Overview of Fermilab muon g-2 experiment

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PhiPsi2015, Hefei

Outline

Introduction about muon anomalous magnetic moment, a_μ

Basic principle of the Fermilab muon g-2 experiment

Overview of the experimental technique

Conclusion

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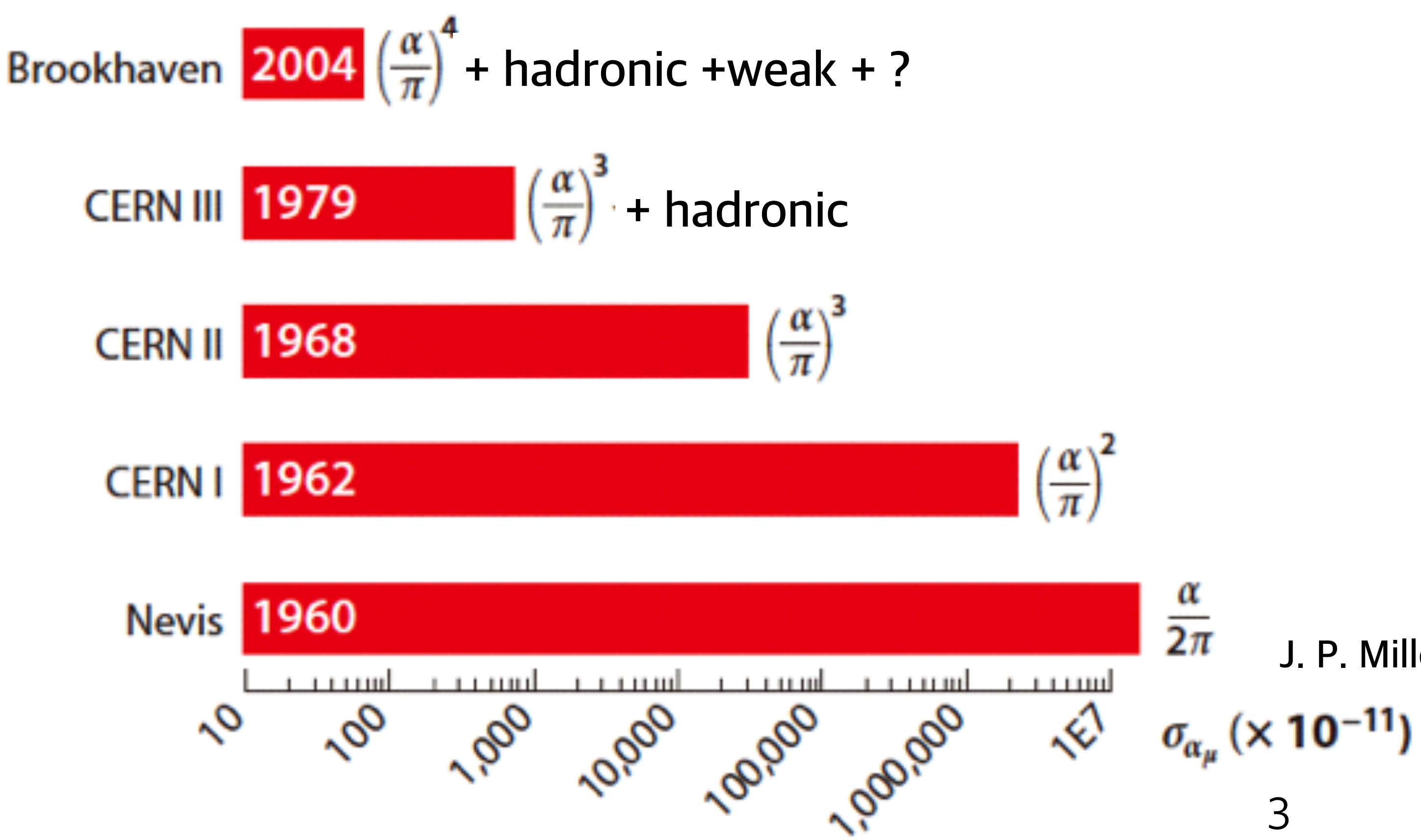
Muon anomalous magnetic moment, a_μ

The muon magnetic dipole moment, $$\vec{\mu} = g\frac{e}{2m}\vec{s} = (1+\frac{g-2}{2})\frac{e}{m}\vec{s} = (1+a_\mu)\frac{e}{m}\vec{s}$$

In the beginning, it was believed that $a_\mu = 0$ (i.e. g=2) by the Dirac theory.

But, repetitive more precise measurement of a_μ have indicated $a_\mu \neq 0$ and unveiled the more sophisticated level of physics like QED and hadronic contribution.



J. P. Miller et al, Annu. Rev. Nucl. Part. Sci. 62, 237

The current status of a_μ

SM prediction

	Value ($\times 10^{-11}$) units	
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$	Aoyama et al, PRL 109, 111808 (2012)
HVP(lo) (1)	$6\,923 \pm 42$	Davier et al, Eur. Phys. J. C71 1515 (2011)
HVP(lo) (2)	$6\,949 \pm 43$	Hagiwara et al, J. Phys. G38 085003 (2011)
HVP(ho)	-98.4 ± 0.7	
HLbL	105 ± 26	"Glasgow Consensus", arXiv:0901.0306v1
EW	153.6 ± 1.0	Gnendiger et al, PRD 88 053005 (2013)
Total SM (1)	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$	~0.4 ppm
Total SM (2)	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$	

Latest measurement (E821 at BNL, PRD 73:072003 (2006))

$$a_\mu^{\text{E821}} = (116\,592\,089 \pm 63) \times 10^{-11} \quad (0.54\,\text{ppm})$$

Comparison between E821 and SM prediction

$$\begin{aligned}\Delta a_\mu(\text{E821} - \text{SM}) &= (287 \pm 80) \times 10^{-11} \quad (1)\\ &= (261 \pm 80) \times 10^{-11} \quad (2)\end{aligned}$$

=> 3.3 – 3.6 σ discrepancy!!!

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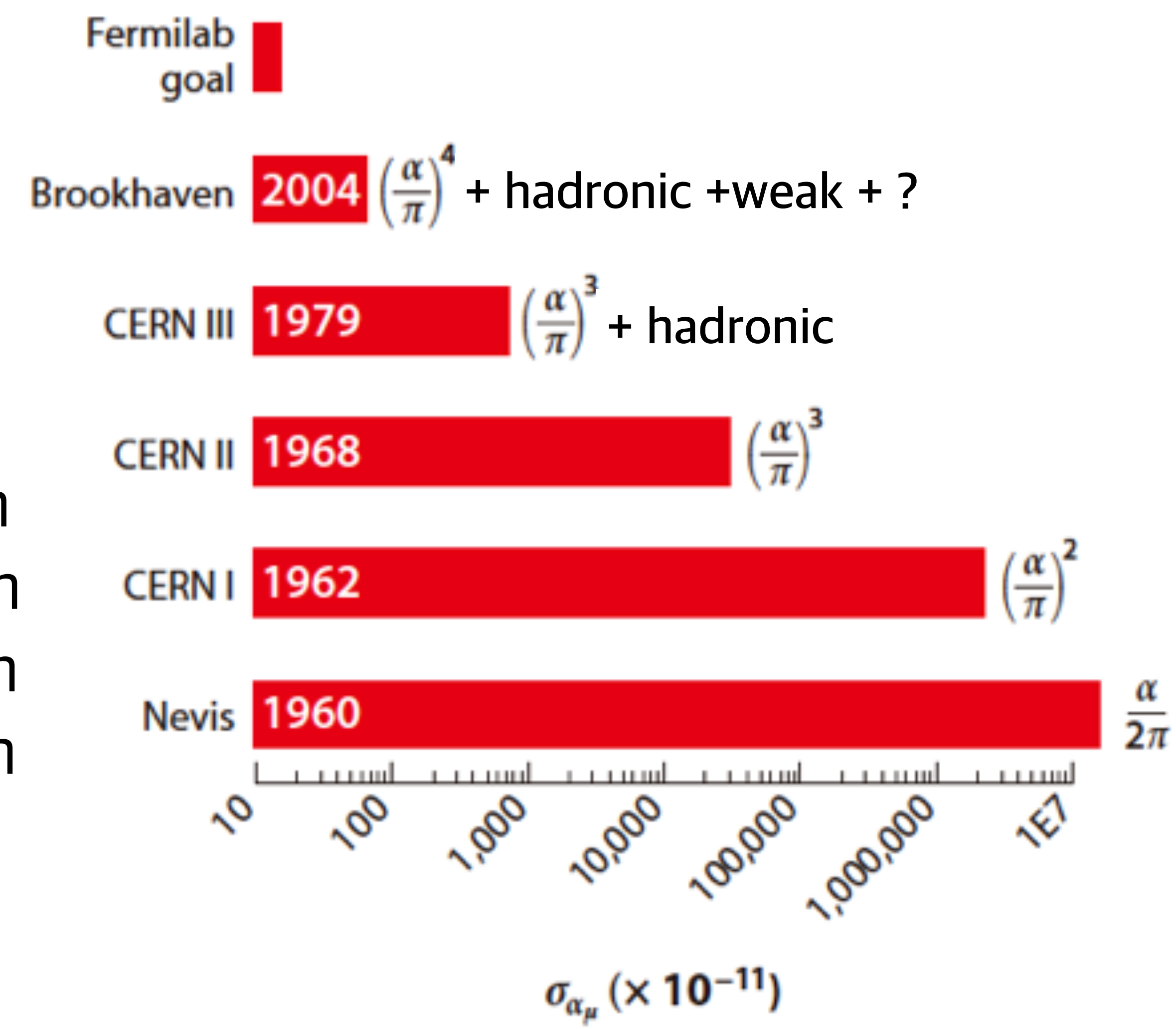
$$= (261 \pm 80) \times 10^{-11} \quad (2)$$

=> 3.3 – 3.6 σ discrepancy!!! **Hint of Beyond SM?**

Fermilab muon g - 2 experiment (E989)

Follow-up experiment of E821 at BNL
=>Well motivated by 3 sigma discrepancy between the latest measurement and the SM prediction
=> Inheriting experiences and peoples and the muon storage ring magnet
=> Exploiting intense muon beam at Fermilab



The goal of the sensitivity

	E821	E989
=> Statistical error of ω_a	: 0.46 ppm	-> 0.10 ppm
Systematic error of ω_a	: 0.18 ppm	-> 0.07 ppm
Systematic error of ω_p	: 0.17 ppm	-> 0.07 ppm
total error	: 0. 54 ppm	-> 0.14 ppm

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The basic principle of the experiment

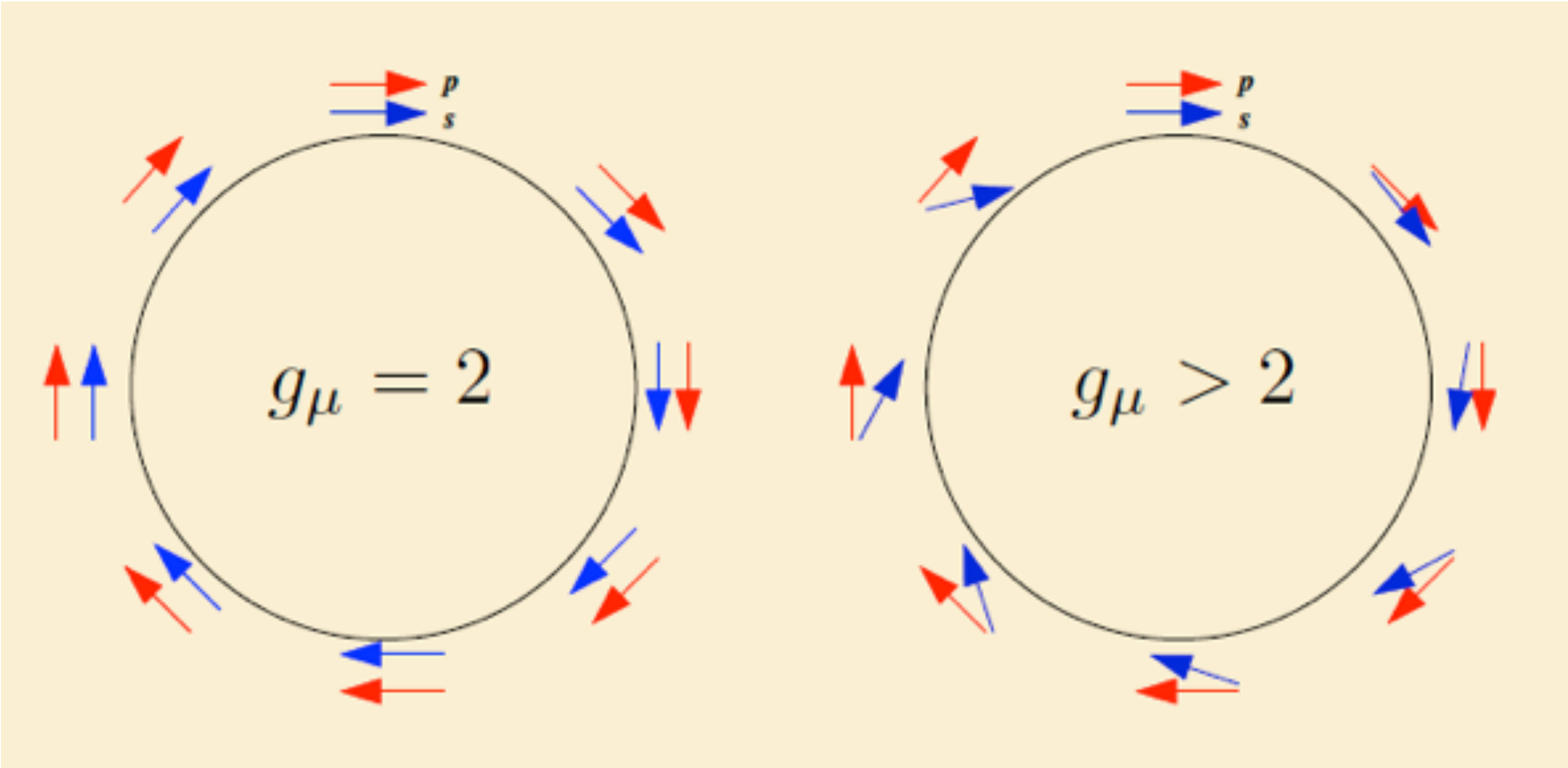
Observe the precession of the spin of the polarized muon relative to the momentum (ω_a) in the uniform magnetic field

Uniform magnetic field: the storage ring magnet with electrostatic vertical focusing

$$\vec{\omega_a} = -\frac{e}{m}[a_\mu \vec{B} - (a_\mu - (\frac{mc}{p})^2)\frac{\vec{\beta} \times \vec{E}}{c}]$$

P_μ = 3.094 GeV is chosen to vanish the E field dependent term
(and correct the result with the actual momentum distribution)

