Status Report from Muon g-2 Experiment at Fermilab

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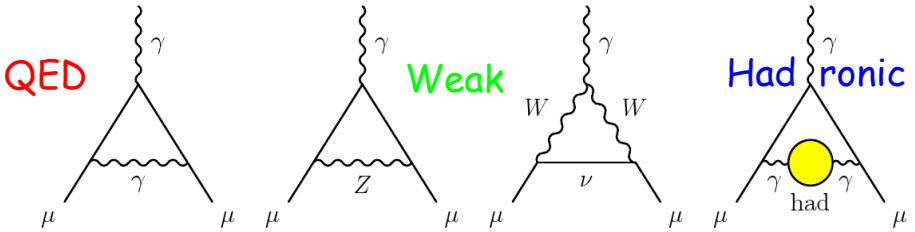
for the Muon g-2 collaboration

XXXIII Workshop in Particle Physics
La Thuile, Aosta Valley, Italy
March 10-16, 2019

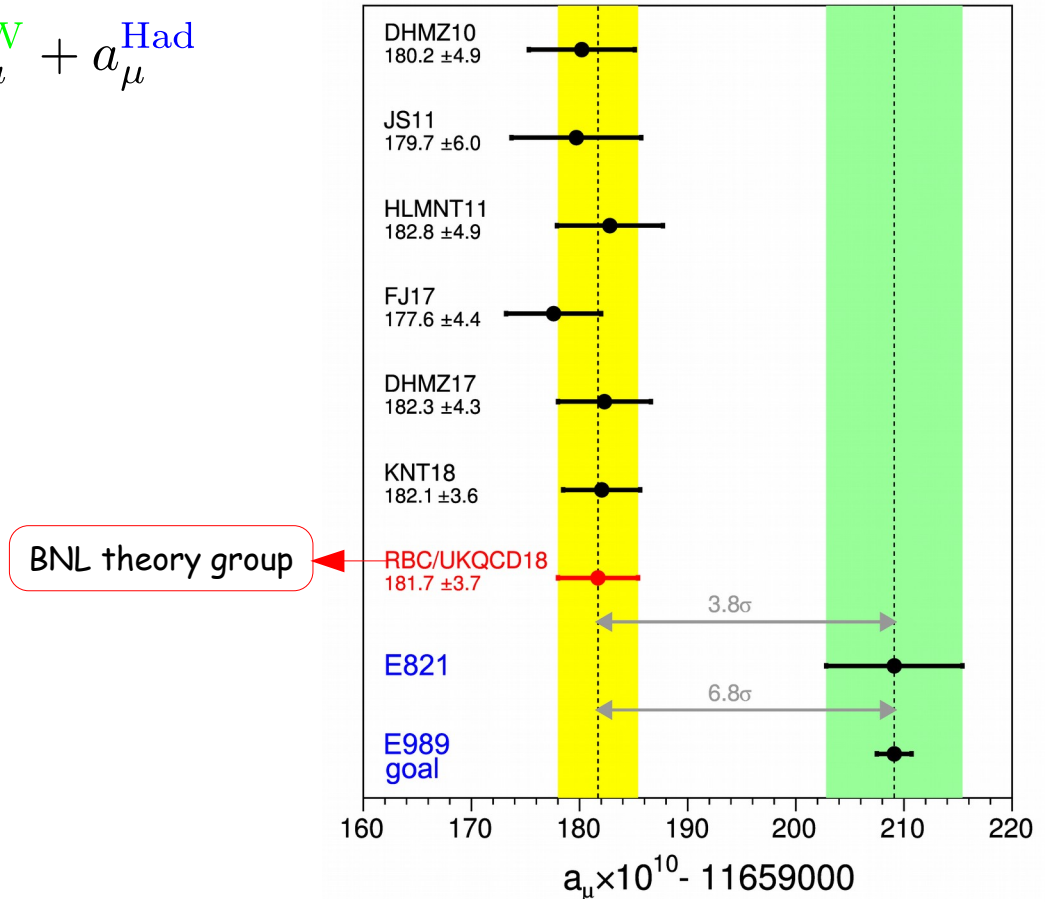
anomalous magnetic moment $a_\mu \equiv \frac{g_\mu - 2}{2}$

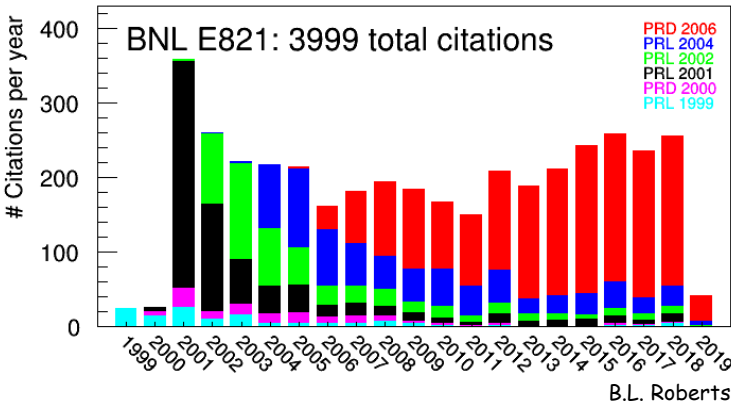
$$\mu_\mu = (1 + a_\mu)\frac{e\hbar}{2m_\mu} \qquad a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm W} + a_\mu^{\rm Had}$$



Source	value ($a_\mu \times 10^{-11}$)	error
QED	116 584 718.95	0.08
EW	154	1
HVP	6850.6	42
HLBL	105	26

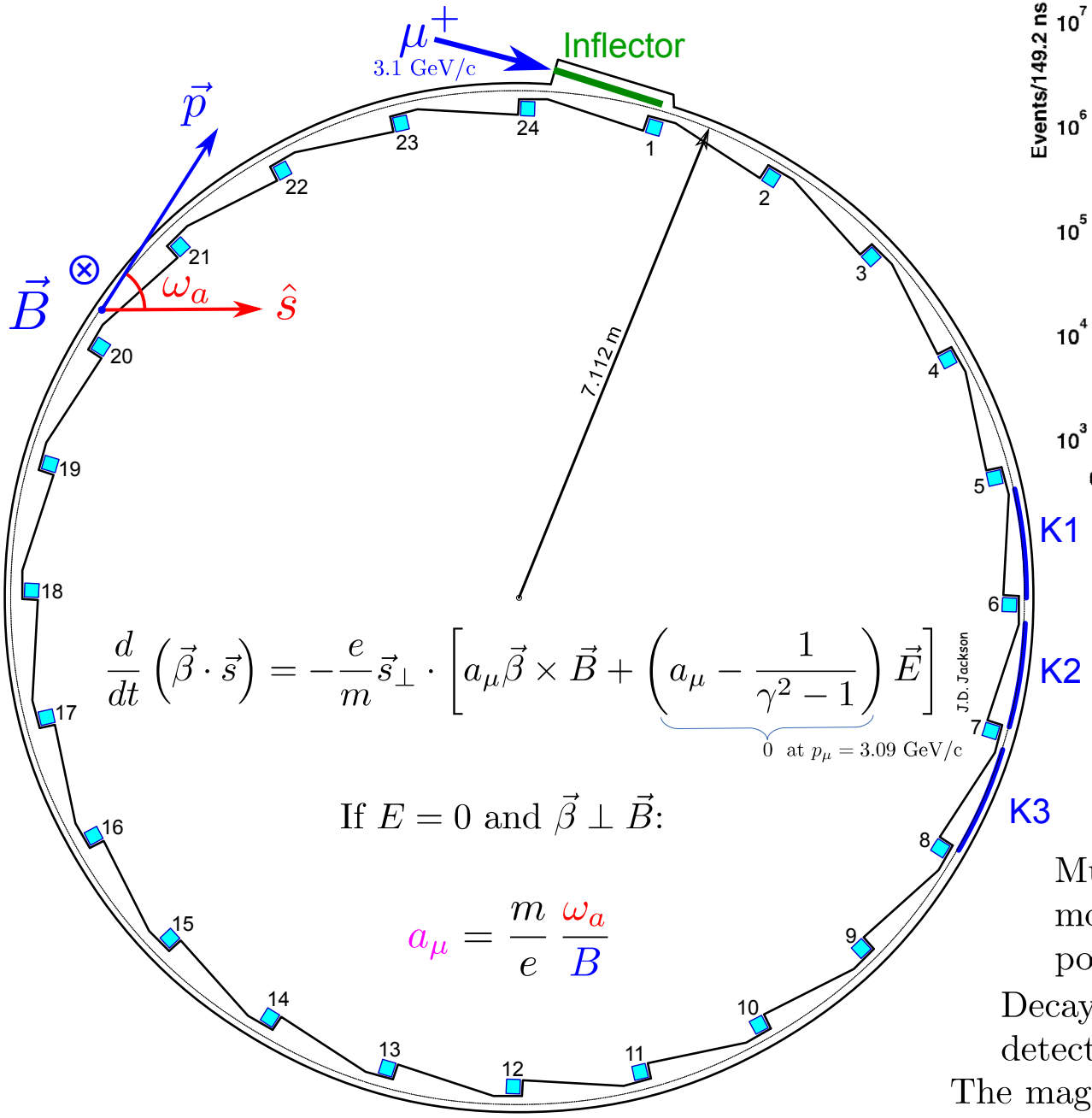
$$a_\mu^{\rm SM} = 116\,591\,803(1)(42)(26) \times 10^{-11}$$
$$a_\mu^{\rm exp} = 116\,592\,089(63) \times 10^{-11} \quad \text{BNL}$$
$$\Delta a_\mu = a_\mu^{\rm SM} - a_\mu^{\rm exp} \approx 3.5\sigma$$

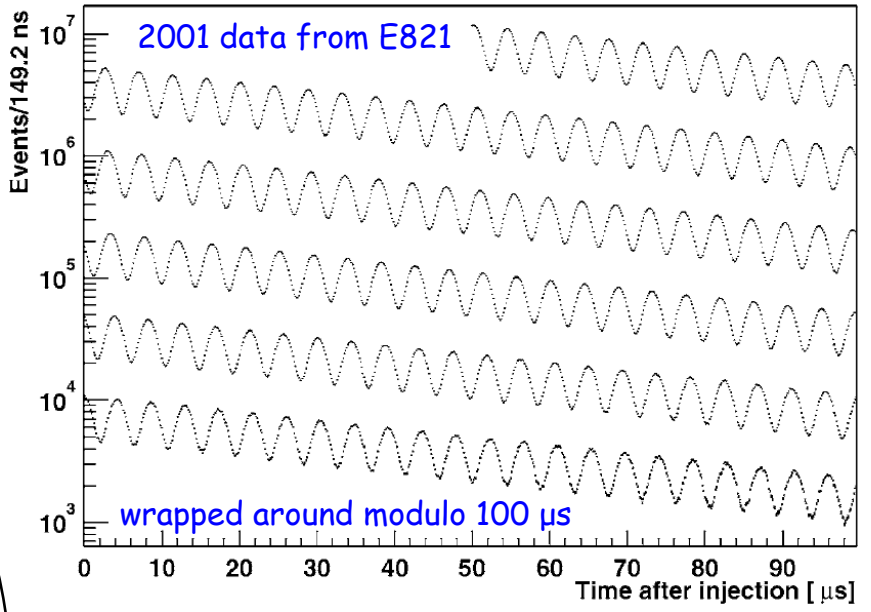




At present there is a tantalizing more than 3σ discrepancy between measured anomalous magnetic moment of the muon and Standard Model prediction. The persistent (for more than ten years) tension between experiment and theory is generating much interest within the particle physics community. To test this discrepancy the new experiment at Fermilab is expected to reduce the uncertainty in the experimental value by a factor of around four.

Muon g-2 experiment in a nutshell





a_μ is determined by by measuring the precession rate ω_a of spin $\hat{s}$ relative to momentum $\hat{p}$ in the magnetic field B of a storage ring.

Muon spin precession translates into energy oscillation of decay electrons in the laboratory frame.

Muon spin precession signal is observed as a modulation of the time distribution of decay positrons by applying energy cut.

Decay positrons are detected by 24 calorimeter detectors.

The magnetic field is measured by 378 fixed and 17 trolley NMR probes $\rightarrow \omega_p$.

uncertainties in E821 and E989 goals

$$a_\mu^{\rm exp} = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$

- Muon $g-2$ experiment delivers two quantities, ω_a and ω_p.
- μ_μ/μ_p must be measured by a separate experiment.

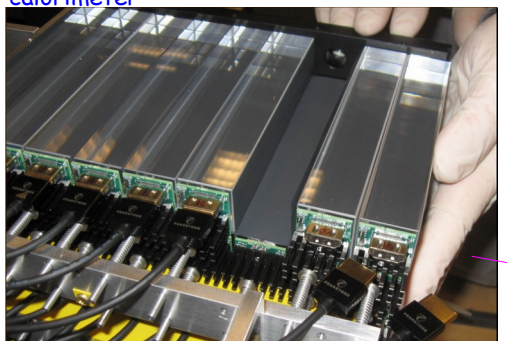
E821: $a_\mu^{\rm exp} = (11659208.0 \pm 6.3) \times 10^{-10}$ (0.54 ppm)
0.46 ppm statistical
0.28 ppm systematic
E989 goal: 0.14 ppm

- statistical goal: x20 more muons
- systematics:

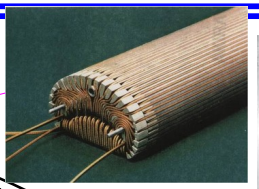
Category	E821 [ppb]	E989 Goal [ppb]
ω_a		
Gain changes	120	20
Pileup	80	40
Lost muons	90	20
CBO	70	< 30
E and pitch	50	30
Total	180	70
ω_p	170	70

g-2 storage ring instrumentation

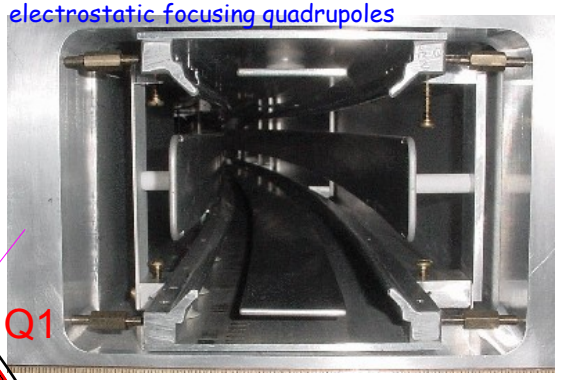
calorimeter

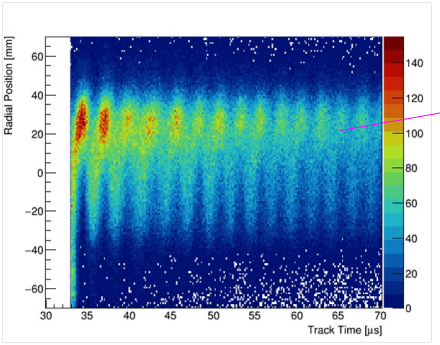


beam monitor



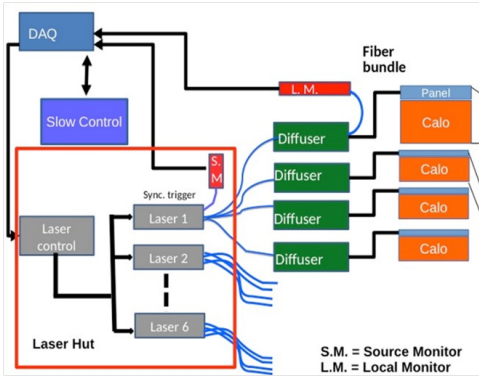
electrostatic focusing quadrupoles

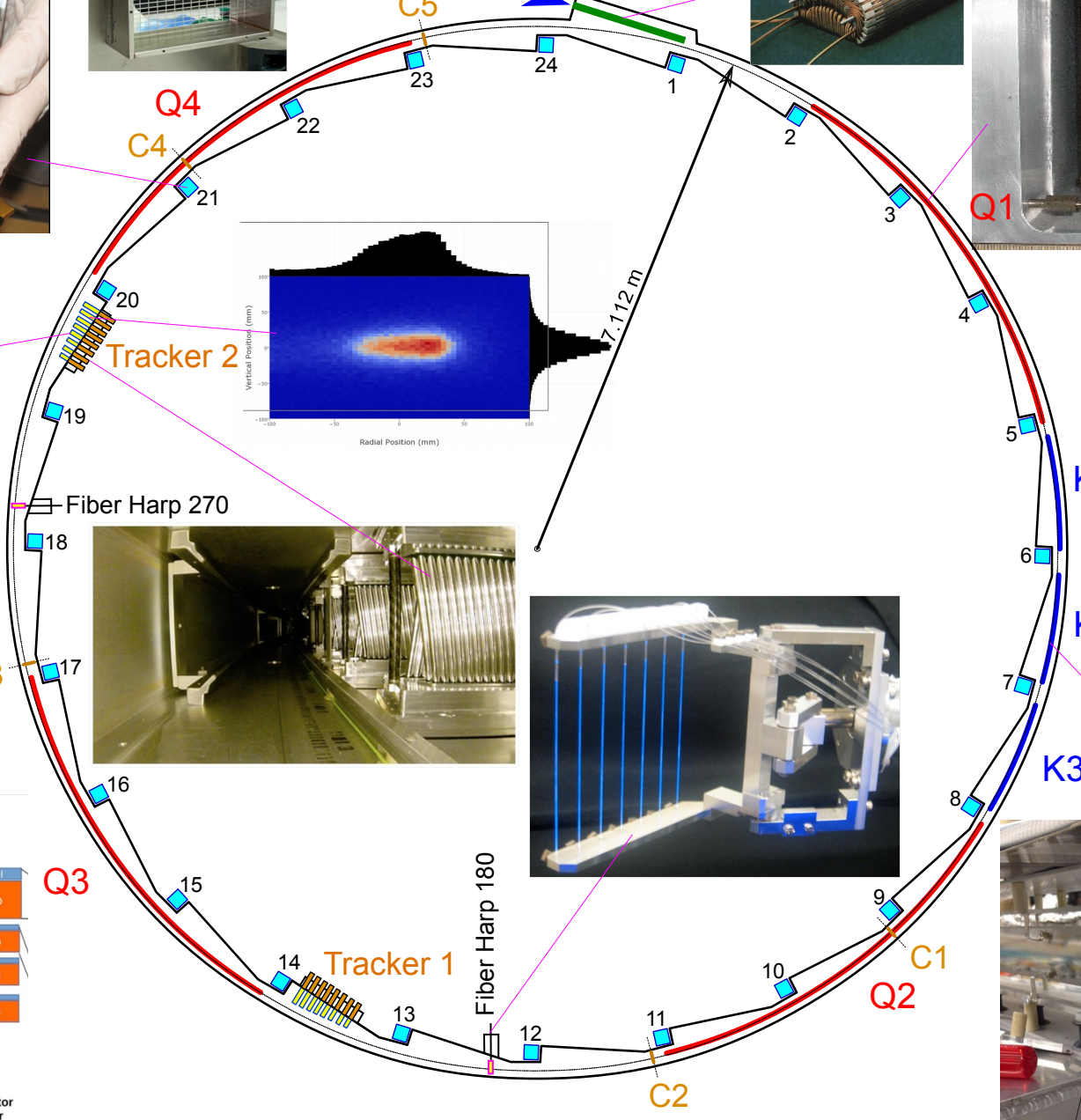




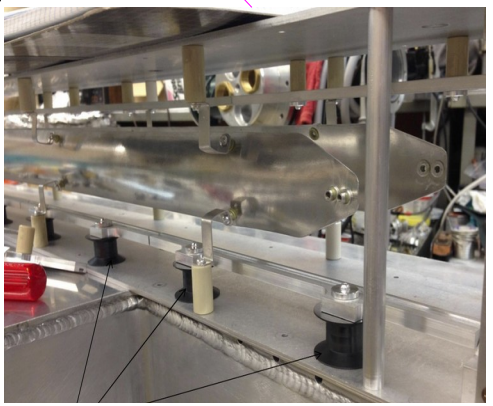
collimator

Laser gain monitoring system





Kickers



E989 proposal submitted

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018

E989 Proposal

The New (g – 2) Experiment:

A Proposal to Measure the Muon Anomalous

Magnetic Moment to ±0.14 ppm Precision

Request: 4×10^{20} **protons on target in 6 of 20 Booster batches during 15 Hz operation**

