Heinz, Tammy A

From: Bunce, Gerry M
Sent: Thursday, June 06, 2002 2:40 PM
To: Heinz, Tammy A
Subject: FW: oops! This week's Physics Colloquium (5/30)
Importance: High

Please print. Thanks. Gerry

-----Original Message-----
From: Colleen Letwinch [mailto:letwinch@ucrac1.ucr.edu]
Sent: Tuesday, May 28, 2002 12:07 PM
To: bunce@bnl.gov
Subject: oops! This week's Physics Colloquium (5/30)
Importance: High

COLLOQUIUM

"The Muon g-2 Experiment"

Dr. Gerry Bunce
Brookhaven National Laboratory

The muon g-2 experiment tests our understanding of the electromagnetic, strong and weak forces. A series of experiments at CERN, completed in the early 1980s, developed the method of storing polarized muons in a special storage ring, and reached a precision of 7 parts per million. This stood as a beautiful test of the
Standard Model of particle physics. At Brookhaven National Laboratory we have built an even higher precision experiment, and have in the past year reached a factor 7 improvement, and counting. I will describe the ideas, the experiment, and where we are now with the Standard Model.

Date: Thursday May 30, 2002
Room Physics 3035
Time: 3:45 pm
Coffee served in Barkas Lounge @ 3:30 pm

****

Colleen Letwinch, AAII
Travel Coordinator
Physics Dept.
University of California, Riverside

Joint Nuclear/EEP Seminar

Dr. Gerry Bunce

Brookhaven National LAB

The Muon g-2 Experiment at Brookhaven

Location: Knudsen 4-134
Date: Wednesday, May 29
Time: 4:30pm

Refreshments at 4:00 pm

The Muon g-2 Experiment

G. Bunce, BNL

May, 2002

1. Introduce muon g-2
2. How?
3. The experiment
4. Results from 10^9 μ^+s
5. Future: 4×10^9 μ^+s, 3×10^9 μ^-s
   - more μ^-?

Particle with spin S:

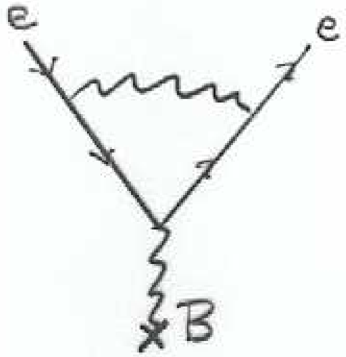
$$\vec{\mu}_m = g\frac{e\hbar}{2mc}\vec{S}$$

1930s: Dirac $g=2$ for point particle, spin $\frac{\hbar}{2}$.

Proton $g = 2.8\times 2$
$= 5.6$

1940s: Electron $g = 2.002$!

Point particle $a_e = \frac{g_e - 2}{2} = \frac{\alpha}{2\pi} + \cdots$



$a_e^{\text{new physics}} \sim \frac{m_e^2}{\Lambda^2}$

	m	$c\tau$
e	0.5 MeV	∞
μ	105 MeV	660 m
τ	1784 MeV	0.1 mm

Electron g-2

$a_{e-} = 1\ 159\ 652\ 188\ (4) \times 10^{-12}$ (4ppb)

$a_{e+} = 1\ 159\ 652\ 188\ (4) \times 10^{-12}$ (4ppb)

Van Dyck et al., Phys. Rev. Lett. 59, 26(1987).

Theory: $a_e(\text{th}) = \alpha/2\pi$

$-0.328478965\ (\alpha/\pi)^2$
$+1.181241456\ (\alpha/\pi)^3$
$-1.5098\ (384)\ (\alpha/\pi)^4$

$+2.721\ 10^{-12}$ (μ, τ loops)
$+1.642(27)\ 10^{-12}$ (hadronic)
$+0.030\ 10^{-12}$ (weak)

$a_e(\text{th}) = 1\ 159\ 652\ 153\ (1)\ (28)\ 10^{-12}$

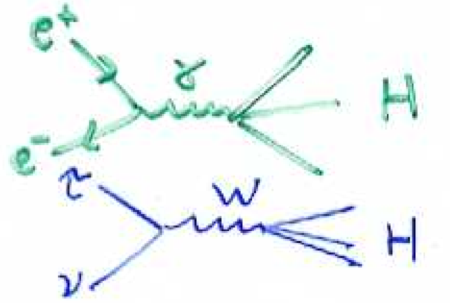
using α(quantum hall).

Feb.,2001

Standard Model Theory [1]

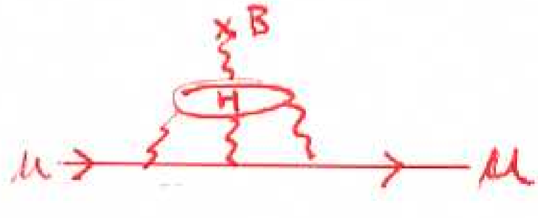
$a_\mu(\text{QED}) = 116584706\ (3) \times 10^{-11}$ $\frac{\alpha}{2\pi} + \cdots$

$a_\mu(\text{Had}_a) = 6924\ (62)$

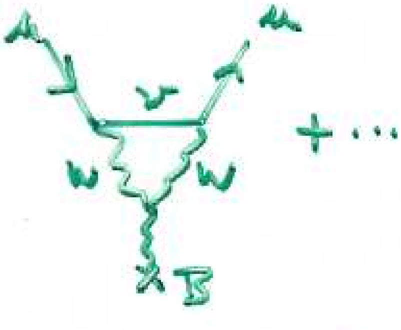


$a_\mu(\text{Had}_b) = -100\ (6)$

$a_\mu(\text{Had}_{ll}) = +85\ (25)$



$a_\mu(\text{EW}) = 151\ (4)$



Total = 116591~~596~~ 768 (67) × 10^{-11} (±0.6 ppm)

1. A. Czarnecki, W. Marciano/Nuclear Physics B (Proc. Suppl.) 76 (1999) 245-252.

+ M. Knecht, A. Nyffeler, M. Perrottet, E. de Rafael Phys. Rev. Lett. 88, 071802 (2002)

Beyond the Standard Model

large variety of possible contributions:
(sensitivity limits for $\sigma_{a_\mu} = 0.35$ ppm)

- muon substructure: $a^{\mu-substr.} \sim \left(\frac{m_\mu}{\Lambda}\right)^2$
  sensitivity: $\Lambda \approx 5$ TeV, LHC domain

- W anomalous magnetic moment a_W
  sensitivity: ~ 0.02
  LEPII: ~ 0.05, LHC: ~ 0.2

- W substructure: $a^{W-substr.} \sim \left(\frac{m_W}{\Lambda}\right)^2$
  sensitivity: $\Lambda \approx 400$ GeV
  LEPII: ~ 100 - 200 GeV

- . . .

(T.Kinoshita and W. Marciano, in "Quantum Electrodynamics",
ed. T. Kinoshita (World Scientific, Singapore 1990))

② "The muon is God's gift to man"

J. Field

	mass	lifetime	
electron	0.51 MeV	∞	
muon	105.7 MeV	2.2 μsec.	$c\tau = 0.5$ miles
tau	1.78 GeV	0.5 psec.	$c\tau = .006''$

Lifetime ⇒ put muon in storage ring, observe change in spin vector compared to momentum

Mass ⇒ sensitive to massive virtual particles

relative to electron, sensitivity is

$$\left(\frac{m_\mu}{m_e}\right)^2 \simeq 4 \times 10^4$$

Electron: QED Muon: QED, strong, weak

The goal of $(g-2)_{muon}$ is to confront the Standard Model.

① Standard Model predicts g-2 precisely.

② Muon is sensitive to new physics

$$(g-2)_{lepton} \propto \left(\frac{m_{lepton}}{\Lambda}\right)^2$$

Λ ← mass scale of new physics

$$\left(\frac{m_{muon}}{m_{electron}}\right)^2 \approx 10\,000$$

③ We can measure $(g-2)_{muon}$ to **±0.35 ppm**

→ BNL experiment

- very high muon rate from AGS

CERN experiment (1977) : ±7.2 ppm

BNL 1998 data : ± 5 ppm

1999 data : ± 1.3 ppm ← this talk

Historical Perspective

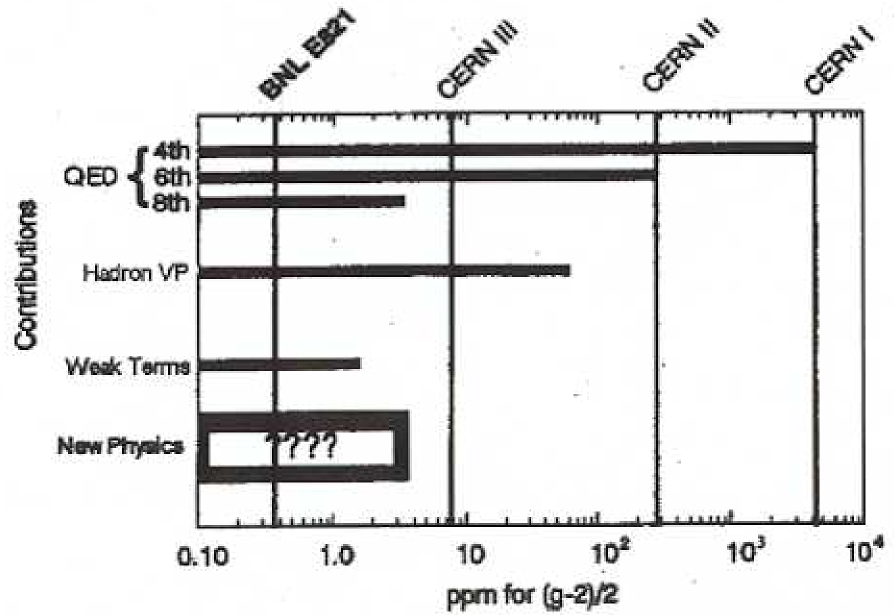
Cern I (1958-1962): Stopped muons, measured (g-2) to 0.4%

Cern II (1962-1968): Muons in flight, magnetic focusing, (g-2) to 270 ppm

Cern III (1969 - 1976): Electric quadrupole focusing, (g- 2) to 10 ppm for positive and negative muons

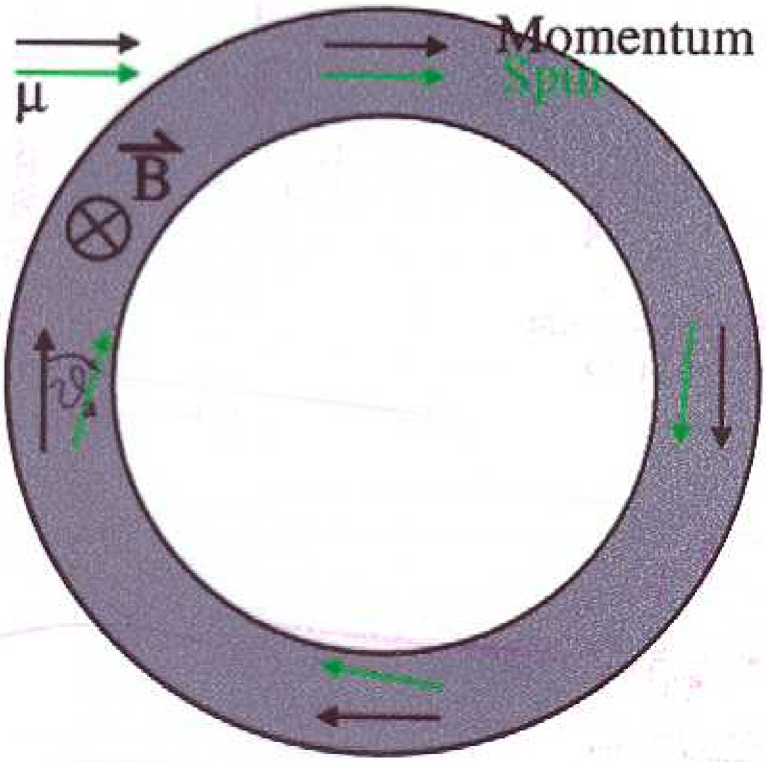
BNL E821: Superferric magnet, high intensity beam, and muon injection scheme...ultimate goal is 0.35 ppm

Theoretical reach of each of the g-2 experiments



Method

Store polarized muons in a homogenous magnetic field and measure difference frequency between spin and momentum precession



measure

$$\vec{\omega}_a = \frac{d\vec{\vartheta}_a}{dt} = \frac{e}{m_\mu c} a_\mu \vec{B}$$

$\frac{g_\mu - 2}{2}$

A.Steinmetz DNP99/9

Measuring g-2

$(g-2)/2 = \omega / B \times (m_\mu c / e)$

ω = measure precession of muon spin in magnetic field

B = measure magnetic field

To measure g-2 to 3/10,000,000, need to know both ω and B to better than that !

