muon g-2/EDM experiment at J-PARC

Y. Sato
KEK IPNS
On behalf of the E34 collaboration
5th Jan. 2017
Muon g-2 Anomaly

- >3σ deviation between muon g-2 measurement by BNL E821 and SM prediction for over 10 years.
- Theoretical prediction is being improved by continuous efforts.
- Need more precise/independent measurement.
- Muon EDM is also important
  - Upper limit: \( d < 1.8 \times 10^{-19} e \cdot cm \) (95% C.L.) by BNL E821
1. Inject **polarized muons** to the storage ring.
   - \( \pi^+ \rightarrow \mu^+ \nu_\mu \) decay

2. **Muon spin precession relative to momentum in cyclotron** is proportional to g-2 under “special” condition.
   \[
   \vec{\omega} = \vec{\omega}_{\text{spin}} - \vec{\omega}_{\text{cyclotron}} = \left( \frac{g-2}{2} \right) \frac{eB}{m_\mu c} = a_\mu \frac{eB}{m_\mu c}
   \]

3. **Detect high energy** \( e^+ \) from \( \mu^+ \) decay

   - \( e^+ \) direction is correlated to muon spin direction.

   - Precise measurement of \( g - 2 \) needs **precise determinations of \( \omega \) and \( B \).**
     - Muon-to-proton magnetic moment ratio is also used instead of \( e/m_\mu \).
Principle of muon EDM Measurement

- Non-zero EDM contributes to spin precession.
  \[ \vec{\omega}_{\text{EDM}} = -\frac{e}{m_\mu} \left[ \frac{n}{2} (\vec{\beta} \times \vec{B}) \right] \]

- EDM can be measured from up-down asymmetry.
  \[ \mathcal{A}_{UD} = \frac{N_{\text{up}} - N_{\text{down}}}{N_{\text{up}} + N_{\text{down}}} \]
Experimental Approaches for $g$-2 and EDM

1. Magic momentum
   $\gamma = 29.3$ ($P = 3.09 \text{ GeV/c}$)

BNL E821 (current best meas.)
& FNAL E989 (upgrade)

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

- FNAL E989 will start from 2017.

2. Zero $E$-field
   $E = 0$ at any $\gamma$

J-PARC E34 (new methods)

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

- Completely different techniques
  - Different systematic uncertainty.
- More simplified equation ($\vec{\omega}_{g-2} \perp \vec{\omega}_{\text{EDM}}$)
  - Clear separation of $\vec{\omega}_{g-2}$ and $\vec{\omega}_{\text{EDM}}$. 
Low Emittance Beam

Methods to storage muon beam

- BNL & FNAL (magic momentum approach)
  - Electric quadrupole field focusing

  Electric focusing

- J-PARC (zero E-field approach)
  - Low-emittance “cold” muon beam.

  \[ \frac{\sigma(p_T)}{p_T} < 10^{-5} \rightarrow 10 \text{ cm spread over } 10 \text{ km travel.} \]

  \[ \frac{\sigma(p_T)}{p_T} < 10^{-5} \rightarrow 10 \text{ cm spread over } 10 \text{ km travel.} \]

  - Low emittance beam can avoid major syst. error at BNL.

<table>
<thead>
<tr>
<th>Sources</th>
<th>ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain changes</td>
<td>0.12</td>
</tr>
<tr>
<td>Pile up</td>
<td>0.08</td>
</tr>
<tr>
<td>Lost muons</td>
<td>0.09</td>
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<tr>
<td>CBO</td>
<td>0.07</td>
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<tr>
<td>E and pitch</td>
<td>0.05</td>
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<tr>
<td>Total for (\omega)</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Off-magic momentum

- Off magic momentum at **300 MeV/c**
  - Compact storage ring provides **precise control of B-field**.
    - 3 T, ~1 ppm local precision.
  - **Spin manipulation of μ beam** cancel various systematics.

### Sources (ppm)

<table>
<thead>
<tr>
<th></th>
<th>Syst. Err. @BNL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sources</td>
</tr>
<tr>
<td>Total for $\omega$</td>
<td>0.18</td>
</tr>
<tr>
<td>Total for $B$</td>
<td>0.17</td>
</tr>
</tbody>
</table>

**BNL & FNAL (P = 3 GeV/c, 1.45T)**

**J-PARC (P = 300 MeV/c, 3T)**
• New muon g-2/EDM experiment at J-PARC MLF with a newly developed method, off-magic momentum with **ultra-cold muon beam**.

