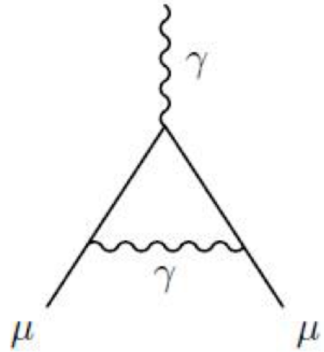
Development of Silicon-strip tracker for muon g-2 and EDM measurements at J-PARC

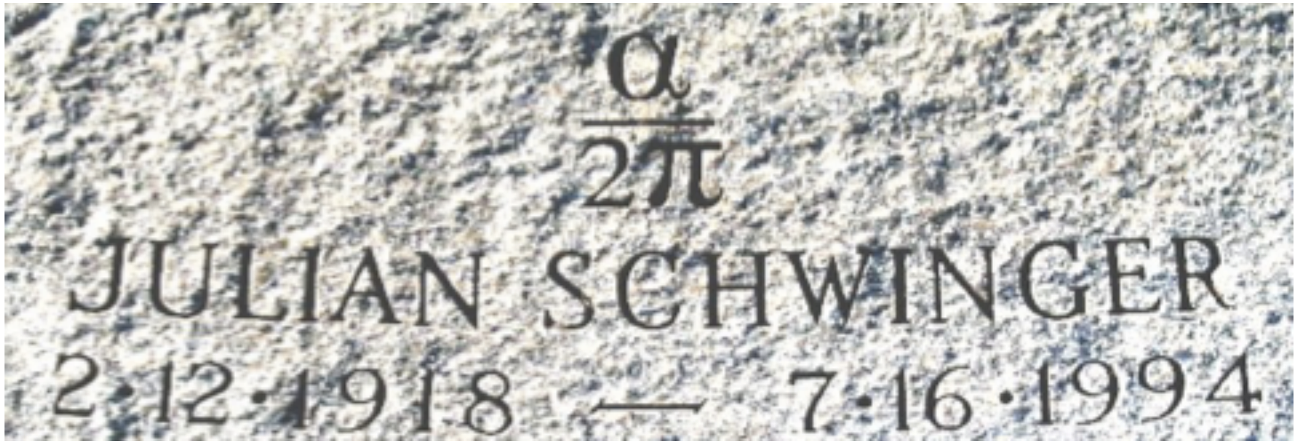
LPNHE, Paris
February 22, 2012

Tsutomu Mibe (KEK)
for the J-PARC muon g-2/EDM collaboration

Quantum loop

The Schwinger term





From Lepton Moments (World Scientific, 2010)

Particle dipole moments

Hamiltonian of spin 1/2 particle includes

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

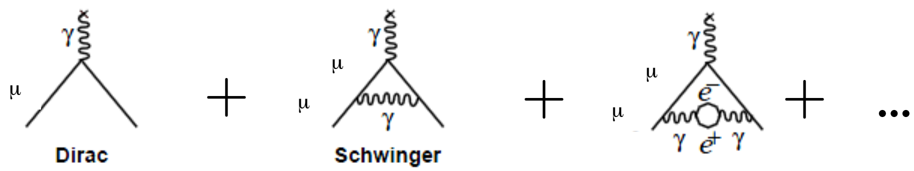
Magnetic dipole moment $\quad \vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s},$

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

Magnetic dipole moment

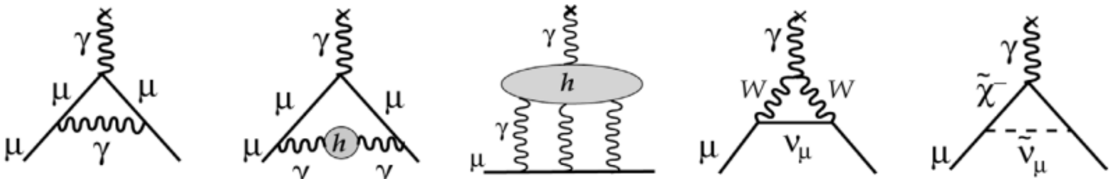
g = 2 from Dirac equation, in general g≠2 due to quantum-loop effects

$$a_\mu = \frac{g-2}{2} =$$



a “anomalous magnetic moment”

More loops



QED Up to 5-loop leading Kinoshita et al	Hadronic vacuum polarization (HVP)	Light-by-light scattering (LBL)	Electroweak at twe-loop level	Beyond SM

QED contribution	11 658 471.808 (0.015) $\times 10^{-10}$	Kinoshita & Nio, Aoyama et al
EW contribution	15.4 (0.2) $\times 10^{-10}$	Czarnecki et al
Hadronic contribution		
LO hadronic	**694.9 (4.3)** $\times 10^{-10}$	HLMNT11
NLO hadronic	-9.8 (0.1) $\times 10^{-10}$	HLMNT11
light-by-light	10.5 (2.6) $\times 10^{-10}$	Prades, de Rafael & Vainshtein
Theory TOTAL	**11 659 182.8 (4.9)** $\times 10^{-10}$	
Experiment	**11 659 208.9 (6.3)** $\times 10^{-10}$	world avg
Exp − Theory	**26.1 (8.0)** $\times 10^{-10}$	**3.3 σ discrepancy**

(Numbers taken from HLMNT11, arXiv:1105.3149)

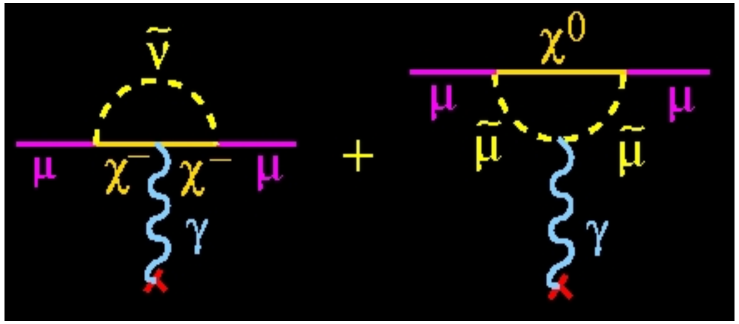
D. Nomura (PhiPsi11)

Anomalous magnetic moment : g-2

- Standard model can predict g-2 with ultra high precision

Lepton (l)	a_l	$\Delta a_l(\exp)/a_l$	$\Delta a_l(SM)/a_l$
electron	$115\ 965\ 218\ 073(28) \times 10^{-14}$	0.24ppb	4.5 ppb
muon	$116\ 592\ 080(63) \times 10^{-11}$	0.54ppm	0.41ppm
tau	$< 2 \times 10^{-2}$		

- Useful in searching for new particles and/or interactions



$$\left|a_\mu^{\rm SUSY}\right| \simeq 130 \times 10^{-11} \left(\frac{100\ {\rm GeV}}{\widetilde{m}}\right)^2 \tan\beta,$$

- Experiment has reached the sensitivity to see such effects...

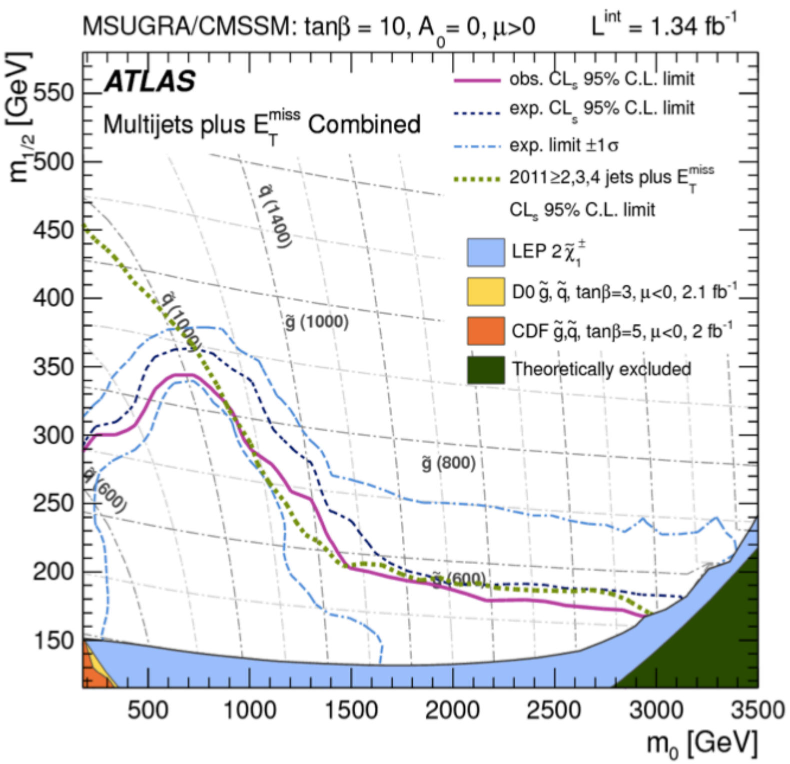
$$a_\mu^{\exp} - a_\mu^{SM} = \begin{array}{l}(261 \pm 80) \times 10^{-11} \\ (259 \pm 81) \times 10^{-11}\end{array}$$

HLMNT11

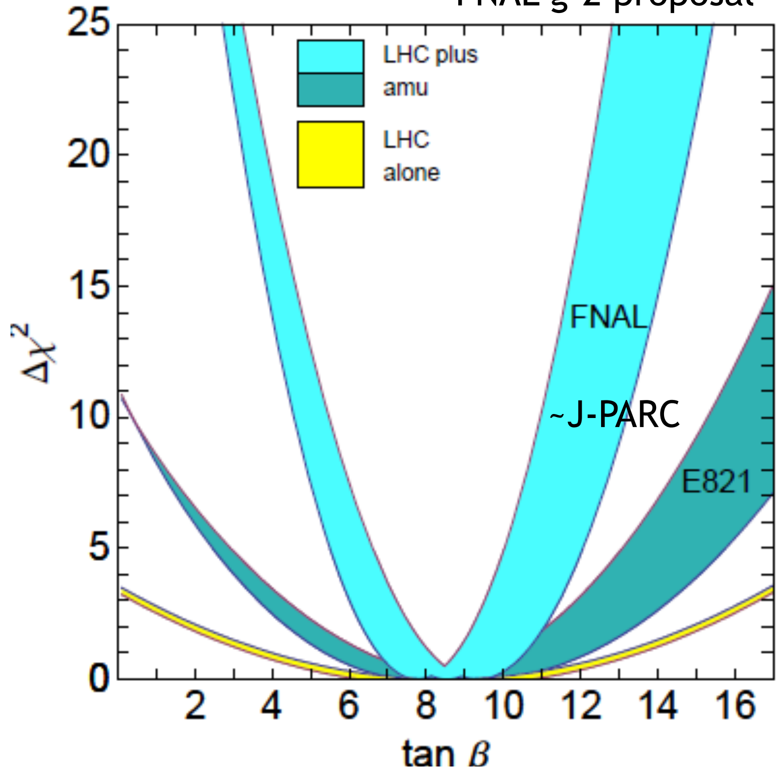
DHMZ, Tau 2010 workshop

➡ 3.3 ”standard deviations“

Hunting for SUSY (or other BSM) signature



FNAL g-2 proposal



$$\left|a_{\mu}^{\mathrm{SUSY}}\right| \simeq 130 \times 10^{-11}\left(\frac{100\ \mathrm{GeV}}{\widetilde{m}}\right)^{2} \tan\beta,$$

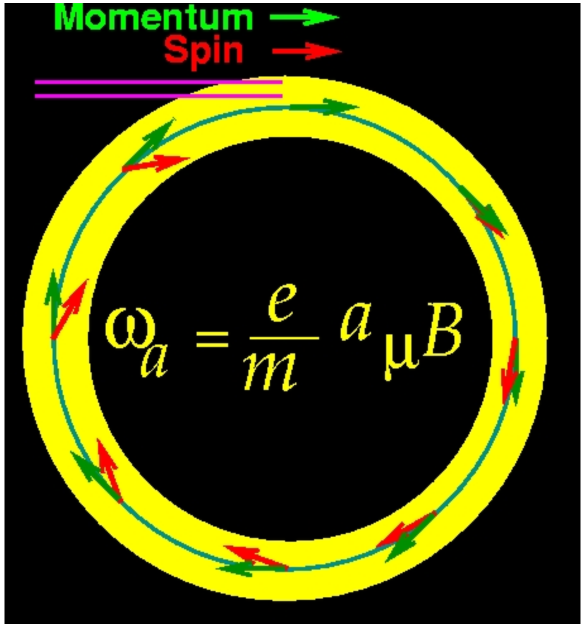
g-2 measurement is complementary to LHC and cLFV

More on physics discussions at Naohito's seminar at LAL/Orsay tomorrow.

Muon anomalous spin precession in B and E-field

- Muon spin rotates "ahead" of momentum due to g-2 >0.
- Precession frequency

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



- BNL E821
  - Focusing **electric field** to confine muons.
  - At the **magic momentum**

    $\gamma = 29.3$, $p = 3.094$ GeV/c → $(a_\mu - 1/(\gamma^2-1)) = 0$

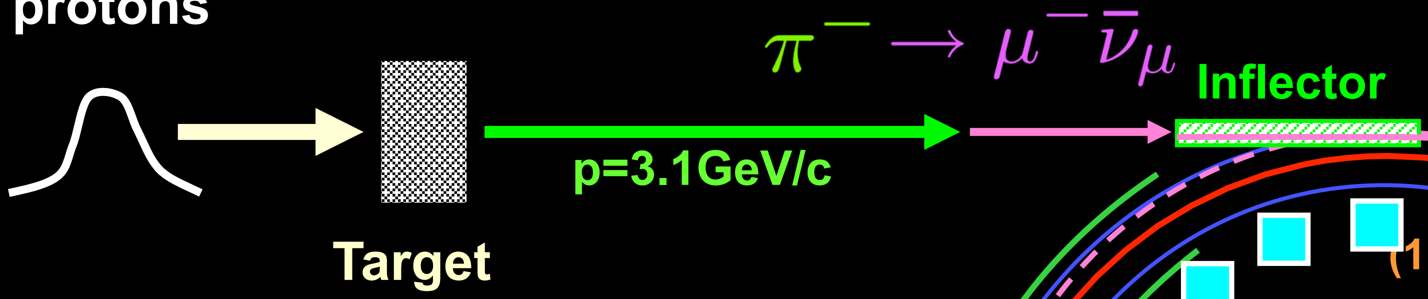
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}} + \cancel{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)}\right]$$

Safely be neglected with current upper limit on EDM

Continuation of the experiment at FNAL is planned.