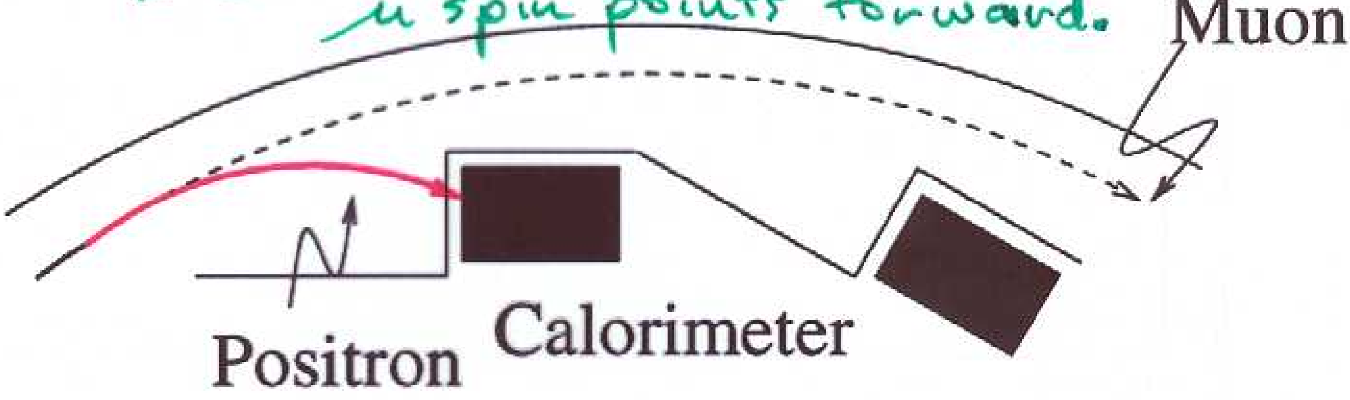
Polarimeter

high energy positrons from muon decay

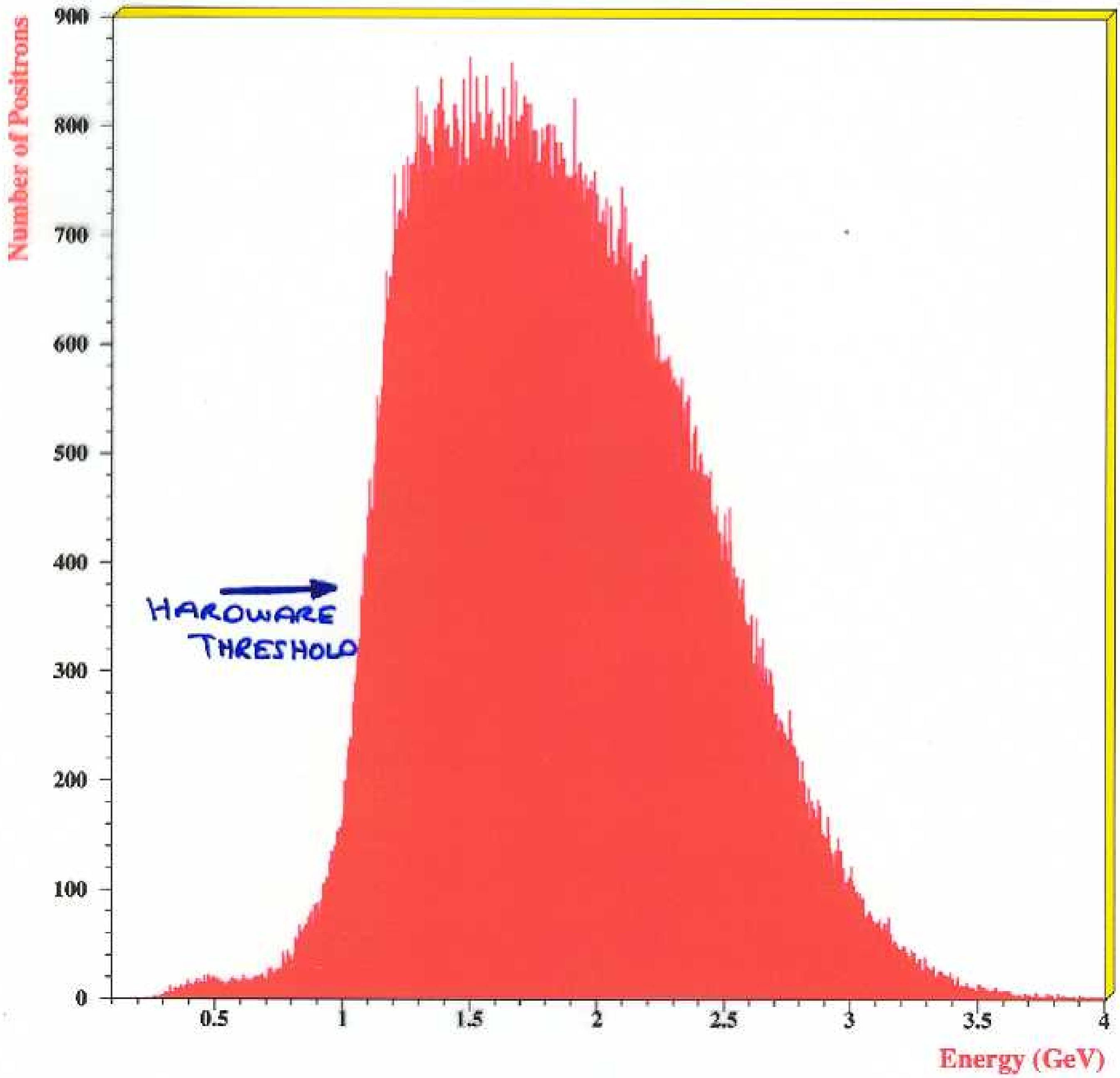
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

Parity violation: more e^+ in direction of muon spin.

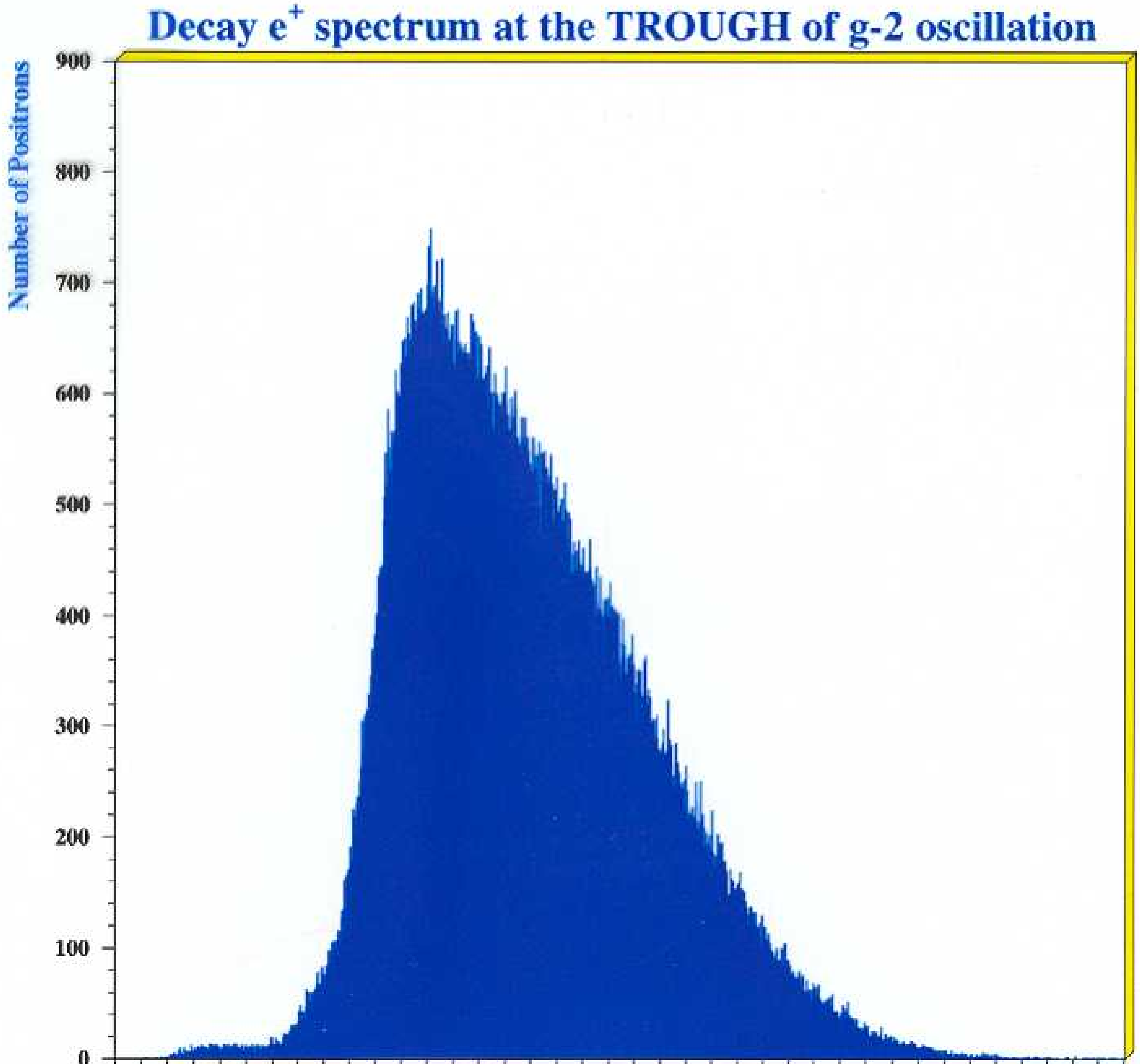
Boost: more high energy e^+ when μ spin points forward.



Decay e^+ spectrum at the PEAK of g-2 oscillation



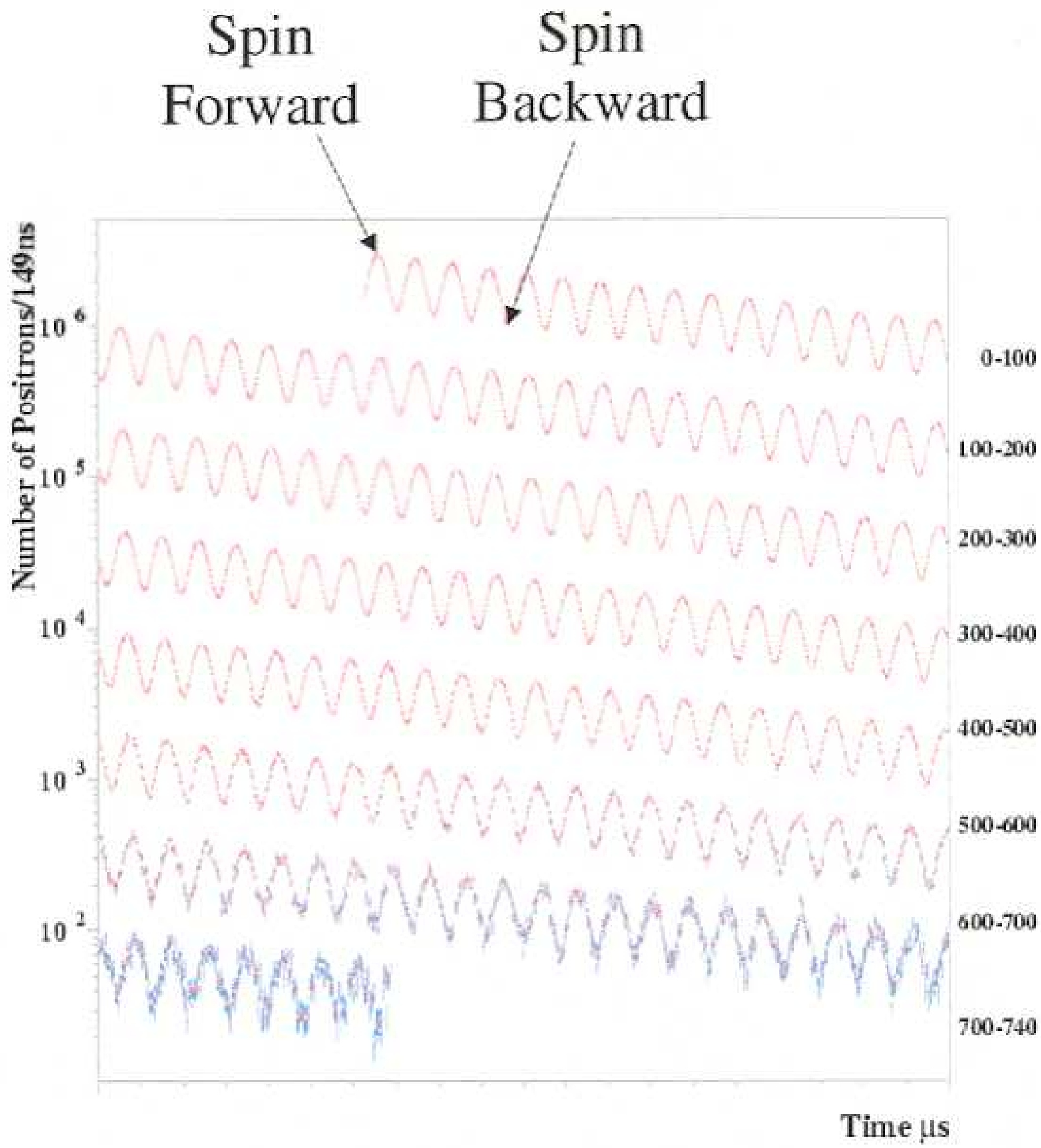
$$\mu^+ \to e^+ \nu \bar{\nu}$$



Decay e+ spectrum at the TROUGH of g-2 oscillation
Number of Positrons
900
800
700
600
500
400
300
200
100
0
0.5
1
1.5
2
2.5
3
3.5
4
Energy (GeV)

The g−2 Oscillation

~1 Billion Positrons



Muon Spin Precession in $\vec{B}$, $\vec{E}$ Field

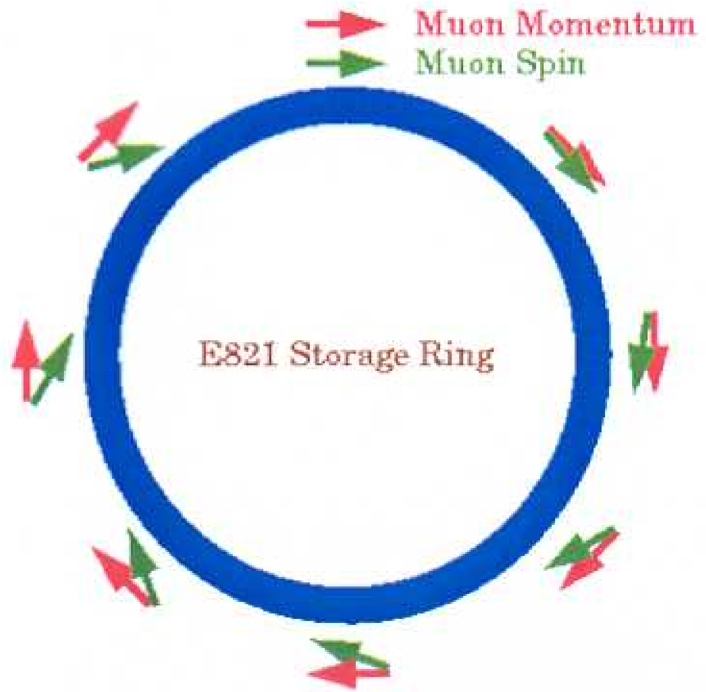
General relativistic formula for spin precession in a rotating frame:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = \frac{e}{mc}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} \right]$$

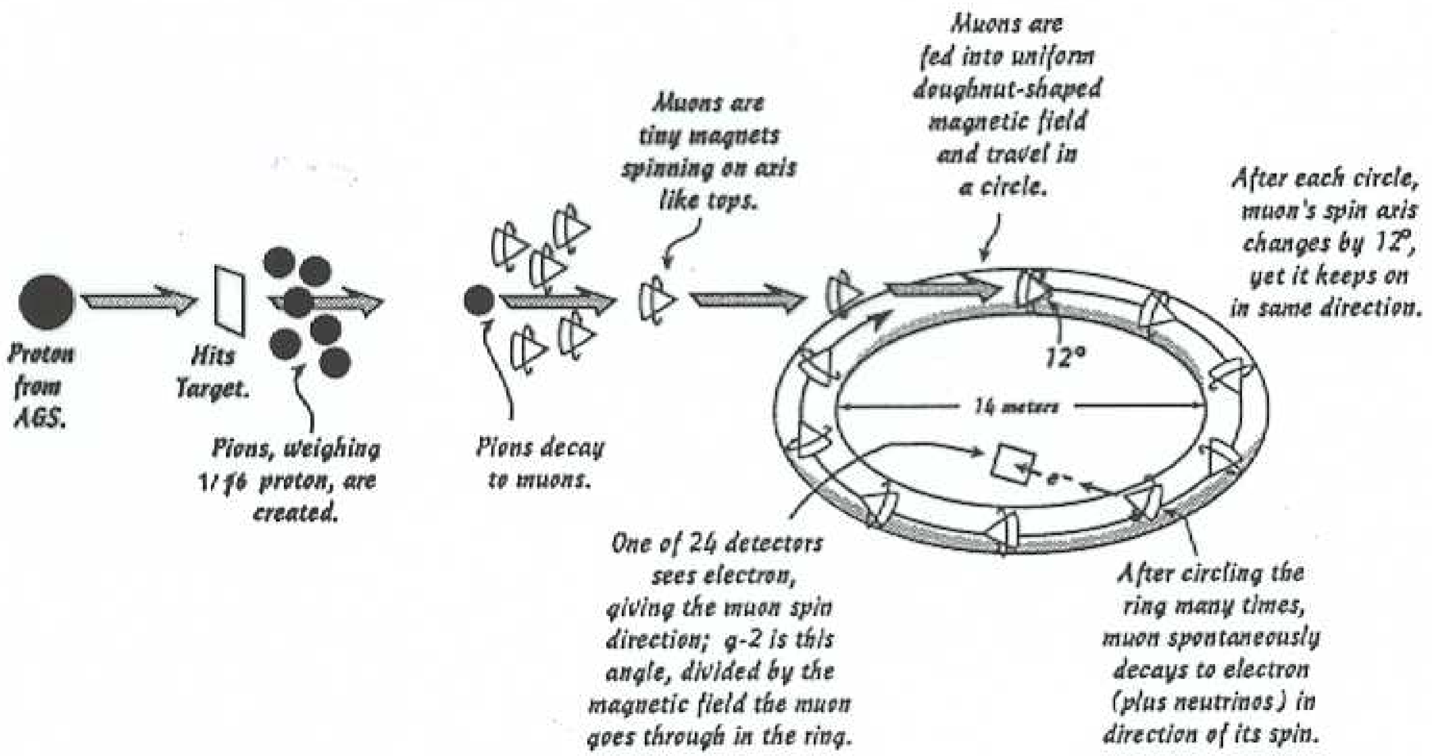
Difference frequency is directly proportional to a_μ ... not g!

