# Muon storage for the muon g-2 experiment at Fermilab

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*on behalf of the muon g-2 collaboration*

ICHEP 2016

# Outline

- Motivation of the experiment
- Principles of measurements
- Importance of the muon beam characteristics for physics measurements
- Collaboration efforts in simulating the muon beam for muon *g*-2 experiment
- Future plans

# The Muon Anomalous Magnetic Moment

$$i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m\psi(x)$$

$$\vec{\mu}_\mu = g_\mu \frac{e}{2m_\mu}\vec{S}$$

$$g_\mu = 2 \quad \text{for} \quad S = 1/2$$

Quantum loop effects: $\mu_\mu = (1 + a_\mu)\frac{e\hbar}{2m_\mu}$ where

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$ - anomalous magnetic moment

# Comparison of Experiment and Theory

- Theory uncertainty: 0.42 ppm
- Experimental uncertainty: 0.54 ppm E821 @ BNL

PDG 2013

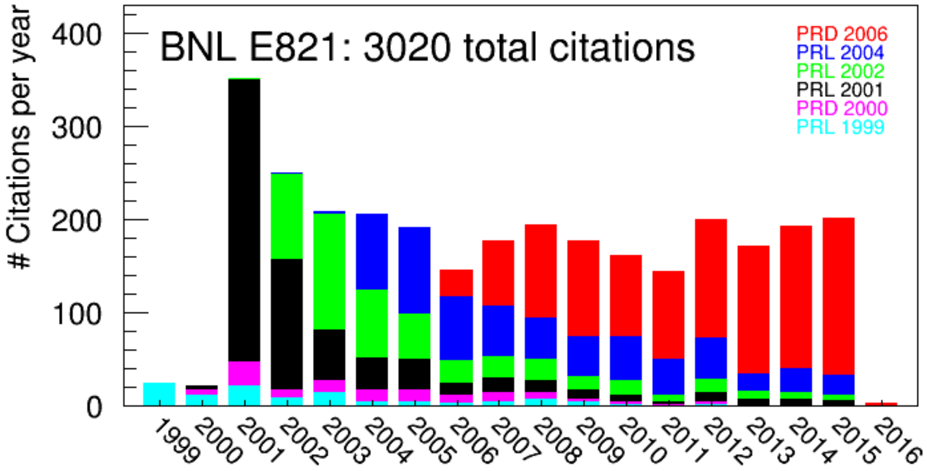
$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = 288(63)(49) \times 10^{-11} \qquad (3.6\sigma)$$

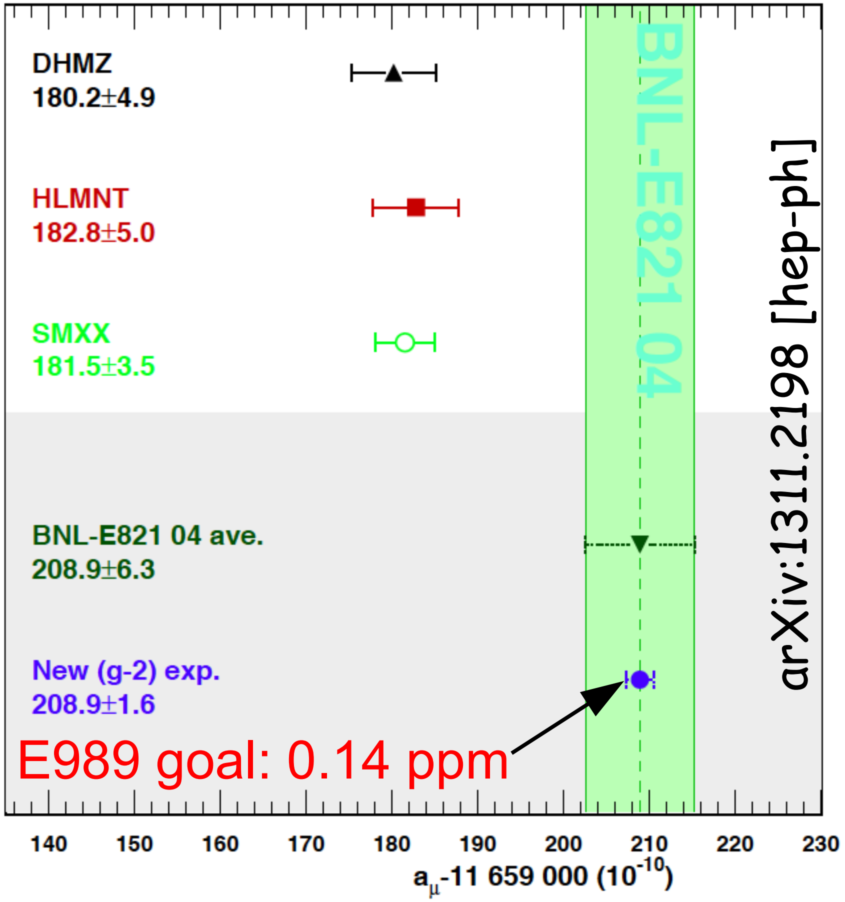
- "interesting but not yet conclusive discrepancy"
- new physics signal?

$$a_\mu^{\mathrm{SUSY}} \simeq \mathrm{sign}(\mu) \cdot 130 \times 10^{-11} \left( \frac{100\ \mathrm{GeV}}{m_{\mathrm{SUSY}}} \right) \tan(\beta)$$

A. Czarnecki and W.J. Marciano, PRD 64 (2001)

$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi} \varepsilon^2 F\left( \frac{m_V}{m_\mu} \right)$$





arXiv:1311.2198 [hep-ph]

Fermilab E989 goal: 0.14 ppm

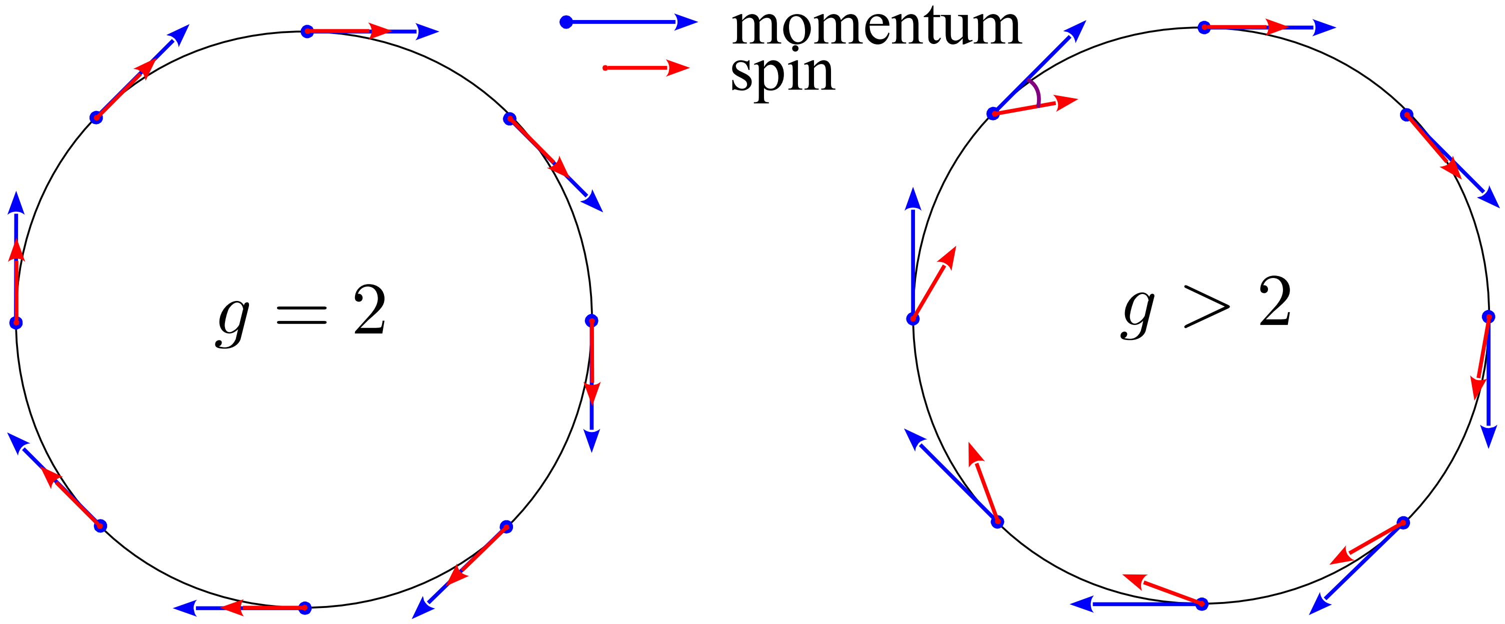
# Muon g-2 experiment in a nutshell

1) Take polarized muons (come naturally from pion decay)

2) Inject muons into a uniform magnetic field

- Momentum precession (cyclotron frequency) $\omega_c = \frac{e}{m\gamma}B$
- Spin precession $\omega_s = \frac{e}{m\gamma}B(1+\gamma a_\mu)$

$$\omega_a = \omega_s - \omega_c = \frac{e}{m}a_\mu B$$

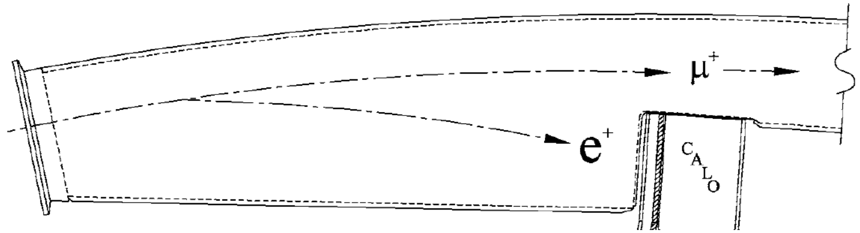


# BNL g-2 experiment in a nutshell

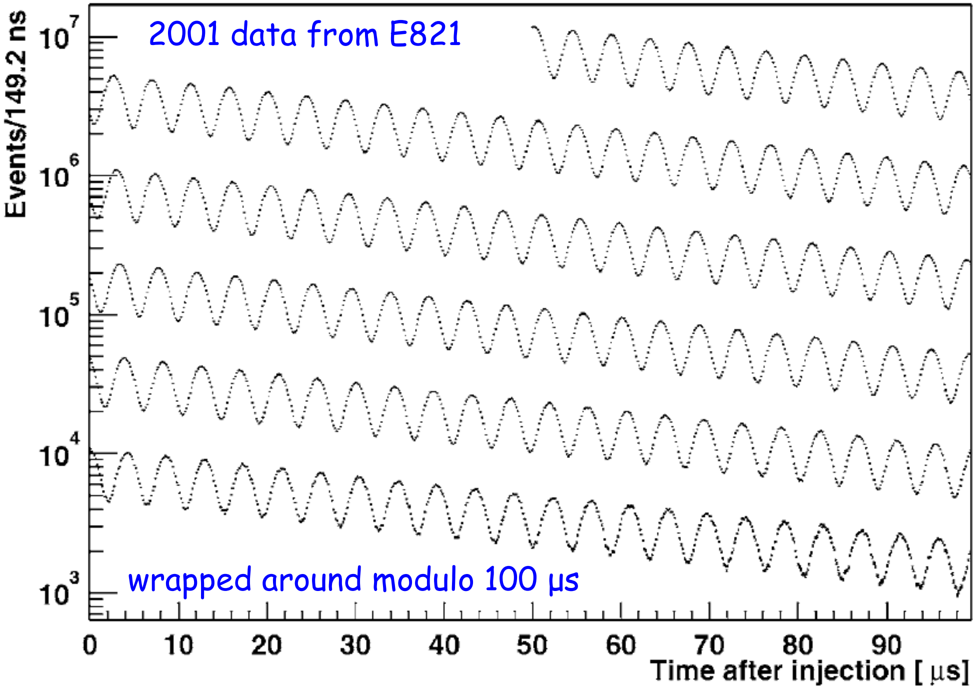
$$a_\mu = \frac{m}{e}\frac{\omega_a}{B}$$