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

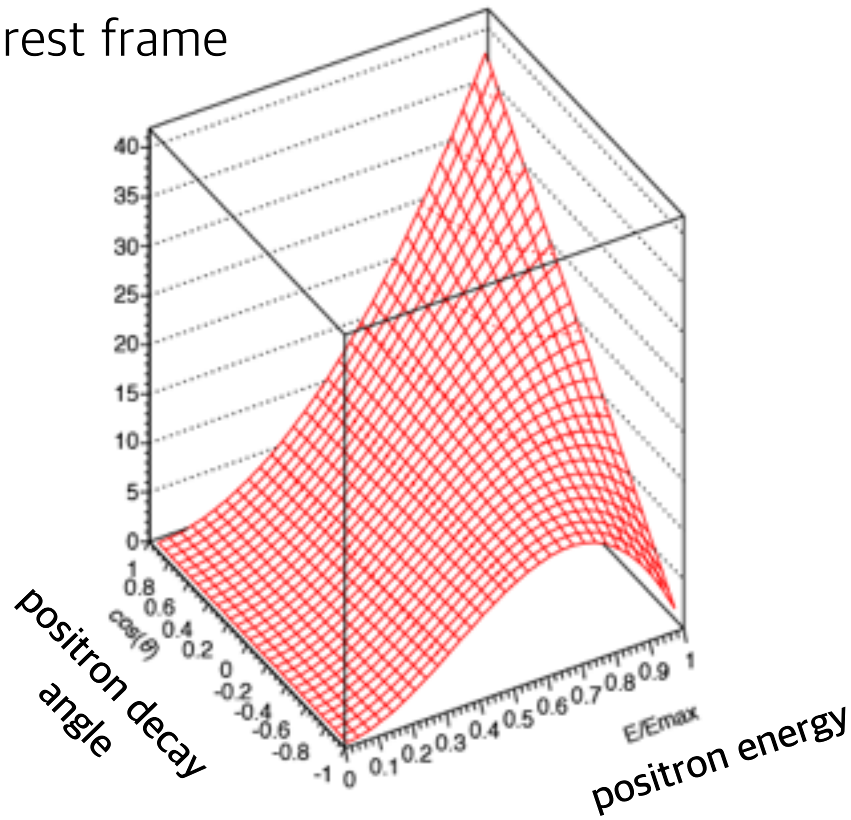


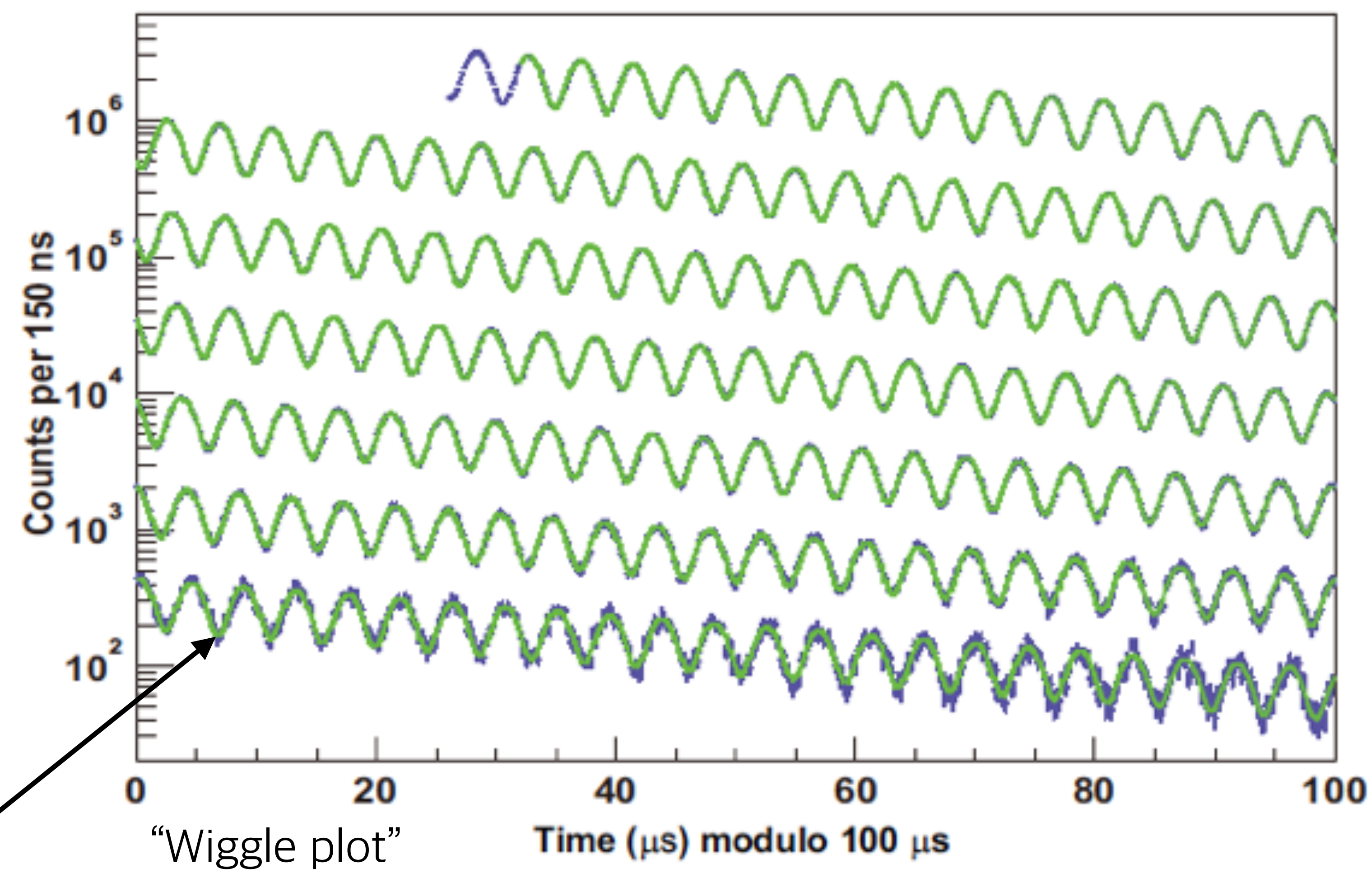
The basic principle of the experiment

The muon spin orientation can be observed by measuring the energy and time of the decaying positron.

Thanks to the P violation of muon decay, the positron is preferentially emitted parallel to the spin orientation.

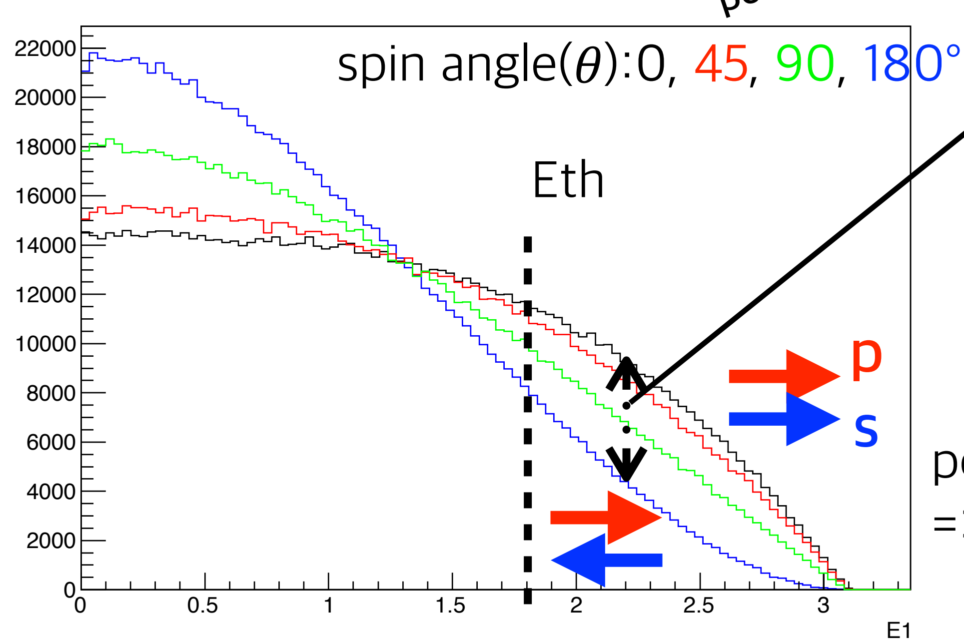
muon rest frame





"Wiggle plot"

=> The modulation of the event rate due to the muon spin precession relative to the momentum = > ω_a



positron energy spectrum in the lab frame (GeV)

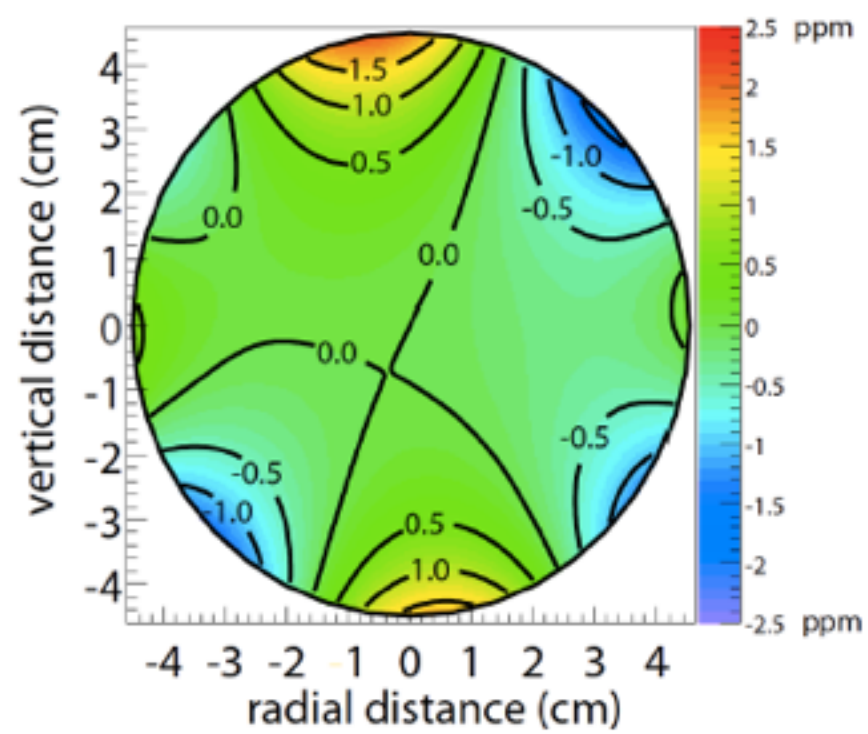
=> $N(t, E) = N_0(E)e^{-t/\gamma\tau}[1 + A(E)\cos\theta(t)]$

The basic principle of the experiment

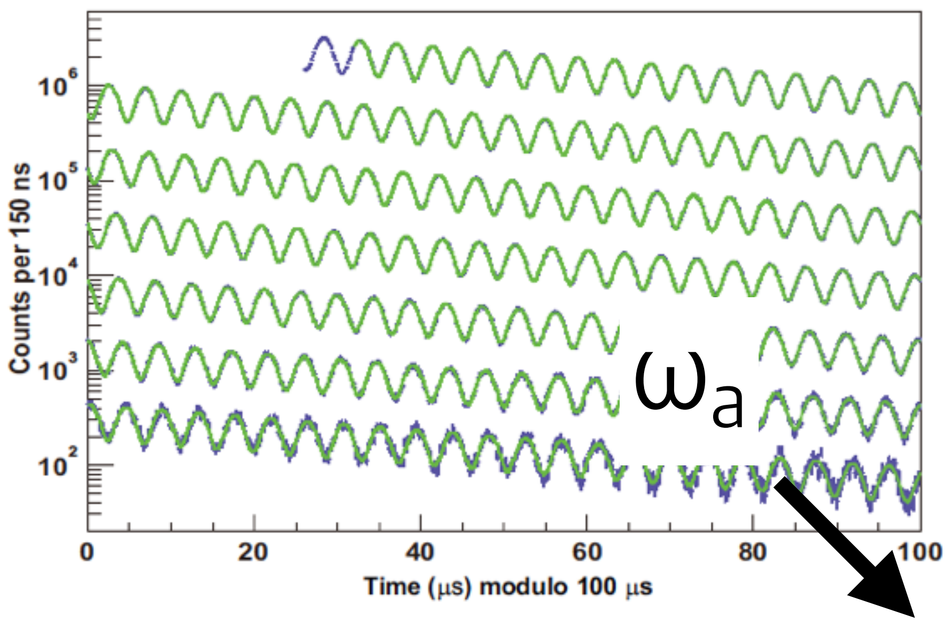
Recalling $\omega_a = -\frac{e}{m_\mu} a_\mu B$, we also need to know B to decide a_μ.

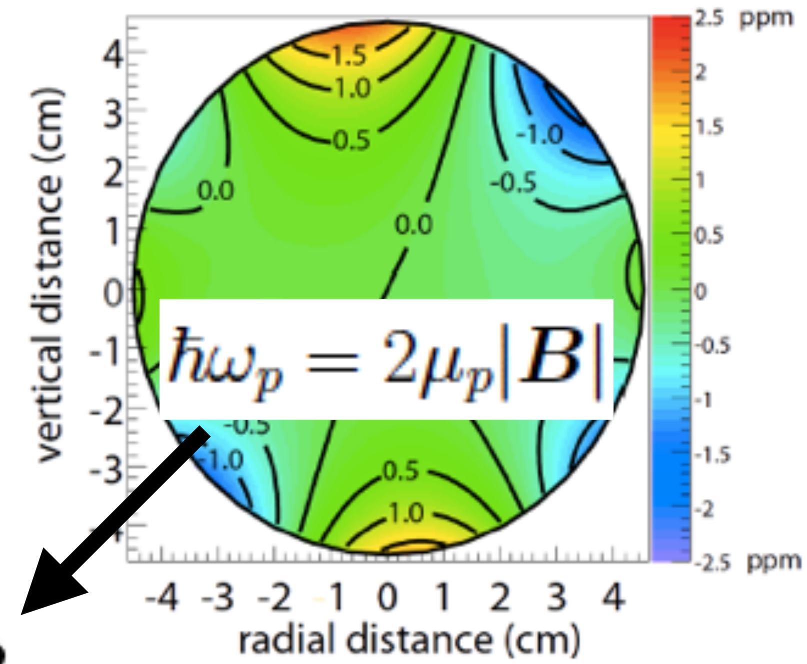
It is very important to achieve the magnetic field as uniform as possible.
=> 1 ppm level uniform field in the muon storage ring magnet

To know the magnetic field experienced by muons precisely,
=> Mapping the magnetic field over the whole muon storage area with proton NMR probes
  =>Frequent scan using the trolley
=>Associate the field map with the distribution of the muons



A contour plot of the magnetic field averaged over azimuth of the ring, 0.5 ppm intervals





$$\omega_a = -\frac{e}{m_\mu} a_\mu B$$

$$a_\mu = \frac{\omega_a}{\omega_p}\frac{2\mu_p}{\hbar}\frac{m_\mu}{e} = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

$\mu_e/\mu_p = -658.210\,6848(54)$ (8.1 ppb)

$m_\mu/m_e = 206.768\,2843(52)$ (25 ppb => Exp + SM theory about the Muonium hyperfine splitting)

Mohr et al, Rev. Mod. Phys. 84 (4), 1527 (2012)

$g_e/2 = 1.001\,159\,652\,180\,73(28)$ (0.28 ppt)

Hanneke et al, Phys. Rev. A 83, 052122 (2011)

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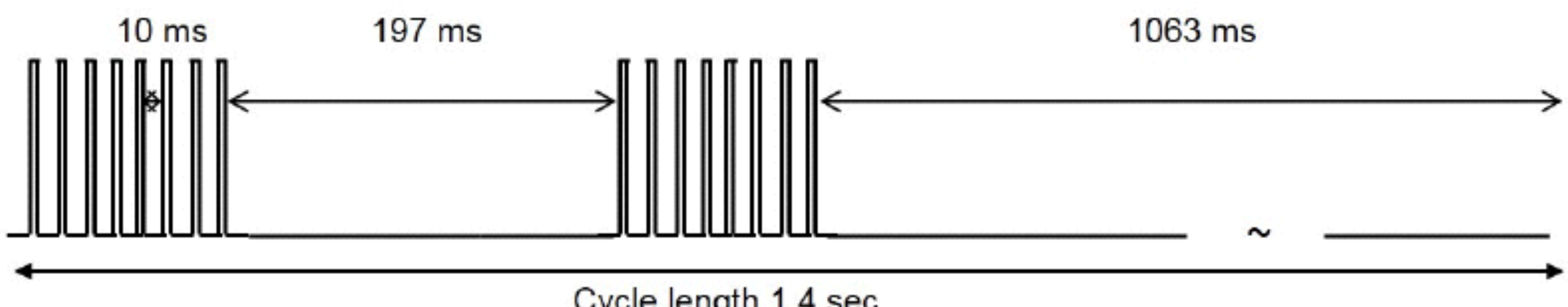
Producing Muon Beam

8 GeV Proton beam
- => target
- => Collecting π^+ with p = 3.11 GeV (±~10%)
- => π^+ to μ^+ decay
- => Collecting μ^+ with p = 3.094 GeV
- => transporting to the muon storage ring

Due to the angular momentum conservation, forward decay muons are highly polarized.