February 9, 2009

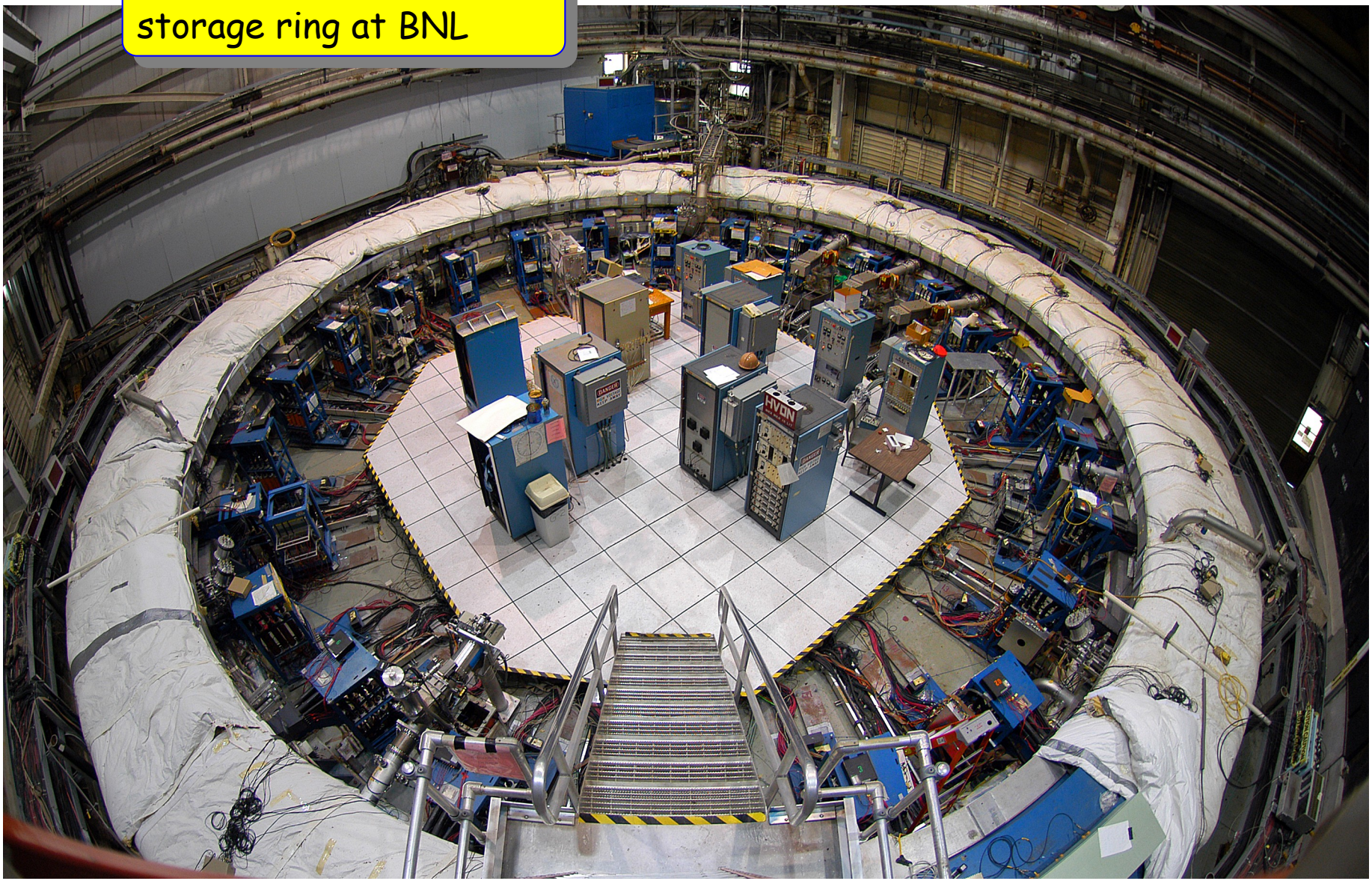
Contactpersons: David W. Hertzog (hertzog@illinois.edu, 217-333-3988)

B. Lee Roberts (roberts@bu.edu, 617-353-2187)

g-2 storage ring at BNL

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018

E989 Proposal approved storage ring at BNL



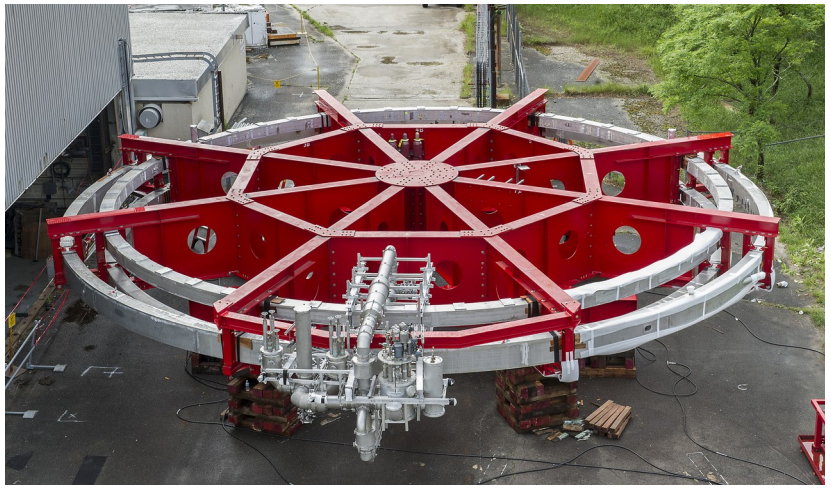
Disassembly of g-2 storage ring at BNL

2009 | 2010 | 2011 | **2012** | 2013 | 2014 | 2015 | 2016 | 2017 | 2018

Disassembly of g-2 storage ring started
First yoke piece removed (Sept.)

transportation of coils from BNL to Fermilab

2009 | 2010 | 2011 | 2012 | **2013** | 2014 | 2015 | 2016 | 2017 | 2018

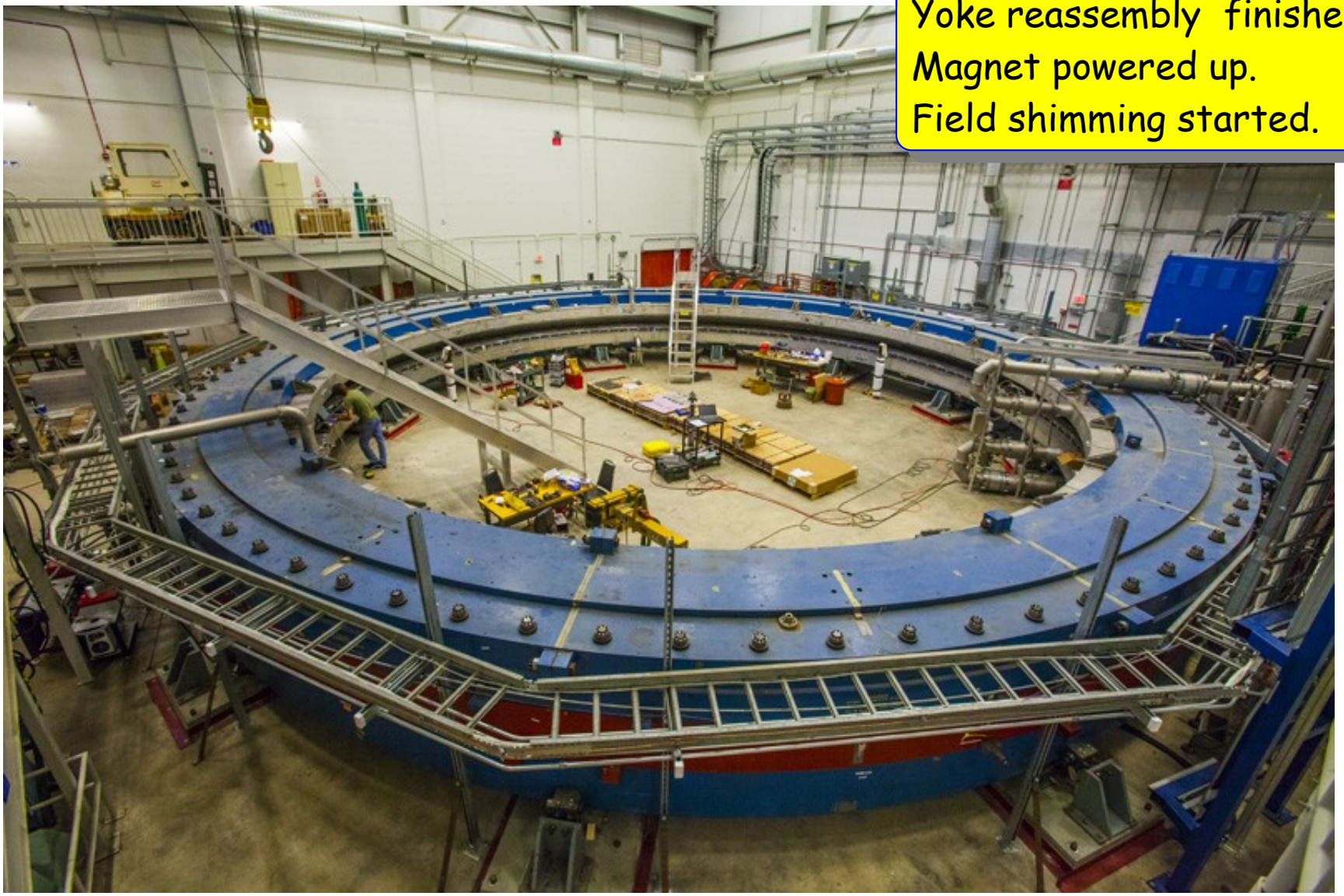


more photos and info: http://muon-g-2.fnal.gov/bigmove

g-2 storage magnet reassembled at FNAL

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | **2015** | 2016 | 2017 | 2018

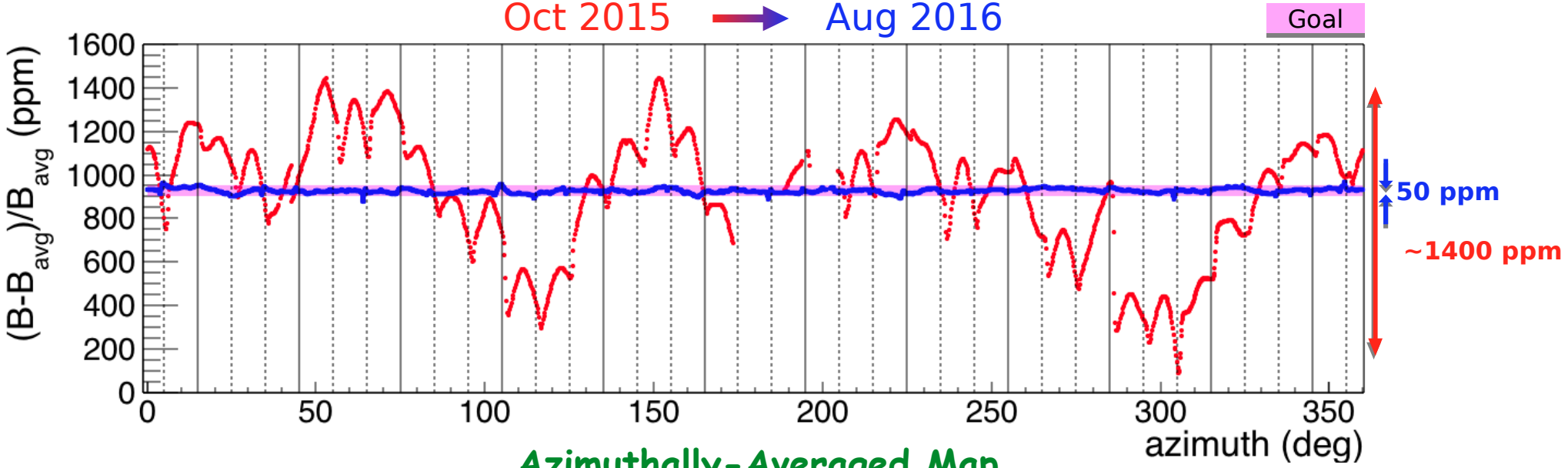
Yoke reassembly finished.
Magnet powered up.
Field shimming started.



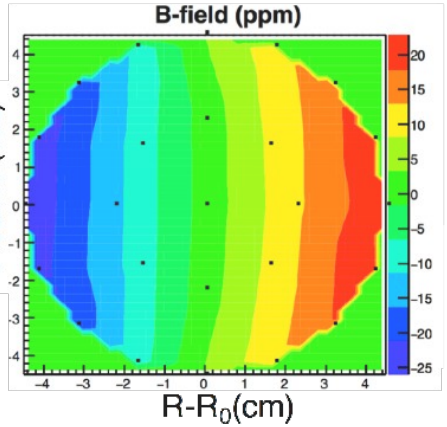
Rough Shimming Results

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | **2016** | 2017 | 2018

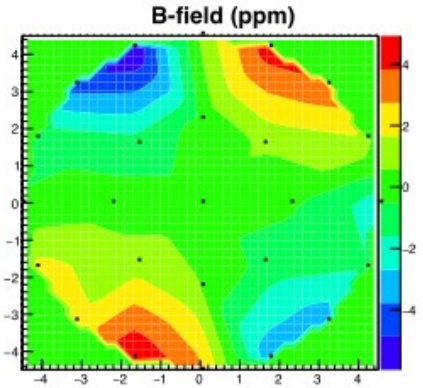
Oct 2015 → Aug 2016



Azimuthally-Averaged Map



	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07



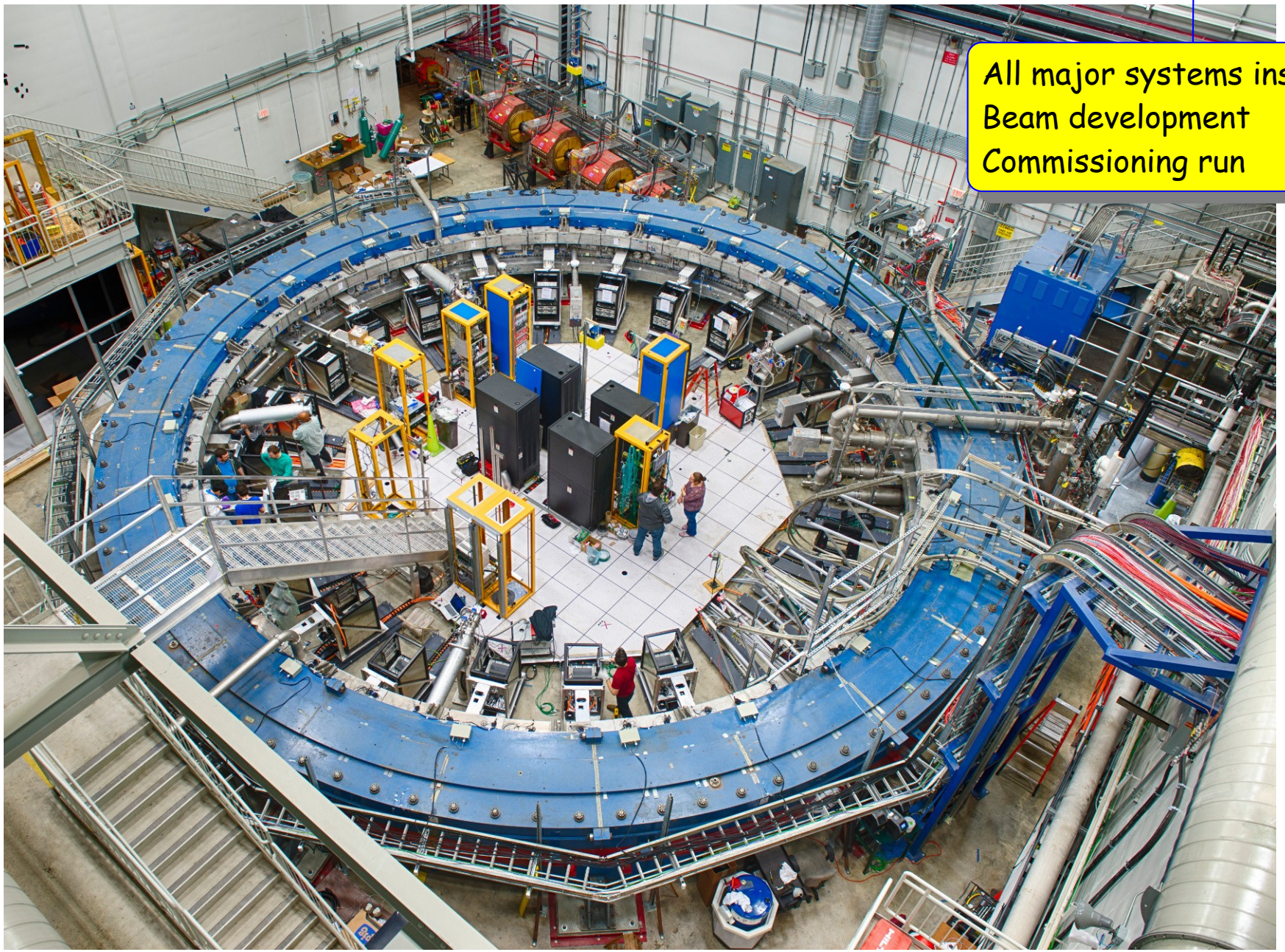
	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

D. Flay

- BNL E821: 39 ppm RMS (dipole), 230 ppm peak-to-peak
- FNAL rough shimming: 10 ppm RMS (dipole), 75 ppm peak-to-peak

Commissioning run

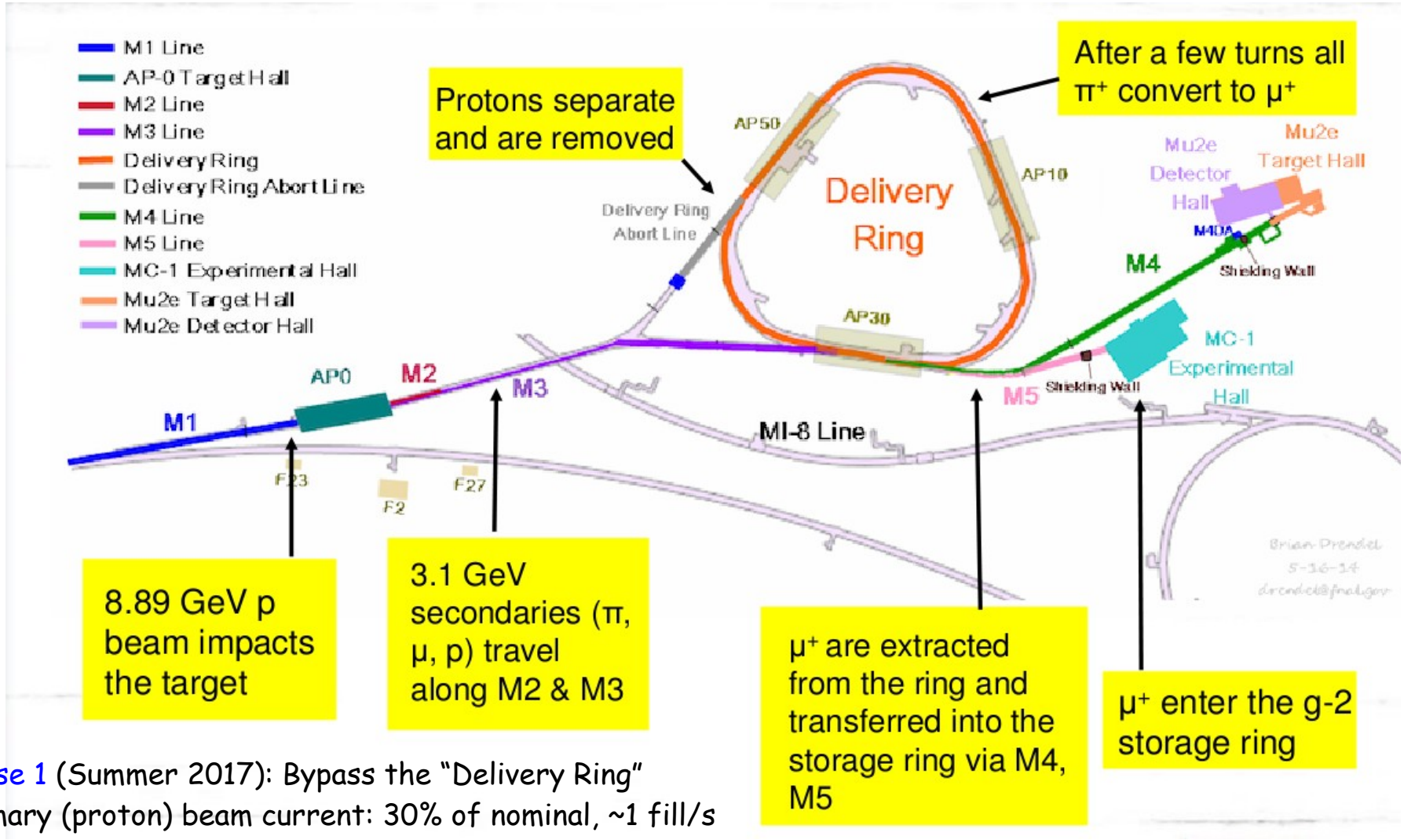
2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | **2017** | 2018



