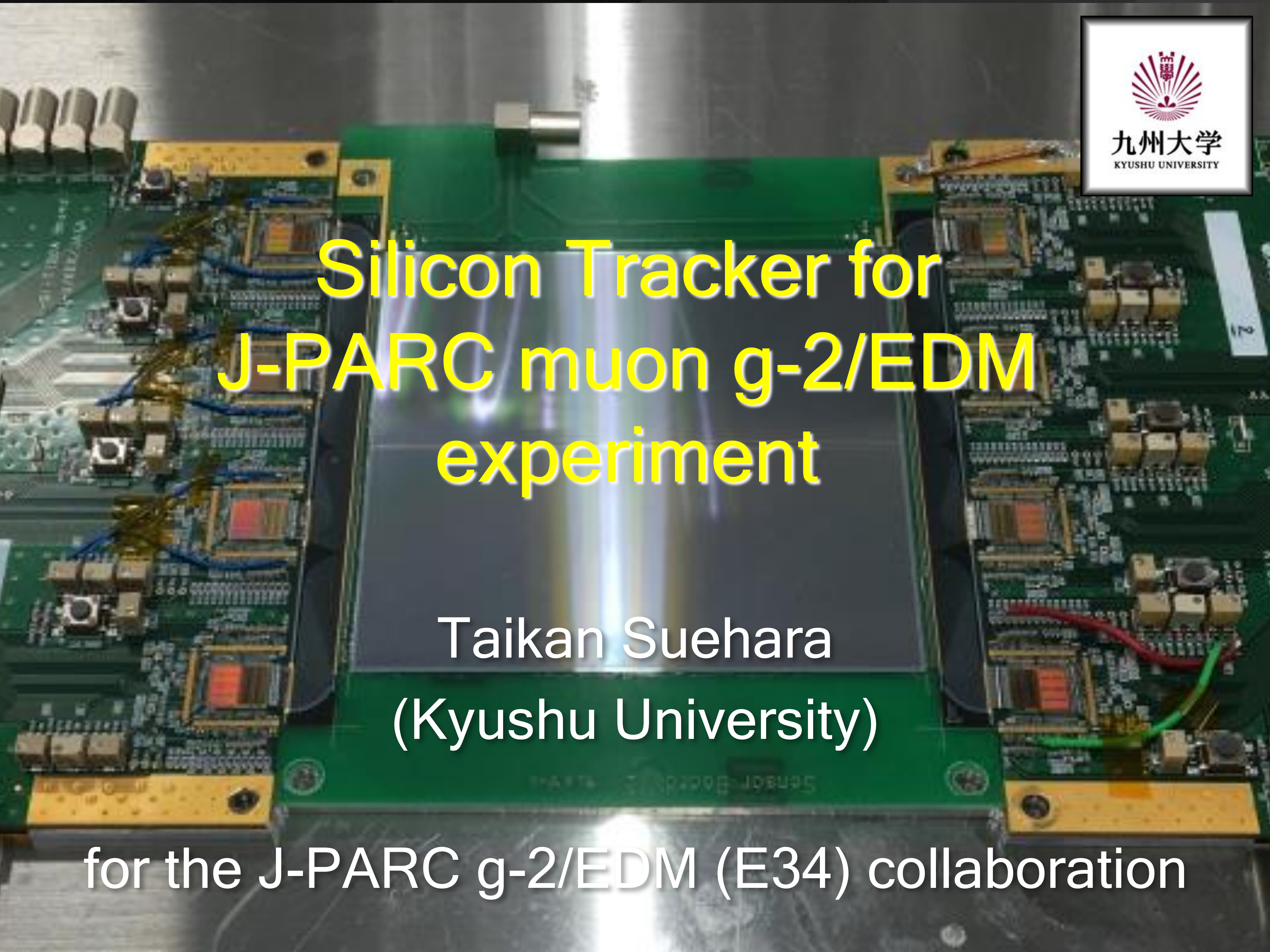


Silicon Tracker for J-PARC muon g-2/EDM experiment

Taikan Suehara

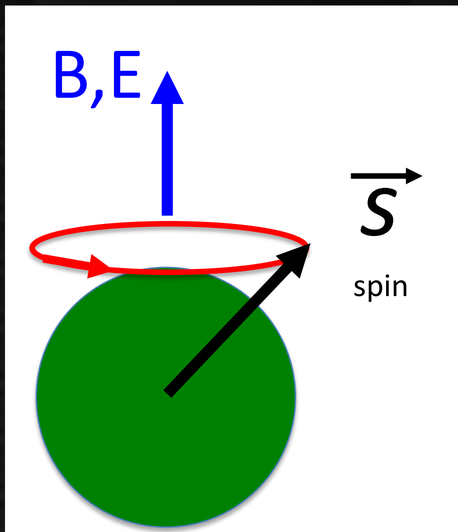
(Kyushu University)

for the J-PARC g-2/EDM (E34) collaboration

九州大学
KYUSHU UNIVERSITY

Muon g-2/EDM

Spin precession



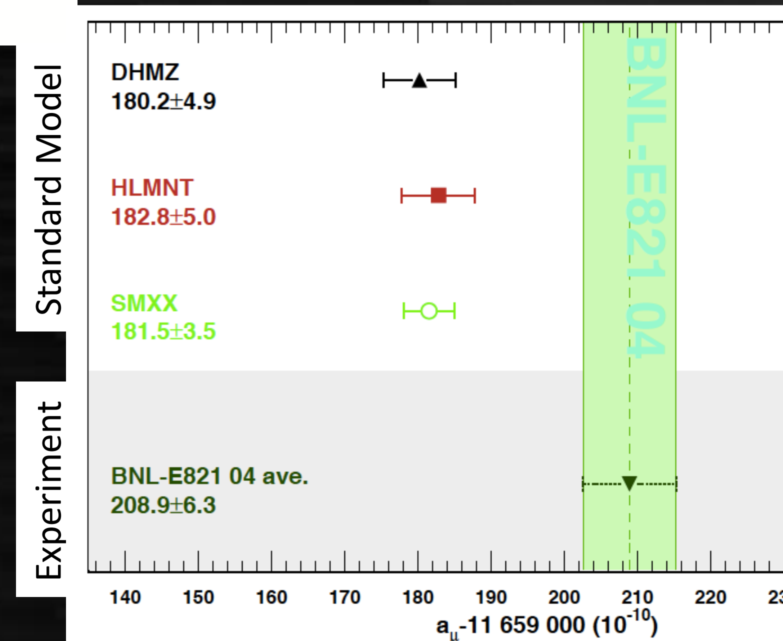
$$\mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

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

Magnetic dipole moment

$g = 2\,(1 + a_{\mu})$

QED, QCD, weak (+BSM) correction



BNL E821 exp. (2004)
3.3 σ deviation to SM calculation

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

Electric dipole moment
SM: ~ 2 x 10^{-38} e cm, lepton T violation term

Muon g-2: Fermilab vs J-PARC

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

general form of spin precession vector:

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

BNL E821 approach
γ=30 (P=3 GeV/c)

