Muon g-2/EDM at J-PARC

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TRIUMF
on behalf of the J-PARC muon g–2/EDM Collaboration

Workshop on Flavour Changing and Conserving Processes
FCCP2017
Anacapri, IT, September 7-9 2017

With thanks for their support to:

- Natural Sciences and Engineering Research Council, Canada
- TRIUMF, Canada's National Laboratory for Particle and Nuclear Physics

Outline

- What g-2/EDM measures
- Overview of the experiment
- Description of major components
    - surface muon beam line
    - muon source
        - TRIUMF muonium experiments
    - muon acceleration
    - injection and storage
    - muon decay detector
- Goals and expectations for statistical and systematic uncertainties

The muon’s magnetic dipole moment

- The magnetic dipole moment μ of a particle is determined by its mass m, charge q, spin S and g-factor:

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

- The spin precession in a magnetic field is:

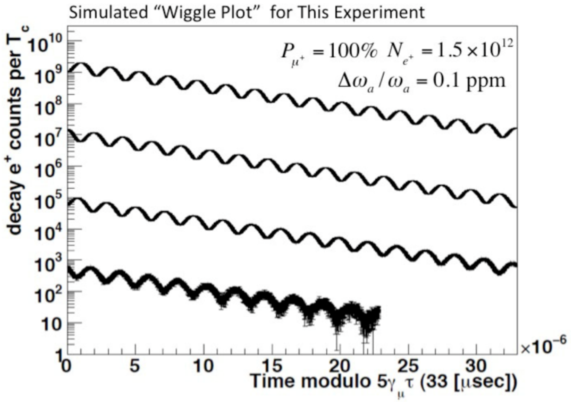
$$\vec{\omega}_s = \left(-\frac{g}{2} - \frac{(1-\gamma)}{\gamma}\right)\frac{q\vec{B}}{m}$$

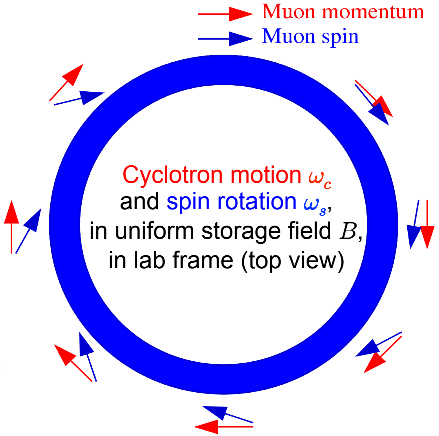
- The cyclotron frequency of rotation is:

$$\vec{\omega}_c = \left(-\frac{1}{\gamma}\right)\frac{q\vec{B}}{m}$$

- **Spin ½ fermions**: for a Dirac particle $g \equiv 2$, but corrections add an anomaly a:

$$\mu = (1+a)\left(\frac{q\hbar}{2m}\right), \quad a \equiv \frac{g-2}{2}$$





Cyclotron motion ω_c
and spin rotation ω_s,
in uniform storage field B,
in lab frame (top view)

- For a **muon** with velocity β perpendicular to a magnetic field B, with an electric field E, there will be cyclotron motion at frequency ω_c while the spin will rotate at frequency ω_s, with difference ω_a:

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

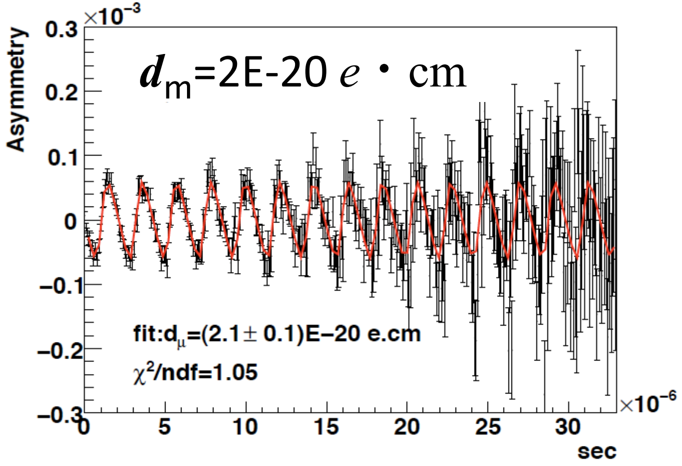
The muon’s electric dipole moment

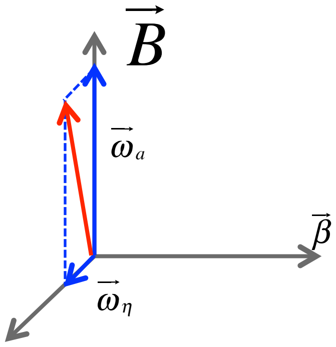
- The electric dipole moment d of is defined similarly in terms of the particle’s mass, charge, and spin S, with proportionality η

$$\vec{d} = \eta \left(\frac{q}{2m}\right) \vec{S}$$

- The fermion’s SM EDM is zero except for possible CP or T violation at higher orders (4 loops)

$$d_\mu^{SM} \sim 2 \times 10^{-38}\, e \cdot \mathrm{cm}$$





Oscillation component *perpendicular* to the storage plane

- In a non-zero electric field, the anomalous muon frequency is modified with a non-zero EDM at frequency ω_η:

$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{q}{m_\mu}\left[\underbrace{a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}_{\omega_a} + \underbrace{\frac{\eta_\mu}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)}_{\omega_\eta}\right]$$

Recipe for precision

- B measured with an array of NMR magnetometers
  - calibrated with respect to an absolute spherical water sample probe measuring ω_p
  - calibrations traceable to same standard used for muonium HFS (Los Alamos, upcoming J-PARC MuSEUM) and other g–2 experiments

$$\omega_L = -g_\mu \frac{qB}{2m_\mu} \qquad \text{(non-relativistic } \omega_s\text{)}$$

$$\lambda = \omega_L/\omega_p = 3.183345107(84) \qquad \text{(0.026 ppm, 2010 CODATA)}$$

  - probes periodically moved through muon storage region to map the muon beam field environment, to measure a *spatial average* ω_p^{avg}