Spin precesses relative to momentum vector by ~12 deg./turn

At the "magic" gamma of 29.3, E-field term vanishes, allowing vertical weak focusing using electrostatic quadrupoles



Life of a Muon : The g-2 Experiment



Construction started in 1989.

Beam in 1996.

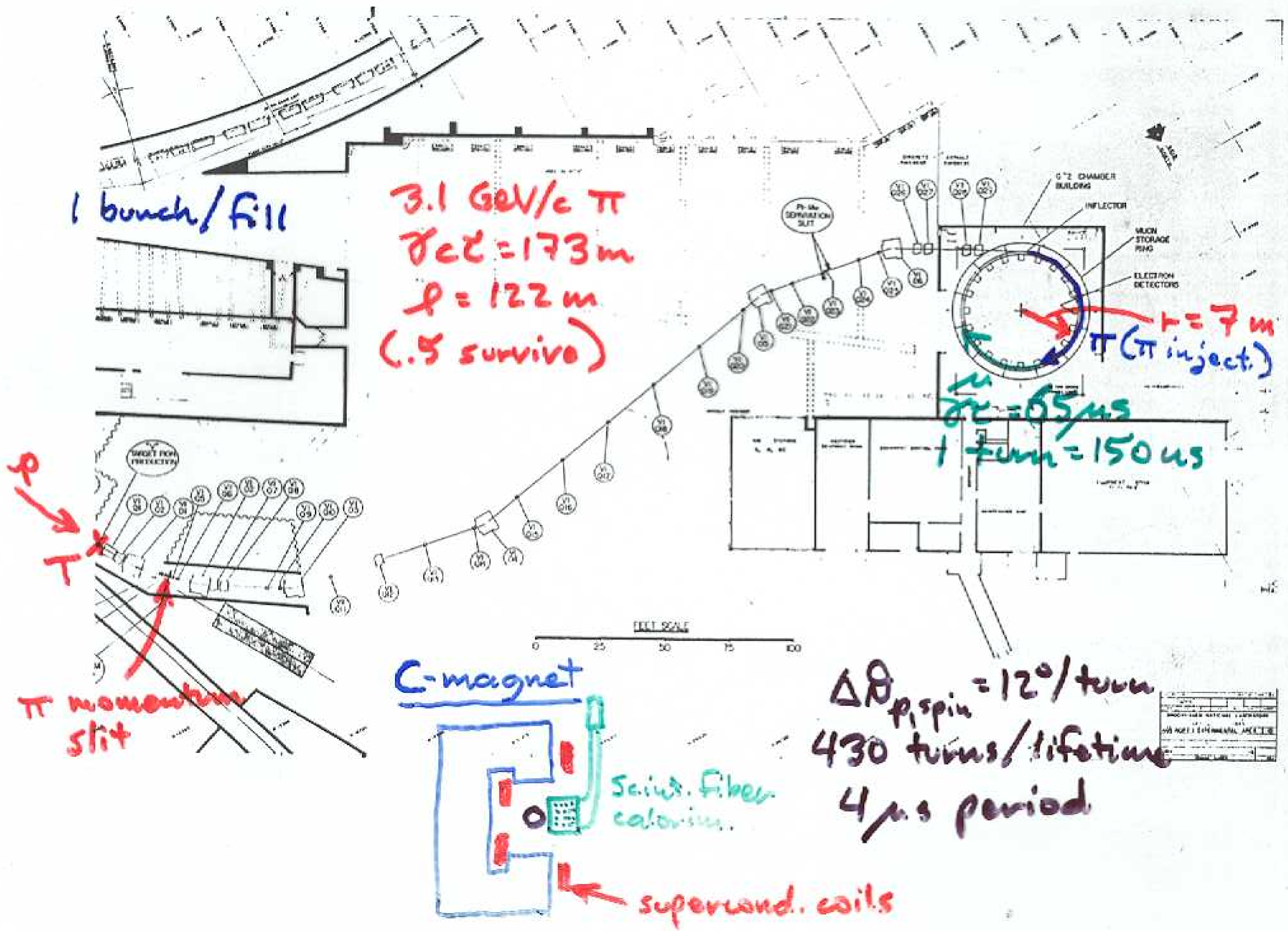
SEUBERT 1a 9/91 IR

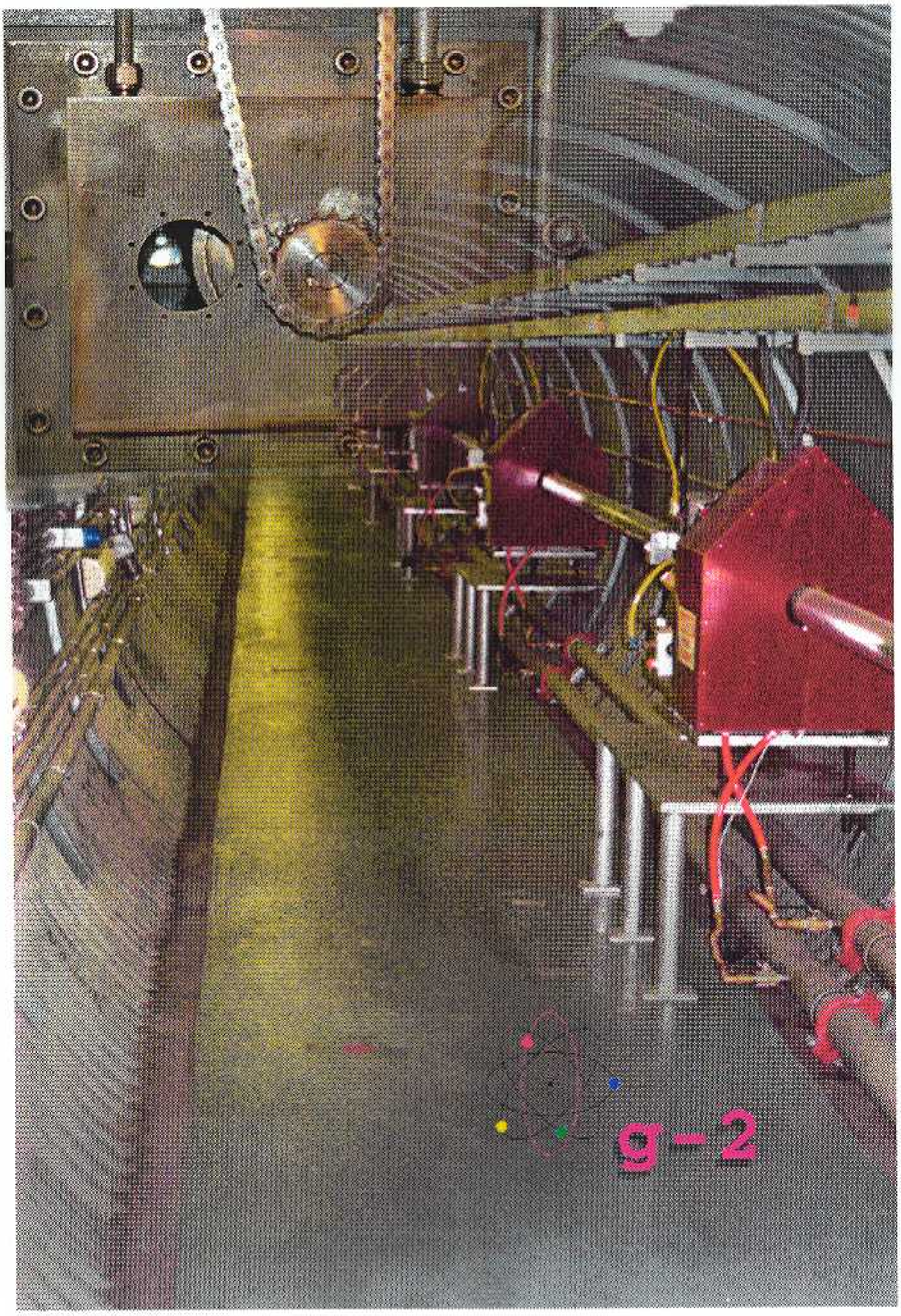
μ g-2 (to 1/3 ppm)

$a_\mu \approx .001$

10^8 πs/fill

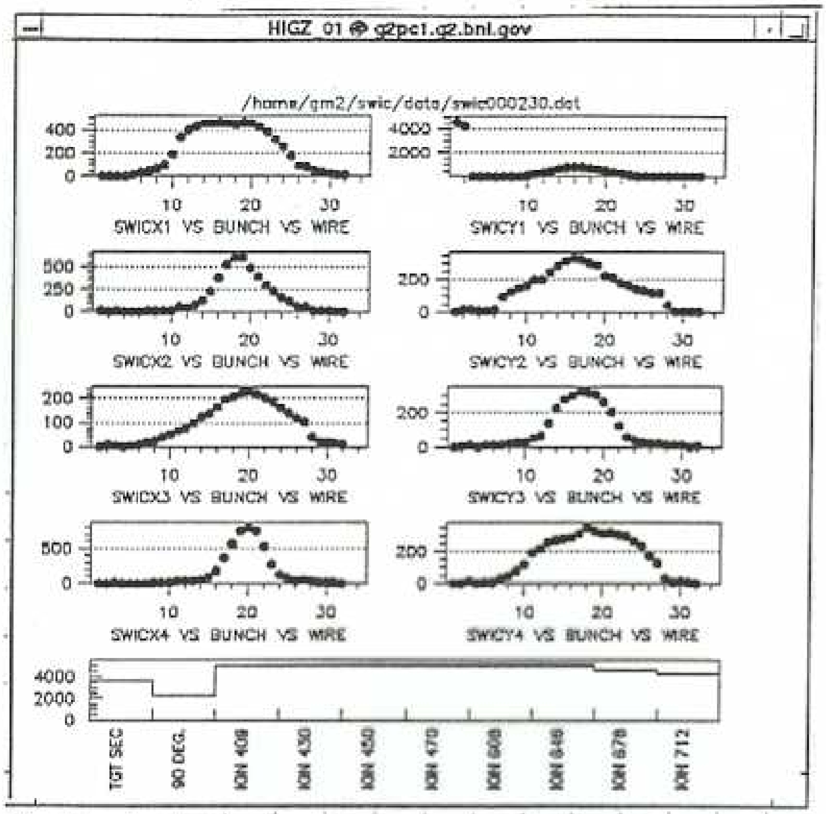
5×10^4 stored μs { μ inject.



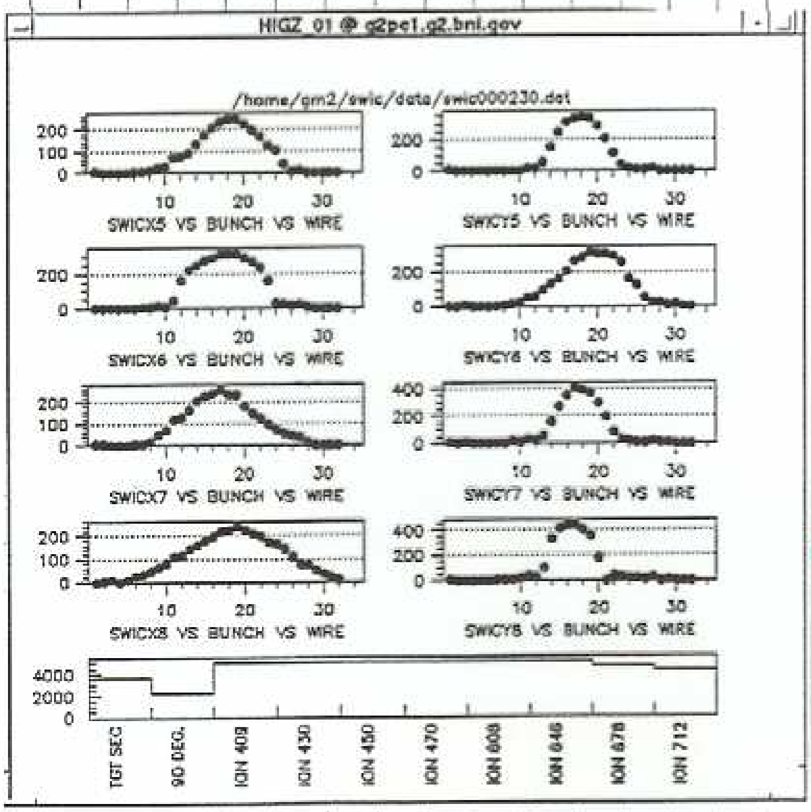

g-2

π/μ Beam : Segmented Wire Ion Chambers For 1 pulse (June 96)