BNL E821 Experimental Technique

25ns bunch of
$\geqslant$ 1 X 10^{12}
protons



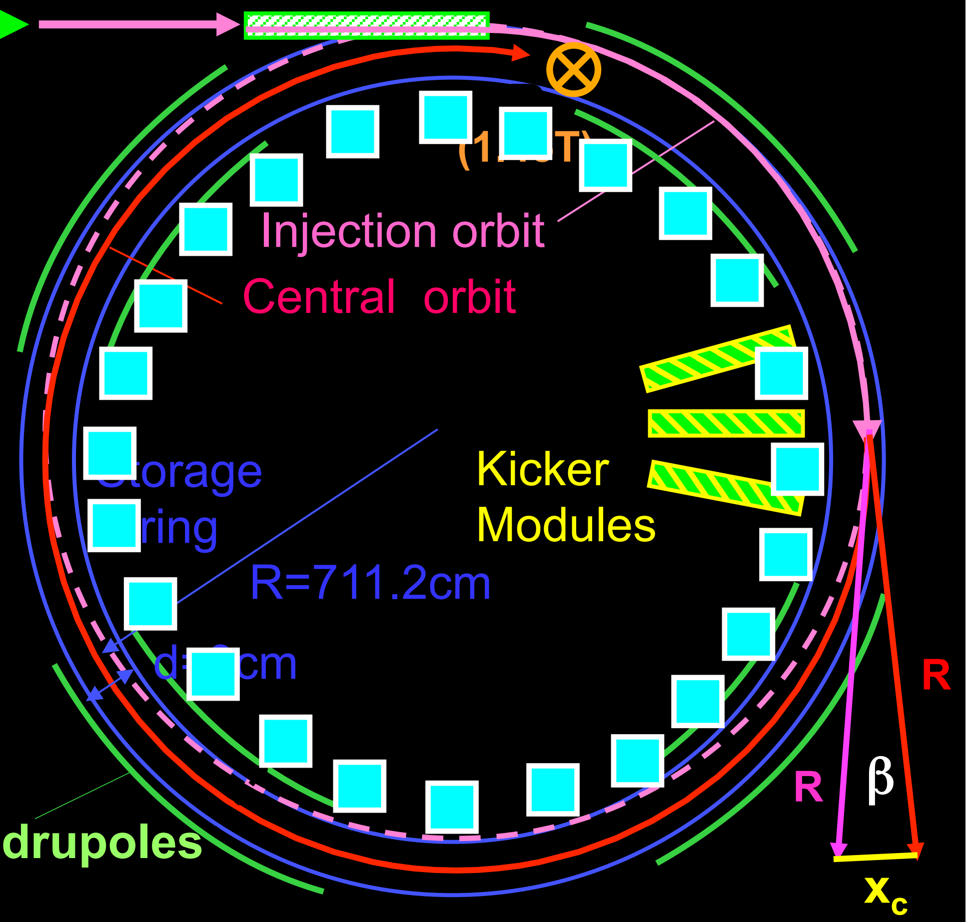
$x_c \approx 77$ mm

$\beta \approx 10$ mrad

B·dl ≈ 0.1 Tm

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

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

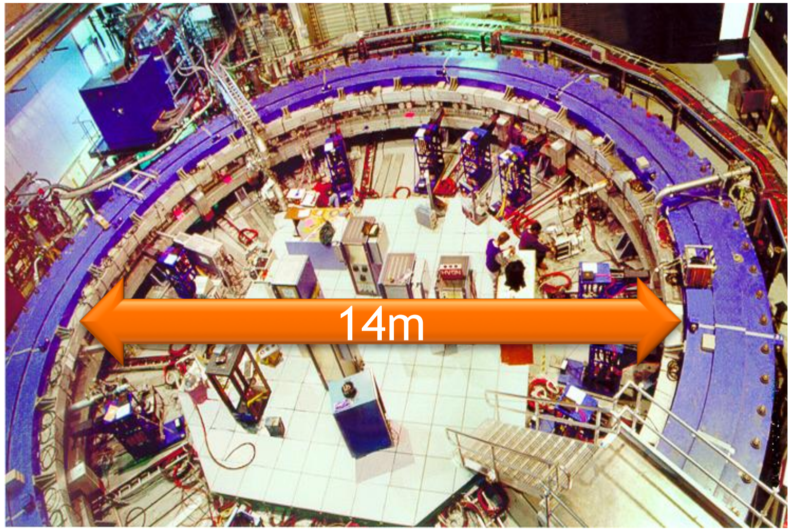


Slide from Lee Roberts

Our approach

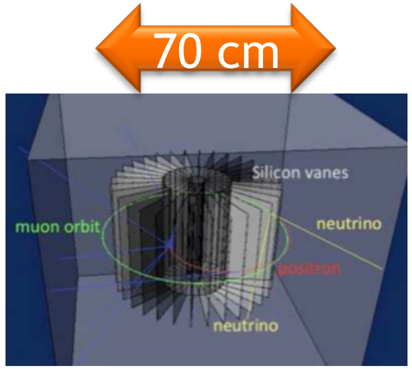
Compact storage ring

BNL E821 / FNAL g-2



P= 3.1 GeV/c , B=1.45 T

J-PARC g-2



P= 0.3 GeV/c , B=3.0 T

– Suited for precision control of B-field
  - Example : MRI magnet , 1ppm local uniformity

- <u>Completely different systematics than the BNL E821 or FNAL</u>

Our approach (cont')

Zero Focusing Electric field (E = 0)

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

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

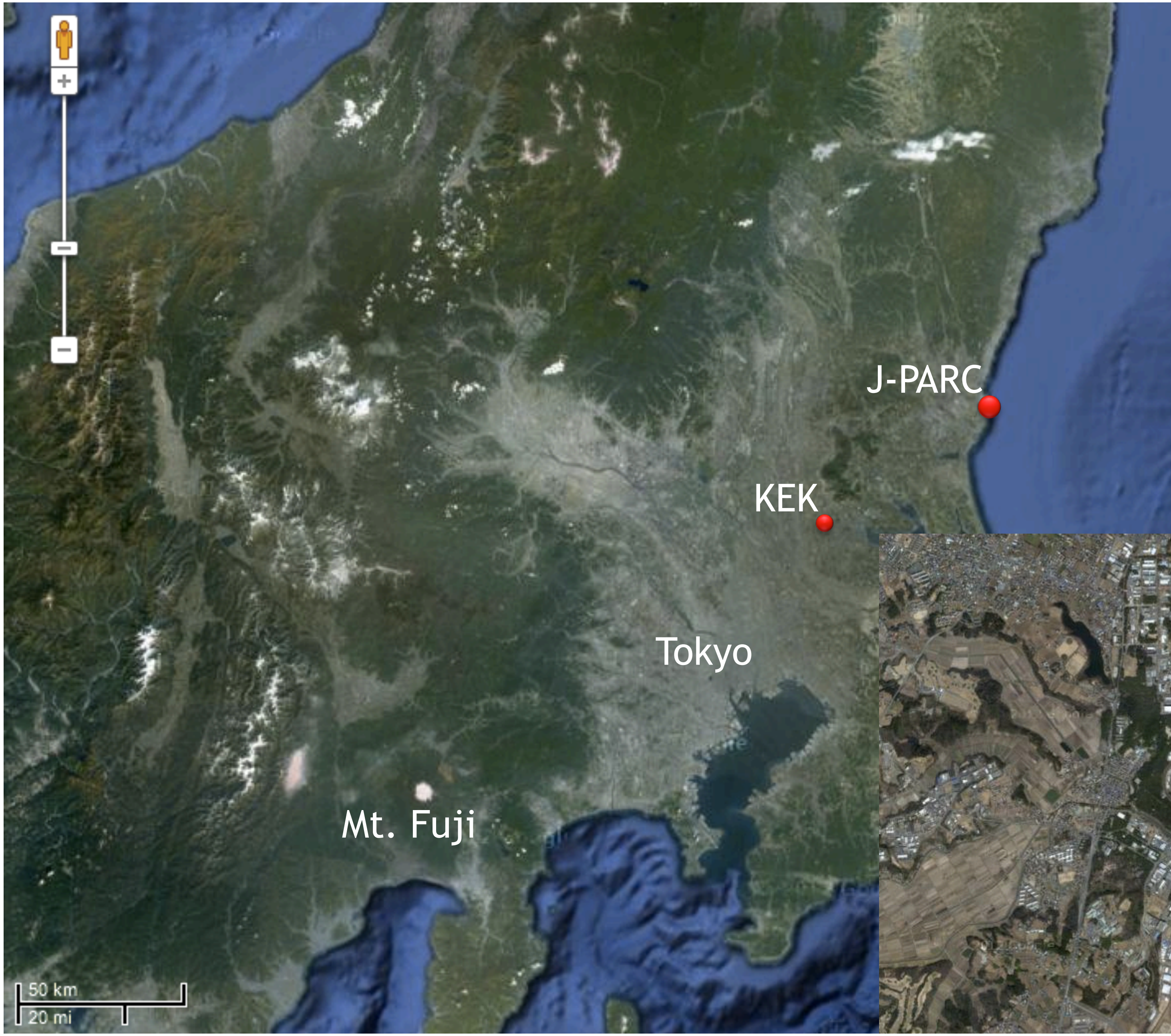
Equations of spin motion is as simple as at the magic momentum

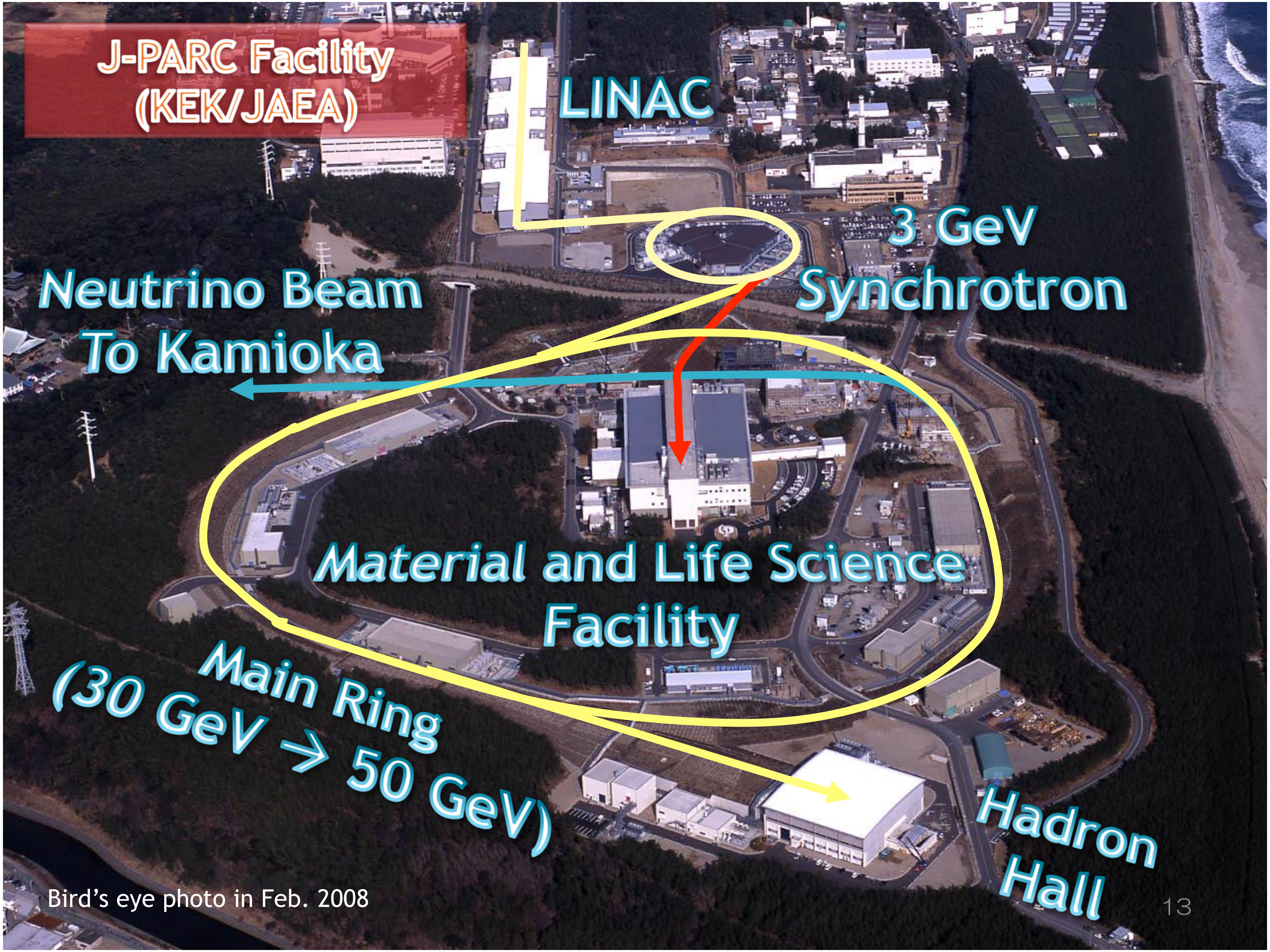
Ultra-cold muon beam ($p_T/p < 10^{-5}$) by utilizing the laser resonant ionization of muonium makes it possible to realize such experimental condition.