<table>
<thead>
<tr>
<th>BNL</th>
<th>Our goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>g-2 : 0.54 ppm</td>
<td>→ 0.1 ppm</td>
</tr>
<tr>
<td>EDM : $1.8 \times 10^{-19} e \cdot cm$</td>
<td>$\rightarrow 10^{-21} e \cdot cm$</td>
</tr>
</tbody>
</table>

- **Low emittance beam**
- **Spin reversal**

- **Advanced injection & storage methods**
- **Good uniformity of B field by compact storage ring**
- **Large acceptance by tracker**

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**J-PARC E34 Experiment**

- **J-PARC proton beam (3 GeV)**
- **Surface μ beam**
- **Ultra-cold μ source**
  - Mu production
  - Laser ionization

**Acceleration**

**Injection & storage & detection**

66 cm diameter
J-PARC Facility (KEK/JAEA)

Neutrino Beam to Kamioka

Main Ring (30 GeV)

Material and Life Science Facility

Linac

3 GeV Synchrotron

Hadron Hall

Bird’s eye photo in January of 2008
New Muon Beam Line ~H-Line~

MLF building
proton beam
(3 GeV)

H-Line
Annex, to be constructed

Muon production target
Transportation line

Three muon experiments
• g-2/EDM
• MuSEUM (Mu-HFS)
• DeeMe (muon cLFV)
Low emittance muon beam is necessary to store muon without E-focusing.

1. Muonium ($\mu^+ e^-$ atom) production by Laser ablated Silica Aerogel

2. Laser ionization

Surface muons from $\pi^+ \rightarrow \mu^+ \nu_\mu$

Low emittance muon beam with $\Delta p_t/p \sim 3\text{keV}/300\text{MeV} \sim 10^{-5}$
Mu prod. target: **Laser ablated Silica Aerogel**

- Succeeded to enhance the Mu production rate.
- The width, pitch, and depth of the holes can be controlled.

Beam test for Mu production is planned in this month at J-PARC.
• Ultra-cold muon beam is transported to **linac (linear accelerator)** with initial acceleration and must be **reaccelerated to 300 MeV/c** by linac
  – in a sufficiently short period to avoid decay loss
  – without substantial emittance growth.
• Different design to realize fast re-acceleration through wide $\beta$ region.

<table>
<thead>
<tr>
<th>Initial</th>
<th>5.6 keV</th>
<th>0.3 MeV</th>
<th>4.5 MeV</th>
<th>40 MeV</th>
<th>212 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acc.</td>
<td>$\beta = 0.01$</td>
<td>$\beta = 0.08$</td>
<td>$\beta = 0.3$</td>
<td>$\beta = 0.7$</td>
<td>$\beta = 0.9$</td>
</tr>
</tbody>
</table>

$\mu \rightarrow$ RFQ $\rightarrow$ IH-DTL $\rightarrow$ DAW $\rightarrow$ Disk-loaded

- Basic reference design for linac has been completed.
  - Recently IH-DTL paper has been published **@M. Otani et al., PRAB19, 040101, 2016.**
Demonstration of Deceleration and Initial Acc.

@ J-PARC MLF test muon beamline
(Feb. 2016)

- Succeed to deceleration & initial acceleration.
  - Next step is muon acceleration with RFQ
Super Precision Storage Magnet
- 3T with local uniformity of 1 ppm by iron shimming.
B-field shimming test with the MuSEUM magnet (1.7 T) at J-PARC

• ppm level uniformity is achieved.
  ➢ Shimming method is established.
• Injection method used at BNL (Horizontal injection + kicker) can not be applied to our experiment due to compact storage ring and strong B field.

• **3D-spiral injection scheme** has been designed.  
  – Smooth connection btw injection and storage regions w/o any sources of error field.
  – Vertical motion is controlled by radial field (Br).

  • **Pulsed magnetic kicker** to guide muon beam into stable orbit.
  • **Weak-focusing magnetic field** to hold muon beam in stable orbit.

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**3D spiral injection + kicker**

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**Higher injection efficiency : ~80%  ⇔ 3-5% @BNL E821 [PRD73 072003 (2006)]**
Demonstration of Spiral Injection

- Demonstration of spiral injection is ongoing.

- Succeeded in observation of first spiral track.

First observation of spiral track (nominal B-field)

Slide by H. Iinuma

Electron gun (112 keV/c)
Positron Tracking Detector

- Compact storage ring gives good uniformity of B-field, but lead to dense muon decay.

