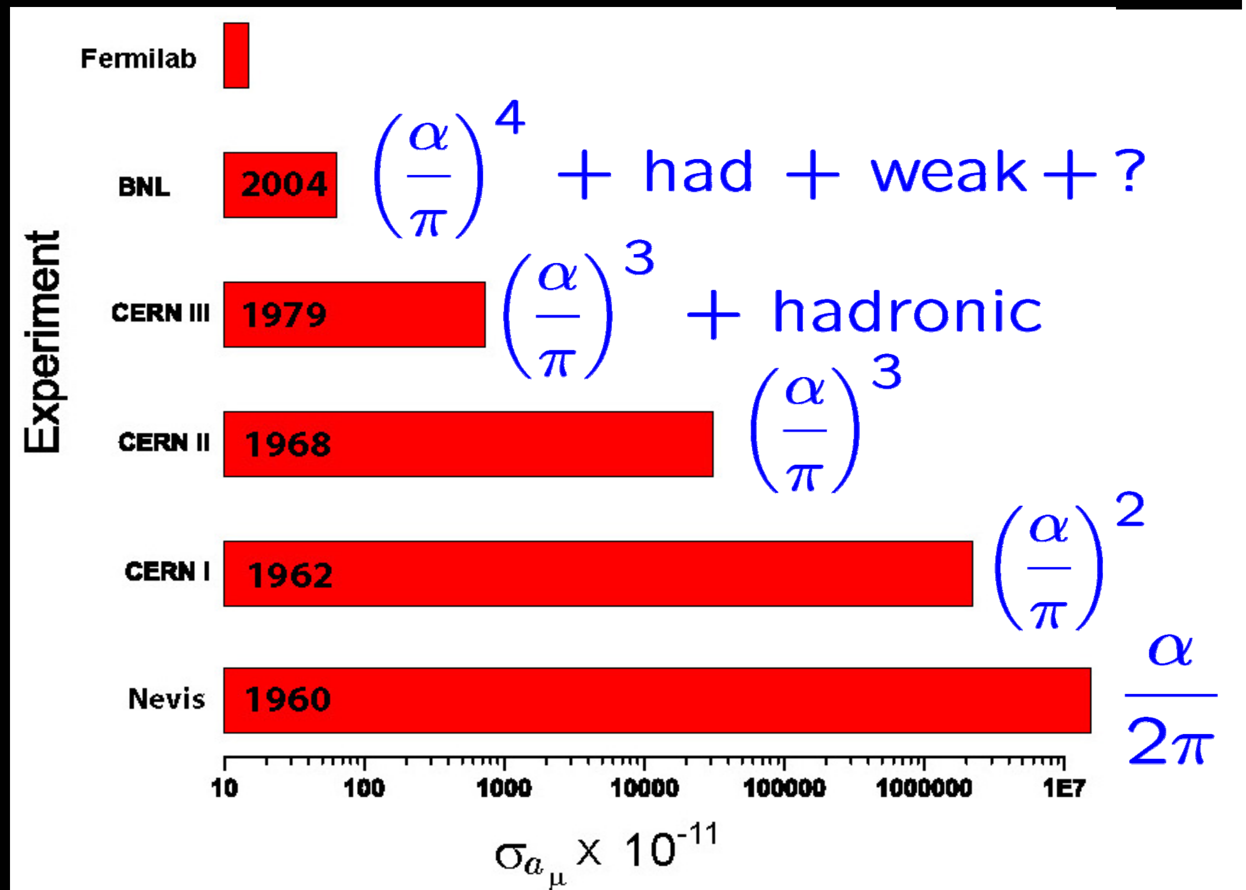
Muon (g-2) Past and Future

With an emphasis
on Beam Dynamics
in the
(g-2) Storage Ring



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The New $g-2$ Experiment:

A Proposal to Measure the Muon Anomalous Magnetic Moment to ± 0.14 ppm Precision

New $g-2$ Collaboration: R.M. Carey[1], K.R. Lynch[1], J.P. Miller[1], B.L. Roberts[1], W.M. Morse[2], Y.K. Semertzidis[2], V.P. Druzhinin[3], B.I. Khazin[3], I.A. Koop[3], I. Logashenko[3], S.I. Redin[3], Y.M. Shatunov[3], E.P. Solodov[3], Y. Orlov[4], R.M. Talman[4], B. Casey[5], B. Drendel[5], K. Genser[5], J. Johnstone[5], A. Jung[5], D. Harding[5], A. Klebaner[5], A. Leveling[5], J-F. Ostiguy[5], N.V. Mokhov[5], J. P. Morgan[5], V. Nagaslaev[5], D. Neuffer[5], A. Para[5], C.C. Polly[5], M. Popovic[5], M. Rominsky[5], A. Soha[5], P. Spentzouris[5], S.I. Striganov[5], M.J. Syphers[5], G. Velev[5], S. Werkema[5], F. Happacher[6], G. Venanzoni[6], M. Martini[6], D. Moricciani[7], J.D. Crnkovic[8], P.T. Debevec[8], M. Grosse-Perdekamp[8], D.W. Hertzog[8], P. Kammel[8], N. Schroeder[8], P. Winter[8], K.L. Giovanetti[9], K. Jungmann[10], C.J.G. Onderwater[10], N. Saito[11], C. Crawford[12], R. Fatemi[12], T.P. Gorringe[12], W. Korsch[12], B. Plaster[12], V. Tishchenko[12], D. Kawall[13], T. Chupp[14], R. Raymond[14], B. Roe[14], C. Ankenbrandt[15], M.A Cummings[15], R.P. Johnson[15], C. Yoshikawa[15], A. de Gouvêa[16], T. Itahashi[17], Y. Kuno[17], G.D. Alkhazov[18], V.L. Golovtsov[18], P.V. Neustroev[18], L.N. Uvarov[18], A.A. Vasilyev[18], A.A. Vorobyov[18], M.B. Zhalov[18], F. Gray[19], D. Stöckinger[20], S. Baeßler[21], M. Bychkov[21], E. Frlež[21], and D. Počanić[21]

http://lss.fnal.gov/archive/test-proposal/0000/fermilab-proposal-0989.shtml

Fermilab P989

- First submitted to PAC in February 2009
  - Great physics, how much does it cost?
- Building etc. costing exercise summer 09, report to PAC in November 2009
  - Great physics, Director must talk with DOE to figure out how to fund it.
- DOE Intensity Frontier Review August 2010
  - result embargoed until Presidential Budget released

Outline of the Talk

- Brief review of magnetic moments -- including the theory of a_μ
- Spin motion in a magnetic field
- Overview of the experimental technique
  - The precision storage ring magnet
  - The fast muon kicker
  - The electrostatic quadrupoles
- Beam dynamics in the storage ring
- Outstanding challenges for the future
- Summary and conclusions

Muon: (2nd generation lepton)

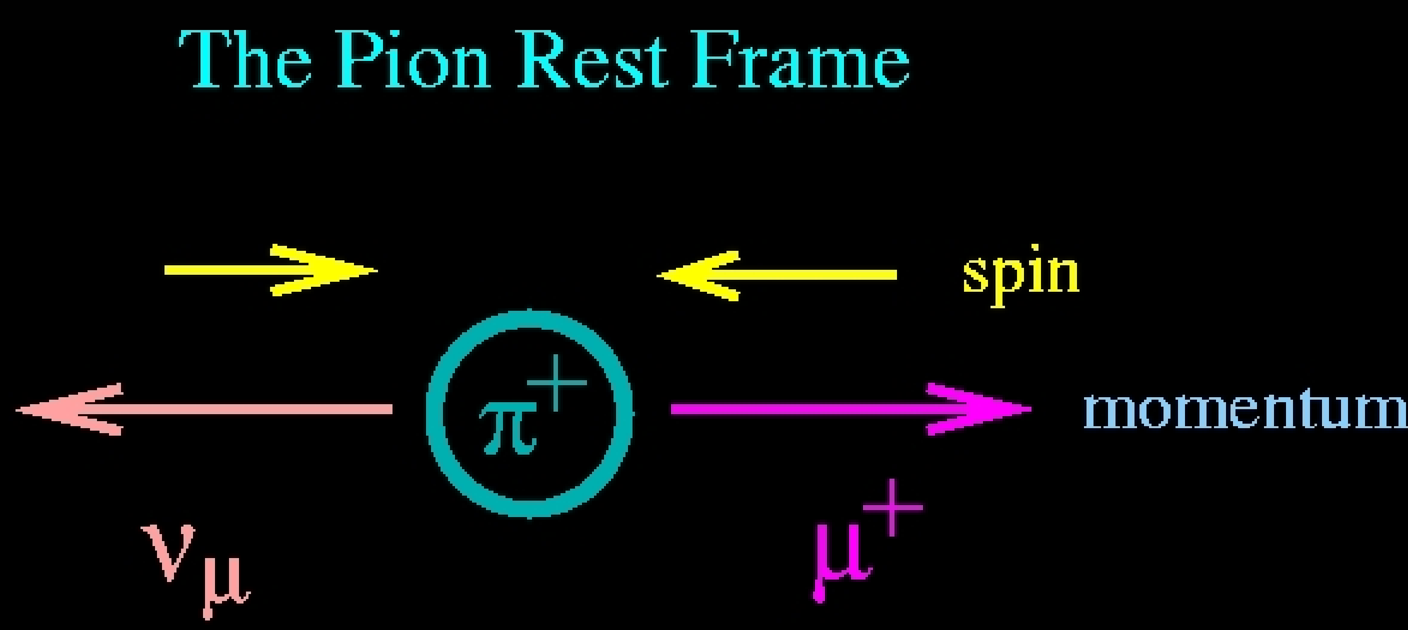
$$\tau_\mu = 2.197\,03(4)\ \mu\mathrm{s}$$

$$m_\mu c^2 = 105.658\,389(34)\ \mathrm{MeV}$$

“Who ordered that?”

Muon: (2nd generation lepton)

Source: weak decay $\pi^- \longrightarrow \mu^- \ \bar{\nu}_\mu$

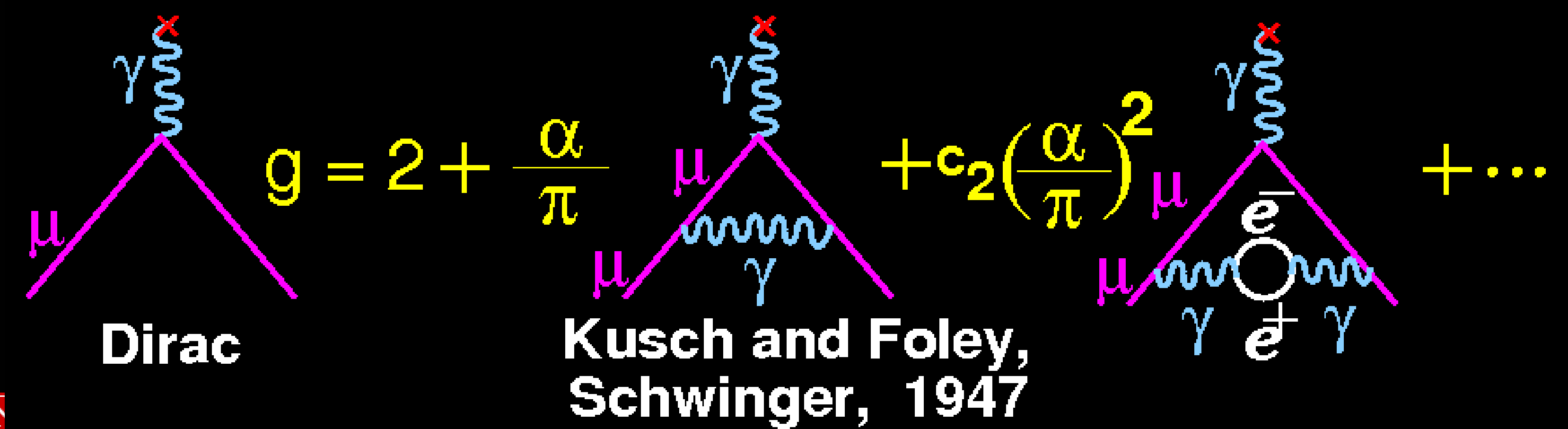


Magnetic Moments: g-factors, etc

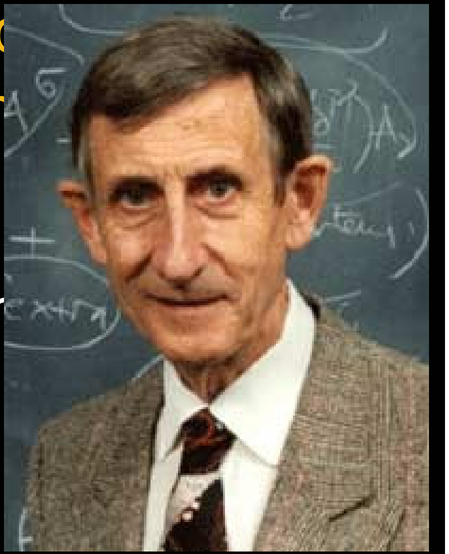
$$\vec{\mu}_s = g_s \left(\frac{e}{2m}\right) \vec{s}$$

μ – magnetic moment g – g value s – spin

- Dirac Equation predicts g $\equiv$ 2
- In nature, radiative corrections make g ≠ 2



An aside: The QED contribution to both electron and (g-2) is calculated through $(\alpha/\pi)^4$, with the $(\alpha/\pi)^5$ term being calculated by Kinoshita et al.



- This level of precision is far beyond what its inventors imagined.

"The main point was that all of us who put QED together, including especially Feynman, considered it a jerry-built and provisional structure which would either collapse or be replaced by something more permanent within a few years. So I find it amazing that it has lasted for fifty years and still agrees with experiments to twelve significant figures. It seems that Nature is telling us something. Perhaps she is telling us that she loves sloppiness."

Freeman Dyson (private communication) – December 2006

Magnetic Moments – ctd.

$$\mu = (1 + a)\left(\frac{e\hbar}{2m}\right) \text{ where } a = \left(\frac{g-2}{2}\right)$$

$$\mu_e = 1.001\ 159\,652\,180\,73(28)\ \frac{e\hbar}{2m_e}$$

$$\mu_\mu = 1.001\,165\,920\,89(63)\ \frac{e\hbar}{2m_\mu}$$

$$\mu_p = 2.792\ 847\ 39\ \frac{e\hbar}{2m_p};\ \ g_p \simeq 5.586$$

The SM value for lepton MDMs is one of the most precisely calculated numbers in physics

The Electron: to the level of the experimental error (4ppb),

$$a_e(\text{Standard Model}) = a_e(\text{QED with } \gamma,\ e)$$

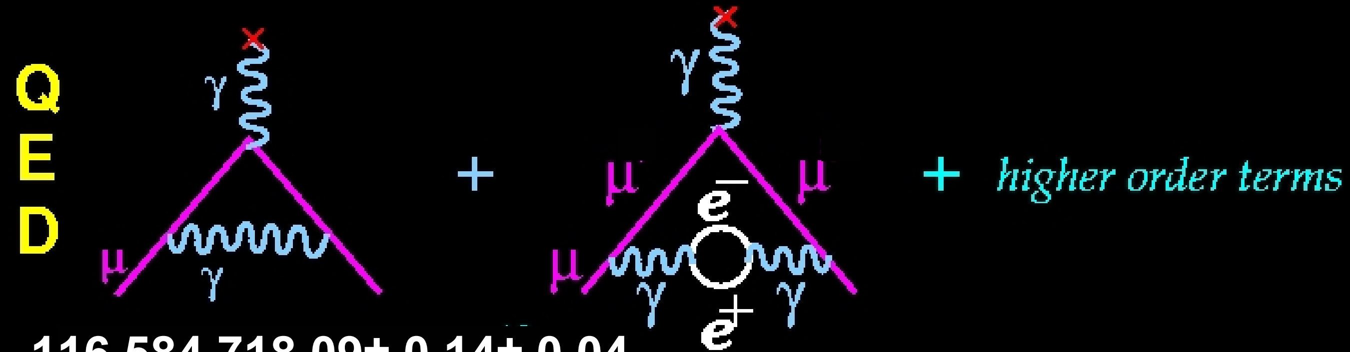
Contribution of μ, (or anything heavier than the electron) is ≤4 ppb.

For the muon, the relative contribution of heavier particles

$$\sim (\frac{m_\mu}{m_e})^2 \sim 40,000 \qquad \Rightarrow$$

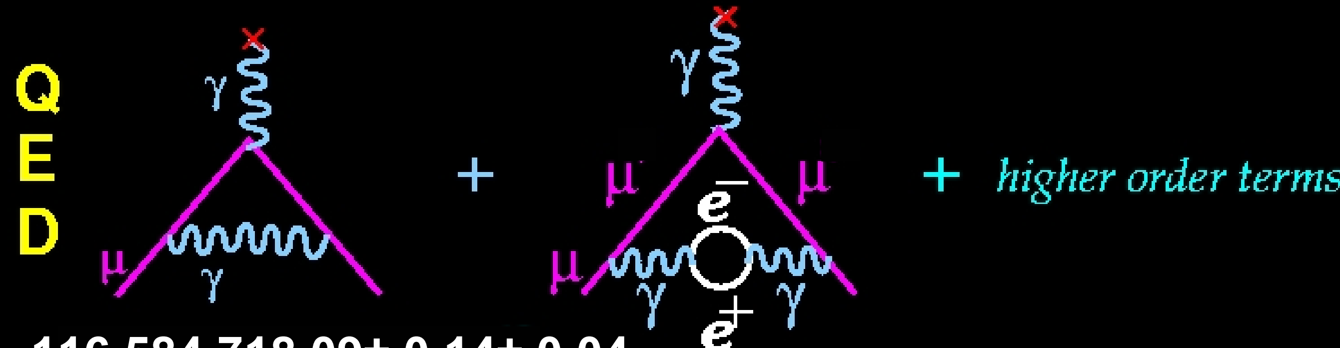
$$a_\mu(\text{SM}) = a_\mu(\text{QED}) + a_\mu(\text{hadronic}) + a_\mu(\text{weak})$$

Standard Model Value for (g-2)

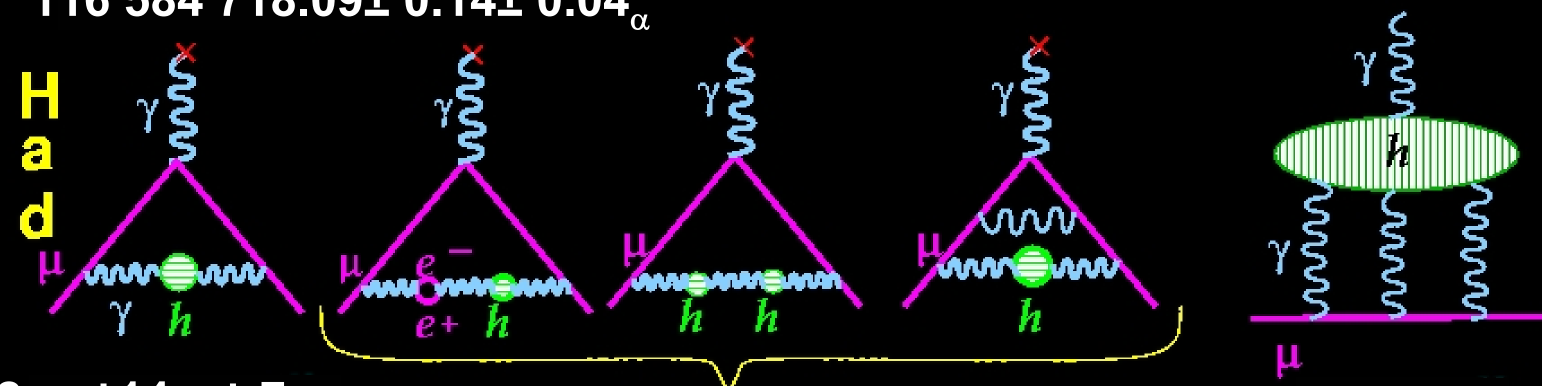


116 584 718.09 ± 0.14 ± 0.04$_\alpha$

Standard Model Value for (g-2)

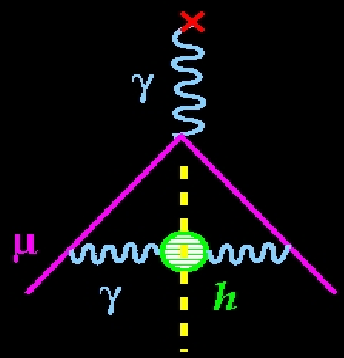


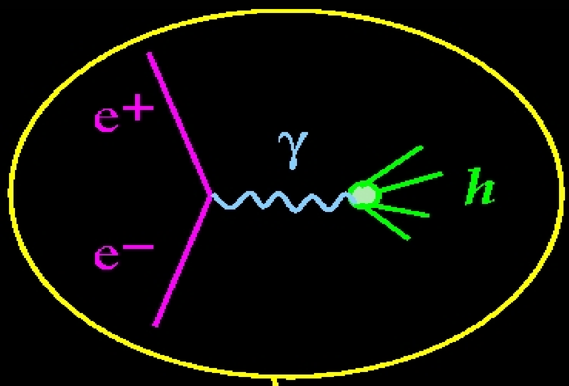
$116\ 584\ 718.09 \pm 0.14 \pm 0.04_{\alpha}$



$6\ 914 \pm 42_{exp}\ \pm 14_{rad} \pm 7_{pQCD}$ $\quad -98\ \ \pm 1_{exp} \pm 0.3_{rad}$ $\quad 105 \pm 26$

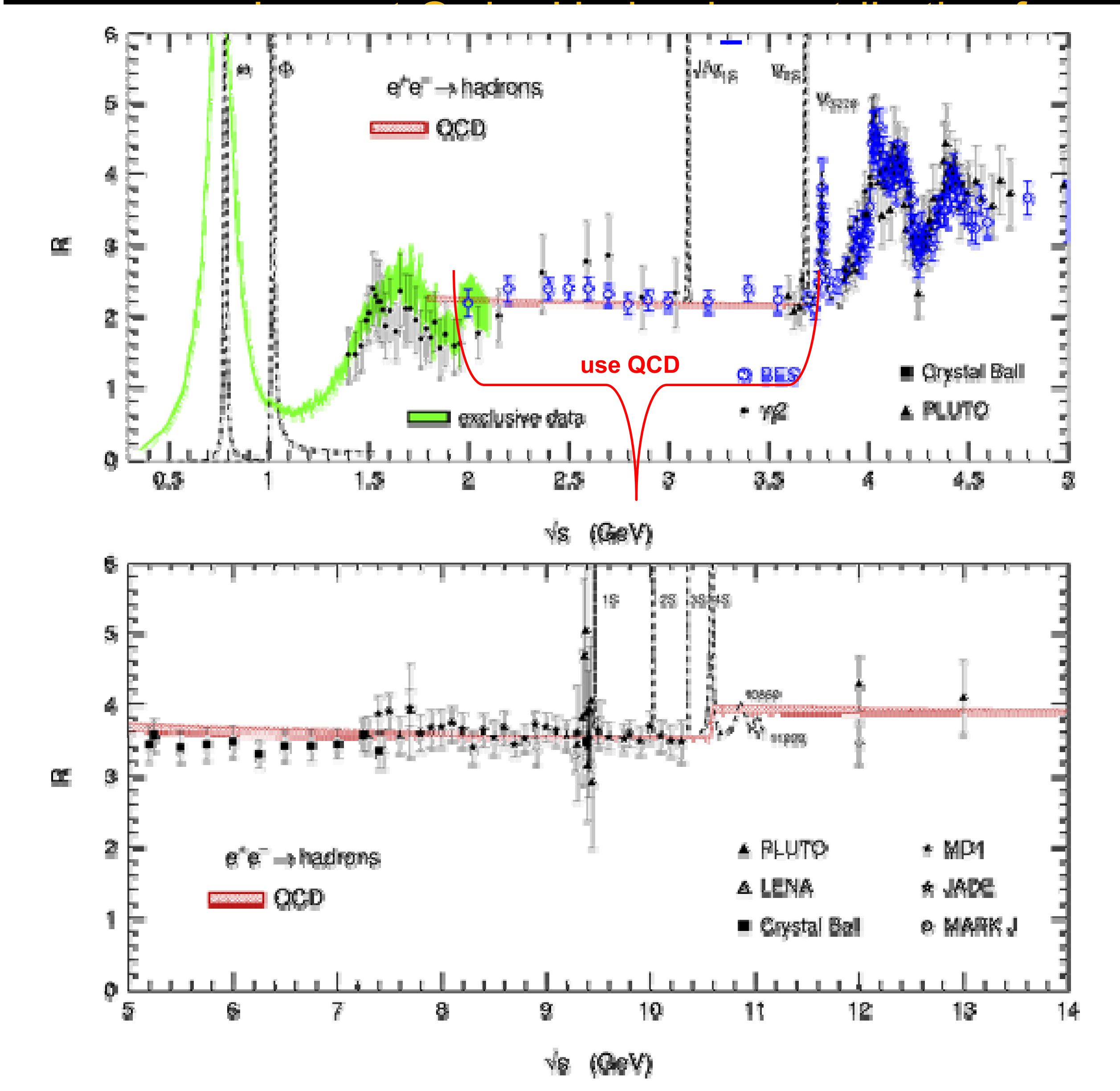
Lowest Order Hadronic contribution from e^+e^- annihilation

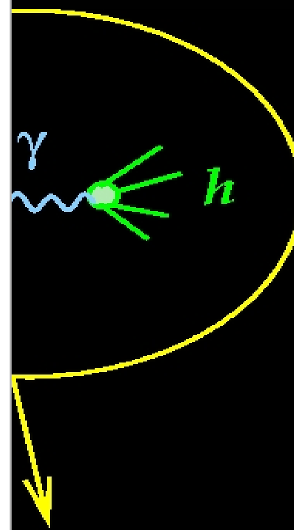




$$a_\mu(\mathrm{had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \left(\frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}\right)$$

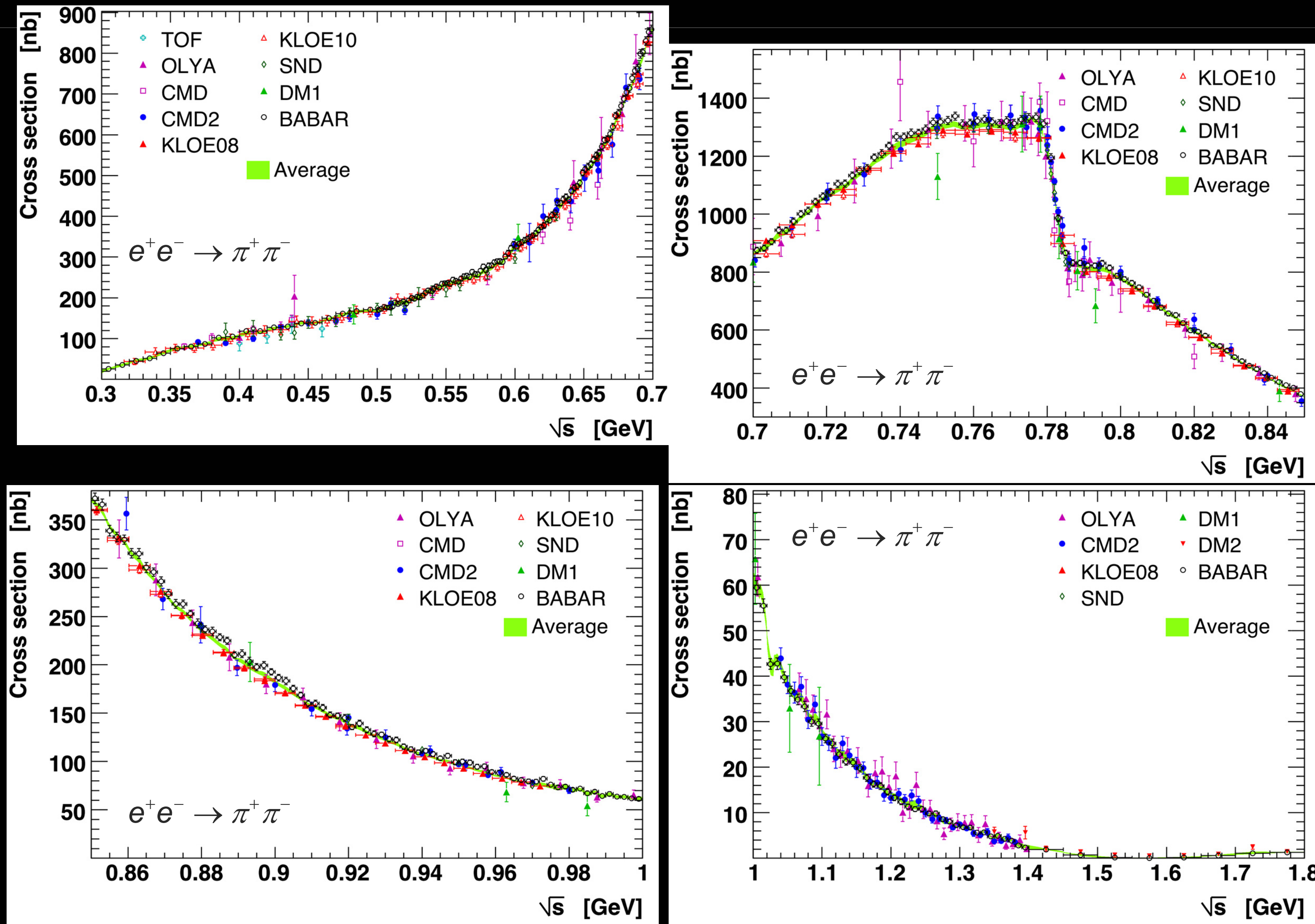
e^+e^- annihilation





$$\frac{{}^+e^- \to \text{hadrons})}{(e^+e^- \to \mu^+\mu^-)}\Bigg)$$

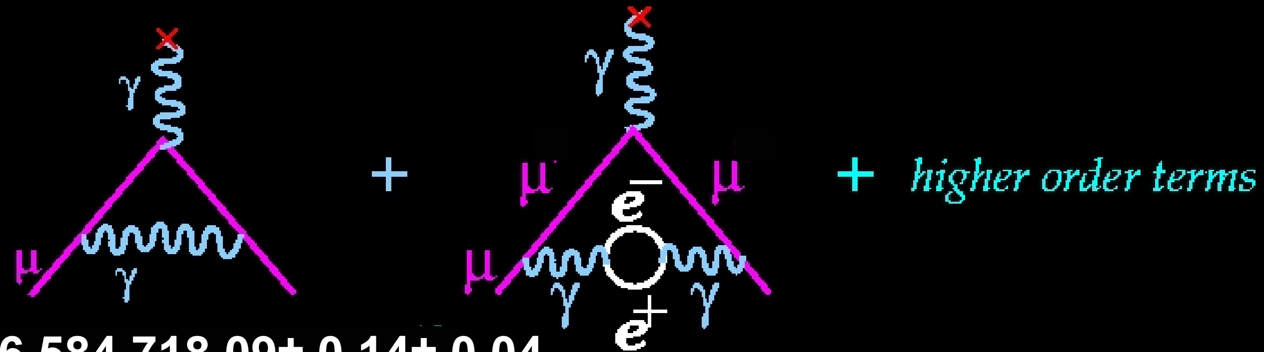
The Dominant 2 π Channel



A. Hoecker Tau2010, Davier, Hoecker, Malaescu and Zhang, arXiv:1010.418v1 [hep-ph]

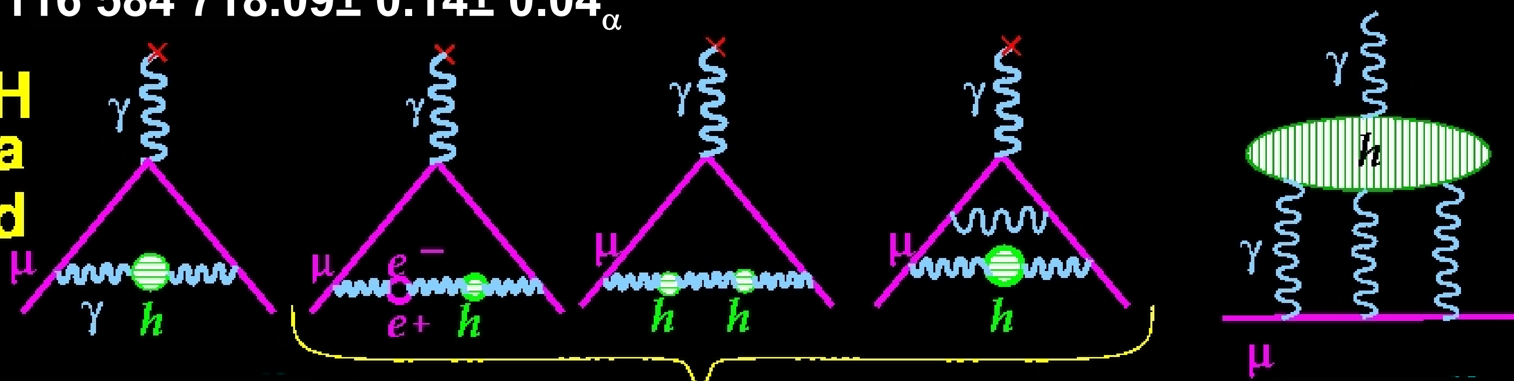
$$a_\mu^{SM} = 116\,591\,793(51) \times 10^{-11}\ (0.44\ \text{ppm})^*$$