All major systems installed
Beam development
Commissioning run

Beam Development

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | **2017** | 2018

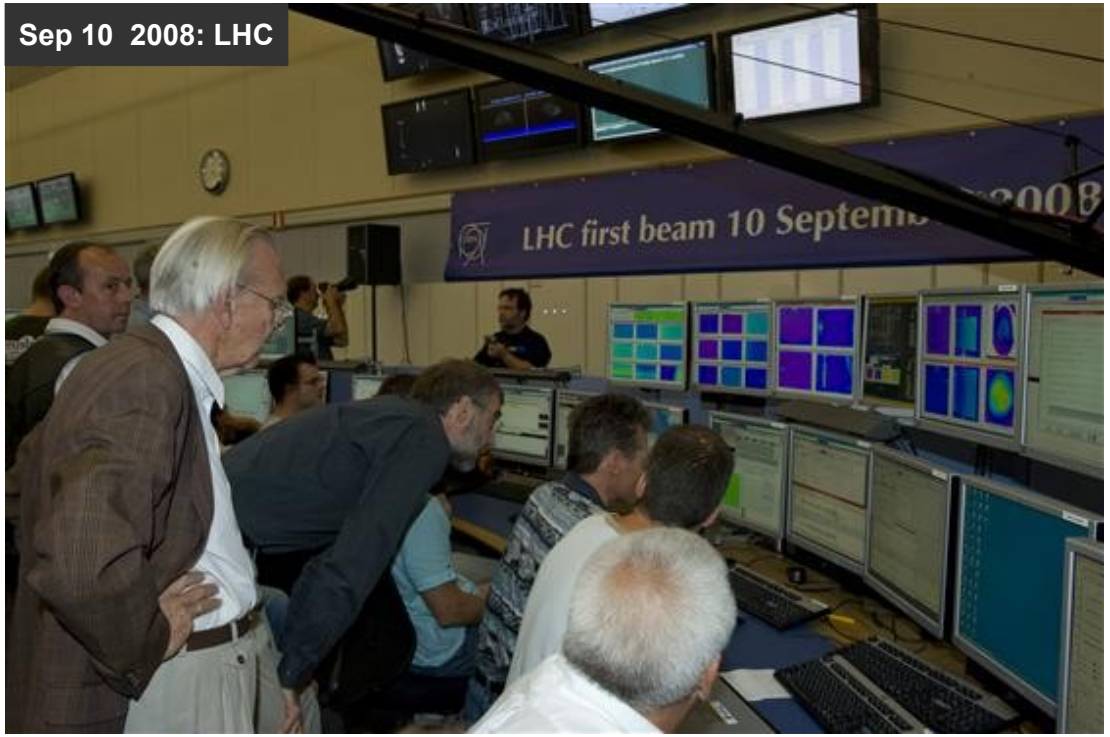


Phase 1 (Summer 2017): Bypass the "Delivery Ring"
Primary (proton) beam current: 30% of nominal, ~1 fill/s (vs. 12 Hz nominal)
Secondary beam: proton contamination

Phase 2 (Fall 2017 – Spring 2018): commissioning the entire beam line, beam development; ramping up to full current

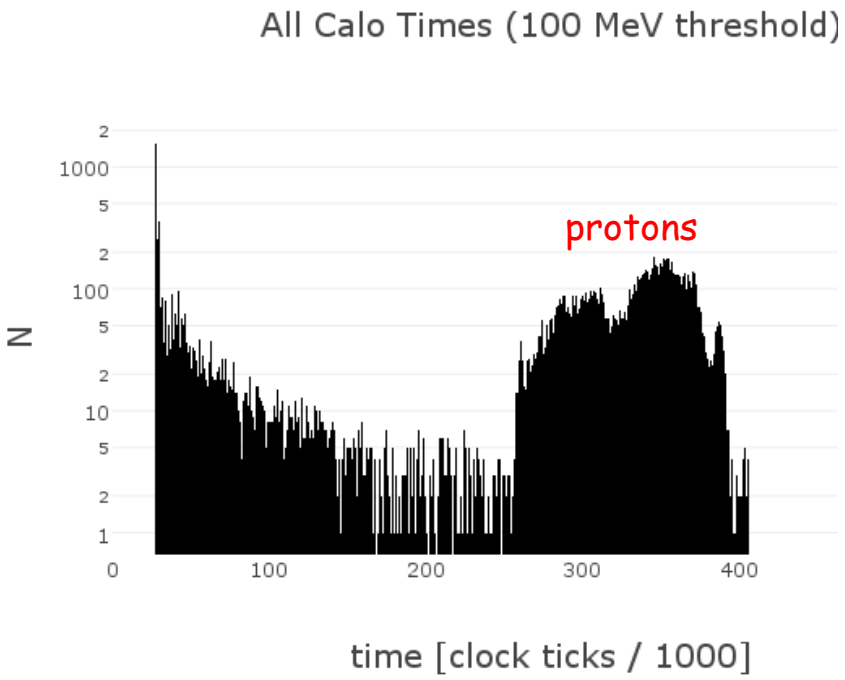
First Beam

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | **2017** | 2018



Commissioning run – Summer 2017

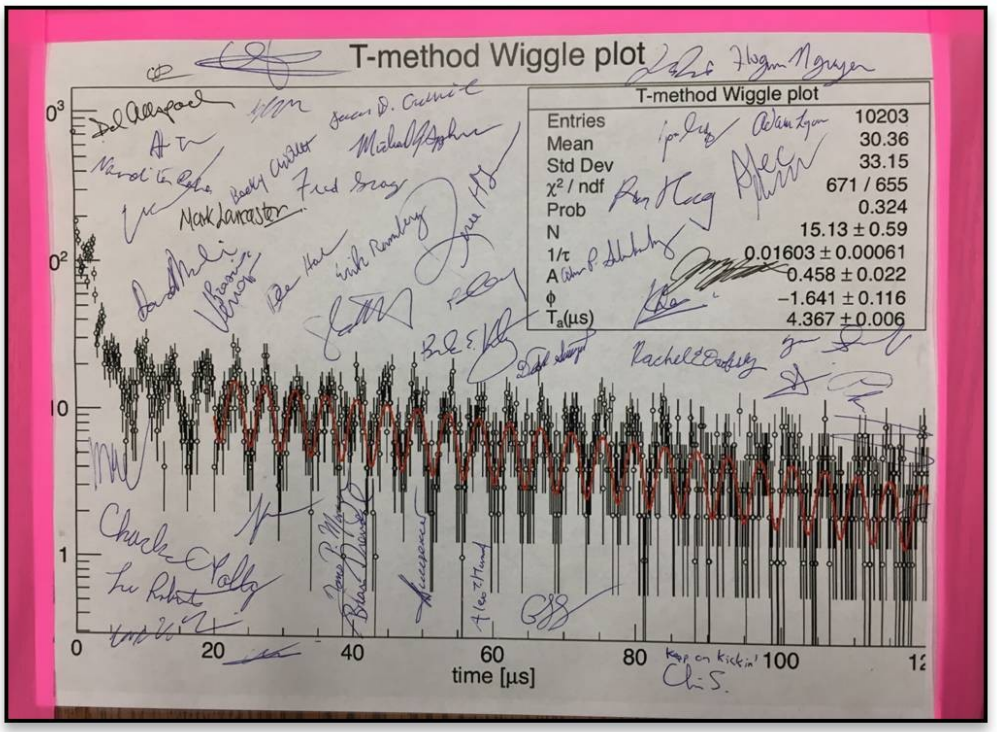
2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | **2017** | 2018



- De-energize quad plates early to release stored protons
- Detect proton "splash" in calorimeters
- Use the intensity of the "splash" as a measure of the stored beam
- Crucial for tuning the beam injection into the g-2 storage ring and beam storage during phase 1.
- Voltage/current scans of the inflector, kicker, electrostatic quadrupoles.

Withing a couple of weeks we had verified that:

- Detectors, electronics, DAQ worked to specification
- Injection systems could store the beam
- Generally, the observations were inline with expectations



First signal of muon spin precession – June 2017

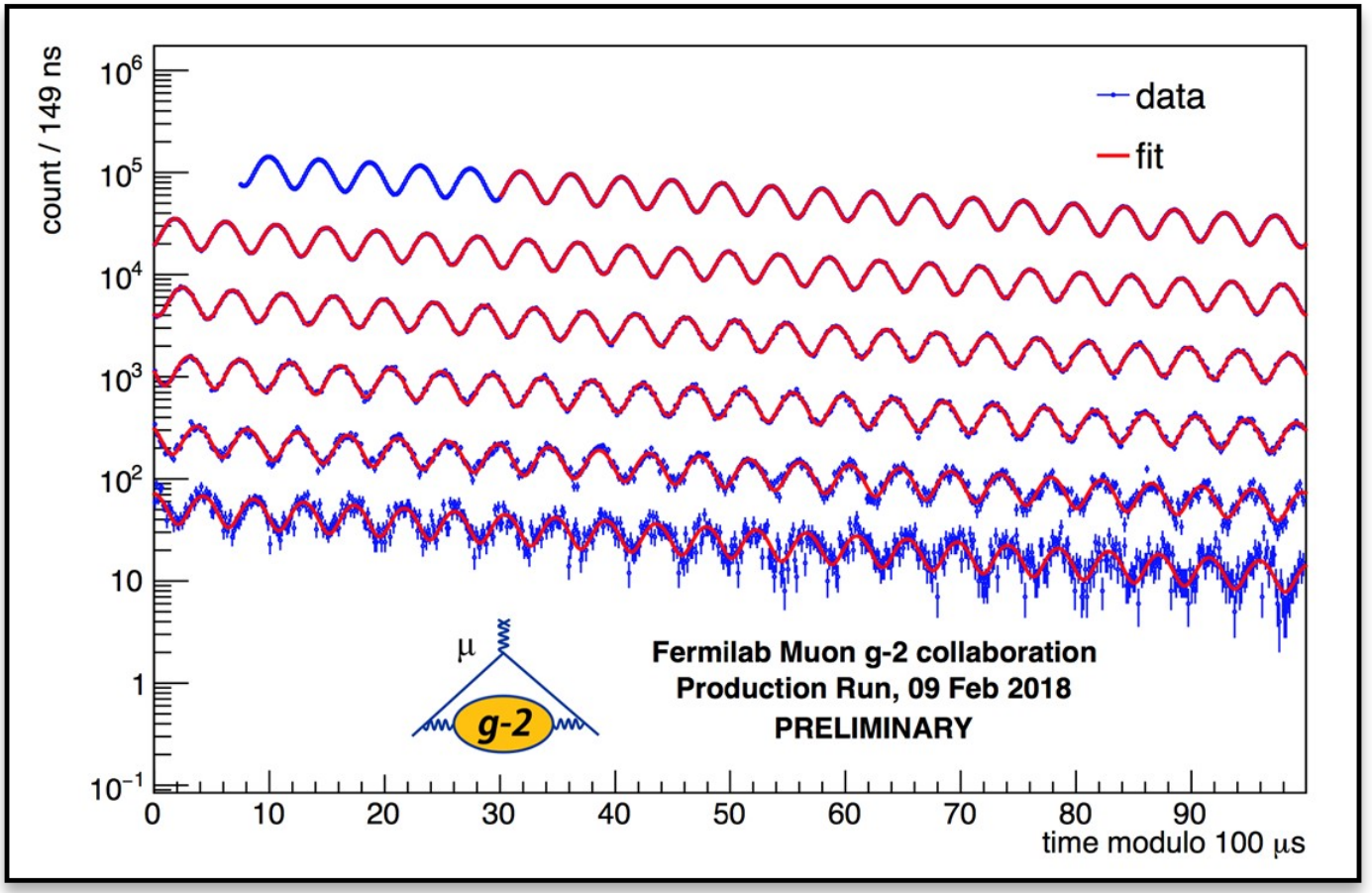
Phase II: Fall 2017 – Spring 2018

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018

Phase 1 (Summer 2017)
15 → 150 muons stored per fill
Phase 2 (Fall 2017 to Spring 2018)
300 → 6,000 muons stored per fill (TDR goal: 10,000 muons)

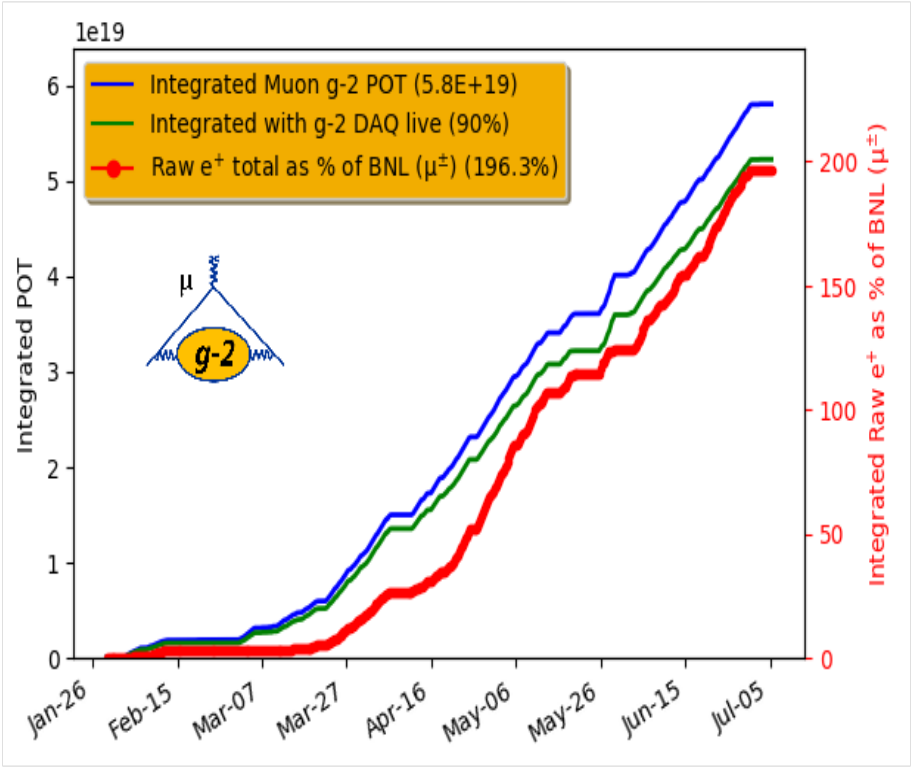
storage per bunch: 400x
storage per second: 10^5x

Highlights:
- Commissioned higher rep rate (12 Hz design)
- Delivery Ring injection
- Implemented proton removal in the Delivery Ring
- Muon flux tune-up
- Field calibration



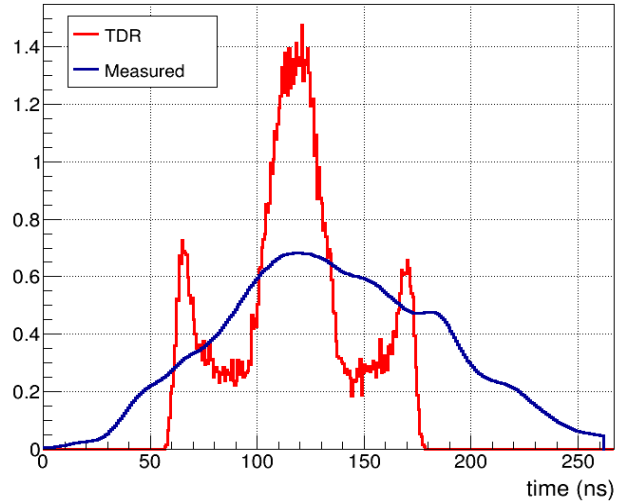
First Production run, 2018

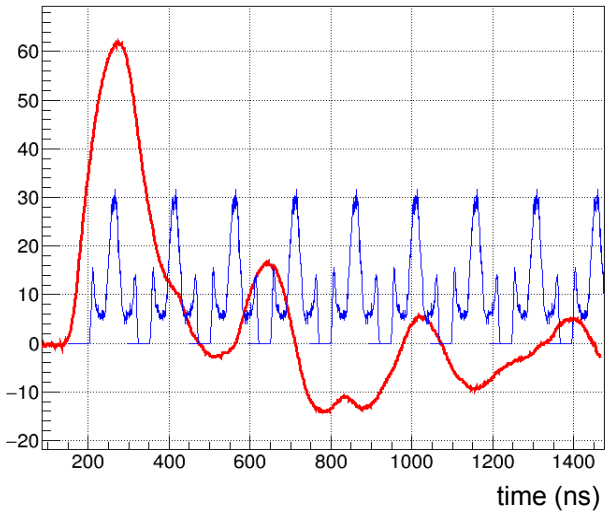
2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | **2018**

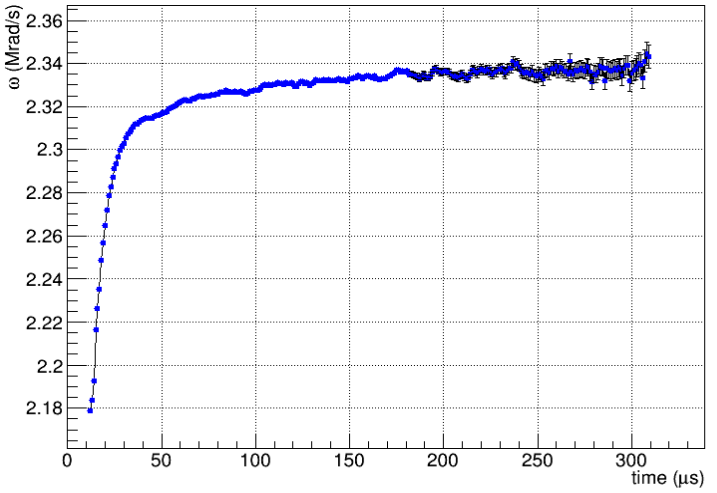


- Run 1 finished in July 2018
- ~1.7xBNL statistics of raw data collected
- Expect ~1xBNL statistics of physics data after data quality cuts.

  Challenges:
- Beam pulse is longer than design expectations
- Kicker current pulse: lower amplitude, ringing
- Non-ideal beam and kicker pulses affect
  - muon storage
  - stored beam momentum
  - stored beam dynamics (CBO amplitude)
- Kicker-quad interference
- Varying CBO frequency

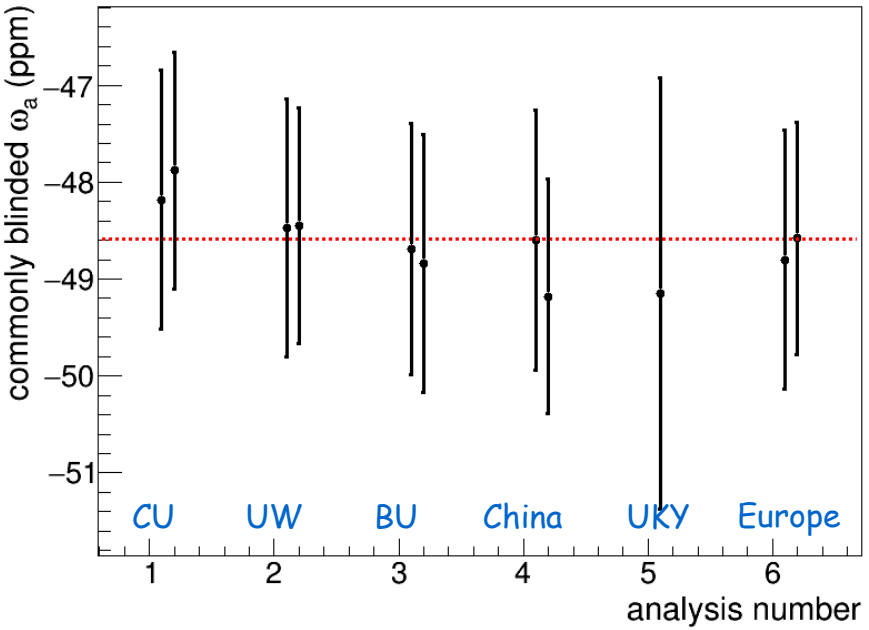






Run 1 analysis status

- Analysis of ω_a and ω_b by independent groups
- Blind analysis
- Two-level blinding (software and hardware) at the level of 25 ppm
- ω_a analysis efforts
  1) East (CU) – T, A
  2) West (UW) – T, A
  3) Europe (Italy, UK) – T, A
  4) BU – Ratio
  5) China – T, A
  6) UKY - Q
  - Independent approaches to pileup correction
  - Relative unblinding on 1.3 ppm data set – February 26, 2019
  - Excellent agreement between various analysis
  - No new systematics discovered
- Analysis of systematic uncertainties due to beam-dynamics by independent groups or independent methods.



