The 44 years

of

Muon g-2

1956

Berestetskii, Krokhin and Klebinkov,
Z.Eksp.Teor.Fiz. 30,788

$$\frac{\Delta a_\mu}{a_\mu} = \frac{2}{3}\frac{m_\mu^2}{\Lambda^2}$$

Phys. Rev. 105, 1415 (1957)

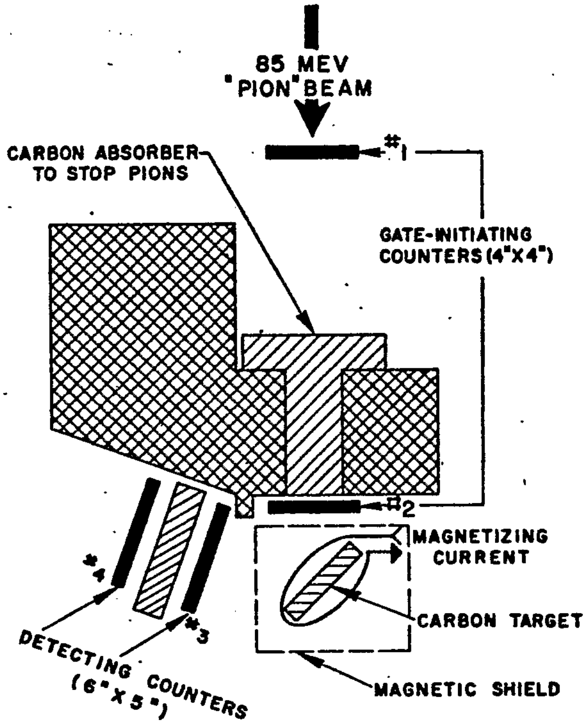
1957

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN,
AND MARCEL WEINRICH

*Physics Department, Nevis Cyclotron Laboratories,
Columbia University, Irvington-on-Hudson,
New York, New York*

(Received January 15, 1957)



Independent evidence that $g=2$ (to $\sim$10%) comes from the coincidence of the polarization axis with the velocity vector of the stopped μ's. This implies that the spin precession frequency is identical to the μ cyclotron frequency during the 90° net magnetic deflection of the muon beam in transit from the cyclotron to the 1–2 telescope.

1958 ANNUAL INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS AT CERN

1958

Panofsky:

......experiments were in progress at Columbia University and are being designed at the Joint Institute of Nuclear Research and in the University of Chicago ......

Marshak:

.... there may be another fundamental length coming in here since the μ meson is different from the electron. It may have a structure yielding deviations which are not quite so small.

Telegdi:

The fact is that everybody has been thinking about the (g-2) experiment ....

..... common impression that the first order term is well accepted and the real interest is to go beyond to the next order which is known to be different for electrons and muons.

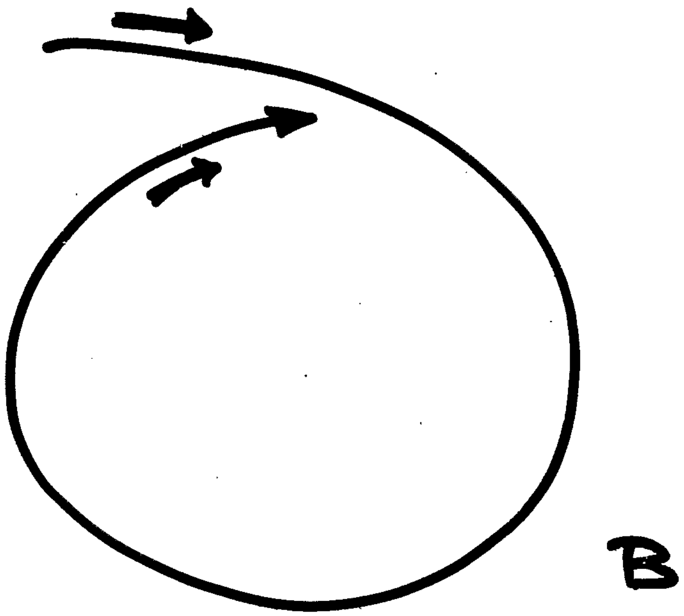
NOW I understand that some theorists feel that maybe even the first order correction might be affected for the μ meson by as much as 10%.

Tamm:

Of course for the μ mesons we can expect quite new effects because of the large mass of the μ meson has to be explained and they may be coming in far earlier than in the case of the electron.

g-2 precession

Non relativistic



$$\omega_c = \frac{eB}{mc}$$

$$\omega_s = g \cdot \frac{e}{2mc} B$$

$$= (1+a) \frac{eB}{mc}$$

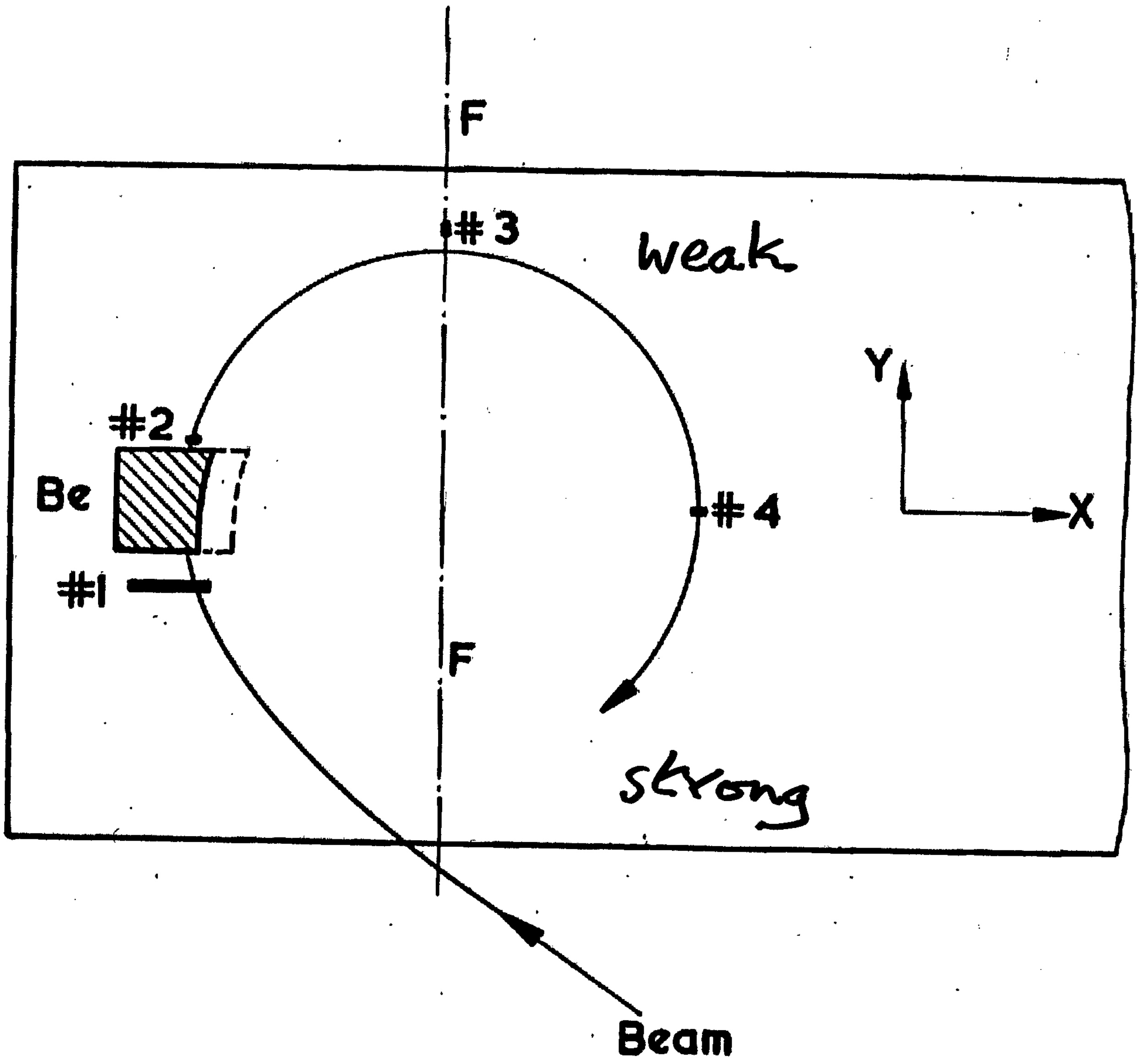
$$\boxed{\omega_a = \omega_s - \omega_c = a \frac{eB}{mc}}$$

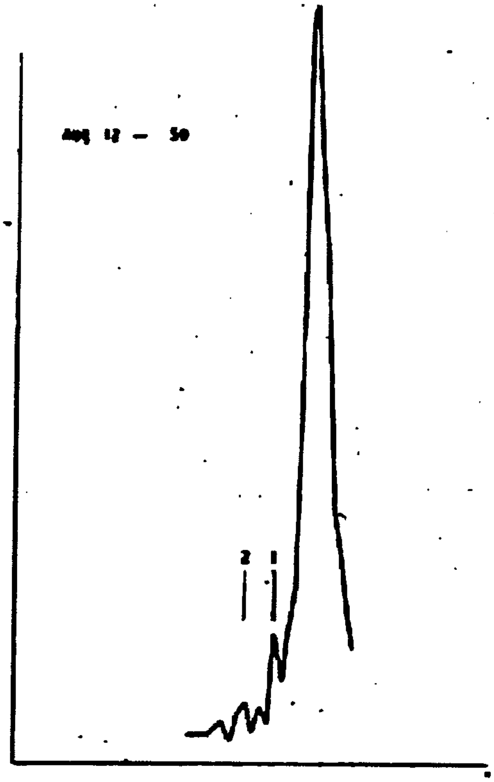
$$\frac{a}{1+a} = \frac{\omega_a}{\omega_s} = \frac{\omega_a / \omega_p}{\omega_s / \omega_p} = \frac{R}{\lambda}$$

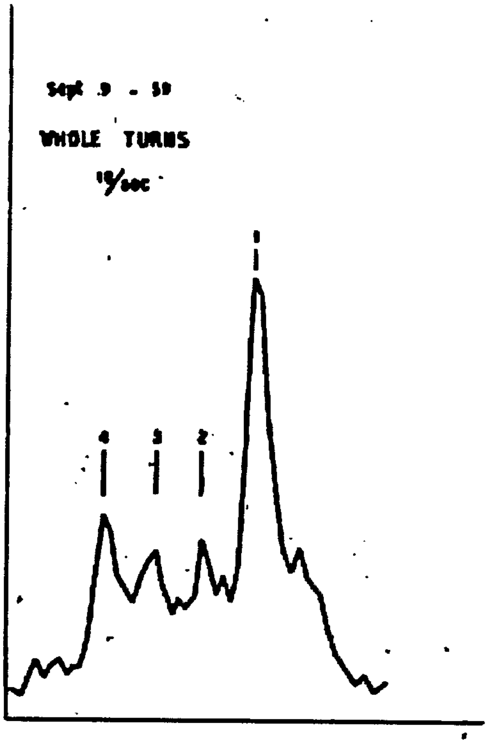
$$a = \frac{R}{\lambda - R}$$

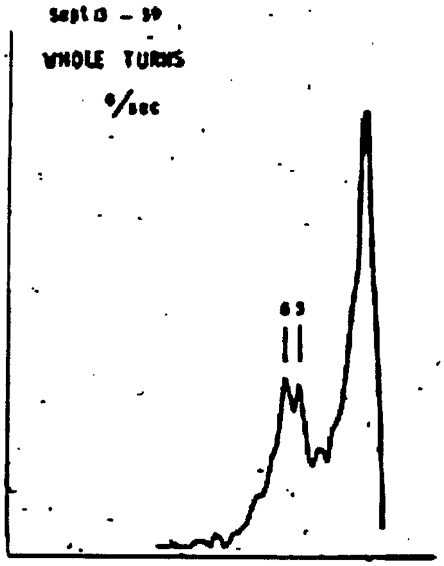
16 kG spin turns once in 4 μs

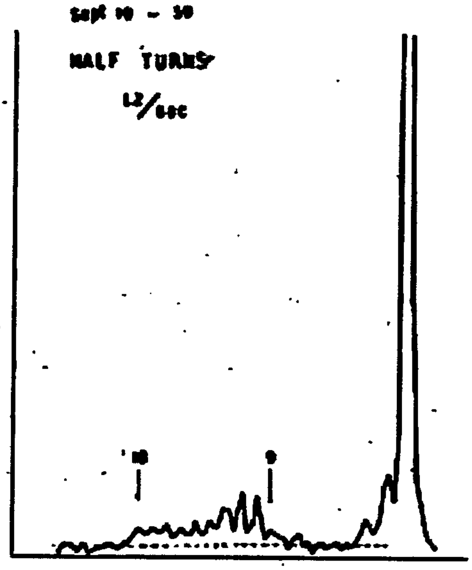
But $\tau = 2.2$ μs → 64 μs

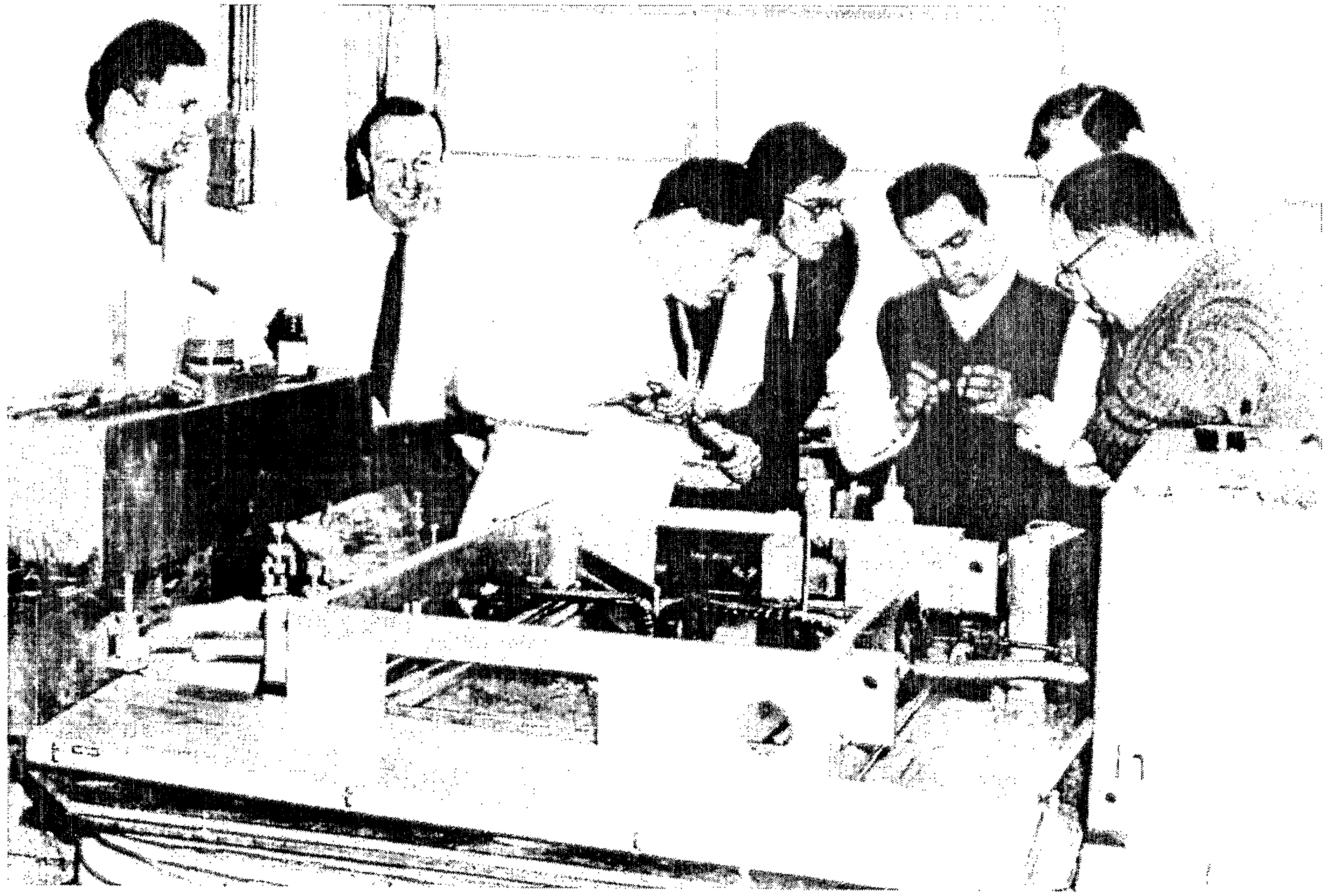

F
#3
weak
Y
#2
Be
#4
X
#1
F
strong
Beam


Aug 12 – 50
2
1

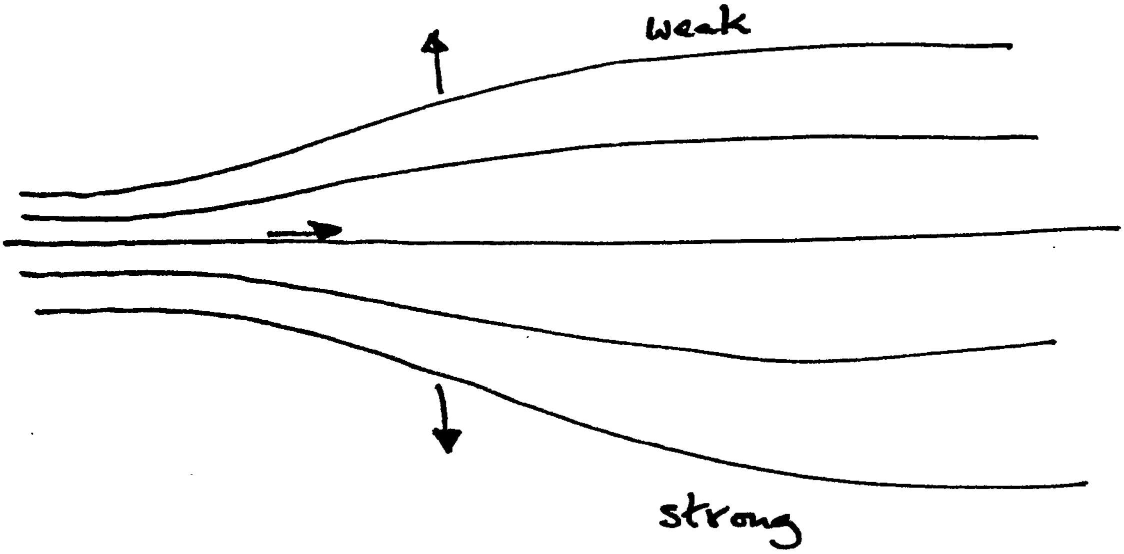

Sept 9 – 50
WHOLE TURNS
10/sec
1
4
3
2


Sept 13 – 50
WHOLE TURNS
6/sec
6 5

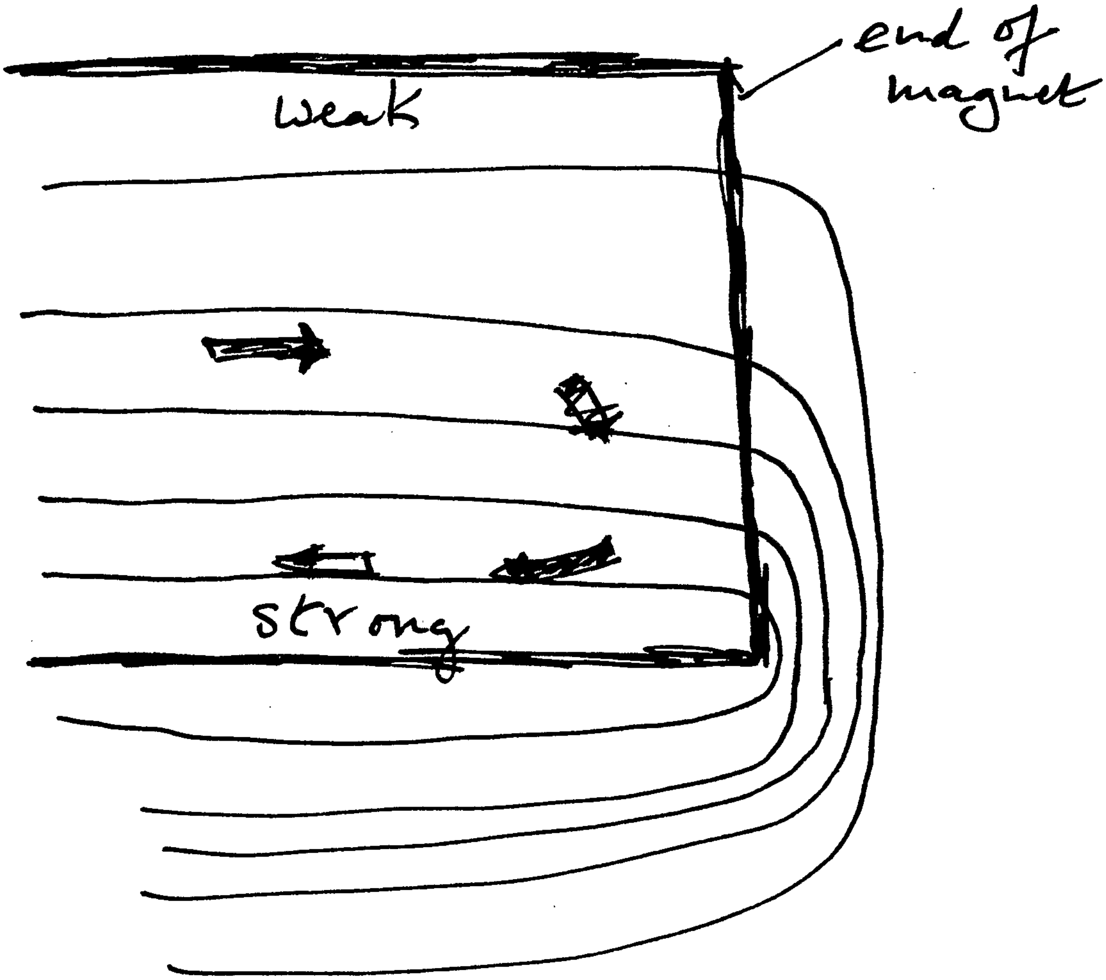

Sept 10 – 50
HALF TURNS
12/sec
10
9



Orbit walks ⊥ʳ gradient
follows contour lines
Flux through orbit is invariant



orbit smells end of magnet & goes back!



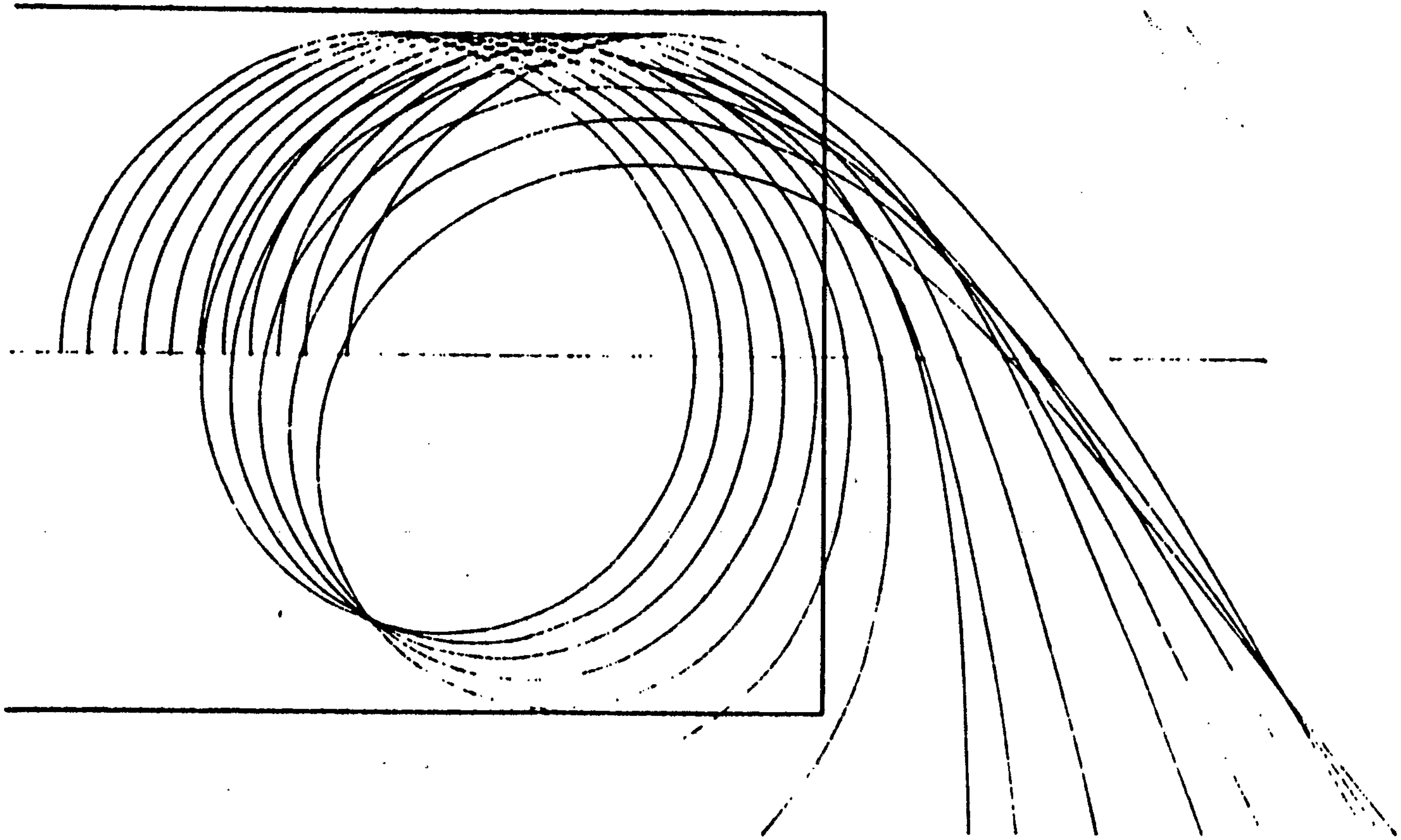


Fig. 6. – Computed orbits at the ejection end of the magnet based on detailed field measurements with the iron block (Fig. 61) in position. The downward movement in the last turn is due to the falling off of the field at the end of the magnet; but this actually improves the ejection by bringing the orbit away from the corner post of the vacuum chamber.

