Precision Physics at CAPP/IBS muon g-2 and storage ring EDM experiments

Young-Im Kim
Center for Axion and Precision Physics Research (CAPP)
Institute for Basic Science (IBS)

2016 Symmetry Tests in Nuclei and Atoms
Sep. 19-23, 2016

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Center for Axion and Precision Physics research. Established 15 October, 2013 at KAIST.

CAPP, April, 2016

srEDM Collaboration Meeting at KAIST, 21 April, 2016

CAPP/IBS's Physics goals address some of the most important issues

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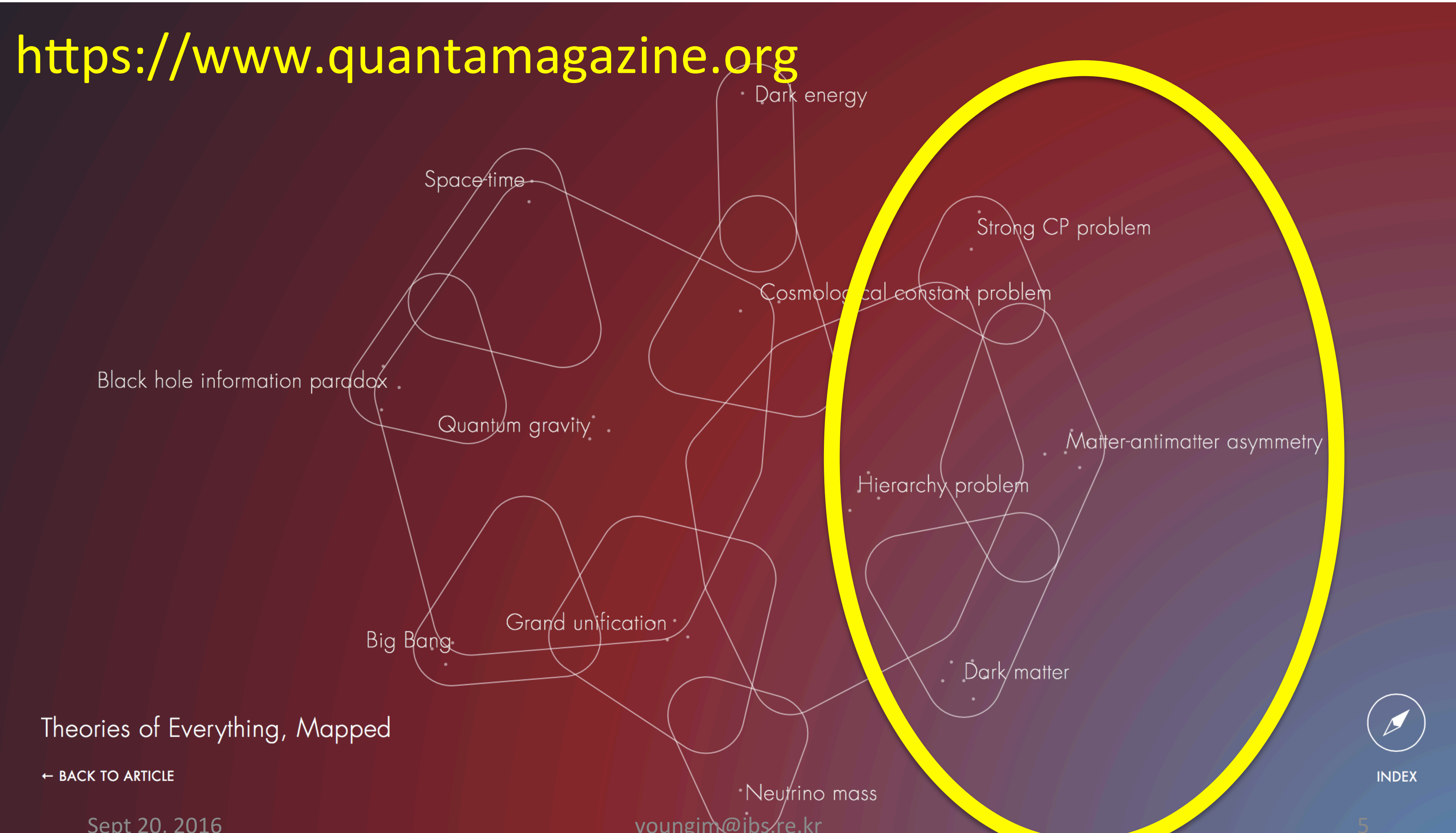
https://www.quantamagazine.org



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CAPP/IBS-Physics

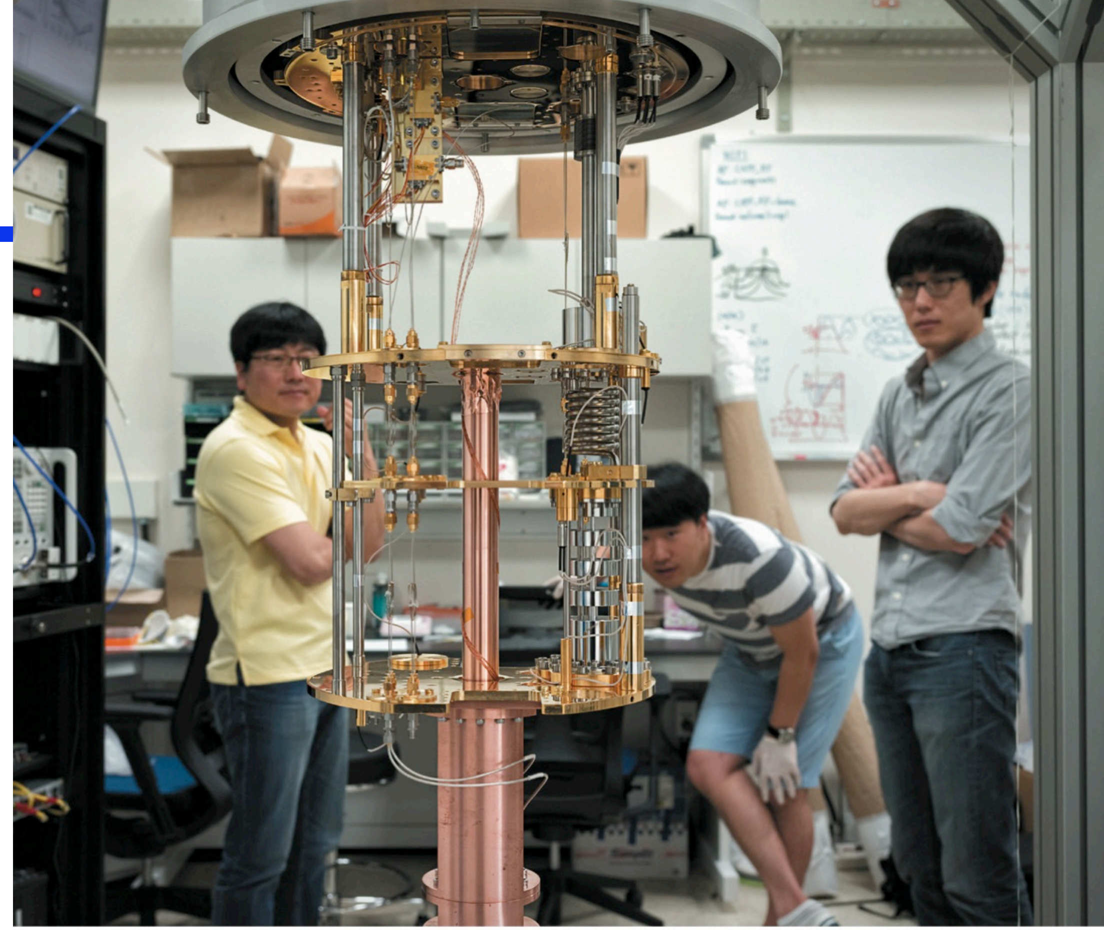
Involved in important physics questions:

- Strong CP problem (Symmetry crisis in strong forces)
- Cosmic Frontier (Dark Matter axions)
- Storage ring proton EDM (most sensitive hadronic EDM experiment, flavor conserving CP-violation, BAU). BAU: Baryon Asymmetry of Universe
- Muon g-2; muon to electron conversion (flavor physics)

Nature Article about CAPP/IBS in Korea

Nature V 534, 2 June 2016

by Mark Zastrow



SHIN WOONG-JAE

South Korea's Nobel dream

The Asian nation spends more of its economic output on research than anywhere else in the world. But it will need more than cash to realize its ambitions.

BY MARK ZASTROW

Behind the doors of a drab brick building in Daejeon, South Korea, a major experiment is slowly taking shape. Much of the first-floor lab space is under construction, and one glass door, taped shut, leads directly to a pit in the ground. But at the end of the hall, in a pristine lab, sits a gleaming cylindrical apparatus of copper and gold. It's a prototype of a device that might one day answer a major mystery about the Universe by detecting a particle called the axion — a possible component of dark matter.

If it succeeds, this apparatus has the potential to rewrite physics and win its designers a Nobel prize. "It will transform Korea, there's no question about it," says physicist Yannis Semertzidis, who leads the US$7.6-million-per-year centre at South Korea's premier technical university, KAIST. But there's a catch: no one knows whether axions even exist. It's the kind of high-risk, high-reward project

STORAGE RING MUON G-2: RIGOROUS TEST OF THE STANDARD MODEL

Magnetic dipole moment

- In the standard model (SM), the magnetic dipole moment (MDM) of muon can be precisely calculated
- A precision measurement of muon MDM can test the SM
- If there is a significant deviation from the SM prediction, it would be an evidence for new physics

$$\vec{\mu} = g\frac{Qe}{2m}\vec{S}$$

- It is useful to break the magnetic moment into two terms:

$$\mu = (1+a)\frac{e\hbar}{2m} \qquad a = \frac{(g-2)}{2}$$

Dirac + anomalous (Pauli) moment

g-2

- The SM prediction for the muon g-2, a_μ can be separated into three terms,

$$a_\mu(\mathrm{SM}) = \mathrm{a}_\mu(\mathrm{QED}) + \mathrm{a}_\mu(\mathrm{EW}) + \mathrm{a}_\mu(\mathrm{had})$$

- The hadronic contribution $a_\mu(\mathrm{had},\mathrm{LO})$ has been calculated by a number of groups

- The SM prediction for the muon g-2 :

$$a_\mu(\mathrm{SM}) = 116\ 591\ 802(49)_{\mathrm{tot}} \times 10^{-11}\ (\pm 0.42\ \mathrm{ppm})$$

- Experiment value

$$a_\mu(\mathrm{E821}) = 116\ 592\ 089(54)_{\mathrm{stat}}(33)_{\mathrm{syst}}(63)_{\mathrm{tot}} \times 10^{-11}\ (\pm 0.54\ \mathrm{ppm})$$

- Deviation between the SM prediction and experiment result

$$\Delta a_\mu = a_\mu(\mathrm{E821}) - \mathrm{a}_\mu(\mathrm{SM}) = (287\ \pm 80) \times 10^{-11}$$

The result is 3.5 s.d. away from theory! What is it?

Comparison of Theory/Experiment

The result is 3.5 s.d. away from theory! What is it?

