.74	52.6
8	86.1	2.84	49.1	8	83.0	2.80	47.3
9	86.1	2.51	49.1	9	85.3	2.60	48.6
10	82.1	2.82	46.8	10	86.8	2.74	49.5
11	91.9	2.51	52.4	11	91.4	2.44	52.1

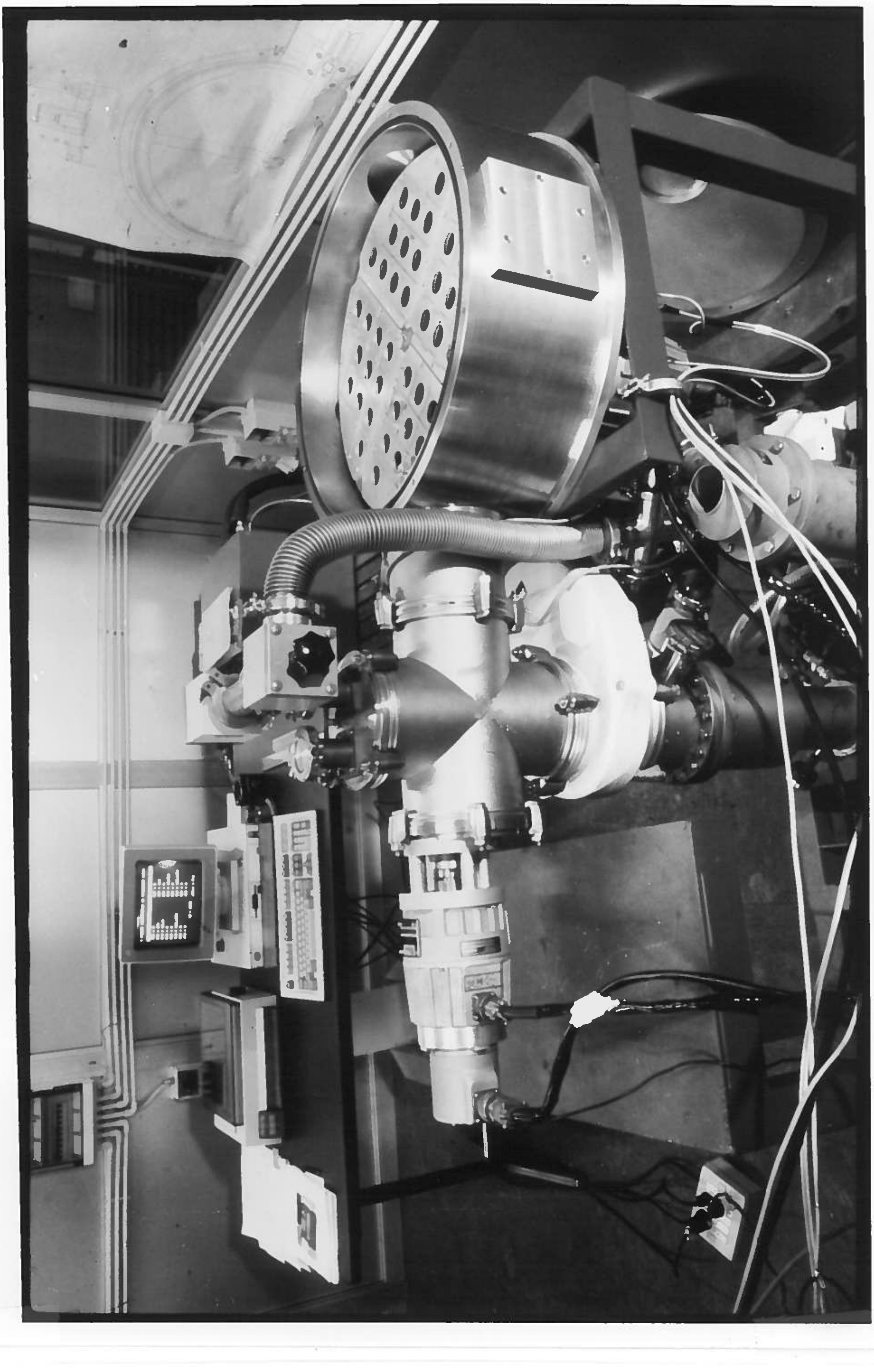

Fig. 1 : General view of CASTM

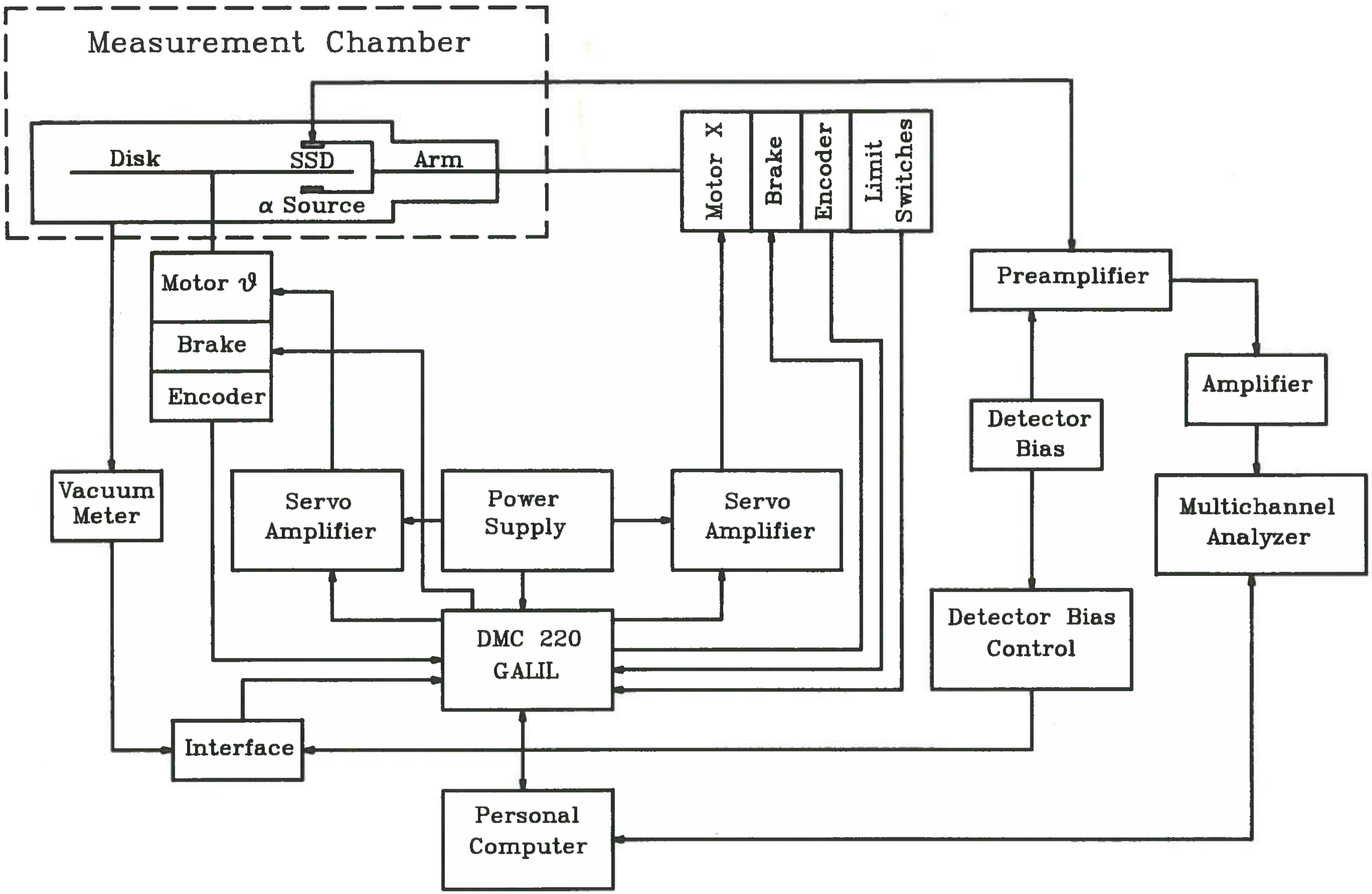

Fig. 2 : Block diagram of CASTM.