Fig. 7

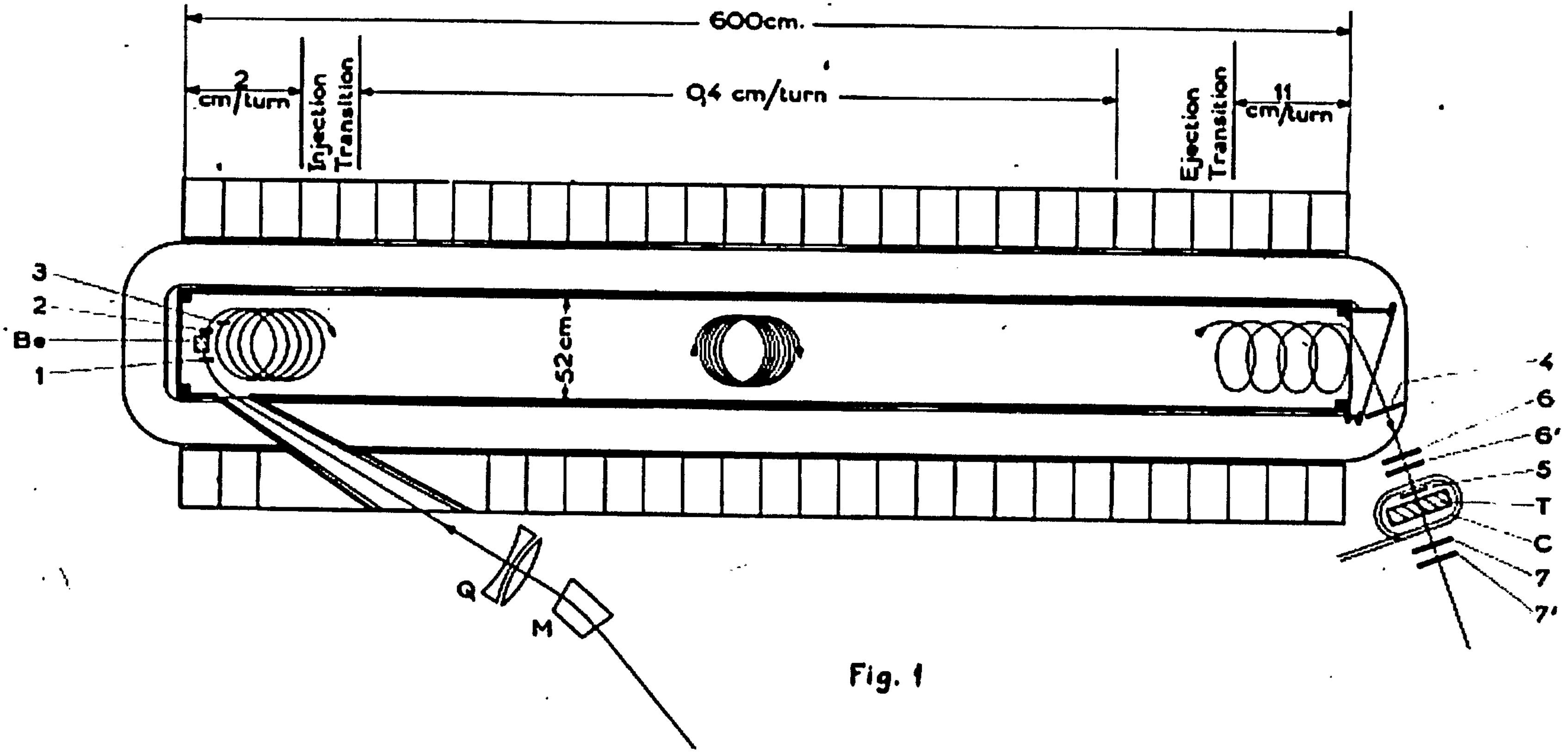
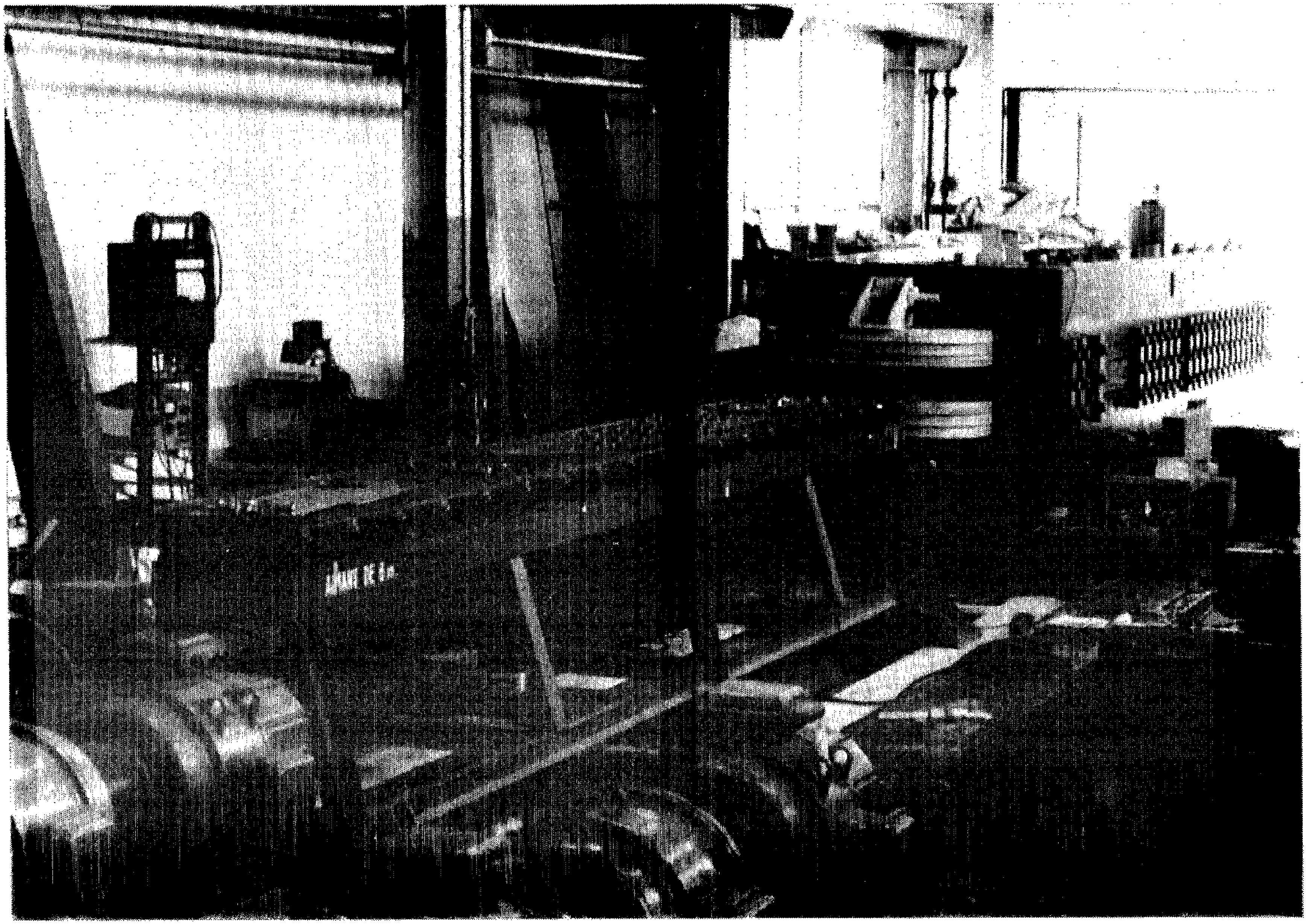
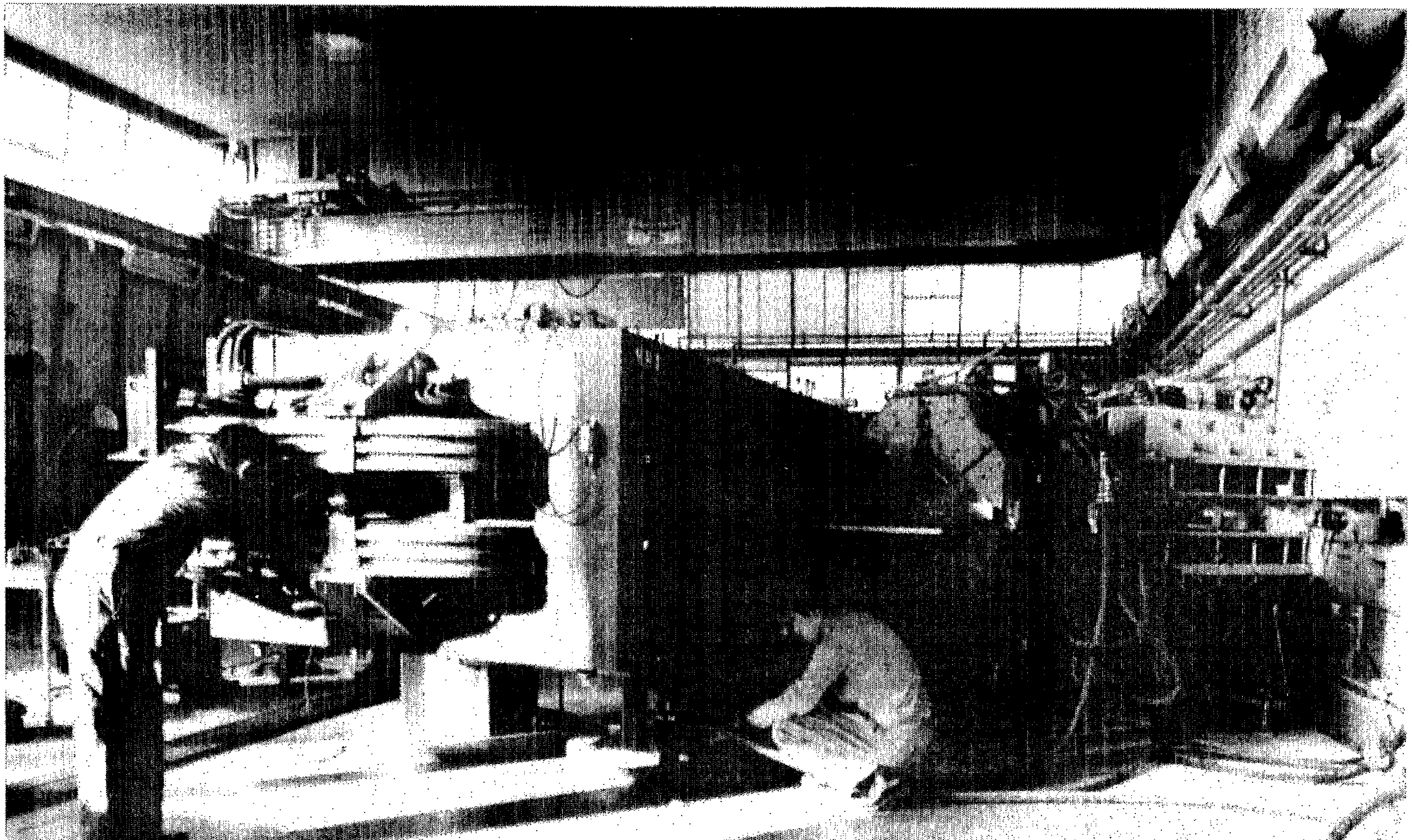

600cm.
2 cm/turn
Injection Transition
0,4 cm/turn
Ejection Transition
11 cm/turn
3
2
Be
1
52cm
4
6
6'
5
T
C
7
7'
Q
M

Fig. 1





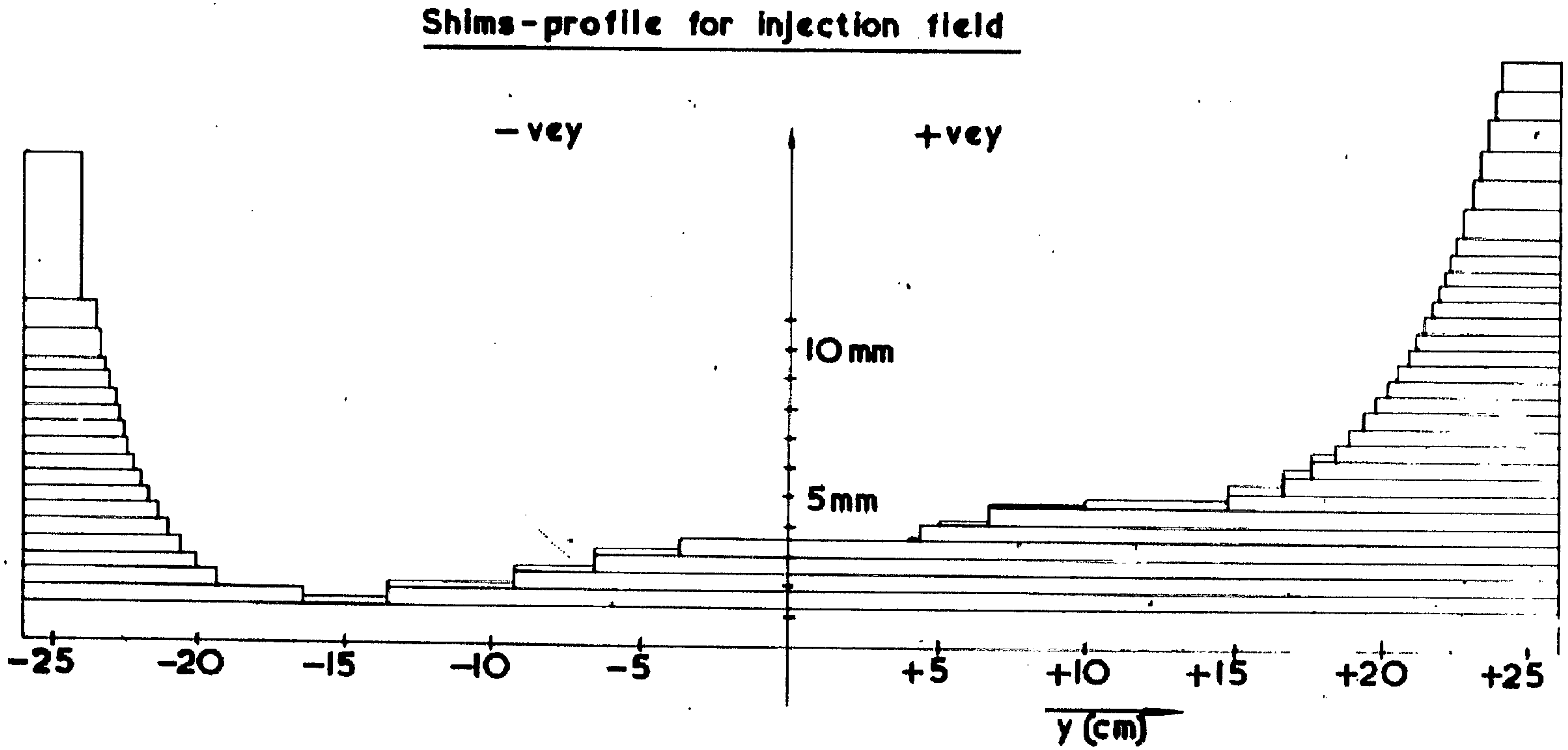

Shims-profile for injection field
−vey
+vey
10 mm
5 mm
−25
−20
−15
−10
−5
+5
+10
+15
+20
+25
y (cm)

Fig. 13

Shims profile for storage

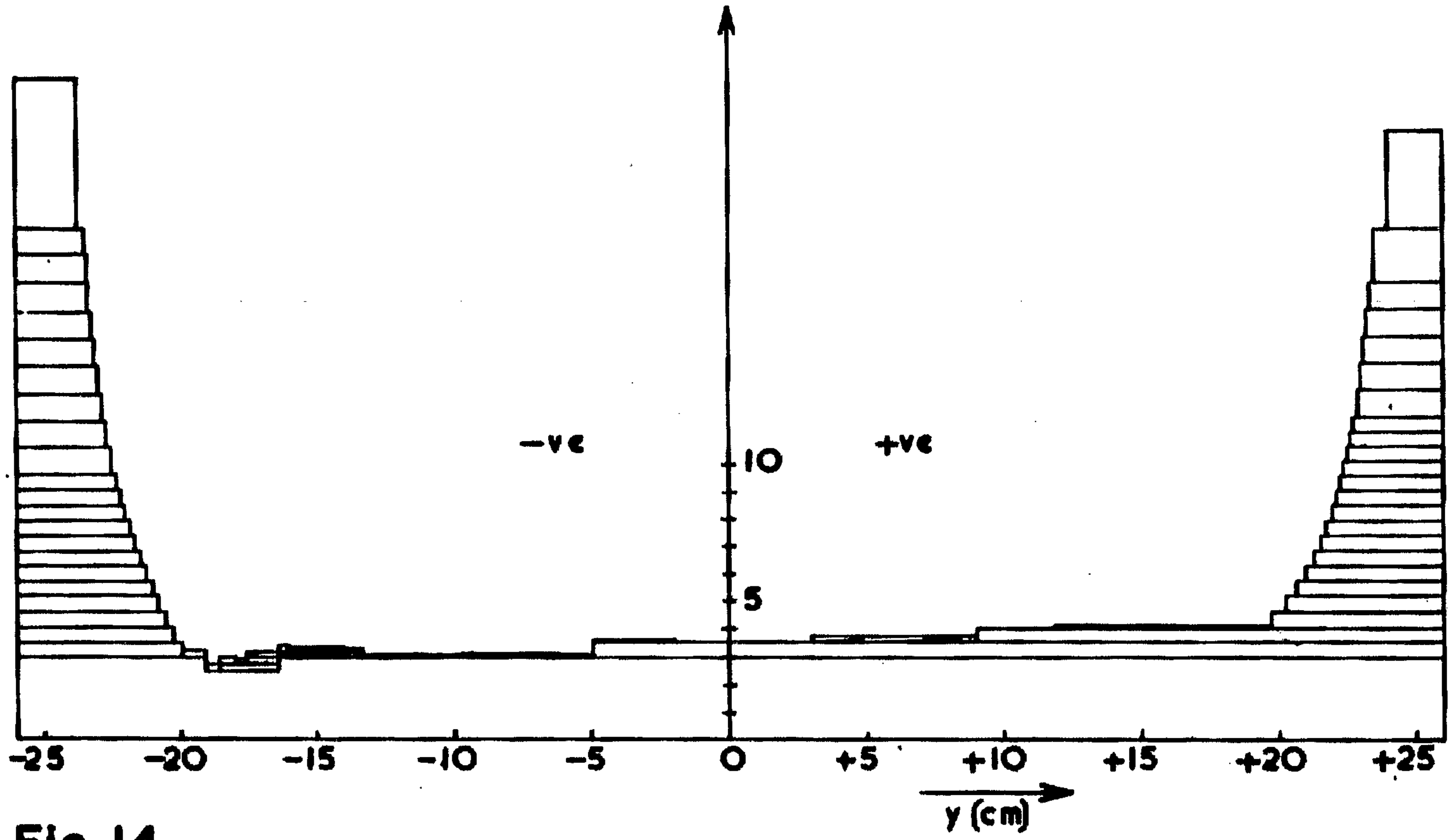


Fig. 14

Shims profile for ejection field ($a=7\times10^{-3}\,cm^{-1}$)

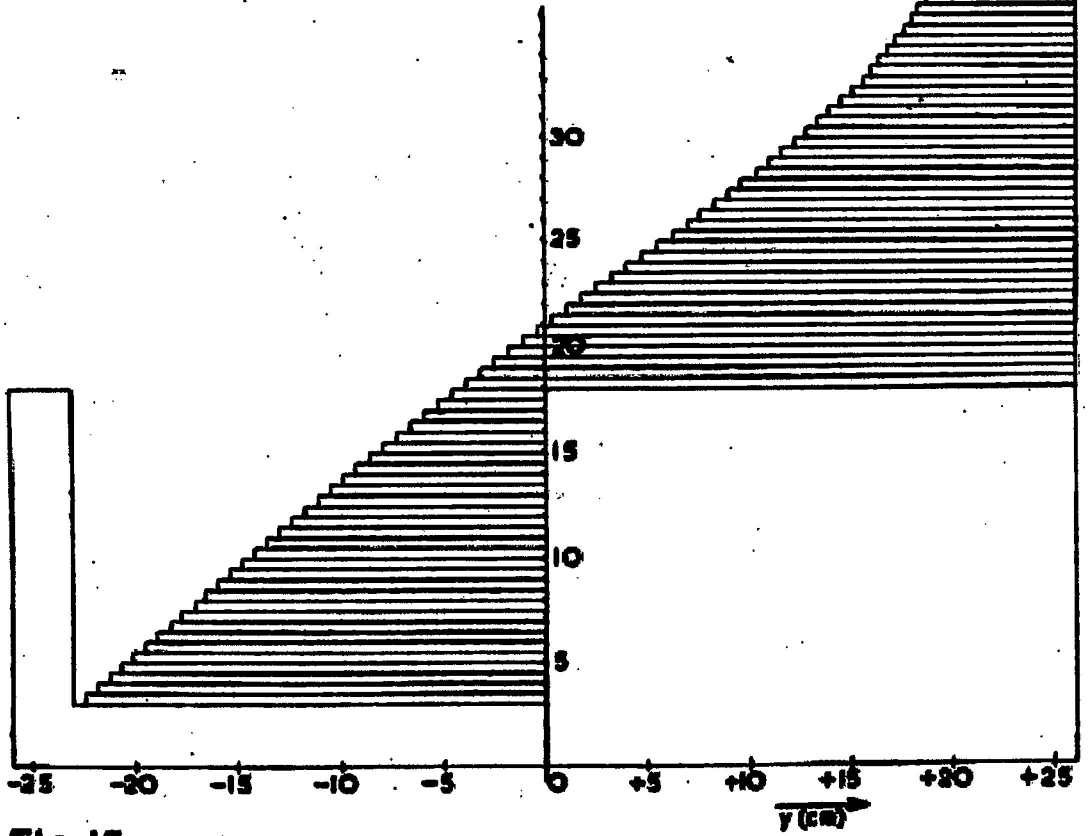
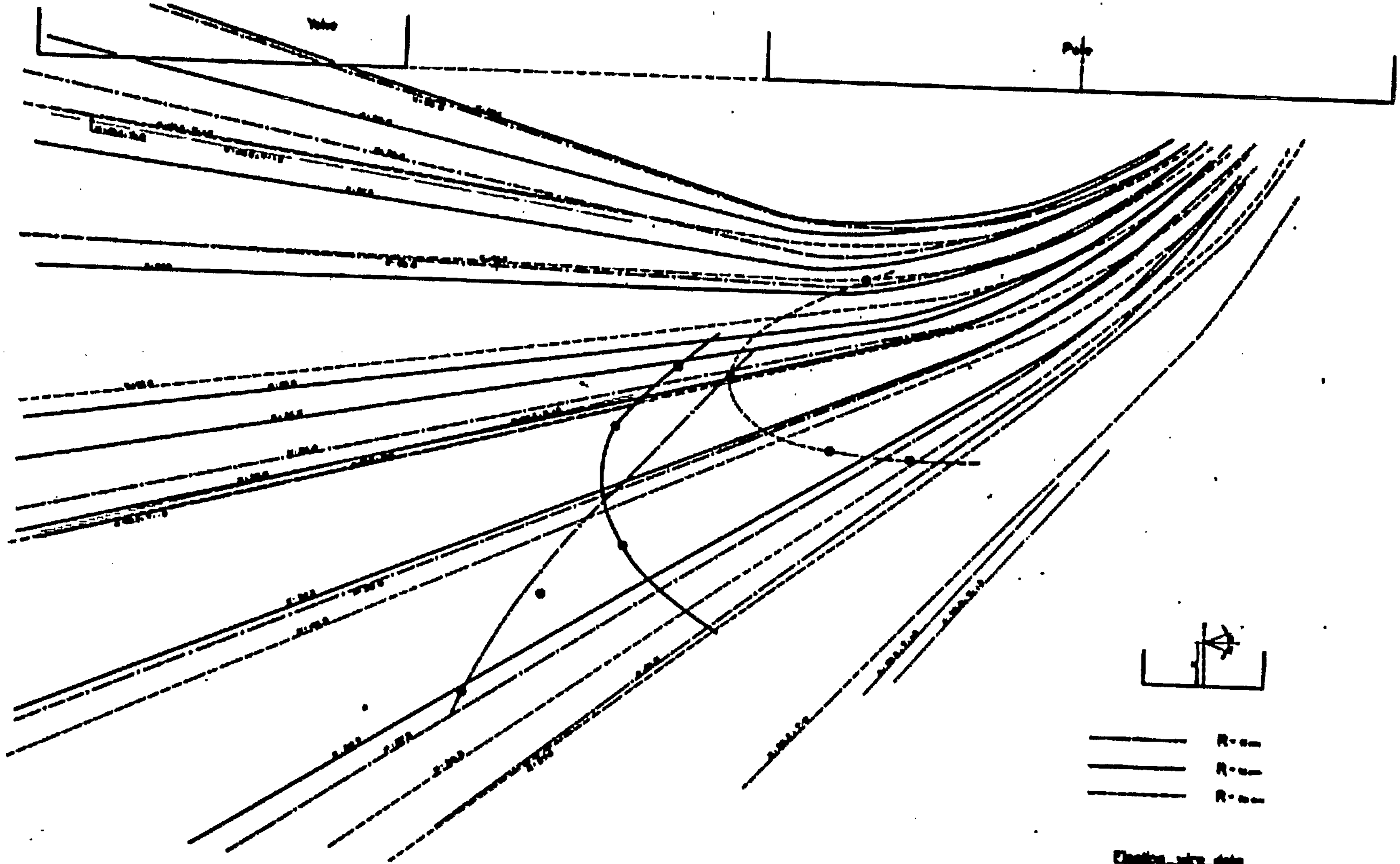
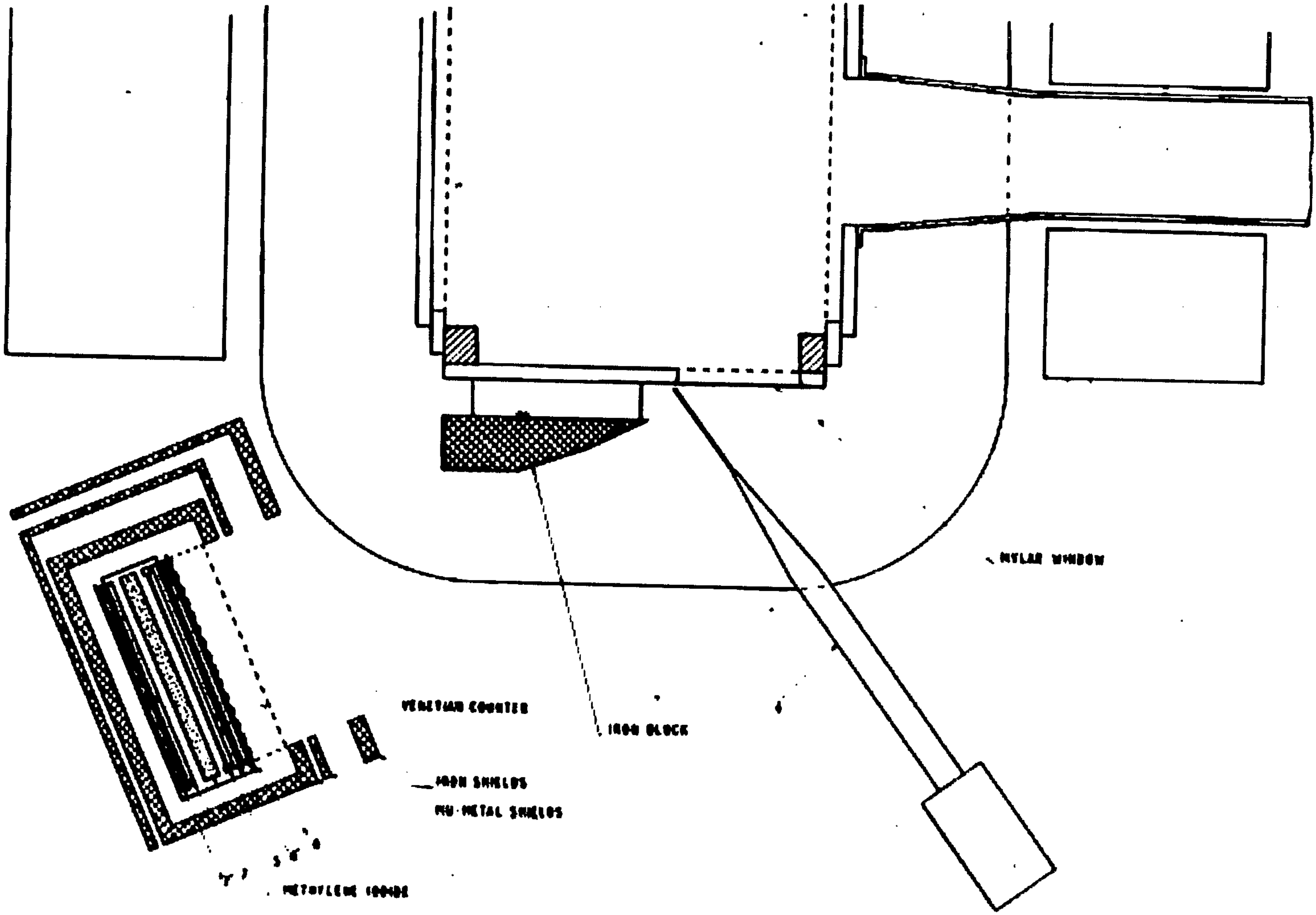