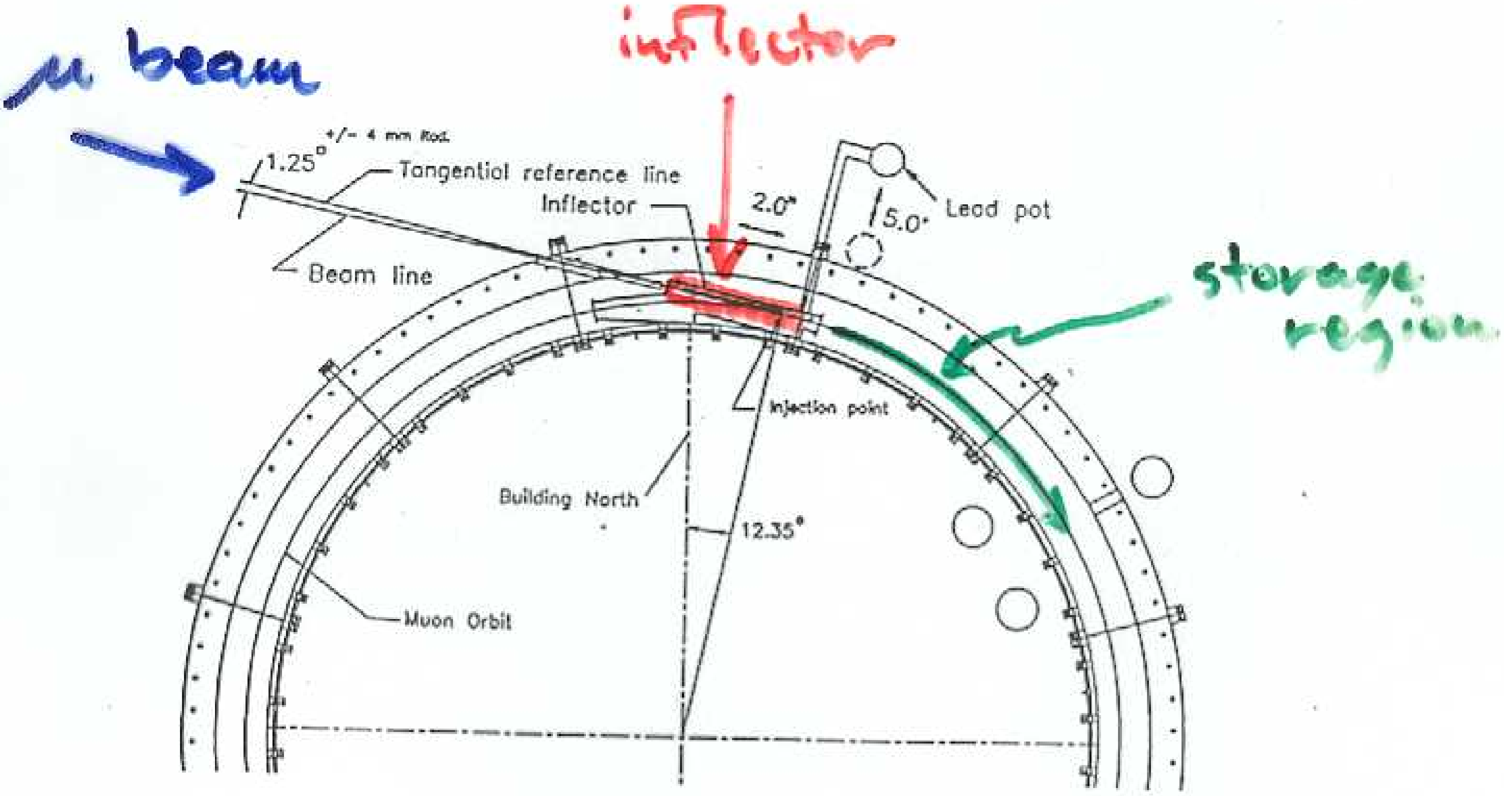
X Y



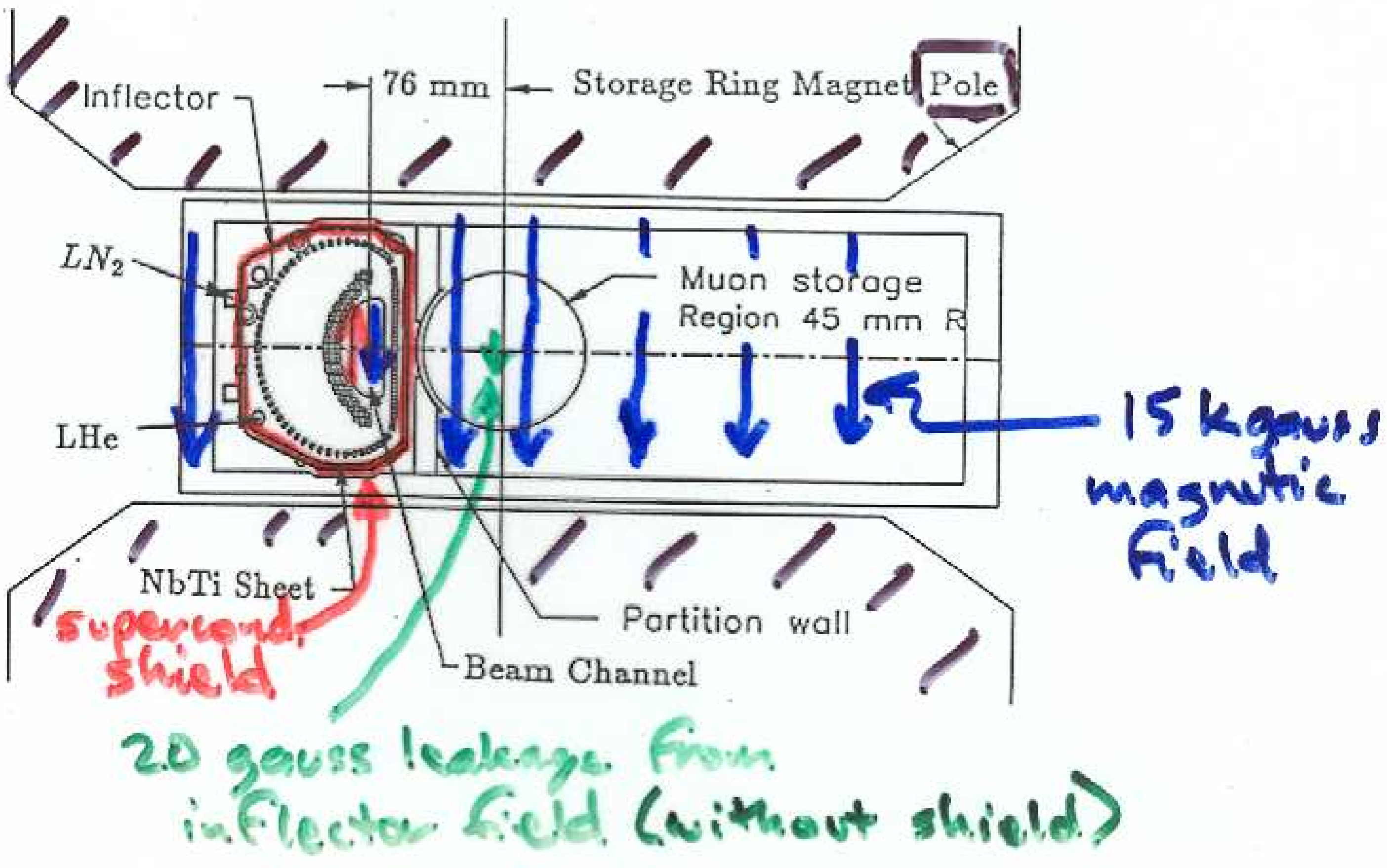
Quad channel



← at entrance to ring

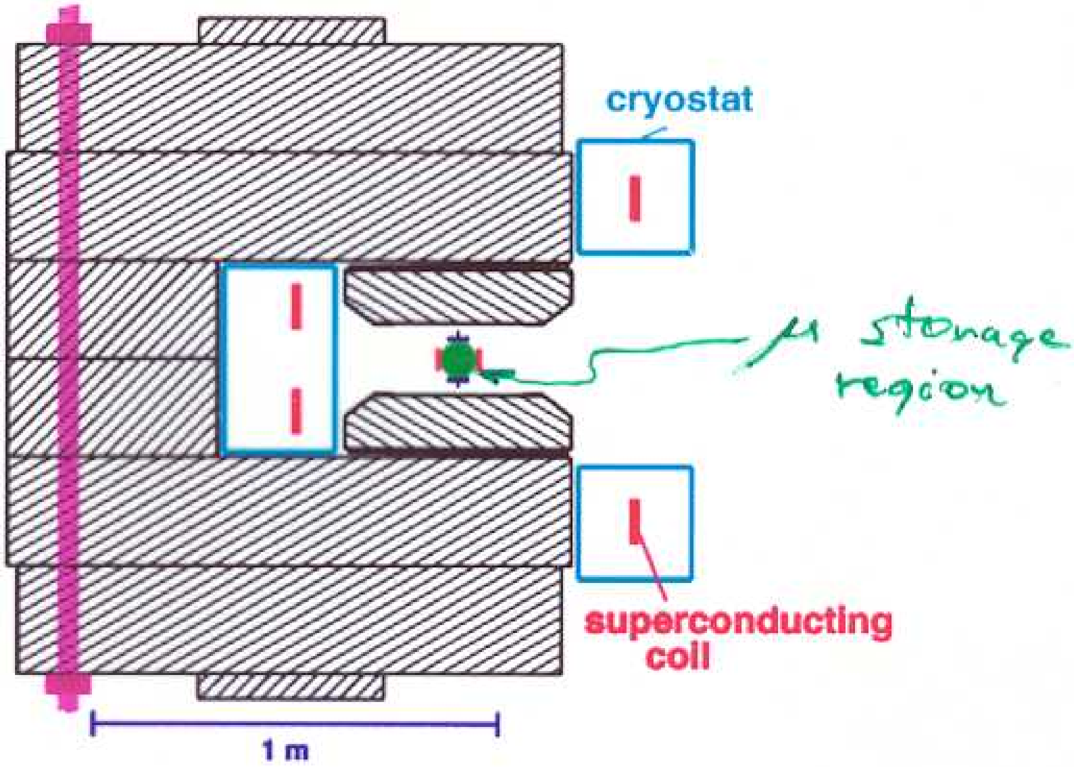


μ beam
inflector
1.25°
+/- 4 mm Rad.
Tangential reference line
Inflector
2.0°
5.0°
Lead pot
Beam line
storage region
Injection point
Building North
12.35°
Muon Orbit

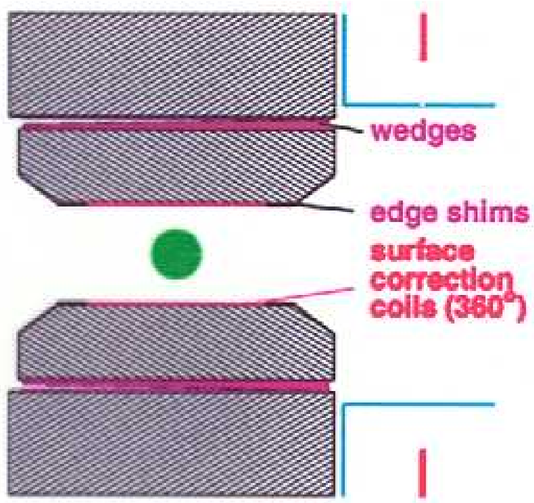


Inflector
76 mm
Storage Ring Magnet Pole
LN_2
Muon storage Region 45 mm R
LHe
15 kgauss magnetic field
NbTi Sheet
supercond. shield
Partition wall
Beam Channel
2.0 gauss leakage from inflector field (without shield)

The E821 Ring Magnet



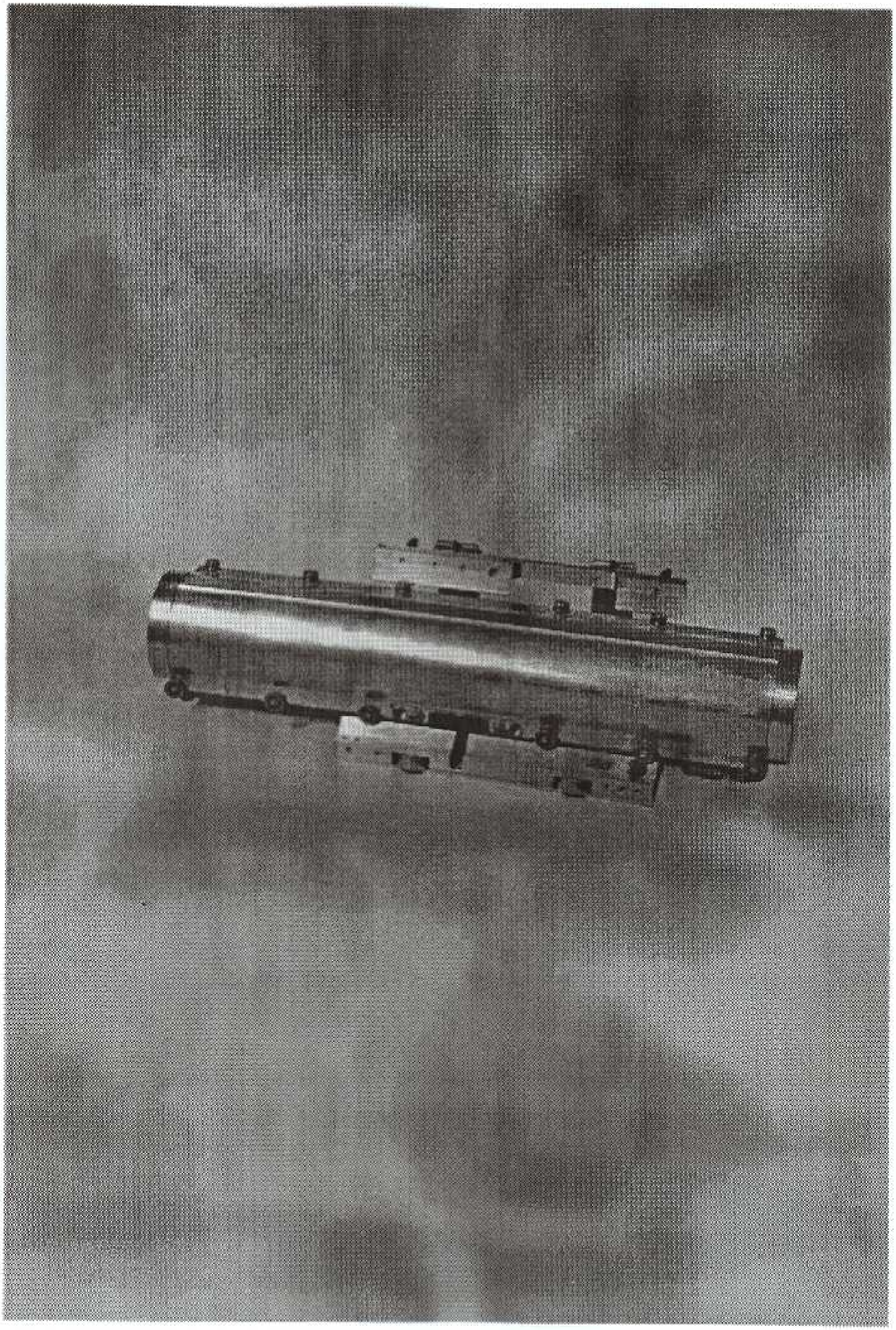
shimming tools:



- world's largest superconducting magnet
- g-2 magnet gap = 18 cm
- circumference ≈ 44 m
- field uniform to ± 1 ppm

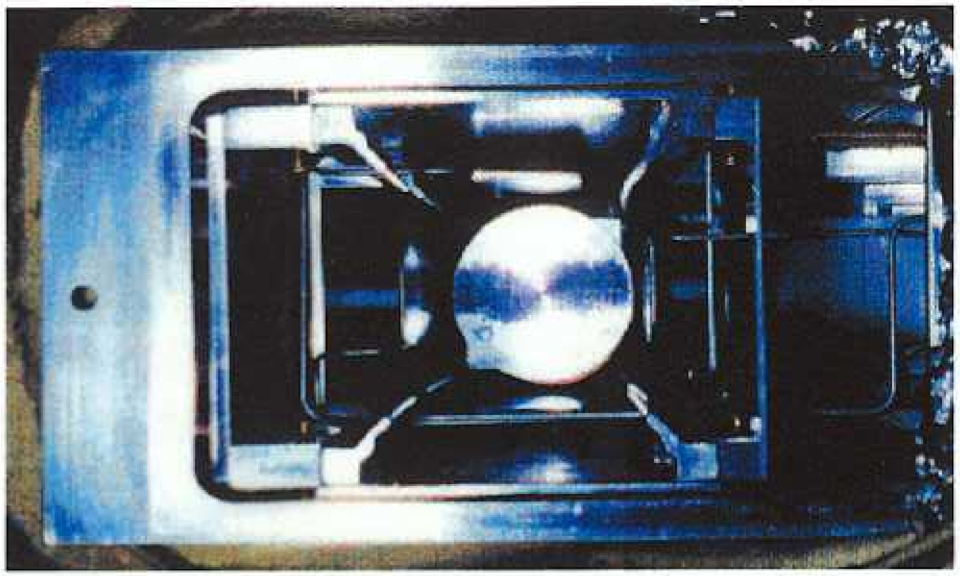
diam. (human hair) ≈ 50 μm

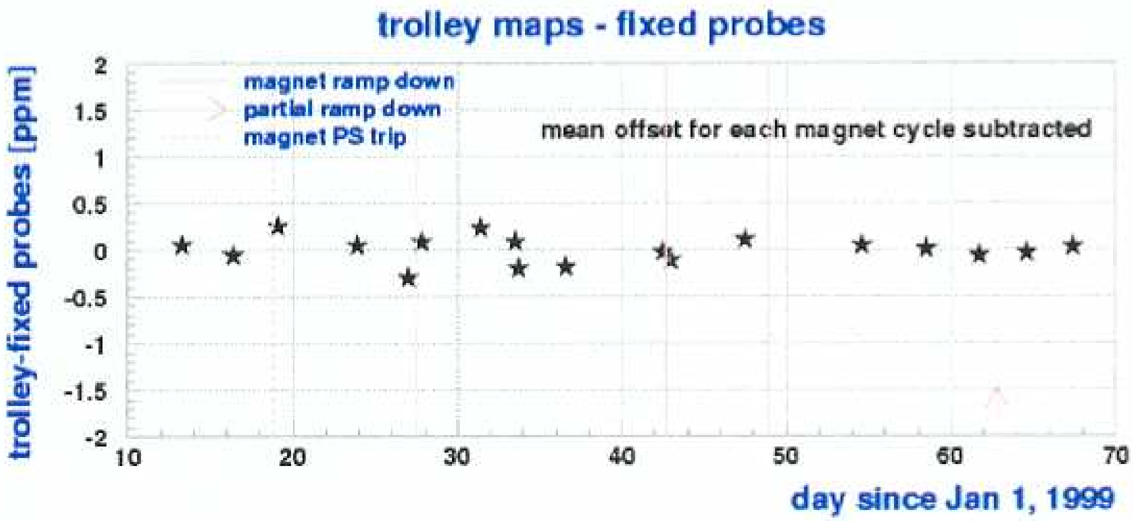
$$\frac{d\,(\text{hair})}{d\,(\text{gap})} = \frac{50 \times 10^{-6}}{2 \times 10^{-1}} = 250 \text{ ppm}$$



