The First CERN Muon *g-2* Experiment by G. Charpak, F. J. M. Farley, R. L. Garwin, T. Mueller, J. C. Sens, and A. Zichichi

Richard L. Garwin
IBM Fellow Emeritus
IBM Thomas J. Watson Research Center
P.O. Box 218, Yorktown Heights, NY 10598

www.fas.org/RLG/
Email: RLG2@us.ibm.com

Presented in the invited APS session,
"History of the Muon *g-2* from 1947 to Present"
Savannah, Georgia

April 8, 2014 at 13:30 PM

Abstract:

The Summary of the 16 June 1965 publication of this experiment in *Il Nuovo Cimento* reads,

"The anomalous part of the gyromagnetic ratio, $\boldsymbol{a} \equiv ½\,(g\text{-}2)$ of the muon has been measured by determining the precession $\theta = \boldsymbol{a}\omega_0\bar{B}\,t$ for 100 MeV/c muons as a function of storage time *t* in a known static magnetic field of the form $B = B_0(1+ay+by^2+cy^3+dy^4)$. The result is $\boldsymbol{a}_{exp} = (1162\pm5)\cdot10^{-6}$ compared with the theoretical value $\boldsymbol{a}_{th} = \alpha/2\pi+0.76\alpha^2/\pi^2 = 1165\cdot10^{-6}$. This agreement shows that the muon obeys standard quantum electrodynamics down to distances ~ 0.1 fermi. Details are given of the methods used to store muons for ~ 10^3 turns in the field, and of measuring techniques and precautions necessary to achieve the final accuracy. Some of the methods of orbit analysis, magnet construction shimming and measurement, polarization analysis, and digital timing electronics may be of more general interest."

The paper is available in full at http://www.fas.org/rlg/060065%20Nuovo%20Cimento.pdf The authors valued highly the presentation of experimental details, which will be the emphasis of this talk, recounting the motivation of choices made with the tools and technology of that era.

The history of the muon is a fascinating story in itself. I begin with a brief recounting of the first measurement of the muon magnetic moment and *g* value as published in our discovery paper.[1] The figures reproduced here show the technology of the time, muons produced by forward decay in flight of pions within the cyclotron, escaping the fringing field and emerging through a port in the shielding wall, where they may be slowed by carbon absorber and stopped in a material of interest. What was different in this case was the realization by Leon Lederman on January 4, 1957 that if the analysis of Lee and Yang[2] was correct, these muons might be polarized, with a mean spin component along their velocity; this violated parity conservation, but that was the point of the theoretical paper!

Leon and I met at the Columbia University cyclotron after dinner that evening and by Saturday morning we had an indication of polarization. By Tuesday morning, January 8, we had completed our experiment and written the paper showing the precession of the muon spin as a linear function of time in a magnetic field provided by a solenoid wound on the carbon block in which the muons were stopped.

[1] "Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon," by R.L. Garwin, L.M. Lederman, and M. Weinrich, *Physical Review*, Vol. 105, No. 4, pp. 1415-1417, February 15, 1957. http://www.fas.org/rlg/021557 Garwin-Lederman-Weinrich.pdf

[2] "Question of Parity Conservation in Weak Interactions," T.D. Lee and C.N. Yang, Phys. Rev. 104, 254

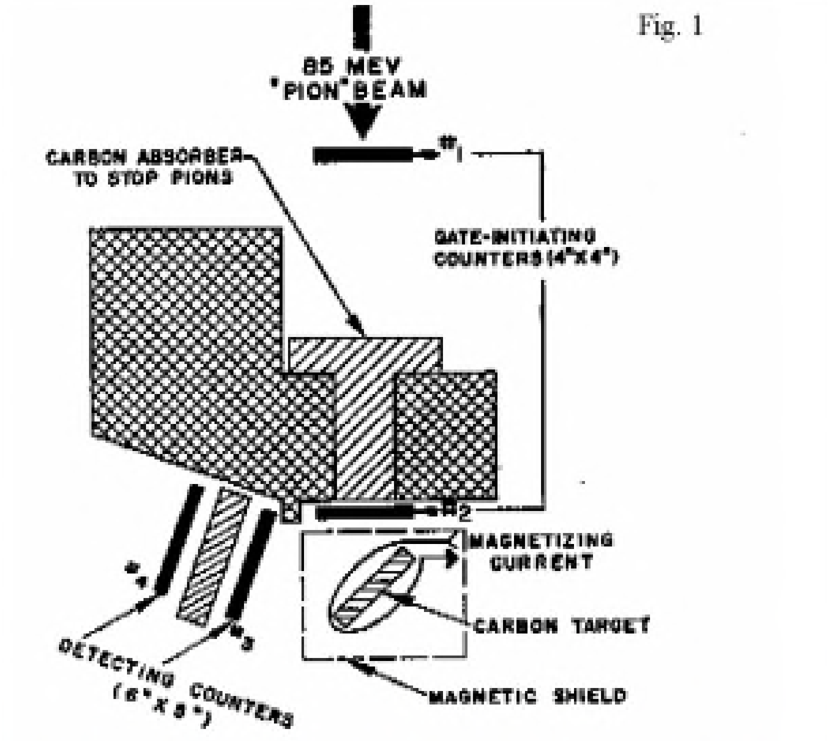

Fig. 1. Experimental arrangement. The magnetizing coil was close wound directly on the graphite to provide a uniform vertical field of 79 gauss per ampere.

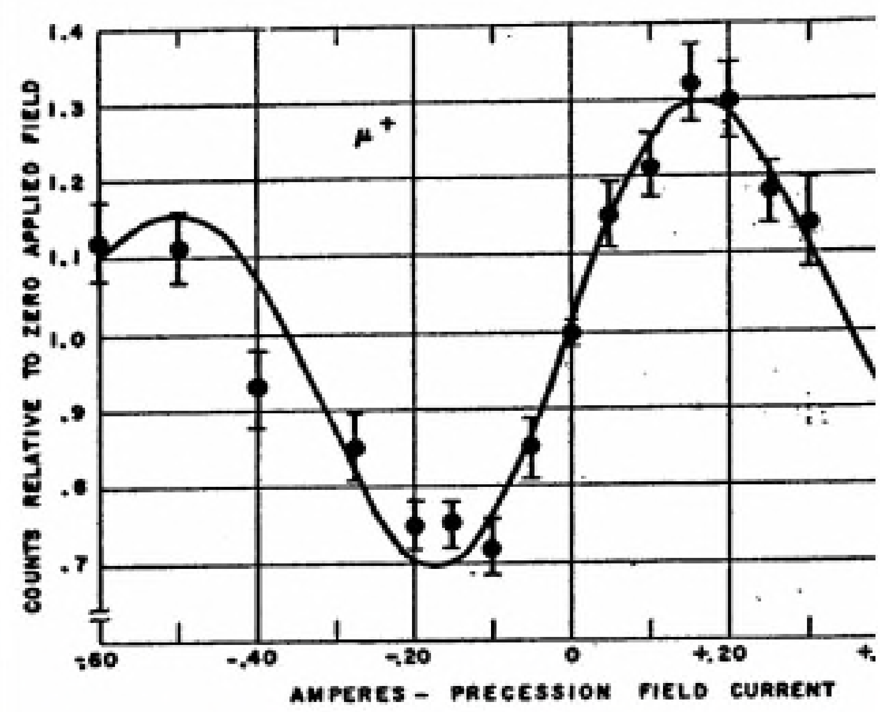

Fig. 2. Variation of gated 3-4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1 - 1/3 \cos\theta$, with counter and gate-width resolution folded in.

The various counters[3] defined the event by use of a coincidence-anticoincidence analyzer[4], both of which I had published in 1951 and 1952, and which became staples of the particle physics effort worldwide.

[3] "The Design of Liquid Scintillation Cells" by .L. Garwin, Review of Scientific Instruments 23, No. 12, pp. 755-757, December 1952.
[4] "A Fast Coincidence-Anticoincidence Analyzer," by R.L. Garwin, Review of Scientific Instruments 24, No. 8, pp. 618-620, August 1953

Not only did we show that parity was strongly violated in the pi-mu decay, but also in the decay of the muon to an electron and two antineutrinos. Muon spin precession in the field of the "magnetizing coil" enabled us quickly to determine the component of muon spin at the time of decay in the direction of the electron-detection counter, rather than using the more obvious but certainly less satisfactory approach of moving a counter in angle around muons stopped in a region largely shielded from magnetic field. Conclusion V of that paper, "The *g* value (ratio of magnetic moment to spin) for the (free) μ^+ particle is found to be +2.00±0.10"

Synchrocyclotrons worldwide were rejuvenated, and their teams re-energized with the opportunity provided by the naturally polarized muons with their wonderfully convenient label of a high degree of decay asymmetry.