Fig. 15

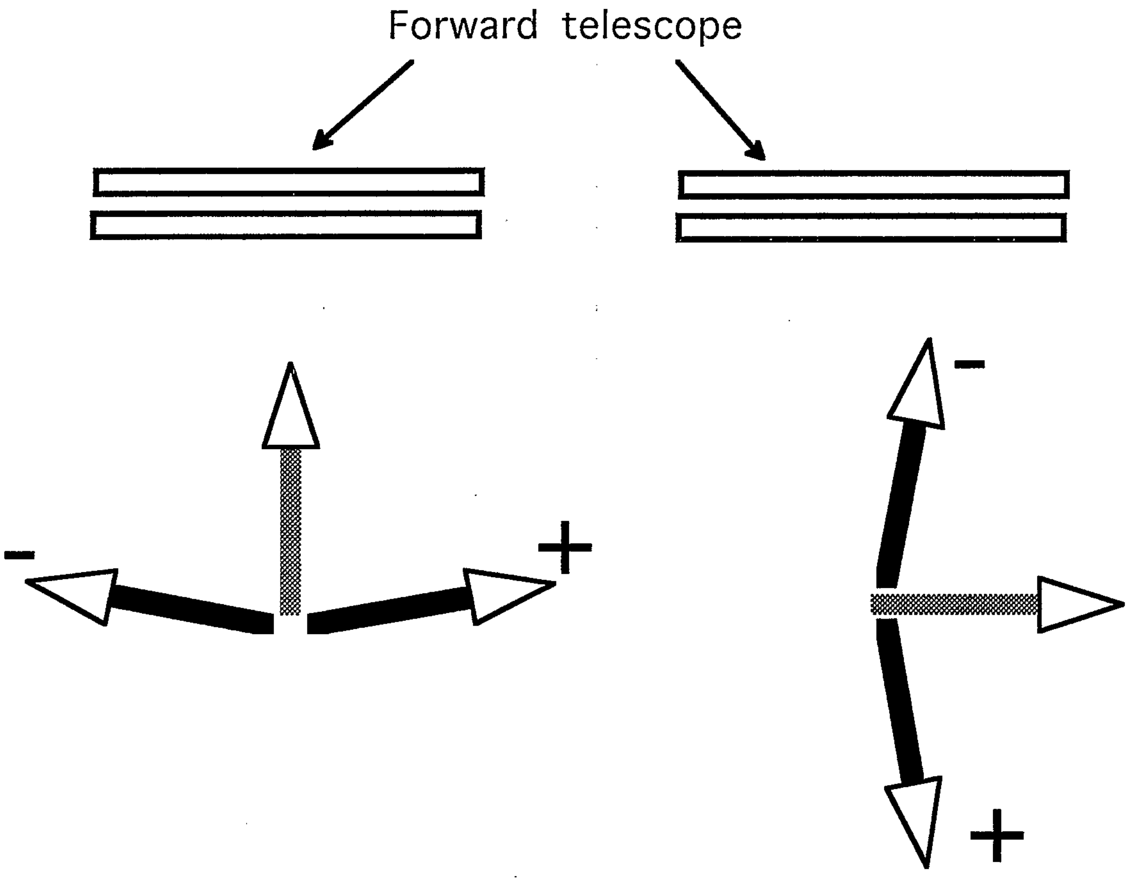


Floating wire data
ejection side


MYLAR WINDOW
VENETIAN COUNTER
IRON BLOCK
IRON SHIELDS
MU-METAL SHIELDS
5
6
8
METHYLENE IODIDE

Flip spin ±90° after muon stops

$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

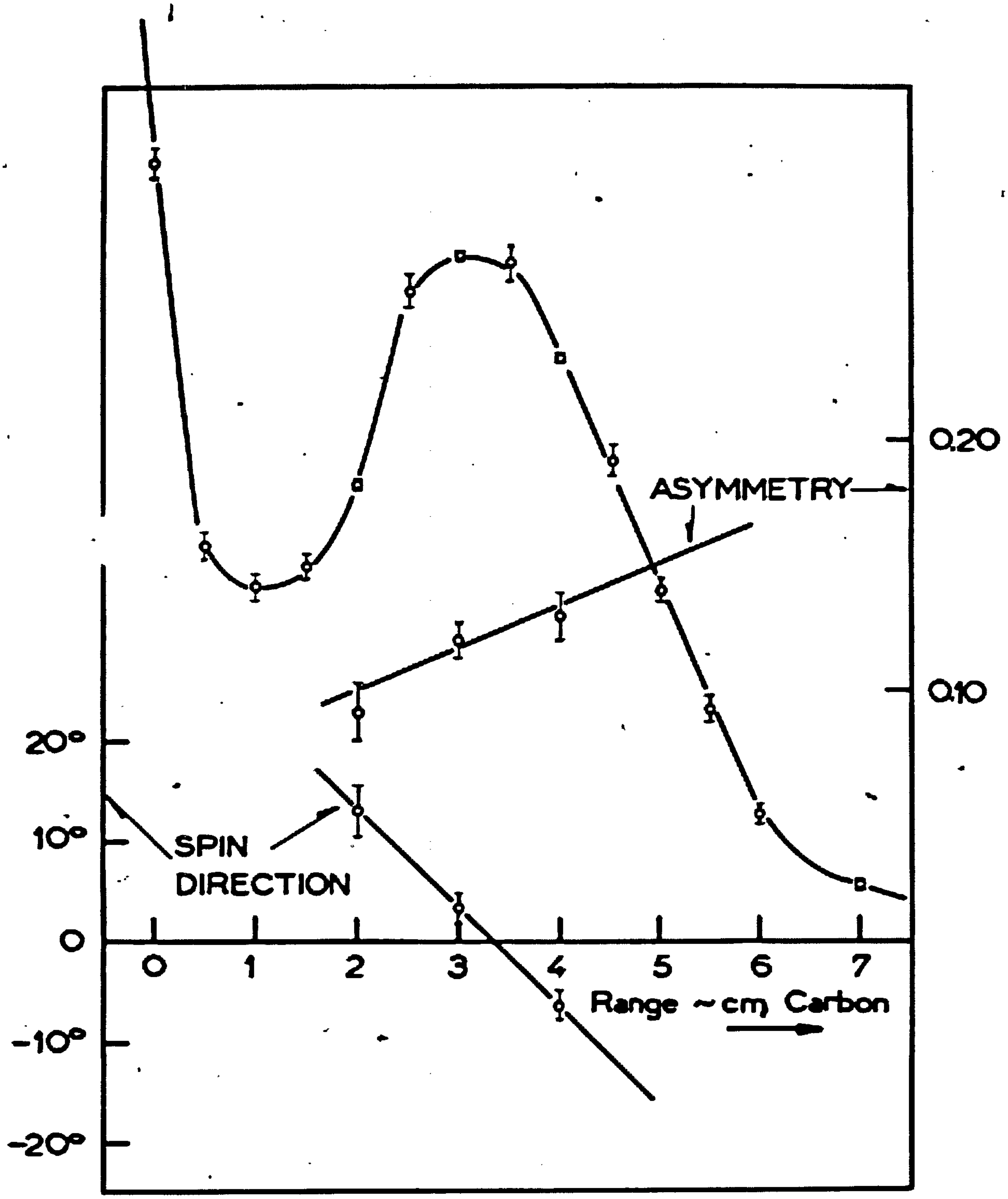


Spin forward - no asymmetry

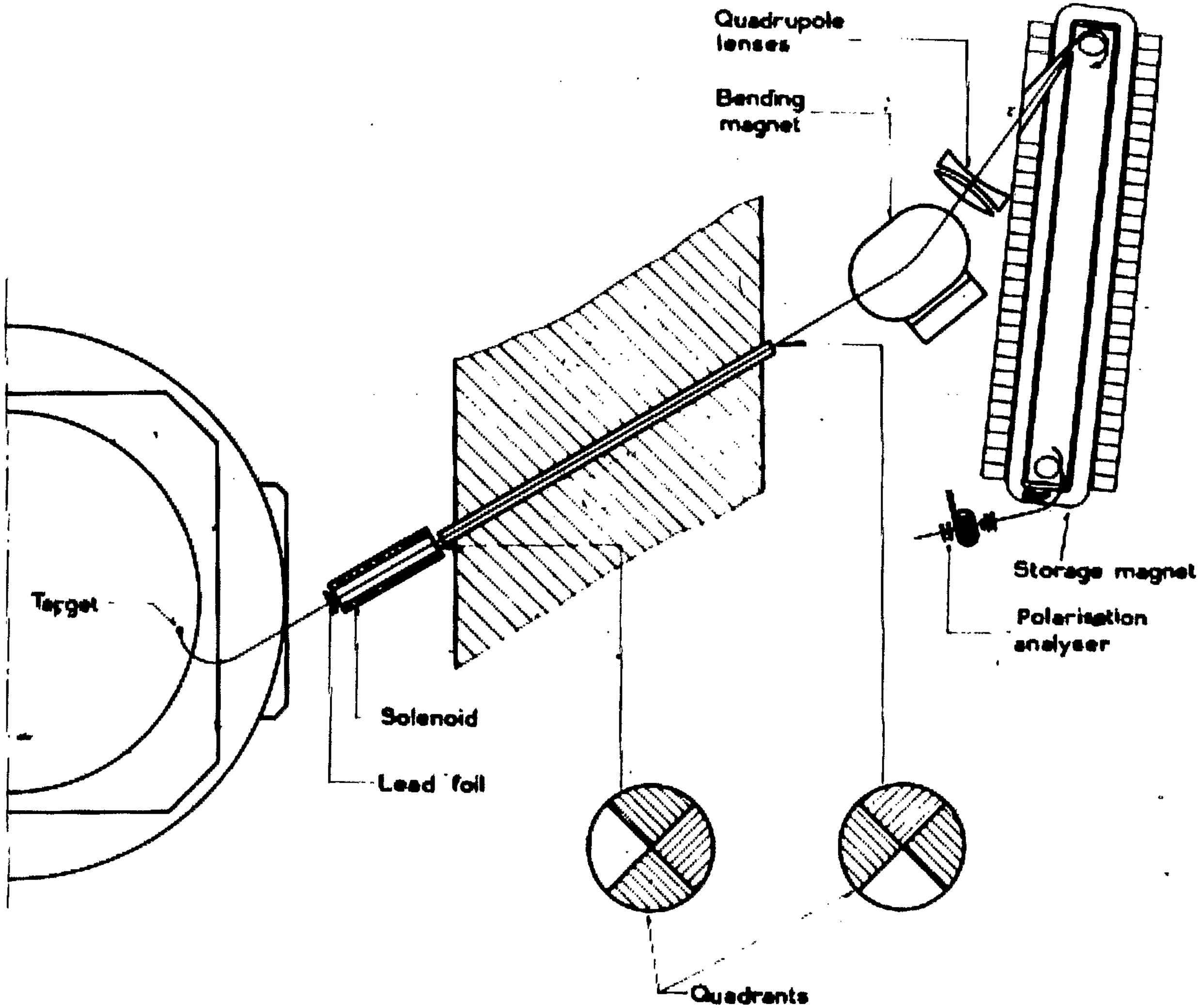
Spin transverse - large asymmetry

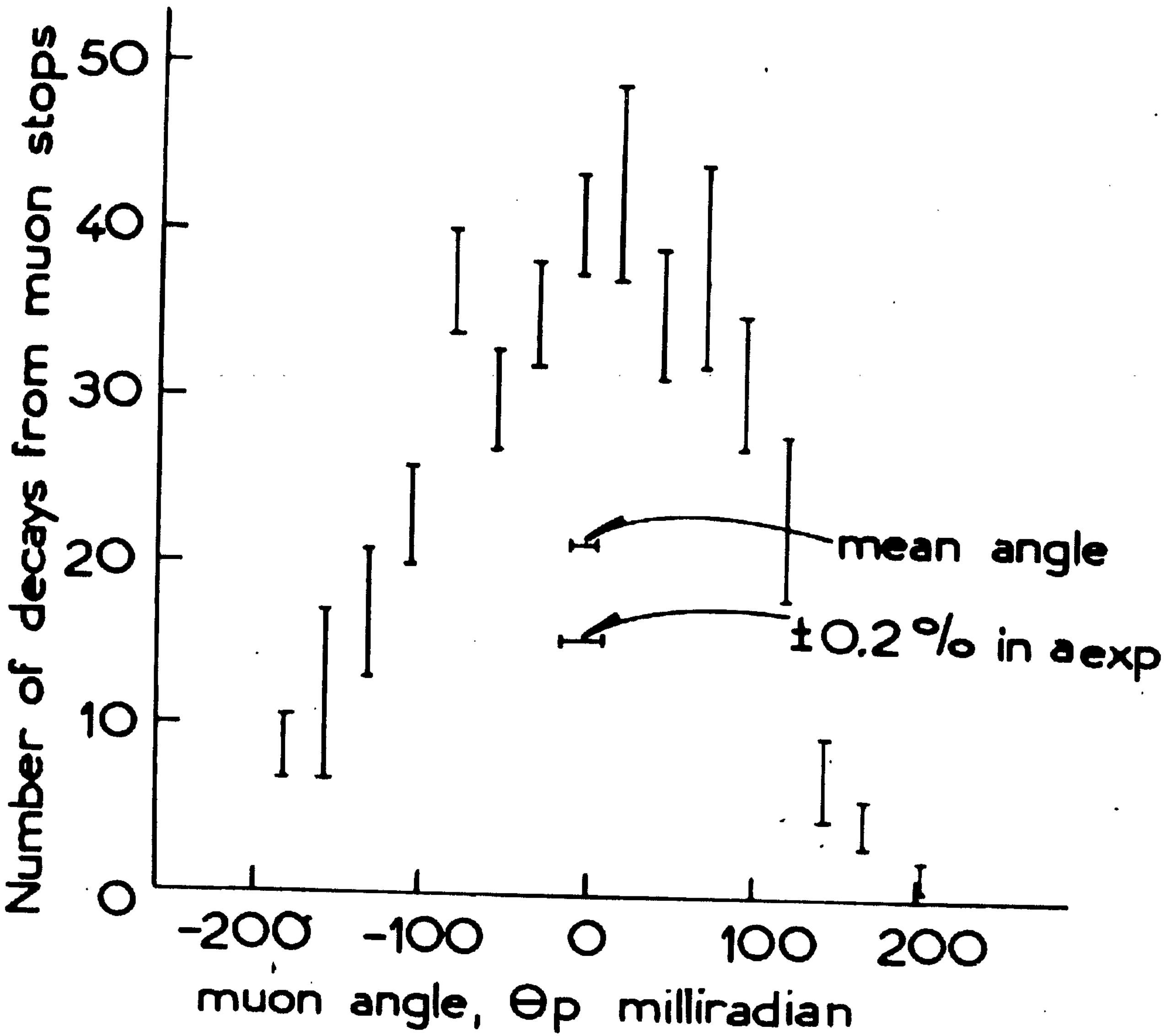
Advantages:

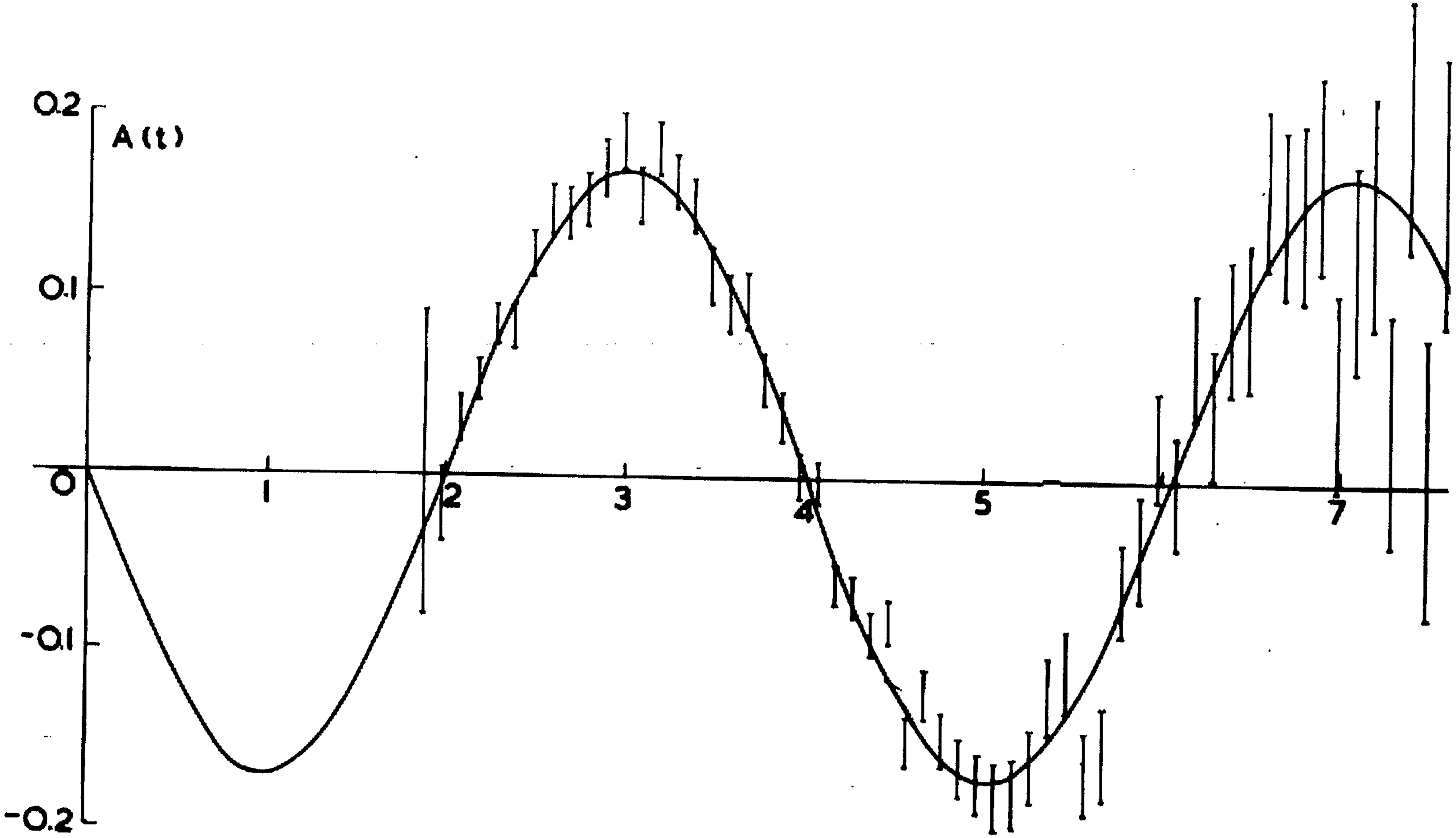
- Flip angle need not be exact
- Telescope efficiency irrelevant



ASYMMETRY
0.20
0.10
20°
10°
0
-10°
-20°
SPIN DIRECTION
0
1
2
3
4
5
6
7
Range ~ cm Carbon


Quadrupole lenses
Bending magnet
Target
Solenoid
Lead foil
Storage magnet
Polarisation analyser
Quadrants


Number of decays from muon stops
50
40
30
20
10
0
-200
-100
0
100
200
muon angle, Θp milliradian
mean angle
±0.2% in aexp


A (t)
0.2
0.1
-0.1
-0.2
0
1
2
3
4
5
7

$$A = \frac{n_+ - n_-}{n_+ + n_-}$$

$$= A_0 \sin \theta_s$$

$$= A_0 \sin\left\{ a\frac{e}{mc}\bar{B}t + \underset{\text{final direction}}{\theta_p} + \underbrace{\theta_s^0 - \theta_p^0}_{\text{initial polarization angle}} \right\}$$

$$\left.\begin{array}{c} \bar{B} \\ \theta_p \\ \theta_s^0 - \theta_p^0 \end{array}\right\} \text{ are all functions of orbit radius (range) \& storage time}$$

$$a = 1162 \pm 5 \times 10^{-6}$$

- Charpak, Farley, Garwin, Muller, Sens, Zichichi
  Nuovo Cimento 37, 1241 (1965)

- Bailey, Bartl, von Bochmann, Brown, Farley, Giesch, Jöstlein, van der Meer, Picasso, Williams
  Nuovo Cimento 9A, 369 (1972)
- Bailey, Borer, Combley, Drumm, Eck, Farley, Field, Flegel, Hattersley, Krienen, Lange, Lebée, McMillan, Petrucci, Picasso, Runolfsson, von Ruden, Williams, Wojcicki
  Nuclear Physics B150, 1 (1979)

Review –

- Farley & Picasso –
  in "Quantum Electrodynamics"
  T. Kinoshita (ed)
  World Scientific, 1990

- **g-2 note #96**

Muon now seen as
heavy electron

QED works
good to any order.

Can we do better?
PS is now running
Dilate lifetime to get
more g-2 cycles

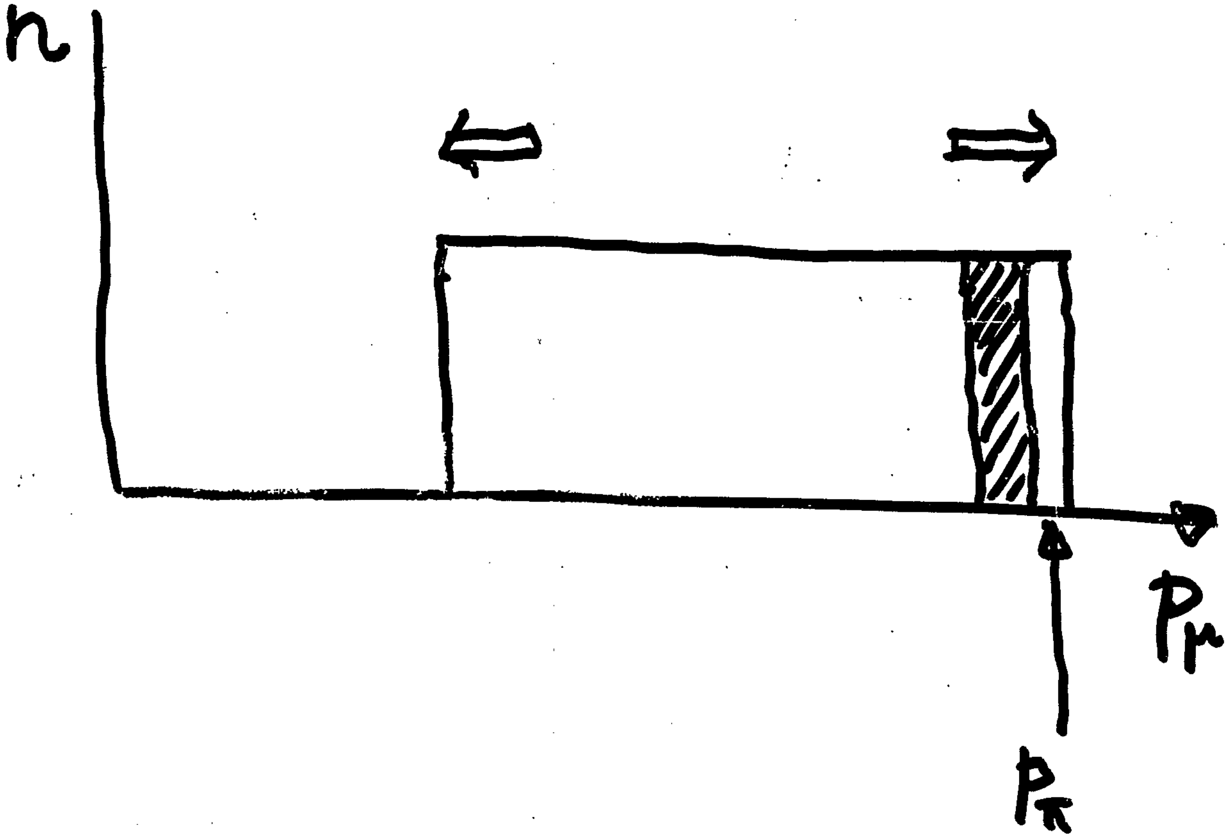
Four miracles of Nature

1) Easy to store muons in a magnetic ring. Just inject pions and wait.

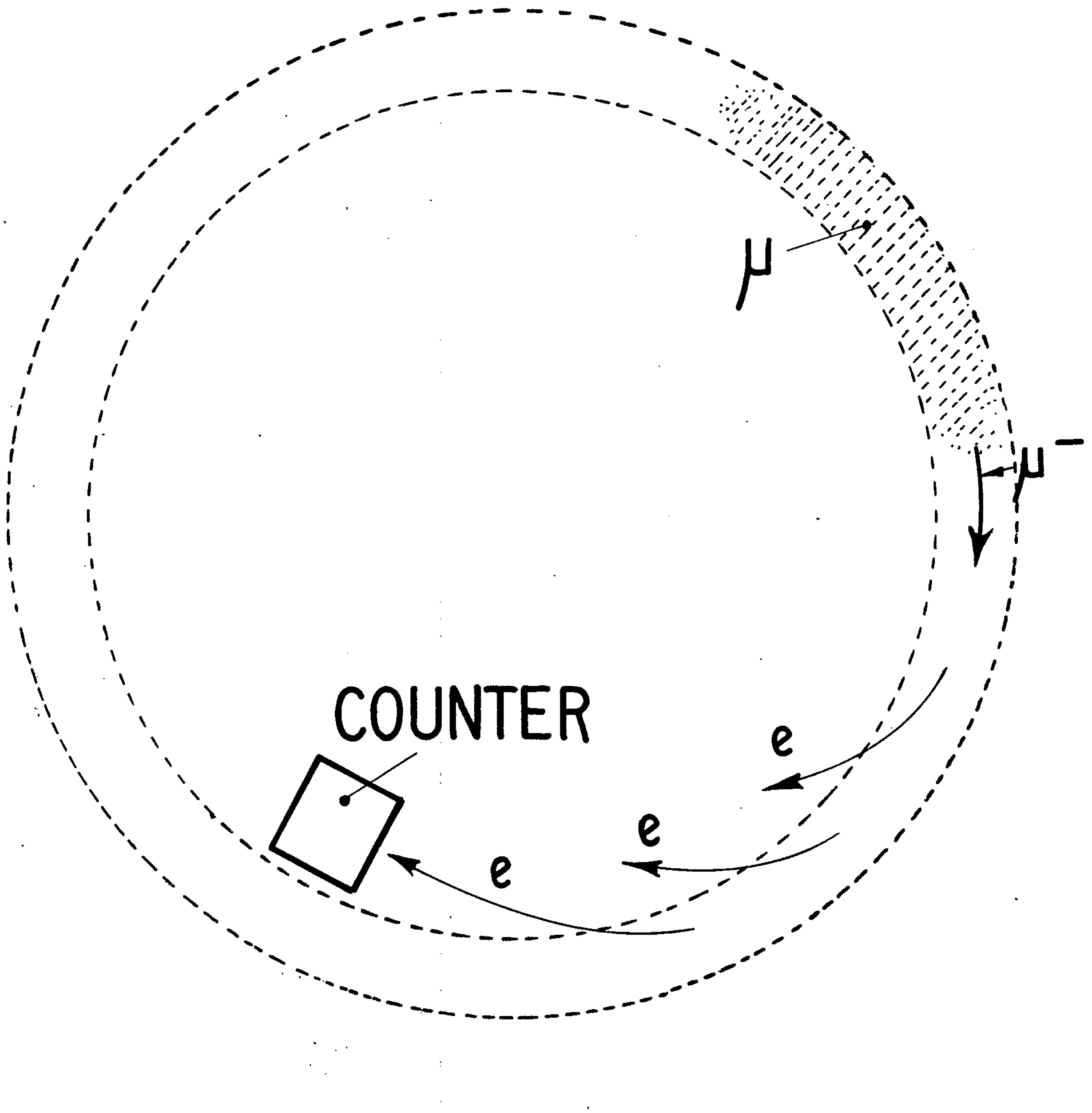
2) The stored muons are longitudinally polarised

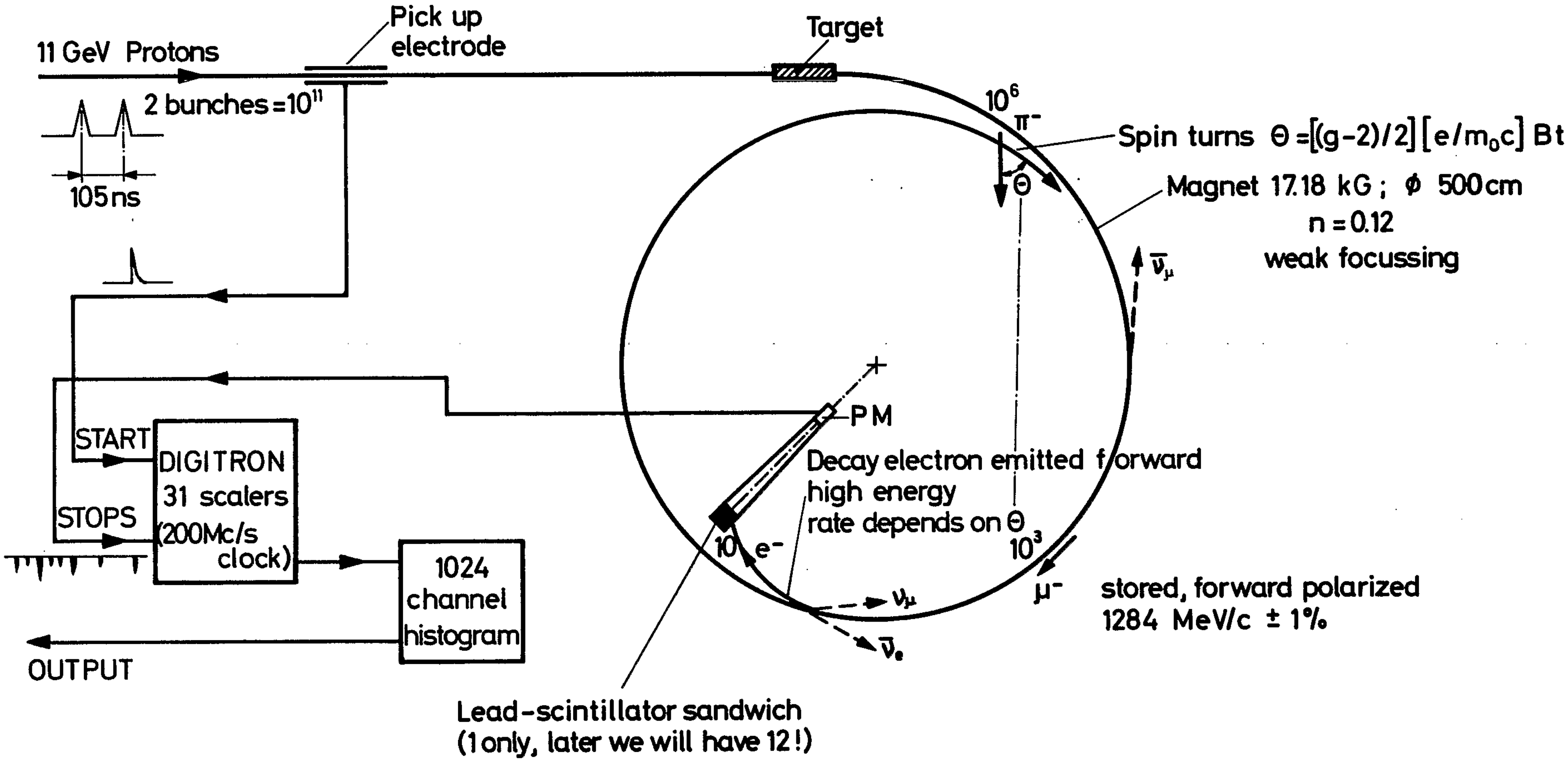
3) Decay electrons come out on the inside of the ring and tell us which way the spin is pointing.