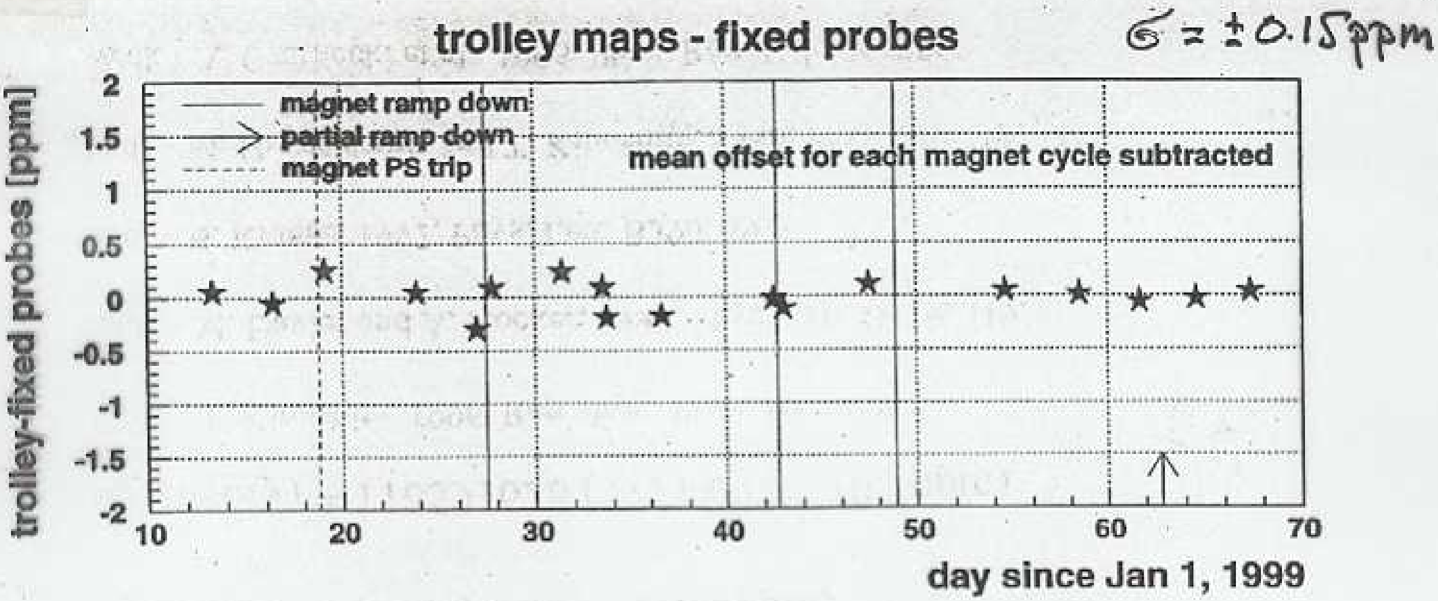
ω_p: *The NMR Beamtube Trolley*

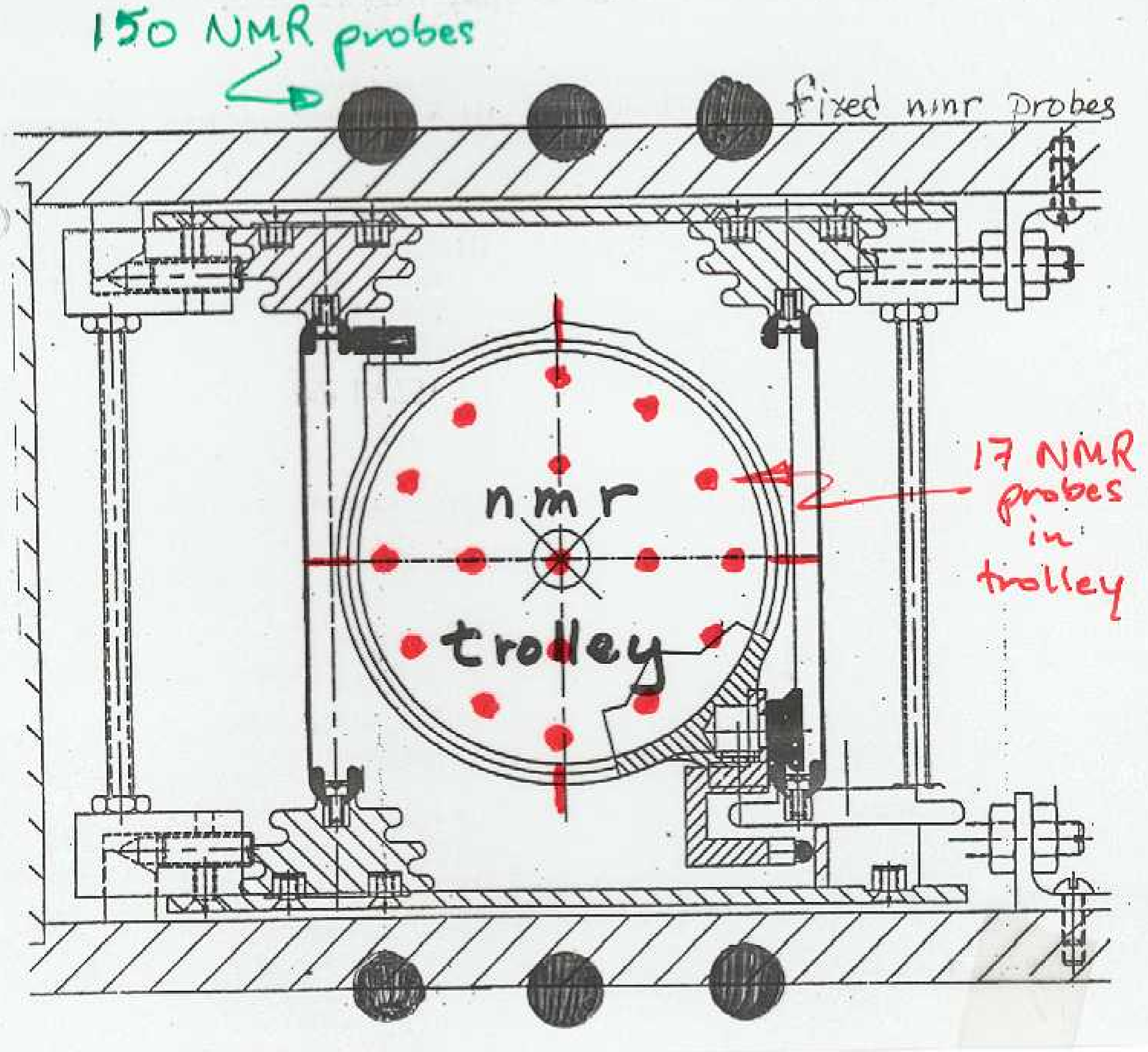
- 17 probe NMR trolley operates in vacuum to map out field in storage region (2-3 times per week)
- Absolute calibration to spherical reference probe before and after data taking periods

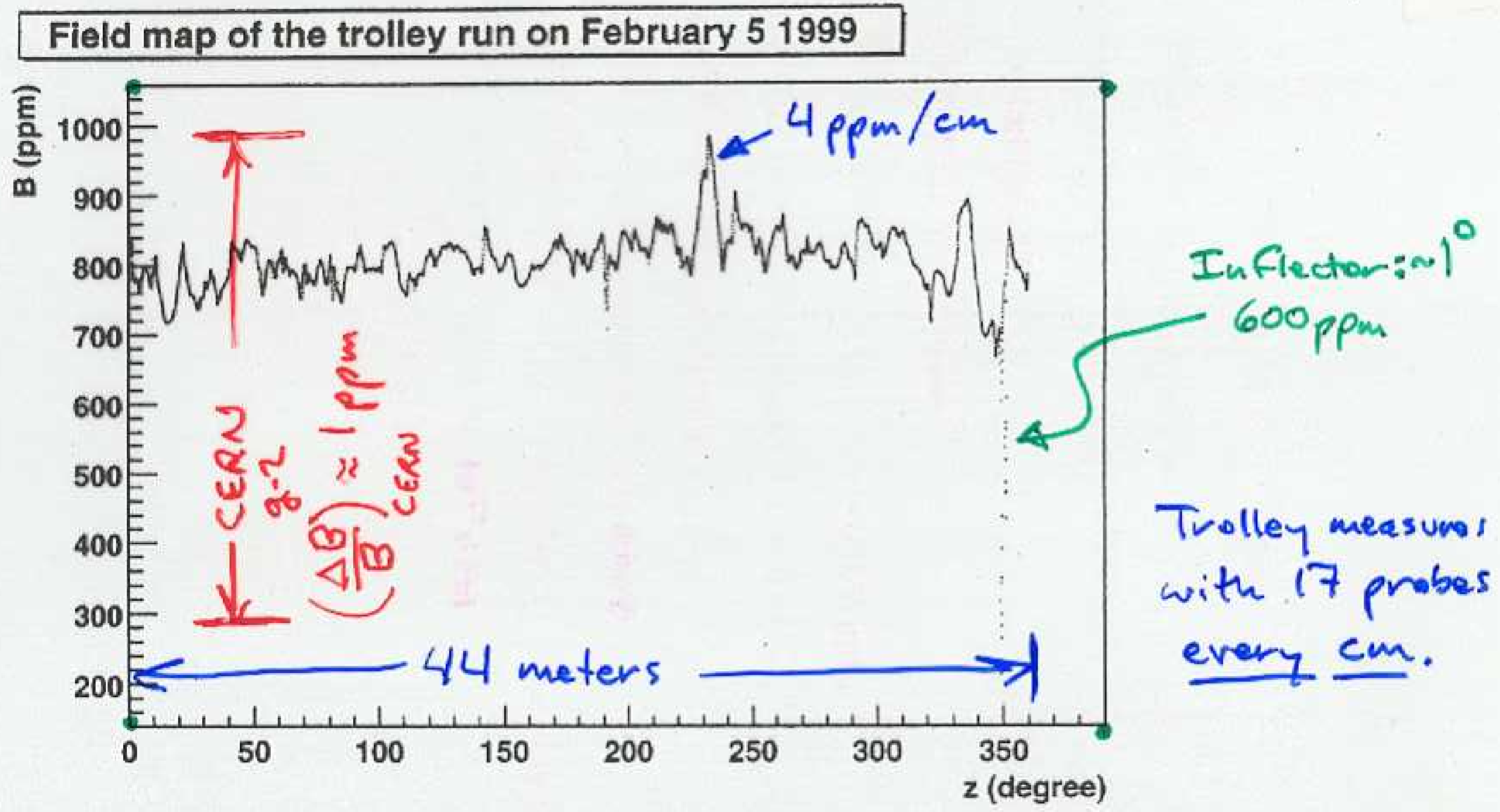




Fixed probes track the field between trolley runs with an uncertainty below 0.15 ppm


trolley maps - fixed probes
σ = ±0.15ppm
magnet ramp down
partial ramp down
magnet PS trip
mean offset for each magnet cycle subtracted
trolley-fixed probes [ppm]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
10
20
30
40
50
60
70
day since Jan 1, 1999


150 NMR probes
fixed nmr Probes
17 NMR probes in trolley
nmr
trolley



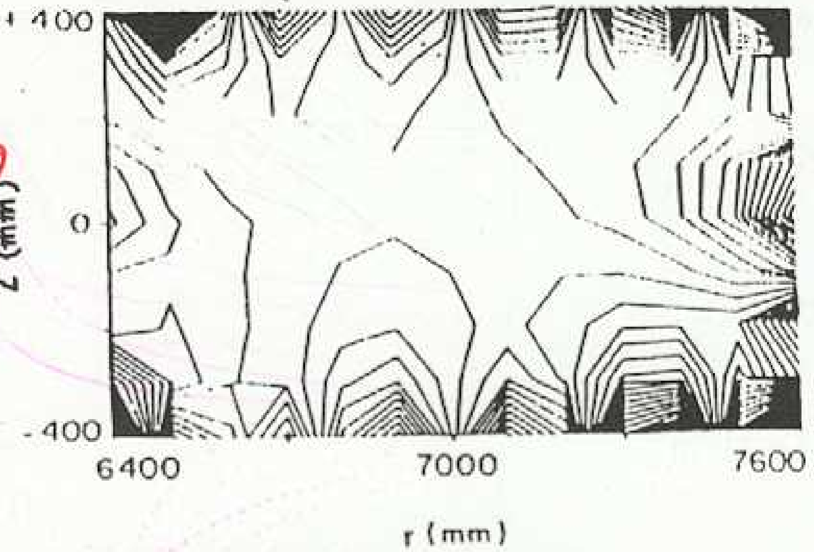
The magnetic field measured with the trolley center probe vs. azimuth for the measurements taken on February 5 1999. The dip at 350° is due to the inflector fringe field.

351° – 349° ± 0.10 ppm (~359° non-inflector)

350° ± 0.20 ppm (~1° inflector)

B-field Uniformity (2 ppm field lines)

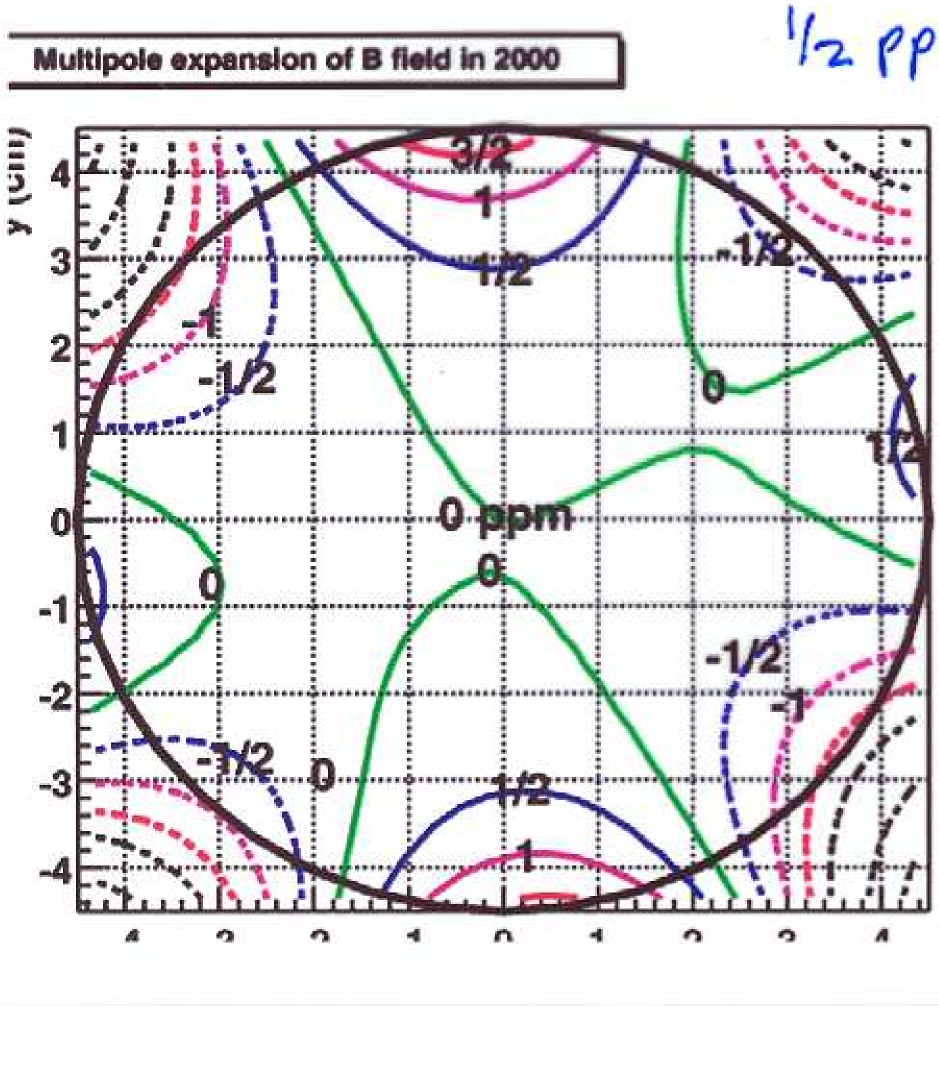
CERN Storage Ring Aperture



CERN
2 ppm contours

Fig. 5. A contour line plot of the magnetic field strength in the muon storage aperture. This map is obtained by averaging a three-dimensional map in azimuth. The interval between the contours of equal field strength is 2 ppm or 3 μT.

