KEK_J-PARC-PAC2009-06

Letter of Intent:
New Measurement of Muon Anomalous Magnetic Moment g-2 and Electric Dipole Moment at J-PARC

V. Vrba

Institute of Physics, Academy of Science of the Czech Republic,
Division of Elementary Particle Physics,
Na Slovance 2, CS-18221 Prague 8, Czech Republic

W.M. Morse

Brookhaven National Laboratory, Upton, NY 11973, USA

B. Shwartz

Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia

K. Nagamine*

University of California, Department of Physics
and Astronomy, Riverside, CA 92521-0413, USA

M. Finger, M. Finger Jr.

Charles University, Institute of Particle & Nuclear Physics,
Faculty of Mathematics and Physics,
V Holesovickach 2, CZ-18000 Praque 8, Czech Republic

T. Kamitani, K. Koseki, H. Iinuma, M. Ikegami, H. Kamiya, T. Mibe, S. Mihara, R. Muto, T. Naito, H. Nakayama, M. Naruki, H. Nishiguchi, K. Oide, T. Ogitsu, N. Saito,† N. Terunuma, A. Yamamoto, K. Yokoya, and K. Yoshimura

KEK, High Energy Accelerator Research Organization,
1-1, Oho, Tsukuba, Ibaraki, 305-0801, Japan

D. Kawall

University of Massachusetts, Department of Physics, *1126 Lederle Graduate Research Tower, Amherst, MA 01003-4525, USA*

T.Toshito

National Institute of Radiological Sciences, 4-9-1,

Anagawa,Inage-ku,Chiba, 263-8555, Japan

M. Aoki, Y. Kuno, A. Sato, and M. Yoshida

Graduate School / School of Science, Osaka University,

1-1 Machikaneyama-cho, Toyonaka, Osaka 560-0043, Japan

P. Bakule

STFC, Rutherford Appleton Laboratory,

ISIS Muon group & RIKEN-RAL Muon Facility, Building R3,

UG16, Chilton, OX11 0QX, Oxfordshire, United Kingdom

K. Ishida, M. Iwasaki, O. Luchev, T. Ogawa, K. Ohishi, N.H. Saito, D. Tomono, S. Wada

RIKEN, Institute of Physical and Chemical Research,

Hirosawa, Wako, Saitama, 351-0198, Japan

A. Deshpande

State University of New York, Department of Physics and Astronomy,

Stony Brook, NY 11794-3800, USA

Y. Sakemi

Cyclotron and Radioisotope Center,

Tohoku University, Sendai, Miyagi 980-8578, Japan

S. Hirota[‡] and S. Komamiya

Physics Department, University of Tokyo,

7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan

Y. Matsuda

Institute of Physics, University of Tokyo,

3-8-1 Komaba, Meguro-ku, Tokyo 153-8902, Japan

(Dated: June 26, 2009)

Abstract

We propose to measure the anomalous magnetic moment of the positive muon a_μ down to the level of 0.1 ppm with a novel technique utilizing *ultra-cold muon beam* and precision magnetic field without focusing field. Such a beam will be also useful in measuring the electric dipole moment beyond current precision.

The proposed measurement will provide a rigorous test of the Standard Model of particle physics as demonstrated by previous experiments. Our measurement will be complimentary to the previous measurement but with completely different systematics.

[*]Also at RIKEN, Institute of Physical and Chemical Research, Hirosawa, Wako, Saitama, 351-0198, Japan

[†]Also at Physics Department, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan

Contactperson: Naohito Saito (naohito.saito@kek.jp)

[‡]Also at KEK, High Energy Accelerator Research Organization, 1-1, Oho, Tsukuba, Ibaraki, 305-0801, Japan

I. INTRODUCTION

The anomalous magnetic moment of the muon, a_μ has been measured for more than a half-century and served as a solid test ground for the Standard Model of the particle physics. The a_μ is defined from the magnetic moment $\vec{\mu_\mu}$ as

$$a_\mu = \frac{g-2}{2}, \qquad \text{where} \qquad \vec{\mu_\mu} = g\frac{e\hbar}{2m_\mu}\vec{s}. \tag{1}$$

It is parallel to the spin, $\vec{s}$, since spin is the only directionality that an elementary particle can have. Similarly the electric dipole moment of muon, d_μ has been searched for long years. In this case, non-zero value immediately means CP violation in the lepton sector. It is defined as

$$d_\mu = \eta\frac{e\hbar}{2m_\mu}\vec{s}. \tag{2}$$

In the presence of the static field $\vec{B}$ and $\vec{E}$, the Hamiltonian of the system can be written as

$$\mathcal{H} = -\vec{\mu_\mu}\cdot\vec{B} - \vec{d_\mu}\cdot\vec{E}. \tag{3}$$

The second term, $-\vec{d_\mu}\cdot\vec{E}$ is odd under P and T transformations. Therefore nonzero value of the d_μ would violate CP, if CPT theorem holds.

Differently from the electron magnetic moment, which is measured down to 0.28 ppt(parts-per-trillion) and is used for the most precise determination of the fine structure constant, α, the muon magnetic moment could have larger contribution from a possible new physics thanks to its larger mass by a factor of ~200. In the case of tau lepton, a possible new physics contribution can be even larger, however, it is difficult to store in a ring to measure its magnet moment due to its short life of $\sim 3\times10^{-13}$ sec. Therefore, muon has a unique position to probe possible new physics contribution through precision measurements.

The most recent measurement of a_μ and d_μ, E821[1] at Brookhaven National Laboratory (BNL), has measured a_μ down to 0.54 ppm[1], and constrained d_μ down to $\leq 1.9\times10^{-19}$e·cm. The obtained value has been compared to the most updated Standard Model predictions, and a_μ exhibits significant deviation of ~3.5 sigma [2], while the d_μ limit is still required to be improved to be comparable to the limit from the electron with the lepton universality. Obviously further clarification is required to conclude the indication of the new physics for a_μ and further improvement is required for the d_μ.

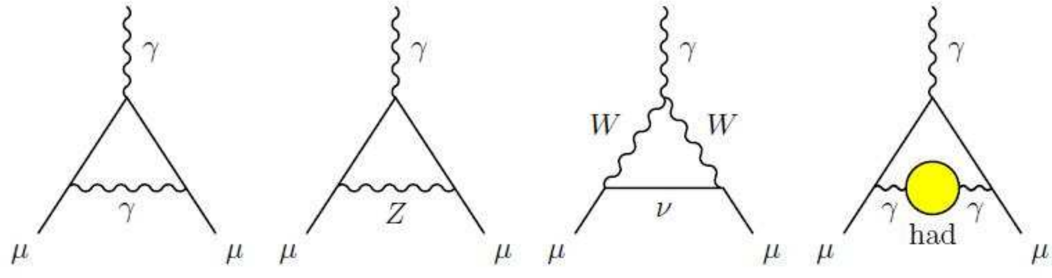

FIG. 1: Representative diagrams contributing to $a_\mu^{\rm SM}$. From the left to right: first order QED (Schwinger term), lowest order weak, lowest order hadronic contributions.