Determining the anomalous magnetic moment requires measuring

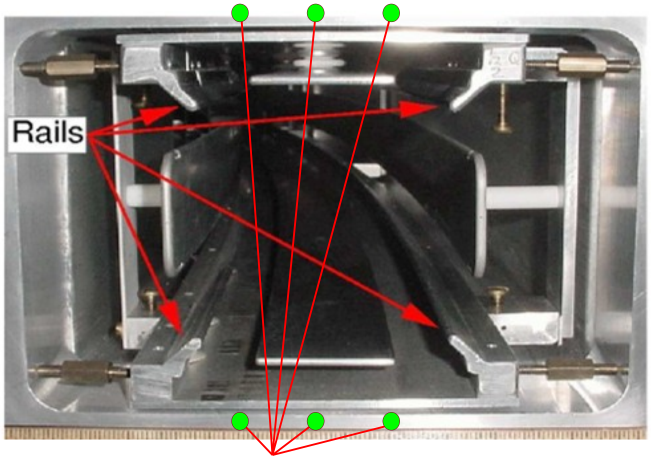
- The spin precession frequency $\omega_a$



muon decay is self-analyzing: higher energy positrons are emitted preferentially in direction of muon spin

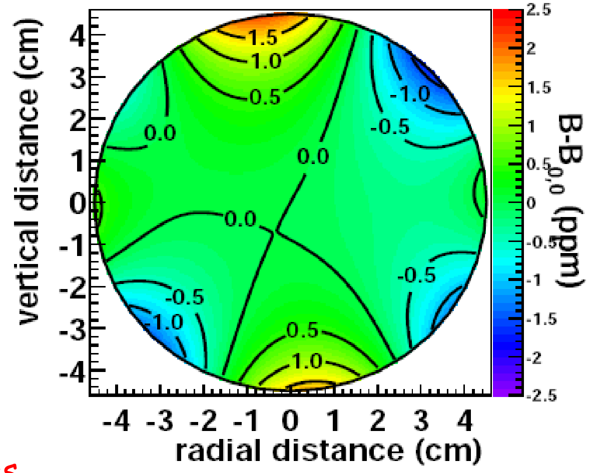


- The magnetic field B ($\omega_p$)



375 fixed NMR probes

17 NMR trolley probes



$$a_\mu^{\text{exp}} = \frac{\dfrac{\omega_a}{\tilde{\omega}_p}}{\dfrac{\mu_\mu}{\mu_p} - \dfrac{\omega_a}{\tilde{\omega}_p}}$$

# Towards the new precision goal (x4)

0.54 ppm → 0.14 ppm

1. improve statistical uncertainty
    - record ×20 more muon decays
2. improve systematic uncertainty
    - uncertainty in $\omega_p$
    - uncertainty in $\omega_a$

# uncertainties in E821 and E989 goals

## $\omega_p$

D. Kawall, UMass

| Category | E821 [ppb] | Main E989 Improvement Plans | Goal [ppb] |
|---|---|---|---|
| Absolute field calibration | 50 | Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics | 35 |
| Trolley probe calibrations | 90 | Plunging probes that can cross calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations | 30 |
| Trolley measurements of $B_0$ | 50 | Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements* | 30 |
| Fixed probe interpolation | 70 | Better temperature stability of the magnet; more frequent trolley runs | 30 |
| Muon distribution | 30 | Additional probes at larger radii; improved field uniformity; improved muon tracking | 10 |
| Time-dependent external magnetic fields | – | Direct measurement of external fields; simulations of impact; active feedback | 5 |
| Others † | 100 | Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients | 30 |
| Total systematic error on $\omega_p$ | 170 | | 70 |

*Improvements in many of these categories will also follow from a more uniformly shimmed main magnetic field.

†Collective smaller effects in E821 from higher multipoles, trolley temperature uncertainty and its power supply voltage response, and eddy currents from the kicker.

# Uncertainties in E821 and E989 goals

## $\omega_a$

| Category | E821 [ppb] | E989 Improvement Plans | Goal [ppb] |
|---|---|---|---|
| Gain changes | 120 | Better laser calibration<br>low-energy threshold | 20 |
| Pileup | 80 | Low-energy samples recorded<br>calorimeter segmentation | |
| Lost muons | 90 | Better collimation in ring | 20 |
| CBO | 70 | Higher $n$ value (frequency)<br>Better match of beamline to ring | $< 30$ |
| $E$ and pitch | 50 | Improved tracker<br>Precise storage ring simulations | 30 |
| Total | 180 | Quadrature sum | 70 |

# Requirements to the g-2 beam storage

- Maximize the acceptance of magic-momentum muons.
  → statistical uncertainty
- Minimize beam-related systematic uncertainties
  - theory
  - simulations
  - measurements

# Muon g-2 Collaboration (E989)

Domestic Universities
  - Boston
  - Cornell
  - Illinois
  - James Madison
  - Massachusetts
  - Mississippi
  - Kentucky
  - Michigan
  - Michigan State
  - Mississippi
  - Northern Illinois University
  - Northwestern
  - Regis
  - Virginia
  - Washington
  - York College
- National Labs
  - Argonne
  - Brookhaven
  - Fermilab
- Consultants
  - Muons, Inc.

Italy
  - Frascati
  - Roma
  - Udine
  - Naples
  - Trieste

China:
  - Shanghai

The Netherlands:
  - Groningen

Germany:
  - Dresden

Japan:
  - Osaka

Russia:
  - Dubna
  - PNPI
  - Novosibirsk

England

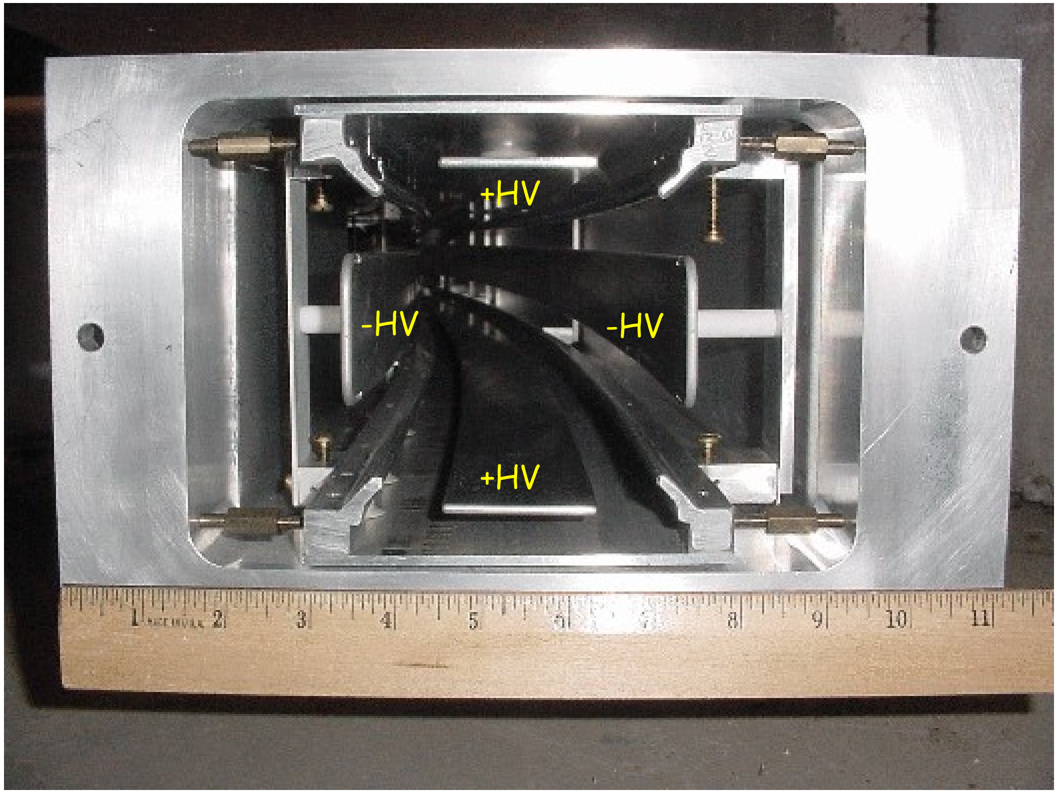
University College London
Liverpool
Oxford
Rutherford Lab
Lancaster