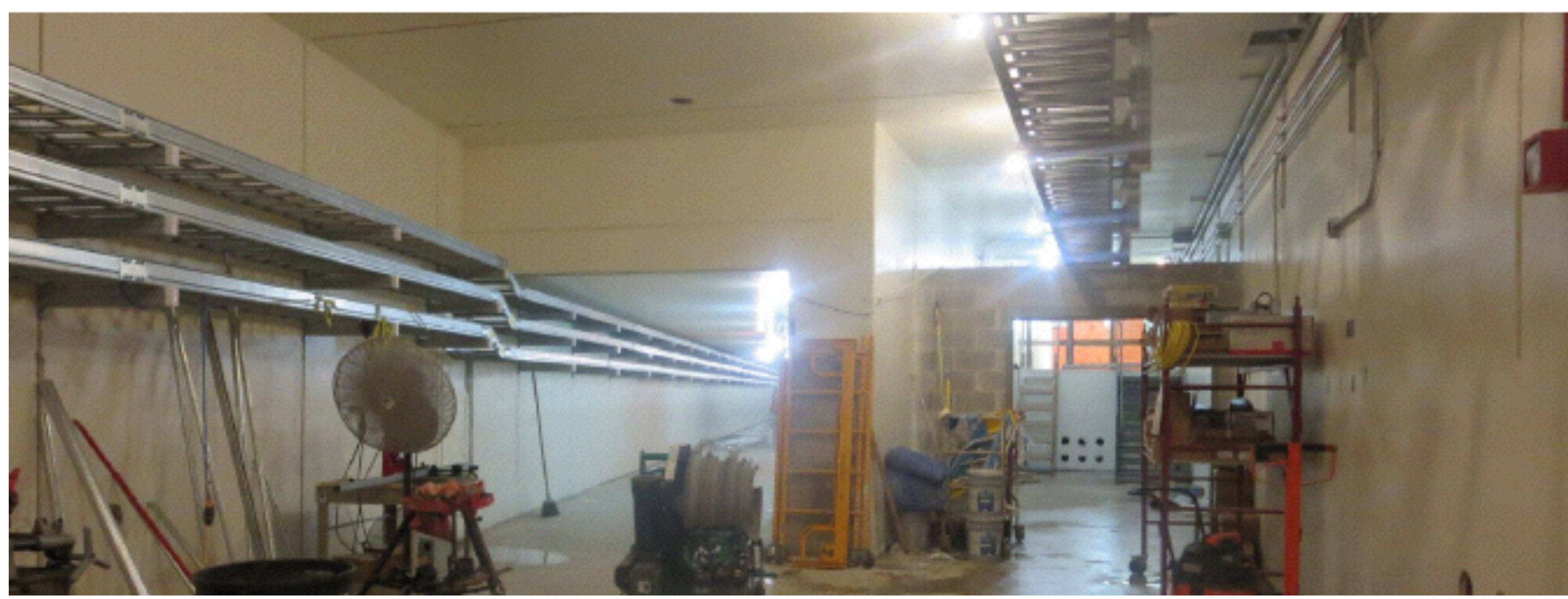
8.1×10^5 muons to the ring, out of 10^{12} protons
then, 1.0×10^4 muons stored

time structure of beam pulses to (g-2)



Beamline enclosure construction (M4,5)

Beamline enclosure construction

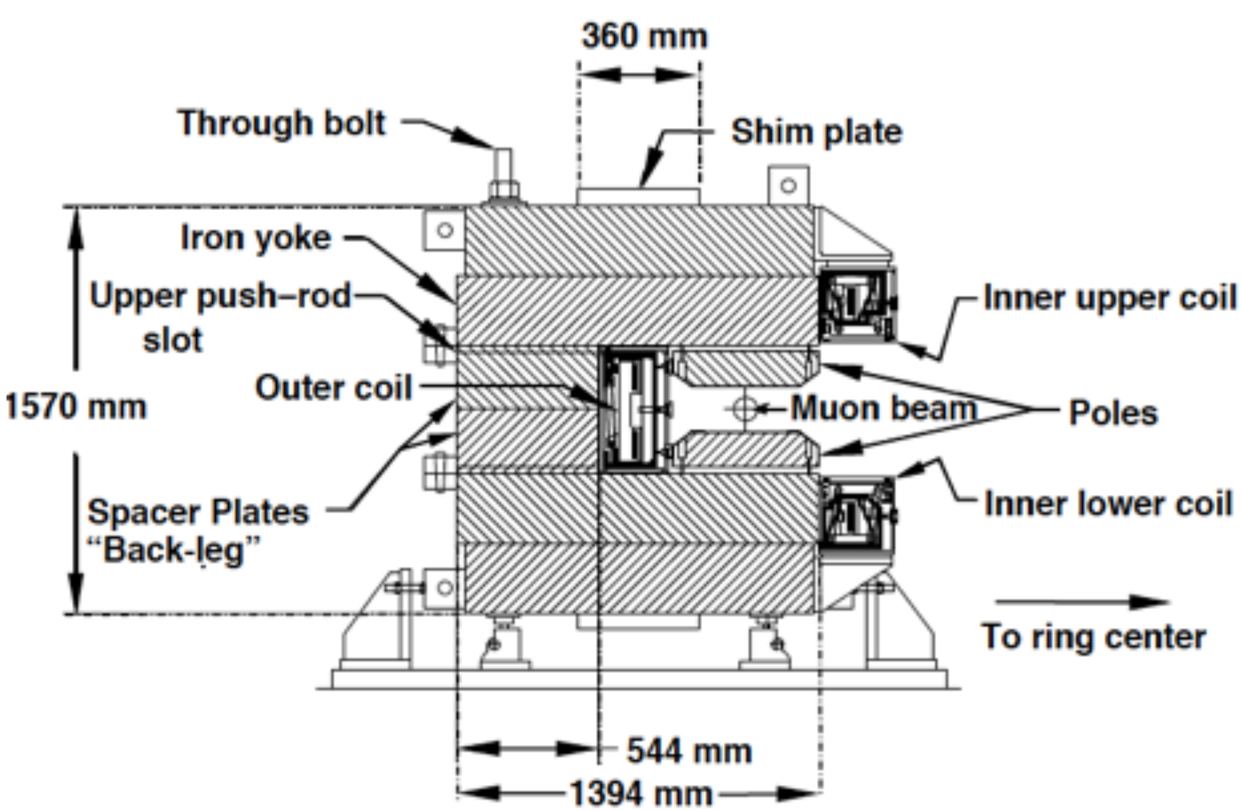


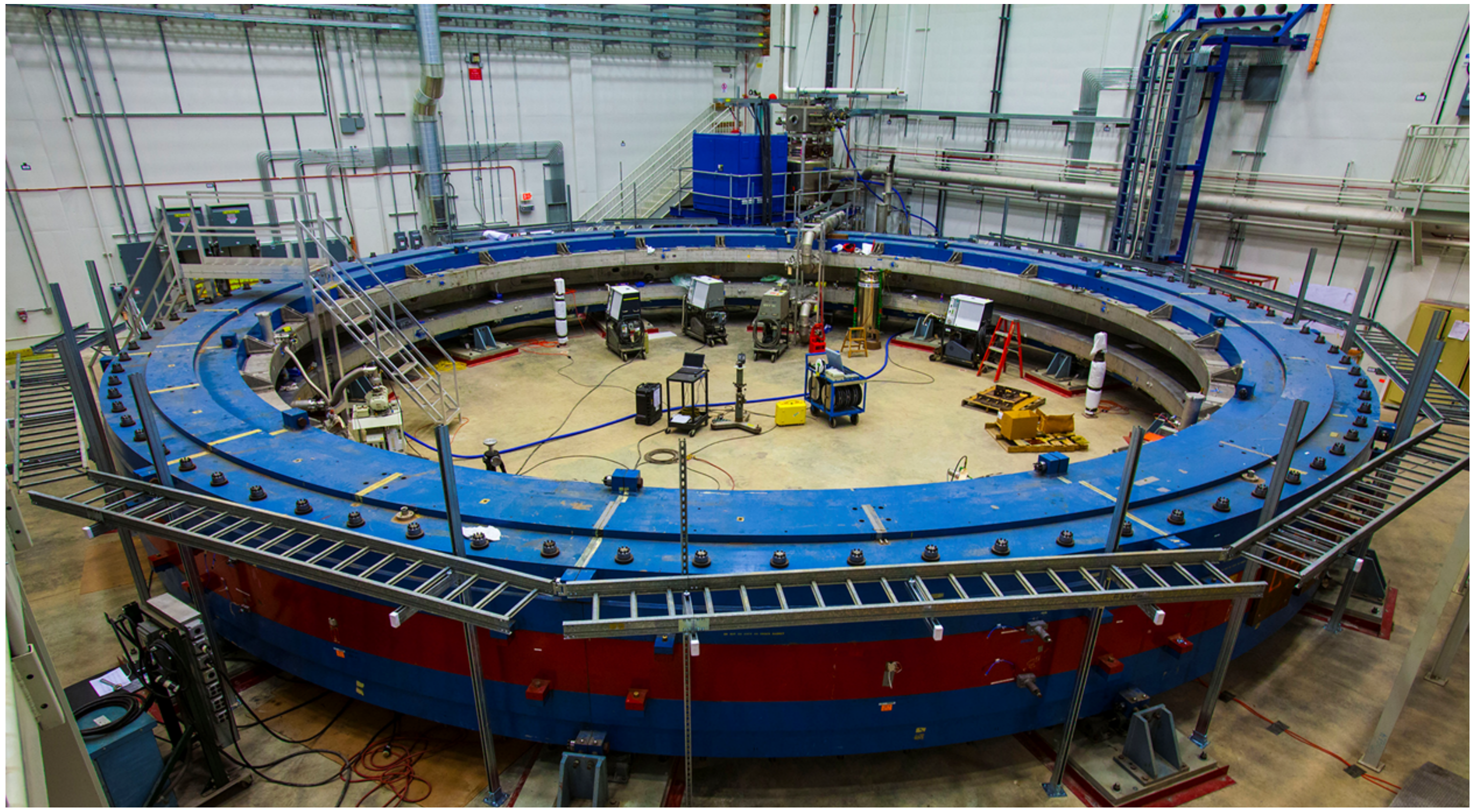
Storage ring magnet

Reusing E821 storage ring magnet
: 1 ppm level uniformity when averaged over azimuth, local variation ≤ 100 ppm

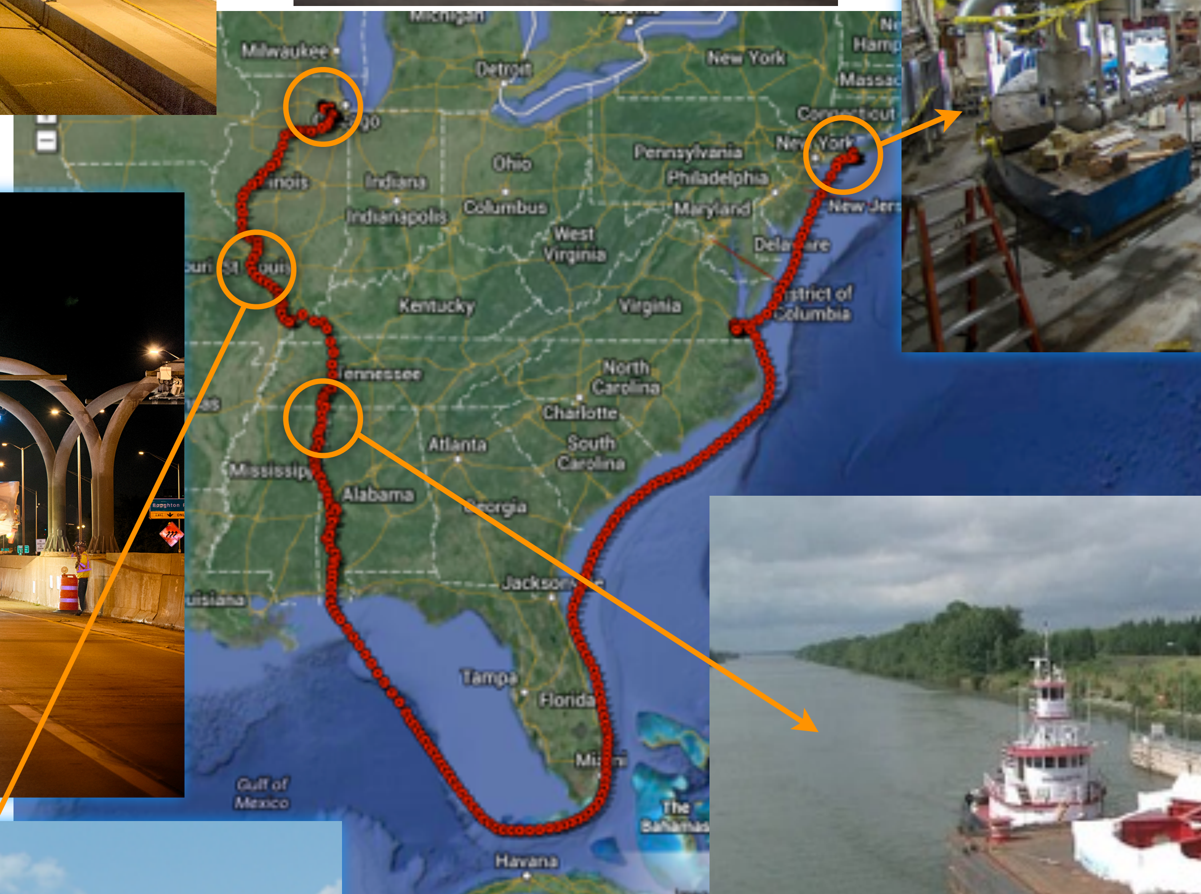
Superferric magnet: an iron magnet excited by superconducting coils.

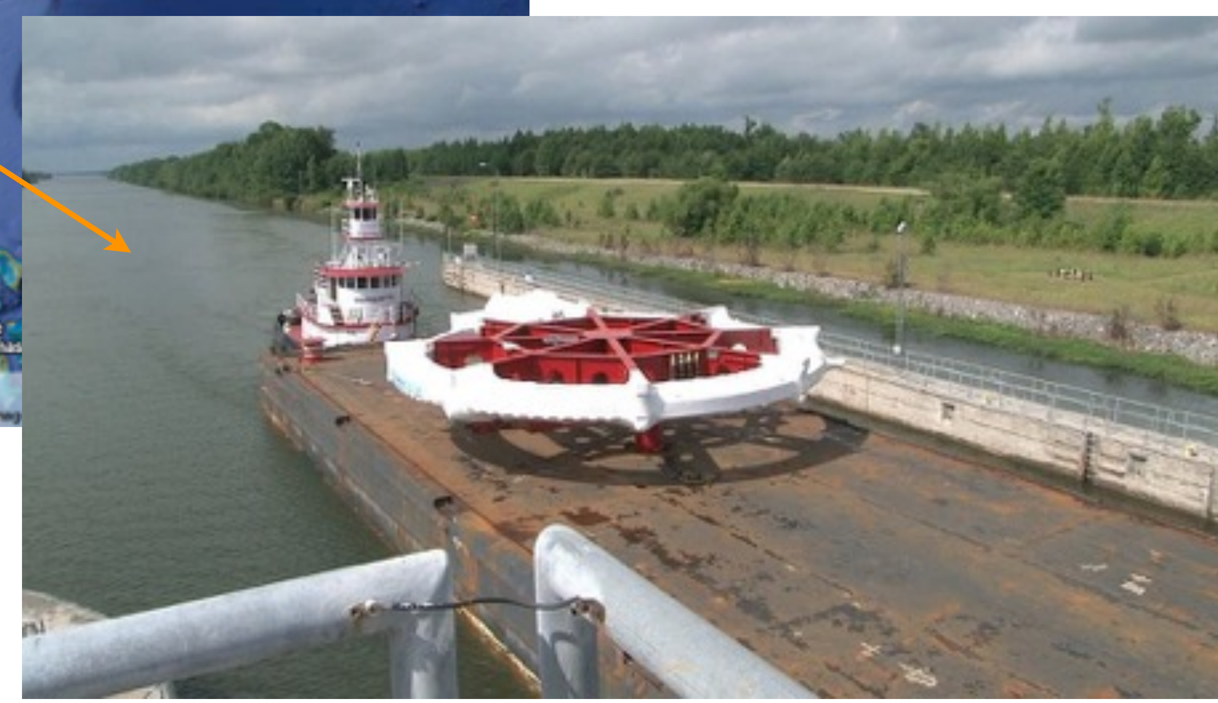
Magnetic field : 1.451 T
Design current: 5200 A
Equilibrium orbit radius : 7112 mm
Muon storage region diameter : 90 mm