J-PARC approach
E = 0 at any γ

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

FNAL E989

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

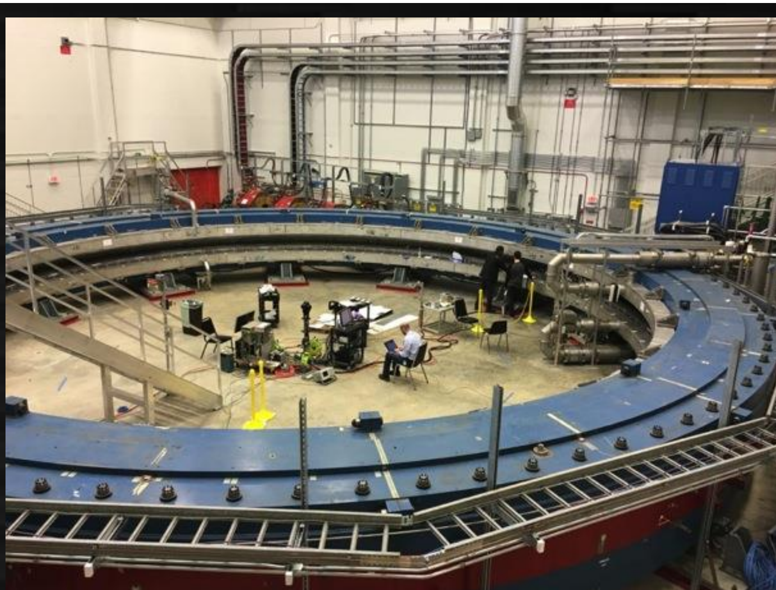
J-PARC E34

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

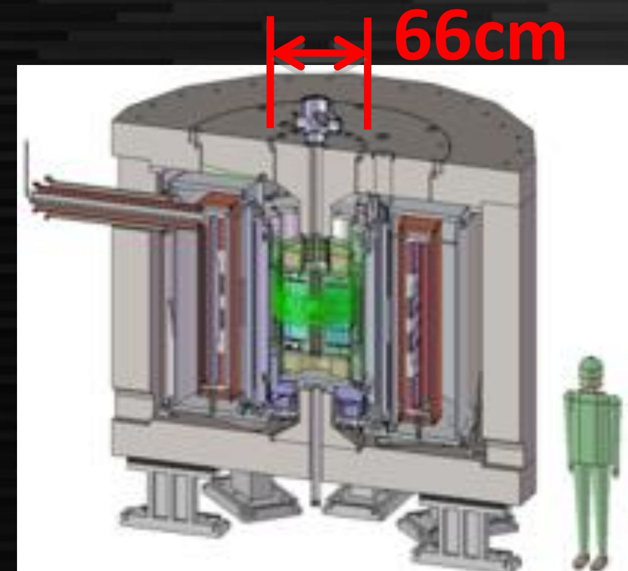
FNAL E989

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

J-PARC E34



P= 3.1 GeV/c , B=1.45 T



P= 0.3 GeV/c , B=3.0 T

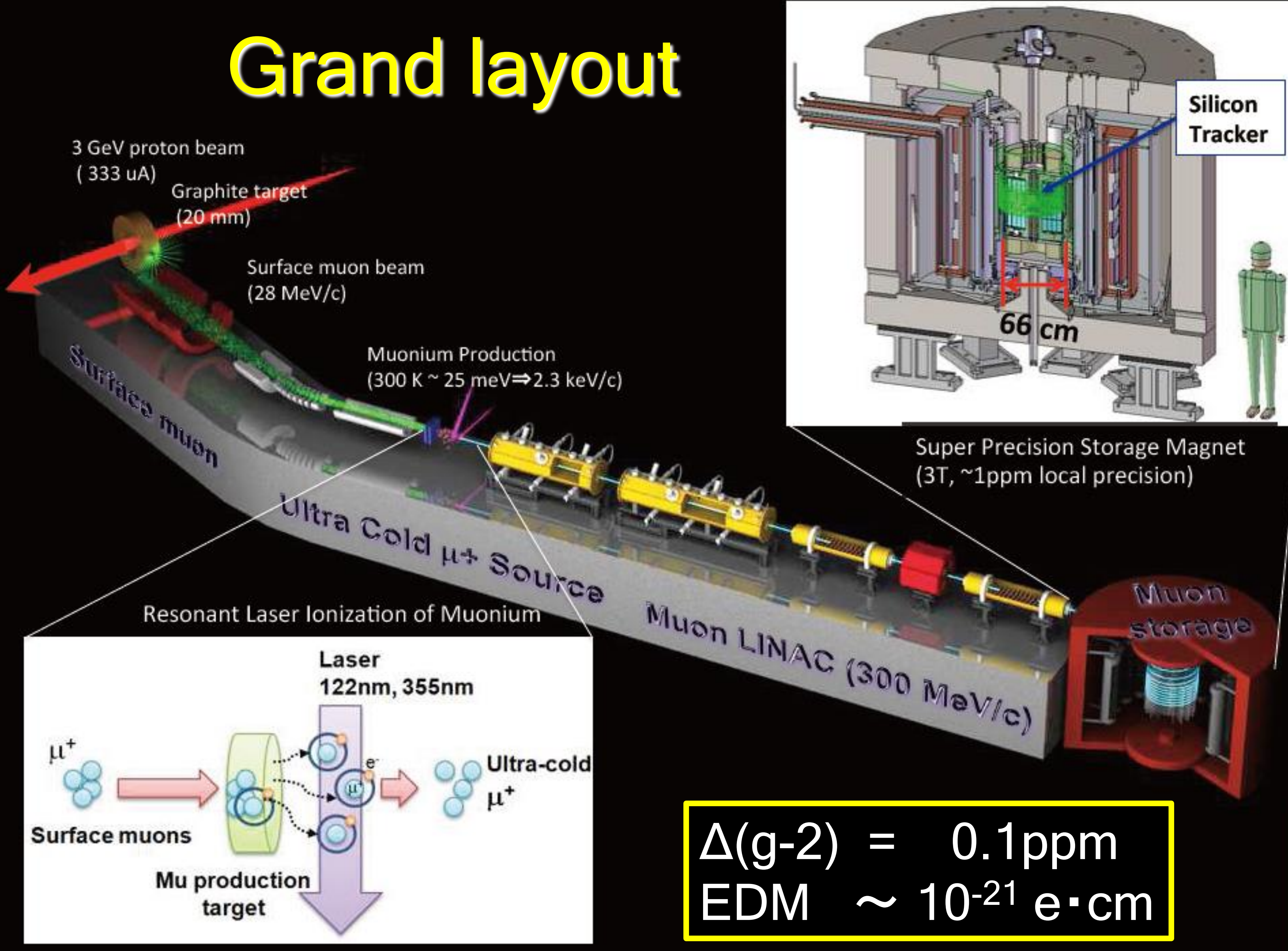
J-PARC E34 will be a compact and independent experiment complementary to FNAL E989 (independent systematics)

J-PARC muon g-2/EDM (E34) Collaboration

144 members, 51 institutions from
Canada, Czech, France, Korea, Japan, Russia, UK, US
Official collaboration recently formed (Spokesperson: T. Mibe)


J-PARC Facility
(KEK/JAEA)
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
Material and Life Science
Facility
Main Ring
(30 GeV)
Hadron Hall
Bird's eye photo in Feb. 2008

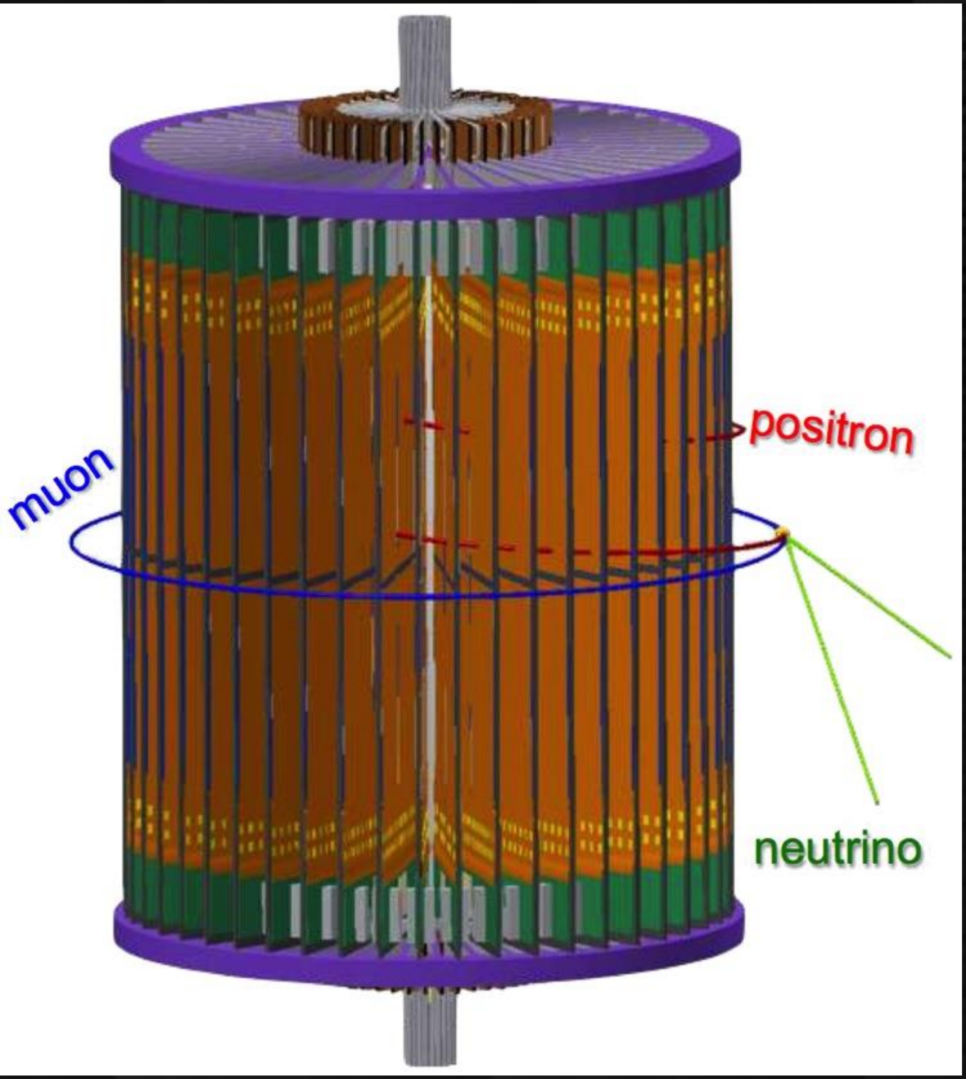
Grand layout



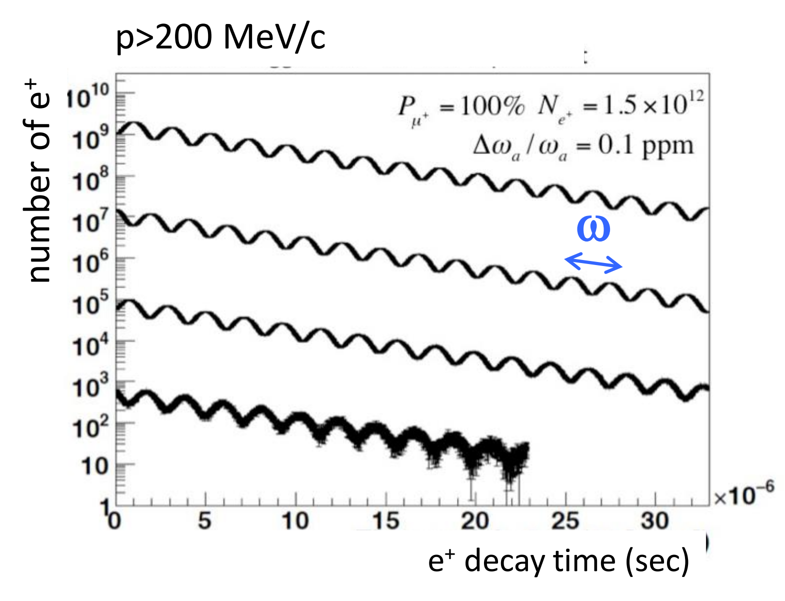
$\Delta(g\text{-}2)$ = 0.1ppm

EDM $\sim 10^{-21}$ e·cm

Positron Tracker



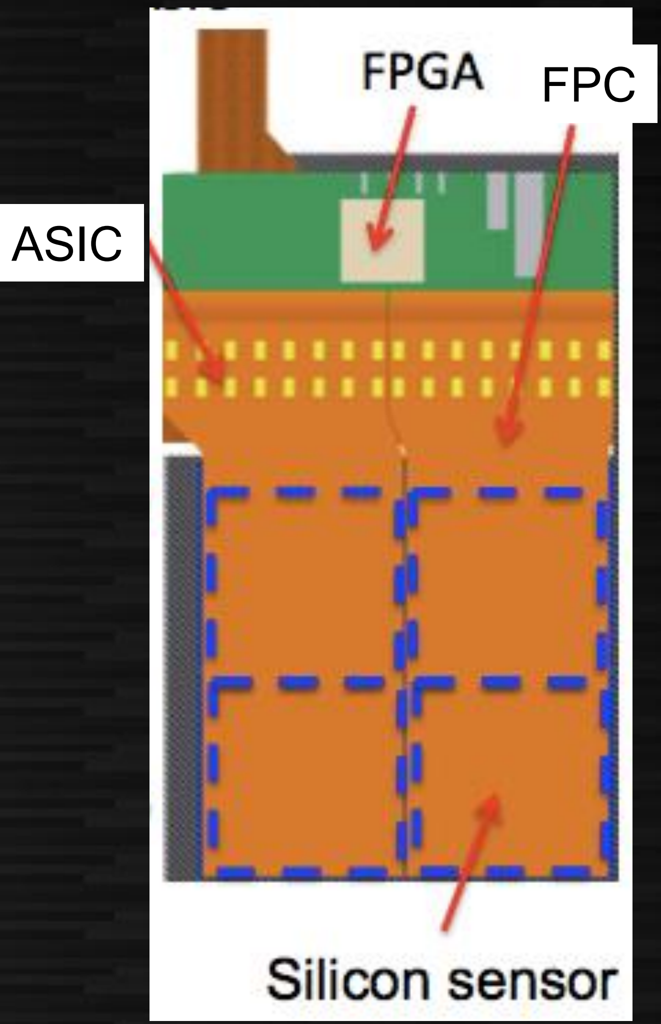
48 layers (vanes)



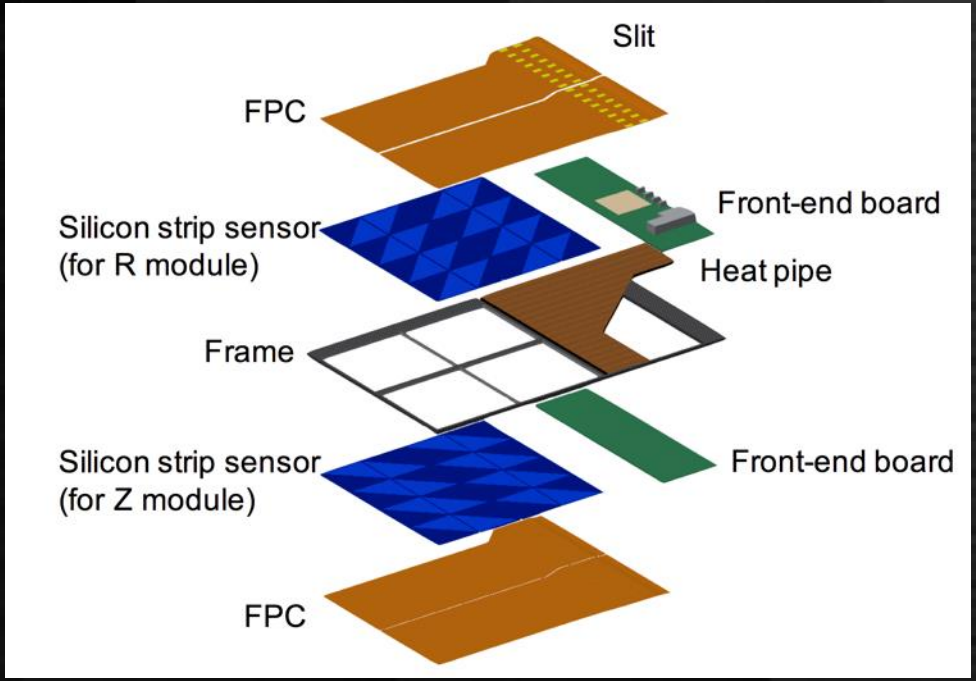
Requirements:

- 0.1 ppm freq. measurement
- 40 μs live time
- Event rate: 1400-10 kHz /strip
- Tracking of 100-300 MeV positrons
- 3 Tesla magnetic field
- 10 μrad angular alignment (for EDM measurement)

Vane structure



Half-vane structure



4 x 2 (R/Z) SSSD per half-vane
32 x 2 ASICs (128 ch / ASIC)

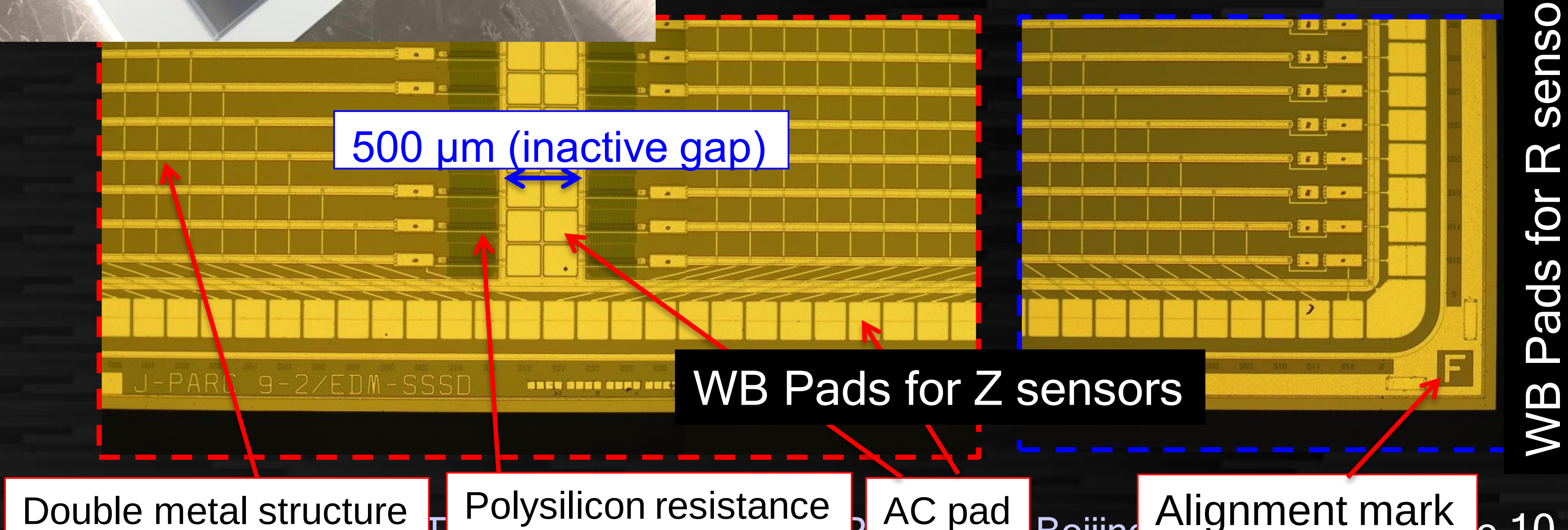
Vacuum operation (liquid cooling of ASICs)
~16 vanes (1/3 of current design)
funded by JSPS (2015-19)

Silicon Sensor

Produced by Hamamatsu

- Size: 97.28 x 97.28 mm
- Thickness: 320 μm
- Full depletion V: ~ 60V
- Strip pitch 190 μm
- Strips: 512 x 2 (split in half)
- Double metal for readout pads

