Status of muon g-2/EDM experiment at J-PARC

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on behalf of the J-PARC muon g-2/EDM collaboration

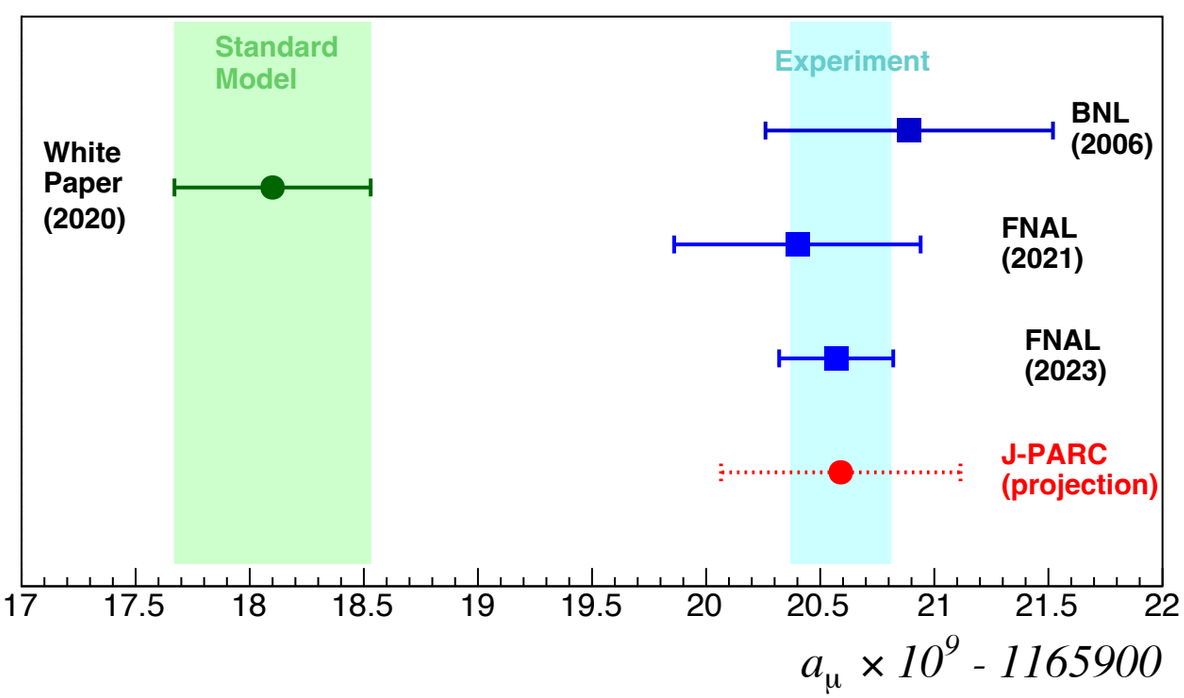
2023.08.25

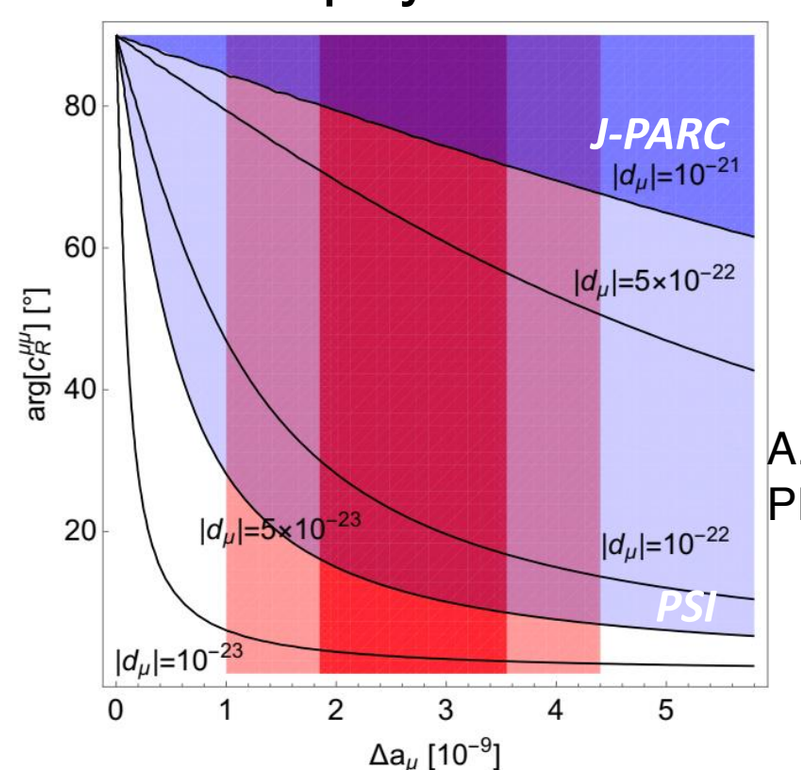
@ NuFact 2023 (Seoul National University)

Muon g-2/EDM

- Muon anomalous magnetic moment (g-2)
  - 5.0 σ discrepancy between FNAL measurement and prediction
  - Measurement (FNAL) : 116 592 055(24) × 10^{-11} (200 ppb)
  - SM prediction : 116 591 810(43) × 10^{-11} (370 ppb)
  - Can be a contribution from new physics

- Muon EDM
  - Upper limit given by BNL : 1.8 × 10^{-9} e・cm (95% C.L.)
  - EDM and g-2 can be induced by the same new physics





A. Crivellin et al., PRD 98, 113002 (2018)

$$c_R^{\mu\mu} = -\frac{e}{4m_\mu}a_\mu - i\frac{1}{2}d_\mu$$

Muon g-2/EDM measurement

Muon g-2/EDM can be obtained by measuring the muon spin precession in a uniform B-field.

- We can reconstruct time dependent spin information by decayed positron energy and momentum.

g-2 EDM

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

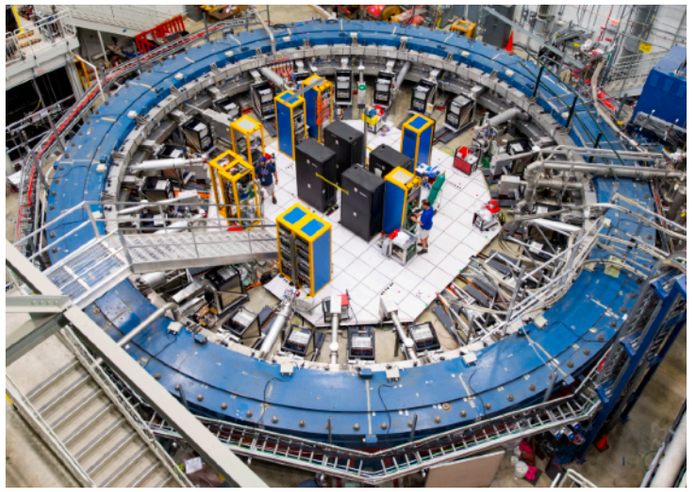
$\vec{\omega} = \vec{\omega_a} + \vec{\omega_\eta}$

BNL/FNAL experiment

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

= 0

- To focus muons in the storage volume, electric field is necessary.
- Magic gamma is selected to cancel out 2nd term.
  - p = 3.1 GeV/c
  - muon orbit : ϕ = 14 m (B = 1.45 T)



Muon g-2/EDM measurement

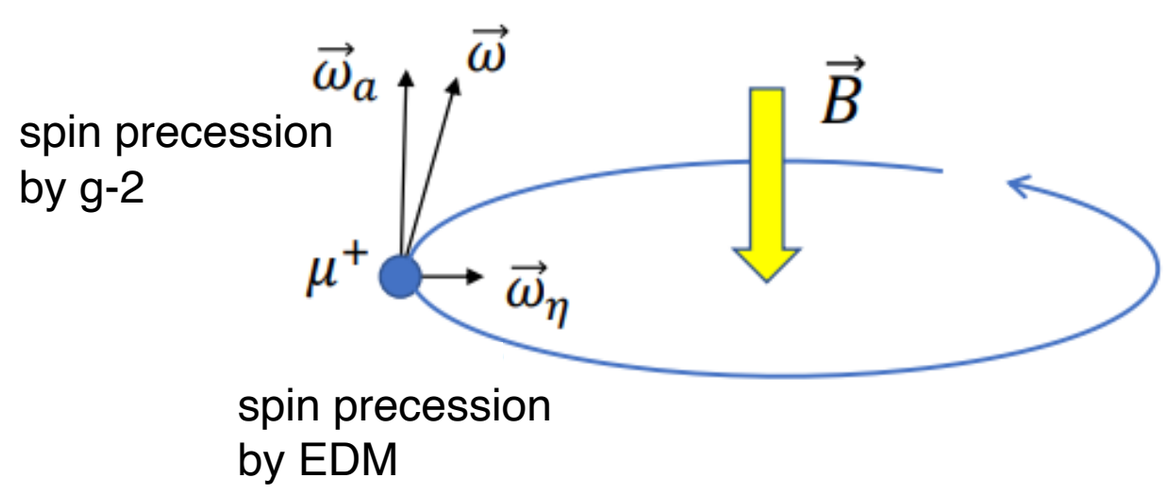
J-PARC experiment

- The electric field is not used to focus the muon beam.
  - A weak gradient magnetic field is used instead.
  - Utilize low emittance muon beam by reaccelerated thermal muon.

$$\vec{\omega} = -\frac{e}{m}\left[\underbrace{a_\mu \vec{B}}_{\text{g-2}} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\underbrace{\frac{\vec{\beta}\times\vec{E}}{c}}_{=0} + \underbrace{\frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \underbrace{\frac{\vec{E}}{c}}_{=0}\right)}_{\text{EDM}}\right]$$

- Measurement at lower muon momentum becomes possible.
  → A compact magnetic storage ring with better uniformity of B-field.
  - p = 0.3 GeV/c, ϕ = 0.66 m (B = 3 T)

- Independent measurement of muon g-2 to validate BNL/FNAL result with different systematic uncertainty.
- Measure g-2 and EDM signal simultaneously.



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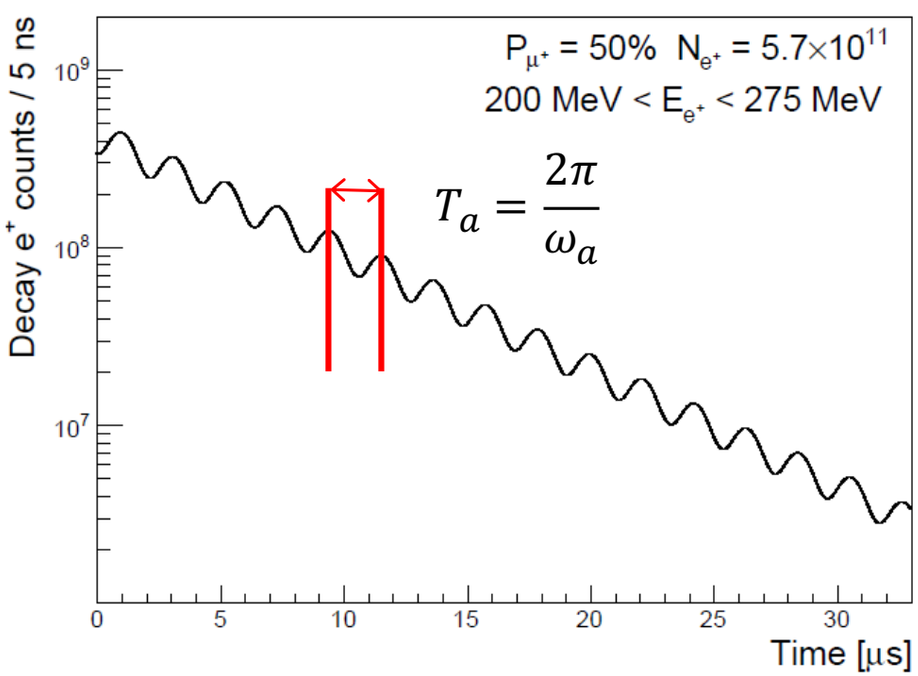
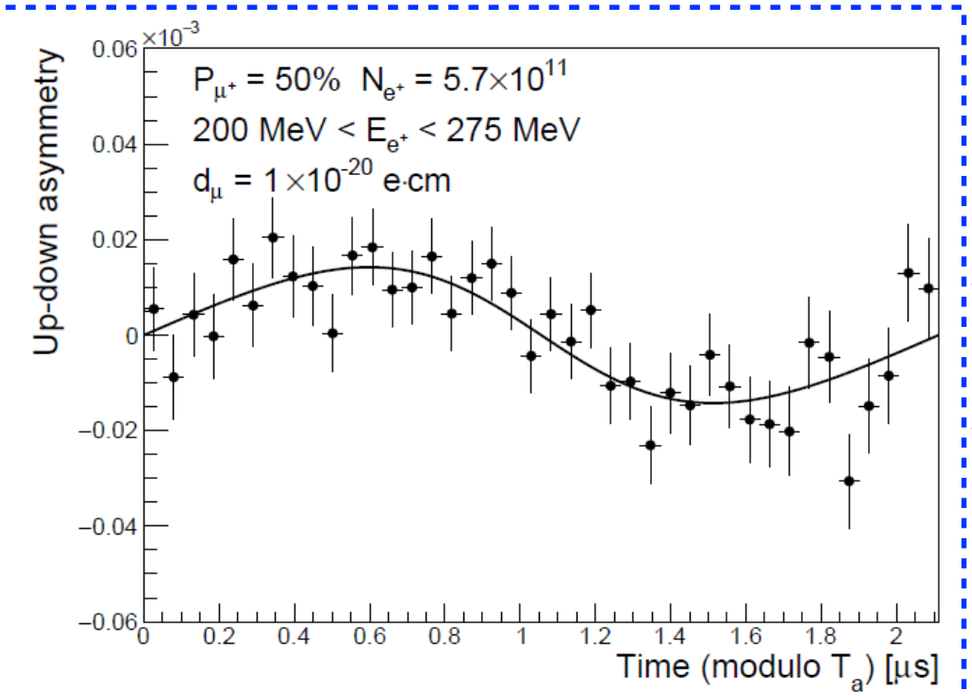
g-2 **= 0** **EDM** **= 0**