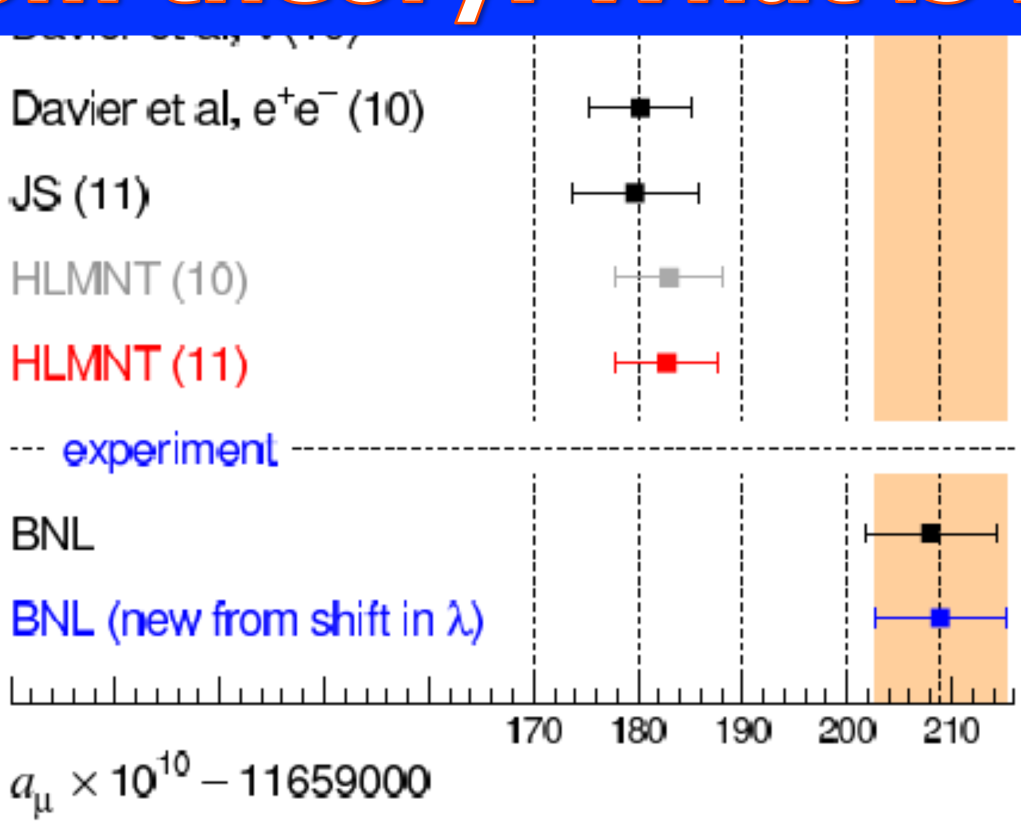


Figure 1: Standard model predictions of a_μ by several groups compared to the measurement from BNL

The muon ring moved to Fermilab (22 June – 25 July 2013)

Muon g-2 experiment, E989

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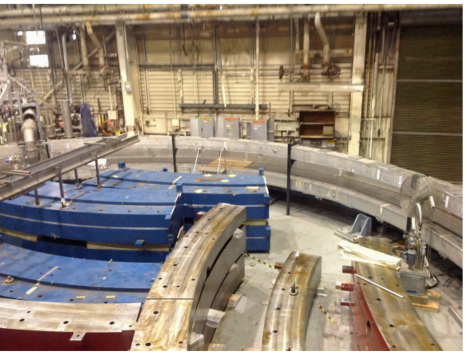

(a) February 2013 disassembly at Brookhaven

(b) May 2013 yoke steel stored at Fermilab

The muon g-2 coil moved to Fermilab for more intense beam

(c) July 2013 storage ring arrives at Fermilab

E989 muon g-2 collaboration

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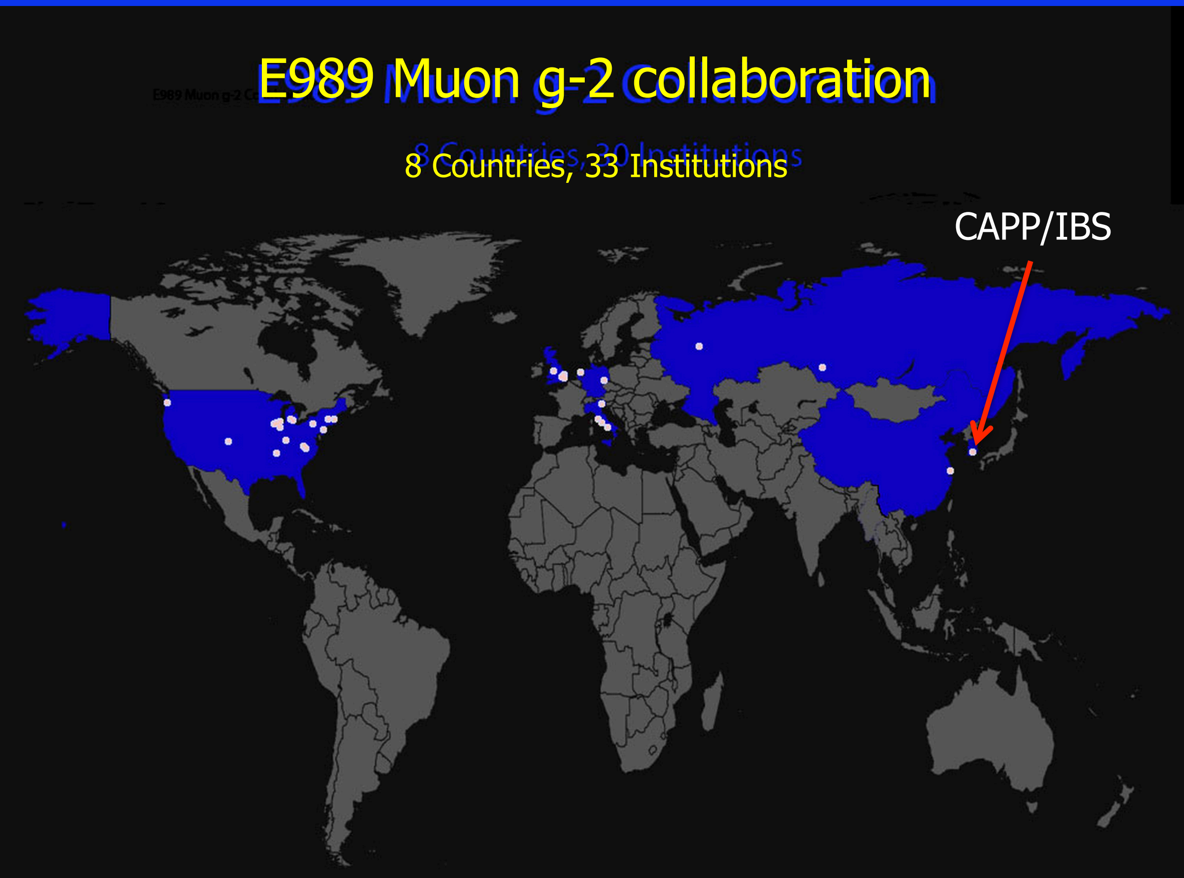
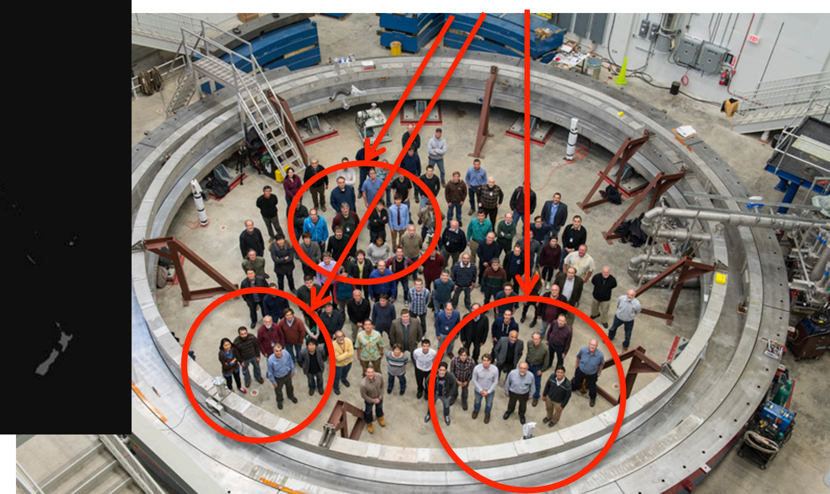


CAPPers



The ring has been reassembled and fully powered to 1.45T! First data: 2017

g-2 and EDM

In uniform magnetic field, muon spin rotates faster than momentum due to g-2 ≠ 0

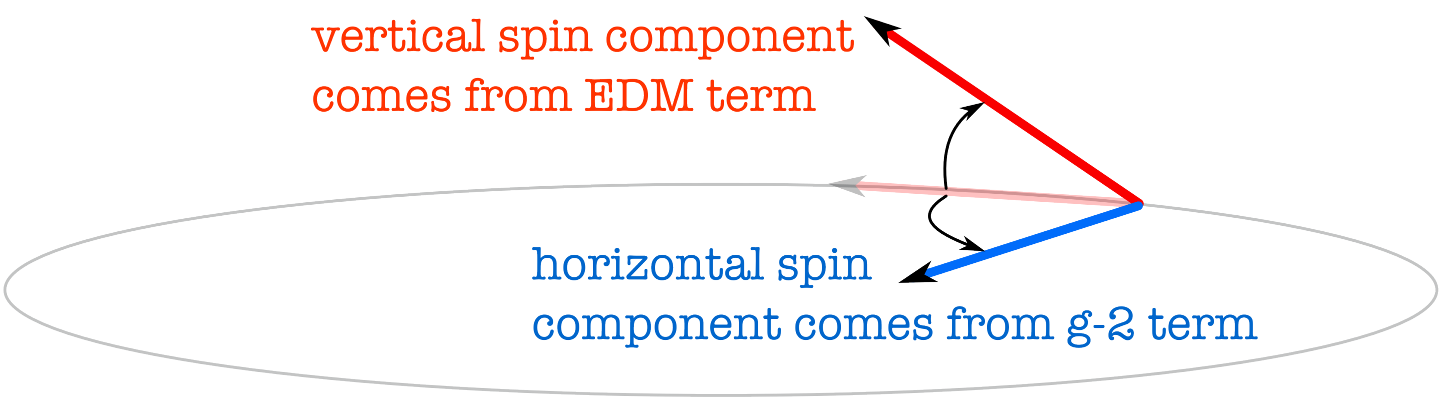
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] - \frac{\eta e}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right]$$

g-2 and EDM

In uniform magnetic field, muon spin rotates faster than momentum due to g-2 ≠ 0

g-2 precession | EDM precession

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



g-2 and EDM

In uniform magnetic field, muon spin rotates faster than momentum due to g-2 ≠ 0

g-2 precession　　EDM precession

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

FNAL, E989

Choose magic momentum

$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09\ \text{GeV}/c$$

$$p = \frac{mc}{\sqrt{a}}$$

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B}\right] - \frac{\eta e}{2m}\left[\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right]$$

J-PARC, E34

Eliminate E-field

E = 0 at any γ

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B}\right] - \frac{\eta e}{2m}\left[\vec{\beta}\times\vec{B}\right]$$

Breakthrough concept

Center for Axion and Precision Physics Research (CAPP)

- Freezing the horizontal spin precession due to E-field

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

- Muon g-2 focusing is electric: The spin precession due to E-field is zero at "magic" momentum
  - 3.1GeV/c for muons, 0.7 GeV/c for protons,…

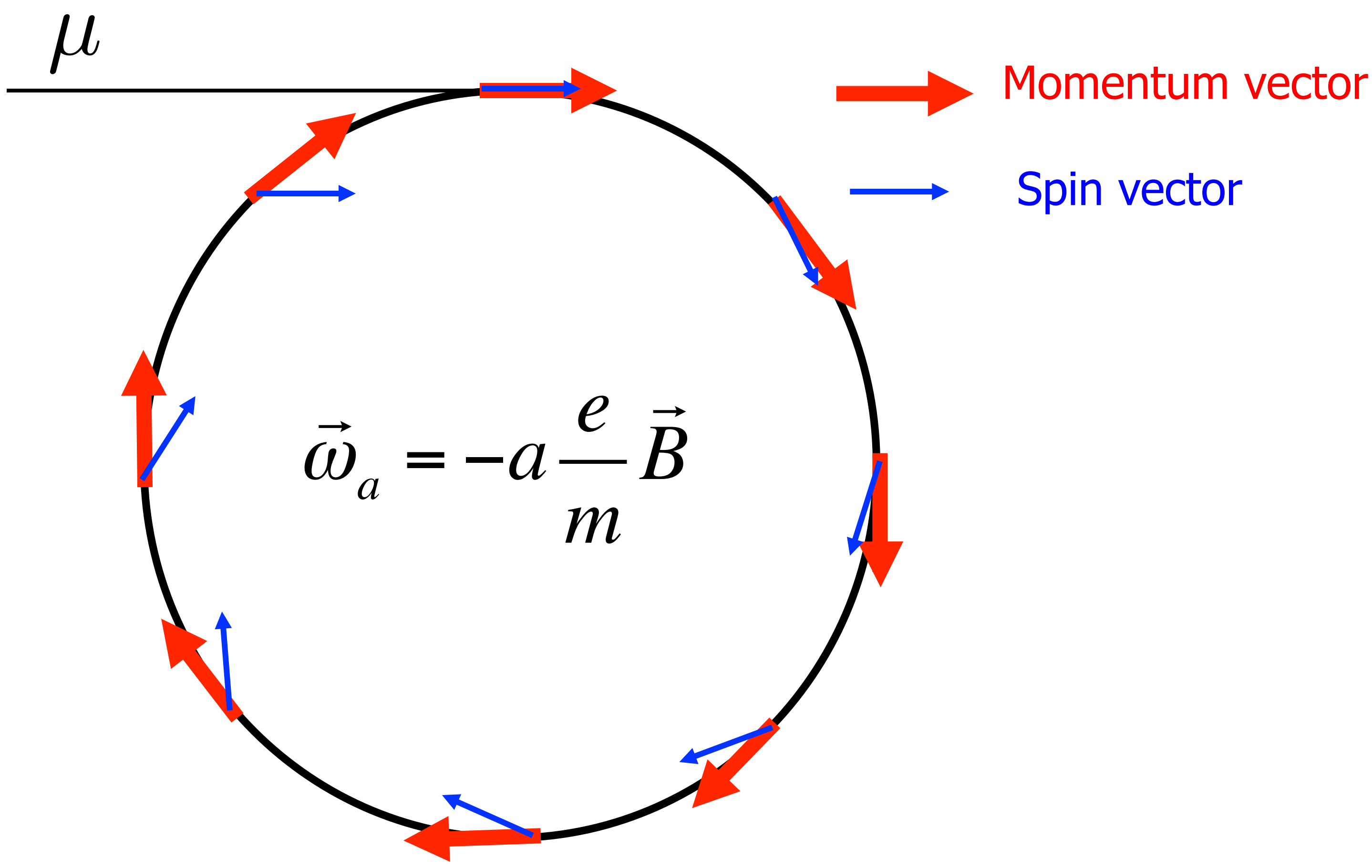
$$p = \frac{mc}{\sqrt{a}}, \text{ with } G = a = \frac{g-2}{2}$$

- The "magic" momentum concept was used in the muon g-2 experiments at CERN, BNL, and …next at FNAL.