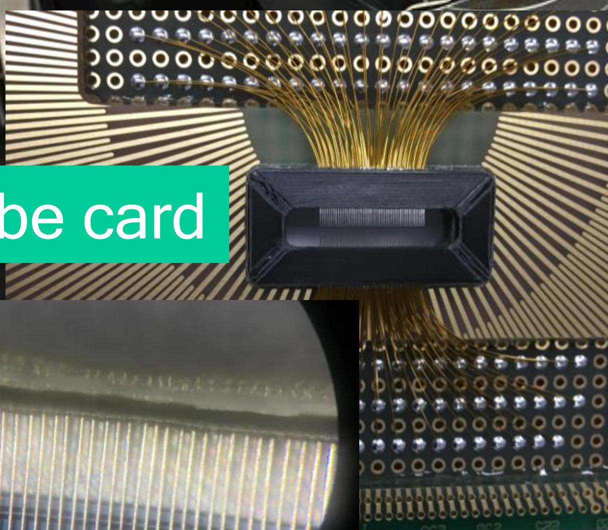
~ 200 sensors produced

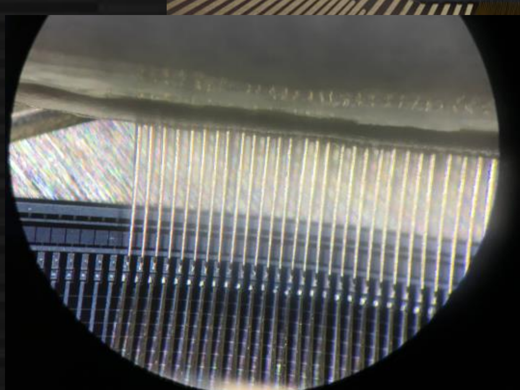


Characteristics of sensor

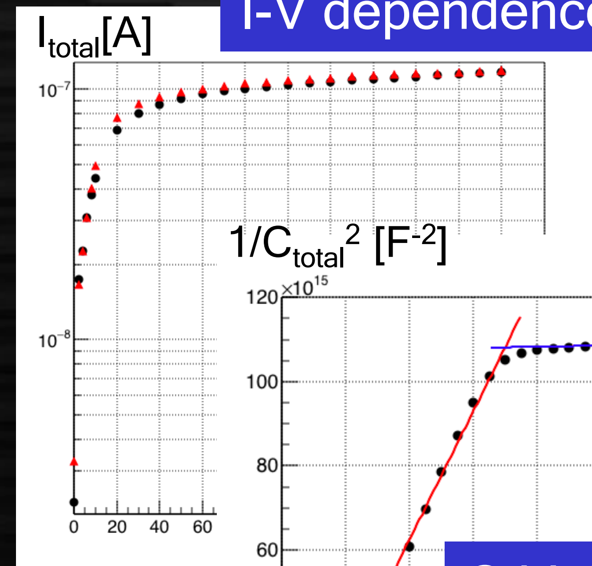
Probe station

Probe card

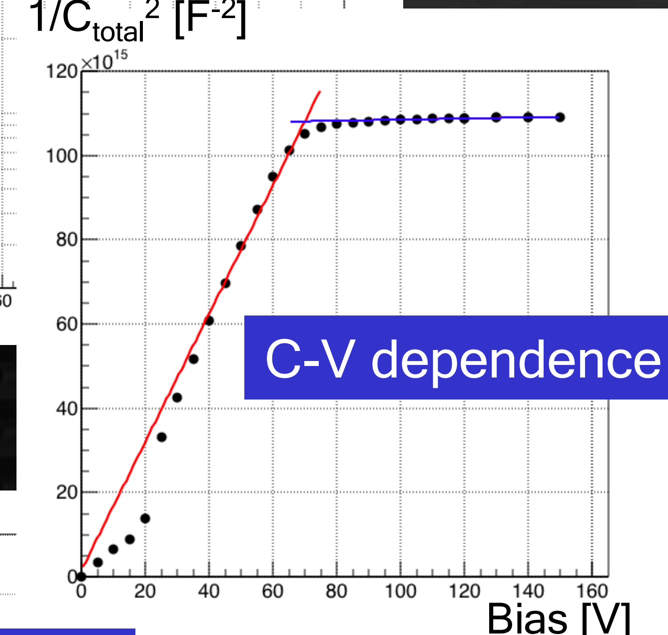




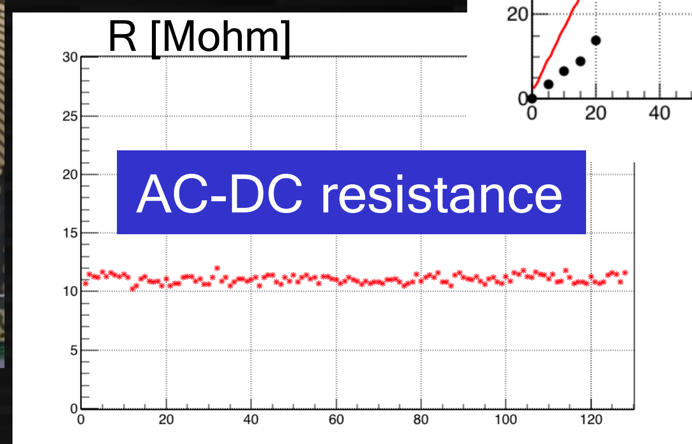
I-V dependence



C-V dependence

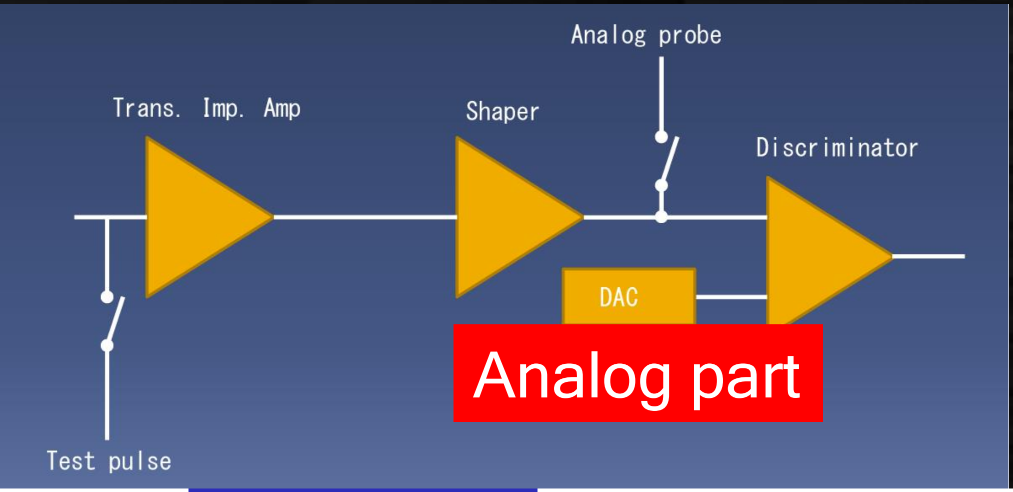


AC-DC resistance

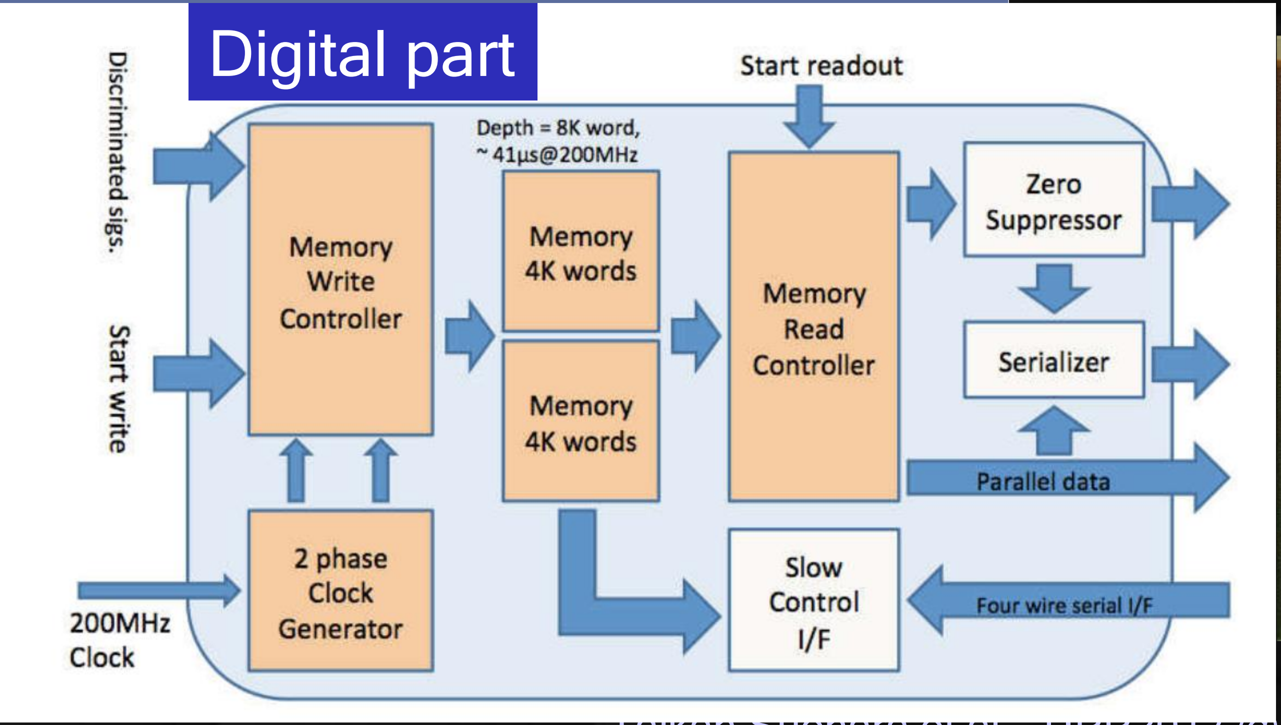


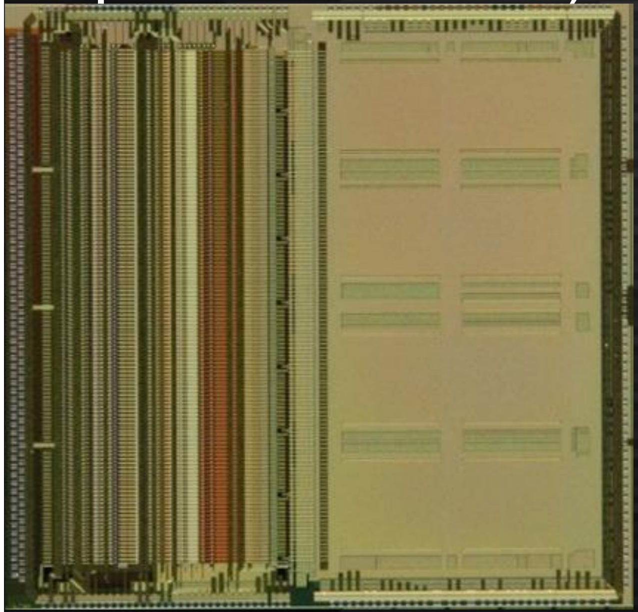
Good quality:
only a few bad channels
per 200 sensors

Readout ASIC: SliT128A (2015)



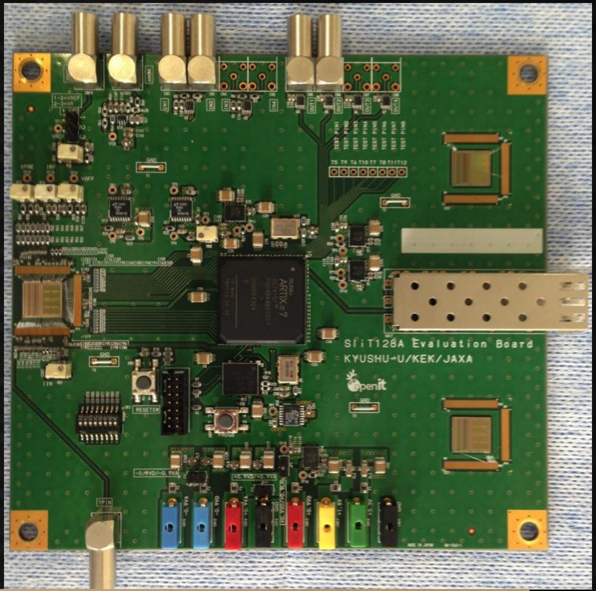
128 ch A/D mixed ASIC
200 MHz binary digitizer
for 5 ns timing & ToT
8 K words (41 μs active time)
Silterra 0.18 μm process
Modification ongoing (TEG chip will come soon)





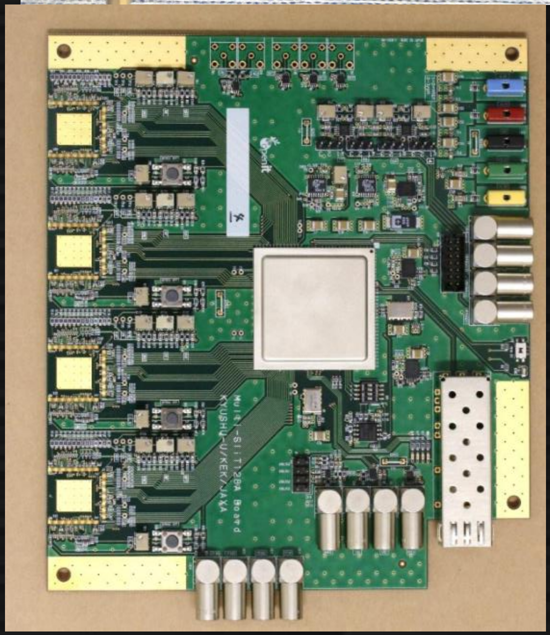
SliT128A (9 x 10 mm)

SliT128A evaluation board



Two types of evaluation boards developed

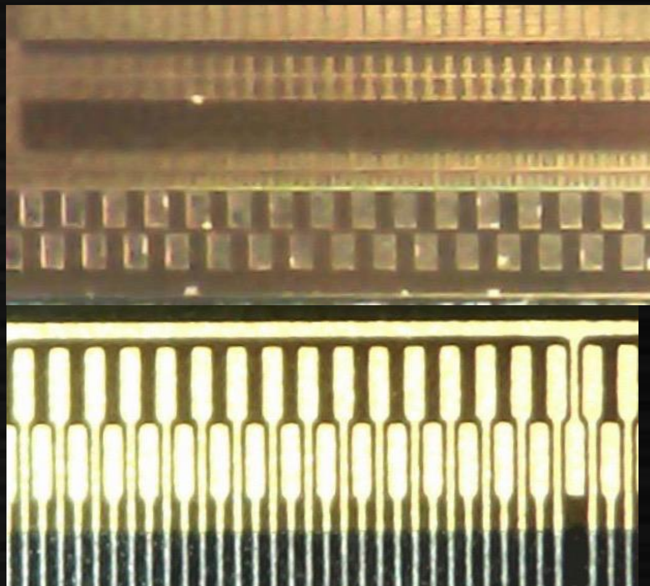
- Single SliT128A test board (2015)
  - Optimization of wire-bonding
  - Evaluation of SliT128A performance
- Multi SliT128A board (2016)
  - For test of sensor with real signal
  - Preparation of making real vanes



Specifications

- 100/100 μm (L/S) wire-bonding pads
- No capacitors under ASIC (for stable WB)
- Artix7 FPGA
- SiTCP readout with optical connector
- Voltage supply
  - 3.3V, 2.4V, 1.5V,1.2V, 1.0V (FPGA)
  - 2.4V, +/- 0.9V (ASIC)