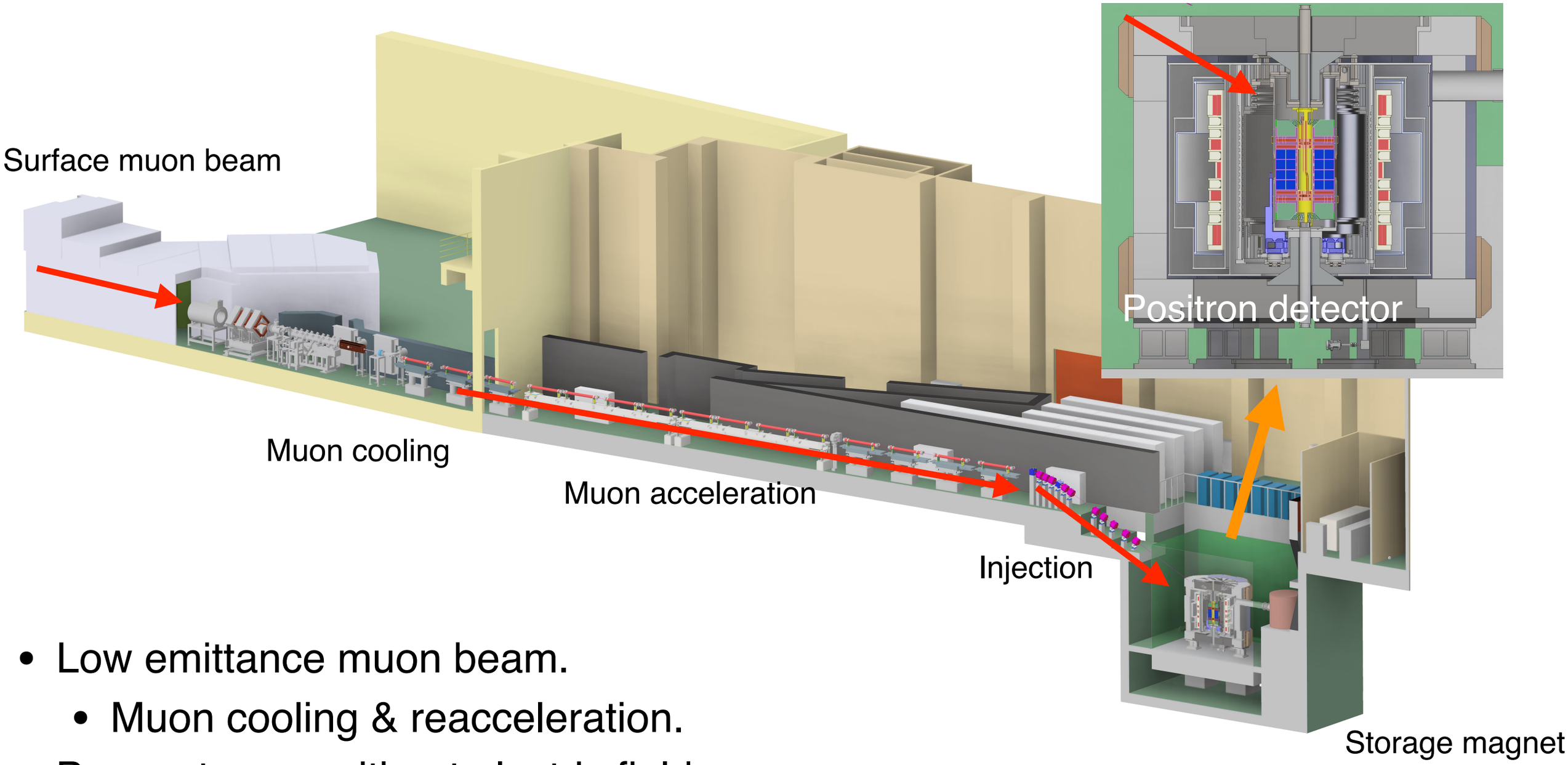
Simulated time spectrum of the number of decay positrons



∝ EDM

Simulated up-down asymmetry of decay positrons

Muon g-2/EDM experiment at J-PARC



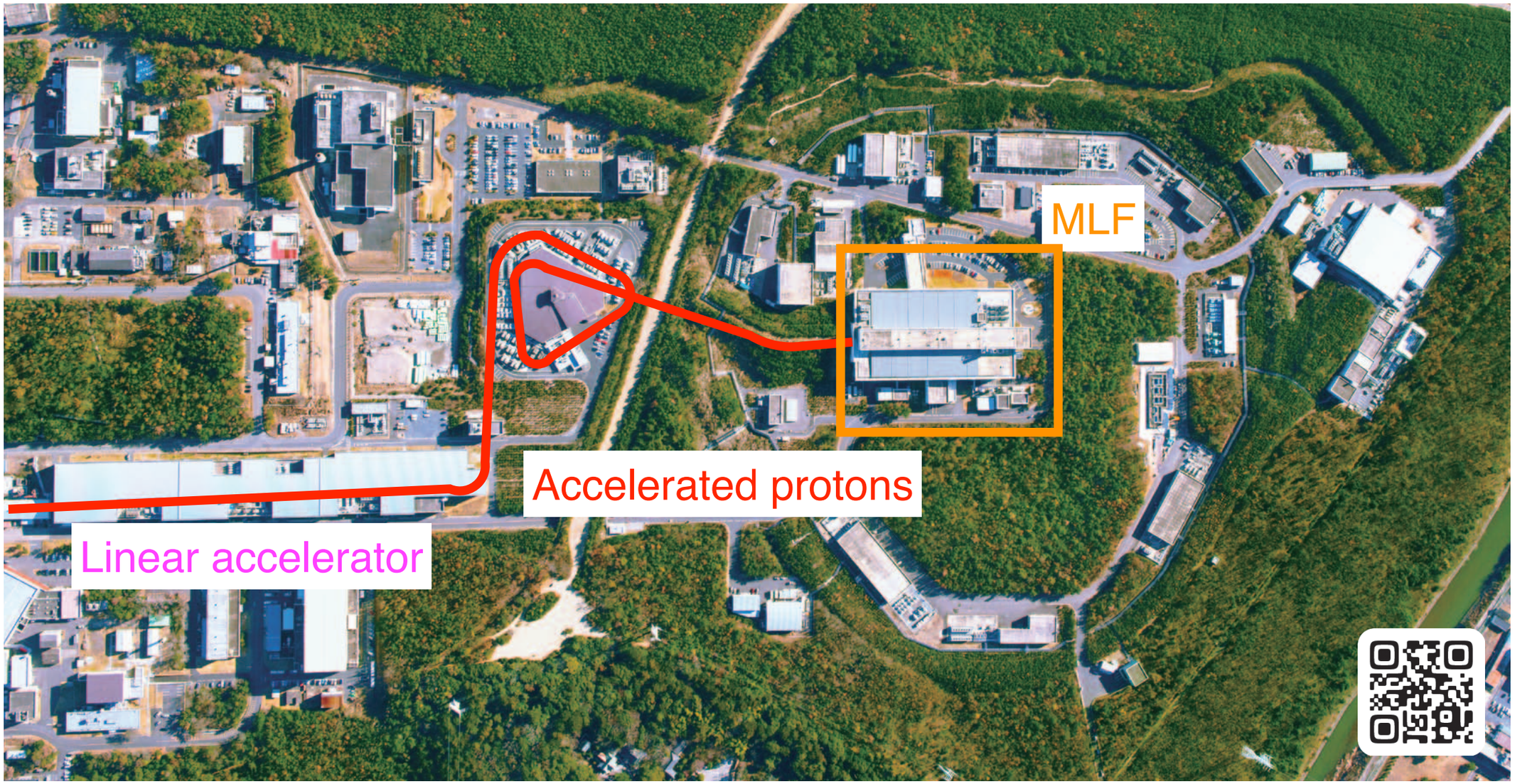
- Low emittance muon beam.
  - Muon cooling & reacceleration.
- Beam storage without electric field.
- High-precision uniform magnetic field.
- Track reconstruction using the silicon detector.

J-PARC MLF

J-PARC (Japan Proton Accelerator Research Complex)

MLF (Materials and Life science experimental Facility)

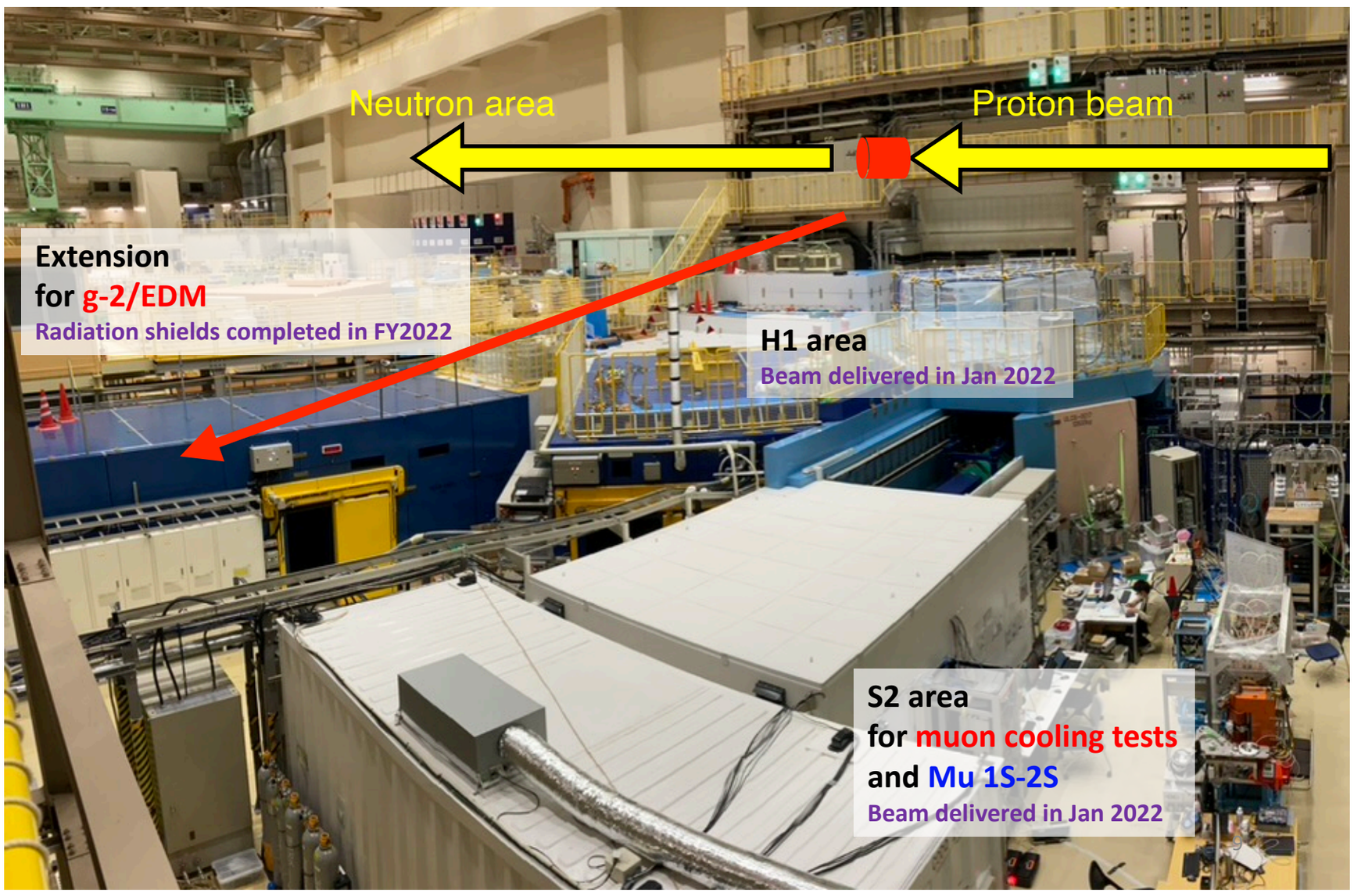
- Beam Power : 1 MW
- 25 Hz rep.
- Use H-line (H2) under construction



Surface μ^+ beam

MLF H2 beam line.

- Target : Graphite
- Surface μ^+ beam : 4 MeV with 25 Hz rep.
- Beam rate : 1.2×10^8 muons/s is expected at the Mu production target (1 MW proton beam).
- H2 area (radiation shield and PPS) was constructed (inside the existing MLF bldg.)



H-line experimental building

A new extension building will be constructed.

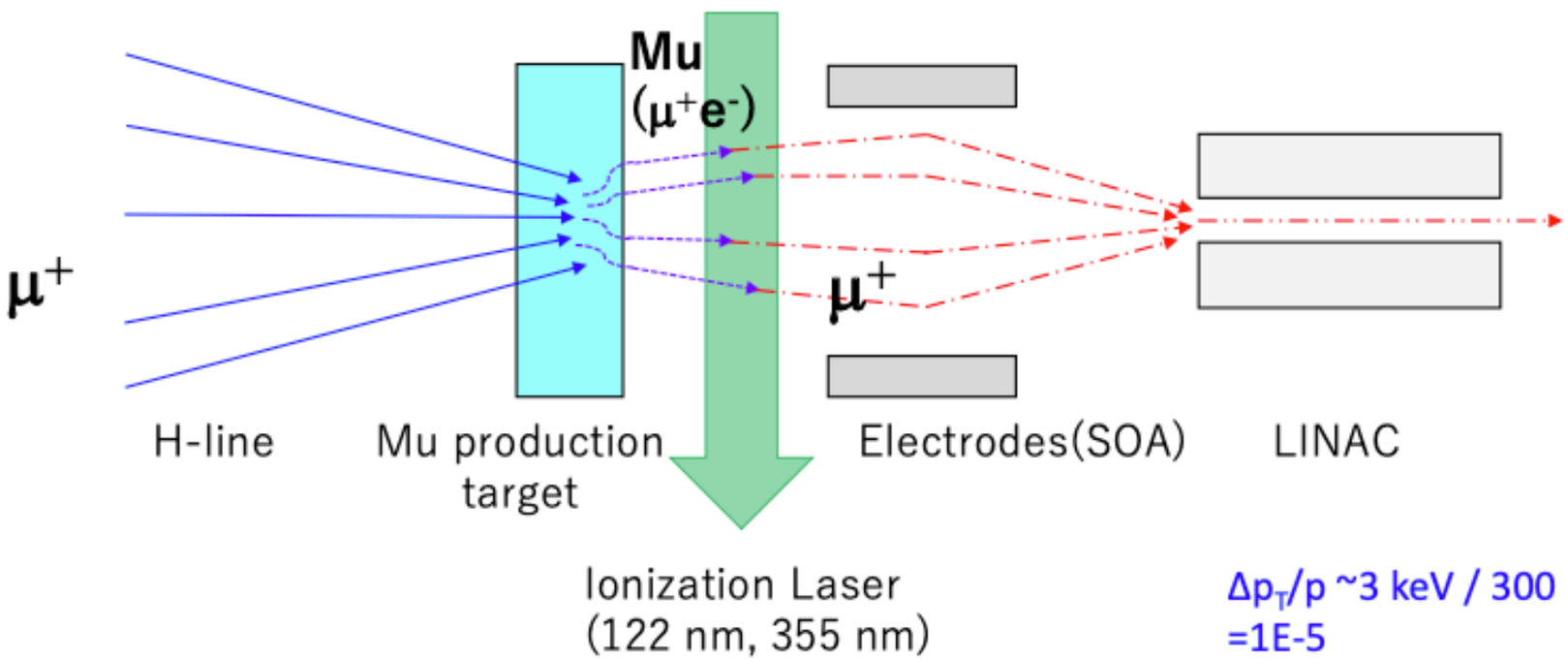
- The design will be completed in FY2023.
- The construction is scheduled to start next year.