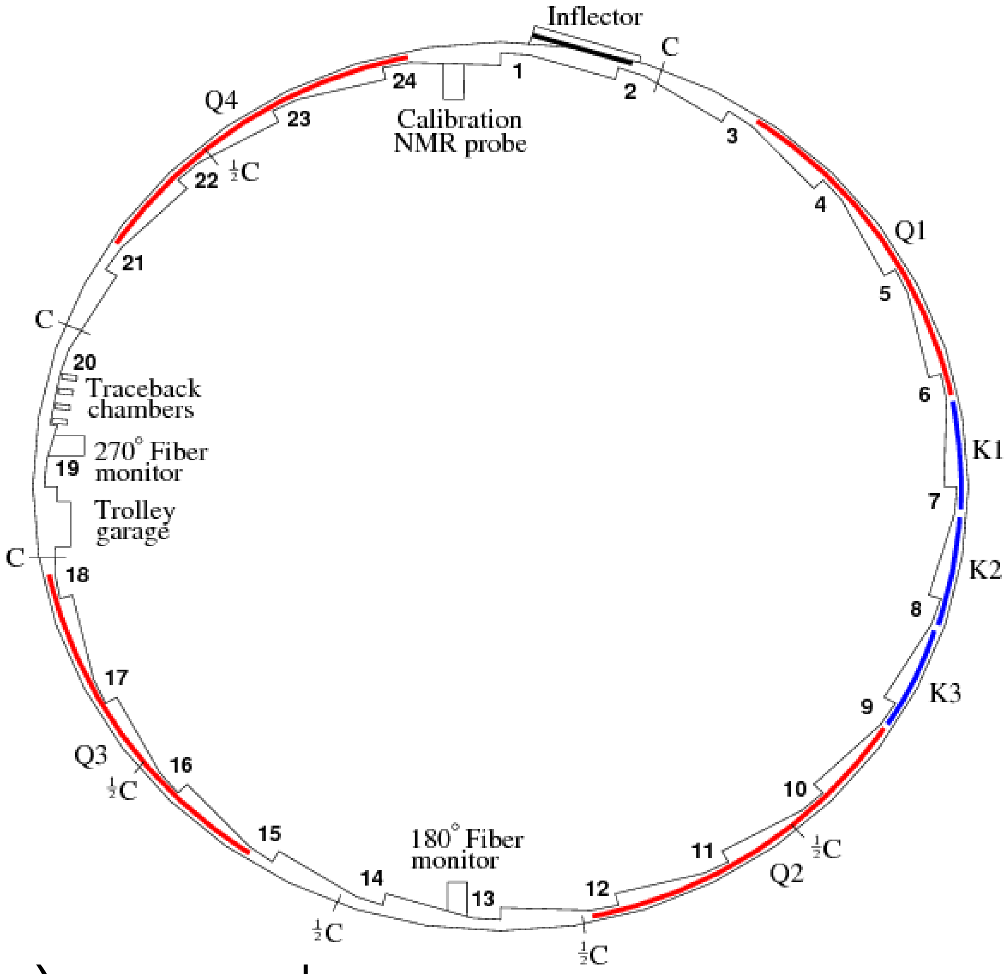
Korea

KAIST

Co-spokespersons: David Hertzog, Lee Roberts
Project Manager: Chris Polly

# Electric quads to contain the beam vertically





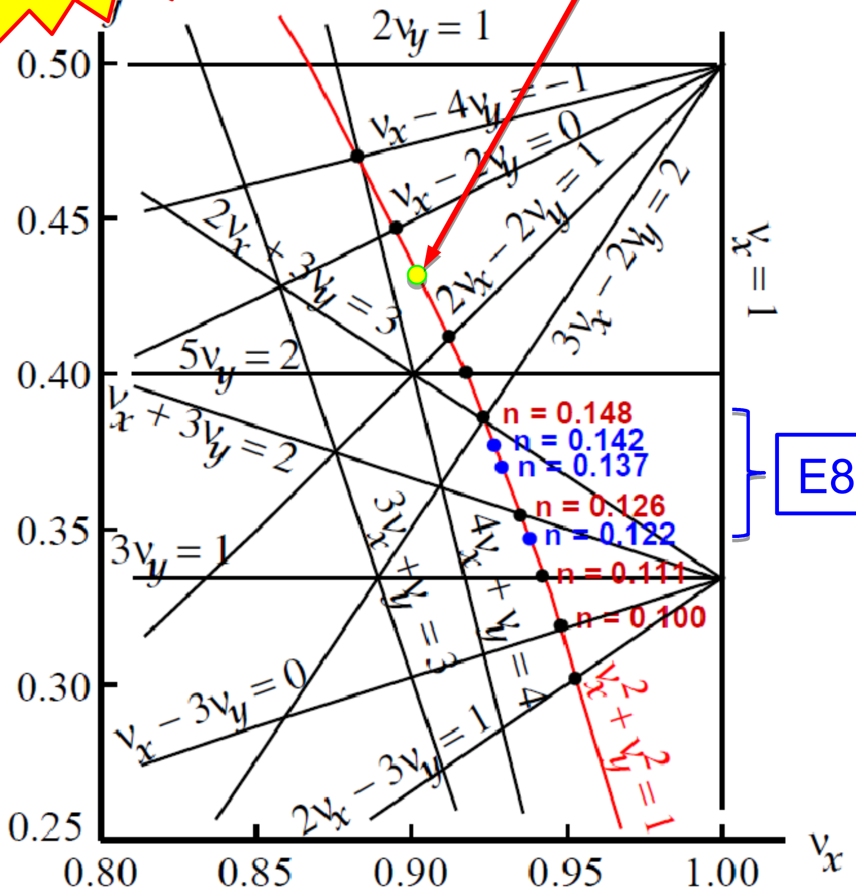
$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}_{=0 \quad \text{for } \gamma = 29.3 \quad (p_\mu = 3.09\ \mathrm{GeV/c})} \vec{\beta}\times\vec{E}\right]$$