Of great interest, of course, was the determination of *g-2*, which would explore electrodynamics and its coupling to much higher energies than that involved in the *g-2* of the electron, despite electrons being universally available and cheap. At the time, electrons were being stored in magnetic fields for long intervals; they were polarized by Mott scattering and analyzed by Mott scattering of the 100-keV stored electrons.

At first the muon *g-2* was most accurately measured by the actual measurement of *g*—the ratio of the magnetic moment to the mass, with muon magnetic moment being determined by stopping the polarized muons in a target, and, for instance[5], measuring the free precession rate in as large and uniform a magnetic field as could be provided, the accuracy being limited by the number of muons that could be counted in an experiment of reasonable duration, and by the 2.2 microsecond half life of the muon at rest. The accuracy of this approach to *g-2* was limited also by the knowledge of the mass, measured most precisely by x-rays emitted in mu-mesic atoms.

So the Columbia groups and others dreamed of an approach in which muons could be stored for many turns in a static magnetic field and measured after many microseconds of storage, taking advantage of the fact that only the anomalous portion of the *g* value (*g-2)* contributes to the departure of mean spin direction from the vector velocity.

Leon Lederman, in particular, was excited by an approach to a "linear magnet" in which, for convenience, the magnetic field B_z would be vertically oriented, perpendicular to a horizontal median storage plane for the muons. Muons would be injected into this magnetic field which would be of the form $B = B_0(1+ay)$ so that the muon orbit would creep in X, with a step size s. For a storage length L, the number of turns would thus be L/s. Leon had a sabbatical at CERN for the academic year 1958-59, supported by the Ford Foundation; he assembled a small team there to explore

[5] "Magnetic Moment of the Free Muon," by R.L. Garwin, S. Penman, L.M. Lederman, and A.M. Sachs, Physical Review 109, No. 3, pp. 973-979, February 1, 1958

actually doing the experiment. Augmenting the initial g-2 team of L.M. Lederman, G. Charpak, F.J.M. Farley, T. Mueller, J.C. Sens, and A. Zichichi were other visitors to CERN including V.L. Telegdi, C.M. York and W.K.H. Panofsky.

Although I had left particle physics in December 1952 when I moved from the Physics Department at the University of Chicago to join the IBM Watson Scientific Laboratory at Columbia University, I had brought with me a coincidence-anticoincidence analyzer, entirely vacuum tubes except for the semiconductor diode that I had added in 1950 to each of the coincidence circuits, that allowed coincidence resolution in the nanosecond range. This had been sitting on my shelf at the new laboratory, until I gave it to the Columbia Cyclotron Lab at Nevis, where it was incorporated by Marcel Weinrich in the measurements he was doing for his Ph.D. under Lederman, on the lifetime of negative muons stopped in various materials.

So although at Columbia I was familiar with the ideas of Lee and Yang and their proposals of 1956 for experiments with beta decay and the pi-mu-e decay chain, I did no work in this field until the weekend of January 4, 1957, when we took over the Weinrich apparatus, provided the precessing magnetic field via a solenoid that I wound that night on a lathe at Nevis, and obtained the results I have shown.

Within a few days I had resigned that part of my IBM job in which I was leading the development of a superconducting computer based on planar thin-film cryotrons, in order to pursue the new fields opened by the “new” muon. I welcomed the idea of a sabbatical to be spent at CERN, but my purpose was really to read in the library and to recharge my knowledge of physics that had been depleted work that I was doing with the U.S. government, and by the frenetic activity with teams at Nevis involving the muon. So when I arrived at CERN with my wife, Lois, and three small children September of 1959 for a one-year sabbatical, I was familiar in general with the ideas of the g-2 team and was pressed into service to lead that effort. After some preliminary publications in 1962[6] we published a full report of our experiment (123 pages) in 1965.[7] And that is what I will discuss now.

Gilberto Bernardini was Director of Research at CERN at the time, responsible for the synchrocyclotron (SC), and, I believe, had chosen the muon g-2 project for its fundamental interest. When I acceded to his plea to lead the group, I was much aware of my one-year tenure at CERN and the need for rapid progress and economy. So it was accepted that I would make the major decisions for the group, with a group meeting every Friday morning, and as much informal interaction as possible and

---

[6] G. Charpak, F.J.M. Farley, R.L. Garwin, T. Muller, J.C. Sens, and A. Zichichi, ‘A New Measurement of the Anomalous Magnetic Moment of the Muon,’ Physical Review Letters 1, No. 1, April 1, 1962.

[7] "The Anomalous Magnetic Moment of the Muon," by G. Charpak, F.J.M. Farley, R.L. Garwin, T. Muller, J.C. Sens, and A. Zichichi, published in *Il Nuovo Cimento*, Serie X, Vol. 37, pp. 1241-1363, CERN - Geneva, June 1965.
http://www.fas.org/rlg/060065%20Nuovo%20Cimento.pdf

necessary in the interim. I terminated work on the "screw," championed by Telegdi, which ultimately fabricated a 20-turn helical path for the muons, in favor of the single effort on the 6-m flat magnet.

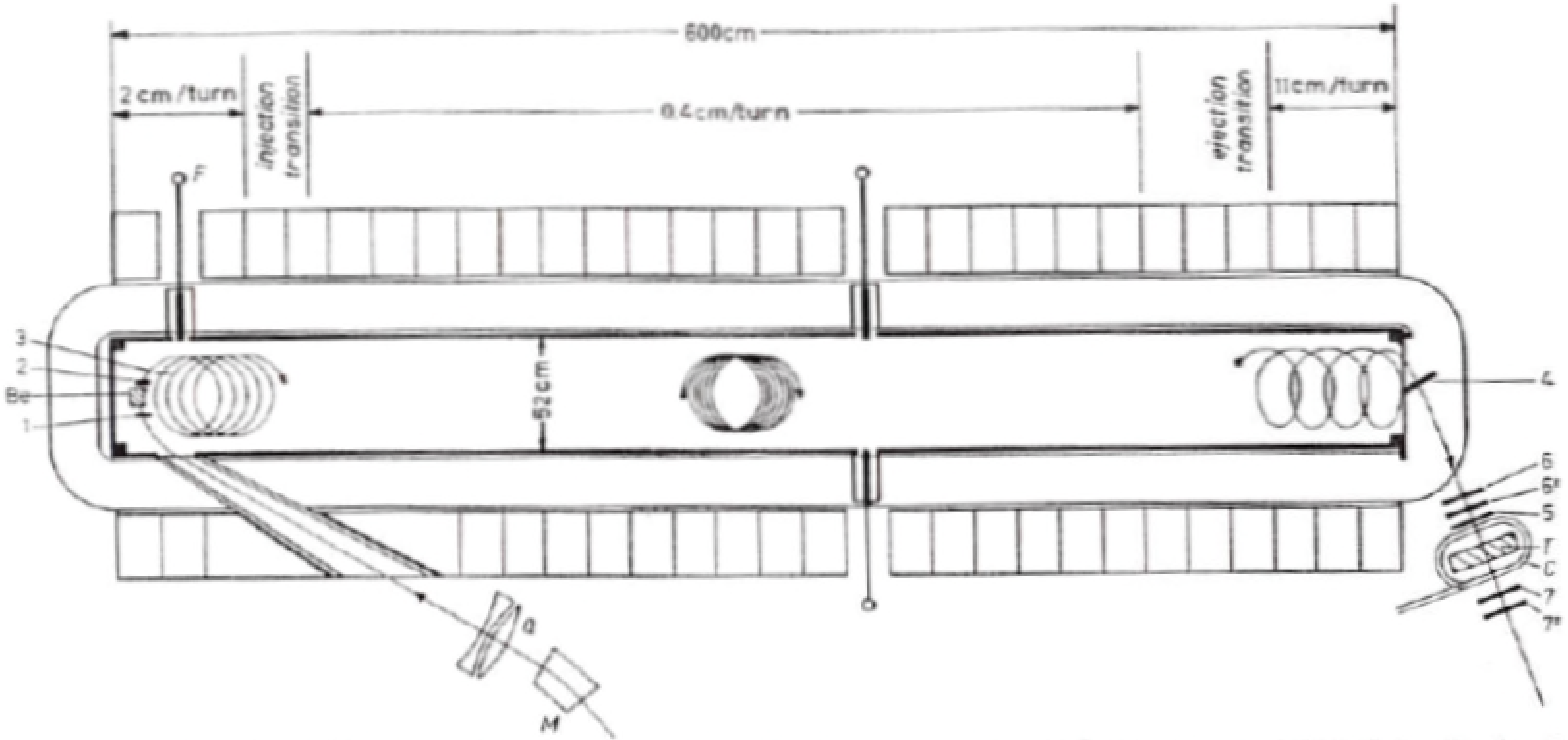

Fig. 1. – General view of the apparatus, showing magnet of pole surface $(600 \times 52)\ cm^2$. Muons, deflected by the bending magnet M and focused by the quadrupole pair Q enter the magnet via a shielded channel. After slowing down in the beryllium moderator Be they describe many turns in the field. The quasi-circular orbit is slowly displaced by the field gradient (2 cm/turn in the *injection* region, 0.4 cm/turn in the *storage* region, and 11 cm/turn in the final *ejection* region). Muons ejected from the magnet are stopped in target T of the polarization analyser where the spin direction is determined by recording the decay electrons. Injected muons are indicated by the counter signature 123. Ejected muons by the signature $466'\,5\bar{7}$. Decay electrons by $66'\,4(\overline{77'})$ and $77'\,\bar{4}(\overline{66'})$. The time of flight of muons between counters 2 and 4 is recorded.