Muon cooling

Cool surface muons before reacceleration

- Silica aerogel target : Stop surface muons, and thermal muoniums are emitted.
- Laser ablated aerogel for muonium production target.

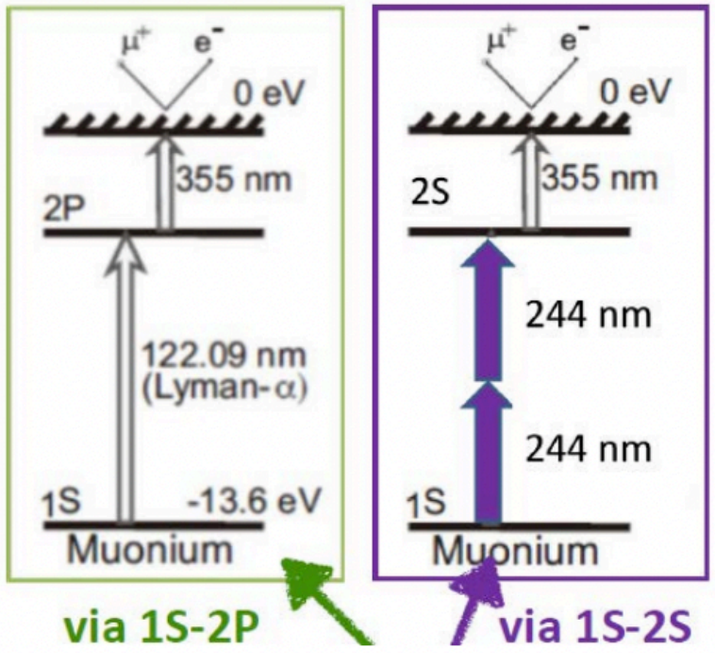
	surface muon	thermal muon	accelerated muon
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
Δ p/p	0.05	0.4	4×10^{-4}



$\Delta p_T/p$ ~3 keV / 300 MeV =1E-5

Thermal muonium ionization by laser.

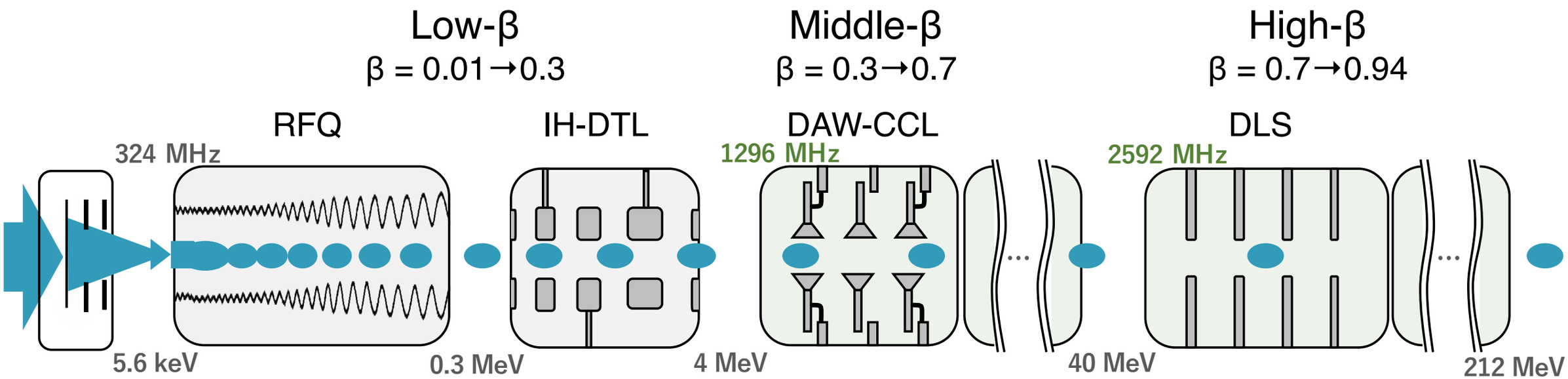
- Two scheme under consideration.
- 1S-2P excitation by 122 nm or 1S-2S excitation by 244 nm



Muon acceleration

Muon reacceleration to 300 MeV/c by muon LINAC.

- 4 types of cavities used.



L= 3.2 m
Acceleration test with thermal μ planned in 2023

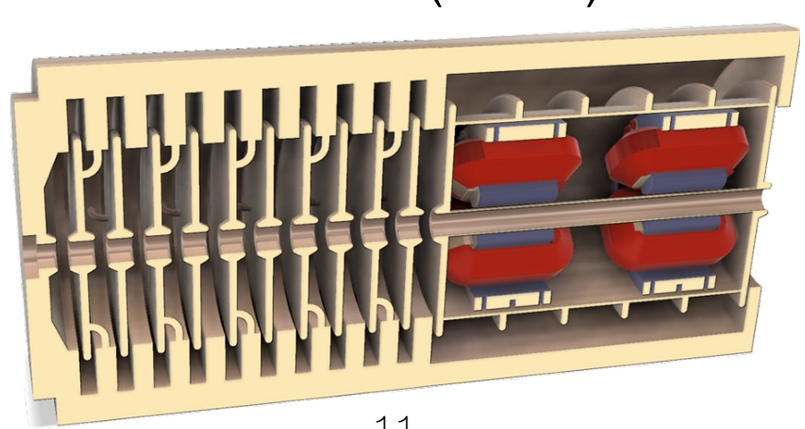
1.4 m
Fabrication completed

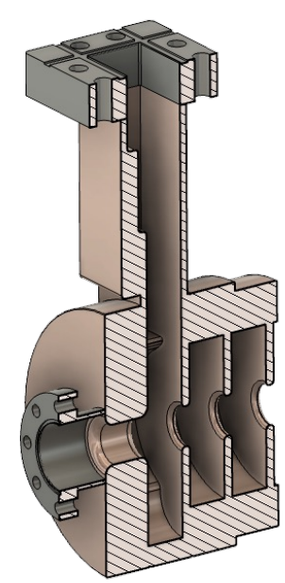
16 m (14 modules)
1st tank under fabrication

10 m (4 structure)
Prototype fabricated in JFY 2022

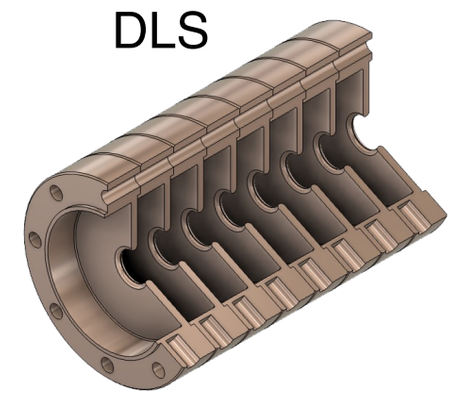
IH-DTL

DAW tank (11 cell)





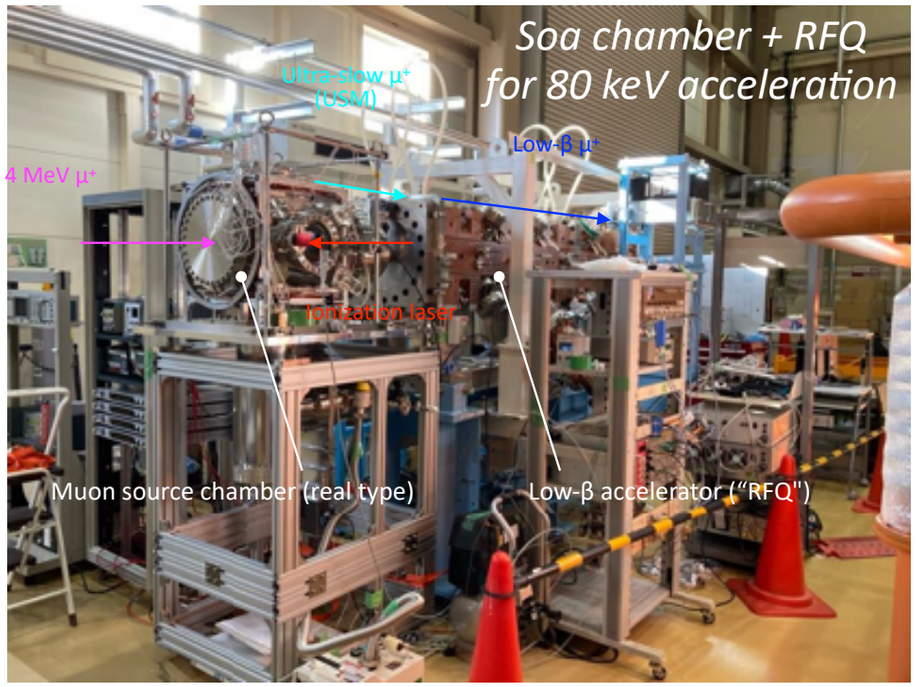
DLS

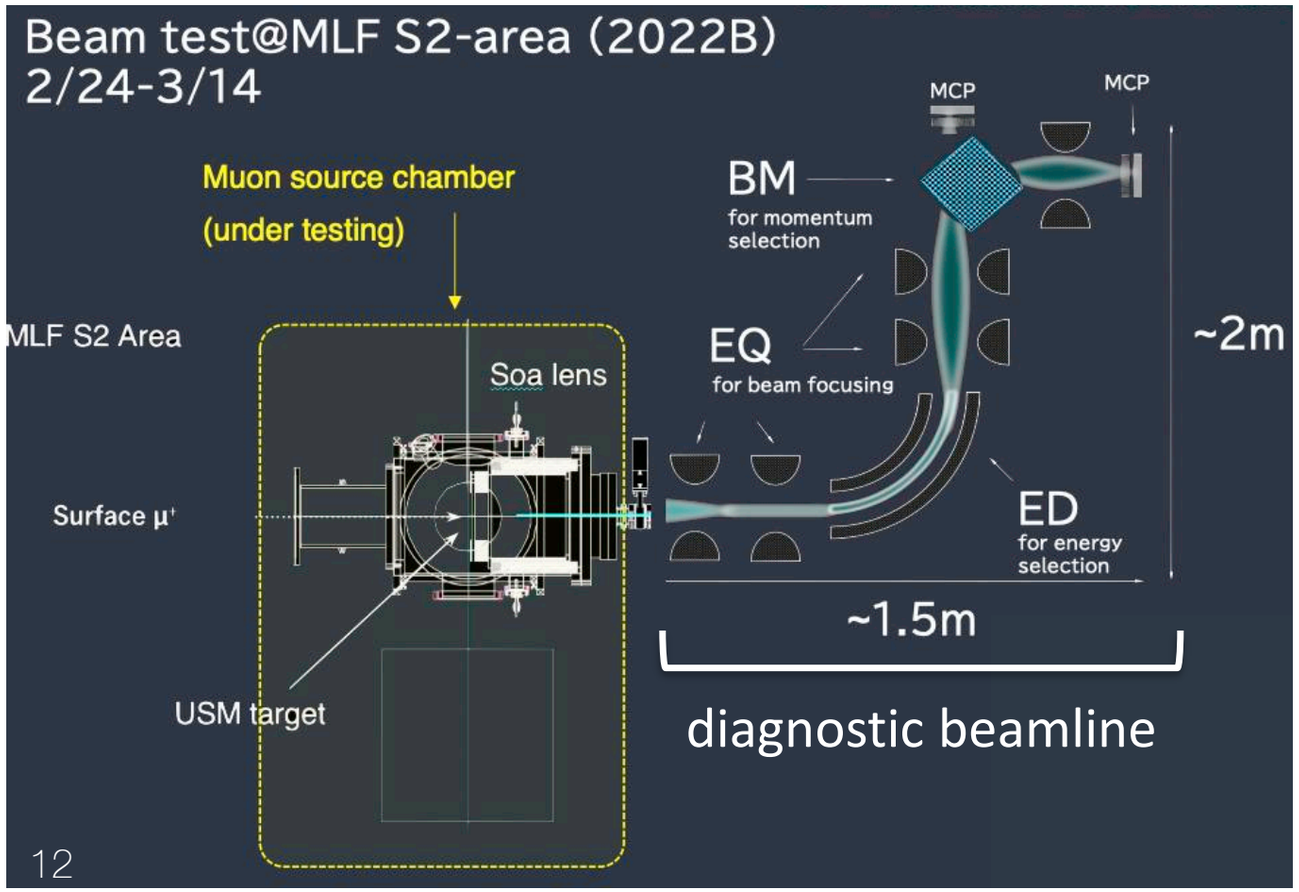


USM acceleration test

A USM acceleration demonstration is ongoing at MLF S2 line.

