The New Muon g-2 Experiment at Fermilab

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Measurement

- Anomalous magnet moment of muon measured in BNL E821 (2001) to be

a_μ = 116592089(54)$_{stat}$(33)$_{sys}$ ×10^{-11}

[± 0.54 ppm]

[a_μ = (g-2)/2]

Standard Model Calculation

- At ~ ppm level all standard model particles contribute to the magnetic moment

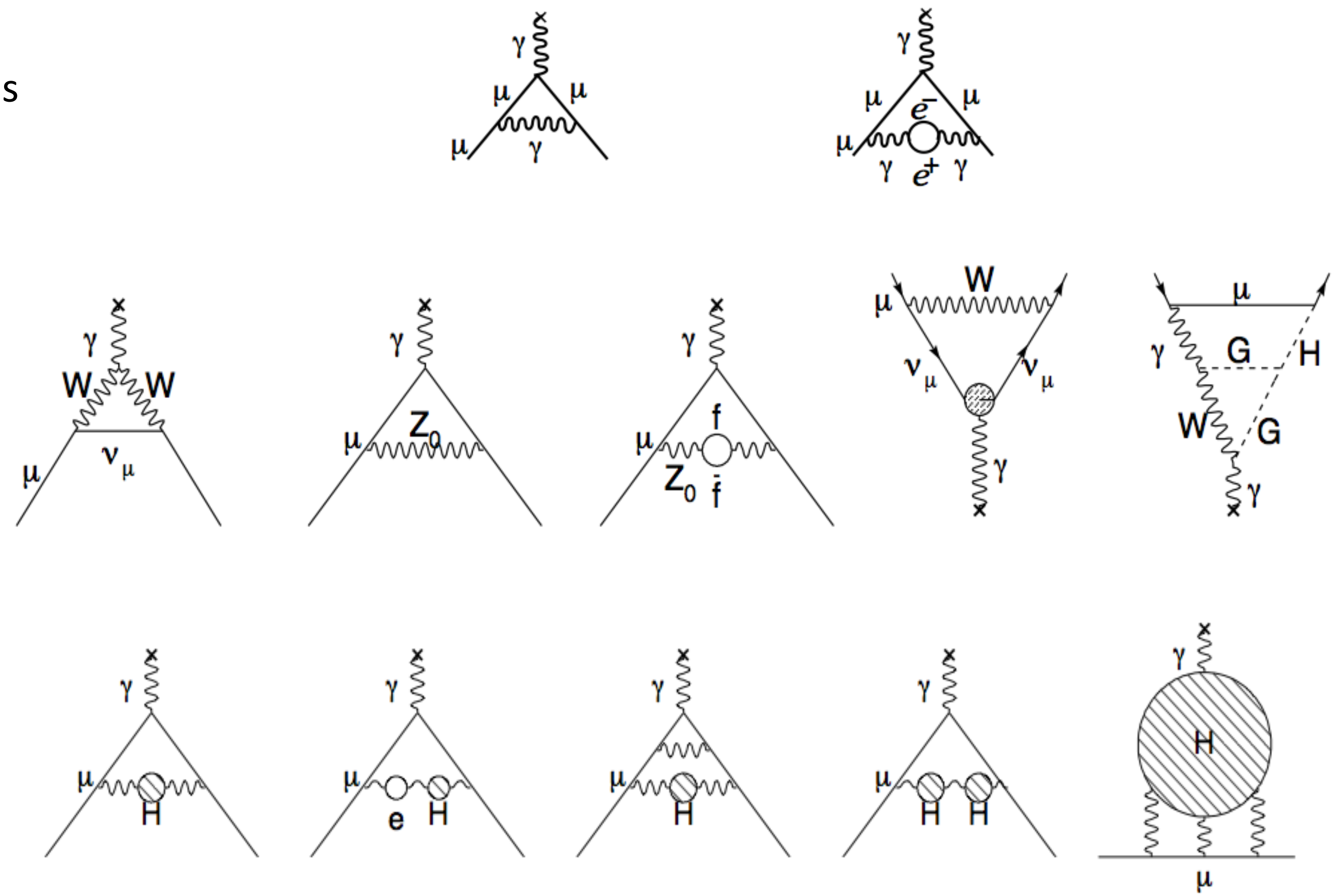
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{hadronic} + a_\mu^{weak}$$

$a_\mu = (g-2)/2$ includes contributions from all standard model particles

QED to 5 loops

Electroweak

QCD



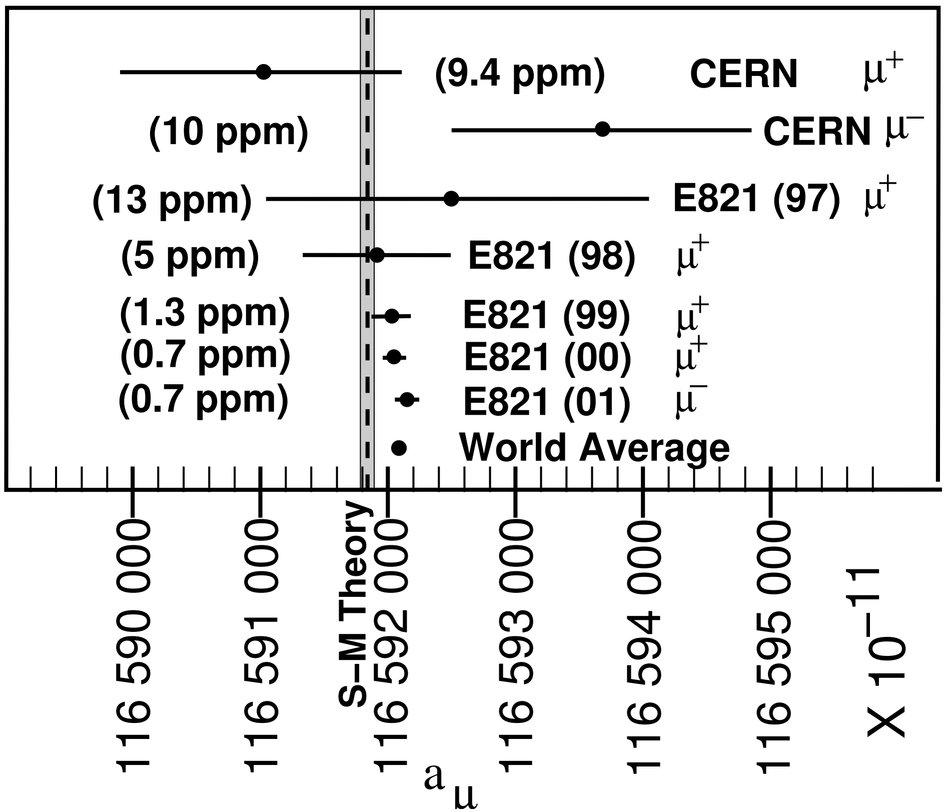
Hadronic vacuum polarization

Hadronic light by light

Contributions to g-2

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_{\alpha}$
HVP(lo) [47]	$6\,923 \pm 42$
HVP(lo) [48]	$6\,949 \pm 43$
HVP(ho) [48]	-98.4 ± 0.7
HLbL [61]	105 ± 26
EW [54]	153.6 ± 1.0
Total SM [47]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [48]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 45_{\text{tot}})$

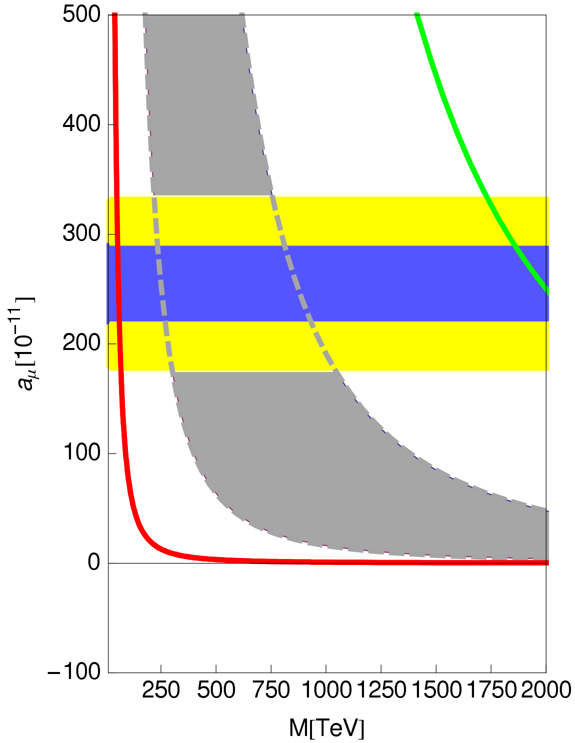
Status of Muon g-2 measurement



Δa_μ (E821-SM)=(261/287±80) × 10^{-11} => 3.3/3.6 standard deviations

Statistical fluctuation or new physics

$$\delta a_\mu(\text{N.P.}) = \mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2, \quad C = \frac{\delta m_\mu(\text{N.P.})}{m_\mu}$$



$\mathcal{O}(1)$	radiative muon mass generation … [Czarnecki,Marciano '01]
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry ($\tan\beta$), unparticles [Cheung, Keung, Yuan '07] extra dim. (ADD/RS) (n_c)… [Davioudasl, Hewett, Rizzo '00] [Graesser,'00][Park et al '01][Kim et al '01]
$\mathcal{O}(\frac{\alpha}{4\pi})$	Z', W', UED, Littlest Higgs (LHT)…

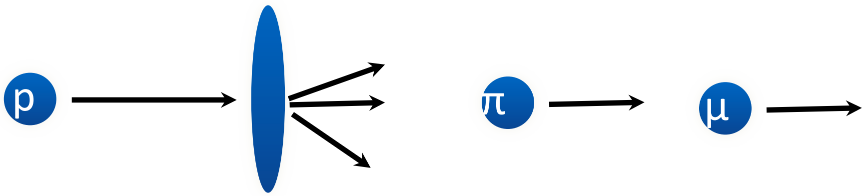
New muon g-2 experiment

- Goal reduce total uncertainty (statistical and systematic combined) 4-fold to < 0.14 ppm
- If the present discrepancy is a statistical fluctuation, and the measurement is consistent with the standard model, a variety of BSM physics is ruled out.
- If the discrepancy persists with the reduced uncertainty, then new physics, and somewhat constrained

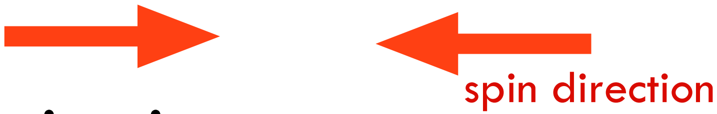
Repeat BNL experiment with more statistics and reduced systematics