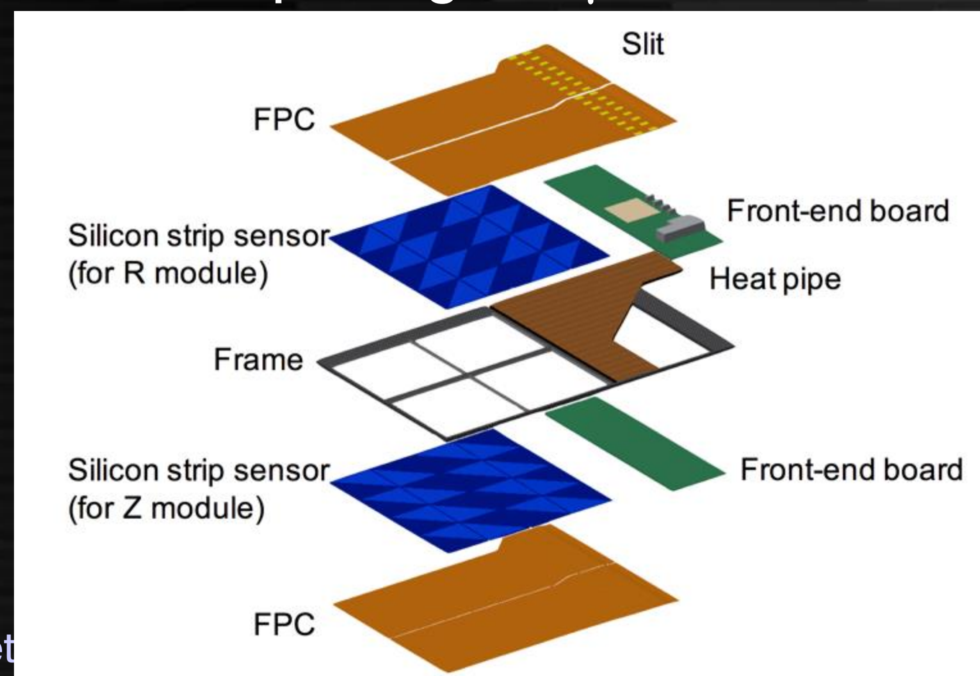
FPC development



SliT128A input pads:
125 μm pitch
houndstooth pattern

FPC (polyimide)
pitch adapter
Minimum spacing: 20 μm

Pitch adapter for SliT128A multi

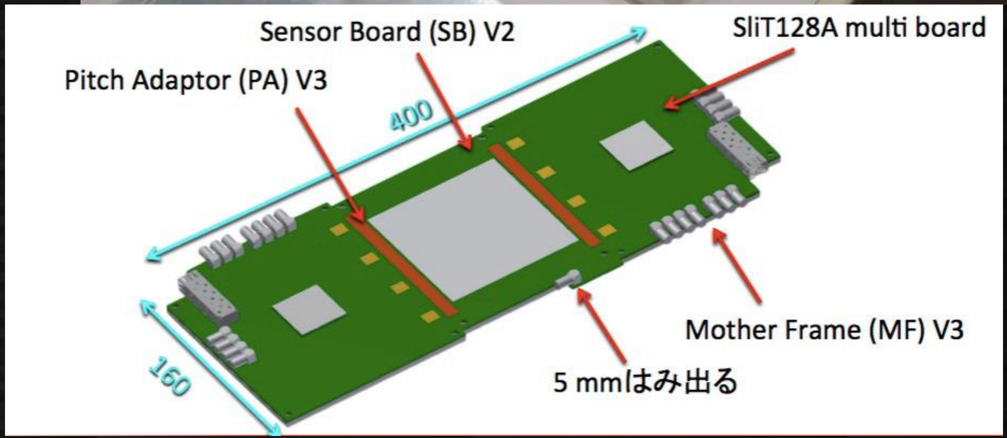


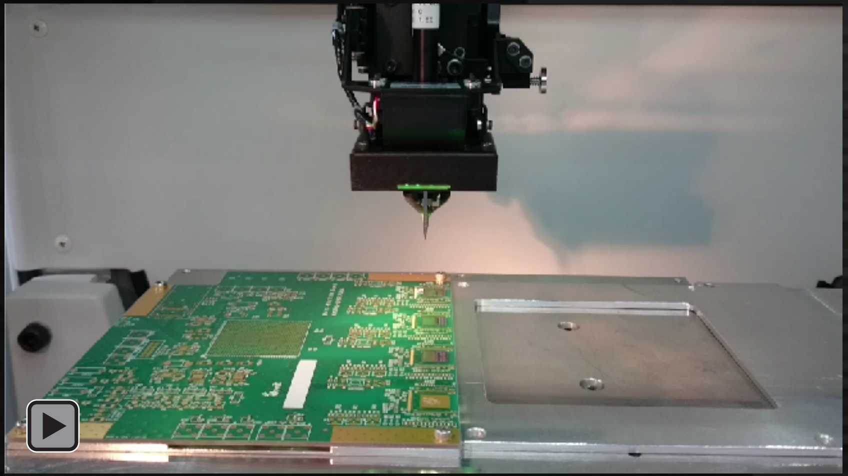
For making “real” vanes, we need large FPCs with fine pitch.
Investigation on possible specification has started, aiming at 40-50 μm line pitch

Assembly of the test system

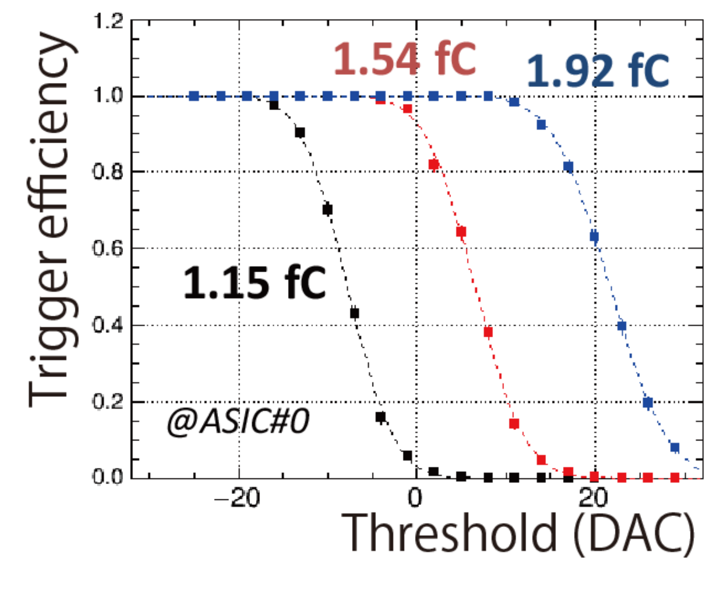
Setup for WB

1. Fix sensor board and SliT128A multi board on mother frame on Al plate
2. Glue pitch adapter, ASIC and sensor
3. Wire bonding of sensor and PA, PA and ASIC, ASIC and multi board

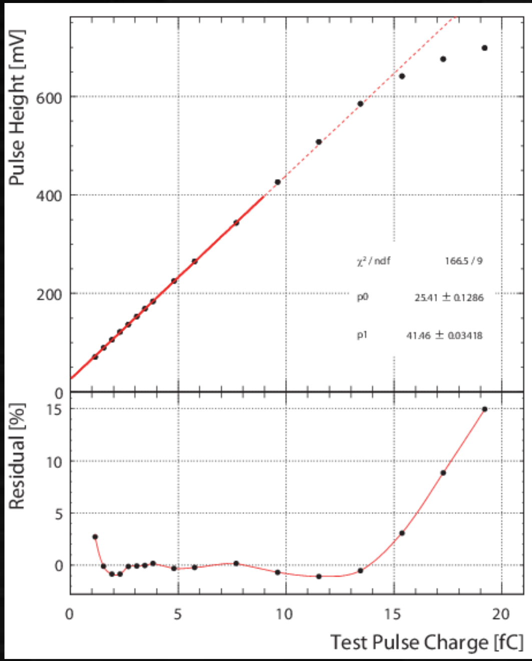




Performance evaluation

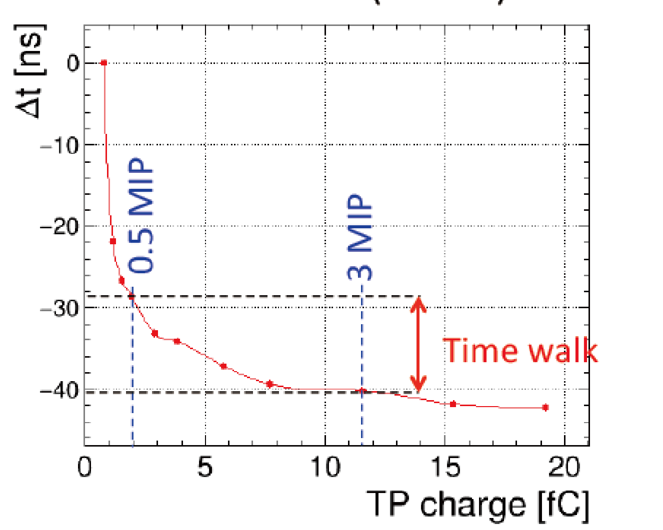


Noise measurement with test pulse by S-curve method: ENC = ~800e (S/N ~ 29 on MIP)



Dynamic range: Linearity < 5 % up to 4 MIPs

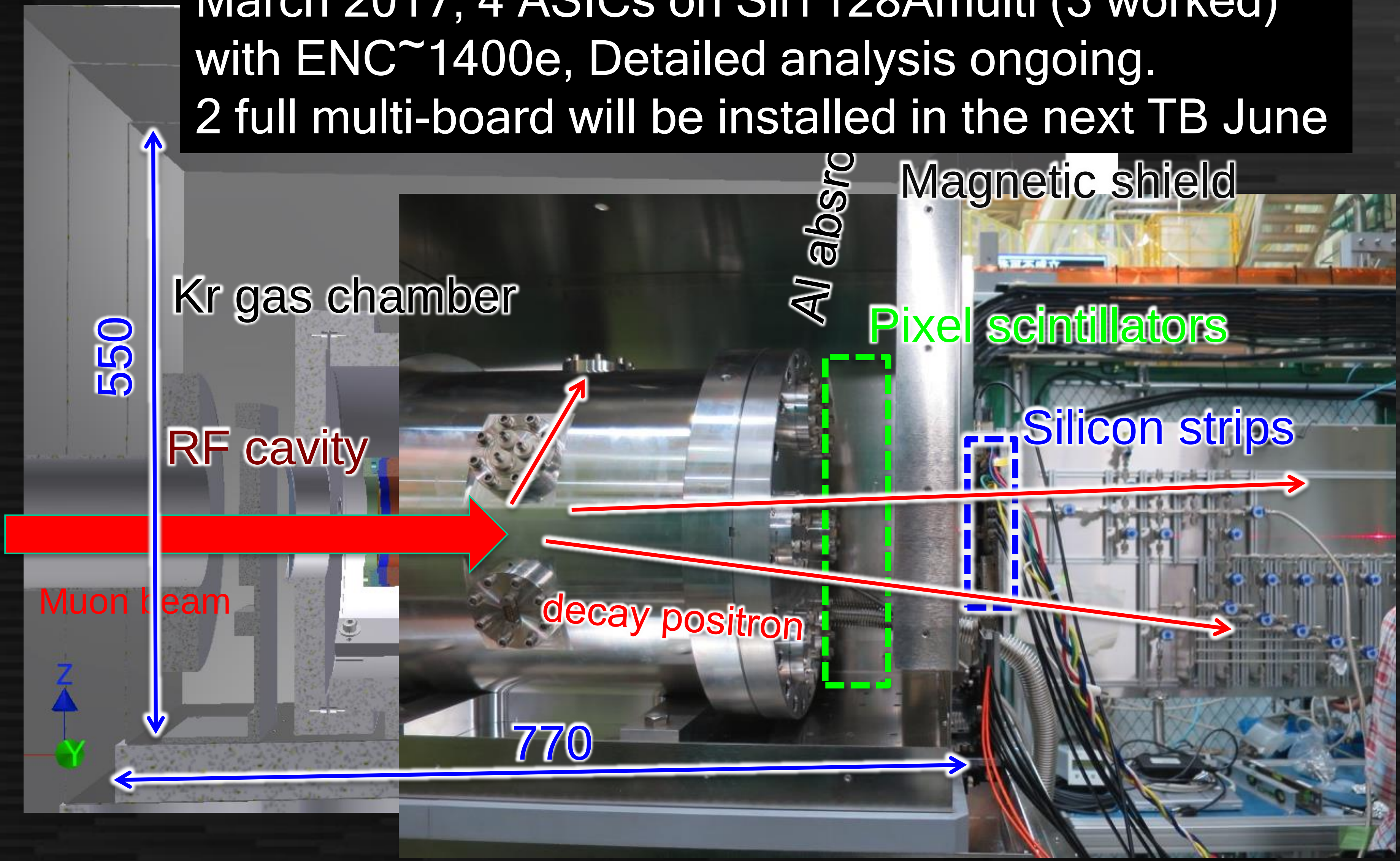
Time walk with 0.2 MIP (~5000e) threshold



Time walk of 11.5 ns (0.5-3 MIP) observed: try to improve in the next version (< 5 ns preferred)

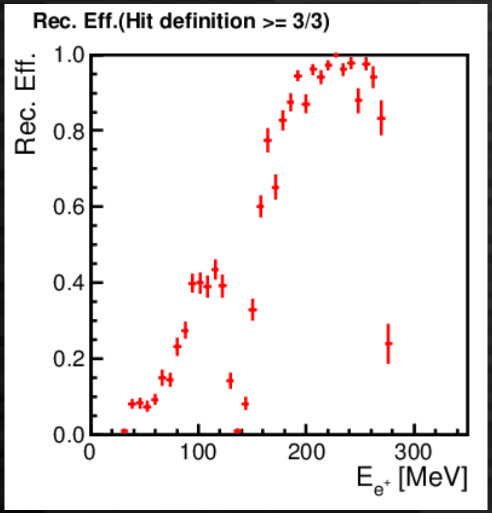
Beam test on Mu-HFS (MuSEUM) exp.