- Measure the USM beam properties with real SOA chamber
  - Mu ionization by the 1S-2S laser
  - Muon acceleration up to 80 keV
  - Profile, emittance, signal rate
- Analysis is on going.





Beam injection

3D spiral injection scheme is adopted for muon beam injection into the storage region.

- Tuning of beam phase space & pulsed B-field
- Expected injection efficiency : ~ 85%

Injection region :

Fringe B-field of solenoid

- Reduces beam pitch angle by B_r.

Kick region :

Pulsed B-field by kicker coil

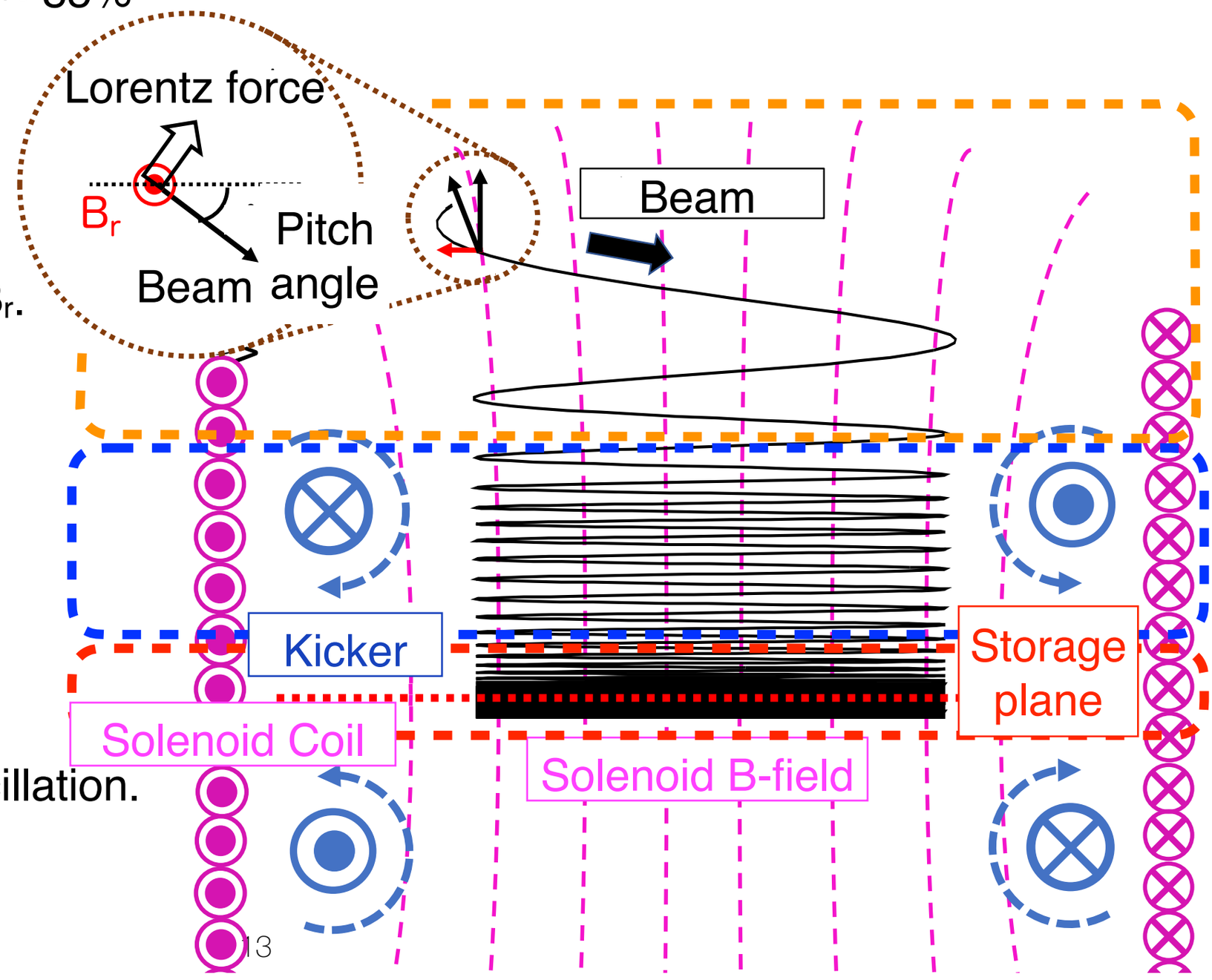
- Vertical kick of beam by B_r.

Storage region :

Weak-focusing B-field

- Beam storage with betatron oscillation.

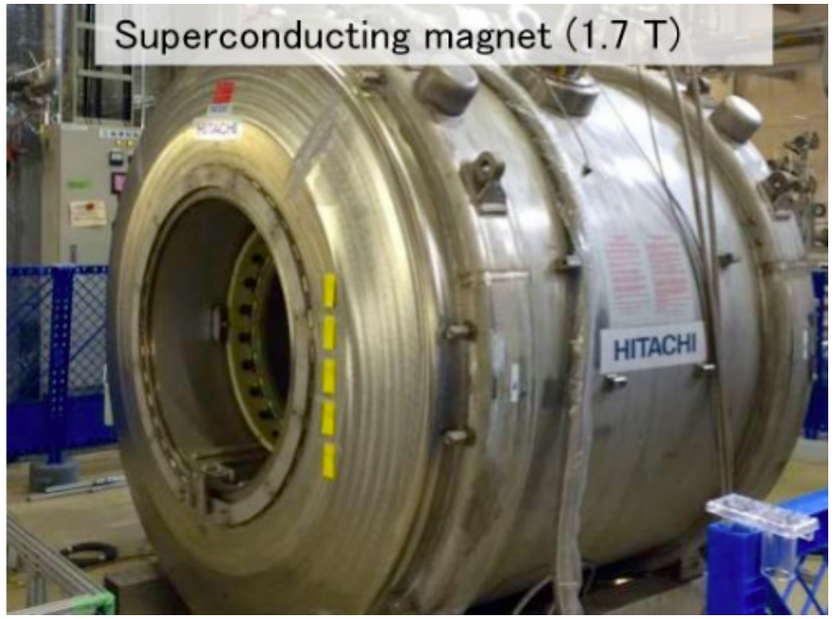
Demonstration is on going by using a electron beam



Storage magnet

High uniform (0.1 ppm) magnetic field will be achieved by shimming.

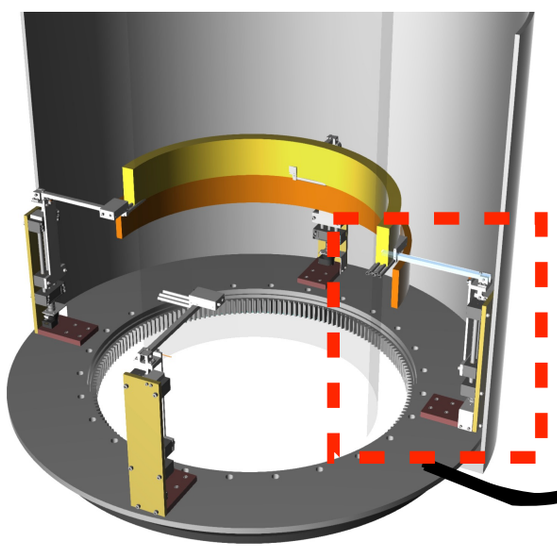
- Compact solenoid magnet based on MRI magnet technology.
- B-field measurement by a high precision NMR probe.

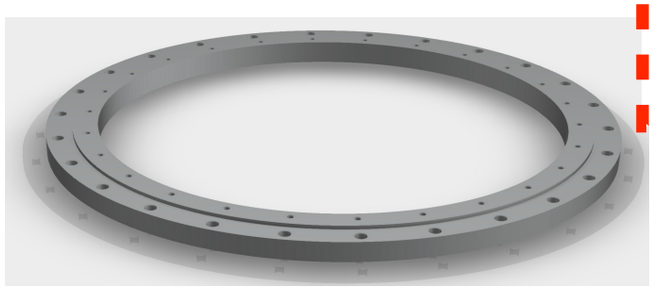


Local uniformity of 1 ppm is already demonstrated by the MuSEUM magnet.

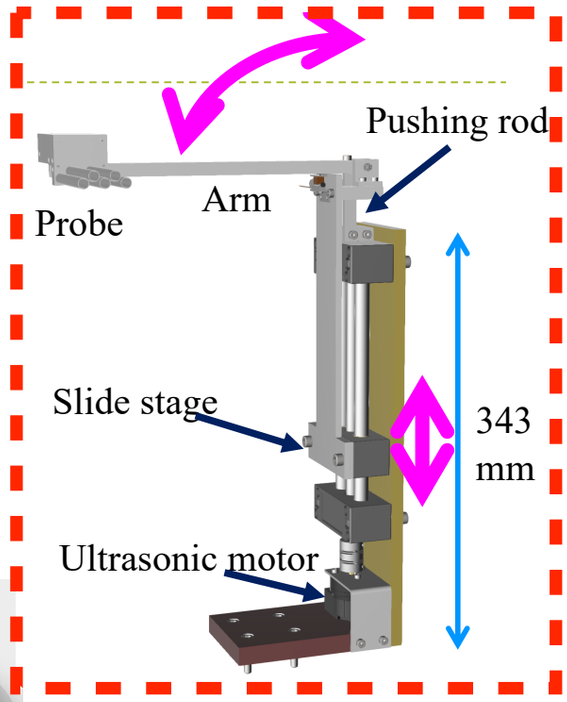
Field mapping system under design

- B-field measurement in the muon storage region.
- Vertical and azimuthal motion.



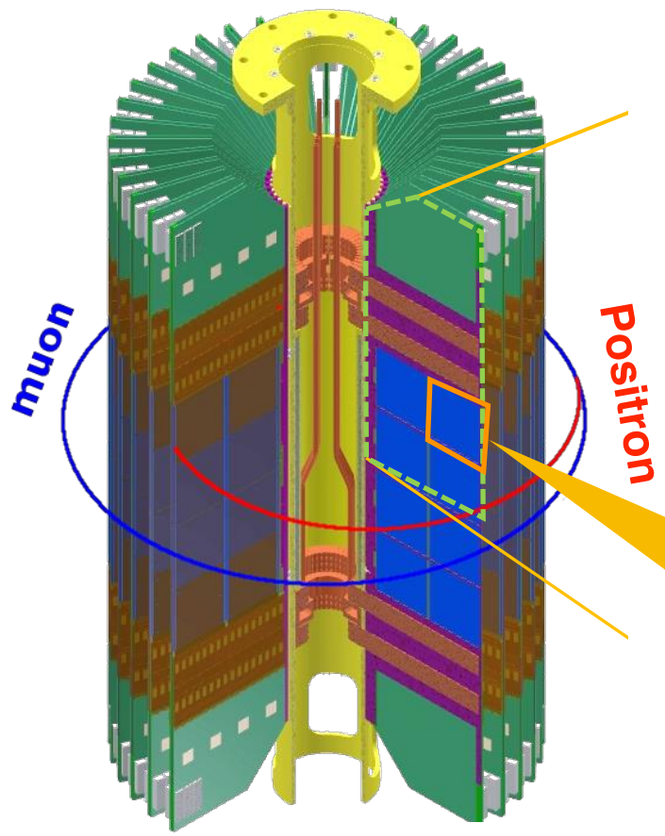


Low-magnetic bearing



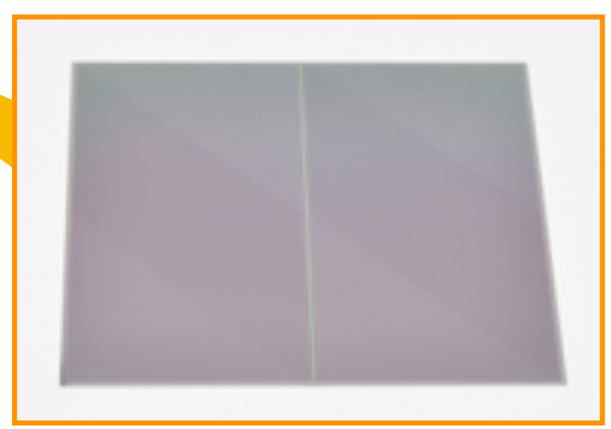
Positron detector

- Silicon detector is used to measure the decay time and momentum of positrons generated by muon decay.
  - Silicon strip sensor : Hamamatsu S13804, 190 μm pitch
  - High hit rate capability (Max : 6 tracks/ns) and stability against rate changes (1.4 MHz - 10 kHz)
  - High efficiency for positrons (p = 200 - 275 MeV/c)