Create a beam of polarized muons

- Production: Muons from $\pi^+ \to \mu^+ \nu$ are polarized



$$\nu \leftarrow \pi^+ \rightarrow \mu^+$$



97% polarization

- Inject the polarized muons into uniform magnetic field – a storage ring

Muons circulate in the B-field

Muon cyclotron frequency for particle of charge "e" in a B field

$$\omega_c = \frac{eB}{m_\mu c\gamma}$$

Muon spin precession rate

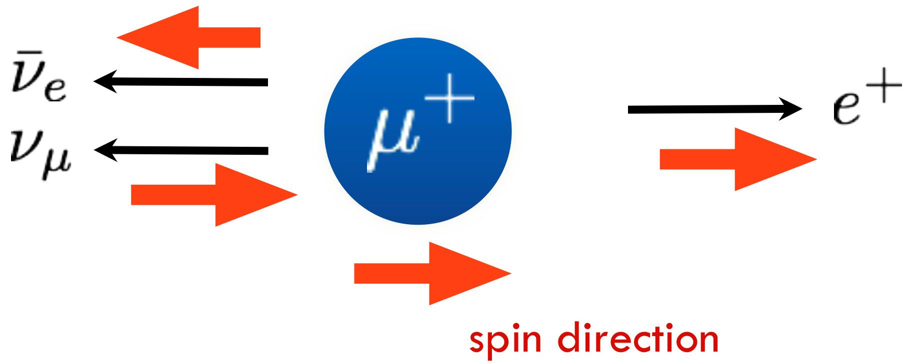
$$\omega_s = \frac{g_\mu eB}{2m_\mu c} + (1-\gamma)\frac{eB}{m_\mu c\gamma}$$

Larmor precession

Thomas precession

Muons circulate and decay to positrons

$$\mu^+ \rightarrow e^+ \nu_\mu \bar{\nu}_e$$

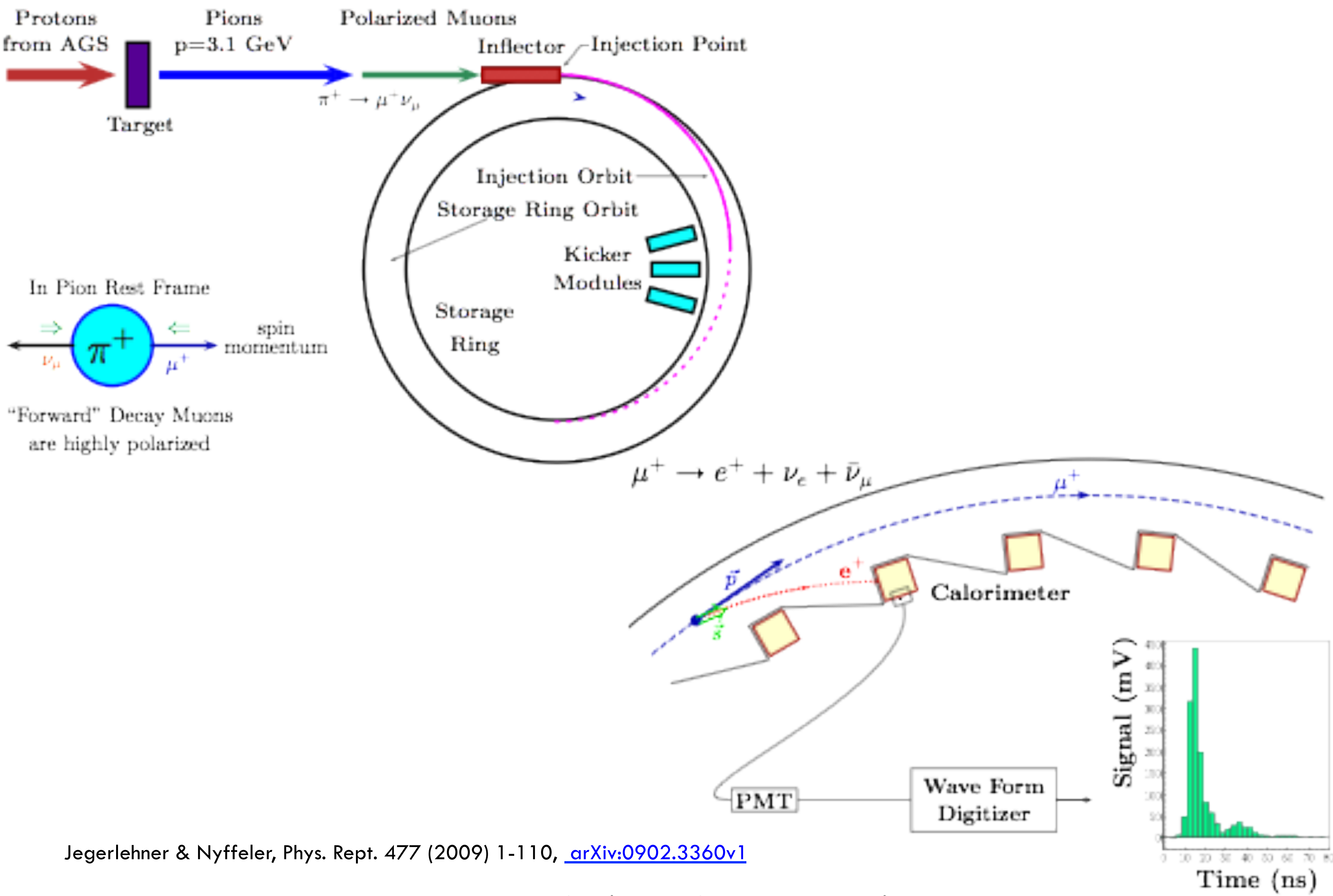


Highest energy positrons emitted along muon's spin direction (in Muon center of mass frame)

Energy of decay electrons is correlated with spin of muons

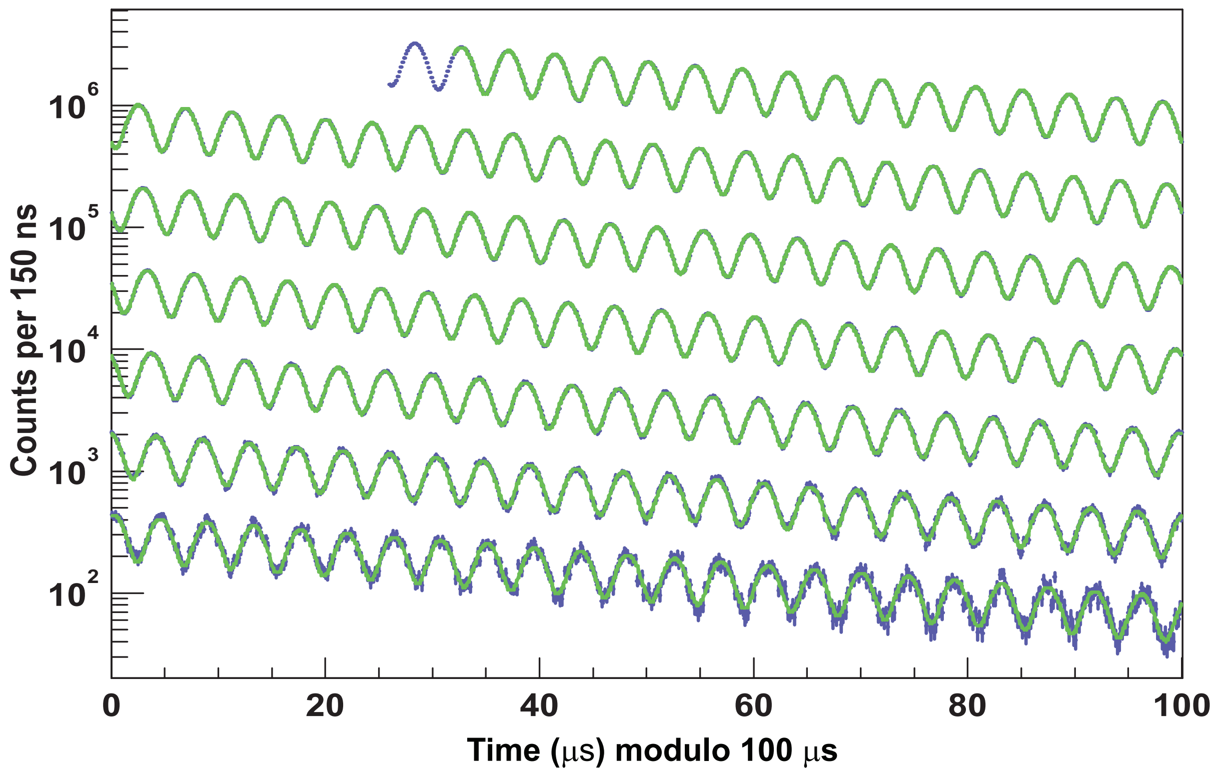
The number of high energy decay electrons will oscillate with frequency ω_a

Schematic of Experiment



Jegerlehner & Nyffeler, Phys. Rept. 477 (2009) 1-110, [arXiv:0902.3360v1]