As for the original concept of the “linear magnet” (this was also called a “wedge magnet” because the magnetic field was assumed to be similar to that in a magnet with wedge-shaped air gap), I had observed that there was no real median plane in such a magnet, and that for focusing toward a median plane and also for the definition of a median plane to prevent small perturbations in the magnetic field from driving the median plane into the pole faces, there needed to be not only a linear term in $B(y)$, but also a quadratic term.

In our CERN *g-2* experiment, team members as individuals “owned” and were primarily responsible for individual portions of the experiment. Thus, Nino Zichichi assumed responsibility for producing the magnetic field of the desired shape, measuring it, and providing quantifiable data for the magnetic field, all on the short timescale commensurate with rapid progress. This was achieved as a result of the design of the 6-m magnet (86 tonnes) with removable upper and lower steel pole faces of 50-mm thickness, and the decision not to machine the pole faces to obtain the desired magnetic field, but to provide a magnetic buildup of the poles by the application of flat Armco steel shim stock of various thicknesses, secured by Scotch tape and ultimately held down in the vacuum by copper lids secured by brass screws into the pole faces. A large portion of the paper and the effort is devoted to details of this work, which resulted in the desired magnetic field profile over the 6-m length, in only three iterations, rather than the five or six years advised to Bernardini by experts in shaped magnetic fields[8],

> *"The high-precision measurement of the anomalous magnetic moment of the muon was an experiment I wanted to encourage when I joined CERN as Research Director responsible for the SC. Many ideas were proposed. Two of them were the "screw-magnet" and the "flat magnet". Here the problem was the complexity of the magnetic field needed: injection, ejection, storage and transition fields. According to the SC greatest magnet specialist, Dr. Bengt Hedin, many months of high precision mechanical work were needed in order to produce just one "shape" of a given polynomial field. In order to reach the final correct shape, further high precision machining was needed. The conclusion was that, in order to shape the "flat-magnet" poles in such a way as to produce the complex polynomial fields needed for the "flat-magnet", the mechanical preparation of the magnet poles required no less than five to six years. The "screw-magnet" started to be built."*

Briefly, our idea was to derive a first-order desired shim profile (mechanical) from the specified magnetic field, to install the shims (cut with scissors, or sheared), reinstall the pole faces, energize the magnet without a vacuum chamber, and measure $B(x,y)$,

[8] "Lepton Physics at CERN and Frascati," edited by N. Cabibbo, *World Scientific Series in 20th Century Phyics—Vol. 8.*

for comparison against the desired magnetic field in the median plane. By then we had realized through a study of the orbit dynamics, that it would be useful to design the magnetic field with third and fourth-order terms, $B = B_0(1+ay+by^2+cy^3+dy^4)$. The even terms provide focusing in the vertical (z) direction, while the odd terms provide creep. In particular, c can be chosen to minimize the variation of s with muon energy or (better) with muon storage time. The c-term incidentally reduces the shim thickness required for a specified step size. The mass of steel shim was about 300 kg.

42 G. CHARPAK, F. J. M. FARLEY, R. L. GARWIN, ETC. [1282]

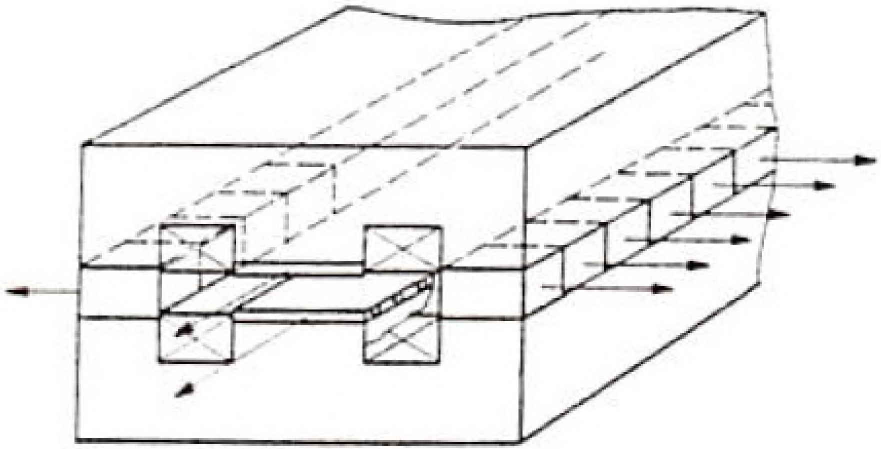

Fig. 23. – Overall view of the magnet showing the removable iron blocks ($20\times20\times\times31\ \text{cm}^3$) in the yokes, and the removable top and bottom pole pieces (5 cm thick). To remove the poles the lower pole was first raised by hydraulic jacks via vertical push rods passing through the lower half of the magnet. An assembly of rollers was then introduced below this pole, and finally the upper and lower poles were rolled out of the magnet together onto a special table also equipped with rollers. Arrows indicate those parts of the magnet which can be taken out.

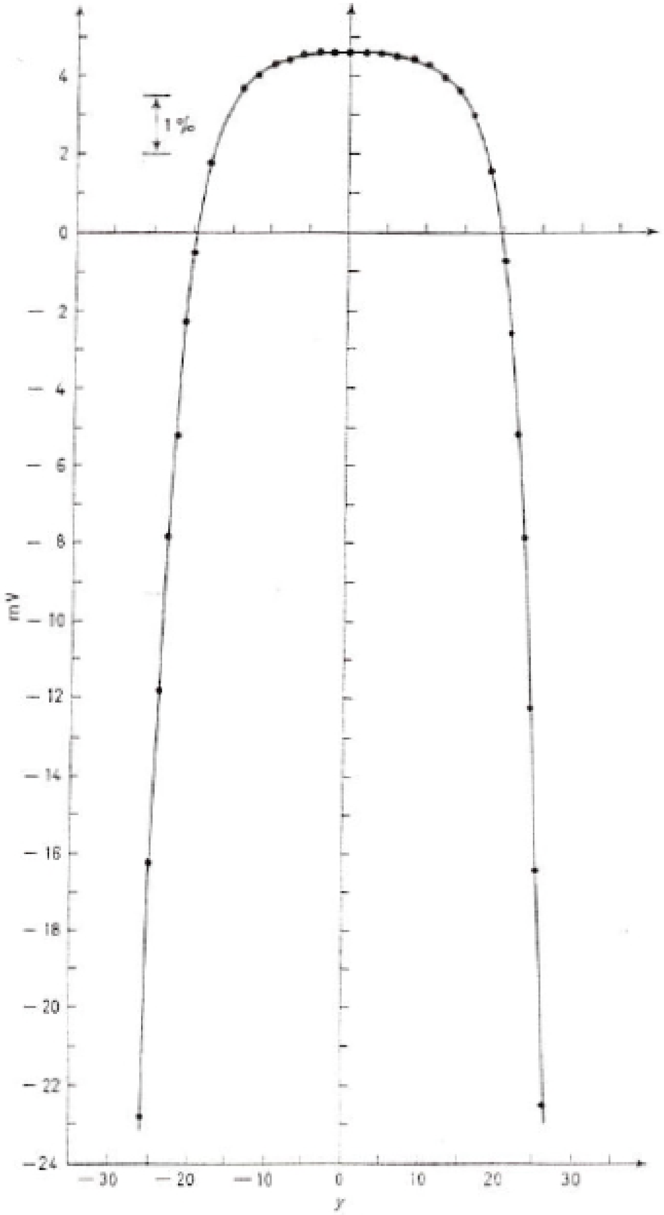

Fig. 12. – Field shape *vs.* y for the unshimmed magnet. The zero of the millivolt scale of Hall voltage is arbitrary.