QED



$116\,584\,718.09 \pm 0.14 \pm 0.04_\alpha$

Had

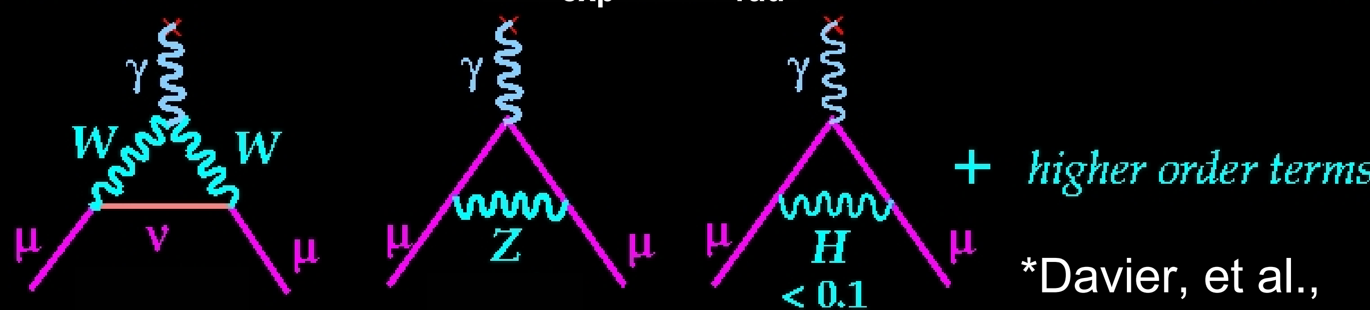


$6\,914 \pm 42_{exp} \pm 14_{rad} \pm 7_{pQCD}$

$-98 \pm 1_{exp} \pm 0.3_{rad}$

105 ± 26

Weak



1st + 2nd Order Weak = $152 \pm 2 \pm 1$

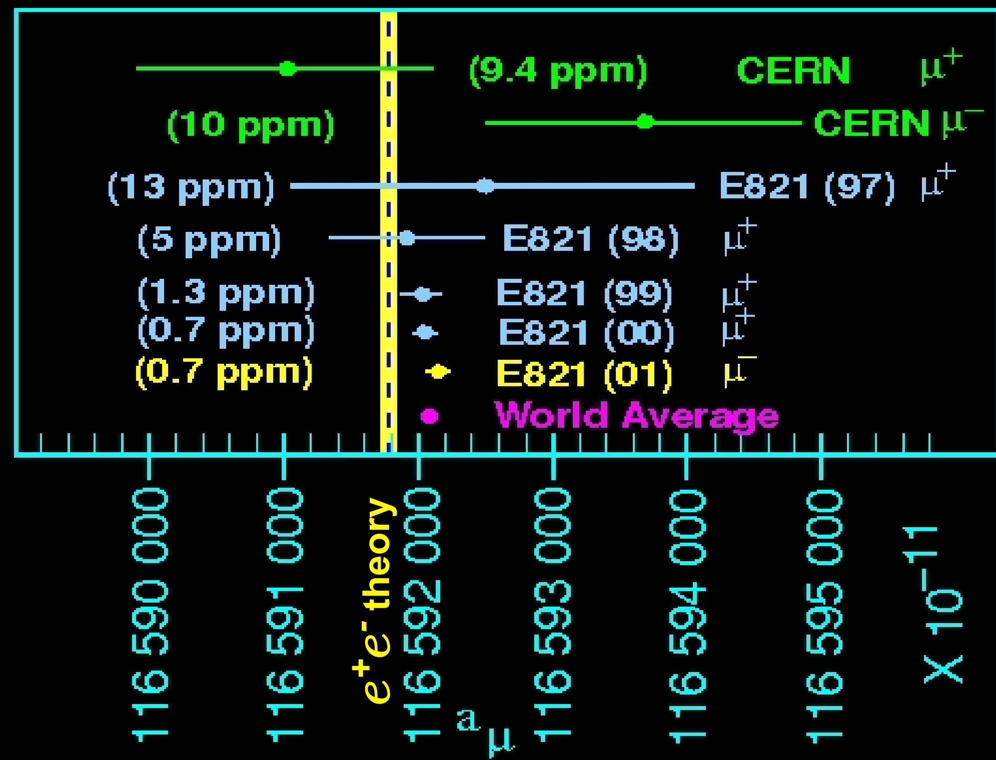
*Davier, et al., arXiv:1010.4180v1 [hep-ph] 20 Oct 2010

BOSTON UNIVERSITY

Present precision: ± 0.54 ppm

$$a_\mu = 116\,592\,089(63) \times 10^{-11} \; (0.54\,\mathrm{ppm})$$

$$a_\mu = \frac{\omega_a}{\frac{e}{mc}B}$$



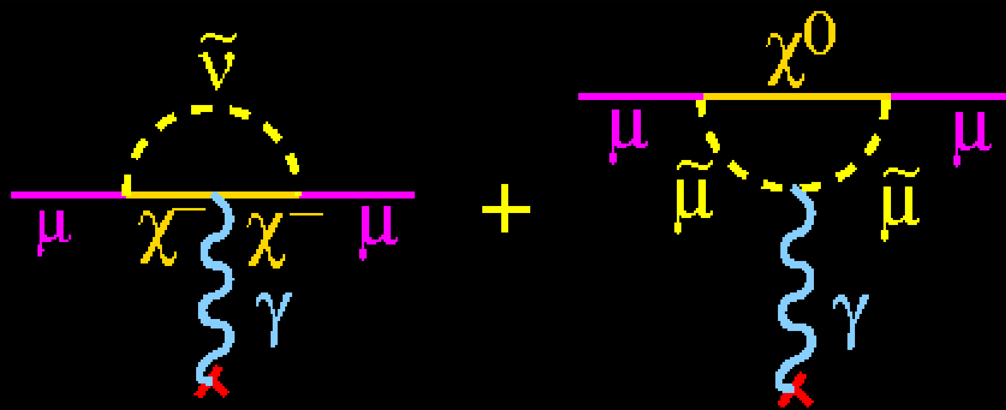
All E821 results were obtained with a "blind" analysis.

$$\Delta a_\mu(\mathrm{E821} - \mathrm{SM}) = (296 \pm 81) \times 10^{-11}$$

using e^+e^- data for the hadronic contribution.

An interesting, but not definitive difference with theory.

Many BSM speculations: e.g SUSY (large tanβ)



$$a_\mu(\text{SUSY}) \simeq \frac{\alpha(M_Z)}{8\pi \sin^2\theta_W} \frac{m_\mu^2}{\tilde{m}^2} \tan\beta \left(1 - \frac{4\alpha}{\pi} \ln \frac{\tilde{m}}{m_\mu}\right)$$

$$\simeq (\text{sgn}\mu)\ 13 \times 10^{-10}\ \tan\beta\ \left(\frac{100\ \text{GeV}}{\tilde{m}}\right)^2$$

Other Models

- Technicolor
  - small Δa_μ
- Littlest Higgs with T-parity
  - small Δa_μ
- Universal Extra Dimensions
  - small Δa_μ
- Randall Sundrum
  - could accommodate large Δa_μ
- Two Higgs doublets, shadow Higgs
  - small Δa_μ
- Additional light bosons that can affect EM interactions (difficult to study at LHC)
  - secluded U(1),etc., could have significant Δa_μ

Traditionally,

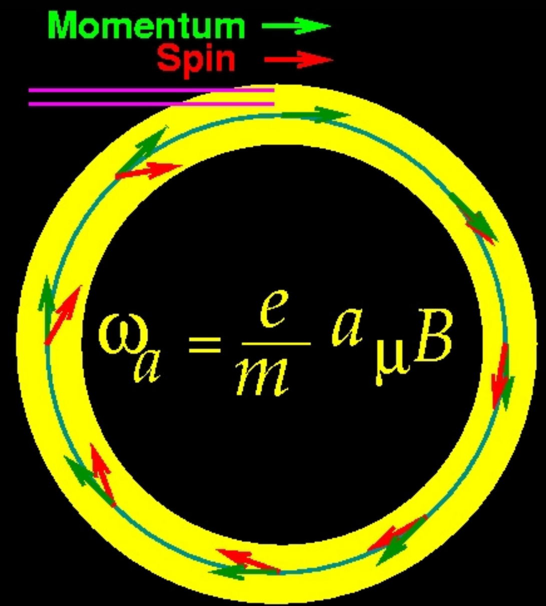
- For many years, muon (g-2) has provided strong and serious constraints on models of physics beyond the standard model.

Spin Precession Frequencies: μ in B field

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

$$\omega_C = \frac{eB}{mc\gamma} \qquad \omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

spin difference frequency: $\omega_a = \omega_s - \omega_c$



The highest energy decay $e^\pm$ are along the muon spin direction

Spin Precession Frequencies: E and B field

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \cancelto{0}{\frac{1}{\gamma^2 - 1}}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

operate at $\gamma_{\text{magic}} = 29.3$

use electrostatic focusing

$$B \Rightarrow \langle B \rangle_{\mu-\text{dist}}$$

Need to know $\langle B \rangle_{\mu-\text{dist}}$

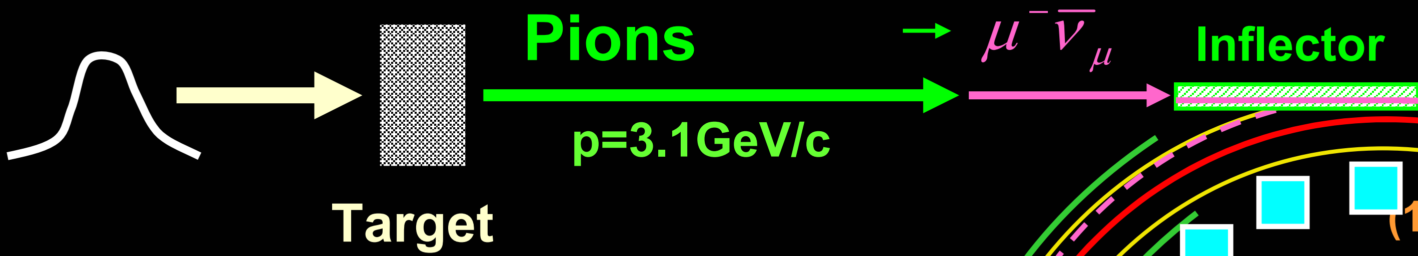
to $\simeq 0.01$ ppm

Experimental Technique

25ns bunch of

1- 5 X 10^{12} p

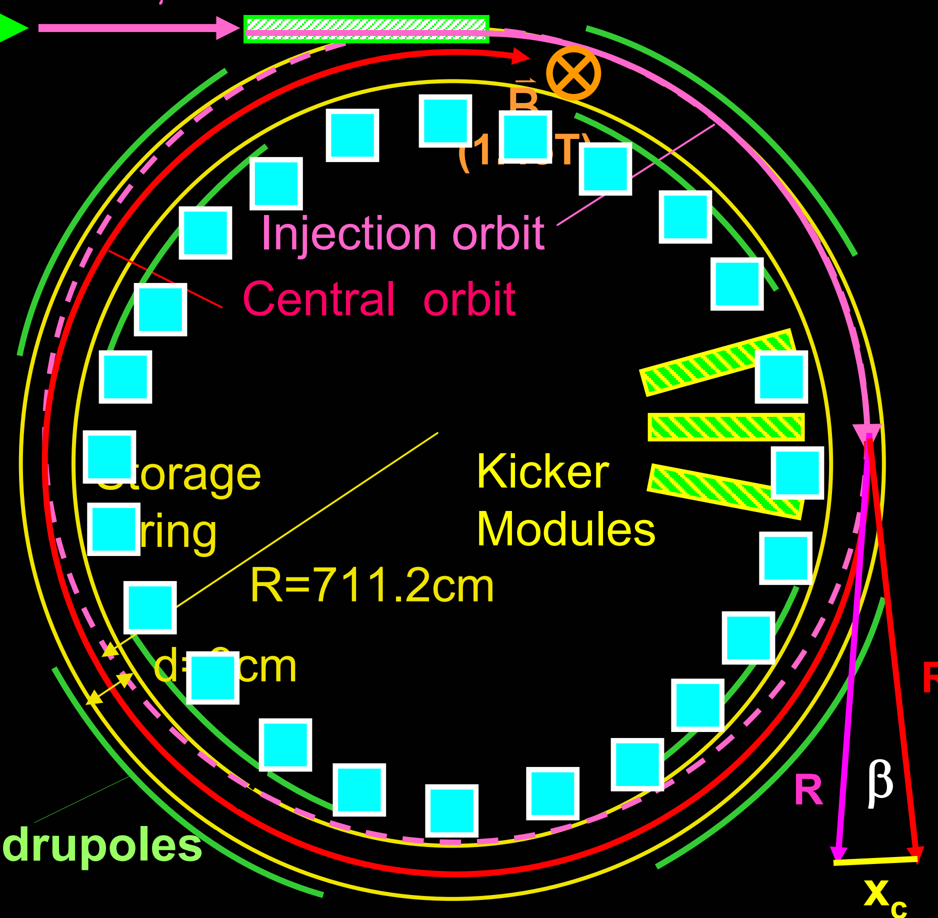
π^-



$x_c \approx 77$ mm

$\beta \approx 10$ mrad

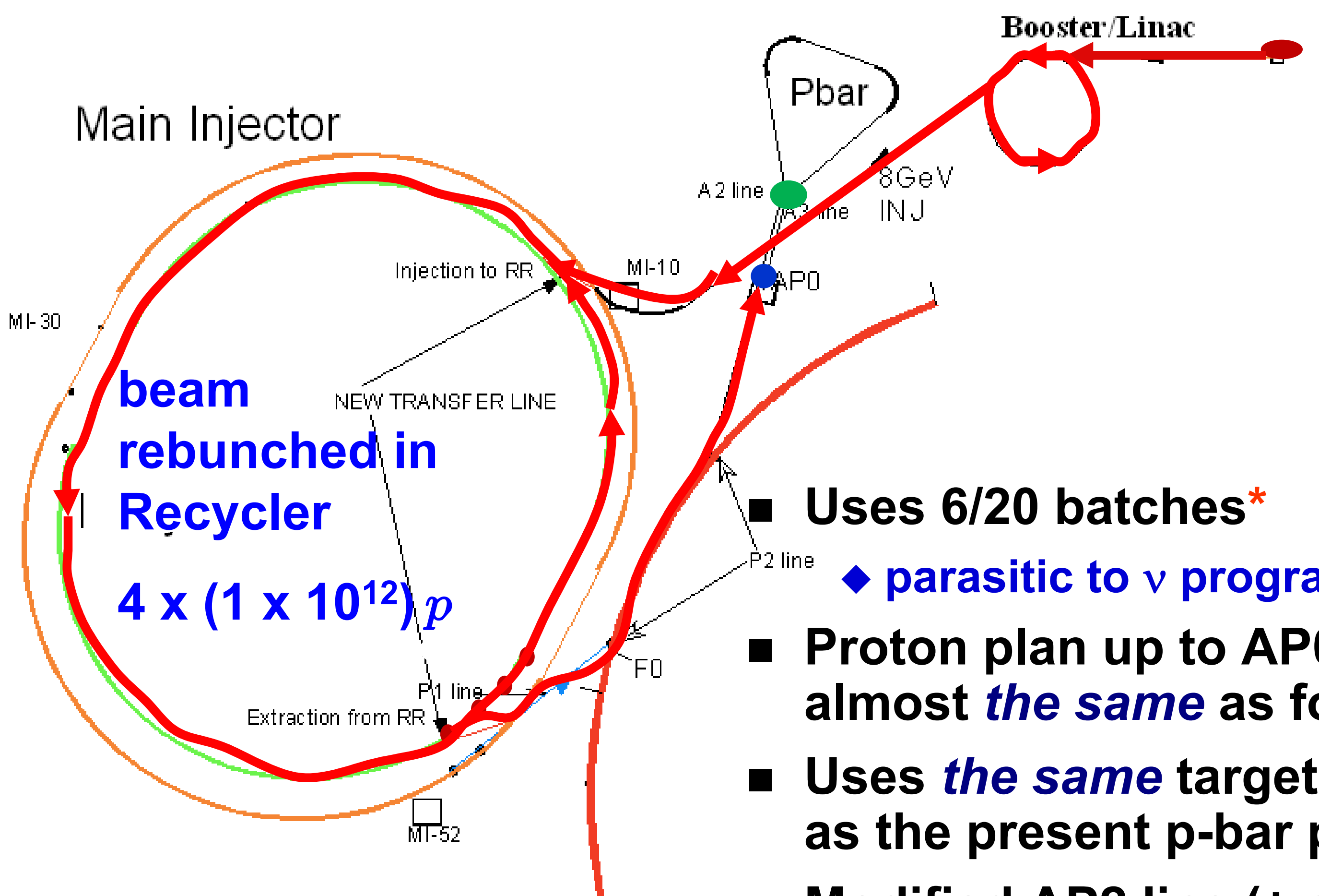
$B \cdot dl \approx 0.1$ Tm



- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

Fermilab Beam Scheme



beam rebunched in Recycler

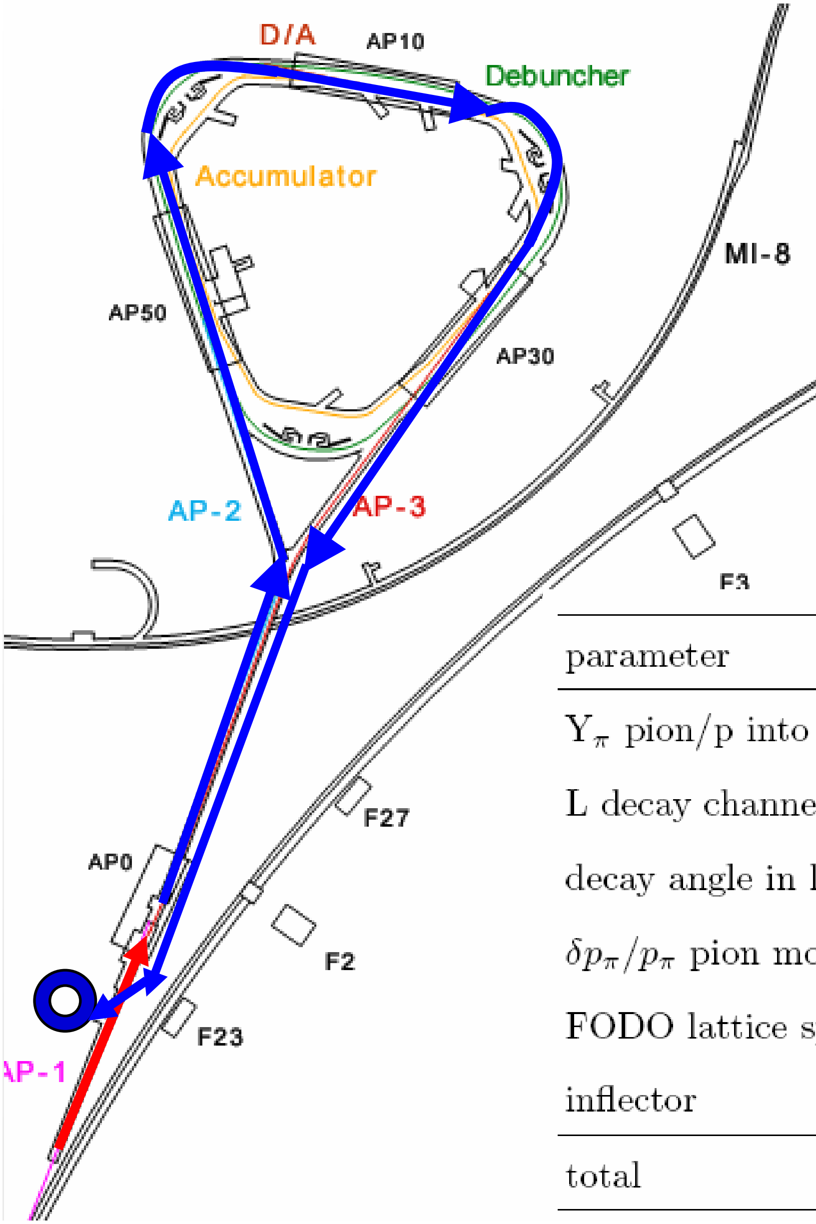
4 x (1 x 10^{12}) p

- Uses 6/20 batches*
  - parasitic to ν program
- Proton plan up to AP0 target is almost *the same* as for Mu2e
- Uses *the same* target and lens as the present p-bar program
- Modified AP2 line (+ quads)
- New beam stub into ring
- Needs simple building near cryo services

*Can use all 20 if MI program is off

The 900-m long decay beam reduces the pion “flash” by x20 and leads to 6 – 12 times more stored muons per proton

(compared to BNL)



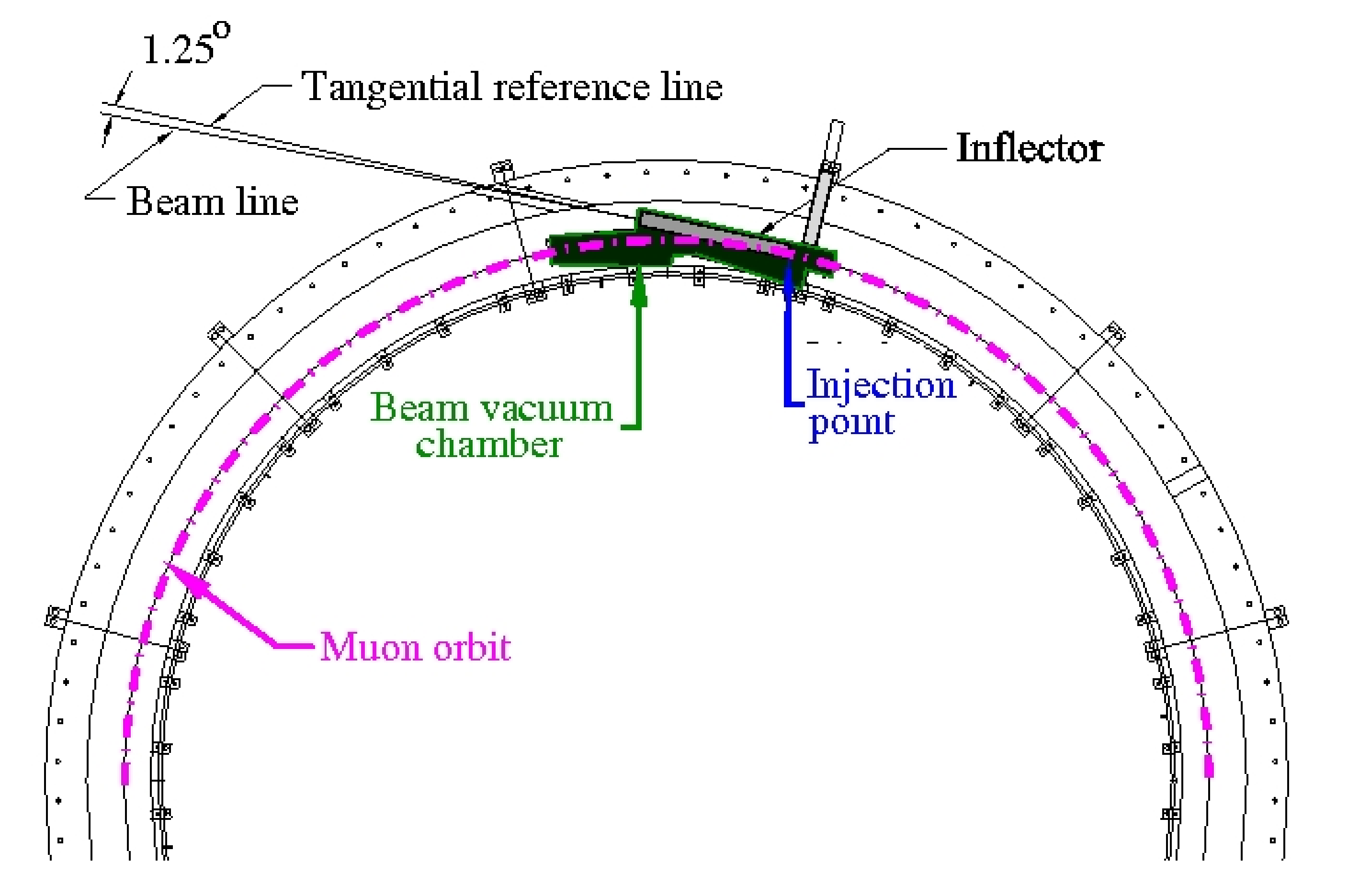
Flash compared to BNL

parameter	FNAL/BNL
p / fill	0.25
π / p	0.4
π survive to ring	0.01
π at magic P	50
Net	0.05

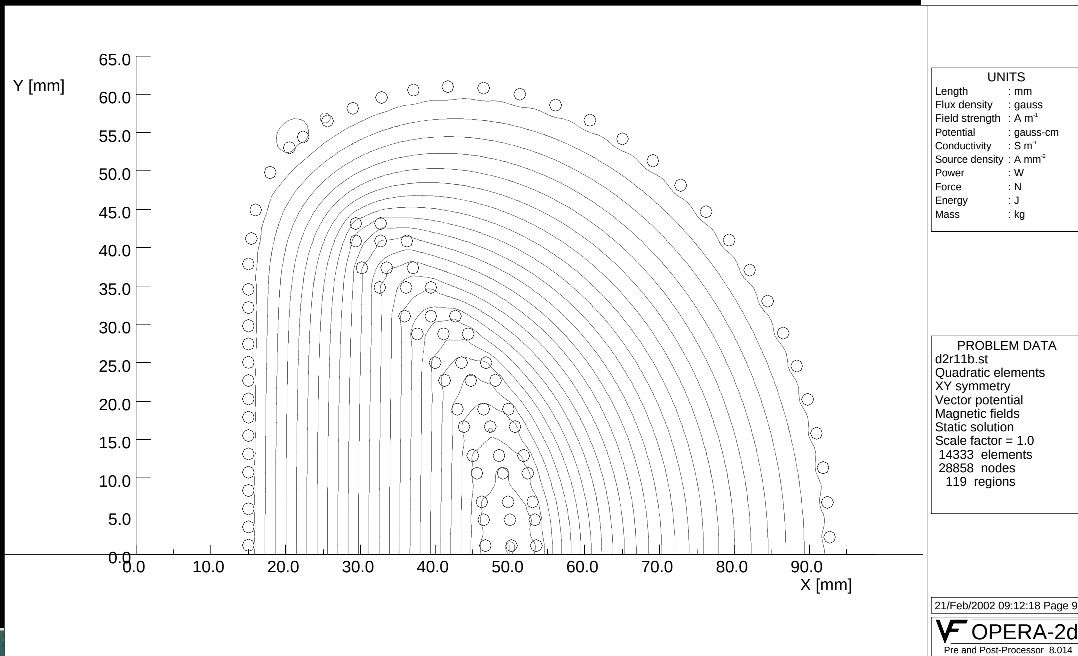
Stored Muons / POT

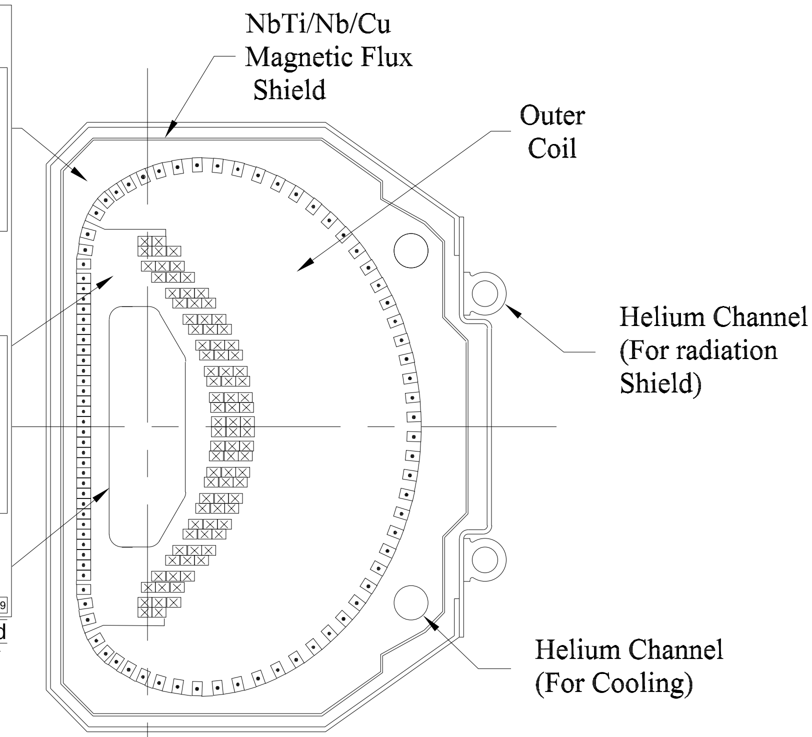
parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	$\approx$ 2.7E-5	$\approx$ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 ± 0.5 mr	forward	3
$\delta p_\pi / p_\pi$ pion momentum band	$\pm 0.5\%$	$\pm 2\%$	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open end	2
total			11.5