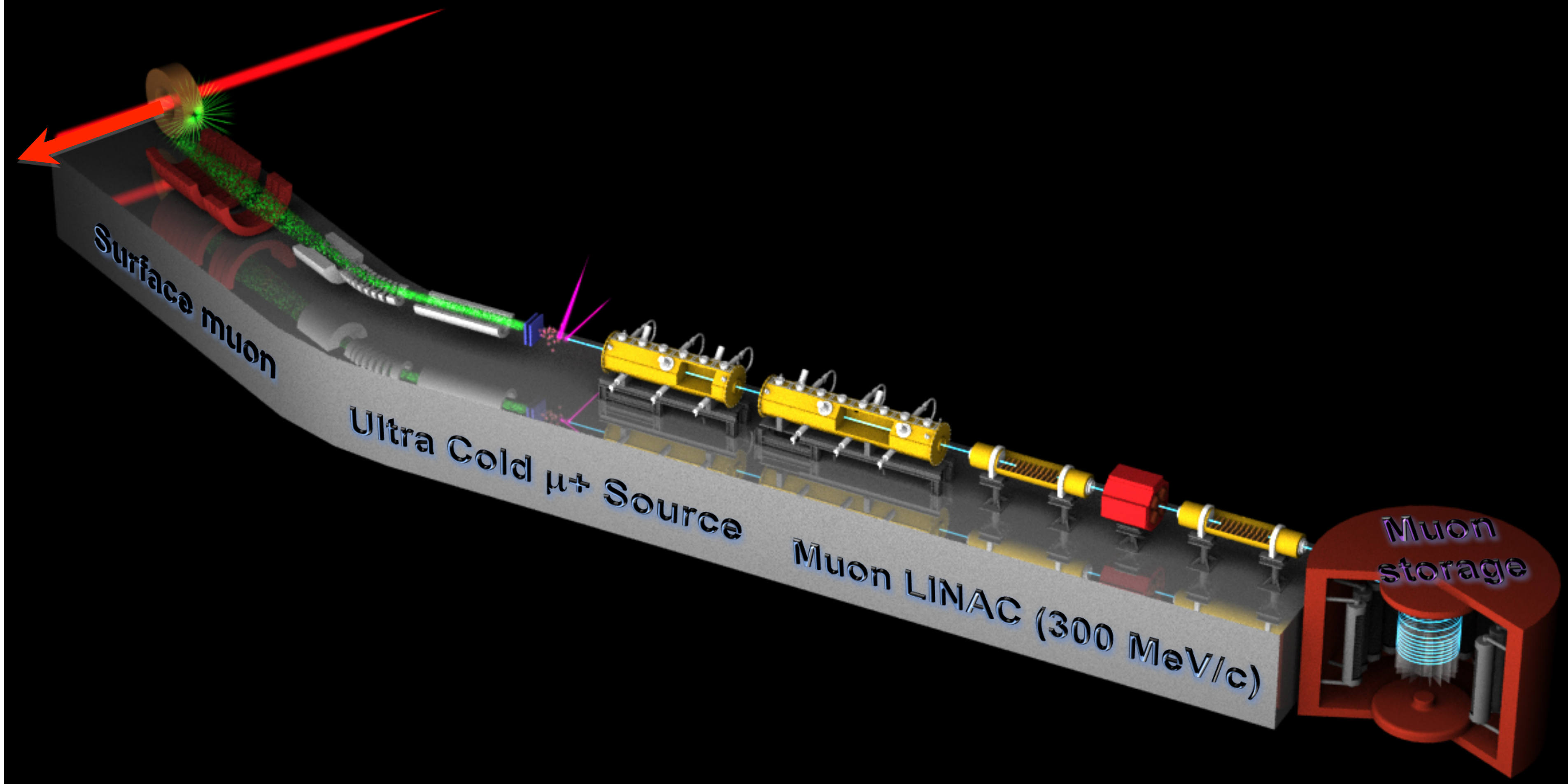
BNL, FNAL, and J-PARC

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

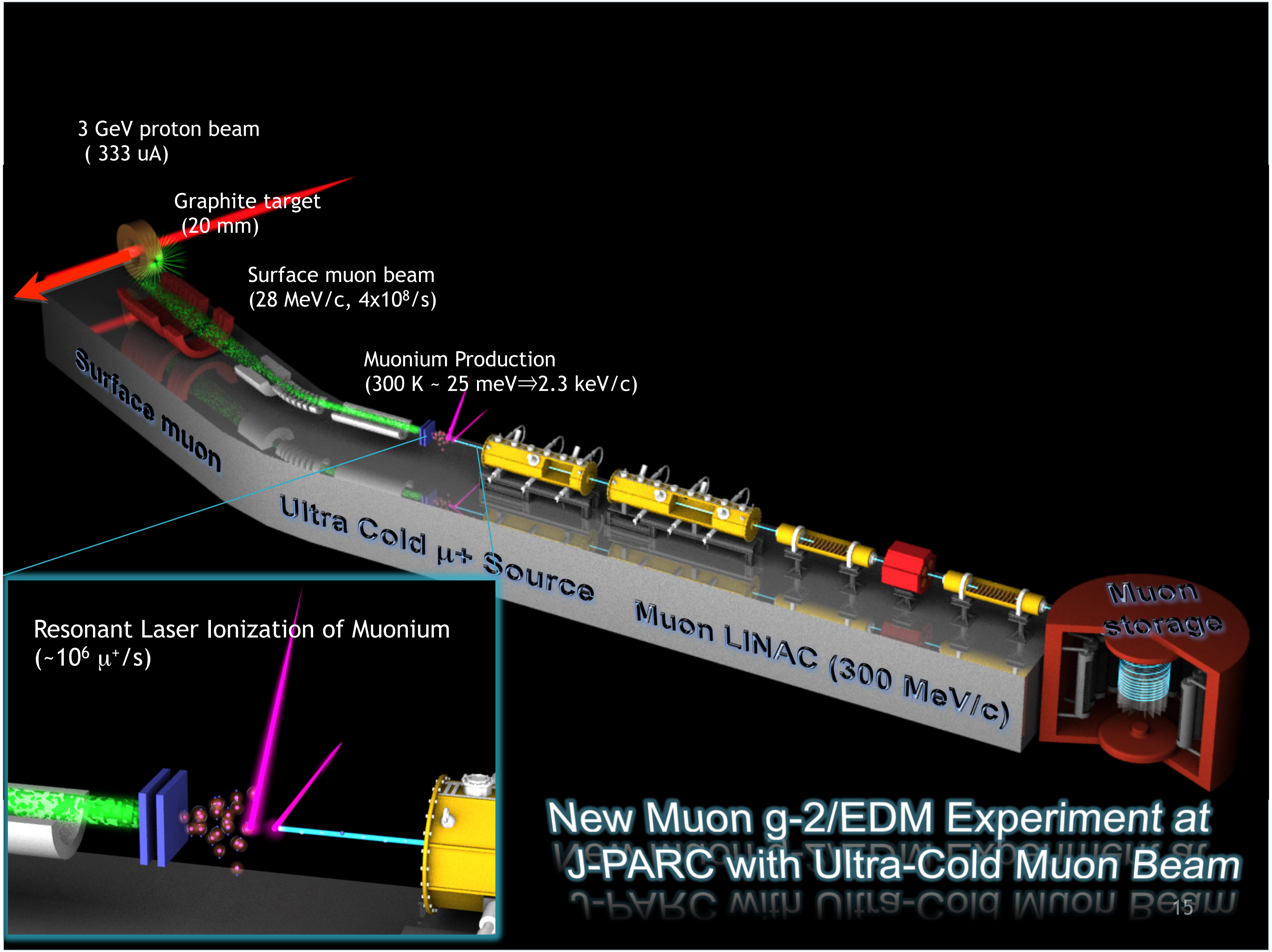
J-PARC (Japan Particle Accelerator Complex)

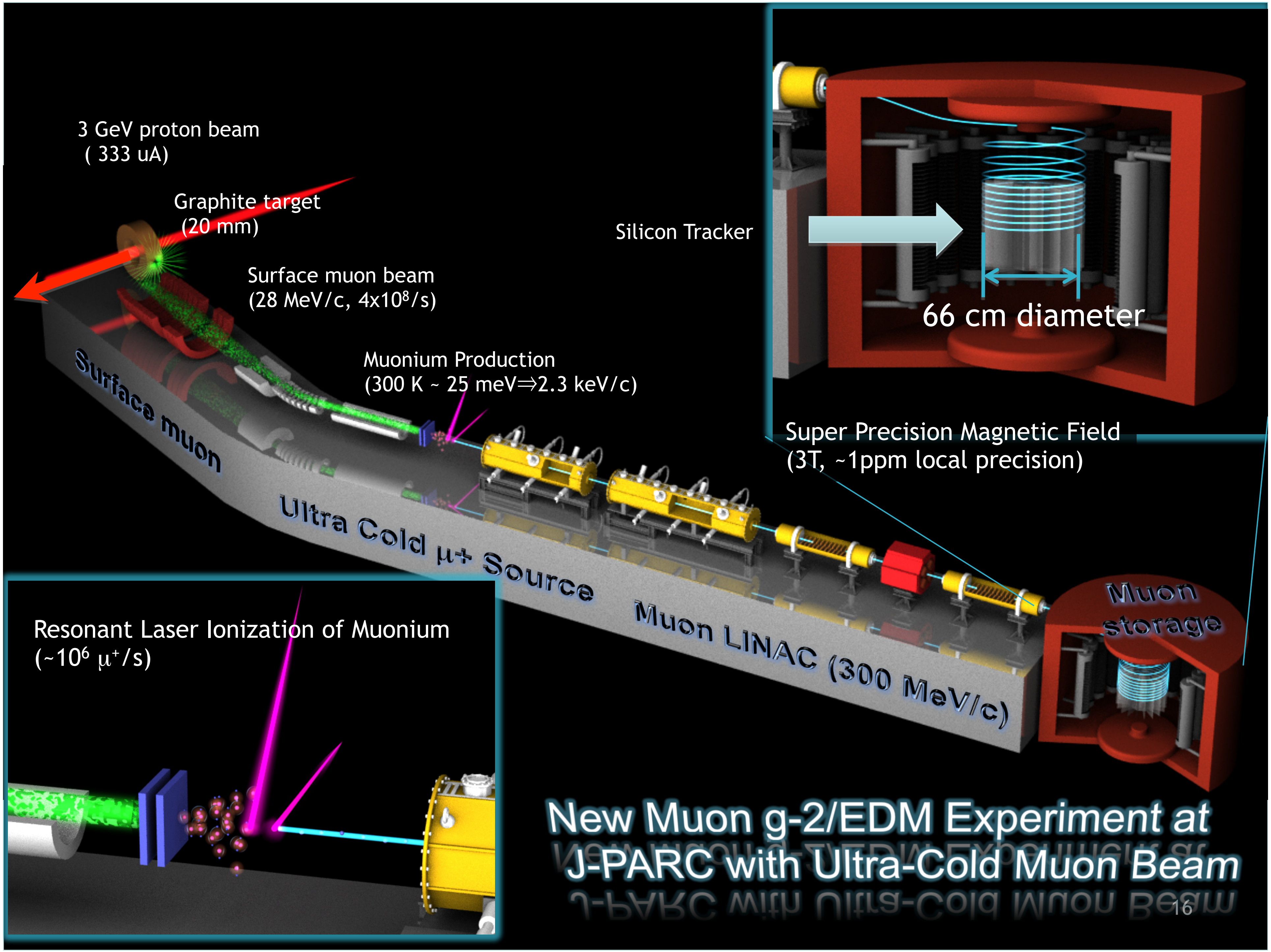



J-PARC Facility
(KEK/JAEA)
LINAC
3 GeV
Synchrotron
Neutrino Beam
To Kamioka
Material and Life Science
Facility
Main Ring
(30 GeV → 50 GeV)
Hadron
Hall
Bird's eye photo in Feb. 2008



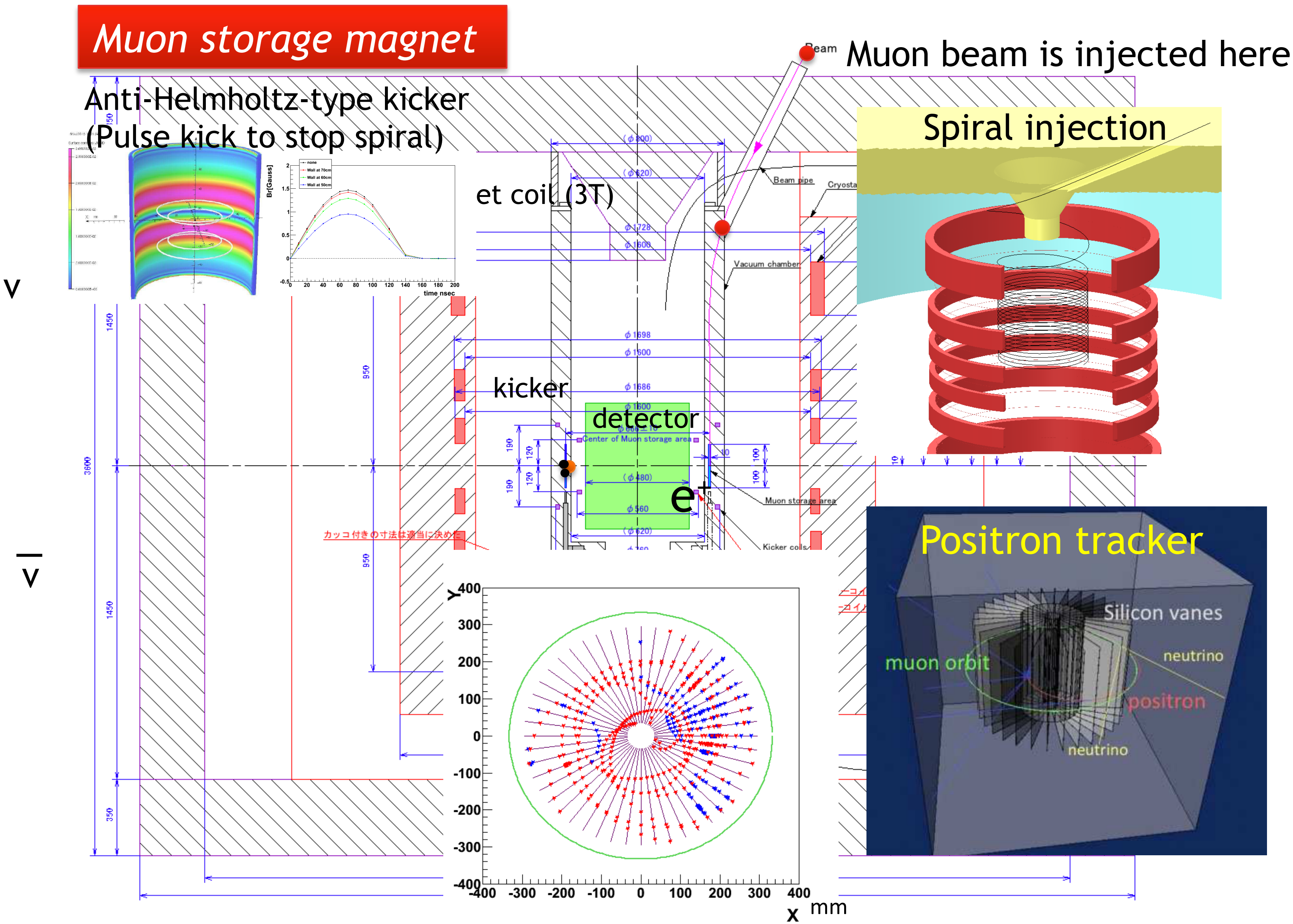
New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam


3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10⁸/s)
Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)
Surface muon
Ultra Cold μ+ Source
Muon LINAC (300 MeV/c)
Muon storage
Resonant Laser Ionization of Muonium
(~10⁶ μ⁺/s)
New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam

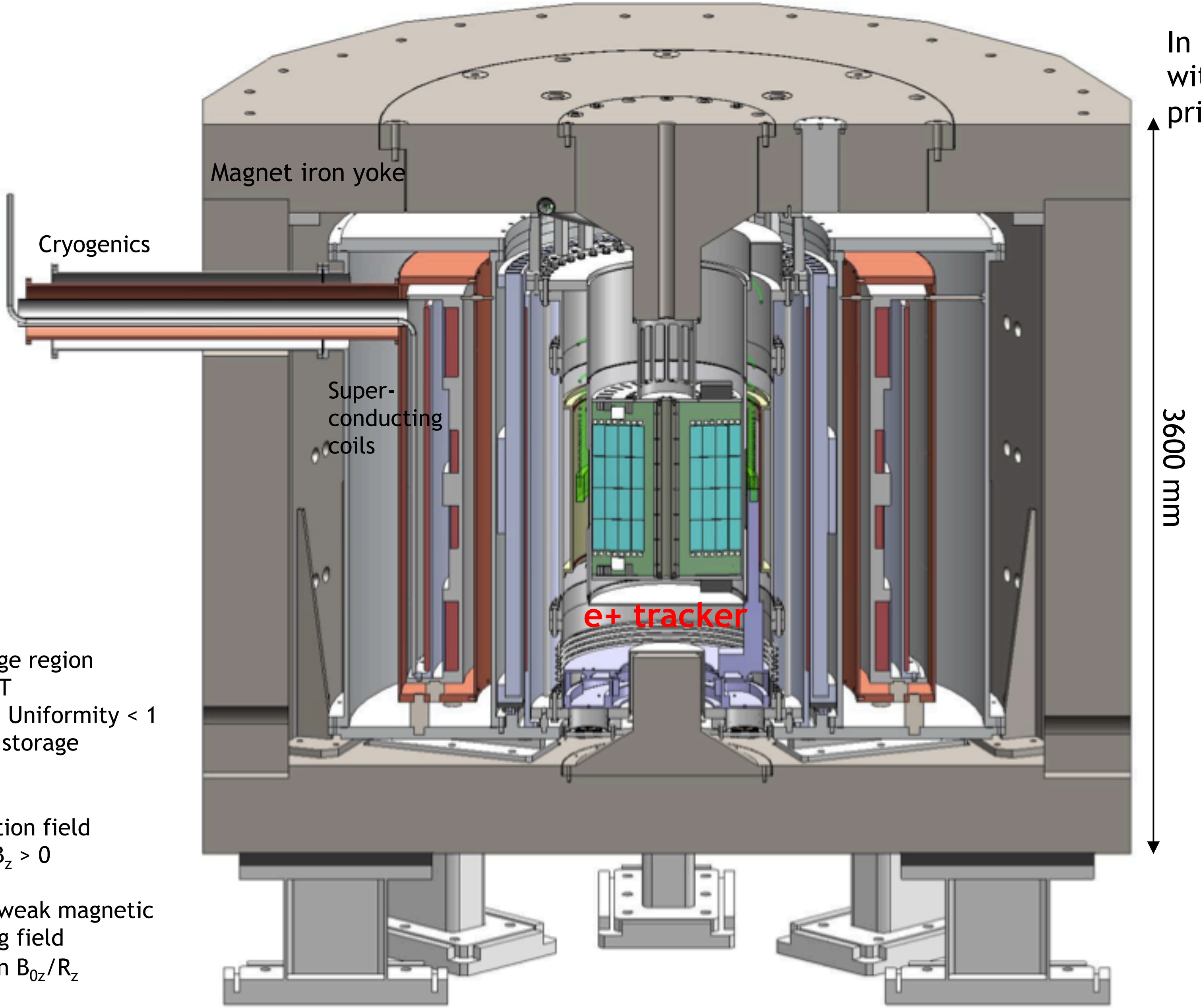


3 GeV proton beam
(333 uA)
Graphite target
(20 mm)
Surface muon beam
(28 MeV/c, 4x10⁸/s)
Muonium Production
(300 K ~ 25 meV⇒2.3 keV/c)
Silicon Tracker
66 cm diameter
Super Precision Magnetic Field
(3T, ~1ppm local precision)
Surface muon
Ultra Cold μ+ Source
Muon LINAC (300 MeV/c)
Muon storage
Resonant Laser Ionization of Muonium
(~10⁶ μ⁺/s)
New Muon g-2/EDM Experiment at
J-PARC with Ultra-Cold Muon Beam