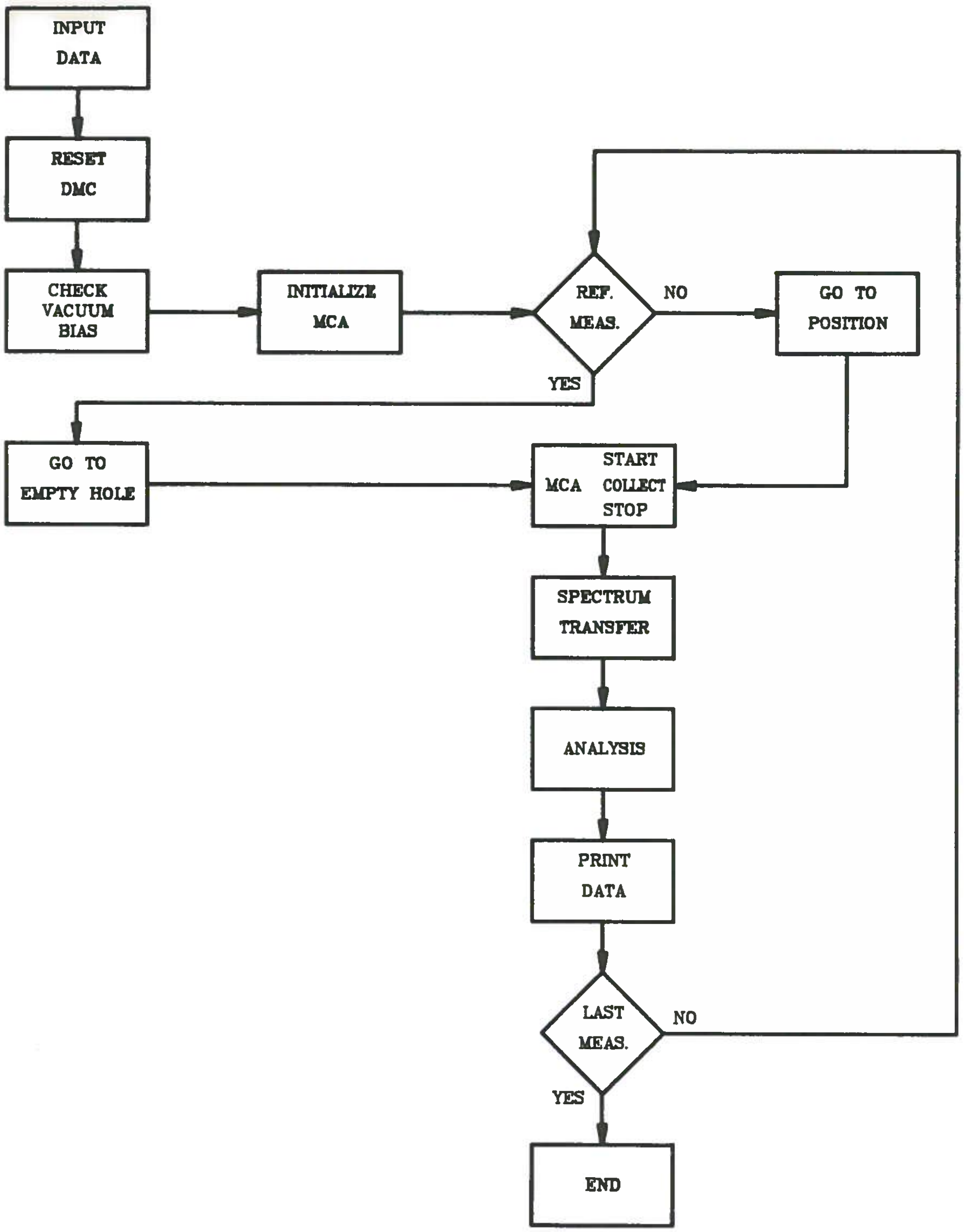

Fig. 3 : Flow chart of the control code.