Silicon strip tracking detector (not calorimeter)
- High position resolution and tracking efficiency
- High hit rate capability and early-to-late stability
  - 40k muons/spill with 25 Hz @final goal
  - Rate changes by a factor of ~1/150 during 5 times dilated lifetime.
- No contamination of electromagnetic field in the muon storage region.
  - $\Delta B/B < 1$ ppm and E-field $\ll 10$ mV/cm

- Detector construction fund is partially covered by Kiban-S.

Move to detector construction phase.
Full-size sensor production
- Basic properties of sensors have been confirmed.
- Mass production will start in this JFY.

Front-end ASIC “SliT128A” (3rd prototype)
- Confirmed to satisfy almost all requirements for ASIC.
- Final version of ASIC will be fabricated in next JFY.

Full-size sensor & 3rd prototype ASIC
- Signal from radiation source is observed as expected.
- Application for muonimun HFS experiment “MuSEUM”
Status of J-PARC E34 Collaboration

- 144 members from 9 countries, 49 institutions (Still evolving).
- Submitted technical design report (TDR).
  - Aim 0.4 ppm as stage 1.
- Approved as one of priority projects in the future by KEK.
- Focused review to move construction stage was held (Nov.15-16, 2016)

<table>
<thead>
<tr>
<th></th>
<th>BNL E821</th>
<th>J-PARC E34</th>
</tr>
</thead>
<tbody>
<tr>
<td>g-2</td>
<td>0.46 ppm</td>
<td>0.37 ppm (→ 0.1 ppm)</td>
</tr>
<tr>
<td>EDM</td>
<td>0.9×10^{-19} e · cm</td>
<td>1.3×10^{-21} e · cm</td>
</tr>
</tbody>
</table>

- Review of the g-2 experiment (E34)
  November 15-16, 2016
  Steve Kettell, Chairperson

- Muon beam and source
  * Klaus Jungmann, KVI
  Hiroaki Miyatake, KEK
  Makoto Fujiwara, TRIUMF
  Thomas Browder, Hawaii
  Steve Kettell, BNL

- Storage and detector
  * David Hertzog, University of Washington
  Gerco Onderwater, Groningen
  Ivan Logashenko, Novosibirsk
  Akira Yamamoto, KEK
  Ryuichiro Kitano, KEK
  Kazunori Hanagaki, KEK/Osaka

- Laboratory Management
  Takashi Kobayashi, KEK
  Takeshi Komatsubara, KEK
  Katsuo Tokushuku, KEK

- LEGEND
  * Writing lead
Summary

- J-PARC E34 experiment measures muon g-2 and EDM by completely different approach: “off-magic momentum with ultra-cold muon beam”.

- A lot of interesting techniques are being developed.
  - No focusing E-field to storage muon beam
    - Low emittance muon beam
      - Efficient muonium production and laser ionization & muon re-acceleration
  - 3D-spiral injection scheme
  - Compact storage ring
    - Good uniformity of B-field & large acceptance by tracking detector.

- TDR was submitted.
  - $g-2: 0.37$ ppm (final goal is $0.1$ ppm)
  - EDM: $1.3 \times 10^{-21}$ e$ \cdot$ cm
  - Statistical precision exceeds BNL E821.

- Moving to construction phase.
  - Partial construction fund (detector) is approved.

- Job opening for the H-Line construction @ hecforum:06663
Backup
**Dipole Moments**

- Electromagnetic interaction Hamiltonian with magnetic and electric fields
  \[ \mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E} \]
  \( (\mu_0 = q/2m) \)

**Magnetic dipole moment (MDM)**
- \( \vec{\mu} = g\mu_0 \hat{s} = 2(a + 1)\mu_0 \hat{s} \)
- Anomalous magnetic moment
  - \( a = (g - 2)/2 \)
- Induced by any interaction.

**Electric dipole moment (EDM)**
- \( \vec{d} = \eta\mu_0 \hat{s} \)
- Induced by T&P-violating interaction.
  - Highly suppressed in the SM
    - \( d^{\text{SM}} \sim 10^{-38} \, e \cdot \text{cm} \)
    - Out of experimental reach.
  - Non-zero EDM is evidence for NP

- Precise test of the SM
Ultra-cold Muon Beam at H-line

- Design of H-line and the muon acceleration test.
RFQ Commissioning

@ J-PARC LINAC facility, Jun. 2015.

- Nominal power (4.6 kW) and duty operation.
- No RF-related background with MCP.