Present status and future plans

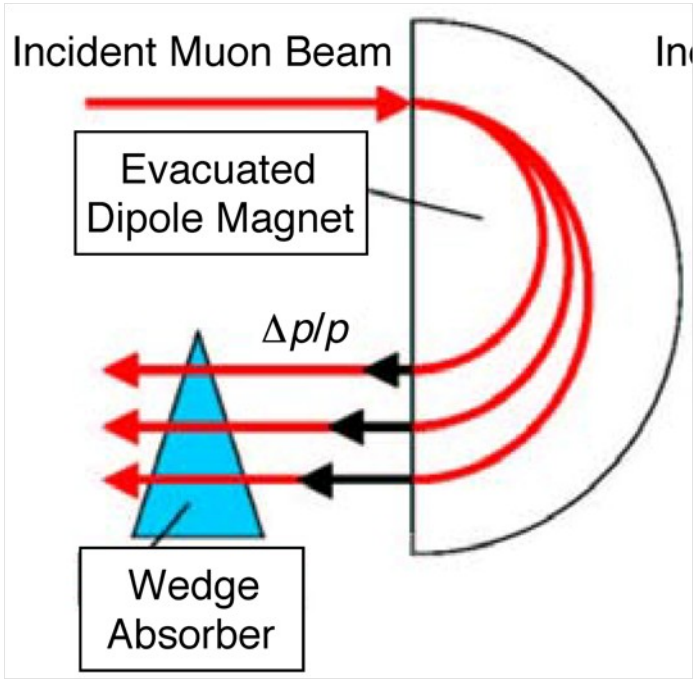
- Addressed hardware problems during shutdown
- Starting 2nd physics run
- Take Run 2 data till summer shutdown
- Thanks to various hardware improvements the rate of stored muons increased by >30% compared to Run 1
- Data collected last week confirm improvements in kicker performance
- On-going effort to increase the rate of magic-momentum muons with momentum wedges in muon beamline
- Installation of new (open-ended) inflector during next shutdown to increase injection efficiency (>20%)

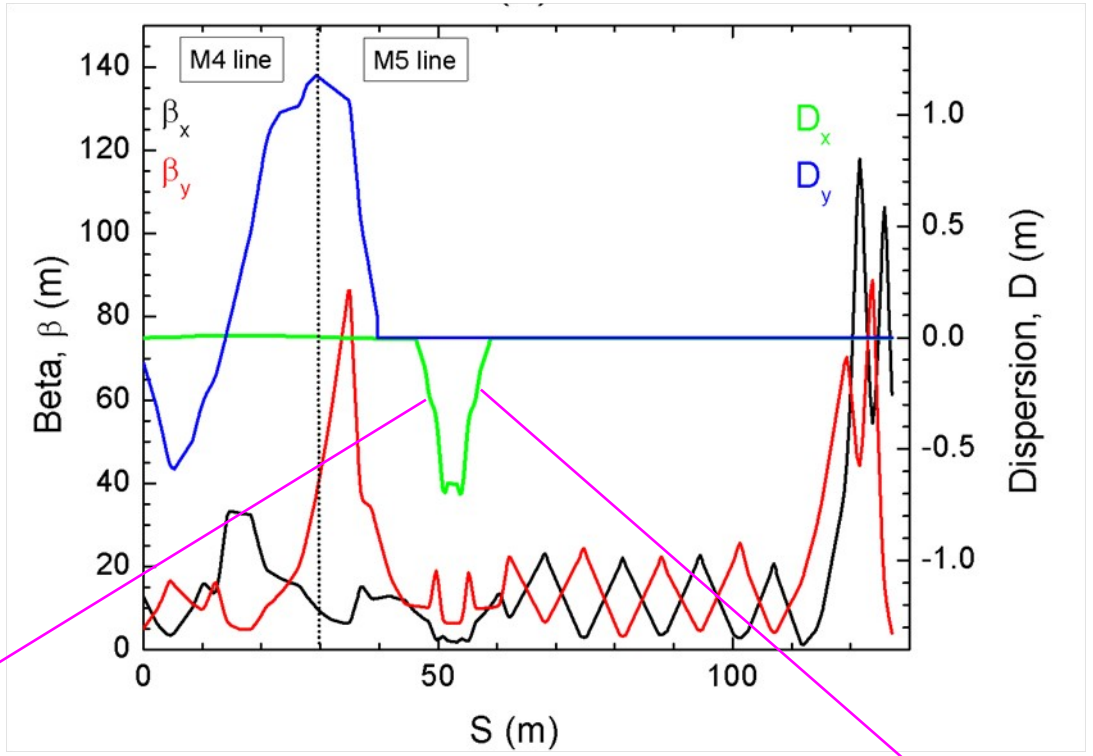
Summary

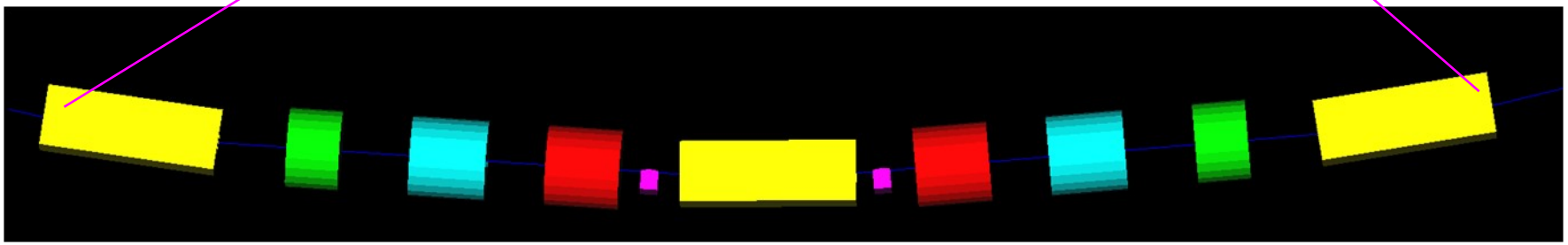
- Muon g-2 experiment at Fermilab completed first physics run
- Accumulated ~1xBNL statistics of physics data
- Data analysis of Run 1 progresses well
- Relative unblinding of independent analysis of 1.3 ppm ω_a data set
- No new systematic error discovered
- Physics Run 2 is starting
- Fixed hardware problems observed in Run 1
- Increased muon storage rate by > 30%

Backup slides

Path to higher flux: momentum wedges

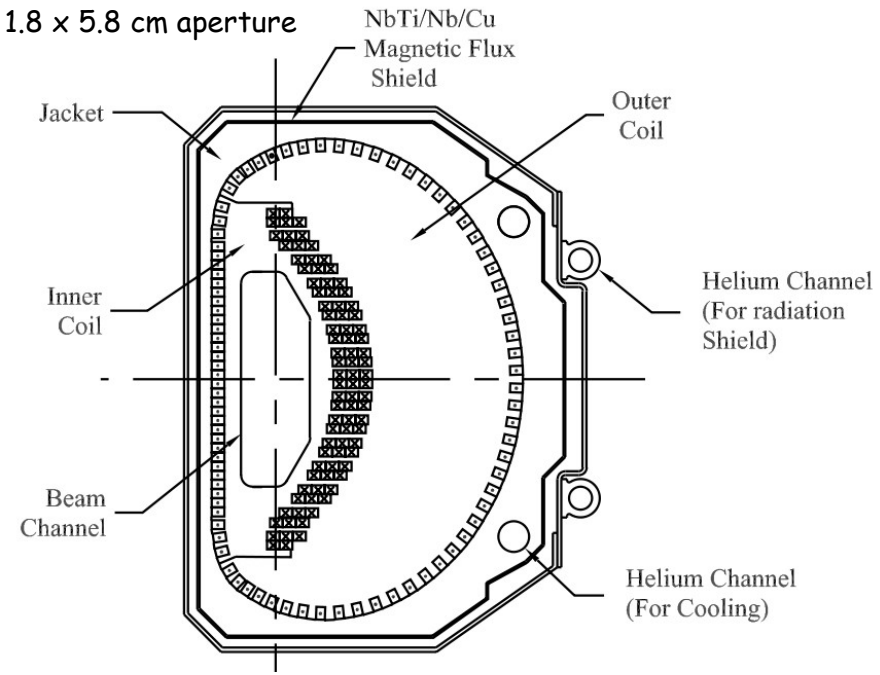


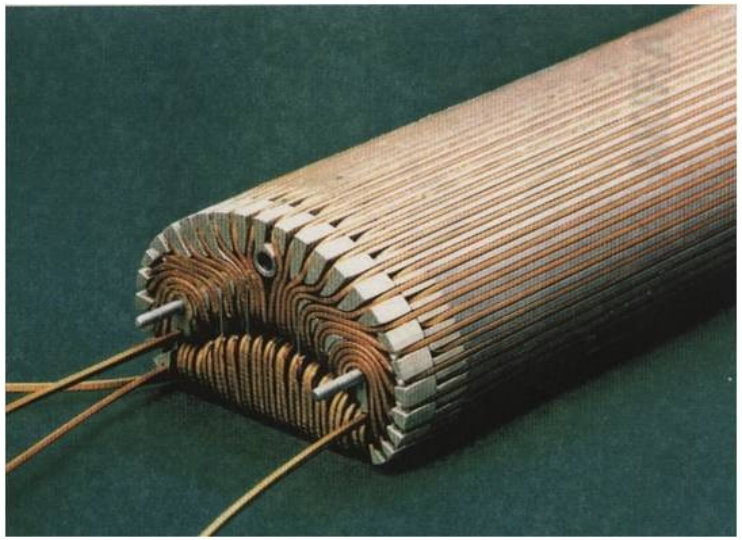




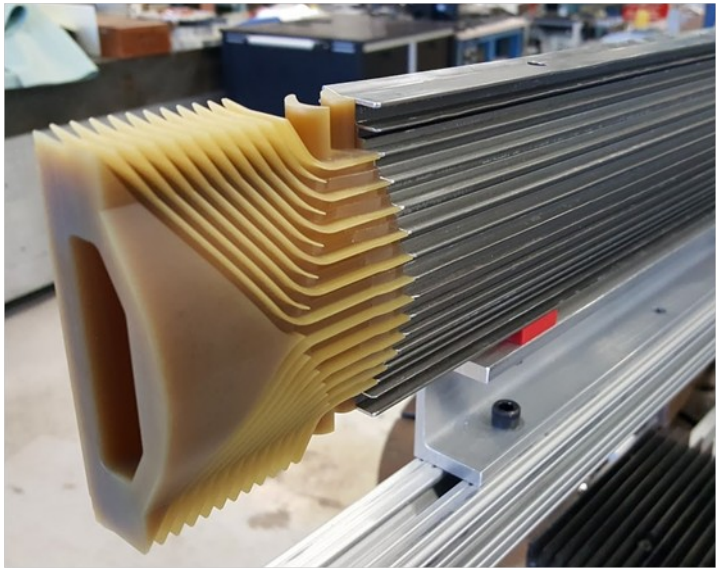
Path to higher flux: new inflector

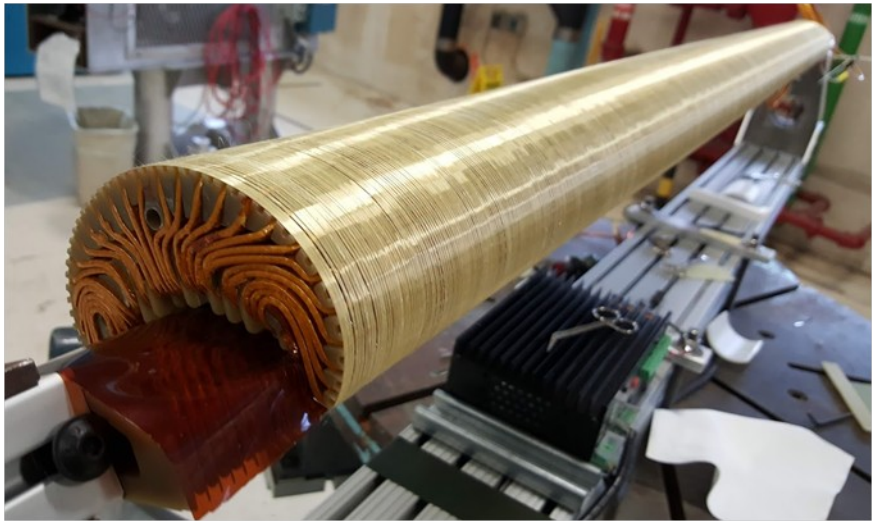
existing inflector





new inflector – open-ended





- expect ~30% higher beam transmission
- plan to install during Summer 2019 shutdown

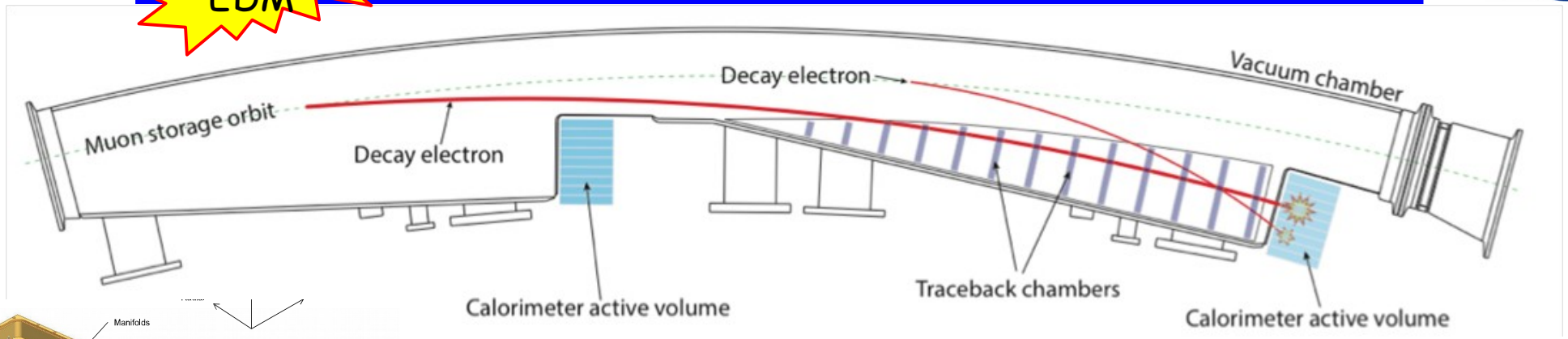
BROOKHAVEN NATIONAL LABORATORY

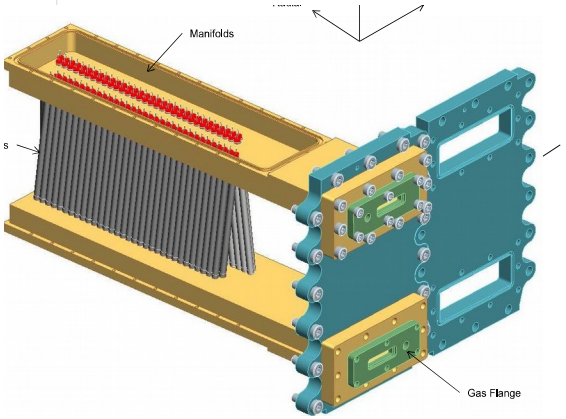
beam, EDM

New Tracker

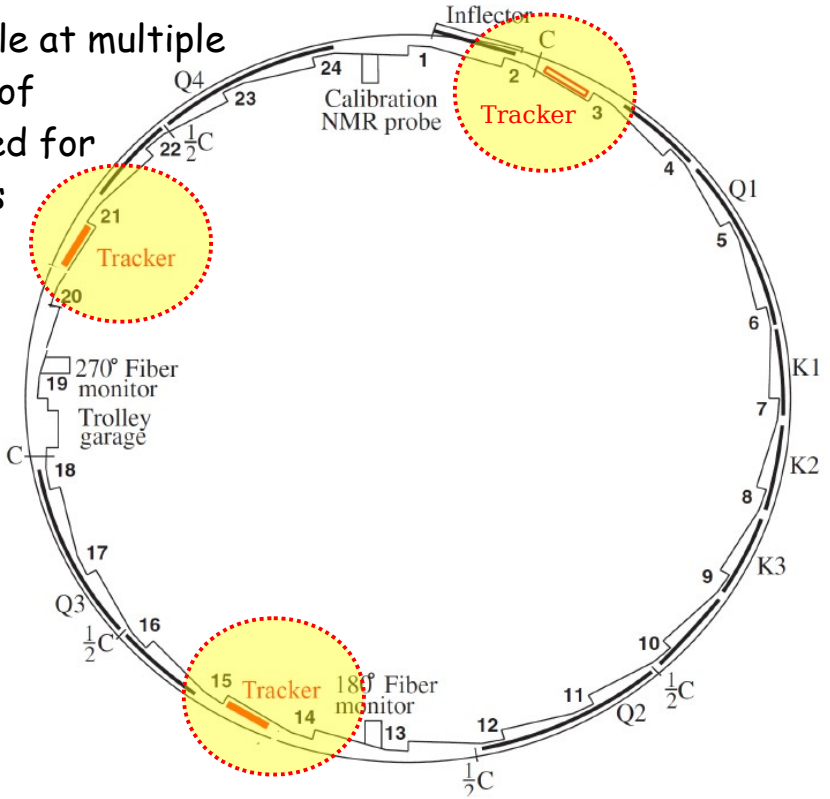
B. Casey, FNAL

g-2





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 ω_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).



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

g-2 ring operating point for 2018 run

The ESQ system defines the operating point of muon g-2 storage ring, which must be chosen such that it is away from betatron and spin resonances. The theoretical analysis of resonance conditions was performed by BNL.

$$\nu_x = \omega_x/\omega_c \approx \sqrt{1-n} \qquad \nu_x^2 + \nu_y^2 \approx 1$$

$$\nu_y = \omega_y/\omega_c \approx \sqrt{n} \qquad n \equiv \frac{kR_0}{vB}$$

resonance conditions:

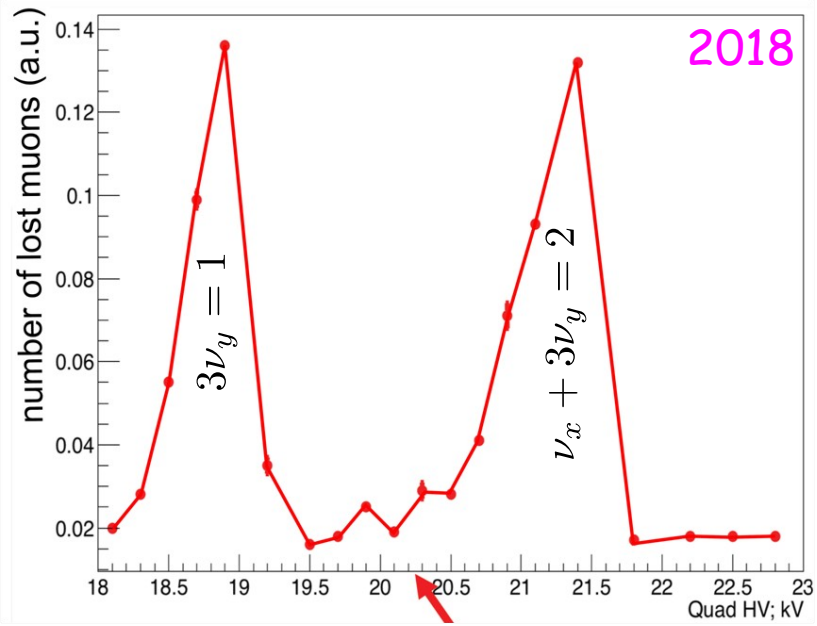
$$L\nu_x \pm M\nu_y \pm N = 0 \text{ (betatron)}$$

$$L\nu_x + M\nu_y \pm N = a_\mu\gamma \text{ (spin)}$$

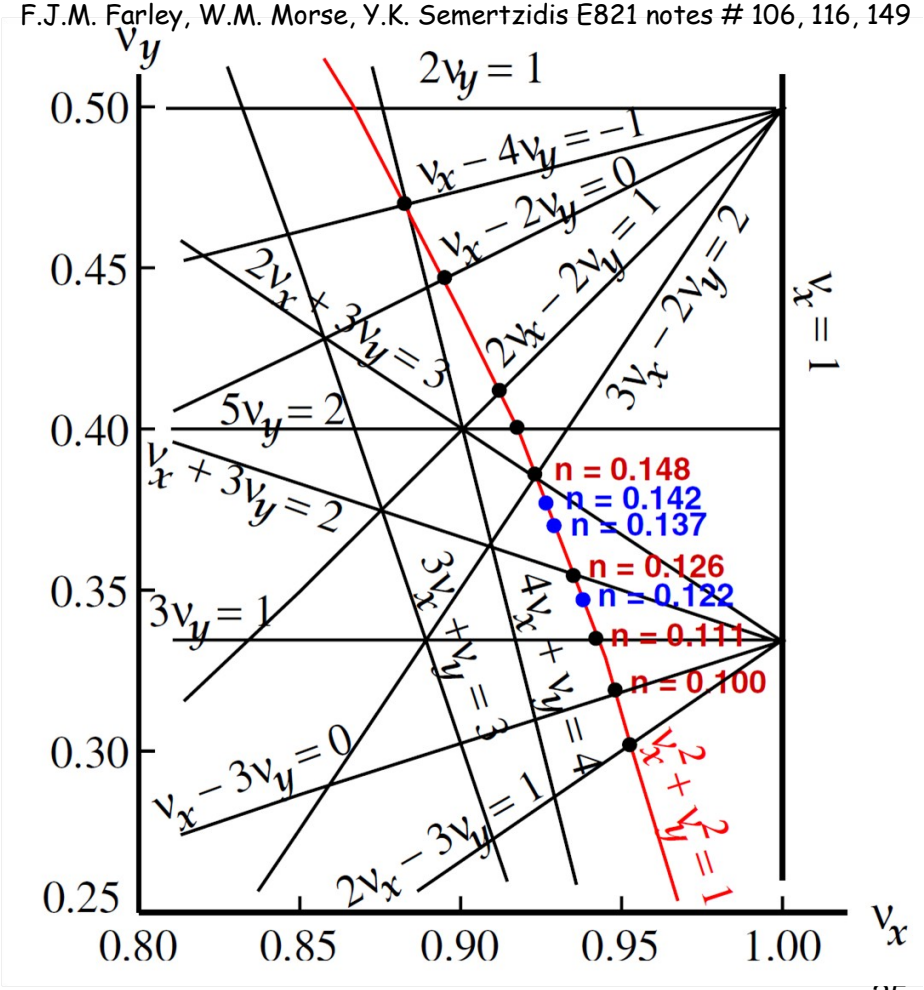
where L, M, N are integers.