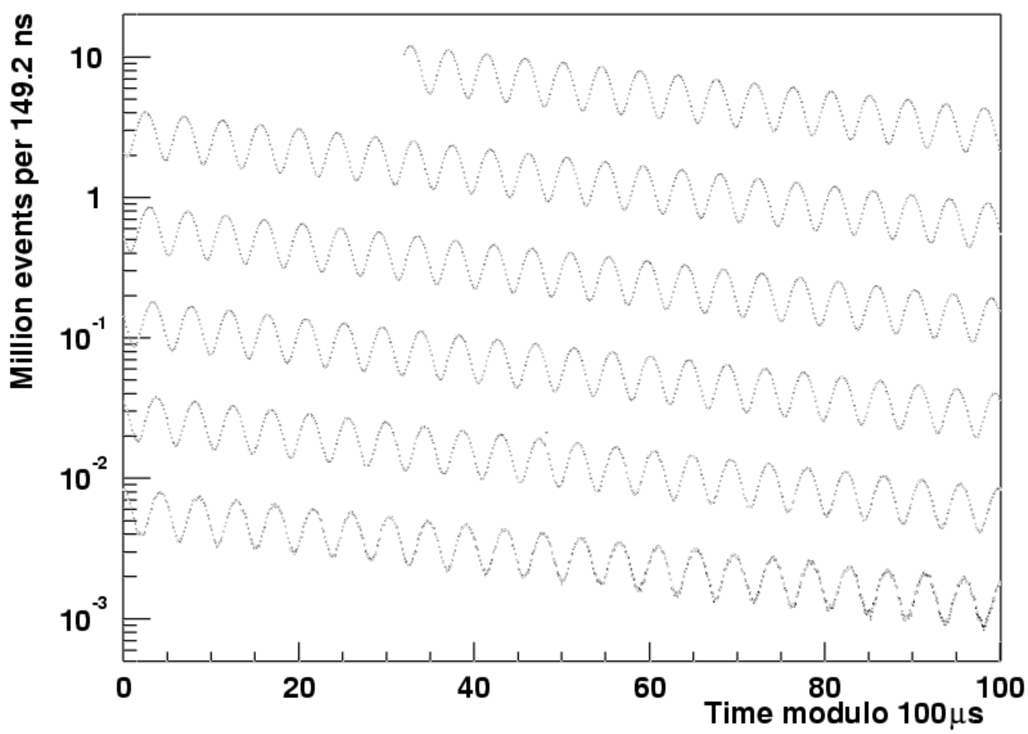

FIG. 2: "*The wiggle plot*" form the previous experiment, E821 at BNL.

After the publication from E821, there are many theoretical activities to investigate the implication of the possible new physics to explain the deviation. For example, a possible effect on charged lepton flavor violation (cLFV) is discussed in Ref.[3]. Furthermore, implications on the electric dipole moment is also discussed in Ref.[4]. These represent that studies of flavor structure in the lepton sector is important, especially in the light of leptogenesis.

The anomalous part a_μ has been determined from the precession frequency $\vec{\omega}_a$ in the ultra-precision magnetic field. The $\vec{\omega}_a$ in the static magnetic field $\vec{B}$ and static electric field

$\vec{E}$ is expressed as

$$\vec{\omega}_a = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right], \tag{4}$$

and in the presence of the electric dipole moment, an additional rotation would be obtained as

$$\vec{\omega}_\eta = \frac{e}{m_\mu}\left[\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]. \tag{5}$$

Here Lorentz factor γ can be chosen to cancel the second term in Eq.(4) to a good precision. Previous precision measurements have been performed based on this concept namely at the magic momentum, p_{magic}.

$$a_\mu - \frac{1}{\gamma^2 - 1} = 0 \qquad \rightarrow \qquad \begin{cases} \gamma_{\mathrm{magic}} = 29.3 \\ p_{\mathrm{magic}} = 3.09\ \mathrm{GeV}/c \end{cases} \tag{6}$$

This choice was unavoidable in the previous measurements for following reasons:

1. muon beam is produced from pion decays in flight and widely spread in the phase space.

2. therefore, focusing field is required to keep reasonable fraction of the beam in the storage ring.

3. the focusing has to be provided electrically. if magnetic, the precession due to a_μ would depend on each muon trajectory.

4. precision control of the electric field in addition to the magnetic field would be challenging. With an approximate cancellation of the electric field by choosing magic γ, the level of required precision would become much more accessible.

This basic concept of the experiment is so beautiful, therefore the experiment is often referred to as a textbook measurement.

The muon beam as a tertiary beam, however, provided some complications in the previous experiment. The muon beam was contaminated by residual pions which damage the early time of the precession measurements in each injection by providing "flash" into the detector system. Since the measurement was based on the calorimetry of decay electrons/positrons, pile-ups of signals originated in "flash" was certainly not welcomed. In addition, muons cannot be fully stored in the ring basically due to its large phase space originated in the decay kinematics and beam line acceptance. The coherent betatron oscillation of the muon beam originated in the focusing field provided additional systematics related to the muon orbits.

The previous measurement E821 has done their very best to reduce these systematic uncertainties. As a result, their measurement was statistically limited. There is an effort to continue this beautiful experiment at Fermilab by moving the existing muon storage ring from BNL. We believe that the proposed Fermilab experiment[5] should run to further improve the precision as a continuation of great efforts made on the experiment. However, we think it is necessary to launch new experiment to measure this fundamental quantity with completely new technique, thus new systematics.

We propose to measure the muon g-2 **without** the focusing field by employing *ultra cold muon beam*, where the transverse momentum dispersion, $\sigma(p_T)$ is significantly smaller than its longitudinal momentum, p_L. It is easy to see that such a beam can circulate in the storage ring without the focusing field for the duration of the measurements. Elimination of the electric field would simplifies the precession frequency as

$$\vec{\omega_a} + \vec{\omega_\eta} = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)\right]. \tag{7}$$

Since the rotation axises due to a_μ and d_μ are orthogonal each other, separation of these signal should be possible. If not, we should rotate muon spin axis from the momentum direction to parallel to the magnetic field. In this way, the precession measurement will become blind to the a_μ.

Differently from the beam storage for collider experiments, where the beam has to circulate for millions of turns, muon precession measurements requires only several thousands of turns because of its short life. For example, we consider the case with

$$\frac{\sigma(p_T)}{p_L} \sim 10^{-5}, \tag{8}$$

with the $B = 3[T]$ and $p = 300$ MeV/c, which corresponds to $r = 33.3$ cm. Five times its dilated lifetime corresponds to about 4,000 turns and 8.3 km. The beam spread due to the transverse momentum dispersion in Eq.(8) is 83 mm after 4,000 turns, which can be easily accommodated in the storage field.

Such a *ultra cold* beam can be produced from ultra-cold muon source, where cold muon is produced from the laser ionization of muonium (Mu). The kinetic energy of the Mu is ∼25 meV (momentum∼ 2.3 keV/c), when produced at room temperature. if we could accelerate them to 300 MeV/c without further increase in the transverse momentum, the condition (8) is satisfied. Since we have no electric field, the $\vec{\beta}\times\vec{E}$ term in Eq. (4) does not exist so that any momentum can be "magic momentum".

While higher momentum is helpful in prolonging the life of muons, lower momentum is beneficial in reducing the size of the experimental apparatus, thus the cost of the experiment. However, the best benefit would emerge from the fact that such a small magnet for muon precession measurement can be made in one piece, therefore it would become easier to control the field precision. Especially thanks to the great advance in the magneto-resonance imaging (MRI) technology, the precision monitoring and control of the magnetic field of ∼1 m diameter has been reaching to 1 ppm precision. This precision can be compared to a local magnetic-field precision of the previous measurement, ∼100 ppm while the field precision integrated over full azimuth was better than 1 ppm[1].

As will be described later, the statistical precision of the measurements would depend on the γ as

$$\frac{\delta\omega}{\omega} \propto \frac{1}{\gamma} \tag{9}$$

The lower value of γ has to be compensated by larger statistical samples, which we expect from the high beam power (∼1 MW) envisioned at J-PARC.

In the end of this section, we briefly mention to the importance of this experiment in the post-LHC era. One could argue that most of the new physics scenario can be studied at LHC. Indeed, most popular interpretation of the deviation from the Standard Model observed by the previous experiment is supersymmetry, and it can be studied very well at LHC, if the energy scale turns out to be appropriate. However, important parameters in the model such as μ and tanβ cannot be determined very well. The muon anomalous magnetic moment a_μ is sensitive to these parameters through following expression;

$$a_\mu(\mathrm{SUSY}) \approx (\mathrm{sgn}\mu)\ 13\times10^{-10}\tan\beta(\frac{100\mathrm{GeV}}{\tilde{\mathrm{m}}})^2. \tag{10}$$

The sensitivity to tanβ is compared to that of LHC experiments in Figure 3.