Spin precession in g-2 ring

Muons rotate in the magnetic field of the storage ring

(Top view)



$$\vec{\omega}_a = -a\frac{e}{m}\vec{B}$$

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Experimental technique

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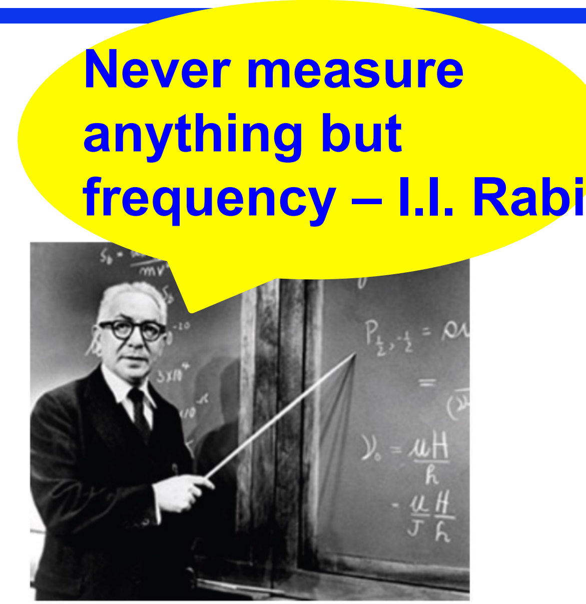
- Measure the difference frequency between the spin and momentum precession

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = -a\frac{Qe}{m}B$$

- With an electric quadrupole field for vertical focusing



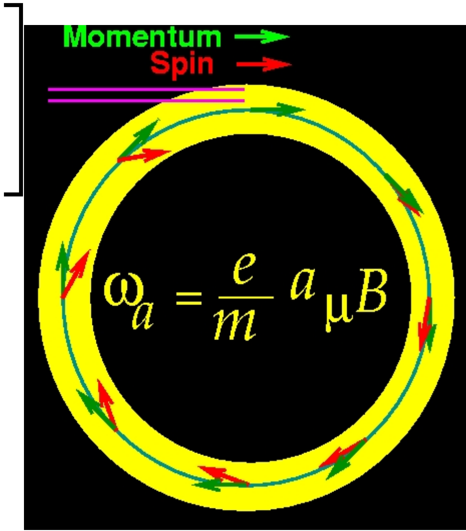
$$\vec{\omega}_a = -\frac{Qe}{m}\left[a_\mu \vec{B} - \left(a_\mu - \left(\frac{1}{\gamma^2 - 1}\right)^2\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

0

$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09\ \text{GeV}/c$$

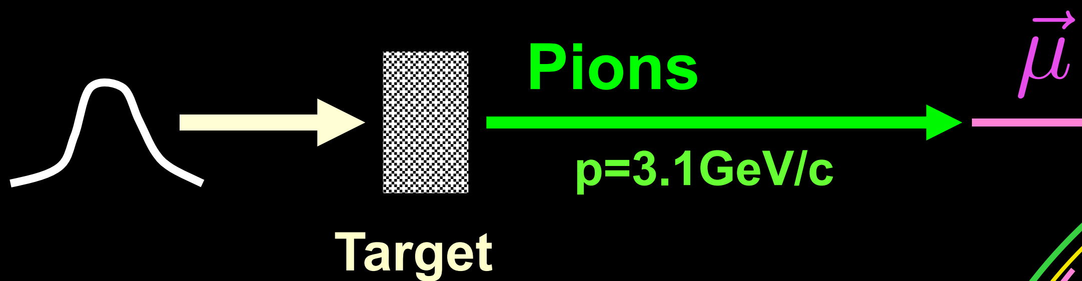
$$p = \frac{mc}{\sqrt{a}},\ \text{with } G = a = \frac{g-2}{2}$$



BNL & FNAL

Experimental Technique

narrow bunch of protons



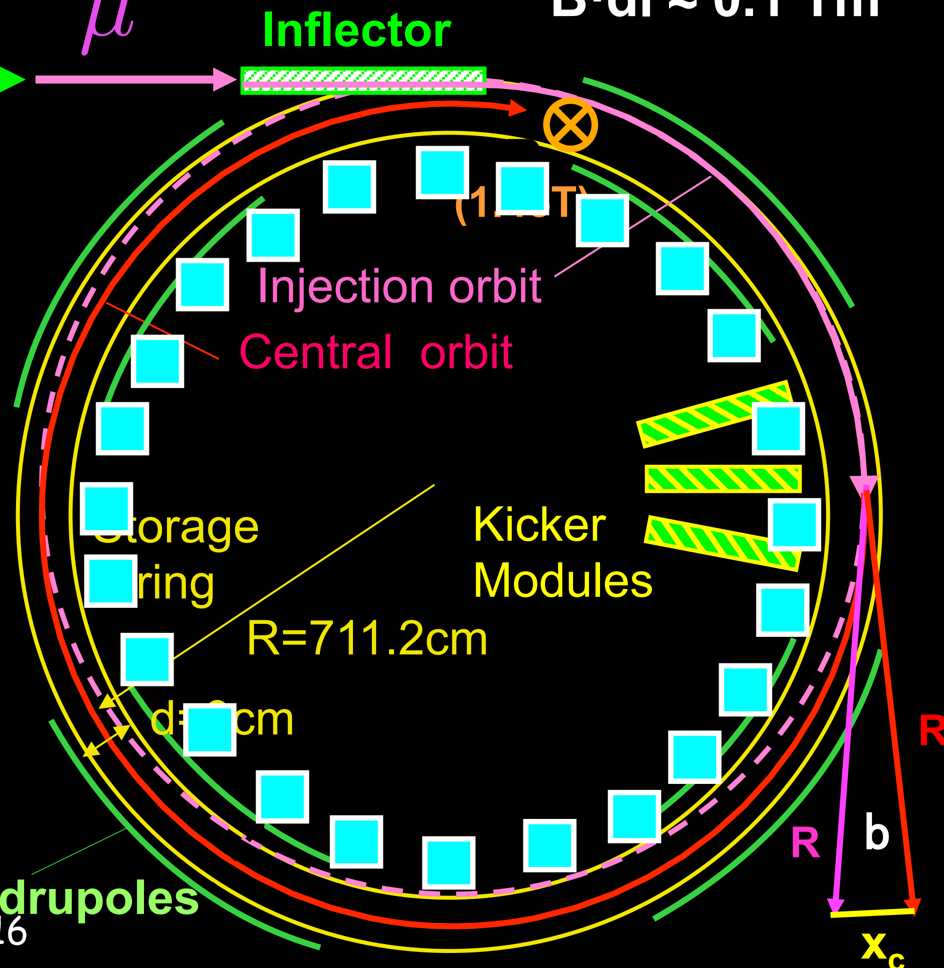
$x_c \approx 77$ mm

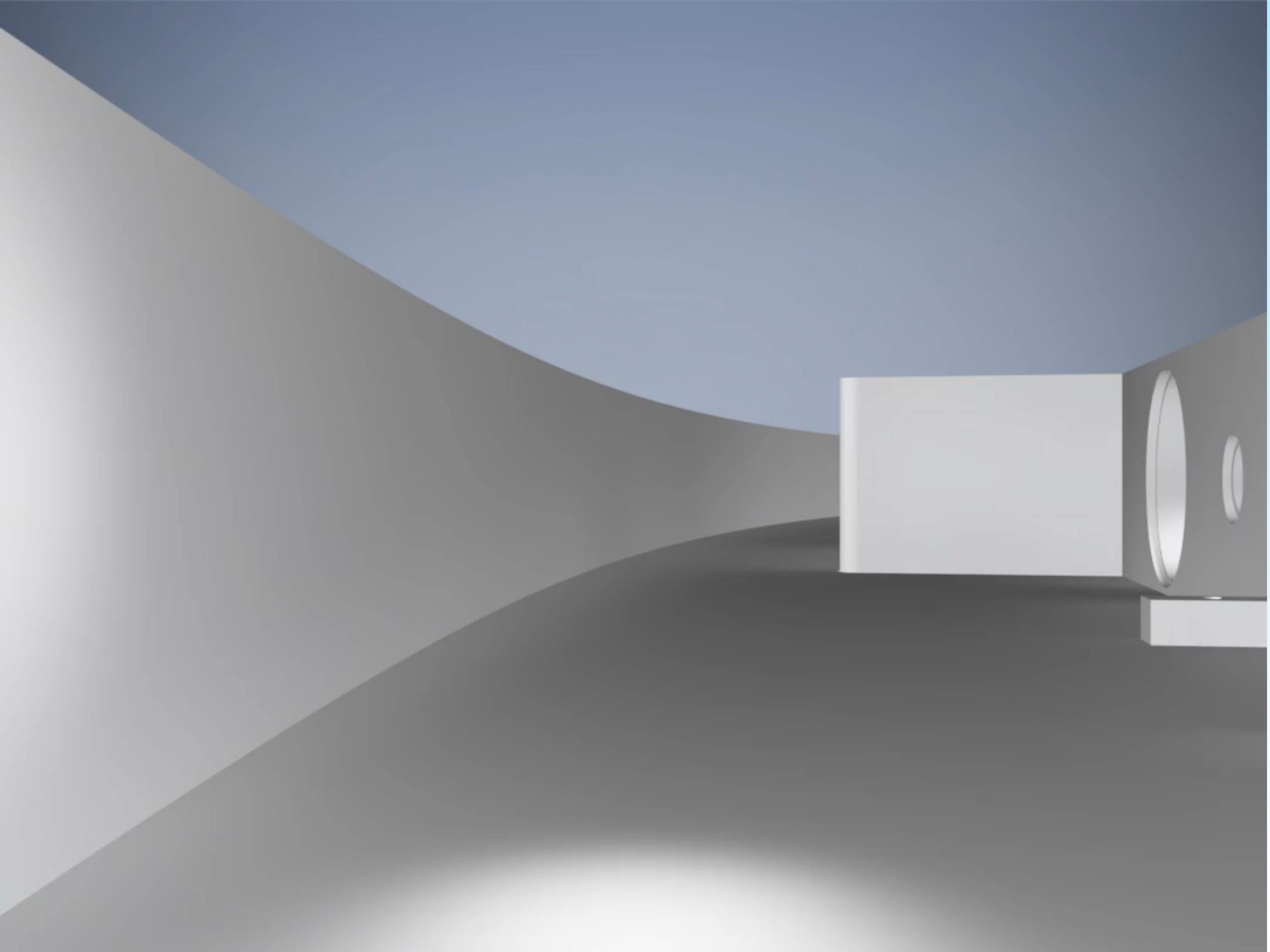
$b \approx 10$ mrad

$B \cdot dl \approx 0.1$ Tm

- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{Qe}{m} a_\mu \vec{B}$$



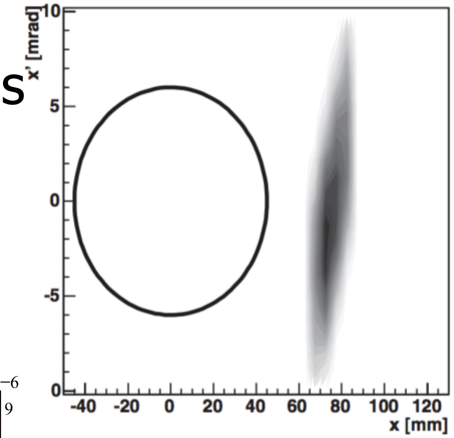


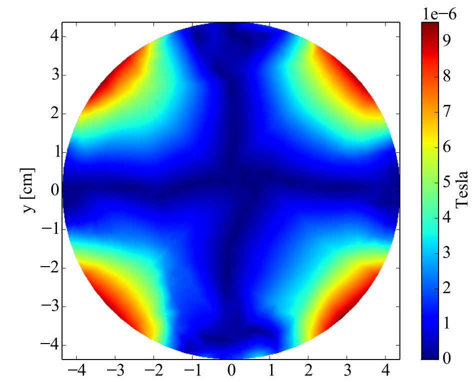
Systematic uncertainties

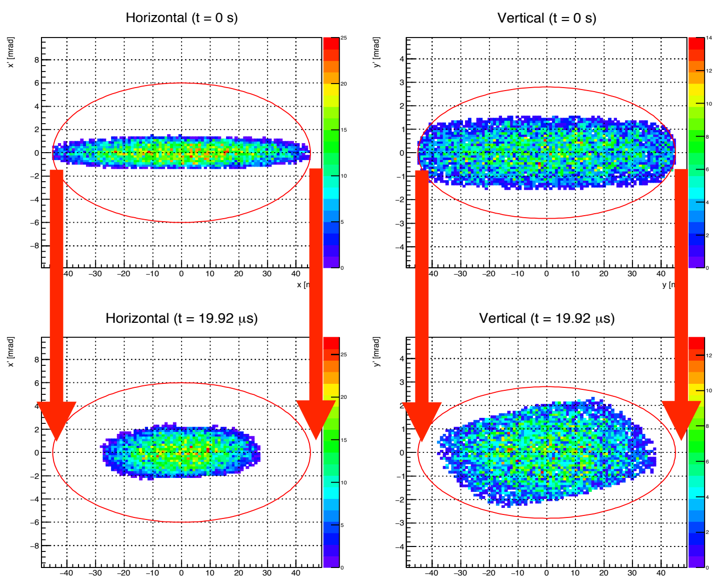
	E821 [ppb]	E989 Improvement plans	Goal [ppb]
Gain changes	120	Better laser calibration low-energy threshold	20
Pileup	80	Low-energy samples recorded calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO (Coherent Betatron Oscillation)	70	Higher n value (frequency) Better match of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