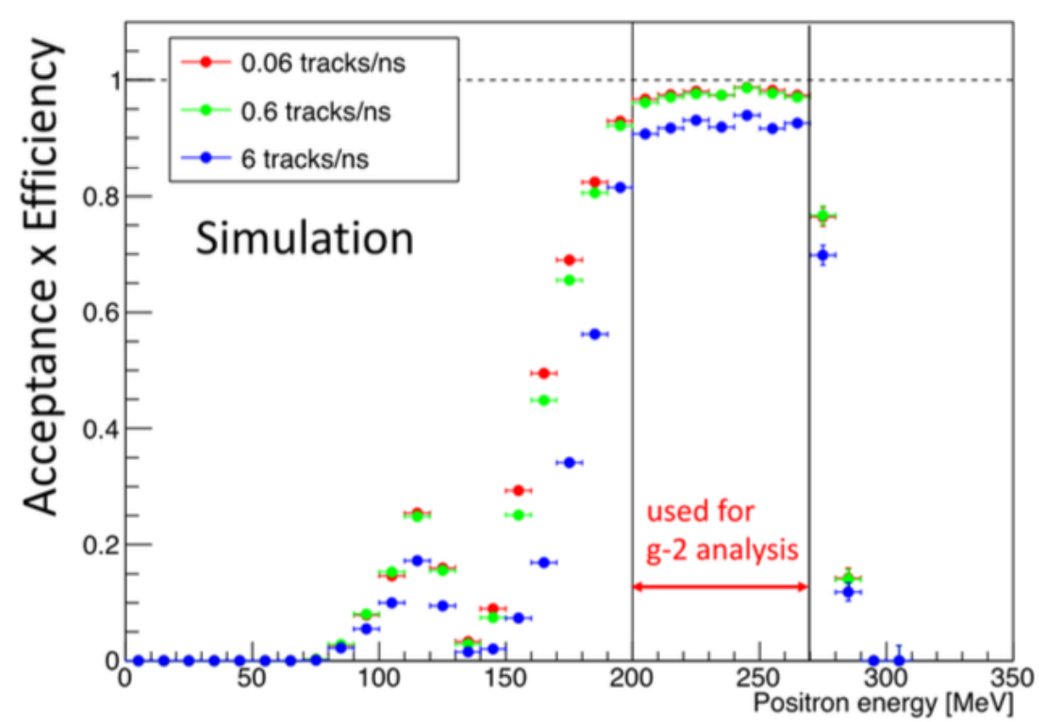


ϕ 580 mm

HPK S13804
- Silicon strip detector
- 100 × 100 mm²
- 190 μm strip

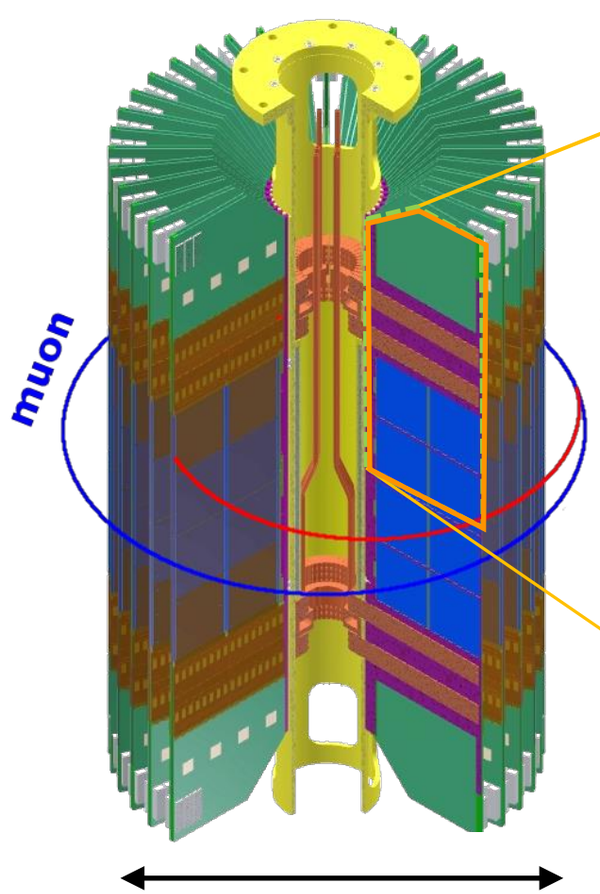


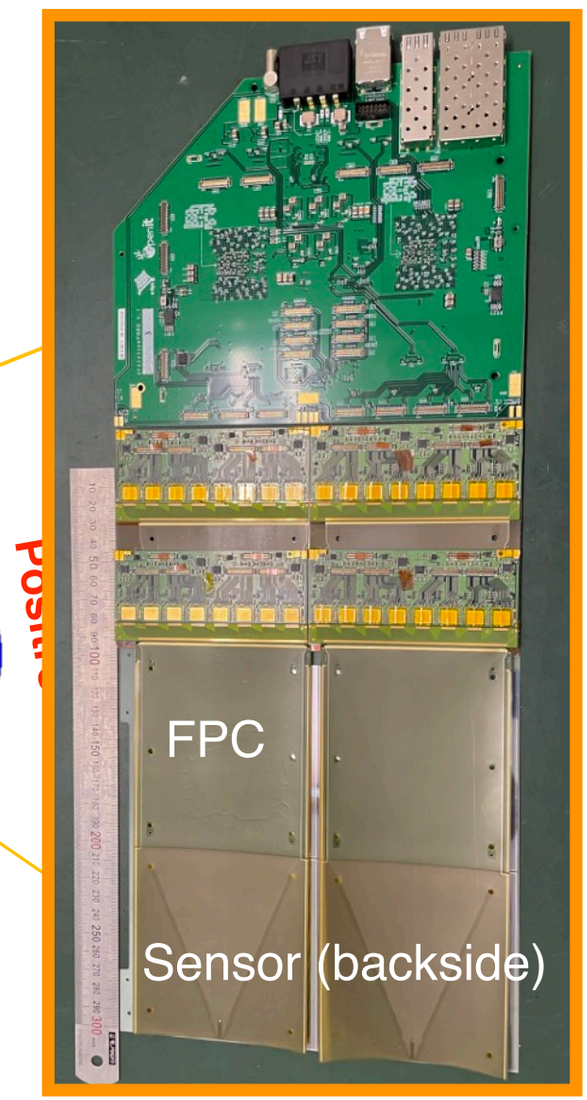
Reconstruction efficiency



Positron detector

- Major components are in or completed the mass-productions.
- Assembly procedure is under R&D.
- A minimum unit of the detector is under readout electronics test.



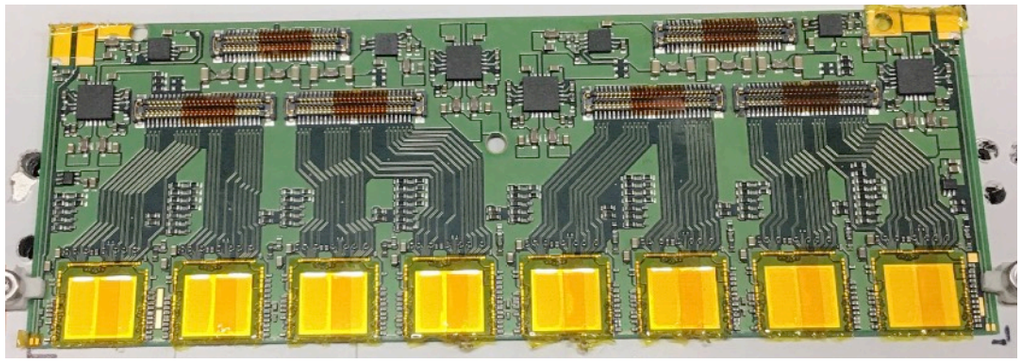


FPGA readout board

- 2 Xilinx Artix-7 FPGAs to suppress hit data of 32 ASICs
- 2 SFPs for receiving clock/trigger signals and sending the hit data

ASIC board

- 8 ASICs (SliT128D)
  - Rising time < 50 ns
  - Time-walk < 1 ns
  - Process 128 ch hit data

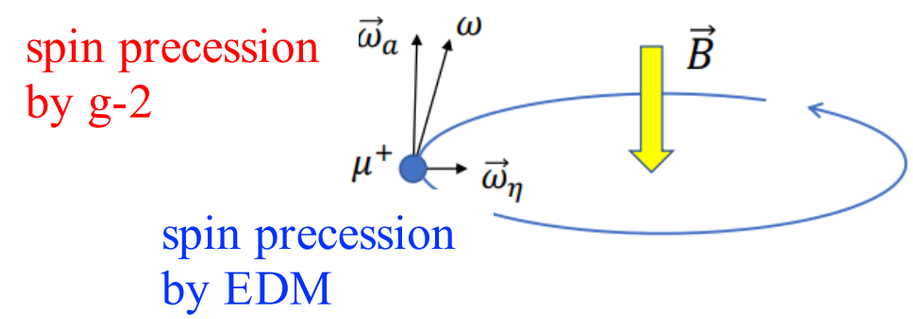


Sensor alignment

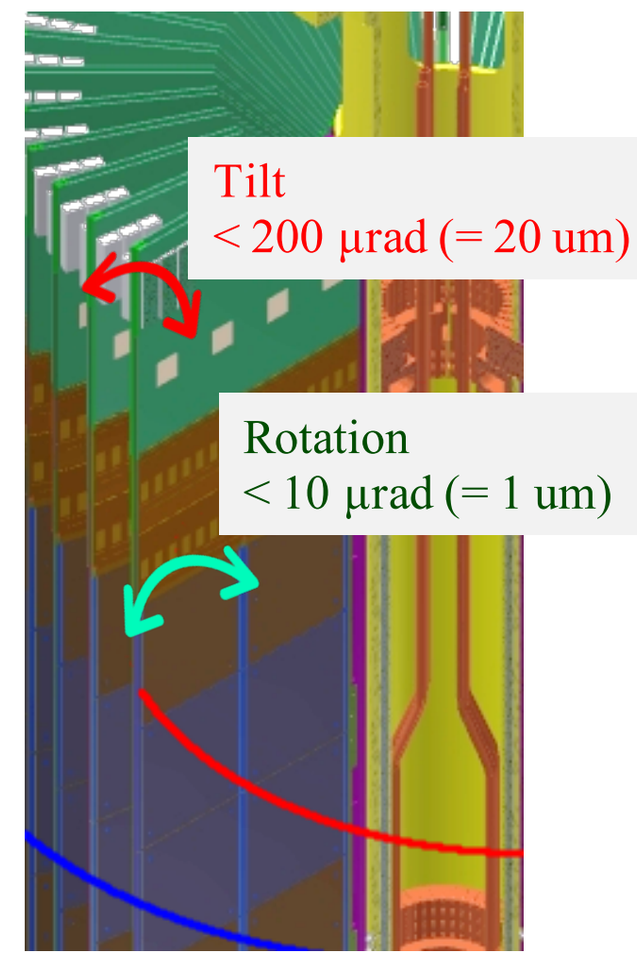
- Precise alignment between detector and B-field is essential for muon EDM measurement.
  - If the alignment is off, “g-2 component” of spin precession comes into “EDM component”.

$$\vec{\omega}_a + \vec{\omega}_\eta = -\frac{e}{m}\left[\frac{g-2}{2}\vec{B} + \frac{\eta}{2}\vec{\beta}\times\vec{B}\right]$$

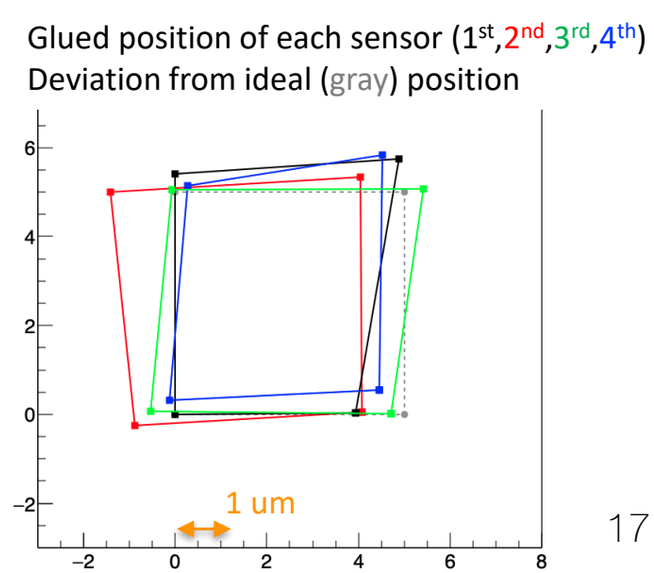
g-2 EDM



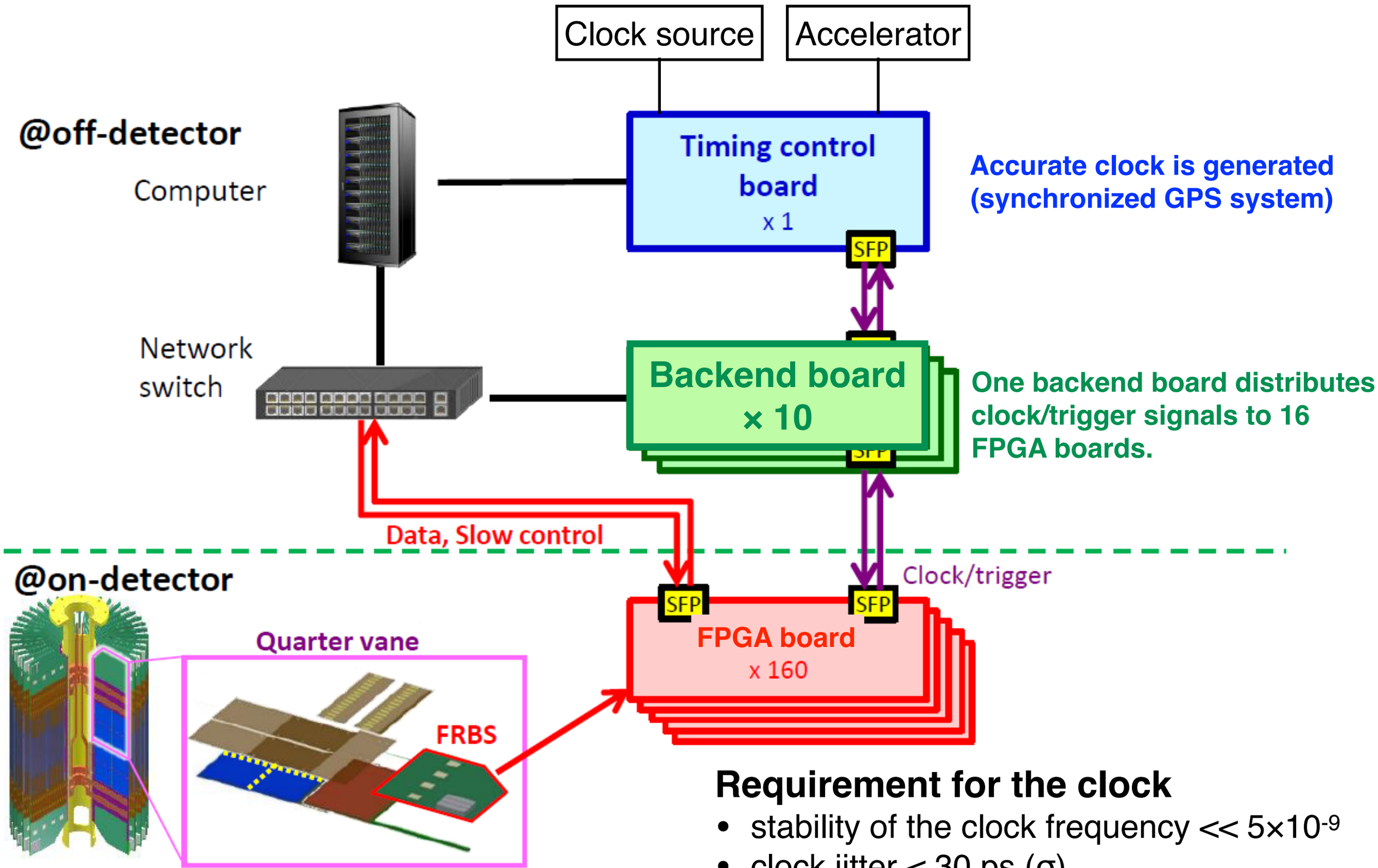
- Goal : 1 μm rotation and 20 μm tilt of each sensor.
  - Precision (rotation) of 2 μm already achieved by using sensor alignment jig + CMM for sensor position/shape measurement



- Track-based alignment during physics DAQ and interferometer based alignment monitor are under consideration.