F.J.M. Farley, W.M. Morse, Y.K. Semertzidis E821 notes # 106, 116, 149

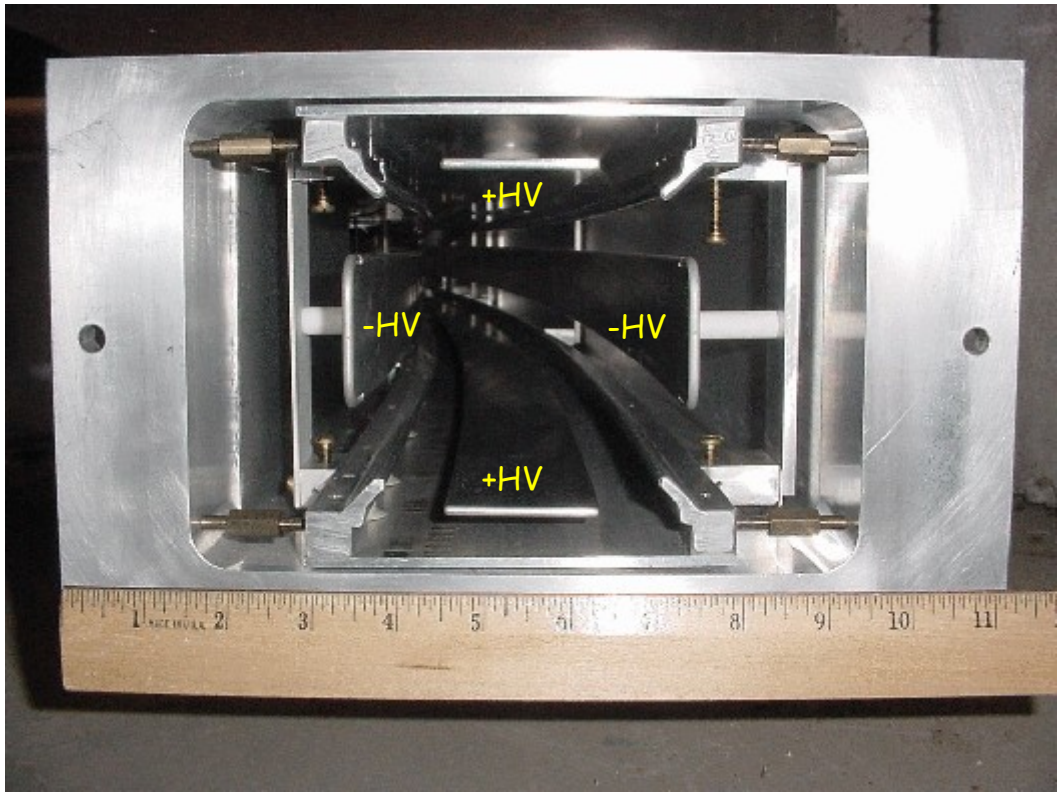
In 2018 run, the operation point of g-2 storage ring was chosen to minimize muon losses. The measured muon loss vs. ESQ voltage curve agrees well with theory expectation.

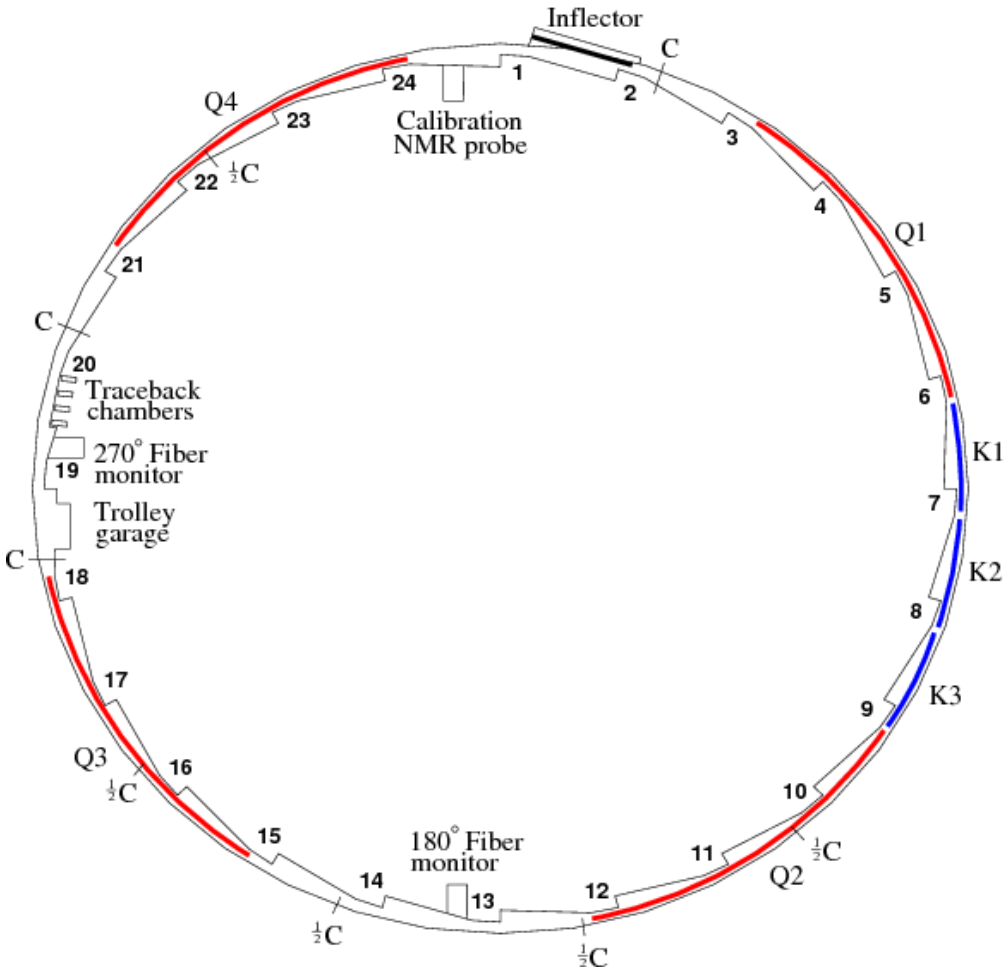


Sudeshna Ganguly, Muon g-2 internal note #11085



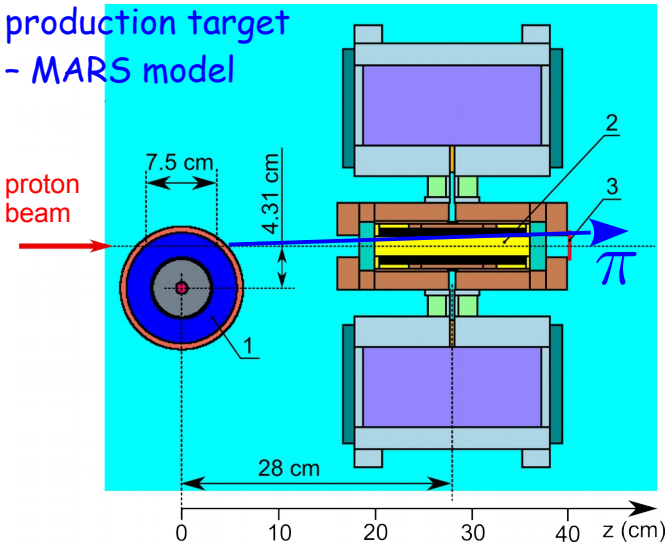
BNL hardware responsibility



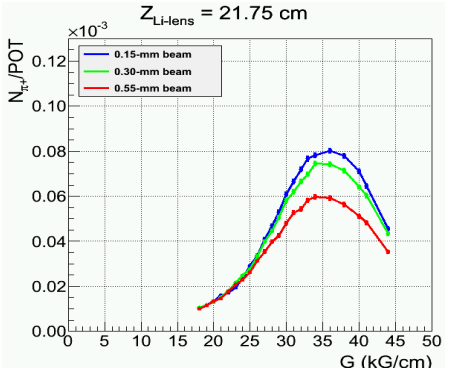


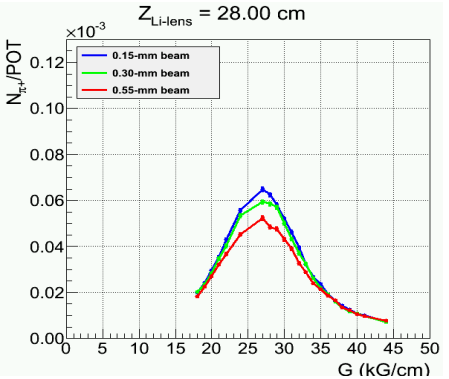
In E989 BNL is responsible for Electrostatic Focusing Quadrupole (ESQ) system. The ESQ plates occupy about 43% of the storage ring circumference and provide vertical focusing of muons.

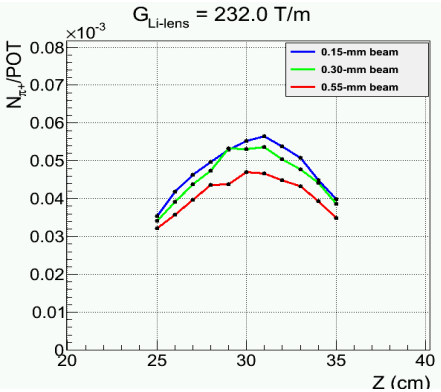
Beam simulations: production and transport - BNL



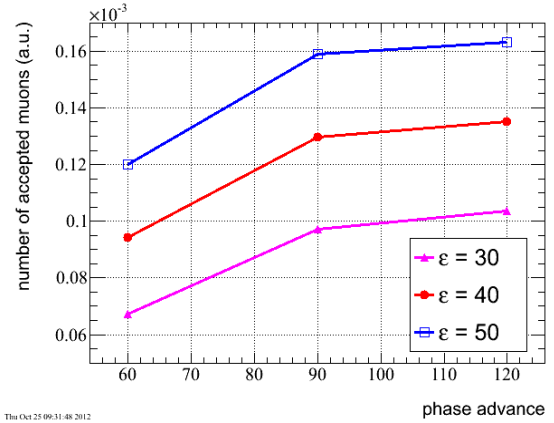
- Optimization studies of production target for pion capture
- Captured pions vs. primary beam parameters

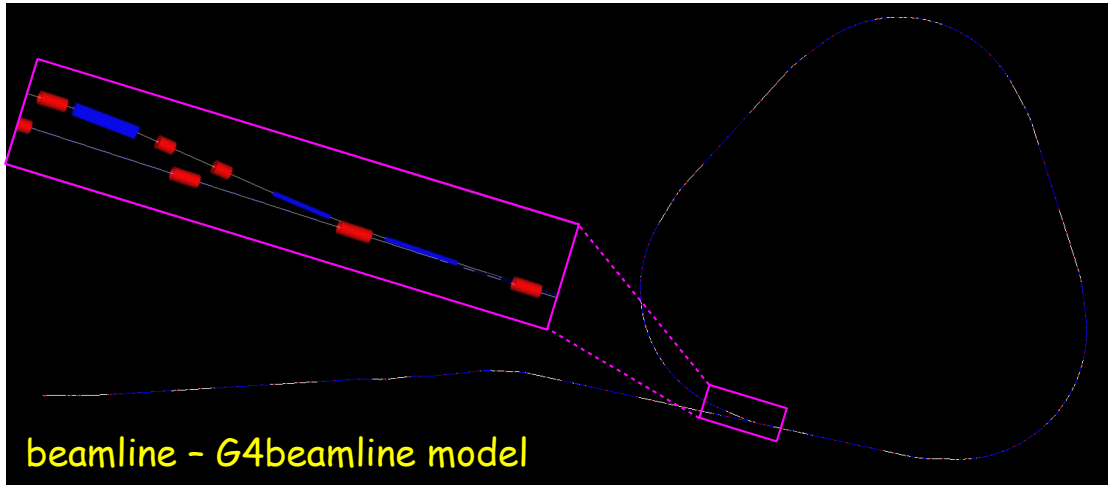


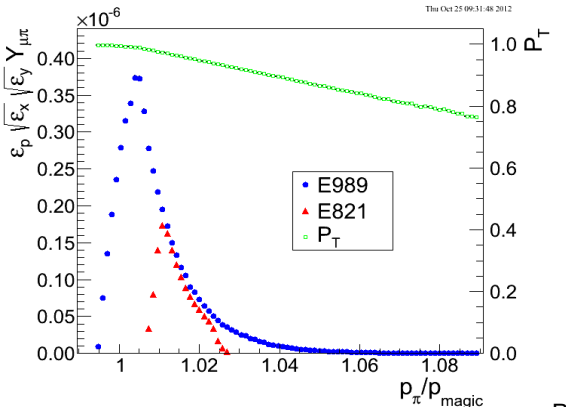




optimization of FODO lattice for muon capture guided the design of g-2 beamlines

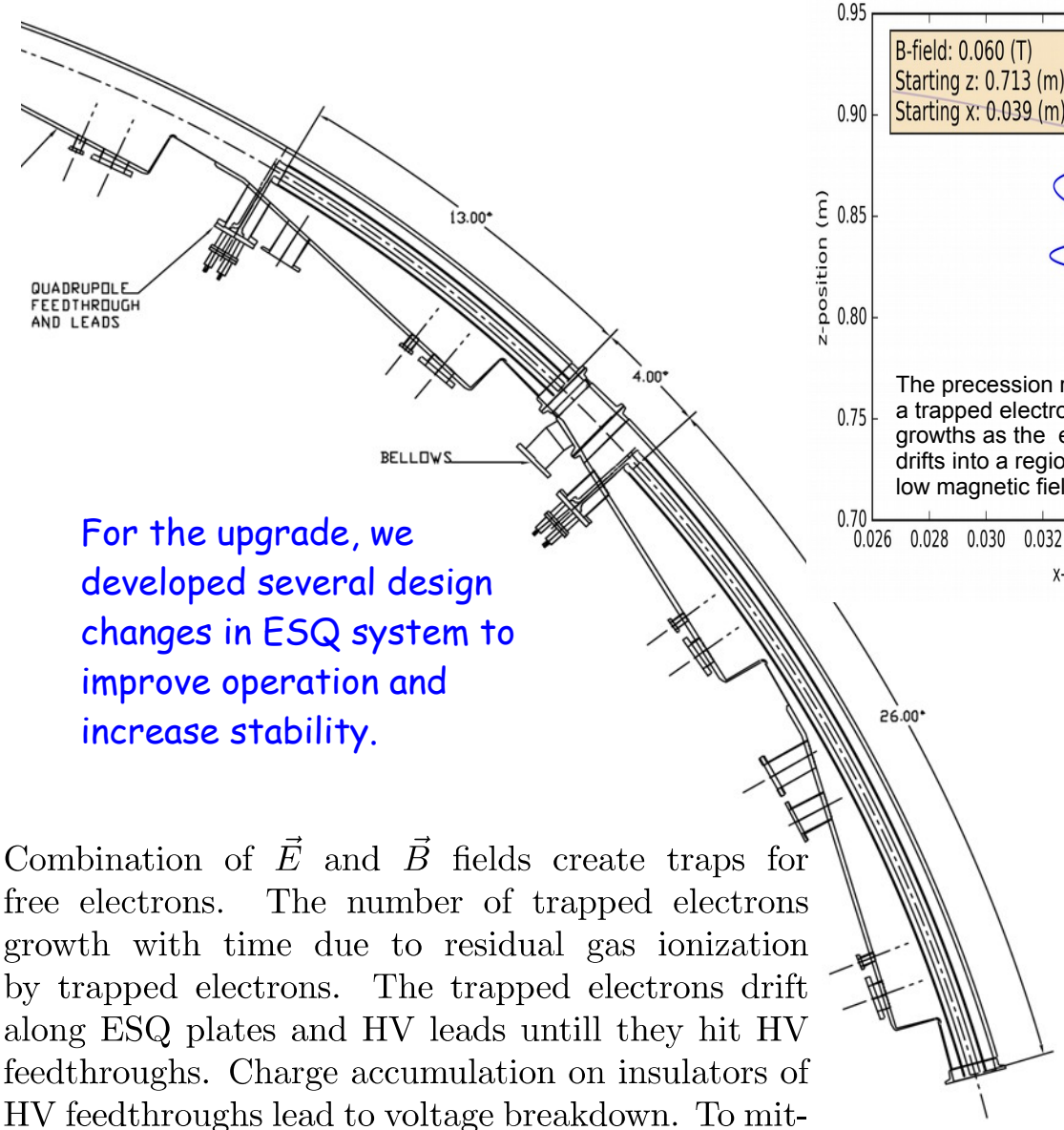


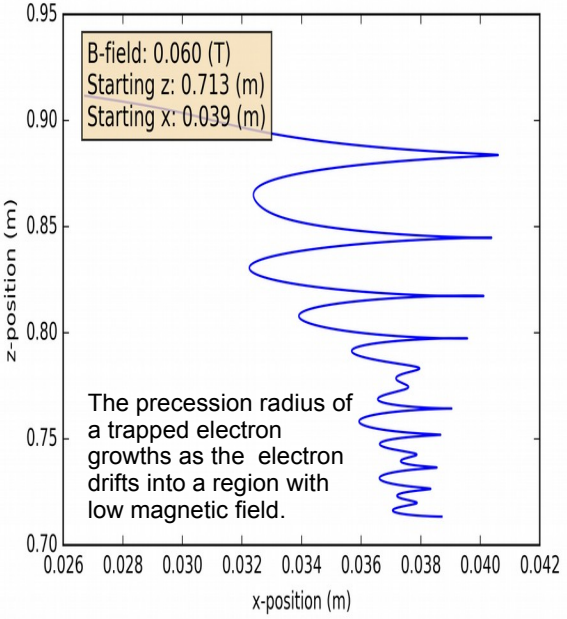


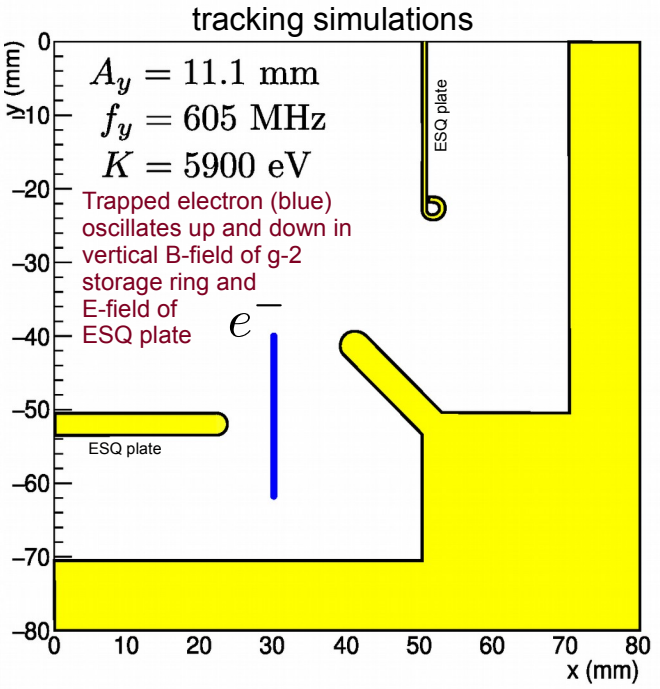


- TDR estimates of characteristics of muon beam (rate, polarization, momentum, emittance, etc.)
- event generator for g-2 ring injection and storage studies
- studies of beam-related systematic uncertainties.

Quad upgrade: HV lead extensions

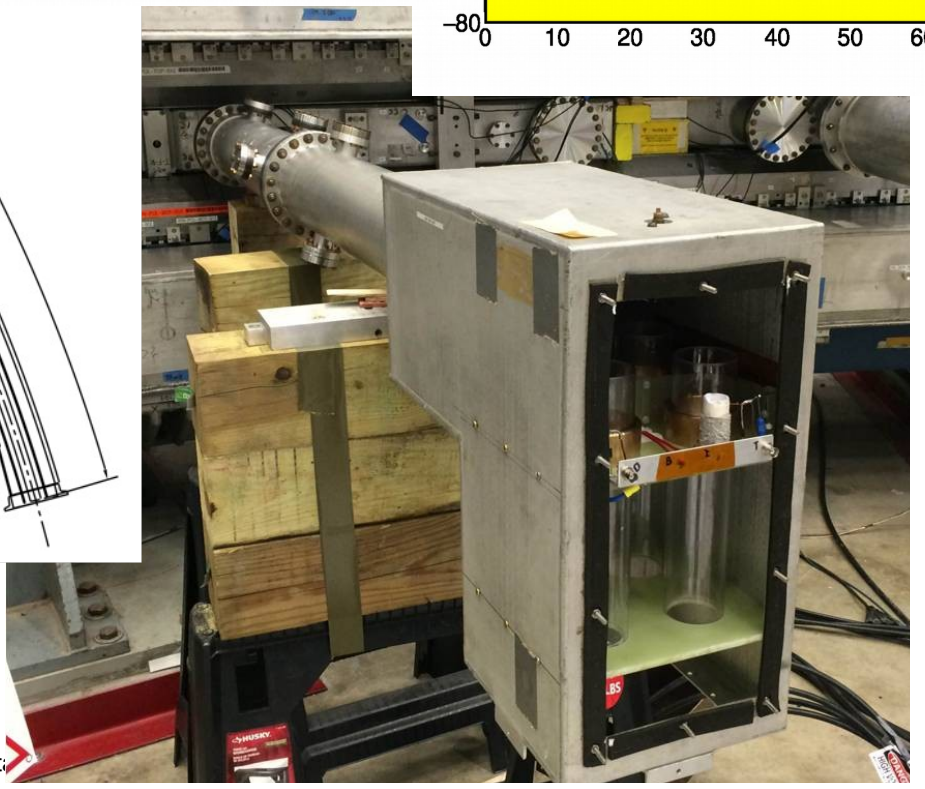






For the upgrade, we developed several design changes in ESQ system to improve operation and increase stability.

