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Fermilab

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A Dedicated Muon EDM Experiment in the `g-2' Storage Ring

AAKAASH NARAYANAN

U.S. DEPARTMENT of ENERGY

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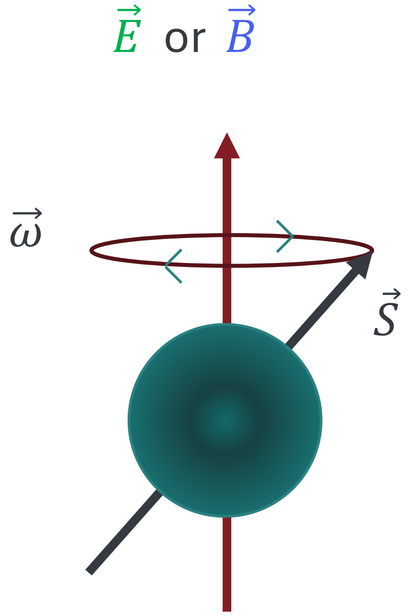
- Future …

The dipole moment (in this context) is a measure of how much the spin of a particle would precess in presence of a given electric or magnetic field.

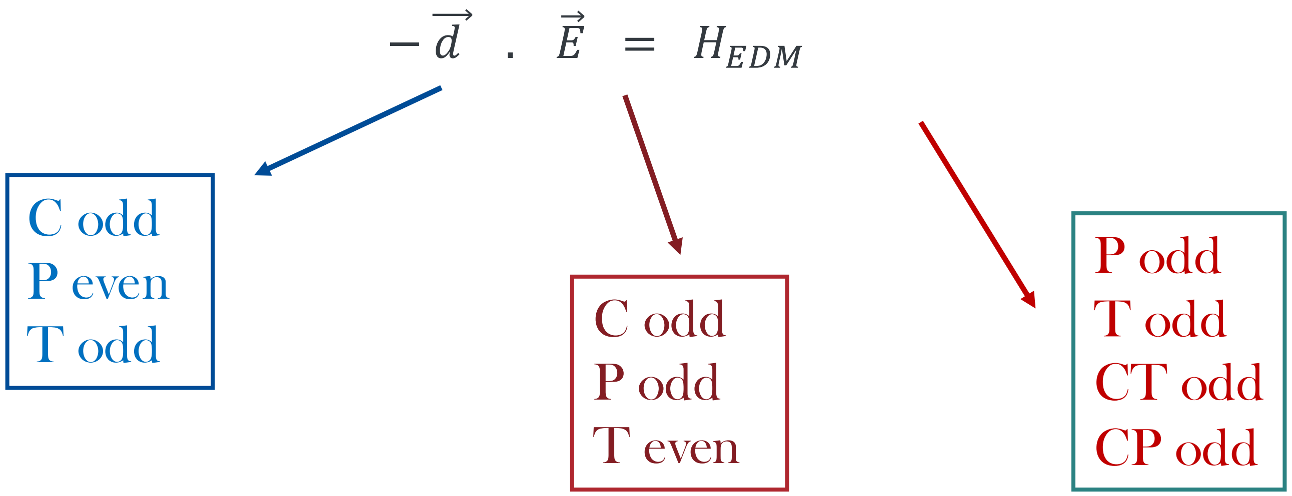
This could be an 'electric dipole moment (EDM)' or 'magnetic dipole moment (MDM)'.

Stronger the $\vec{E}$ or $\vec{B}$-field, stronger will the spin precess.

Similarly, higher the value of its intrinsic EDM or MDM, faster will be the spin precession!



Motivation for EDM Search



$$-\vec{d}\ .\ \vec{E}\ =\ H_{EDM}$$

C odd
P even
T odd

C odd
P odd
T even

P odd
T odd
CT odd
CP odd

A non-zero EDM implies P and T symmetry violation.

If there exists a permanent EDM, assuming CPT is invariant, then CP must also be violated!

The CP violation could explain the matter anti-matter asymmetry we observe in the Universe.

Motivation for measuring *muon's* EDM

- EDM of a muon is heavily suppressed in the Standard Model (˜ 10^{-38}) unlike in BSM models - an excellent probe for new physics.
- The current muon EDM limit of $d_\mu < 1.8 \times 10^{-19}$ is the the only EDM of fundamental particle probed directly on a bare particle, that too done using the same `g-2' storage ring!
- The current existing tension between the muon `g-2' measurement and theory is a good cause to look for BSM physics in muon spin precession experiments.
- We have the combined wisdom of operating the `g-2' storage ring for over two decades.

EM fields for Muon ‘g-2’ Storage Ring

Should the dipole field be magnetic or electric?

Should the quadrupole field be magnetic or electric?

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

Since we are measuring the **MDM** of the muon, keeping the dipole field magnetic provides a natural solution.

Since we want the particle to experience only ONE value of magnetic field, the quadrupoles could simply be made electric.

The `g-2’ ring has only vertical focusing quadrupoles as the dipole provides for a natural first order horizontal focusing.

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BUT… there is a problem!

EM fields for Muon ‘g-2’

The E and B fields in the lab frame would not be the same to the particle in its rest frame due to special relativistic effects.

The Lorentz transformed spin precession rate is given by the Thomas-BMT equation:

MUON REST FRAME

$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B}\right]$$

LAB (OUR) FRAME

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

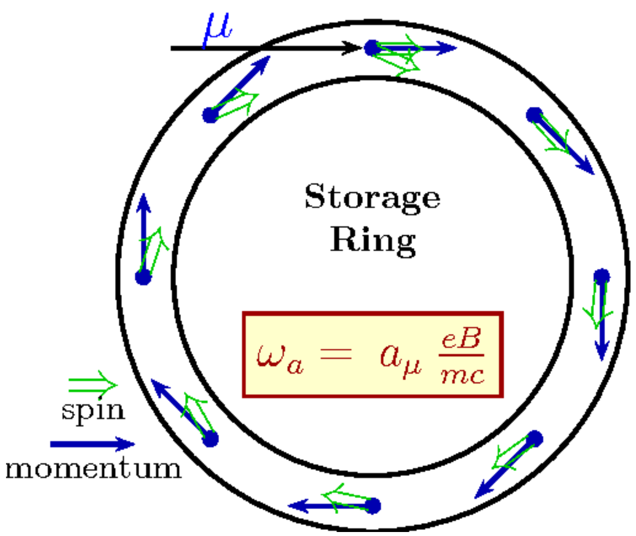
where γ is the relativistic Lorentz factor, and η is a measure of the EDM of the particle.

How to overcome this to measure the MDM of the muon?

EM fields for Muon ‘g-2’… a little magic!

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

Since we already know a_μ to a large accuracy, we can delicately choose the γ such that the second term cancels away! This way, the ω_a precession rate depends only on $\vec{B}$ and not on $\vec{E}$.

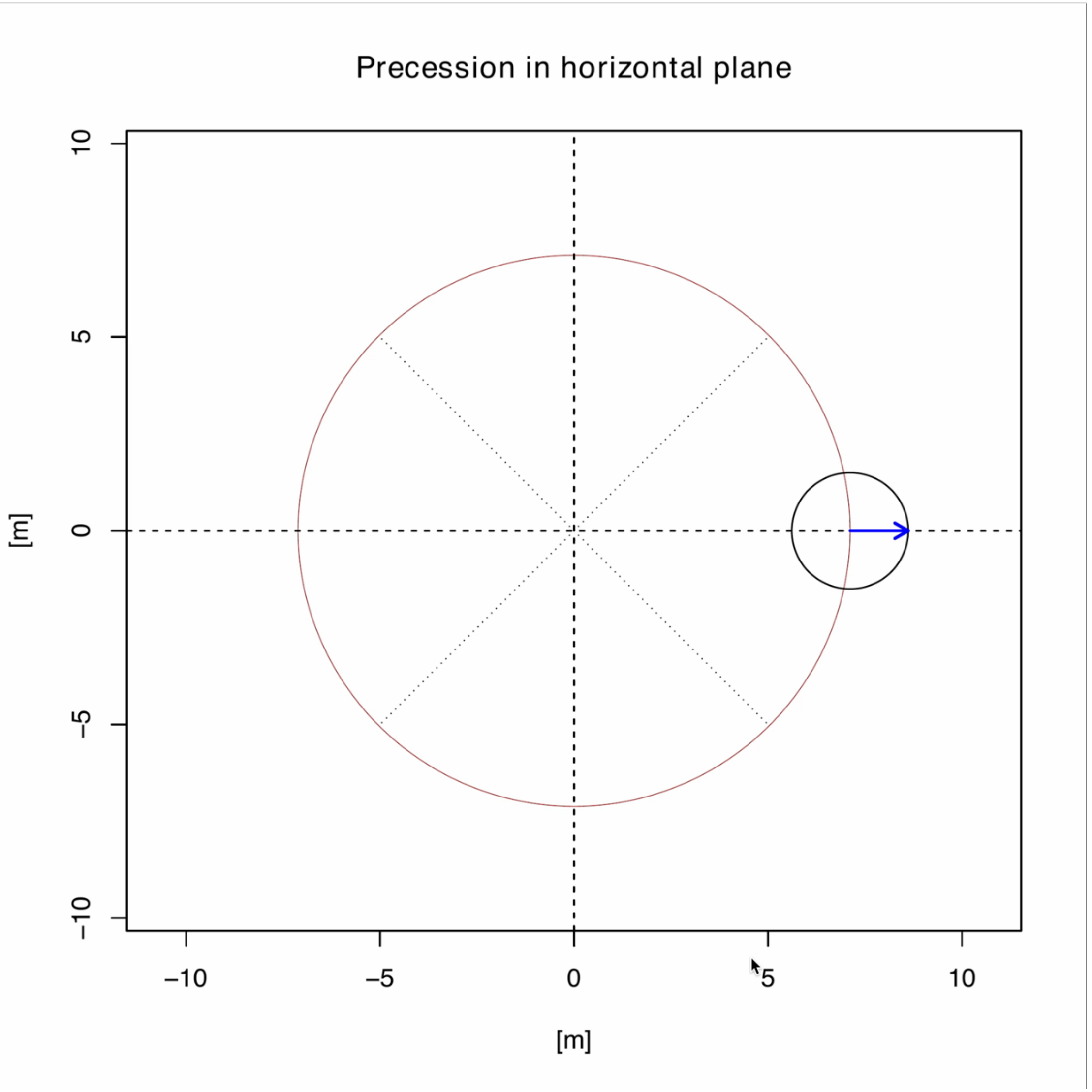


The momentum for this particular value of γ is called the ‘magic momentum’, it happens to be about p_μ ~ 3.094 GeV/c for muons. (Thank Nature for that!)

The muon’s spin precesses IN the plane of the ring at a rate that depends purely on the magnetic field

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

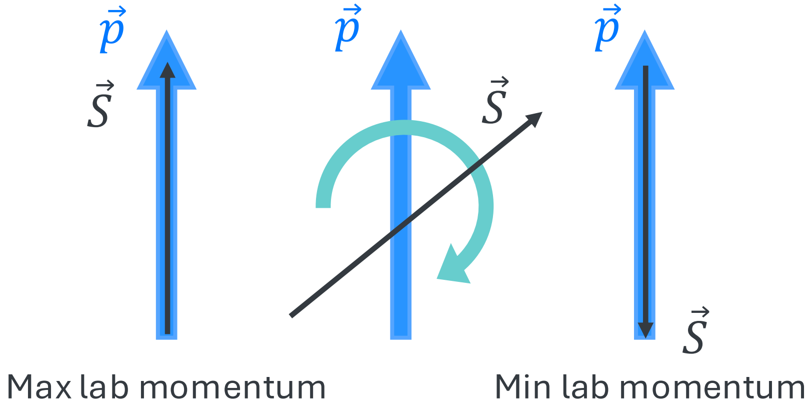
How to measure the spin precession?



How to measure the spin precession?