thicknesses varying from 0.03 mm to 5 mm. By combining them in such a way as to have the profile of the poles with the desired shape [polynomial form eq. (73)], we were able to construct in three successive approximations the magnetic field desired. Figure 12 shows the shape of the magnetic field without any shimming. In Fig. 13 the shape of the « storage » field obtained after shimming is shown. In Fig. 14

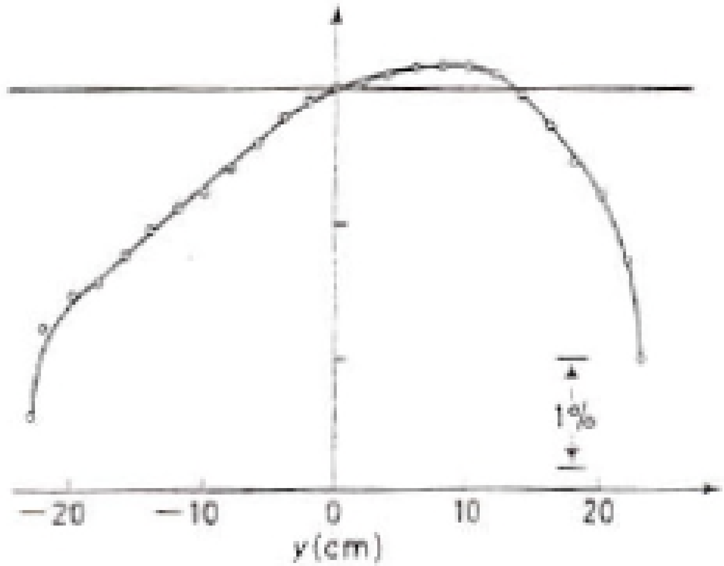

Fig. 13. – Final field shape in *storage* region measured at $x=350$ cm. Storage field at $x=350$.

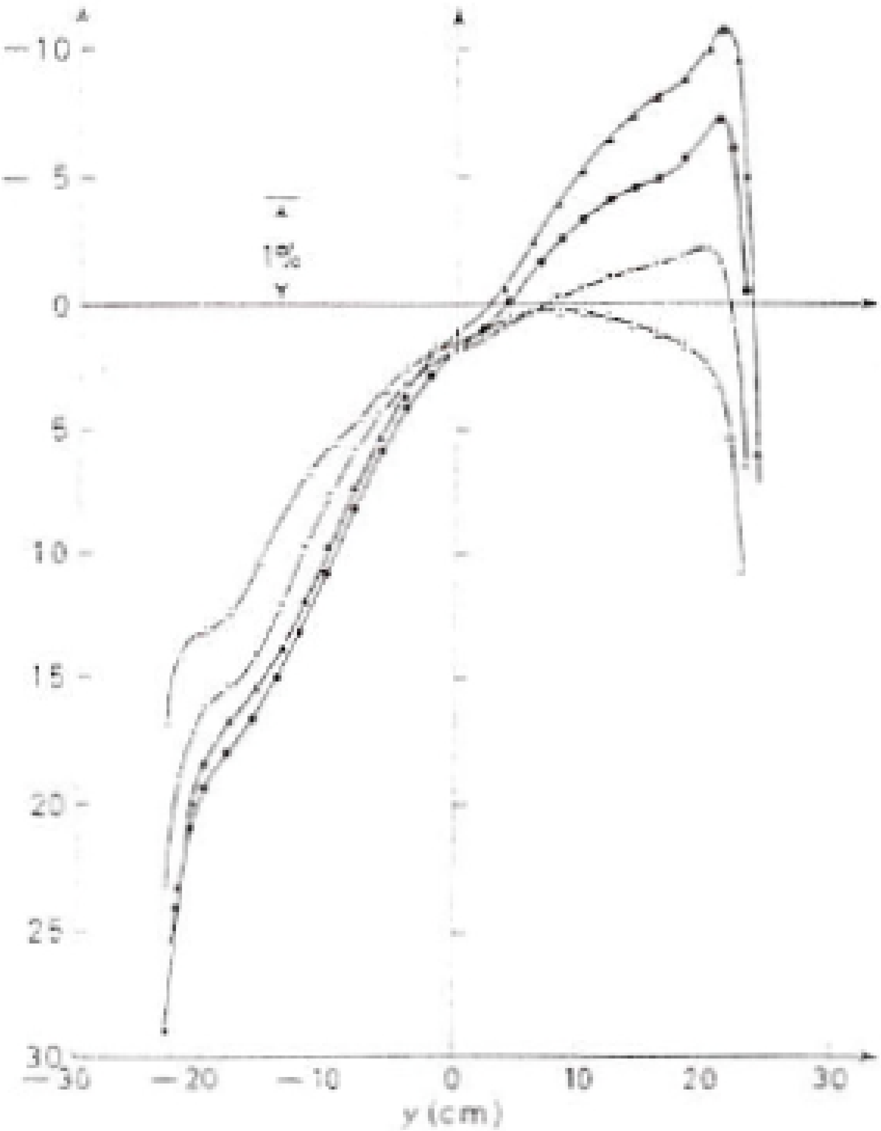

Fig. 15. – *Injection* fields at various values of x, showing gradual transition from the steeper injection gradient to the storage field in Fig. 13.

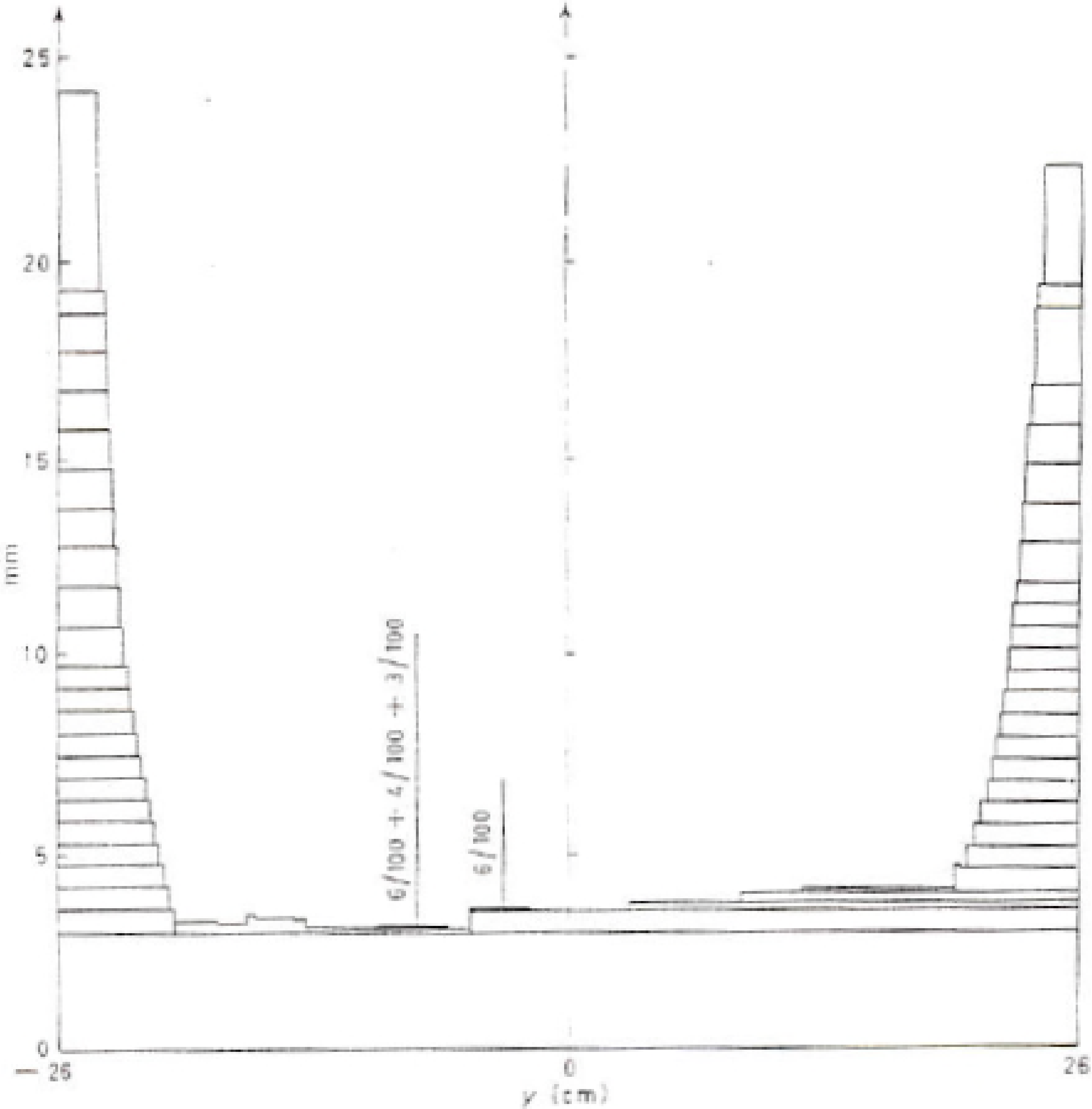

Fig. 14. – Shim heights in millimetres, required to produce the storage field of Fig. 13.