- Dividing ω_a by ω_p^{avg} determines a_μ in terms of *ratios* of frequencies

$$a_\mu = \frac{\omega_a}{\omega_L - \omega_a} = \frac{(\omega_a/\omega_p^{\text{avg}})}{\lambda - (\omega_a/\omega_p^{\text{avg}})}$$

- Using ω_L from independent Mu HFS experiment, a_μ depends on two frequencies, ω_a from muon decay time spectrum and ω_p from magnetic field measurements.
  - natural division of contributions to uncertainties from two sources

Compare: Fermilab and J-PARC

Fermilab

$$-\frac{q}{m_\mu}\left[a_\mu\vec{B} - \left(\cancel{a_\mu - \frac{1}{\gamma^2-1}}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

- eliminate effect of E-field via "magic" momentum:
  - $\gamma^2 = 1 + a^{-1}$
  - p_μ = 3.09 GeV/c required
- B = 1.45 T ➔ ρ = 7 m
- electric quadrupole field focusing
- periodic segmented calorimeters with tracker modules

Improves on the BNL method

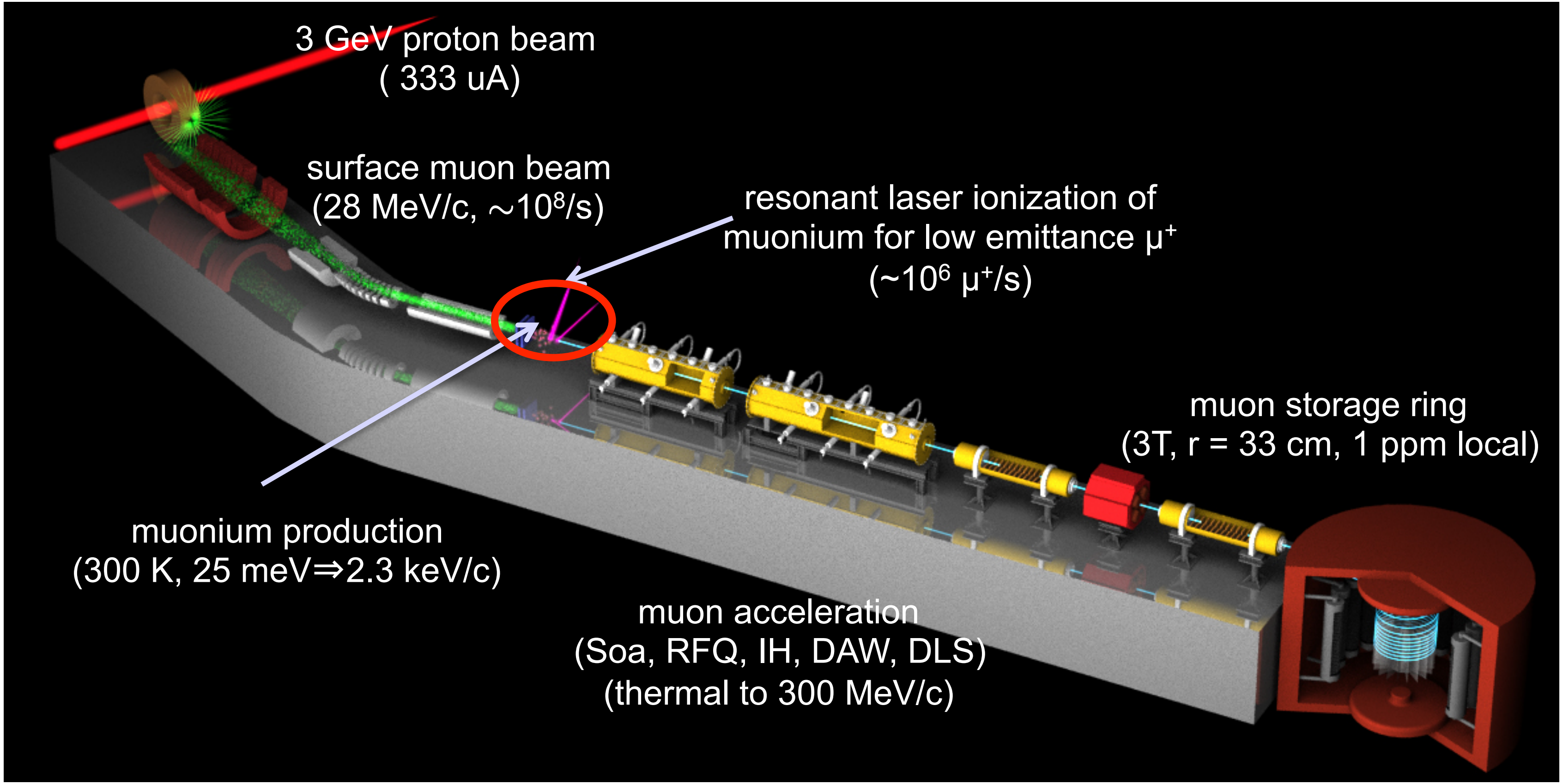
J-PARC

$$-\frac{q}{m_\mu}\left[a_\mu\vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\cancel{\frac{\vec{\beta}\times\vec{E}}{c}}\right]$$

- eliminate effect of E-field via E = 0
  - choose p_μ = 0.3 GeV/c
- B = 3 T ➔ ρ = 0.33 m
  - very uniform B in compact storage region
- weak B field focusing, no E focusing – must use low-emittance "cold" μ beam
  - polarization reduced to 50%
  - allows polarization reversal (spin flipping)
- uniform tracker detection of decay location throughout stored orbit
  - EDM sensitivity

A new method with quite different systematics

A new and different method at J-PARC



3 GeV proton beam
(333 uA)

surface muon beam
(28 MeV/c, ~10^8/s)

resonant laser ionization of
muonium for low emittance μ^+
(~10^6 μ^+/s)

muon storage ring
(3T, r = 33 cm, 1 ppm local)