Relocating the ring magnet from BNL to Fermilab

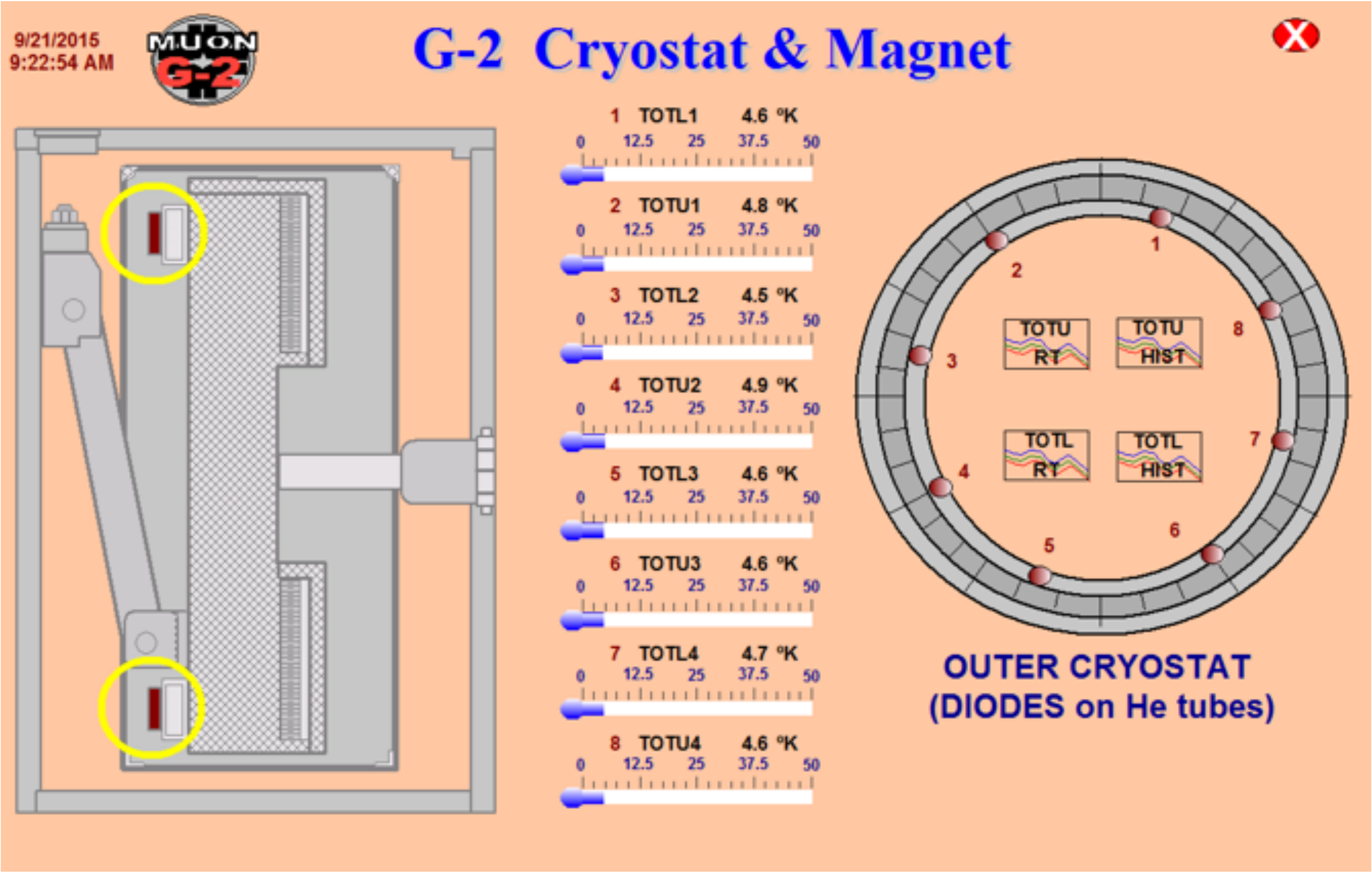




35 days, 3200 miles travel

15 m diameter coils, 1 mm vertical flex tolerance

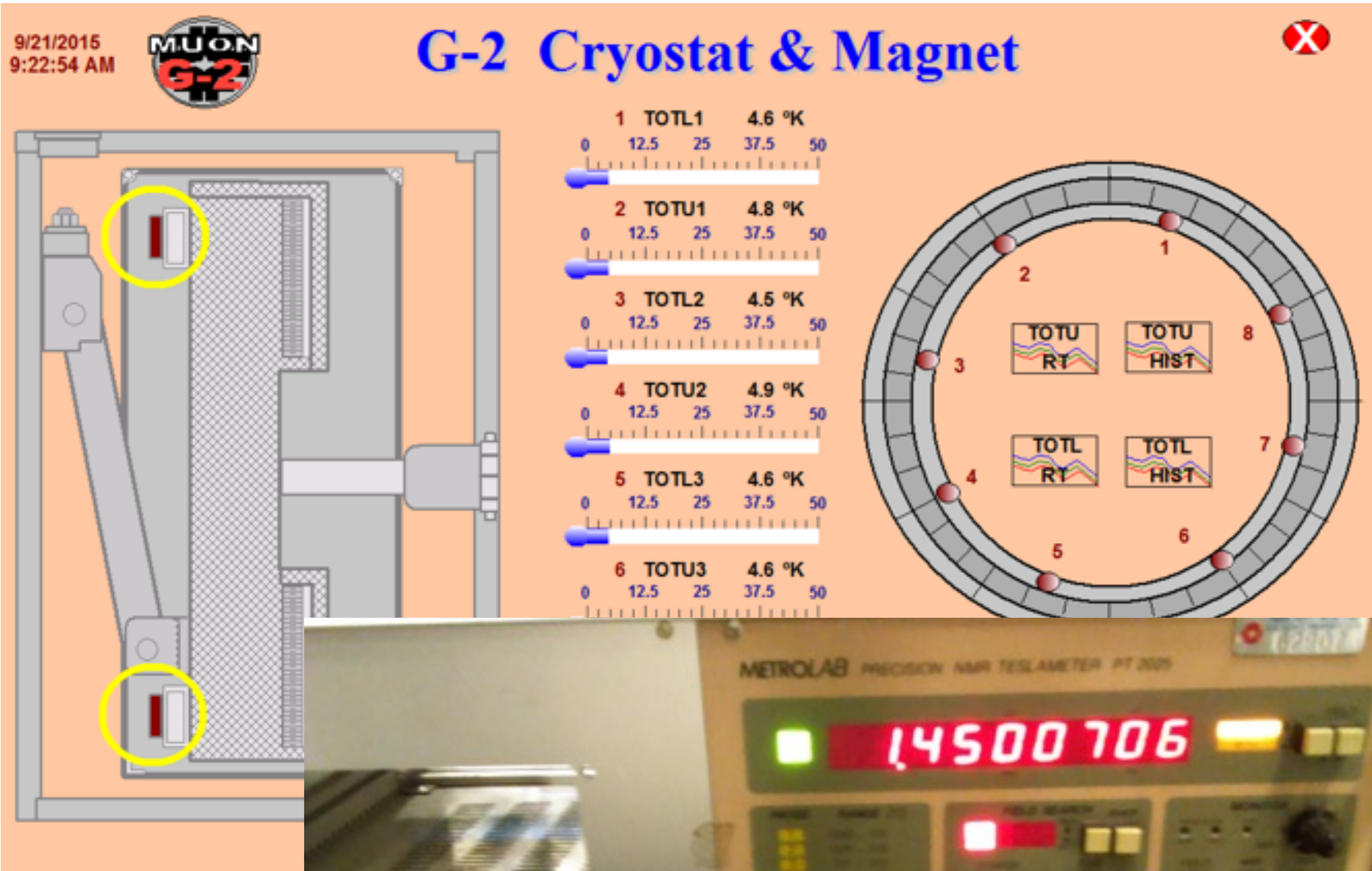
“Awakening the giant magnet!!!”



Current temperature

Powering the magnet,
which was not used since 2001

“Awakening the giant magnet!!!”

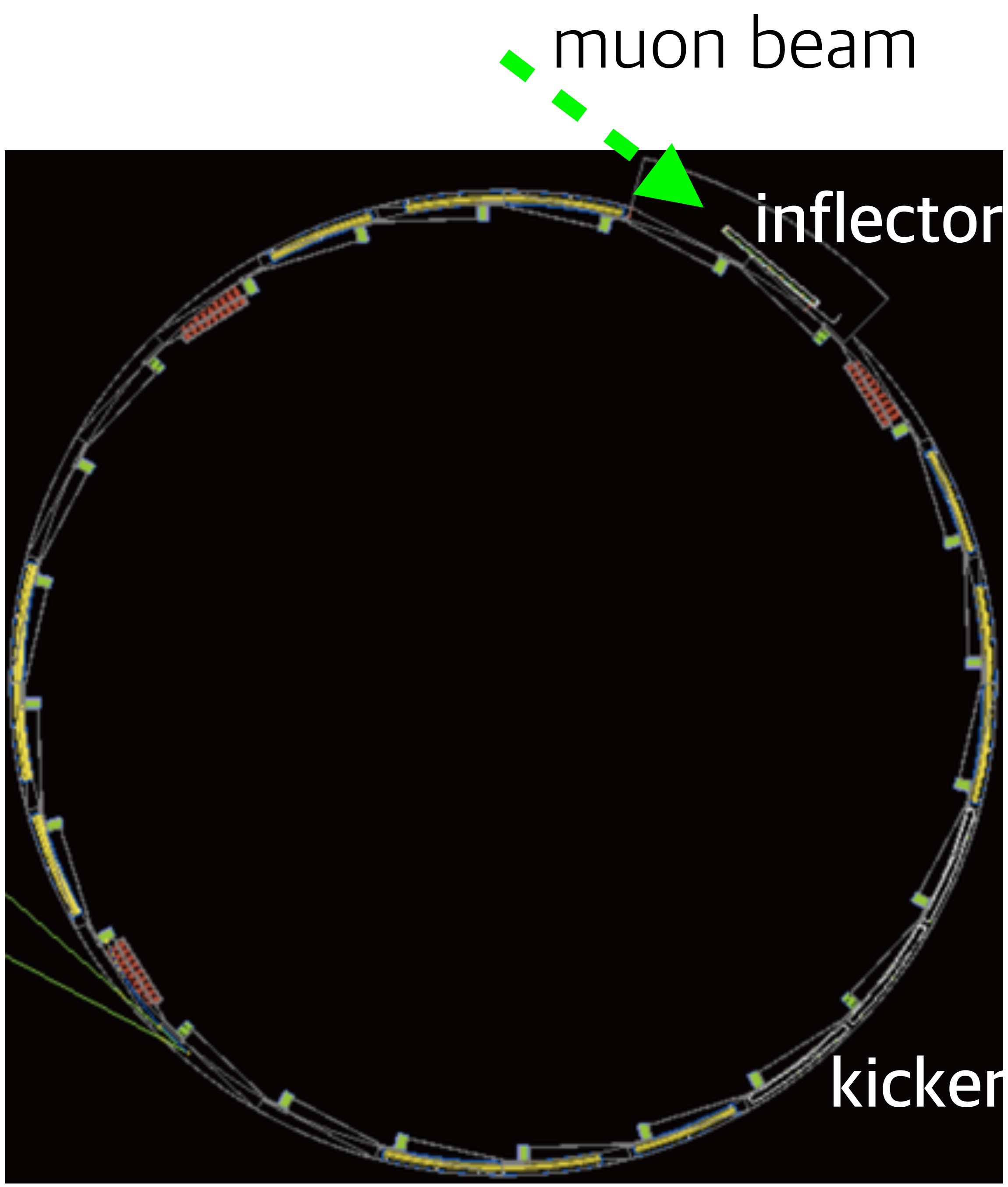


Current te

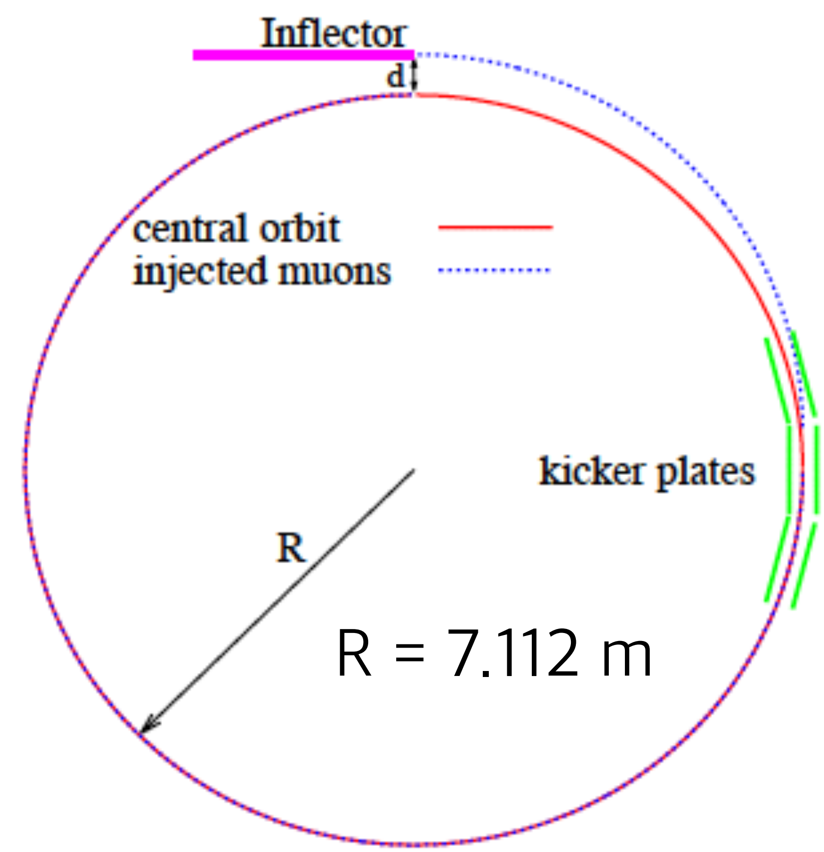
achieved 1.45 T just two days ago!

Powering the magnet,
which was not used since 2001

Injecting muon beam into the storage ring



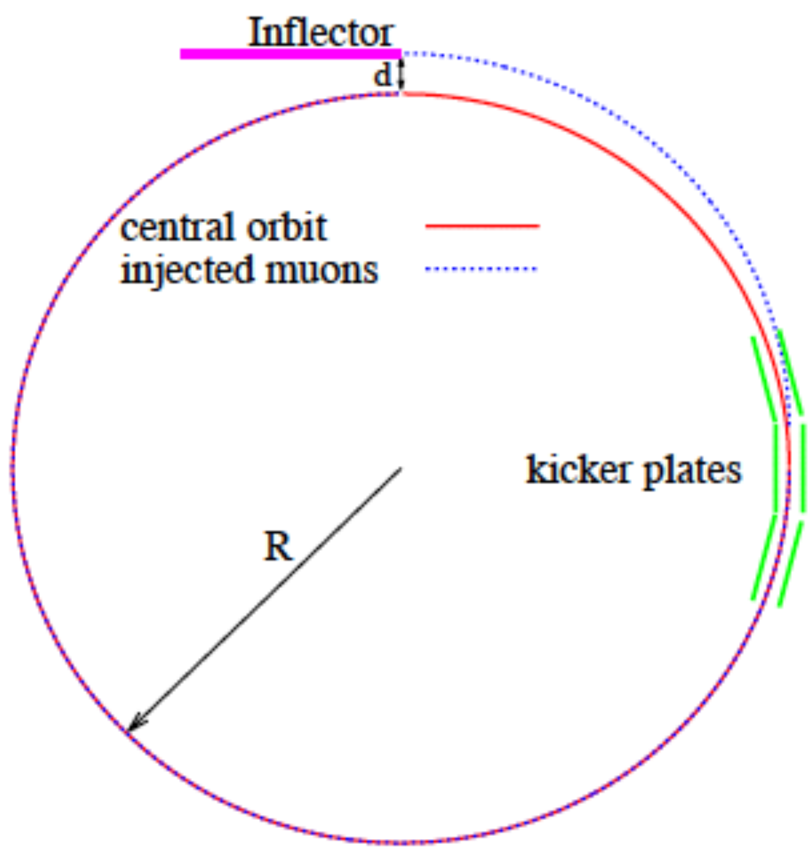
The layout of the storage ring



Muon beam comes into the storage ring through the inflector and gets pushed into the stable orbit by the kicker.

Inflector : canceling the fringe field

Kicker



Injected muons cross the central orbit at 10.8 mrad.