Beam phase space matching

- A radio frequency (rf) can be applied to a quad structure to eliminate CBO and reduce the muon losses
- Creating a healthy gap of the beam from the apertures
- Korean contribution
- Tracking simulation
- Computer Simulation Technology (CST) simulation
- System design



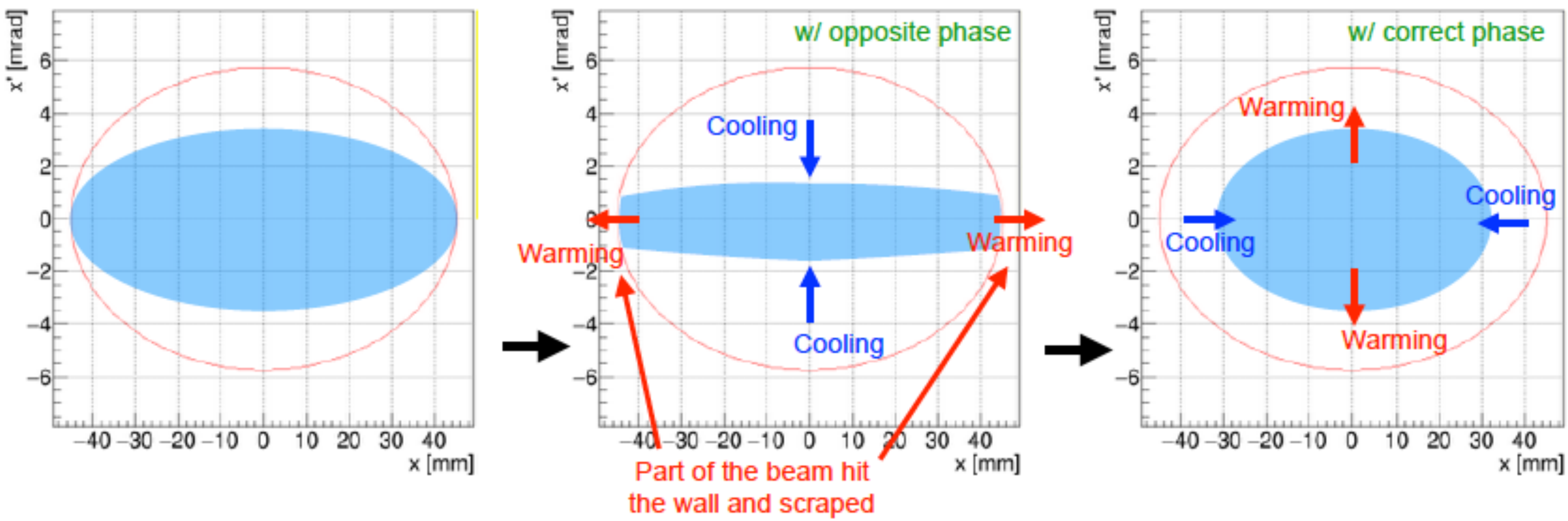




- 9 cm diameter of the muon storage region, the strongest magnetic field ~ 10^{-6} T
- Assuming 20 us of rf beam phase space matching, produces no measurable spread in the muon spins.
- No effect in muon polarisation

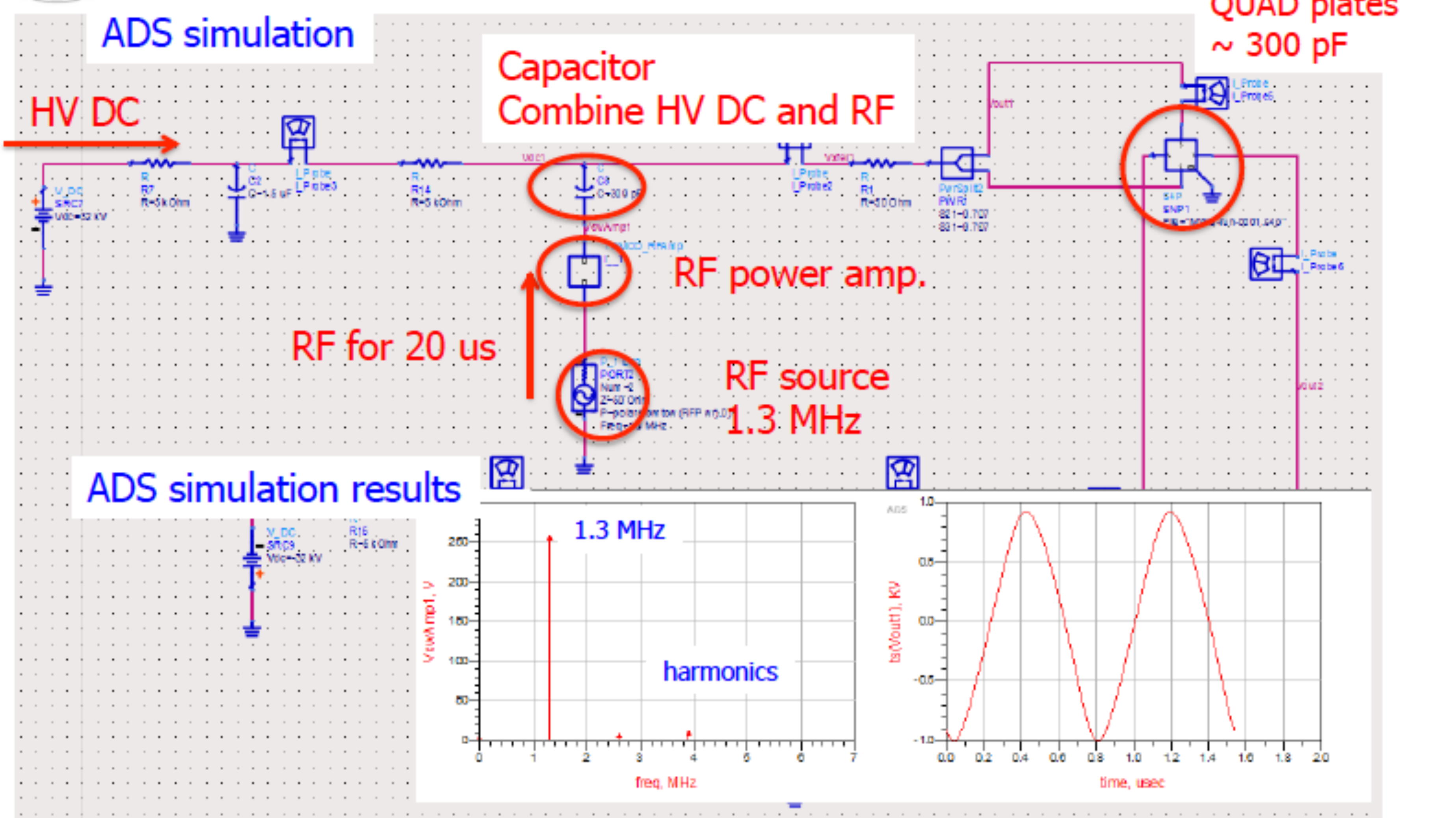
Yet another idea with RF matching

- RF matching can be another solution for the scraping
- Stretching the beam with opposite phase, and bring it back with correct phase

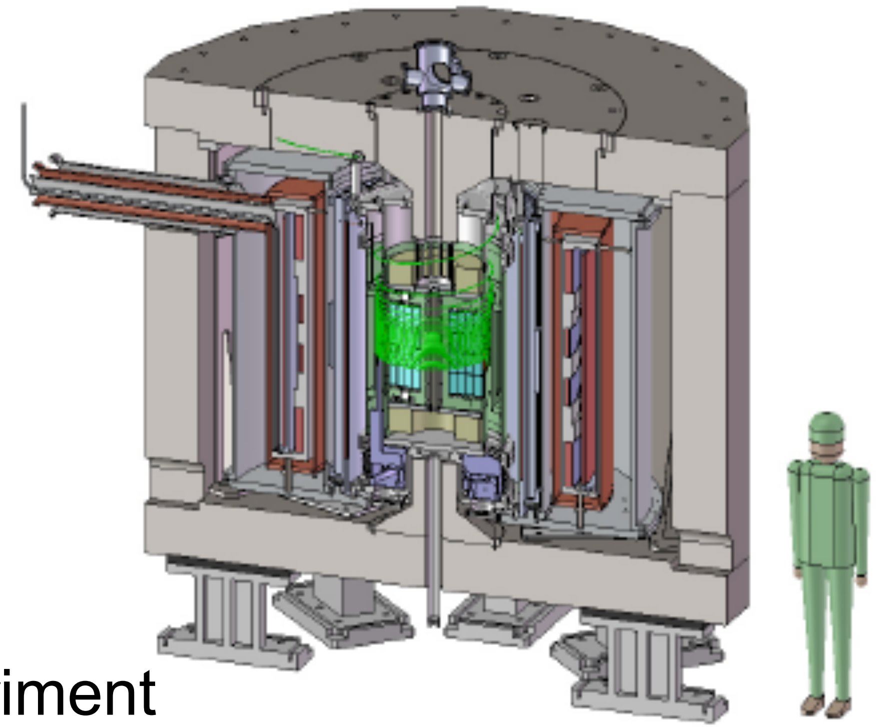


Simulation: Dr. Soohyung Lee

Circuit simulation



J-PARC Muon g-2 experiment



- Totally independent experiment
- Very different systematic errors
- Much more uniform B-field
- Accepting all muon decays

FUNDAMENTAL PARTICLE EDM: STUDY OF CP-VIOLATION BEYOND THE STANDARD MODEL

Electric Dipole Moments

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P and T-violating when $\vec{d}$ // to spin

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	-	+	+
C	-	-	-
T	+	-	-

Magnetic Dipole Moment

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}$$

Even under all three symmetries

Electric Dipole Moment

$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$

Odd under P and T

The EDM is a CP-odd quantity, if observed, it would be a new source of CP violation.