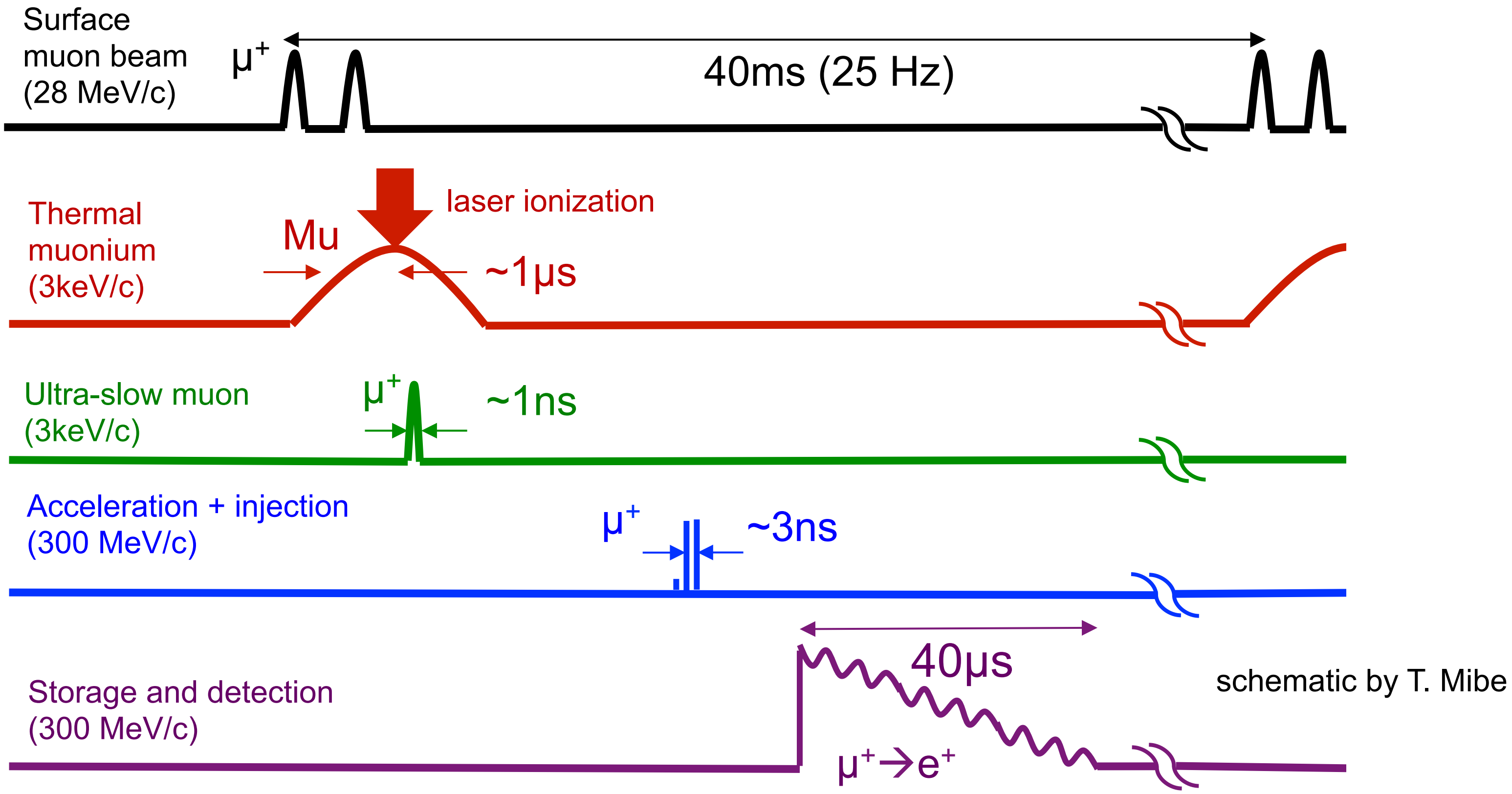
muonium production
(300 K, 25 meV⇒2.3 keV/c)

muon acceleration
(Soa, RFQ, IH, DAW, DLS)
(thermal to 300 MeV/c)

Status of J-PARC g-2/EDM

- July 2012 – Stage 1 approval recommended by PAC, granted by IPNS Director
- May 2105 – Technical Design Report submitted to PAC
- October 2016 – revised TDR submitted
- November 2016 – Focused Review on technical design
  - Review recommendations:
    - **Develop a "fast track" plan** to achieve the Phase-1 result in a timely and cost-effective manner
    - ~0.5 ppm, equivalent to BNL
    - Phase-2 goal is ~0.1 ppm
    - **This committee finds that Phase-1 of the E34 experiment is technically ready for Stage-2 approval.**
    - **subject to resolution of the remaining technical issues...**
- July 2017 − request for Stage 2 approval