BNL g-2
1/2 ppm contours



BNL Storage Aperture

Multipoles (ppm)

	normal	skew
Quad	0.03	0.09
Sext	-0.63	0.27
Octu	-0.02	0.00
Decu	1.09	0.53

ω_p: Systematics

TABLE I. Systematic errors for the $\tilde{\omega}_p$ analysis

Source of errors	Size [ppm]
Absolute calibration of standard probe	0.05
Calibration of trolley probes	0.20
Trolley measurements of B_0	0.10
Interpolation with fixed probes	0.15
Inflector fringe field	0.20
Uncertainty from muon distribution	0.12
Others †	0.15
Total systematic error on $\tilde{\omega}_p$	0.4

† higher multipoles, trolley temperature and its power supply voltage response, and eddy currents from the kicker.

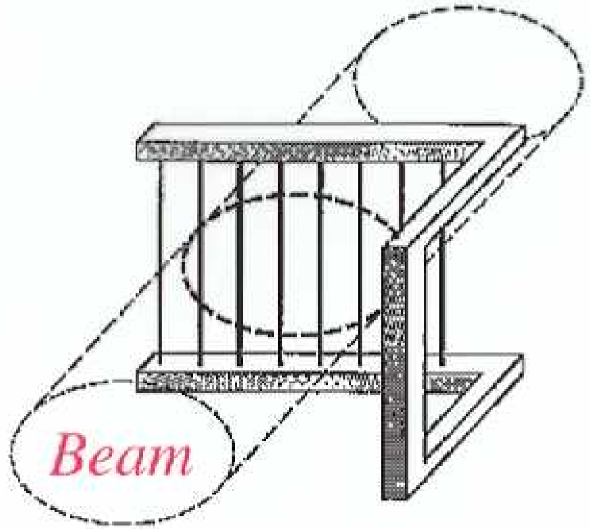
Beam tracking simulations show <B> over muon distribution agrees with B measured at beam center

$$\omega_p/2\pi = 61{,}791{,}256 \pm 25\,Hz$$

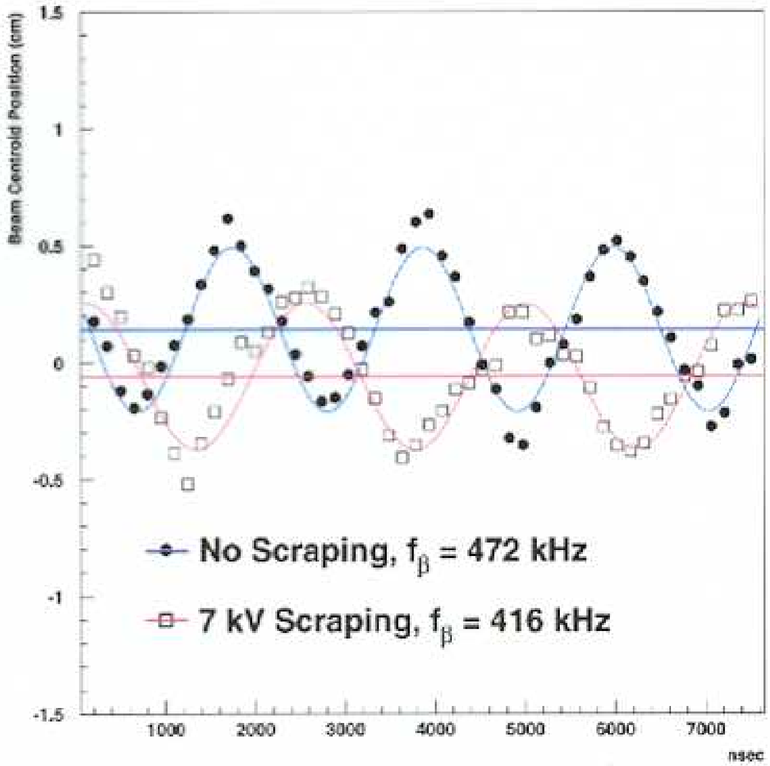
ω_a: *Coherent Betatron Oscillation*

Scintillating fiber plunging beam monitor:

- 7 x 0.5 mm thick fibers
- 13 mm spacing



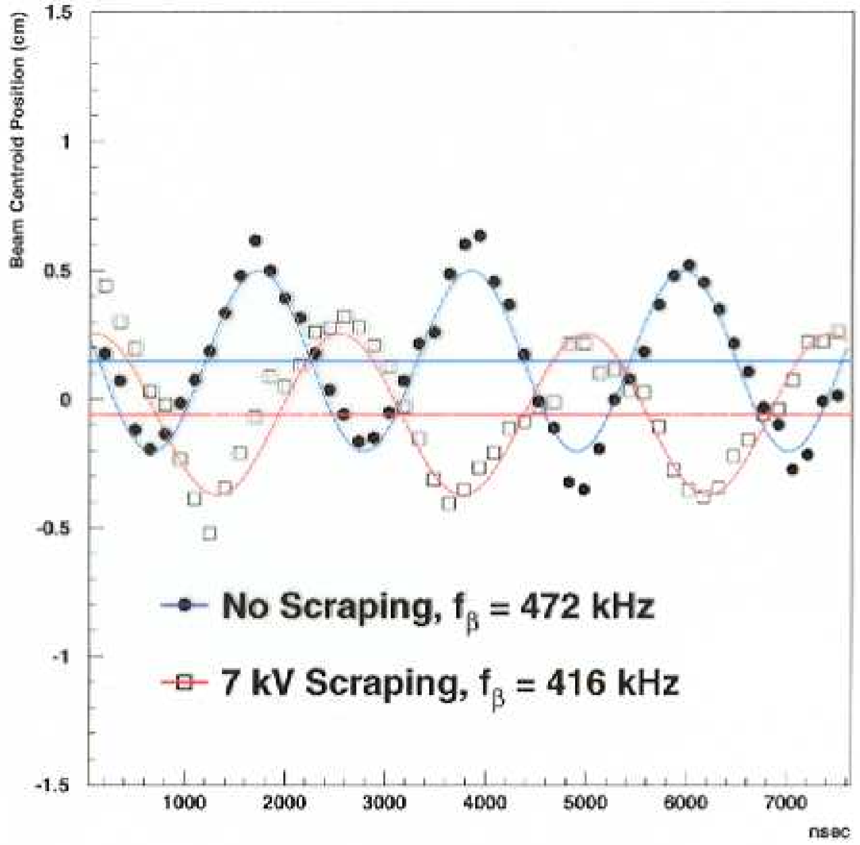
Direct observation of CBO



$$\omega_{CBO} = \omega_c \left(1 - \sqrt{1-n}\right)$$

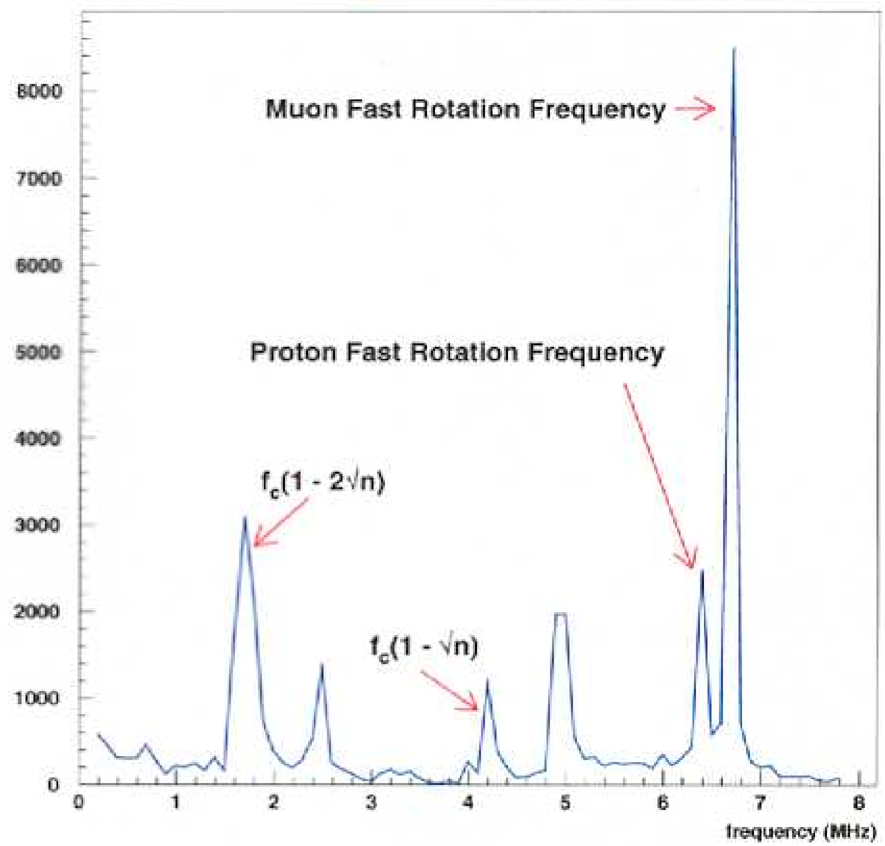
Measurement of Beam Dynamics and Composition

Turn–by–turn Evolution of Radial Beam Centroid



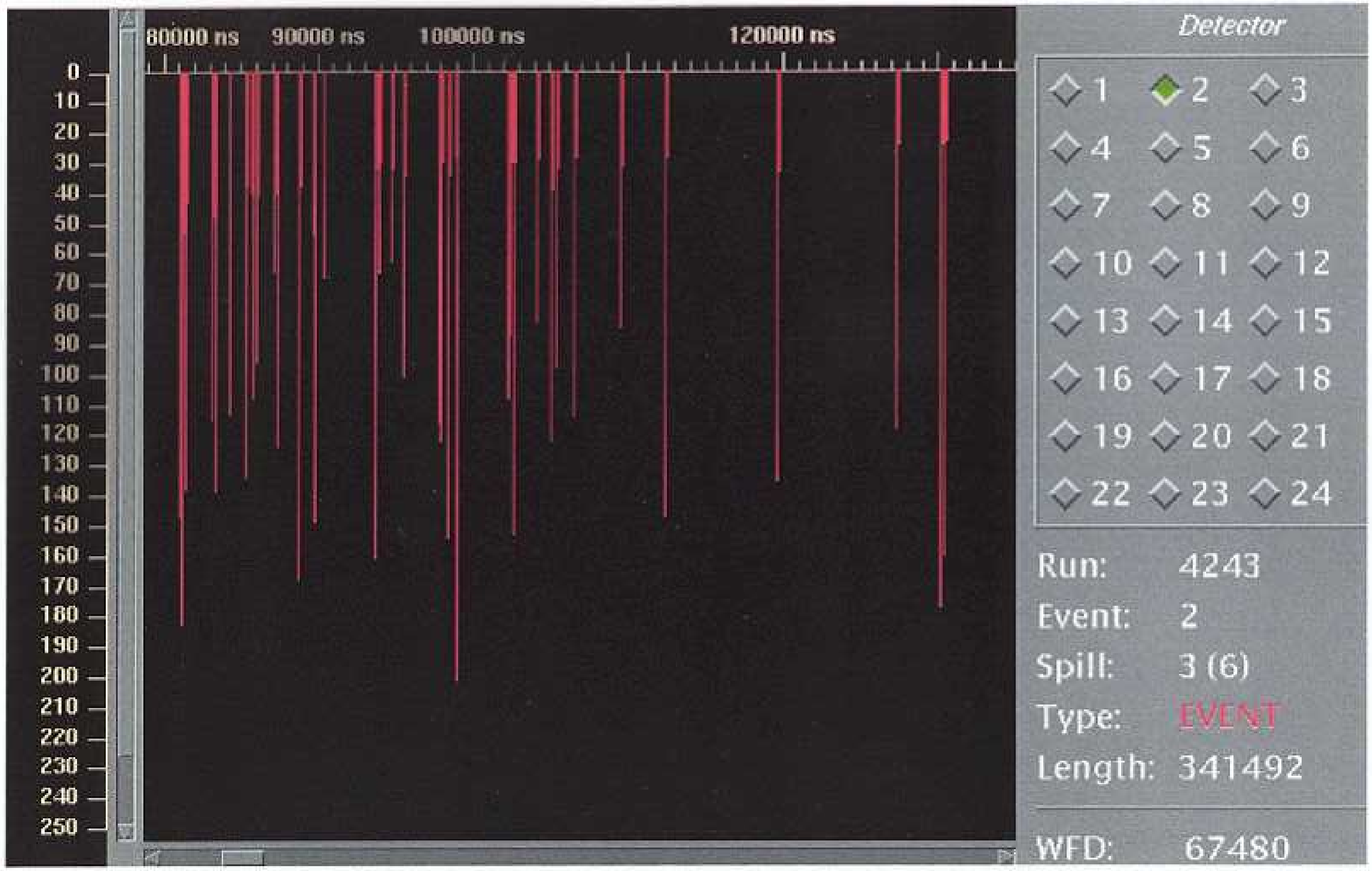
n–value of storage ring changes from 0.136 to 0.120 during 7 kV quadrupole scraping