- RFQ is ready.
- Muon acceleration with RFQ is planned.
**Technically driven schedule**

|---------------|--------|--------|--------|--------|--------|--------|--------|--------|

| Month | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 |
|-------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|---...
### Table 14.1: Comparison of experimental techniques between the E821 experiment and this experiment.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>BNL-E821</th>
<th>J-PARC E34</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>muon momentum</td>
<td>3.09 GeV/c</td>
<td>0.3 GeV/c</td>
<td>ultra-cold muons for J-PARC</td>
</tr>
<tr>
<td>storage ring radius</td>
<td>7 m</td>
<td>33 cm</td>
<td>MRI-type magnet for J-PARC</td>
</tr>
<tr>
<td>storage field</td>
<td>1.45 T</td>
<td>3 T</td>
<td></td>
</tr>
<tr>
<td>local field uniformity</td>
<td>50-200 ppm</td>
<td>1 ppm</td>
<td>a factor of 50 better uniformity for J-PARC</td>
</tr>
<tr>
<td>injection scheme</td>
<td>inflector/kick</td>
<td>spiral/kick</td>
<td>clean, non-center for J-PARC</td>
</tr>
<tr>
<td>injection efficiency</td>
<td>3–5%</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>storage focus</td>
<td>E (magic gamma)</td>
<td>very weak B</td>
<td>( n = 1.5 \times 10^{-4} ) for J-PARC</td>
</tr>
<tr>
<td>muon spin reversals</td>
<td>not possible</td>
<td>pulse-to-pulse</td>
<td>&gt; 10⁶ reversals over data collection period for J-PARC</td>
</tr>
<tr>
<td>positron measurement</td>
<td>calorimeters</td>
<td>tracking</td>
<td>at threshold ( E_e/E_{max} = 0.6 )</td>
</tr>
<tr>
<td>positron acceptance</td>
<td>65%</td>
<td>100%</td>
<td>higher P(mu) under study for J-PARC</td>
</tr>
<tr>
<td>muon polarization</td>
<td>100%</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>events to 0.14 ppm</td>
<td>( 2 \times 10^{11} )</td>
<td>( 2 \times 10^{12}(P=1) )</td>
<td>fewer precessions at J-PARC due to lower muon momentum</td>
</tr>
<tr>
<td>events to 0.46 ppm</td>
<td>( 9 \times 10^9 )</td>
<td>( 5 \times 10^{11}(P=0.5) )</td>
<td></td>
</tr>
<tr>
<td>Quantity</td>
<td>Reference</td>
<td>Efficiency</td>
<td>Cumulative</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------</td>
<td>-------------</td>
<td>------------</td>
</tr>
<tr>
<td>Mu emission</td>
<td>[3]</td>
<td>3.82E-03</td>
<td>6.17E-04</td>
</tr>
<tr>
<td>Laser ionization</td>
<td>[4]</td>
<td>7.30E-01</td>
<td>4.50E-04</td>
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<td>Metal mesh</td>
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<td>7.76E-01</td>
<td>3.49E-04</td>
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<tr>
<td>Init.Acc.trans.+decay</td>
<td>[5]</td>
<td>7.18E-01</td>
<td>2.51E-04</td>
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<td>RFQ decay</td>
<td>[6]</td>
<td>8.13E-01</td>
<td>1.93E-04</td>
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<tr>
<td>IH transmission design goal</td>
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<td>1.00E+00</td>
<td>1.93E-04</td>
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<td>IH decay</td>
<td>[7]</td>
<td>9.84E-01</td>
<td>1.90E-04</td>
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<td>DAW transmission</td>
<td>design goal</td>
<td>1.00E+00</td>
<td>1.90E-04</td>
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<td>DAW decay</td>
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<td>9.94E-01</td>
<td>1.88E-04</td>
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<tr>
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<td>9.80E-01</td>
<td>1.85E-04</td>
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<tr>
<td>High beta decay</td>
<td>[9]</td>
<td>9.88E-01</td>
<td>1.83E-04</td>
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<tr>
<td>Injection transmission design goal</td>
<td></td>
<td>1.00E+00</td>
<td>1.83E-04</td>
</tr>
<tr>
<td>Injection decay</td>
<td>[10]</td>
<td>9.90E-01</td>
<td>1.81E-04</td>
</tr>
<tr>
<td>Detector start time</td>
<td>[10]</td>
<td>9.27E-01</td>
<td>1.67E-04</td>
</tr>
<tr>
<td>Muon at storage</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>
Figure 5.8: Evolution of muonium into a laser ionization region following diffusion and emission from a laser-ablated aerogel production target. This is the result of a diffusion simulation with parameters that fit the results of TRIUMF S1249 as shown in Fig. 5.7, after changing the muon stopping distribution to match that produced from the G4beamline J-PARC H-line simulation and G4 beam energy loss simulation in the aerogel target. The double pulse of the beam causes the time structure at the leading edge.
Fake EDM Signal by Misalignment

- EDM is measured from up-down asymmetry “$A_{UD}$”.