Injection, storage, and positron detection



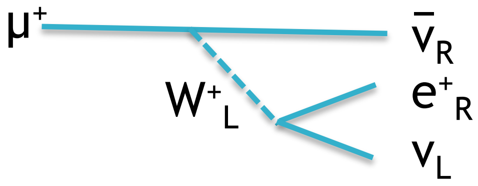
The muon storage magnet



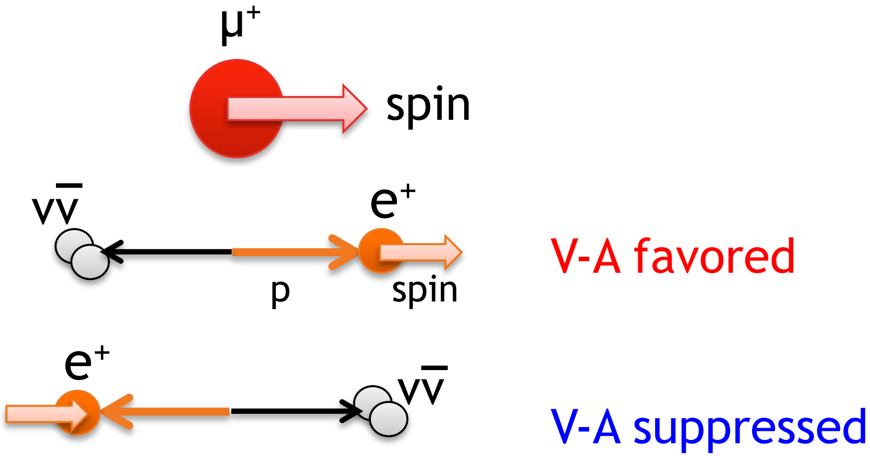
In collaboration with a Japanese private company

- Storage region
  - B_z =3T
  - Local Uniformity < 1 ppm in storage Region
- Injection field
  - $B_r \times B_z > 0$
- Very-weak magnetic focusing field
  - $B_r = -n\, B_{0z}/R_z$

$\mu \rightarrow e^+ \nu \bar{\nu}$ decay kinematics

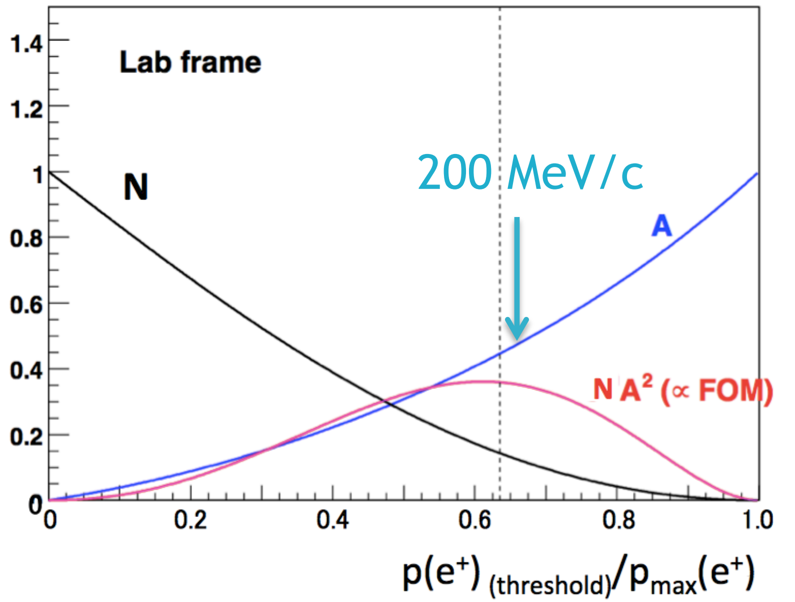


Positron emission in muon rest frame



Laboratory frame

$N(p>p_{(threshold)}) = N\,(1 + A\,\vec{s}\cdot\vec{p}\,/(|s||p|)$



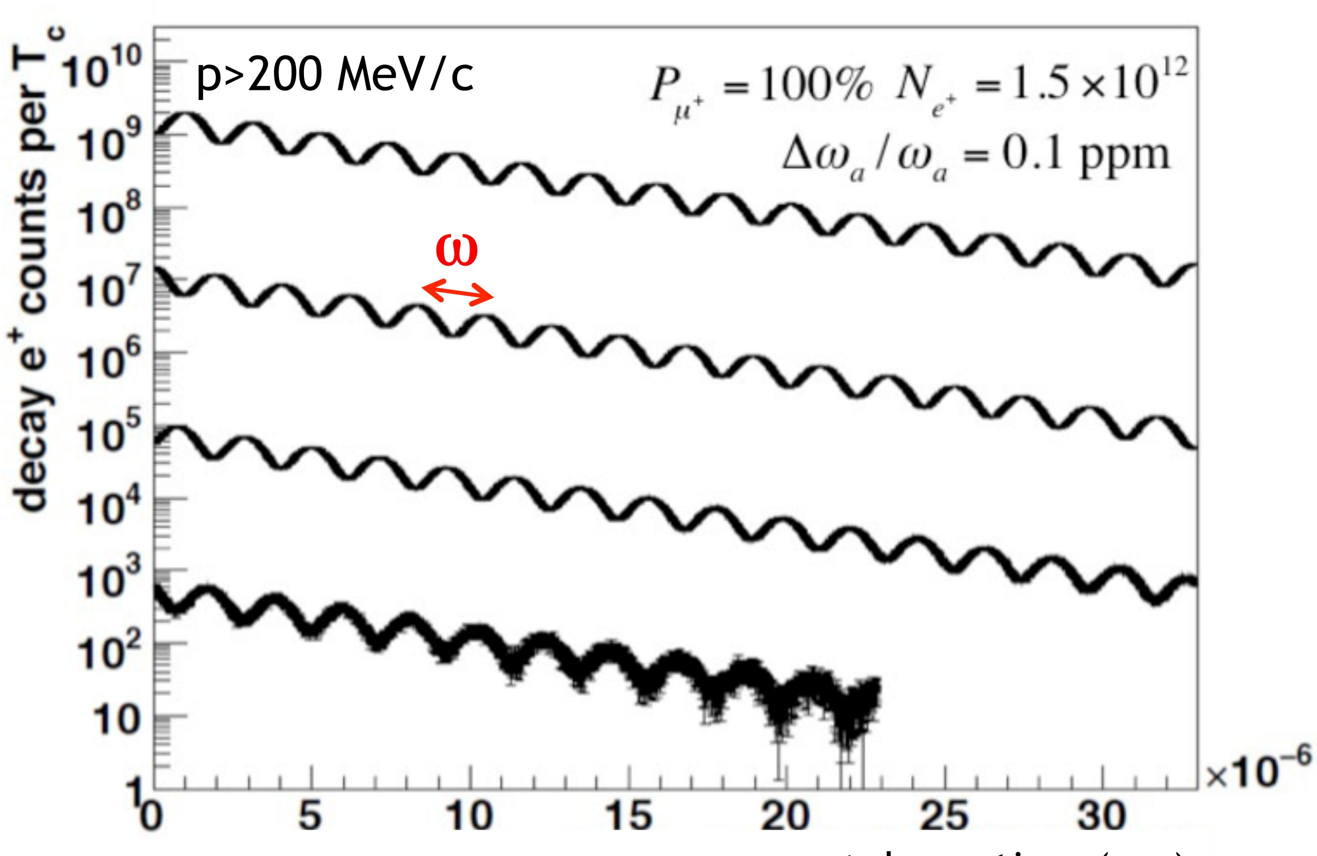
- The e+ angular distribution is subject to the V-A structure of weak interaction.
- High energy positron tends to be emitted into the direction of muon spin.
- The optimum e^+ momentum threshold is around 200 MeV/c.

Expected time spectrum of $\mu \rightarrow e^+\nu\bar{\nu}$ decay

Muon spin precesses with time.

→ number of high energy e^+ changes with time by the frequency :

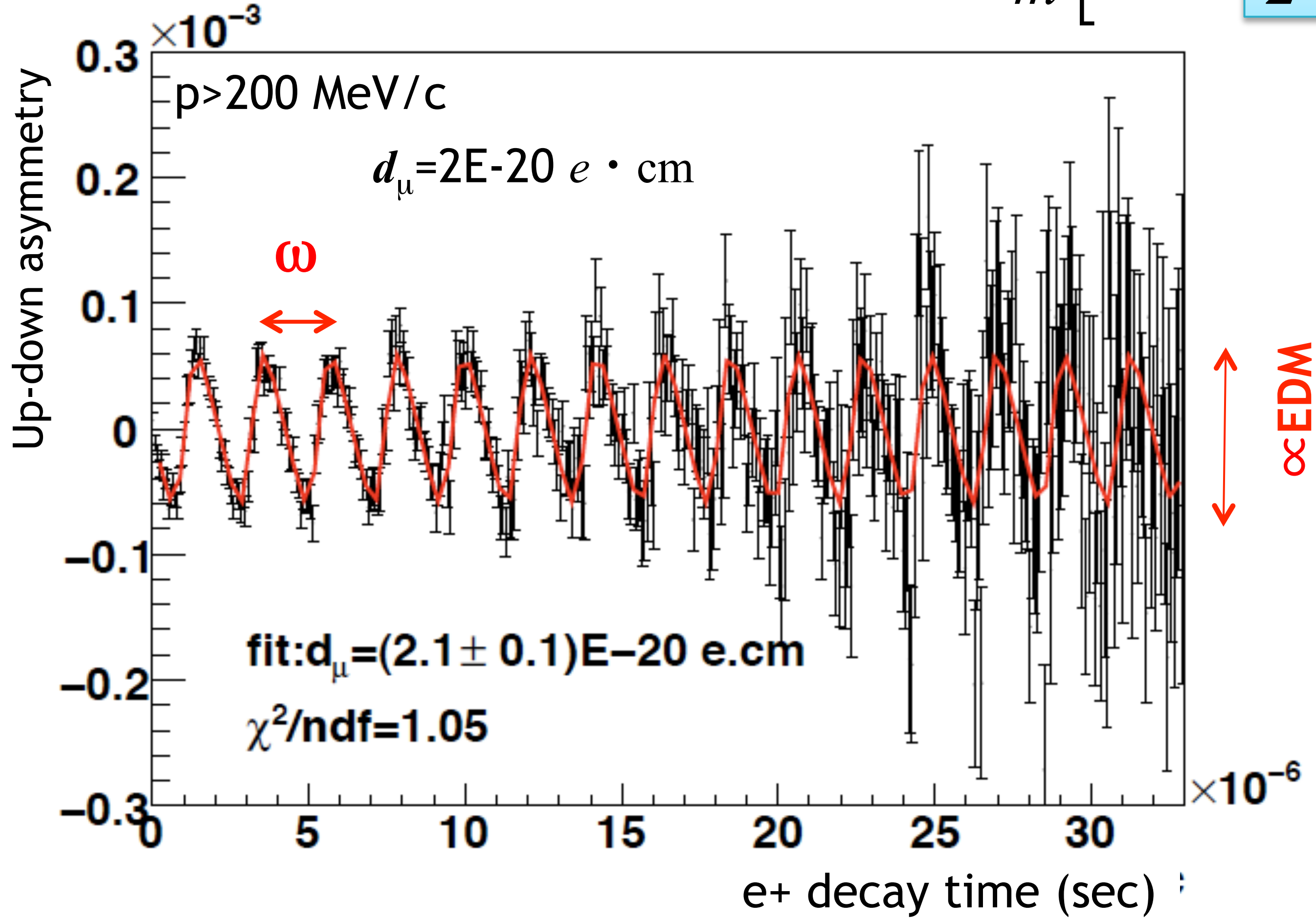
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$



Expected time spectrum of $\mu \rightarrow e^{+}\nu\bar{\nu}$ decay

EDM tilts the precession axis.
→ This yields an up-down decay asymmetry in number of e+
(oscillates with the same frequency ω)

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



Requirements to the e+ tracker

- **Detector should be efficient for**
  - Positron track with p = 200 - 300 MeV/c in 3T solenoidal B-field
  - with a radial vertex resolution of σ=1 mm.

- **Immune to early-to-late effect**
  - The decay positron rate changes by two orders of magnitude.
  - 1.6 MHz/strip → 10kHz/strip for 200 um pich Silicon strip.
  - The positron detector must be stable over the measurements.