Combination of $\vec{E}$ and $\vec{B}$ fields create traps for free electrons. The number of trapped electrons growth with time due to residual gas ionization by trapped electrons. The trapped electrons drift along ESQ plates and HV leads untill they hit HV feedthroughs. Charge accumulation on insulators of HV feedthroughs lead to voltage breakdown. To mitigate the problem, HV lead extensions were designed and built where the electrons drift into a low $\vec{B}$-field region and get lost due to collisions with the walls of vacuum chamber.



New calorimeters

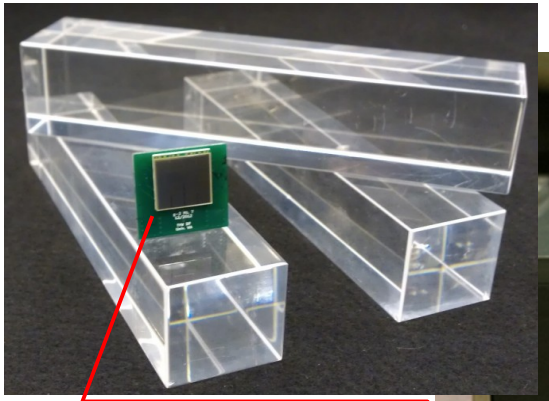
D. Hertzog, UW

pileup

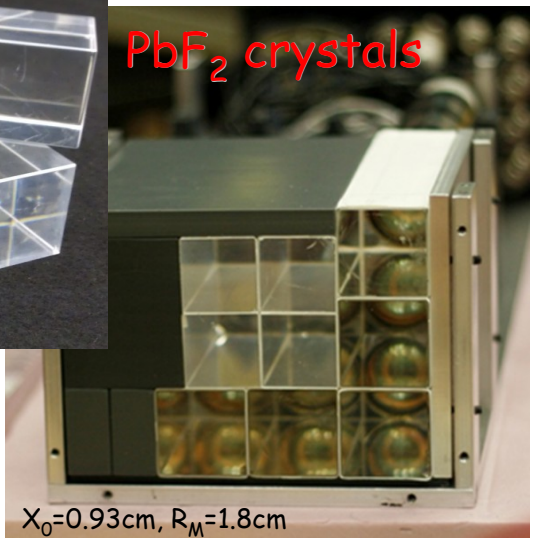
- **Compact** based on fixed space
- **Non-magnetic** to avoid field perturbations

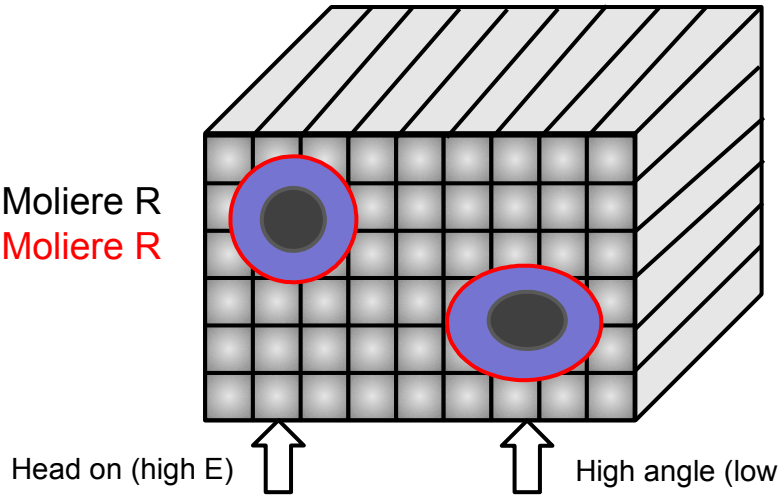
- **Resolution** not too critical for dw_a
  - Useful for pileup, gain monitoring, shower partitioning and low thresholds
  - Goal <5% DE/E at 2 GeV (a soft requirement)

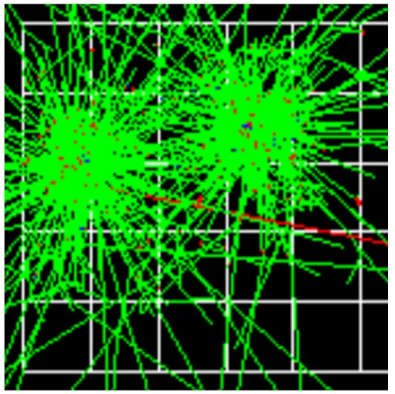
- **Gain stability** depends on electronics and calibration system
  - Goal: Short term < 0.1% DG/G in 600 ms
  - Goal: Longer term < 1% DG/G in 24 h
- **Pileup** depends on signal speed and shower separation
  - Subdivide calorimeter
  - Use Cherenkov
  - Goal: 2-pulse separation by space: 2 out of 3
  - Goal: 2-pulse separation by time: Dt > 5 ns

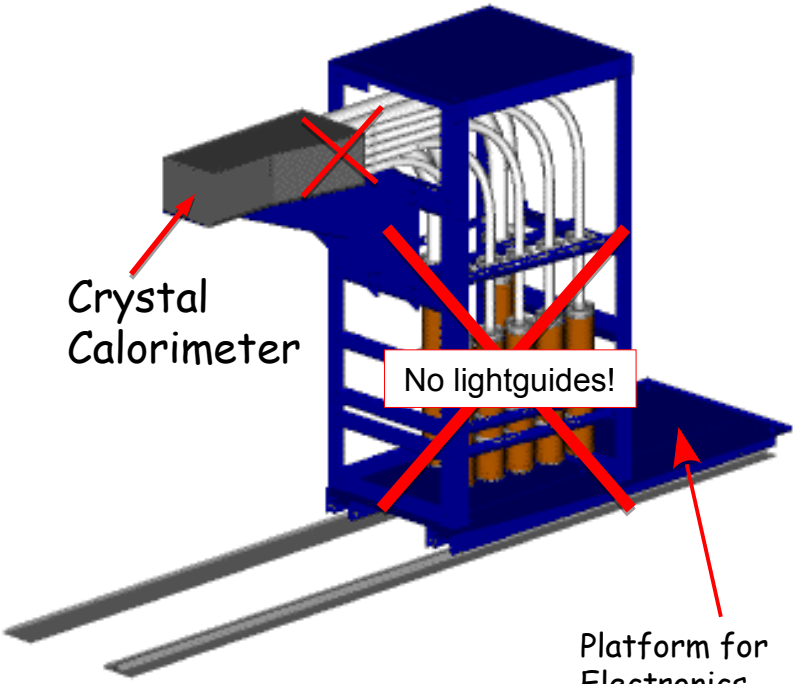


SiPM readout

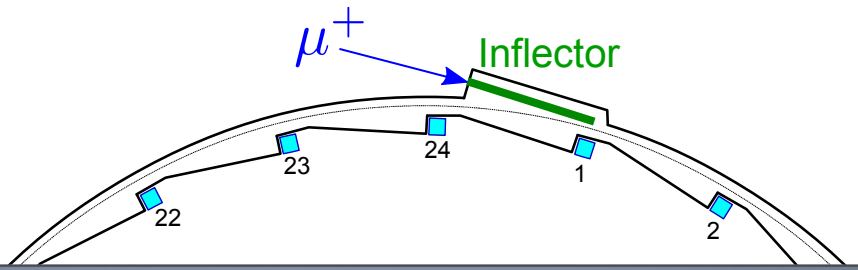


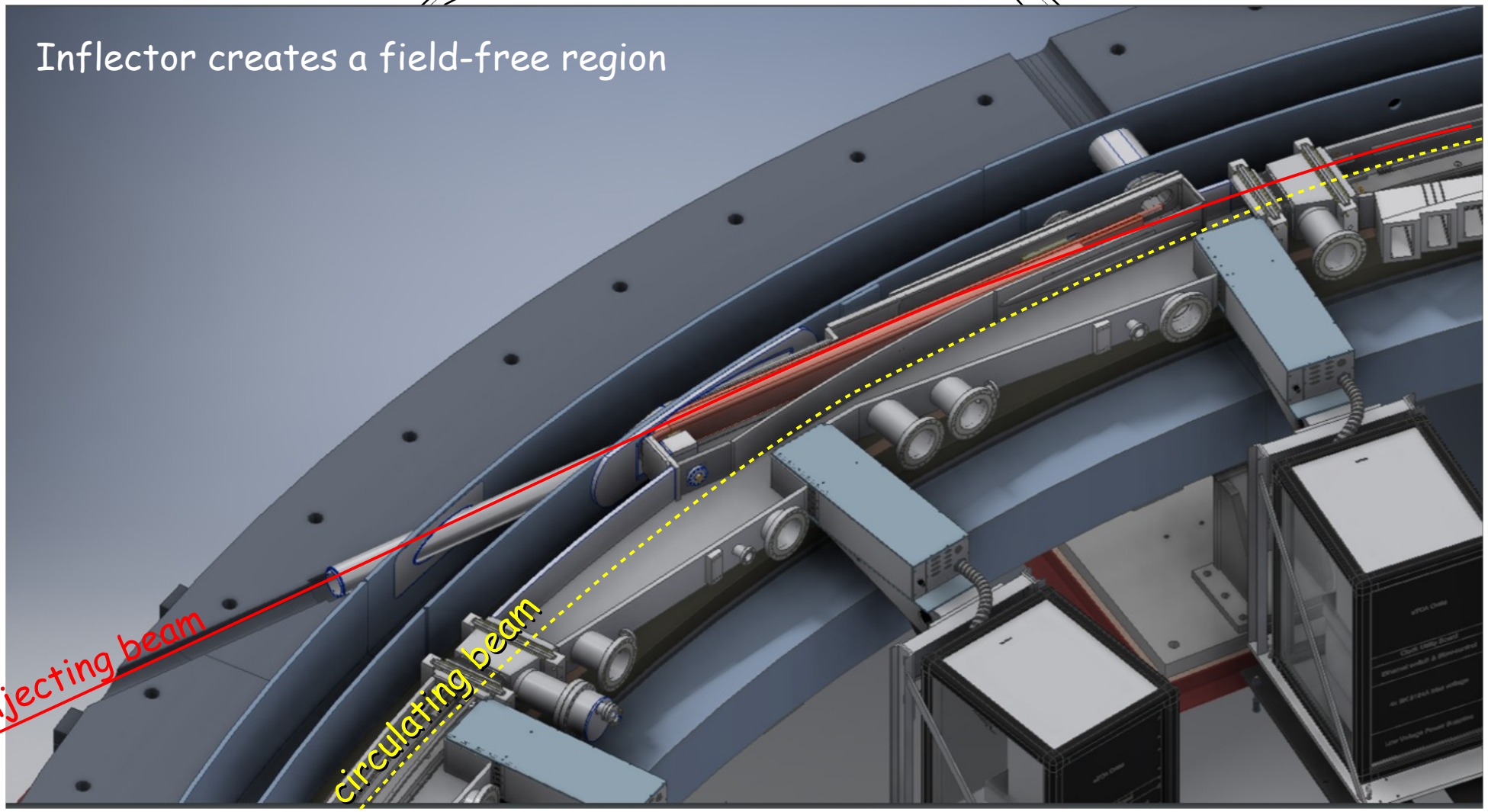




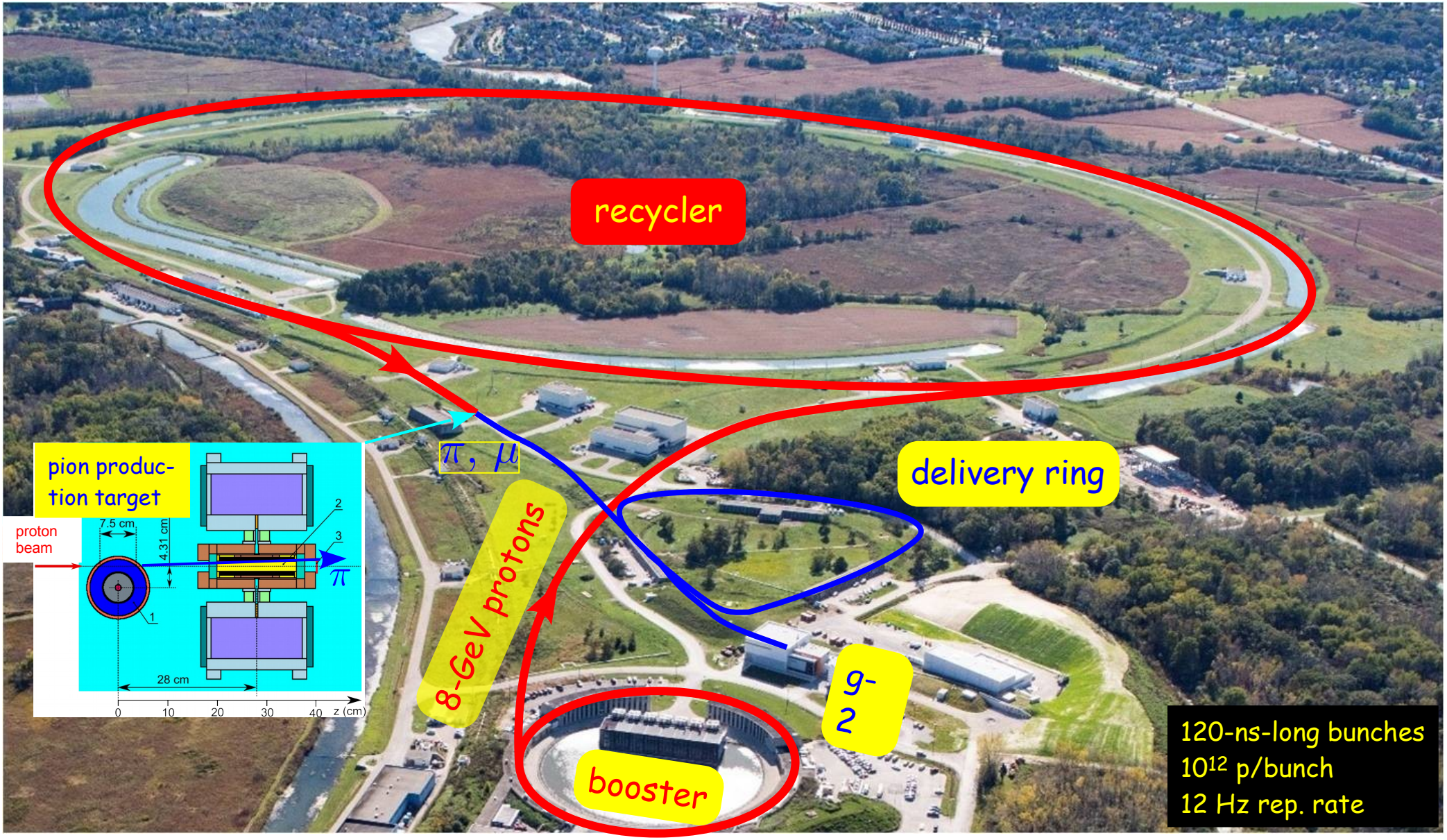


Superconducting Inflector





muons for g-2 (goal: 20x more than at BNL)

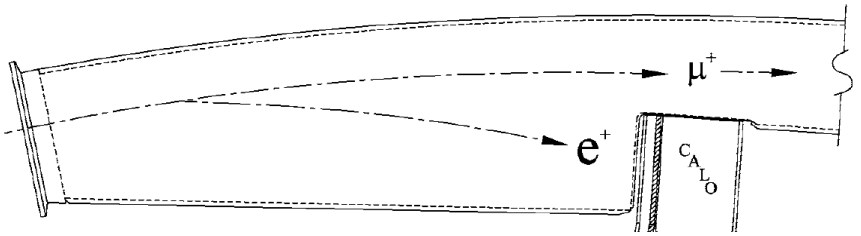


BNL g-2 experiment in a nutshell

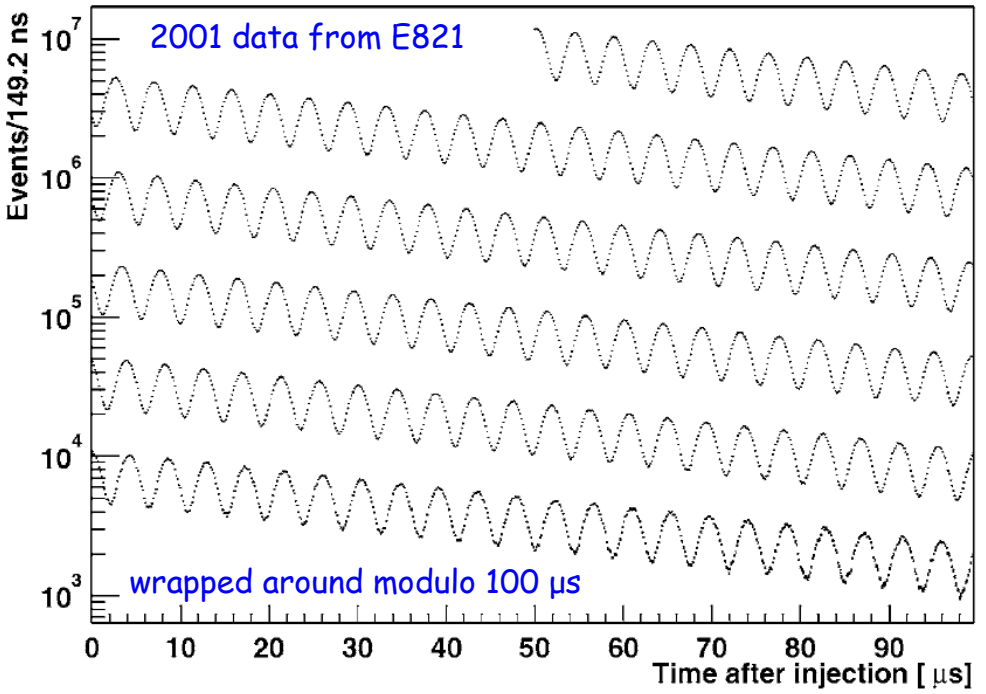
$$a_\mu = \frac{m}{e}\frac{\omega_a}{B}$$

Determining the anomalous magnetic moment requires measuring

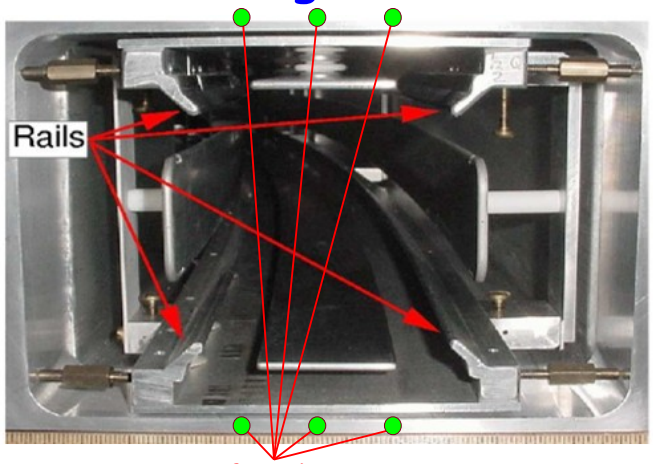
- The spin precession frequency ω_a



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

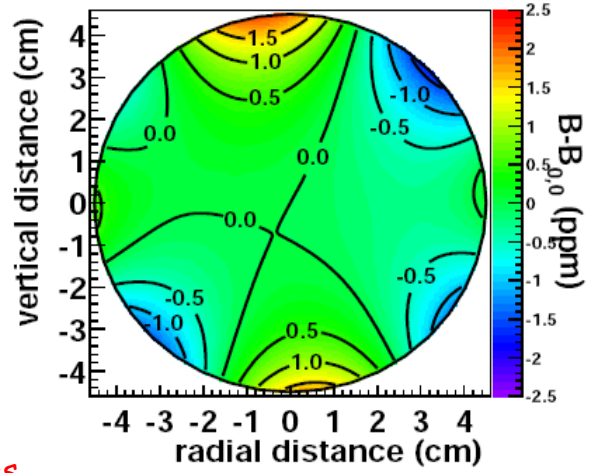


- The magnetic field B (ω_p)