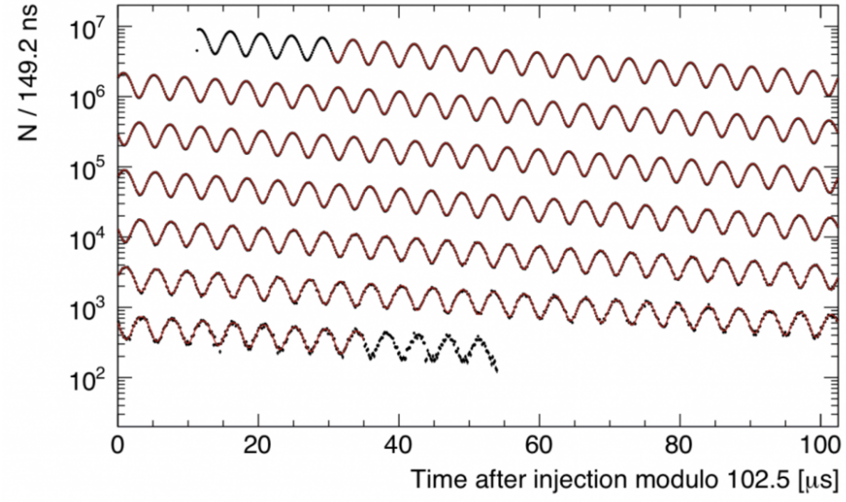
As the spin rotates, it aligns and anti-aligns with the momentum vector and thus modulates the momentum seen in the lab-frame due to Lorentz boost.

The muons decay to positrons, whose energy is modulated exactly by the spin precession frequency.

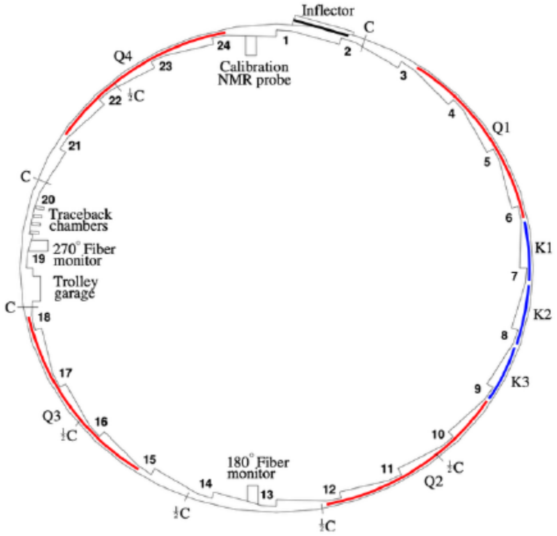


Thus, simply `counting' the number of positrons above a particular threshold will give us the precession frequency!

$$N = Ae^{-\frac{t}{\tau}}\cos(\omega t + \phi)$$



The present `g-2’ Storage Ring



- The ring has a radius of 7.112 meters and is four-fold symmetric.

- It has highly purified constant vertical dipole magnetic field 360 degrees around the ring and four isometrically placed electrostatic quadrupoles for vertical focusing.

- Each 90-degree section consists of:
  - 51 degrees of dipole $\vec{B}$-field only region
  - 39 degrees of (dipole $\vec{B}$ +quadrupole $\vec{E}$ (region

- There are no dipole electric fields in the `g-2’ storage ring at present.

PROPOSED SCHEME – A HYBRID STORAGE RING

1. Freeze the MDM spin precession.

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Freezing the MDM is advantageous because it greatly enhances the EDM signal.

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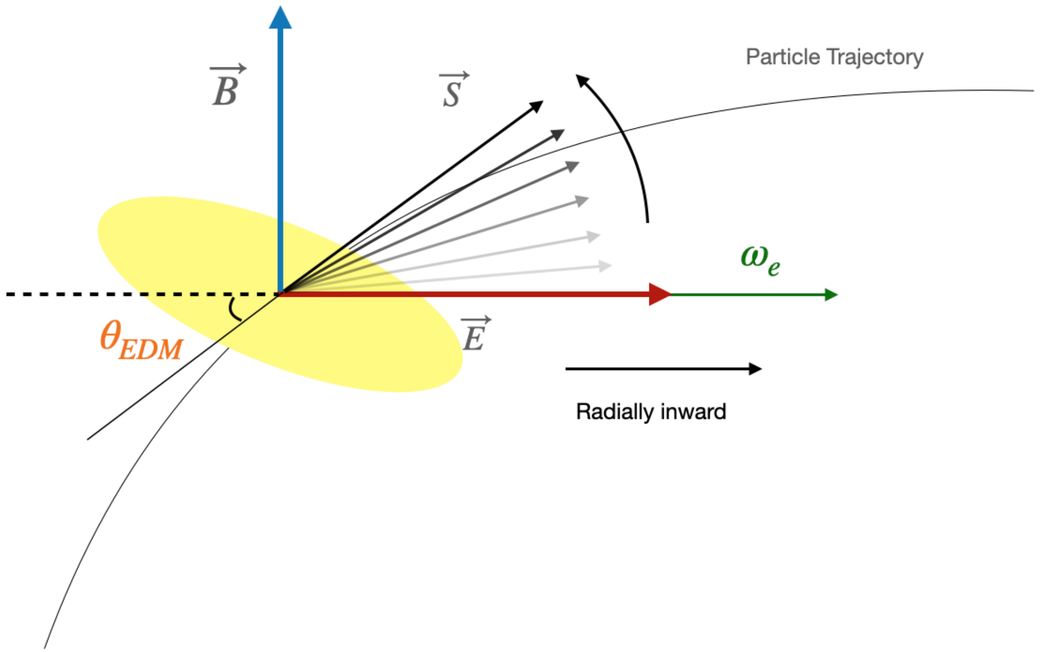
$$\vec{\omega}_{net} = \cancel{\vec{\omega}_{MDM}} + \vec{\omega}_{EDM}$$

Introducing a dipole electric field makes the spin vector precess about the radial direction. This makes the spin vector tip out of the plane of the ring in the vertical direction.



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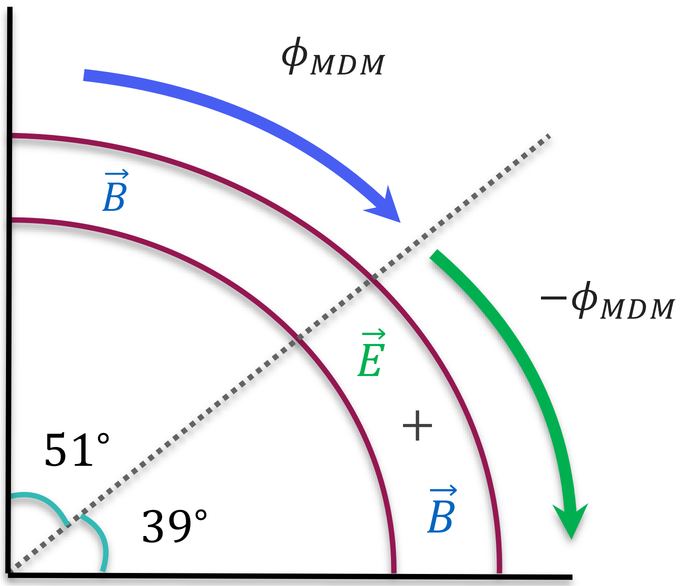
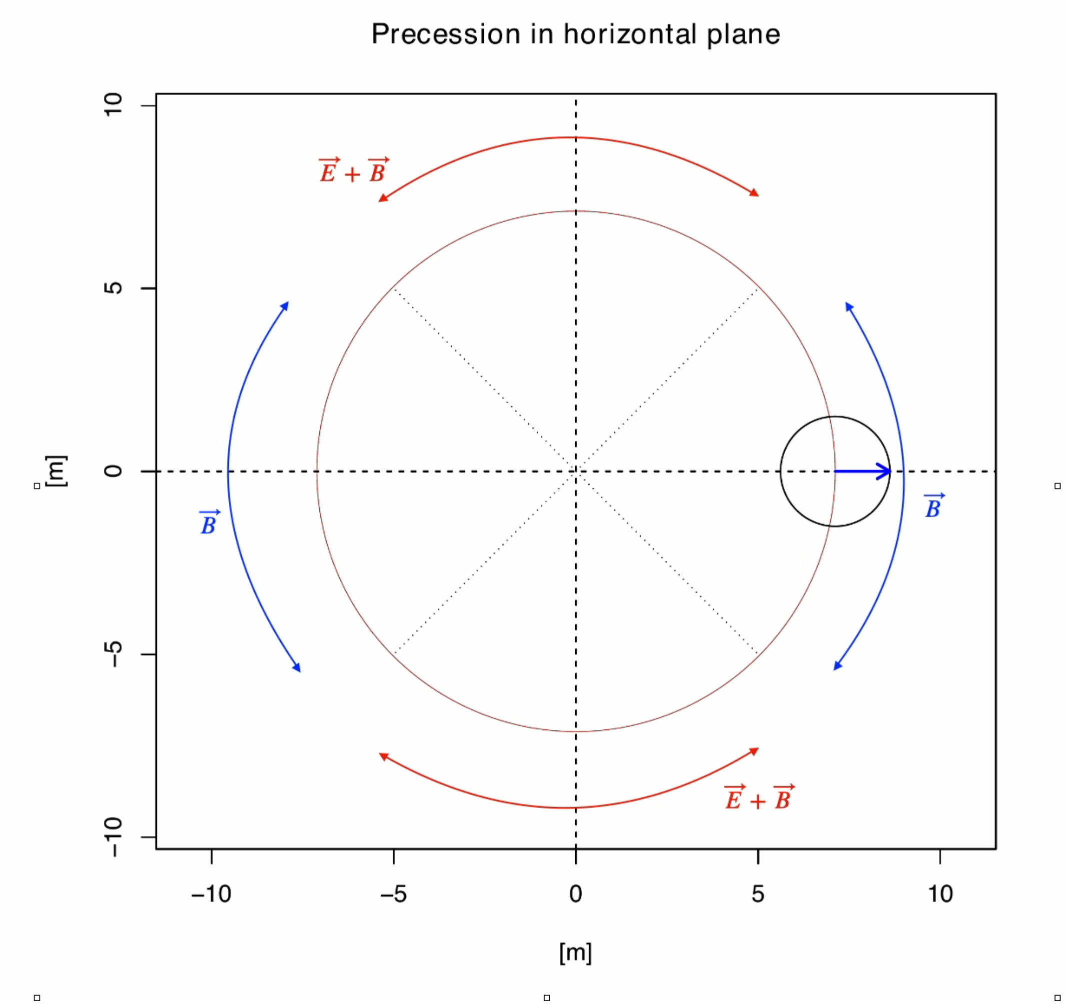


The idea:

1. The μ^+ traverses through the **51° B-only** section.
2. The **MDM** component of the spin precession increases by an amount Φ_{MDM} due to the **B**-field.
3. The μ^+ then enters the 39° of (E+B) section.
4. The dipole E-field (along with B) is chosen such that the **MDM** precesses the spin in the opposite direction by the same precession angle $-\Phi_{MDM}$.