- **Zero E-field (<<10^{-2} V/cm) at muon storage area**

- **Not spoil the precision B-field (<10ppm) at muon storage area**

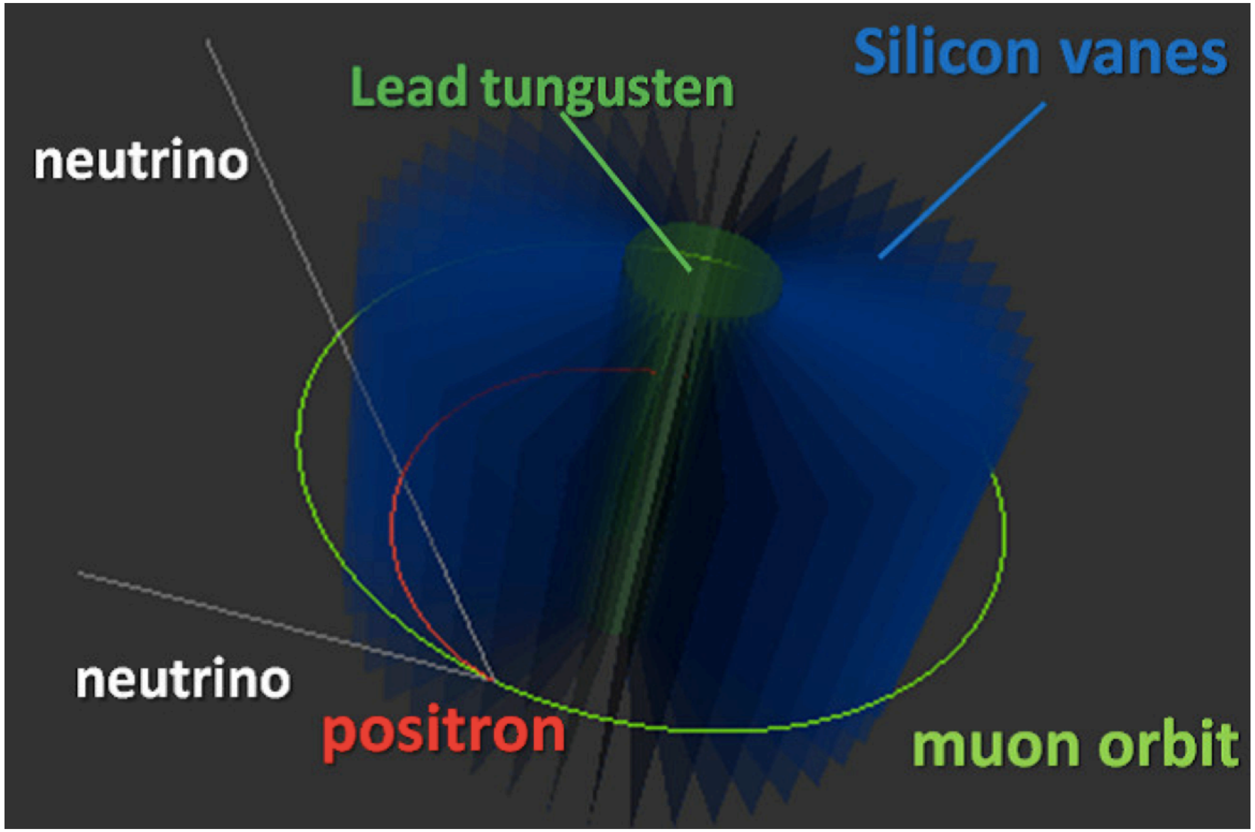
- **Efficient readout in compatible with the J-PARC beam pulse structure**

Detector design concept

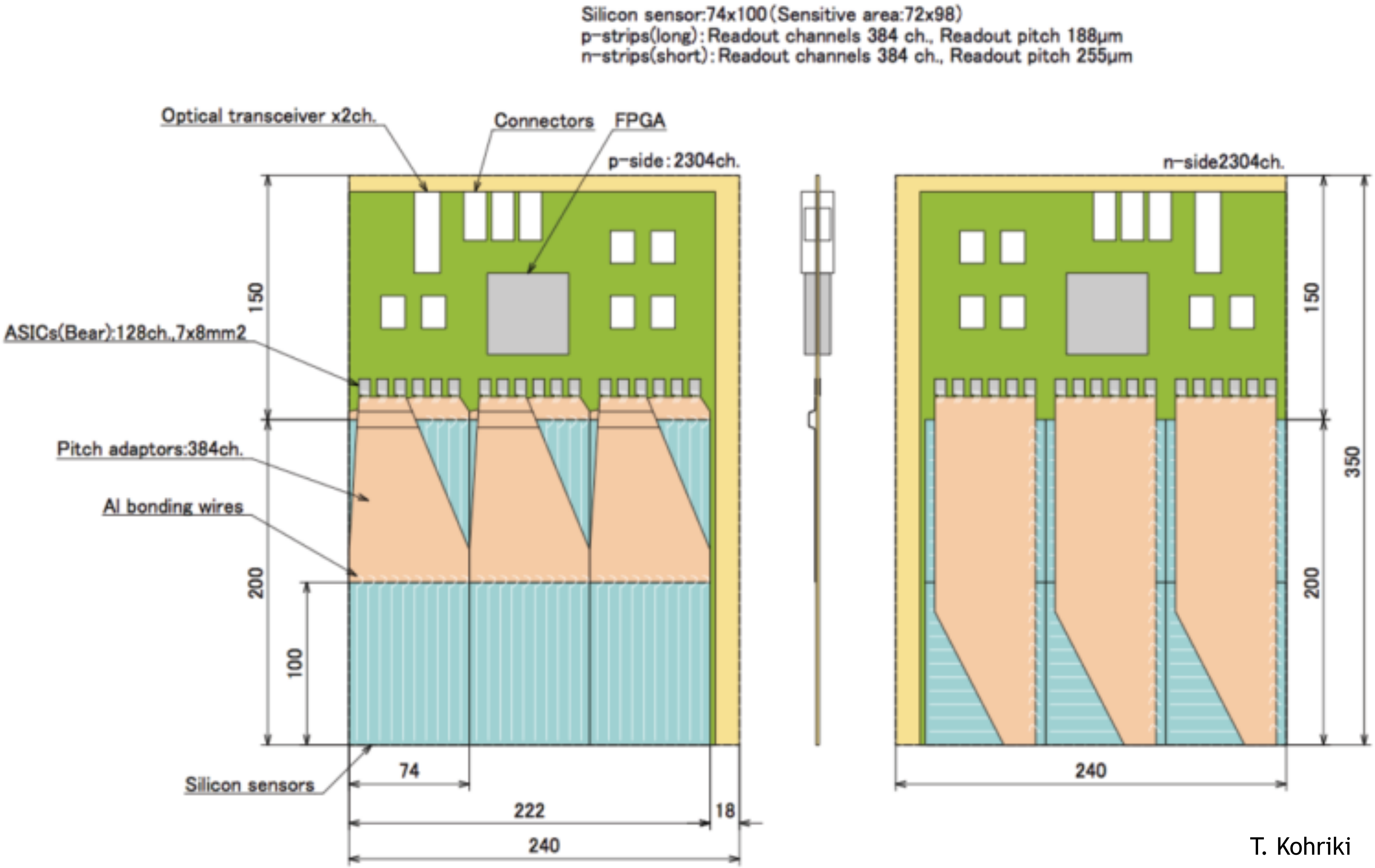
Tracking planes consists of silicon-strip vanes.

Silicon sensors :

high granularity
reasonably fast signal
good stability expected



The Silicon vane



T. Kohriki

Detector modules will be placed in vacuum environment (P<0.1Pa)

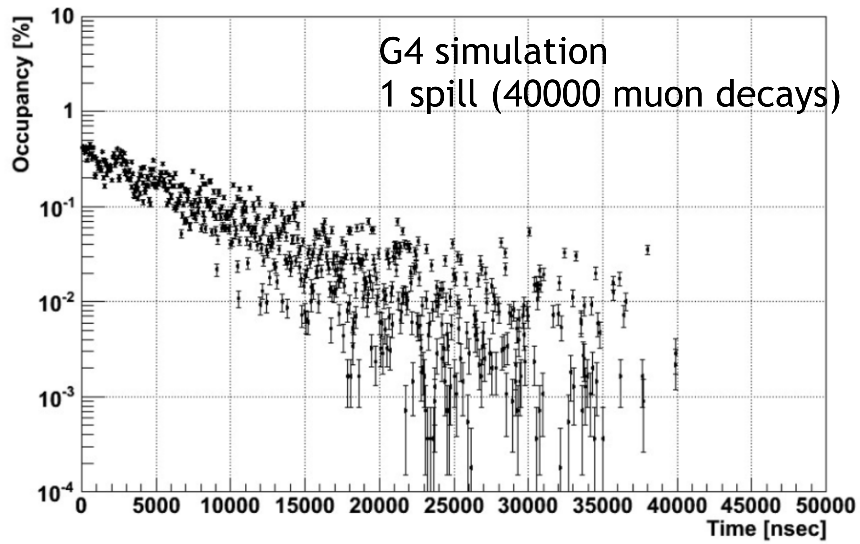
Design parameters

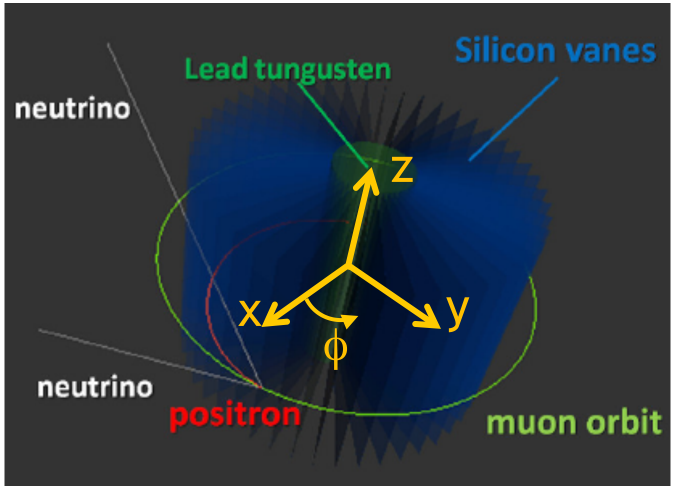
Item	Specifications
Fiducial volume	240mm (radial) x 400 mm (axial)
Number of vane	48 (still subject for optimization)
Sensor technology	Double- or single-sided Silicon strip sensor
Strip	axial-strip : 188μm pitch, 72mm long , 384 ch radial-strip: 255μm pitch, 98mm long, 384 ch
Sensor dimension	74 mm x 98 mm x 0.32mm
Number of sensor	576 (12 sensors per vane)
Number of channel	442,368 ch
Time measurement	Period : 33μs, Sampling time : 5ns

K. Ueno

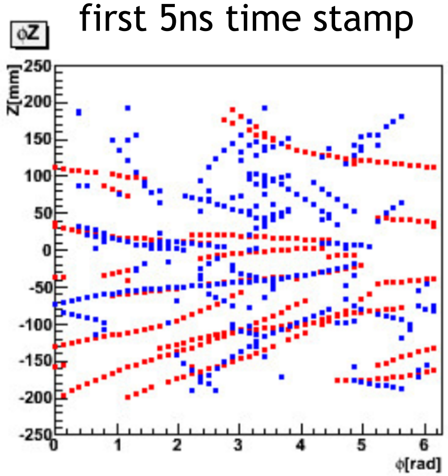
Raw occupancy and hit distributions

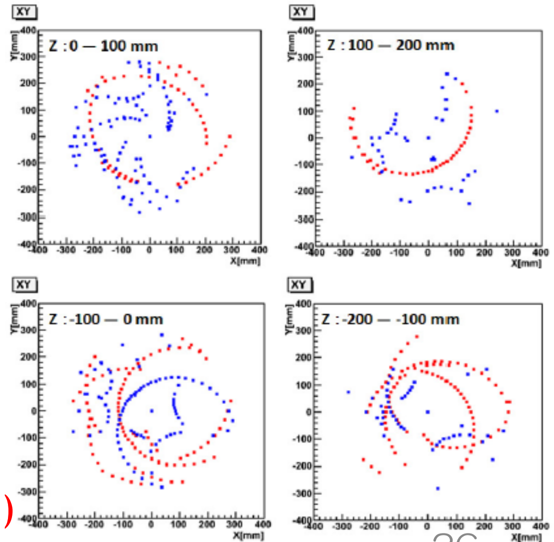
- A GEANT4 simulation has been carried out to evaluate positrons hits as well as background hits.
  - BG consists of EM processes: such as bremsstrahlung, annihilation, pair creation etc...
- Occupancy is less than 0.5% per 5ns time stamp (5 hits/strip/spill).
- Positron tracks at the beginning:
  - 15 signal e+ tracks with p>200 MeV at first 5ns
  - 30 BG e+ tracks with p<200 MeV at first 5ns
  - Strong hit correlations in ϕZ plane and XY plane.





G4 simulation
first 5ns time stamp

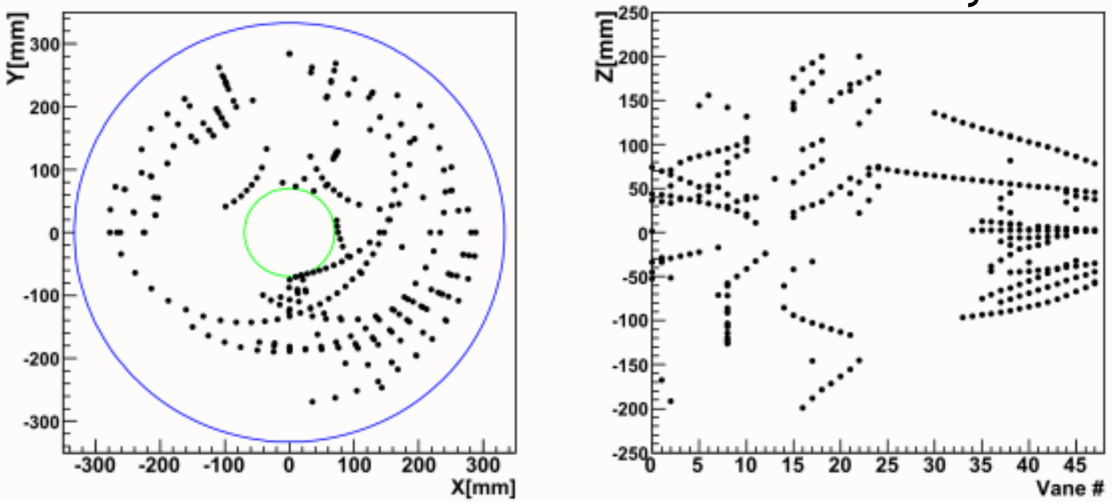




- signal e+ (p>200MeV/c)
- BG e+ (p<200MeV/c)

Time evolution of track hits

By Kazuki Ueno



Event#	Ene.[MeV]	Event#	Ene.[MeV]
363	133.0	32482	206.2
507	184.0	32496	41.5
4183	235.6	36545	278.6
4323	208.1	37554	203.1
4353	153.5	37816	186.4
7515	47.3	38071	35.1
8274	116.4	39128	53.4
8506	60.0	39175	111.4
9223	110.4		
10940	159.1		
11824	64.3		
14710	126.6		
16289	41.3		
18030	67.0		
19429	44.5		
21634	236.7		
22985	233.8		
24324	123.8		
25395	31.2		
30493	205.5		

Event#	Ene.[MeV]	Event#	Ene.[MeV]

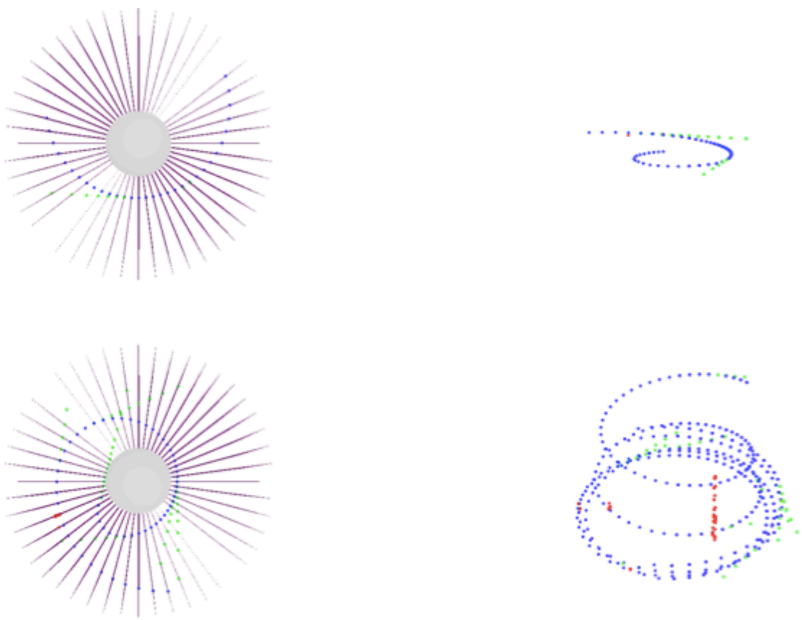
All : 28
Signal : 8

0 - 5 [ns]

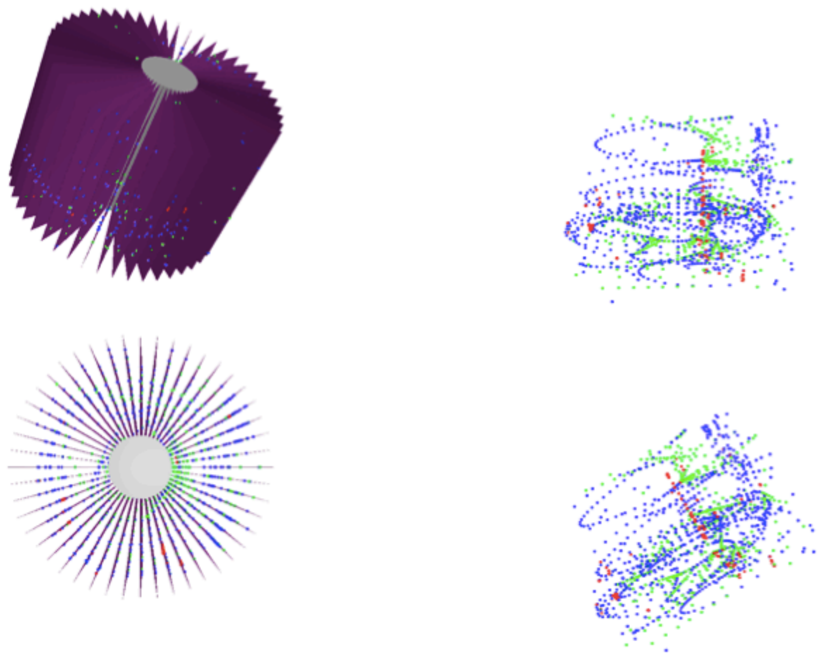
Event gallery

A 3D MC event display has been developed with ROOT/EVE framework by Wilfrid Da Silva and Frederic Kapusta.