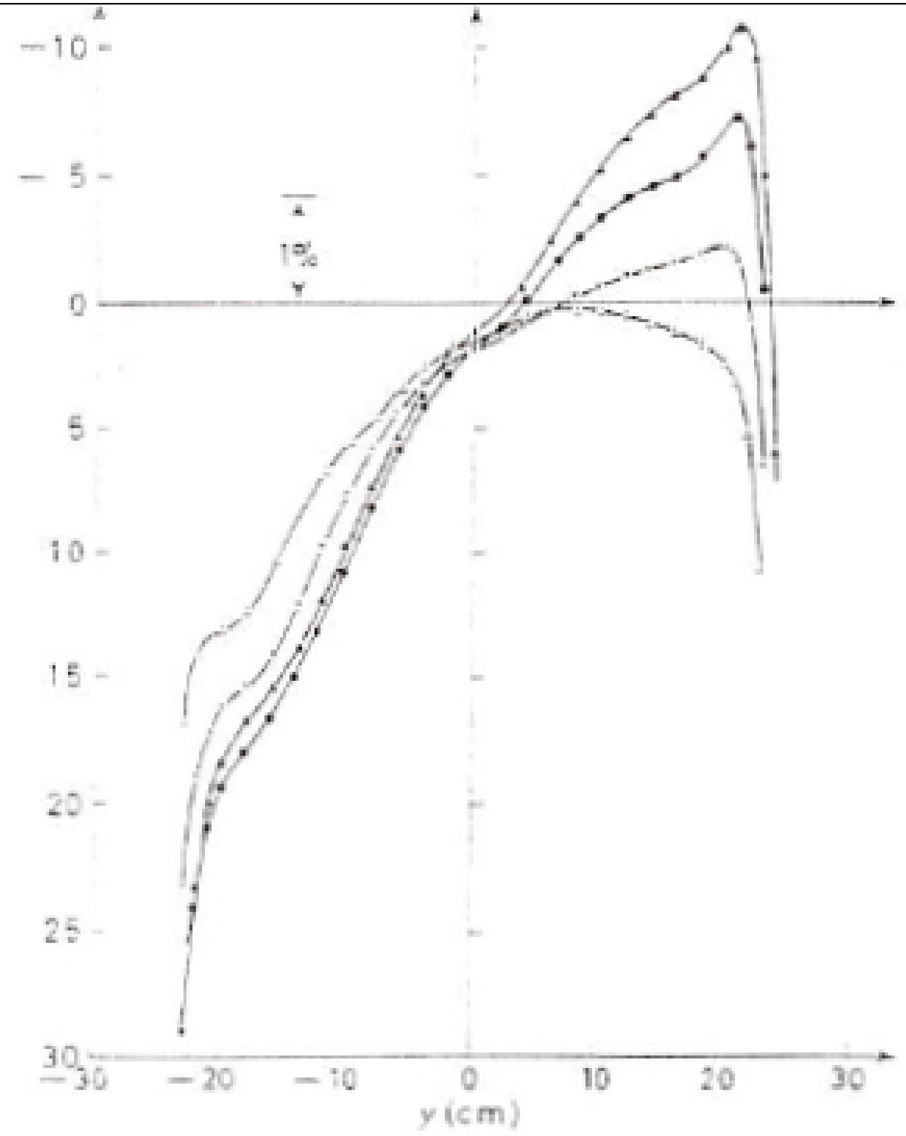

Fig. 15. – *Injection* fields at various values of x, showing gradual transition from the steeper injection gradient to the storage field in Fig. 13.

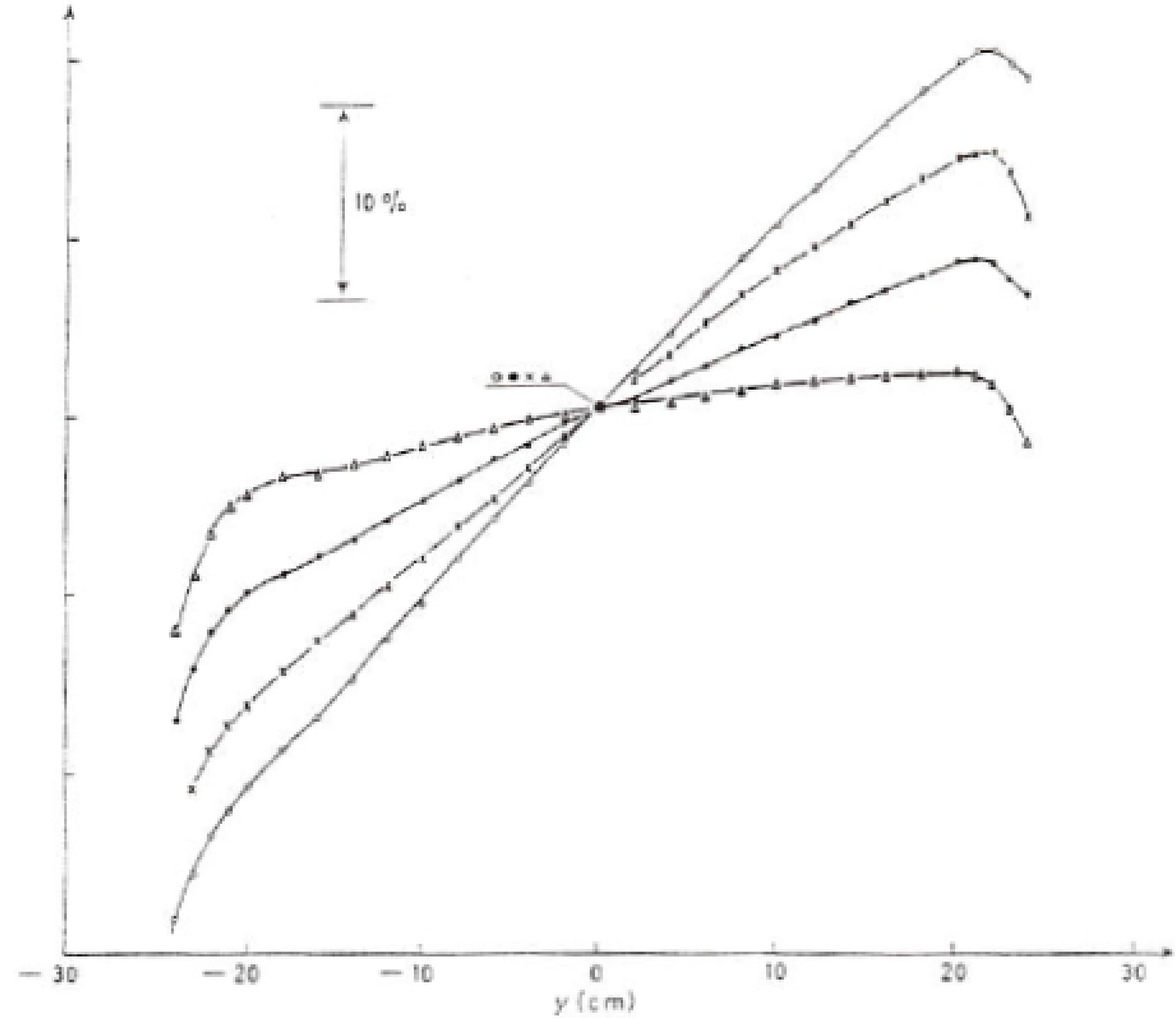

Fig. 17. – Transition fields from storage to ejection.

Zichichi's special responsibility (and his alone) was the job of producing the bizarre magnetic field in our large storage magnet, which he accomplished with imagination, energy and efficiency. Indeed, this apparently crude "additive shim approach" established a new technology for the rapid realization of precision magnetic fields.

As might be imagined, measuring magnetic field every few cm in a plane 60 x 600 cm in extent is a big job, and we did not have automated stepper systems to do that. Our work was greatly aided by the observation that we really wanted the integral of magnetic forces over an orbit of nominal 18-cm radius, which could be provided by the use of a circular search coil of that radius. Measuring the flux change induced by motion of the coil would thus ignore the uniform component of the vertical field and if moved in y would measure the a,b,c, and d terms. Of course, measurements in the median plane would define the field everywhere, but only if the field is symmetric in z. The storage concept is very sensitive to displacement of the median plane, because the orbits in the design 1000-turn regime have plenty of opportunity to be totally depopulated if the median plane scrapes against the upper or lower pole face.