Inject by $\pi - \mu$ decay

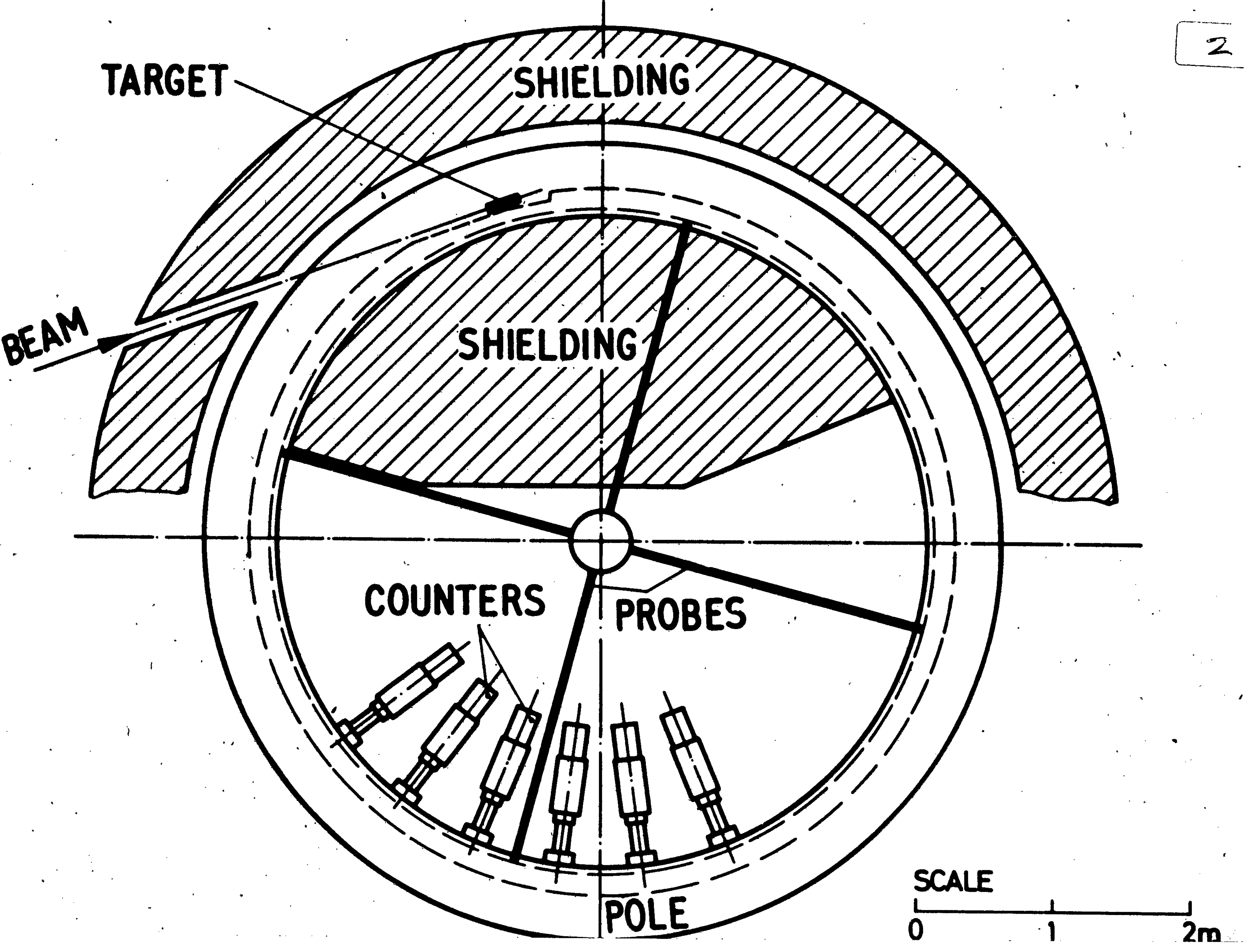


- Inject π for $\frac{1}{2}$ turn
- Forward polarized μ are automatically stored

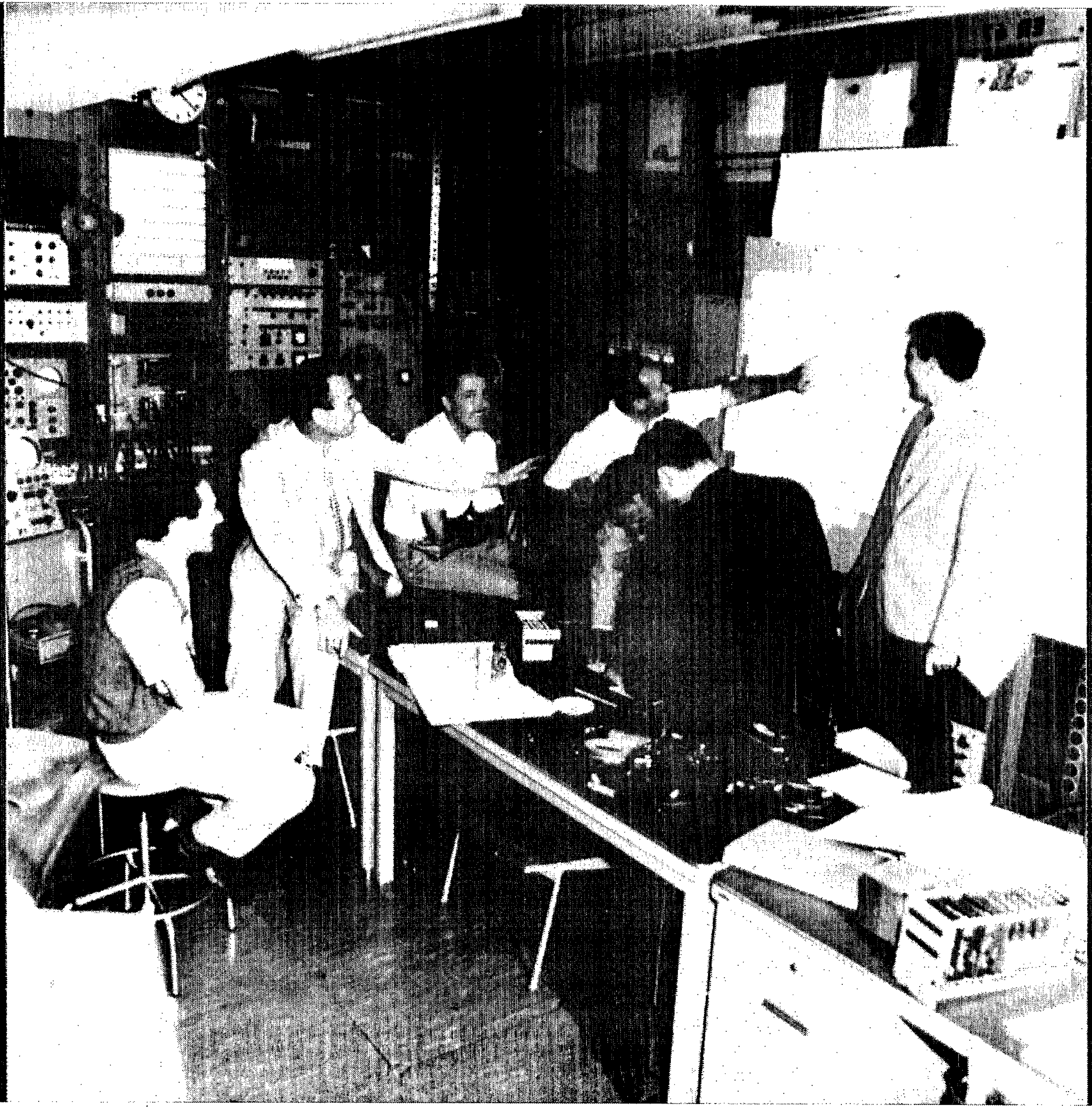

μ
μ⁻
COUNTER
e
e
e

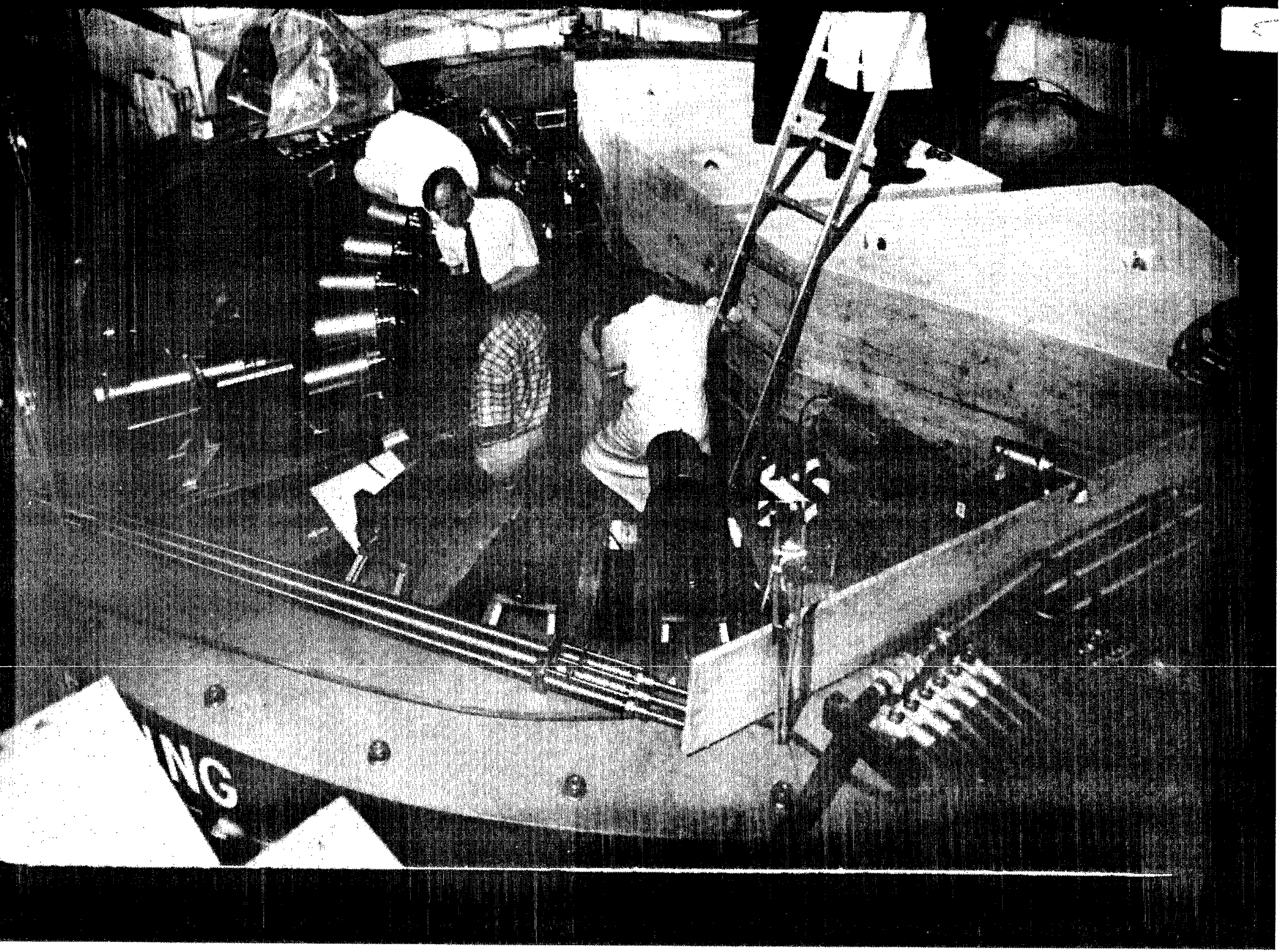

11 GeV Protons
Pick up electrode
Target
2 bunches = 10^{11}
105 ns
10^6 π^-
Spin turns $\Theta = [(g-2)/2]\,[e/m_0c]\,Bt$
Θ
Magnet 17.18 kG ; ϕ 500 cm
n = 0.12
weak focussing
$\bar{\nu}_\mu$
START
STOPS
DIGITRON
31 scalers
(200Mc/s clock)
1024 channel histogram
OUTPUT
PM
Decay electron emitted forward
high energy
rate depends on Θ
10^3
10 e^-
μ^-
stored, forward polarized
1284 MeV/c ± 1%
ν_μ
$\bar{\nu}_e$
Lead-scintillator sandwich
(1 only, later we will have 12!)

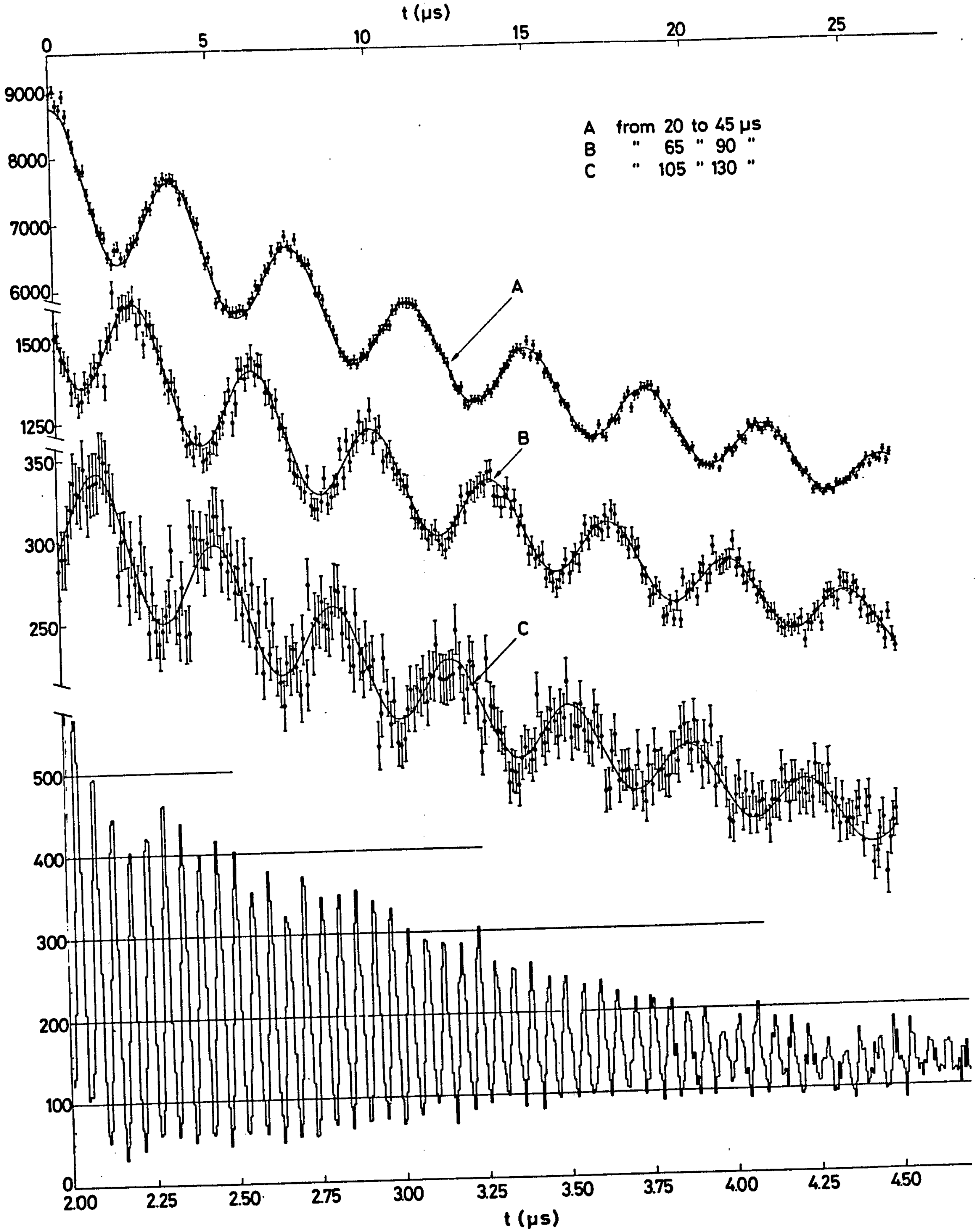
2

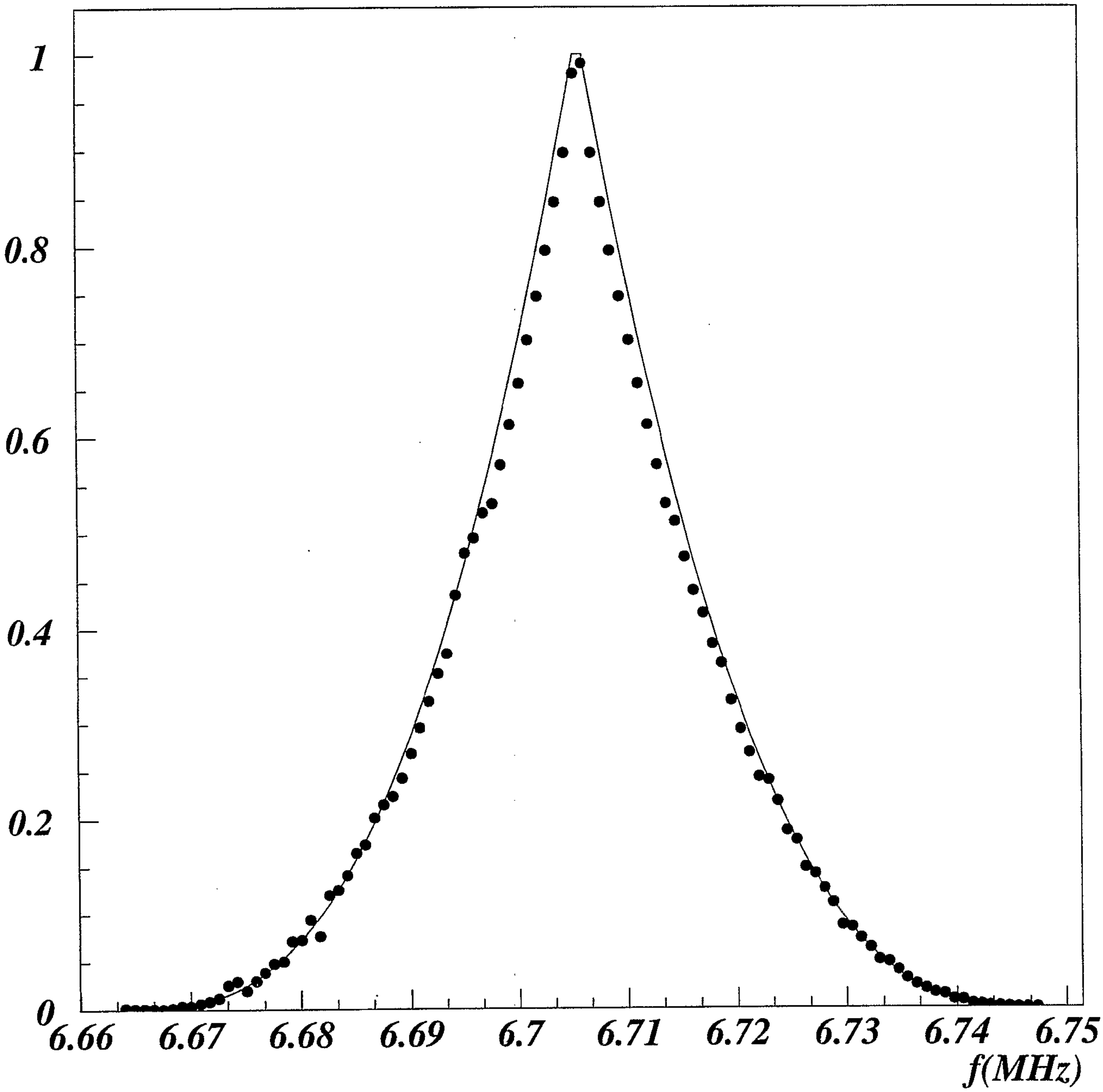

TARGET
SHIELDING
BEAM
SHIELDING
COUNTERS
PROBES
POLE
SCALE
0
1
2m

3




NG


t (μs)
0
5
10
15
20
25
9000
8000
7000
6000
1500
1250
350
300
250
A from 20 to 45 μs
B " 65 " 90 "
C " 105 " 130 "
A
B
C
500
400
300
200
100
0
2.00
2.25
2.50
2.75
3.00
3.25
3.50
3.75
4.00
4.25
4.50
t (μs)


1
0.8
0.6
0.4
0.2
0
6.66
6.67
6.68
6.69
6.7
6.71
6.72
6.73
6.74
6.75
f(MHz)

$a = 1162 \pm 5 \times 10^{-6}$

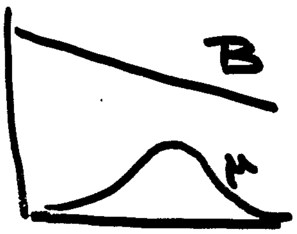
$a = 116\,616\,(31) \times 10^{-8}$

450 ± 270 ppm

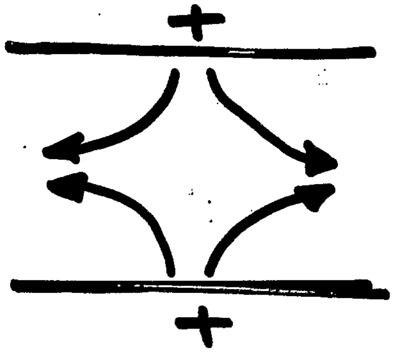
$\longrightarrow 240 \pm 270$ ppm

Vertical focusing

- Magnetic gradient would create error in B



- Use electric quadrupole



- Radial electric field does not affect spin motion if

$$\gamma = \sqrt{1 + \frac{1}{a}} = 29.3$$

$$p_\mu = 3.094 \text{ GeV}/c$$

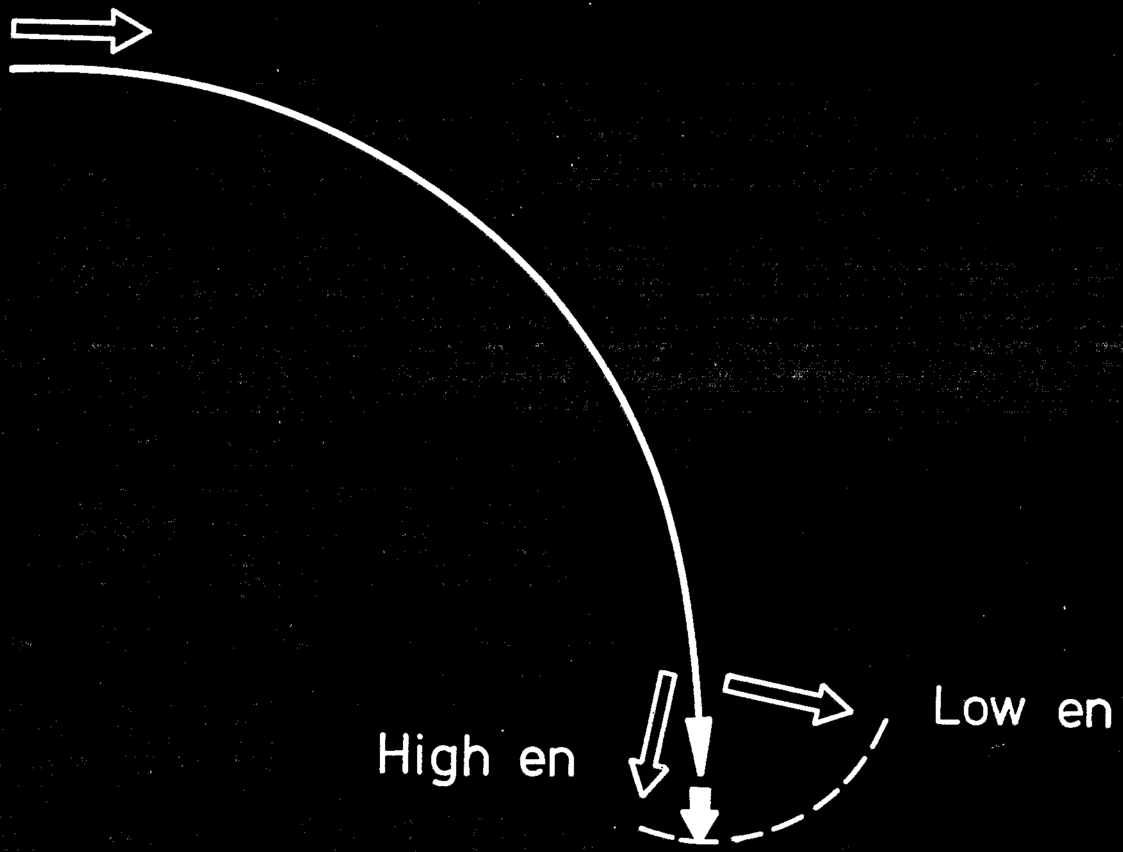
MAGIC GAMMA

- UNIFORM B

  ELECTRIC FOCUSING

$$\theta = \theta_s^* - \theta_i^* - \theta_p = a_\mu \left(\frac{e}{mc}\right) Bt\,[1 + (\beta - 1/a_\mu\beta\gamma^2)(E_r/B)]$$