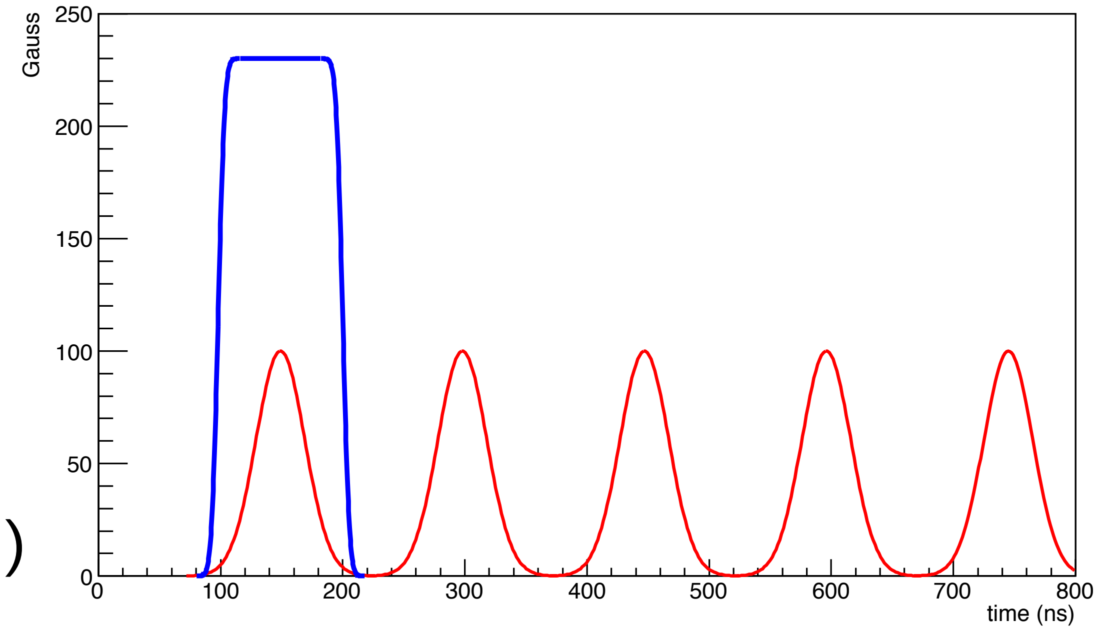
10.8 - 12.8 mrad compensation kick
=> 1.1 -1.3 kG-m

3 independent 1.27 m long magnets

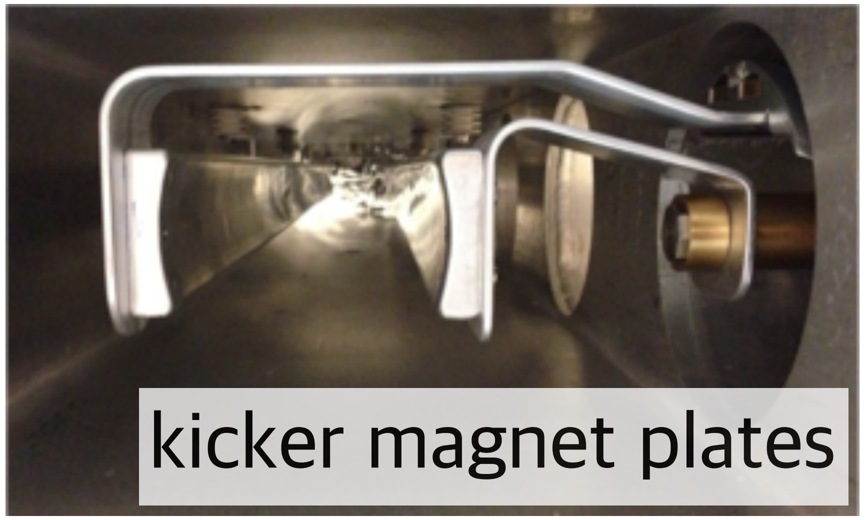
kicker pulse width > 120 ns (beam width)
< 149 ns (cyclotron period)

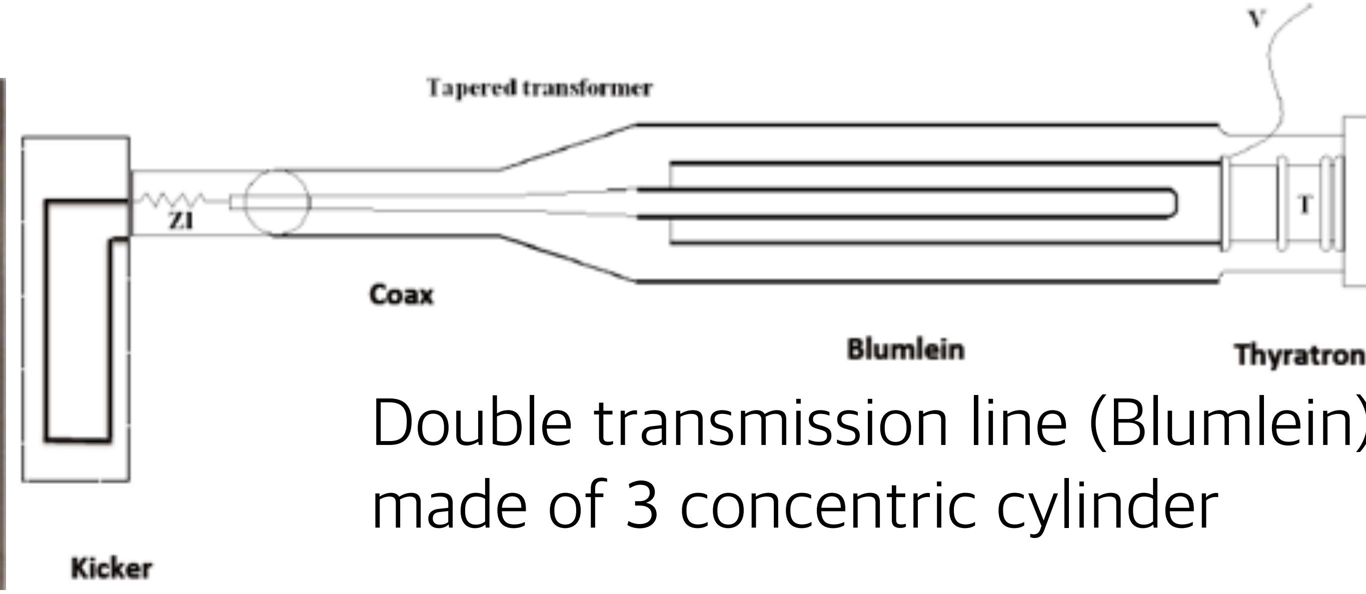
Influences on the muon capture efficiency and the amplitude of coherent betatron oscillation

Ideal kicker waveform (blue) &
injected beam with 149 ns cyclotron period (red)