Freezing the MDM precession



Freezing the MDM precession

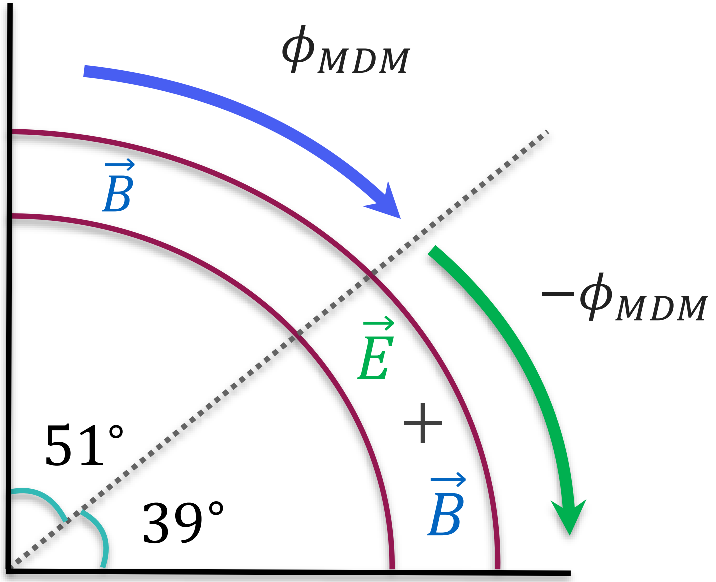
The amount of spin's MDM precession in the 51° of $\vec{B}-$ only region is given by:

$$\Phi_{MDM,B} = \frac{q}{m}\ GB.\frac{51^\circ}{90^\circ}.\frac{T_{rev}}{4}$$

The amount of spin's MDM precession in the 39° of $\vec{E} + \vec{B}-$ region is given by:

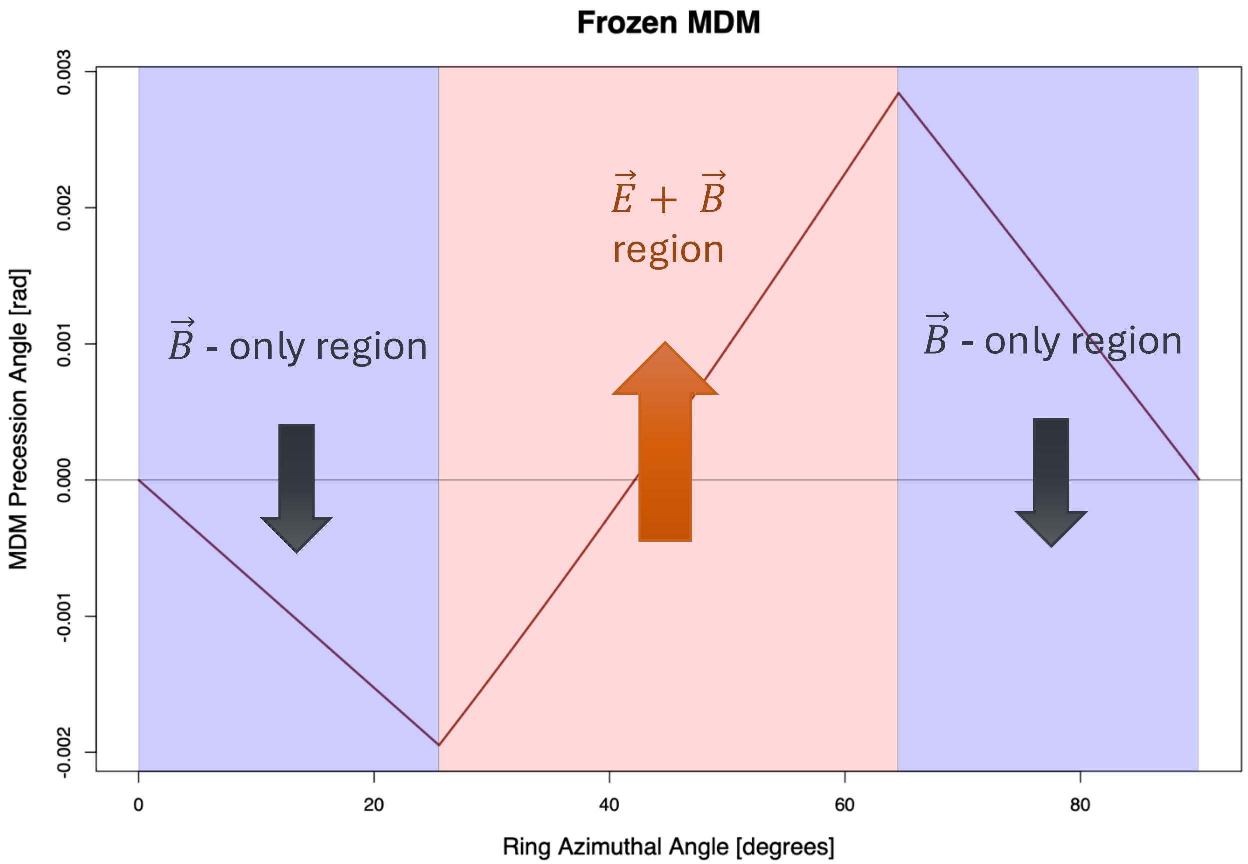
$$\Phi_{MDM,\,E+B} = \frac{q}{m}\ [GB.-\left(G\ -\frac{1}{\gamma^2-1}\right)\frac{\beta E}{c}\,\frac{39^\circ}{90^\circ}.\frac{T_{rev}}{4}$$

Equating the above two equations, we can solve for the electric field value needed to cancel the MDM precession accumulated in the B-only section.



Freezing the MDM precession

Net MDM precession = 0



Finding The $\vec{E}$ and $\vec{B}$ Field Values

Simplifying the equation for frozen MDM precession, we have a linear equation in E and B:

$$\vec{E} - \vec{B}.\left[\frac{Gc}{\beta}\frac{90°}{39}\left(G - \frac{1}{\gamma^2 - 1}\right)^{-1}\right] = 0$$

CONSTRAINT #1

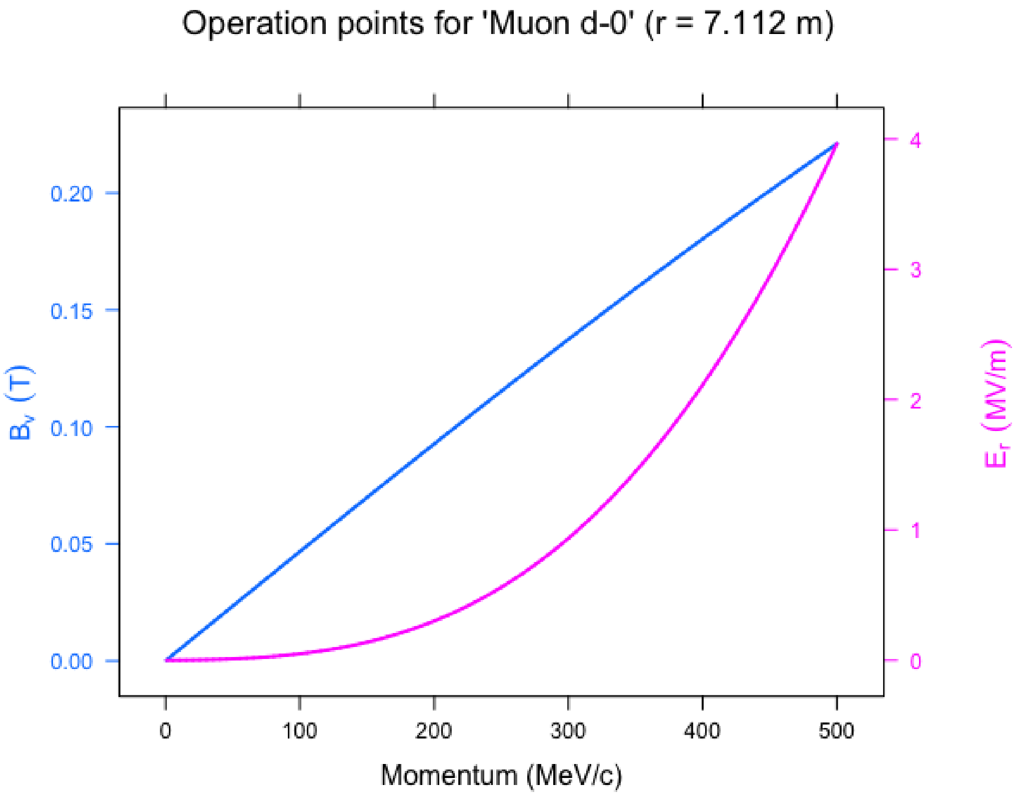
Since we look to re-use the `g-2' storage ring, the radius of the ring imposes a condition via the centripetal Lorentz force required to keep the muons on the 7.112 meter orbit:

$$\vec{E} + v\,\vec{B} = \gamma\frac{mv^2}{qr}\,\hat{r}$$

CONSTRAINT #2

Since we could use both E and B-fields in the ring, there is no constraint to operate on the magic momentum anymore.

Possible Field Values for Frozen MDM Condition



Momentum (MeV/c)	Vertical Magnetic Field (Tesla)	Radial Electric Field (MV/m)
100	0.046	0.048
200	0.092	0.300
300	0.137	0.935
400	0.180	2.113
500	0.220	3.963

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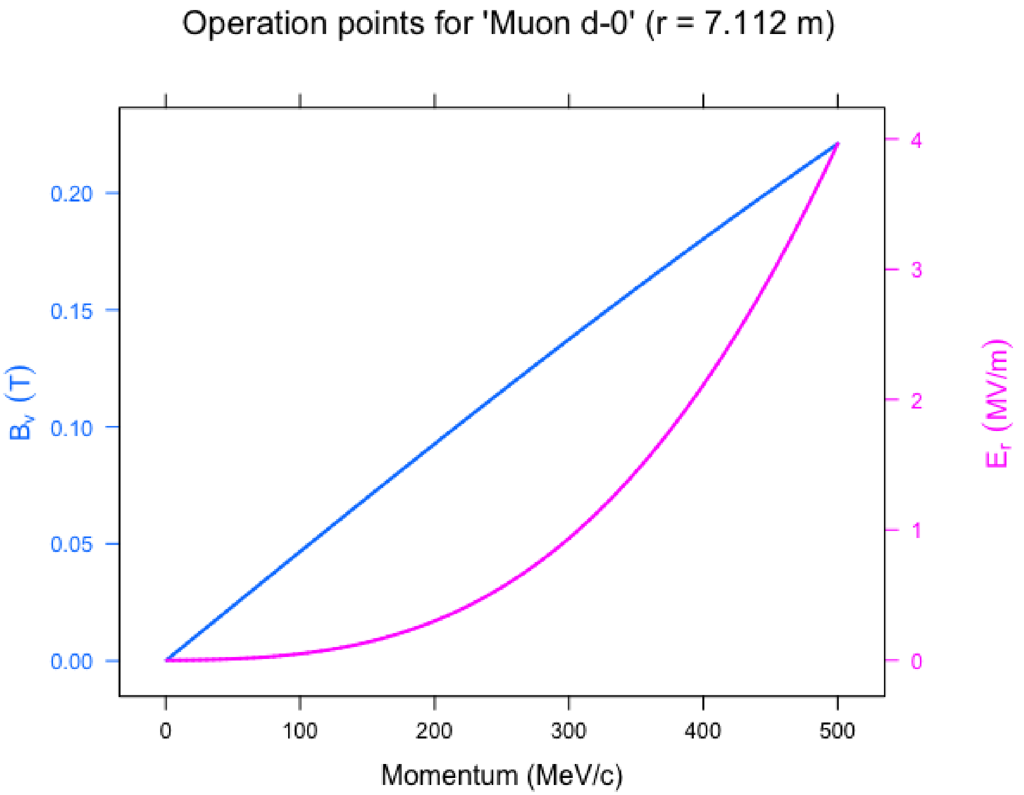

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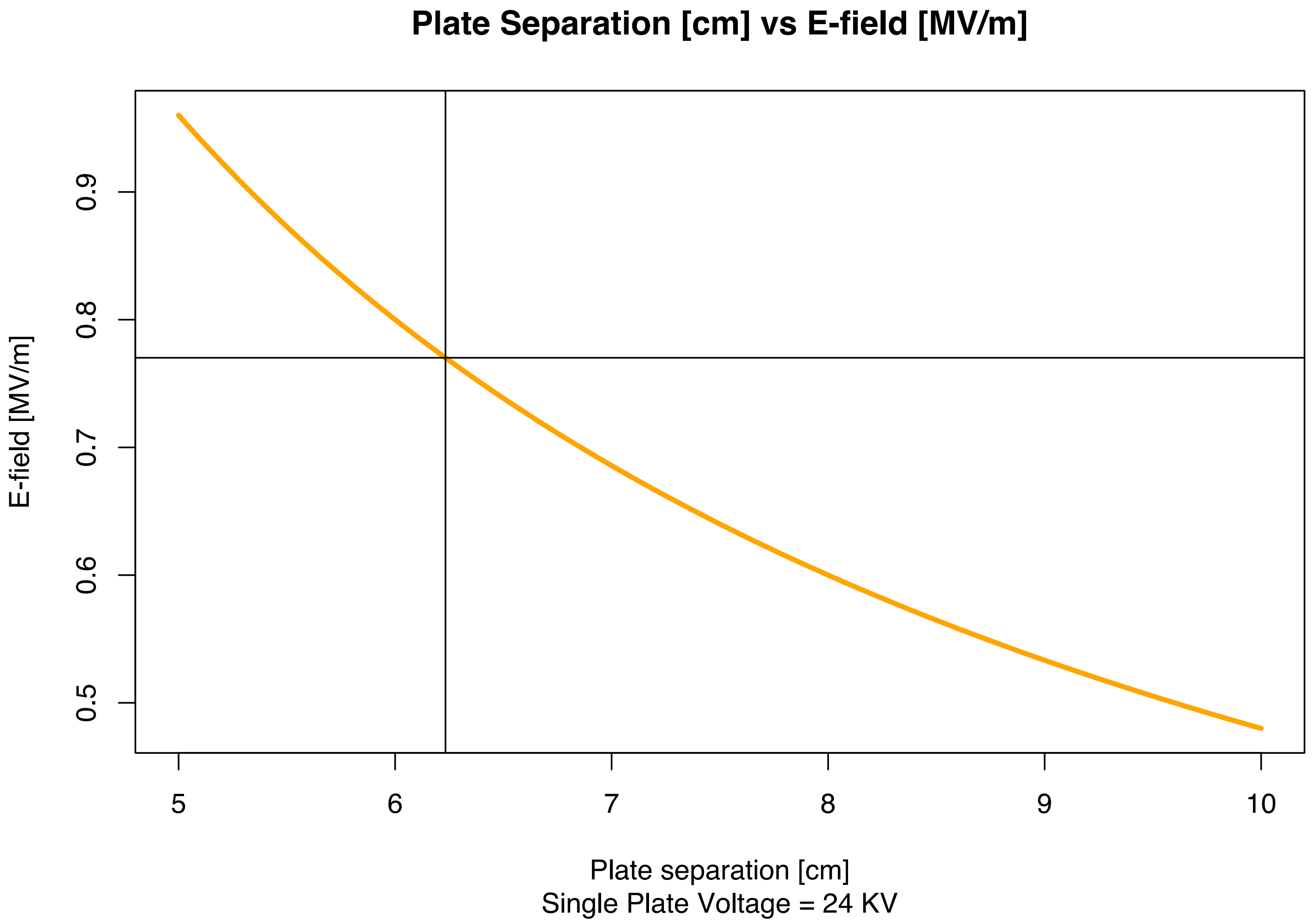
Plate separation vs radial E-field