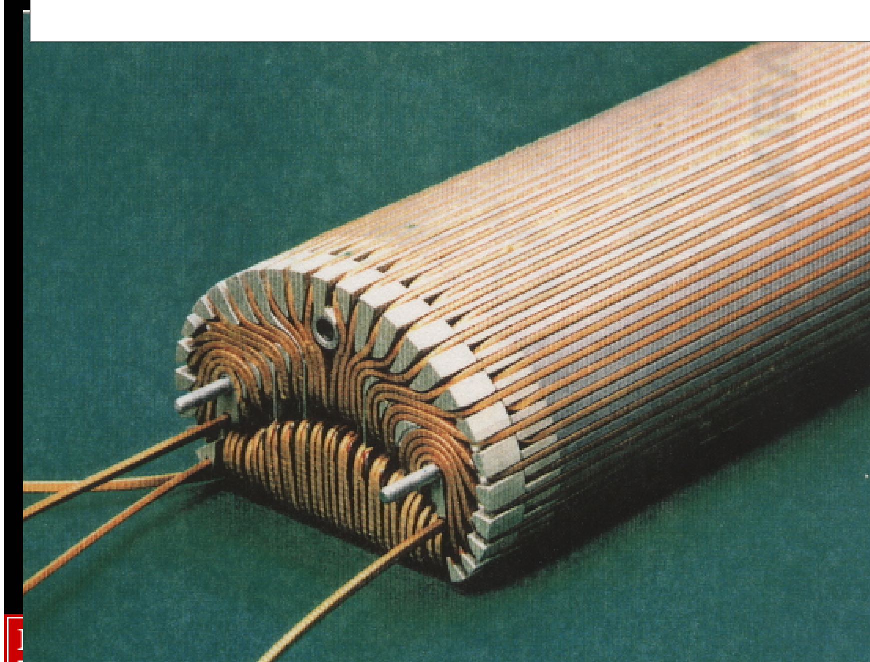
Plan View of the Injection Line



The Inflector



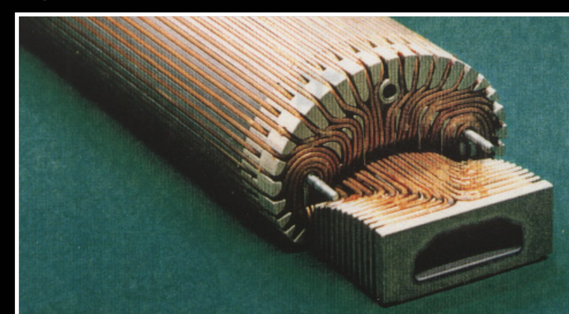




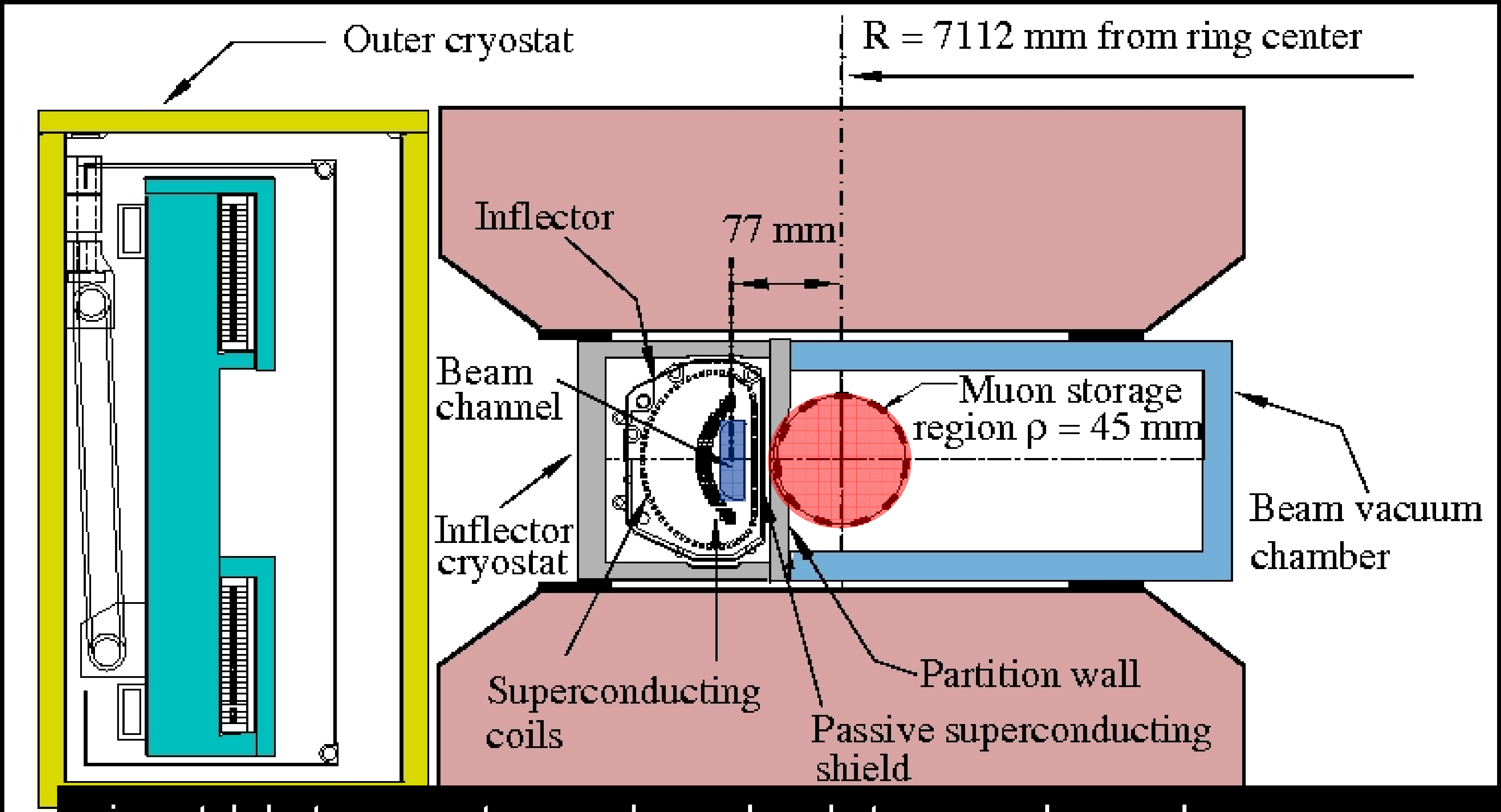
Length = 1.7 m

Central field = 1.45 T

E821 Prototype
Open End

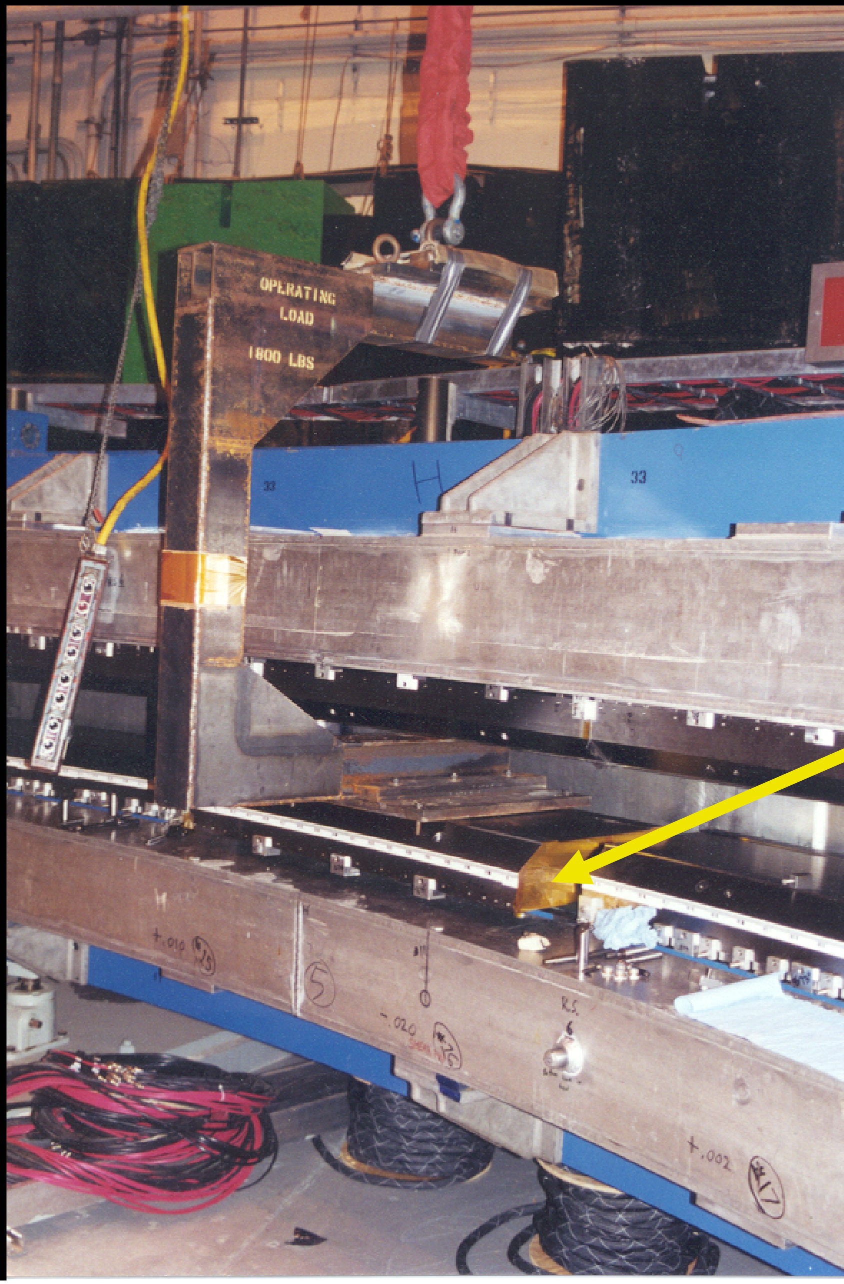


The requirement of a uniform magnetic field means no gaps for injecting the beam. Everything has to fit between the pole pieces.



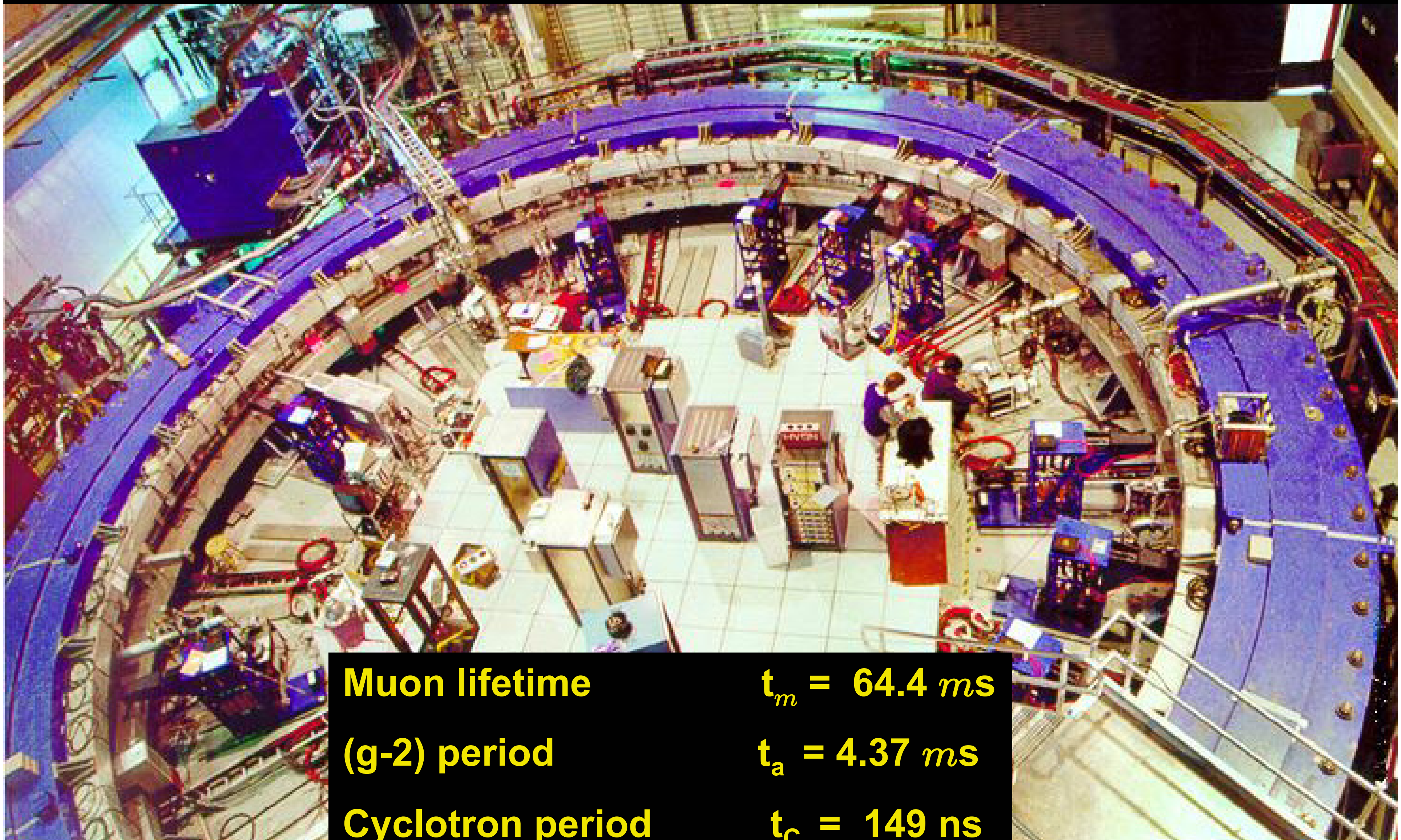
mismatch between entrance channel and storage volume, plus an imperfect kick and momentum distribution causes coherent beam oscillations

Inserting a Pole Piece



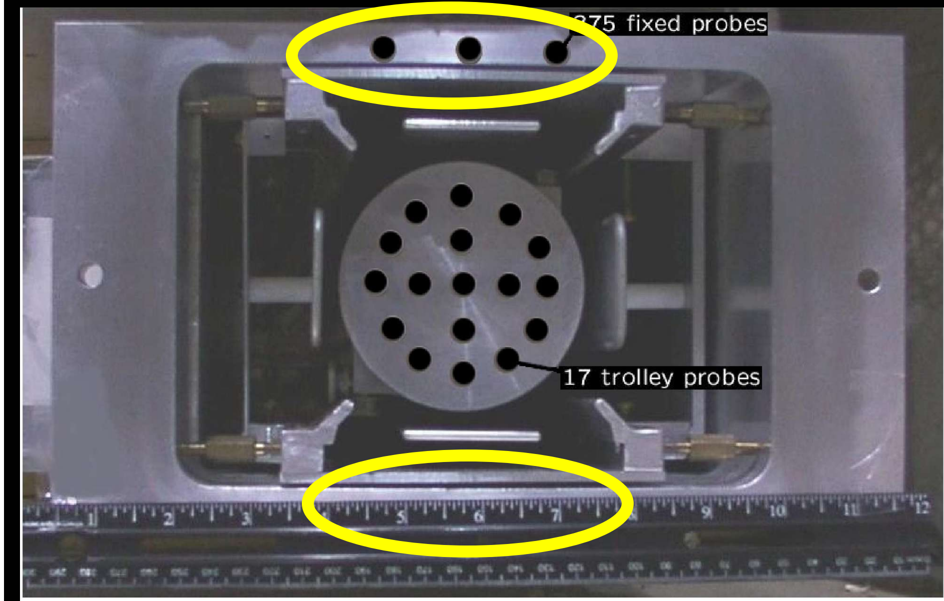
Kapton insulation to prevent eddy currents from running around the ring, especially during an energy extraction or quench.

muon (g-2) storage ring

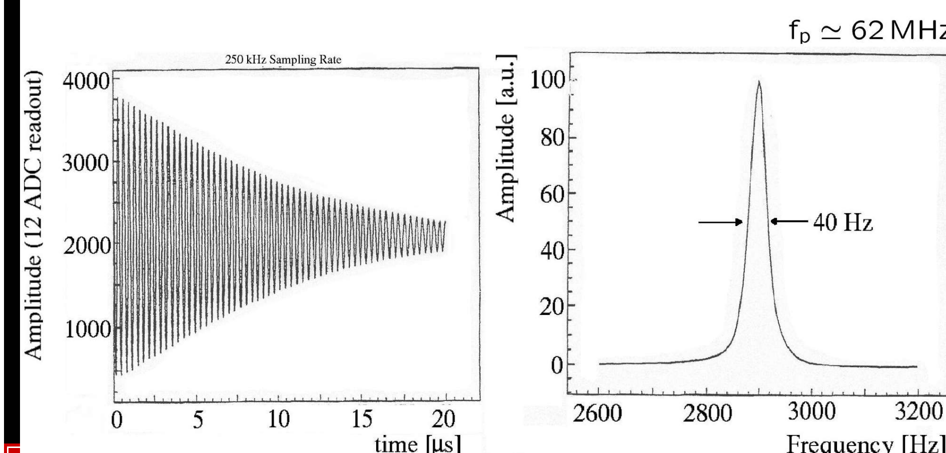


Muon lifetime	**t_m = 64.4 ms**
(g-2) period	**t_a = 4.37 ms**
Cyclotron period	**t_C = 149 ns**
# of turns in ring	**4000**

Mapping the Field

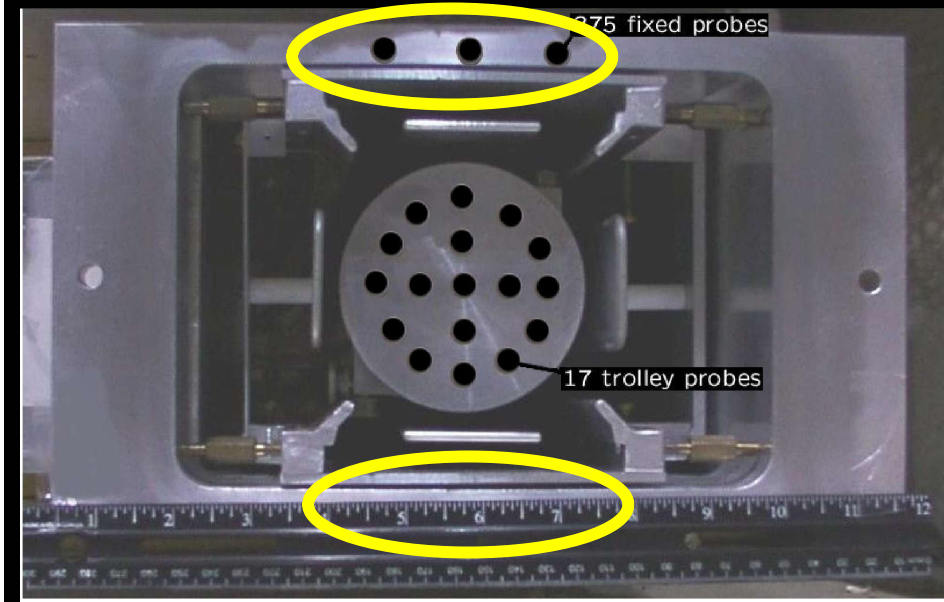


Free induction decay signals:

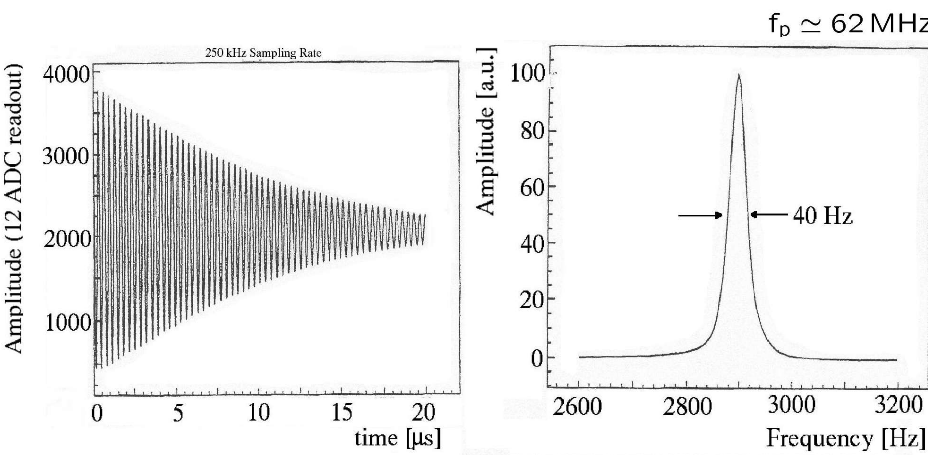


NMR B-field mapping trolley

Mapping the Field

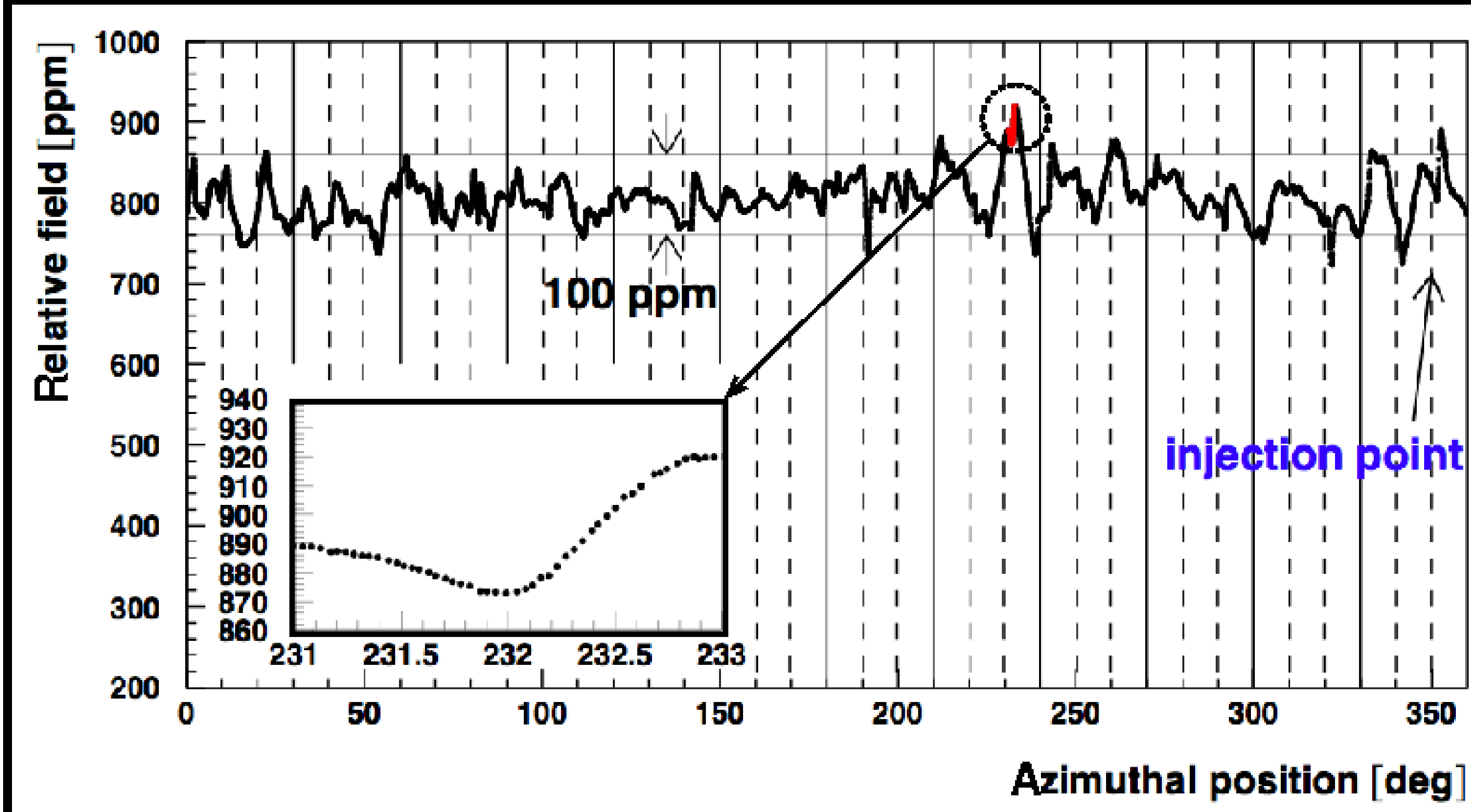


Free induction decay signals:



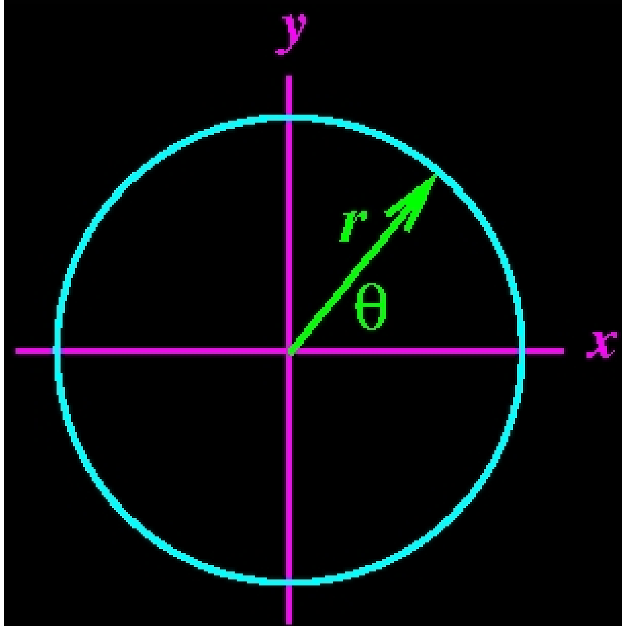
Fixed probes monitor dipole <u>and</u> quadrupole field components

Azimuthal Variation



Average Field Seen by the Muons

$$< B >= \int M(r,\theta) B(r,\theta) r dr d\theta$$



In the average, B couples multipole by multipole with the moments of the muon distribution.

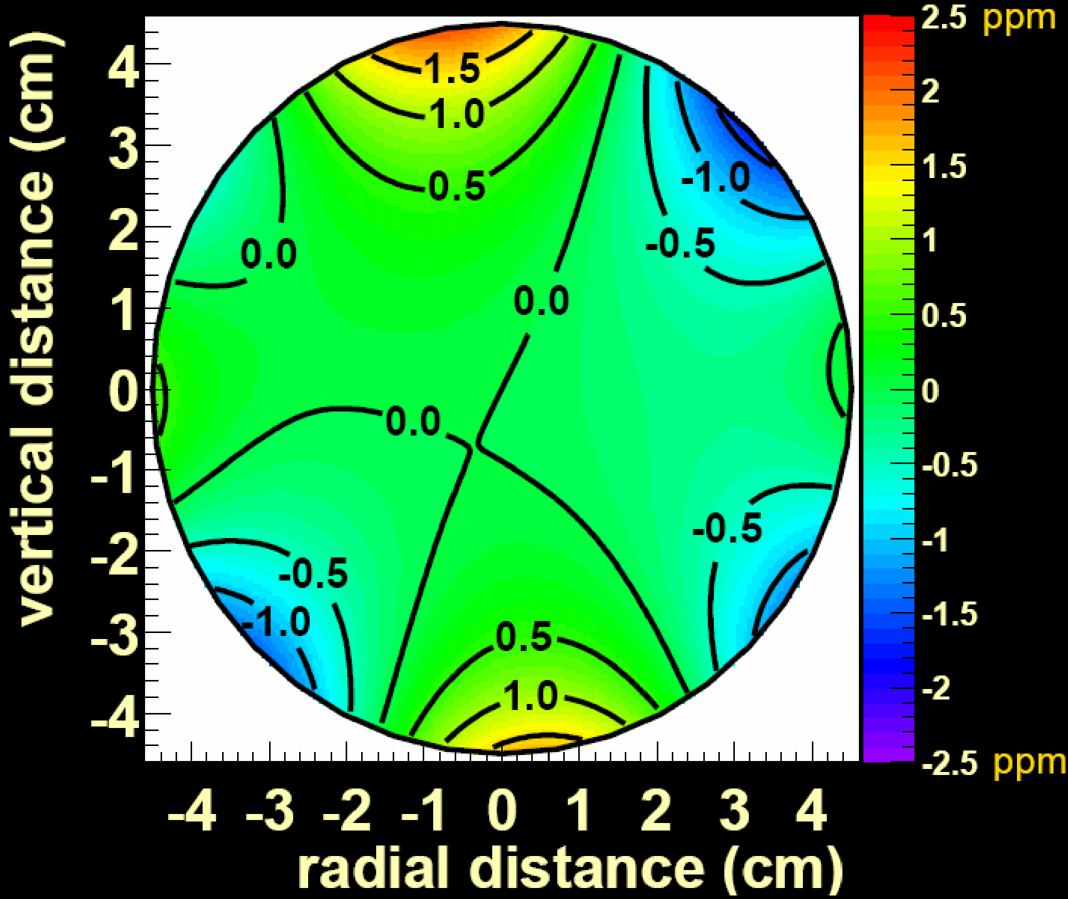
A circular aperture minimizes the effect of higher multipoles on $\langle B \rangle$

$$B(r,\theta) = \sum_{n=0}^{\infty} r^n \left[c_n \cos n\theta + s_n \sin n\theta\right]$$

$$M(r,\theta) = \sum [\gamma_m(r) \cos m\theta + \sigma_m(r) \sin m\theta]$$

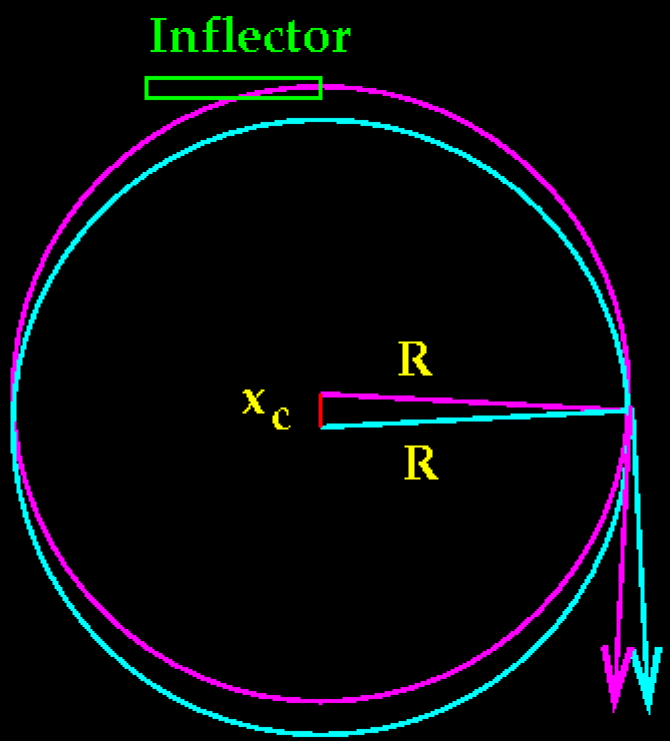
$\langle B \rangle_\phi$ *for 2001* averaged over azimuth