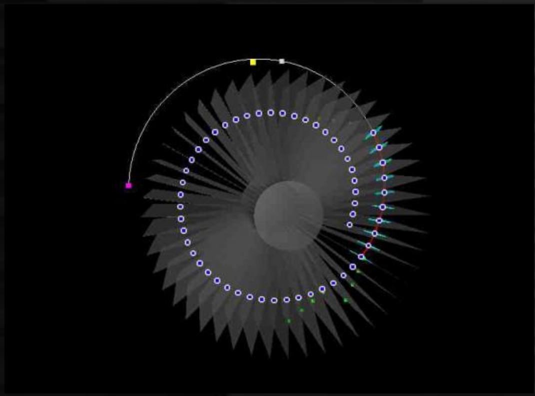
March 2017, 4 ASICs on SliT128Amulti (3 worked) with ENC~1400e, Detailed analysis ongoing.
2 full multi-board will be installed in the next TB June



Other developments

- DAQ
  - Based on DAQ middleware (KEK)
  - Synchronization on multiple FPGA under work
- Tracking software
  - Modular framework under study
  - Hough transform for track finding
  - Kalman filter (GenFit) for tracking
- Alignment
  - Laser alignment (with freq-comm technique) under study
- Timing synchronization with GPS
- Thermal study with novel heat pipe





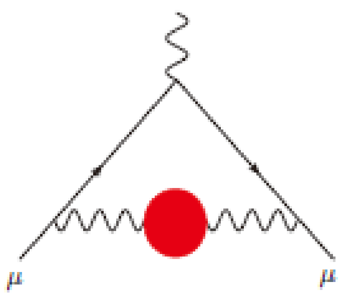
Summary and Prospects

- J-PARC E34: muon g-2/EDM measurement with novel method complementary to BNL/FNAL exp.
  - Target date: ~2019
- Silicon tracker is the main detector component
- >200 SSSD produced at HPK, with excellent quality
- SliT128A ASIC has been developed in KEK, meeting basic quality criteria, upgrade ongoing
- First detector prototype fabricated with a PCB with 4 ASICs connected with automatic wire-bonding
  - First test OK, preparing 2 layers/16 ASICs for MuSEUM run in June
- First real vane will be ready in ~ 1 year

Muon $g-2$: current status

Contribution	$a_\mu \times 10^{11}$	Reference
QED (leptons)	116 584 718.853 $\pm$ 0.036	Aoyama et al. '12
Electroweak	153.6 $\pm$ 1.0	Gnendiger et al. '13
HVP: LO	6889.1 $\pm$ 35.2	Jegerlehner '15
NLO	-99.2 $\pm$ 1.0	Jegerlehner '15
NNLO	12.4 $\pm$ 0.1	Kurz et al. '14
HLbL	116 $\pm$ 40	Jegerlehner, AN '09
NLO	3 $\pm$ 2	Colangelo et al. '14
Theory (SM)	116 591 794 $\pm$ 53	
Experiment	116 592 089 $\pm$ 63	Bennett et al. '06
Experiment - Theory	295 $\pm$ 82	3.6 σ

$a_\mu^{\mathrm{HVP}} =$

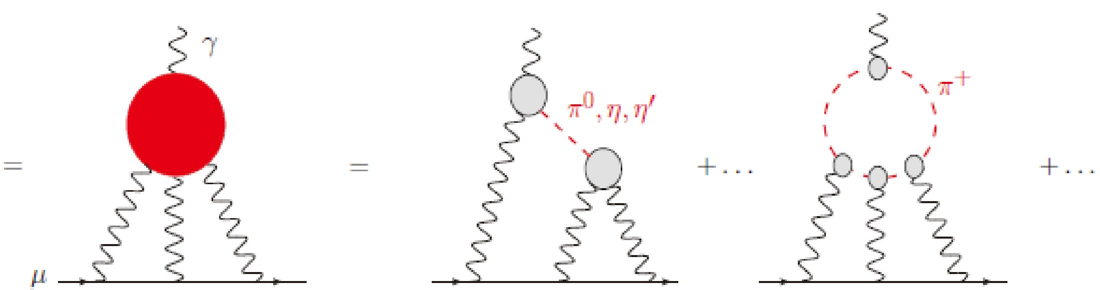


$$a_\mu^{\mathrm{HVP}} = \frac{1}{3}\left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty \frac{ds}{s} K(s)\, R(s),$$

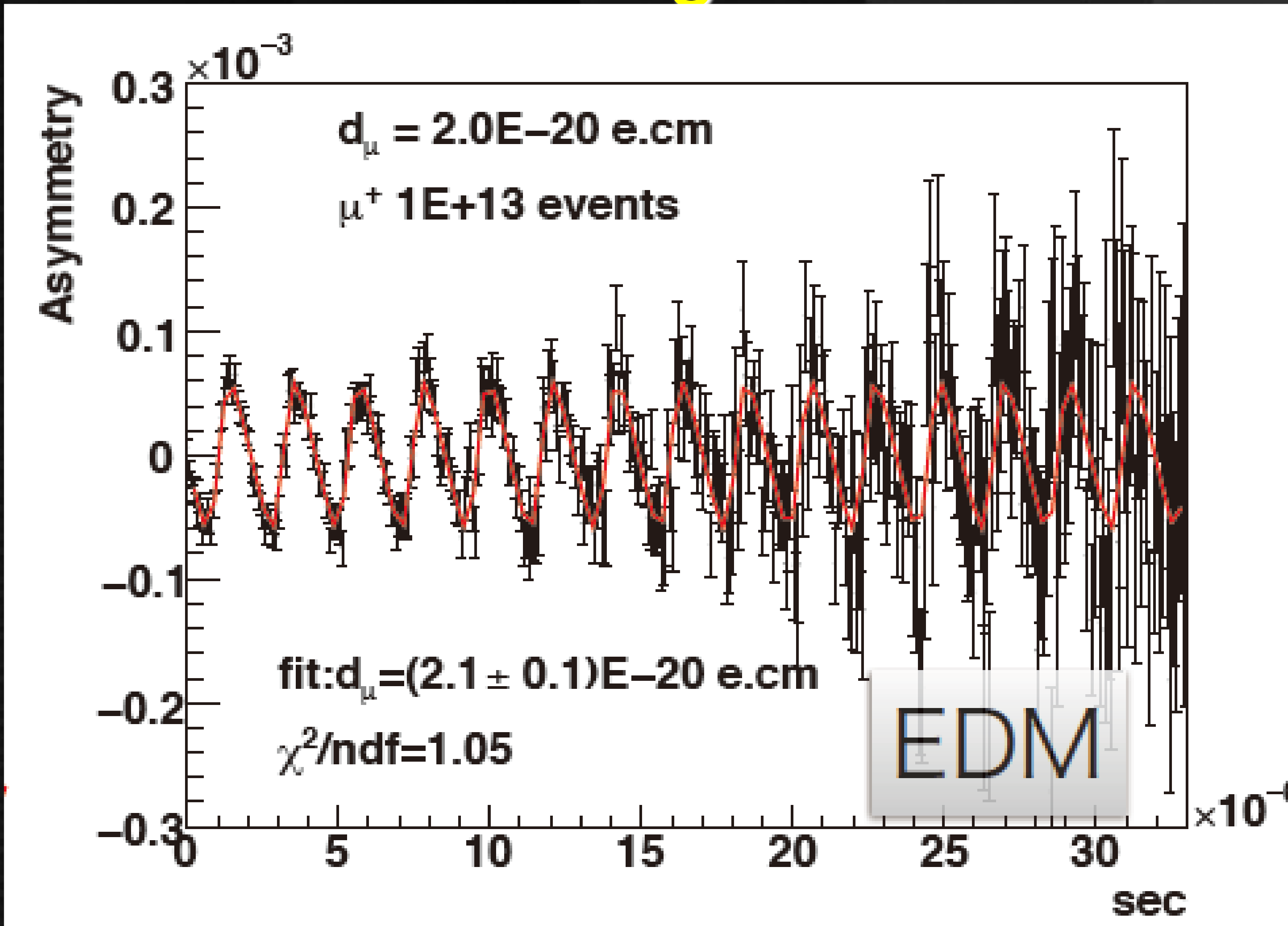
$$R(s) = \frac{\sigma(e^+e^- \to \gamma^* \to \mathrm{hadrons})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

Hadronic light-by-light scattering in muon $g-2$ from strong interactions (QCD):

$a_\mu^{\mathrm{had.\,LxL}} =$



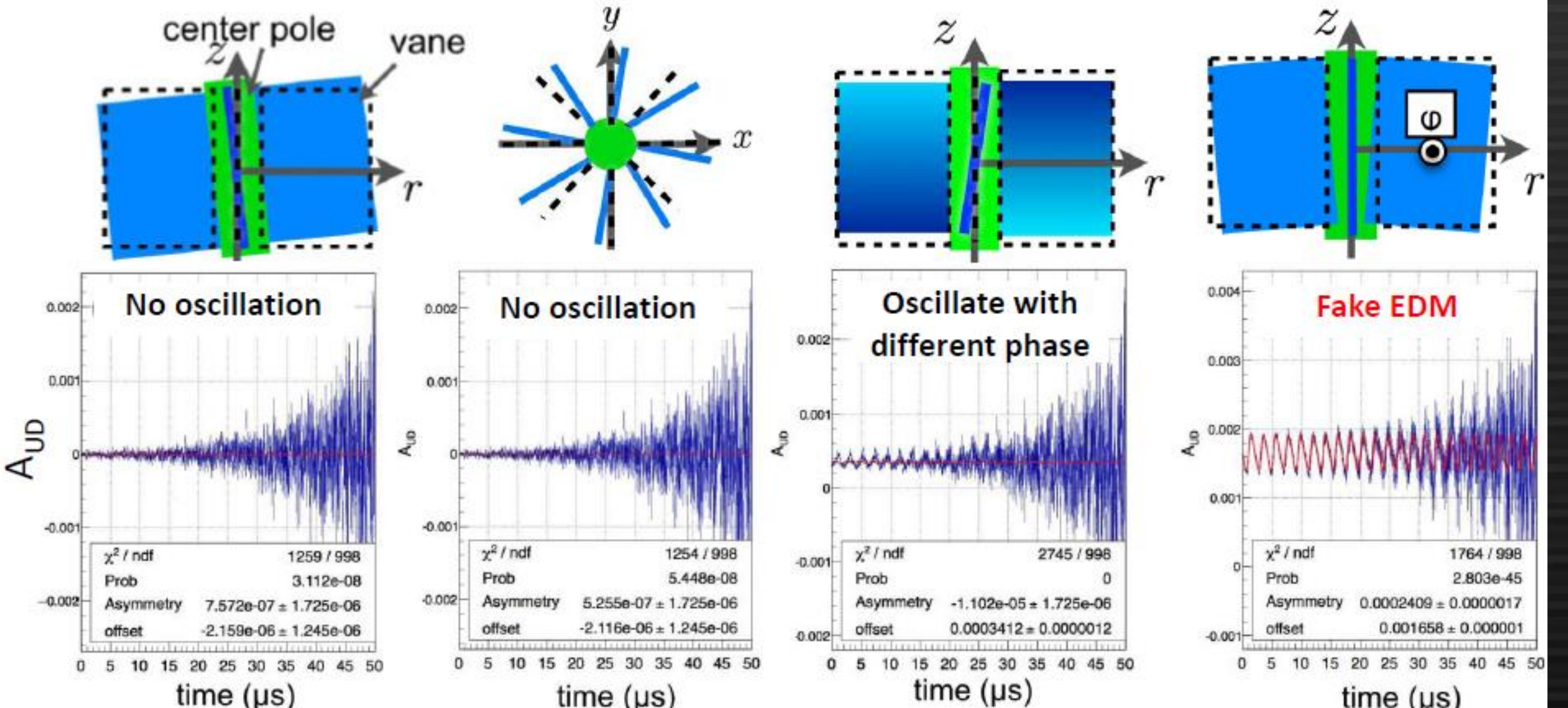
EDM signature



Fake EDM Signal by Misalignment

- EDM is measured from up-down asymmetry "A_{UD}".