RADIAL ELECTRIC FIELD



$$\gamma = \sqrt{\frac{1}{a} + 1} \quad = 29{\cdot}304$$

$$E_\mu = 3{\cdot}096 \text{ GeV}$$

$$f_a' / f_a = 1 + \left(\beta - \frac{1}{a\beta\gamma^2}\right) E/B$$

IMPROVEMENTS

Uniform B, electric focusing

Pion injection

40 point NMR stabilizer

Grinding magnet pole

Electric scraping

3 GeV $\tau \rightarrow 64\ \mu s$

Nuclear Physics B150 (1979) 1–75
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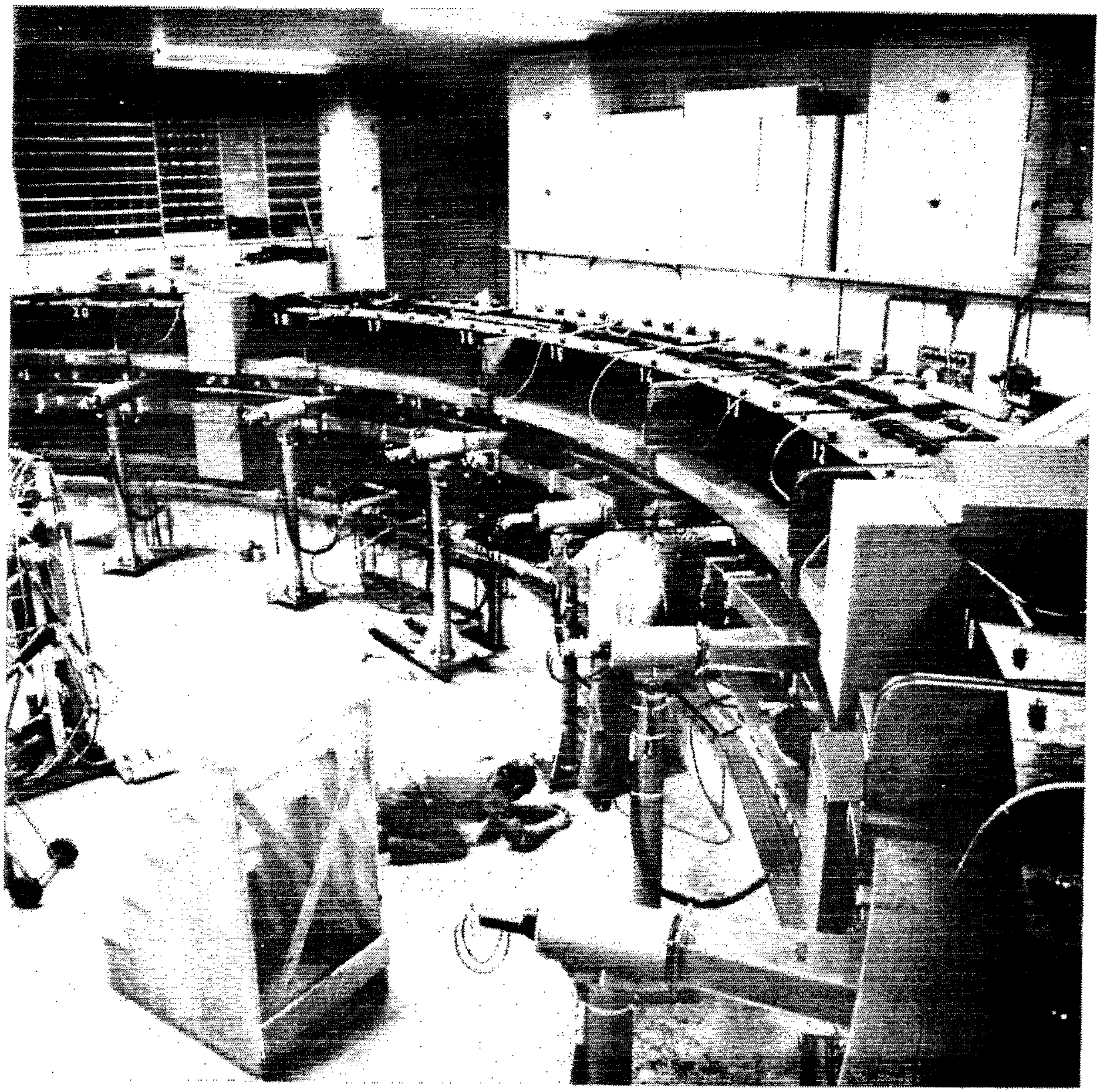
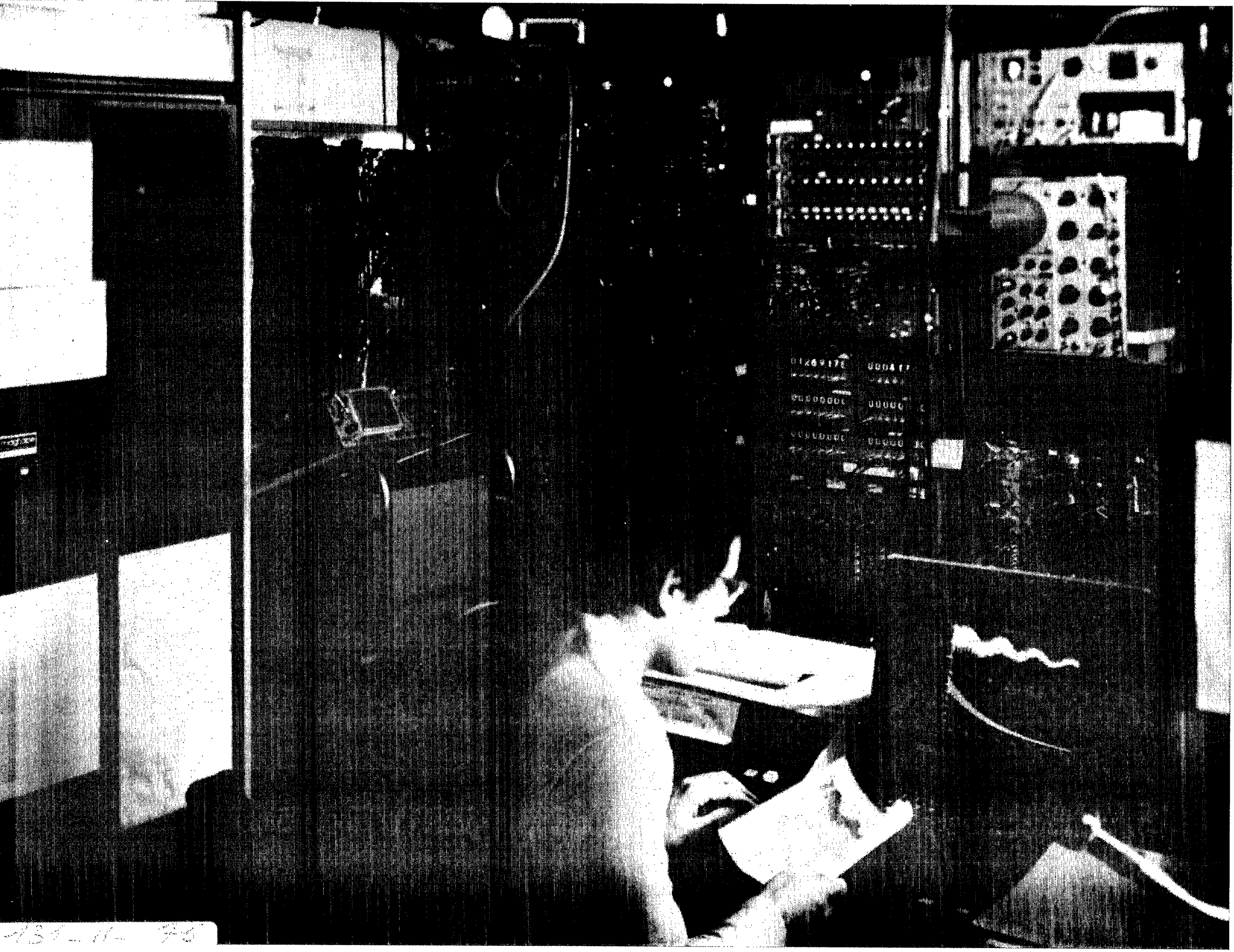
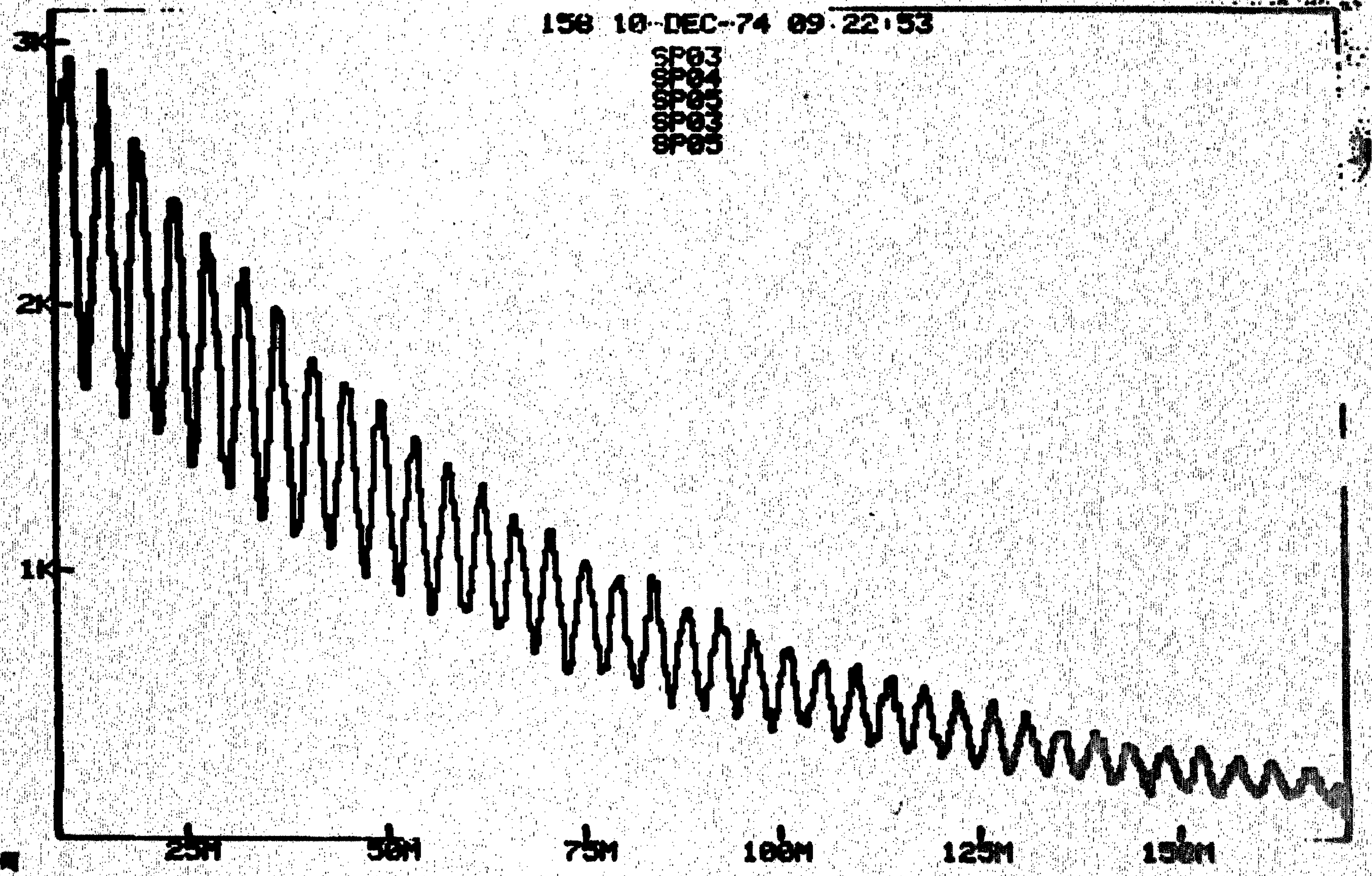
FINAL REPORT ON THE CERN MUON STORAGE RING INCLUDING THE ANOMALOUS MAGNETIC MOMENT AND THE ELECTRIC DIPOLE MOMENT OF THE MUON, AND A DIRECT TEST OF RELATIVISTIC TIME DILATION

J. BAILEY 1), K. BORER 2), F. COMBLEY 3), H. DRUMM 4), C. ECK 4), F.J.M. FARLEY 5), J.H. FIELD 6), W. FLEGEL 6), P.M. HATTERSLEY 7), F. KRIENEN 6), F. LANGE 4), G. LEBÉE 6), E. McMILLAN 8), G. PETRUCCI 6), E. PICASSO 6), O. RÚNOLFSSON 6), W. von RÜDEN 4), R.W. WILLIAMS 9) and S. WOJCICKI 10)
CERN-Mainz-Daresbury Collaboration


20
19
17
16
15
14
13
12

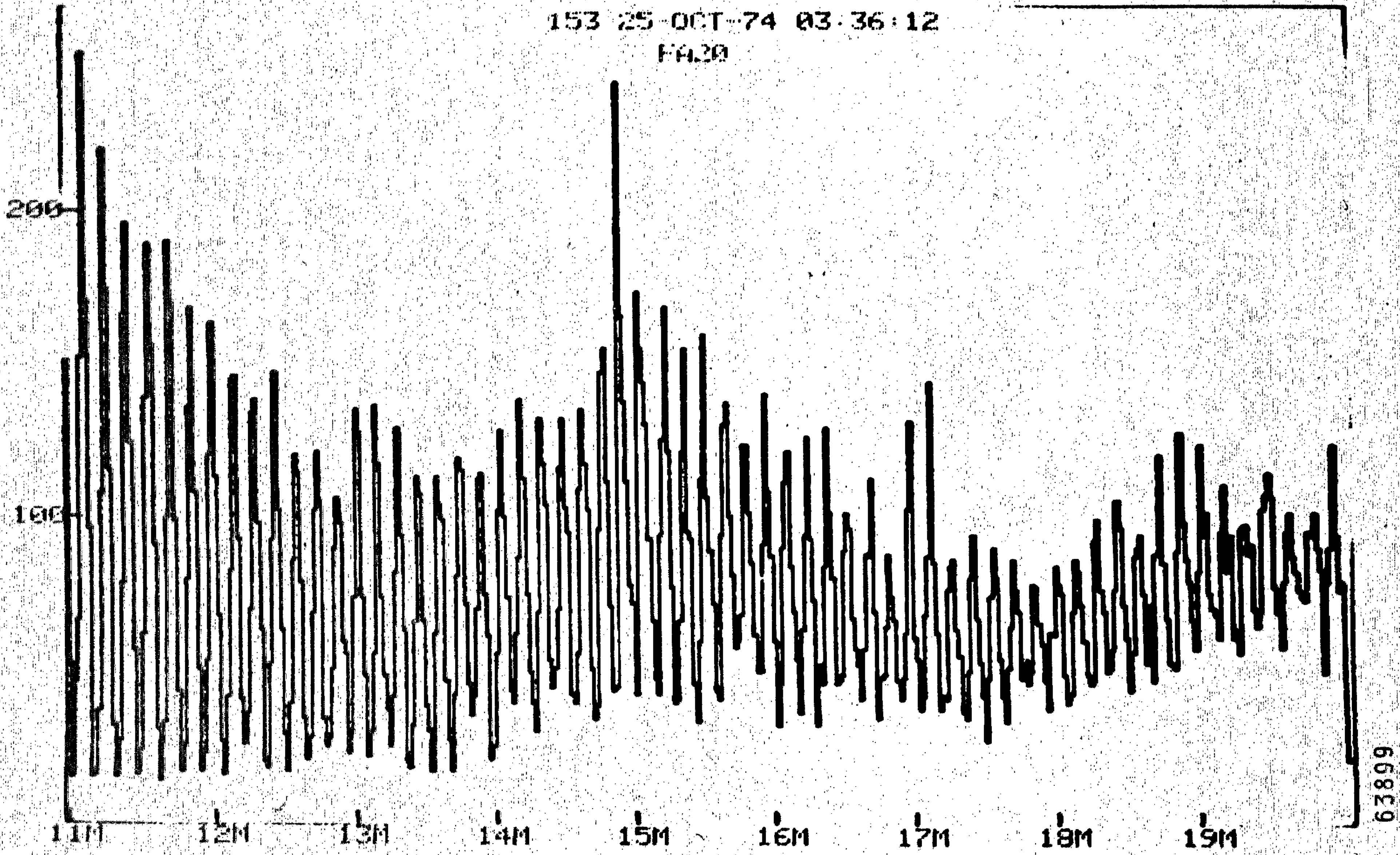


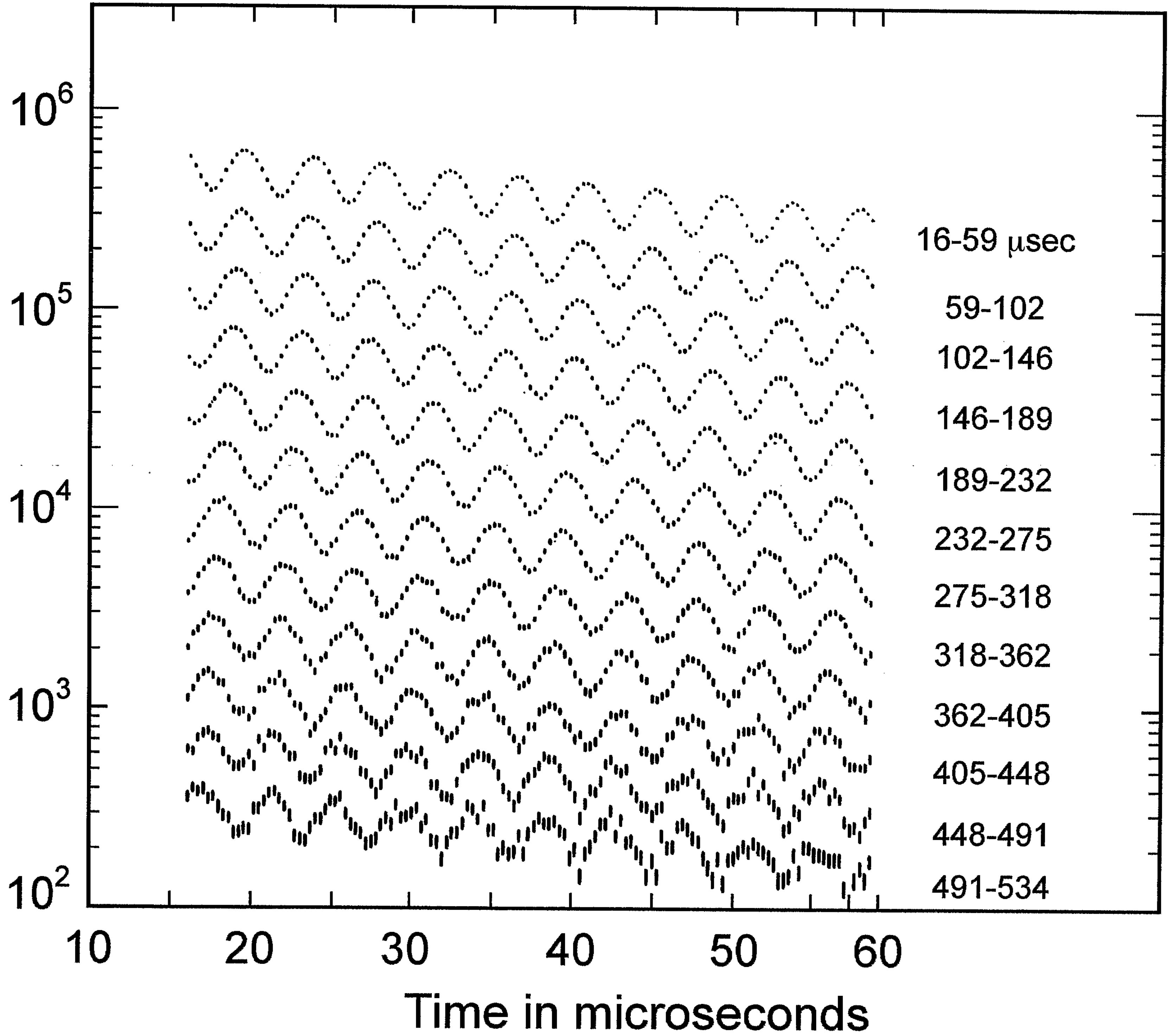
-137-11-78


158 10-DEC-74 09:22:53
SP03
SP04
SP05
SP03
SP05
3K
2K
1K
25M
50M
75M
100M
125M
150M

63915

10


153 25-OCT-74 03:36:12
FA20
200
100
11M
12M
13M
14M
15M
16M
17M
18M
19M
63899



10^6
10^5
10^4
10^3
10^2
10
20
30
40
50
60
Time in microseconds
16-59 μsec
59-102
102-146
146-189
189-232
232-275
275-318
318-362
362-405
405-448
448-491
491-534

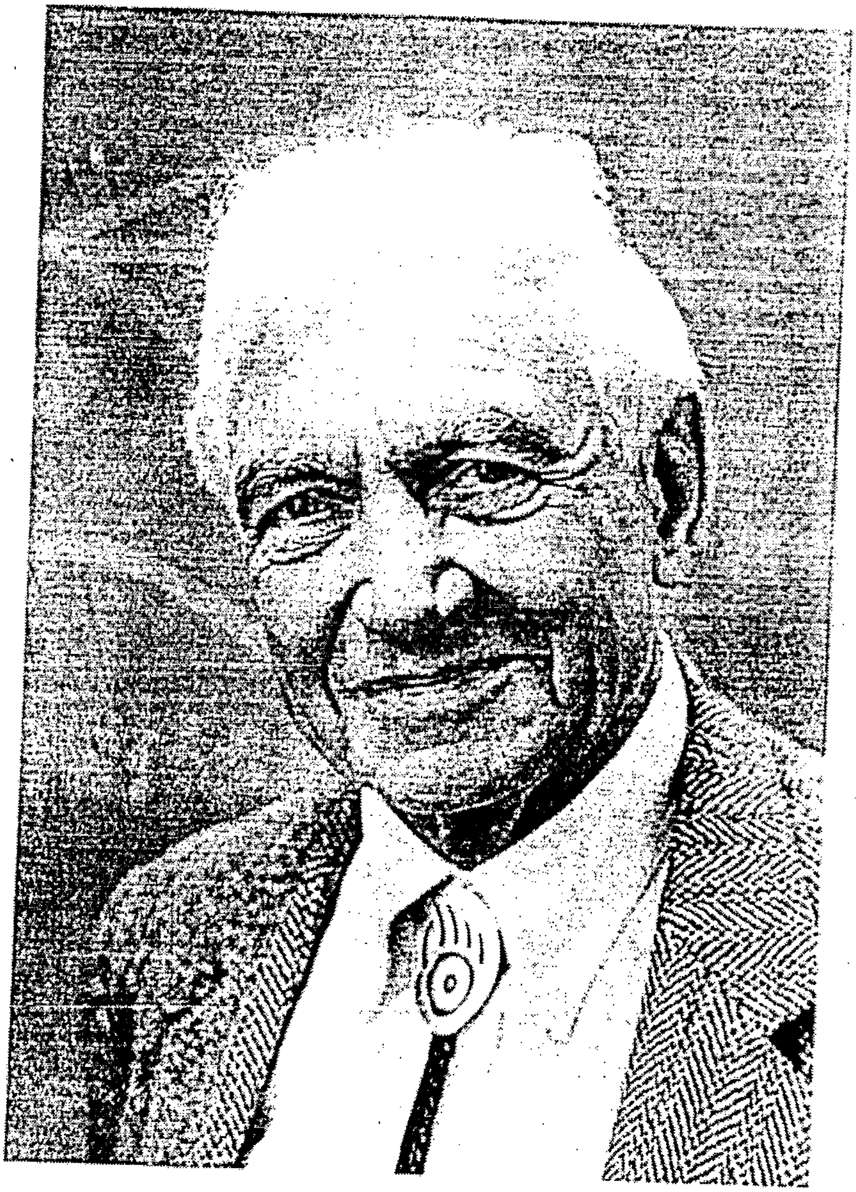


Figure 24 At Brookhaven National Laboratory, summer 1984. *Standing, from left:* Gordon Danby, John Field, Francis Farley, Emilio Picasso, and Frank Krienen; *kneeling, from left:* John Bailey, Vernon Hughes, and Fred Combley.

/

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Precise Measurement of the Positive Muon Anomalous Magnetic Moment

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Muon (g − 2) Collaboration
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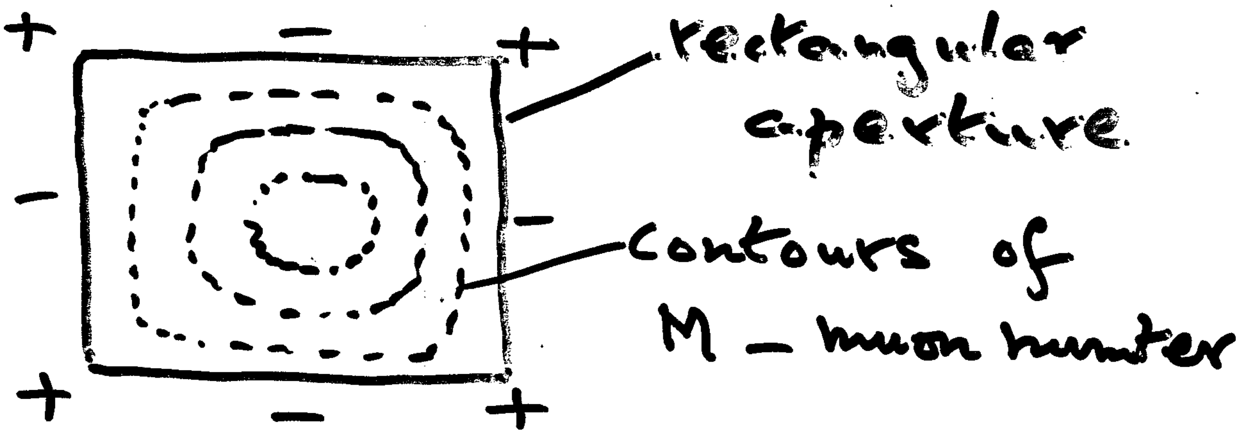
20 × more events
Better knowledge of magnetic field

Review article:
Farley & Picasso in QED (1990)

Improvements introduced in BNL 821

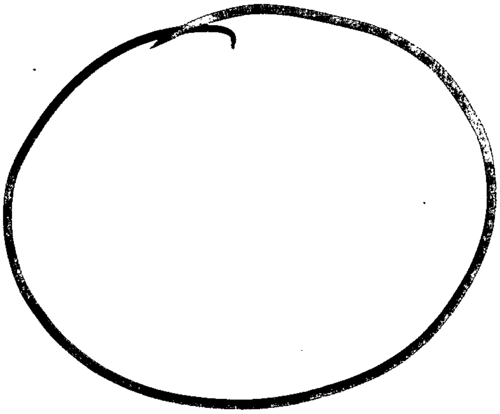
Larger magnet aperture	Field more uniform
Superconducting coils	Field more stable
Pole face windings	To trim field
Trolley with NMR probes in vacuum	
Pulsed NMR good to 0.1 ppm	
Circular magnet aperture for muons	$\langle B \rangle$ less sensitive to multipoles
Trace back to find mu position	
Superconducting inflector	
Muon injection	More stored mu, less flash
Muon kicker	
Improved electric quadrupoles	Avoid resonances, no losses
Scalloped vacuum chamber	Higher asymmetry
Increase in primary proton intensity	
Many counter channels	Reduce overlap at high rates
12 separate fills per AGS cycle	" " " "



I_4 is large – $r^4 \cos 4\theta$

∴ 4^{th} multipole of field must be small

I_8, I_{12} also large !!