Fast Fourier Transform of Single Fiber Trace



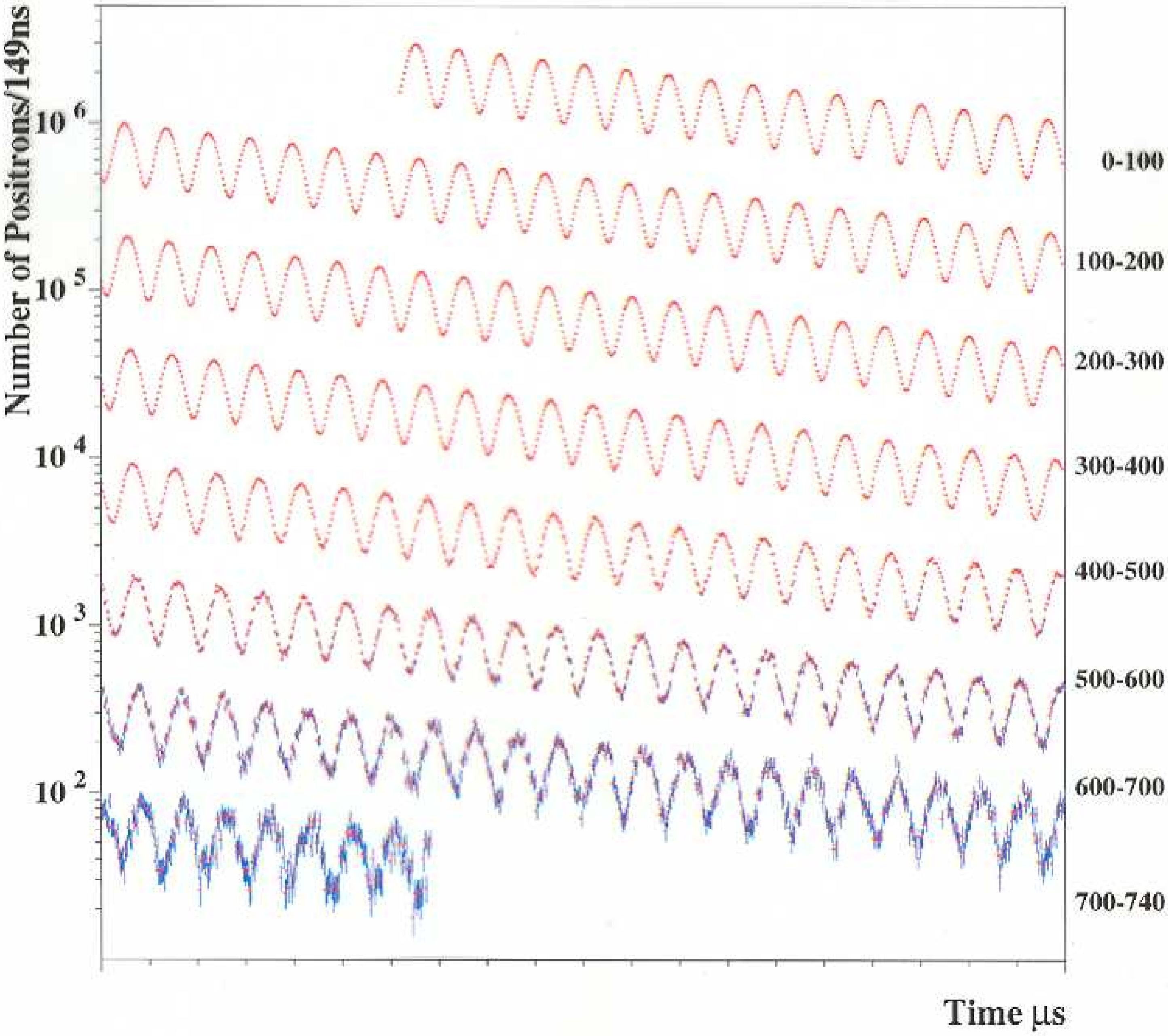
Measurement of fast rotation frequency, betatron frequency, and evidence of stored protons

Muon Injection



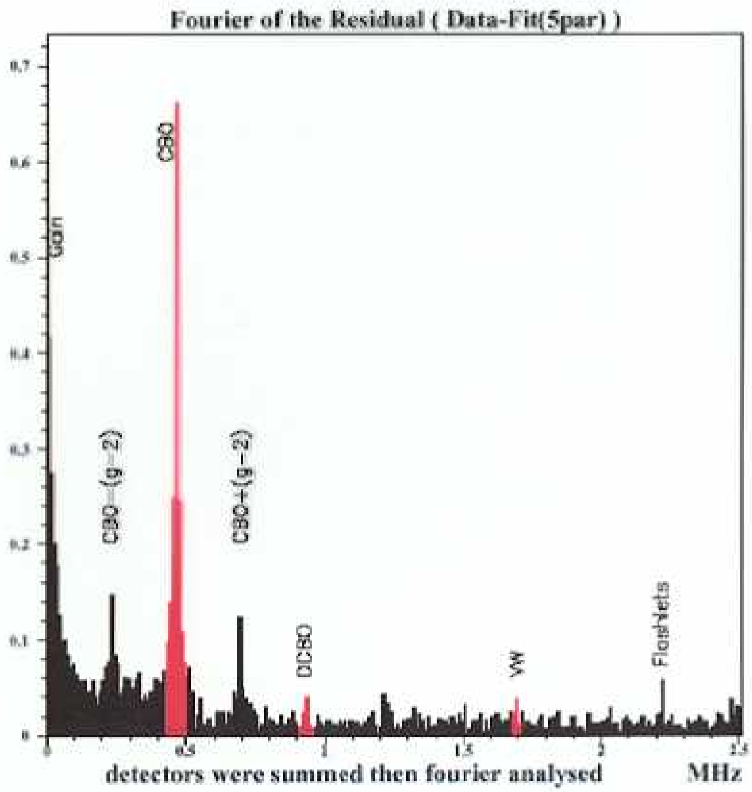
Positron Signal

digitized with 400 MHz



Number of Positrons/149ns
10 6
10 5
10 4
10 3
10 2
0-100
100-200
200-300
300-400
400-500
500-600
600-700
700-740
Time μs

ω_a: Coherent Betatron Oscillation



Since calorimeter acceptance depends on muon decay position, CBO modulates the positron time spectra.

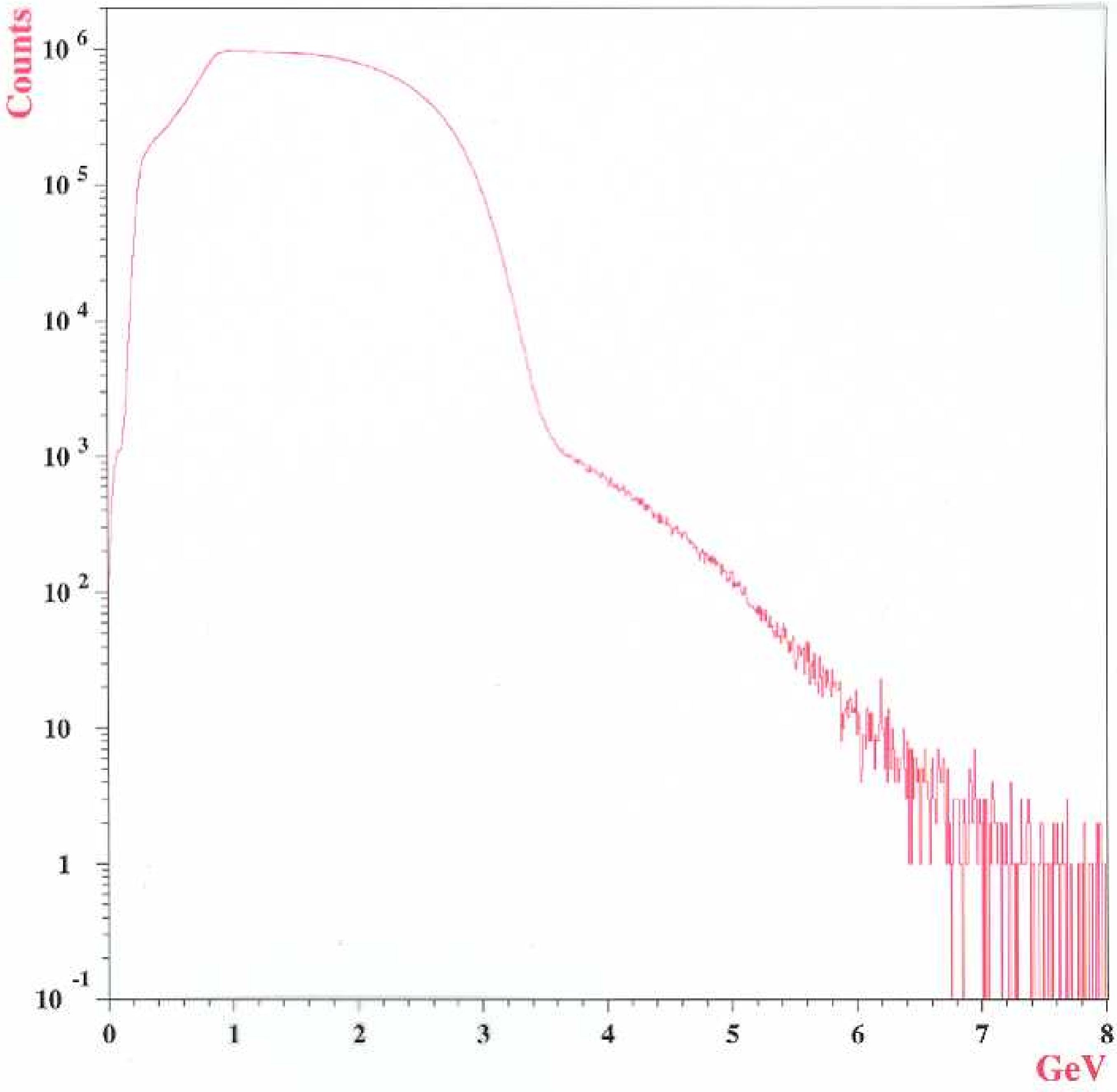
With high statistics, the effect is large and visible in the residuals of the 5 parameter fit.

Oscillations dephase slowly with a time constant of ~100 μsec.

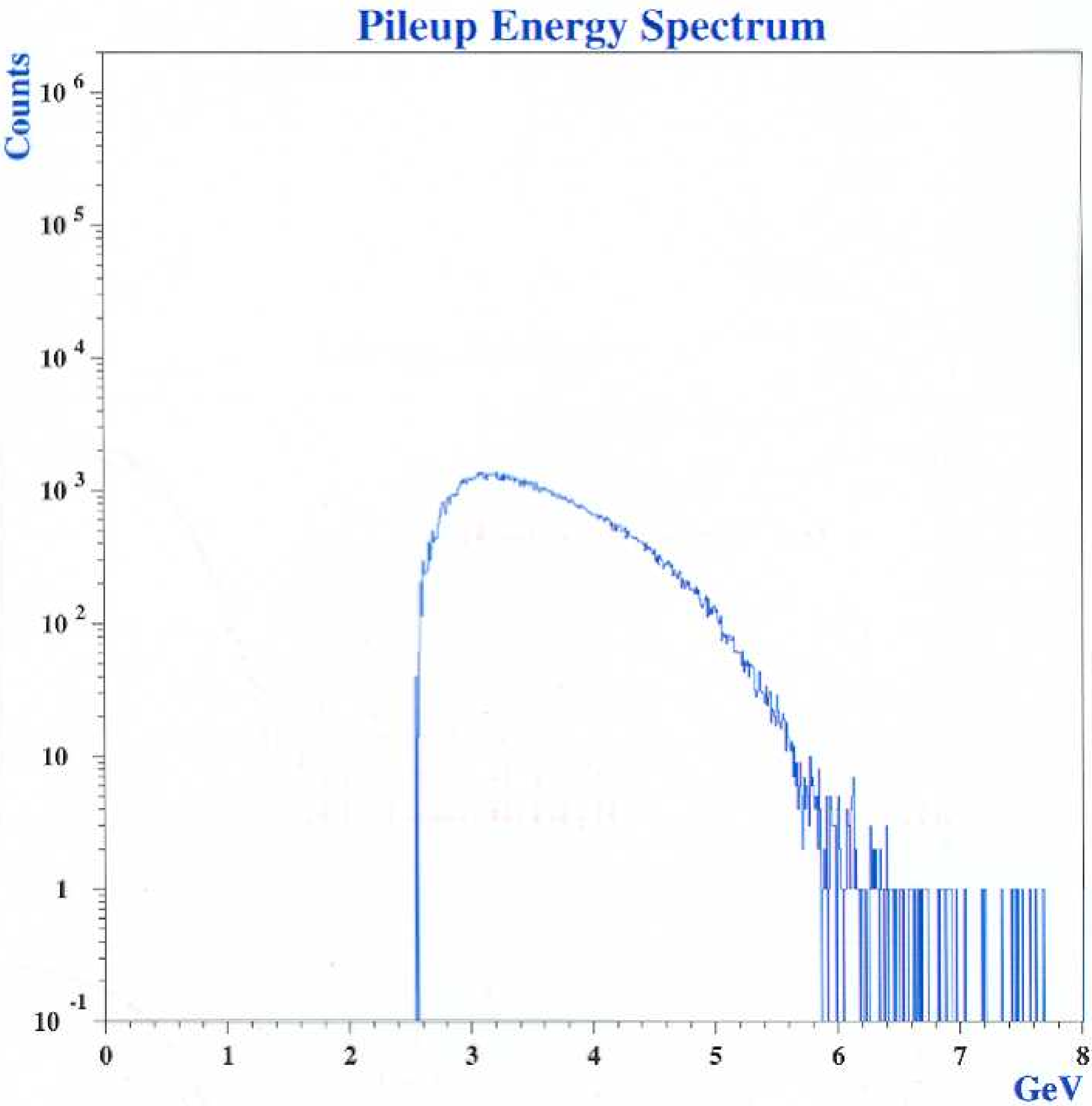
Modify fit function:

$$F_{CBO} = 1 + A_{CBO} e^{-t^2/\tau^2_{CBO}} \cos(\omega_{CBO} t + \phi_{CBO})$$

Detected Positron Energy Spectrum

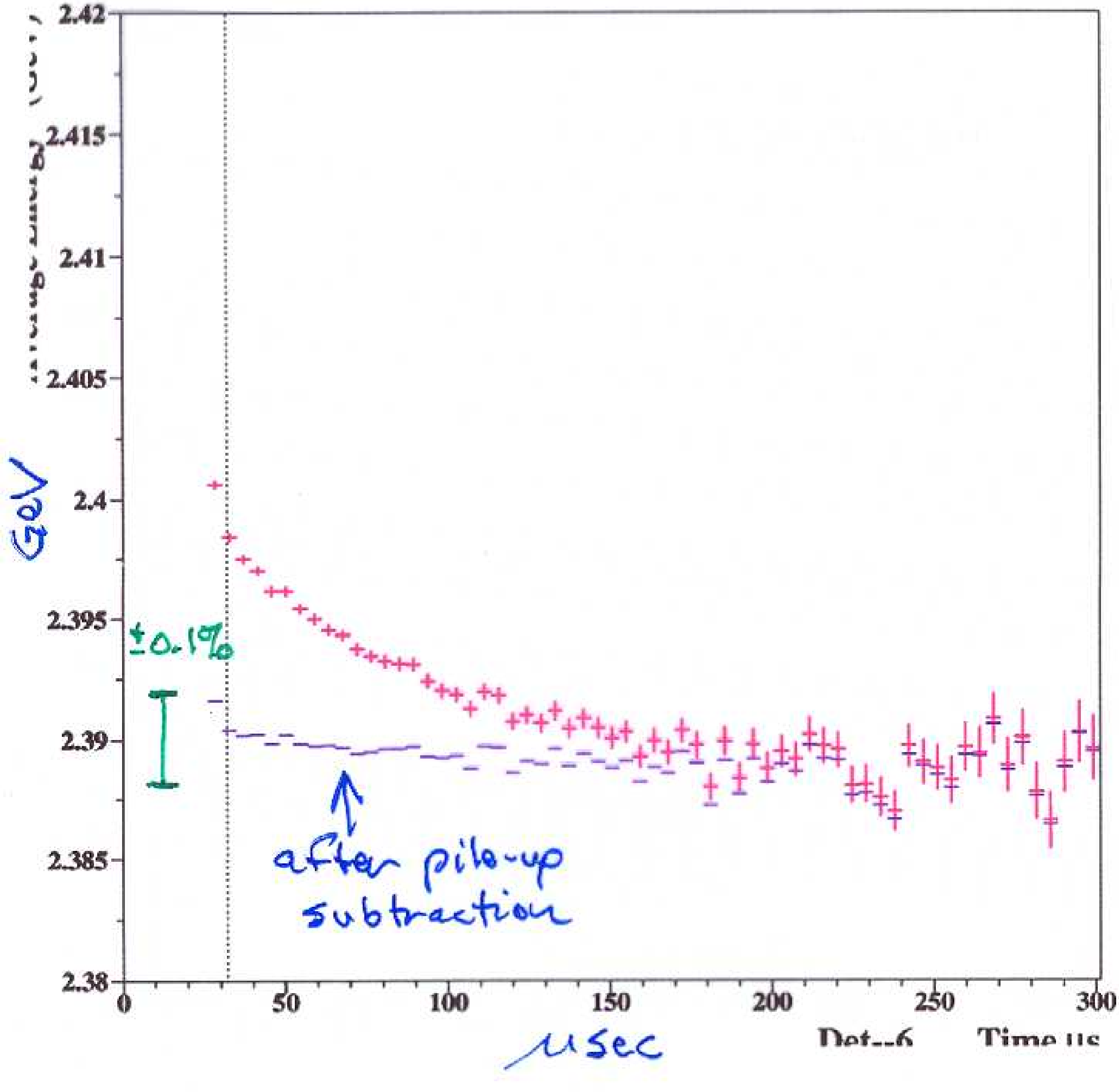


Double Pulse



Pileup Energy Spectrum
Counts
10 6
10 5
10 4
10 3
10 2
10
1
10 -1
0
1
2
3
4
5
6
7
8
GeV

Average Energy seen in Detector 6
vs. time after injection



1999 ω_a Analysis

1. Data are energies every 2.5 nsec over a 1 GeV threshold.

2. Fit pulses, obtain pedestal, energy, time from injection.

   ---many details: pulse shapes, analyze pedestal vs. time, self-consistency checks; 2 approaches used, ...