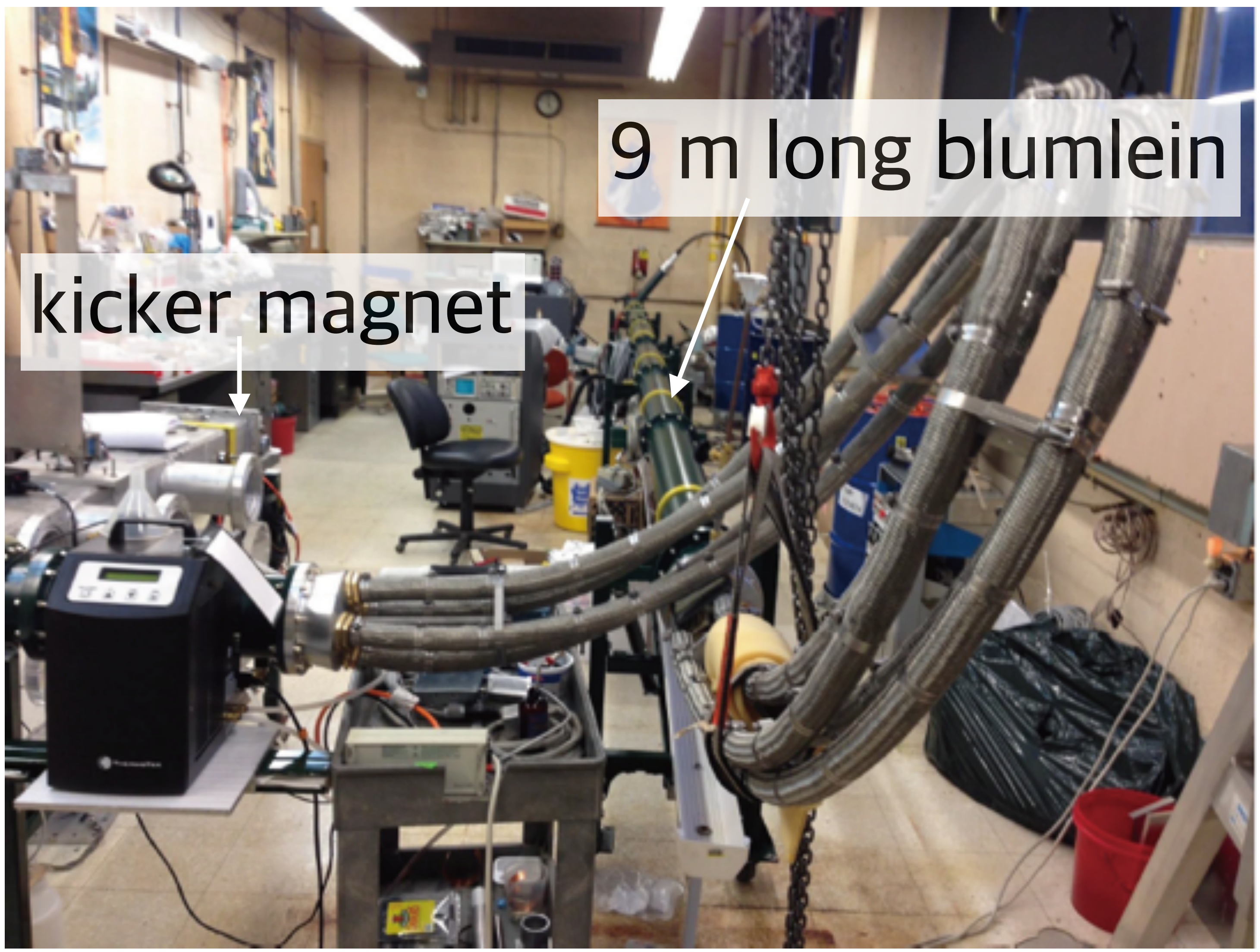


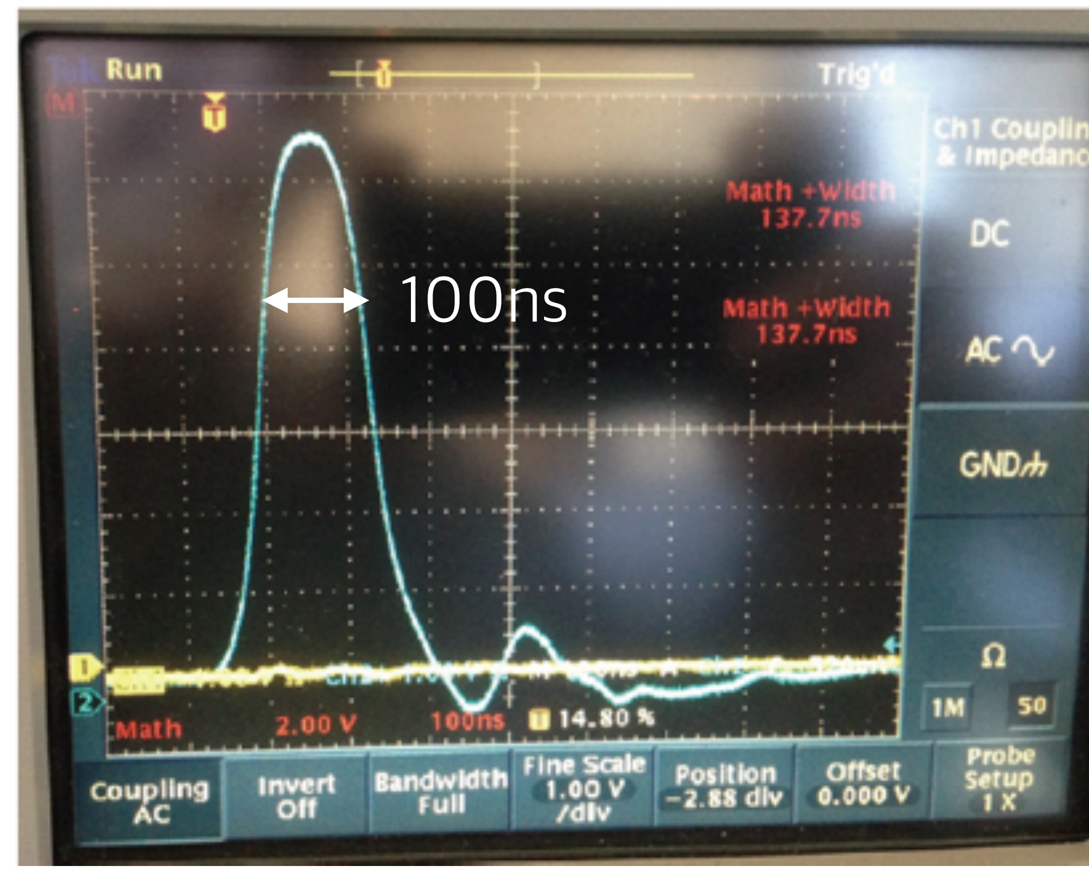
Kicker





Double transmission line (Blumlein) made of 3 concentric cylinder

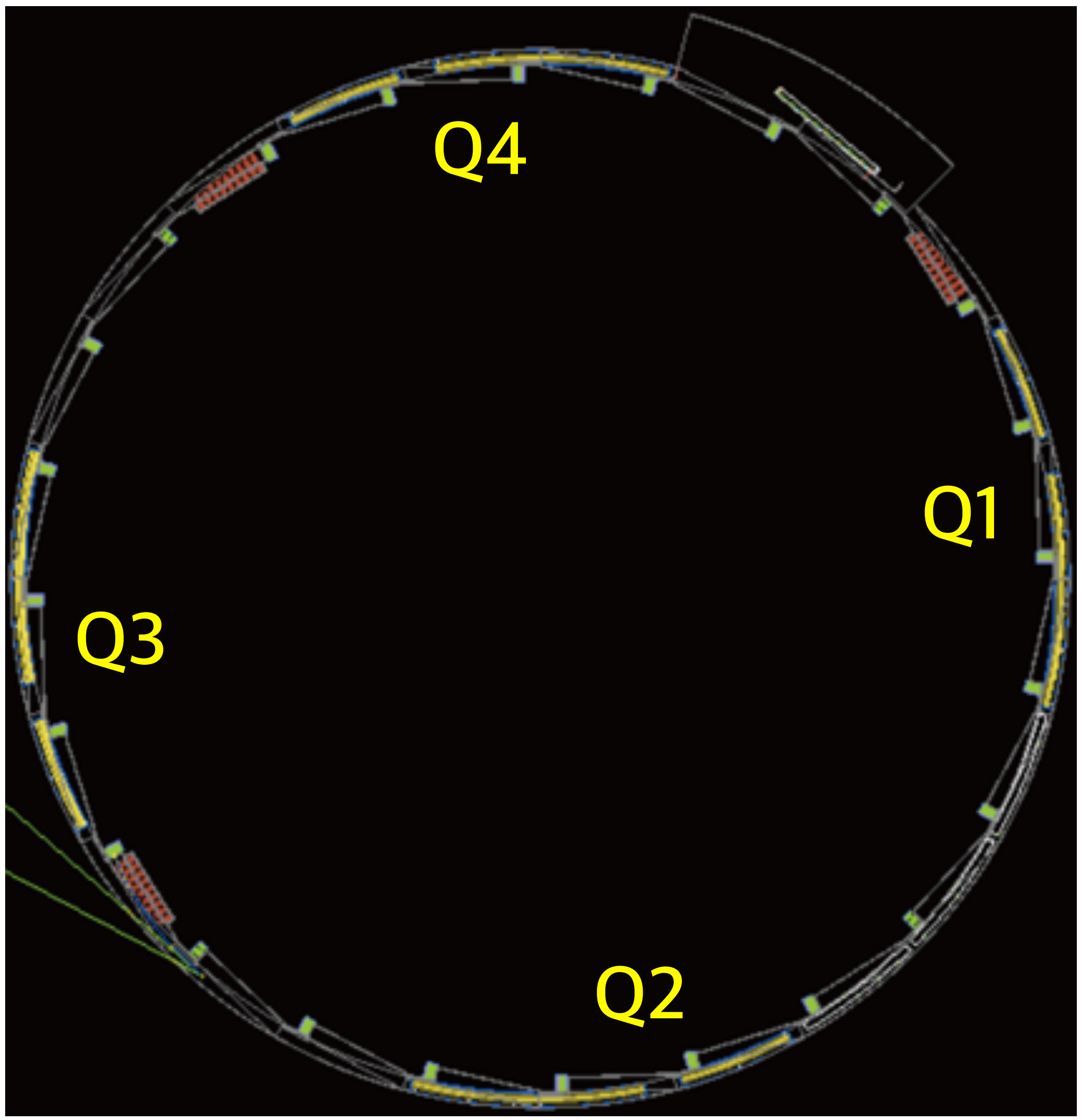




kicker pulse profile from test set up

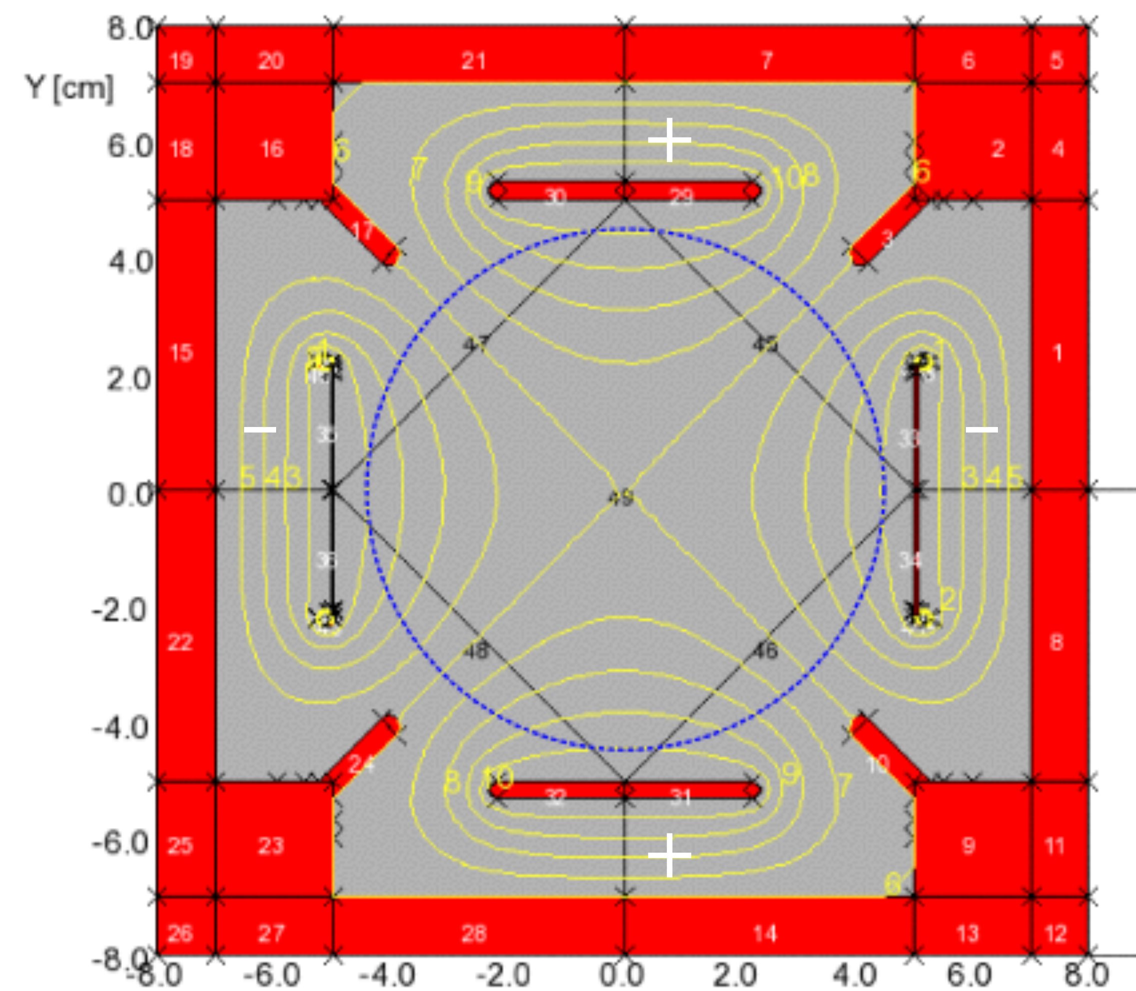
peak magnetic pulse : 292 Gauss (=> 4.5kA via kicker magnet)

Storing the muon beam in the storage ring



The layout of the storage ring

Electrostatic Quadrupoles
=> provide the vertical focusing
 to confine muons vertically
=> Divided into 4 sections (Q1-4)
 with 4 fold symmetry

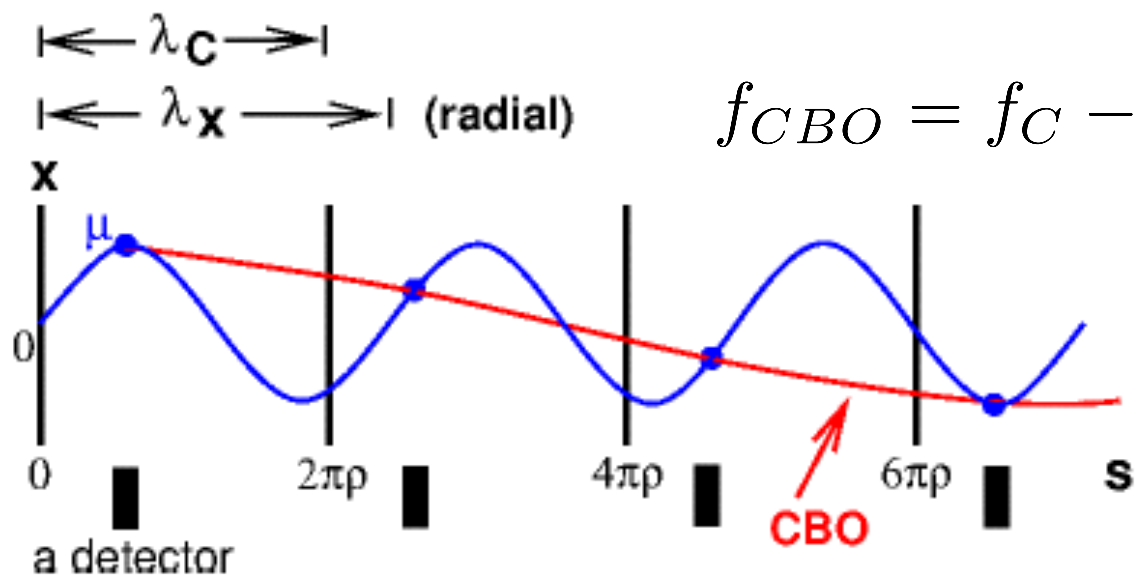


An OPERA model of electrostatic quadrupole

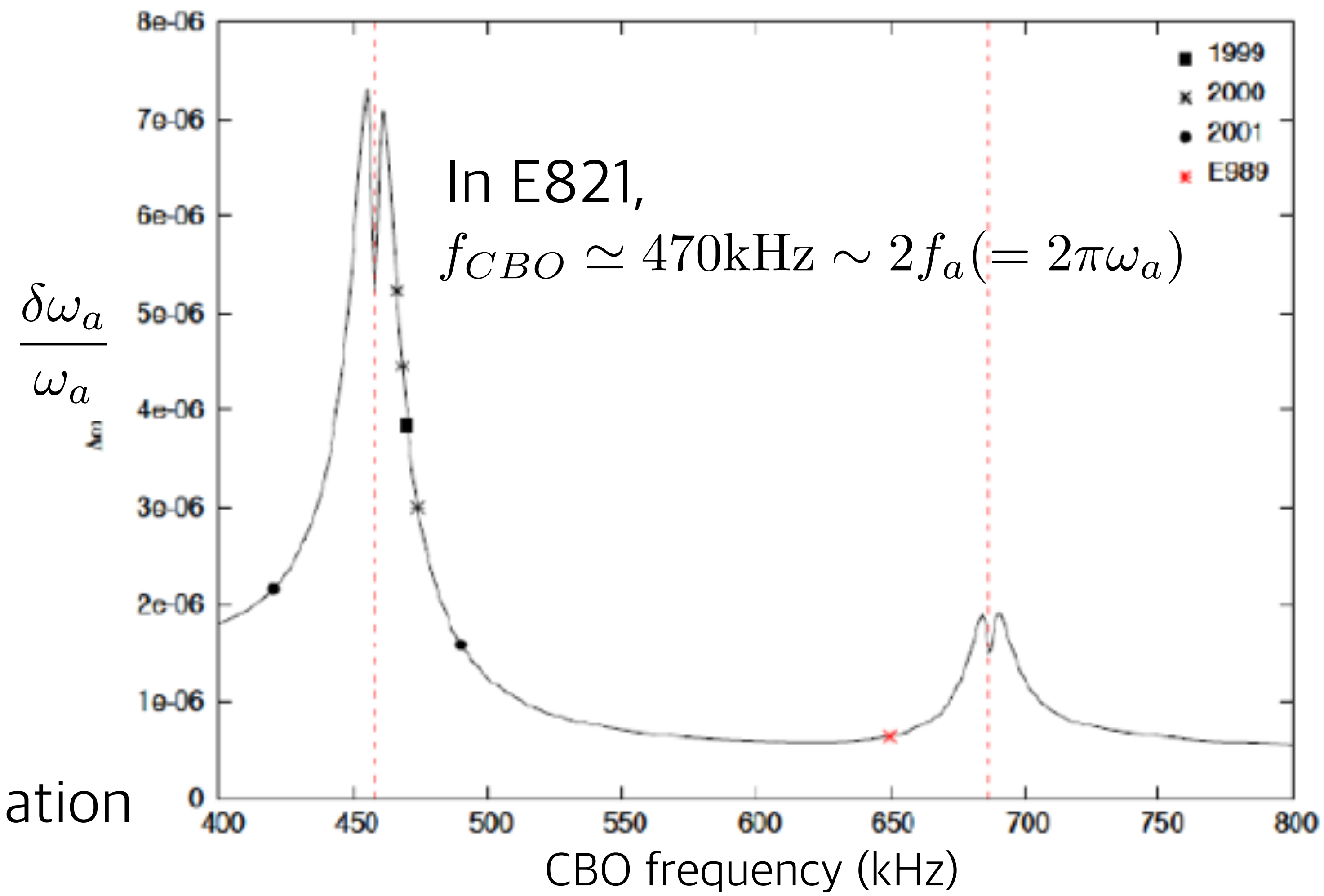
Electrostatic Quadrupoles

Quadrupole determines the betatron oscillation of the beam.