However, we emphasize that it represents one of the possible importance of this measurement. The precision measurement of the fundamental quantities like magnetic and electric dipole moments of elementary particles has its own value.

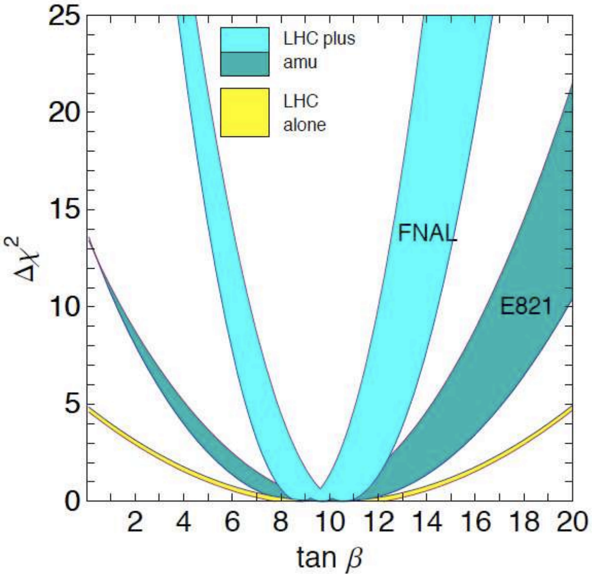

FIG. 3: Possible future tanβ determination from the measurement of a_μ, assuming that the MSSM reference point SPS1a is realized. The yellow band is from LHC alone which gives tan$\beta^{\mathrm{LHC-fit}}$ = 10.0 ± 4.5 [6, 7]. The darker blue band labelled E821 assumes $a_\mu = (295 \pm 81) \times 10^{-11}$, which comes from the present values for a_μ and the Standard-Model contribution, the lighter blue band labelled FNAL corresponds to $a_\mu = 295(34) \times 10^{-11}$, which has similar sensitivity projection to the proposed experiment at J-PARC.

In section II, we describe the overview of the experiment. In section III, statistical precision expected from this measurement is discussed basing the simulations and the knowledge of the previous measurement. Section V describes *ultra cold muon beam* including the source and the linear accelerator, Muon Linac. In section VI, the beam injection into the storage volume is discussed. A concept of the detector system is discussed in section VII. Finally the requirement for the facility is listed in section VIII.

II. OVERVIEW OF EXPERIMENT

We plan to launch this experiment at the Muon Facility in the Material and Life Science Facility (MLF) at J-PARC. The facility receives the 3 GeV proton beam of 333 μA in a form of dual pulses separated by ∼600 ns in 25 Hz.

A graphite target of 6% absorption is located to produce the muons for the Muon Facil-

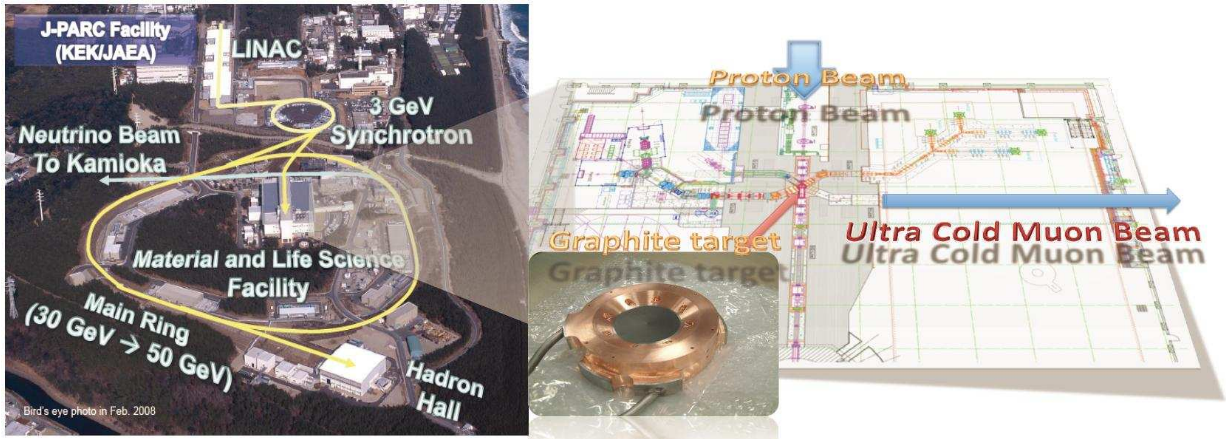

FIG. 4: J-PARC, Japan Proton Accelerator Complex, and schematic view of Material and Life Science Facility (MLF). A possible location of the *Ultra Cold Muon Beam* line is indicated.

ity. The rest of the beam will be delivered to the Mercury target downstream to produce spallation neutron. There are fours ports opened from the graphite target. Current plan for this measurement is to utilize the H-line as displayed in Figure 4. Produced muons are mostly *surface muons*, which is produced from two body decays of pions nearly stopped at the surface of the target material through parity-violating weak interaction. Therefore, it is monochromatic with a kinetic energy of 4.1 MeV and 100% polarized. They are captured by the capture solenoid and transported to the experimental area guided by the super-conducting curved solenoid.

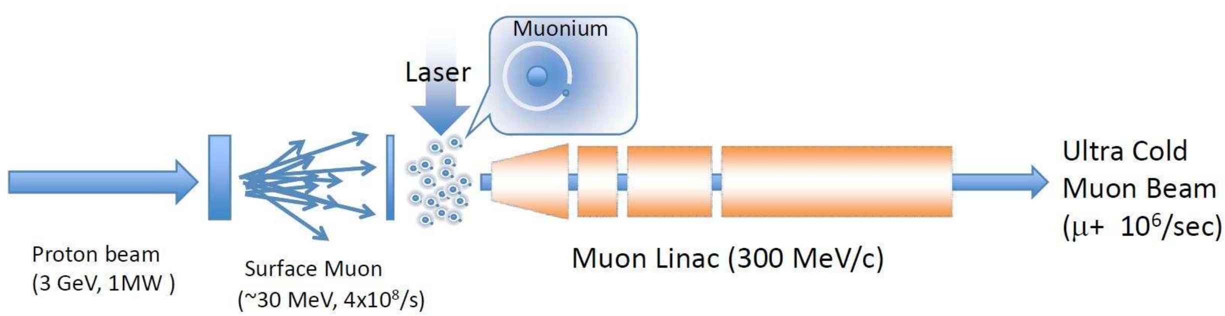

FIG. 5: Overview of *ultra cold muon beam*.

Those muons are further absorbed in the target in the muonium production chamber to produce Mu atoms. They are evaporated from the target at the room temperature, which corresponds to 25 meV of kinetic energy *i.e.* 2.3 keV/c in momentum with spin polarization in the direction of surface muon momentum. Since Mu atoms are thermalized at the room temperature, they are moving in any directions with this typical momentum. Mu states can be ionized by laser to produce positive muons at the similar temperature to that of Mu atoms themselves. Previous experiment at RIKEN-RAL beam line has chosen two step ionization process, 1S→2P→unbound. Figure 6 shows the time-of-flight spectrum of the produced muons after being accelerated to 9 kV. The peak shows a Gaussian shape with FWHM of about 7 nsec, which is slightly wider than the pulse width of ionizing lasers. This is considered to be originated from the finite volume of ionization region where electric field was applied for initial acceleration of muons, while further experimental clarification is necessary [11].

The produced muons can be further accelerated by LINAC. We have produced conceptual design of the linac system, which composed of low-beta linac (LBL) and high-beta linac. The are connected at $\beta = 0.7$, which is 200 MeV/c in momentum. The system is designed to minimize the transverse momentum spread through the acceleration process, especially to keep the condition of ultra-cold muon beam, $\sigma(p_T)/p_L \leq 1 \times 10^{-5}$. We estimate that such acceleration can be done within 0.3 μsec, which is significantly shorter than the muon lifetime.