0.5 ppm contours



$\sigma_{\rm syst}$ on $\langle B \rangle_{\mu-\rm distribution} = \pm 0.03$ ppm

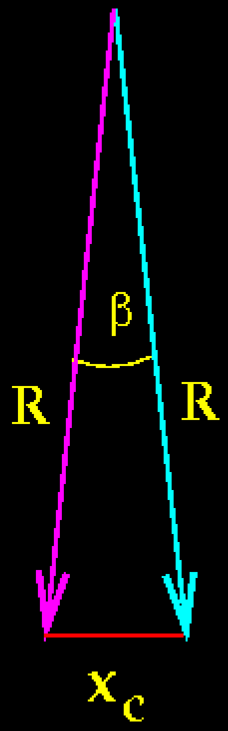
The Kick



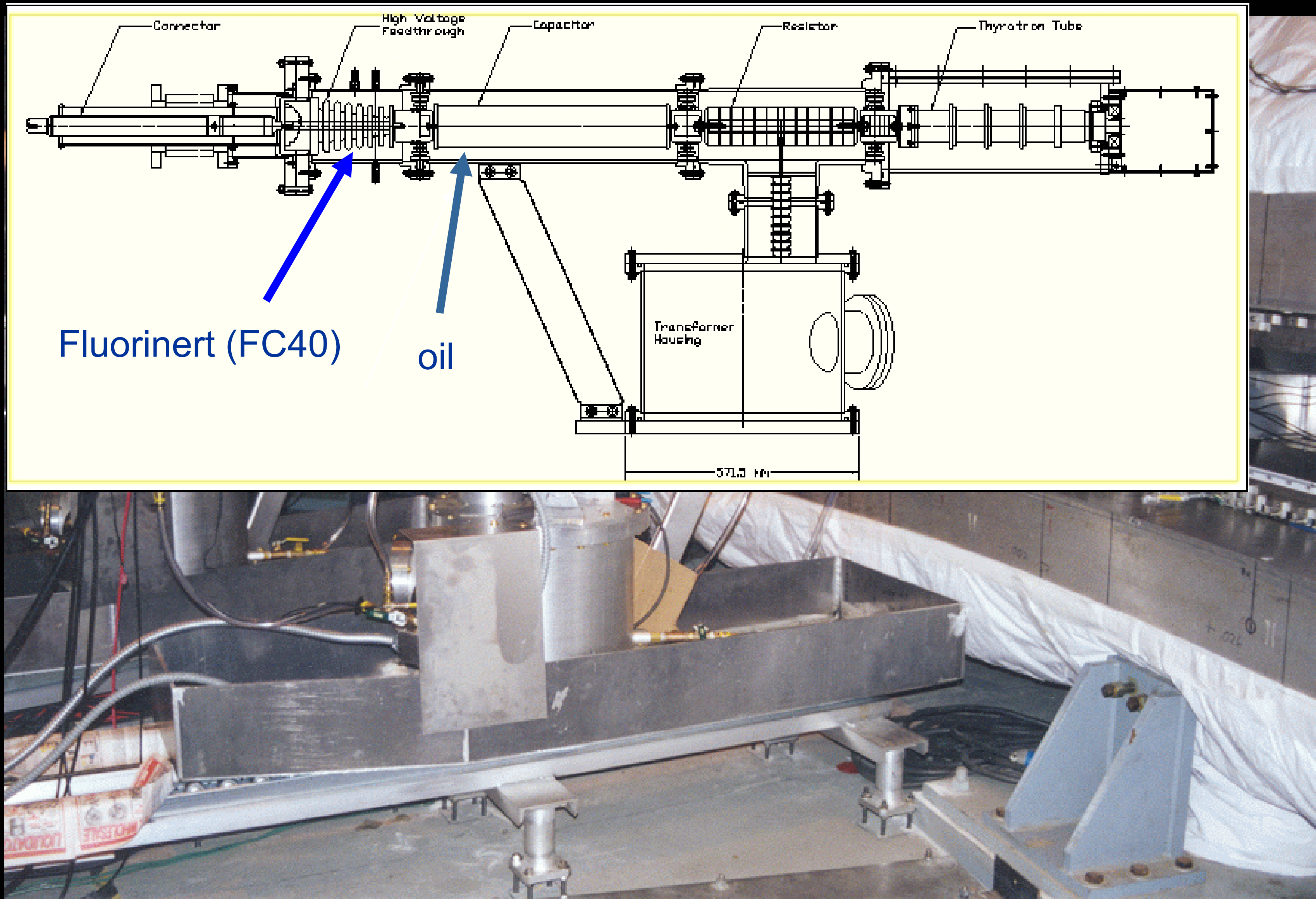
$$x_c \cong 77 \text{ mm}$$

$$\beta \cong 10 \text{ mrad}$$

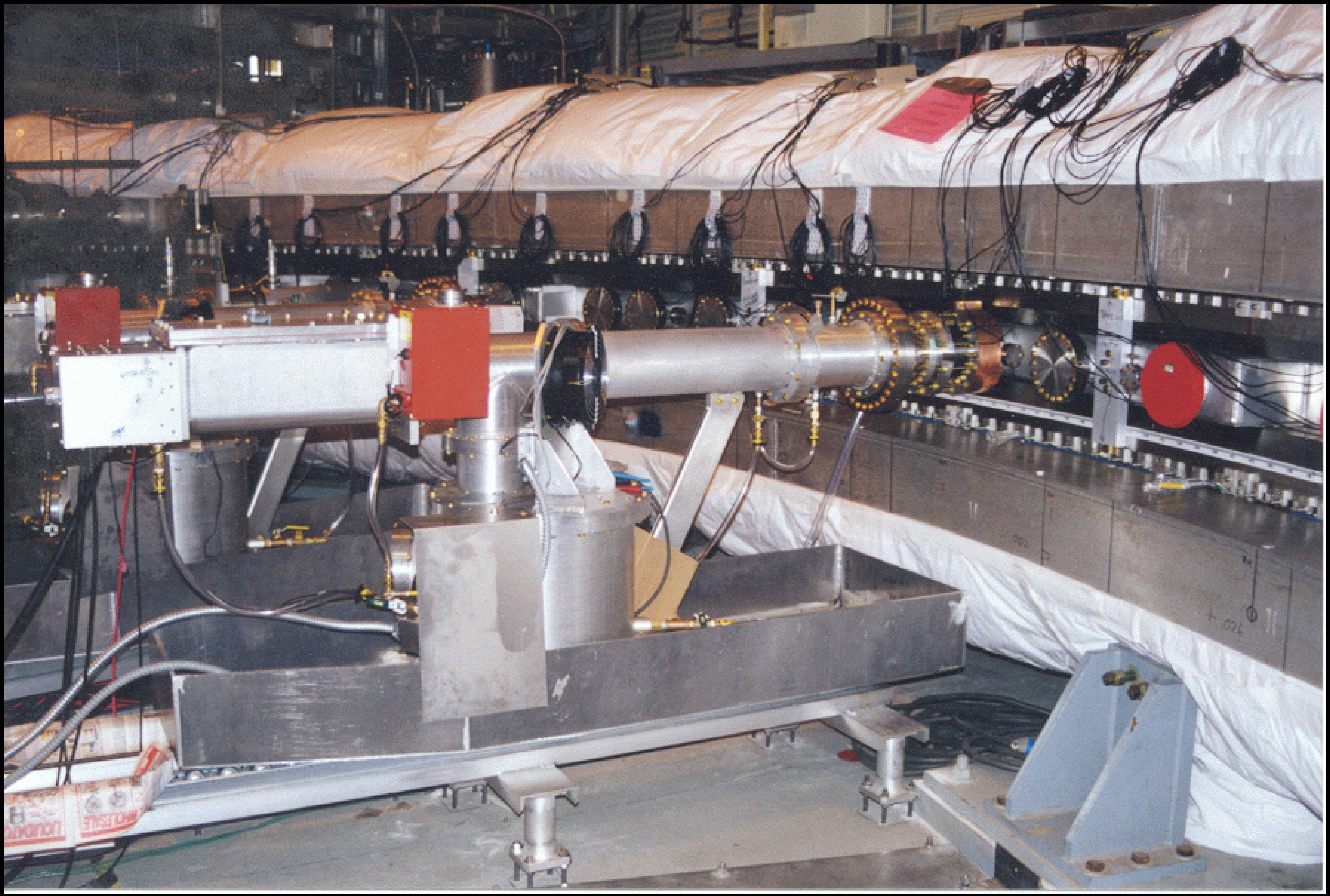
$$B \cdot dl \cong 0.1 \text{ Tm}$$



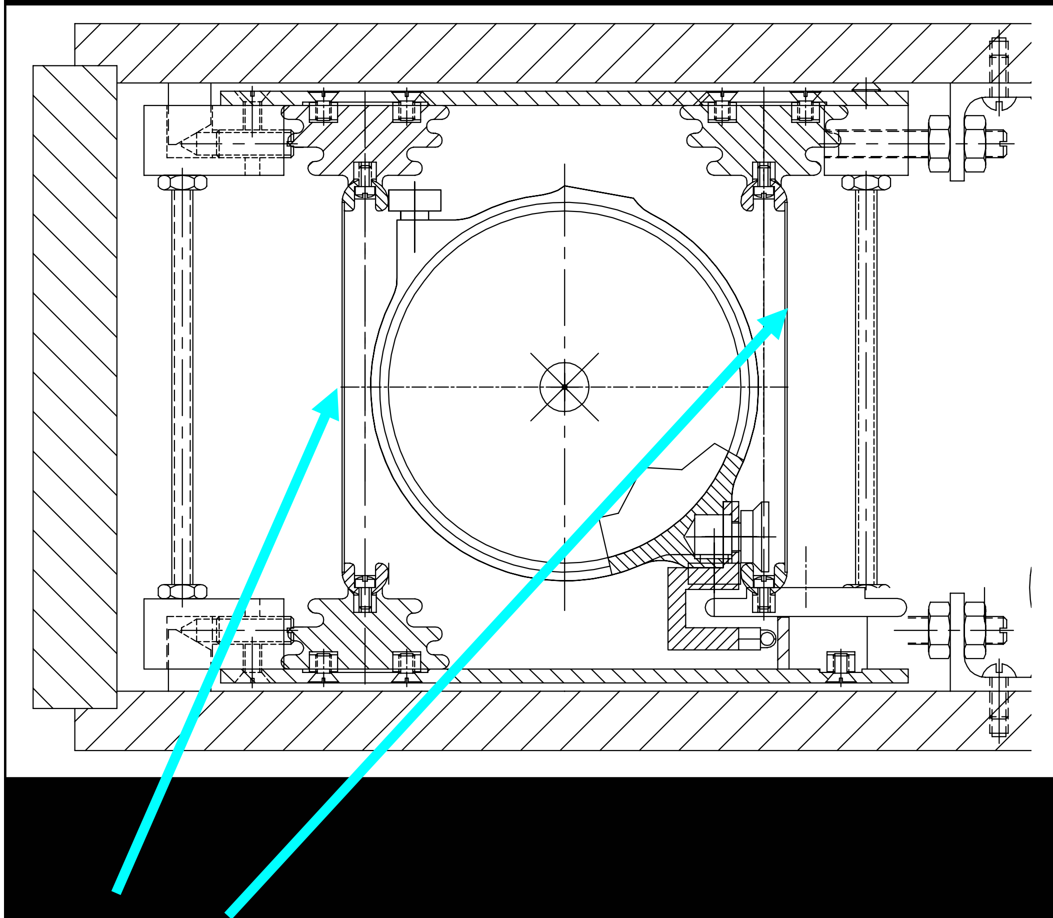
The Kicker Modulator



The Kicker Modulator

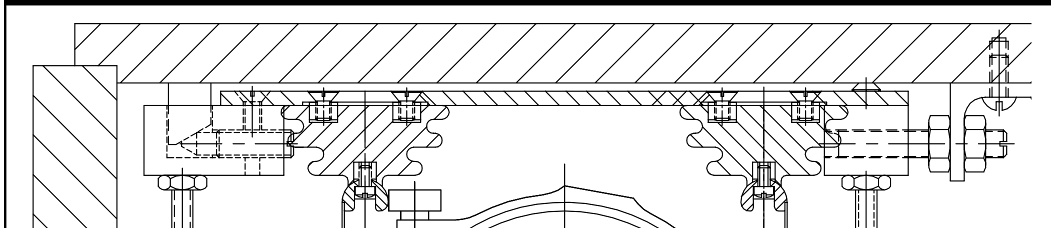


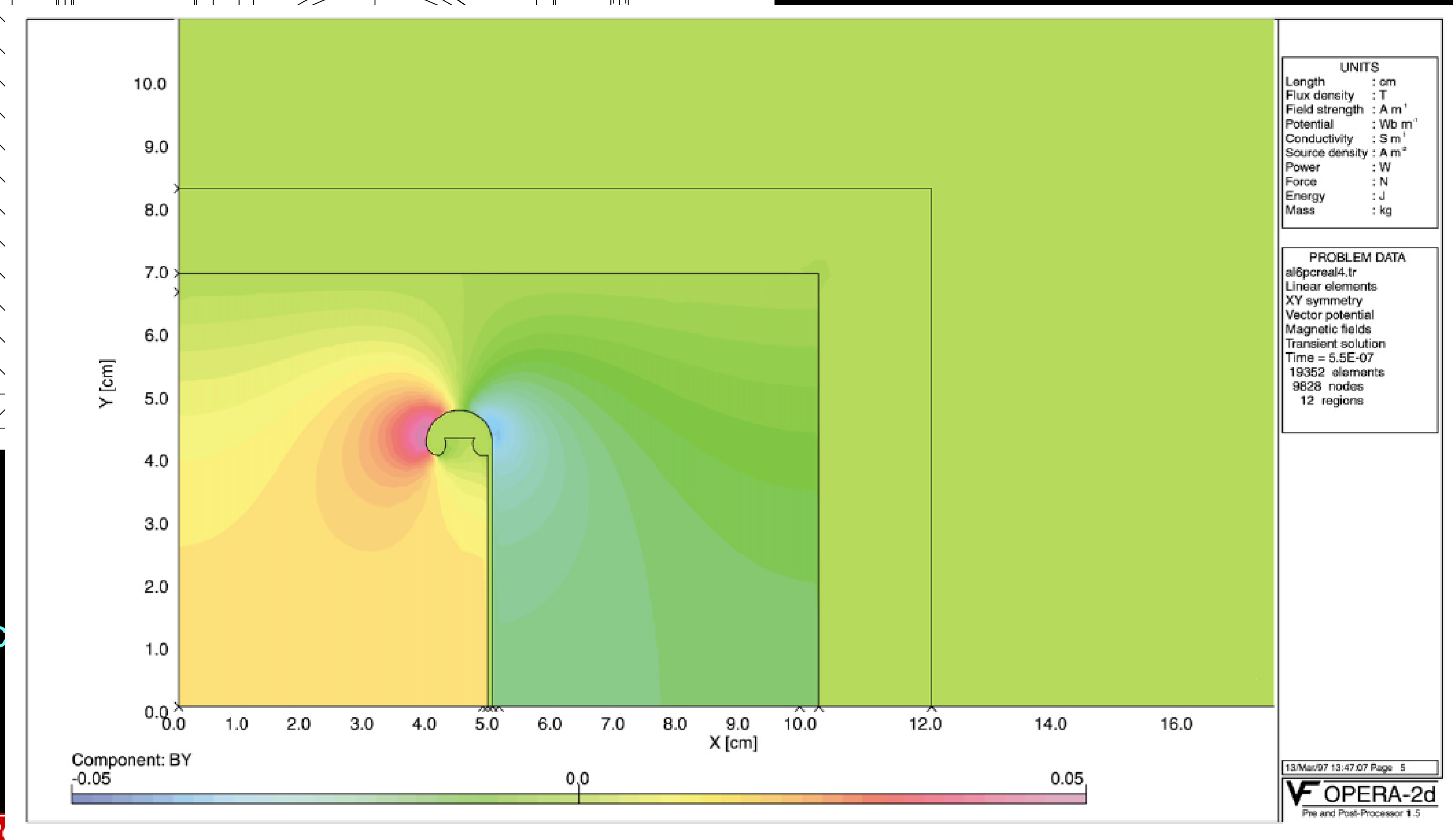
Kicker Plate Geometry



electrodes

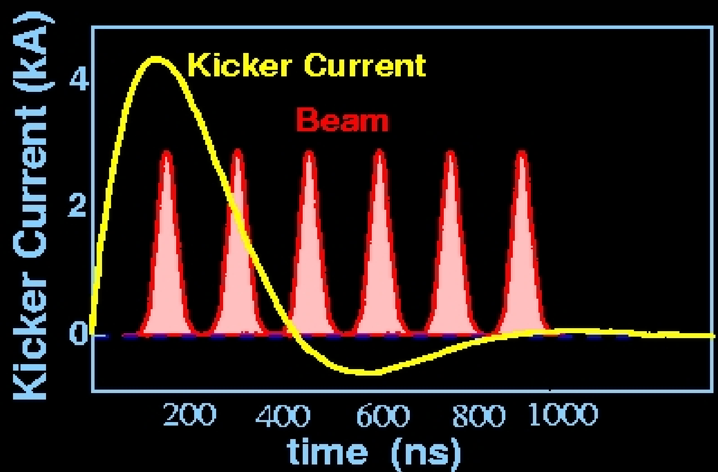
Kicker Plate Geometry



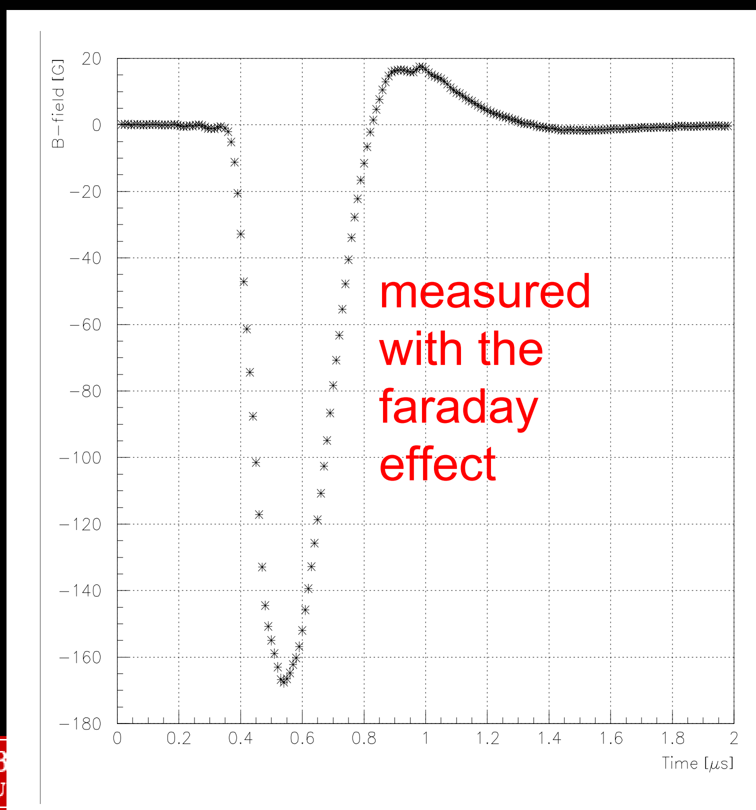


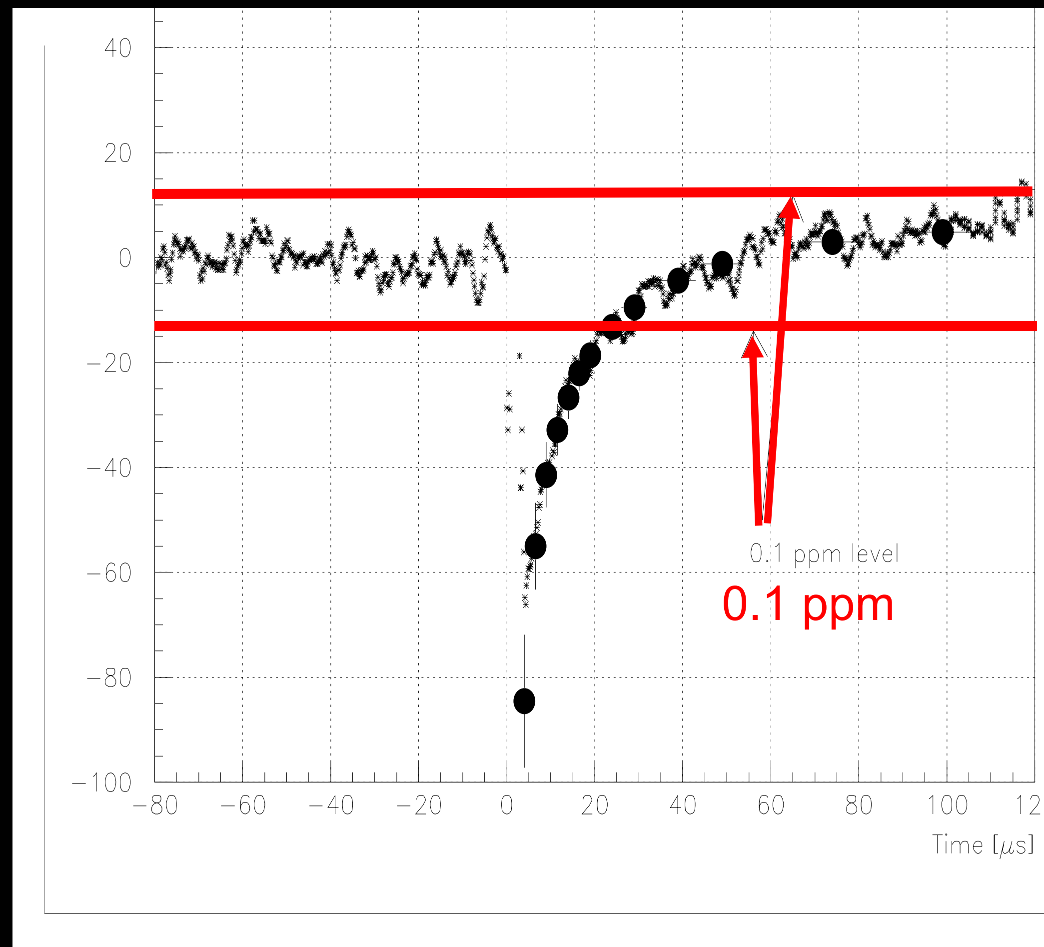
elec

The Kicker Current Pulse

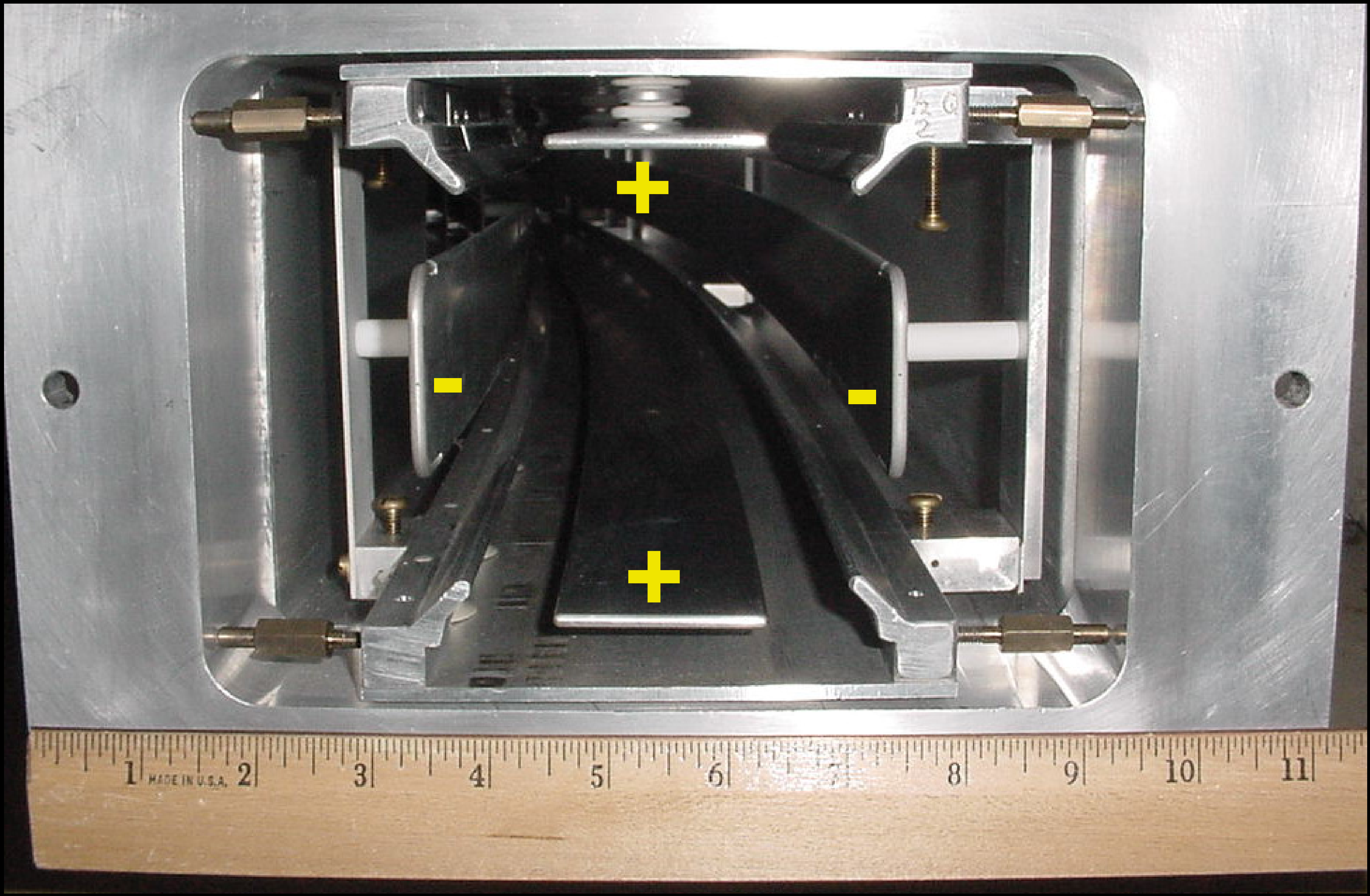


eddy currents less than 0.1 ppm on B·dl after 20 μs



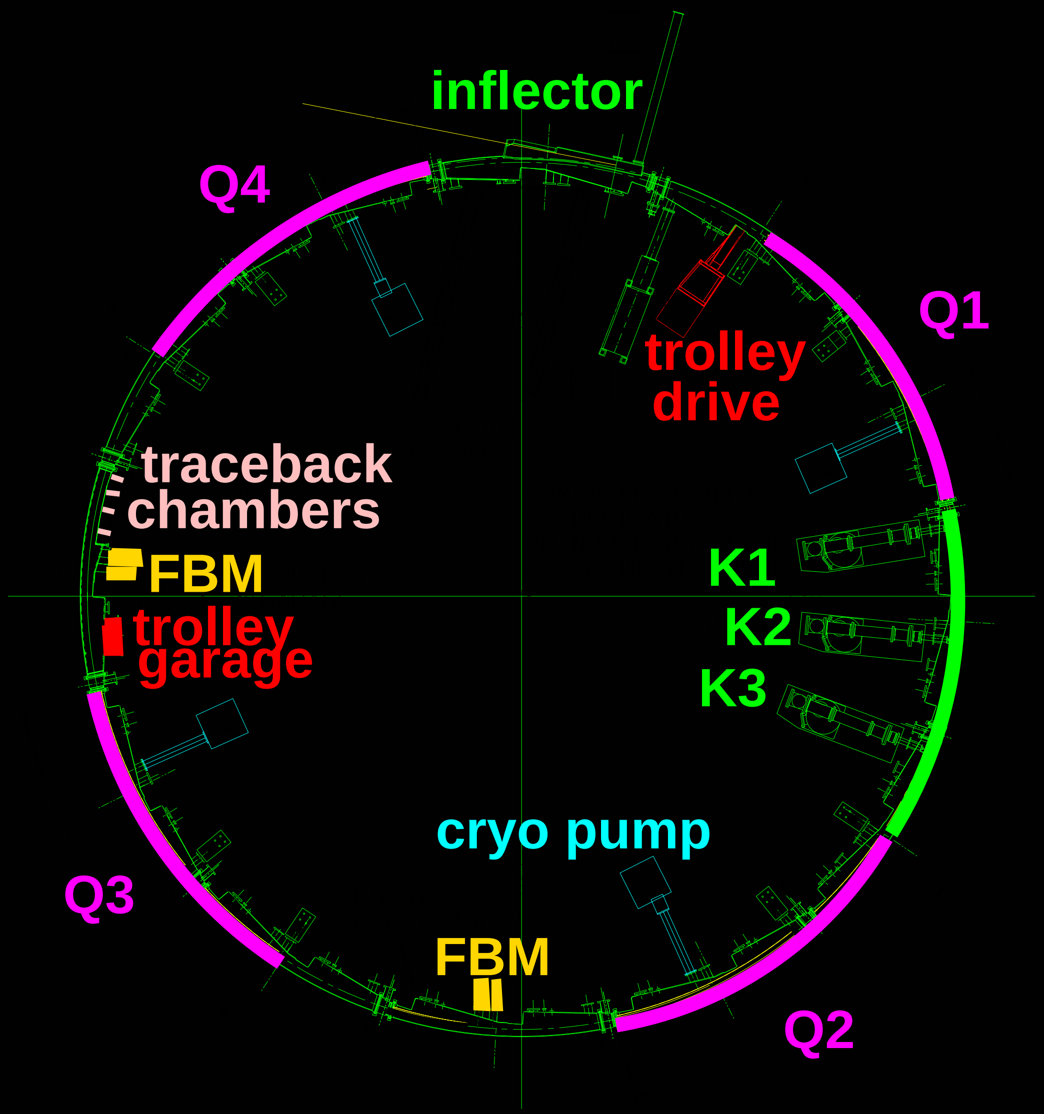


The Electrostatic Quadrupoles: μ^+ polarity



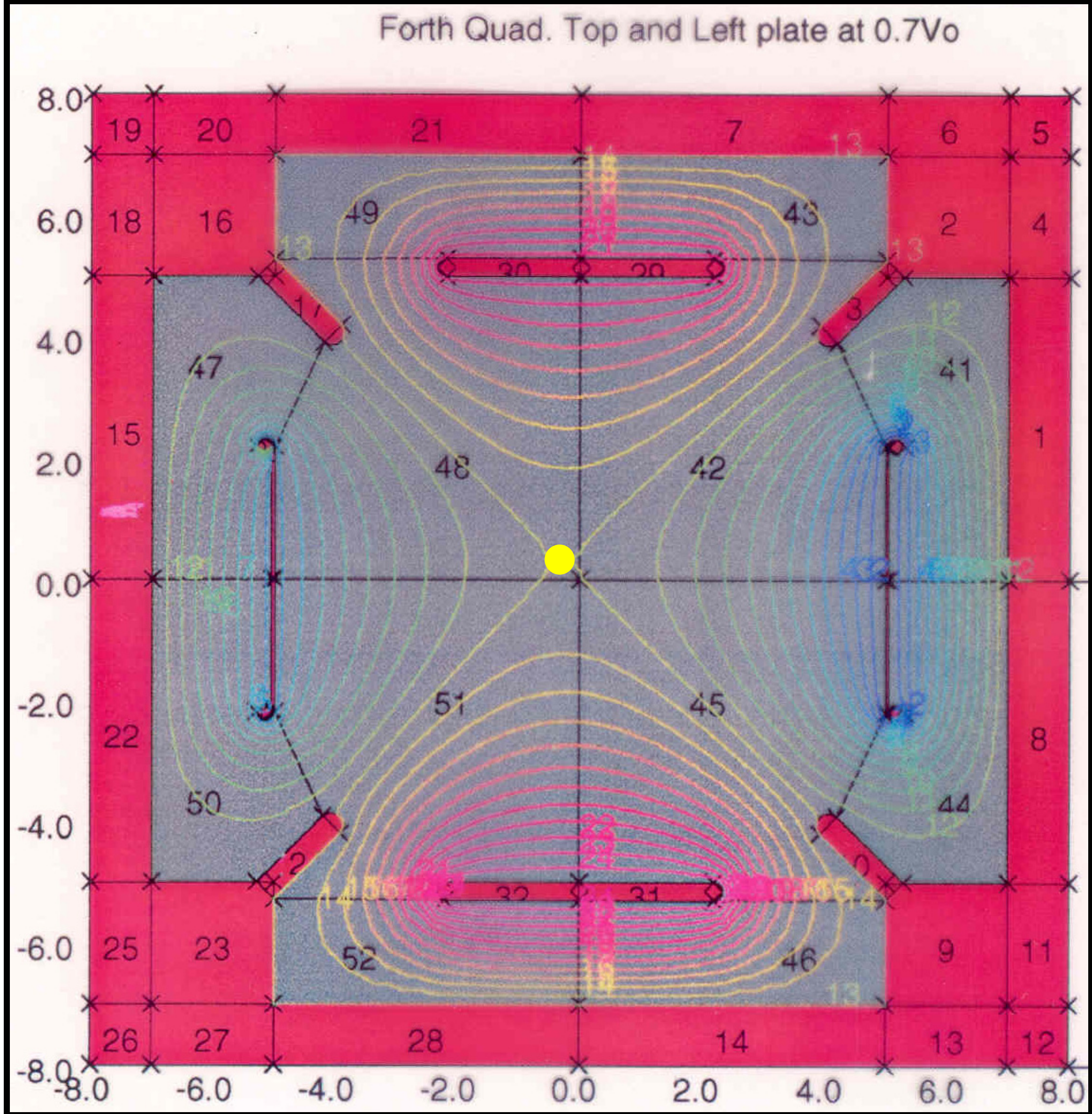
~ ± 24 kV at full power,   17 kV for beam scraping after injection

The Ring Layout



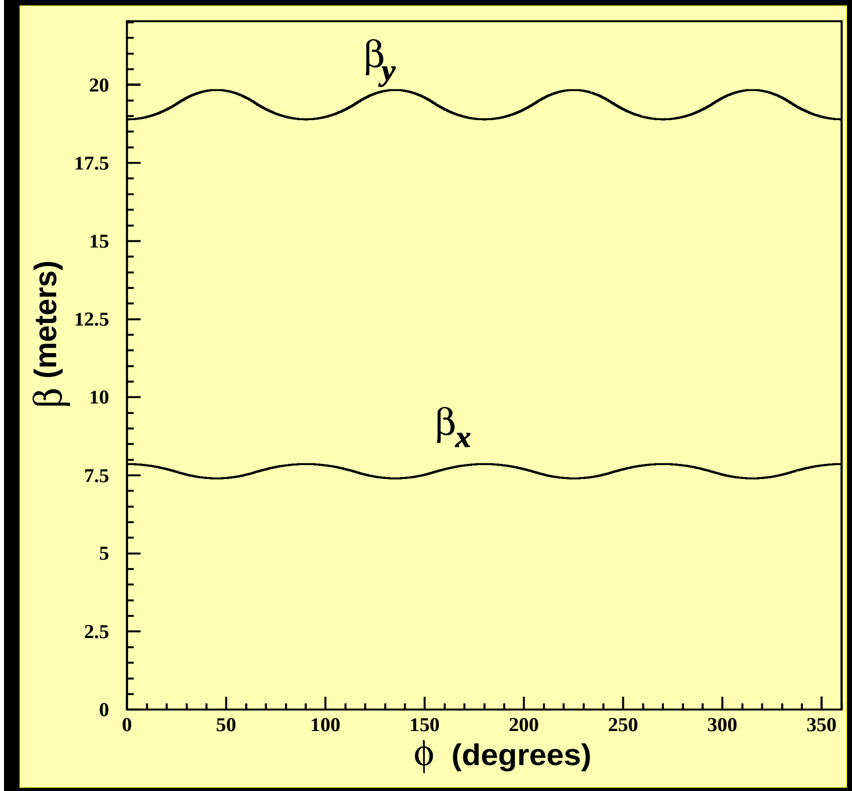
quads cover 43% of the ring

Scraping the Beam



- $V_0 = \pm\ 24$ kV
- $V_S = 17$ kV
- Beam is lifted and moved sideways
- Scraped on collimators to minimize losses