Circular aperture

Higher moments all small

Multipoles of field do not matter – $\overline{B}$ stays same

Magnetic field averaged in azimuth, expanded as multipoles

$$B = \sum c_n r^n \cos(n\theta)$$

Muon distribution $M(r,\theta)$

$$\overline{B} = \sum_n \int M(r,\theta) c_n r^n \cos(n\theta)\, r\, dr\, d\theta$$

$$= \sum_n c_n \int M(r,\theta)\, r^n \cos(n\theta)\, r\, dr\, d\theta$$

$$= \sum_n c_n I_n$$

$$I_n = \int M(r,\theta)\, r^n \cos(n\theta)\, r\, dr\, d\theta$$

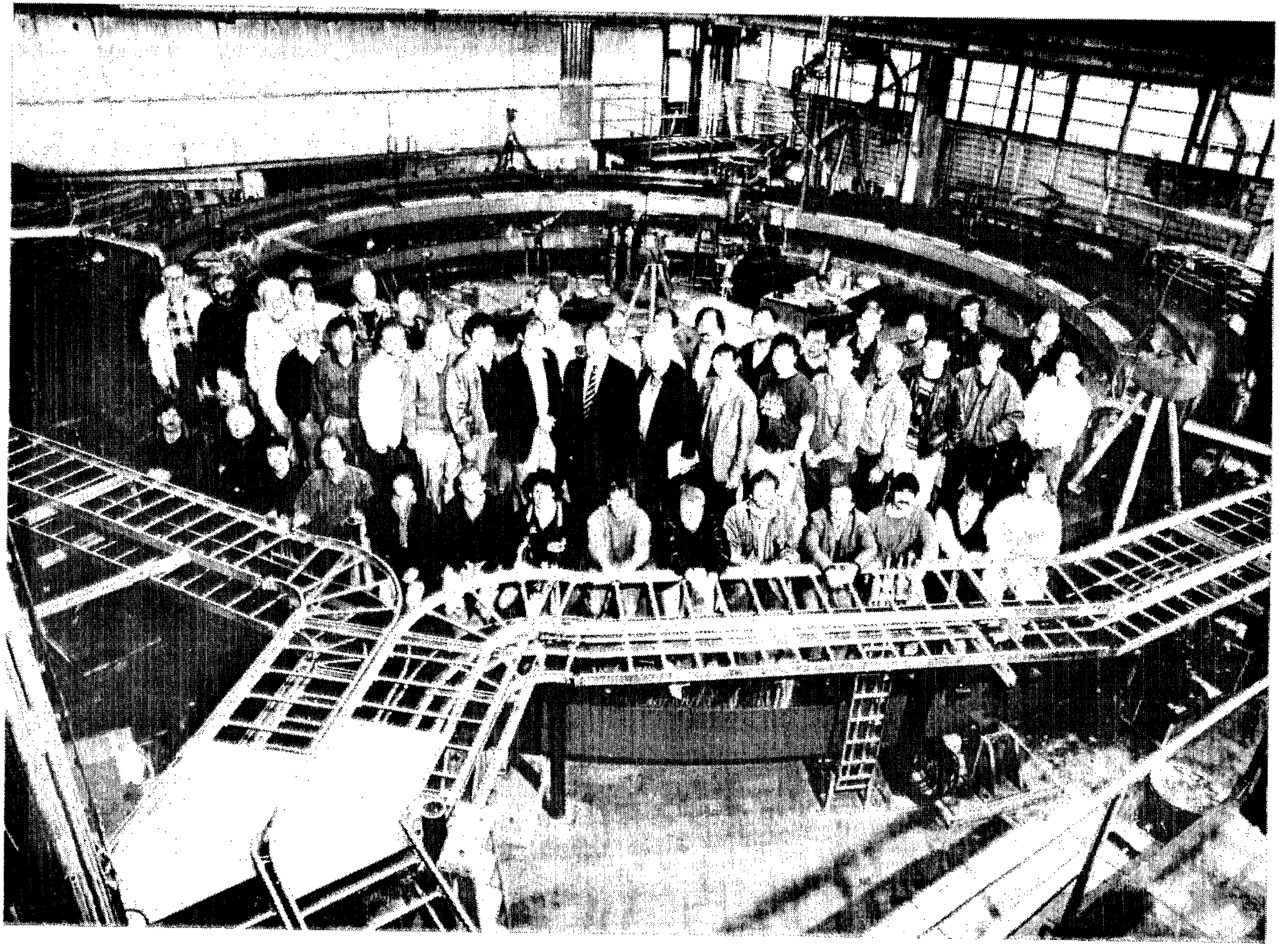
I_n is n th moment of the muon distribution

n th moment only couples to multipole of same n

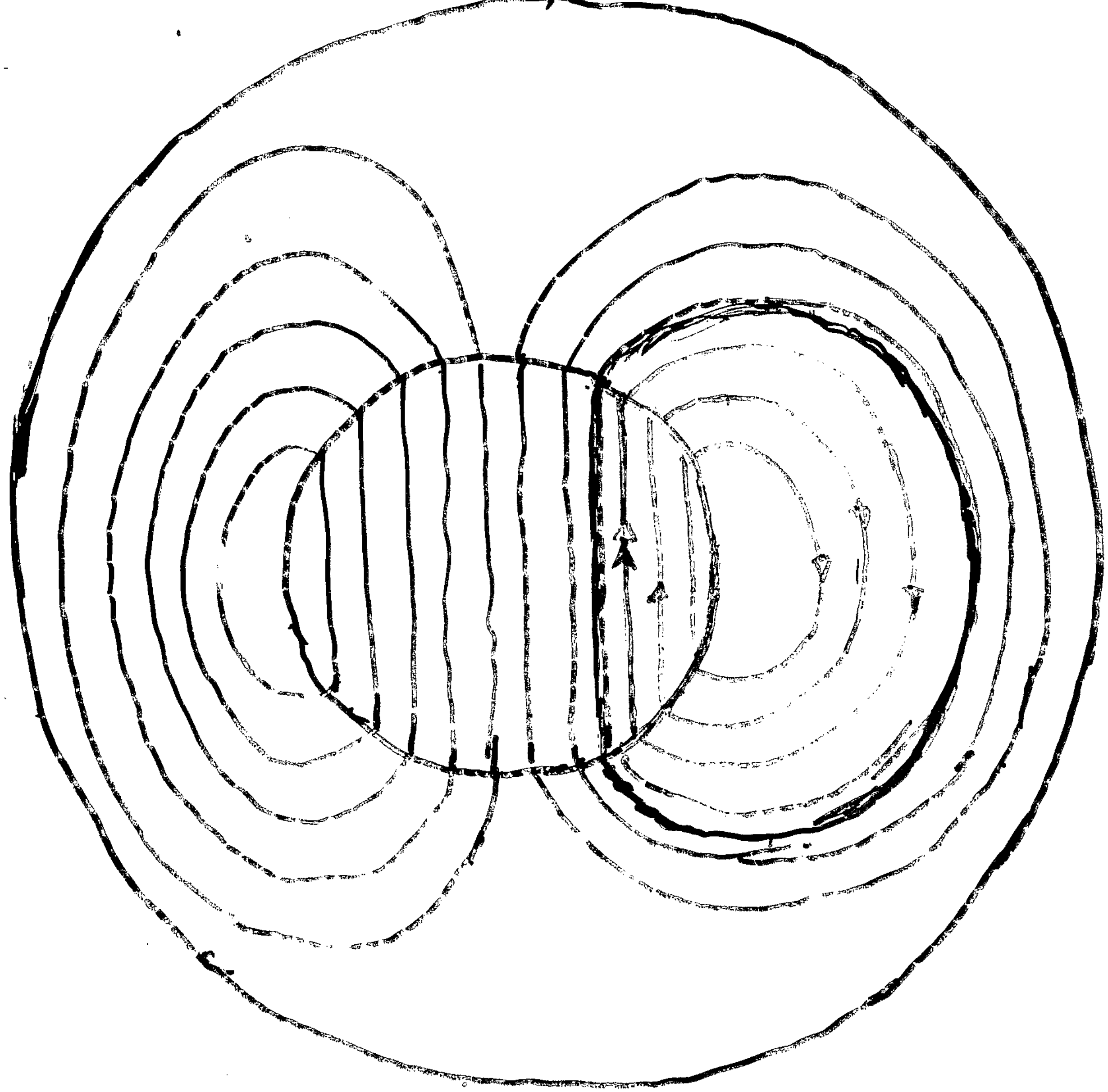
If I_n is small, higher multipoles do not change $\overline{B}$

g-2

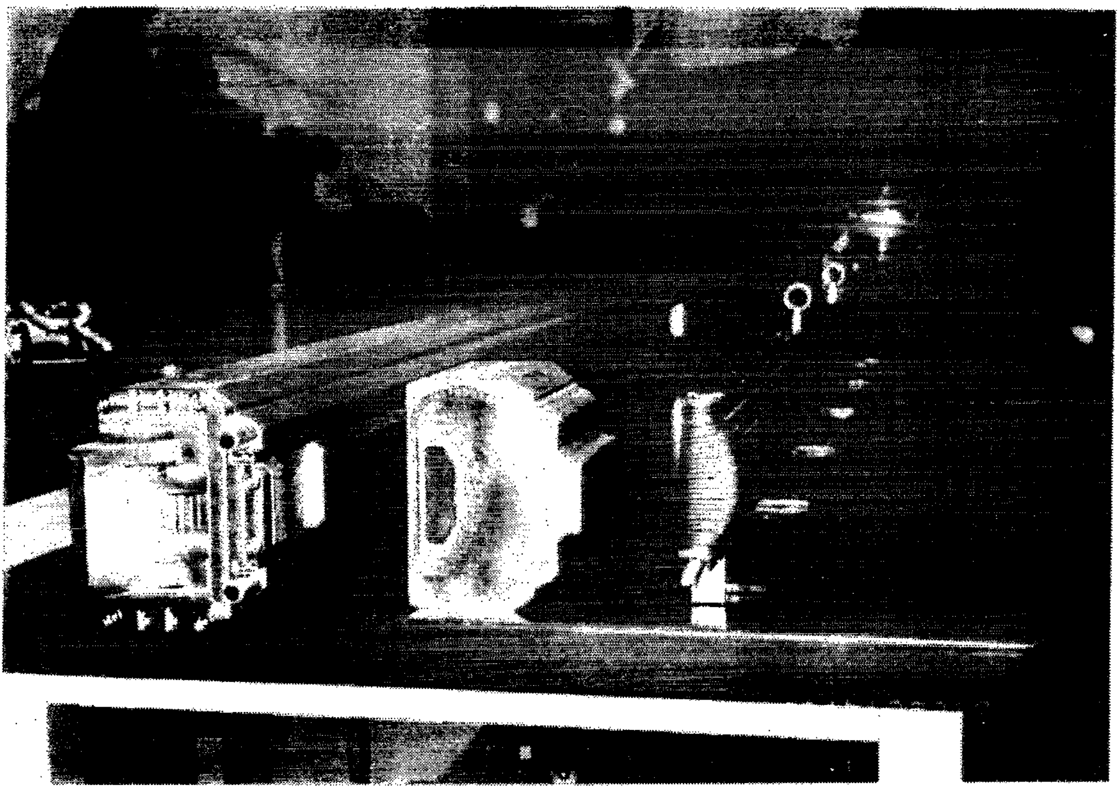
photo RIPP BOWMAN

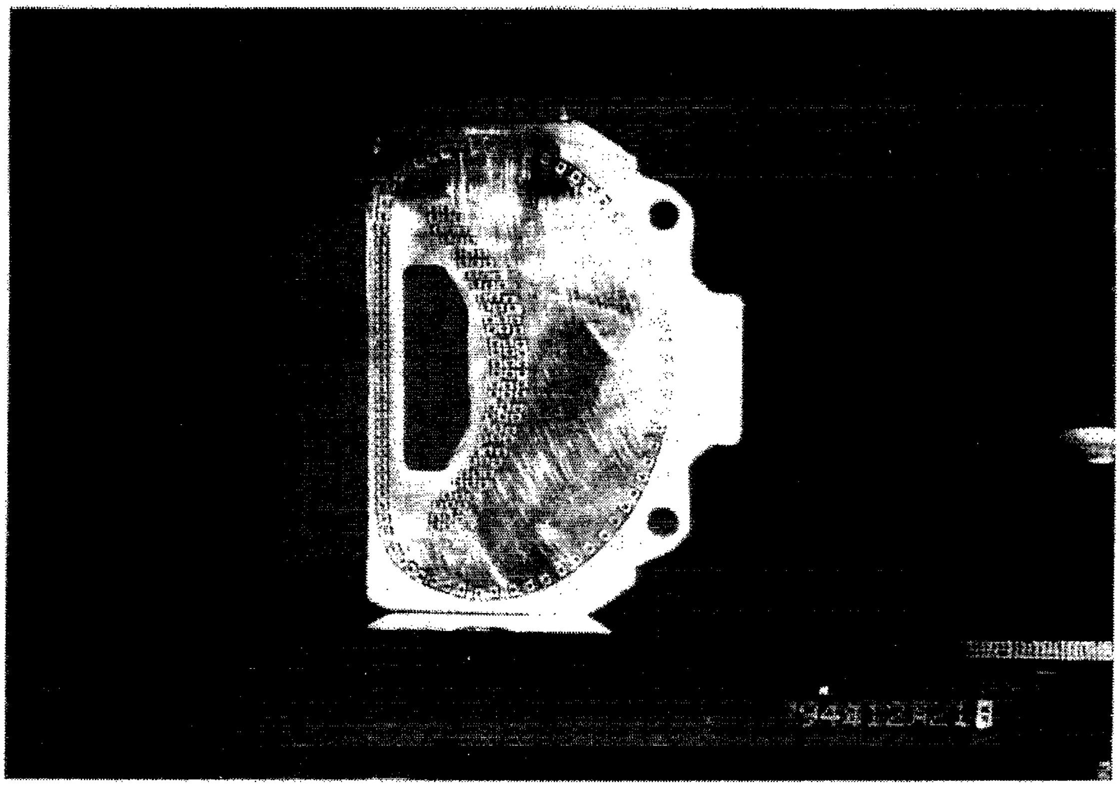


FRANK KRIENEN



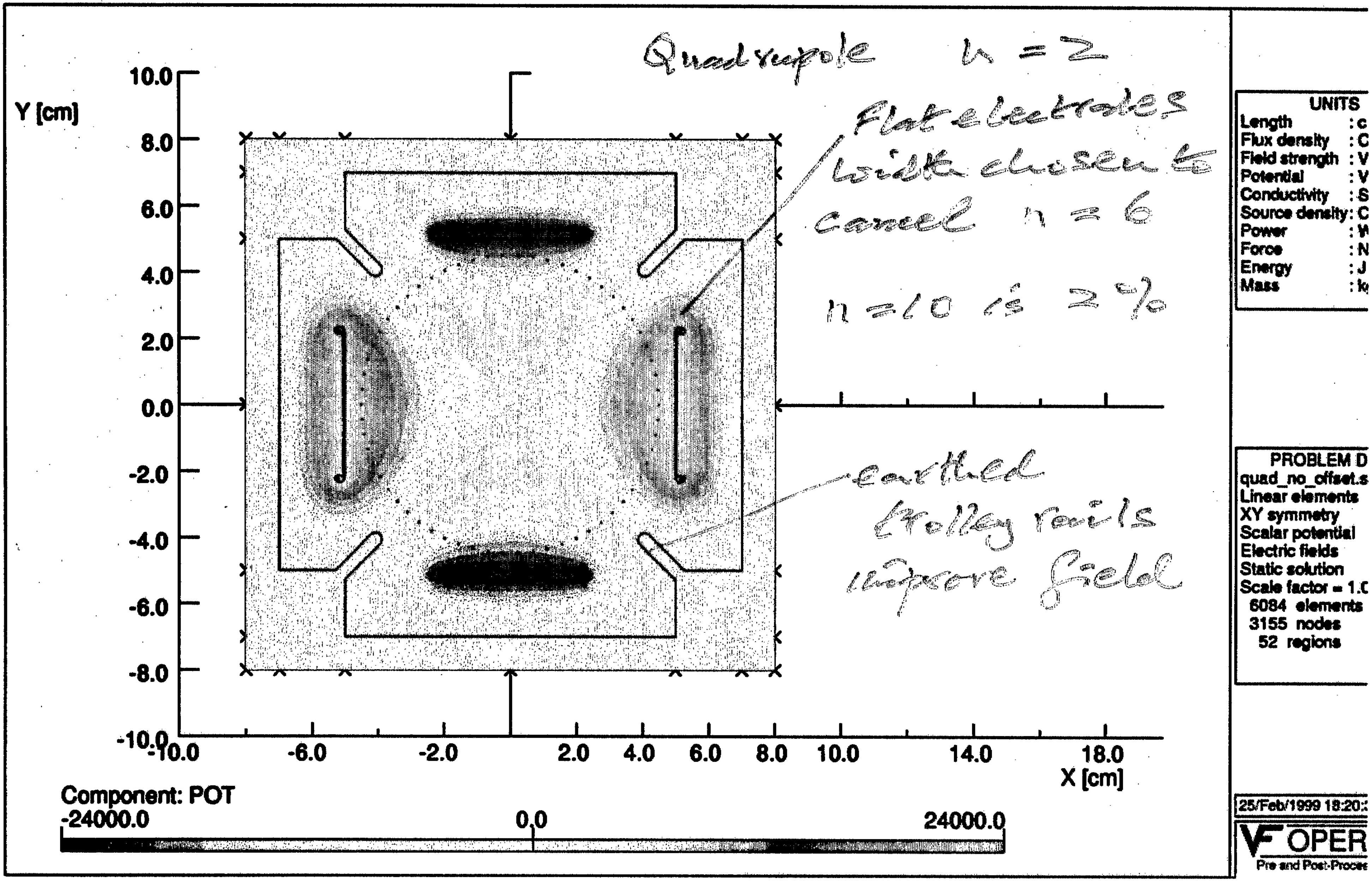
SUPERCONDUCTING INFLECTOR




'94 12 21

SEMERTZIDIS

$V = x^n \cos n\theta$

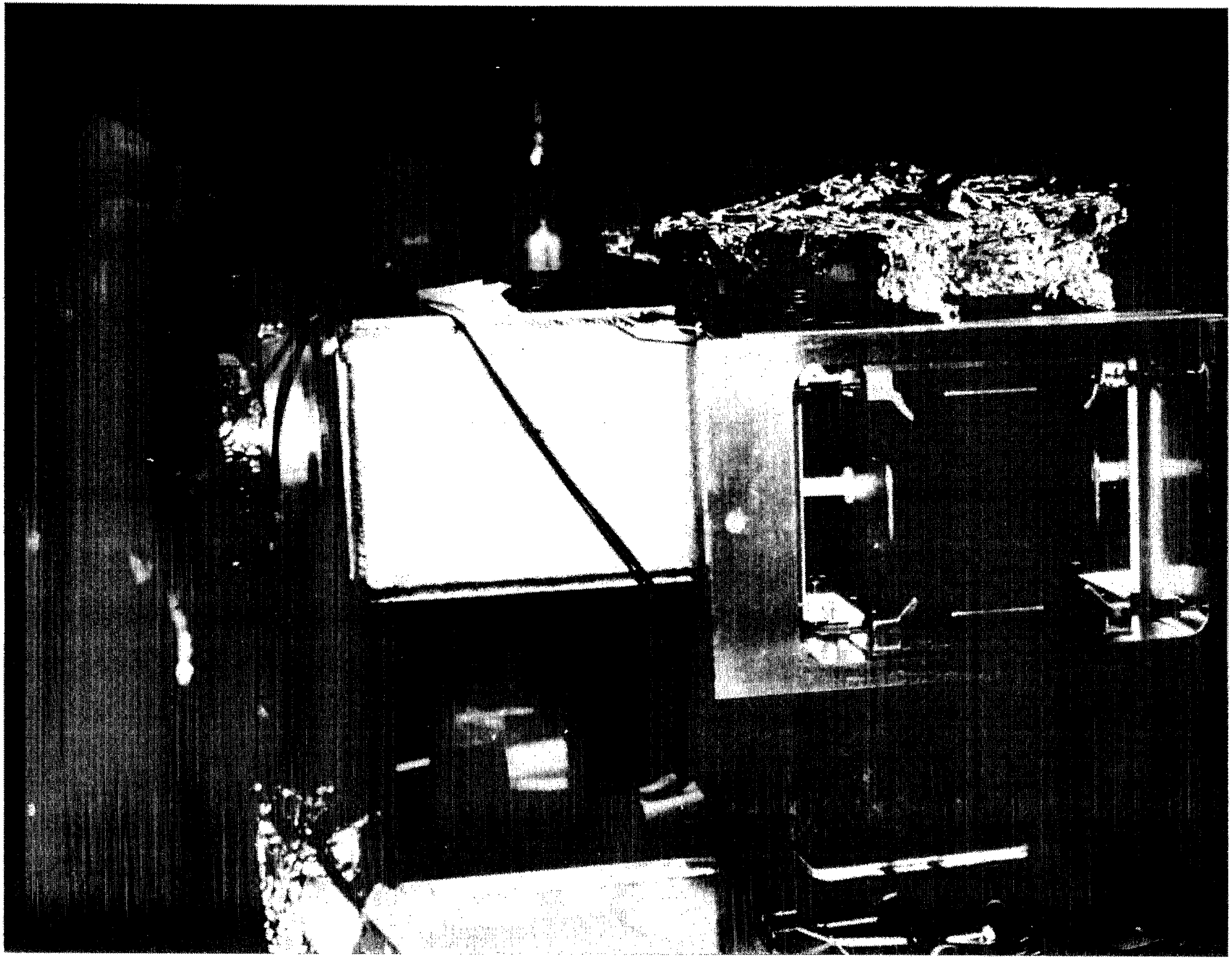


Quadrupole $n = 2$

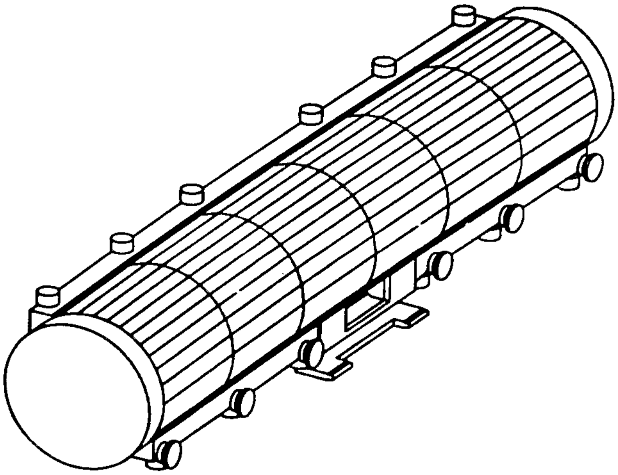
Flat electrodes width chosen to cancel $n = 6$

$n = 10$ is 2%

earthed trolley rails improve field



Alex Grossmann } Heidelberg
Klaus Jungmann
Ralf Prigl



Runs on rails

Pulled by cable

Goes through

Quadrupoles

Kicker

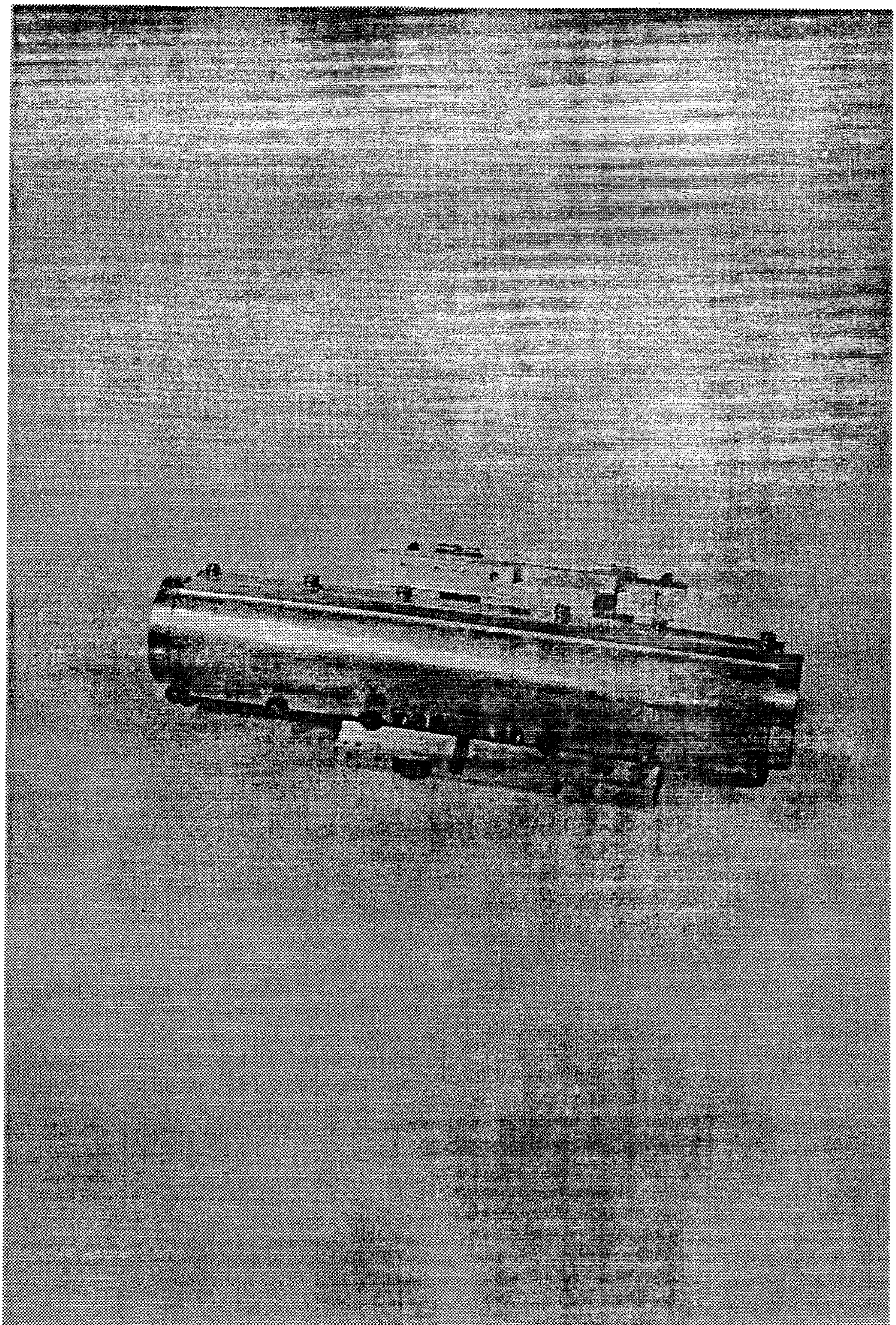
Pick up electrodes

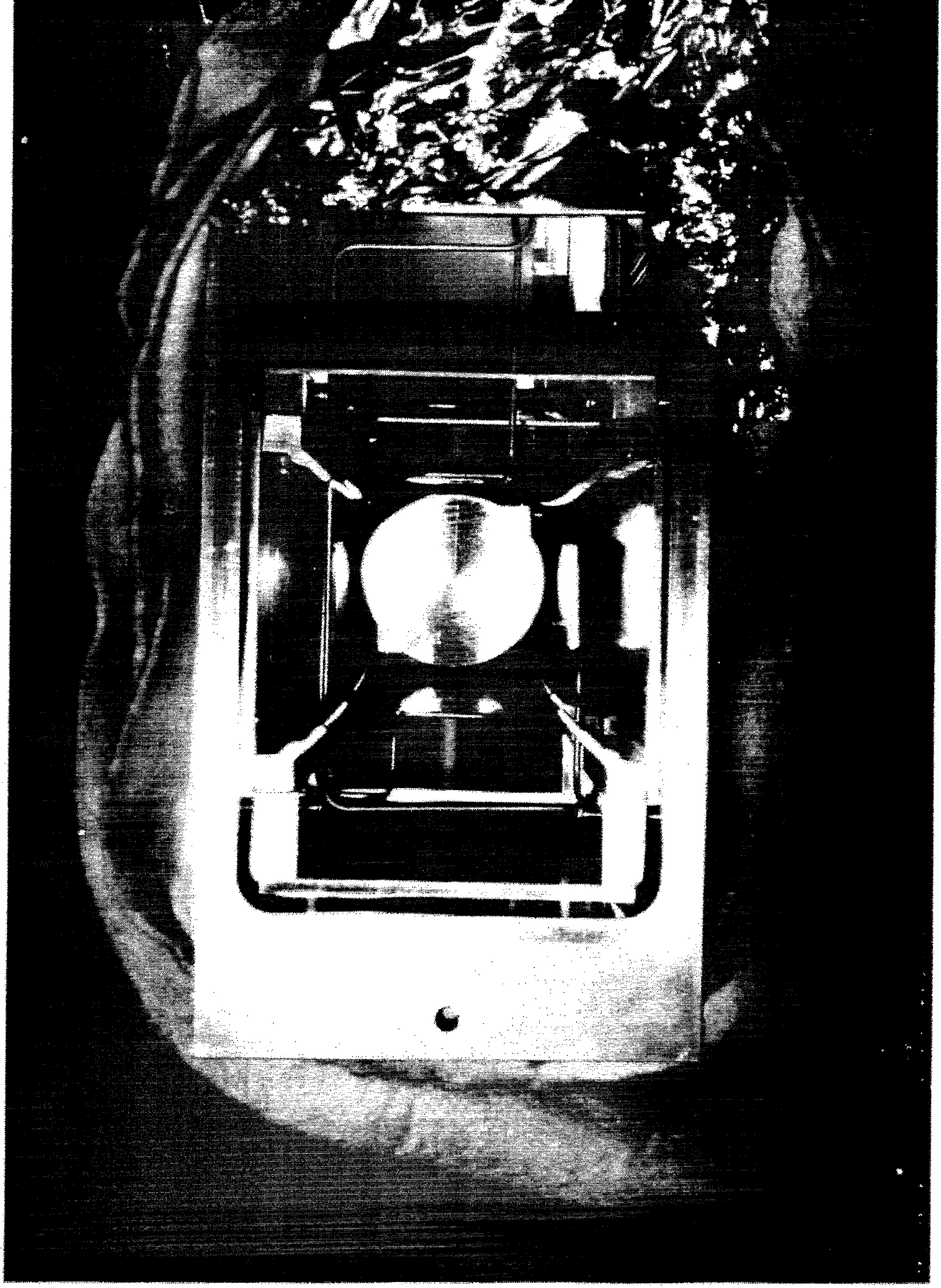
A tour de force !