E-field contribution vanishes

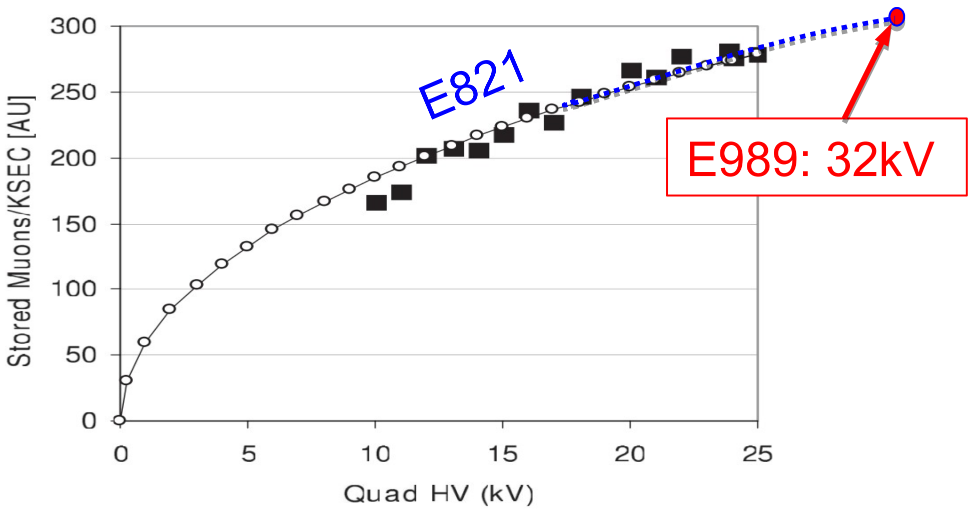
# Upgrade of Quadrupoles to higher HV

CBO
Lost Muons

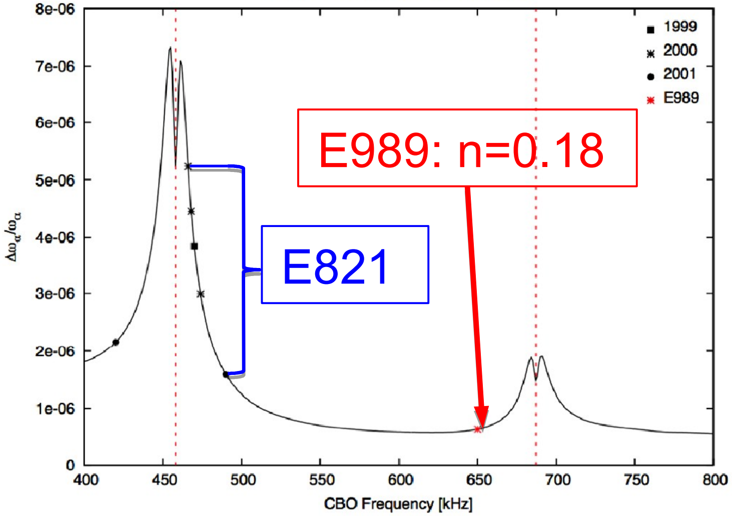
E989 goal



E821



E989: 32kV

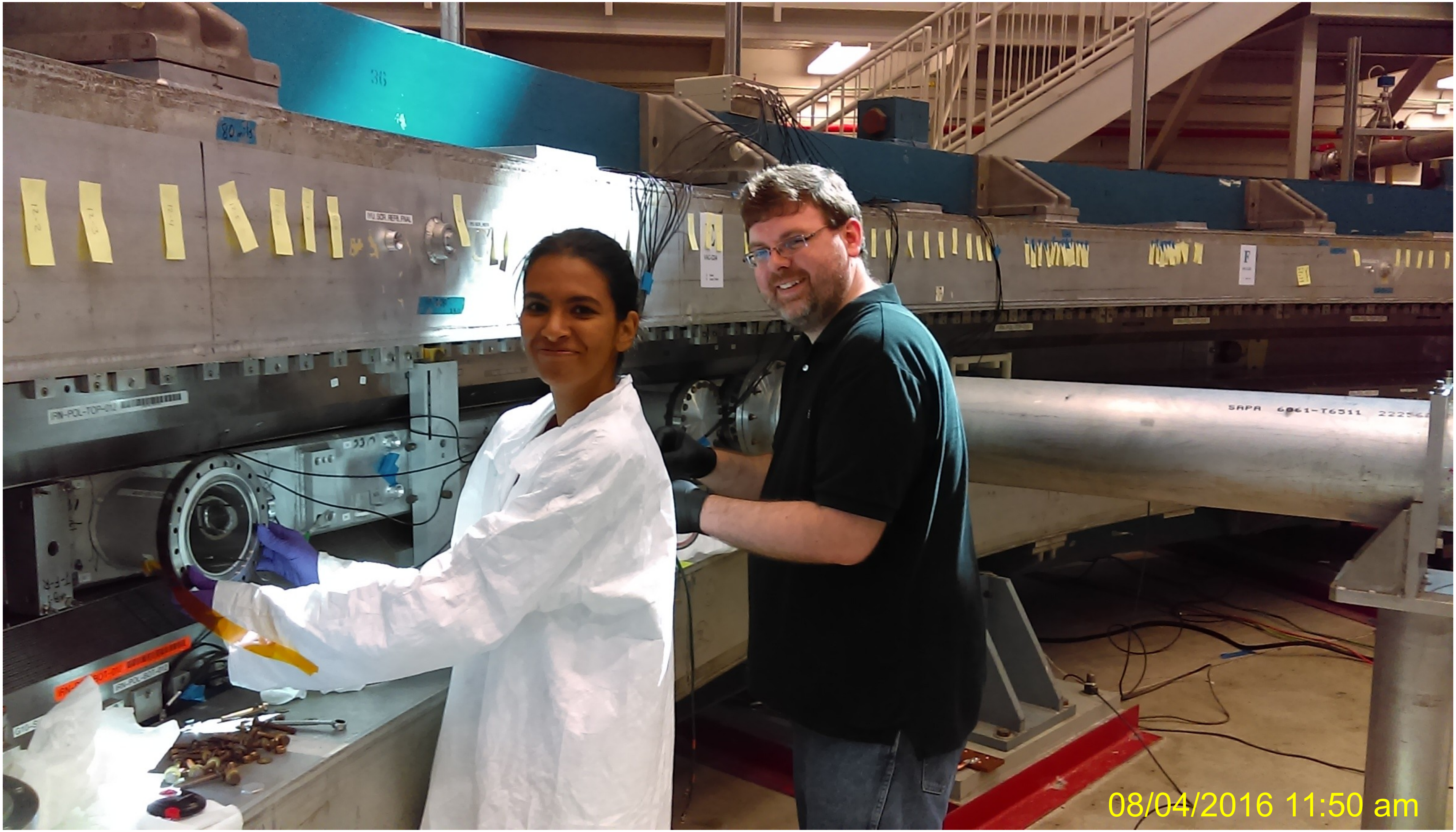


E989: n=0.18

E821

- Higher admittance of the (g-2) storage ring
- Lower CBO systematic error
- Lower muon loss systematic error

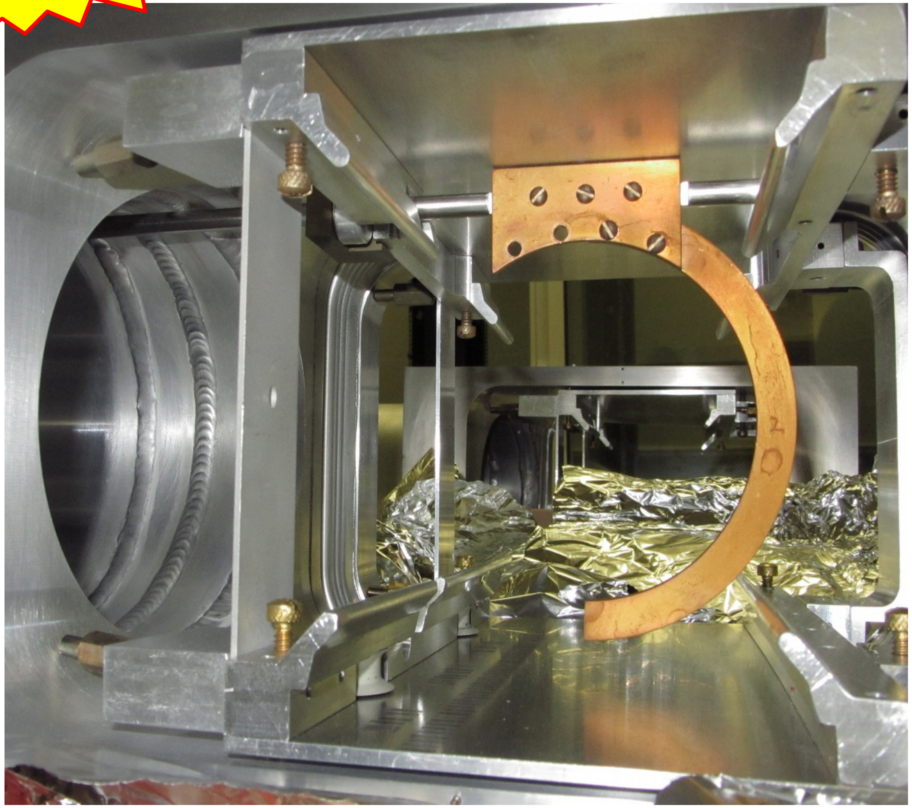
# 32-kV voltage test

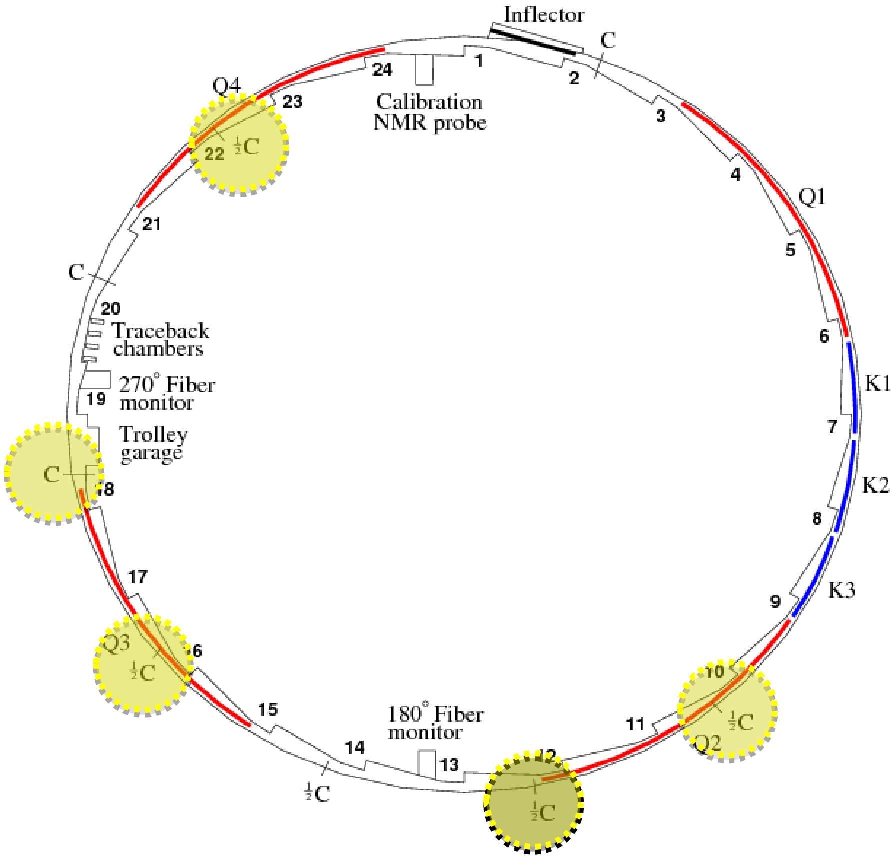


08/04/2016 11:50 am

Lost Muons

# New beam collimators





Baseline plan:

- Manufacture new collimators
- Elliptical profiles to match beta-functions of the g-2 storage ring
- Optimized thickness of collimators
- Replace $\frac{1}{2}$-collimators (see picture above) with full-collimators
- The number of collimators will be reduced due to conflicts with new tracking chambers

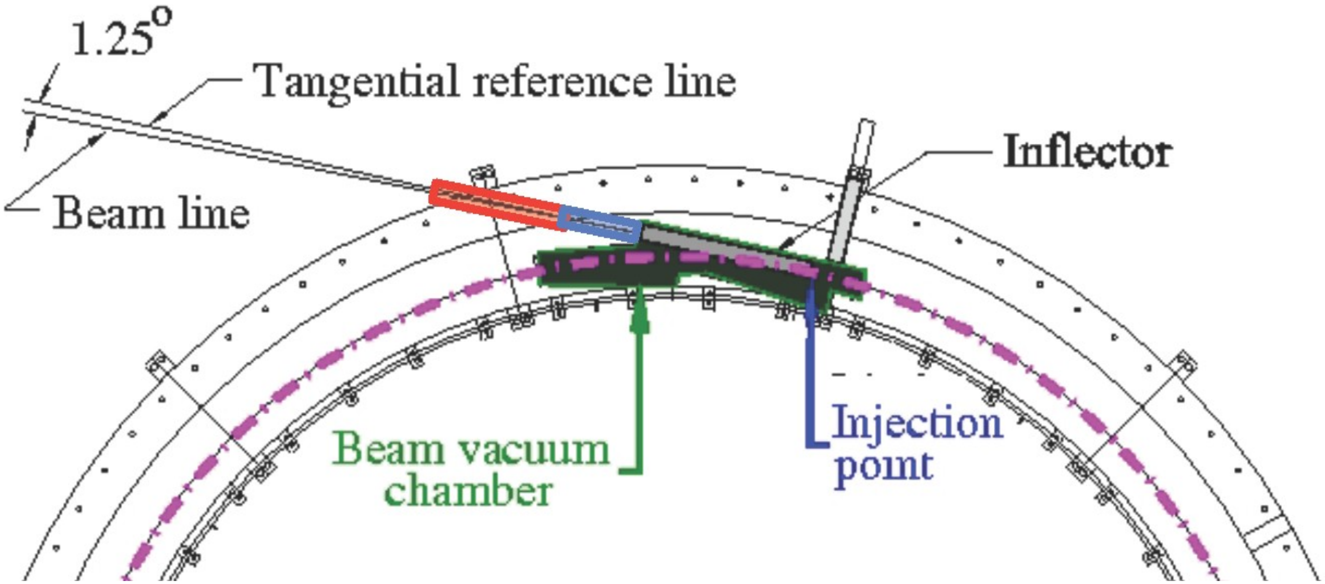
# Injection channel into the g-2 storage ring

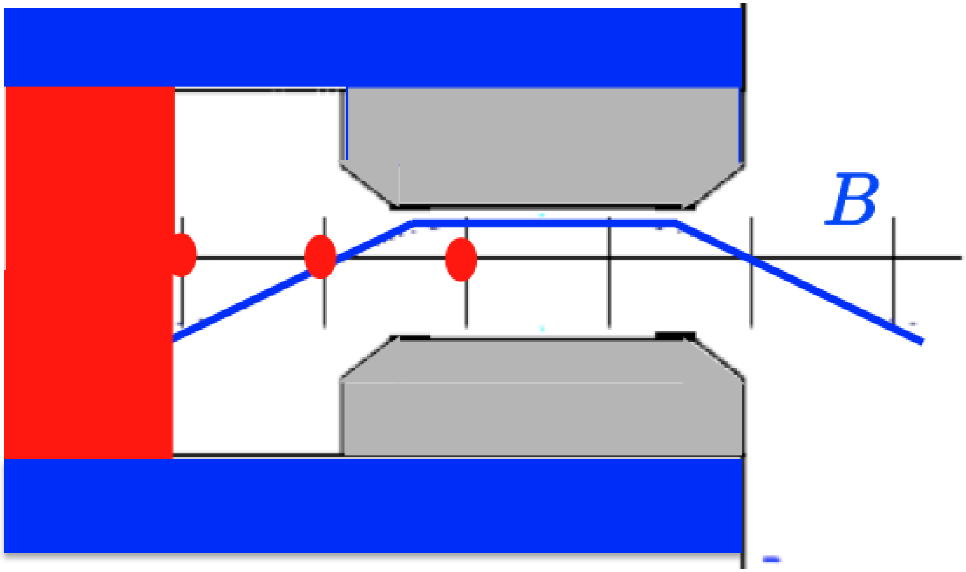
Muons come to the end of the M5 line and then propage through