T-violation: assuming CPT cons. → CP-violation

Storage ring EDM

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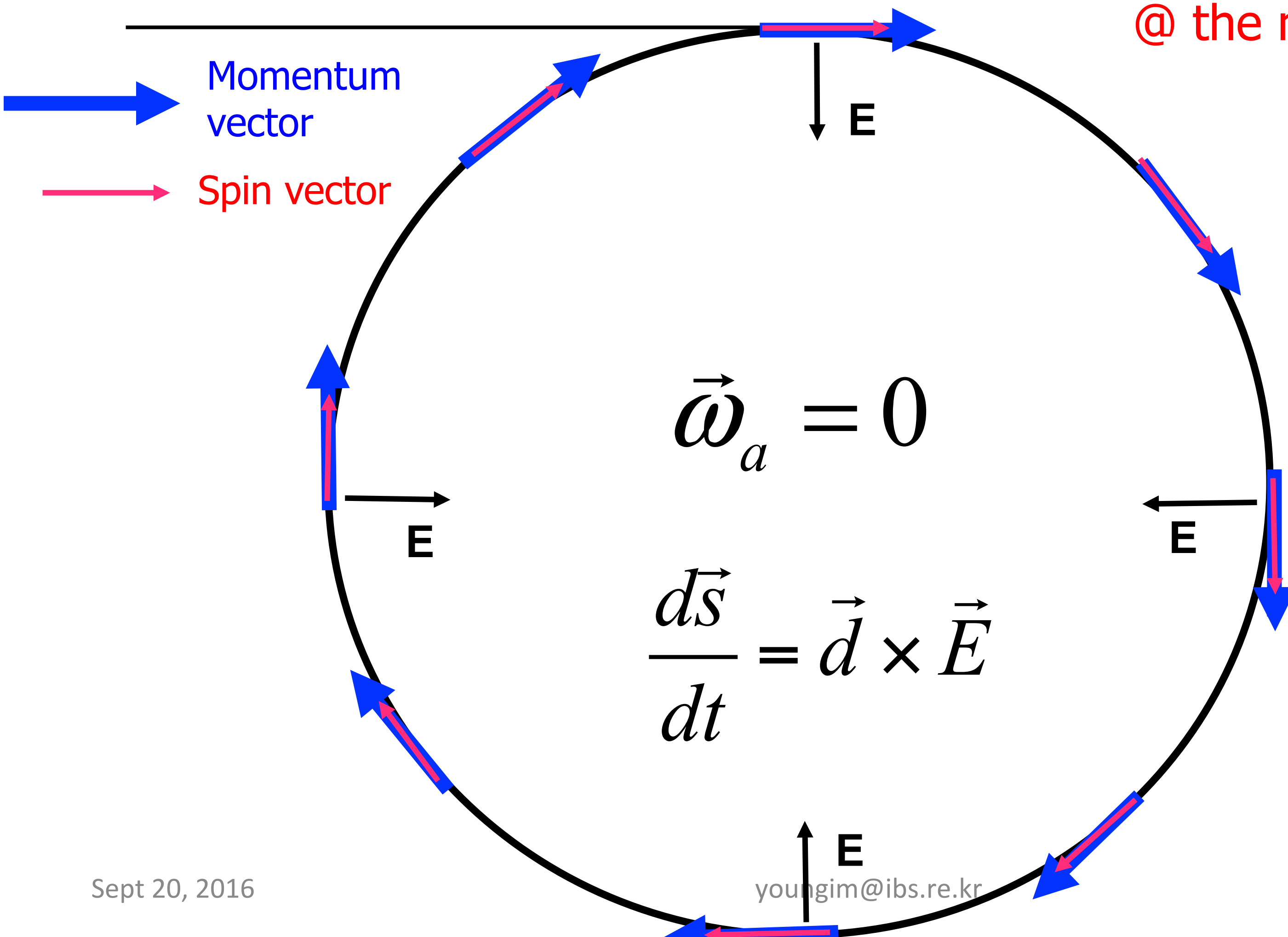
Electric dipole moment precesses in an Electric field

The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector

@ the magic momentum



$$\vec{\omega}_a = 0$$

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

As in muon g-2 experiment at BNL and FNAL

$$p = \frac{mc}{\sqrt{a}} = 0.7\ \mathrm{GeV/c}$$

$$p = \frac{mc}{\sqrt{a}} = 15\mathrm{MeV/c}$$

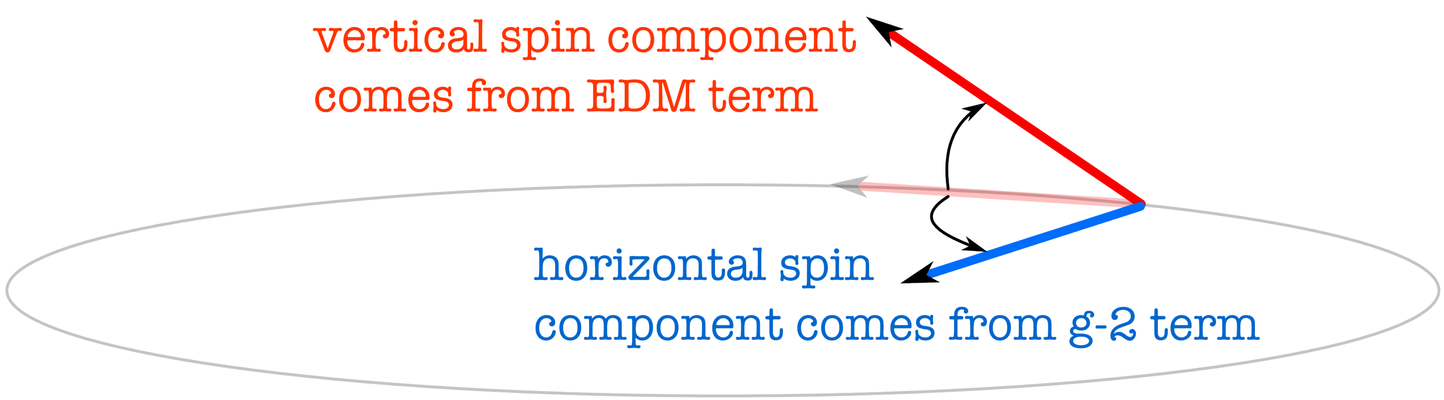
for electrons!

pEDM experiment

- Polarised counter-rotating beams will be injected at magic momentum into the ring
- CW and CCW beams will pass through each other
- Radial E-field will couple with EDM to grow vertical spin component
- Each storage will be 1000 s. Total 10^7 s measurement time
- The particles will be extracted continuously for the polarimeter to measure vertical spin precession rate

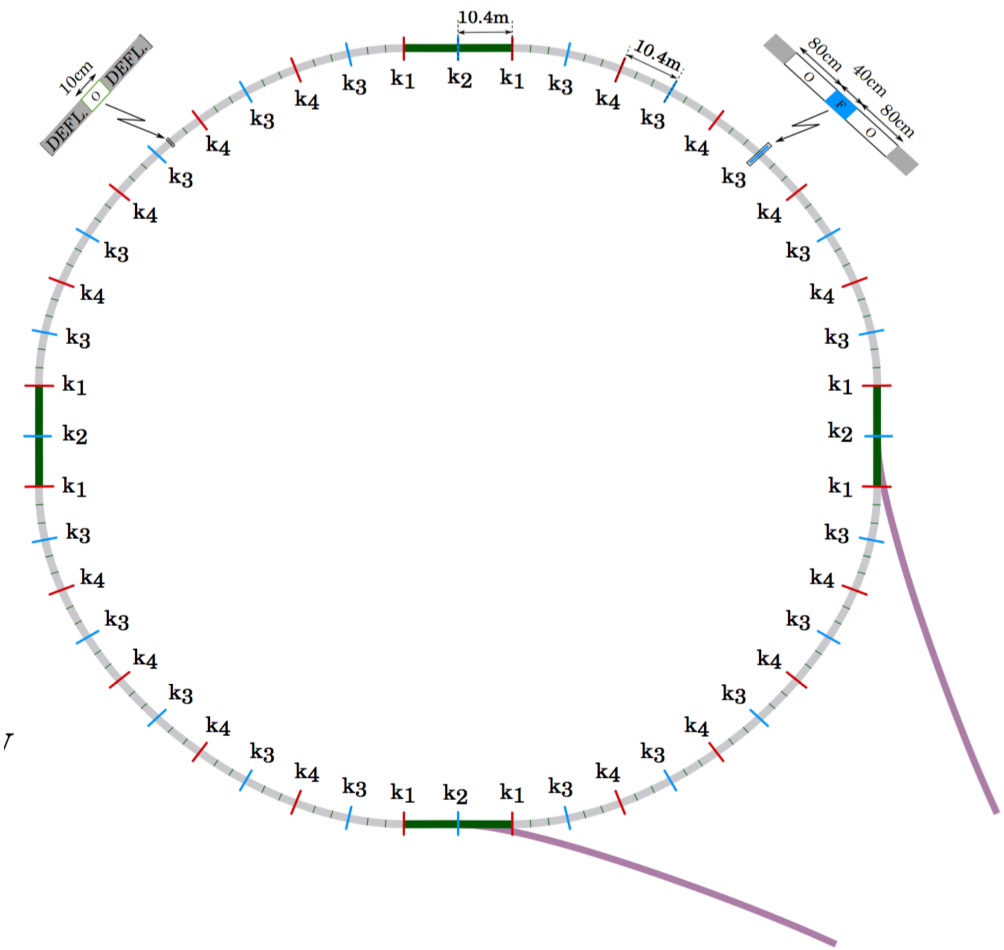
Spin coherence time

- Horizontal spin component cancelled at magic momentum
- But not all particles are at magic momentum
- Horizontal spin component should not go beyond 90 degrees
- The time that this condition is satisfied is called spin coherence time
- Spin coherence time in the electric ring was a major concern of accelerator people 5 years ago

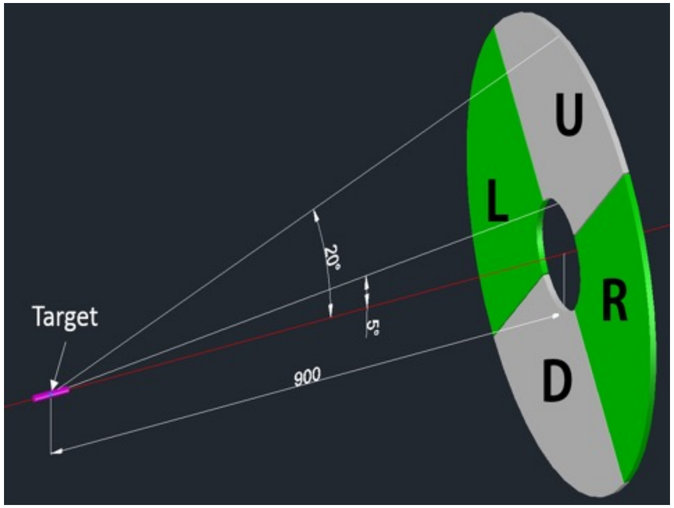


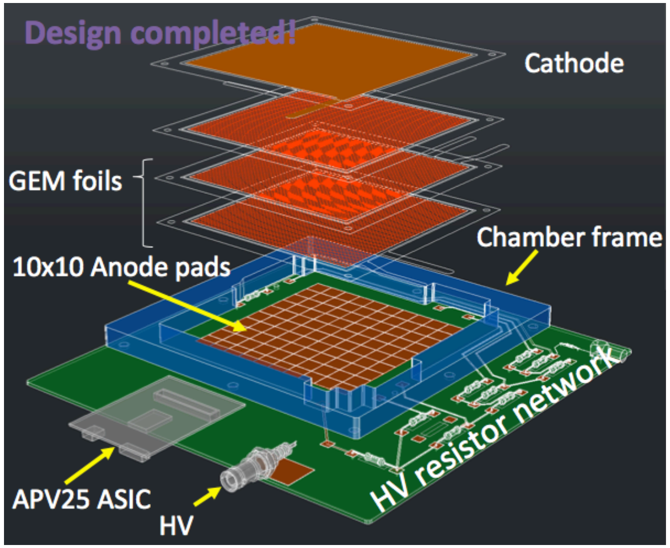
Spin coherence time

- Studied various all-electric ring designs with home-made Runge-Kutta codes
- Finally found out that rings with quad-based alternating focusing give longer spin coherence time than we need
- This can even be improved using RF cavity



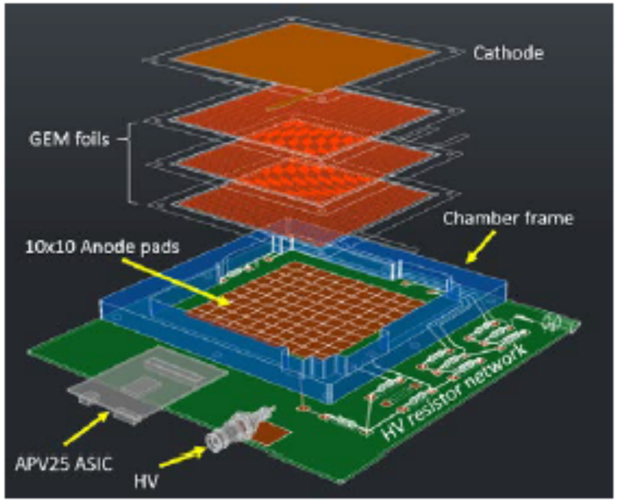
Polarimeter

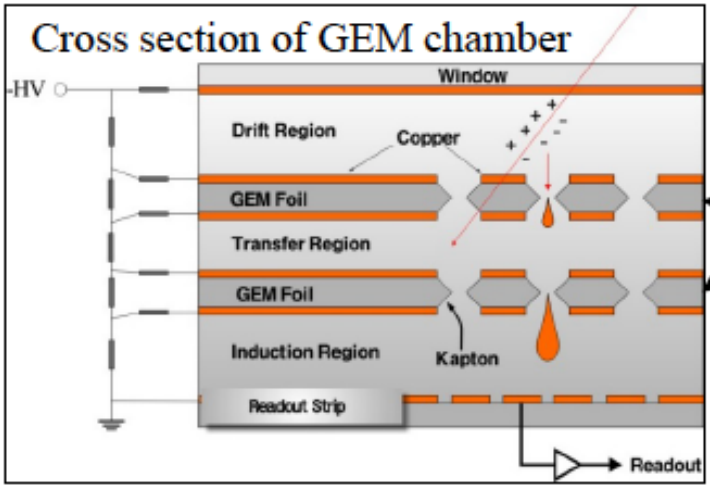




- spin precession occurs due to the proton's EDM and it can be measured by the polarimeter
- GEM (Gas Electron Multiplier)
  - ~100 % detection efficiency
  - High resolution (40 um)
  - Response time (toy model :15 ns -> will be less than 1 ns)