Measurement of ω_a



High energy positrons vs time for 700 us run

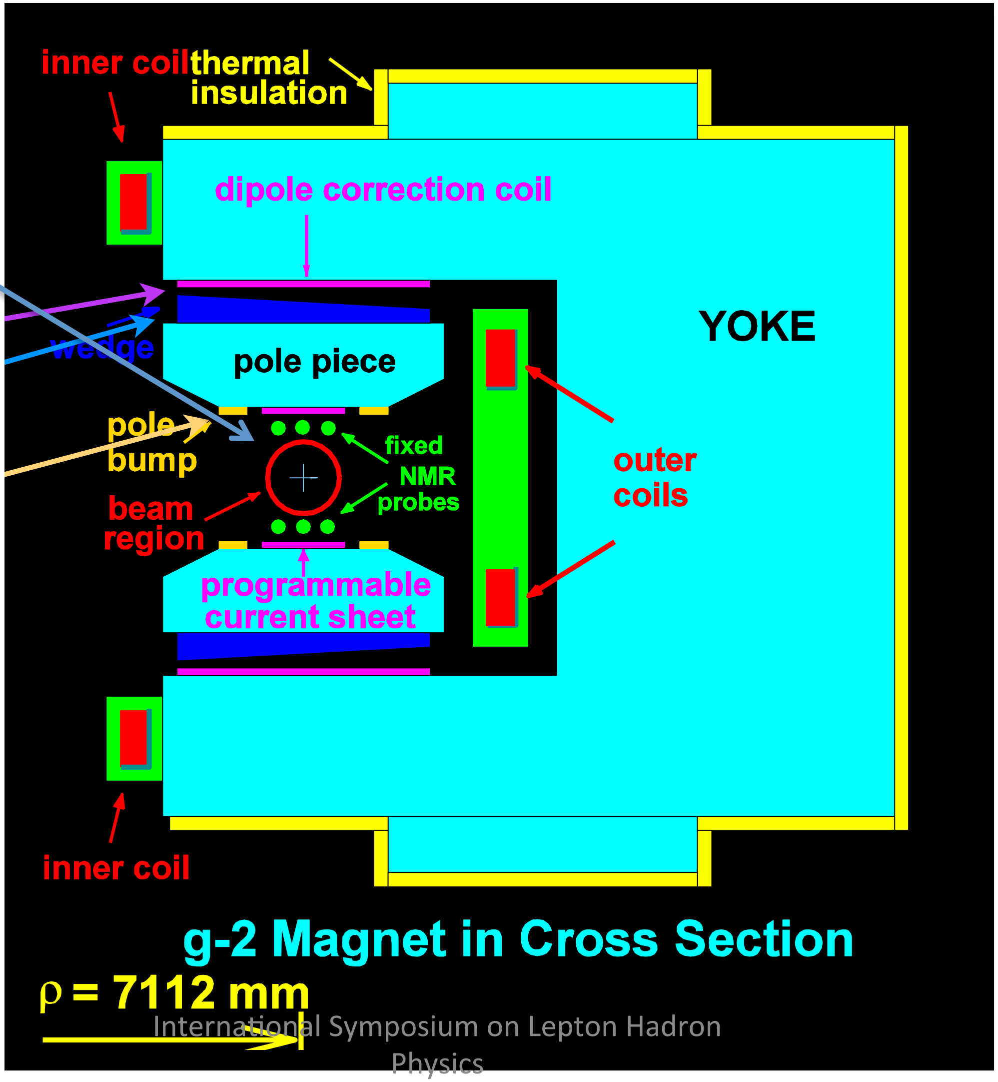
Precision B-field

Storage volume
10 cm diameter

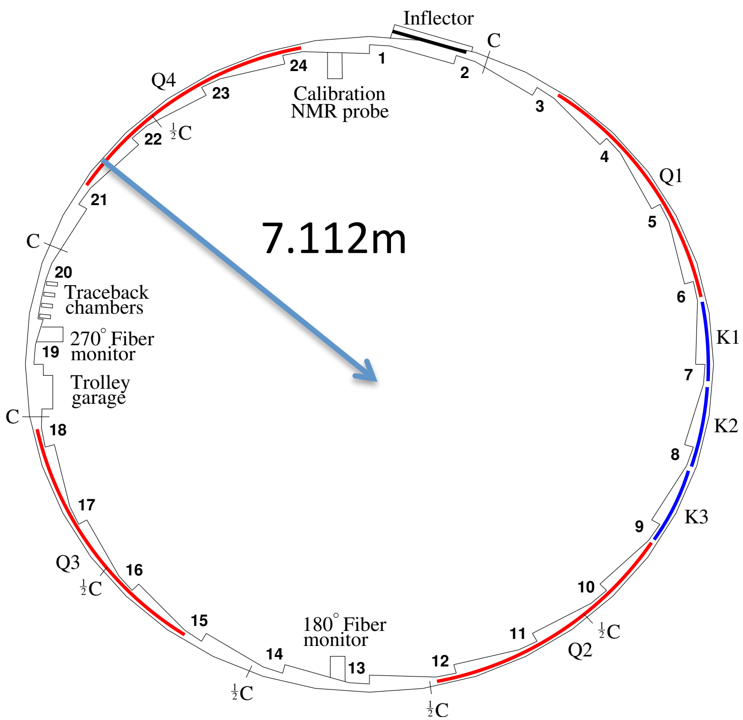
Dipole
Quadrupole

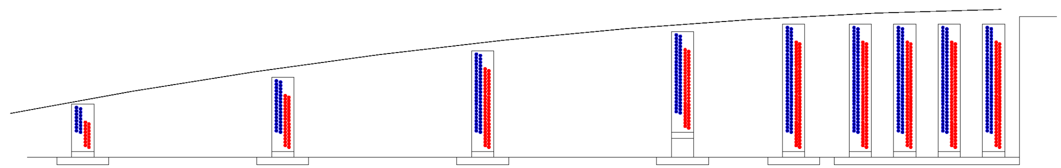
Sextupole

~1 year to shim to
0.07 ppm uniformity



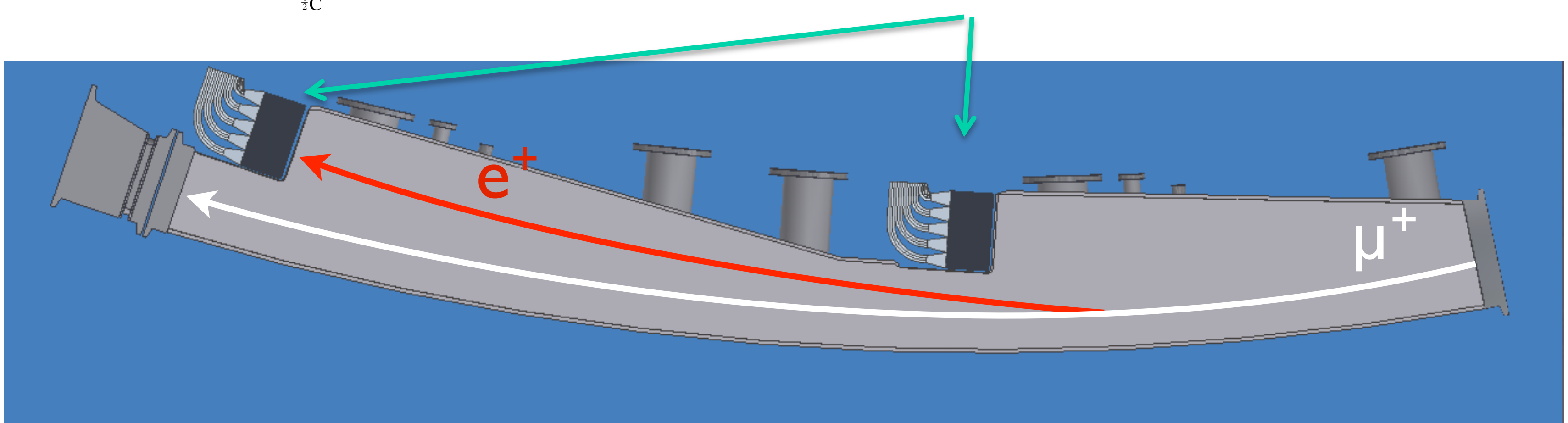
Storage Ring and Detectors





Straw tubes in front of two PbF_2 calorimeters track positrons => muon EDM tips precession out of plane of B-field

Calorimeters segmented to reduce pileup



$$\omega_a = a_\mu \frac{eB}{m_\mu c}$$

To extract a_μ need to know the magnetic field B
B is measured in terms of precession of free protons in the same B field as muons

We can write
$$a_\mu = \frac{\omega_a}{\omega_L - \omega_a}$$

ω_p from NMR probes

And then
$$a_\mu = \frac{\omega_a/\omega_p}{\omega_L/\omega_p - \omega_a/\omega_p} = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

Ratio of magnetic moments from muonium hyperfine measurement (30 ppb)

Vertical focusing

In a perfectly uniform B-field, there is no stable orbit. Particles stray from the plane of the orbit. In order for particles to circulate for 4500 turns require focusing

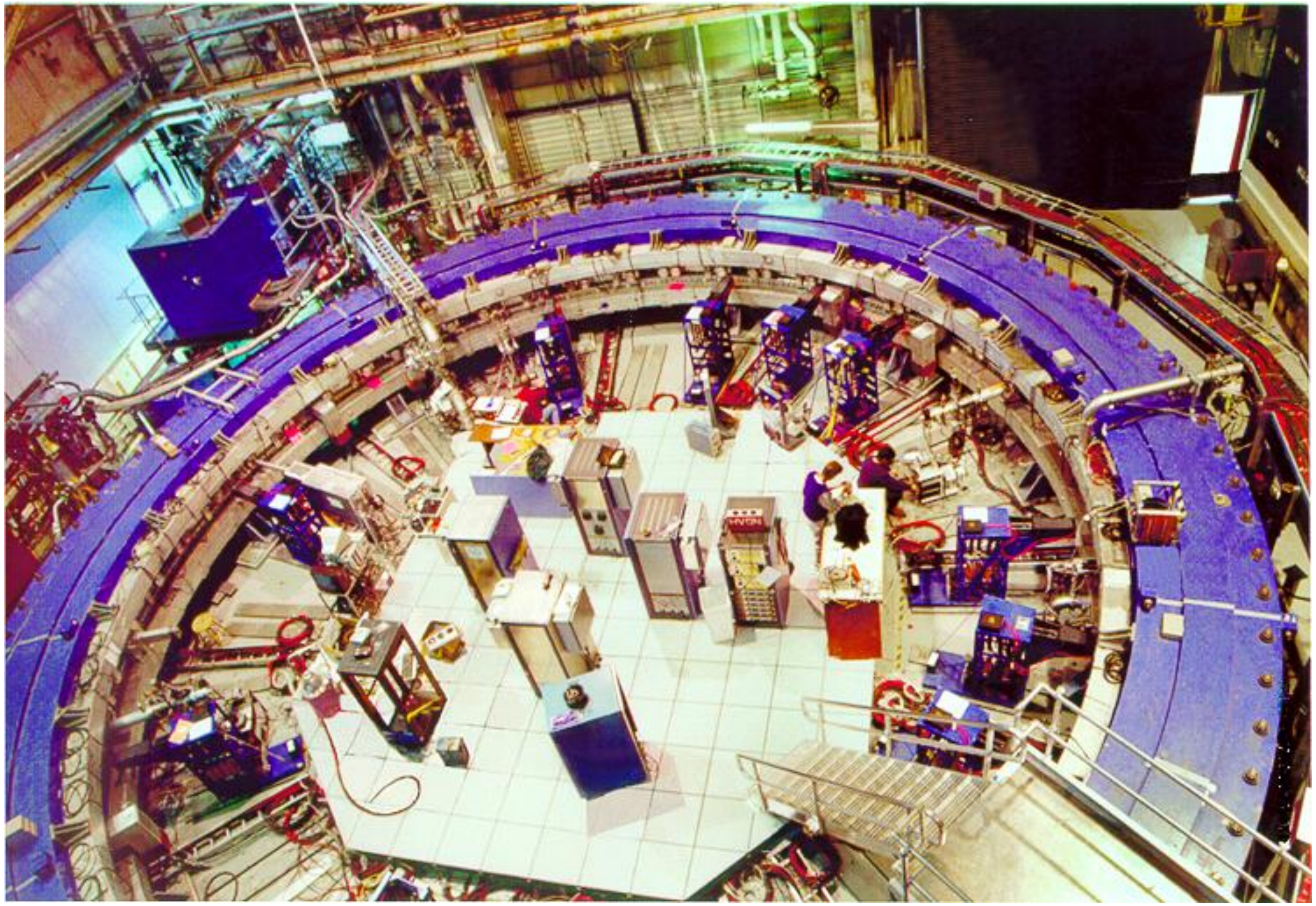
- Magnetic focusing is precluded as the field would no longer be uniform and it would be difficult to extract a_μ
- ? Electrostatic focusing?