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



Induced shift vs CBO frequency



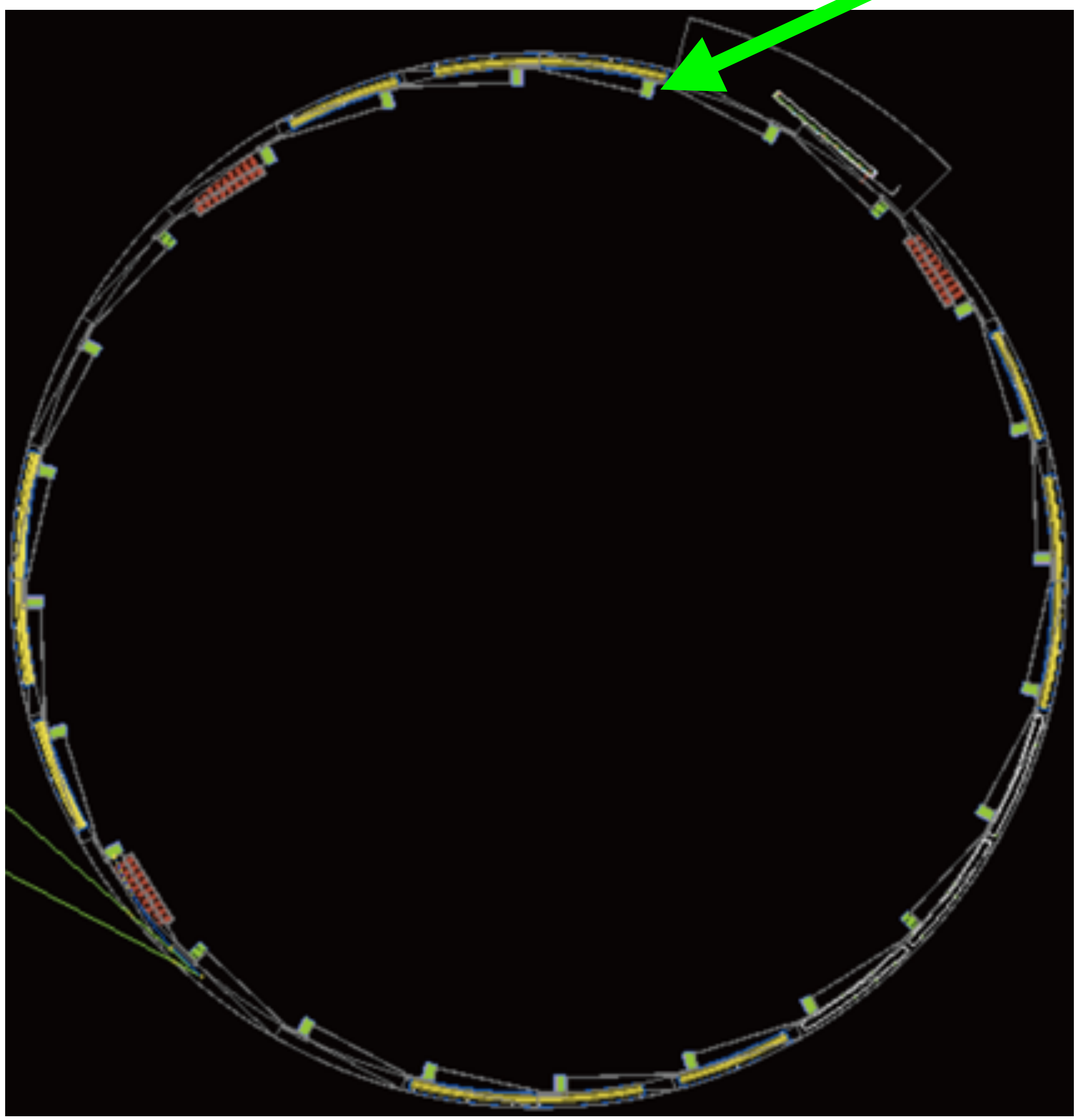
In E821,

$$f_{CBO} \simeq 470\mathrm{kHz} \sim 2f_a (= 2\pi\omega_a)$$

Effect of CBO on ω_a determination

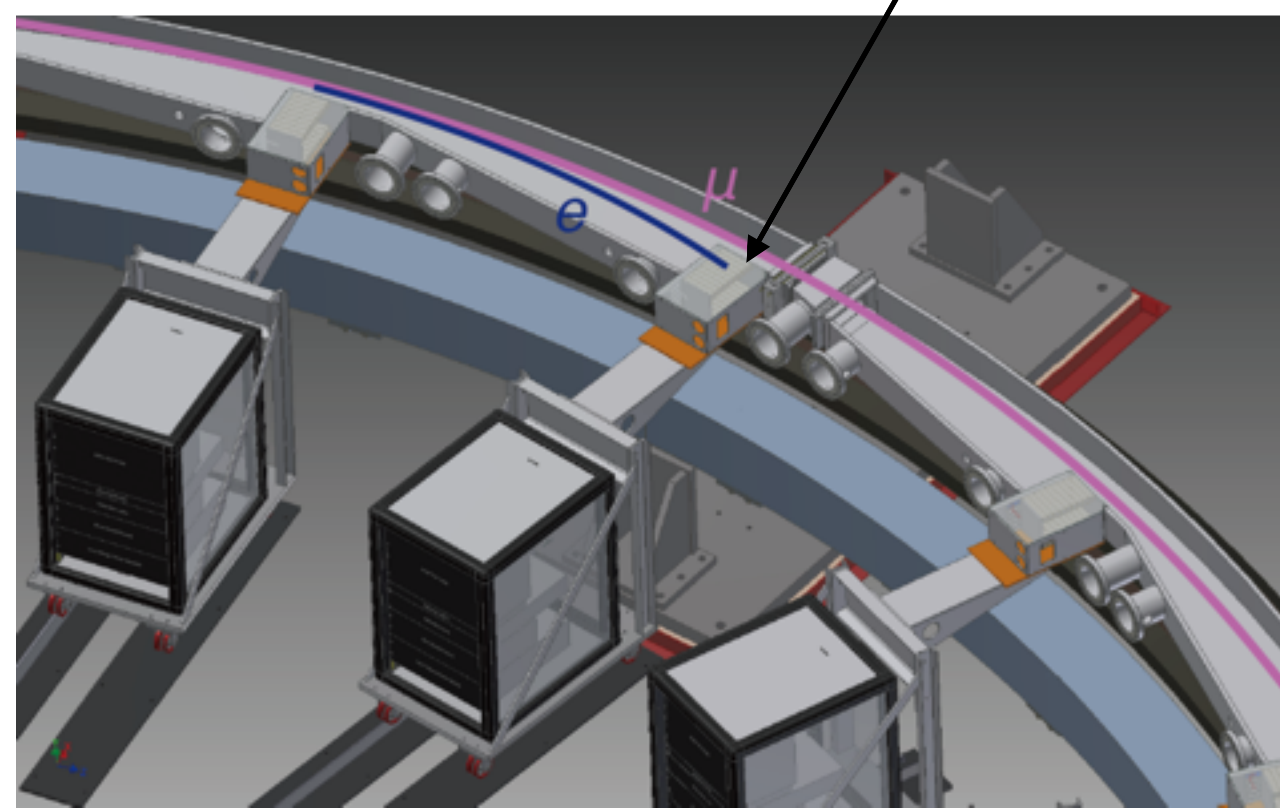
Detecting positron from muon decay

Calorimeter
total, 24 stations



The layout of the storage ring

calorimeter



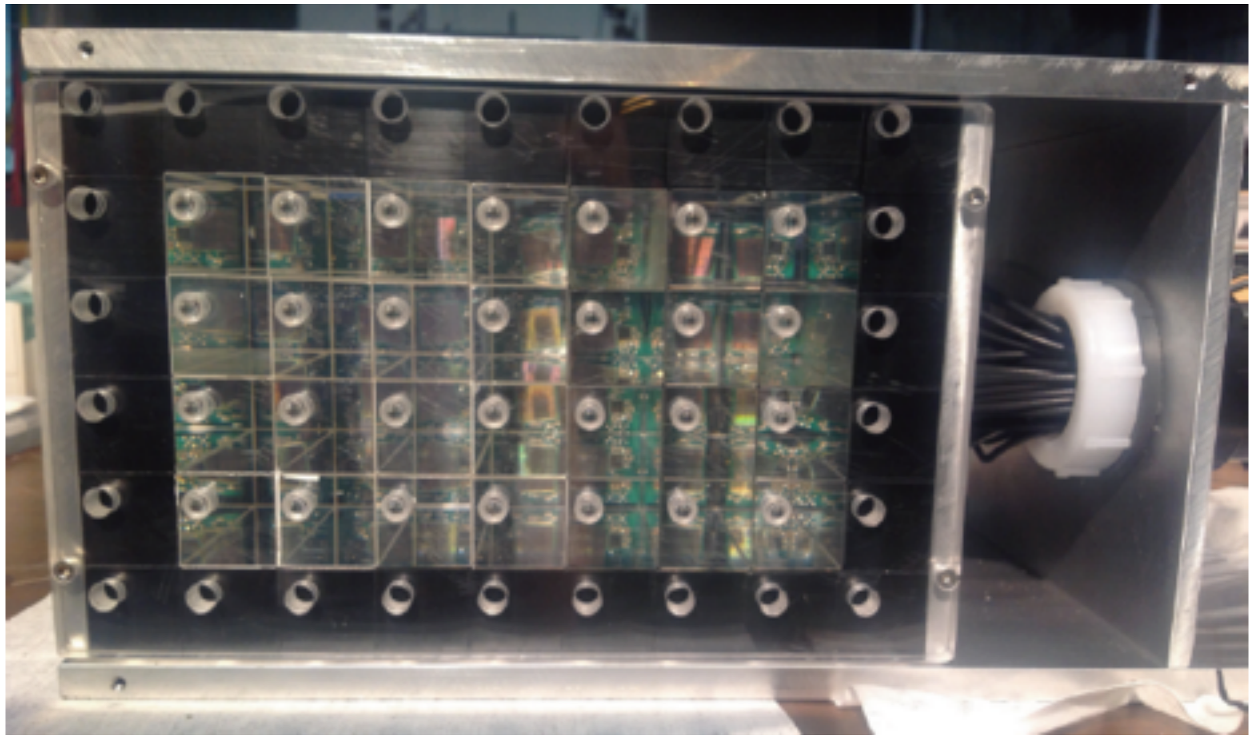
Calorimeter

Detecting positron (0-3GeV) from muon decay
=> Measuring hit time and energy

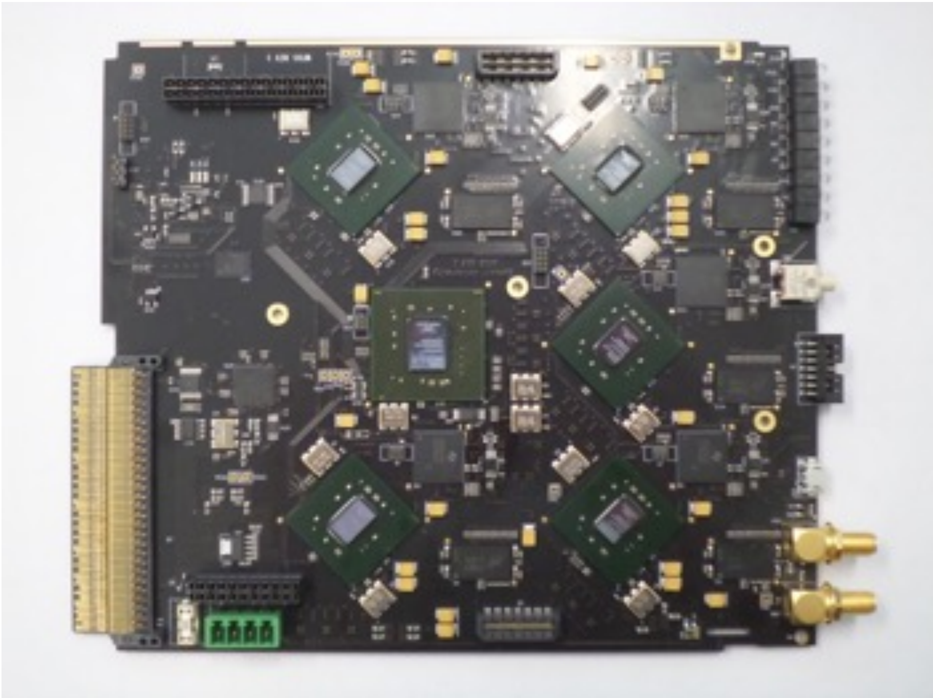
PbF_2 crystal : good energy resolution and fast Cherenkov signal response

SiPM photodetector : high efficiency, fast time response, not perturbing the ring field
Hamamatsu surface-mount 16 channel SiPM

Waveform digitiger (WFD): 12 bit @ 800Msamples /sec, 1,296 channels



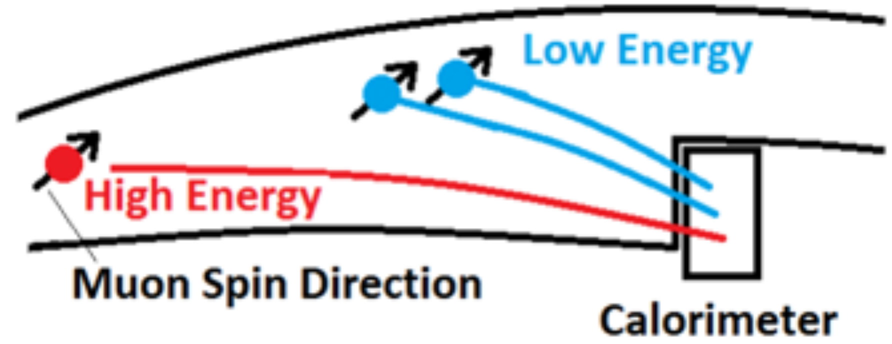
crystal array for a beam test



WFD

Calorimeter
-Pile up event identification!

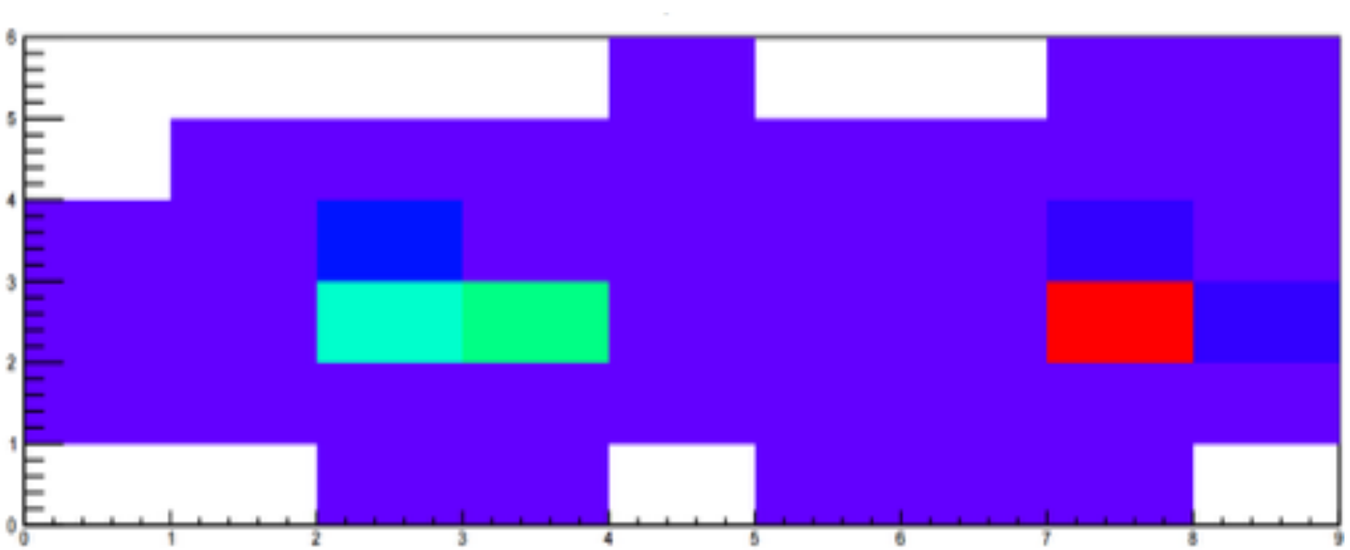
Distorting the phase of the wiggle plot



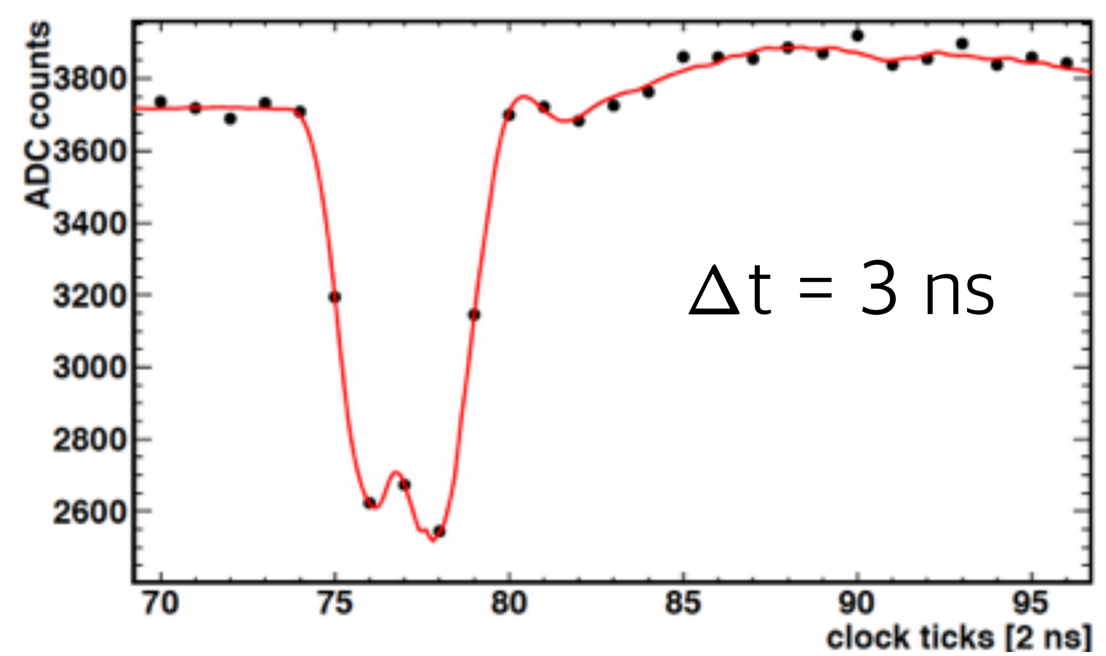
Pile up rate decreases exponentially with half the life time of muon decay
=> time dependent phase shift => pulling ω_a

6 x 9 array (2.5 x 2.5 x 14 cm^3 for one crystal) for one station
~4-5 fold reduction of pileup compared to a monolithic calorimeter (E821)

Thanks to the fast response, events which occur in longer than 3 ns interval can be reliably separated.



two positrons hit



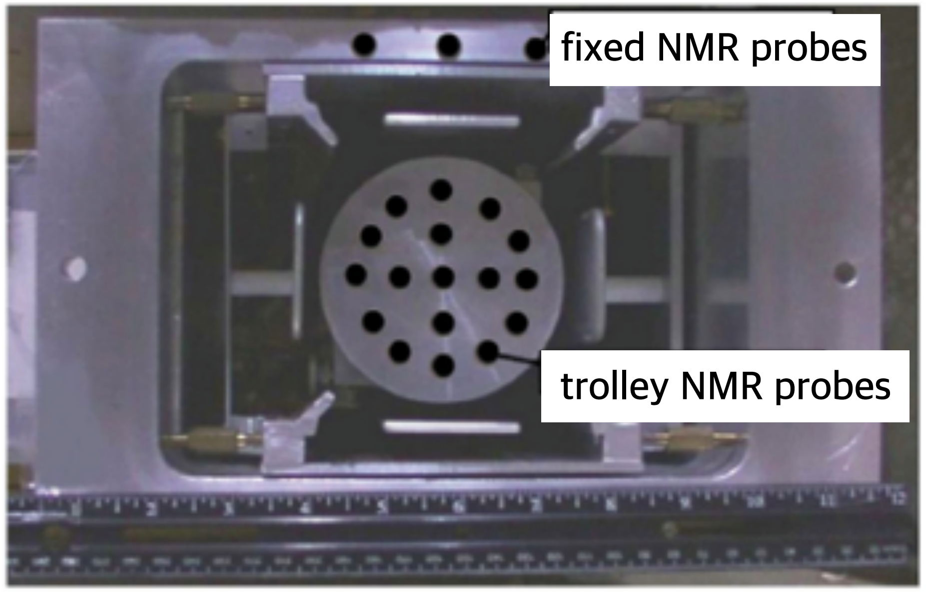
Measuring Magnetic field in the muon storage region

E989 goal : to know the magnetic field averaged over running time and the muon distribution to an uncertainty of 70 ppb.

=> Monitoring B to the 20 ppb level around the storage region during data collection
  => Using NMR of protons in a water sample or petroleum jelly
  => 378 NMR probes at 72 locations

=> Periodically mapping the field throughout the storage region
  => mapping the field with 17 NMR probes in the trolley at 6000 location
  => Using same NMR probes as the monitoring probes
  => cross calibration with monitoring information

=> Obtaining an absolute calibration of the B-field to the free proton Larmor frequency with an accuracy of 35 ppb.



Conclusion

The calculation and measurement of a_μ have been an important issue for many decades.

The Latest measurement of a_μ at BNL was done with 0.54 ppm uncertainty and shows non-negligible tension with the current SM prediction.

New experiment to measure a_μ at Fermilab using the intense muon beam
=>Designed, Under construction and data taking expected in 2017

From all the recent developments in the experiment,
it is expected that the measurement of 0.14 ppm uncertainty will be conducted in a few years.

=> $\Delta a_\mu(E989 - SM) \sim 5\sigma$ (w/ current central values)

$\sim 8\sigma$ (w/ current central values
+ expected theory improvement ~ 0.2ppm)

E989 Collaboration: 35 Institutes; >150 Members

USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern (thy)
- Regis
- Texas
- Virginia
- Washington
- York College
- Argonne
- Brookhaven
- Fermilab

Italy
- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China
- Shanghai

The Netherlands
- Groningen

Germany
- Dresden (thy)

England
- University College London
- Liverpool
- Oxford
- Rutherford Lab

Korea
- KAIST

Russia
- Dubna
- Novosibirsk

Thanks!

Back up

The basic principle of E821 experiment

From the proton NMR frequency, $\omega_p = 2\mu_p B$ and $\omega_a = -\frac{e}{m_\mu} a_\mu B$

We can obtain a_μ straightforwardly but there're uncertainties in μ_p and $\frac{e}{m_\mu}$.