DAQ system



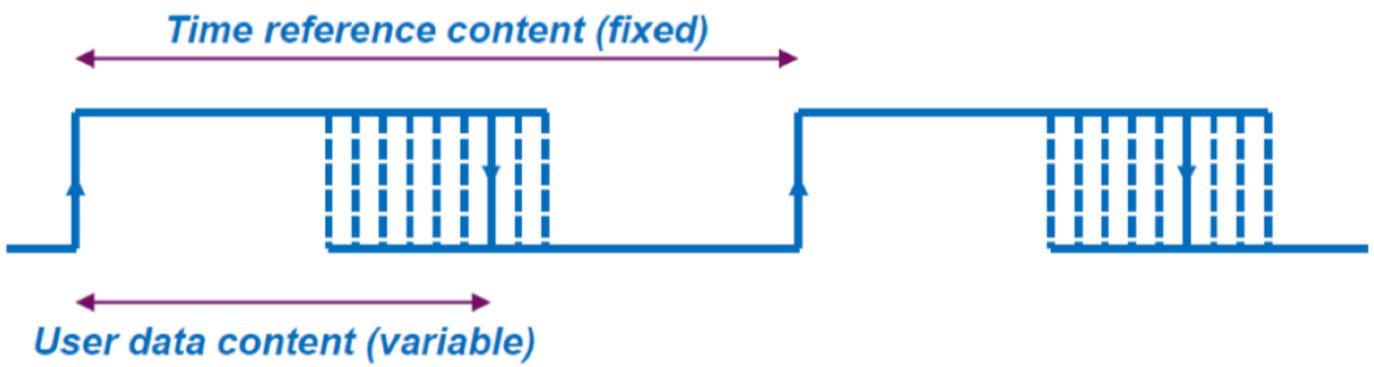
Requirement for the clock

- stability of the clock frequency << 5×10^{-9}
- clock jitter < 30 ps (σ)

Principle of clock/trigger distribution

Adopting clock-duty-cycle-modulation (CDCM) as a core technology

- CDCM is a **data-on-clock** type modulation. (8b10b is a clock-on-data type)
- Data bits are embedded to the trailing edges of the clock signal.



Denis Calvet,
IEEE TNS (Volume: 67, Issue: 8, Aug. 2020)

Ryotaro Honda,
23rd IEEE Real time

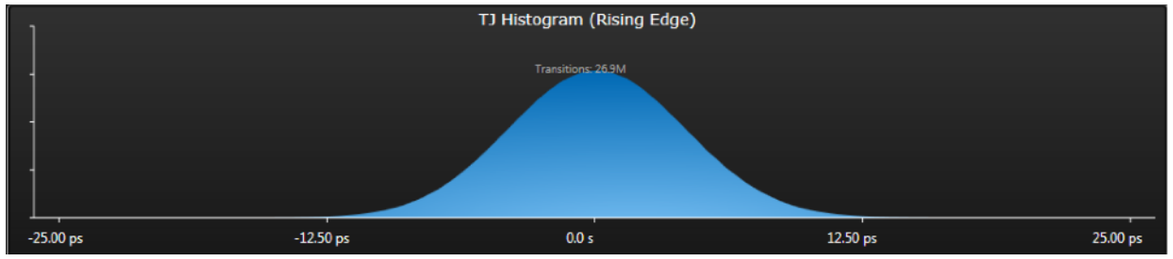
Advantages

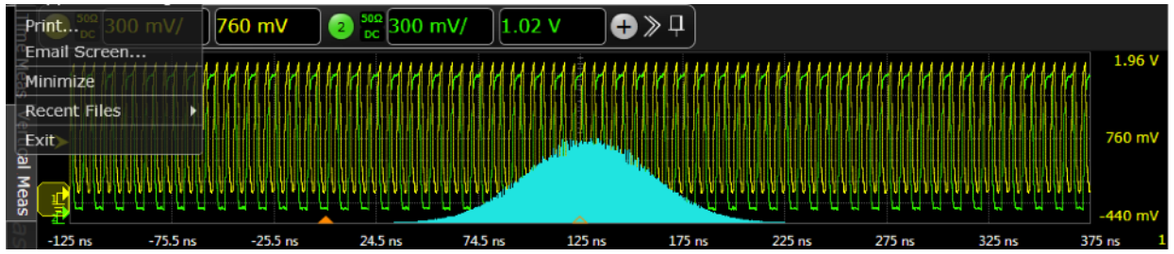
- This modulated clock can be directly input to PLLs and MMCMs in FPGA and **external jitter cleaner ICs**.
- Output clock skews from MMCMs respect to the input modulated clock are automatically adjusted by using the global clock network in FPGA.
    - Automatic phase alignment among front-end electronics.

Clock/trigger distribution test

Jitter measurement : ~ 10 ps < 30 ps (requirement)

- Time Interval Error measurement
  - Periodic jitter (RMS) : 2.3 ps
  - Random jitter (RMS) : 3.4 ps
- Phase jitter between master and slave clocks : 6.1 ps

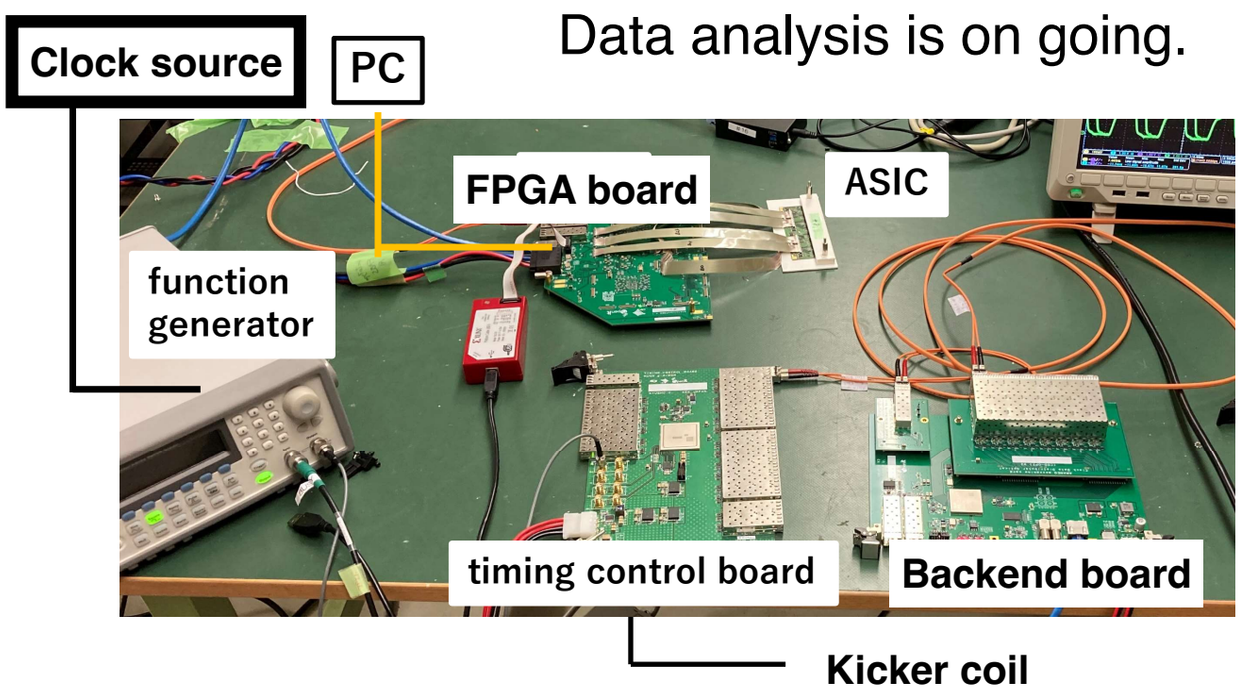


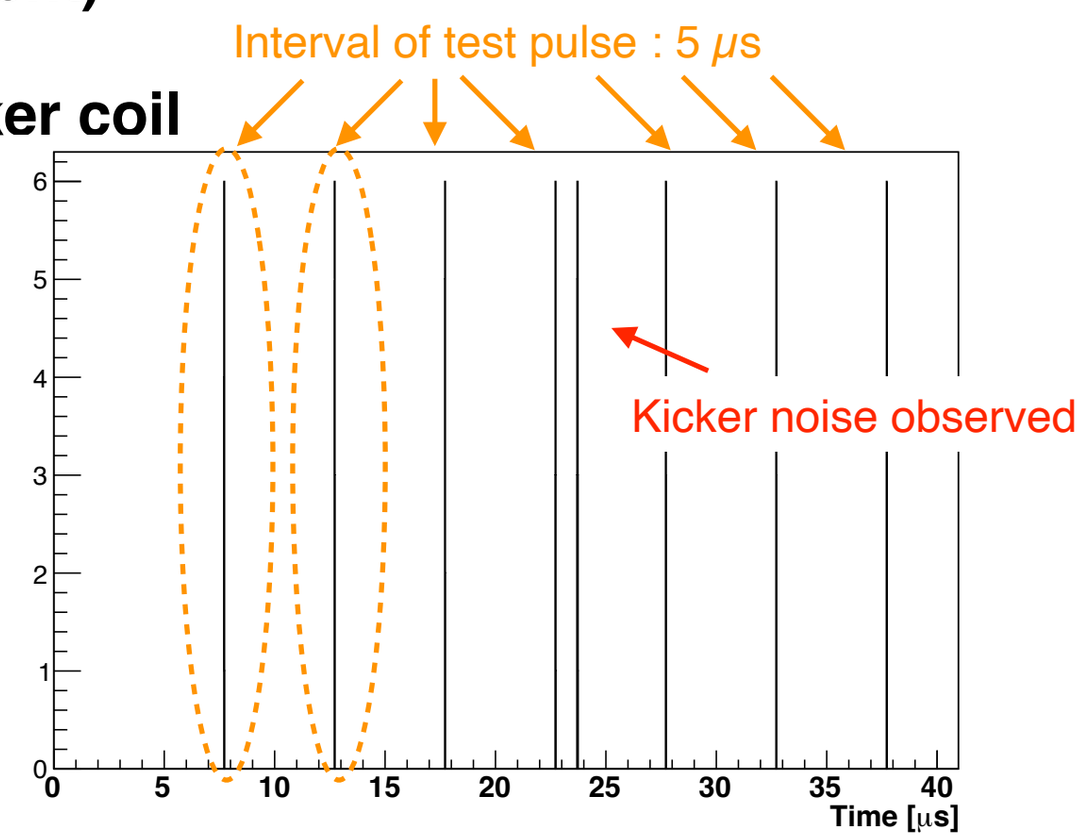


Frequency stability : ~ 2×10^{-10} < 5×10^{-9} (requirement)

Trigger distribution test synchronized with the kicker coil

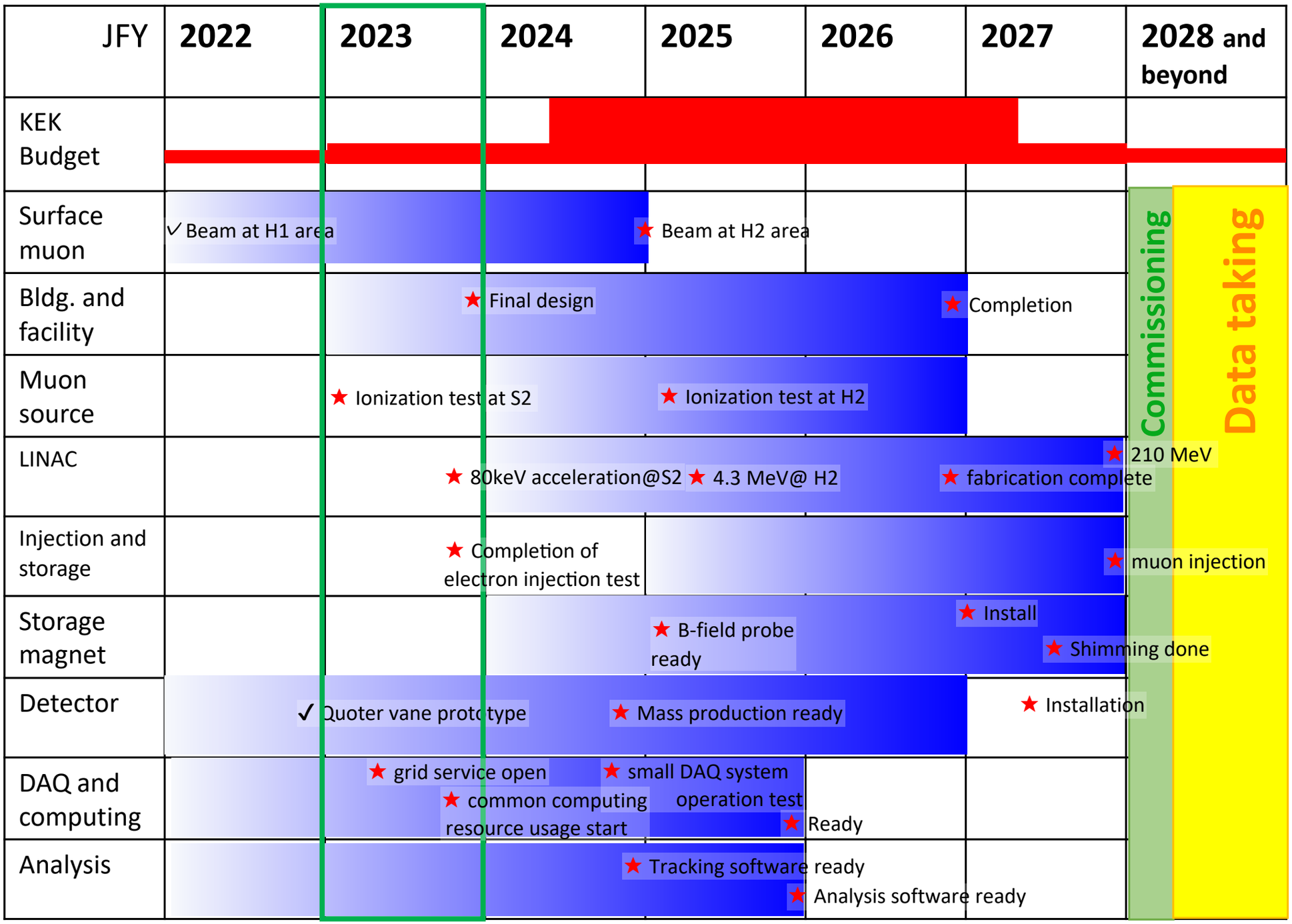
Data analysis is on going.