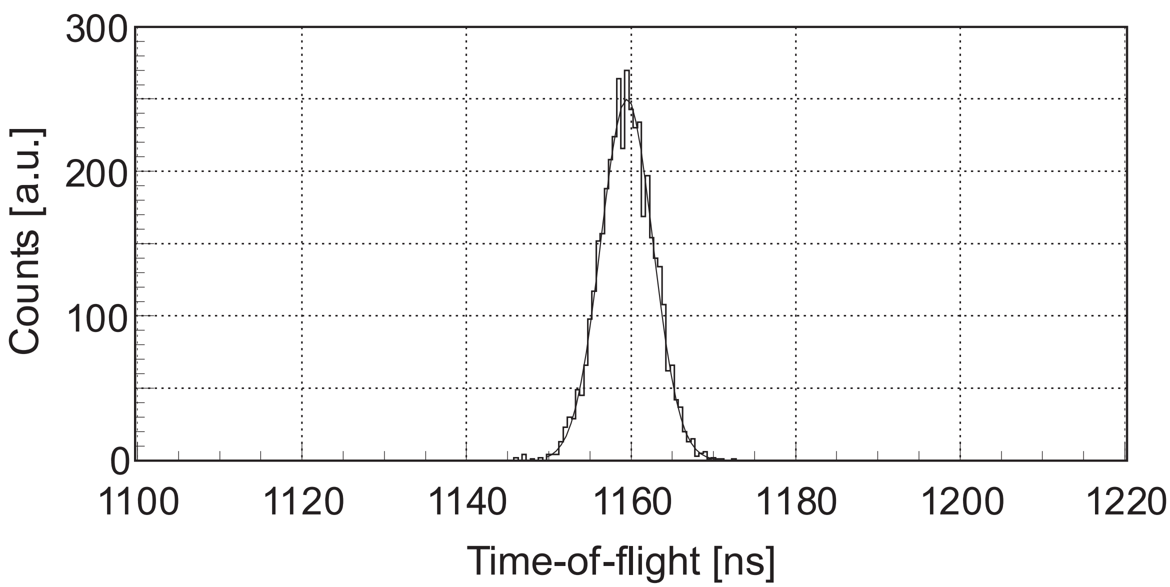

FIG. 6: Time-of-flight spectrum of muons produced at RIKEN-RAL beam line at Rutherford Appleton Laboratory.

The ultra-cold muon beam will be injected to the solenoidal field through a flux exclusion tube with an injection angle of ~55° downwards[2]. The solenoidal field is designed with adequate radial field around the injection area to deflect the vertical component of the muon momentum so that muon beam would circulate horizontally. We expect that we can control the level of residual vertical component of muon momentum to be 10^{-3} after ~20 turns. The muon beam can be further kicked by the strip-line kicker to be moved to a *"good field region"*, where the magnetic field is shimmed down to the level of 1 ppm locally.

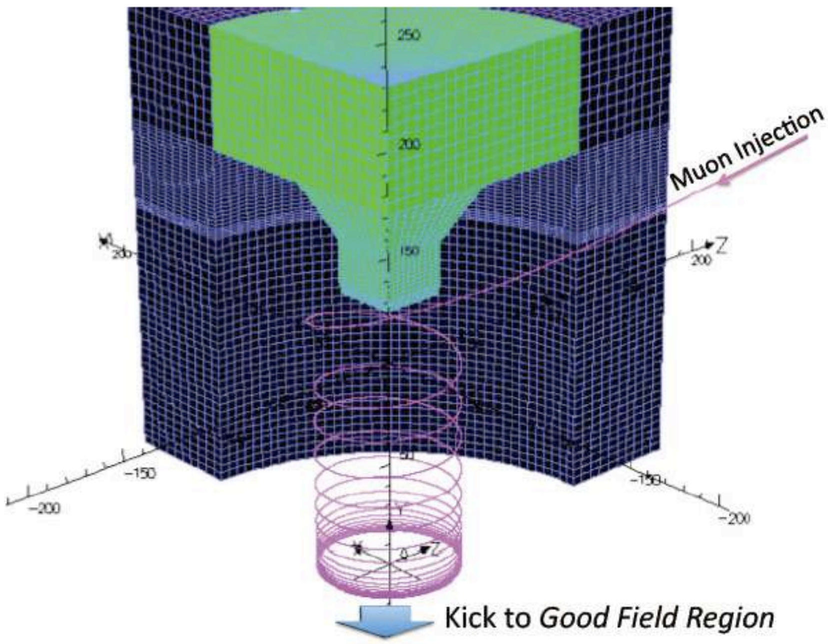

FIG. 7: Preliminary design of the injection part solenoid. Only one eighth of the iron yoke (black and green) is displayed without coils. Injected muon trajectory is also shown. Below the displayed part, *good field region* of ±20 cm follows.

As for the shimming process, we would be benefited from the smallness of the magnet. So far only conceptual design has been done for the solenoidal field based on OPERA and ANSYS. Inclusion of the kicker, filed monitor, and detectors would deform the field. Therefore, shimming process would be irreducibly important in this experiment. Such process has been developed for Magneto-Resonance Imaging technology for years. We are discussing with Hitachi Ltd. in this regard.

After the beam was moved to the good field region, we start the the measurement of the precession frequency. The measurement will continue for five times life time, i.e. 33 μsec, which corresponds to 4,000 turns ≈ 8.3 km. Thanks to the ultra-cold muon beam, the beam of remaining muons would spread to only ±83 mm, which can be easily accommodated in the storage ring.

TABLE I: Storage ring parameters.

muon momentum	300 MeV/c
storage field	solenoidal field of 3 T
muon orbit radius	33.3 cm
good field region	$r \leq 35$ cm and $\lvert z \rvert \leq 20$ cm
cyclotron period	7.5 nsec

Within the circulation period, we will see most of the muon decays. The decay positrons will be detected by the detector system. Current design of the detector system comprises time-projection-chamber utilizing the μ-PIC technology (μ-TPC) and Si-W based sampling electro-magnetic calorimeter (SiWCal) as displayed in Figure 8. The μ-TPC has high rate capability as high as 10^7/mm^2/sec [8] and will be useful for full-track reconstruction. The calorimeter will provide positron identification through $E - p$ matching. The calorimeter also works as absorber of the positrons. Otherwise the same positron would leave many turns of spiral trajectory in the detector, which is not useful for kinematic reconstruction.

After 33 μsec, we will turn on the kicker again to remove the remaining muons as well as decay positrons.

As mentioned in the previous section, the EDM measurement can be performed with rotate spin direction from normal to parallel to the magnetic field. In this way, the precession measurement will become blind to a_μ. A possible EDM signal will be observed as gradual oscillation of the spectrum due to a_μ. Once the signal is found, we should consider to apply electric field in a radial direction so that the signal can be enhanced. Sensitivity studies are ongoing.

III. STATISTICAL PRECISION

While the systematics is the most important issue for this type of the precision experiments, large enough statistics is still the necessary condition for the successful measurement. We estimate the number of μ^+s based on the measured value at RAL-RIKEN beam line.