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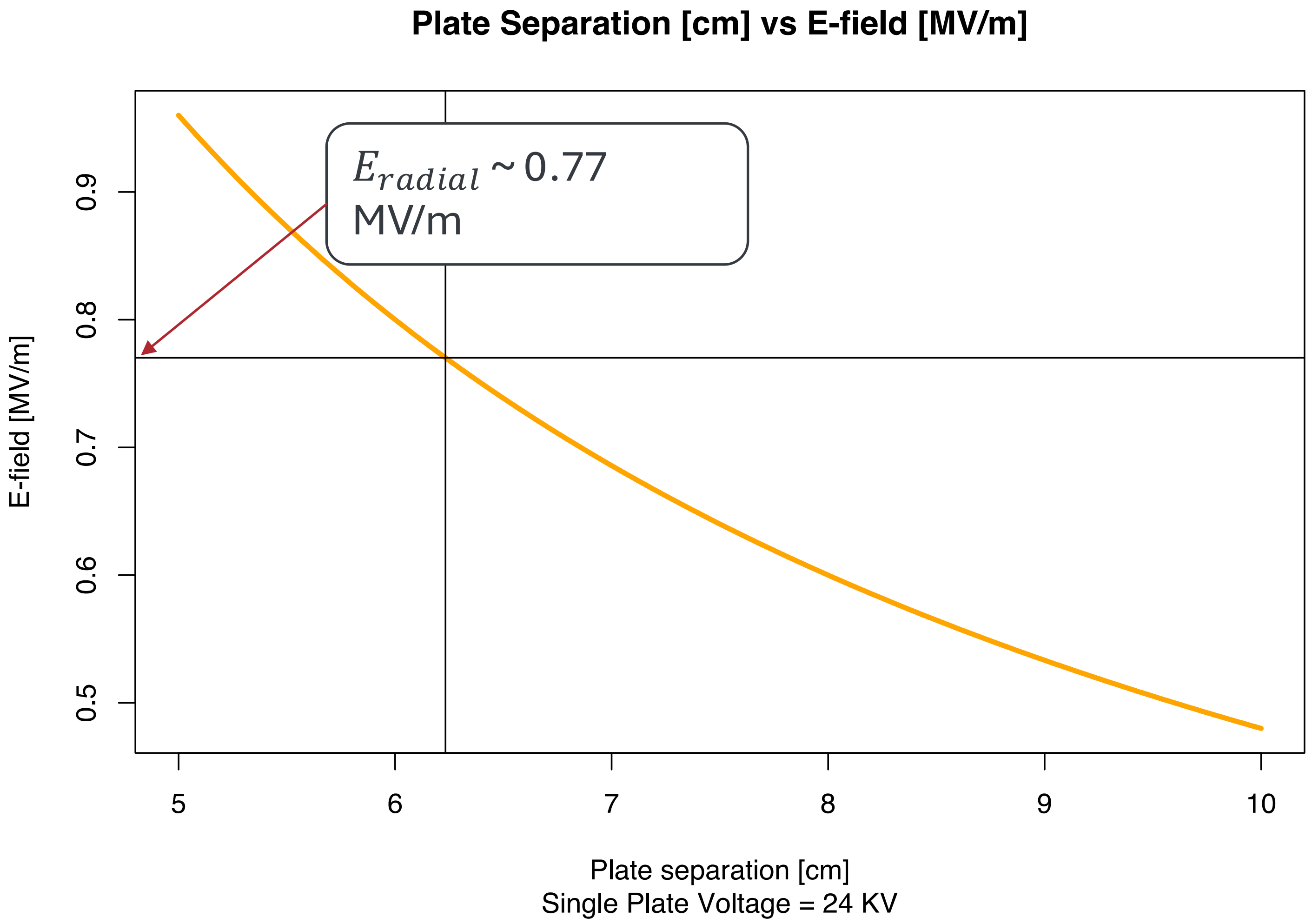
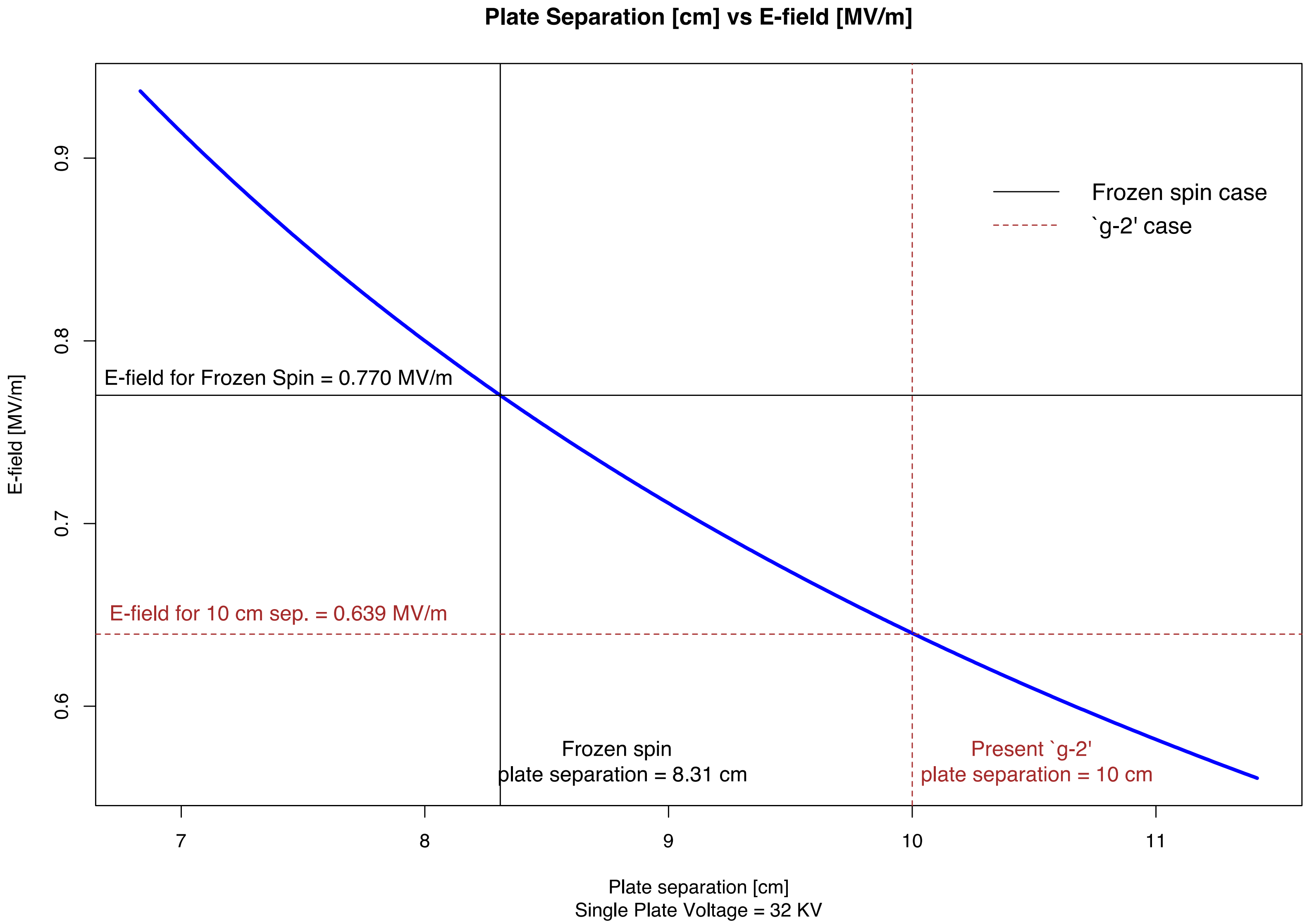


$E_{radial} \sim 0.77$ MV/m

Plate separation vs radial E-field



Beam Dynamics

The next question: with both electric and magnetic dipole fields, can we have a stable closed orbit inside the ring with frozen MDM precession conditions?

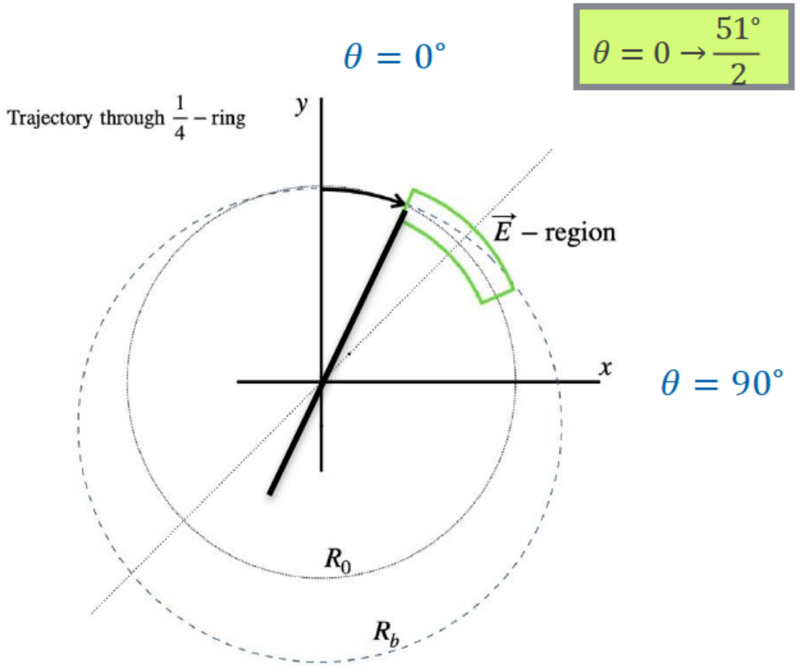
The answer : YES!

Only that the stable closed orbit will not be a perfect circle anymore.

Let us assume our ‘quarter section’ starts with the second half of a ‘$\vec{B}$-only’ section.