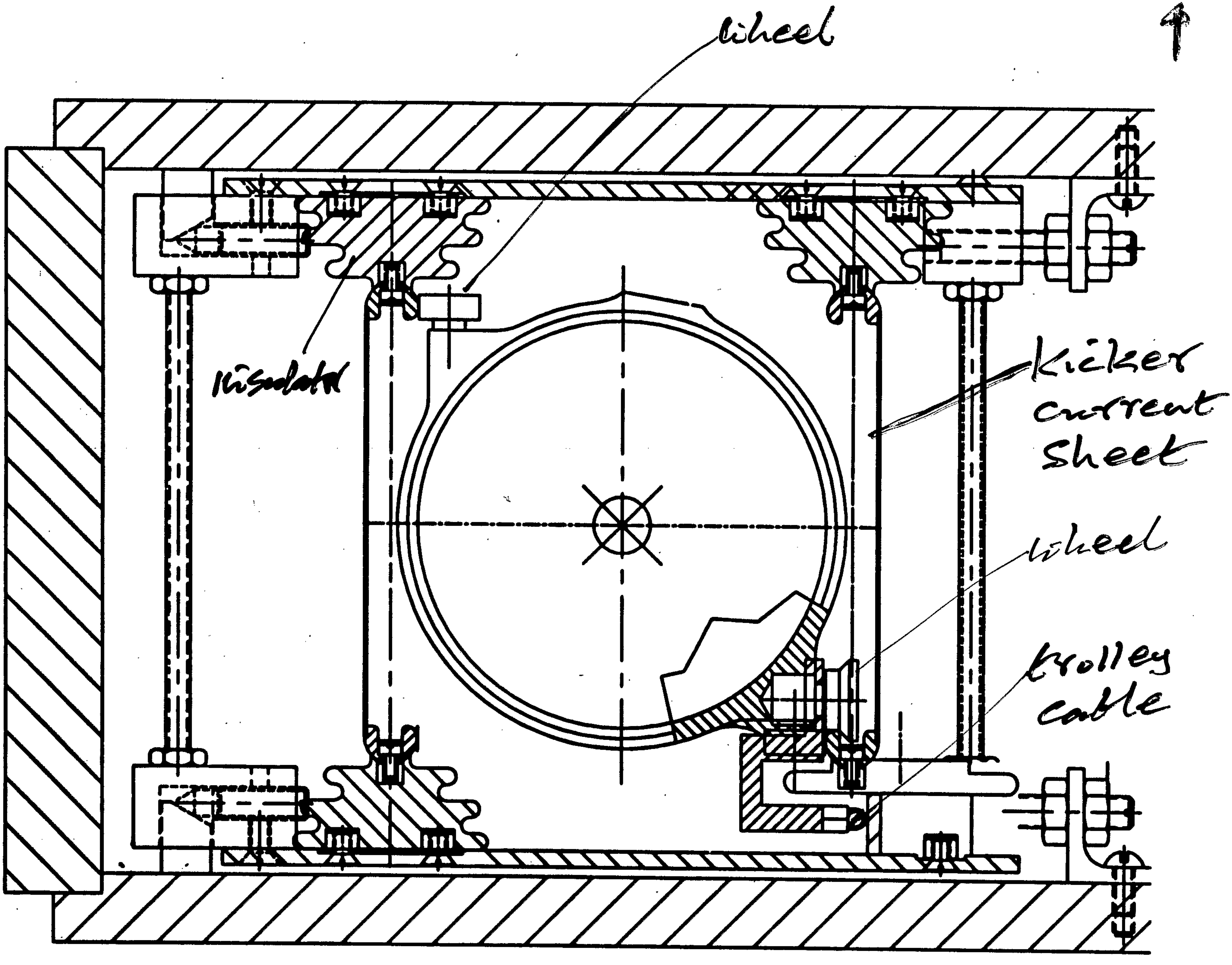
17 NMR probes

Computer

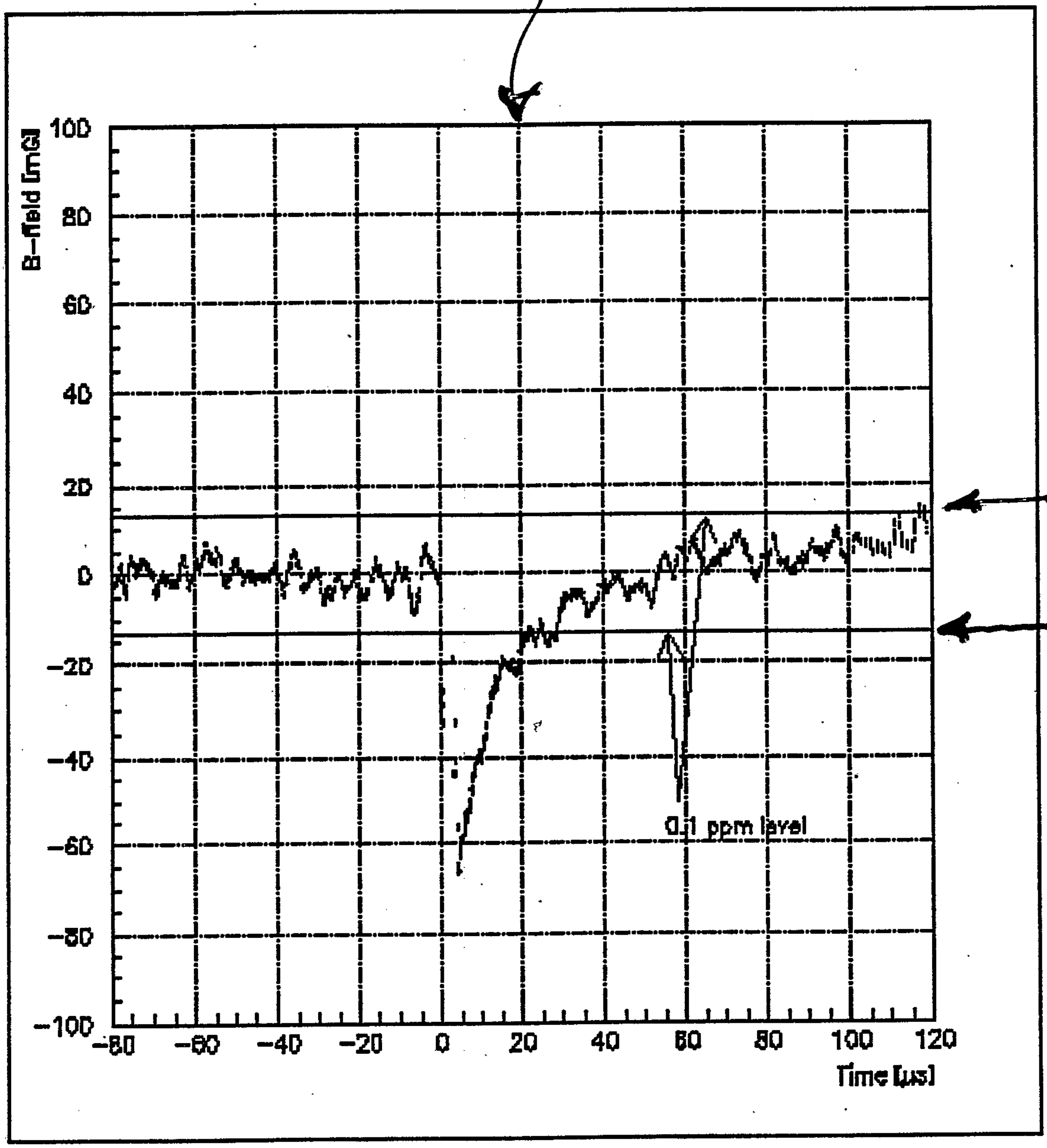
reference f via cable





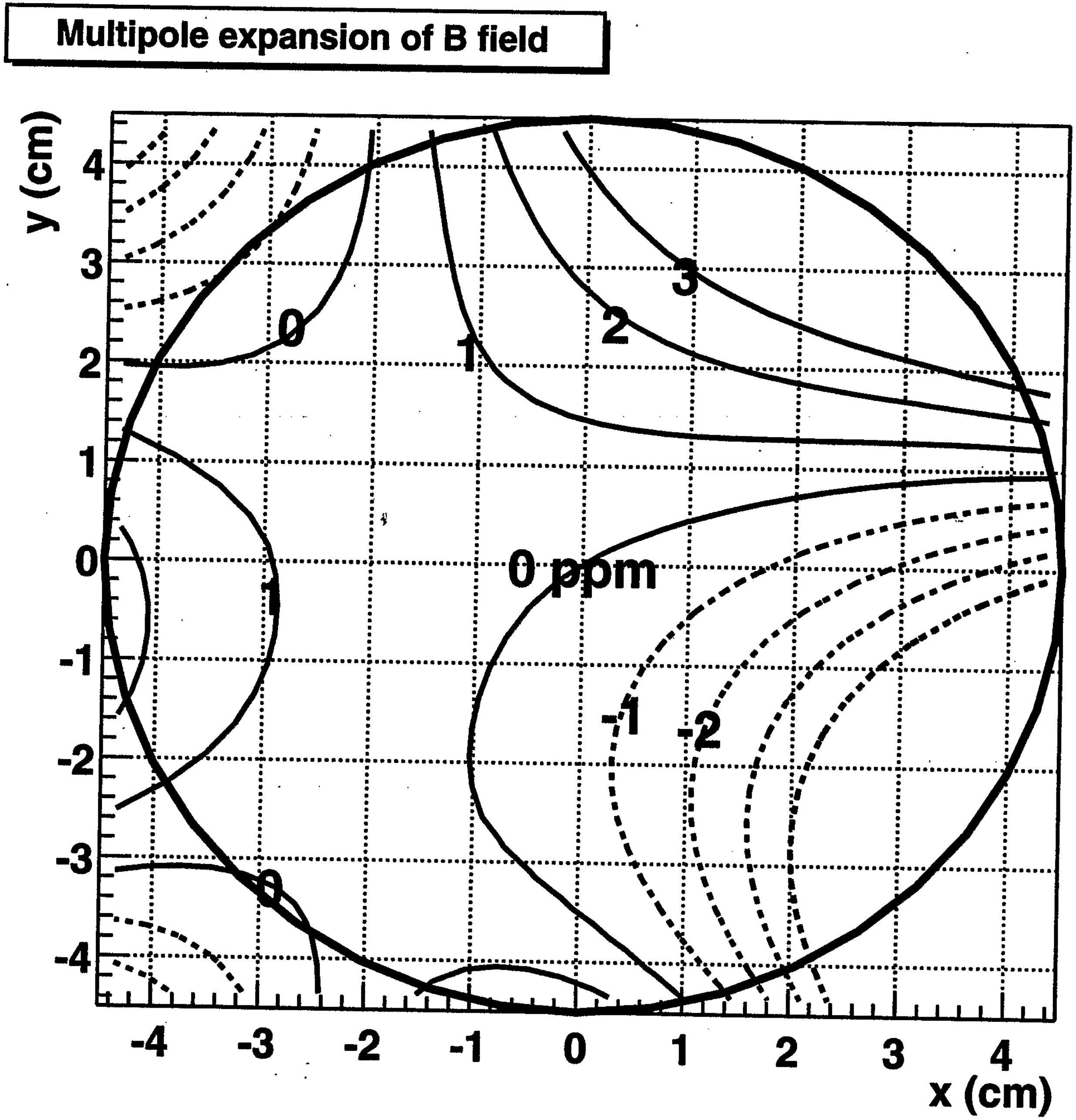

wheel
Insulator
Kicker current Sheet
wheel
trolley cable

Residual field negligible after 20 μs



0.1 ppm

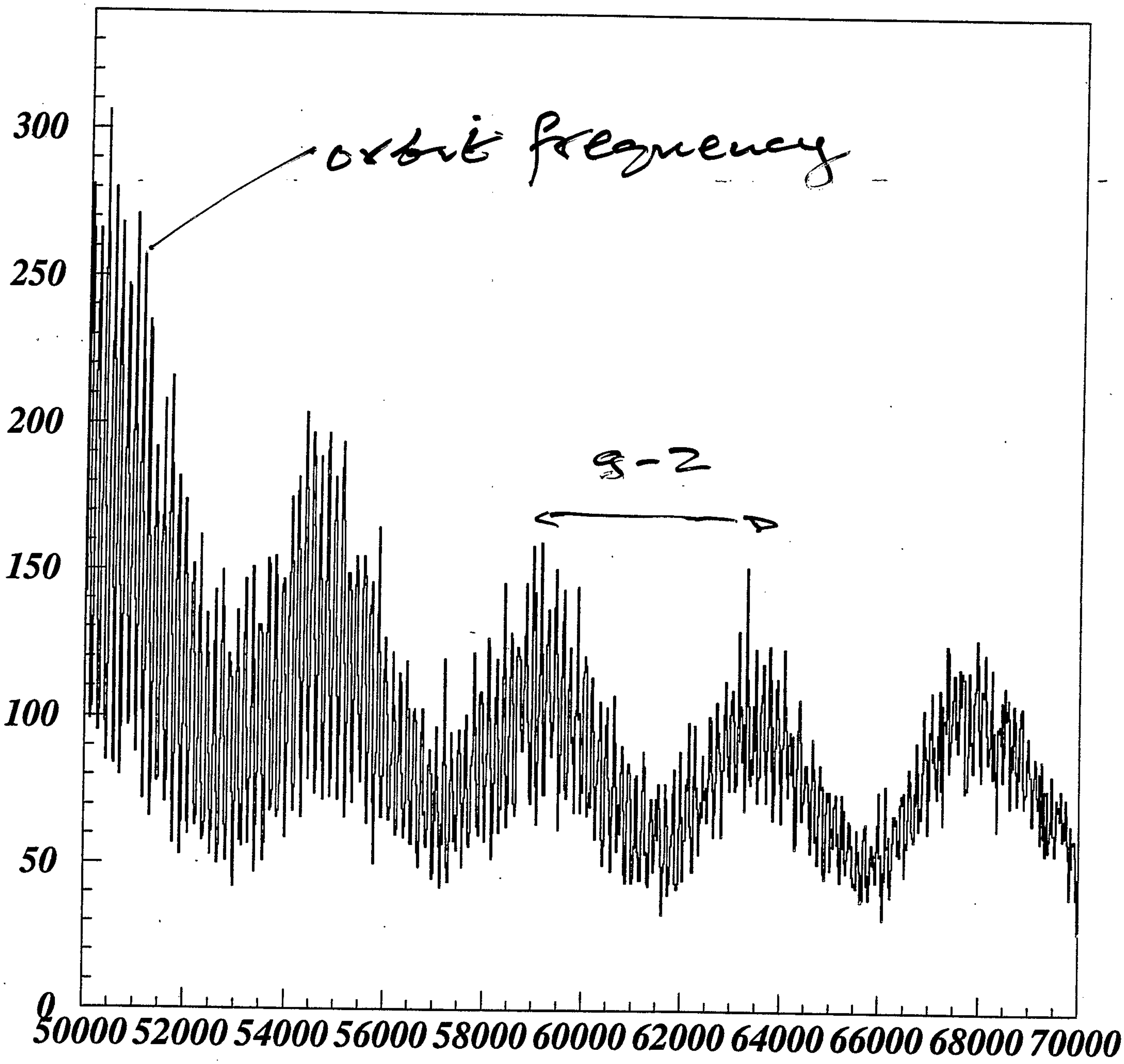
0.1 ppm



B=1.451229 T (804.6 ppm)

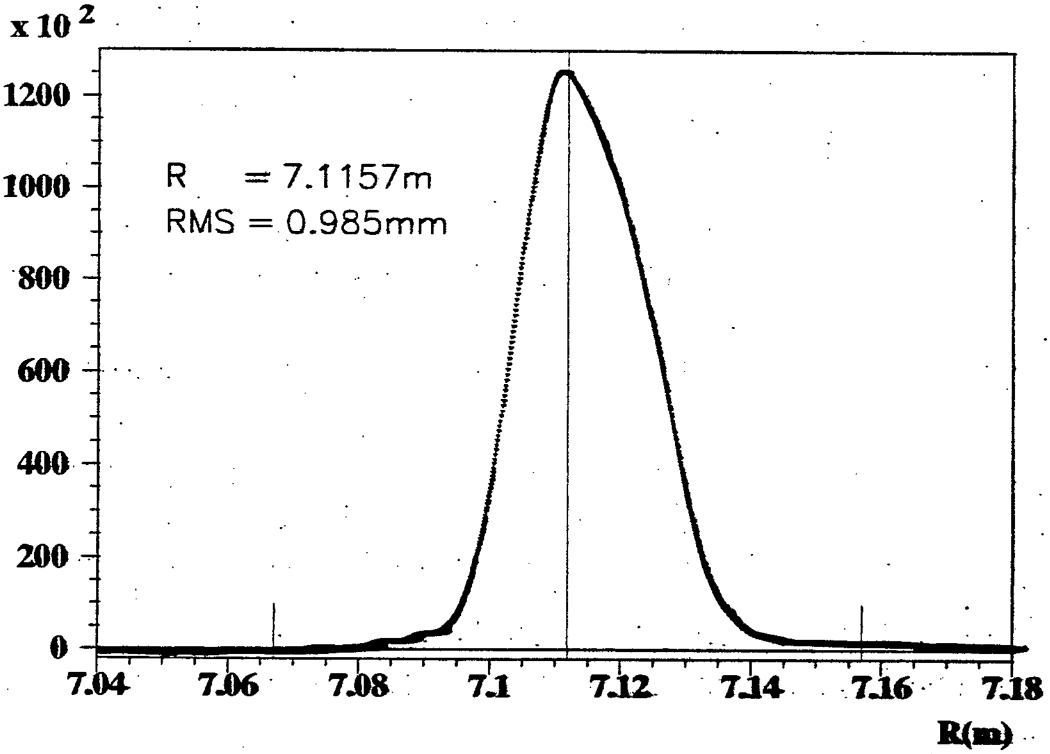
Multipoles (ppm)

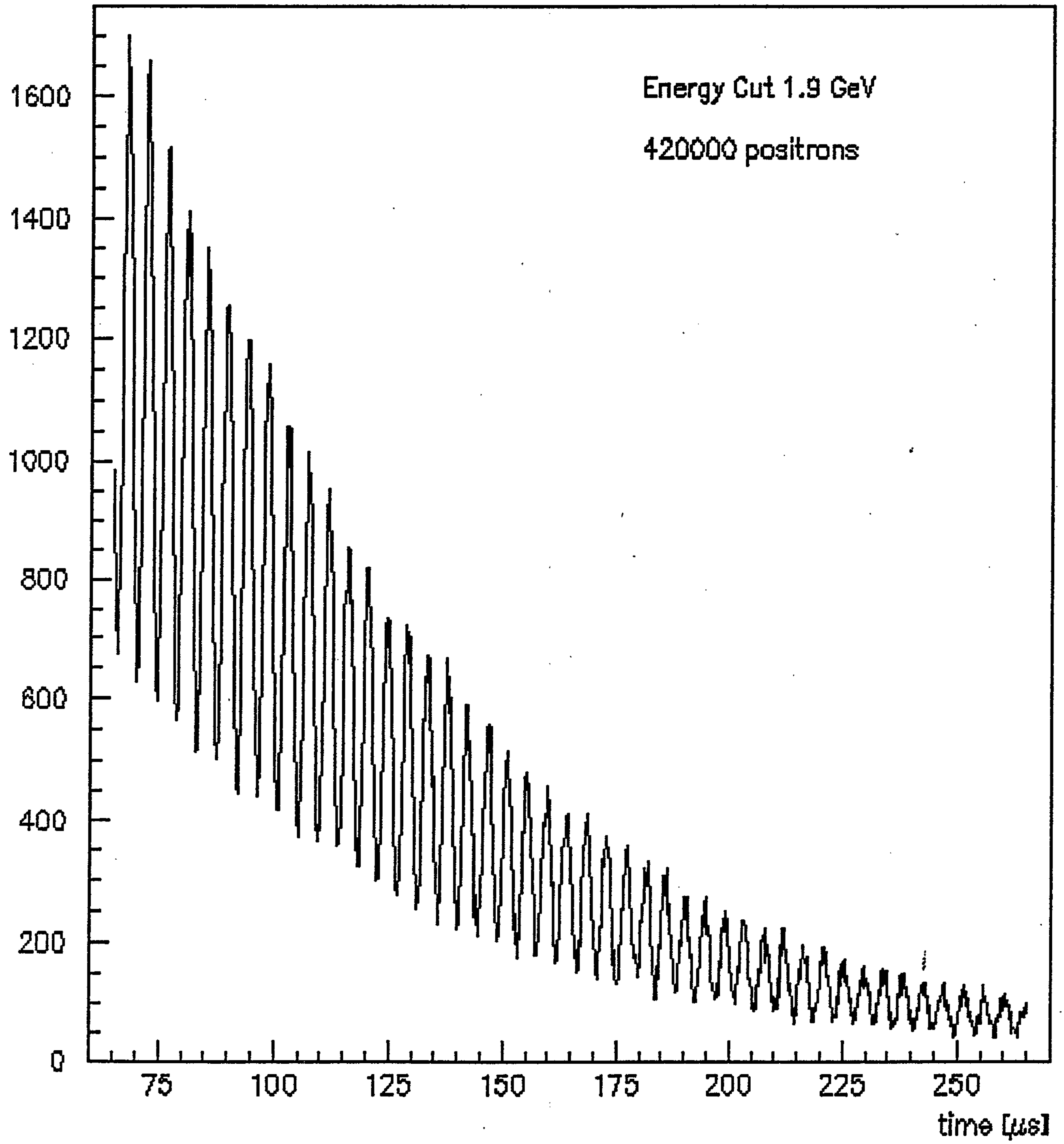
	normal	skew
Quad	-1.80	2.73
Sext	-1.61	3.70
Octu	-1.29	1.76
Decu	0.91	0.72


orbit frequency
g-2
300
250
200
150
100
50
0
50000
52000
54000
56000
58000
60000
62000
64000
66000
68000
70000

FOURIER TRANSFORM OF
ORBIT FREQUENCY

N_μ vs radius

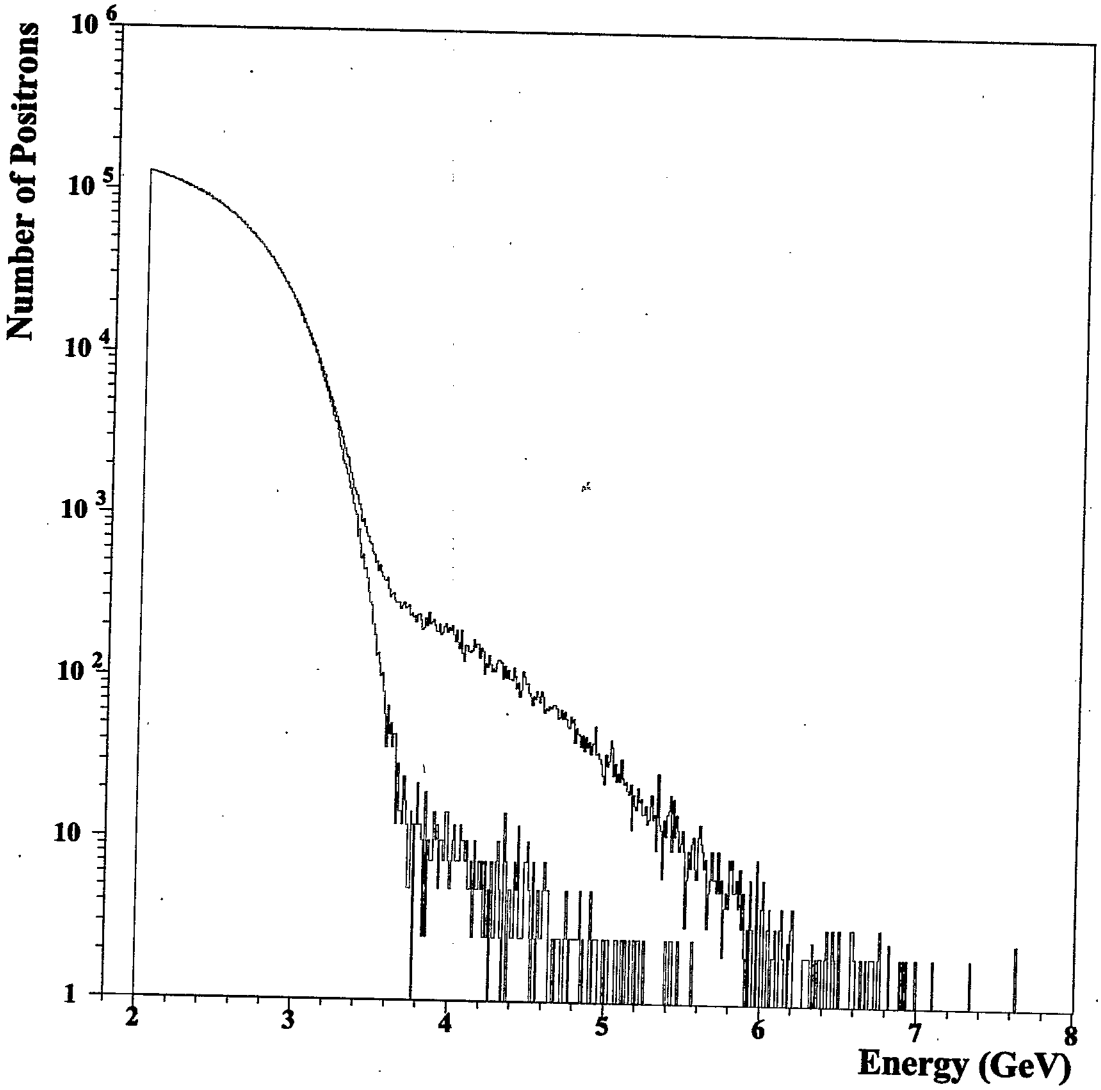



Energy Cut 1.9 GeV
420000 positrons
1600
1400
1200
1000
800
600
400
200
0
75
100
125
150
175
200
225
250
time [μs]

Small effects in the counting data

Signal overlap
Extra counts at early times
Gain change with time
Horizontal oscillations