10x10 cm² test detector

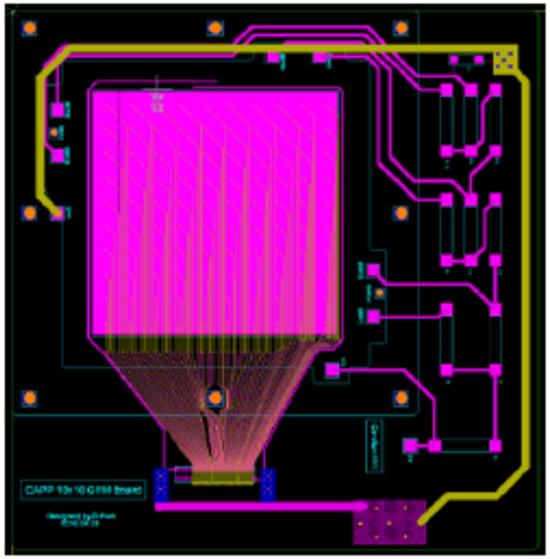


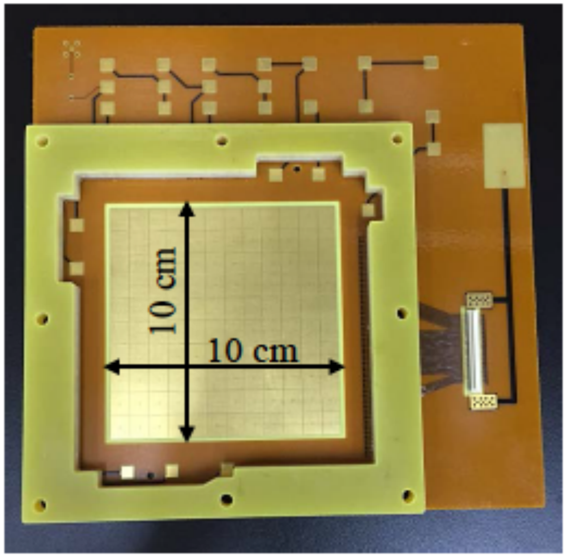


10x10 GEM foil

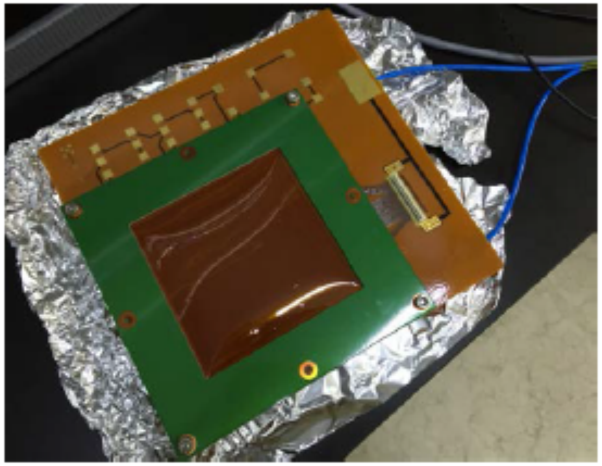
Slide: Dr. SeongTae Park

PCB layout



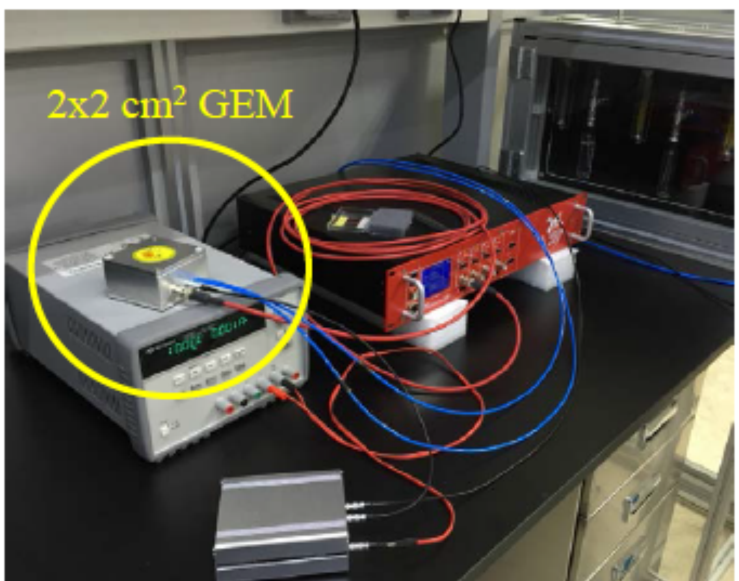


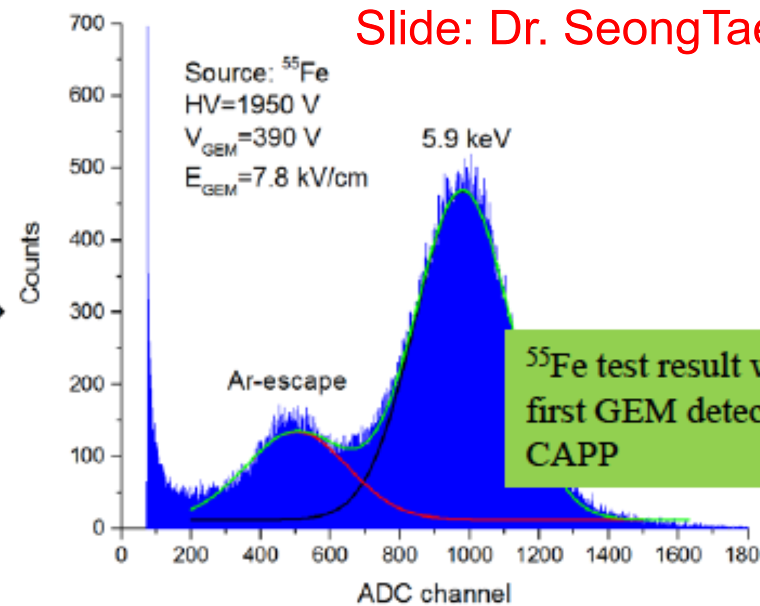
Under assembling.
Will be tested soon and go beam test with APV25.



New polarimeter lab is ready

Clean booth (class 10,000)





Slide: Dr. SeongTae Park

^{55}Fe test result with the first GEM detector at CAPP

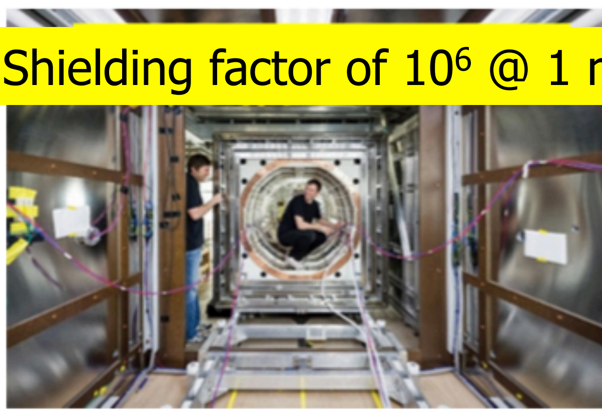
B-field shielding

S. Haciomeroglu

- One major source of systematic error is radial magnetic field
  - Even very small magnetic field can mimic an EDM effect
- Shielding: 1 nT B-field with 0.1 nT/m gradient
  - 10 pT stability per injection is required

Collaboration with Prof. **Peter Fierlinger** (Technical University of Munich)

Shielding factor of 10^6 @ 1 mHz



Physics Today: http://scitation.aip.org/content/aip/magazine/physicstoday/news/10.1063/PT.5.7171, Shielding factor of 10^6 over a $4 m^3$ an order-of-magnitude improvement

Two layers of 1 mm thickness
2.25 m long
60 and 65 cm inner diameters
Cylinder inside, octagonal outside

Under development by Selcuk Haciomeroglu at CAPP/IBS

$$\text{SF} = \frac{\text{B-field without shield}}{\text{B-field with shield}}$$

Depends on frequency

- SF>600 @ 1mHz
- SF>700 @ 10mHz

B-field shielding

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S. Haciomeroglu

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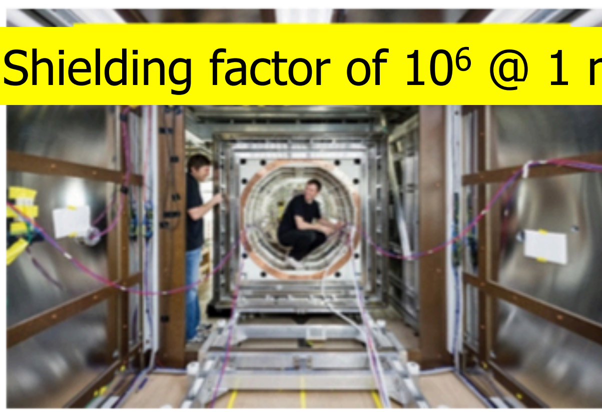


Physics Today: http://scitation.aip.org/content/aip/magazine/physicstoday/news/10.1063/PT.5.7171, Shielding factor of 10^6 over a $4m^3$ an order-of-magnitude improvement

Under development by Selcuk Haciomeroglu at CAPP/IBS

Achieved so far:
Absolute field: <0.5nT
Gradient field: <2.0nT/m
Almost there!

$$SF = \frac{\text{B-field without shield}}{\text{B-field with shield}}$$

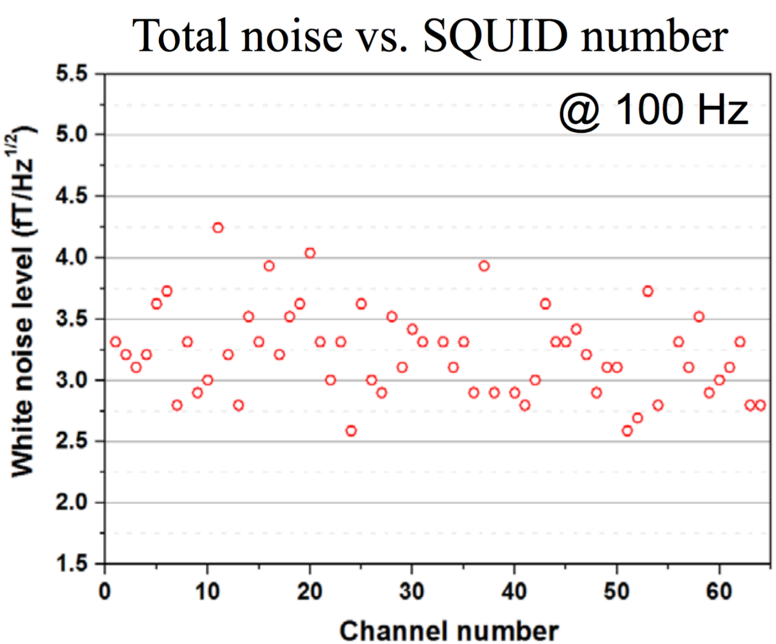
Depends on frequency

- SF>600 @ 1mHz
- SF>700 @ 10mHz

SQUID-based BPMs

S. Haciomeroglu

- Designed and being developed by Yong-Ho Lee from KRISS
- aT B-field can be measured by averaging with 3 fT/√Hz SQUIDs
- Should be shielded to nT level
- The volume is roughly 1 m^3
- Will be delivered by the end of this year