Time sequence: muon production to decay



schematic by T. Mibe

Muons produced to muons stored

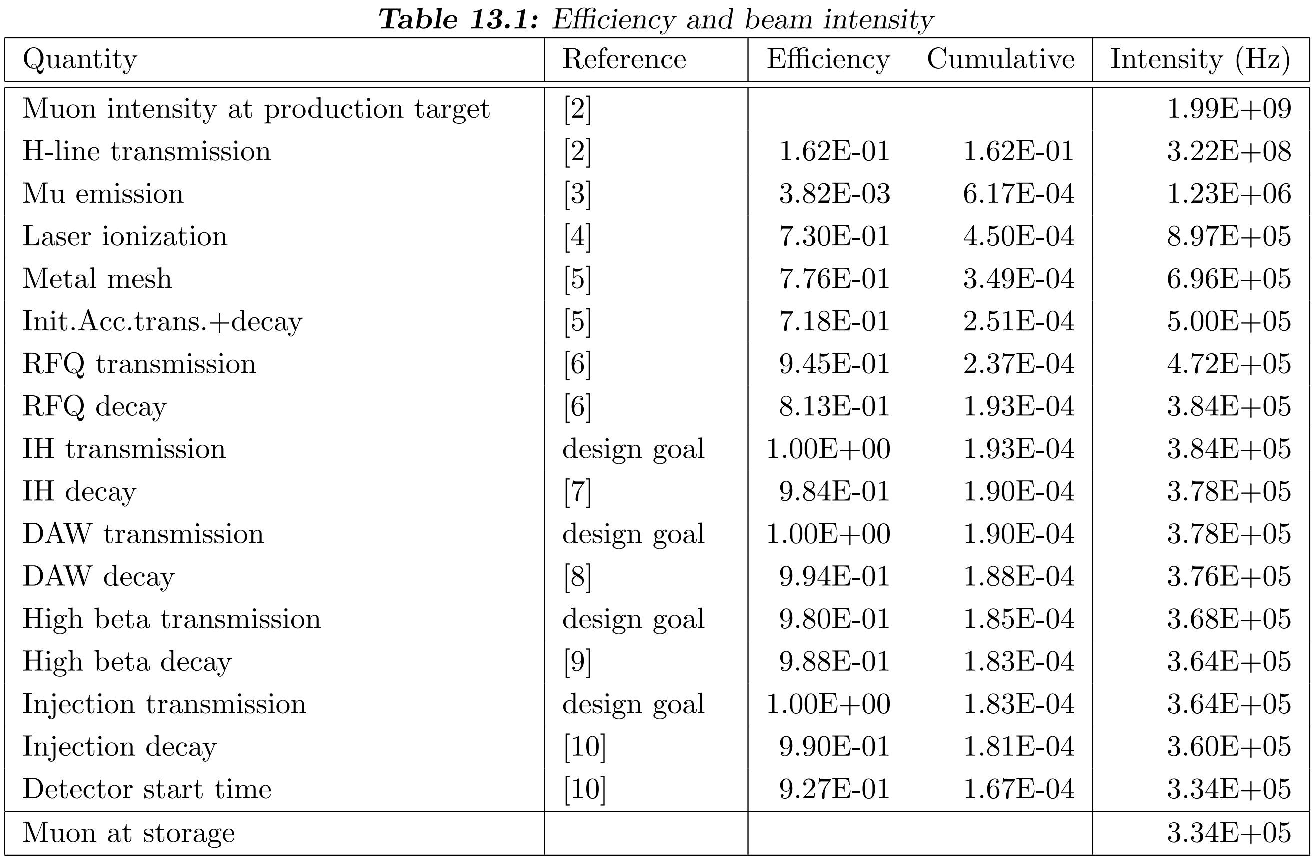


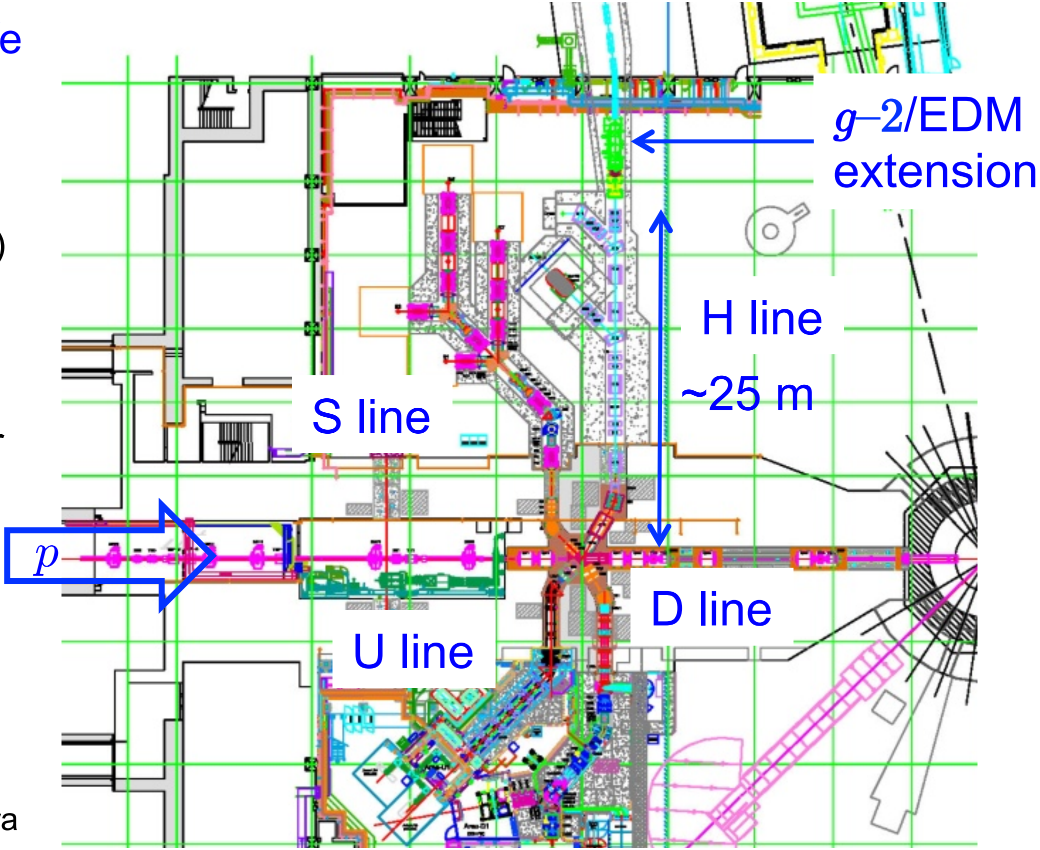
Table 13.1: *Efficiency and beam intensity*

Quantity	Reference	Efficiency	Cumulative	Intensity (Hz)
Muon intensity at production target	[2]			1.99E+09
H-line transmission	[2]	1.62E-01	1.62E-01	3.22E+08
Mu emission	[3]	3.82E-03	6.17E-04	1.23E+06
Laser ionization	[4]	7.30E-01	4.50E-04	8.97E+05
Metal mesh	[5]	7.76E-01	3.49E-04	6.96E+05
Init.Acc.trans.+decay	[5]	7.18E-01	2.51E-04	5.00E+05
RFQ transmission	[6]	9.45E-01	2.37E-04	4.72E+05
RFQ decay	[6]	8.13E-01	1.93E-04	3.84E+05
IH transmission	design goal	1.00E+00	1.93E-04	3.84E+05
IH decay	[7]	9.84E-01	1.90E-04	3.78E+05
DAW transmission	design goal	1.00E+00	1.90E-04	3.78E+05
DAW decay	[8]	9.94E-01	1.88E-04	3.76E+05
High beta transmission	design goal	9.80E-01	1.85E-04	3.68E+05
High beta decay	[9]	9.88E-01	1.83E-04	3.64E+05
Injection transmission	design goal	1.00E+00	1.83E-04	3.64E+05
Injection decay	[10]	9.90E-01	1.81E-04	3.60E+05
Detector start time	[10]	9.27E-01	1.67E-04	3.34E+05
Muon at storage				3.34E+05

from TDR

Surface muon beam

- H line at J-PARC MLF (Meson and Life Sciences Facility: μ and n)
    - other muon beams from D, U, and S lines, for condensed matter
    - H line serves also MuSEUM (Mu HFS) and DeeMee ($\mu^- \rightarrow e^-$)
    - large aperture μ capture and transport solenoids
    - weak field parallel optics for Wien filter or kicker
- g–2/EDM extension
    - small focus (quad triplet)
    - small fringe fields
    - $>10^8$ s^{-1} at 1MW