$$\vec{\omega_a} = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

If ϒ = 29.3 and p_μ = 3.09GeV/c, no effect on ω_a => magic momentum
B = 1.45T => R = 7.112 m

Electrostatic quadrupoles are used to vertically focus the muons
⇒ Very weakly focusing storage ring

G-2 storage ring at BNL



Moving the ring from Brookhaven to Fermilab

The hard part is moving the three superconducting coils

Continuously wound coils, can't break into pieces - can't flex > 3mm

They're big!
50 ft diameter
(takes up ~ 4 lanes on the highway). Not terribly heavy at 15 tons

Traversing Brookhaven National Lab

Photo: Brookhaven

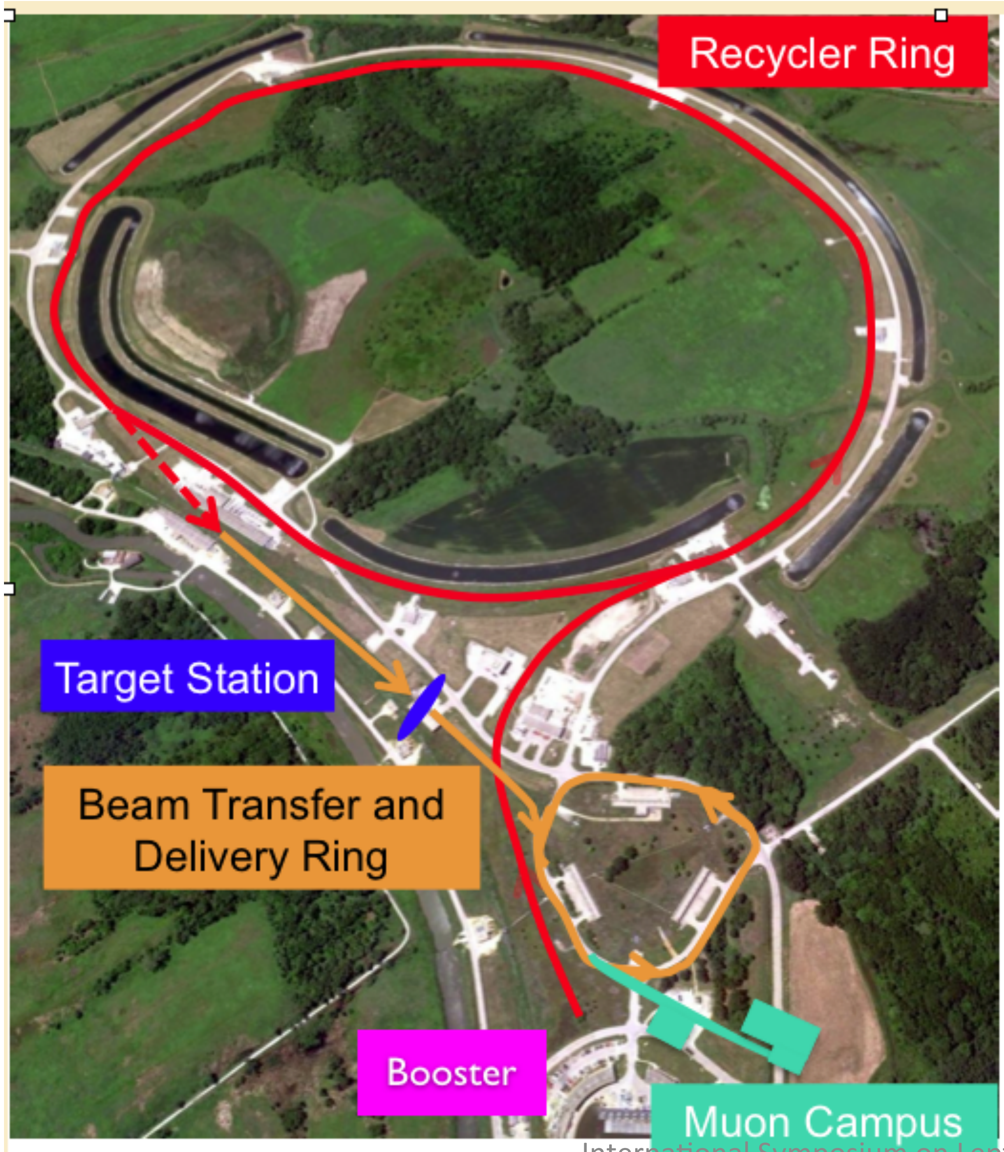
Off it goes

Photo: Brookhaven/Emmert

off the barge in Illinois

Wednesday night, on the Tollway

Fermilab Beam Improvements



`Recycler Ring'

Splits each Booster Batch into 4 smaller batches 8-12 msec apart, each 100 nsec wide. (reduces instantaneous rate)

Target Station

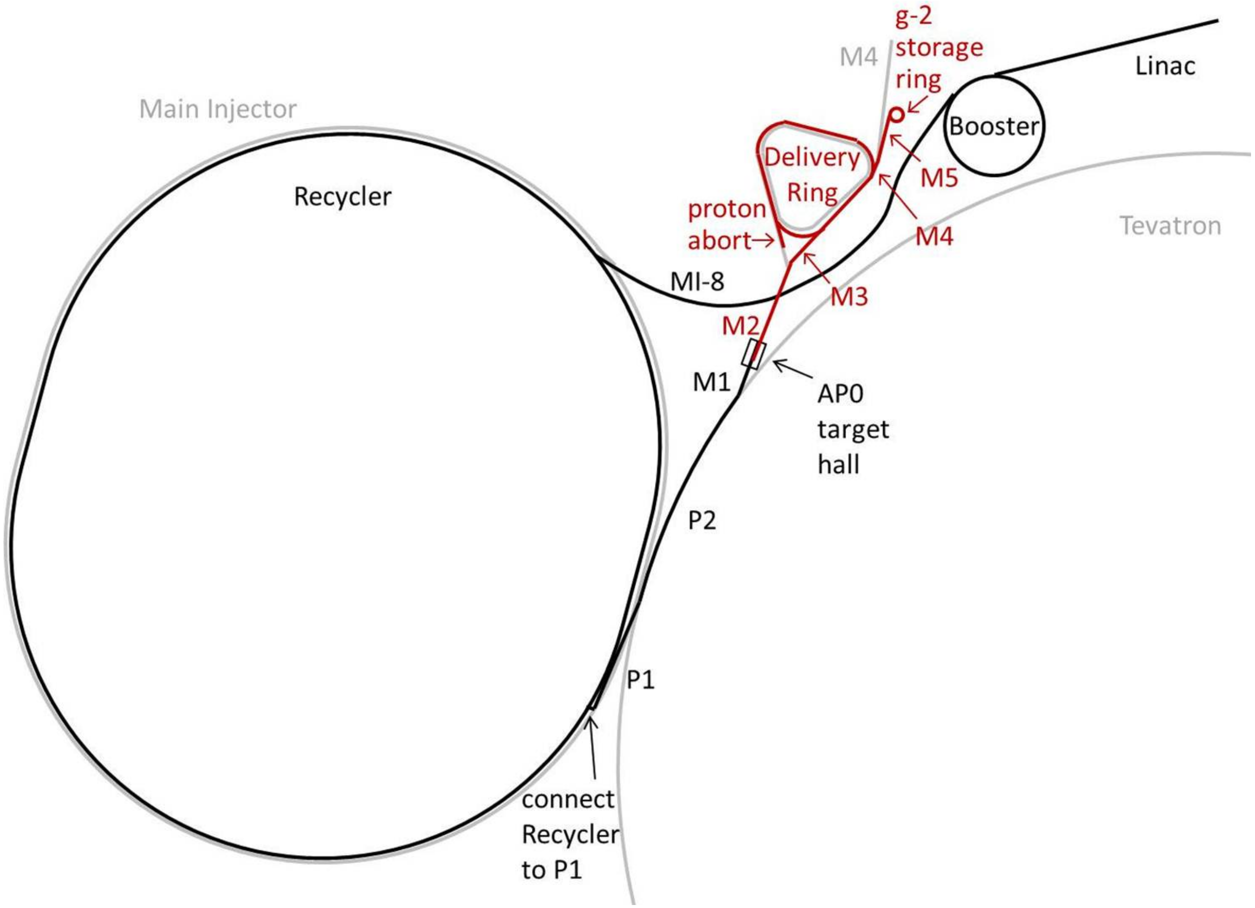
Reuse "Lithium Lens" that was used to make antiprotons

Longer pion decay channel
Larger Acceptance

`Antiproton Accumulator and Debuncher'

Additional decay line
Time-of-flight separation of background protons.

Muon production

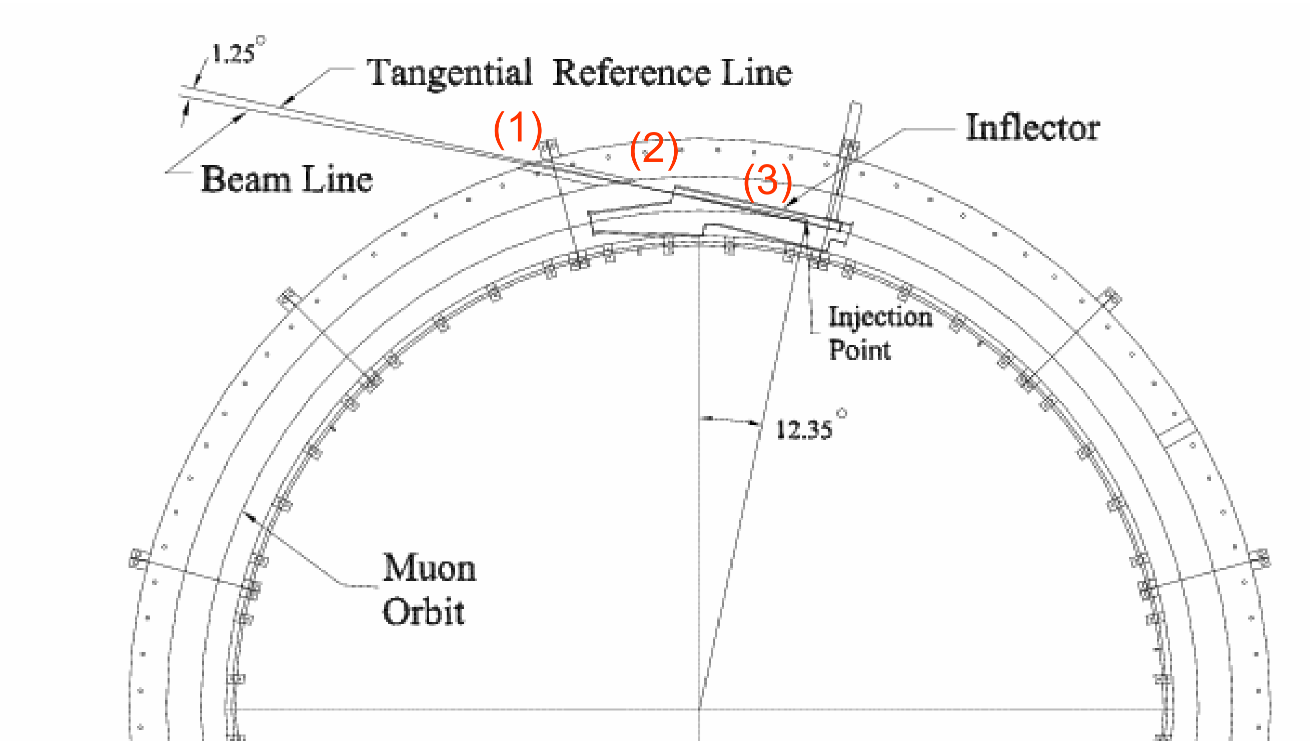


The Destination (2014)