Simulation with 1 mrad misalignment and null EDM signal

- The alignment must be controlled with 10 µrad accuracy to measure EDM with $10^{-21} \, e \cdot cm$.

The alignment must be controlled with 10 µrad accuracy to measure EDM with $10^{-21} \, e \cdot cm$. 
Interferometer by optical frequency comb with a ball-lens target

- Absolute length can be measured with μm level up to 10 m.

- Try to measure absolute length by ourselves and apply it in our detector system.
- “Ball-lens” will be located on the detector as a target to measure the position of detector.
  - Incoming beam with any direction will focus at the ball-lens end surface.
  - The reflected beam retraces its incoming path in the opposite direction.
Second challenge – $\omega_a$ systematics

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

- Tackling each of the major systematic errors with knowledge gained from BNL E821 and improved hardware
Third challenge – $\omega_p$ systematics

<table>
<thead>
<tr>
<th>Category</th>
<th>E821 [ppb]</th>
<th>Main E989 Improvement Plans</th>
<th>Goal [ppb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute field calibration</td>
<td>50</td>
<td>Improved $T$ stability and monitoring, precision tests in MRI solenoid with thermal enclosure, new improved calibration probes</td>
<td>35</td>
</tr>
<tr>
<td>Trolley probe calibrations</td>
<td>90</td>
<td>3-axis motion of plunging probe, higher accuracy position determination by physical stops/optical methods, more frequent calibration, smaller field gradients, smaller abs cal probe to calibrate all trolley probes</td>
<td>30</td>
</tr>
<tr>
<td>Trolley measurements of $B_0$</td>
<td>50</td>
<td>Reduced/measured rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients</td>
<td>30</td>
</tr>
<tr>
<td>Fixed probe interpolation</td>
<td>70</td>
<td>Better temp. stability of the magnet, more frequent trolley runs, more fixed probes</td>
<td>30</td>
</tr>
<tr>
<td>Muon distribution</td>
<td>30</td>
<td>Improved field uniformity, improved muon tracking</td>
<td>10</td>
</tr>
<tr>
<td>External fields</td>
<td>–</td>
<td>Measure external fields; active feedback</td>
<td>5</td>
</tr>
<tr>
<td>Others †</td>
<td>100</td>
<td>Improved trolley power supply; calibrate and reduce temperature effects on trolley; measure kicker field transients, measure/reduce $O_2$ and image effects</td>
<td>30</td>
</tr>
<tr>
<td>Total syst. unc. on $\omega_p$</td>
<td>170</td>
<td></td>
<td>70</td>
</tr>
</tbody>
</table>

- Need to know the average field observed by a muon in the storage ring absolutely to better than 70 ppb, many hardware improvements
- Very challenging…first major step is making the field as uniform as possible
  - Has been our main thrust over the last 9 months
Making the Precision Field

- Magnet achieved full power September 21, 2015
- Field started out with a peak variation of 1400 ppm
- June 2016 peak to peak variation was reduced to 200 ppm
- The goal of shimming is 50 ppm with a muon weighted systematic uncertainty of 70 ppb
- BNL achieved 100 ppm with an RMS value about 30 ppm
- They estimated their systematic uncertainty at 140 ppb
## Project Timeline

<table>
<thead>
<tr>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>

**Construction (Project & Muon Campus):**
- MC-1 (GPP)
- g-2 Cryo Plant (AIP)
- Ring Assembly
- Shim Field
- Prep Chambers/Install
- Construct/Install Sub-systems
- Accelerator Modifications

**Operations (Laboratory):**
- Ring Cold
- Detector/DAQ Commission
- Beam Tune-up
- Physics Production Running

**Analysis (Collaboration):**
- Analysis Tools Development
- Mock Data
- 1-2 x BNL statistics
  - 1st Results
  - 2nd Results
  - ~5-10 x BNL
  - 21 x BNL
  - Final Results
Take-home messages

- The Muon g-2 experiment will reduce error by a factor of 4 compared to the previous Muon g-2 (BNL E821)
- The storage ring magnet has been operational for a year and our rough shimming targets have been achieved
- Beamline commissioning begins in April 2017, with real data collection starting Autumn 2017
- We anticipate a result with the same precision as E821 by mid-2018
- We expect to report three results with 100%, 50% and 25% of the E821 uncertainty