Schedule

Physics data taking expected from JFY 2028.



Expected sensitivity

Total efficiency of muon will be 1.3×10^{-5}.

(The expected number of positrons is 5.7×10^{11} for 2.2×10^{7} s)

Subsystem	Efficiency	Subsystem	Efficiency
H-line acceptance and transmission	0.16	DAW decay	0.96
Mu emission	0.0034	DLS transmission	1.00
Laser ionization	0.73	DLS decay	0.99
Metal mesh	0.78	Injection transmission	0.85
Initial acceleration transmission and decay	0.72	Injection decay	0.99
RFQ transmission	0.95	Kicker decay	0.93
RFQ decay	0.81	e^+ energy window	0.12
IH transmission	0.99	Detector acceptance of e^+	1.00
IH decay	0.99	Reconstruction efficiency	0.90
DAW transmission	1.00		

Muon g-2

- Systematic uncertainty : less than 70 ppb
- Statistical uncertainty : 450 ppb (2.2×10^{7} s ~ 2 years of data taking) → 100 ppb (Final)
  - Uncertainty comparable to BNL can be reached.
  - Possibility of further improvement under discussion.

Anomalous spin precession (ω_a)	
Source	Estimation (ppb)
Timing shift	< 36
Pitch effect	13
Electric field	10
Delayed positrons	0.8
Diffential decay	1.5
Quadratic sum	< 40

Magnetic field (ω_p)	
Source	Estimation (ppb)
Absolute calibration	25
Calibration of mapping probe	20
Position of mapping probe	45
Field decay	< 10
Eddy current from kicker	0.1
Quadratic sum	56

Muon EDM

- Systematic uncertainty : 0.4×10^{-21} e・cm
  - mainly from detector mis-alignment
- Statistical uncertainty : 1.5×10^{-21} e・cm

Summary

- Muon g-2/EDM experiment at J-PARC aims to measure muon g-2/EDM by utilizing
  - Low emittance muon beam stored by weak focusing magnetic field.
  - Compact storage magnet with low momentum muon.

- An independent measurement from BNL/FNAL with different systematics.

- All sub-system of this experiment are getting ready for realization.
  - Some of them are already in “construction phase”.

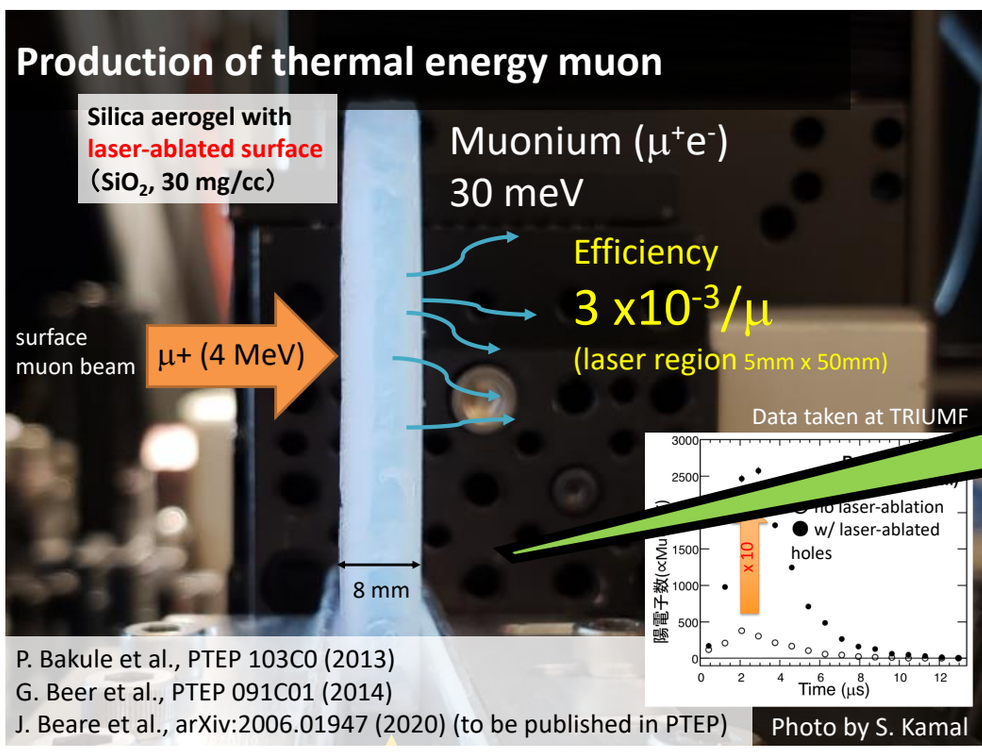
- Expected data taking from JFY 2028.

- After 2 years of data taking,
  - muon g-2 measurement at 450 ppb (stat.) : comparable to BNL
  - muon EDM sensitivity at 1.5×10^{-21} e・cm (stat.) : 2 orders of magnitude improvement.

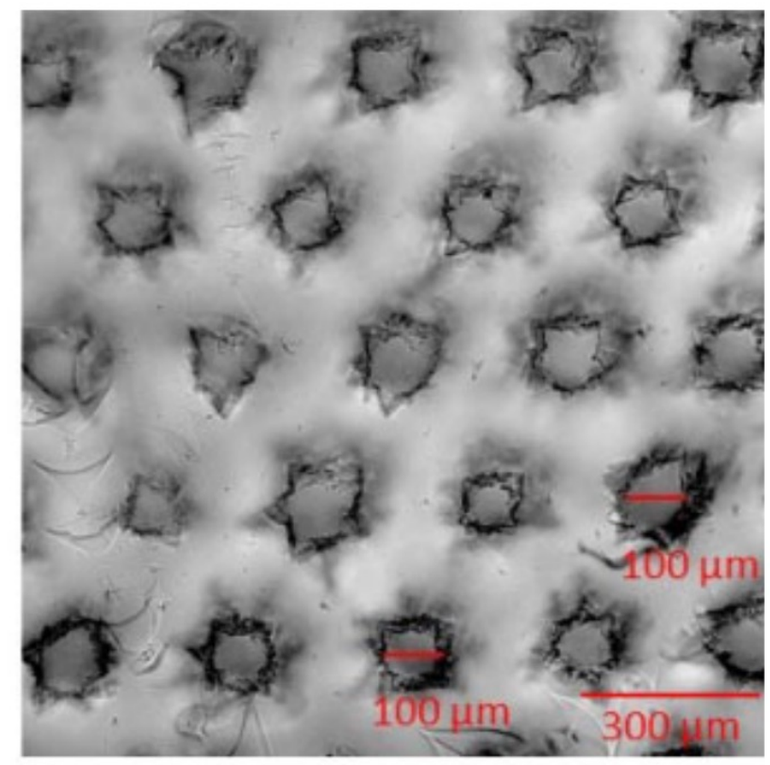
Back up

Laser ablated aerogel target

- Laser ablated aerogel target has been developed
  - Small holes at surface by irradiation of fs laser.
  - Increase surface area : only Mu near the surface are emitted to vacuum



Example of surface of aerogel



Laser development

- Two possible choice of excited state = wavelength: Pros and Cons
  - 2P state: 122nm for excitation & 355nm for unbound
  - 2S state: 2 × 244nm for excitation & 244nm for unbound

2P state

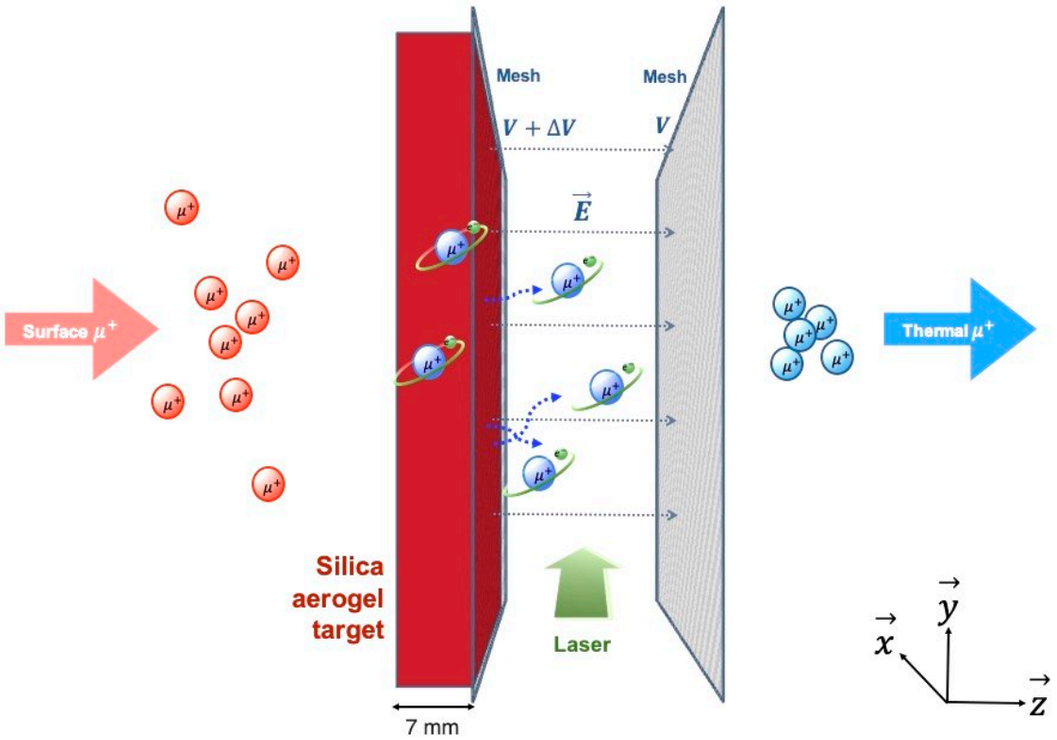
Plan A

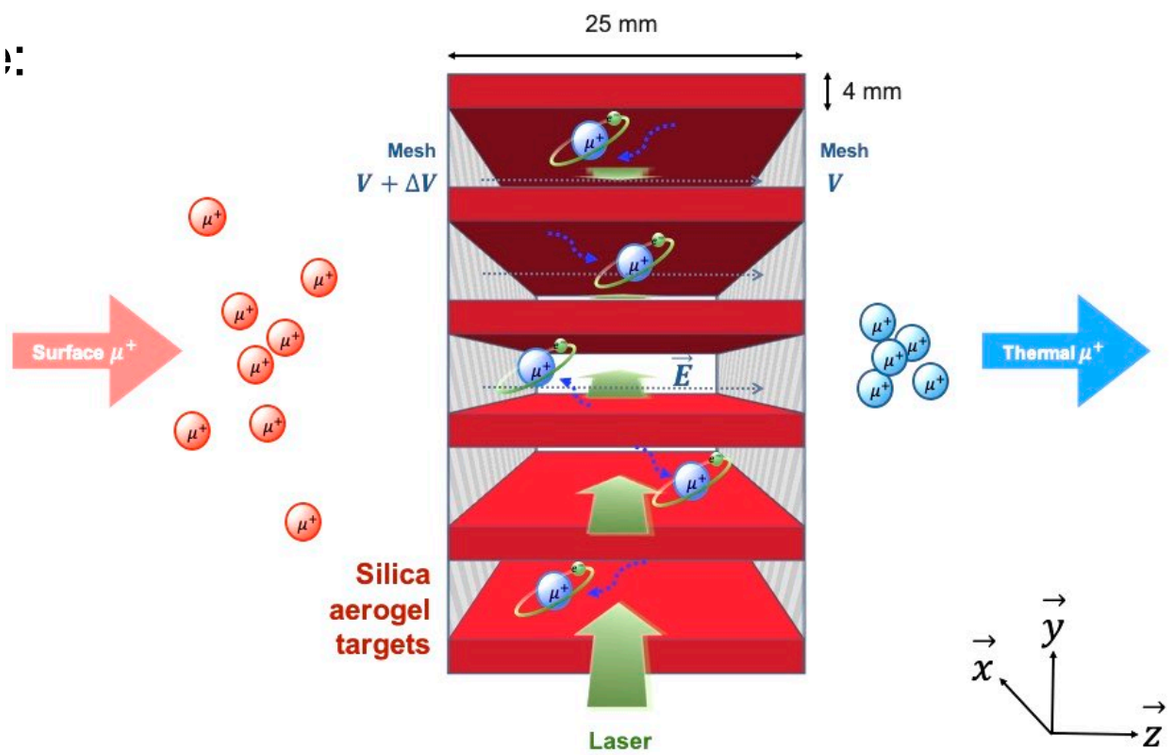
- Pros
  - Large cross section. **Less laser energy.**
  - Long history @ KEK
  - Easier alignment. (Robust)
- Cons
  - **λ=122nm**: difficult to generate
  - Handling is difficult: × air
  - Damage of optics (photon eneryg)

2S state

- Pros
  - **λ=244nm: well-established**
  - Doppler free
  - Selectively excites spin triplet: better spin polarization.
- Cons
  - **Small cross section**: Two photon
  - Precise alignment is required
  - Damage of optics (high intensity)