Since there is only $\vec{B}$-field, the particle will orbit with a radius R_B , given by:

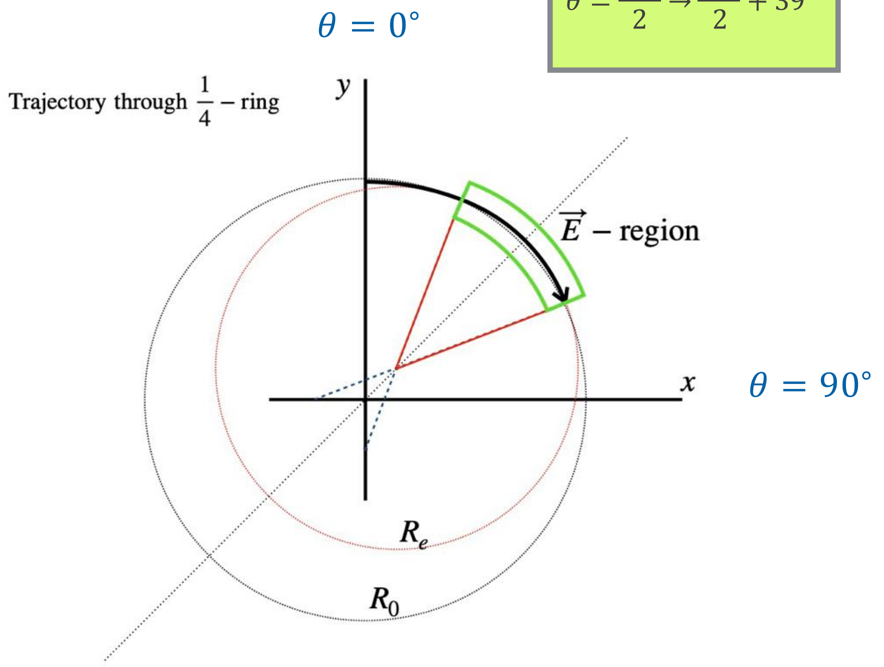
$$R_B = \frac{\gamma m v^2}{q v B}$$



Closed Orbit – Geometric Analysis

As the particle next enters the $(\vec{E} + \vec{B})$ region, it is going to orbit in a circle again but of a tighter radius R_E given by,

$$\theta = \frac{51^\circ}{2} \rightarrow \frac{51^\circ}{2} + 39^\circ$$



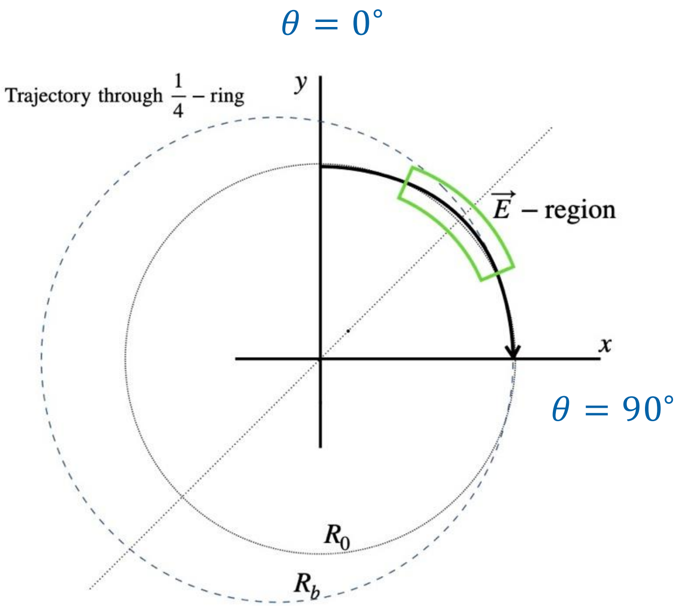
$$R_e = \frac{\gamma m v^2}{qvB + qE}$$

Because of the tighter radius, the particle will 'curve in' with respect to the 7.112 m orbit and the circle will have a different center.

Closed Orbit – Geometric Analysis

As the particle exits the $(\vec{E} + \vec{B})$ region, it is going to orbit in a circle again but of a wider radius R_B again just as it did in the first 25.5°.

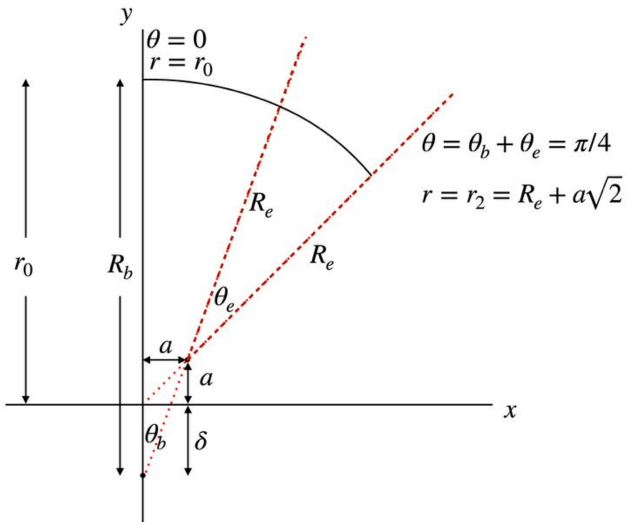
$$\theta = \frac{51^\circ}{2} + 39^\circ \rightarrow 90^\circ$$



If we were to plot the closed orbit with respect to the 7.112 m orbit, we would have a 'wiggle'.

But how large are these deviations from the 7.112 meter orbit?

Closed Orbit – Geometric Analysis



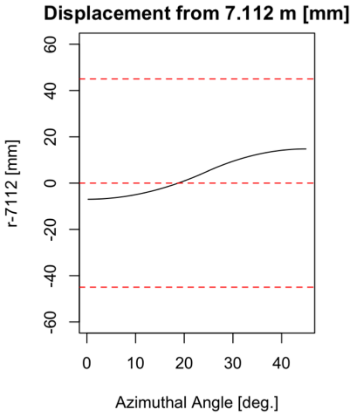
With some geometric analysis, we find that,

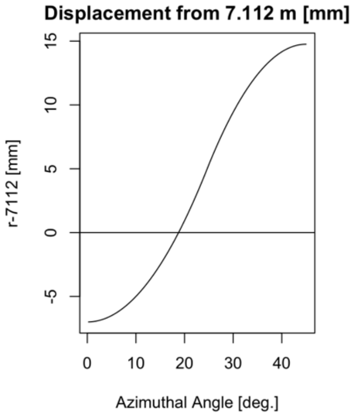
$$r_0 = R_b[1 - \cos(\theta_b) + \sin(\theta_b)] + R_e[\cos(\theta_b) - \sin(\theta_b)]$$

$$r_2 = \sqrt{2}R_b\sin\theta_b + R_e(1 - \sqrt{2}\sin\theta_b)$$

For example, with the parameters of :

$$p = 387\ \text{MeV/c}$$
$$\vec{E} = 1.98\ \text{MV/m}$$
$$\vec{B} = 0.178\ \text{T}$$





The maximum radial orbital deviations from the 7.112 meter circular orbit are only ± 10.9 mm!

Particle Tracking

One could verify the previous geometric analysis with actual particle tracking to see if we indeed can have a stable closed orbit.

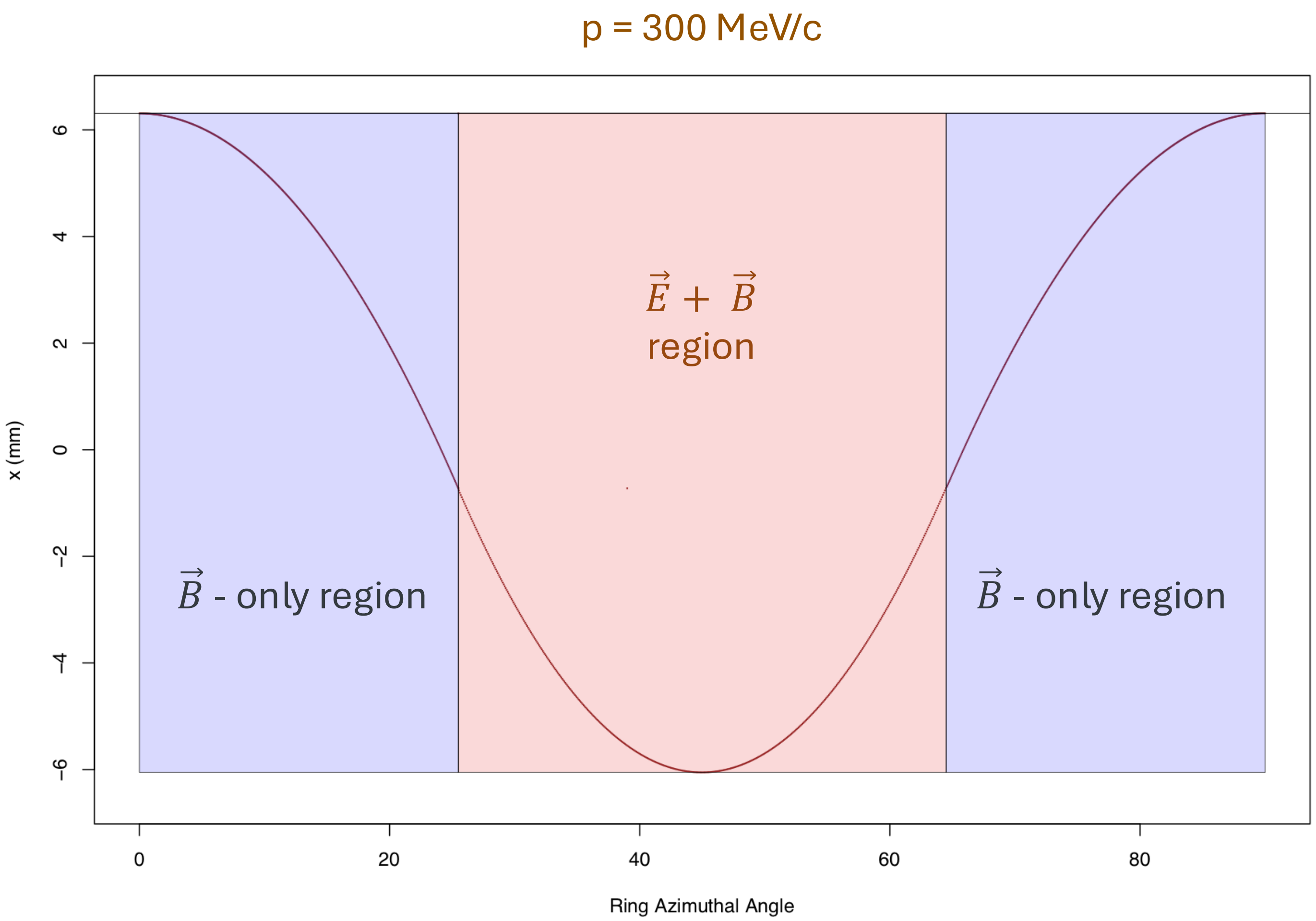
A particle tracking simulation was thus done by solving the coupled differential Lorentz equations in the $\vec{B}$-only region and $\vec{E} + \vec{B}$-region for various momenta values at a time step of 1 nanosecond.

$$\frac{dx_\circ}{dt} = v_{x_\circ} \qquad \frac{dy_\circ}{dt} = v_{y_\circ}$$

$$\frac{dv_{x_\circ}}{dt} = \frac{q}{m}E\cos\theta + \frac{q}{m}v_{y_\circ}B_z \qquad \frac{dv_{y_\circ}}{dt} = \frac{q}{m}Esin\theta - \frac{q}{m}v_{x_\circ}B_z$$

where $x_\circ$ and $y_\circ$ are the coordinates in the horizontal plane of the ring with (0,0) being the centre of the ring.