Using $\mu_\mu = (1 + a_\mu)\frac{e}{2m_\mu}$

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

So, the results of E821!

$$a_\mu^{\mathrm{E821}} = (116\,592\,089 \pm 63) \times 10^{-11} \quad (0.54\,\mathrm{ppm})$$

The uncertainty of ω_a : 0.46(stat) + 0.18(syst) ppm
The uncertainty of ω_p : 0.17 ppm
The uncertainty of μ_μ/μ_p : 30 ppb (Exp + SM theory about the Muonium hyperfine splitting)

W.Liu et al, PRL 82 711 (1999), Rev. Mod. Phys. 80:633 (2008)

ω_a systematic error

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

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 ω_p	170		70

Storage ring magnet

Shimming

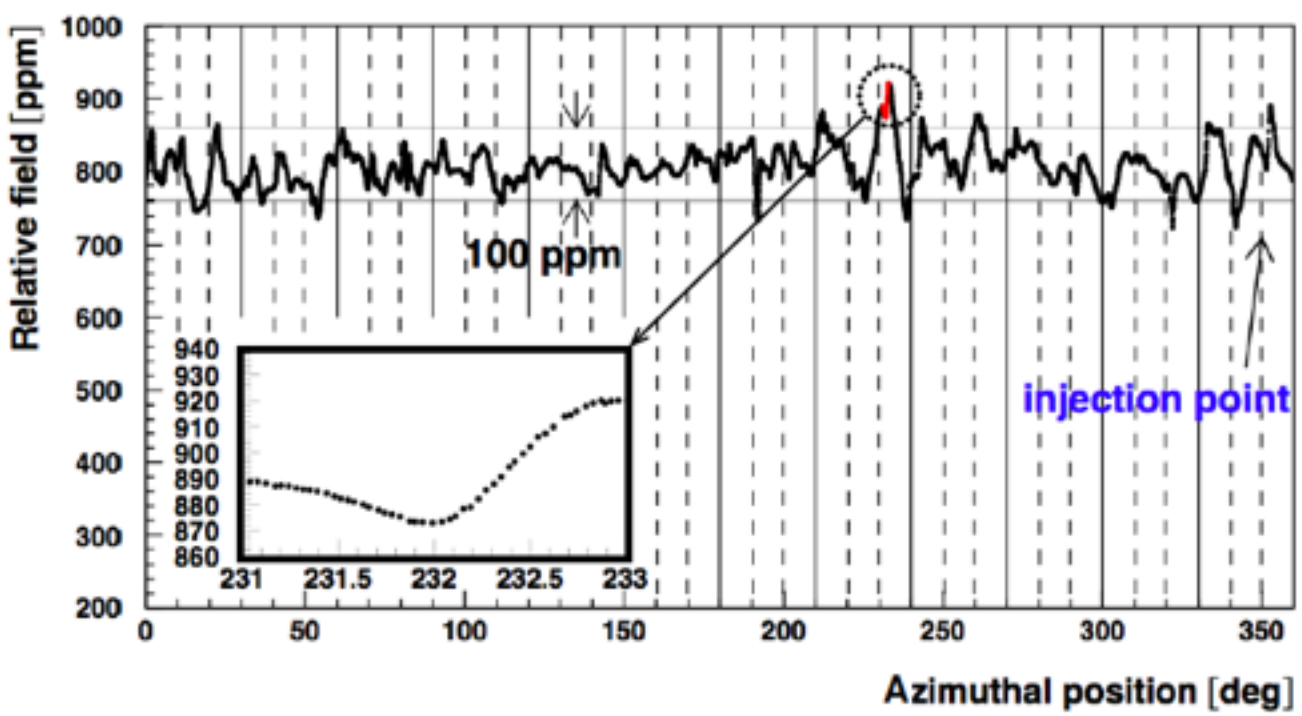
=> procedure to maximize the uniformity of the magnetic field

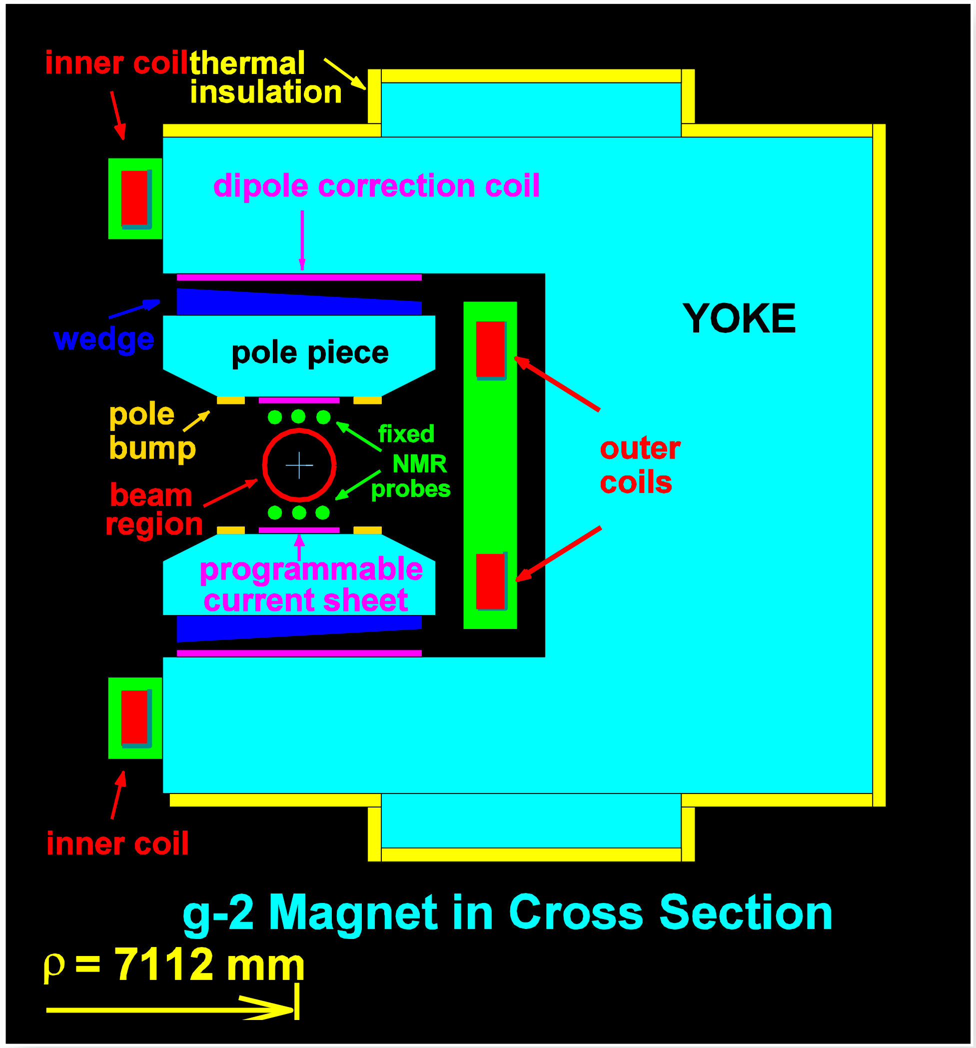
=> Goal : azimuthal field variation (100 ppm (E821) -> 50 ppm)

quadupole averaged over azimuth ≤ 250 ppb

higher multipoles at the 100 ppb

Hall temperature stability < ± 1 ℃ (>2 times better than E821)

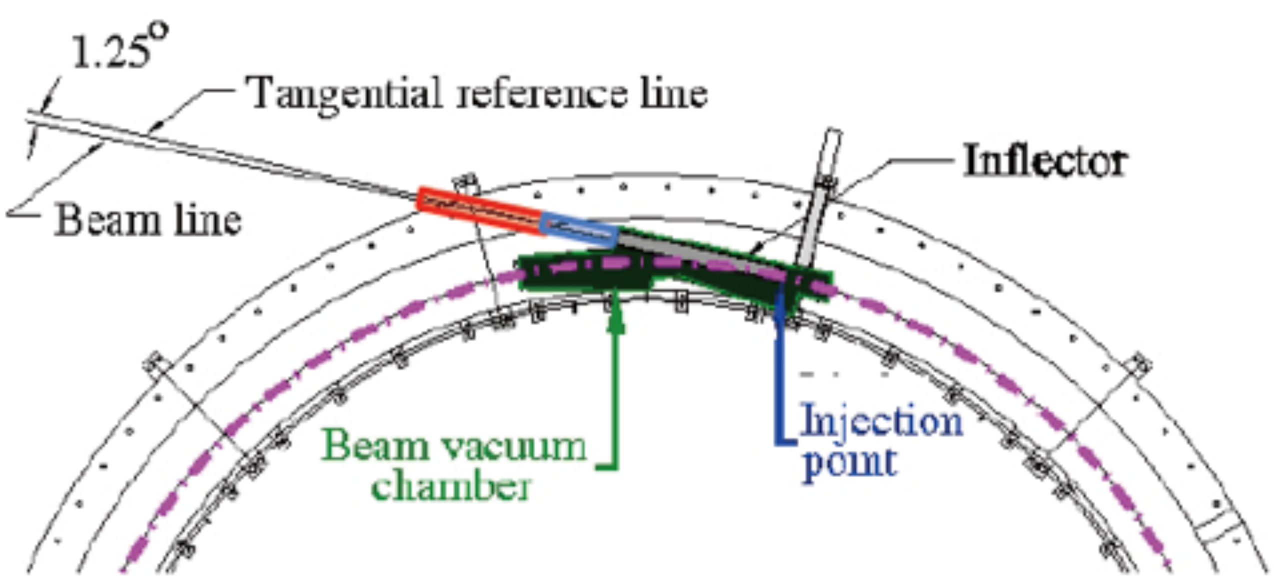


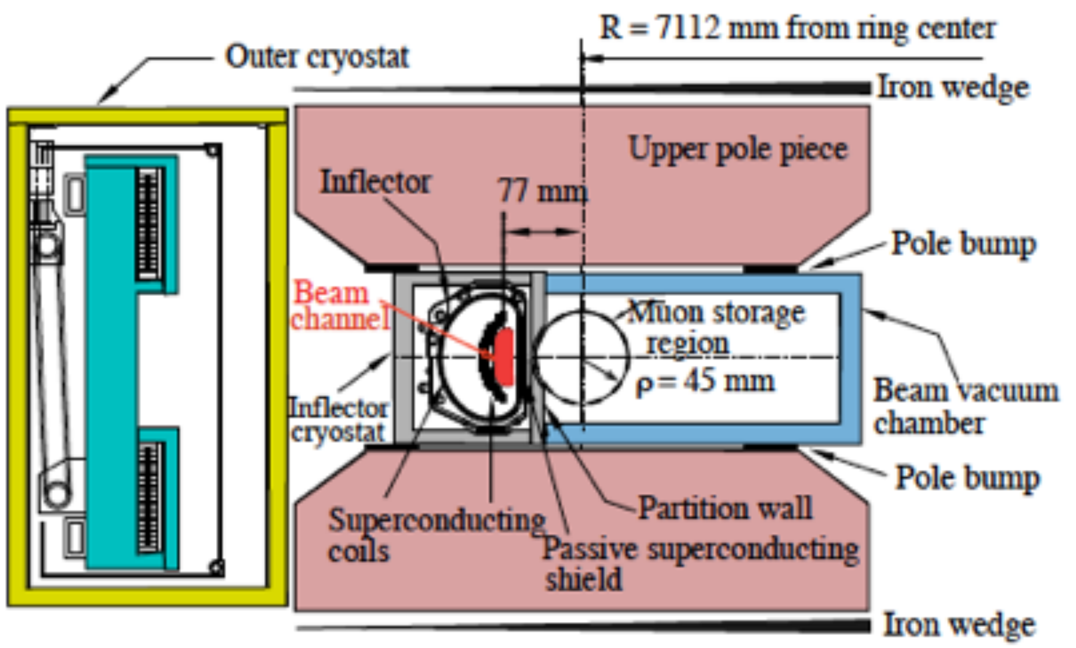


Inflector

Canceling fringe field from 1.45T magnet field to avoid the deflection of the beam

also should be careful not to distort the uniform field of the ring because of the inflector



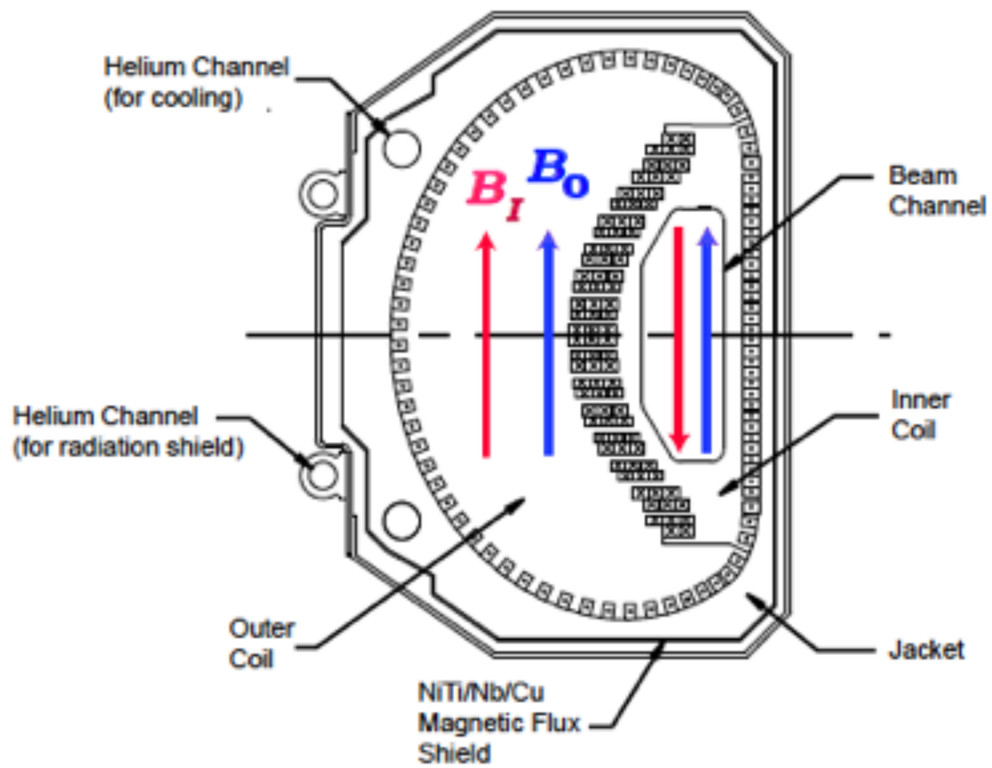


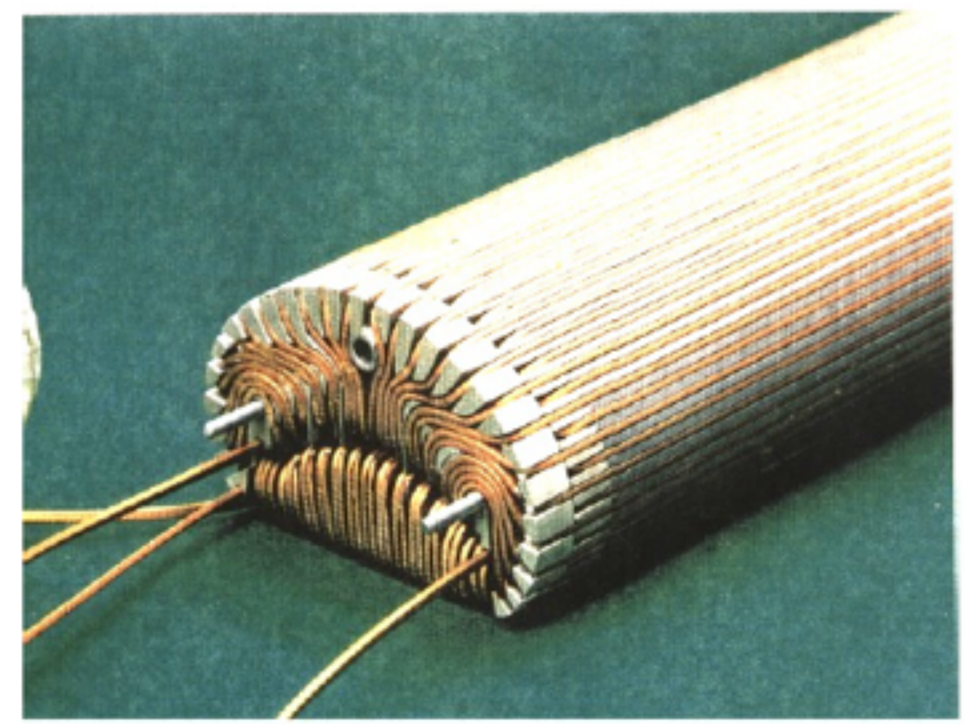
Injection point cross section

Inflector

Baseline plan: E821 inflector

Double cos θ magnet





Small aperture :18 mm x 56 mm
=> large oscillation of β-function, beam amplitude(A) =$\sqrt{\epsilon\beta}$
=> causing beam loss at the collimator in the ring.

Closed ends : to prevent the magnetic field leak (But, at the cost of multiple scattering)

New inflector design is going on in parallel.