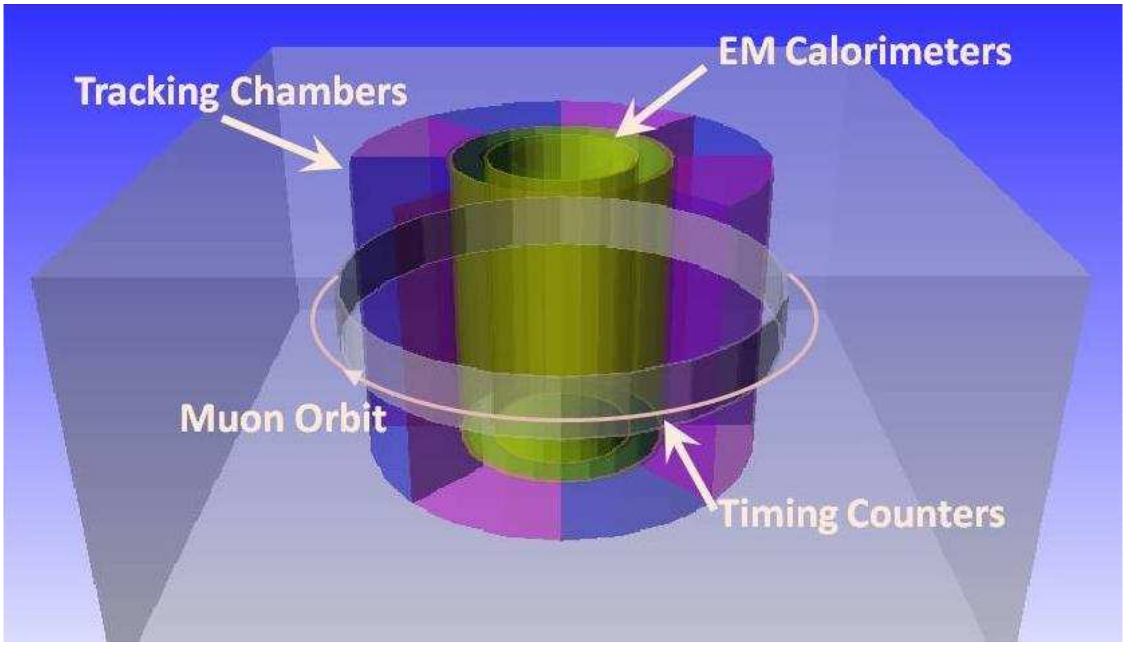

FIG. 8: Conceptual schematics of the detector system comprising tracking chambers, EM calorimeters, and timing counters. Muon orbit is also displayed.

They have established the rate of ultra-slow muon to be $\sim 20\mu^+$s/sec. This number is achieved with the surface muon flux of $1.2 \times 10^6\mu^+$s/sec.

On the other hand, the expected number of surface muon is $4\times10^8\mu^+$s/sec[9] at J-PARC, when it is operated at a beam power of 1 MW. Therefore, we can expect the number of ultra-cold muon at J-PARC to be;

$$20\ \mu^+/\text{sec} \times \frac{50\text{Hz}}{25\text{Hz}} \times \frac{4.0\times10^8/\text{sec}}{1.2\times10^6/\text{sec}} \times 100 = 1.3\times10^6/\text{sec} \tag{11}$$

The last multiplier, a factor of 100 is expected from the higher power laser to be utilized. The linearity of the number of produced muons with respect to the laser power is one of the R & D items for this experiment. Figure 9 displays the laser power dependence of the number of muons. Clearly the study needs to be extended to higher power by a factor of 100, which we are planning at the RAL-RIKEN facility.

Figure 10 displays the projected "wiggle plot" from this experiment. Number of decay positrons detected in the detector system with the momentum cut of ≥ 200 MeV/c is plotted as a function of time. It clearly shows faster decays compared to previous measurements due to the lower storage momentum.

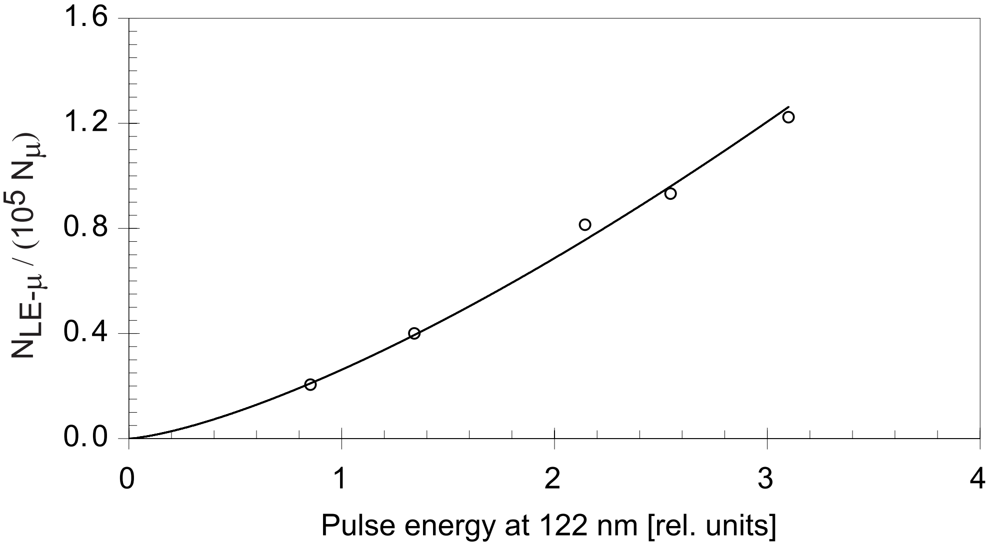

FIG. 9: Linearity of number of muons with respect to the laser power for 122 nm wavelength. The plot obtained at RIKEN-RAL beam line and transcribed from Ref.[11].

The "wiggle plot" is fitted to the function

$$\frac{dN_e(t)}{dt} = N_0 \cdot \exp\left(-\frac{t}{\gamma\tau}\right)[1 - A\cos(\omega_a \cdot t)]\,. \tag{12}$$

The number of decay electrons will be exponentially decreased with the dilated life time of $\gamma\tau$, but oscillates at the frequency of ω_a due to the anomalous magnetic moment a_μ in the static magnetic field B as

$$\omega_a = \frac{q \cdot a_\mu}{m_\mu} B. \tag{13}$$

Actual spin direction of the muon would follow the momentum direction if the anomalous magnetic moment is zero. Since a_μ is non-zero even within the standard model, the frequency ω_a would be observed as a modulation to the cyclotron frequency.

Our goal is to determine the ω_a within statistical error of 0.1 ppm, i.e.

$$\frac{\Delta\omega_a}{\omega_a} \sim 0.1 \text{ ppm} \tag{14}$$

$$\frac{\Delta\omega_a}{\omega_a} \propto \frac{1}{A \cdot \gamma B \cdot \sqrt{N_e^{\text{cut}}}} \tag{15}$$

We summarize parameters of previous and proposed experiments in Table II, which are relevant to the statistical precision. Since we have chosen the γ to me 10 times smaller than the previous experiments, we will loose the sensitivity accordingly. To compensate this

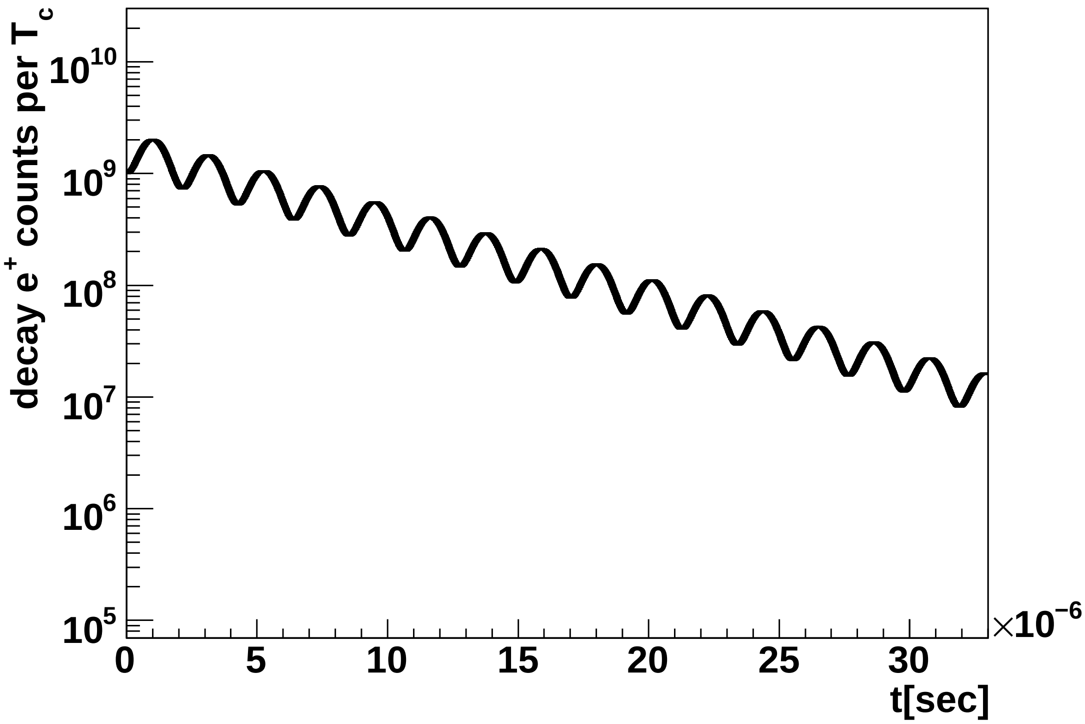

FIG. 10: Statistically projected wiggle plot for the proposed experiment.

deficit, we have chosen to apply higher magnetic field of 3 T, which is higher by factor of 2. Therefore, it would require ∼25 times statistics to achieve the similar precision to that of previous measurement. In fact, it is possible to accumulate three orders of magnitude larger statistics in three years with reasonable acceptance and analysis cut.