Typical e+ track



A typical event in 5ns time stamp



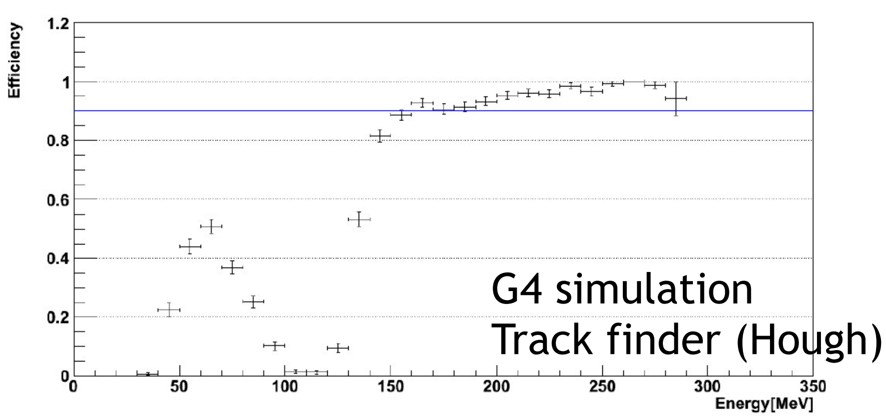
Positron
Electron
Photon

Track reconstruction

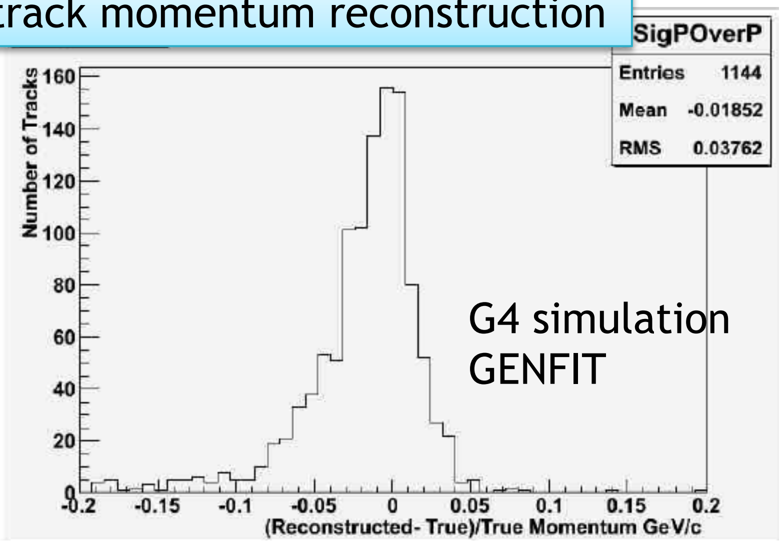
K. Ueno
W. Da Silva
F. Kapusta

- Track finding
  - Initial search with Hough transformation algorithm in ϕz plane
  - Track finding efficiency for a single-track is >90%.
- Track fitting
  - Fitter with GENFIT (track fitting tool kit with Karman filter) is being developed by W. Da Silva and F. Kapusta.
- Evaluation of multi-track reconstruction is the next step.

single track finding efficiency

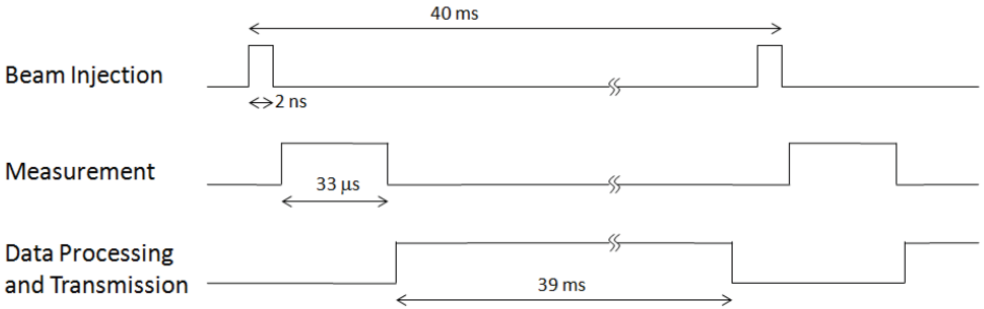


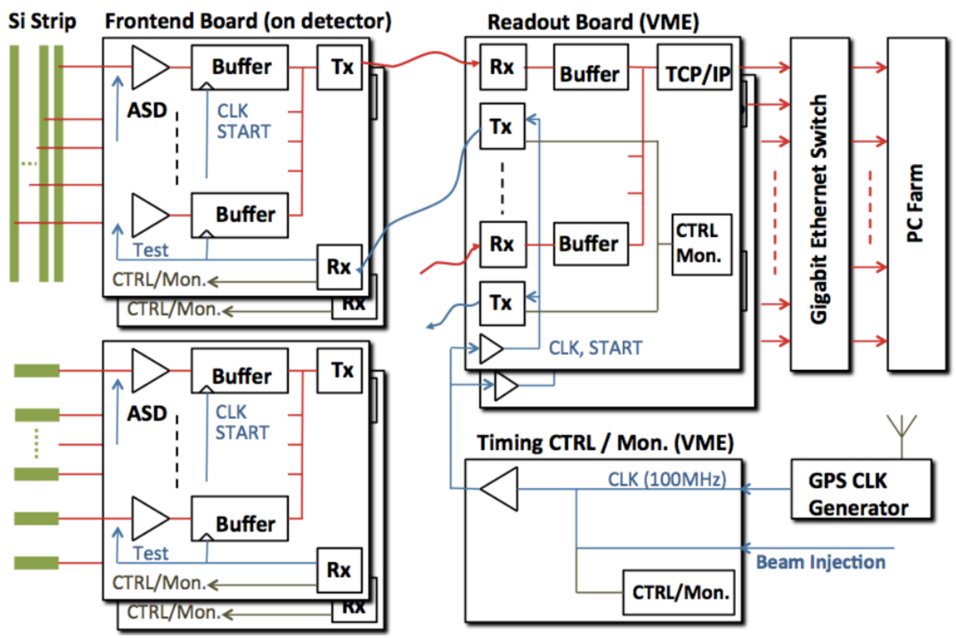
track momentum reconstruction



Readout electronics and DAQ

O. Sasaki
M. Tanaka
T. Uchida
J.F. Genat



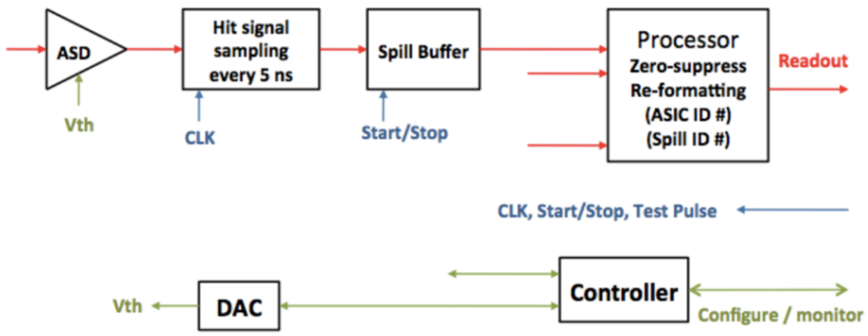


- Readout electronics and DAQ are designed to match the time structure of the J-PARC beam.
- Signals in Silicon sensors are amplified and digitized at Front end, then transmitted to the backend readout boards.

Quantity	Value
Hit data size	8 byte/hit
Number of hits per frontend	11.5k hits/spill
Data size from frontend board	2.3MB/s (92kB/spill)
Data size from readout board	18MB/s (740kB/spill)
Total data size	440MB/s (18MB/spill)
Total data size(w/ reduction)	280MB/s (11MB/spill)
Disk write speed of PC	100MB/s (4MB/spill)
Number of PC	10
Data storage space	2.8 PB

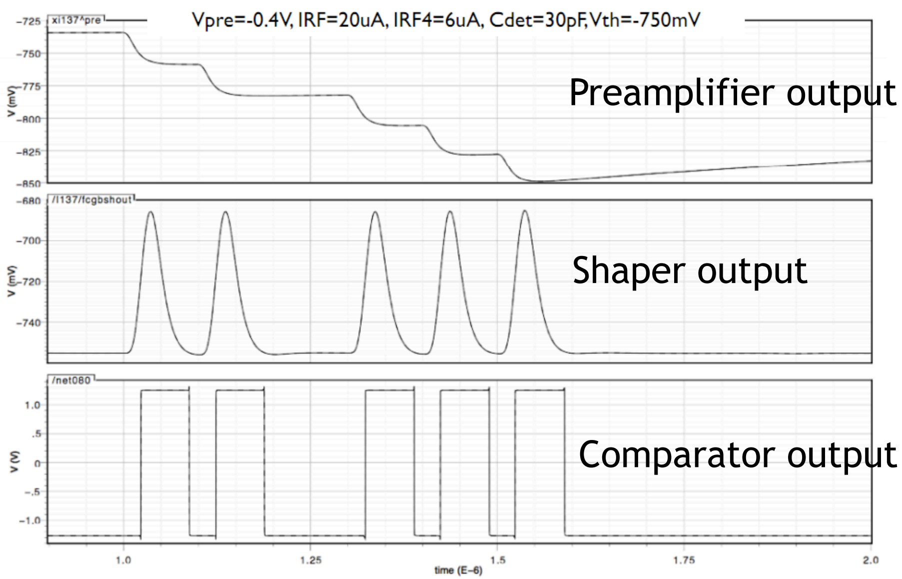
Front-end ASIC

M. Tanaka, T. Uchida
M. Ikeno, O. Sasaki

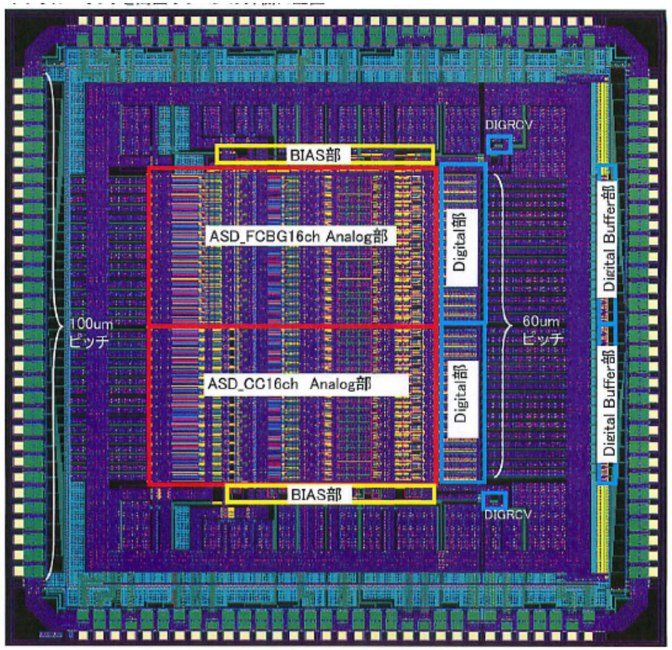


Block	Parameter	Value
Preamplifier	conversion gain	5–10 mV/fC
	dynamic range	-16 MIP to +16 MIP
Shaper	pulse width	100 ns
	gain	50 mV/fC
	dynamic range	-3 MIP to +3 MIP
	peaking time	50 ns
Others	power consumption	<5 mW/ch
	noise	$< 3000\ e^{-}$ (C_d=30 pF)
	number of channel	128

Simulated pulse shape in ASD

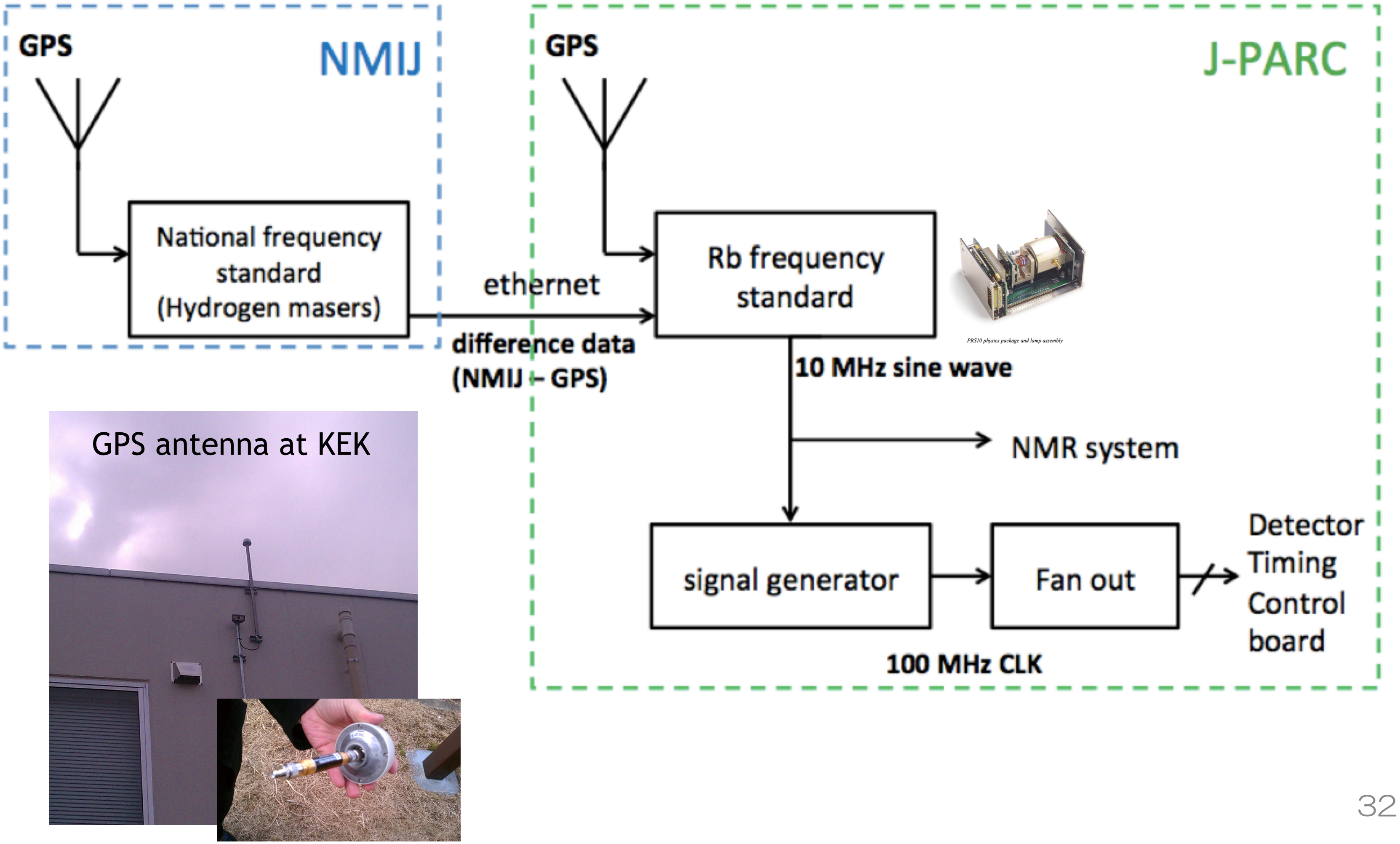


- Analog and digital part of the ASIC has been designed in JFY2011.