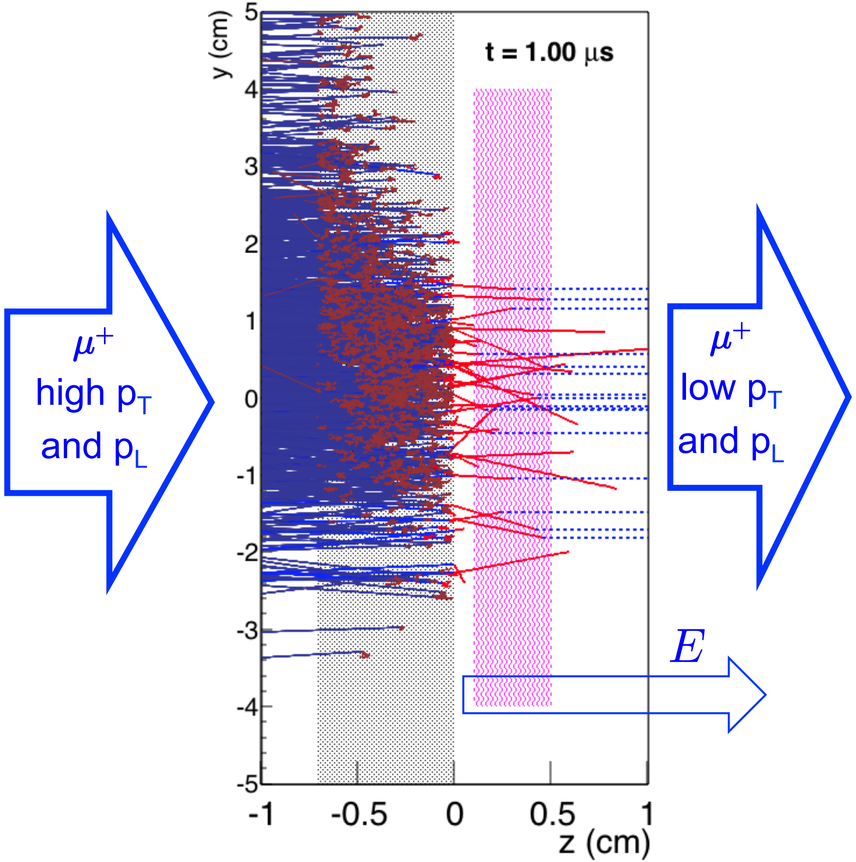
from N. Kawamura

Surface muons to ultra-cold muons

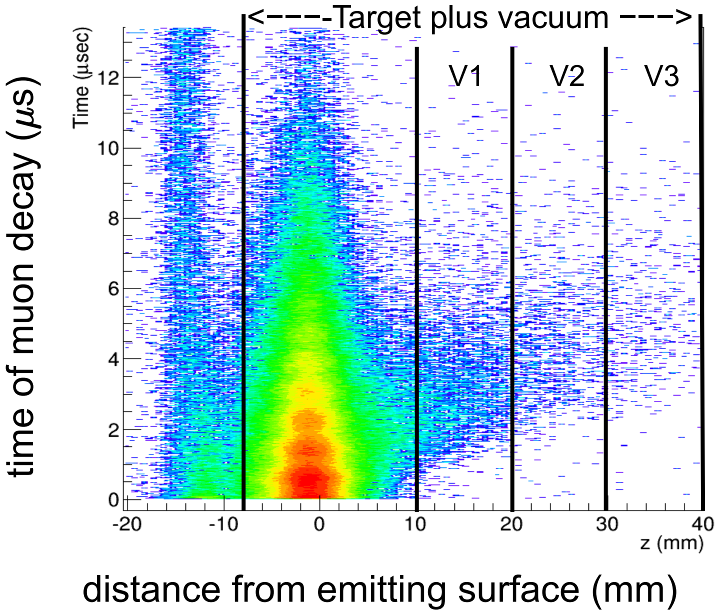
- Thermalization of ~10^8 s^{-1} surface muons

	Surface beam	Thermal beam
E_k, MeV	3.4	0.03×10^{-6}
p, MeV/c	27	2.3×10^{-3}
$\Delta p/p$, rms	0.05	0.4
Δp, MeV/c	1.3	1×10^{-3}

- Thermal diffusion of Mu (μ^+e^-) into vacuum
  - decay length ∼14 mm
  - TRIUMF experiment S1249
- Ionization
  - 1S→2P→unbound (122 nm,355 nm)
- Acceleration
  - E field, RFQ, linear structures
  - adds to p_z but not significantly to Δp



Mu from laser-ablated aerogel (TRIUMF)



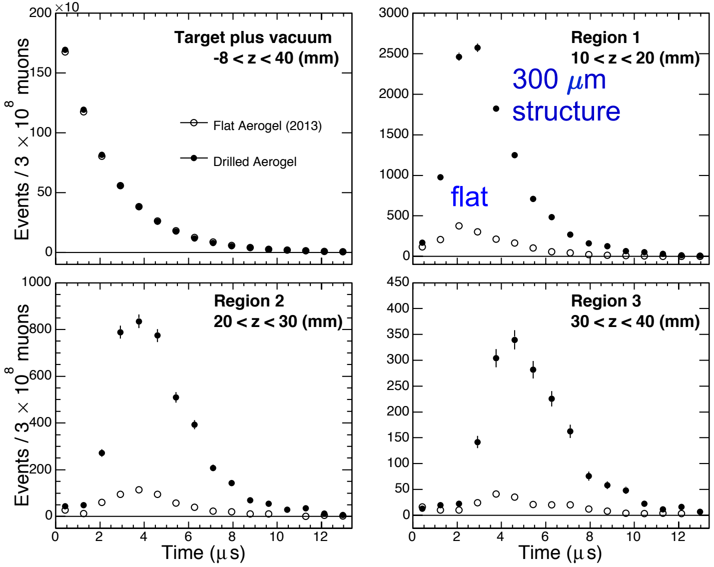


Table 1 Yield of Mu in the vacuum region 1–3. For all laser processed samples, the diameter of the structure is 270 μm.