Ring β-Function



$$x(s) = A\sqrt{\beta_x}\cos(\psi + \delta)$$
$$\psi(s) = \sqrt{K}s$$

$$\sqrt{\frac{\beta_{max}}{\beta_{min}}} = 1.03$$

for 4-fold symmetry

Weak Focusing Betatron

$$\text{Field index: } n = \frac{\kappa R_0}{\beta B_0} \simeq 0.135$$

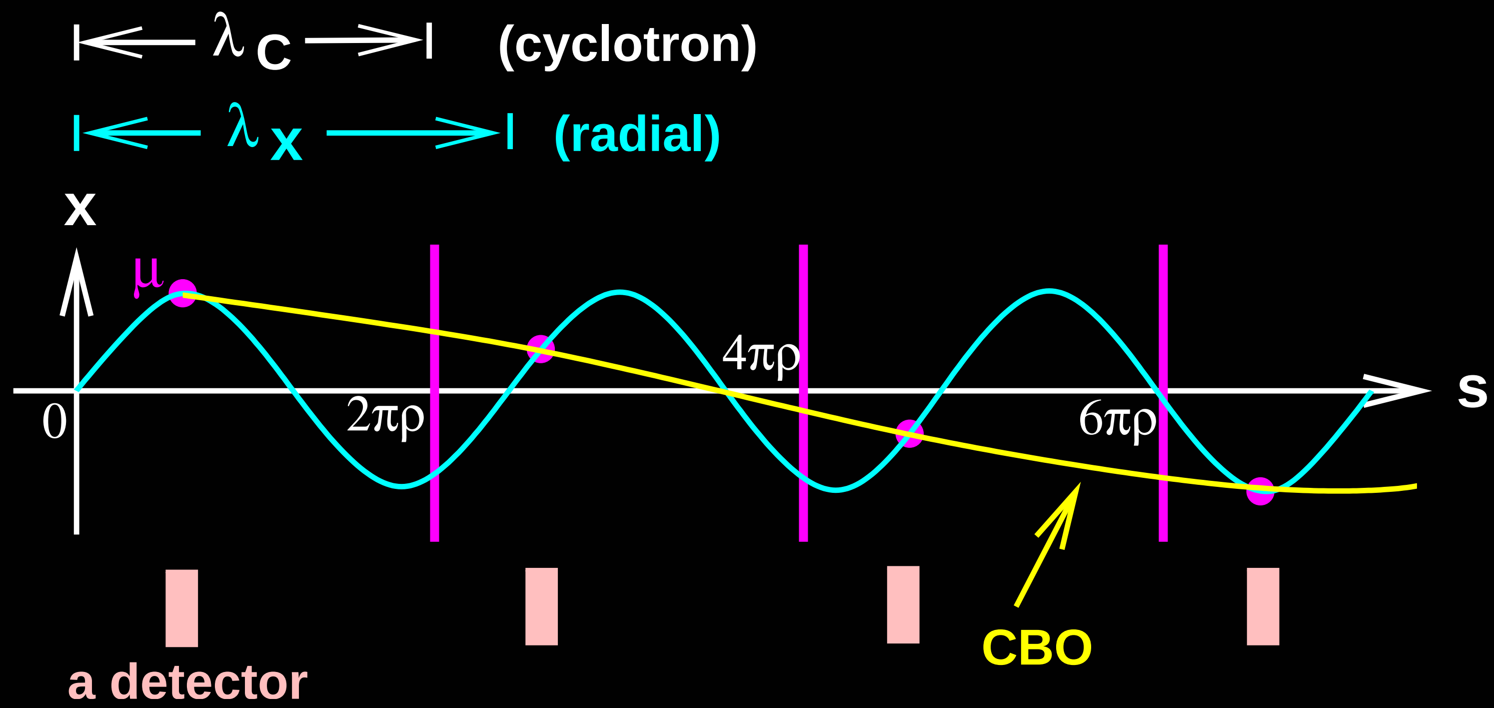
$$f_y = f_C\sqrt{n} \simeq 0.37 f_C;$$

$$f_x = f_C\sqrt{1-n} \simeq 0.929 f_C$$

- Detector acceptance depends on the radial coordinate x. The beam moves coherently radially relative to a detector with the "Coherent Betatron Frequency" (CBO)

$$f_{\text{CBO}} = f_C - f_x = (1 - \sqrt{1-n}) f_C$$

Coherent Betatron Frequency

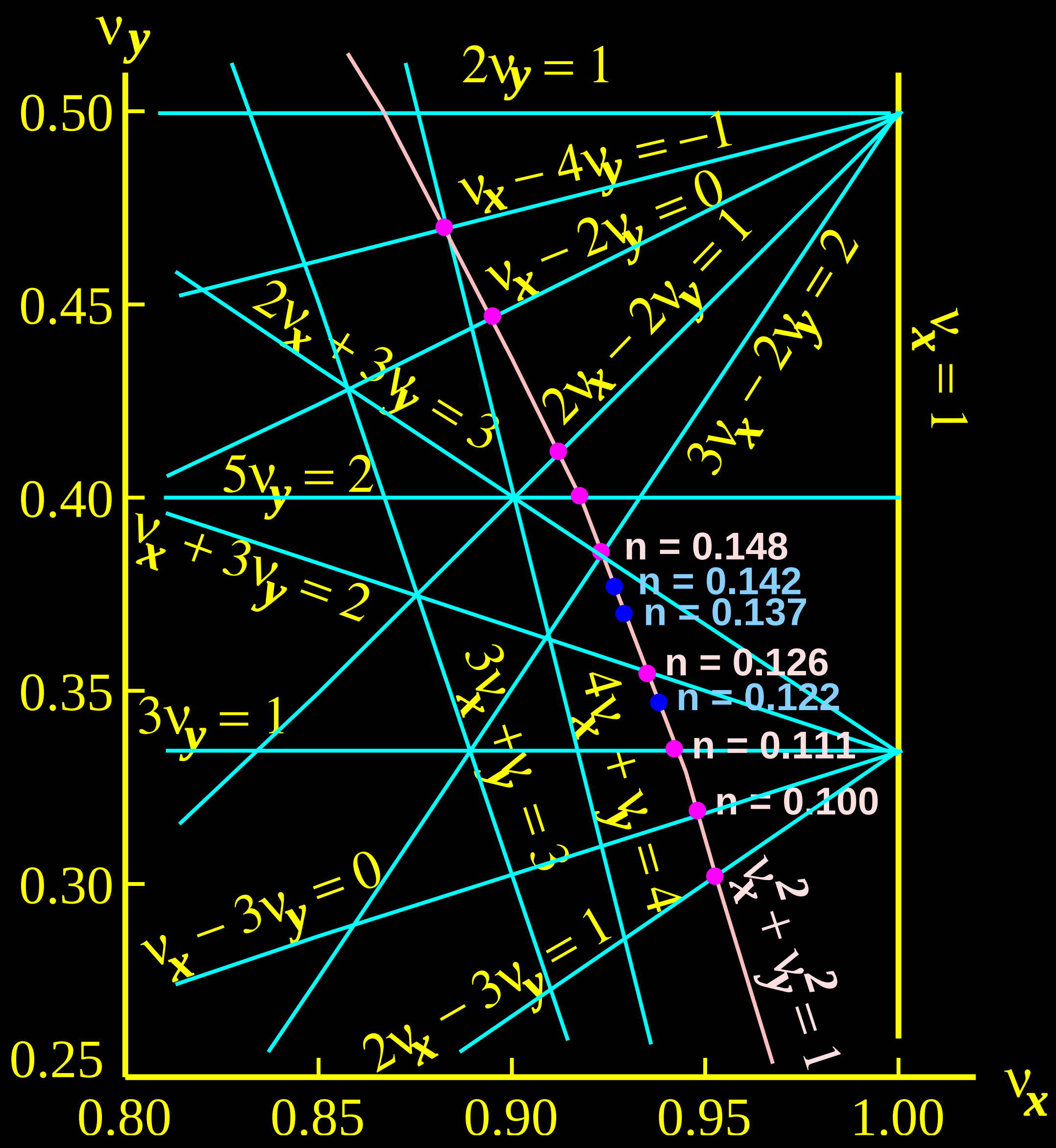


$$f_{\mathrm{CBO}} = f_C - f_x = (1 - \sqrt{1-n})f_C$$

$$\lambda_{CBO} \simeq 14 \text{ turns}$$

CBO amplitude modulates the signal in the detectors.

Tune Plane



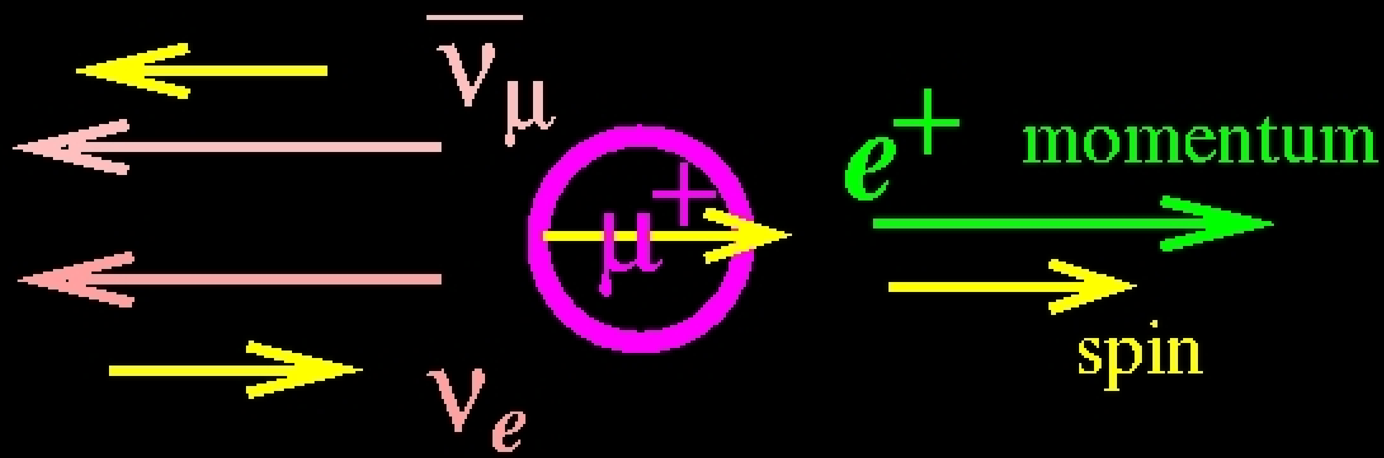
$$\nu_x = \sqrt{1-n}$$

$$\nu_y = \sqrt{n}$$

Muon Decay

μ-decay: parity violating $\mu^- \rightarrow e^- \; \bar{\nu}_e \; \nu_\mu$

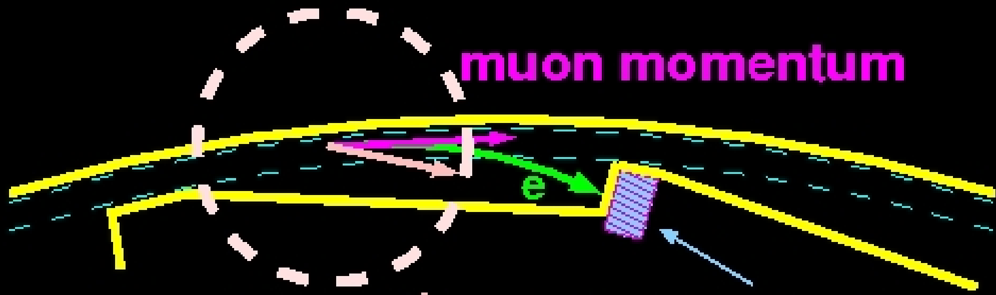
The Muon Rest Frame



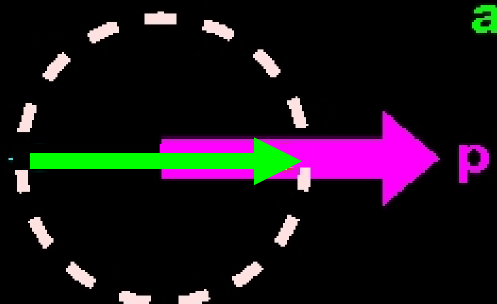
Highest energy e^+ are along muon spin

The positron carries the muon spin

$e^{\pm}$ from $\mu^{\pm} \to e^{\pm}\ \nu\ \nu$ are detected

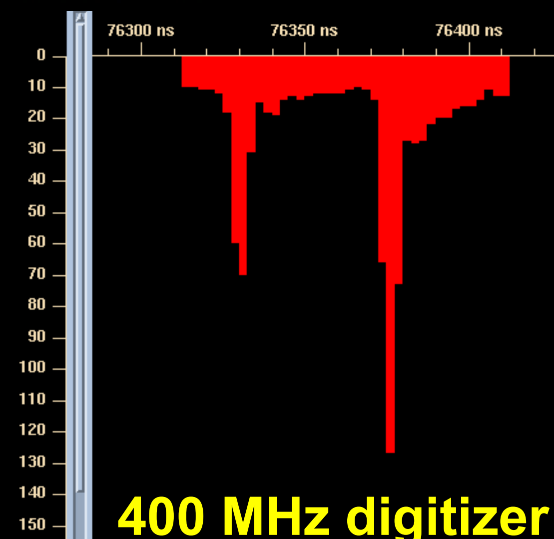


Measures Energy and time



spin forward, more high energy e

spin backward, less high energy e

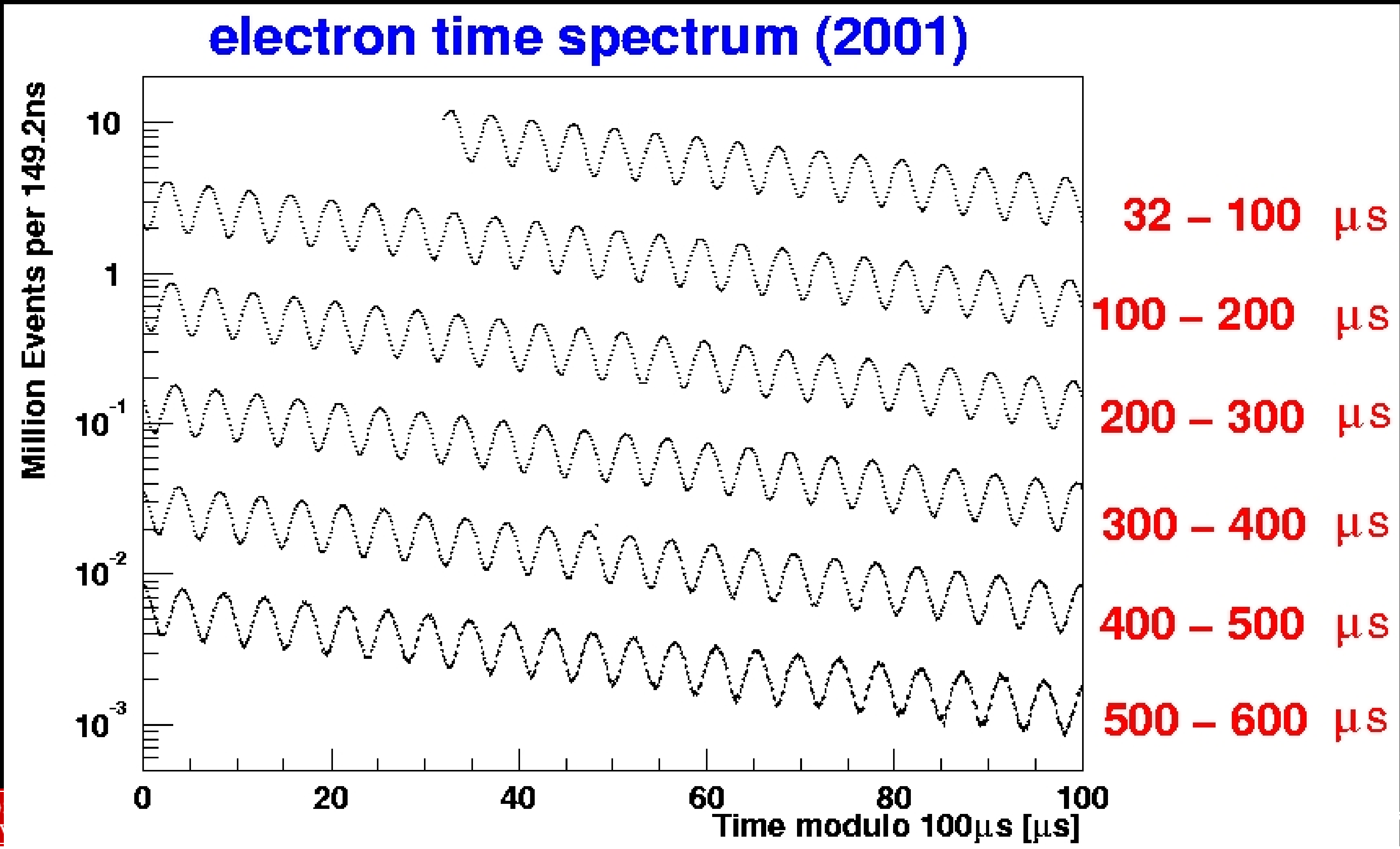


400 MHz digitizer gives t, E

Count number of e^- with $E_e \geq 1.8$ GeV

$$4 \times 10^9 \quad e^-, \; E_{e^-} \geq 1.8 \text{ GeV}$$

$$f(t) = N_0 e^{-\lambda t}[1 + A\cos\omega_a t + \phi)]$$

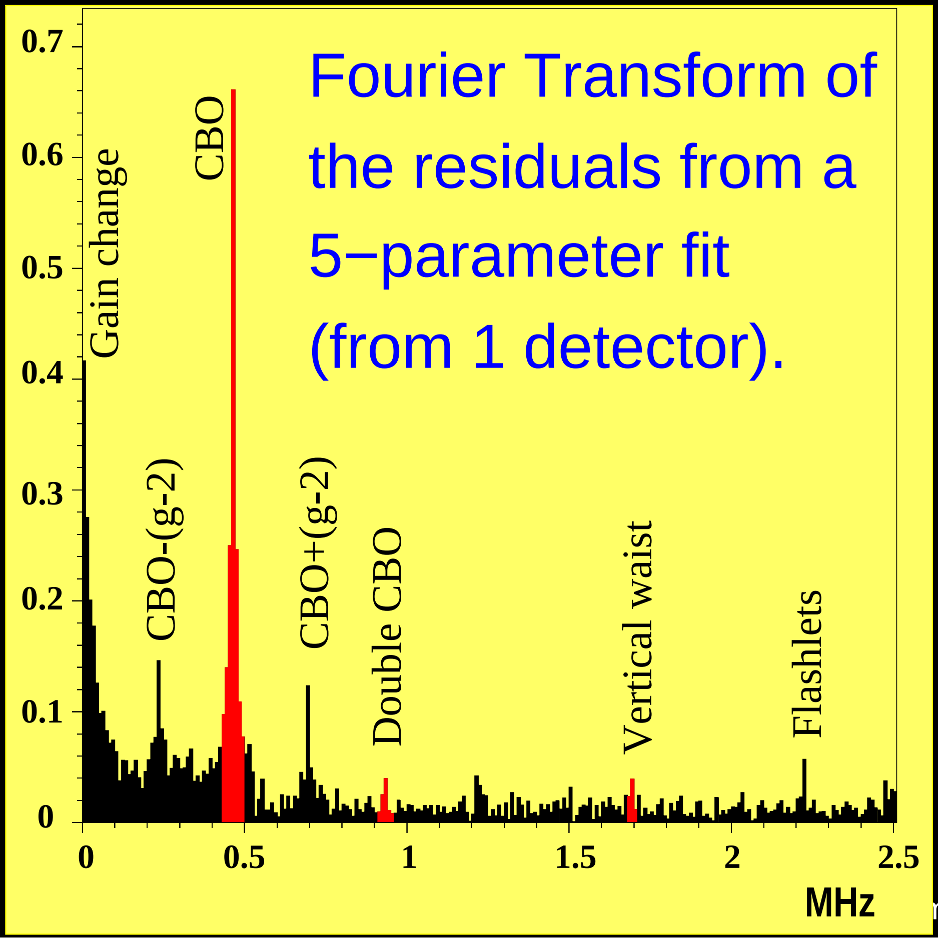


In the 1999 Data Set: A Surprise

Nature gives us 5 parameters:

$$f(t) = N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$$

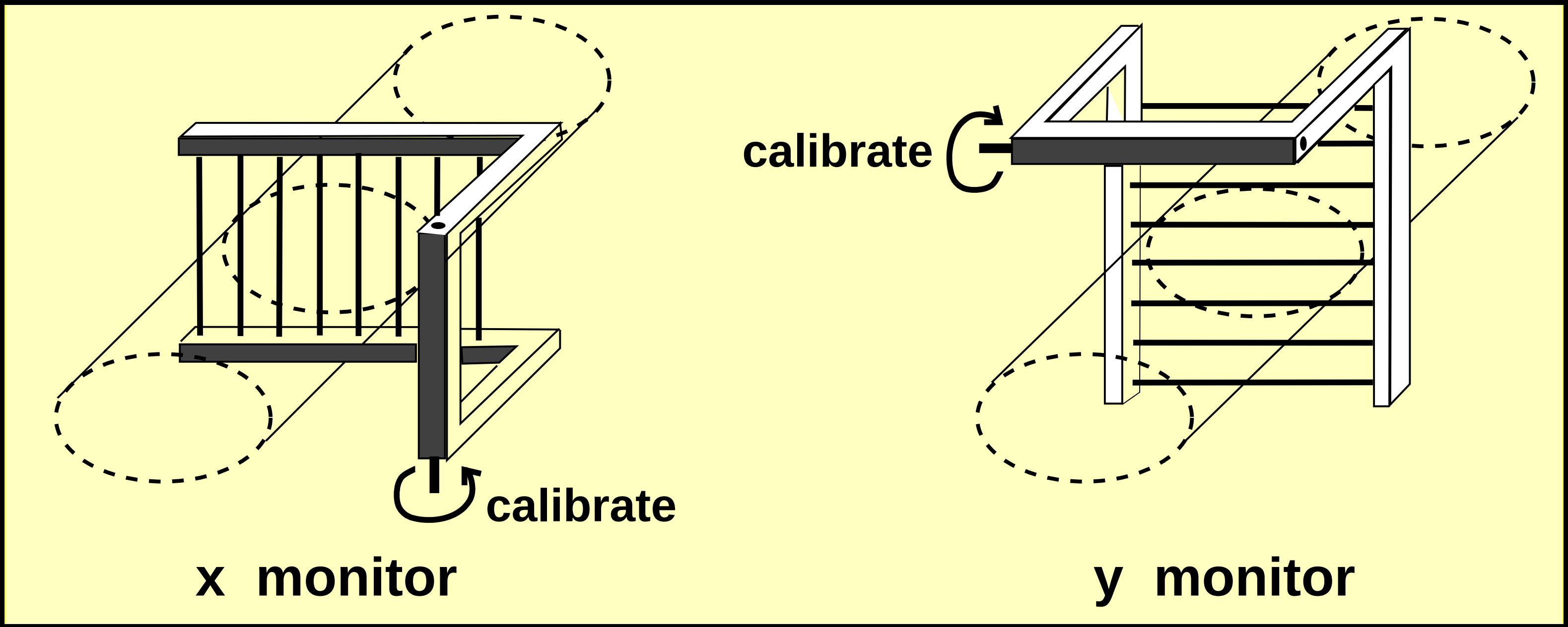
Storage ring plus bunched beam gives us more:



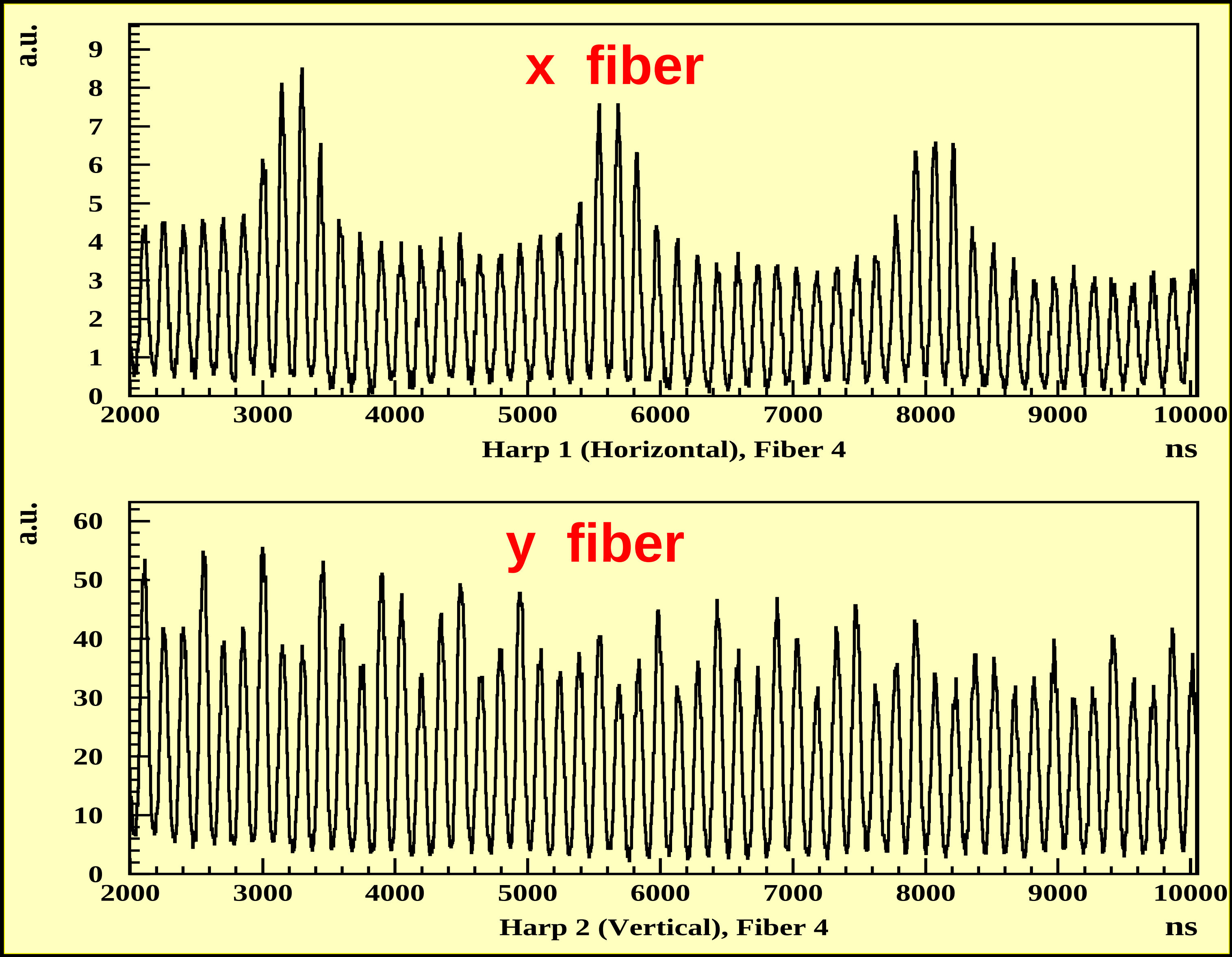
Frequencies in the (g-2) Ring

Quantity	Expression	Frequency	Period
f_a	$\frac{e}{2\pi mc} a_\mu B$	0.23 MHz	4.37 μs
f_c	$\frac{v}{2\pi R_0}$	6.7 MHz	149 ns
f_x	$\sqrt{1-n} f_c$	6.23 MHz	160 ns
f_y	$\sqrt{n} f_c$	2.48 MHz	402 ns
f_{CBO}	$f_c - f_x$	0.477 MHz	2.10 μs
f_{VW}	$f_c - 2 f_y$	1.74 MHz	0.574 μs