`Muon Campus'

New building for g-2

How do twiss parameters propagate through iron, cryostat, inflector into ring

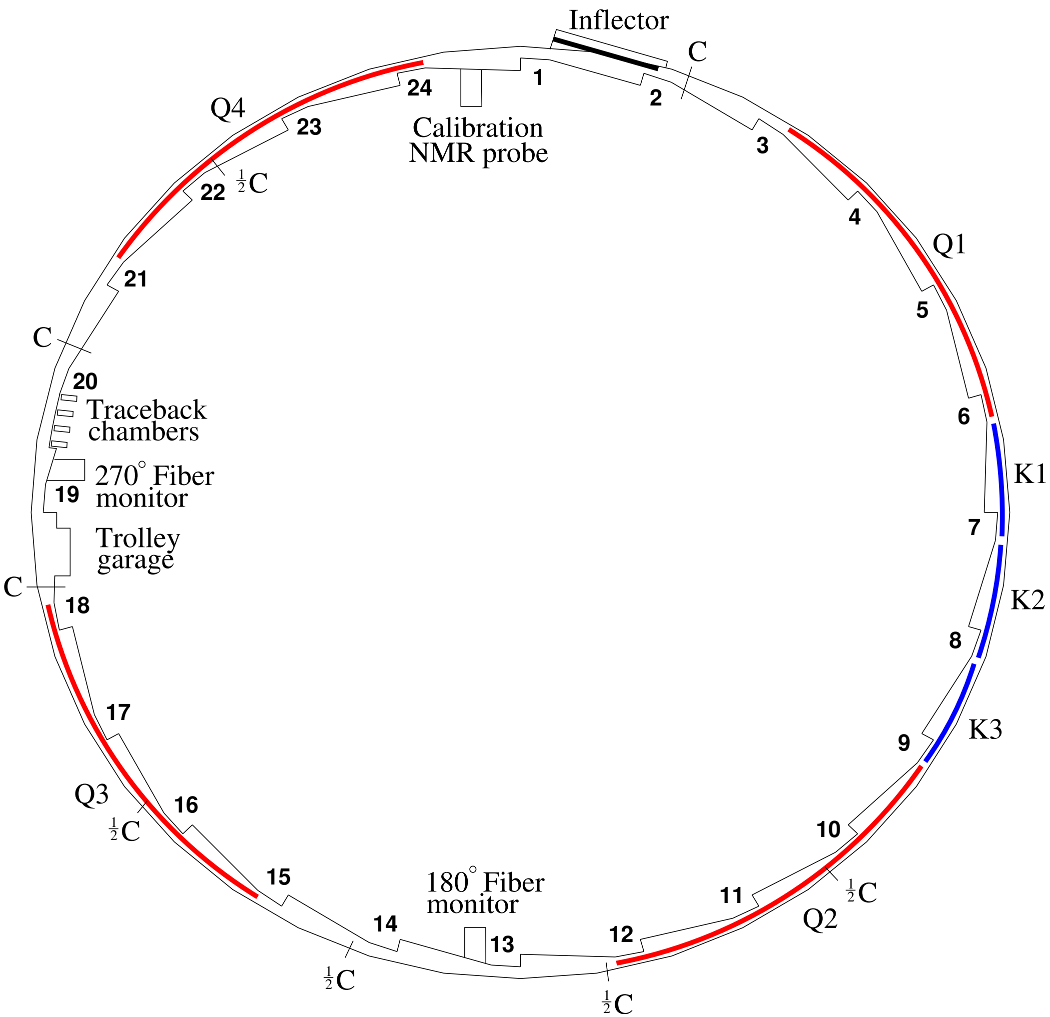


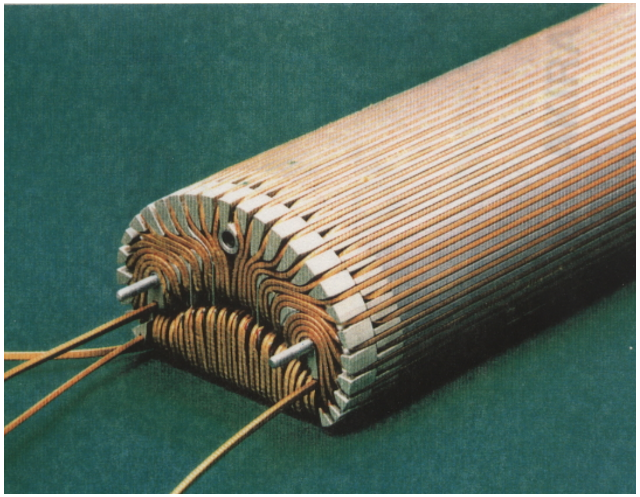
(1) hole in back leg, (2) storage ring fringe field, (3) inflector channel

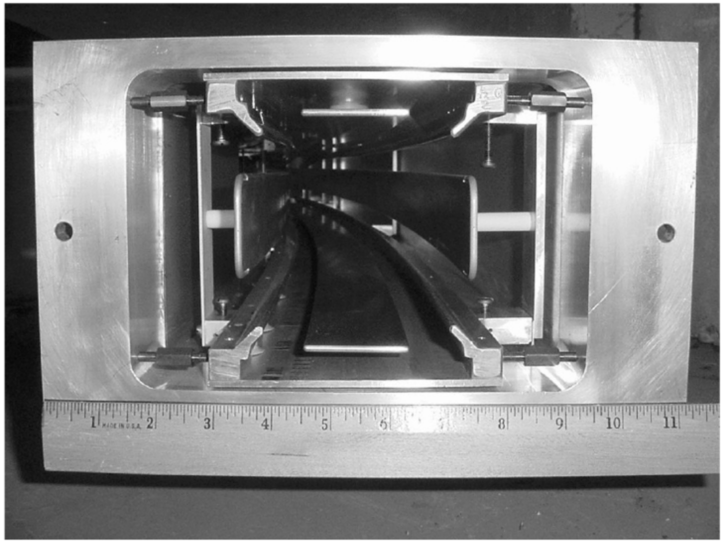
Beam through inflector is tangent to magic radius
displaced 77 mm from the center of the storage region

Internally Inflector cancels main dipole field

Muon storage ring







Electrostatic quadrupole in vacuum chamber

Storage Ring Kicker

Kickers steer injected muons onto the ring closed orbit

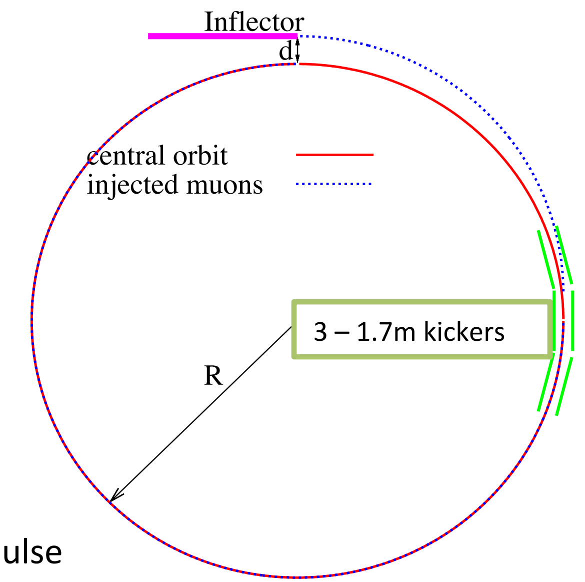
Requirements:

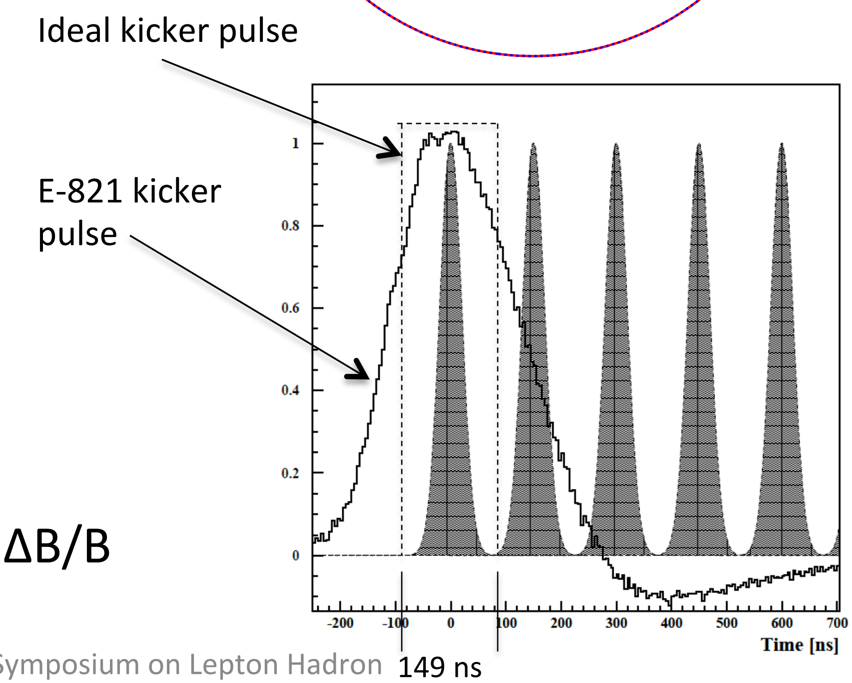
Kick angle ~ 14 mrad
Kicker B-field ~ 280 Gauss
Integrated B-field ~ 1.4 kG-m