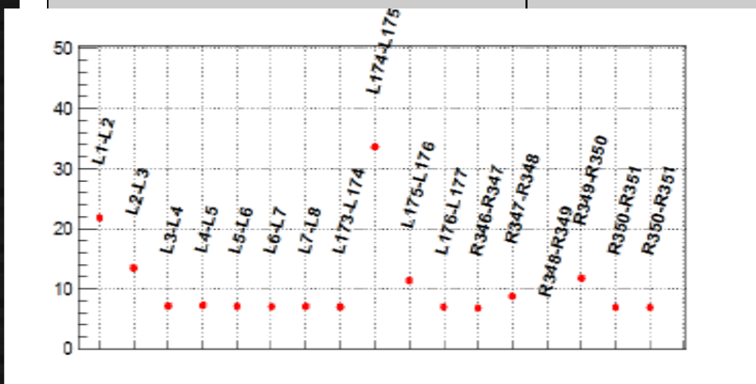
Simulation with 1 mrad misalignment and null EDM signal



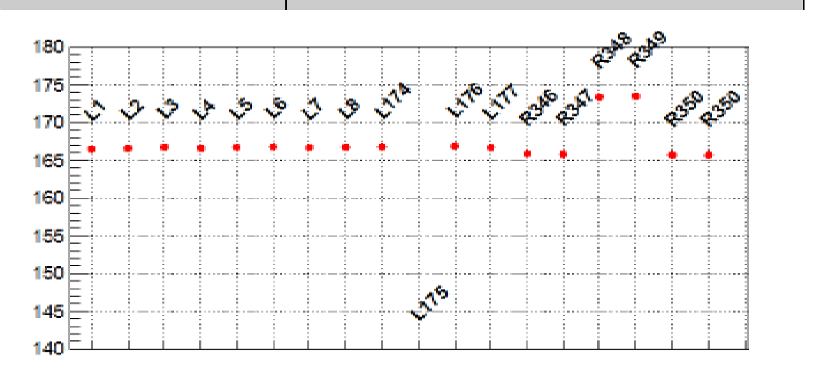
➢ The alignment must be controlled with 10 μrad accuracy to measure EDM with $10^{-21} e \cdot \mathrm{cm}$ (final goal).

Silicon sensor DC characteristics

測定項目	測定結果	理論値
I-V	plateau were observed	-
C total	3050 pF	3100 pF
Full depletion voltage	~ 80 V	~ 80 V
C interstrip	7.1 pF	3.0 pF + α
Detector Capacitance	17 pF	9 pF + α
C coupling	167 pF	164 pF
R Polysilicon	～12 MΩ	5～15 MΩ