The same flux coil provides a sensitive determination of the median plane if moved from $z = 0$ to, for instance, $z = +/- 2$ cm, and that is a far simpler job than mapping the entire magnetic field.

We also used a nylon ball in a diamagnetic solution of manganese ions to find the local median plane, by placing a plastic tube containing the solution and the ball in the magnetic field, with the tube walls aligned with *z*.

The design of the magnetic field benefitted greatly from the contributions of “Pief” Panofsky, whose knowledge of orbits and of German enabled him to find a reference that was then obtained by inter-library loan. It turned out that the requested article had been excised with a razor blade, but the following article in the volume was more relevant and very helpful, on the solution of a Hill differential equation.

The motion of a charged particle in the specified field experiences instabilities for certain regions of the spatial parameter variation, and I soon moved to calculations on the Ferranti Mercury Computer to determine the “stop bands” and “pass bands” and the limits that were thus placed on the coefficients of the magnetic field. Our paper sets forth some theorems that enable a perturbation approach that was used with the computer calculations, to design the magnetic field while respecting the stability limits on the orbit.

The group recognized from the first that a small step size was desirable in order to have as long a storage time as possible in a magnet of given volume. The injection of muons into the storage orbits was to be realized by slowing of a muon beam in a small Be moderator within the magnet, so that the muon of 150 Mev/c momentum could enter the largely uniform magnetic field from outside, while the slowed muon of mean momentum 100 Mev/c will be trapped. Of course, in a uniform magnetic field that muon would be sure to strike the moderator again, on the first orbit if the orbit were in the median plane, but eventually, even if the muon were scattered so that its velocity had a component along z. So the idea was to inject in a region with step size *s* enough to displace the muon orbit in *x* to clear the Be moderator. Then there was to be a transition from the injection region of magnetic field *B(y)* uniform along *x*, to the storage region with smaller *s*.

Ultimately, because the flux through the “circular orbit” is an adiabatic invariant, instead of ejecting from the far end of the 6-m magnet, the orbits would creep to the far end, make a right-angle turn, and eventually return as they approached the other long boundary of the magnetic field.

Ejection of the muons required an increase in *s* from 20 mm in the injection region and 4.4 mm in the storage region to 120 mm per turn in the ejection region, so that the muons would approach the magnetic field termination at a large angle rather than creeping up to it. Of course, there would be a spray of muons coming out, largely in the median plane.

Measurement of polarization of the ejected muons

Georges Charpak assumed responsibility for polarization measurement—"PM". In principle, this could be done by adopting a technique pioneered at Columbia, in which muons polarized in the horizontal plane would have their spins "flipped" by 90° about the *Z* axis, so that the transverse component of the spin would be in the longitudinal direction. More precisely, if there is no steady ambient field in the region of the muons stopped in the polarization-measuring target, a vertical pulsed magnetic field applied with a certain integral of *B(t)* (a "90° pulse") would rotate the transverse component of polarization perpendicular to the flipping field into the front-back direction, and in zero field the spin components would remain fixed through the microseconds of further muon life. The now-longitudinal polarization would be measured by determining the electron decays front and back, making use of the strong decay asymmetry established in the first experiment of January 1957.

This made double use of the counters of the PM, first to define the stopping muon and then to count the electrons over several ensuing half lives.

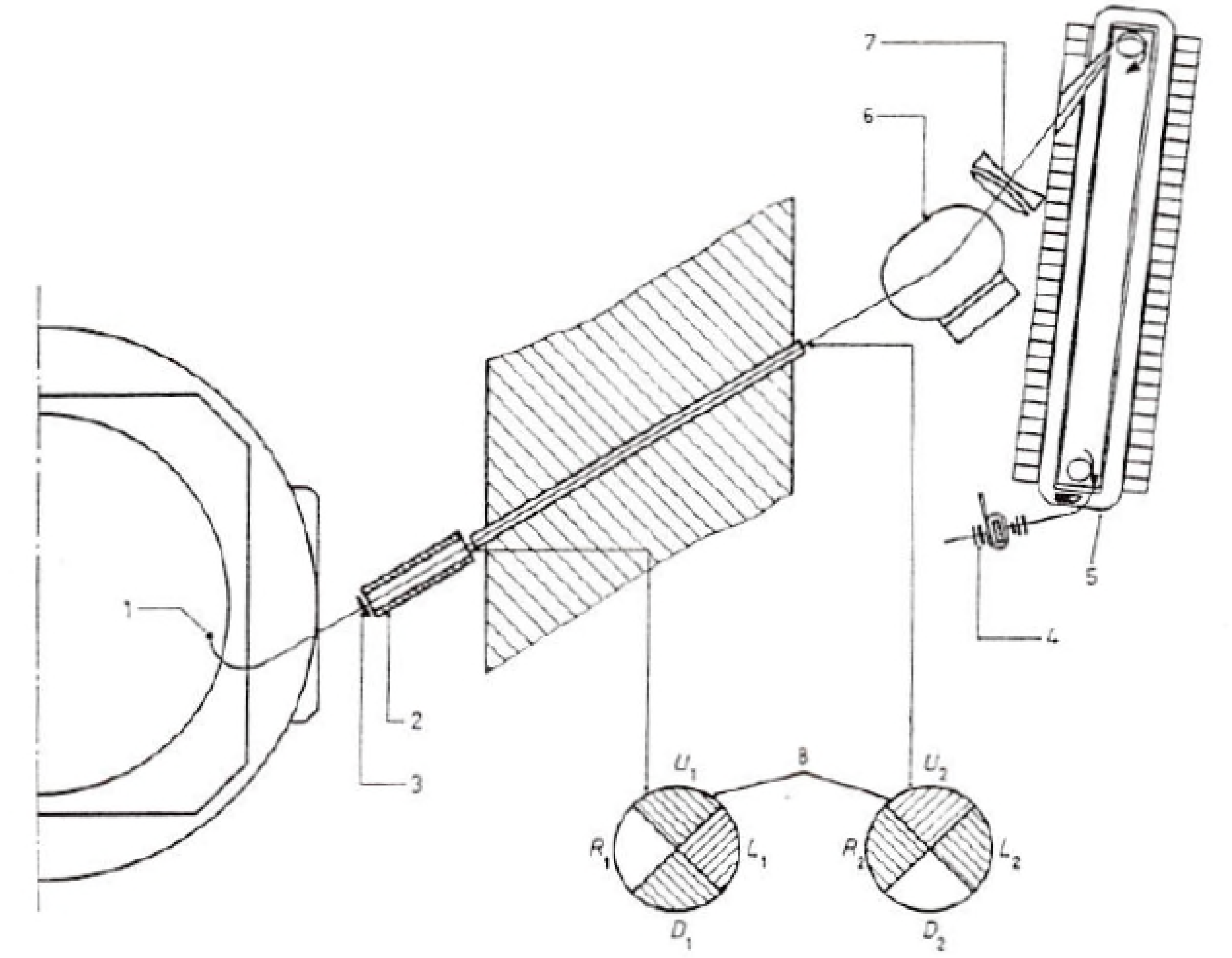

Fig. 48. – Final layout of experiment, showing cyclotron, solenoid, pipe through shielding wall with the possibility of dividing each end of the pipe into quadrants to study beam structure. Note the lead scattering foil added to scramble the muons into different beam cells, thus reducing spin-angle/position correlations. 1) target; 2) solenoid; 3) lead foil; 4) polarization analyser; 5) storage magnet; 6) bending magnet; 7) quadrupole lenses.

In the above figure is shown the pipe through the shielding wall that we divided for test purposes by blocking one 90^{o} sector at each end, thus allowing measurement of transverse muon polarization in 16 different regions of solid angle in order to compensate for initial polarization. The lead scattering foil (3) averaged the input polarization, and an along-pipe solenoid flipped the residual transverse polarization to an innocuous vertical orientation.

ing a minimum power from the flipping field generator; it is nonconductive, a necessary condition for the flipping method to be used; and, finally, it does not dissolve lucite, thus allowing the easy construction of containers of any size or shape, with thin walls.