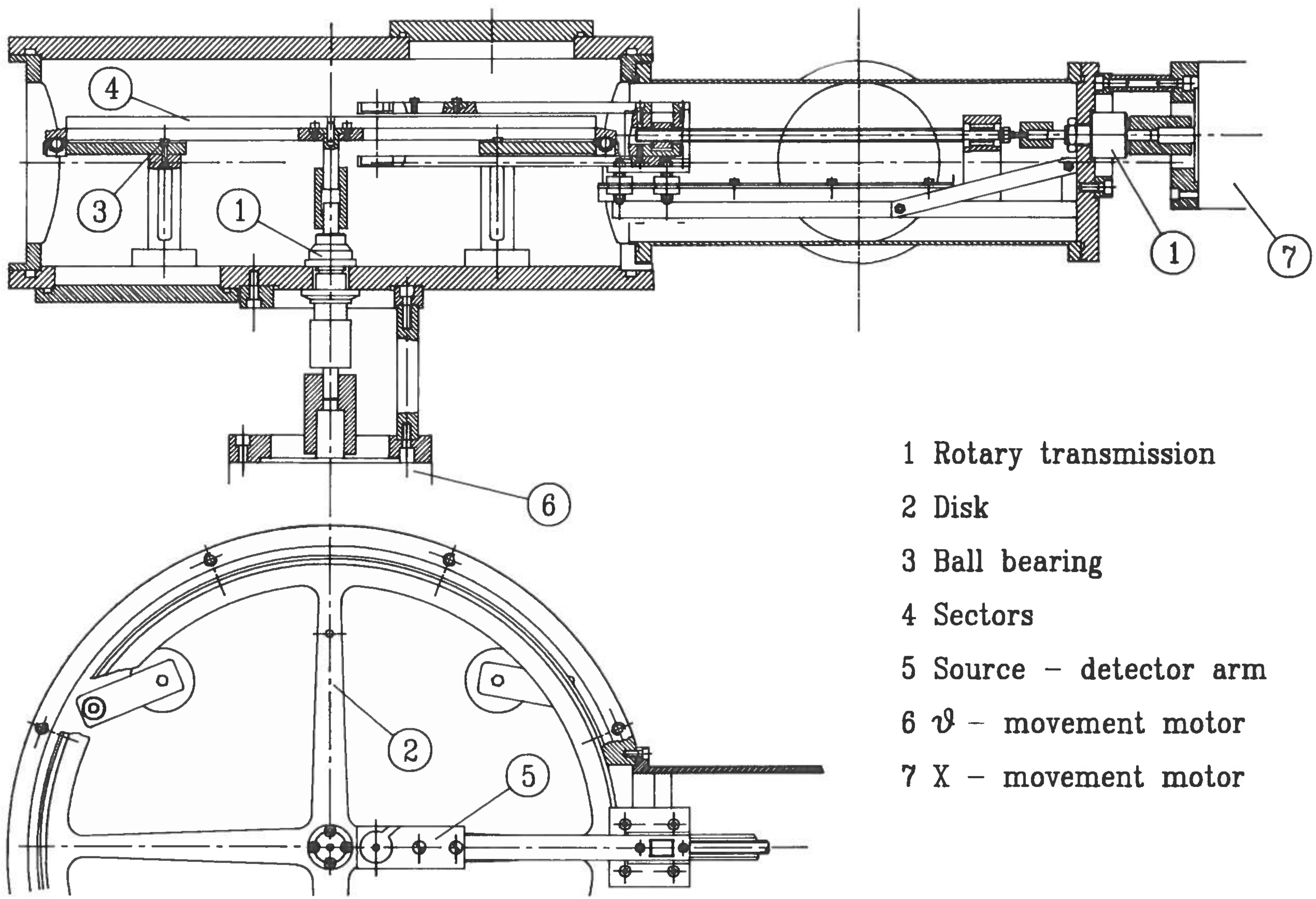

Fig. 4 : **Mechanical details of the vacuum chamber.**

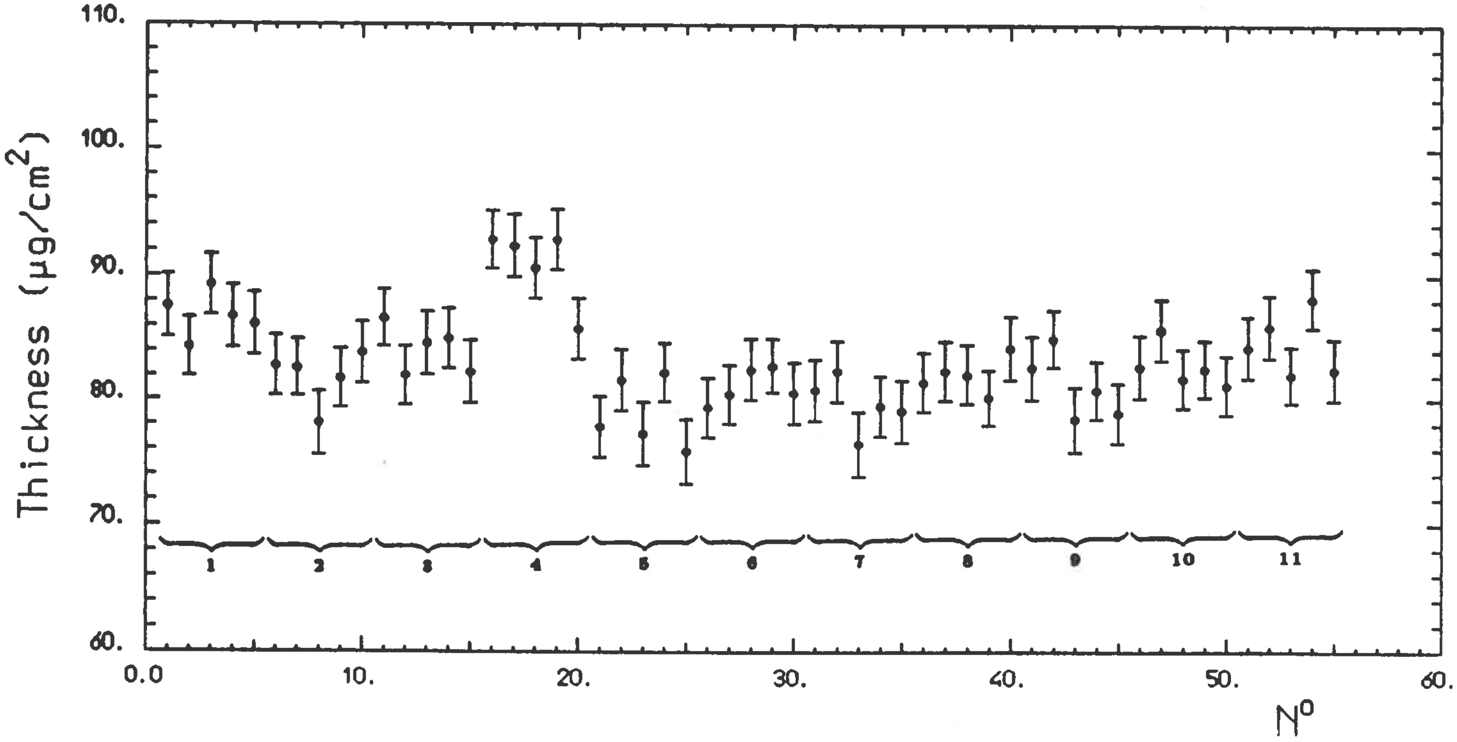

Fig. 5 : Results of an uniformity test of the thickness of 11 absorbers. The thickness has been measured in five positions for each absorber.