High precision clock

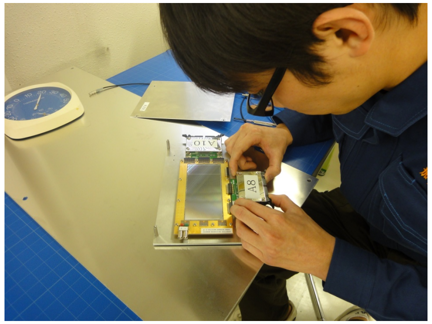
The system clock utilizes the high precision Rb frequency standard with remote calibration from the national frequency standard NMIJ as well as GPS to realize frequency stability of $\Delta f/f < 5 \times 10^{-9}$/s.



R&Ds for early-to-late effects

T. Kakurai, T. Mibe, O. Sasaki, T. Kohriki

- A silicon-sensor test system with IR laser was built.
- The IR laser could be pulsed at repetition rate as high as 80MHz with an asynchronous external trigger.
- Systematic studies on early-to-late effects are in progress.



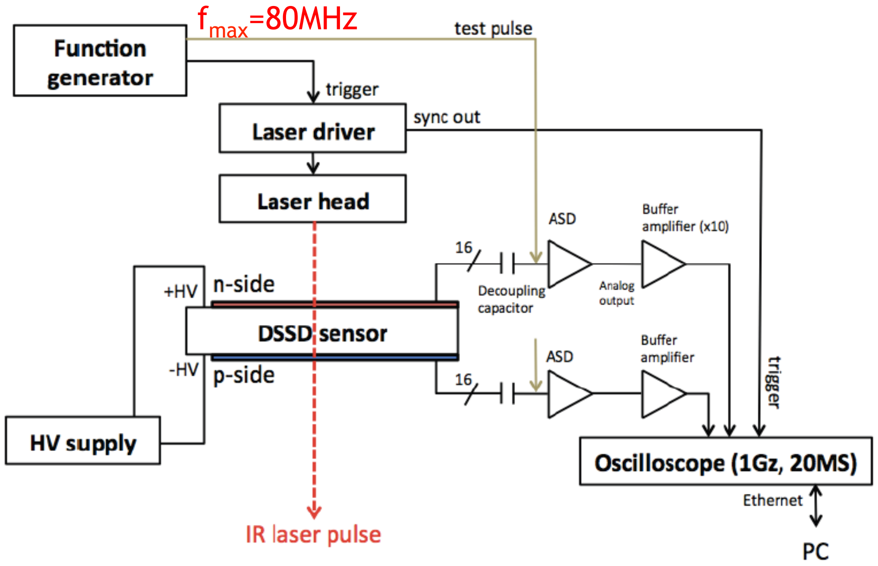


Figure 7.28: Diagram of the silicon sensor test set up

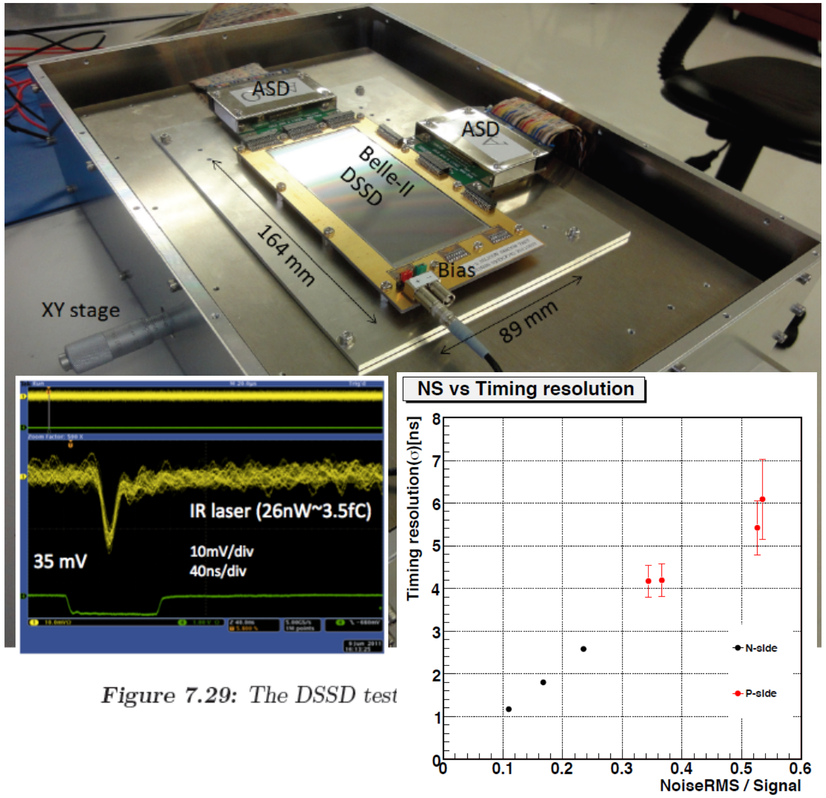
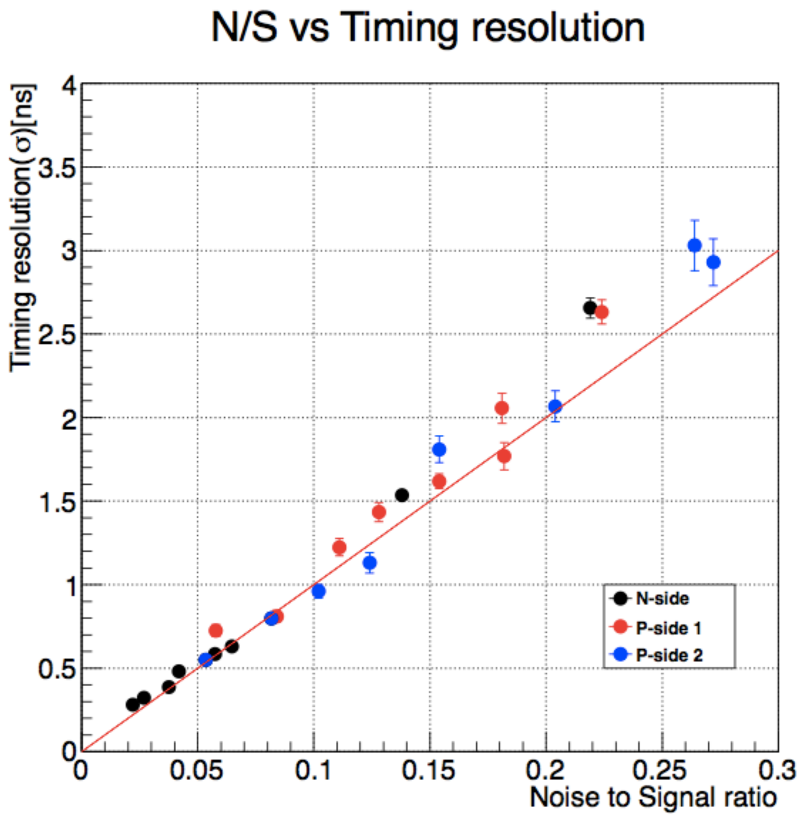
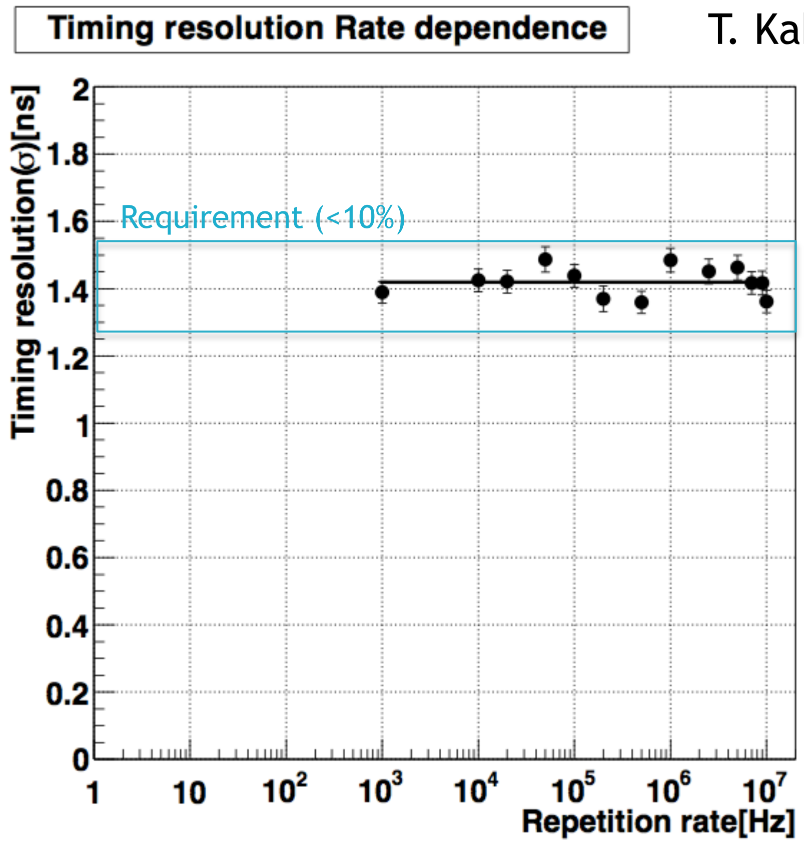


Figure 7.29: The DSSD test

Timing resolution and rate dependence

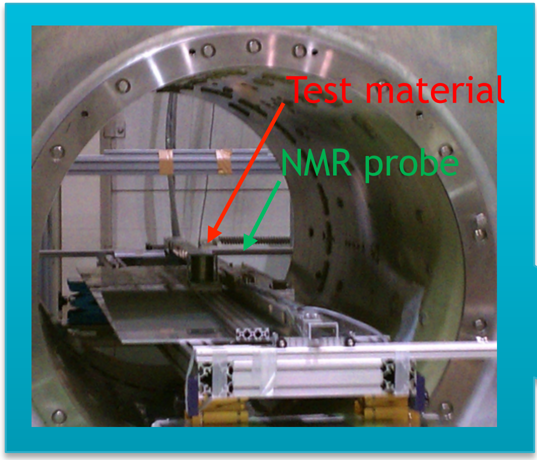


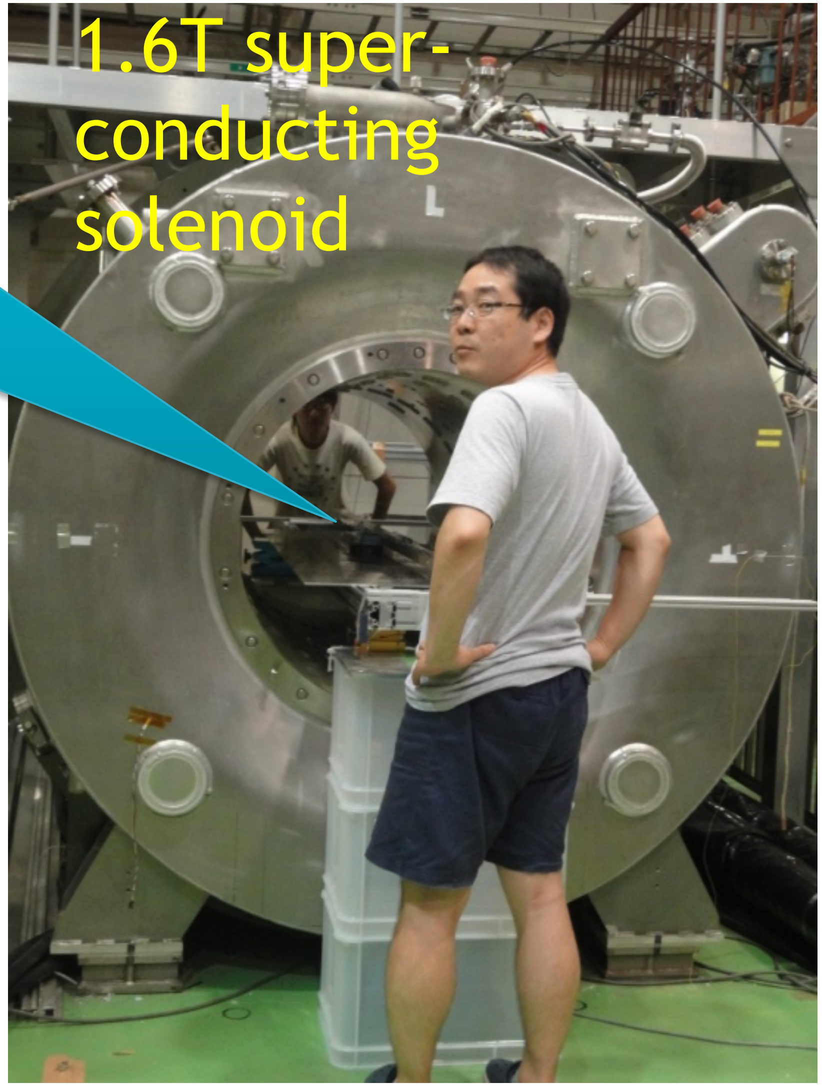


T. Kakurai

Effect of detector components in the precision B-field

K. Sasaki, T. Kakur
T. Mibe, O. Sasaki



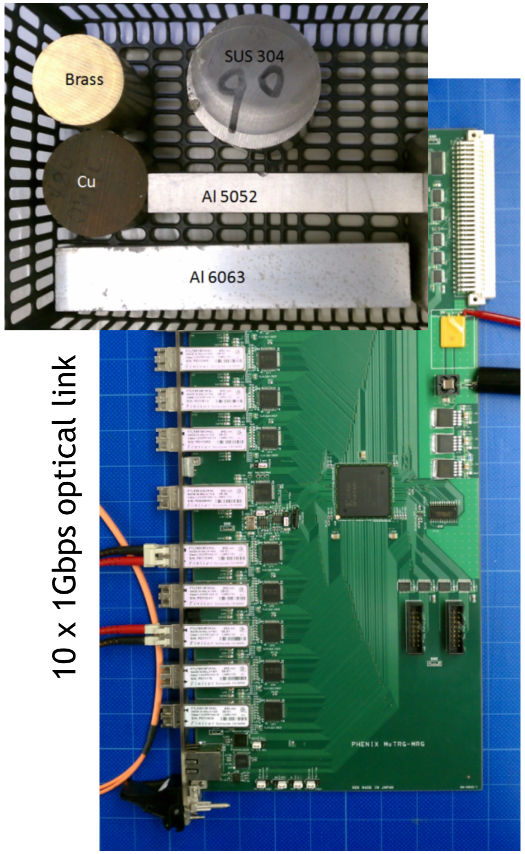


- B-field in the vicinity of material and detector components were measured by NMR probe.