IV. SYSTEMATICS

There are several origins of the systematics in this experiment. Since we are going to use pure muon beam there would be no flash at all in the initial stage of the measurement.

According to Eq. (12), systematic uncertainty on a_μ comes from two major parts; the static magnetic field $\vec{B}$ and the precession frequency $\vec{\omega_a}$.

As we discussed in introduction, smaller $\gamma(=3)$ and stronger static magnetic field $|\vec{B}|(=3$ [T]) allow us to design a small, one-piece-type storage ring. Such volume of static magnetic field is expected to be of great advantage to control its uniformity and stability up to sub-ppm level. Therefore, we would discuss systematic uncertainty in ω_a, here. There are several

	BNL-E821	Fermilab	J-PARC
p_μ	3.09 GeV/c		0.3 GeV/c
γ	29.3		3
storage field	$B = 1.45$ T		3 T
focusing field	Electric Quadrupole		None
# of detected μ^+ decays	5.0×10^9	1.8×10^{11}	1.5×10^{12}
# of detected μ^- decays	3.6×10^9	–	–
achieved/expected precision (stat)	0.46 ppm	0.1 ppm	0.11 ppm

TABLE II: Key parameters of the previous and proposed experiments relevant for the statistical precision

factors which distort positron time spectrum (wiggle plot) in Eq. 16, and may be origins of systematic uncertainty.

$$N(t) = N_0 \cdot \exp\left(-\frac{t}{\gamma\tau}\right) \times [1 - A\cos(\omega_a \times t + \delta_0)], \tag{16}$$

possible factors of *wiggle distortion* are listed below:

1. Energy dependent efficiency of positron detection, as well as energy resolution,
2. Time dependent efficiency of positron detection:
   (a) Pileup (especially for just after the muon beam injection),
   (b) Growth of the muon beam size along the $\vec{B}$ direction cased by non-zero transverse muon beam momentum (p_T),
   (c) Transverse motion of the muon beam orbit,
3. Distribution of the muon beam longitudinal momentum ($\Delta\gamma/\gamma = \Delta p_L/p_L$),
4. Depolarized muon beam decreases amplitude A,
5. Smearing effect by limited energy resolution also decreases amplitude A,

6. Commingling of $\sin(\omega_a \times t)$ with $\cos(\omega_a \times t)$ caused by detector acceptance unbalance. This may change amplitude A and initial phase δ_0. But the g-2 frequency, ω_a, does not change.

Note that above items do *not* change the precession frequency ω_a, but change its amplitude A and/or exponential slope. Because we do not need an electric focusing field in the storage ring, there is no need of related correction on ω_a as previous measurement E821 did apply [3]. Good control of residual electric field less than 10 [mV/m] guarantees *non* deviation of ω_a in the level of ppb.

In order to understand the degree of distortion of wiggle plot, we plan to utilize energy sliced wiggle plots. Twelve plots in Figure 11 display time spectra of different energy bins. Amplitude A and initial phase δ_0 change as a function of positron energy. Time spectra of less than 100 MeV (more than 175 MeV) correspond to *backward-decay* (*forward-decay*). Spectra of $100-175$ MeV correspond to *left-* and *right-decays*, which can not be seen wiggles without sorting positrons by decay angle information. In order words, spin effect for both *left-* and *right-decays* are canceled each other out in these spectra.

We plan to design a detector to cover positrons more than 100 MeV in order to obtain such energy-sliced wiggle plots. Especially, by use of spectra of $100 - 175$ MeV, the *flat* exponential slope will be obtained. And we should find if there is artificial components:

- time dependent shift of detection efficiency,
- the muon beam momentum deviation $\Delta\gamma$,
- commingling of $\sin(\omega_a \times t)$ and $\cos(\omega_a \times t)$,
- etc.

Growth of the muon beam size along the $\vec{B}$ direction and transverse motion of the muon beam orbit should be minimized by enough big detector acceptance. While strong advantages of new measurement method, some challenging R&D items, ex. depolarization effect and unknown factors related to the muon beam injection scheme into the storage ring, are there.

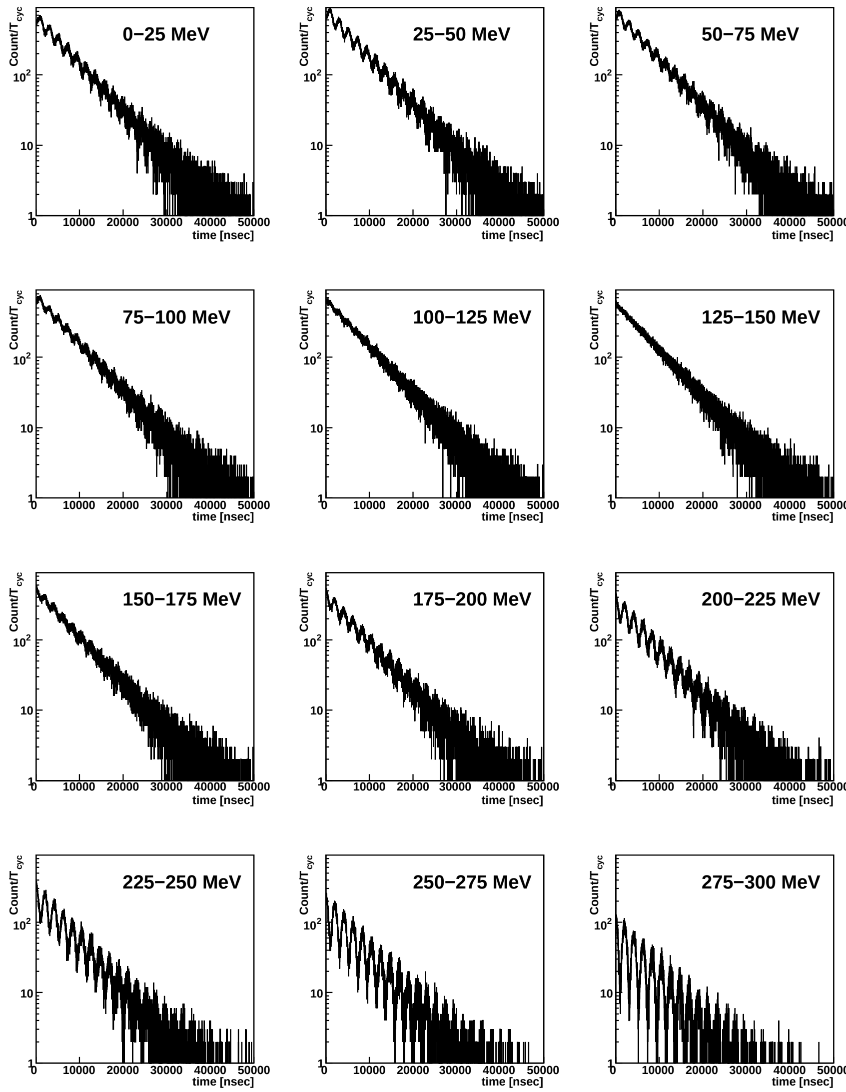

FIG. 11: Energy sliced positron time spectra (wiggle plots) generated by GEANT4 for 65M events only. Amplitude A and initial phase δ_0 change as a function of positron energy, but the precession frequency ω_a do not change.