Pulse width(τ)
80ns < τ < 149ns

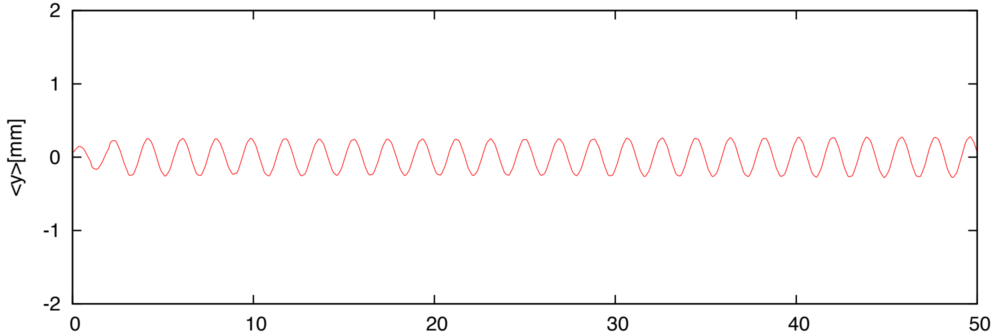
Repetition rate ~100 Hz

Field uniformity over storage volume ΔB/B < 10%

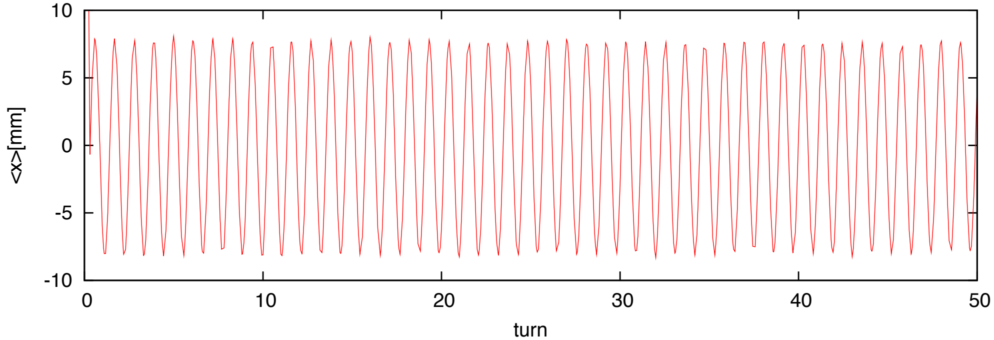




Coherent oscillations of centroid of imperfectly matched beam

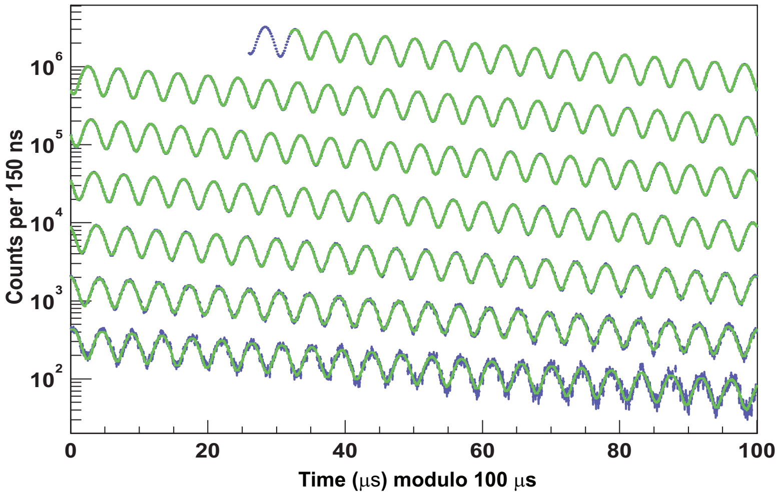


vertical



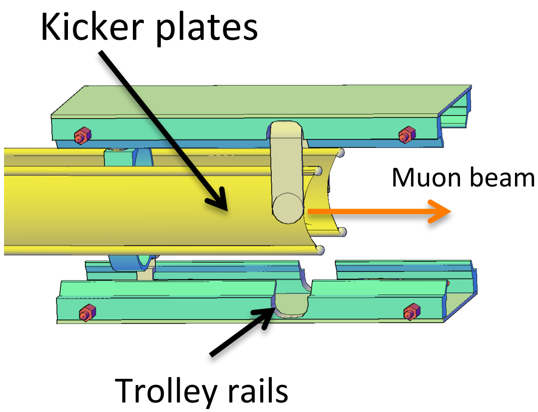
horizontal

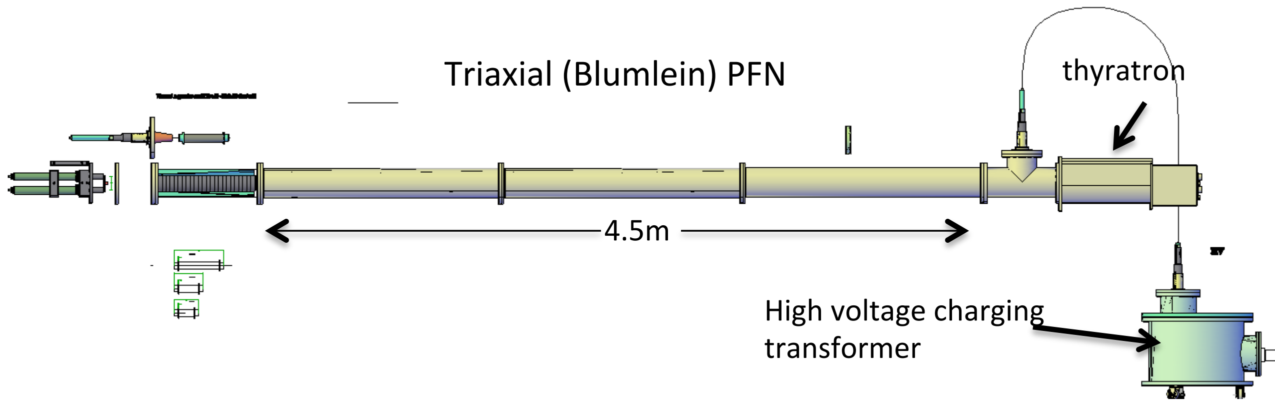
Decay positrons



If frequencies are related, beam oscillations systematically effect acceptance of decay positrons and measure of ω_a

Reduce oscillations (better kicker)
Shift tune away from ω_a (stronger focusing)