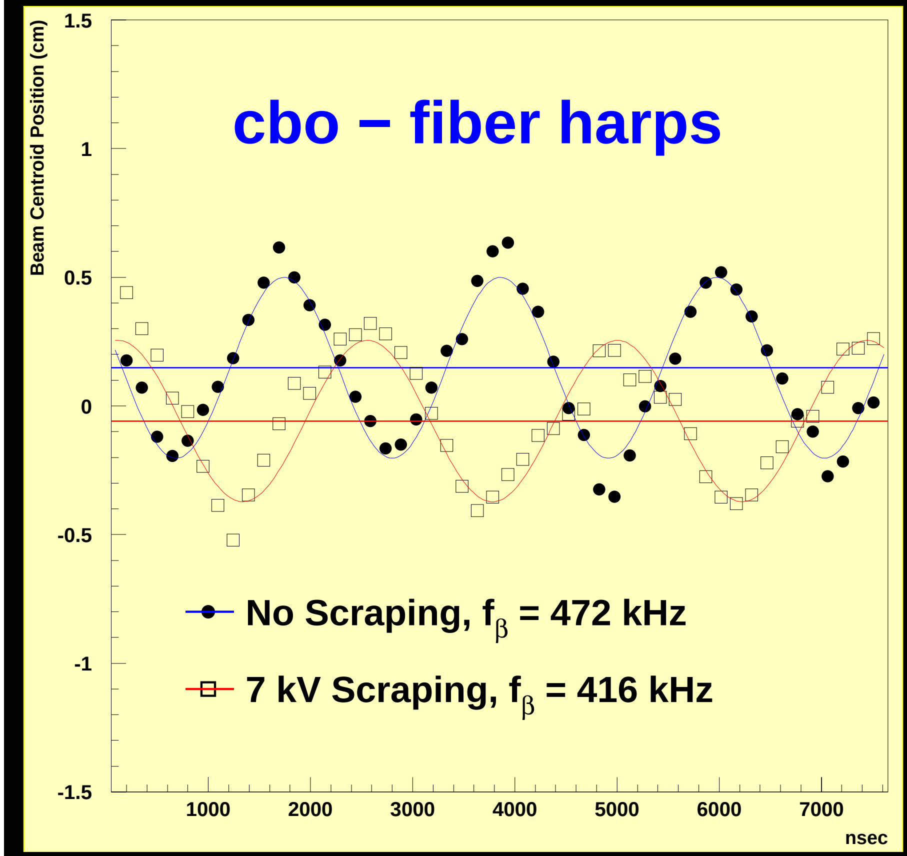
Fiber Beam Monitors

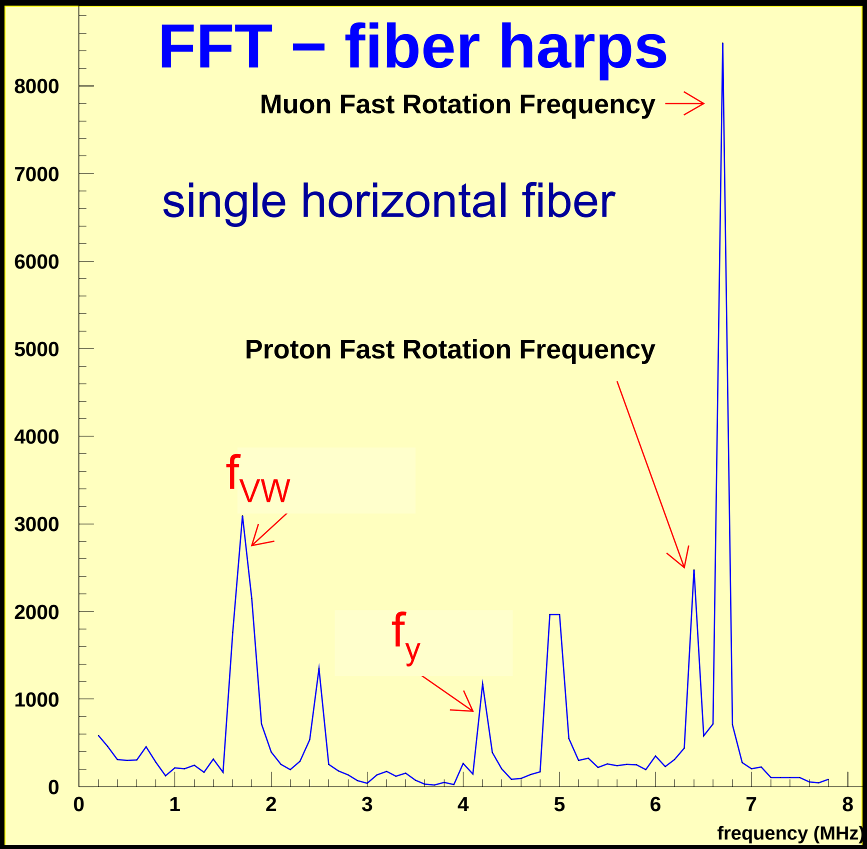


Measuring the Tune from a single fiber



The Tune During Scraping



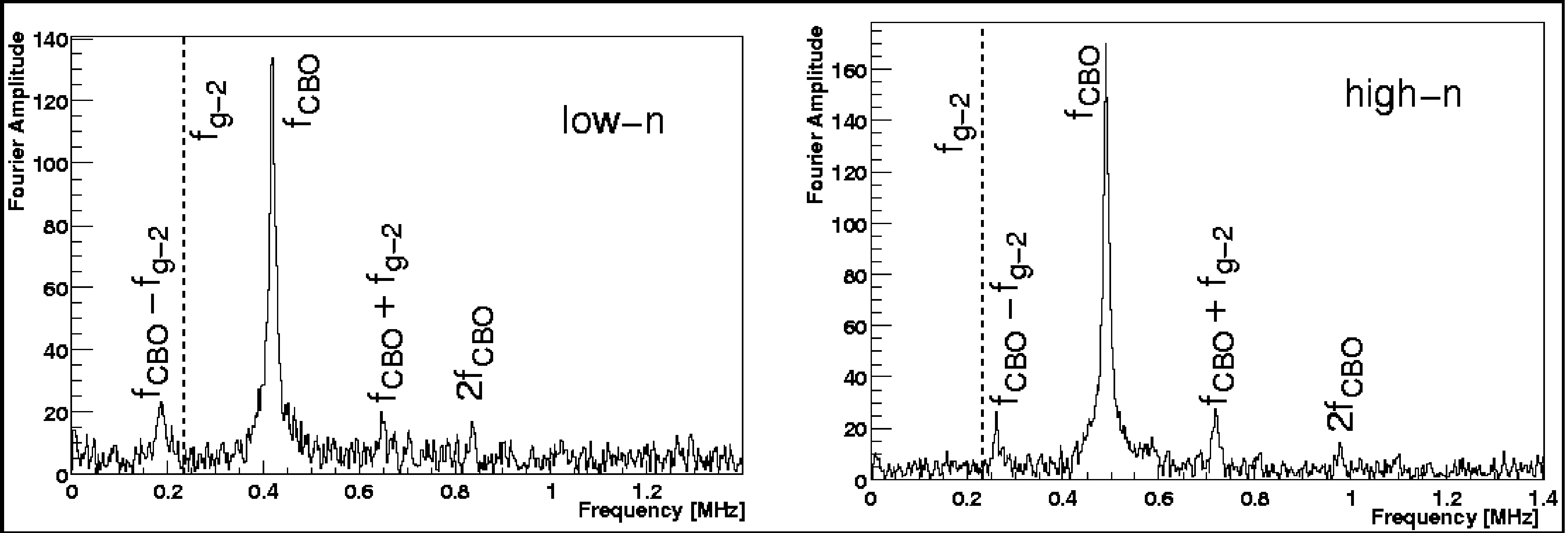


- The tune change with scraping is clearly visible from the fiber harps

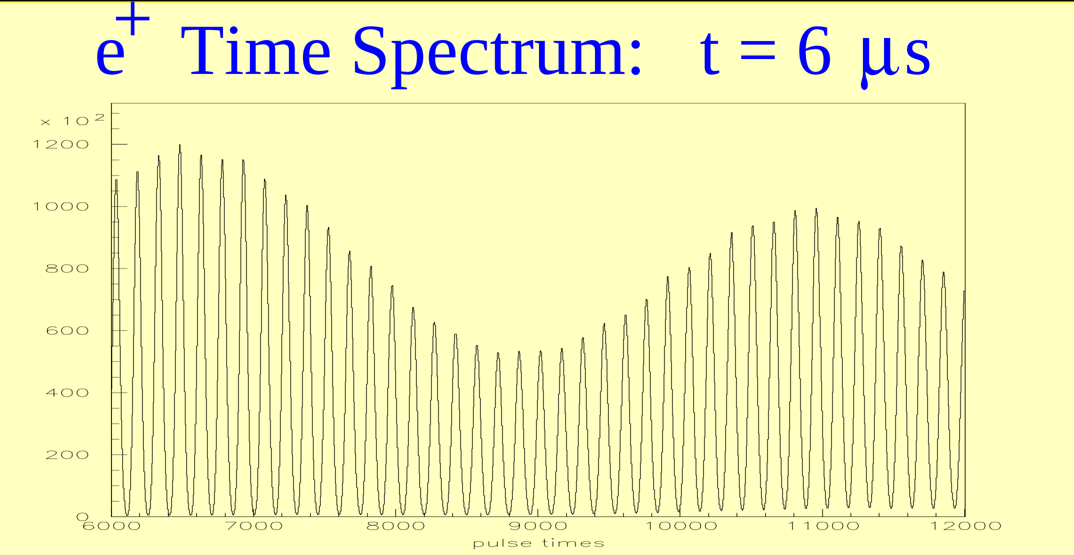
CBO in the 2001 Data Set

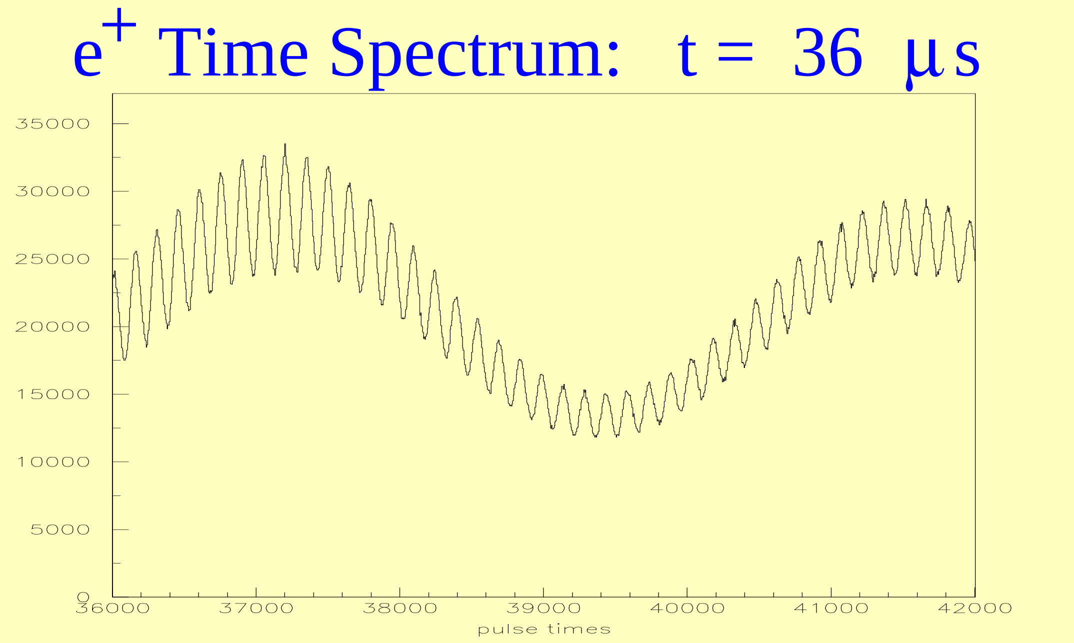
$$f(t) = N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$$

Residuals from fitting the 5-parameter function



Beam Debunching after Injection

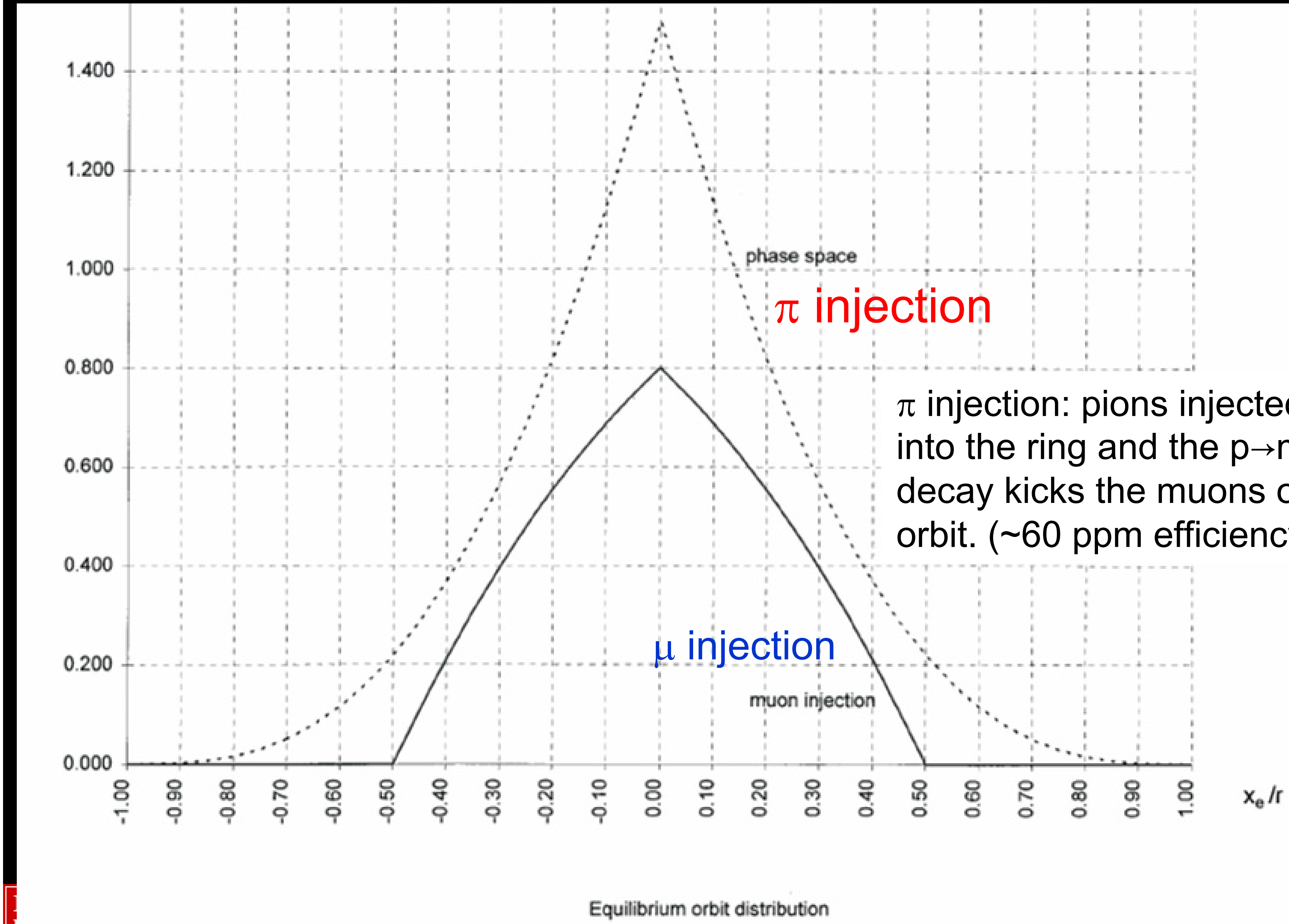




Ring momentum acceptance

$$\frac{\Delta p}{p} = \pm 0.5\%$$

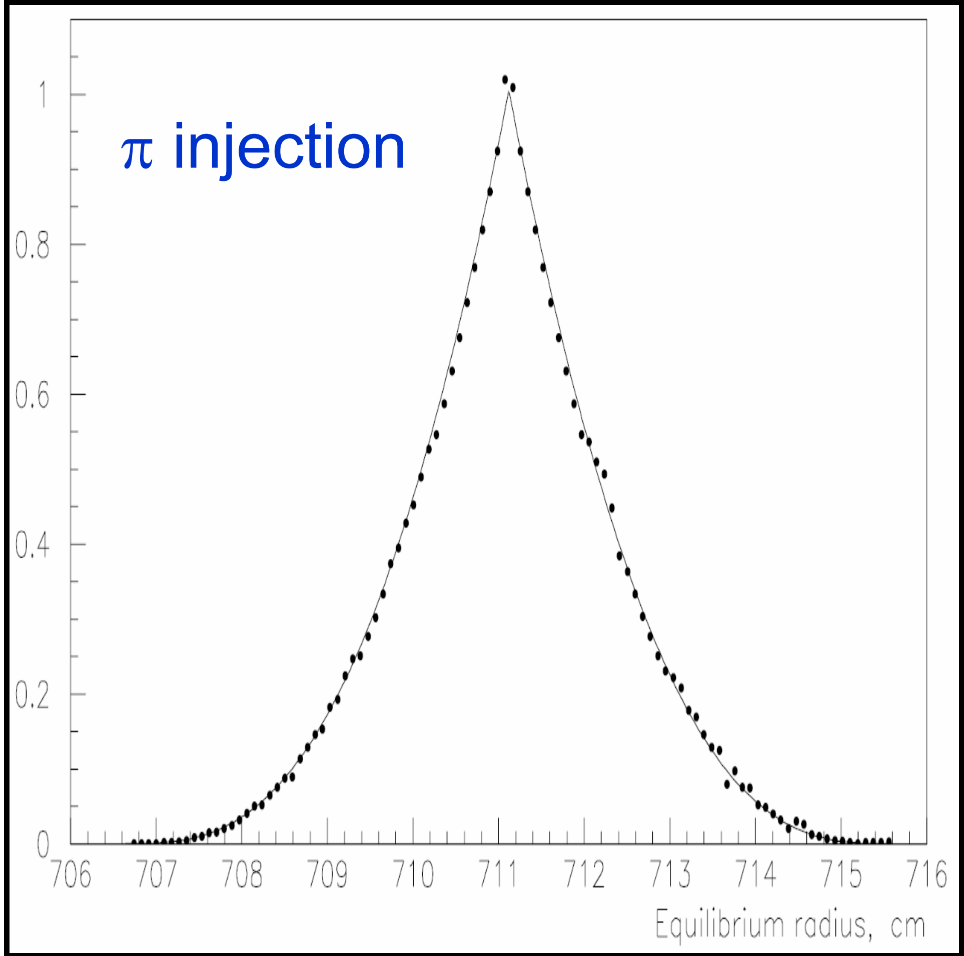
What do we expect for distribution of equilibrium radii?

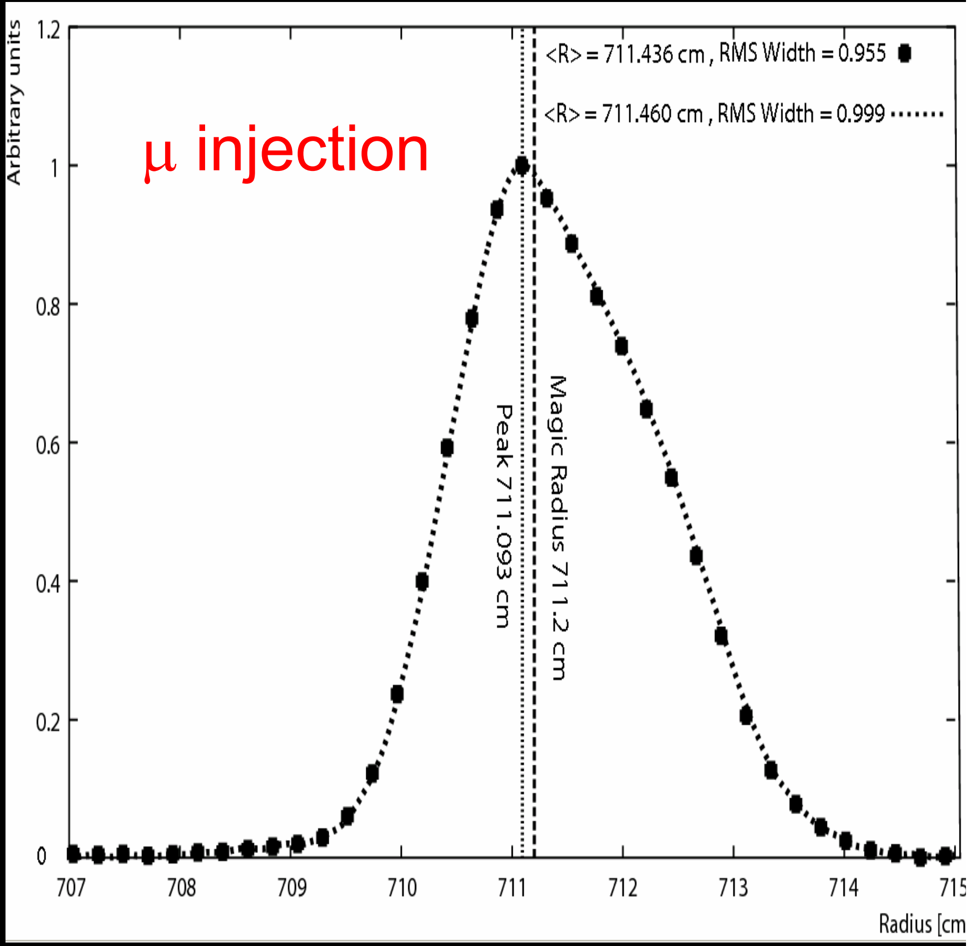


Farley, g-2 note #311

π injection: pions injected into the ring and the p→m decay kicks the muons on orbit. (~60 ppm efficiency)

Distribution of Equilibrium Radii





1997 π-injection run

● Modified FT

— Phase space

2001 μ-injection run

● Debunching model

······ modified FT

E989: Systematic Error Goal

Systematic uncertainty (ppm)	1998	1999	2000	2001	E989 Goal
Magnetic field – ω_p	0.5	0.4	0.24	0.17	0.07
Anomalous precession – ω_a	0.8	0.3	0.3	0.21	0.07

Systematic errors on ω_a (ppm)

$\sigma_{systematic}$	1999	2000	2001	P989
Pile-up	0.13	0.13	0.08	0.04
AGS Background	0.10	0.10	*	------
Lost Muons	0.10	0.10	0.09	0.02
Timing Shifts	0.10	0.02	0.02	
E-Field, Pitch	0.08	0.03	*	0.03
Fitting/Binning	0.07	0.06	*	
CBO	0.05	0.21	0.07	0.04
Beam Debunching	0.04	0.04	*	
Gain Change	0.02	0.13	0.13	0.02
total	0.3	0.31	0.21	0.11

Beam manipulation

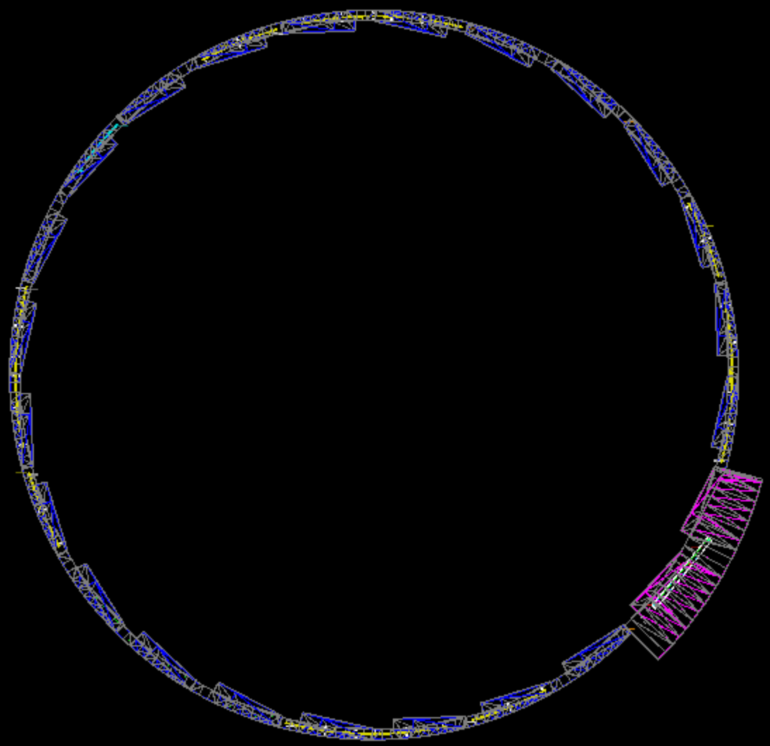
900 m beamline

$\Sigma^* = 0.11$

Outstanding Beam Issues

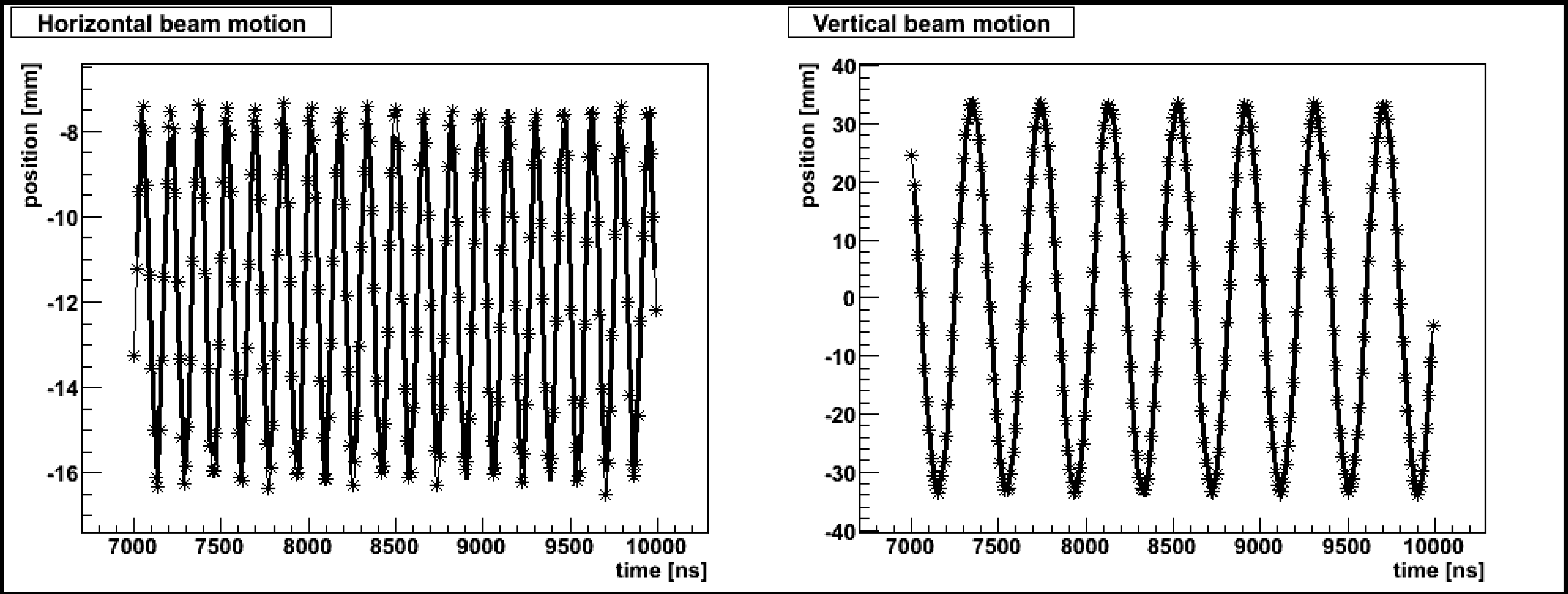
- The Kicker: can it be improved?
  - What's the real injection efficiency in E821 and can it be simulated?
- Elimination of the CBO

We have developed a new simulation tool to guide our improvements. It includes all major subsystems



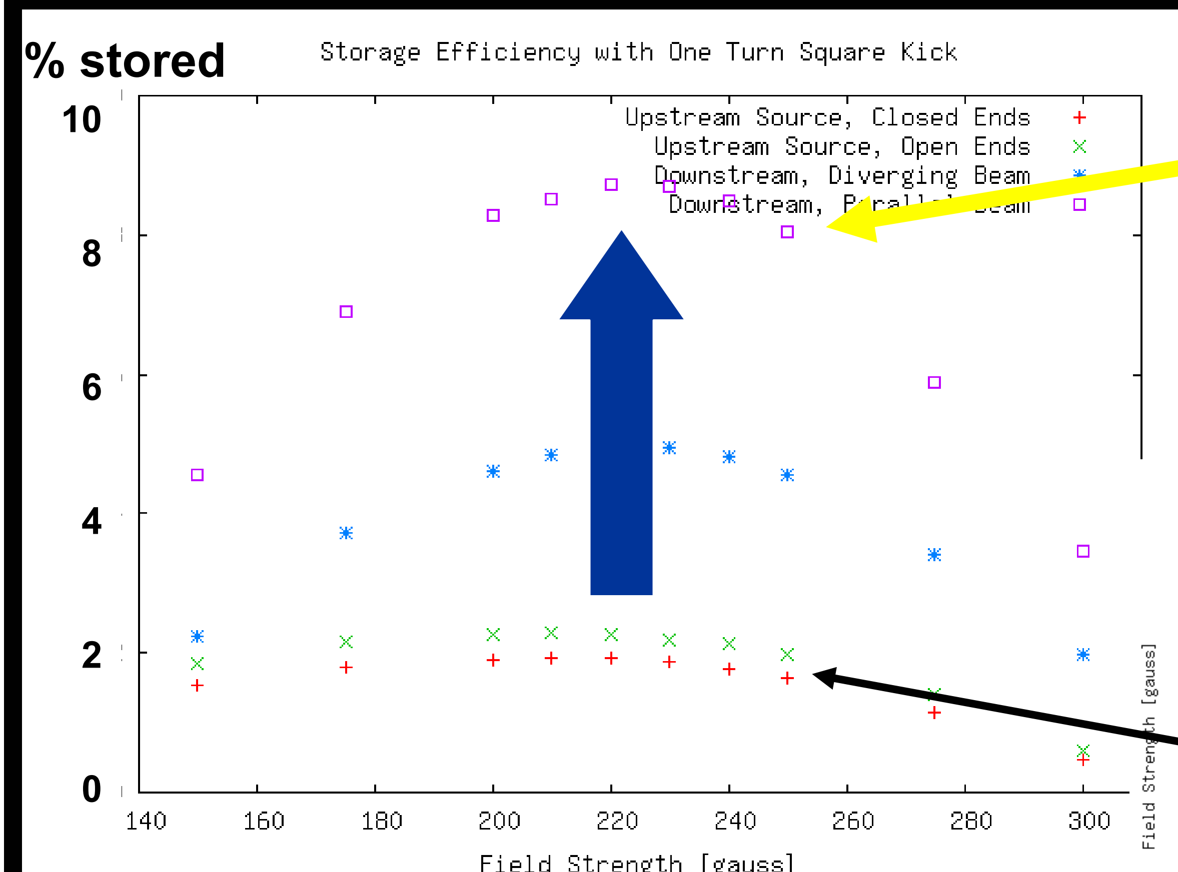
- Vacuum vessel
- Inflector
- Kickers
- Quadrupoles
- Collimators

Example: Collective beam motion for stored muons is reproduced

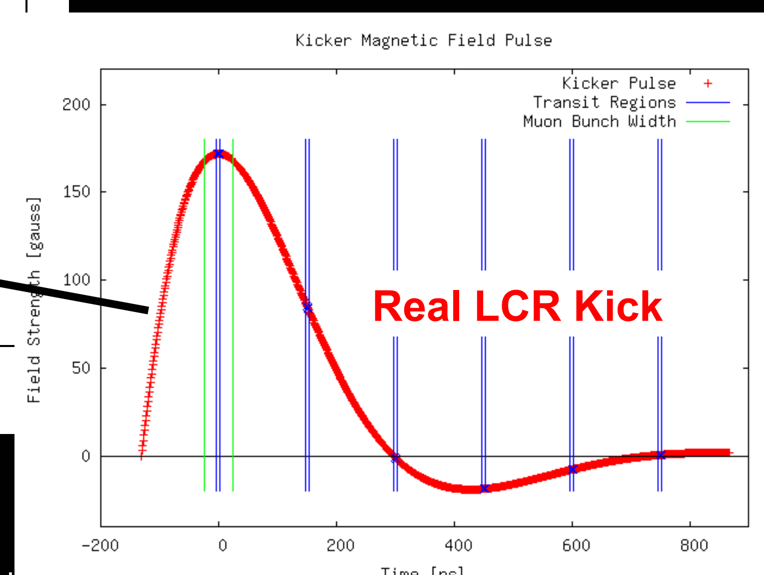


The predicted horizontal and vertical betatron oscillation frequencies match measured values from E821 at the percent level.