- Hole in magne yoke
- Dipole fringe field
- Inflector

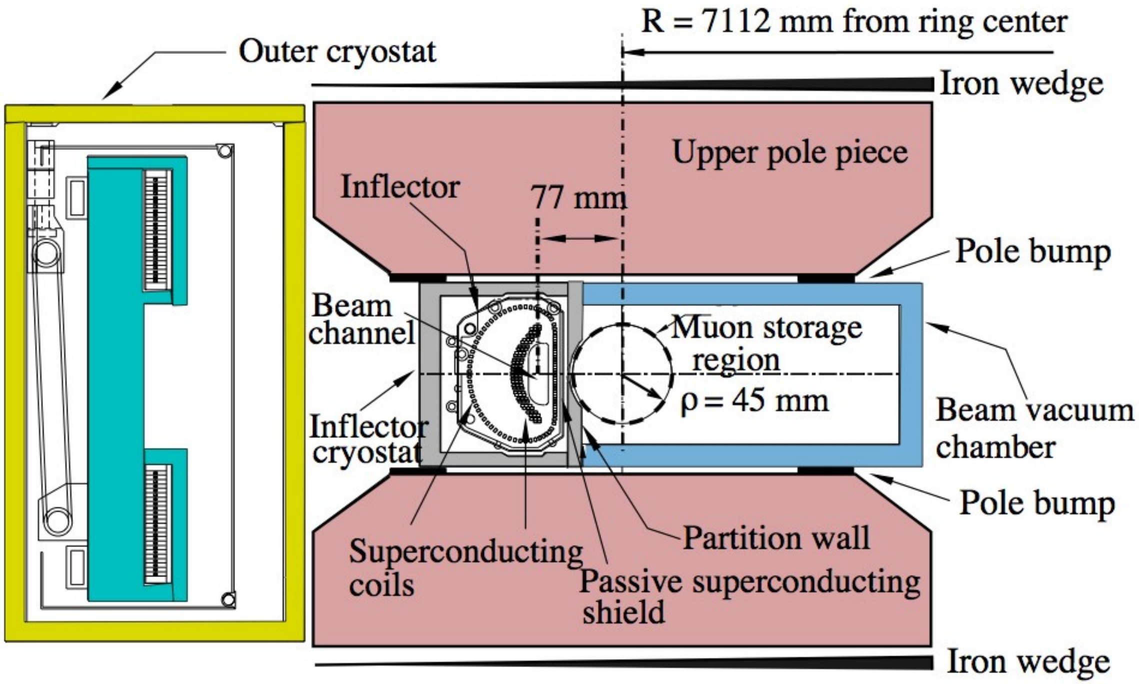
And exit inflector 77 mm from the center of the dipole aperture.

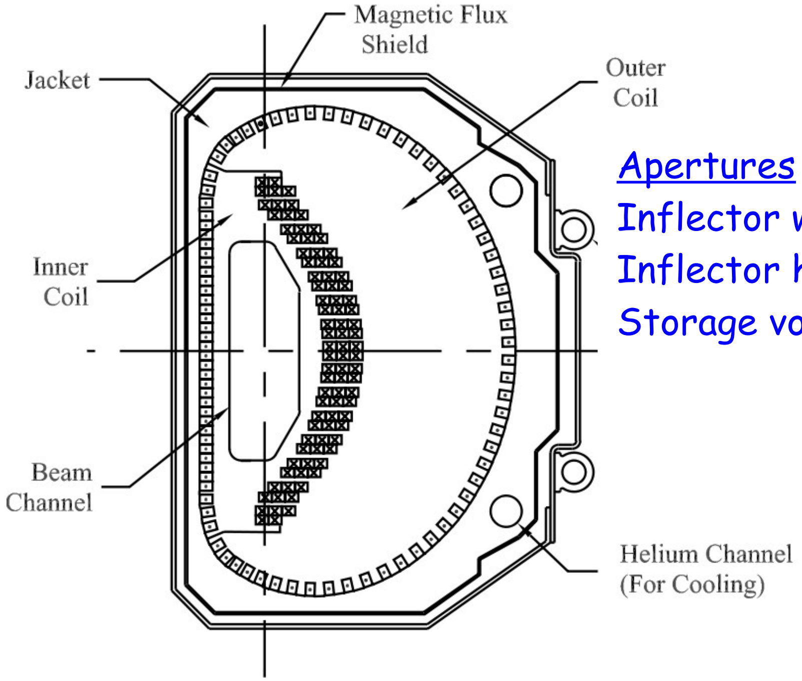
The magnetic field is near zero at the inner surface of the yoke, and rises to 1.45 T between the magnet polses, over a distance of ~39 cm.





# Injection aperture



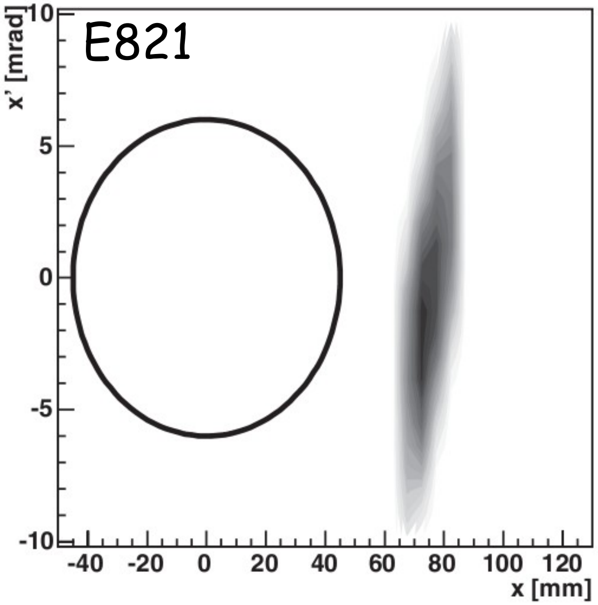


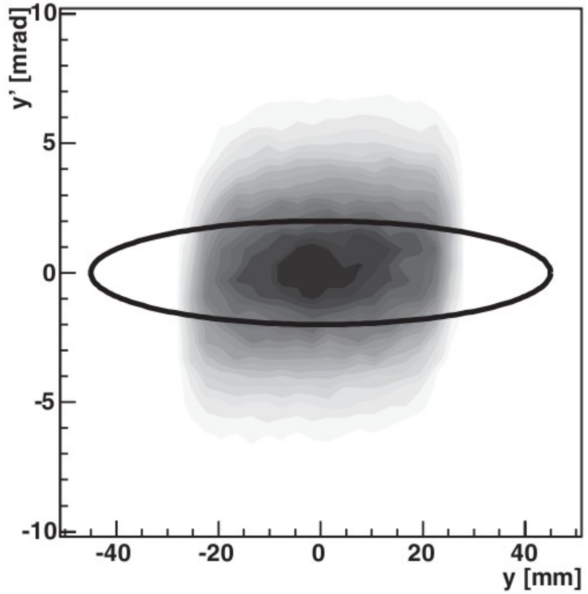
<u>Apertures</u>

Inflector width: 18 mm

Inflector height: 56 mm

Storage volume radius: 45mm





CBO

# New Kicker

D. Rubin, Cornell

Kickers steer injected muons onto the closed orbit of the storage ring

## Requirements:

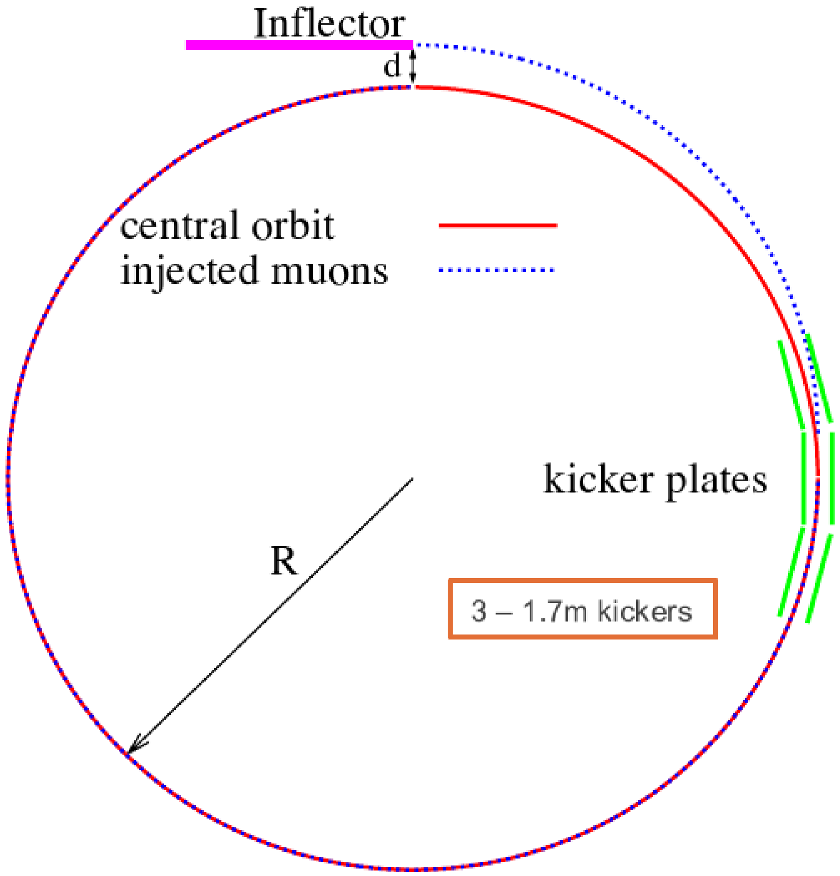
| | |
|---|---|
| Kick angle | ~ 10.8 to 12.1 mrad |
| Kicker B-field | ~ 218 to 245 Gauss |
| Integrated B-field | ~ 1.11 to 1.25 kG-m |