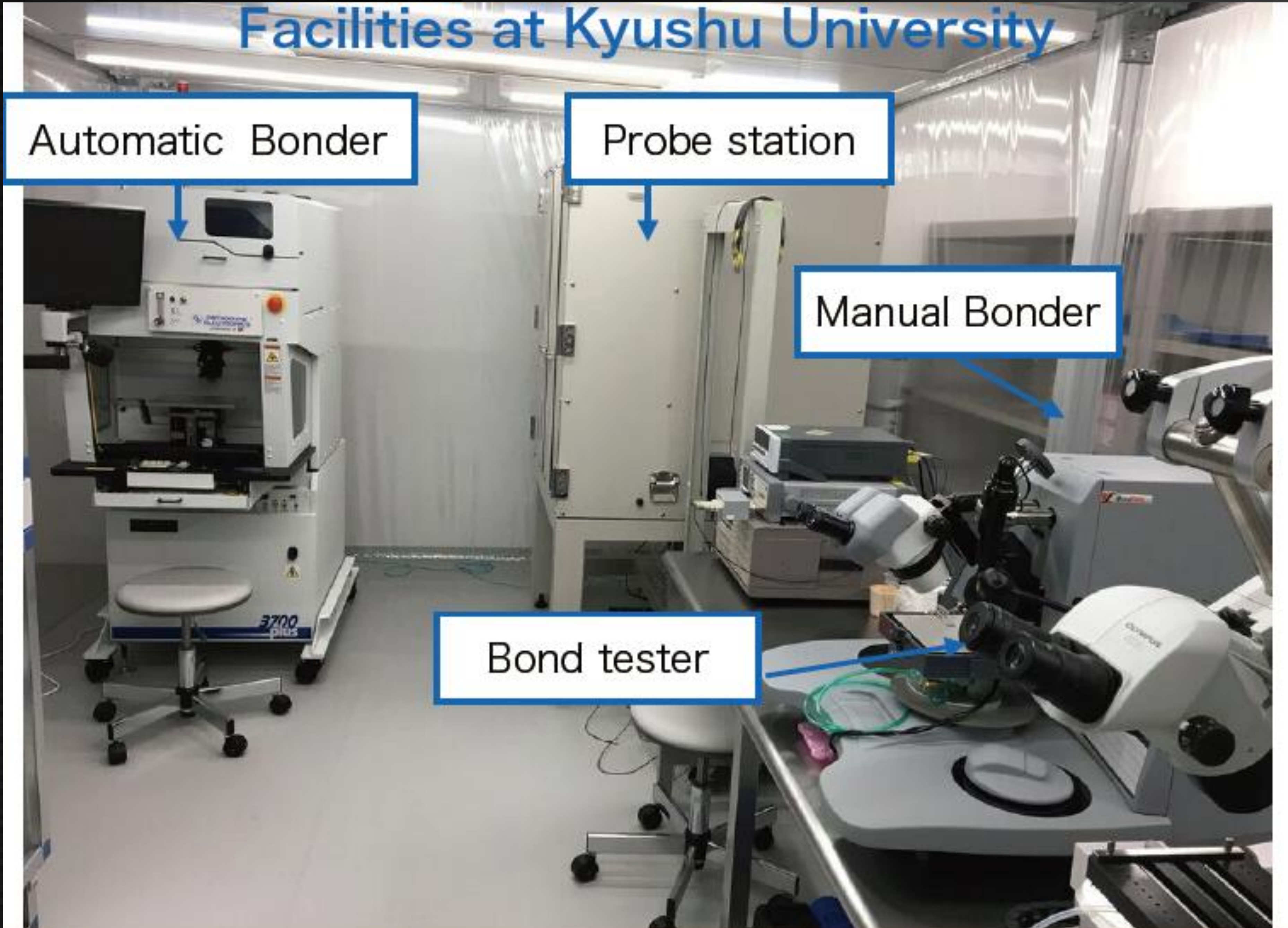


C interstrip

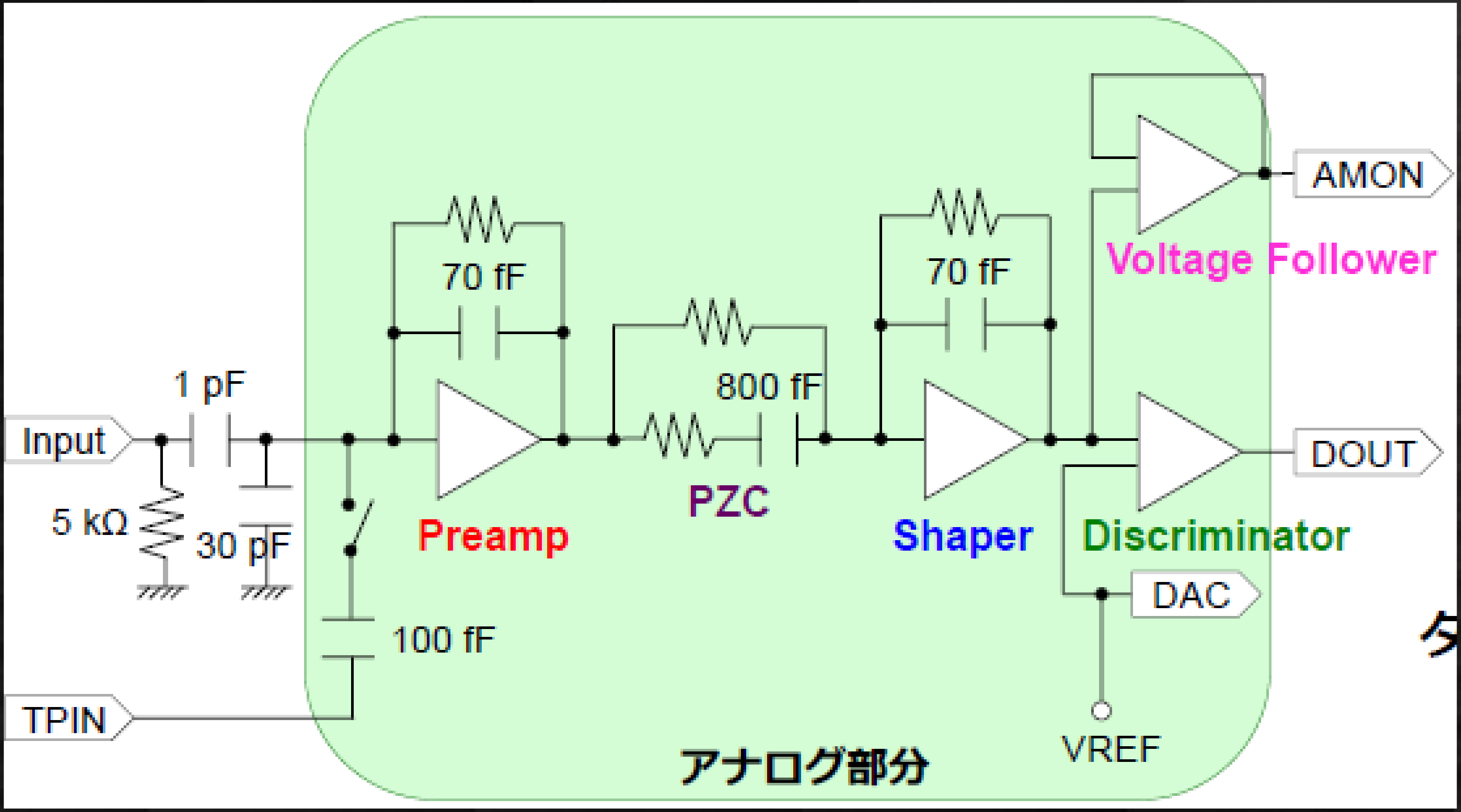


C coupling

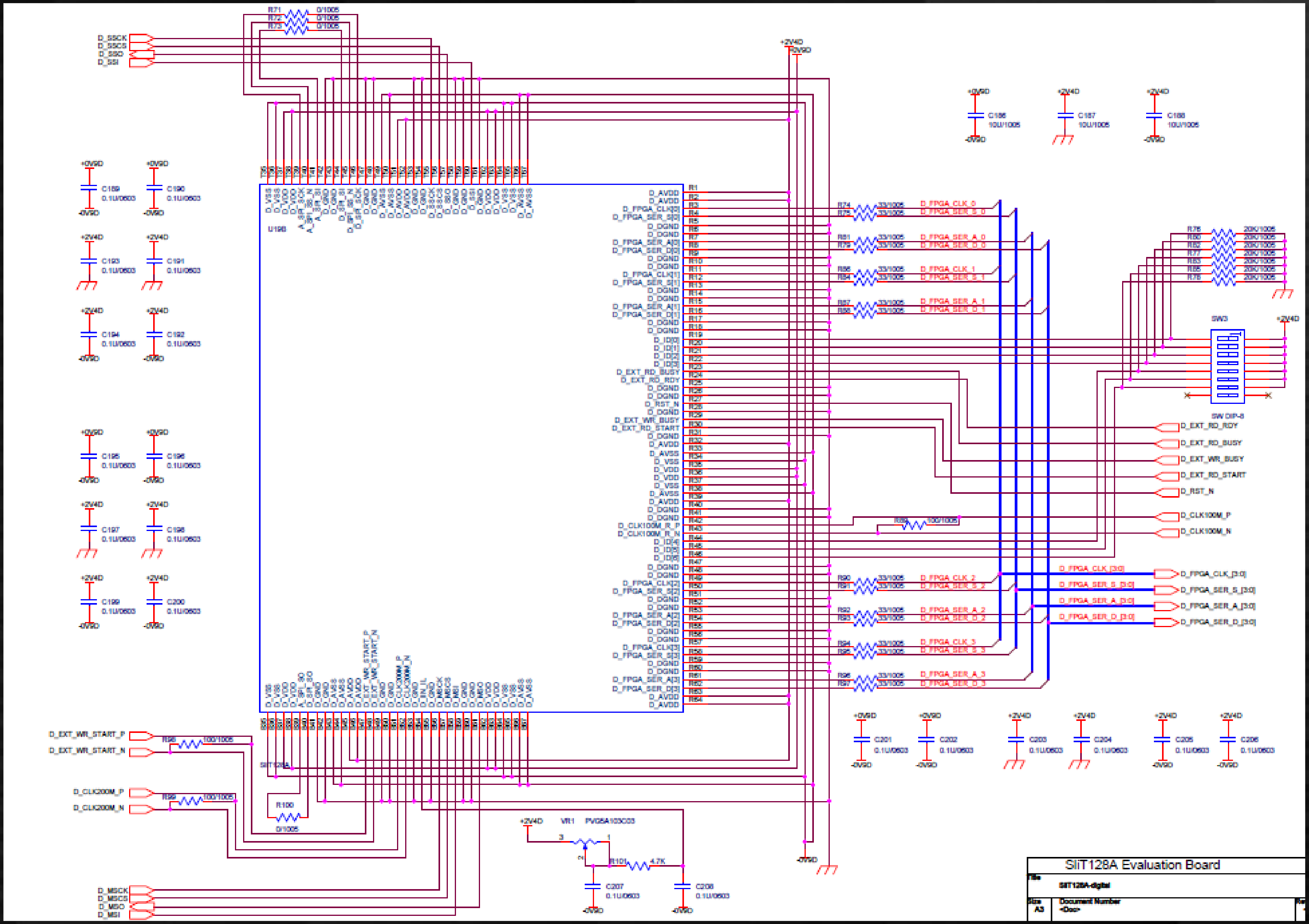
Facilities at Kyushu University



SliT128A: analog part

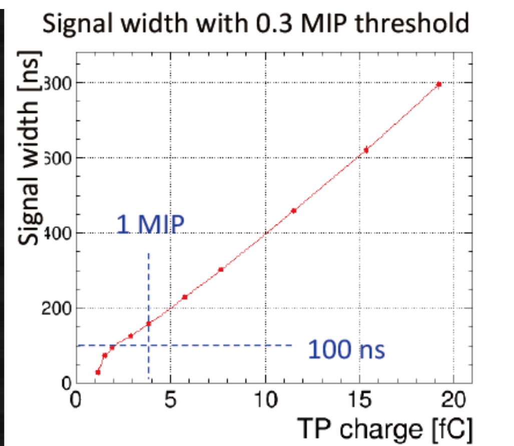


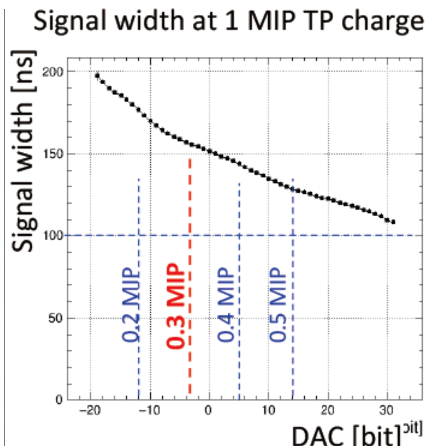
SliT128A: digital I/F

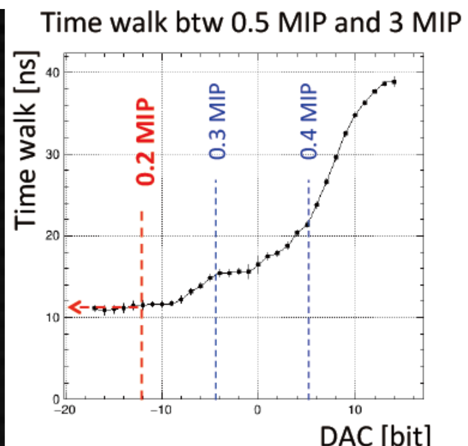


SliT128A without sensor

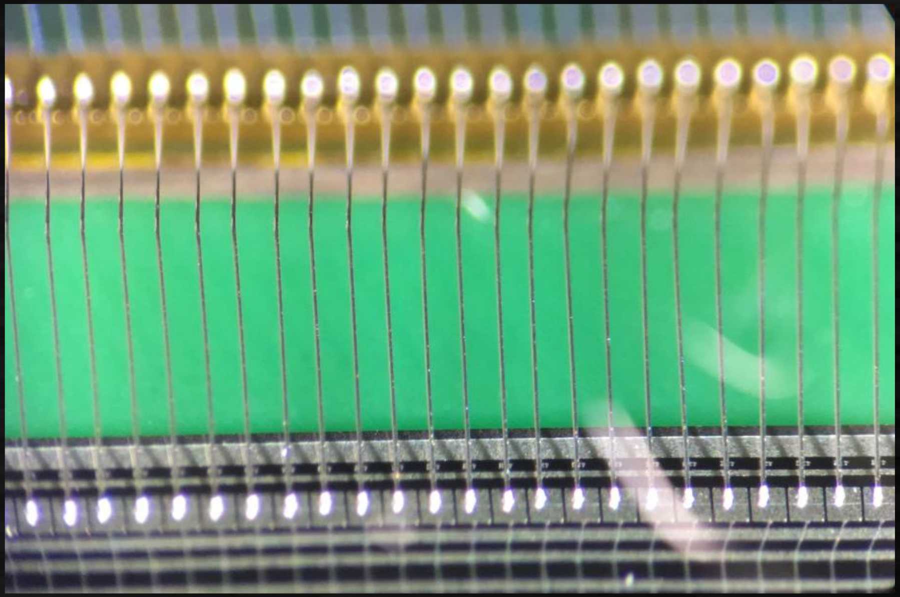
Parameter	Requirement	SliT128A TEG Simulation	SliT128A TEG Result	SliT128A Result
Dynamic range	~ 3 MIP	~4 MIP	~3 MIP	**4 MIP**
ENC	< 1600 e	1210 e	1070 e	430 e
Pulse width (1 MIP)	< 100 ns	53.5 ns	96.0 ns	155 ns
Time walk (0.5 - 3 MIP threshold)	< 5 ns	6.5 ns	14.6 ns	11.5 ns
Power consumption	5 mW/ch	-	-	**0.44 W/chip**



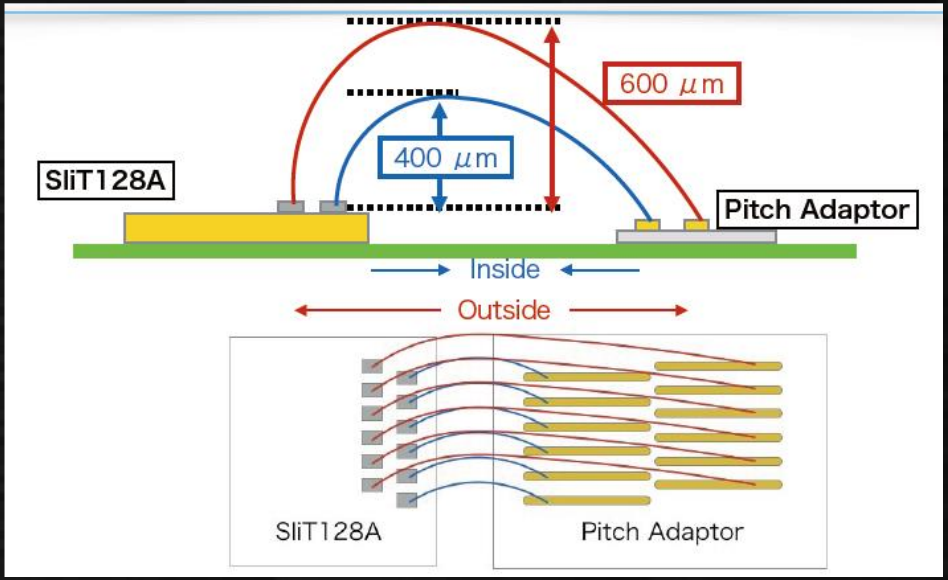


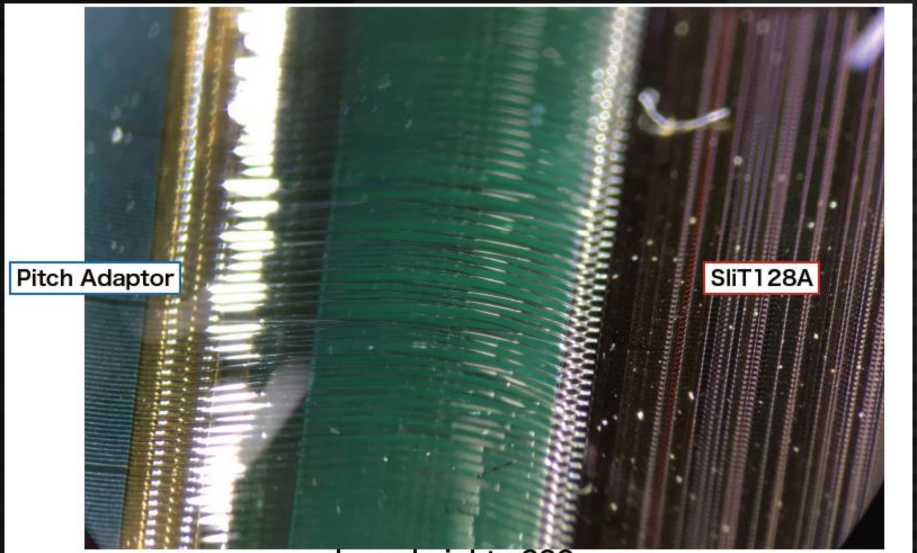


Wire bonding



25 μm aluminum wire
Bonding force: 8-9 g





Loop height : 600 μm