375 fixed NMR probes

17 NMR trolley probes

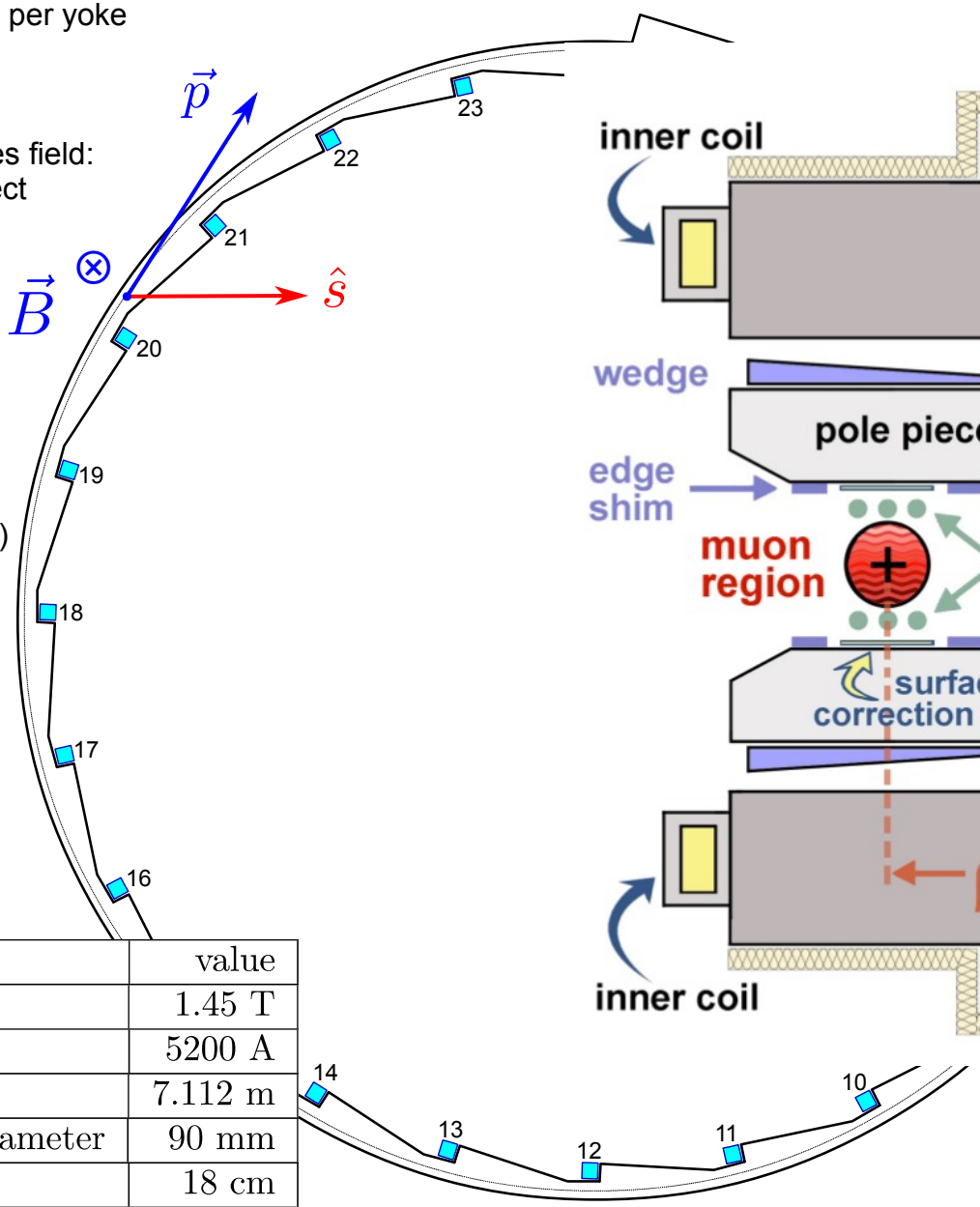


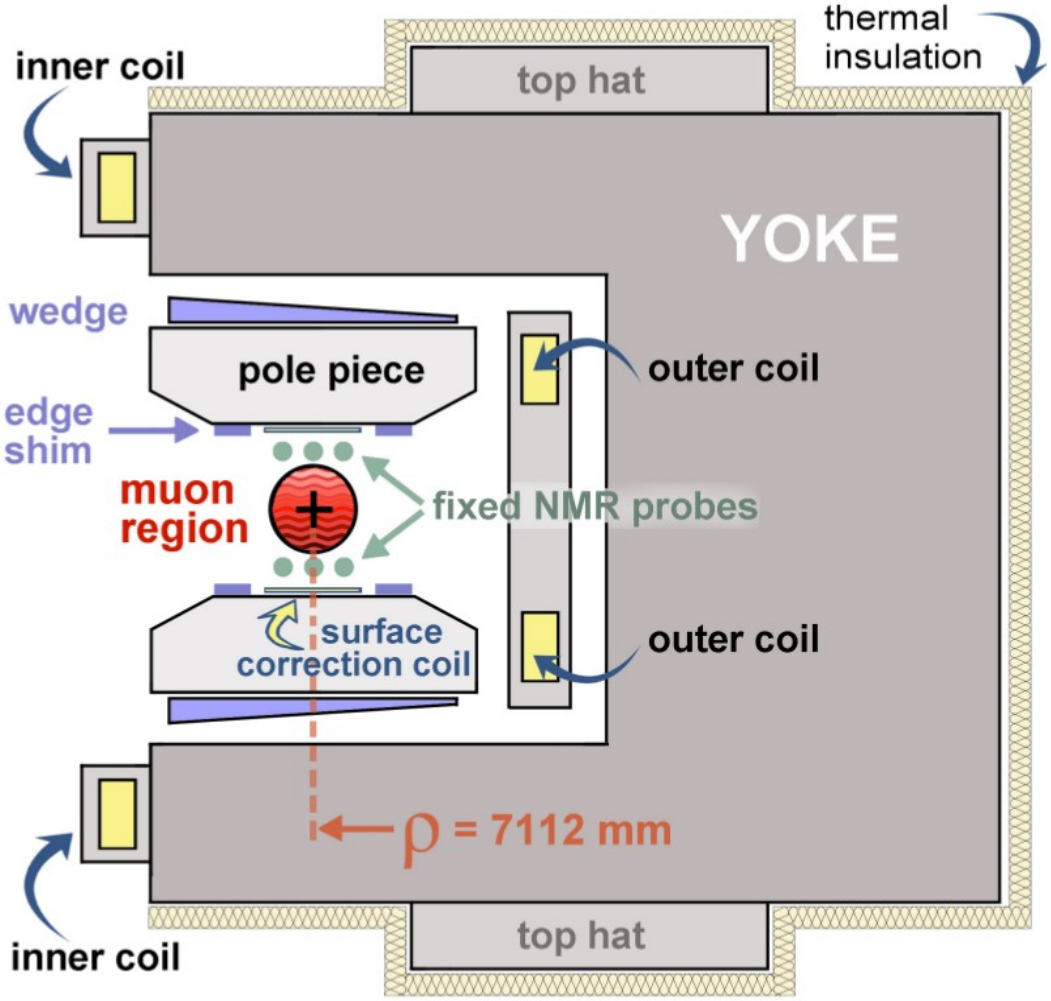
$$a_\mu^{\exp} = \frac{\dfrac{\omega_a}{\tilde{\omega}_p}}{\dfrac{\mu_\mu}{\mu_p} - \dfrac{\omega_a}{\tilde{\omega}_p}}$$

Magnet anatomy

12 C-shaped yokes
- 3 upper and 3 lower poles per yoke
- 72 total poles

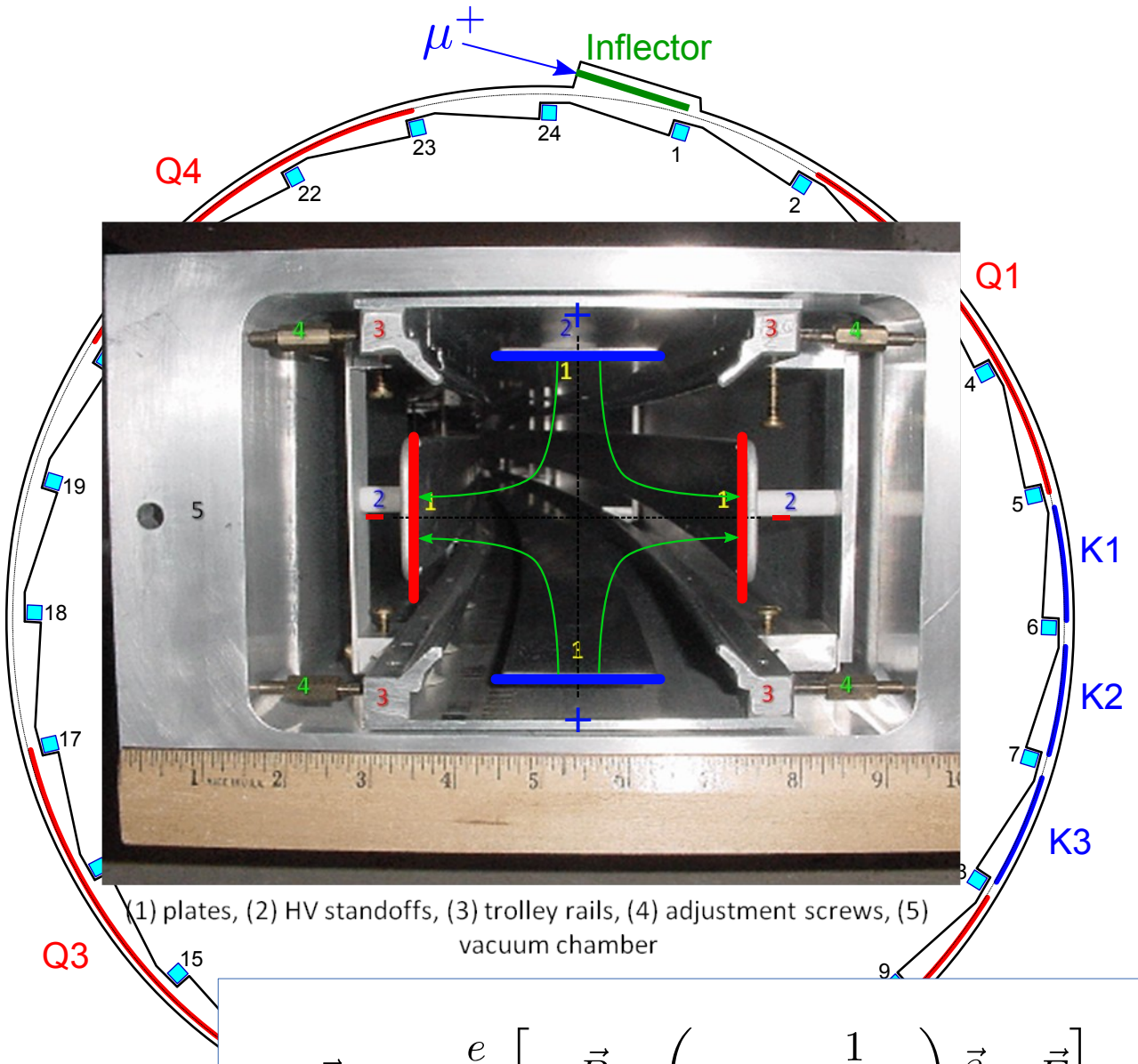
Shimming knobs
- Pole separation determines field: pole tilts, non-flatness affect uniformity
- Top hats (dipole)
- Wedges (dipole, quadrupole)
- Edge shims (dipole, quadrupole, sextupole)
- Laminations (dipole, quadrupole, sextupole)
- Surface coils (quadrupole, sextupole,…)





name	value
Magnetic field	1.45 T
Current	5200 A
Design orbit radius	7.112 m
Muon storoage region diameter	90 mm
Magnet gap	18 cm
Stored energy	6 MJ

Electrostatic Focusing Quadrupoles



(1) plates, (2) HV standoffs, (3) trolley rails, (4) adjustment screws, (5) vacuum chamber

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

E-field contribution vanishes at this "magic" momentum

New Kicker

D. Rubin, Cornell

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

Requirements:

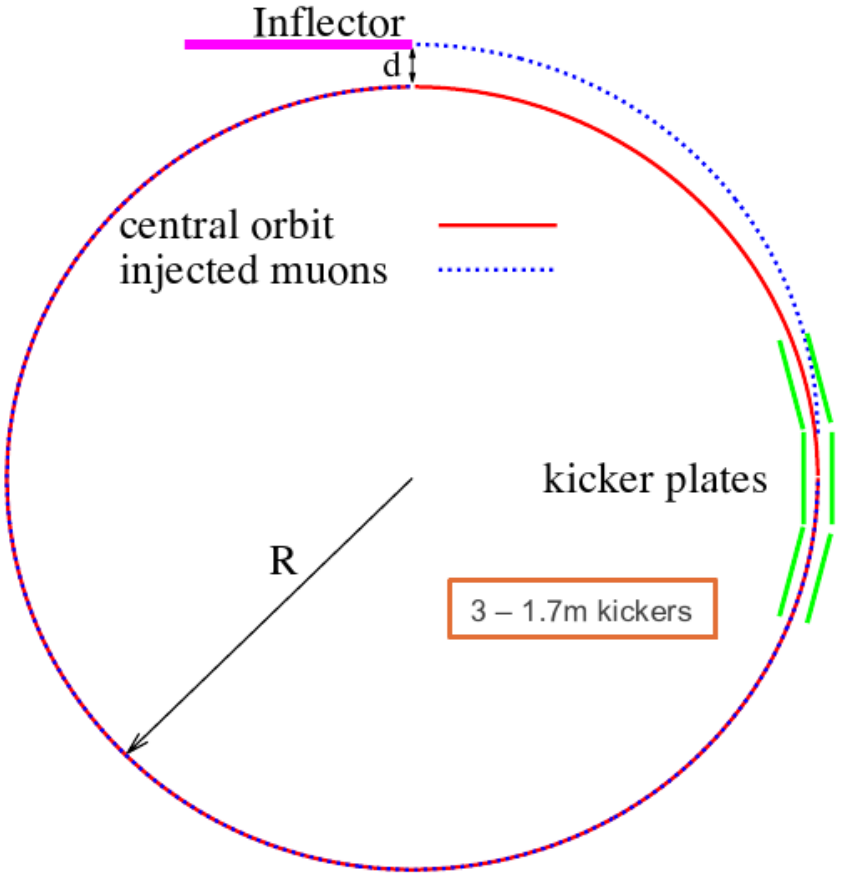
Kick angle ~ 10.8 to 12.1 mrad
Kicker B-field ~ 218 to 245 Gauss
Integrated B-field ~ 1.11 to 1.25 kG-m

Pulse width(τ_{wid})