Pulse width($\tau_{wid}$)

$120\text{ns} < \tau_{wid} < 149\text{ns}$

Repetition rate

~100Hz peak, 12Hz average



$\tau_{rev} = 149$ ns

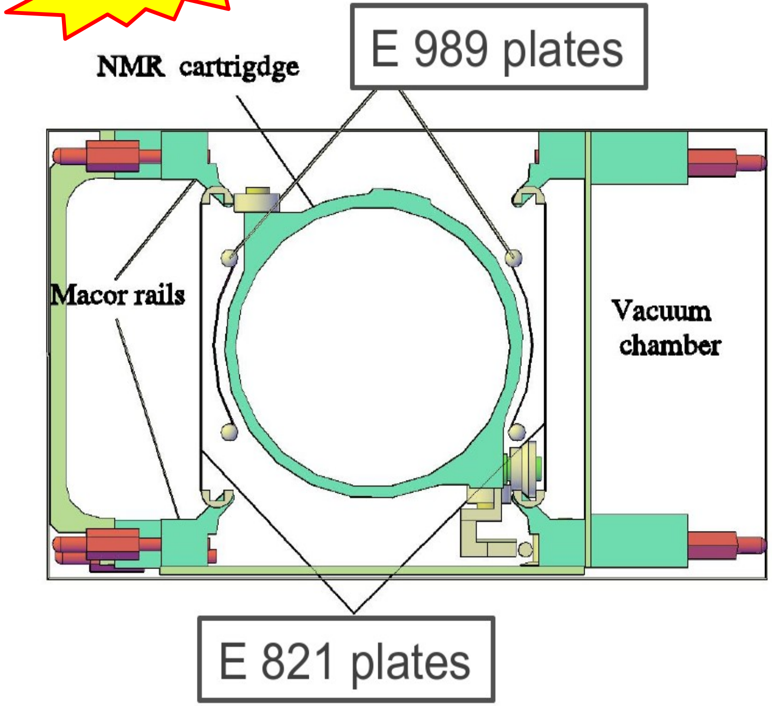
d = 77 mm, R=7112 mm

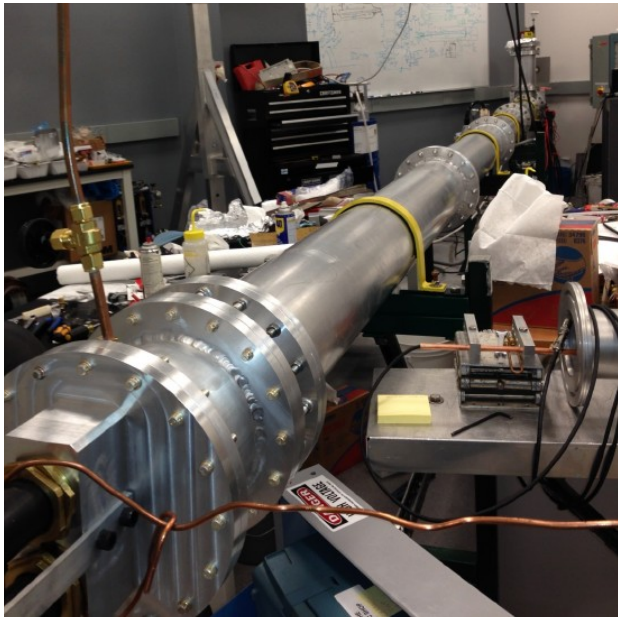
kick angle $\theta = d/R = 10.8$ mrad

CBO

# New Kicker

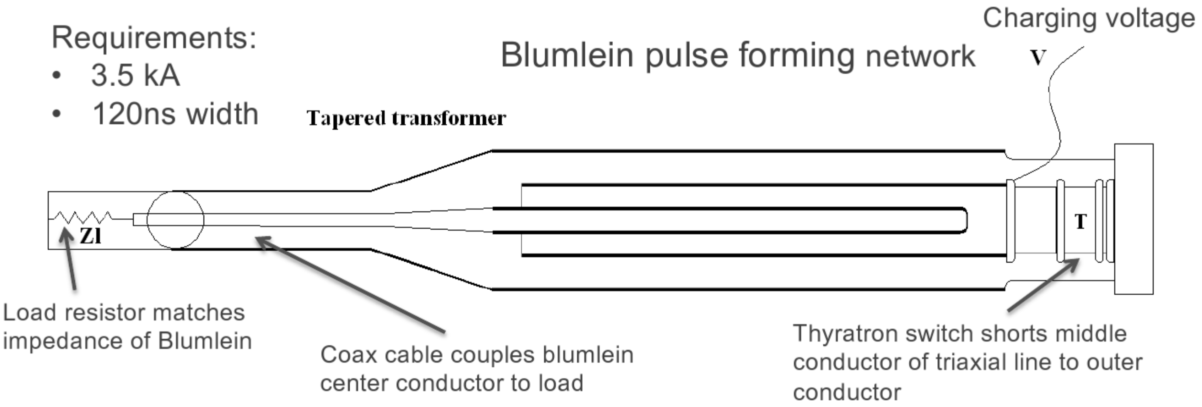
D. Rubin, Cornell





Requirements:

- 3.5 kA
- 120ns width



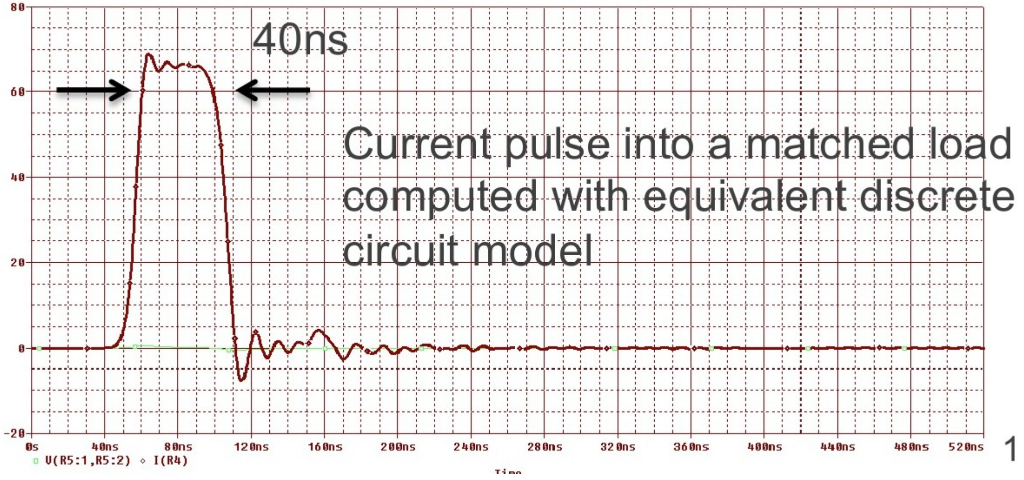
Blumlein pulse forming network

Charging voltage

Load resistor matches impedance of Blumlein

Coax cable couples blumlein center conductor to load

Thyratron switch shorts middle conductor of triaxial line to outer conductor

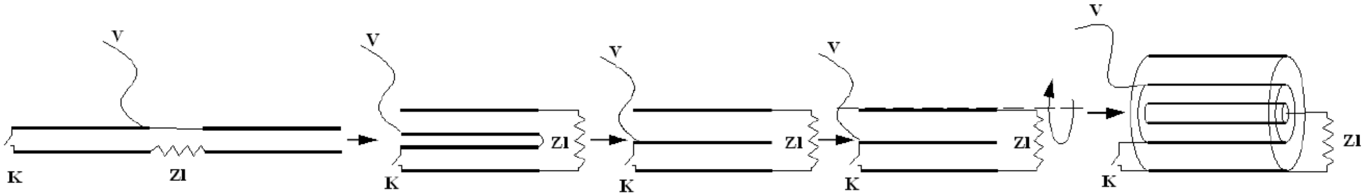


40ns

Current pulse into a matched load computed with equivalent discrete circuit model

$$\tau = \frac{2L}{v}$$

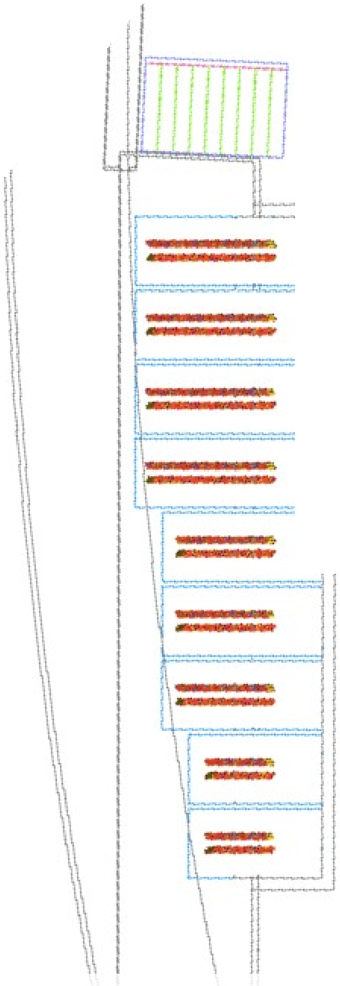
width of pulse is proportional to length of blumlein