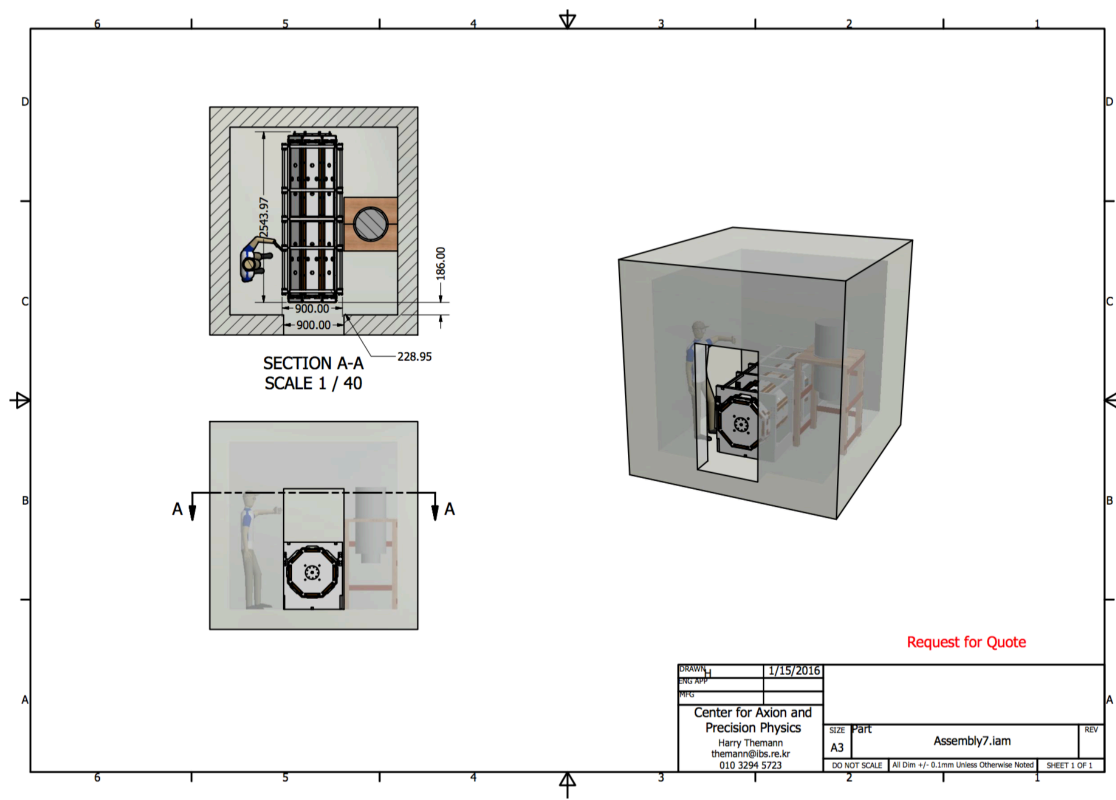
Total noise of commercially available SQUID gradiometers at KRISS

Goal ~ 10^{-30} ecm sensitivity

Magnetically Shielded Room

S. Haciomeroglu

- MSR is required for
  - Pretest measurements
  - BPM measurements for pEDM
  - BPM measurements for g-2/EDM



Precision spin tracking

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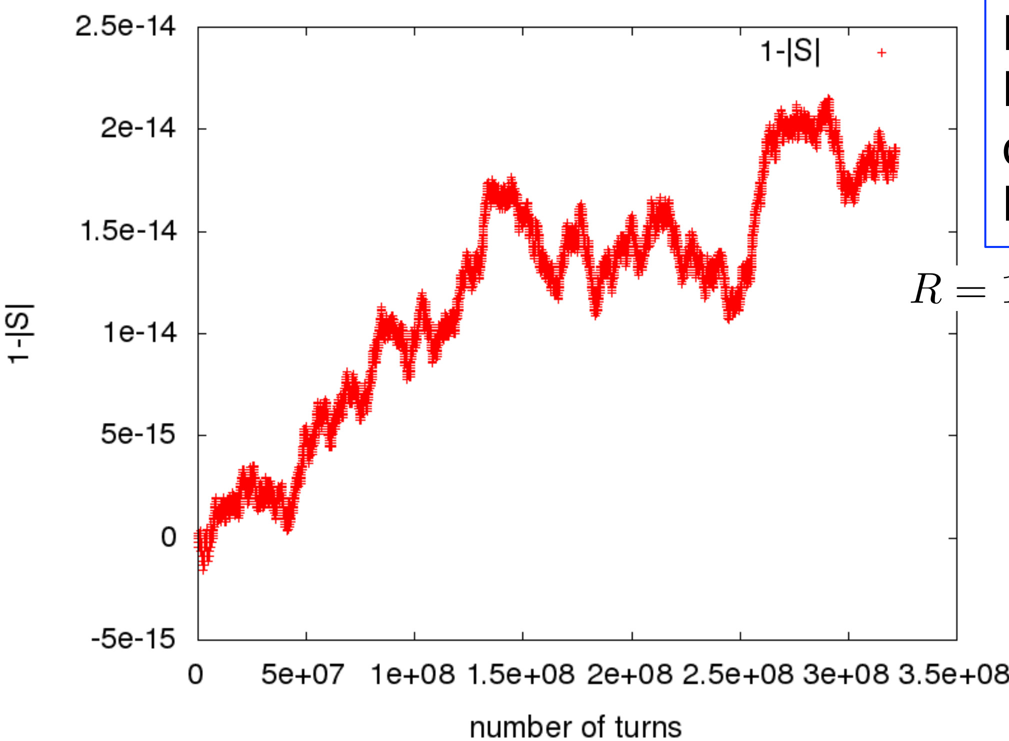
Axion and Precision
Physics Research

M. Gaisser

- Complete: program for precision studies
  - Test different algorithms
  - Use different (arbitrary precision) data types
  - Use for different lattices
  - Parallelized for CPU/GPU
  - benchmarked



Example:
Loss of spin magnitude as quality check, off-axis Muon in magnetic ring, 8th order RK-Algorithm

$$R = 10m,\ n = 1.1,\ \gamma = 29.3,\ T \approx 67s,\ \Delta t = 10^{-9}s$$

Precision spin tracking
current work

M. Gaisser

- Use Geometric Algebra* (Clifford Algebra)
  - Combine eqm. and T-BMT equation into one first order equation in 5d
  - Use special solver to retain symmetry properties
  - Expect higher accuracy
  - Expect fast code
  - Can maybe even solve equation analytically
  - Hope to calculate accurate fields

*Gull, S., Lasenby, A., & Doran, C. (1993). Imaginary numbers are not real—the geometric algebra of spacetime. Foundations of Physics, 23(9), 1175-1201.

Technically driven pEDM timeline

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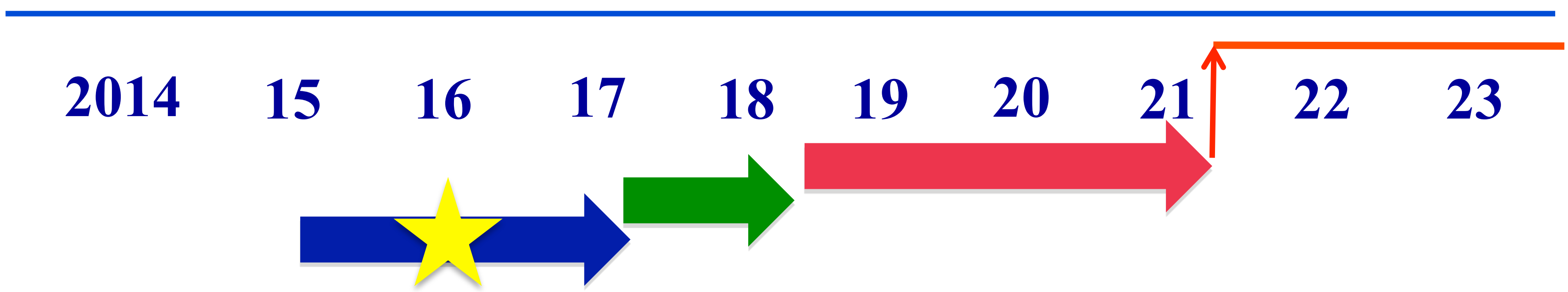

- Two years systems development (R&D); CDR; ring design, TDR, installation
- CDR by fall of 2017
- Proposal to a lab: fall 2017

Summary

- Muon g-2 @ FNAL
  - commissioning start 2017
  - Making Korean contribution
- srEDM
  - pEDM very exciting experiment
  - Possibly, together with LHC upgrade, the most likely place to make a breakthrough discovery
  - Low cost/Low risk
  - Can be built on short timescale
  - R&D on the storage ring EDM experiment
  - Storage ring EDM experiments (proton, electron) in Korea?!

More slides

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AXION

Axion

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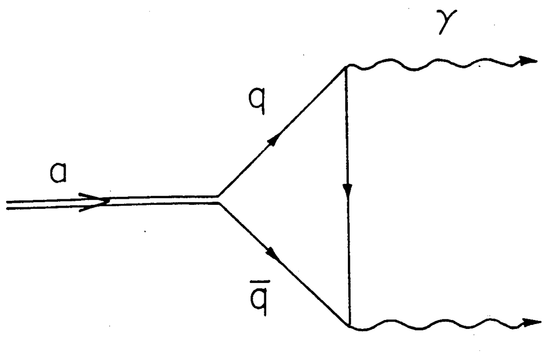
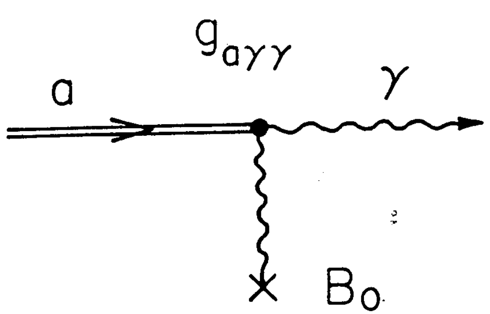
- Motivated by two major issues of contemporary physics
  - The strong CP problem
    - The observed charge and parity (CP) violation in strong interactions is 10 orders of magnitude smaller than predicted by the SM
    - Peccei and Quin proposed a solution whose natural consequence (Weinberg and Wilczek), is the extence of a particle named Axion
  - Dark matter
    - Known to exist for nearly one century, DM represents ~25 % of the energy balance of our universe. J. E. Kim realised that if the axion mass is very small, in μeV range, it would also solve the DM problem
    - mass range: 1 μeV to 300 μeV (CAPP primarily focuses on 1 to 100 μeV)

Cold DM Axion Detection

- Based on the axion coupling to two photons in the presence of a strong magnetic field





$$\mathcal{L} = g_{a\gamma\gamma} a(t) \overrightarrow{E(t)} \cdot \overrightarrow{B}$$

$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a};\ g_\gamma = 0.97\ \text{(KSVZ) or -0.36 (DFSZ)}$$

$g_{a\gamma\gamma}$: coupling constant(model dependent)

$a(t)$: axion field

$\overrightarrow{E(t)}$: Electric field associated with the outgoing photon

$\overrightarrow{B}$: Provides a virtual photon enhancing the conversion probability

Microwave cavities

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- Suitable for axion detection
  - The axion-to-photon conversion probability is further enhanced in a microwave cavity that resonates to the frequency of the axion mass (Sikivie)
- On resonance axion conversion power in a microwave cavity

$$P \approx g_{a\gamma\gamma}\left(\frac{\rho_a}{m_a}\right)B^2 \cdot Q \cdot V \cdot C$$

$$Q = 2\pi f \frac{\text{Stored Energy}}{\text{Power Loss}}$$ Quality factor

$$C = \frac{1}{B_0^2 V}\frac{\left|\int \boldsymbol{B}\cdot\boldsymbol{E} d^3x\right|^2}{\int \boldsymbol{E}\cdot\boldsymbol{E} d^3x}$$ Geometry factor

The axion to photon conversion power is very small, a great challenge to experimentalists.

- Maximise (B), quality factor (Q), cavity volume (V), geometry factor (C)

Detecting Axion

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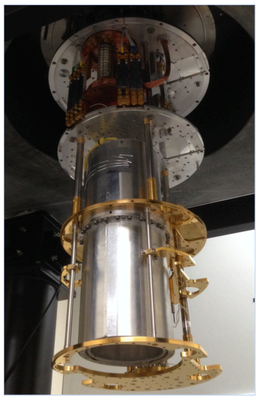
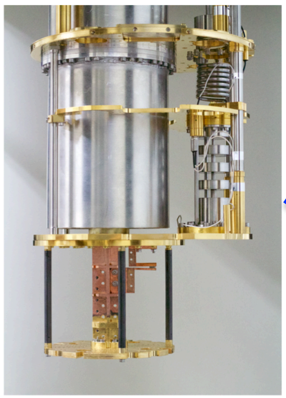
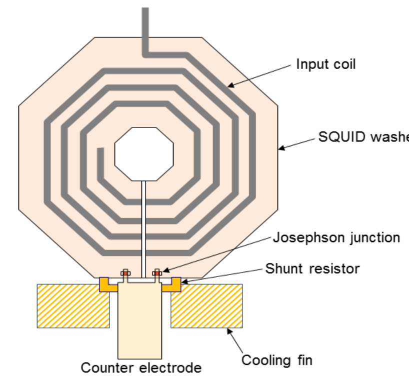
Cryogenics
<100mK

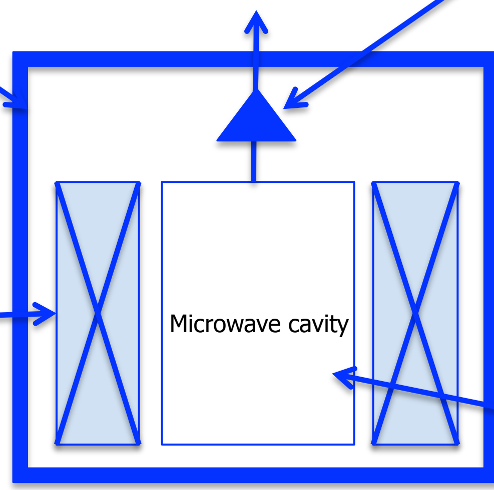




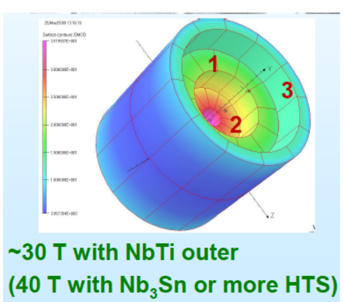
SQUID Amplifier
Outsourced Research from KRISS