K. Sasaki, T. Kakur
T. Mibe, O. Sasaki

Materials and components

metals



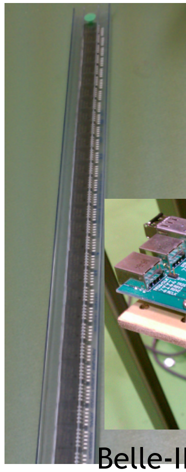
10 x 1Gbps optical link

PHENIX trigger board

PCB board (G10+Cu, 10 layer)

Optical transceiver

Voltage regulator



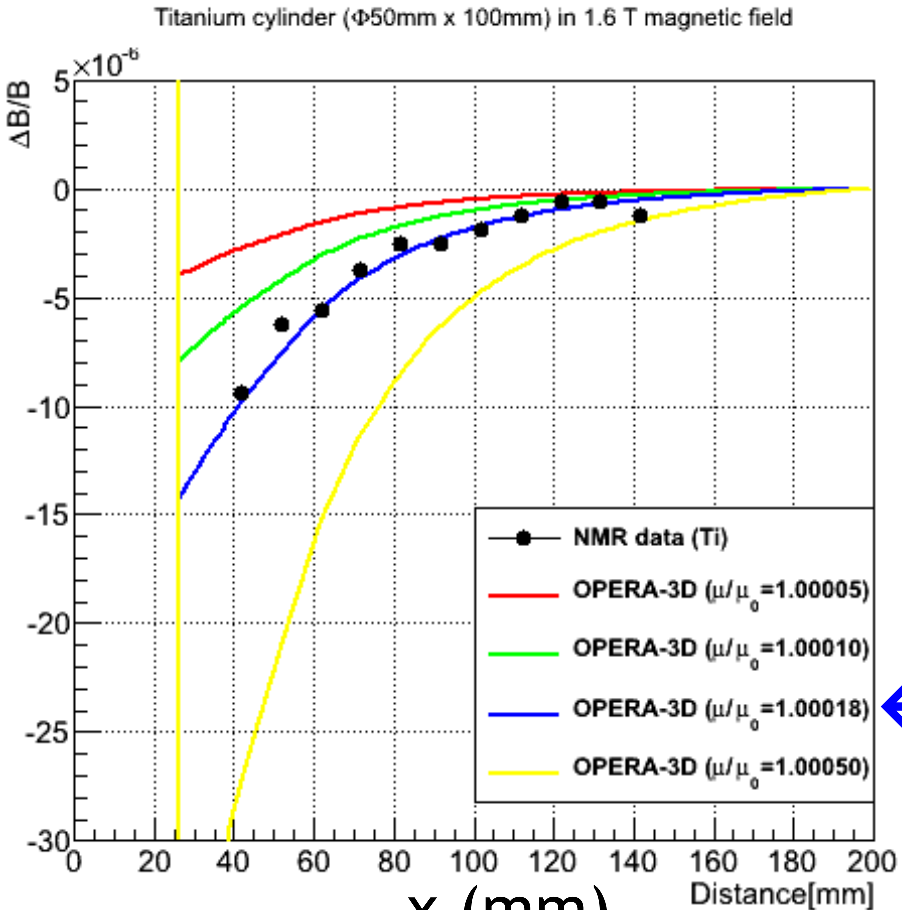
Belle-II data transmission test boa

Registers, capacitors

FPGA/PROM

Solder (with Pb, Pb-free)

Comparison with calculation (Ti)

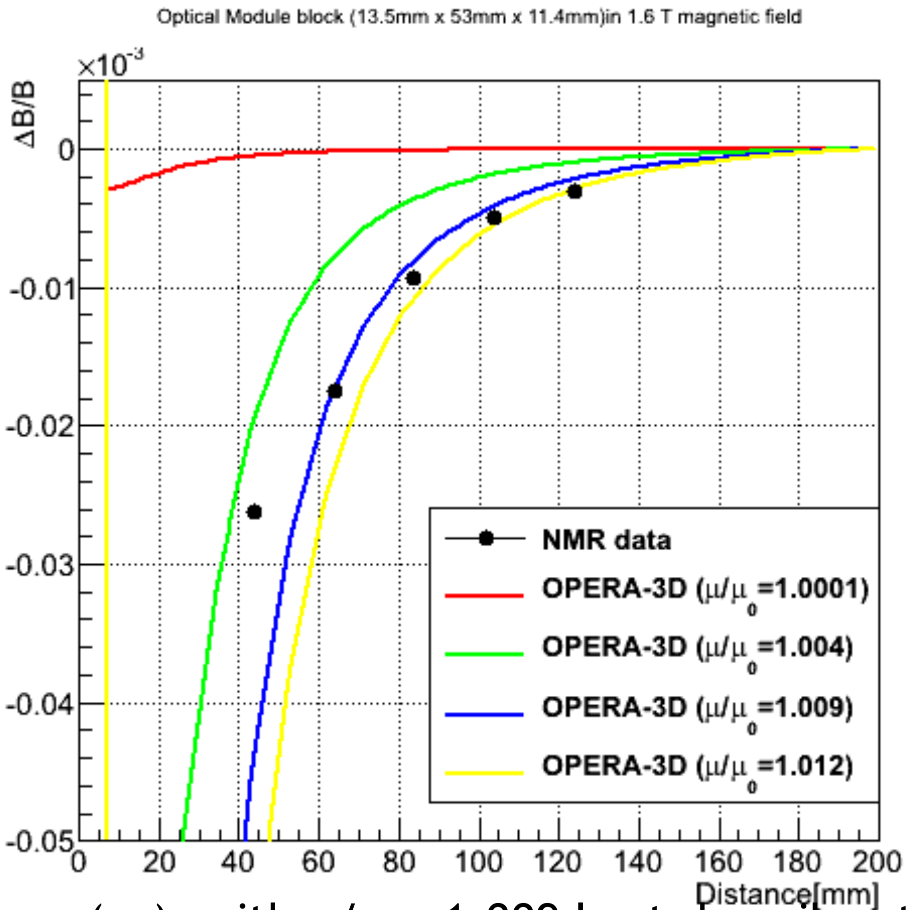


← CRC value

x (mm)

Calculated curve (—) with expected μ/μ_0 value agrees with data.

Comparison with calculation (optical module)

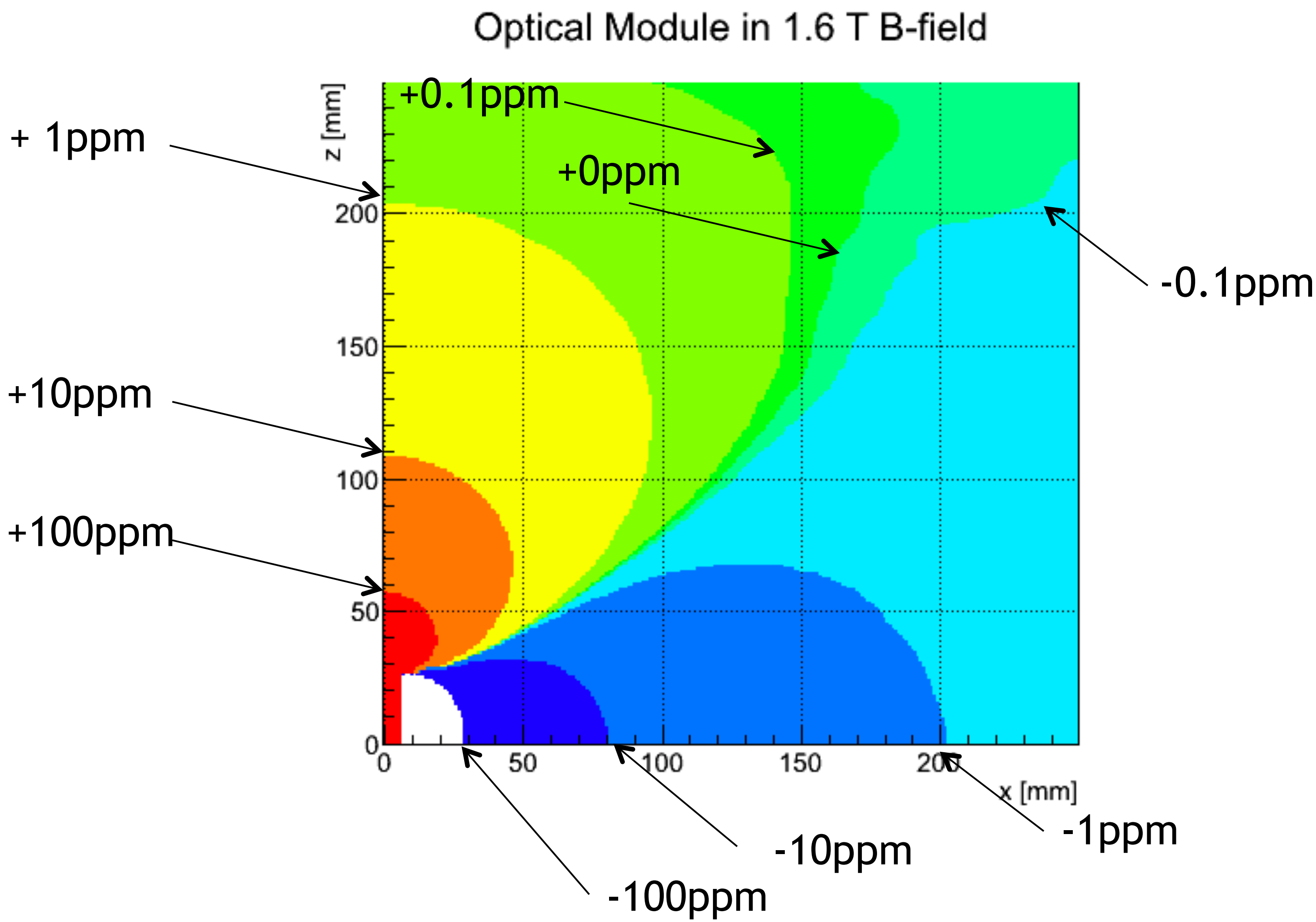


Calculated curve (—) with μ/μ_0 =1.009 best describes the data.

Not very good agreement with data, maybe due to ambiguity of source volume

Best estimate μ/μ_0 -1 = (9,000 +/- 750) E-6.

ΔB/B contour


Optical Module in 1.6 T B-field
+ 1ppm
+0.1ppm
+0ppm
-0.1ppm
+10ppm
+100ppm
-100ppm
-10ppm
-1ppm
z [mm]
x [mm]
0
50
100
150
200

Core R&D tasks

- **Detector should be efficient for**
  - Positron track with p = 200 - 300 MeV/c in 3T solenoidal B-field
  - with a radial vertex resolution of σ=1 mm (if very-weak focusing is applied).
- **Immune to early-to-late effect**
  - The decay positron rate changes by two orders of magnitude.
  - 1.6 MHz/strip → 10kHz/strip for 200 um pich Silicon strip.
  - The positron detector must be stable over the measurements.
- **Zero E-field (<<10^{-2} V/cm) at muon storage area**
- **Not spoil the precision B-field (<<0.1ppm) at muon storage area**
- **Efficient readout in compatible with the J-PARC beam pulse structure**

GEANT4 simulation, toy MC
Track finding studies

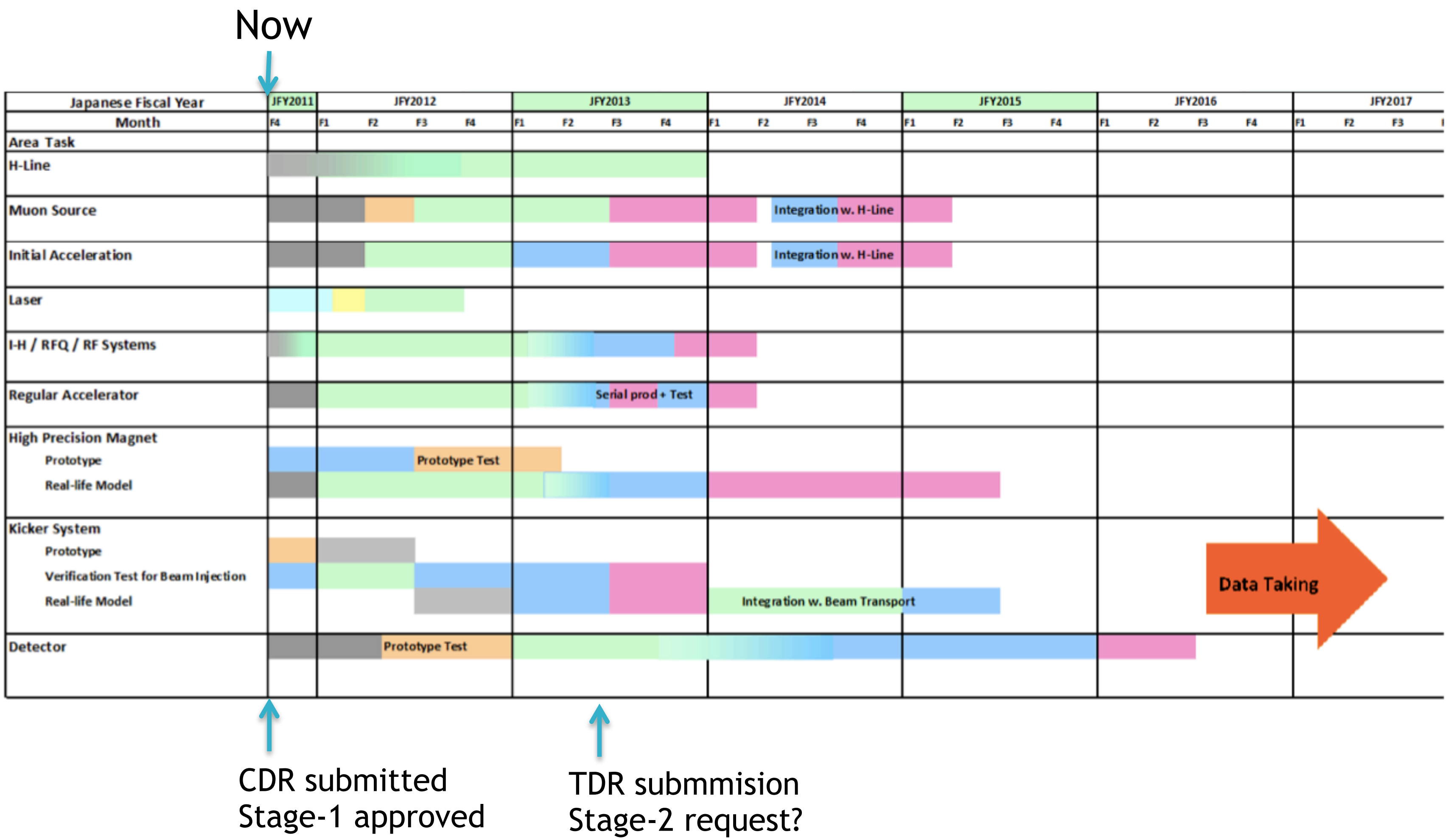
feedback

DSSD sensor evaluation

E-field calculation model
B-field measurements by NMR

Front-end electronics

Projected schedule



Summary

- A new muon g-2/EDM experiment at J-PARC:
  - Off magic momentum + compact g-2 ring
  - Complementary to FNAL g-2
  - Start in 2016

- Silicon tracker for g-2
  - A tracker for incoming low energy positrons
  - Stringent requirements on early-to-late effect, E-field and B-field
  - Conceptual design has been developed.

- LPNHE group has made significant contribution in the detector design.
- Looking forward to continuous (possibly larger) contribution from LPNHE and other French group in the future.