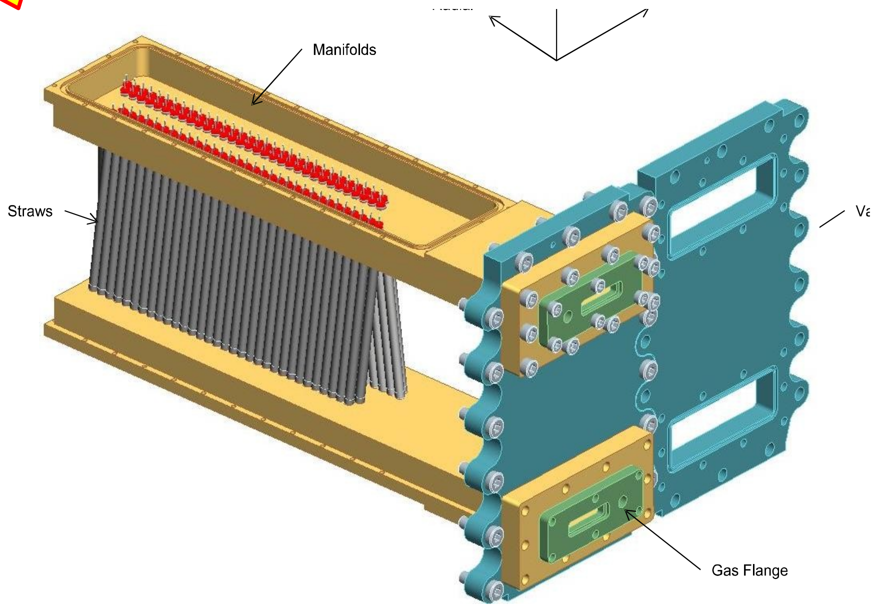


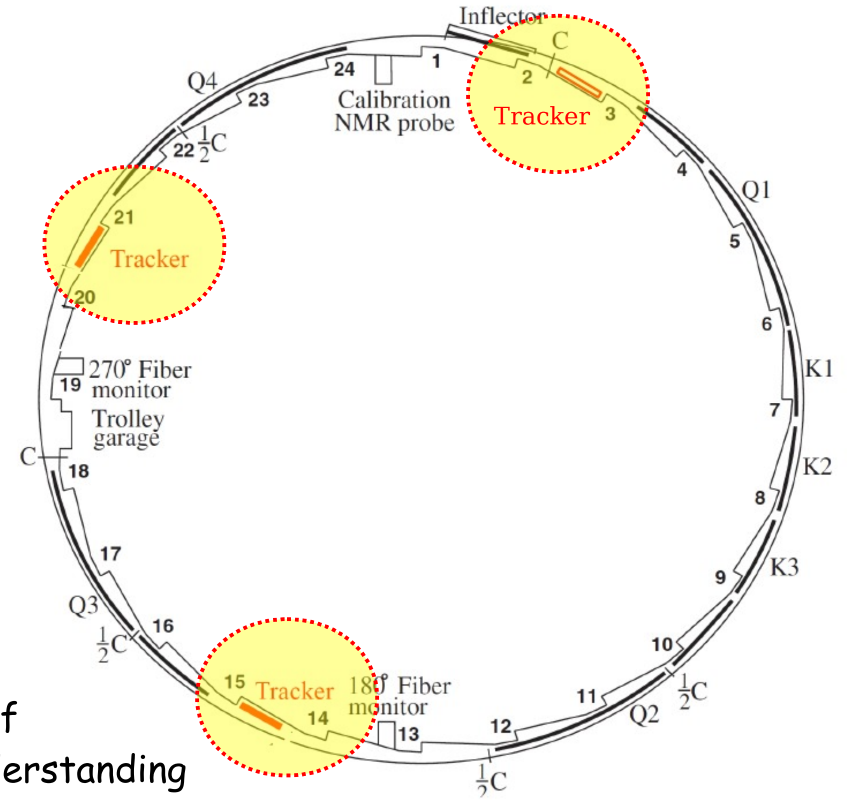
**beam, EDM**

# New Tracker

B. Casey, FNAL







**Purpose:** measure the muon beam profile at multiple locations around the ring as a function of time throughout the muon fill. Is needed for understanding systematic uncertainties associated with with $\omega_a$ measurements (calorimeter pileup, calorimeter gain, muon loss, differential decay syst. uncertainty, etc). Will also be used to search for a tilt in the muon precession plane away from the vertical orientation (which would be indicative of an EDM of the muon).

9 independent tracking modules

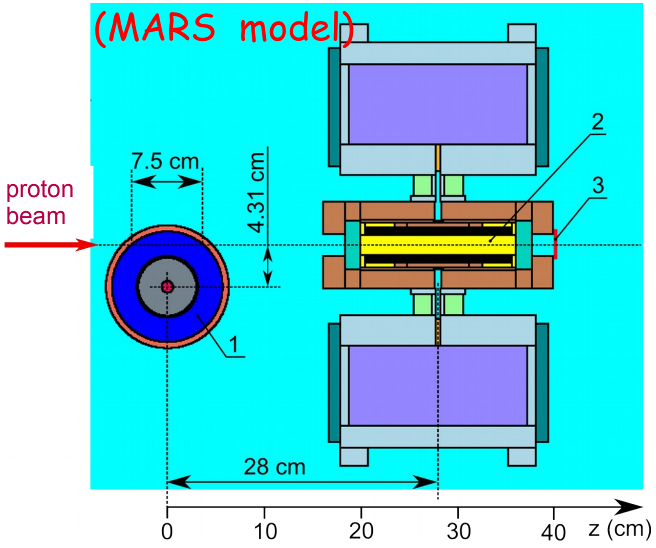
**Design:** 5-mm-diameter 10-cm-long straw UV doublets at 7.5°.
straw walls: 6 μm Mylar
sense wires: 25 μm gold-plated tungsten at 1500 V
gas: 80:20 Argon:$CO_2$
readout: ASDQ chips

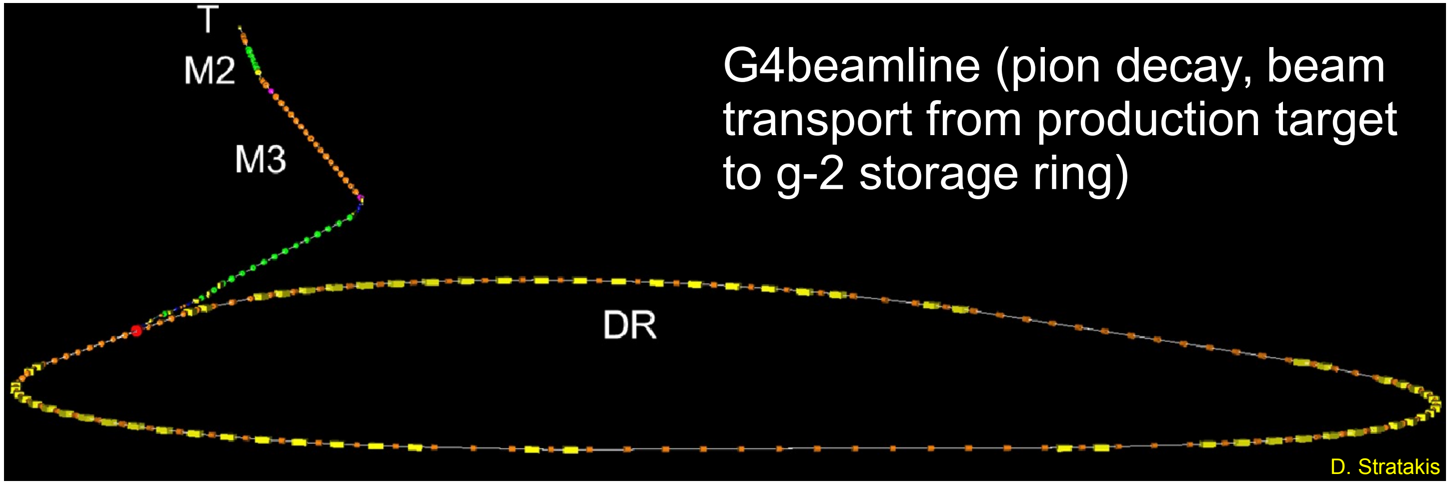
# Beam simulations in g-2

- MARS
- G4beamline
- Geant
- BMAD
- E821 particle tracking code(s) (Y. Semertzidis)

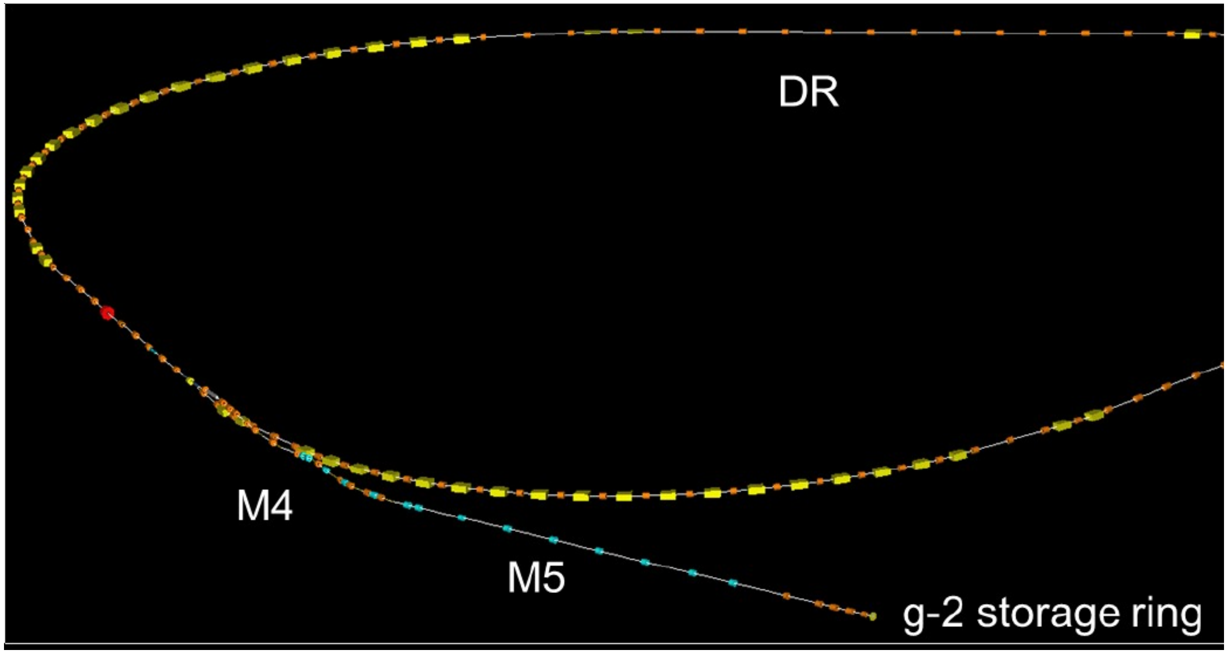
# End-to-end simulation effort

Pion production target
(MARS model)