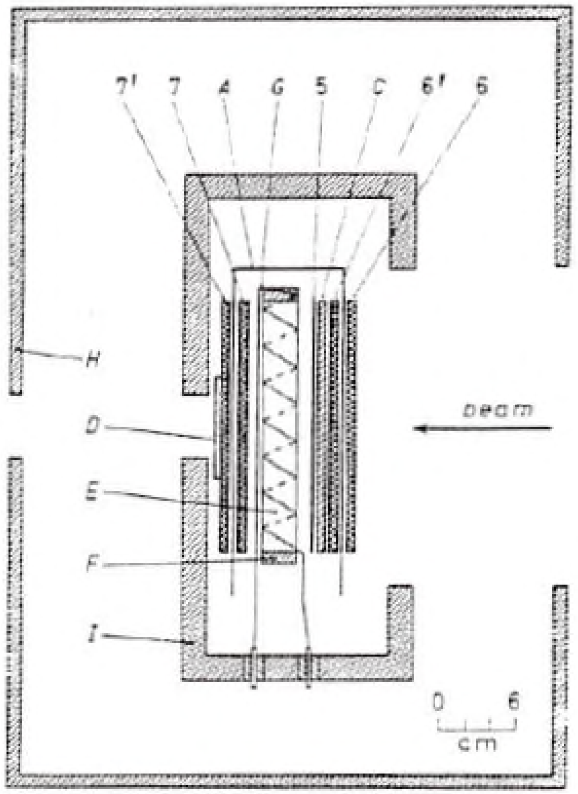

Fig. 41. – Polarization analyser with thick target. *E*, methylene iodide in thin-walled plexiglas box. *F*; *H*, *I*, iron shields. For other symbols see caption to Fig. 40.

Two types of target are used; a thin target for the analysis of the polarization of beams as a function of the range of the muons (Fig. 40), and a thick target for the analysis of the muons ejected from the storage magnet (Fig. 41). The first one consists of a mylar bag, of wall thickness 0.01 mm containing the liquid, and compressed between styrofoam slabs with an average thickness of the CH_2I_2 of about 8 mm. The second one consists of a lucite container with 1 mm thick walls, 30 cm wide, 20 cm high, and 2 cm thick.

The coil for the pulsed magnetic field consists of aluminium tape of 14 mm width, 0.1 mm thickness, wrapped around the targets at one turn per 1.8 cm.

4'1.3. Magnetic shielding. The shielding is done in three steps. Two iron boxes surround the counting assembly and the target. They are made of 1 cm and 2 cm thick Armco iron with beam apertures in the front face of high, located immediately in front of the target. A stopped muon is defined by the signature $66'\,5\overline{7}$, in coincidence with one or several upstream counters. Counter 5 is thin to reduce the number of muons which stop in it before reaching the CH_2I_2 and thus reduce the electron asymmetry.

Careful checks have been done with beams traversing all five counters in order to prove that the efficiency of the counters is uniform and especially that it does not exhibit a right-left asymmetry. The efficiency of the counters $66'\,77'$ was proved to be very close to 100 % for fast charged particles.

The whole assembly of counters and target is held tight in correct geometrical position by clamps and spacers. A mirror, glued on the back of the last counter, allows accurate positioning of the assembly. The entire assembly

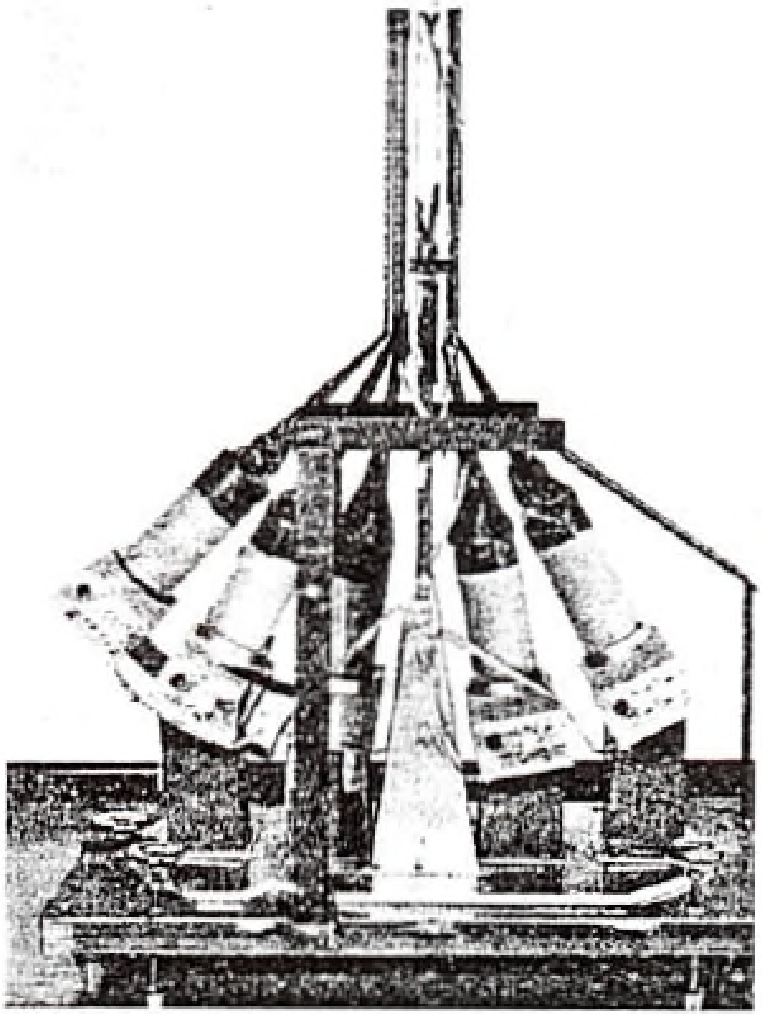

Fig. 42. – Polarization analyser assembly with iron shields removed. The whole assembly can be rotated on the trolley for fine angular adjustment.

The resulting polarization vs. *t* is shown in the figure.

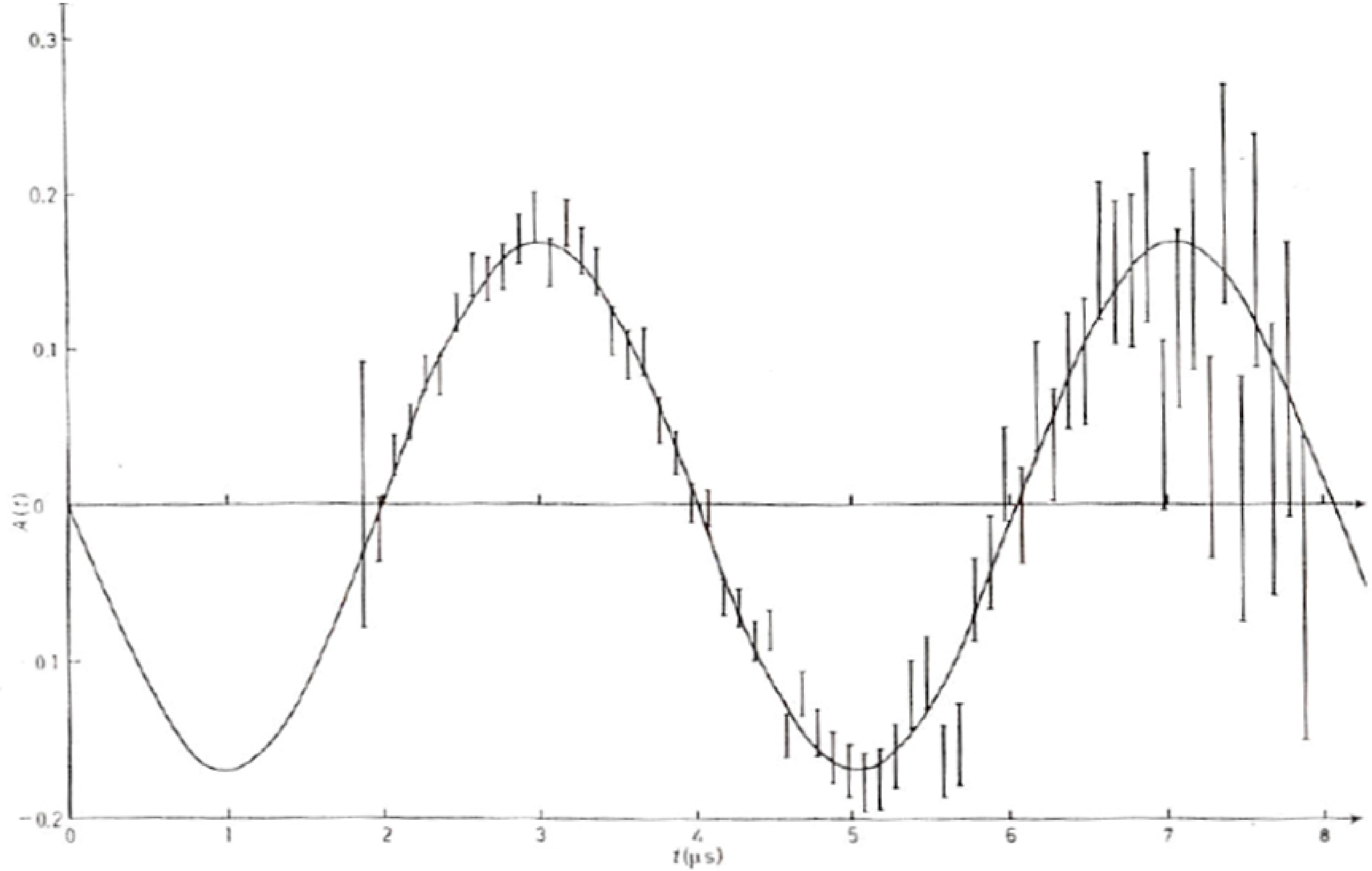

Fig. 73. – **Precession** curve due to the anomalous **magnetic** moment of the **muon**. The frequency of this curve essentially determines $\mathbf{a}_{exp}$. Electron asymmetry $A(t)$ for $\pm 90°$ flipping (combined data from backward and forward telescopes) is plotted *vs.* storage time t. The curve shows the best fit obtained by varying A_0 and **a** in eq. (108).