4-th order Runge-Kutta simulation

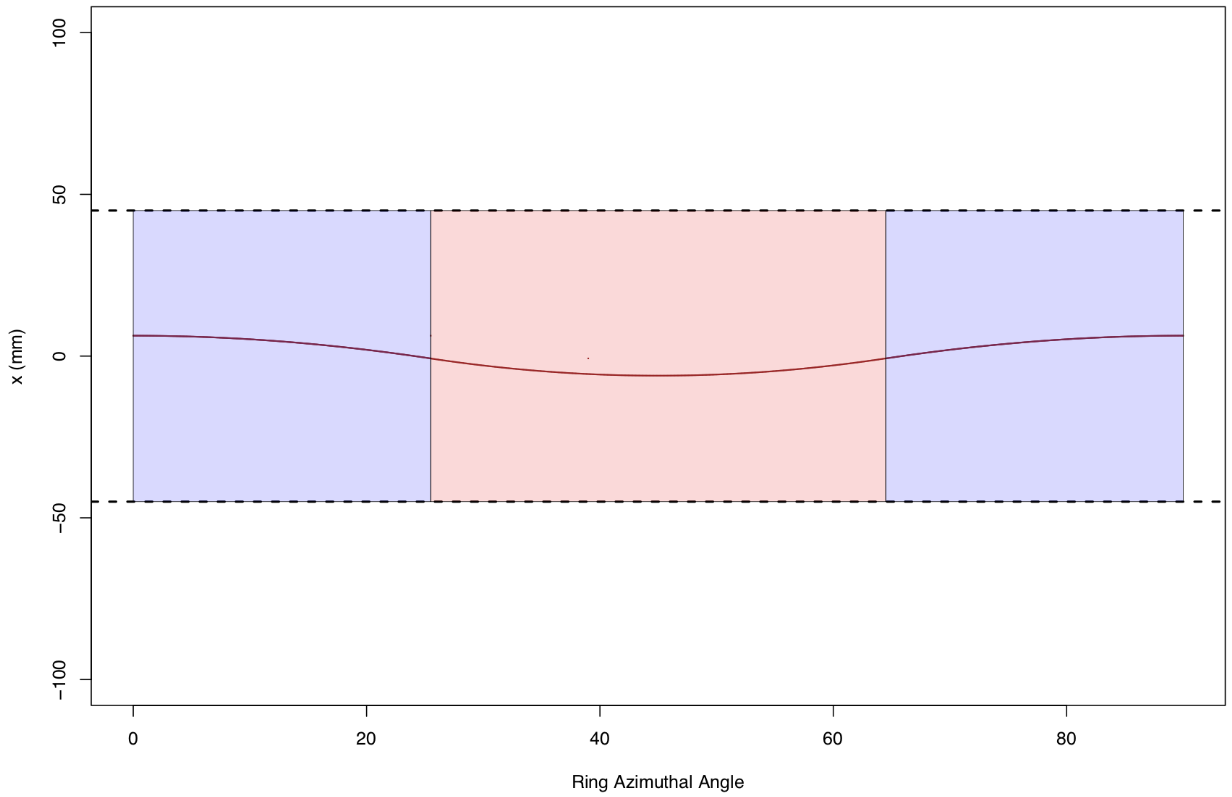


RK4 simulation validated our geometric analysis!

4-th order Runge-Kutta simulation

With a ±45 mm horizontal aperture, the scale of a typical closed orbit would look like:

p = 300 MeV/c



Low momentum muon delivery efforts

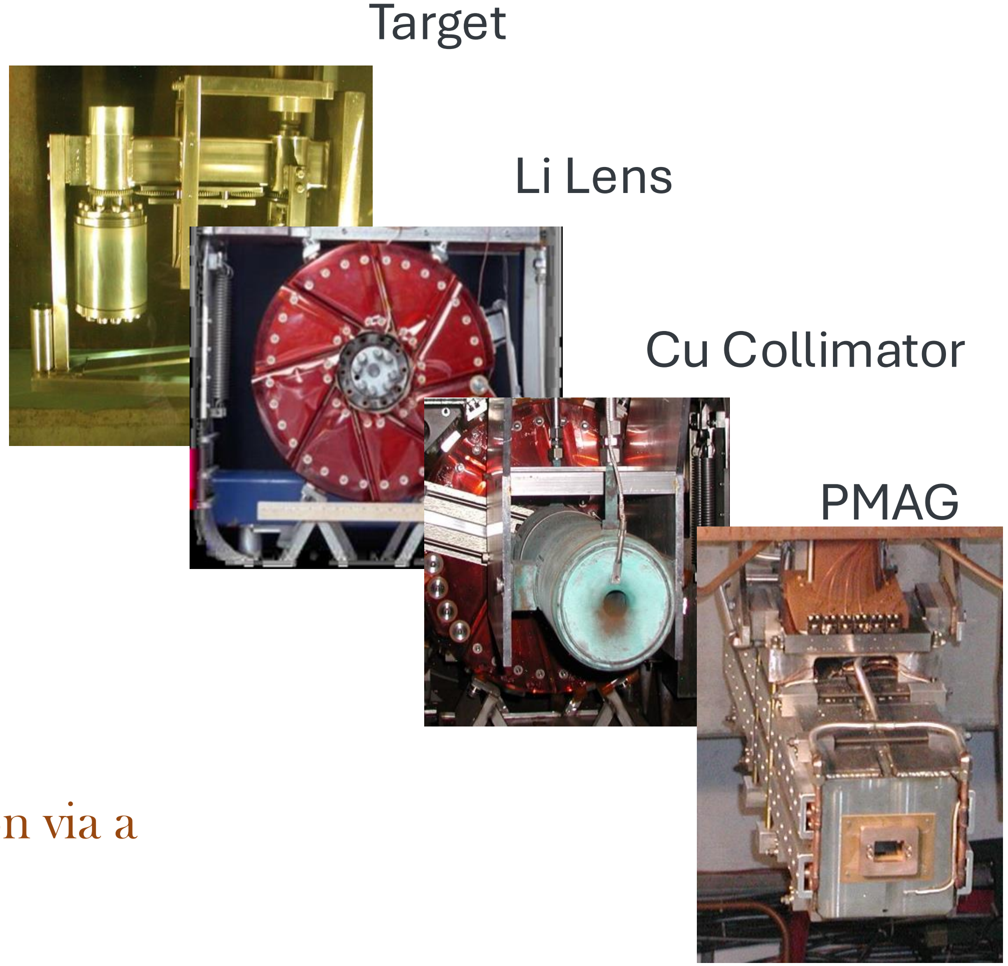
8 GeV primary proton beam is incident on an Inconel-600 target.

Secondary pions are produced and focused by a lithium lens towards a horizontal bending magnet (PMAG).

A copper collimator sits between the lens and PMAG.

PMAG provides momentum selection via a 3° horizontal bend into the M2/M3 transport line.

Low momentum acceptance for transport, $\Delta p/p \approx 4\%$



Steven Boi

Low $\vec{p}$ muon delivery – G4BL

Steven Boi

Location		Per POT Yield	π^+ 300 MeV/c ± 12 MeV/c	π^+ 3.1 GeV/c ± 124 MeV/c	Ratio
Lithium Lens	Upstream		1.0×10^{-3}	1.4×10^{-3}	0.74
	Downstream		9.7×10^{-4}	9.8×10^{-4}	0.99
Downstream PMAG			4.7×10^{-6}	8.5×10^{-5}	0.05
Upstream CMAG			2.1×10^{-7}	3.8×10^{-5}	0.005

- 300 MeV/c pions created in target have very large angular spread
  - Yield curves show more muons at this low momentum, but few at low angles
  - Existing lithium lens focusing device poorly suited for 300 MeV/c
  - Scattering a much more significant issue than with 3.1 GeV/c
  - Only 21 pions in 300 MeV/c case compared to 3,808 pions in 3.1 GeV/c case (x180)
- Alternative focusing devices simulated, showed promise
  - Improved 300 MeV/c pion count to 400, still down factor of 10 from 3.1 GeV/c case

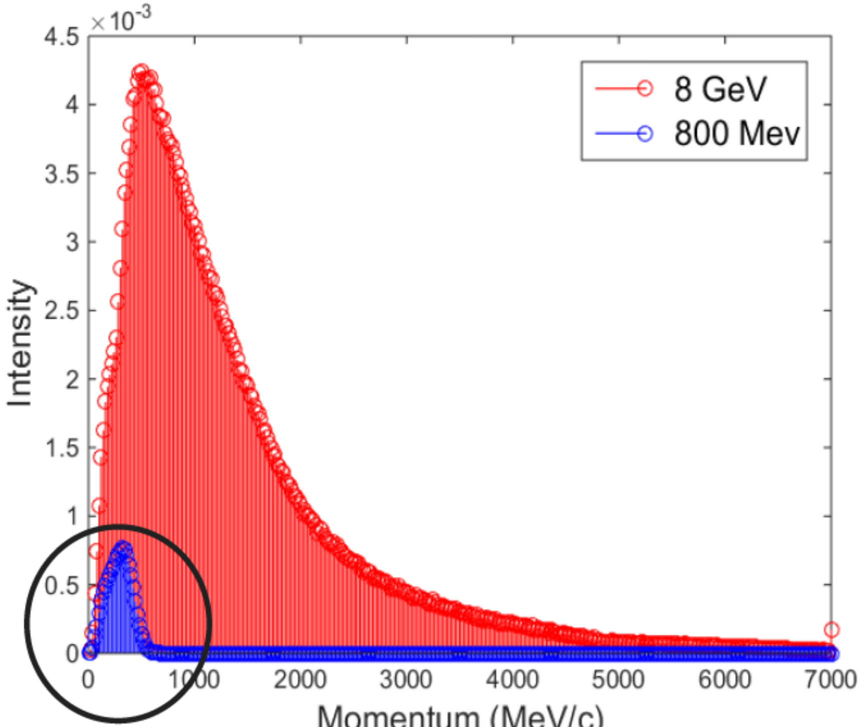
Low $\vec{p}$ muon delivery – Beam Study

Jim Morgan

- Studies performed in April and May 2023
- Scaled power supply currents down from 3.1 GeV/c, used for g-2 operation
  - Numerous power supply issues at the lower currents
  - Delivery Ring injection and extraction kickers unable to operate this low
  - Instrumentation in the beamlines had difficulty with the low intensities
- Power supply problems all appear to be solvable
  - Would take engineering time and hardware modifications
- Instrumentation worked okay after adjustments but near lower limit of sensitivity.
- Made incremental improvements with tuning, intensity still very low
  - Lithium lens tuning improvements implied large angular spread on muons
- Demonstrated that yield reduction from scattering large for 300 MeV/c
  - Inserted upstream Ion Chamber IC804 and observed yield change on IC740
  - Yield reduction 2% for 3.1 GeV/c, 40% for 300 MeV/c
- Best performance after tuning was still down a factor of 150

Muon EDM in the PIP-II Era

- Simulation results of a preliminary study of muon production by PIP-II protons performed by Diktys Stratkis 👉
- We see that the peak intensity of muon distribution is exactly around the 300 MeV/c range.
- After performing aperture cuts on these pions/muons (plot not shown) with a momentum window of $\pm 0.5\%$, the results gave 1.2×10^{-5} pions per proton.



Particle Rates

RMS Current from PIP-II Linac	0.002 A
Pulse length for `g-2' storage ring	?
No. of PIP-II bunches per EDM pulse	
Protons per EDM pulse	
Good' pions/muons off the target	
Muon storage duration	
Muons stored per year	

Particle Rates

RMS Current from PIP-II Linac	0.002 A
Pulse length for ` g-2’ storage ring	120 ns
No. of PIP-II bunches per EDM pulse	?
Protons per EDM pulse	
Good’ pions/muons off the target	
Muon storage duration	
Muons stored per year	

Particle Rates

Assuming PIP-II operates at 162.5 MHz.
PIP-II bunches = 120 ns × 162.5 MHz
= 19.5 bunches

RMS Current from PIP-II Linac	0.002 A
Pulse length for `g-2’ storage ring	120 ns
No. of PIP-II bunches per EDM pulse	19.5
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Particle Rates

RMS Current from PIP-II Linac	0.002 A
Pulse length for `g-2' storage ring	120 ns
No. of PIP-II bunches per EDM pulse	19.5
Protons per EDM pulse	1.5×10^9
Good' pions/muons off the target	?
Muon storage duration	
Muons stored per year	

Assuming PIP-II operates at 162.5 MHz.
PIP-II bunches = 120 ns × 162.5 MHz
= 19.5 bunches

No. of protons per EDM pulse is simply (0.002 Coulombs/s) × 120 ns = 2.4×10^{-10} Coulombs $\approx 1.5 \times 10^9$ protons.

Particle Rates

RMS Current from PIP-II Linac	0.002 A
Pulse length for `g-2' storage ring	120 ns
No. of PIP-II bunches per EDM pulse	19.5
Protons per EDM pulse	1.5×10^9
Good' pions/muons off the target	18000 per EDM pulse
Muon storage duration	?
Muons stored per year	

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PIP-II bunches = 120 ns × 162.5 MHz
= 19.5 bunches

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Muon storage duration	83 μs
Muons stored per year	?

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Muons stores per second = Rep. rate × pions off target × LDF = 0.86×10^{7} muons/s.

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Say we get only 1% in reality from above guesstimates:

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$0.86 \times 10^5 \times (3 \times 10^7)$ muons/year!