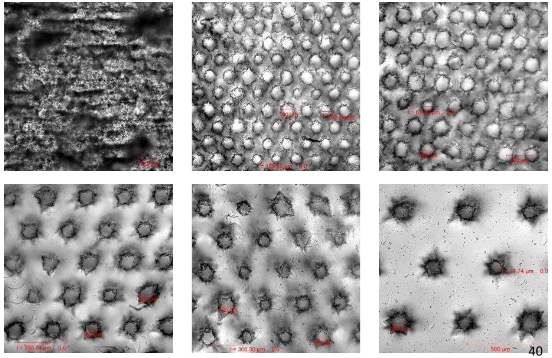
Sample	Laser-ablated structure (pitch)	Vacuum yield (per 10^3 muon stops)
Flat	none	3.72 ± 0.11
Flat (Ref. [7])	none	2.74 ± 0.11
Laser ablated	500 μm	16.0 ± 0.2
Laser ablated	400 μm	20.9 ± 0.7
Laser ablated	300 μm	30.5 ± 0.3

- Used a ***model-independent approach*** to estimate yields
- For 0.3 mm structure, observed 10 times yield previously reported from 2011 data.

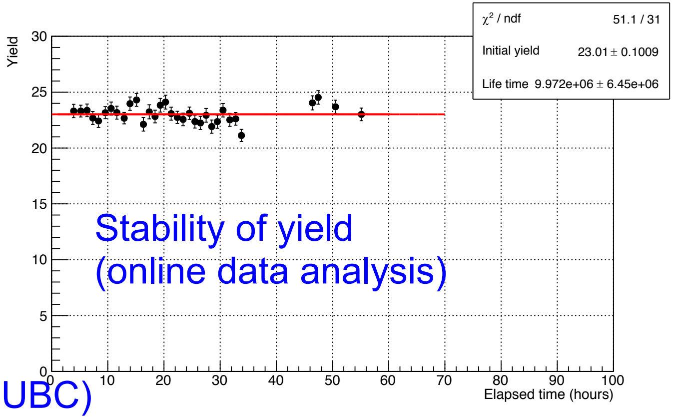
G.A. Beer et al., Prog. Theor. Exp. Phys. 2014, 091C01 (2014).

Mu emission: new results from TRIUMF

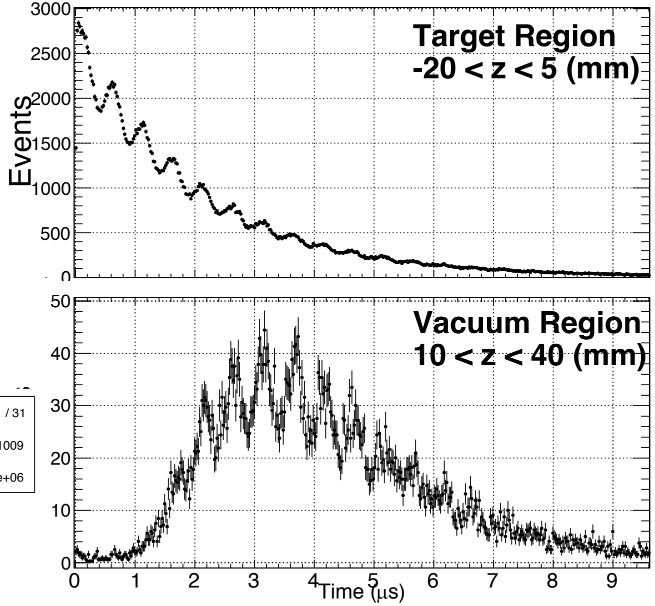
- June-July 2017
- Measurements of 25 samples in 3 weeks
  - most were produced from ablations in run period
  - reproduced previous high yields
- One single target measured over 2.5 days
  - no degradation in yield was observed
- Polarization confirmed for Mu in vacuum
  - consistent with 50% expected from Mu HFS



Some ablation patterns (S. Kamal, UBC)



Stability of yield
(online data analysis)



Mu polarization from spin rotation in target and vacuum
(online data analysis)

Laser ionization of Mu

- Two steps
  - Lyman α 1S→2P at 122 nm
  - 2P→unbound at 355 nm
- Lyman α
  - two-photon resonance four-wave mixing in Kr
  - pump with 212.55 nm
  - generate 122 nm via difference mixing with 820 nm
  - goal is 100 μJ in 2 ns pulse with 80 GHz width at 25 Hz