For each of the muons emerging, the storage time is measured in “bins” of width 100 ns by means of a digitron, the implementation and test of which was the responsibility of Hans Sens and Theo Mueller.

The digitron accepted digital signals from the counters defining the entering muons and the exit muons, and recorded them in a single, modified 1024-channel pulse-height analyzer (PHA). This was fed by a time-to-amplitude converter that generated a linear ramp with a Start pulse, and gated out the value of the ramp at the time of a Stop pulse. A digital offset in the storage was provided so that four portions of the PHA memory could be used independently to store counts in 256 time bins—each portion corresponding to the forward- and back-decay telescopes in the PM, for + and -90° flipping.

With a synchrocyclotron pulse of length 200 microseconds, repeated 50 times per second, it was important not to waste the time of the digitron, so in fact the ramp was *started* by a muon traversing the *exit* telescope, and *stopped* by the pulse corresponding to the *entrance* muon, delayed by a fixed 10-μs delay line. The tests and precautions applied to ensuring that random and systematic background did not contaminate the muon records are fully described in the Report.

Francis Farley assumed responsibility for the counter system defining the entrance beam and also, quite separately, for translating the digitron counts into a *g-2* value. This had to take into account the mean angle of entrance to the PM as a function of storage time, the mean energy of the muons involved, and any polarization in the input beam. Farley had pioneered the use of the CERN Ferranti computer (punched paper tape input) in graphing trajectories of the external beams from the synchrocyclotron, designing the placement of the beam pipes through the concrete shielding—essential infrastructure on which all experiments depended.

The beam of muons entering the 6-m magnet was measured carefully in position and angle and found initially to have a substantial transverse component of polarization in addition to the essential high longitudinal degree of polarization. The effect of the initial transverse polarization was nullified by steady current in a small solenoid that flipped the transverse polarization on the average to the Y axis, so as not to contribute to the measured secular increase in transverse polarization as a function of storage time in the magnet.

Much of the difficulty of such a precision experiment is involved not with the accumulation and reduction of data but in the testing and compensation for undesired effects. Furthermore, there is always the possibility of errors and blunders, so in addition to calculating the orbits and designing of the magnetic field configuration, I worked out a simulation of the overall system, assuming an arbitrary value *a* for (*g-2*), Using Monte Carlo assumptions as to beam position and scattering, I calculated an expected number of counts in the four sections of the digitron. When Farley had his analysis program operating, I could give him these mock results and ask him to blindly reduce them via his analysis program to determine the "*g-2*" that resulted. Of course, I was not constrained to provide an *a* anywhere near the theoretical a_{th} of 1165 ppm, so I could choose one twice as large and with the opposite sign, for instance. We got it right after a couple of trials, with enhanced confidence that various effects had been taken into account. I felt this was a much better approach than trying to check Farley's analysis and program.

The Report details the least-squares analysis of the individual bins; the primary data were reported to me at IBM Yorktown Heights by Western Union telegraph so that I could independently replicate the least-squares procedure.

In addition, I did a maximum-likelihood analysis using the individual counts, which, for small numbers of counts in the bins is more accurate and more fundamental than the least-squares approach. The results agreed.

We found $\boldsymbol{a}_{exp} = (1162 \pm 5) \times 10^{-6} = \boldsymbol{a}_{th} \times (0.997\,4 \pm 0.004\,3)$.

Of the overall error of 0.43 %, statistics of the asymmetry constitutes 0.30 %, errors in the initial polarization 0.18 %, in the injection scattering 0.20 %, and in the final[9] mean beam direction 0.11 %.

I reproduce here the Acknowledgment section of the Report. Evidently, success of the CERN g-2 experiment depended heavily upon the superb infrastructure that had been created there, as well as on the technology and knowledge, both theoretical and experimental accumulated by physicists over the years.

> *This project owes much to several decisions and suggestions of Prof. G. BERNARDINI, and to the initiative of Prof. L. M. LEDERMAN during his visit to CERN in 1959. We express our particular appreciation also to Profs. W. K. H. PANOFSKY, V. L. TELEGDI and C. M. YORK for their contributions at various stages of the experiment. We are indebted especially to our technicians Messrs. B. NICOLAI, R. BOUCLIER and J. BERBIERS for their untiring support through long periods of arduous preparation. We wish to thank also Dr. B. HEDIN and Messrs. F. BLYTHE., and A. ALBRECHT for contributions to the magnet design and mechanical parts. Finally we are grateful to Mr. E. LEYA and the cyclotron operators, for their collaboration during our many tests and runs on the CERN Synchro-cyclotron.*

---

[9] A result accurate to 2% and largely limited by statistics was published in brief as *G. Charpak, et al,* Phys. Rev. Letters 6, 128 (1961), and to 0.4$ as *G.Charpak, et al, Phys. Letters 1, 166 (1962)*

Some Personal Remarks

To maximize the working flexibility, I postponed some decisions to years later, in order not to have to do the work to define procedures at the time of the design of the experiment. In particular, quailing at the thought of prescribing to a few-mm accuracy the placement of the 86-ton magnet on the experimental floor of the cyclotron, I decided that the crane operators should put it down anywhere in the space of a meter or so, on loose steel sheets that covered the concrete floor, with the joints between the sheets taped. I then designed four 1-m-diam air bearings to be placed on the floor with the magnet to be set on top of them, with Tygon hoses to the laboratory air supply. After the magnet was delivered, I was working to position it, turned on the air and discovered to my delight that the magnet rose barely perceptibly, and to my horror that the experimental floor was not level, and that the horizontal component of 86,000 kg (times the misalignment with the horizontal) was more than I could fend off with one hand. Closing the air cock solved the problem.

Farley went on to further, more professional, and vastly improved (and more expensive) muon *g-2* ventures at CERN and at Brookhaven[10]. Charpak was so enthusiastic about his participation in the experiment that he resolved never to do

[10] See his very readable account in “The 47 years of muon g-2,” by Farley, F. J. M.; Semertzidis, Y. K., *Progress in Particle and Nuclear Physics*, Volume 52, Issue 1, p. 1-83., 03/2004.

particle physics again because he felt he could not top that experience; he insisted that he would devote himself to improving his particle detectors for biological and medical research and application, for which he received the 1992 Nobel Prize in Physics.

One major hitch was apparent in June of 1960, just as I was about to leave for two weeks in Bombay at the invitation of Homi J. Bhabha. When we tested the multiple solid-state coincidence-anticoincidence front-end units with a pulse generator and then with a beam, they failed to perform adequately in rejecting background and in not requiring adjustments.

So I left for Bombay with a stack of blank drawing translucencies, provided by the electronics shop at CERN, and returned with the design of fully transistorized pre-amplifiers and coincidence-anticoincidence circuits, using also Zener diodes for standardizing the input pulses. Except for one mis-wiring, these worked fine.

While I did not accomplish what I set out to do at CERN—a year of quiet time in the library, re-learning Physics, I was well pleased with the outcome and with the opportunity to form good personal and scientific friends in the CERN environment that was novel to me.

I close by quoting from a March 2014 letter to me from Francis J.M. Farley,

"When I look back, this experiment was extraordinary. We poured muons into the magnet at one end. They turned and turned for up to 10 microseconds and then came out at the other end OF THEIR OWN ACCORD. No pulsed fields, no control signals of any sort. Quite amazing. Nothing like this has ever been done before or since."

Francis Farley, Hans Sens, Georges Charpak, Theo Muller, Antonino Zichichi with the 6-meter *g-2* magnet