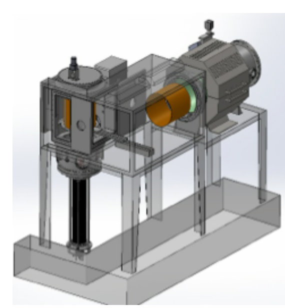
To RF Receiver

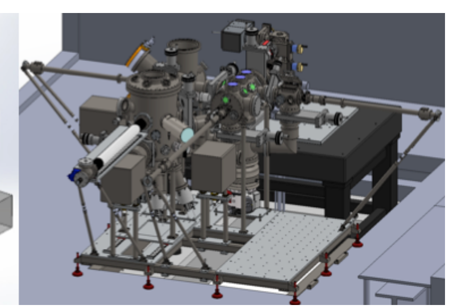


High Field Magnet
25T and then 35T or 40T
From BNL (HTS Technology)



High Q Tunable Cavity
Superconducting Coating
From Prof. Jhinhwan Lee of KAIST





Slide by W. Chung

Axion target plan @ CAPP/IBS

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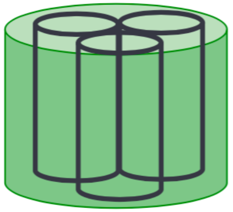
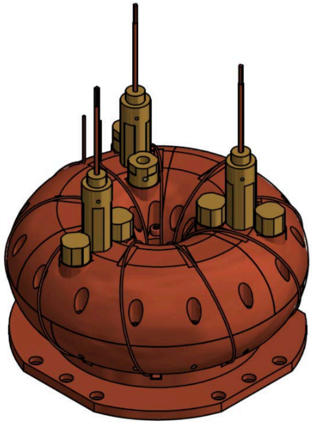
- Scanning rate

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \approx \frac{1\ \text{GHz}}{year}\left(g_{a\gamma\gamma}10^{15}\text{GeV}\right)^4\left(\frac{5\ \text{GHz}}{f}\right)^2\left(\frac{4}{SNR}\right)^2\left(\frac{0.25\ \text{K}}{T}\right)^2 \times\left(\frac{B}{25T}\right)^4\left(\frac{c}{0.6}\right)^2\left(\frac{V}{5l}\right)^2\left(\frac{Q}{10^5}\right)$$



Multiple small cavities

- Major improvement elements:
  - High field solenoid magnets: B (up to 35 T)
  - High volume magnets/cavities: V (multi cavities, toroid)
  - High quality factor of cavity: Q
  - Low noise amplifiers: T_N
  - Low physical temperature: T_{ph}



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ADMX goal and CAPP plan

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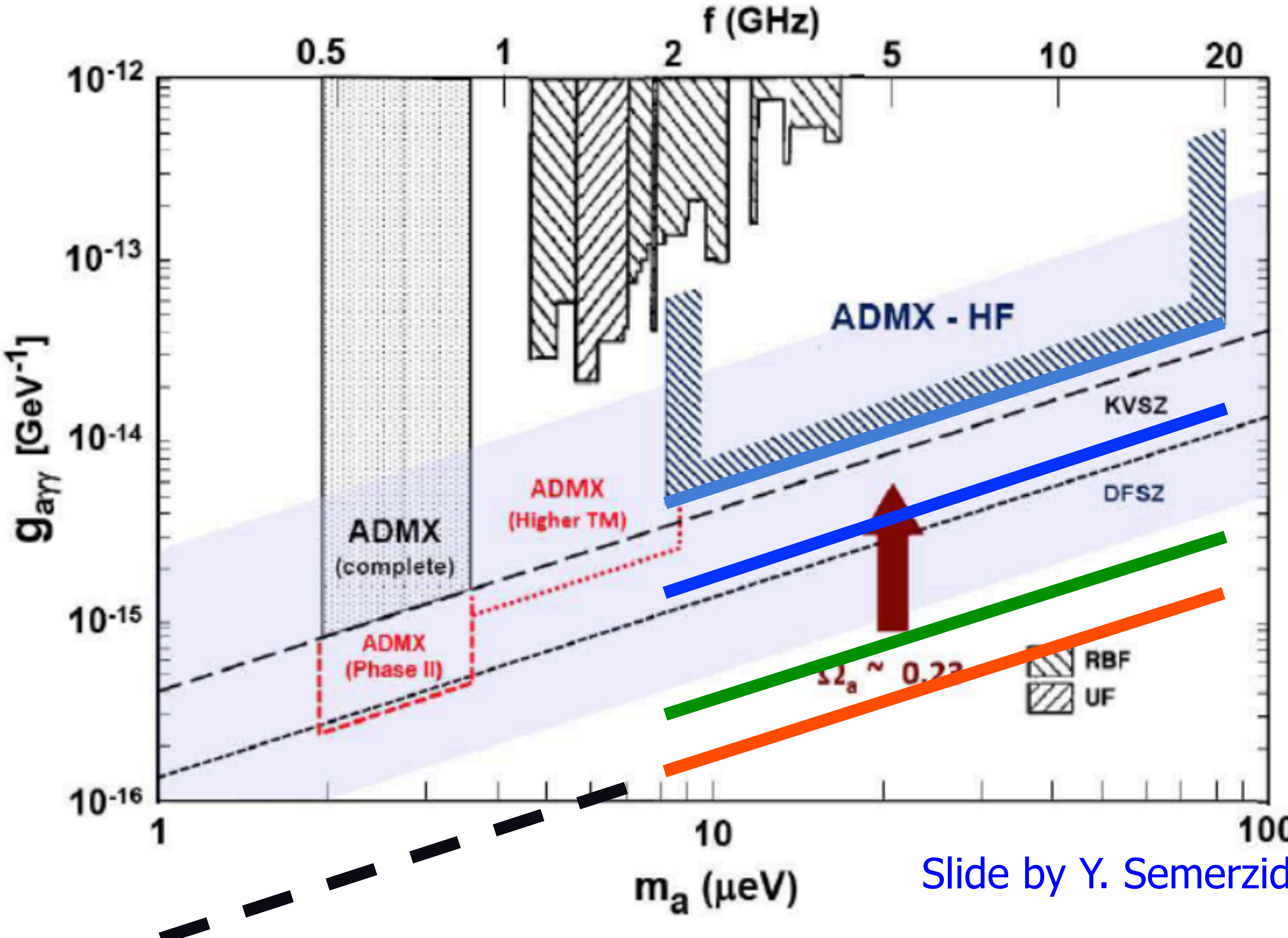


Current plan, low T

B-field

High-Q V

B-field

Slide by Y. Semerzidis

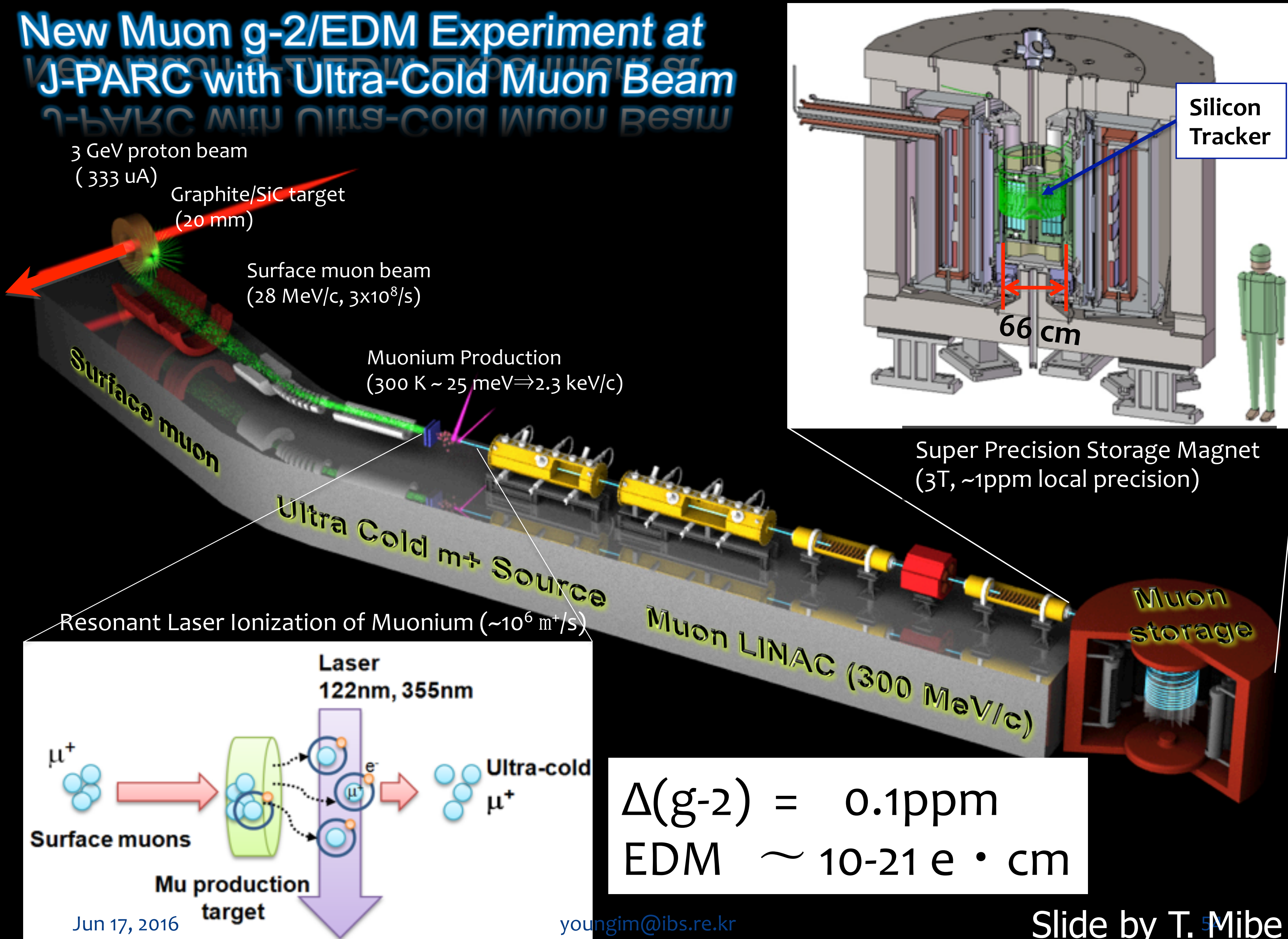
J-PARC

- TDR completed and submitted!
  - 400 pages
  - 136 members
  - 49 institutes
  - 8 countries
- 0.37 ppm in the beginning, aiming for 0.1 ppm as a ultimate goal

Technical Design Report
for
the Measurement of the Muon Anomalous Magnetic Moment $g-2$ and Electric Dipole Moment at J-PARC

Revised in January 12, 2016
Originally released in May 15, 2015

New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam



$\Delta(g\text{-}2) = 0.1\text{ppm}$

EDM $\sim$ 10-21 e・cm

Slide by T. Mibe

Comparison

	BNL-E821	FNAL-E989	J-PARC
Muon momentum	3.09 GeV/c		0.3 GeV/c
γ	29.3		3
Polarisation	100%		> 90%
Storage field	B = 1.45 T		B = 3.0 T
Focusing field	Electric Quad		Very-week magnetic
Cyclotron period	149 ns		7.4 ns
Anomalous spin precession period	4.37 µs		2.11 µs
# of detected e^+	5.0×10^9	1.8×10^{11}	1.5×10^{12}
# of detected e^-	3.6×10^9	-	-
Statistical precision	0.46 ppm	0.1 ppm	0.1 ppm

J-PARC : 0.37 parts per million (ppm) in the beginning, aiming for 0.1 ppm as a ultimate goal

Physics strength comparison (Marciano)

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System	Current limit [e cm]	Future goal	Neutron equivalent
Neutron	$<1.6\times10^{-26}$	$\sim10^{-28}$	10^{-28}
^{199}Hg atom	$<10^{-29}$		10^{-25}-10^{-26}
^{129}Xe atom	$<6\times10^{-27}$	$\sim10^{-30}$-10^{-33}	10^{-26}-10^{-29}
Deuteron nucleus		$\sim10^{-29}$	3×10^{-29}-5×10^{-31}
Proton nucleus	$<7\times10^{-25}$	$\sim10^{-29}$-10^{-30}	10^{-29}-10^{-30}