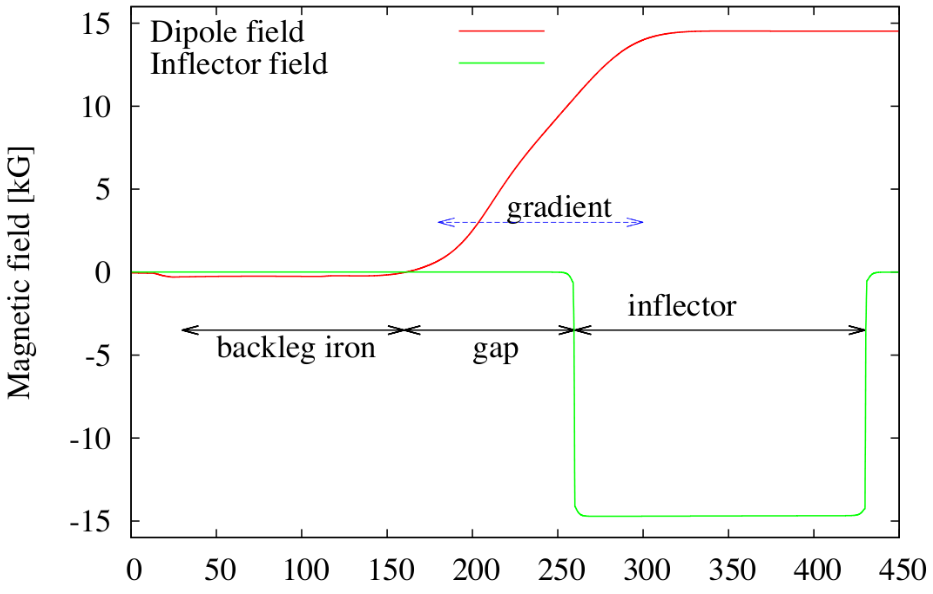
G4beamline (pion decay, beam transport from production target to g-2 storage ring)

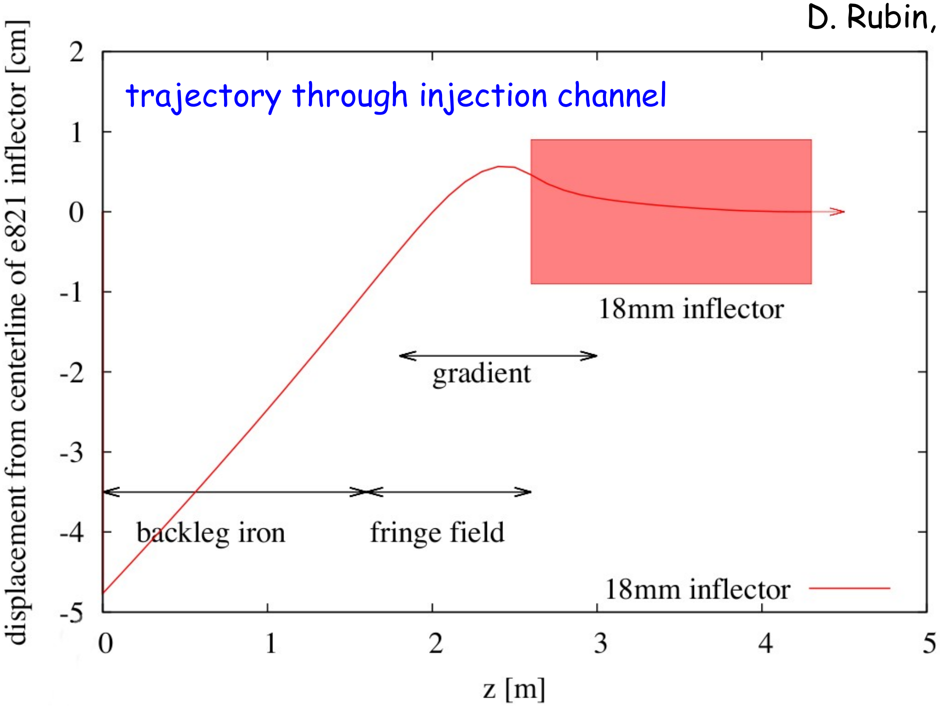


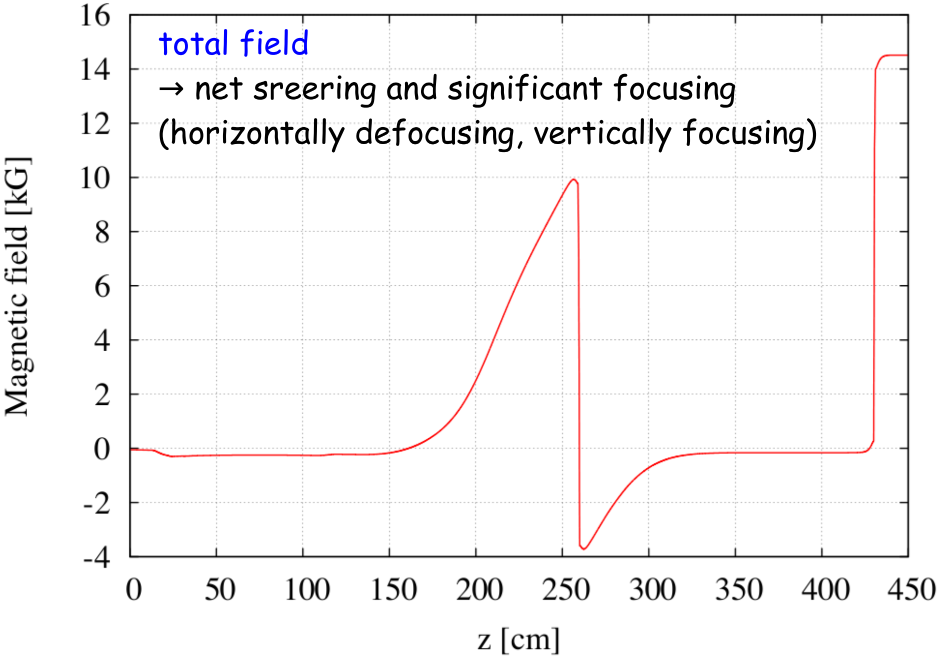
muons at the entrance to the g-2 storage ring: $2.4\times10^{-7}$ POT ($\Delta p/p = \pm\ 0.5\%$)

# Propagation through injection channel

D. Rubin, Cornell




trajectory through injection channel


total field

→ net sreering and significant focusing

(horizontally defocusing, vertically focusing)

Based on field maps of injection channel we have identified

- (ideal) trajectory that emerges tangent to central orbit of muon ring
- twiss parameters at end of M5 beamline that maximize acceptance through injection channel into ring.

# Muon storage ring

$$p_0 = 3.094\ GeV/c$$

$$B = 1.45\ T$$

$$R_0 = \frac{3.3356 p_0}{B} \approx 7.1\ m$$

$$\omega_c = \frac{\beta c}{R_0} \approx 4.2 \times 10^7\ Rad/s$$

$$f_c = \omega_c / 2\pi \approx 6.7\ MHz$$

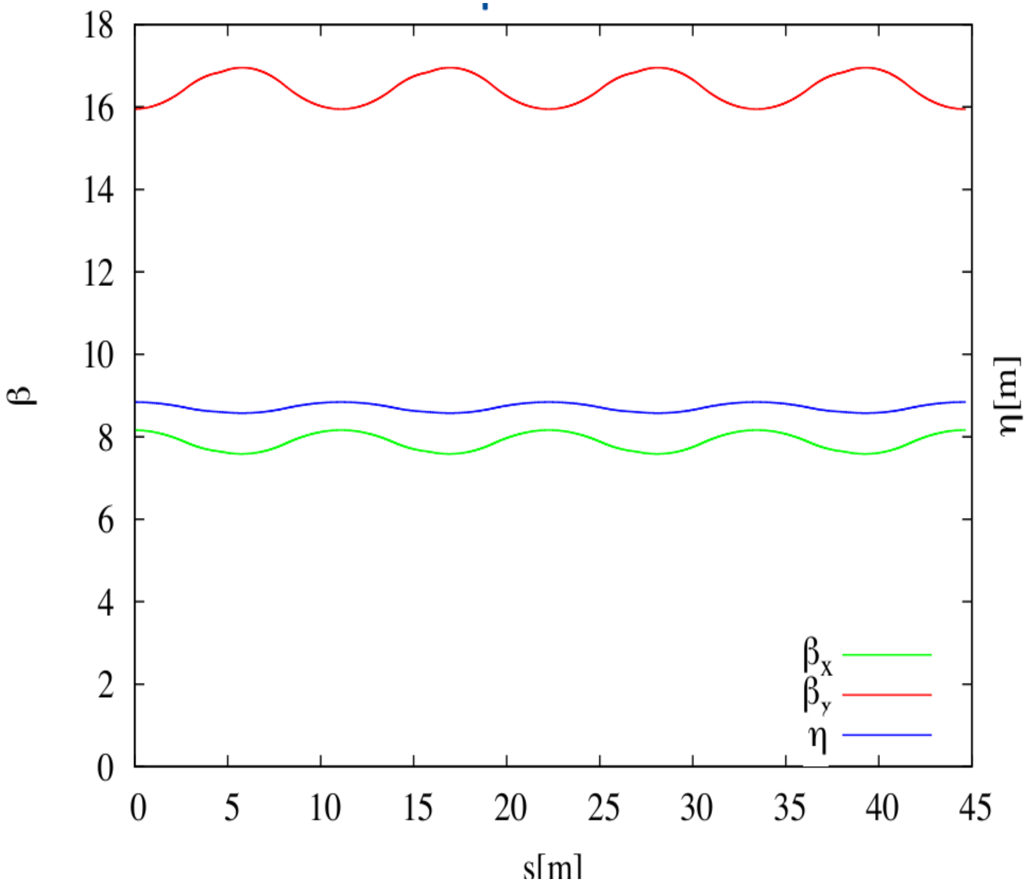
$$\alpha = \frac{\Phi}{y^2 - x^2} \approx 1.3 \times 10^7\ V/m^2$$

$$n = \frac{2\alpha q R_0}{vB} \approx 0.18$$

$$f_x = \frac{\omega_c}{2\pi}\sqrt{1-n} \approx 6.1\ MHz$$

$$f_y = \frac{\omega_c}{2\pi}\sqrt{n} \approx 2.8\ MHz$$

$$f_{\text{CBO}} = f_c - f_x = 634\ kHz$$



$$\nu_x = \sqrt{1-n} \approx 0.9$$

$$\nu_y = \sqrt{n} \approx 0.4$$

$$\nu_x^2 + \nu_y^2 = 1$$

# Summary and future plans

- To achive the new precision goal, the Muon *g*-2 collaboration is building new equipment for the muon storage ring (kickers, collimators, trackers) and upgradig the existing one (electrostatic focusing quadrupoles).
- We have developed a Geant, BMAD, MARS and G4beamline models for pion production in the target, pion capture by the beamline, pion decay, muon capture by the beamline, beam transport, beam injection into the *g*-2 storage ring, beam storage in the *g*-2 ring.
- The beam simulation software has been successfully used to

  - optimize the pion producton target

  - optimize the interface (beamline to storage ring) parameters

  - optimize the detector geometry

  - preliminary estimate of the systematic uncertainties in the experiment

- Future plans: study systematics effects in the experiment.