V. ULTRA-COLD MUON BEAM

A. Ultra-Slow Muon Source

It was demonstrated that the Mu, the bound state of μ^+ and e^- can be produced from a hot and high purity tungsten foil placed at the primary beam of 500 MeV protons [10]. Resonant ionization ($1s \to 2p \to$ unbound) with laser was done to produce ultra-slow muon beam. In this experiment the tungsten target was heated to 2000° to reduce the .... As a result, obtained number of LE-μ^+ and its mean energy is

$$0.2\ \mu^+/\text{sec} \quad @ \quad 160\ \text{meV}$$

This technique is further explored at Rutherford Appleton Laboratory (RAL) at RIKEN beam line (RAL-RIKEN) [11]. They have successfully produced $15\mu^+$/sec at mean kinetic energy of 160 meV. While the low-energy muon source has been developed for more than 10 years especially for muon spin-rotation (μSR) studies, RAL-RIKEN is the only beam line which produces the LE-μ^+ beam with sub-eV level of kinetic energy.

The intensity of Ultra-Slow-μ^+ beam we need for the experiment is $\sim 10^6\mu^+$/sec. According to the design of the Muon Facility at MLF, expected intensity is $1.3 \times 10^6\mu^+$/sec.

B. Muon Linac

The muons form the ultra-muon source will be further accelerated to 300 MeV/c by Muon Linac. The muon linac comprises RFQ in the early stage acceleration, low-beta linac (LBL) , and high-beta linac (HBL). The linac is carefully designed not to increase the transverse momentum dispersion.

1. Low-Beta Linac (LBL)

Since the muon is much heavier than electron, its initial acceleration would be much similar to that of the proton. Therefore, we describe the current design of the LBL basing on our experience on the proton LINAC.

The requirements for LBL would be satisfied with a conventional proton linac structure. To realize the small beam divergence required for this experiment, it is essential to avoid excess emittance growth. In the case of a proton linac, the emittance growth is predominantly caused by the space-charge effects. However the effects can be neglected in the LBL due to the small number of muons ($\leq 10^5\mu^+$s/pulse) assumed in a bunch at the muon source.

Even in the presence of modest space-charge effects in the proton case, typical emittance growth is known to be around or less than 20%. Accordingly, the increase in the beam divergence in the LBL is expected to be around or less than 20% after the beam is manipulated to be parallel and to have the same beam width with that at the injection. Its parallelism is expected to be in the tolerable range considering the small transverse divergence assumed at the muon source.

Although the detailed configuration of LBL is still under optimization, the primary choice would be a conventional configuration consisting of a Drift Tube Linac (DTL) and a Coupled-Cavity Linac (CCL). In this configuration, the muon beam from the RFQ will be accelerated with a DTL up to around β=0.4, and then with a CCL to β=0.7.

Although we have a wide flexibility in choosing the operational frequencies for DTL and CCL, the S-band frequency assumed in HBL should be their multiple. One possible choice of the frequency is to adopt the same frequency with the J-PARC linac, where the frequencies for DTL and CCL are respectively 324 MHz and 972 MHz. This choice would be advantageous in reducing development cost for the RF source and in sharing spare components with J-PARC linac. This choice also allows us to adopt electro-magnetic quadrupole magnets for DTL, with which we have a wider tunability in the transverse beam manipulation. With a modest choice of the accelerating field for DTL and CCL, the total length of LBL would be around 20 m. Consequently the traveling time through LBL is expected to be around 0.2 μsec.

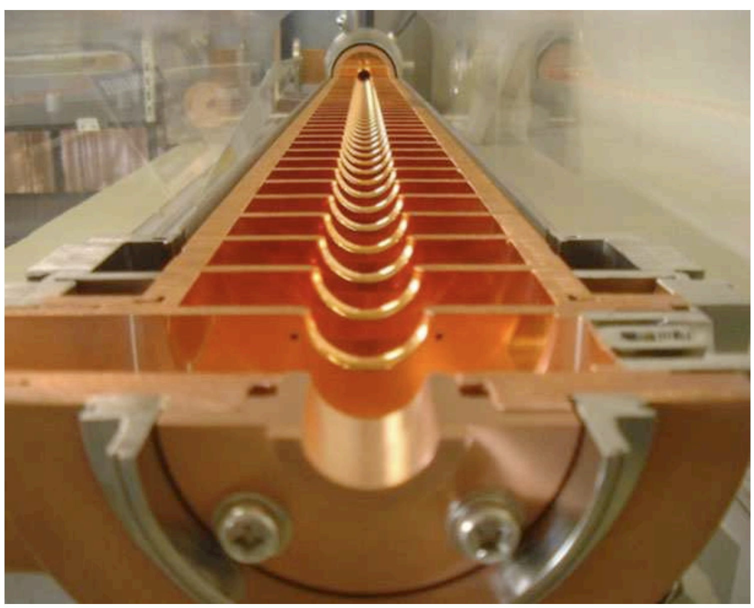

FIG. 12: Traveling-wave type acceleration tube used for the linac at KEKB.

2. High-Beta Linac (HBL)

Once the muon beam is accelerated to a large value of β, say 0.7, then linac acceleration would become much similar to the electron. Here we apply the technology developed for e^+e^- collider like KEKB. One of the candidates to be employed for high beta linac (HBL) is S-band (2856 MHz; 10.5 cm wave length) acceleration tube of traveling wave type. It has a structure of disk-loaded circular wave guide as displayed in Figure 12. The distances between each disk should be adjusted according to the phase velocity of the particles.

Detailed simulation studies are ongoing including the connection with the LBL.

VI. MUON INJECTION AND STORAGE

Injection has been one of the area which requires the creative idea in the past. Since the idea is to store the muon beam for precision measurement of either magnetic moment or electric dipole moment, it requires storage ring especially to accumulate the large enough statistics for the duration of muon life. In general, the higher momentum is preferred for longer life time, thus longer measurements.

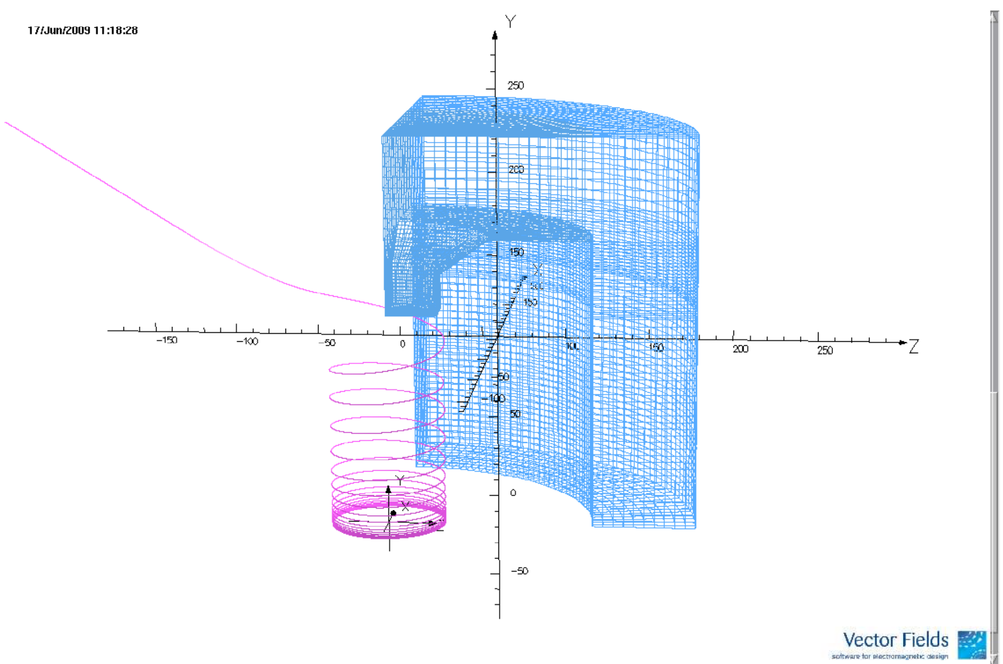

FIG. 13: A trajectory of injected single muon with the one eighth of the solenoid magnet.