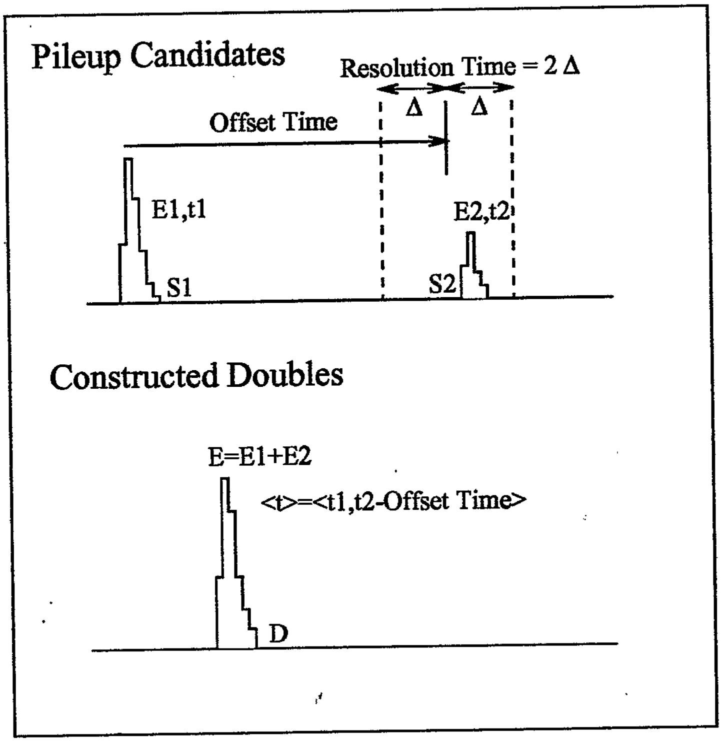
SIGNAL OVERLAP



— early times

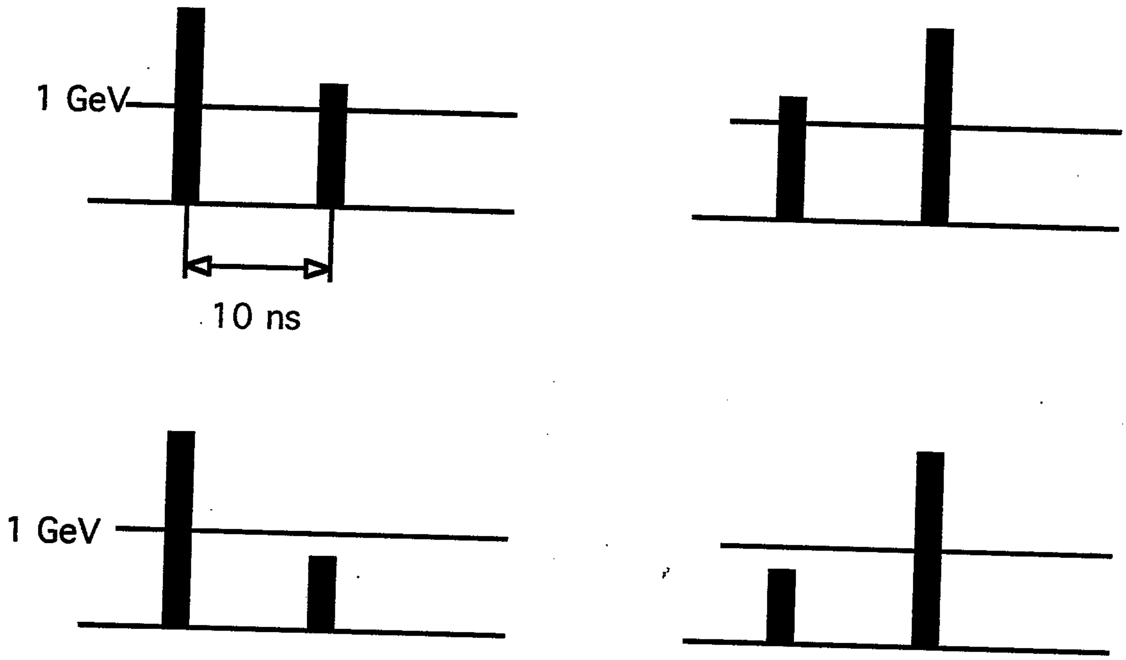
— late times

overlap increased by g-2 modulation
& bunch structure



overlap adds D

kills S1 & S2



count this twice

not seen

Pseudo overlaps - with 1 GeV threshold

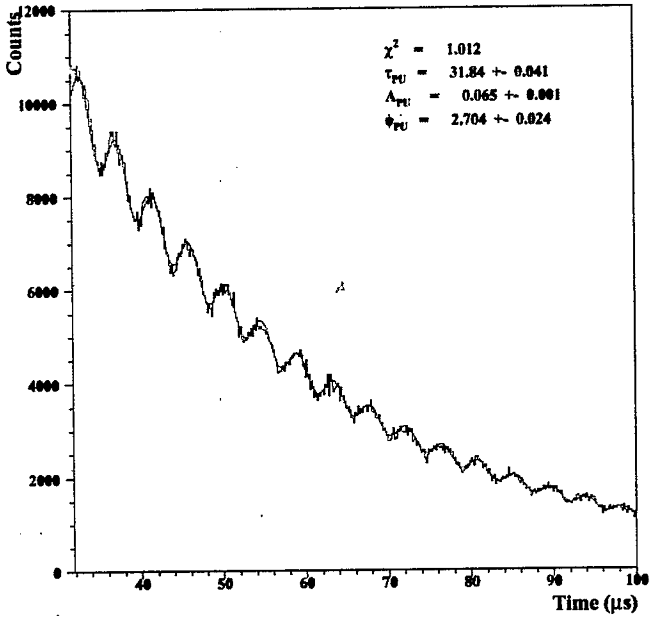
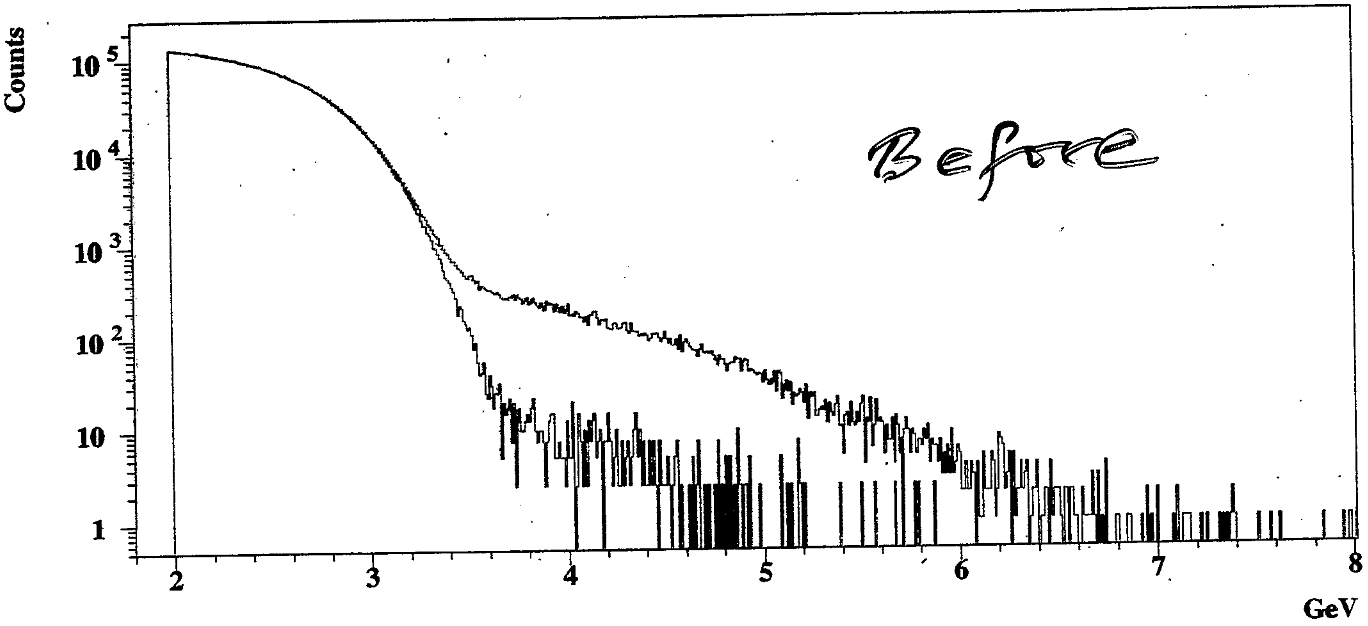


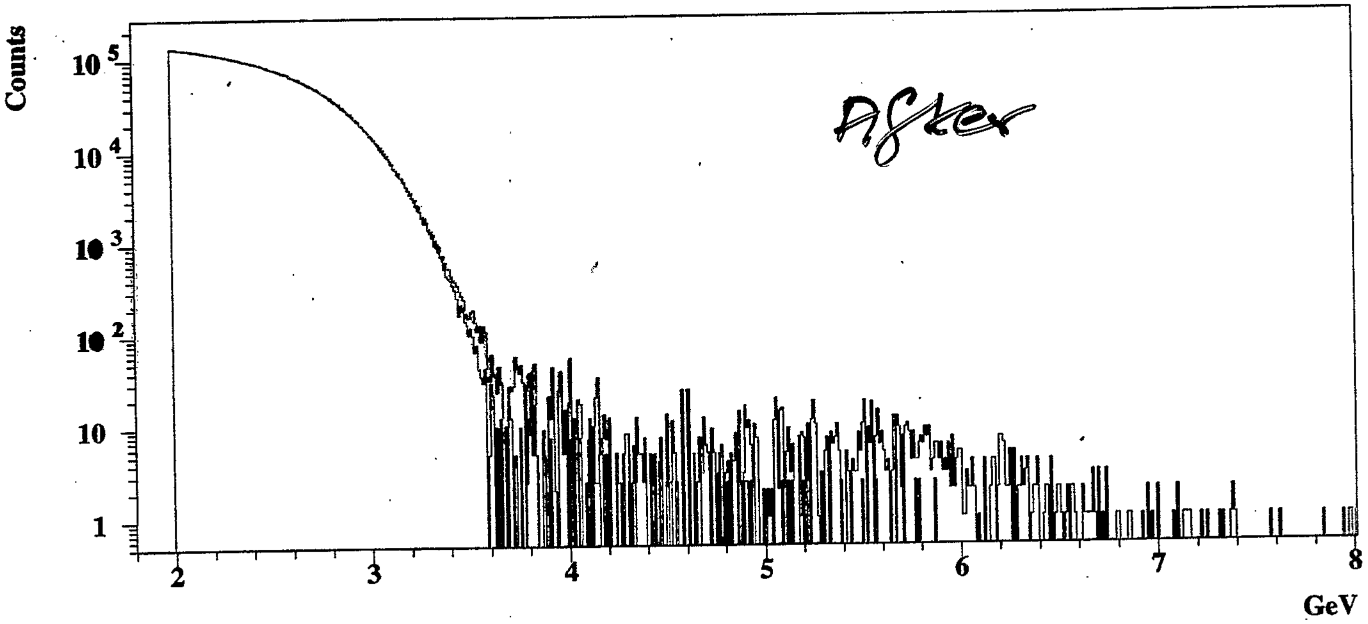
Figure 20 : Fit to pileup ($D - S_1 - S_2$).

τ = 32 μs

A = 0.06

wrong phase !!

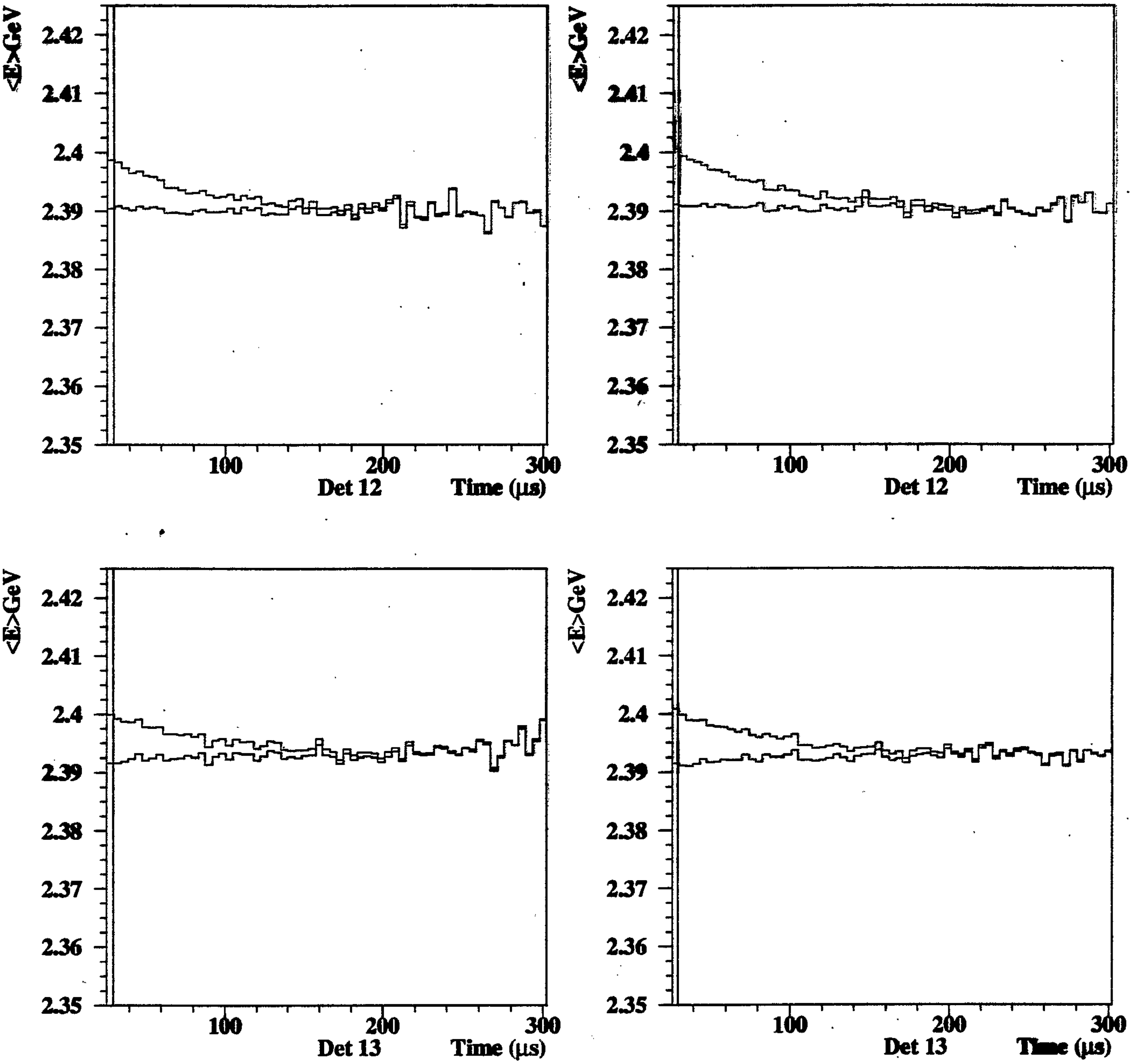

Counts
10 5
10 4
10 3
10 2
10
1
2
3
4
5
6
7
8
GeV
Before


Counts
10 5
10 4
10 3
10 2
10
1
2
3
4
5
6
7
8
GeV
After

— early

— late

Average Energies ; before and after removing the pileup



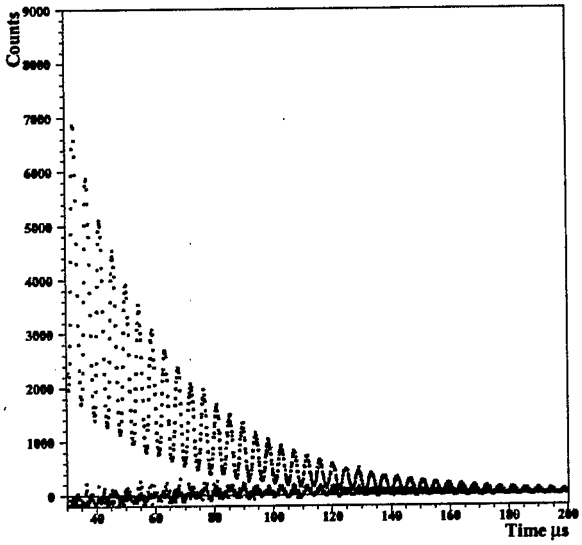
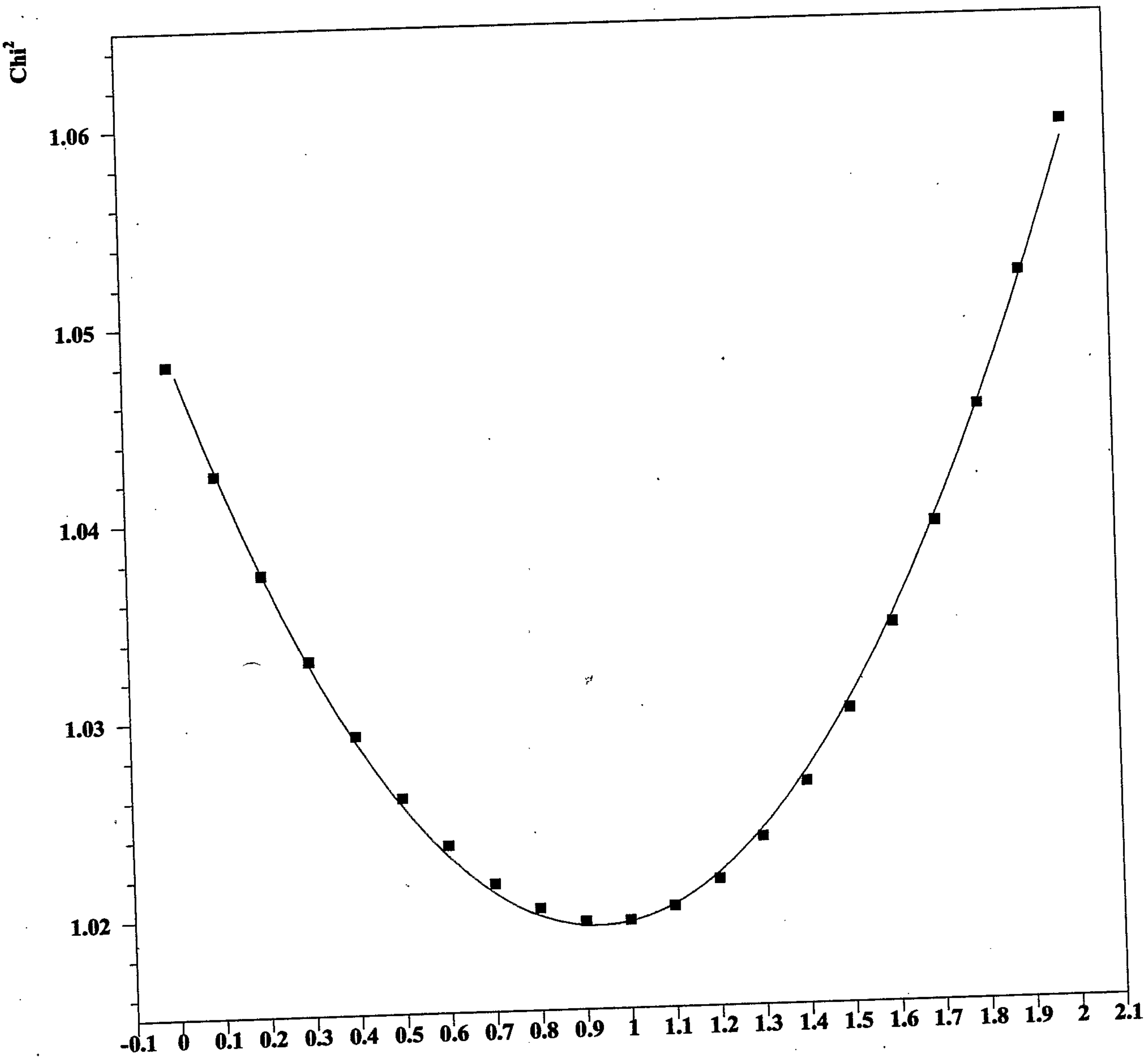


Figure 23 : The comparison of time spectra ($E \geq 3.5GeV$) with and without the pileup subtraction. No energy scale correction was done.

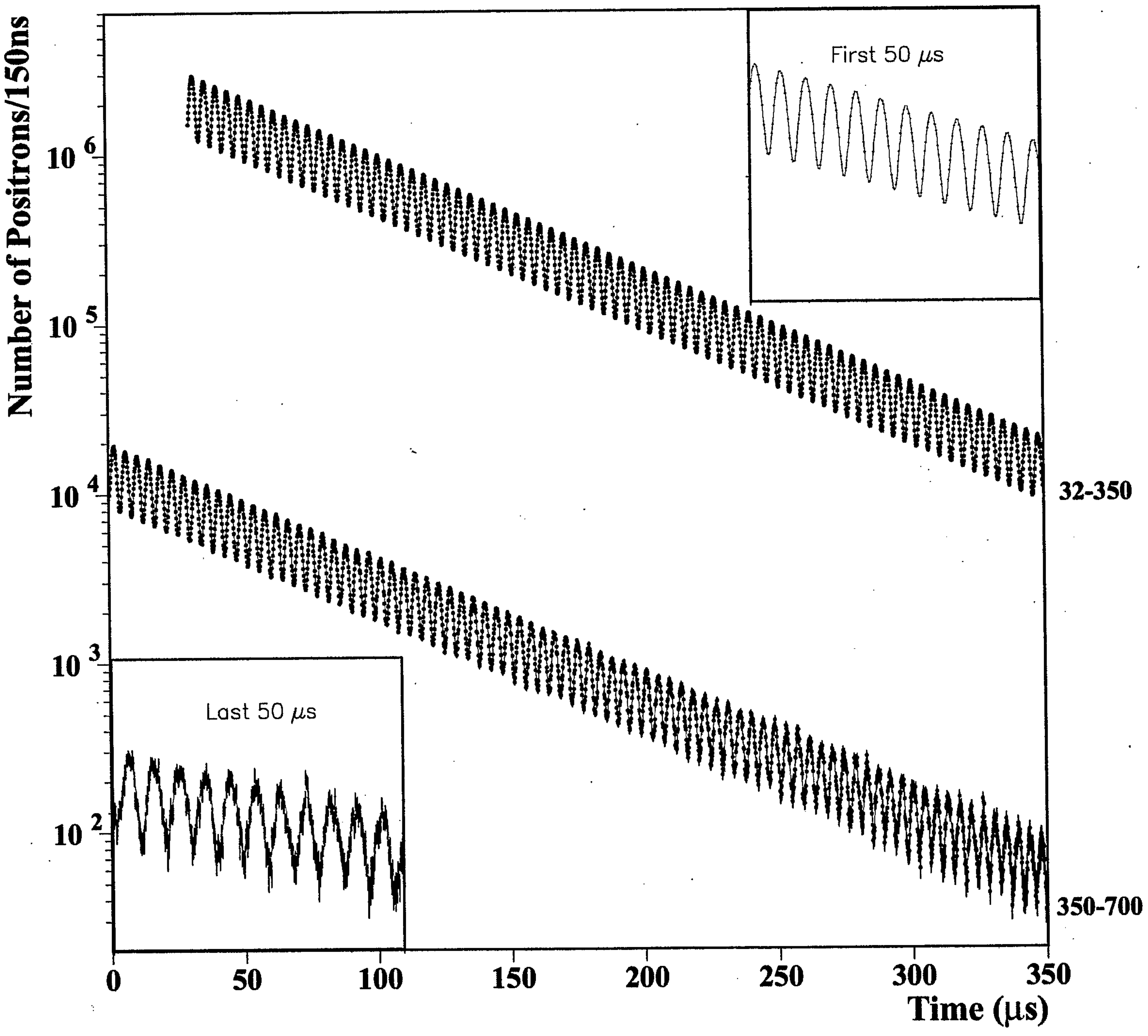
E > 3.5 GeV raw data

— after subtracting pileup

Pileup Systematic with smaller steps

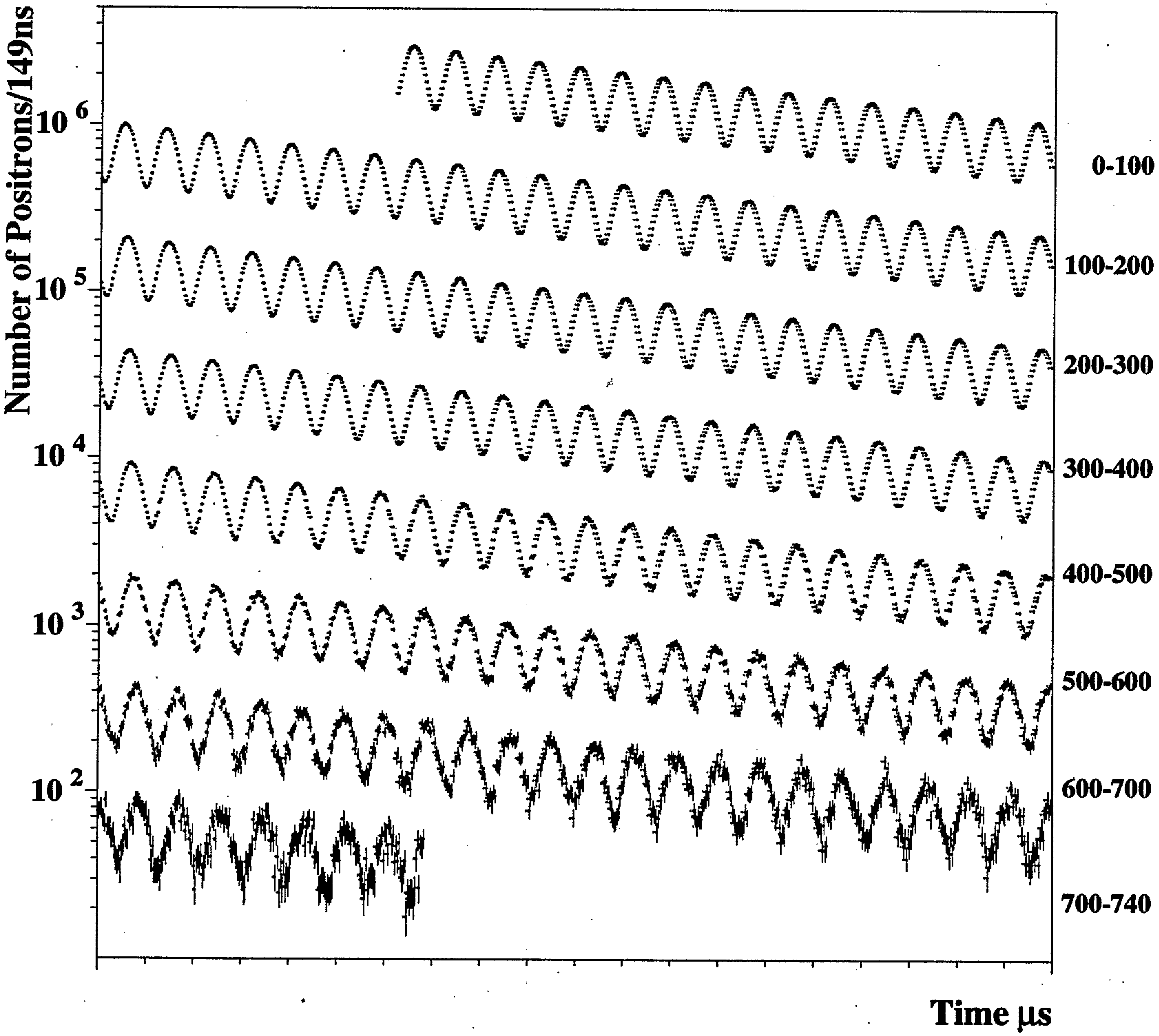


99 data



Number of Positrons/150ns
10 6
10 5
10 4
10 3
10 2
First 50 μs
Last 50 μs
32-350
350-700
0
50
100
150
200
250
300
350
Time (μs)

99 data – 10^9 e^+ > 2.0 GeV



Blind analysis

Separate analyses of ω_a

Values in ppm with common offset

	frequency	statistical error	systematic error
BNL group	143.37	1.24	0.17
Boston	143.25	1.24	0.25
Illinois	143.30	1.23	0.10
Ratio method 1	143.37	1.28	0.14
Ratio method 2	143.03	1.28	0.16

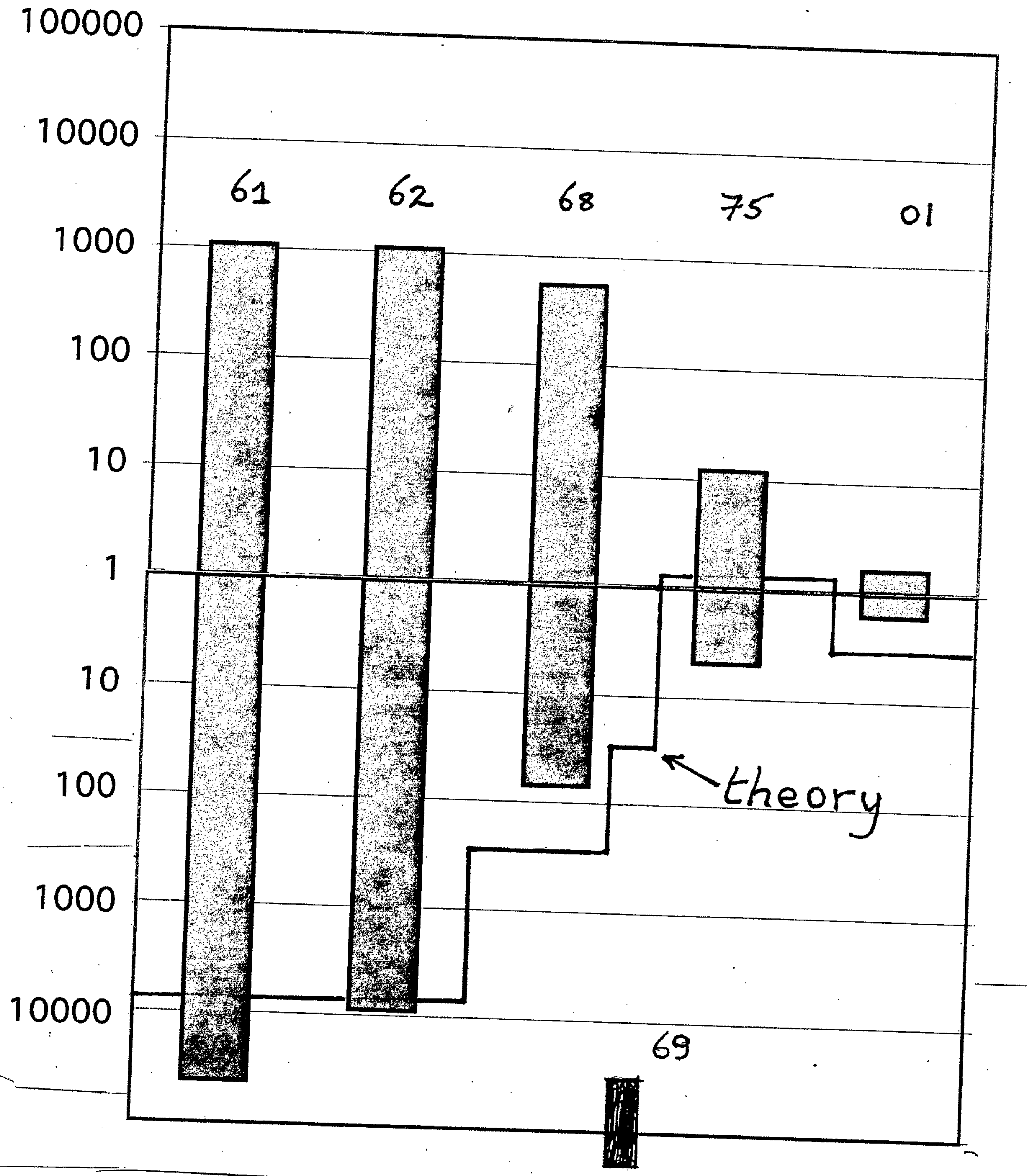
Two analyses of ω_p with common offset, weighted according to number of e^+ detected hour by hour,

agree to 0.03 ppm

Feb 2001

Values of muon anomalous moment

	10^{-9} ×	error (ppm)	
CERN with latest λ	11659 23	7.3	
BNL - 97	11659 25	12.9	
BNL- 98	11659 19.1	5.06	
BNL - 99	11659 20.20	1.34	
world average	11659 20.26	1.27	
Theory	11659 15.96	0.57	
difference	4.30	1.39	
difference (ppm)	3.69	1.39	2.65 σ



100000
10000
1000
100
10
1
10
100
1000
10000
61
62
68
75
01
69
theory