3. g-2 "wiggle" plot. Fit with 5 parameters:

$$F(t) = \underline{N_0}\, e^{-t/\underline{\tau_\mu}} \left[1 + \underline{A} \cos(2\pi \underline{f} t + \underline{\phi})\right]$$

4. poor χ^2 : plot residuals

   ---coherent betatron oscillation from kick

      ---also seen in fiber monitor

   ---include CBO in fit

5. fast rotation---beam arrives bunched, 149 nsec period of ring

   ---bin in 149 nsec bins

   ---also generates pile-up

      ---used to study pile-up

6. pile-up---more at early times than late

   ---use "shadow" pulses to directly measure and remove pile-up

7. average energy seen in detectors vs. time---flat!

8. chi^2/DF flat, 0.995, all fit parameters well behaved vs. start time.

ω_a: *Fit Results*

Institute	Production	Fit Start	Fit Par.	χ^2/DOF	(R ± Stat. Err.) ppm
B.U.	Fort/PAW	32 μs	13	1.012 ± 0.023	143.25 ± 1.24
BNL	Fort/PAW	32 μs	10	1.005 ± 0.023	143.08 ± 1.24
Illinois	C++/ROOT	25-56 μs	9	1.016 ± 0.005	143.30 ± 1.23
Minn	C++/ROOT	34 μs	3	0.986 ± 0.025	143.37 ± 1.28

13 fit par: CBO, lost muons, pileup (ϕ_p from study)
10 fit par: CBO, lost muons, pileup corrected
9 fit par: CBO, lost muons fixed, pileup corrected
3 fit par: Ratio of shifted time spectra - $A\cos(\omega_a t+\phi)+\tau_a^2/16\tau_\mu^2$

All numbers agree within standard statistical tests. The final answer is the weighted average of the four results, accounting for the strong correlations.

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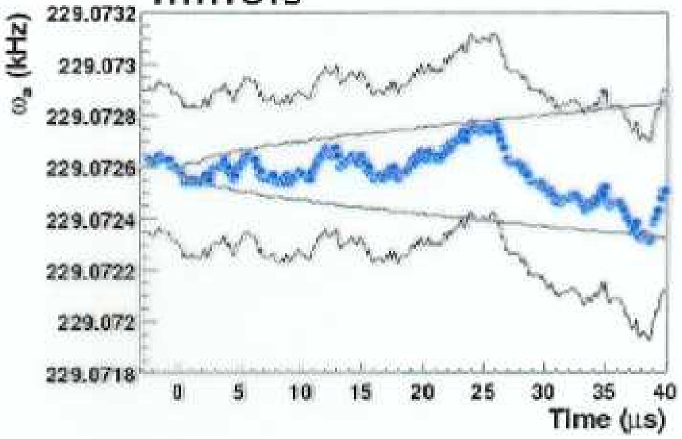
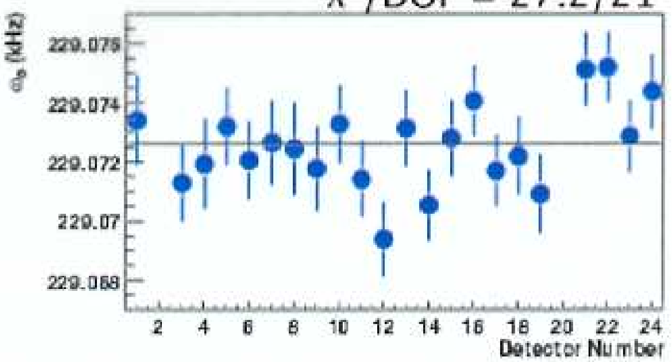
All numbers agree within standard statistical tests. The final answer is the weighted average of the four results, accounting for the strong correlations.

ω_a: *Consistency Checks*

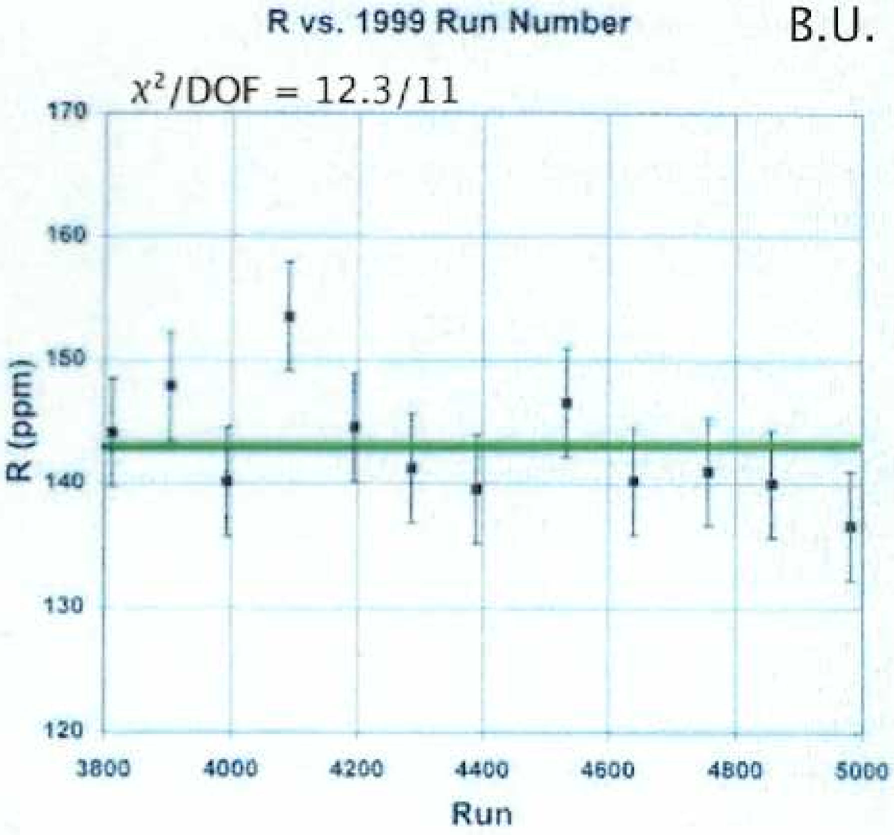
Illinois



$\chi^2/DOF = 27.2/21$



B.U.



Feb., 2001

1999 Run Analysis Systematic Error

ω_p	ppm
Standard probe absolute calibration	0.05
Calibration of B_0 against standard probe	0.20
B_{av} from trolley probes due to position uncertainty	0.10
Inflector fringe field	0.20
Tracking by fixed probes	0.15
Average over muon distribution	0.12
Others (kicker eddy current, higher multipoles,...)	0.15
Total ω_p	0.4

ω_a	ppm
Timing shifts	0.10
E field and pitch	0.08
Flashlets	0.10
Coherent betatron oscillation	0.05
Lost muons	0.10
Pileup subtraction/pileup phase	0.13
Detector energy scale	0.02
Fitting method/binned data	0.07
Spin resonances	0.01
Fast rotation/randomization	0.04
Others (fit start time, clock, ...)	0.01
Total ω_a	0.3

0.2 Long Duong Thesis

Total 1999 run systematic error 0.5ppm.

Stat. error 1.2ppm
Total " 1.3ppm

Feb. 2001 Talk

Conclusions

99 run: $a_{\mu^+} = 116\ 592\ 02\ (16) \times 10^{-10}$

SM[1] $a_\mu = 116\ 591\ \sout{59.6}\ 76.8\ (6.7) \times 10^{-10}$

Difference: ($\sout{42}$ 25 $\pm$ 16) $\times 10^{-10}$

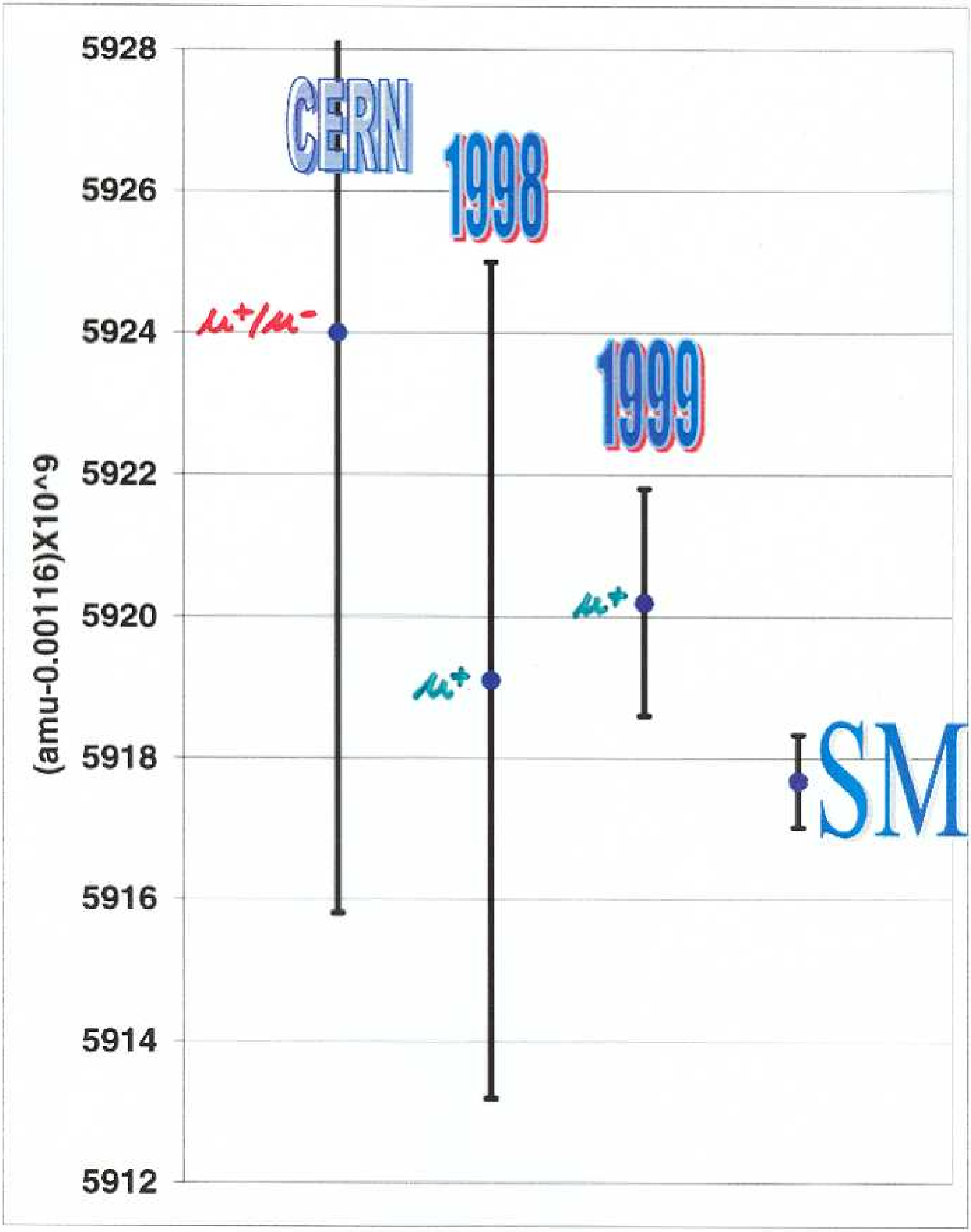
($\sout{3.6}$ 2.1 $\pm$ 1.3) ppm or $\sout{2}$1.6 σ

Coming attractions: now analyzing 2000 run μ^+ data, with result probably late 2001 or early 2002. ($\sim 4 \times$ $\mu^+ \to e \nu \bar{\nu}$)

Feb.-Apr. 2001 run with μ^-.

Request additional μ^- run.

1. A. Czarnecki and W. Marciano Nucl. Phys. B(Proc. Suppl.) **76** (1999) 245.



5928
5926
5924
5922
5920
5918
5916
5914
5912
(amu-0.00116)X10^9
CERN
1998
1999
SM
μ+/μ-
μ+
μ+

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November 15, 2001

Dr. Tom Kirk
Associate Laboratory Director
for High Energy and Nuclear Physics
Building 510F
BNL
Upton, NY 11973

Dear Tom,

I write in support of Proposal P962 to the Brookhaven PAC, for additional experimental work to determine accurate values of the muon and anti-muon magnetic moments.

The group has already done beautiful work on this subject at Brookhaven. Their accomplished measurements give indications of a possible discrepancy with the Standard Model. These results lie in the fuzzy area between tantalizing hints and definitive discoveries. The proposal is a compelling extension. Given a relatively small additional investment, d the value of the whole body of work would be substantially enhanced, and the central issue standard model, or more – might well be settled one way or the other.

From my perspective as a theoretical high-energy physicist, there are few if any experimental initiatives of equal significance on the near horizon. A whole complex of ambitious ideas involving unification and low-energy supersymmetry make the possibility of a discrepancy in magnetic moments with roughly the magnitude in question quite plausible. These ideas successfully account for the relative values of the strong, weak, and electromagnetic couplings, and thereby (if correct!) profoundly enhance our understanding of Nature, as well as suggesting many promising new directions for theoretical and experimental work. Even a negative result would be extremely significant, in constraining the realization of these and other ideas. It would also, we should remember, be an extraordinary scientific triumph. The "standard model" calculations of magnetic moments, at the level of accuracy contemplated here, employ the full apparatus of quantum field theory, renormalization, etc., while the experiments are brilliantly ingenious.

The important Physical Review Letter from the group, in March, immediately inspired dozens of papers, reflecting and elaborating the points of my preceding paragraph. It also aroused considerable public interest. For your edification, I enclose a copy of a small piece I wrote for Nature at the time.

With sincere best wishes,

Frank Wilczek
Professor of Physics

/jb

The Muon g−2 Collaboration

Precise measurement of the positive muon anomalous magnetic moment

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Muon $(g-2)$ Collaboration

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(February 16, 2001)

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