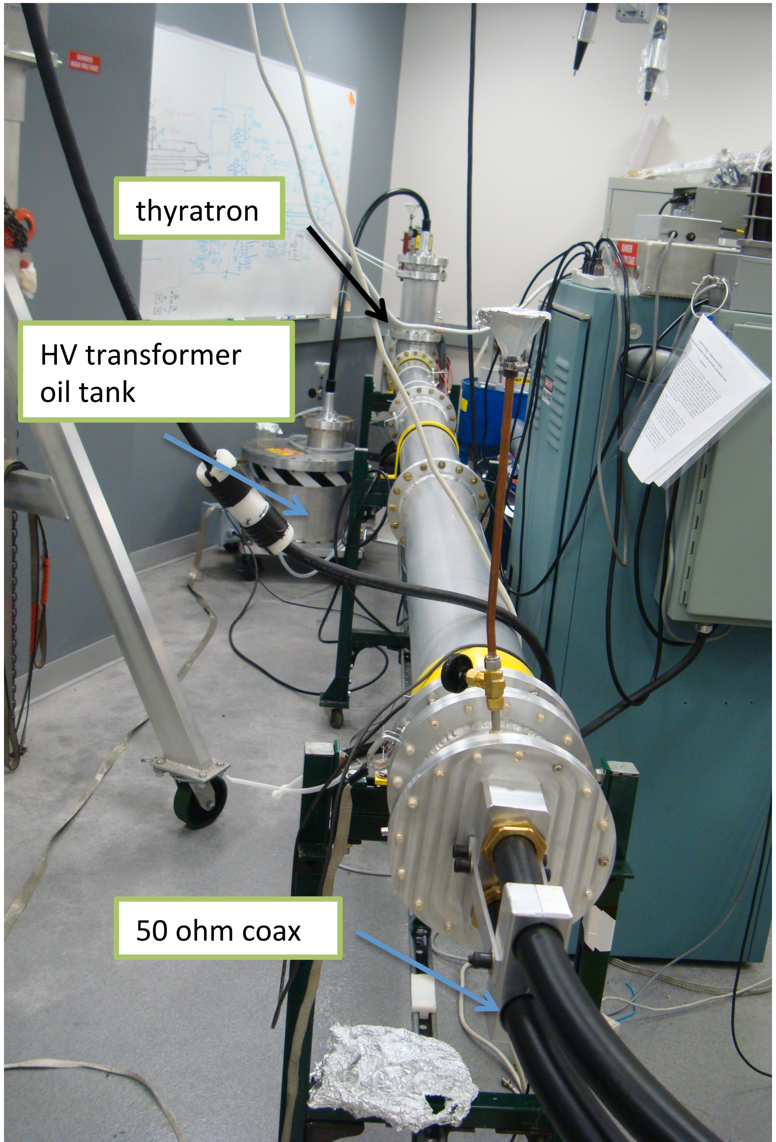


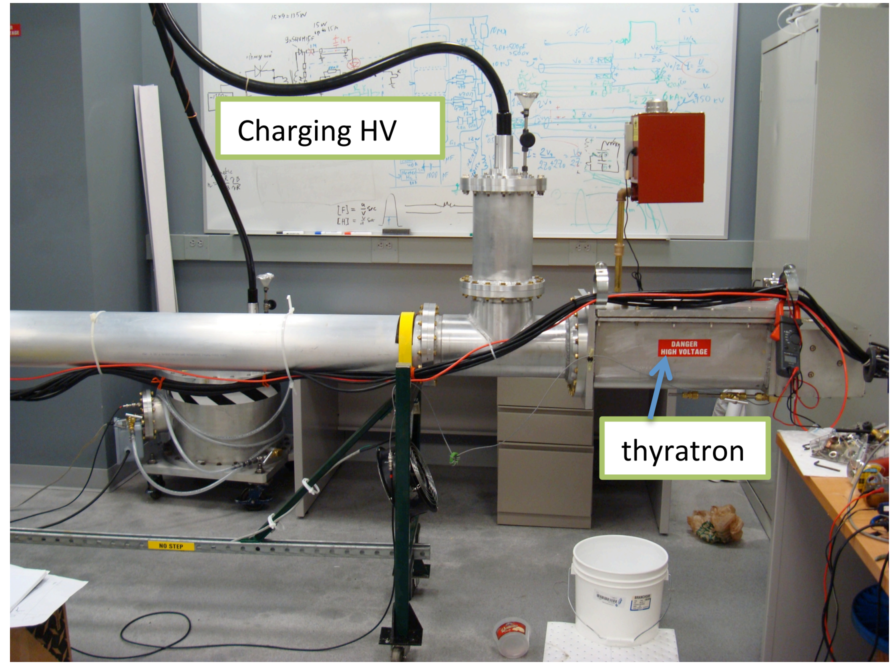


Transmission line Pulse Forming Network

Ring Injection Kicker

Kicker System – Blumlein PFN

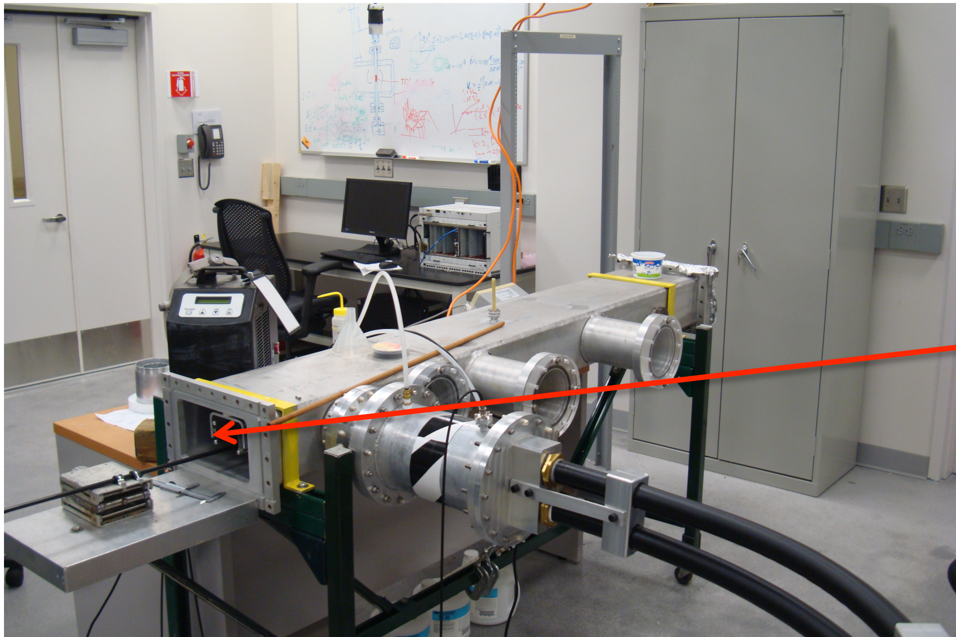


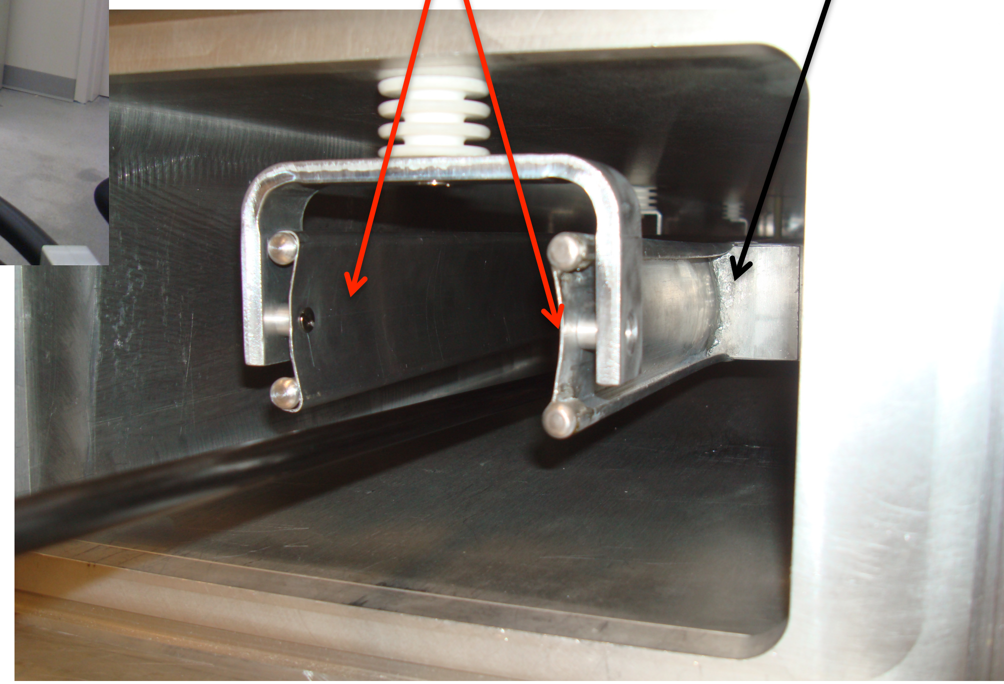


Blumlein prototype

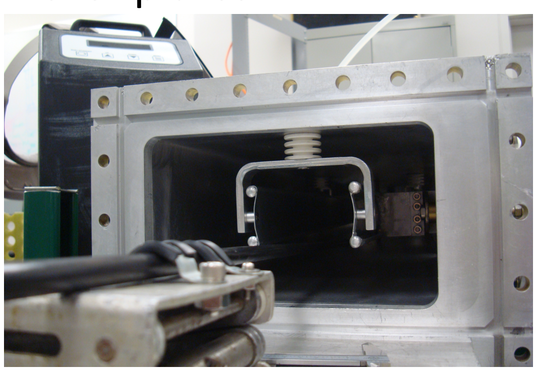
- Length – 5m
- Pulse width – 50ns
- Impedance – 25 ohms
- 561 Transformer oil – ε = 2.7

Kicker system R&D – kicker plates



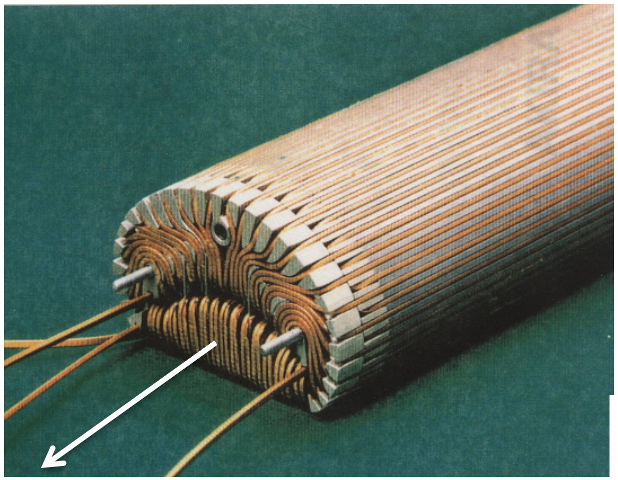


Prototype vacuum chamber and kicker plates



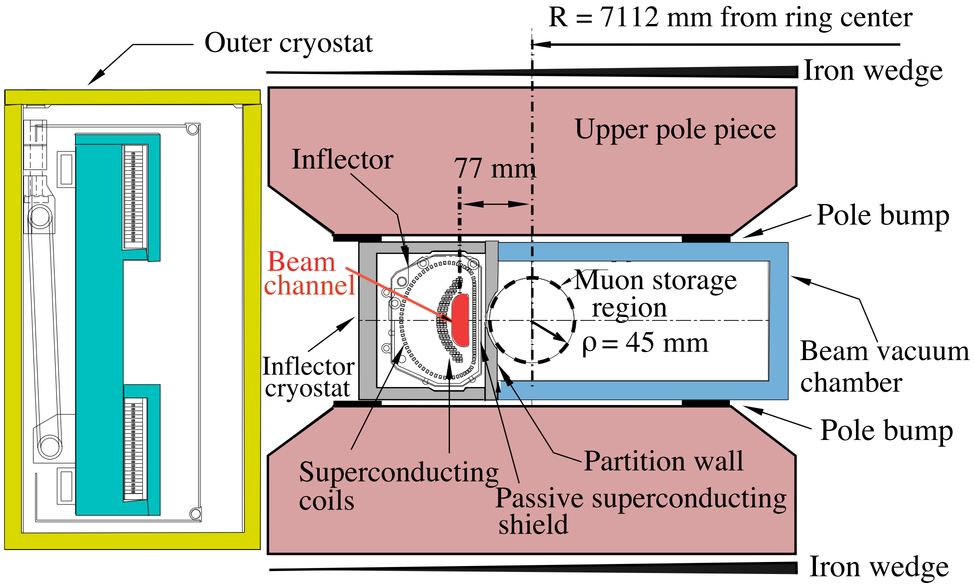
Inflector

E821 Inflector



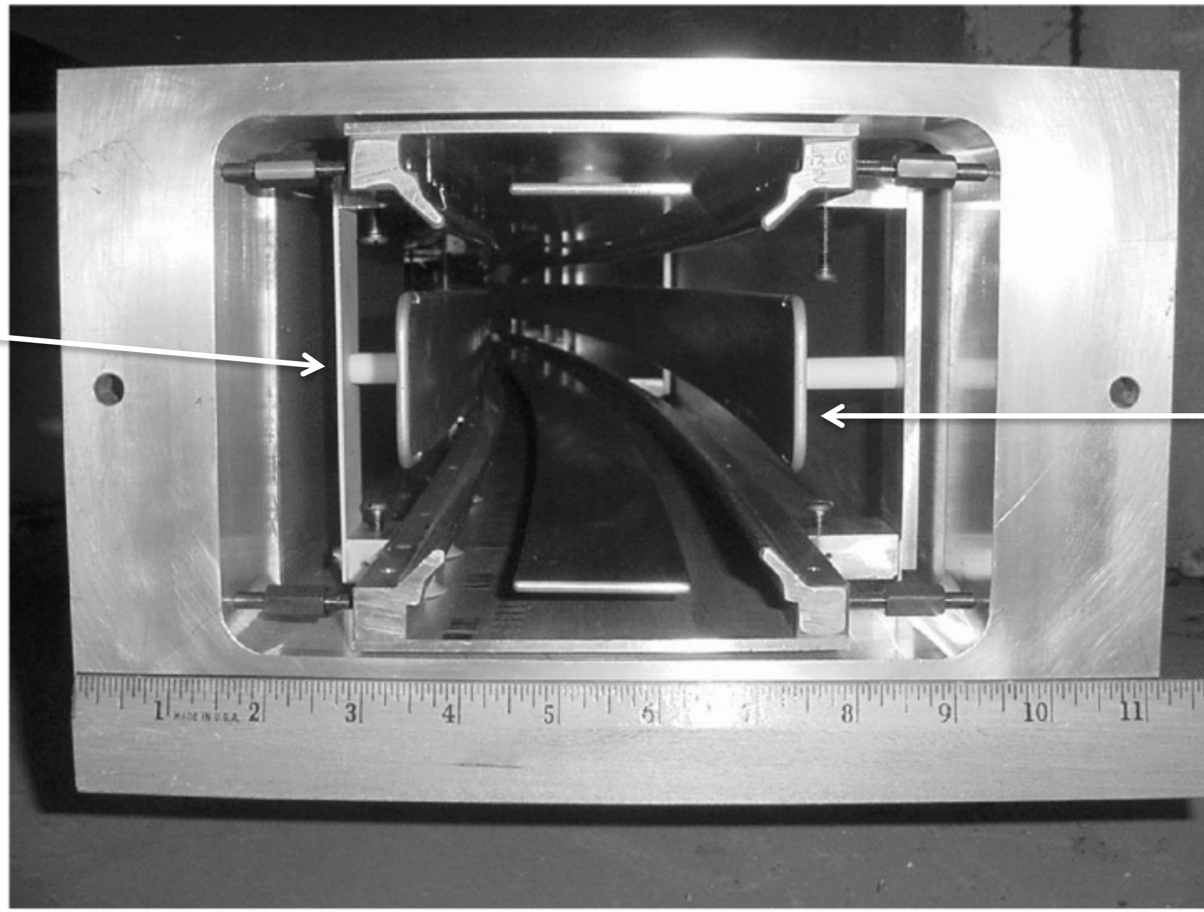
Beam
Went
Thru Coil
Windings !