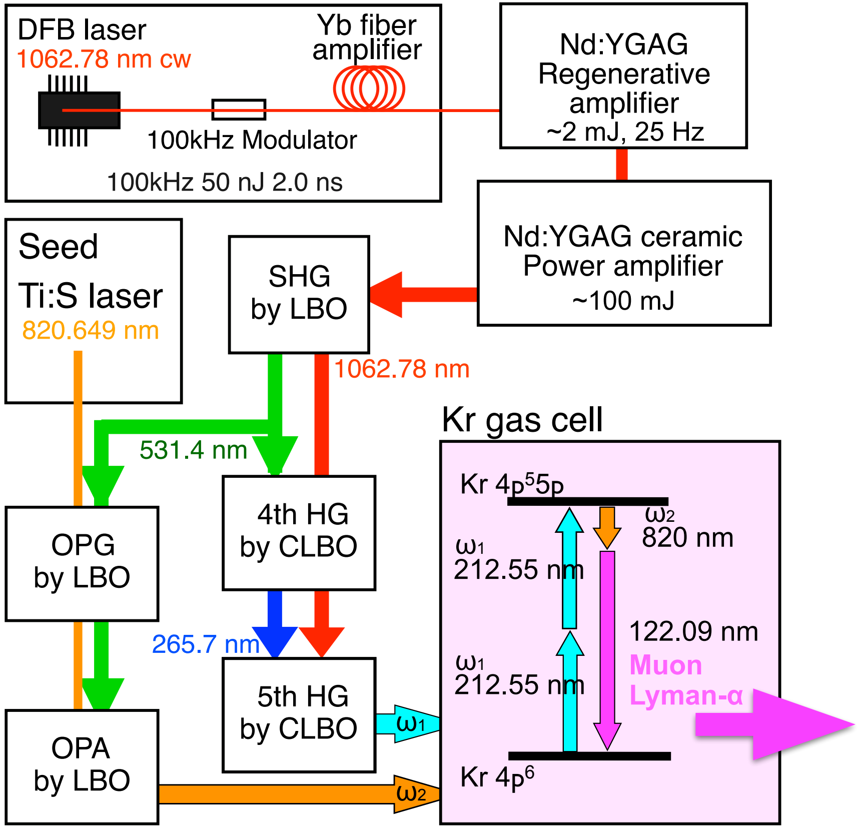
122 nm, μJ

355 nm, mJ

	20	40	60	80	100	120
50	0.097	0.151	0187	0.210	0.226	0.238
100	0.171	0.268	0.327	0.366	0.393	0.412
150	0.228	0.356	0.433	0.482	0.516	0.540
200	0.273	0.424	0.514	0.570	0.608	0.635
250	0.310	0.479	0.577	0.639	0.679	0.708
300	0.339	0.521	0.627	0.691	0.733	0.762
350	0.363	0.556	0.666	0.733	0.775	0.804
400	0.383	0.585	0.698	0.766	0.809	0.857

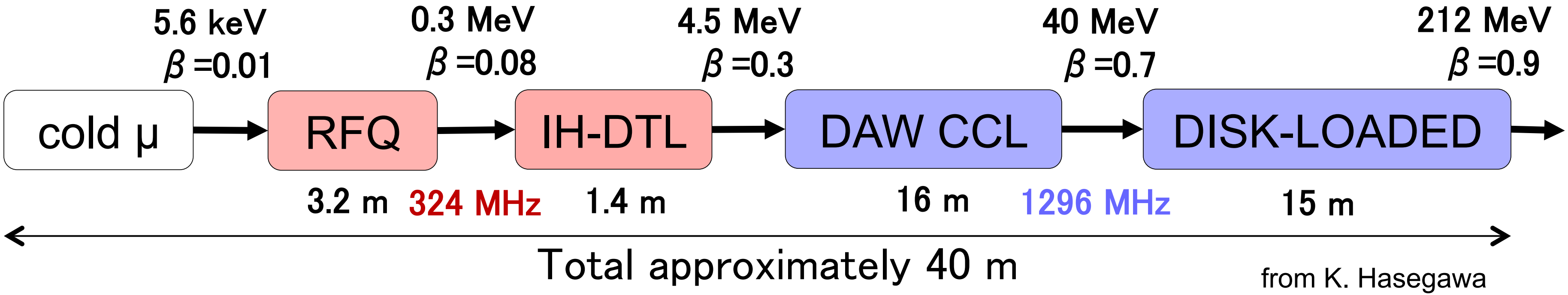
from K. Ishida

Calculated ionization efficiencies (2 cm^2 area)



from Y. Oishi

Acceleration of thermal muons



5.6 keV β =0.01

0.3 MeV β =0.08

4.5 MeV β =0.3

40 MeV β =0.7

212 MeV β =0.9

cold μ → RFQ → IH-DTL → DAW CCL → DISK-LOADED →

3.2 m 324 MHz 1.4 m 16 m 1296 MHz 15 m

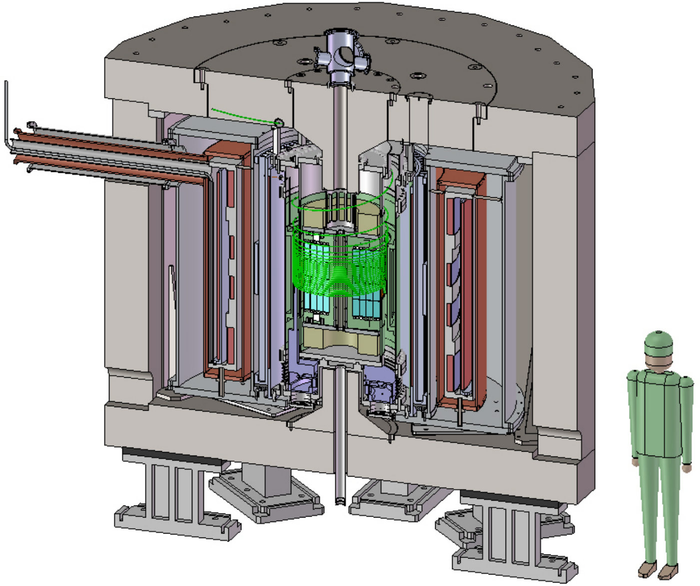
Total approximately 40 m

from K. Hasegawa

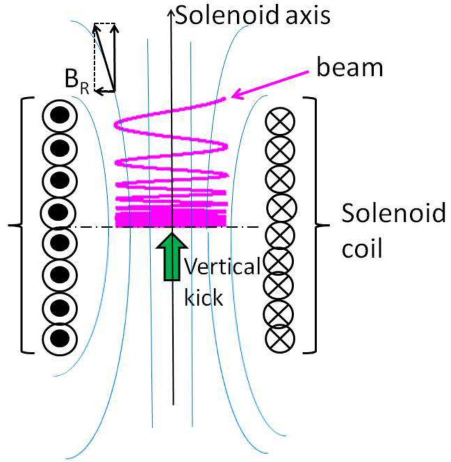
- Requirements
  - fast acceleration to reduce decay losses
    - (τ_μ = 2.2 μs at rest)
  - control/reduce emittance growth to enable injection and capture by storage ring