Multi-layer target

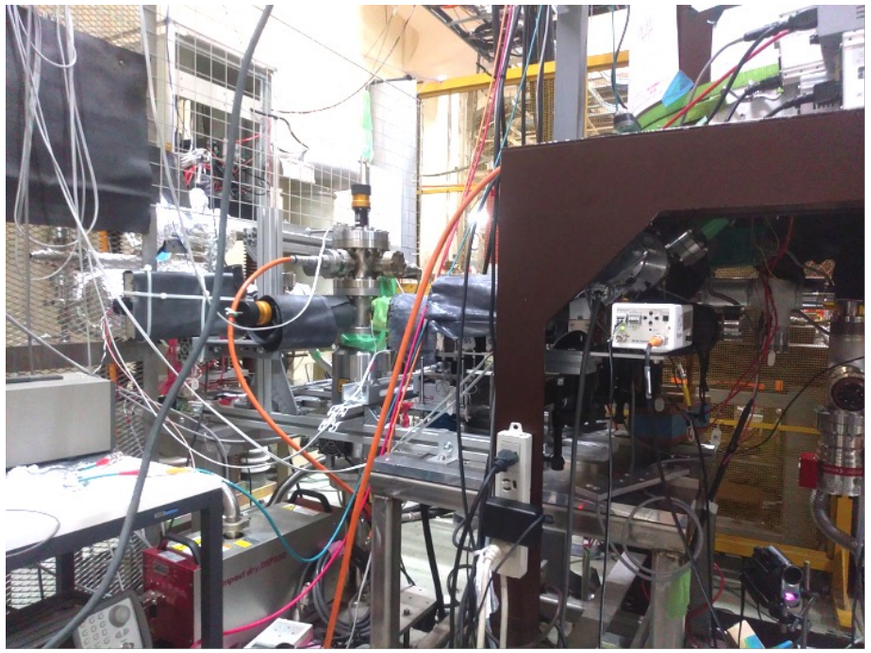


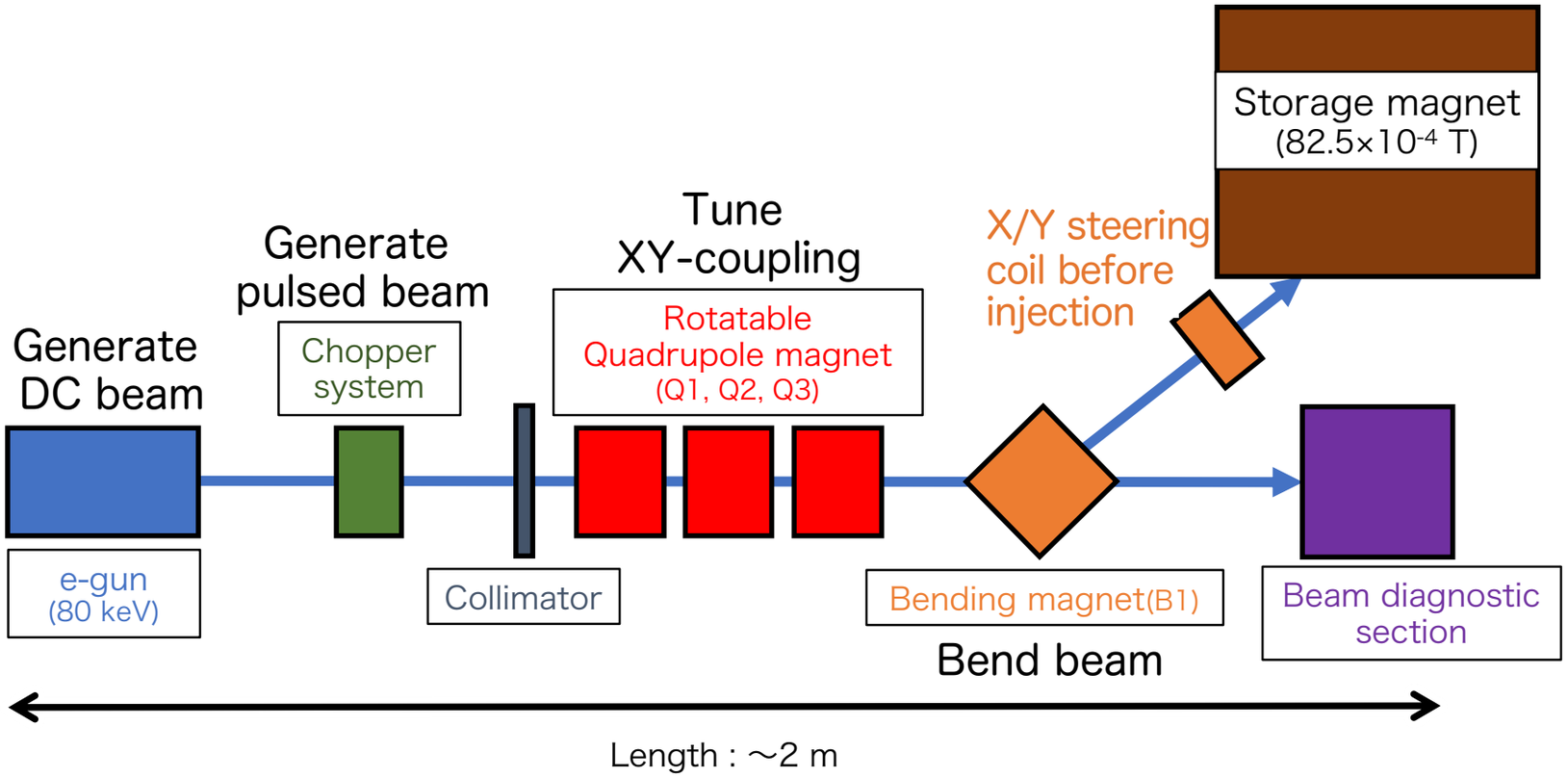


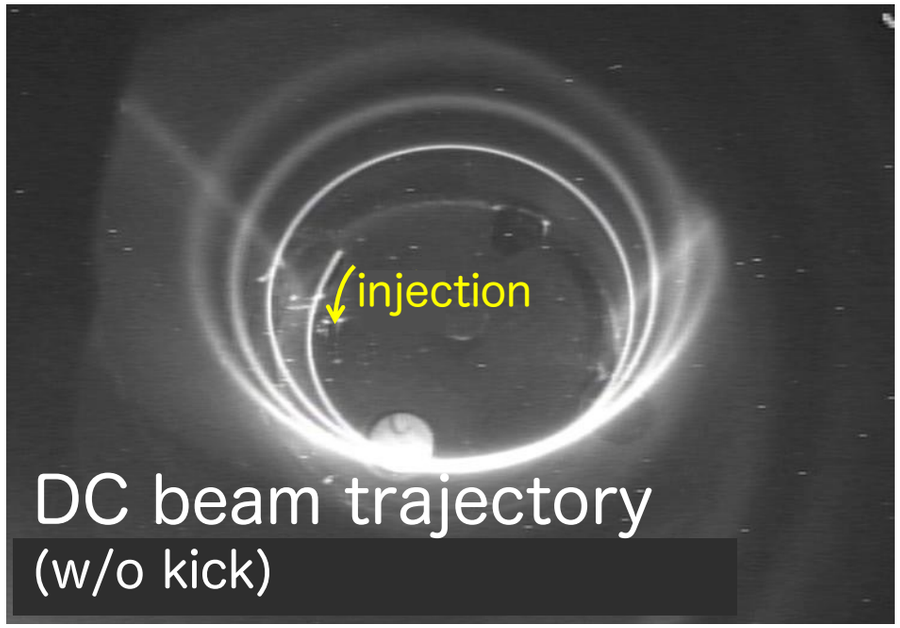
	Single-layer	Multi-layer (6 layers, Interval = 7 mm)
Muon stopping	0.418	0.454
Mu formation	0.52	0.52
Mu vacuum yield	0.058	0.179
Laser spatial constraints	0.264	0.283
Total efficiency	0.0034	0.012

Demonstration beamline

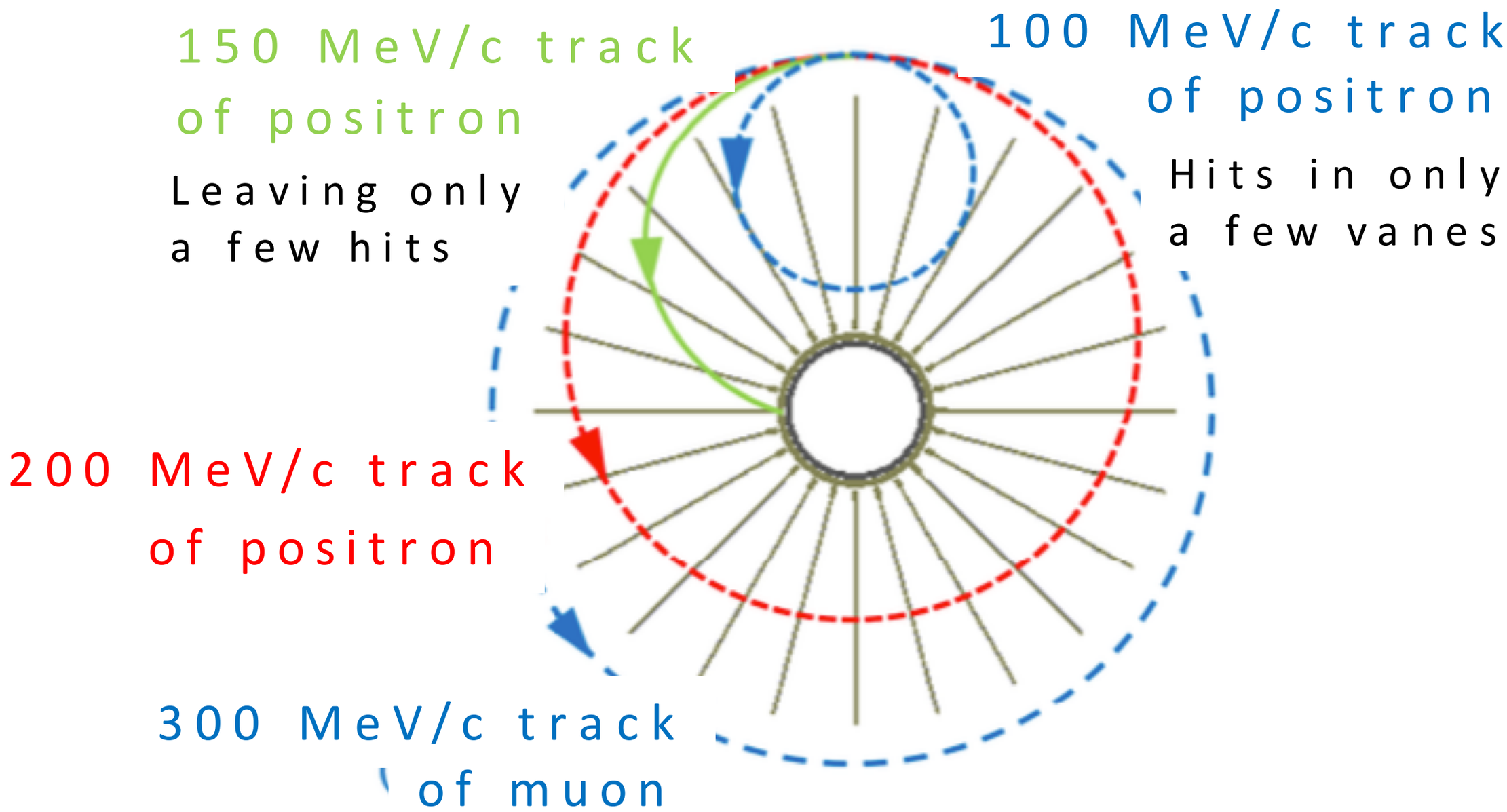
- Construct demonstration beamline (@LINAC bldg.)
  - Particle : e^-
  - Momentum : 297 keV/c
  - Storage solenoid field : 82.5 x 10^{-4} T
- Component to tune the beam
  - Rotatable quadrupole magnet: XY-coupling
  - X/Y-steering coil: Injection angle





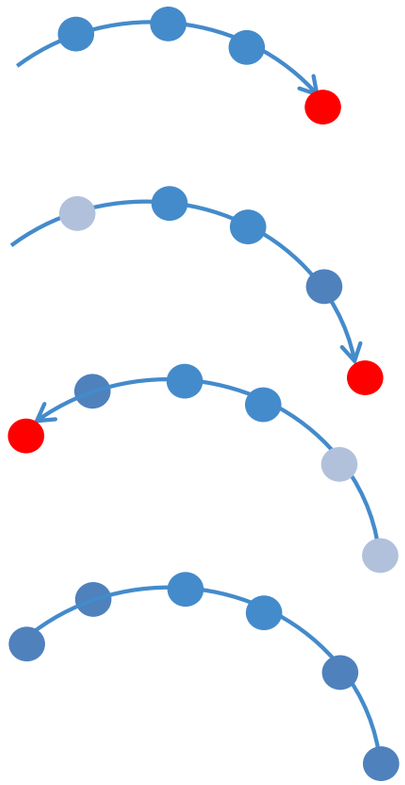


Trajectory


150 MeV/c track of positron
Leaving only a few hits
100 MeV/c track of positron
Hits in only a few vanes
200 MeV/c track of positron
300 MeV/c track of muon

Track finding algorithm

1. Decide the time window and search for reconstructed hits in a straight line in (z,ϕ) plane in this time widow
2. Select 3 hits (seeds) from hits on the same line and extrapolate a helix orbit to neighboring vanes to find hits consistent with the same track
3. If a hit satisfies the condition to be regarded as the same track origin, update seeds for searching and repeat an extrapolation until there is no candidate to be added.
4. Repeat the same procedures in backward
5. If a track candidate includes more than 4 hits, that candidate is regarded as a “reconstructed track” and hits used in this track are removed for further track finding
6. Repeat the procedures 2-5 until there is no candidate hit
7. Move time window to the next and repeat the same procedures



Statistical uncertainty

$$\sigma_{\omega_a}^{\exp} = \frac{\sqrt{2}}{\gamma \tau A \sqrt{N}}$$

Relativistic factor of muons

Normalization to the oscillation term of the decayed positron

$$N(t) = N_0 e^{-t/\gamma\tau}[1 - A\cos(\omega_a t + \phi)]$$