In the injection part, muon beam has to be introduced to the storage ring with minimum interference to the storage field. In the previous experiments, the device called inflector has been employed. After introducing the beam into the storage region, the beam would be kicked by the kicker to be moved to the central orbit.

In our experiment, this idea does not work; muon beam has to be kicked by order 30 mrad at the first turn to avoid hitting the inflector itself. The kick angle is order of magnitude larger than the kick with any existing technology.

Therefore, we have decided to employ, **spiral injection scheme** instead. The beam will be injected with a finite angle of $\sim$55 degree. In this way, the beam will be separated from the injecting point by $\sim$10 cm so that there would not be no disturbance for the beam to be circulated.

The vertical component of the beam momentum should be deflected to horizontal component by radial magnetic field. The magnetic field should be carefully shimmed not only for the vertical field for the muon storage but also for the radial field so that there would not be significant remaining vertical momentum.

Once the vertical component becomes 10^{-6} level, and as far as it is stable for the duration of the experiment, deflection by the kicker with achievable voltage and stability would be enough.

VII. DETECTOR SYSTEM

Figure 8 displays the conceptual schematics of the detector system. The system comprises tracking chambers, electromagnetic calorimeters and the timing counters. We intend to reconstruct the positron tracks event-by-event to determine its momentum as well as its energy based on the energy observed in the electromagnetic calorimeter. While we do not expect any backgrounds in this system, reconstruction of both momentum and energy would be useful in identifying the positron. Furthermore the full reconstruction of the kinematics would allow determination of the decay points in the muon orbit so that the we will have a good understanding of the beam dynamics during the measurements.

We are interested in the positrons with momentum more than 175 MeV/c. This momentum threshold is determined to maximize the figure-of-merit, $A^2 \times N$, where A is the asymmetry and N stands for number of detected positrons.

Figure 11 displays the energy spectrum of the decay positrons. In the rest frame of the muon, decay positrons are emitted preferably to the muon spin direction. Therefore, high energy positron in the laboratory frame is more sensitive to the spin direction.

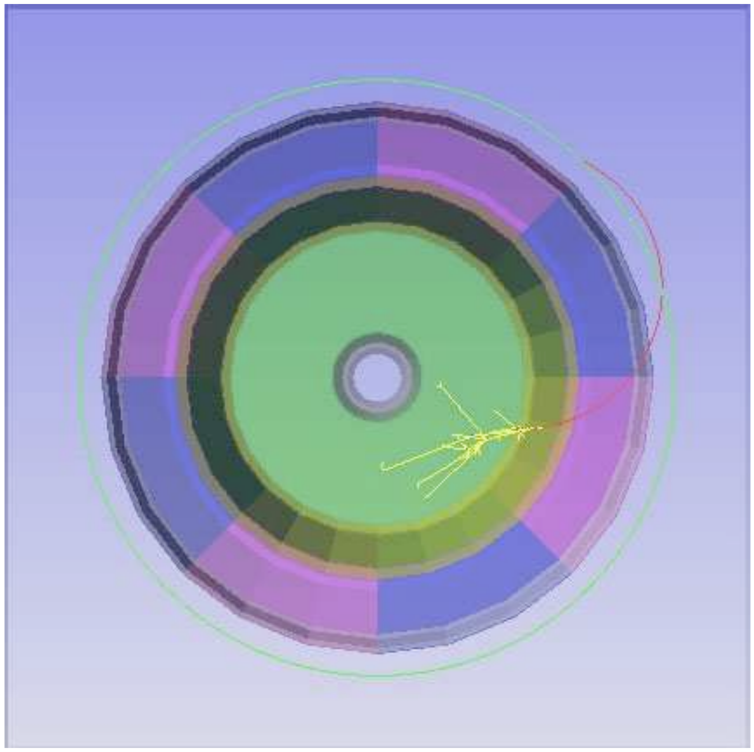

FIG. 14: A typical event of muon decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu_\mu}$.

Figure 14 depicts a typical simulated event of muon decays modeled by GEANT[4]. The decay positron would leave charged tracks in the time projection chambers so that its curvature can be measured to determine its momentum component normal to the magnetic field. Then the positron would further traverse into the electric calorimeter to deposit its full energy. We estimate that several radiation length would be enough to fully absorb its energy.

A possible candidate for the tracking chamber would be a time projection chamber based on the μ-PIC technology[12].

Obviously further optimization needs to be done for the detector design. Especially we needs to clarify how useful the charged track information for event reconstruction including the determination of decay vertices.

If we are to utilize the same detector system for EDM measurement, where we may rotate the spin direction to vertical, the detector coverage might have to be enhanced to measure up and down asymmetry without too much geometrical bias. The choice of solenoid would be beneficial in this regard, too, since it is easier to produce the good field region long enough to accommodate such a detector system.

VIII. REQUIREMENTS FOR THE FACILITY

The current plan is to launch this experiment at H-line of Muon Facility at MLF. The port from the target to this beam line is fully closed with the concrete shield at this point, and there is no solid plan to implement the beam line elements such as capture solenoids as well as curved solenoid. As the beam power increase, the radiation level at the location of capture solenoid would become more serious, it is urgent and important to implement the capture solenoid as soon as possible.

In addition, the mun linac itself becomes longer to that extent that it cannot be fully included in the Muon Facility. As Figure5 depicts, the beam line sticks out of the wall of the Muon Facility like in the case of neutron beamline in the neutron facility downstream of the Hall. While the linac itself does not require very serious building, it is still true that we need to utilize the parking lot area of the hall.

---

[1] G.W. Bennett *et al.* Muon G-2 Collaboration, Phys. Rev. **D73** (2006) 072003.

[2] M. Passera, W.J. Marciano, and A. Sirlin, Phys. Rev. **D78** (2008) 013009.

[3] J. Hisano and K. Tobe, Phys.Lett.**B510** (2001) 197-204.

[4] J.P. Archambault, A. Czarnecki, and M. Pospelov. Phys. Rev. **D70** (2004) 073006.

[5] Proposal submitted to Fermilab; *The New (g 2) Experiment: A Proposal to Measure the Muon Anomalous Magnetic Moment to ±0.14 ppm Precision*, New $(g-2)$ Collaboration. Contact-persons: D. Hertzog, and B. Roberts.

[6] R. Lafaye, T. Plehn, M. Raunch and D. Zerwas, arXiv:0709.3985 [hep-ph].

[7] M. Alexander, S. Kreiss, R. Lafaye, T. Plehn, M. Rauch, and D. Zerwas, Chapter 9 in M. M. Nojiri et al., arXiv:0802.3672 [hep-ph].

[8] K. Hattori, K. Tsuchiya, K. Ito, Y. Okada, K. Fujii, H. Kubo, K. Miuchi, M. Takata, T. Tanimori and H. Uekusa. J. Synchrotron Rad. (2009). 16, 231-236

[9] Communication with the Muon Facility Group, J-PARC.

[10] K. Nagamine *et al.*, Phys. Rev. Lett. **74** (1995)4811-4814.

[11] P. Bakule *et al.*, Nucl.Inst.Meth. **B 266** (2008) 335-346.

[12] K. Hattori *et al.*, J. Synchrotron Rad. bf16, 231-236 (2009).

---

[1] The experiment measured both positive and negative muons separately down to 0.70 ppm. Quoted precision of 0.54 ppm represents the combined results assuming CPT invariance.

[2] A smaller injection angle might be helpful from the viewpoint of magnet design. Such optimization is underway.

[3] Although E821 employed the magic momentum muon beam to cancel the electric field effect, there are still small deviation of beam momentum of $\sim 0.3\%$, and their precession frequency is reduced. They apply a correction for this effect +0.8 ppm.

[4] Spin orientation and its decay distribution is correctly represented in GEANT 4.9.1 or later version.