Inflector aperture is narrow (18mm)
Poor match to storage ring acceptance



Electric Quadrupole System Upgrades (BNL)

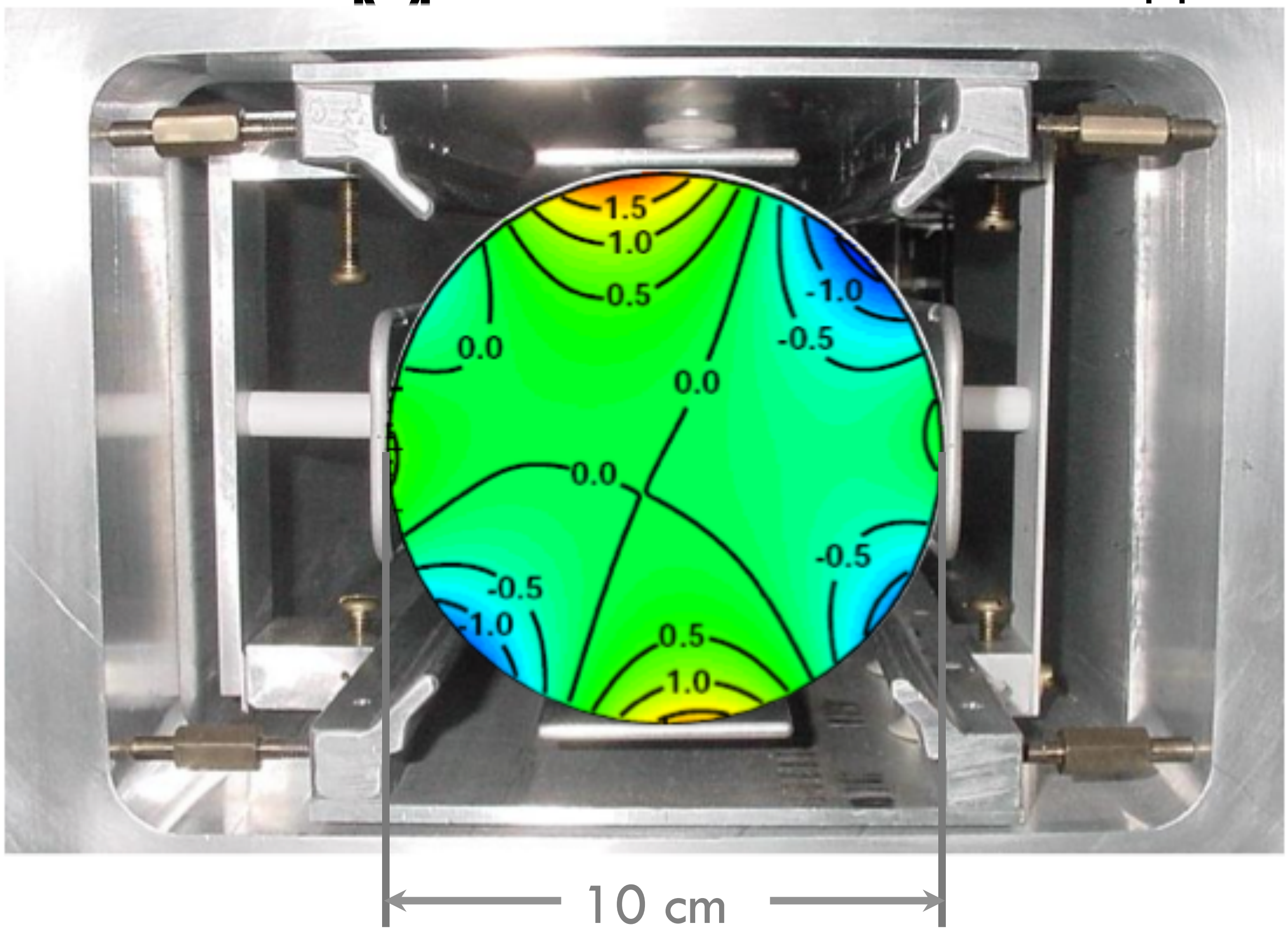
Thinner Quadrupole Plates And Support Structures



Stronger Focusing

E821: Portions Chemically Thinned to 100 µm Aluminum

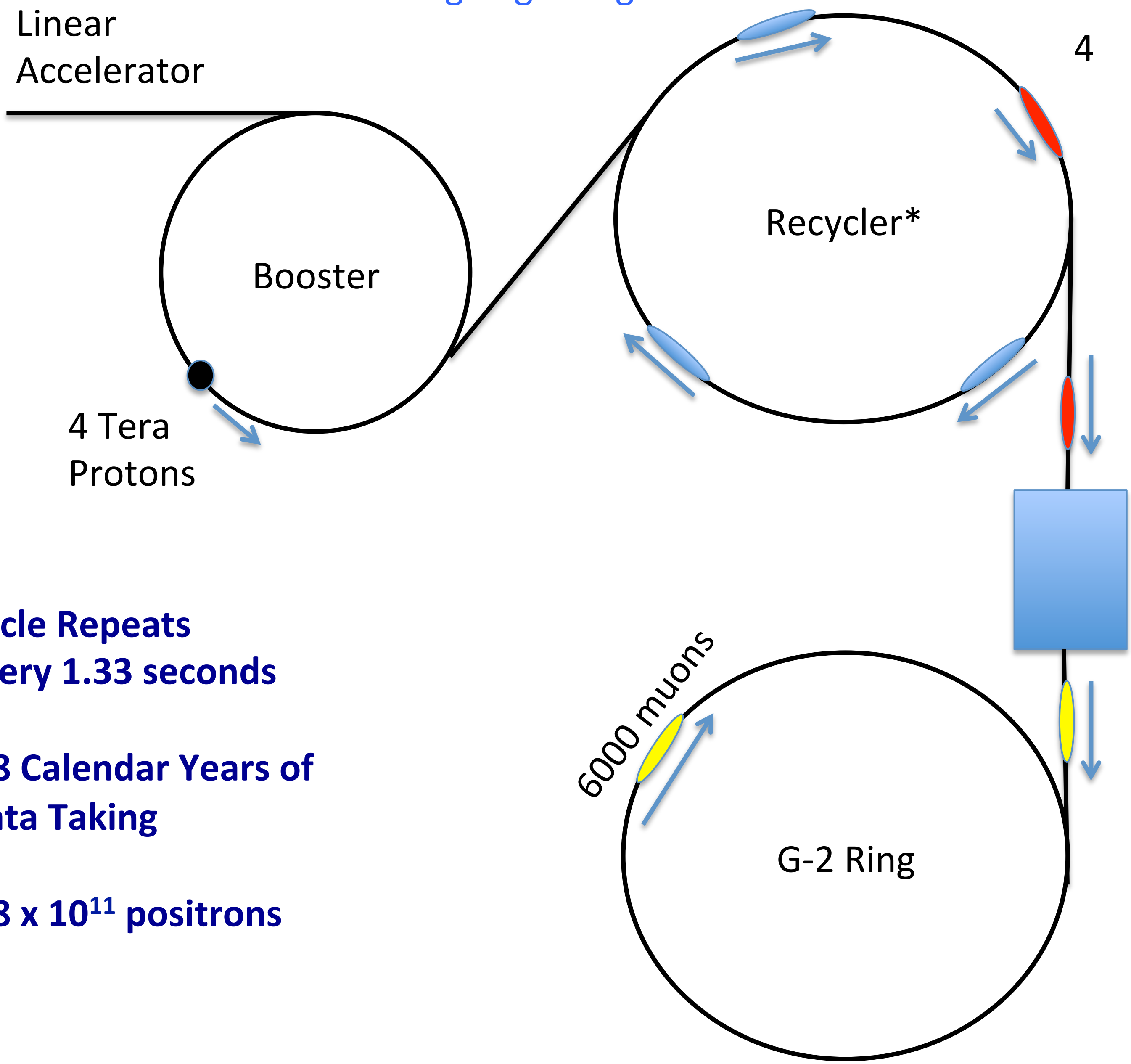
Contours are ppm



Systematics

- Coherent betatron oscillations
  - Horizontal oscillations modulate acceptance of positron detectors
- Electric field – not all muons are at precisely the magic momentum
- Pitch – vertical betatron motion – velocity is not perpendicular to B-field
- Differential decay – pions decay in a bend so that muon spin is correlated with energy
- Spin momentum correlation due to bend fields in delivery ring
- Lost muons –
- Pile up in detectors (two positrons hit at nearly the same time confusing energy measurement)
- Drift of detector gain early to late in fill
- Magnetic field uniformity => 0.07 ppm

Data taking beginning 2016-2017



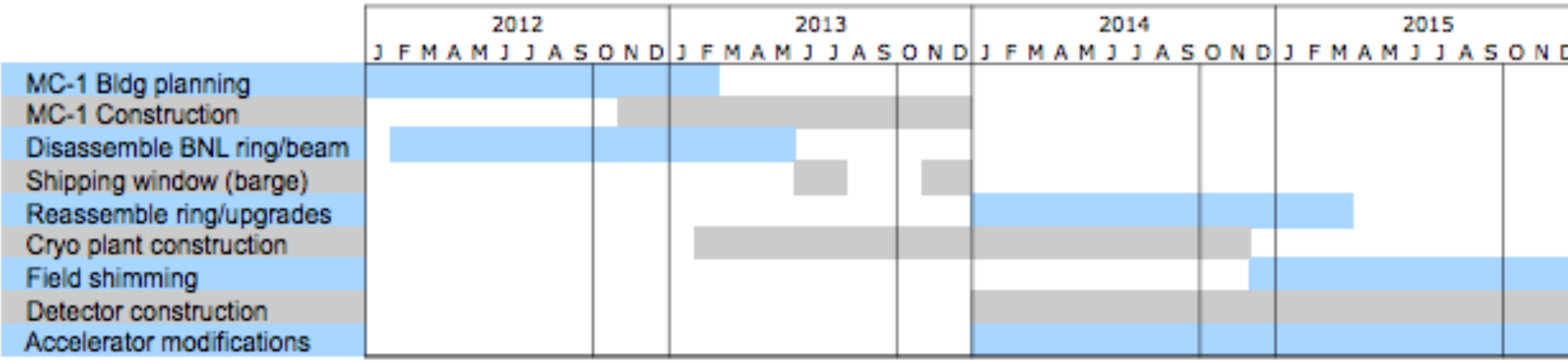
Cycle Repeats Every 1.33 seconds

1.8 Calendar Years of Data Taking

1.8 x 10^{11} positrons

Expect > 6x more Efficiency than BNL Beam

Just passed DOE CD-1 Review!



End

BNL E821 Innovation: Muon Injection into Ring

Kicker to Put Stored Muons onto Stable Orbit

Special Field-Cancellation Magnet for Muon Injection ('Inflector')