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Say we get only 1% in reality from above guesstimates:

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EDM Bound Sensitivity

$$\vec{\omega}_e = \frac{2d}{h}\left(\vec{\beta}c \times \vec{B} + \vec{E}\right)$$

where ω_e is the EDM precession frequency leading to vertical build-up of the polarization:

$$\left|\vec{\Pi}(t)\right| = P(t) = P_0 \sin(\omega_e t)$$

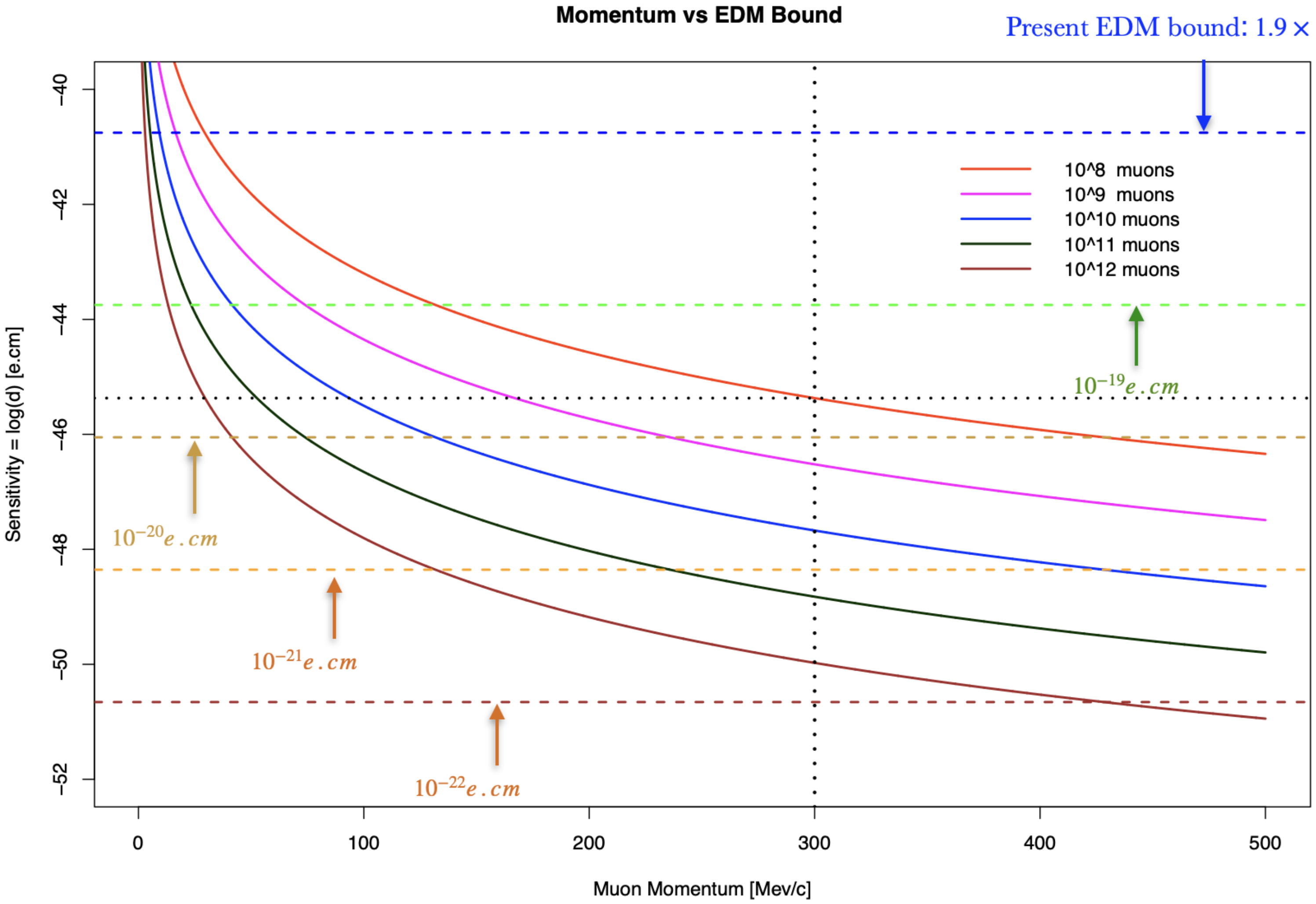
$$\approx P_0 \omega_e t$$

$$\approx 2P_0 \left(\frac{d_\mu E}{a\hbar\gamma^2}\right) t$$

Multuplying by the mean analysis power of the final polarization A, and replacing t with mean free laboratory time in the detector $\gamma\tau_\mu$ and scaling $1/\sqrt{N}$ for Poisson statistics, we calculate the EDM sensitivity to be:

$$\boxed{\sigma(d_\mu) = \frac{a\hbar\,\gamma}{2P_0 E\,\sqrt{N}\tau_\mu A}}$$

EDM Bound Sensitivity



$$d = \frac{\gamma h G}{2AEP\tau_\mu\sqrt{N}}$$

A = Asymmetry

P = Polarization

E = Electric field

N = No. of μ^+

τ_μ = Mean μ^+ lifetime

Where?

OPTION 1 – PRESENT LOCATION

$$\gamma = \sqrt{1 + \frac{p^2}{m^2 + c^2}}$$

$$t = \frac{L}{c\sqrt{1 - 1/\gamma^2}}$$

For L ~ 420 meters and p ~ 300 MeV/c, and the time of flight is approximately 1.48 μs , which is about 22% of a 300 MeV/c muon lifetime.

Where?

OPTION 1 – PRESENT LOCATION

Jim Morgan

- 300 MeV/c muon yield is much lower than 3.1 GeV/c for 8 GeV primary protons
  - With present Target Station, 300 MeV/c muon yield 150 times lower than 3.1 geV/c

An alternative Target Station focusing scheme could improve yield

- Focusing horn most attractive, but solenoid is possibility too

Existing Inflector in g-2 Ring is not compatible due to “closed” ends

- 300 MeV/c muon scattering would effectively prevent muons from circulating
- Open ended Inflector was built prior to g-2 Operation and could be used

Numerous accelerator power supplies would need to be modified

Regulation poor at 300 MeV/c, far below what the supplies were designed for

Injection septum, injection and extraction kickers may need hardware modifications

Kickers could be replaced by trim dipoles for a dedicated running period

Where?

OPTION 2 - PRESENT LOCATION
NEW BEAMLINE


300 MeV/c muons

800 MeV/c protons

Muon Production Target

Where?

OPTION 2 – PRESENT LOCATION
NEW BEAMLINE

$$\gamma = \sqrt{1 + \frac{p^2}{m^2 + c^2}}$$

$$t = \frac{L}{c\sqrt{1 - 1/\gamma^2}}$$

For L ˜ 510 meters and MeV/c, and the time of flight is approximately 1.80 μs , which is about 27% of a 300 MeV/c muon lifetime.

Where?

OPTION 3:
RIGHT IN FRONT OF PIP-II

Conclusion

We could envision having an EDM experiment in the `g-2 storage ring by constructing a new quadrupole system to create a radial electric dipole field pointing radially inward.

The E and B fields can be carefully chosen to freeze the MDM precession (in space) and while constantly accumulating the EDM signal.

The new system would not be significantly different from the current set-up, other than

- The radius of curvature for the plates would be different,
- The inner/outer plates would be at higher potentials than the upper/lower plates in order to create the electric dipole field

Electric field levels of ~1 MV/m are not impossible to achieve difficult with potentials of about ±32 kV for plate separations on the scale of 30 to 80 mm.

Since the muons' central momentum could be around 300 MeV/c, it makes the requirements for the existing magnetic dipole field, inflector system, and kicker system reduce by a factor of ten.

Muons' central orbit would still remain 7112 mm but with deviations of just ±7 mm.

PIP-II, with good focusing element, could provide intense 300 MeV/c range muons, facilitating higher EDM statistics and bound by orders of magnitude.

I would like to thank and acknowledge the following for their valuable contributions, suggestions, and soundboarding.

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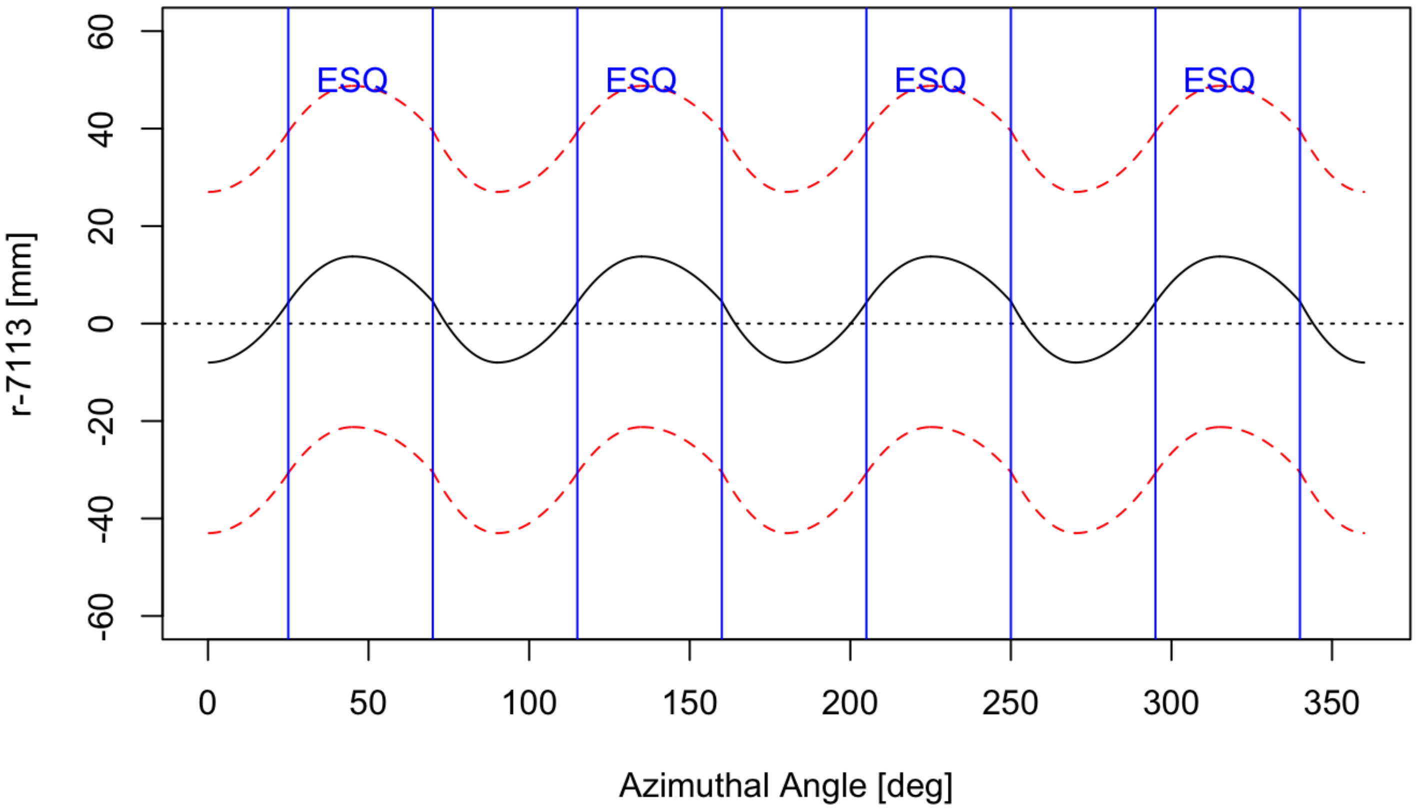
THANKS!

Next steps…

- What is the natural first-order focusing due to set of curved 'dipole' plates?
- What quadrupole gradient would we need? What tunes to choose (especially vertical tune)?
- What would be the expansion coefficients of the E-field due to plate distortions and misalignments? What are its effect on EDM measurement?
- How bad can the radial and azimuthal magnetic field be? Background contribution?
- To what accuracy must the E-field be measured in the ring? And how to do it?
- Detector related systematics (and others).

BACKUP

Plate re-arrangement



EDM Signal

Unlike the MDM, the precession due to EDM at a given point in the ring is going to keep constantly building up until the muon decays.