120ns < τ_{wid} < 149ns

Repetition rate

~100Hz peak, 12Hz average



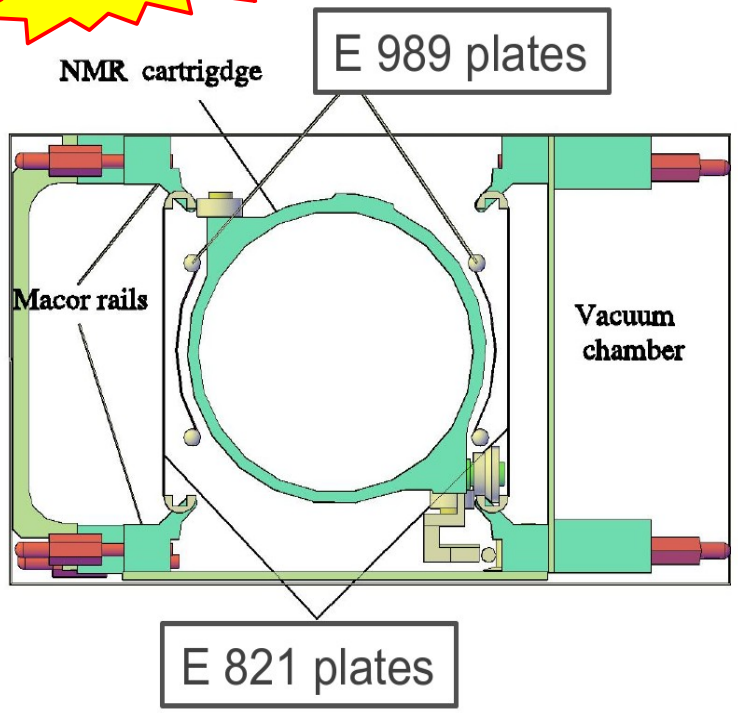
τ_{rev} = 149 ns

d = 77 mm, R=7112 mm
kick angle θ = d/R = 10.8 mrad

New Kicker

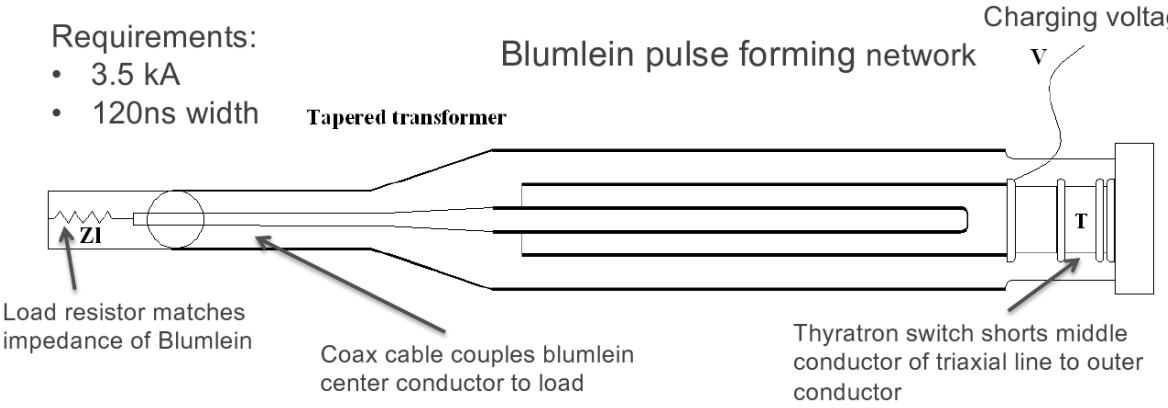
D. Rubin, Cornell

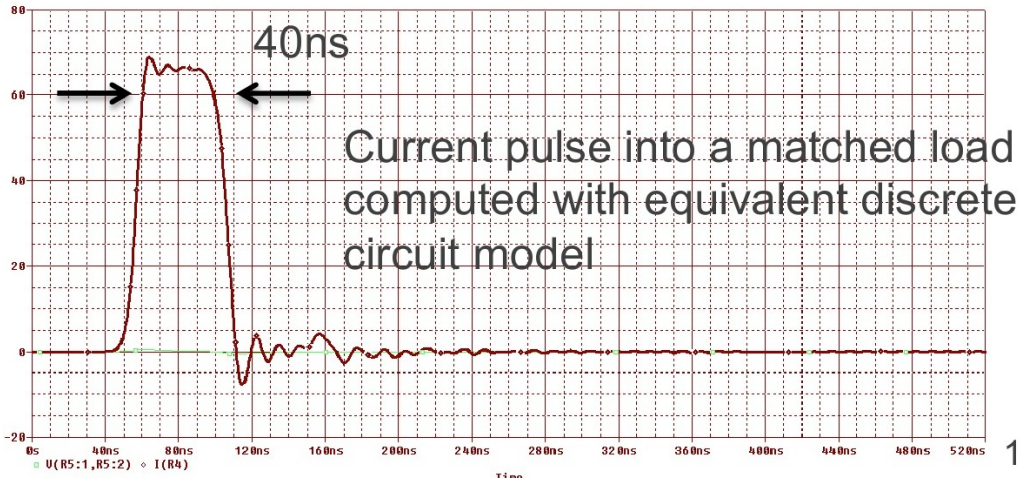
CBO

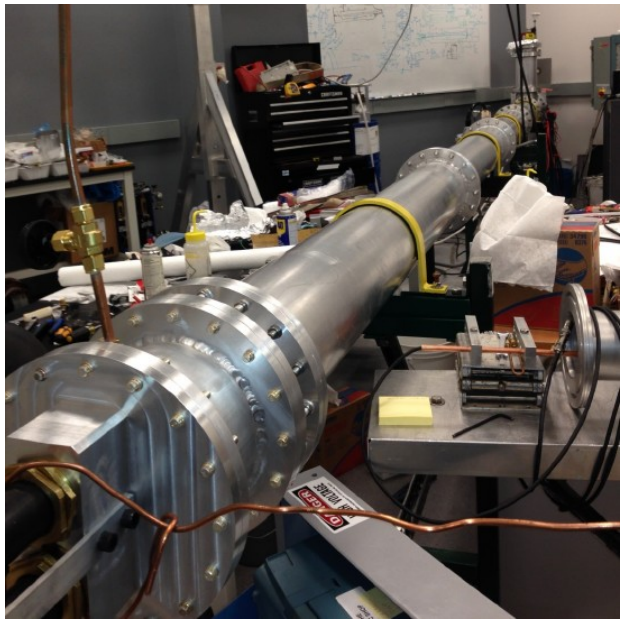


Requirements:
- 3.5 kA
- 120ns width

Blumlein pulse forming network

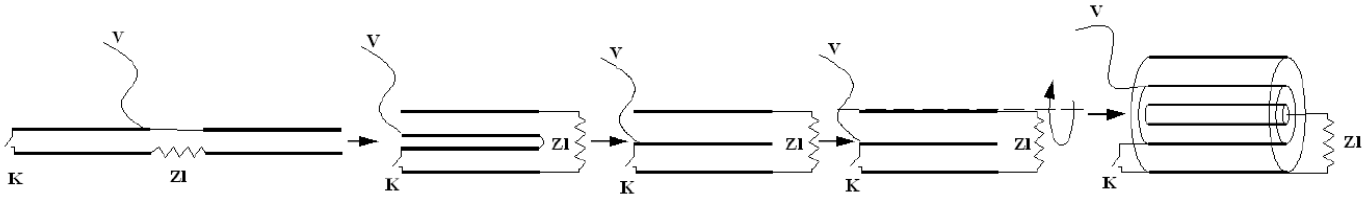




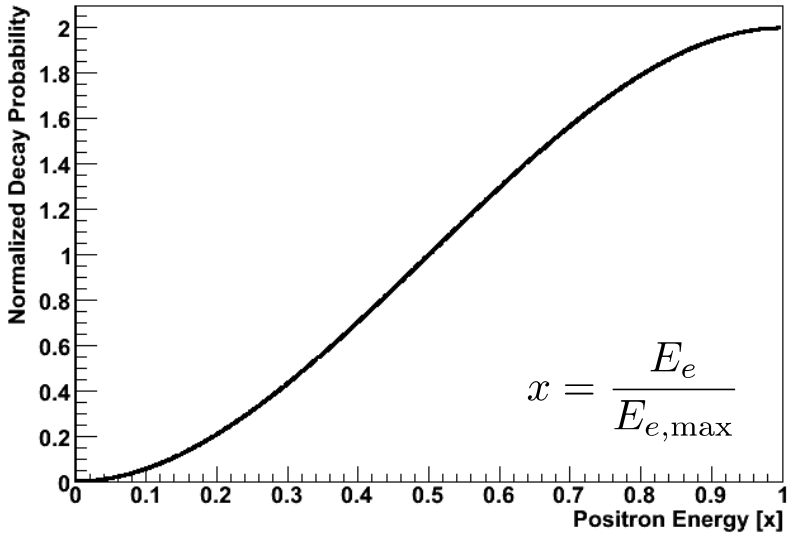


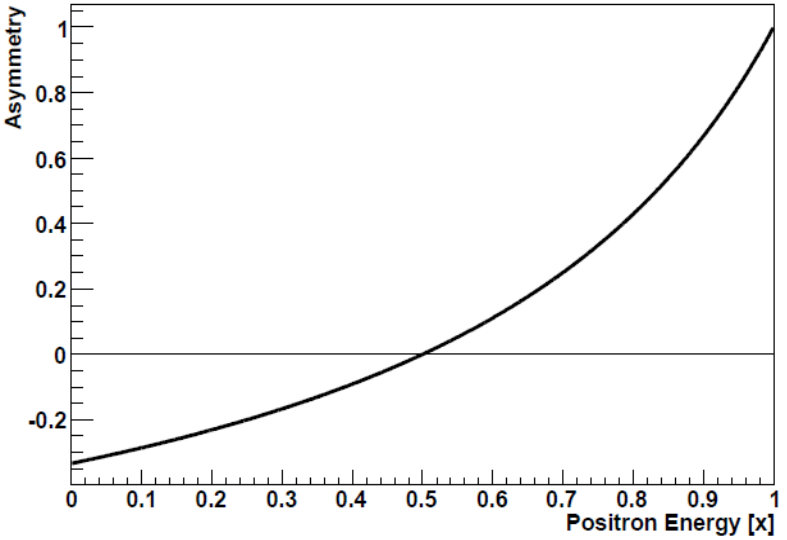
$$\tau = \frac{2L}{v}$$

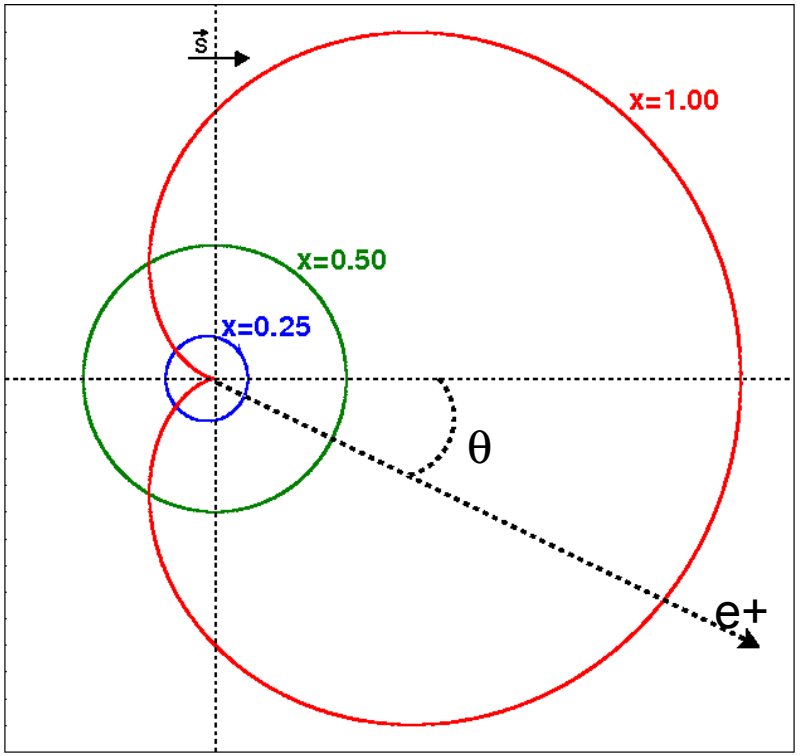
width of pulse is proportional to length of blumlein



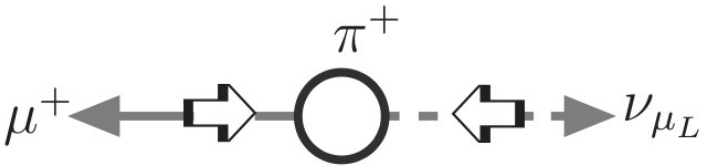
muon – “self analyzing polarimeter”



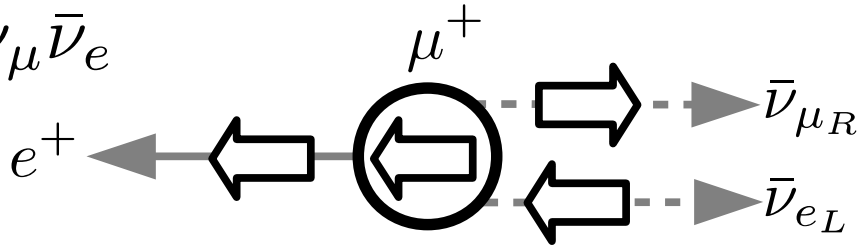




$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

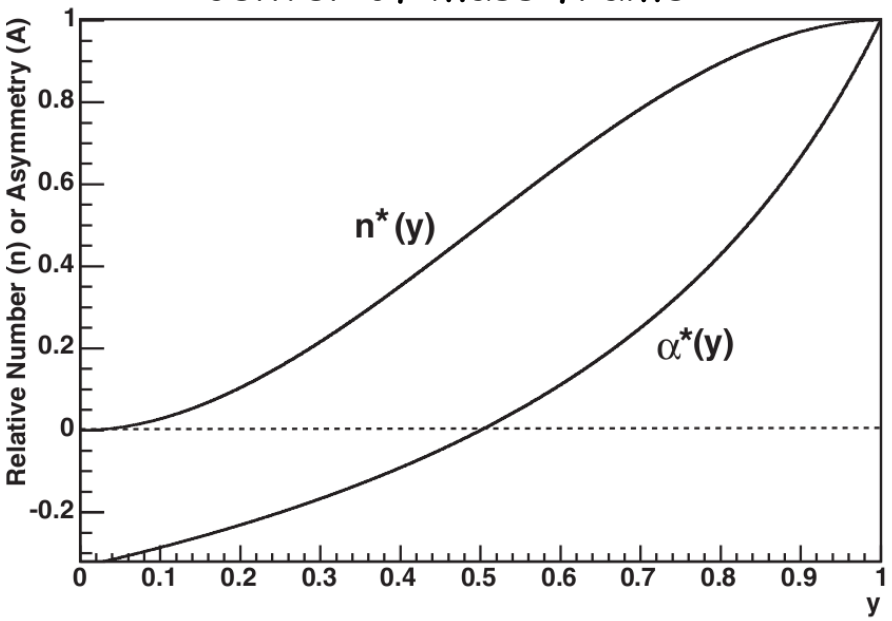


$$\mu^+ \rightarrow e^+ \nu_\mu \bar{\nu}_e$$



positrons from muon decay

center of mass frame



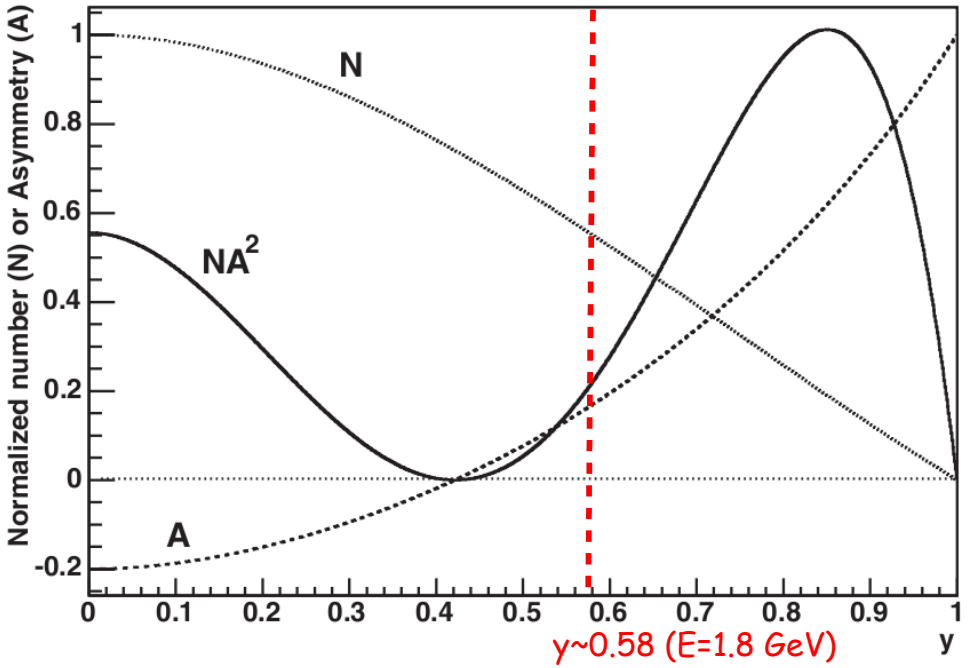
$$y = E^*/E_{\max} \qquad E_{\max} = 52.8 \text{ MeV}$$

$$\frac{dP(y,\theta^*)}{dy d\Omega} = (1/2\pi) n^*(y)[1 - \alpha^*(y)\cos\theta^*]$$

$$n^*(y) = y^2(3 - 2y)$$

$$\alpha^*(y) = \frac{q}{e}\frac{2y-1}{3-2y}$$

laboratory frame



$$E_{\text{lab}} = \gamma(E^* + \beta p^* c\cos\theta^*) \approx \gamma E^*(1 + \cos\theta^*)$$

$$E_{\max} \approx 3.1 \text{ GeV}$$

BNL beam

TABLE III. Selected AGS proton beam and secondary pion beamline characteristics.

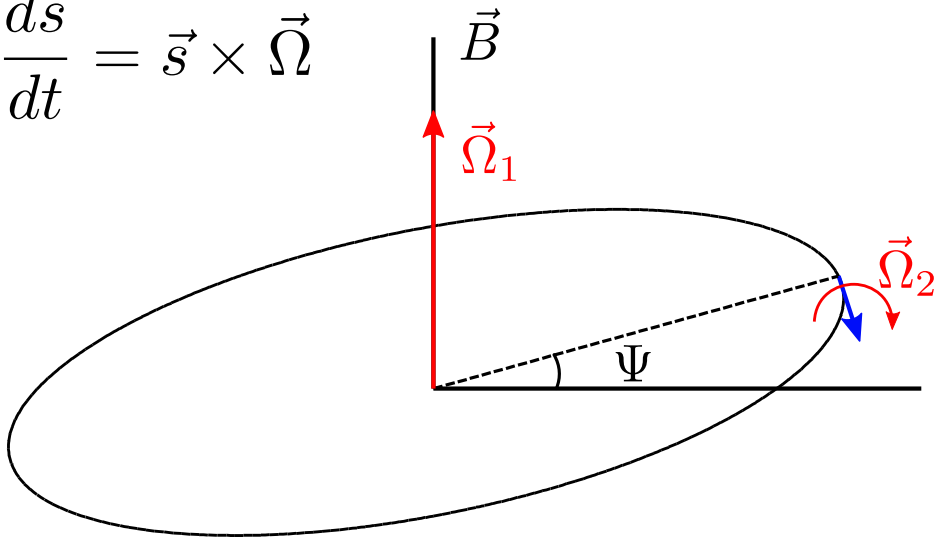
Proton Beam	Value	Pion Beamline	Value
Protons per AGS cycle	5×10^{13}	Horizontal emittance	42π mm-mrad
Cycle repetition rate	0.37 Hz	Vertical emittance	56π mm-mrad
Proton momentum	24 GeV/c	Inflector horizontal aperture	± 9 mm
Bunches per cycle	6–12	Inflector vertical aperture	± 28 mm
Bunch width (σ)	25 ns	Pions per proton[a]	10^{-5}
Bunch spacing	33 ms	Muons per pion decay[b]	0.012

[a]Captured by the beamline channel;
[b]Measured at the inflector entrance

Pitch correction

$$\vec{\Omega} = \frac{e}{m}\left[\left(a_\mu + \frac{1}{\gamma}\right)\vec{B} - a_\mu \frac{\gamma}{1+\gamma}\left(\vec{\beta}\vec{B}\right)\vec{\beta} - \left(a_\mu + \frac{1}{1+\gamma}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

$$\frac{d\vec{s}}{dt} = \vec{s}\times\vec{\Omega}$$



$$\frac{\Delta\omega_a}{\omega_a} = -\frac{1}{2}\Psi^2$$

$$\Psi(t) = \Psi_m \sin(\omega_y t + \varphi_y)$$

$$\frac{\Delta\omega_a}{\omega_a} = -\left\langle \frac{1}{4}\Psi_m^2 \right\rangle = -n\frac{\langle y^2\rangle}{R_0^2}$$

F.J.N. Farley, Phys. Lett. 42 (1972) 66

E821 C_p = 270 ± 40 ppb

E989 goal for C_E and C_p combo: 30 ppb

Electric field correction

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

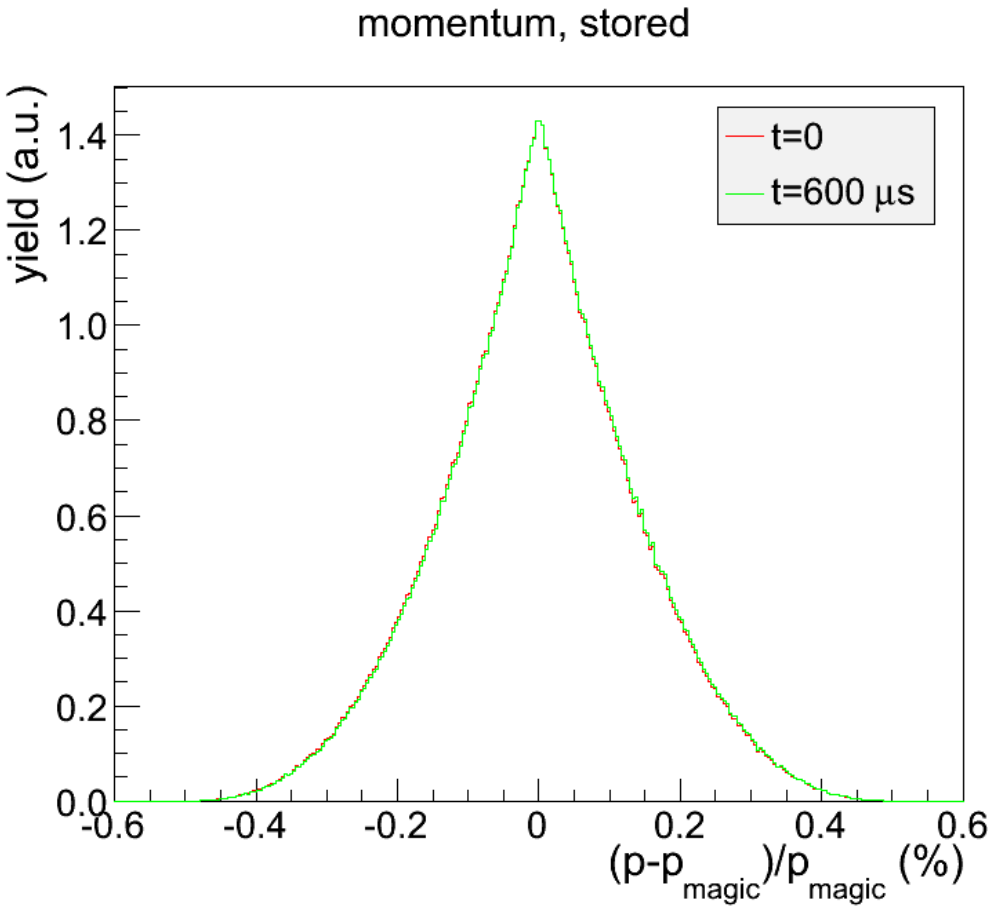
$$\Delta\vec{\omega}_a = -\frac{e}{m}\left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E} = -\frac{e}{m}\left(a - \frac{m^2}{(p_0 + \Delta p)^2}\right)\vec{\beta} \times \vec{E}$$

$$E_x = kx = \frac{n\beta B}{R_0}\left(x_e + A_x \cos(\omega_x t + \varphi_x)\right)$$

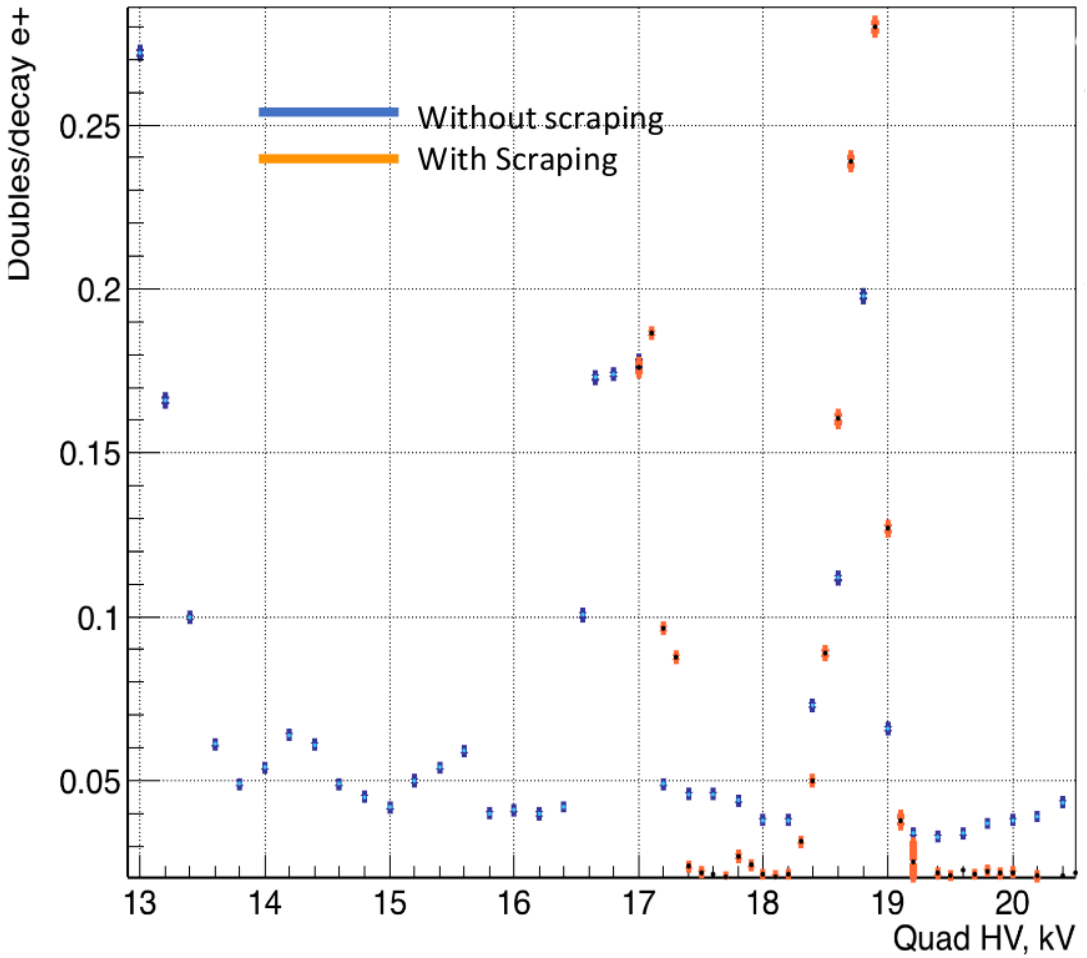
$$\Delta p = \frac{x_e}{R_0} p_0 (1 - n)$$

$$a = \frac{m^2}{p_0^2}$$

$$\left\langle \frac{\delta\omega_a}{\omega_a} \right\rangle = -2\beta^2 n(1 - n)\left\langle \left(\frac{x_e}{R_0}\right)^2 \right\rangle$$



E821 C_E = 470 ± 50 ppb

E989 goal for C_E and C_p combo: 30 ppb

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