Injection and storage of muons

- Superconducting solenoid
  - cylindrical iron poles and yoke
  - vertical B = 3 Tesla, <1ppm locally
  - storage region r = 33.3±1.5 cm, h = ±5 cm
  - tracking detector vanes inside storage region radius
  - storage maintained by static weak focusing
    - $n = 1.5 \times 10^{-4}$, $rB_r(z) = -n\,zB_z(r)$ in storage region
- Spiral injection
  - dipole-quadrupole transfer line from end of linac with downward deflection
  - hole in upper yoke for beam entrance
    - permits entry, shields beam from field
  - pulsed radial field on injection
    - reduces vertical momentum to match a trapped orbit



from K. Sasaki



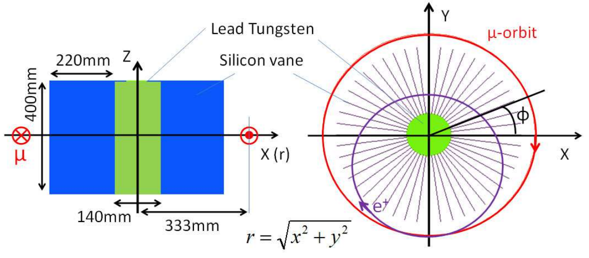
from H. Iinuma

Decay positron tracking detector

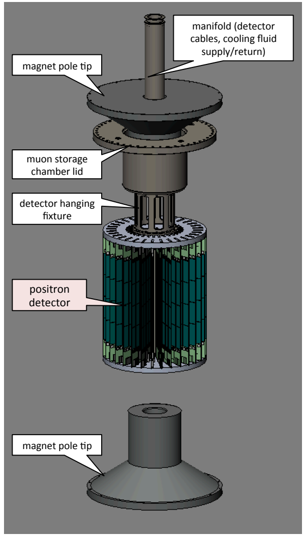
- Detect e^+ at higher range of energies (200−290 MeV/c)
  - typically one turn of track hits
- Core of lead-tungsten to absorb multiple turns

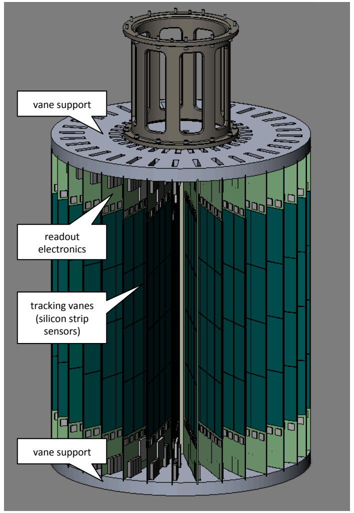
Item	Specifications
Fiducial volume	~200mm (radial) x ~400 mm (axial)
Number of vane	48
Sensor technology	Single-sided Silicon strip sensor (p-on-n)
Sensor dimension	98 mm x 98 mm x 0.32mm
Number of sensor	768 (16 sensors per vane)
Number of channel	786, 432ch

from T. Yoshioka



(side view) (top view)





J-PARC $g\text{–}2$ statistical goals

Statistical uncertainty estimates

- $\Delta\omega_a/\omega_a$ = 0.35 ppm (0.163/PN$^{1/2}$)
  - BNL E821 σ_{stat} = 0.46 ppm
- Δd_μ = 1.2×10^{-21} $e \cdot$ cm (sensitivity)
  - BNL E821 (-0.1±0.9)×10^{-19} $e \cdot$ cm
  - d_e < 0.87×10^{-28} $e \cdot$ cm

Main assumptions

- Running time
  - measurement only: 2×10^7 s
- Muon rate from H-line
  - 1MW, SiC target: 3.32×10^8 s^{-1}
- Conversion efficiency to ultra-slow muons
  - Mu emission (S1249), laser ionization
  - 2.25×10^{-3} (stage 2 goal is 0.01)
  - polarization 0.5
- Acceleration efficiency including decay
  - RFQ, IH, DAW, and high-β: 0.52
- Storage ring injection, decay, and kick
  - 0.92
- Stored muons
  - 3.58×10^5 s^{-1}

Systematic goals compared with E821: ω_a

Source	E821 (ppm,R01)	J-PARC (ppm)	
Pileup	0.08	<0.05	tracking rather than calorimeter
Beam background	<0.1		only muons stored
Lost muons	0.09	<<0.09	requires low emittance beam
Timing shifts	<0.1	<<0.1	no PMTs, track
E-field, pitch	<0.1	<<0.01	no E field, small divergence
Fitting/binning	<0.1	<<0.1	fewer oscillation cycles
CBO	0.07	<<0.1	small focusing field
Track reconstruction		<<0.1	must maintain rate independence
Gain changes	0.12	<<0.1	assess with spin flip comparison
Others		TBD	beginning to utilize simulations
Total	**0.21**	**<0.07**	

Systematic goals compared with E821: ω_p

Source	E821 (ppm,R01)	J-PARC (ppm)	
Absolute probe calibration	0.05	<0.03	sphericity of probe, common with E821 and E989
Moving probe calibrations	0.09	<0.03	better field uniformity
Moving probe measurements	0.05	<0.05	better uniformity so less sensitive to position corrections
Fixed probe interpolations	0.07	<0.07	better field uniformity
Muon distribution	0.03	<0.03	all decays tracked, bunched beam
Weak focusing field		<0.05	weak magnetic field gradient in storage region
Decay of persistent field		?	0.01 ppm/h, measured and corrected in ω_a analysis
Others	0.10	<0.1	temperature, kicker eddy currents, higher multipoles
Total	**0.17**	**<0.07**	

- Ongoing: converting comparisons into justifiable estimates for J-PARC g–2/EDM

Summary

- J-PARC muon g-2/EDM should be able to confirm the muon $g-2$ result at the precision of the BNL experiment, as a Phase 1 step
  - systematic limitations are expected to be quite different, and still require more careful estimation
  - the result should also yield the best limit for muon EDM
- The resource-limited schedule requires four years prior to data taking
  - unlike the Fermilab group which has done the experiment before, we will have to learn the method’s limitations and how to control systematics
  - currently considering fast-track plan to first results
- The collaboration has over 90 registered members, with opportunities for participation in the many technologies required to make the experiment a success
  - for more information, see http://g-2.kek.jp

Thank you
Mille grazie