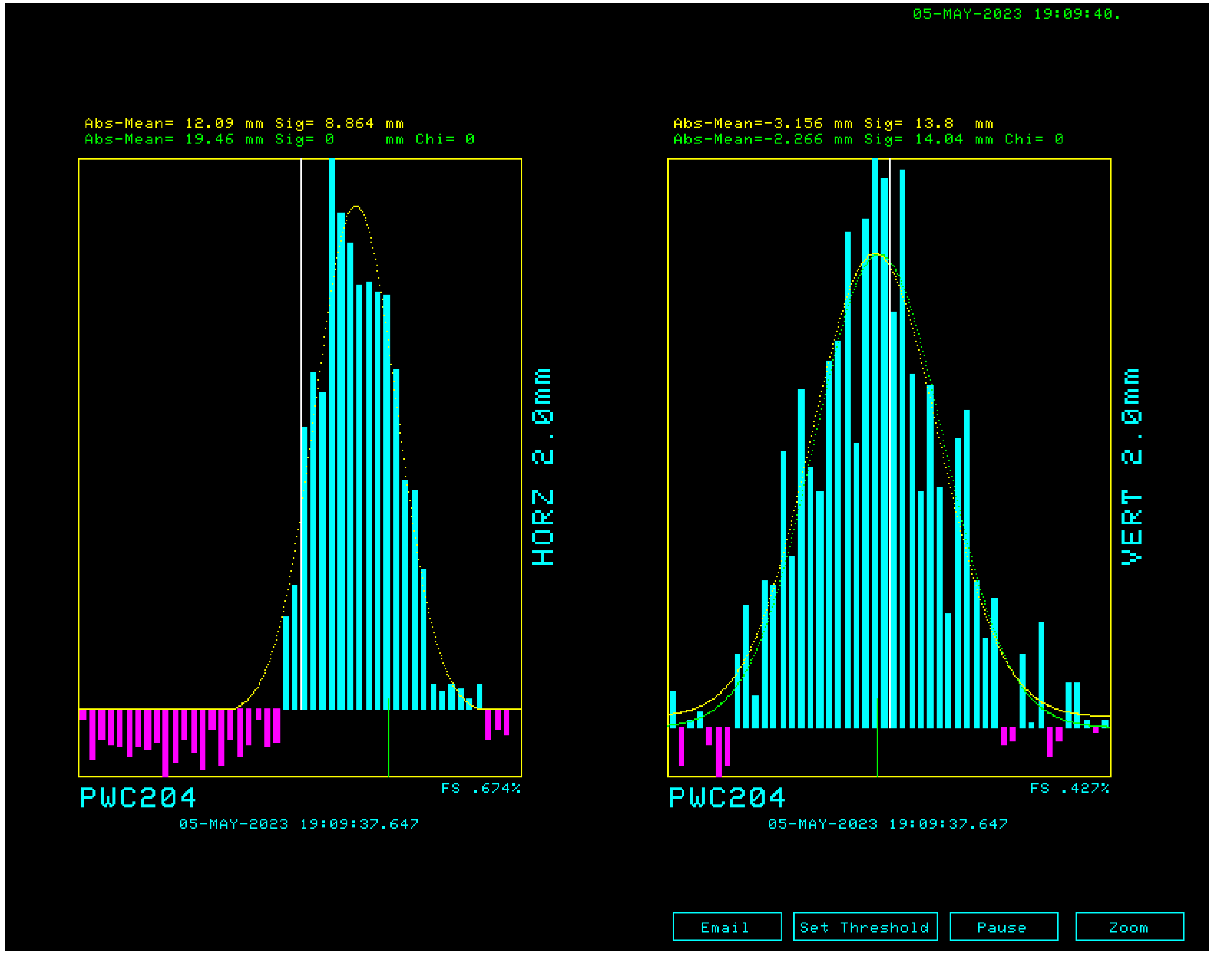
Since we have two distinct regions within a quarter section, the rate of precession will *slightly* vary within the $\vec{B}$-only section and the $(\vec{E} + \vec{B})$-section.

The total precession through a half-quadrant will be:

$$\Delta\phi_{EDM} = \frac{d}{S} . B_0[\ell_b + \ell_e(1 + \frac{E_0}{B_0 \beta c})]$$

Plugging in appropriate set of field values for a momentum range of 300 MeV/c and the path lengths, we see that the EDM precesses in the order of 10 mrad for 5 muon lifetimes!

Low p muon delivery – PWC204 (in the DR US of Extraction Lambertson.



```
Abs-Mean= 12.09 mm Sig= 8.864 mm
Abs-Mean= 19.46 mm Sig= 0      mm Chi= 0
```

```
Abs-Mean=-3.156 mm Sig= 13.8  mm
Abs-Mean=-2.266 mm Sig= 14.04 mm Chi= 0
```

Accelerator summary

- 300 MeV/c muon yield is much lower than 3.1 GeV/c for 8 GeV primary protons
  - 8 GeV/c primary beam comes from the Recycler and is not adjustable
  - With present Target Station, 300 MeV/c muon yield 150 times lower than 3.1 geV/c
- Measurements and simulations agreed well
  - Yield measured x150 lower in studies, simulations had x180 lower
- An alternative Target Station focusing scheme could improve yield
  - Focusing horn most attractive, but solenoid is possibility too
- Alternative target materials should be considered
  - Low Z target of graphite or beryllium may improve low angle muon yield
- Existing Inflector in g-2 Ring is not compatible due to “closed” ends
  - 300 MeV/c muon scattering would effectively prevent muons from circulating
  - Open ended Inflector was built prior to g-2 Operation and could be used
- Numerous accelerator power supplies would need to be modified
  - Regulation poor at 300 MeV/c, far below what the supplies were designed for
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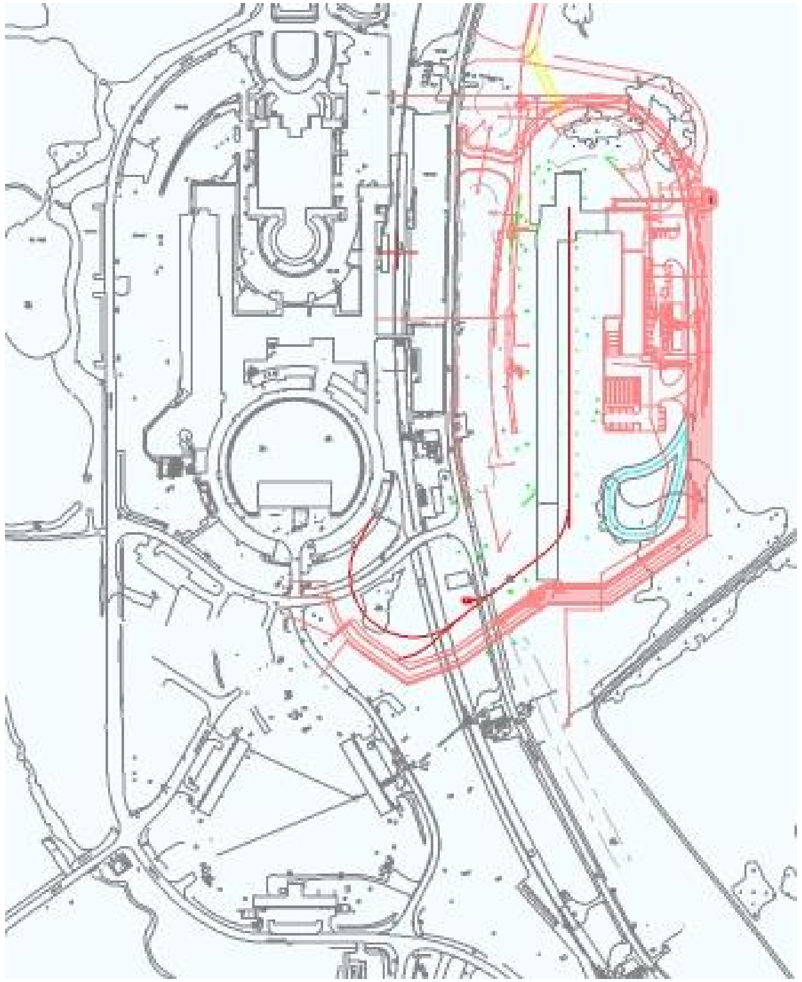
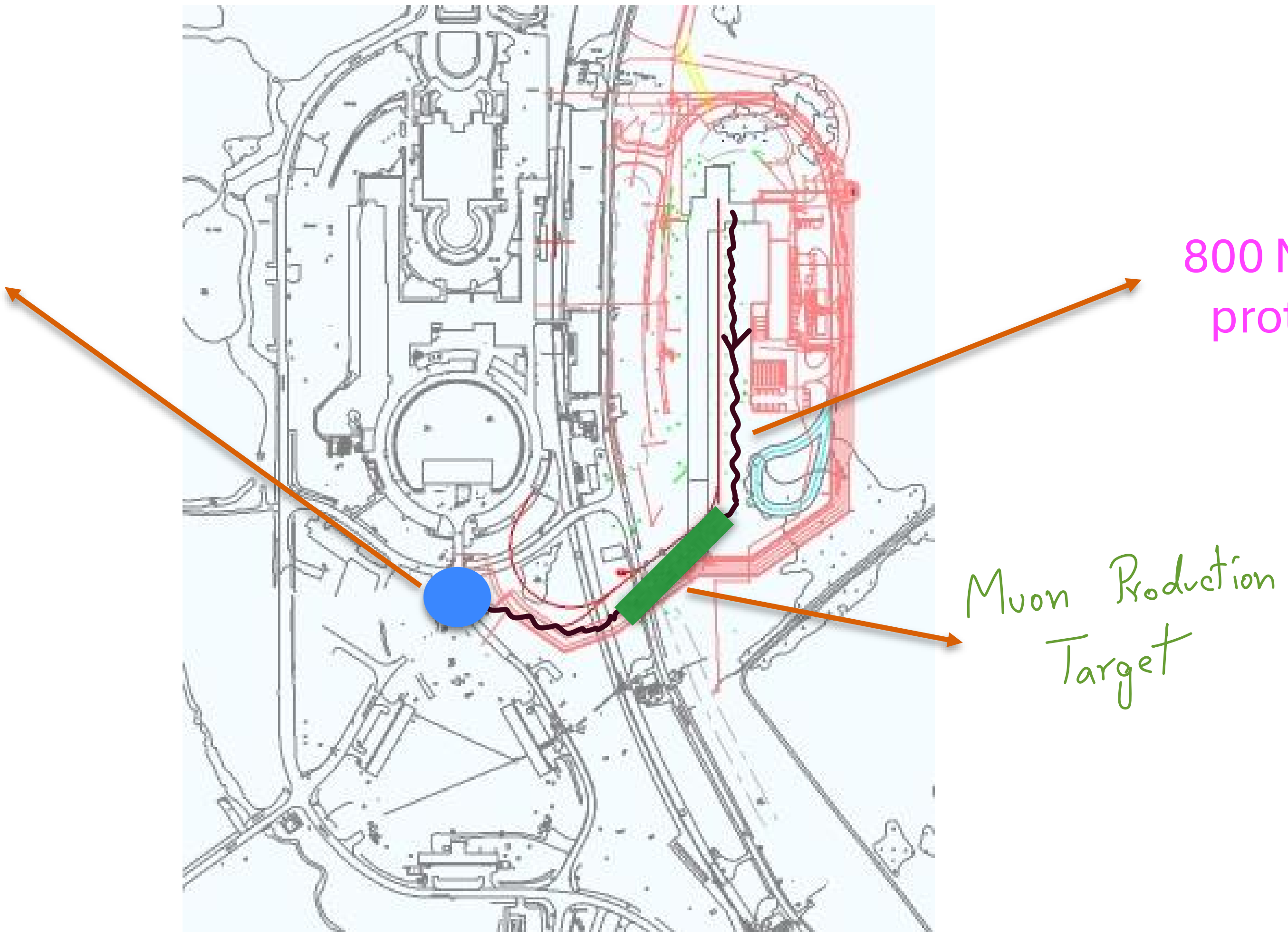
  - Kickers could be replaced by trim dipoles for a dedicated running period

PIP-II Layout



PIP-II Beam Potential for `d-0' EDM Experiment



300 MeV/c
muons

800 MeV/c
protons

Muon Production
Target

Experiment Parameters

Parameter	Value	Unit
Muon Momentum	387	MeV/c
Magnetic Field	0.178	T
Radial Electric Field	-1.98	MV/m
Plate Separation	± 35	mm
Plate Voltage	± 69.283	kV
Quadrupole Gradient	TBD	MV/m/m
Central Orbit Radius	7112	mm
Radial Orbit Deviations	± 10.9	mm
Ring Admittance (Horiz., central momentum)	153	π mm-mrad

NEXT UP…

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