We can simulate modified kicker pulse shapes to predict storage improvements

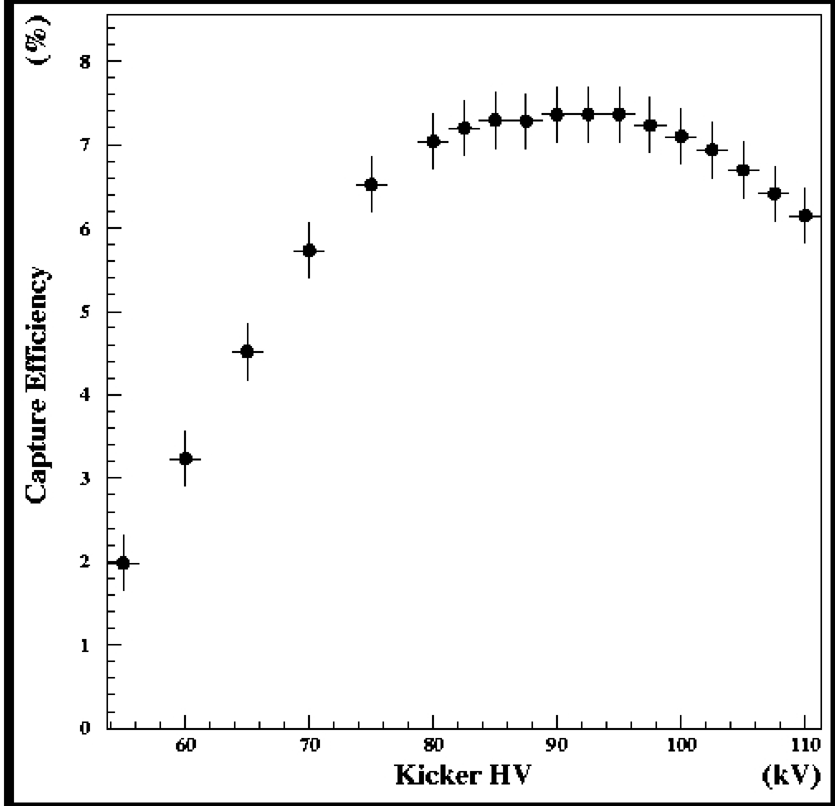


Ideal Square Kick

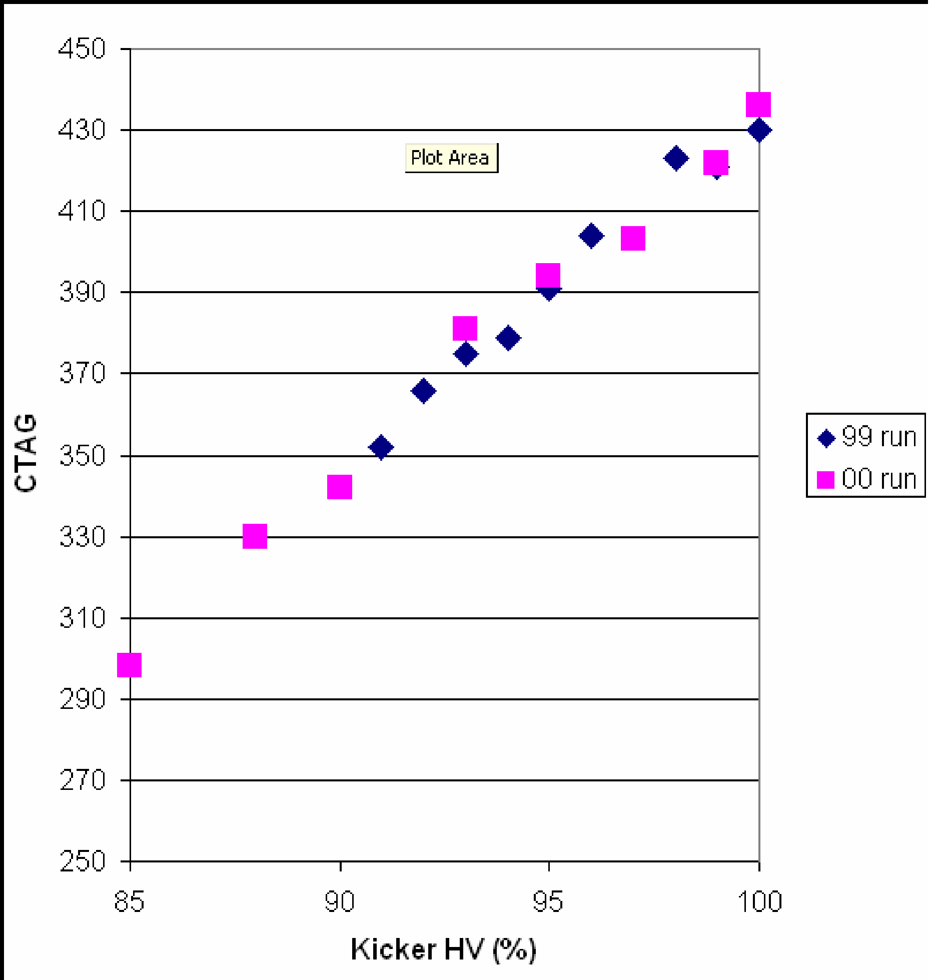


in the NIM paper we said:

but …



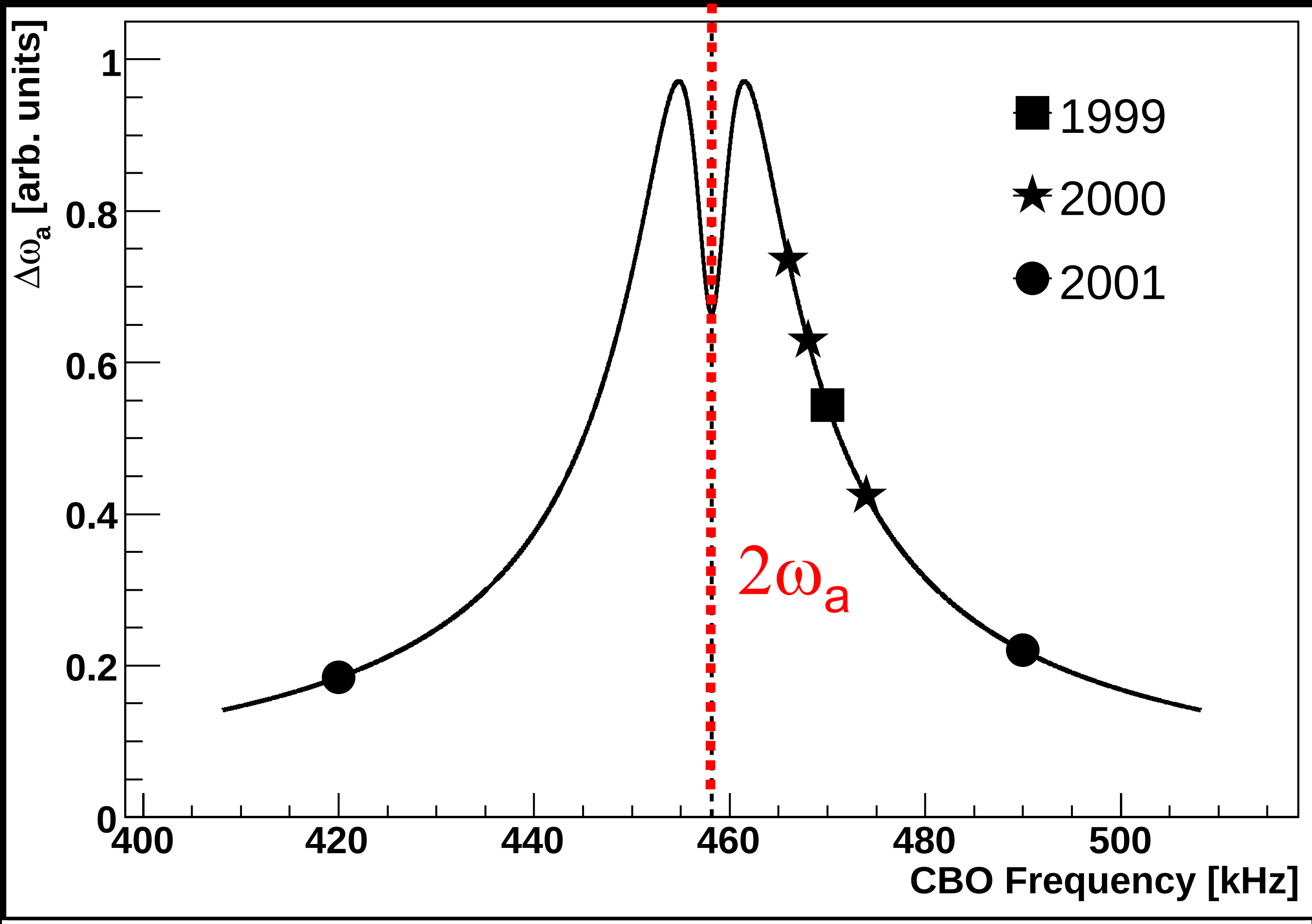
100% ≡ 87, 93, 92 kV



slope = $\frac{2\%\ \text{CTAGS}}{1\ \%\ \text{HV}}$

we never saw it turn over…

Relative Amplitude of the CBO effect if not accounted for



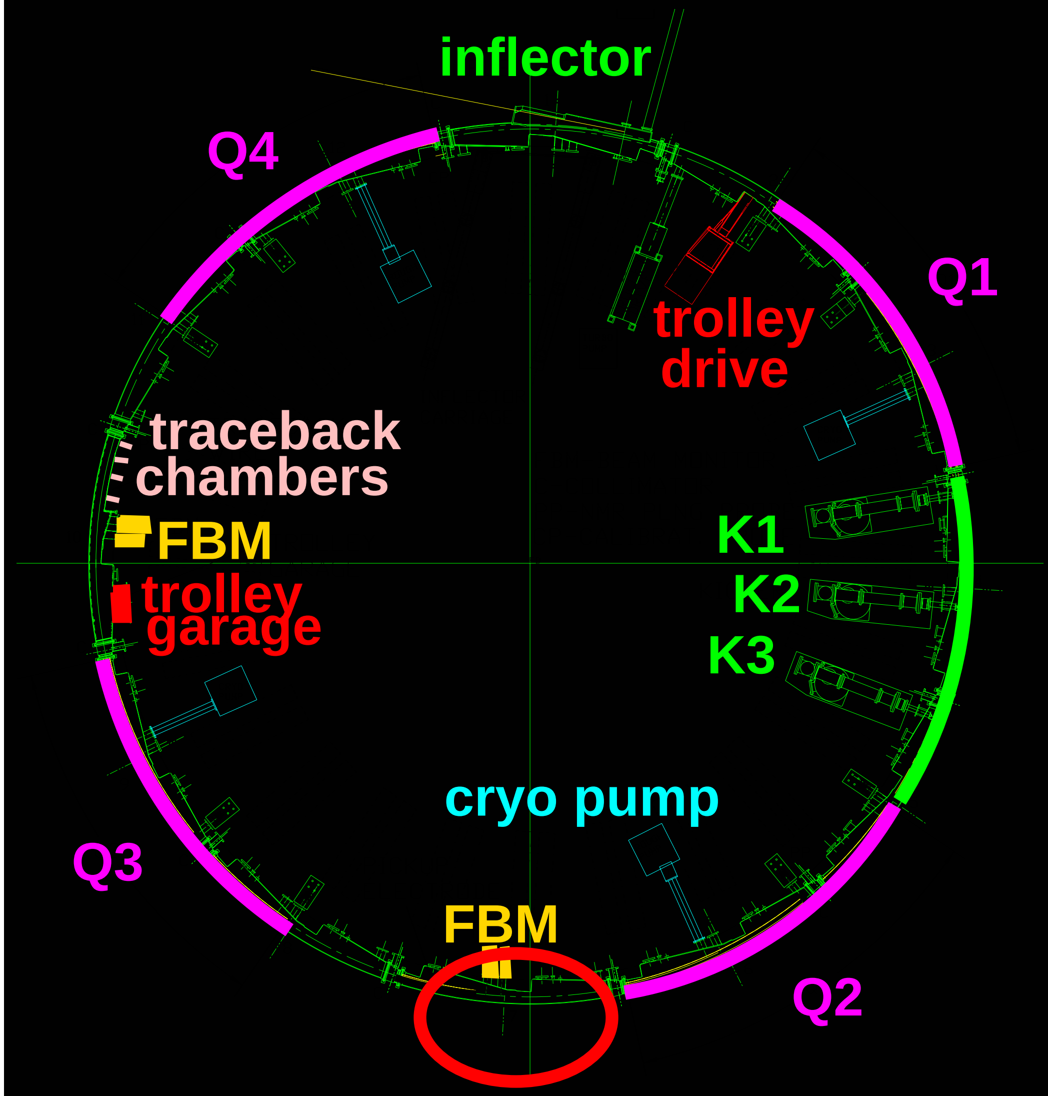
	1999	2000	2001	E969
CBO $\sigma_{systematic}$		0.21	0.07	0.04
total	0.3	0.31	0.21	0.07

BOSTON UNIVERSITY

Lost Muons and CBO are Major Issues

- Two schemes proposed to eliminate CBO and losses
  - Drive CBO with an oscillating dipole to scrape, then slip the phase by π and damp it
    - Suggested by Yuri Orlov
  - Pulsed Octupole for 30 turns
    - Suggested by Yuri Shatunov

Oscillating Dipole Solution



- Use Fiber Harps to measure phase of CBO

Sample Parameters

$L = 0.5$ m

$N = 20$ turns

$E_{x0} = 7.4$ kV/cm

$f = 470$ kHz

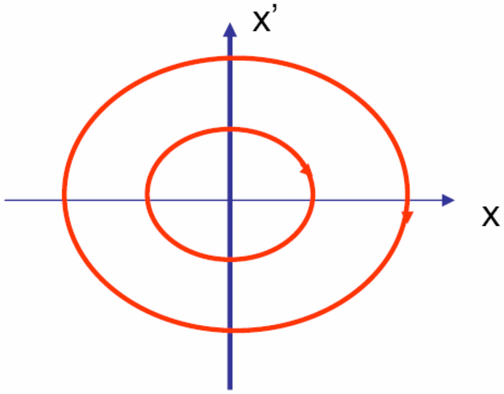
CBO cure: betatron phases mixing by nonlinear fields

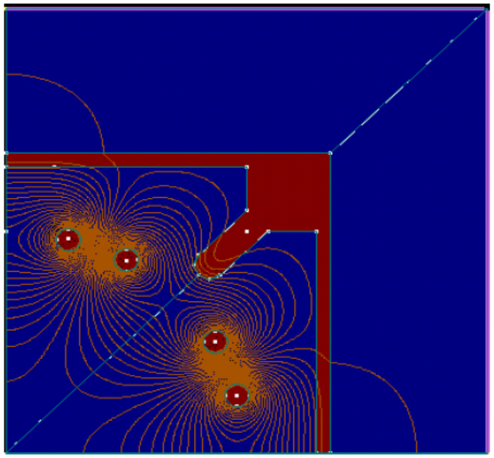
$$\Delta B_x + i\Delta B_y = B_0 \sum_n (b_n + i a_n)(x+iy)^n$$

$$octupole:(n=3)$$

$$\boxed{\begin{aligned} B_x &= O(s)\left(y^3 - 3x^2 y\right) \\ B_y &= O(s)\left(x^3 - 3y^2 x\right) \end{aligned}}$$

$$\beta\left(\partial\nu \big/ \partial a^2\right) \cong \frac{3}{8}\left\langle \beta^2 b_3 \right\rangle_s$$



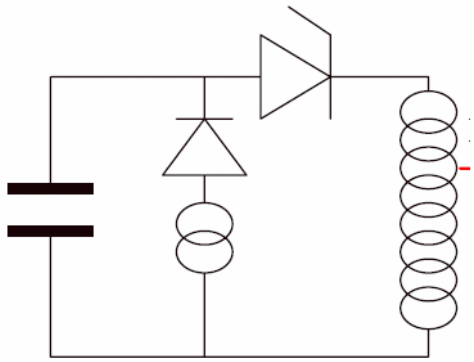


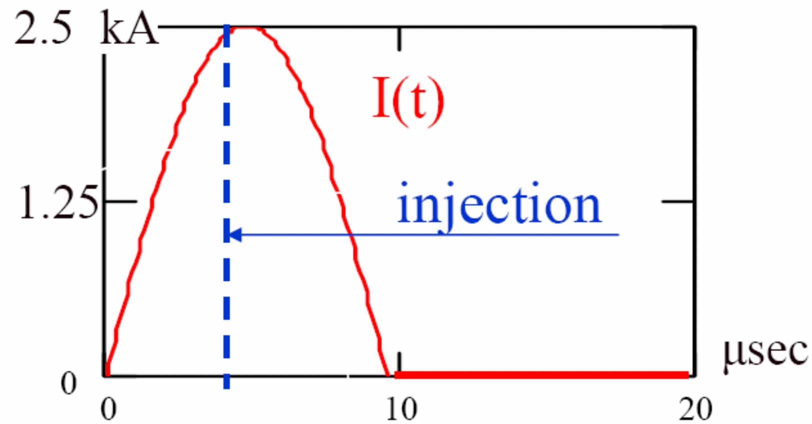
g-2

2-meter long coil!

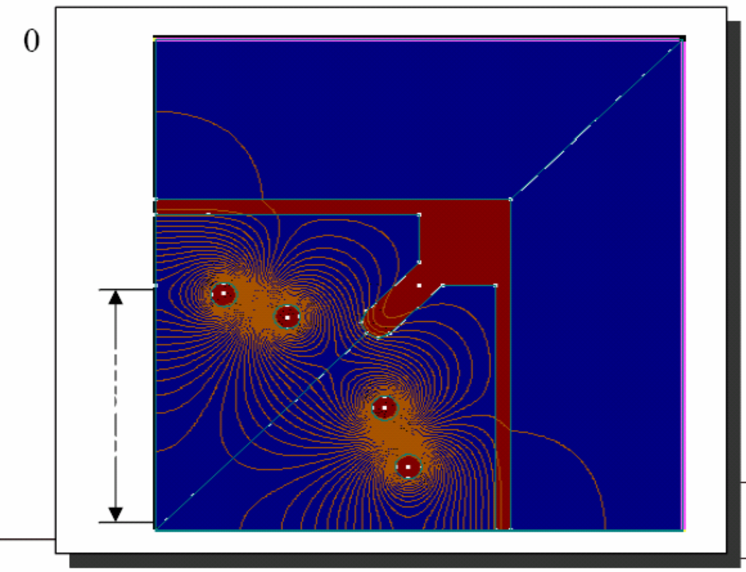
Y. Shatunov, SPIN04

Octupole coil and parameters of generator



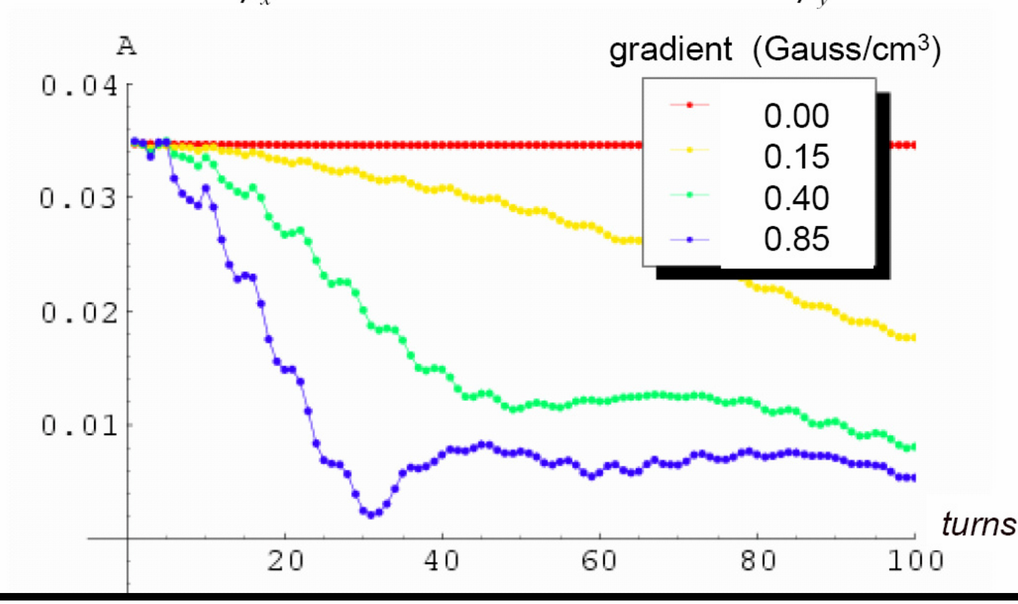


Coil length	16×2	m
Current	2.5	kA
Capacitor	1	µF
Voltage	1.3	kV
Energy	1.0	J
Half period	10	µsec

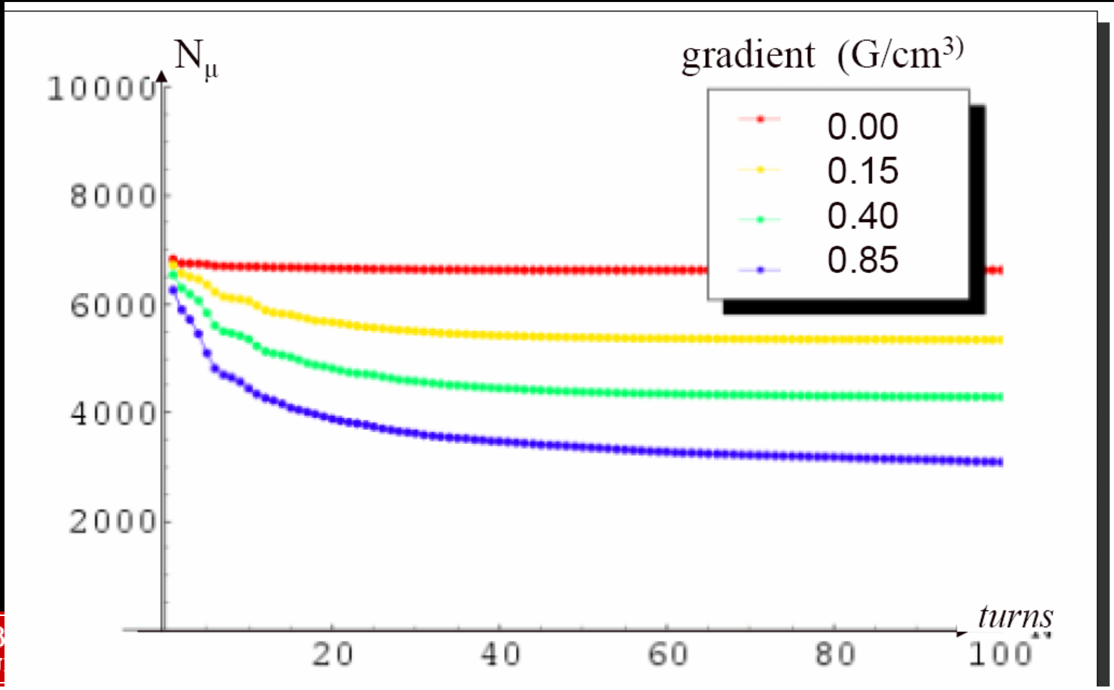


Y. Shatunov, SPIN04

$$A=\sqrt{\frac{(1+\alpha_x^2)\langle x\rangle^2+2\alpha_x\beta_x\langle x\rangle\langle x'\rangle+\beta_x^2\langle x'\rangle^2}{\beta_x}+\frac{(1+\alpha_y^2)\langle y\rangle^2+2\alpha_y\beta_y\langle y\rangle\langle y'\rangle+\beta_y^2\langle y'\rangle^2}{\beta_y}}$$



CBO damping



Muon population

Challenges with Octupole

- Eddy currents affecting B_0?
  - We can only tolerate effects on $\int B \cdot d\ell$ at the < 0.03 ppm level

- Too many muons lost?

Summary

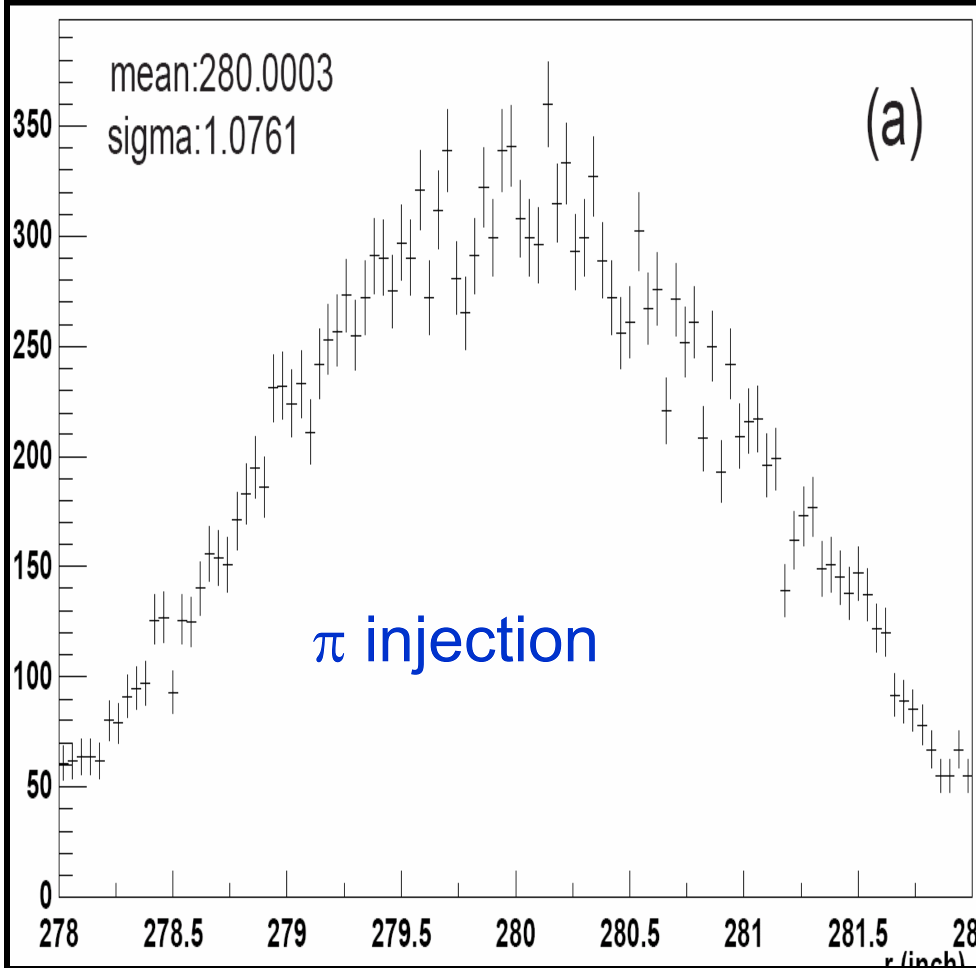
- E821 at BNL achieved 0.54 ppm relative accuracy on a_μ
  - 0.46 ppm statistical
  - 0.28 ppm systematic
- This represents a factor of 14 over the CERN experiment

Summary

- E821 at BNL achieved 0.54 ppm relative accuracy
  - 0.46 ppm statistical
  - 0.28 ppm systematic
- This represents a factor of 14 over the CERN experiment
- P/E989 Aims to achieve an additional factor of 4
  - from 0.54 ppm $\rightarrow$ 0.14 ppm
- Will more than double the physics reach when confronting theory
- Many kind words, no $ yet.

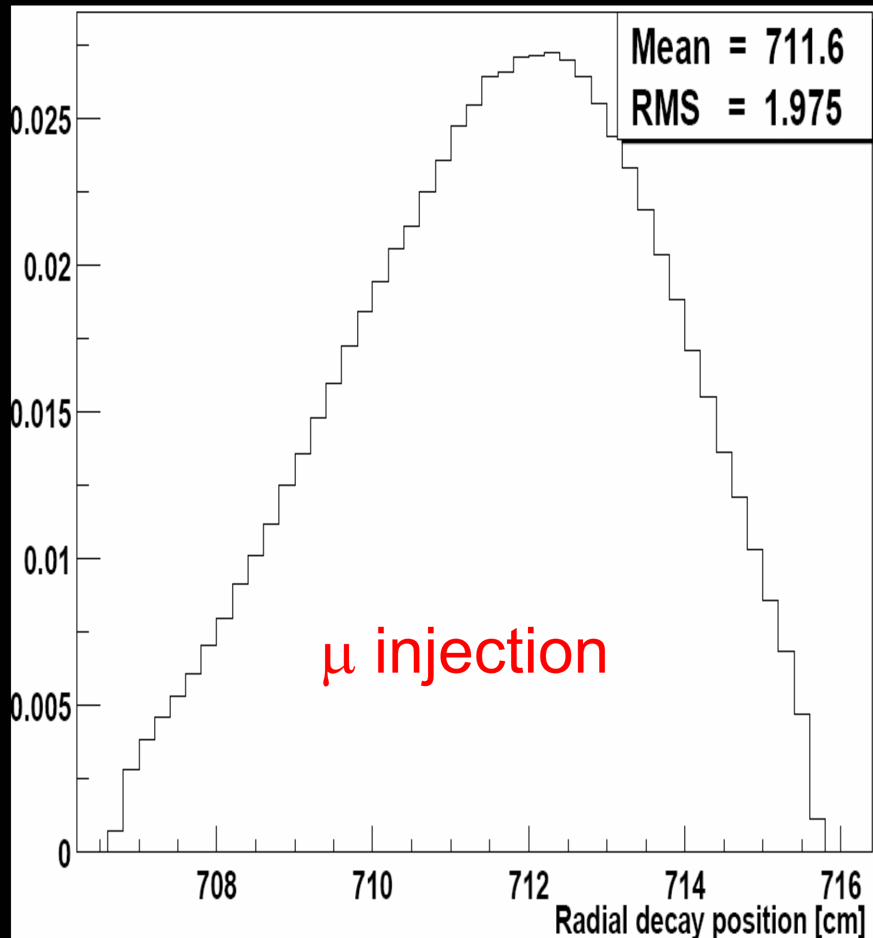
–Please come join us!

Traceback: π Injection vs. μ Injection



Radial distribution from traceback:

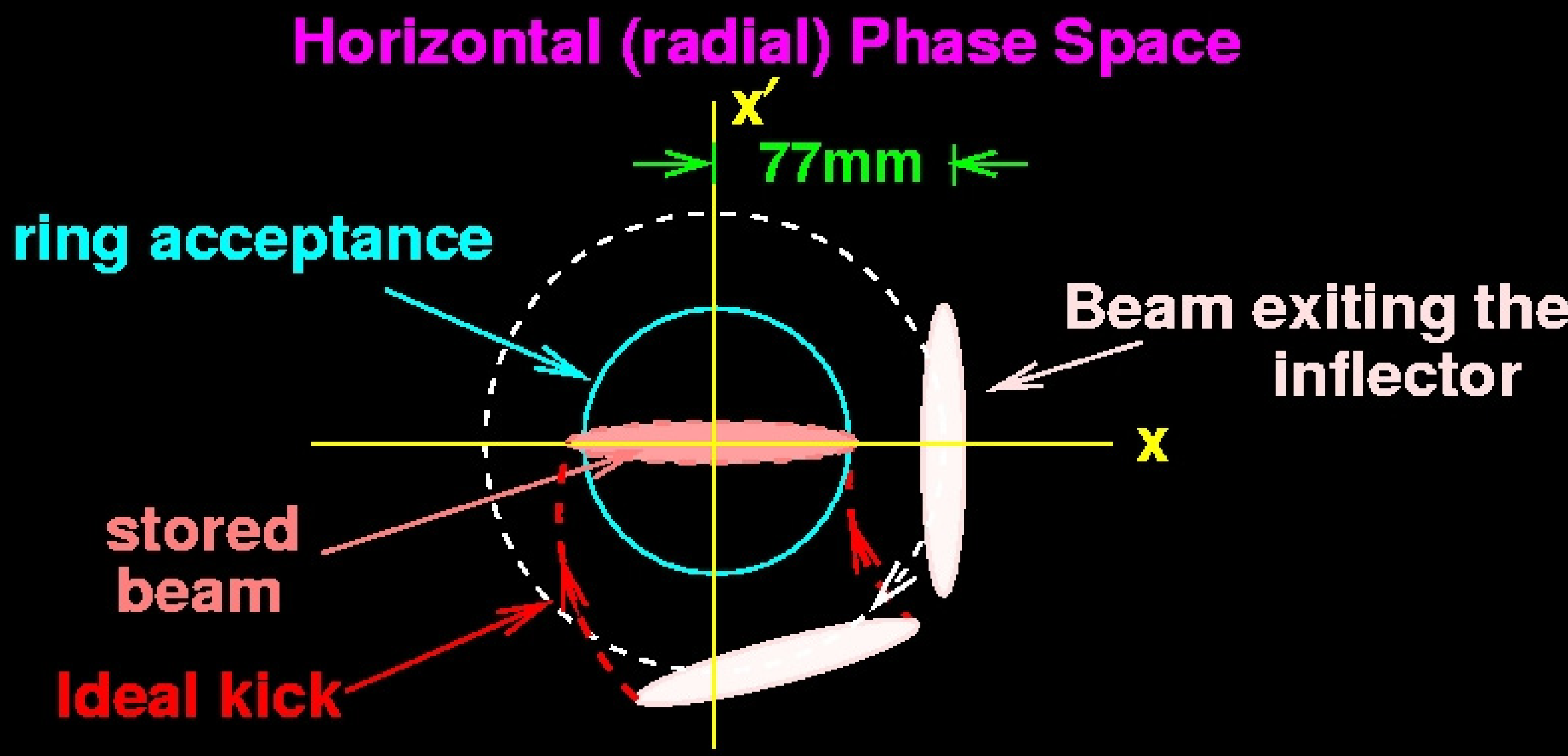
Denninger Thesis 1997 π-injection run



Radial distribution from traceback:

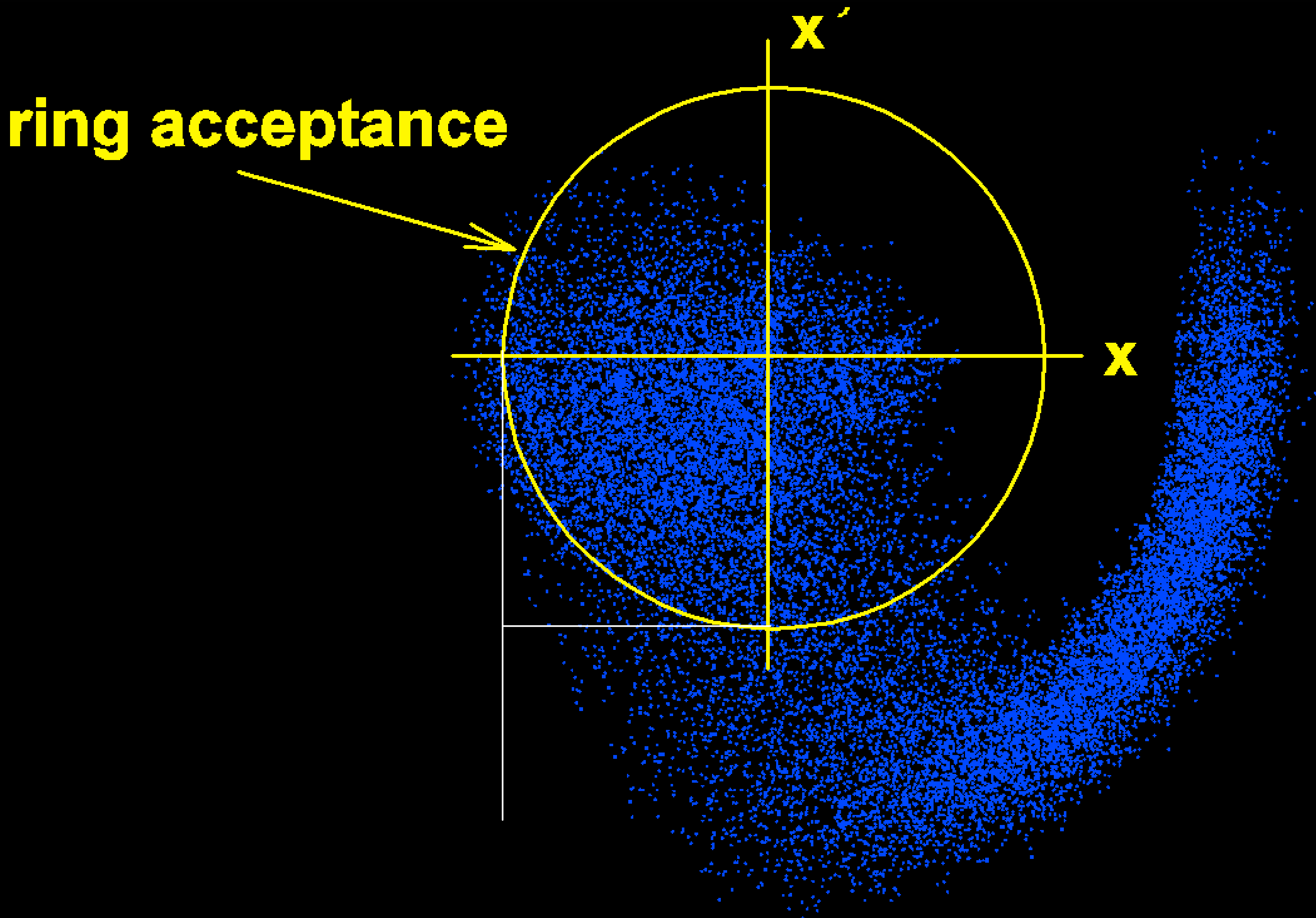
Sossong Thesis 1999 μ-injection run

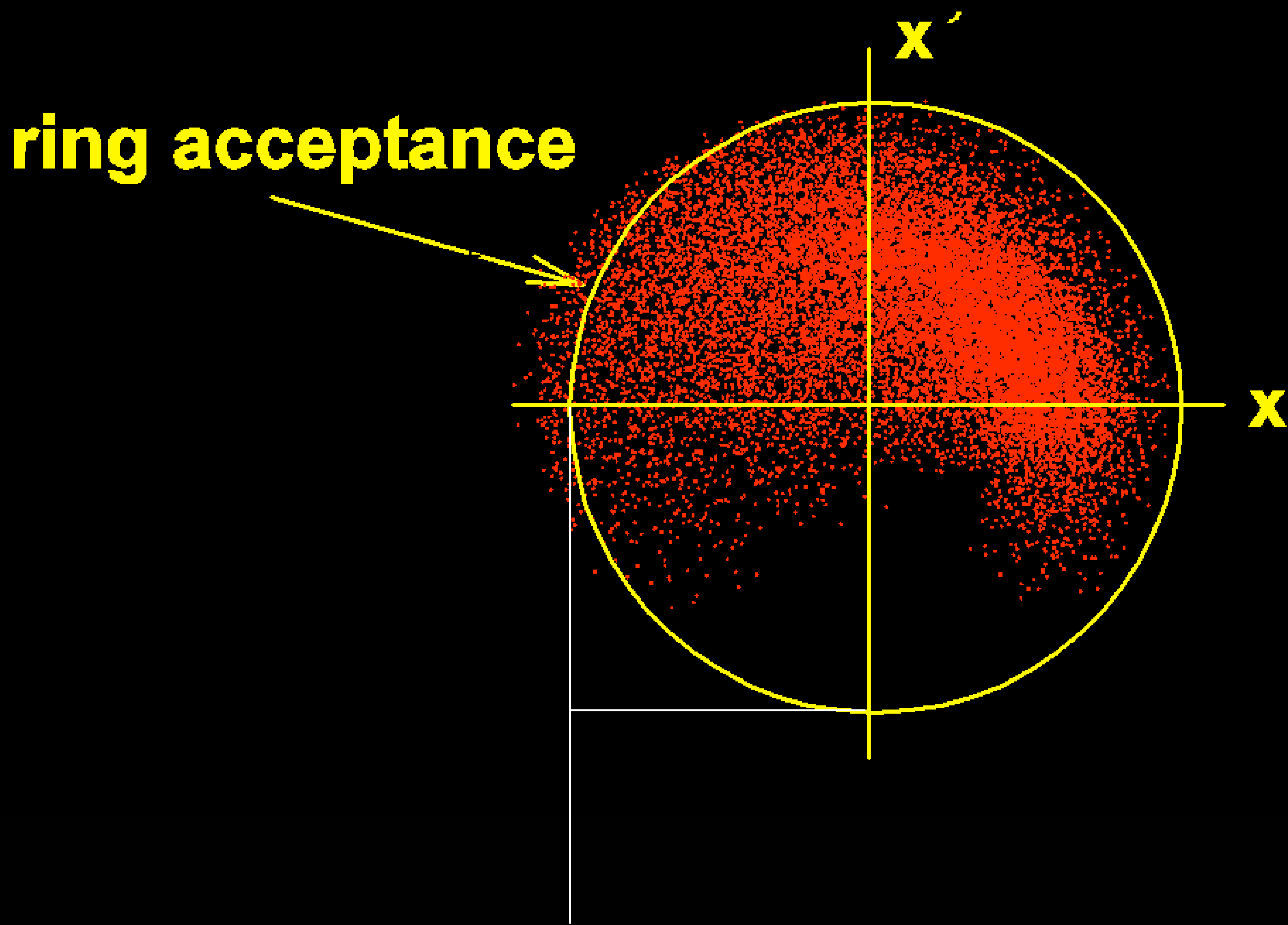
The Kick

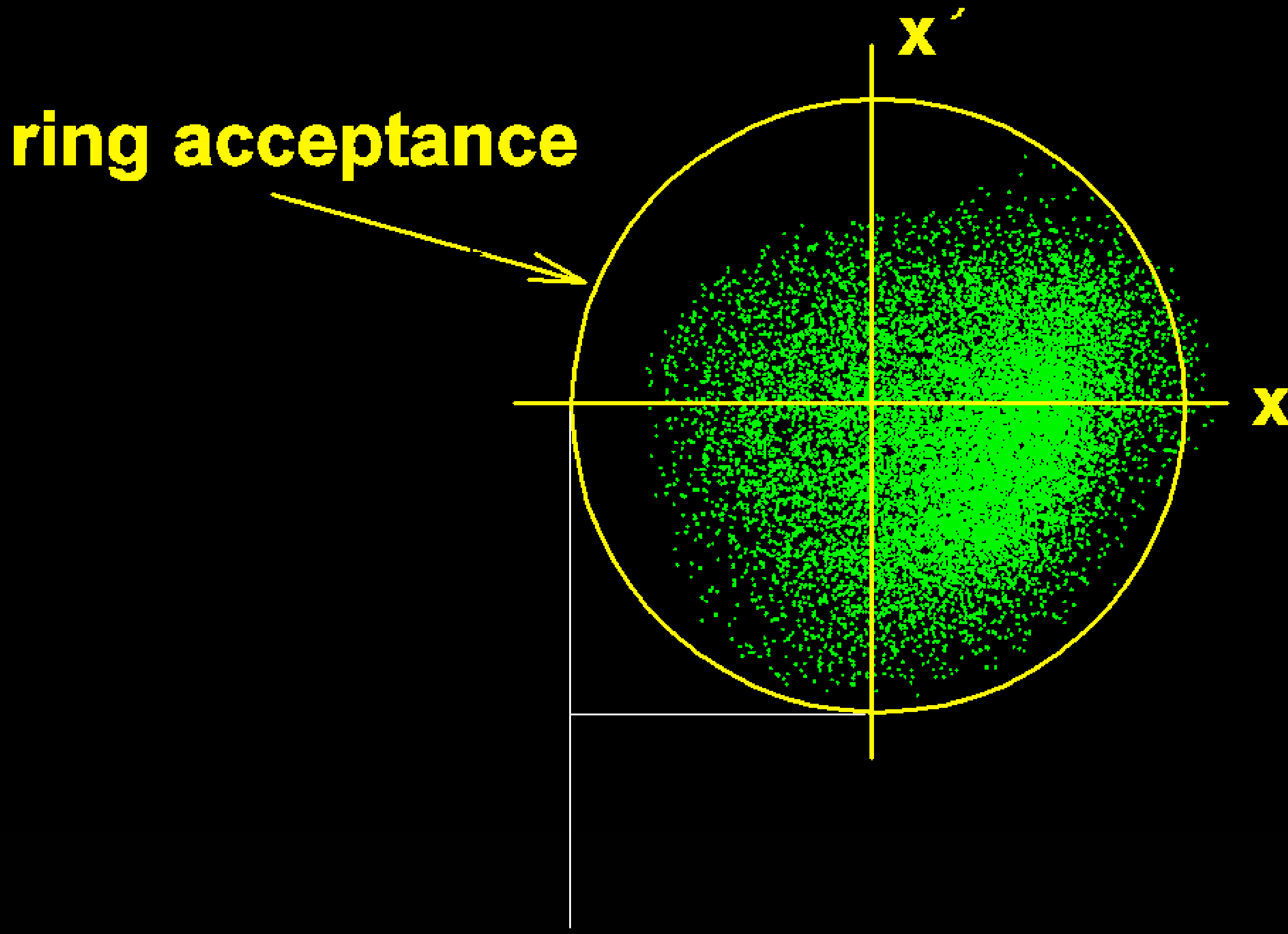


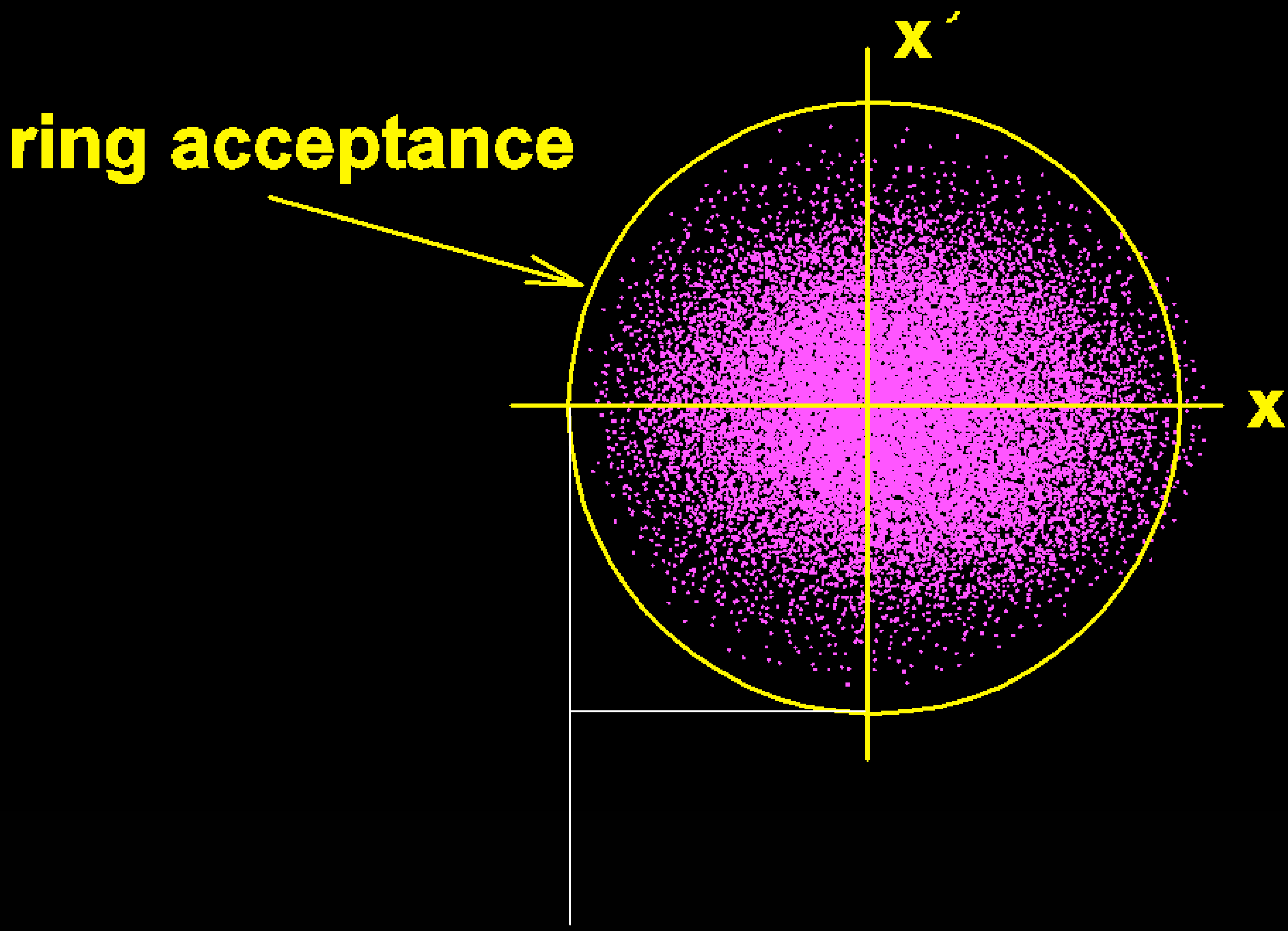
Horizontal (radial) Phase Space
x′
77mm
ring acceptance
Beam exiting the inflector
x
stored beam
Ideal kick

Injection Simulation

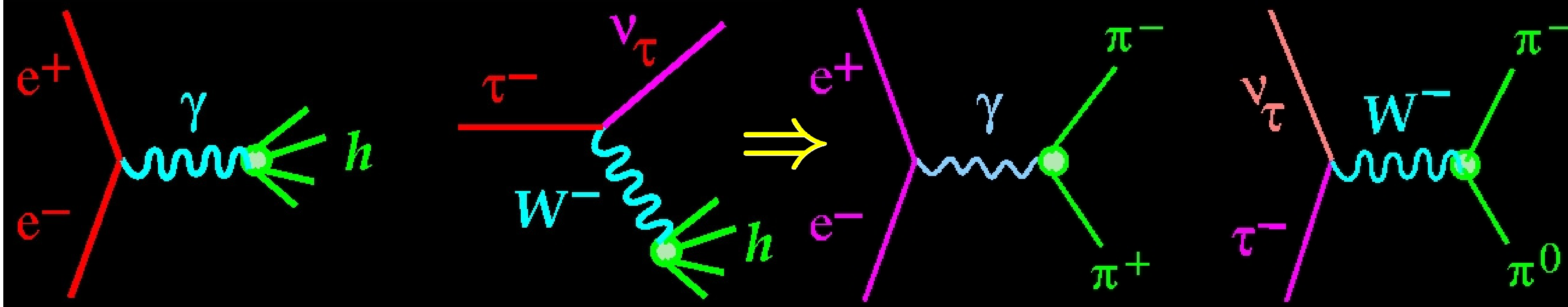



ring acceptance
x´
x


ring acceptance
x´
x


ring acceptance
x´
x

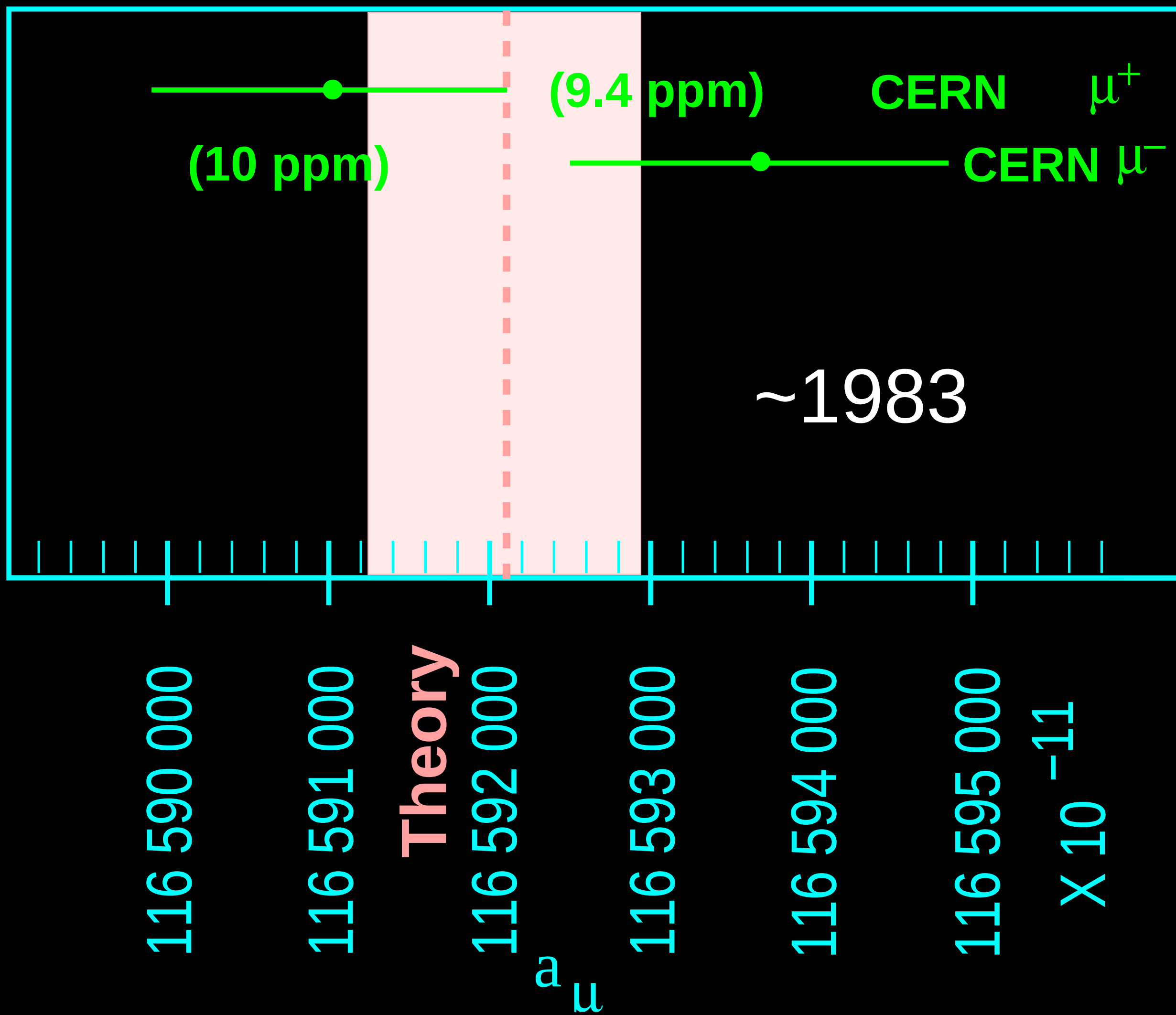
a(had) from hadronic τ decay?



- Assume: CVC, no 2nd-class currents, isospin breaking corrections.
- n.b. τ decay has no isoscalar piece, while e^+e^- does
- Many inconsistencies in comparison of e^+e^- and τ decay:
  - Using e^+e^- data and CVC to predict τ branching ratio gives 2.1 to 3.6 σ discrepancies with reality.
  - F_π from τ decay has different shape from e^+e^-.

In summary, there are unanswered questions from the τ data.

Where we came from:

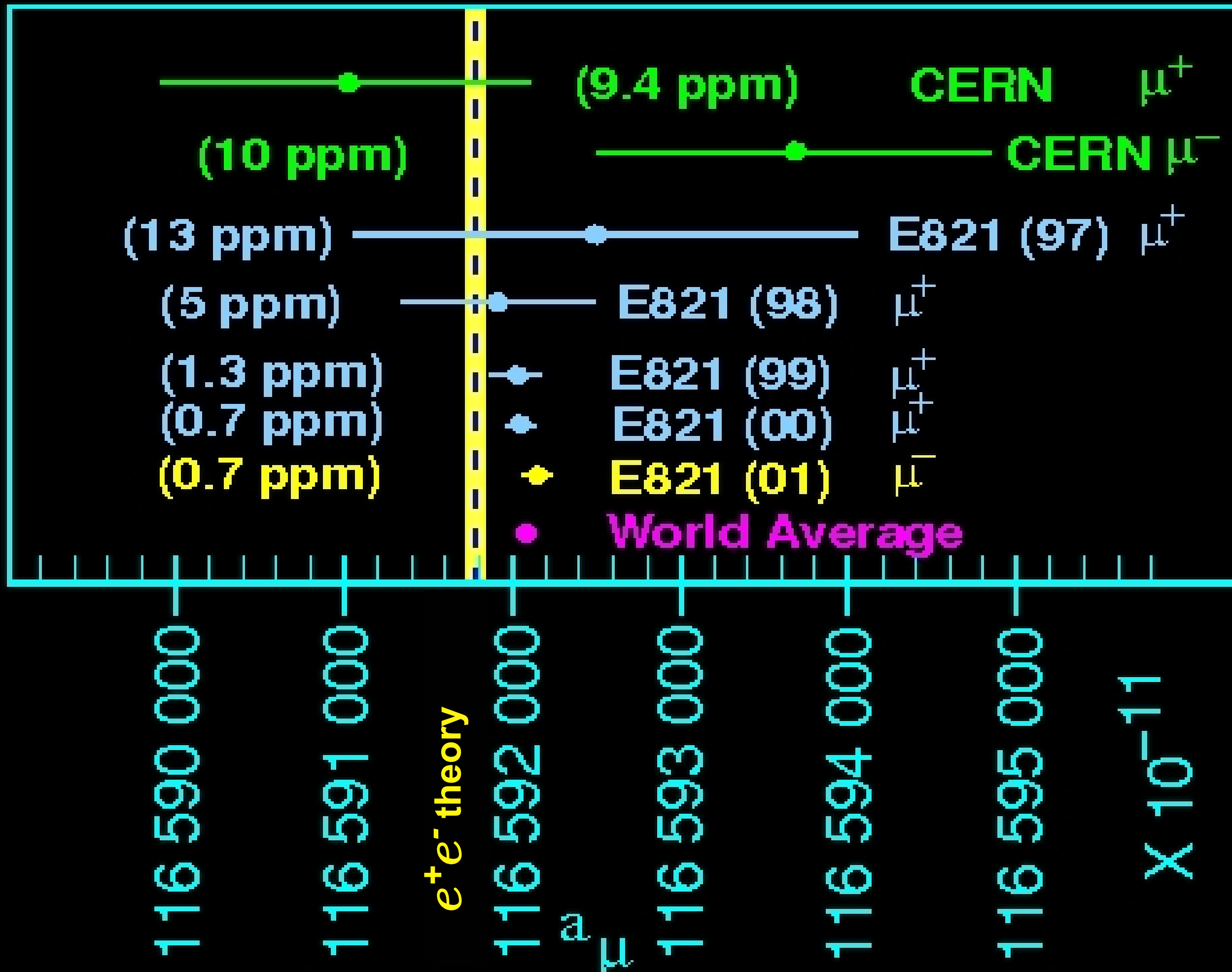


Today with e^+e^- based theory:

All E821 results were obtained with a “blind” analysis.

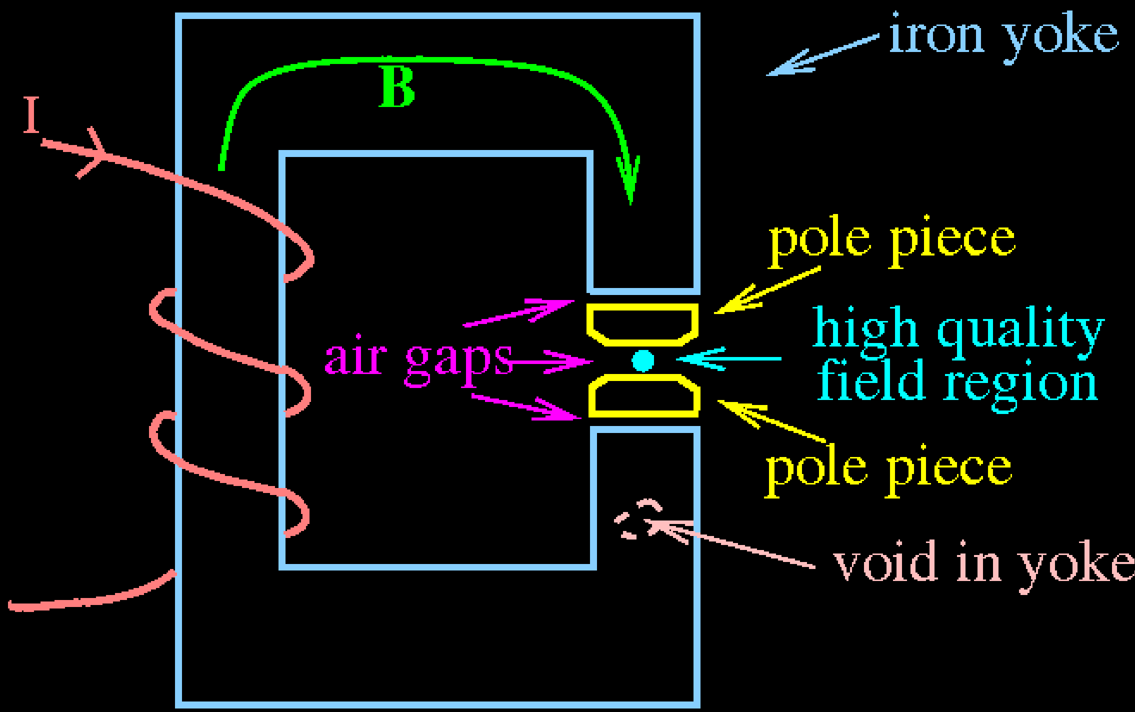
$\sim 3.6\sigma$ difference wi[t]

e^+e^- SM val[u]



$$a_\mu = 116\,592\,089(63) \times 10^{-11} \ (0.54\,\text{ppm})$$

Magnetic Circuits



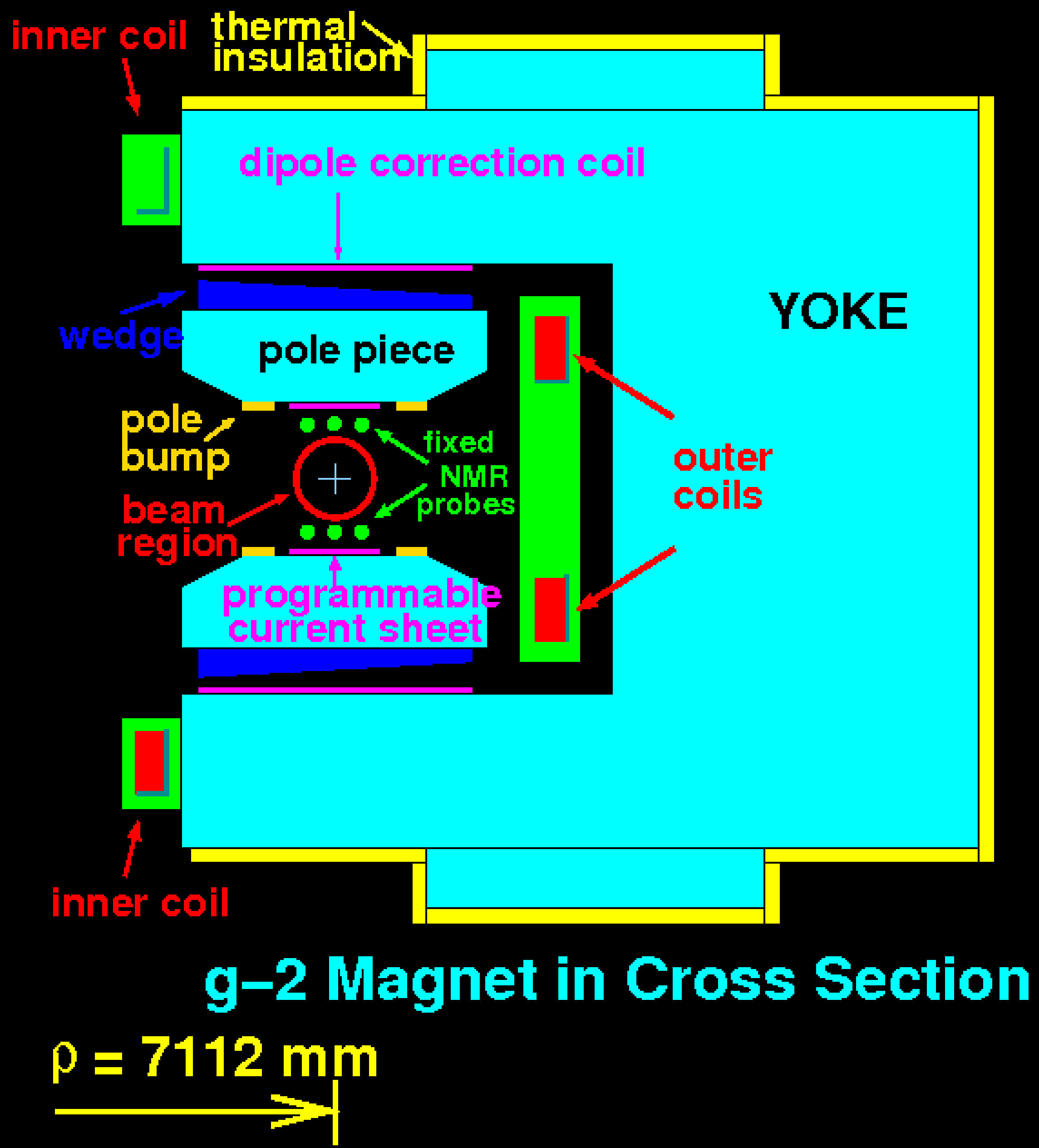
$\mu_{air} = 1$

$\mu_{steel} \sim 10^6$

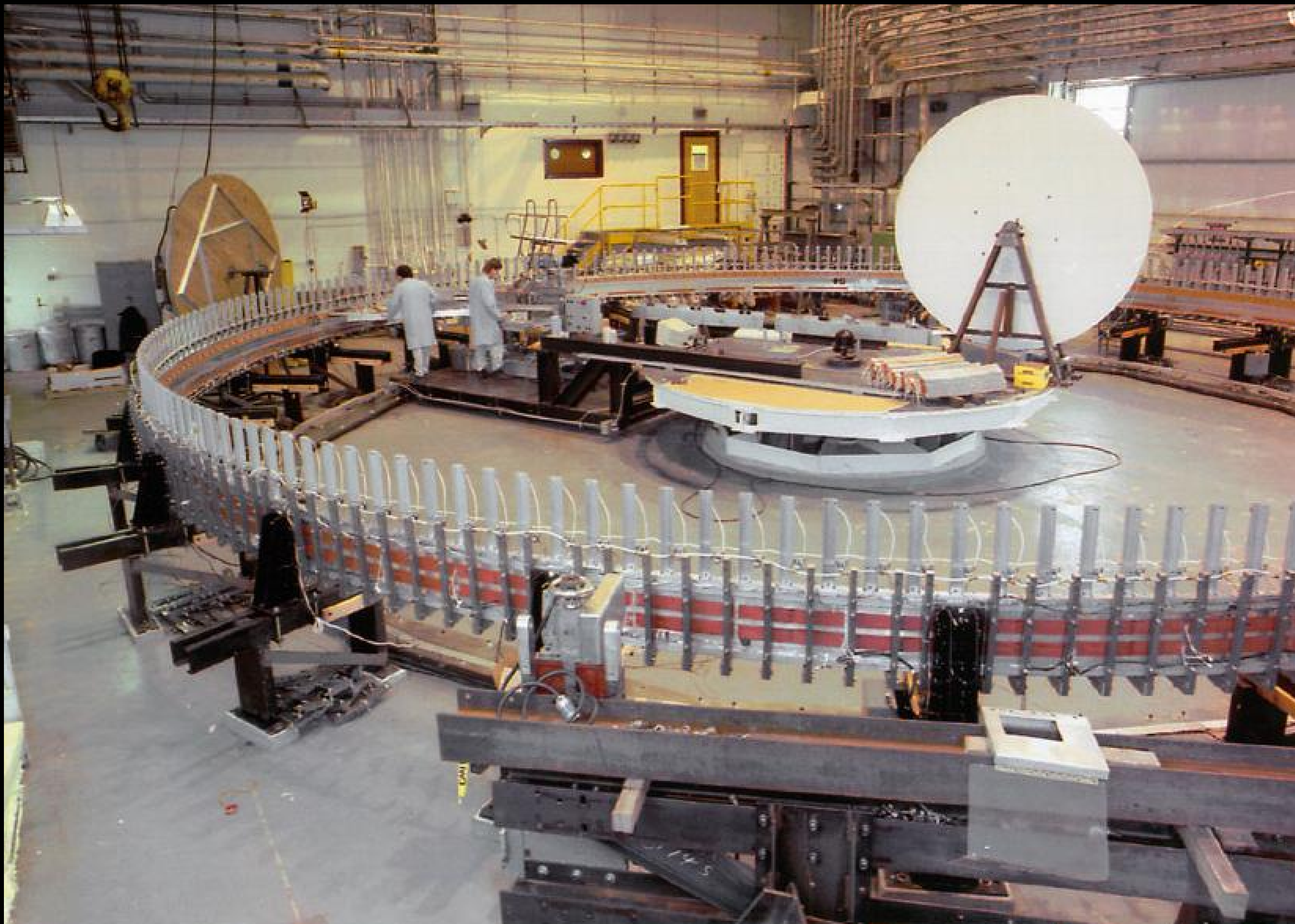
$$\Phi \oint \frac{d\ell}{\mu A} = NI \qquad \Phi \Re = MMF$$

Ohm's law

Schematic of the Magnet



Winding the Coils



The Finished Coils

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Coil Interconnect