Challenging quest of three-dimensional spiral injection scheme to store the 80 keV electron beam in 12 cm diameter ring for New Muon g-2/EDM experiment at J-PARC (E34)

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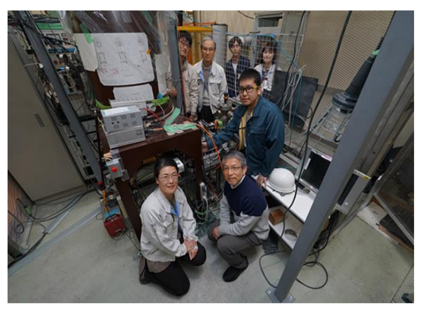
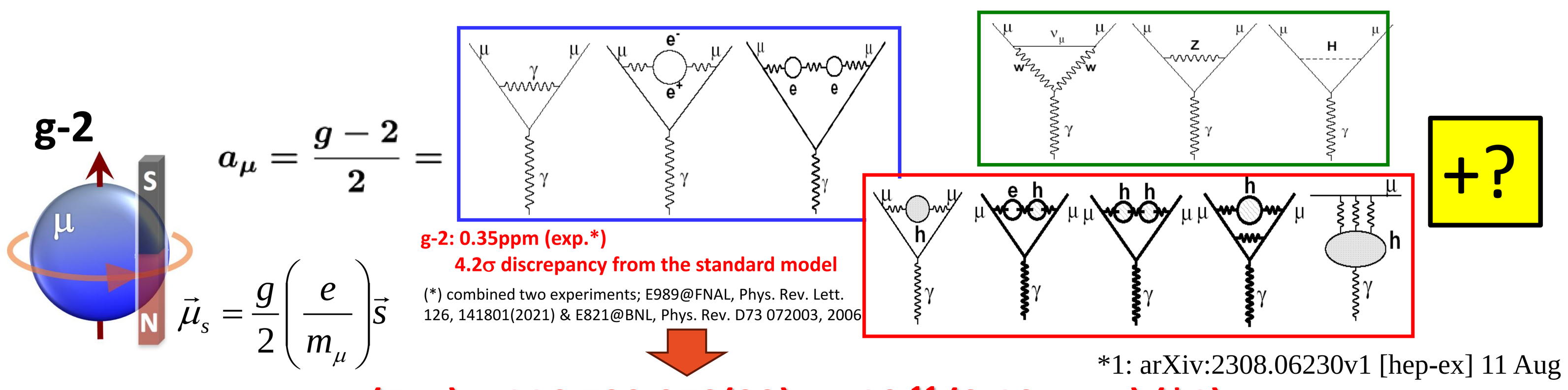


1. Physics goal : Explore the beyond standard model



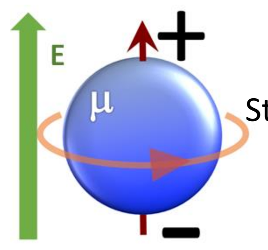
$$a_\mu = \frac{g-2}{2}, \quad \vec{\mu}_s = \frac{g}{2}\left(\frac{e}{m_\mu}\right)\vec{s}$$

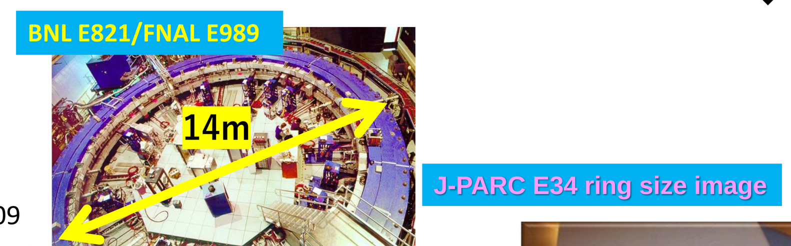
*1: arXiv:2308.06230v1 [hep-ex] 11 Aug 2023

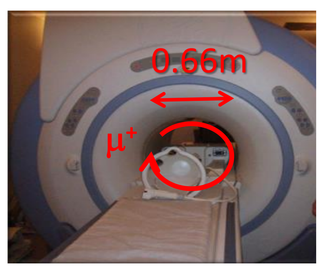
a_μ(Exp) = 116 592 059(22) × 10^{-11} (0.19 ppm) (*1),
5-σ discrepancy from the SM.

Non-zero observation = new physics

Standard Model expects ∼ 2 x 10^{-38} e·cm
Upper limit (E821) < 1.9 x 10^{-19} e·cm (90% CL)
E821@BNL, Phys. Rev. D 80, 052008, 2009

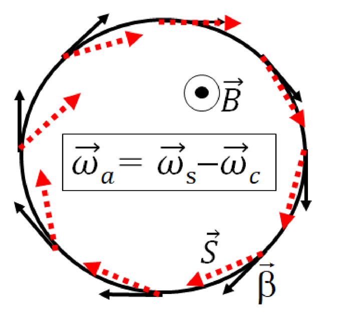






Goal: **g-2 :0.45ppm (statistical uncertainty)**
(2023-E989 0.20ppm (*1))
EDM sensitivity:1.5 x 10^{-21} e.cm

2. Muon spin precession probes g-2 and EDM…*catch the new physics!*



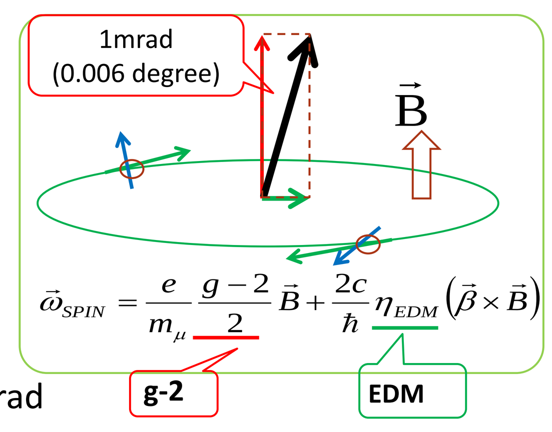
We measure $\vec{\omega}_a$ =Spin motion – cyclotron motion

$$\vec{\omega}_a = -\frac{q}{m}\left[\left(\frac{g-2}{2}\right)\vec{B} - \left(\frac{g-2}{2} - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E} + \frac{\epsilon_{EDM}}{2}\left(\vec{\beta}\times\vec{B}\right) + \frac{\epsilon_{EDM}}{2}\vec{E}\right]$$

g-2 EDM

- ◆Electric field $\vec{E}$=0
- ◆Store muon beam in the uniform magnetic field (<0.1ppm)
- ◆Very precise control of the muon storage orbit
  - ◆Angle between $\vec{\omega}_a$ and magnetic field $\vec{B}$ is estimated to be 1mrad assuming EDM upper limit from the previous experiment.
  - ◆If we measure such angle with 0.01mrad precision, we perform very precise EDM measurement with 100 better sensitivity than previous exp.

Assuming EDM upper limit ~ 1e-19 e.cm

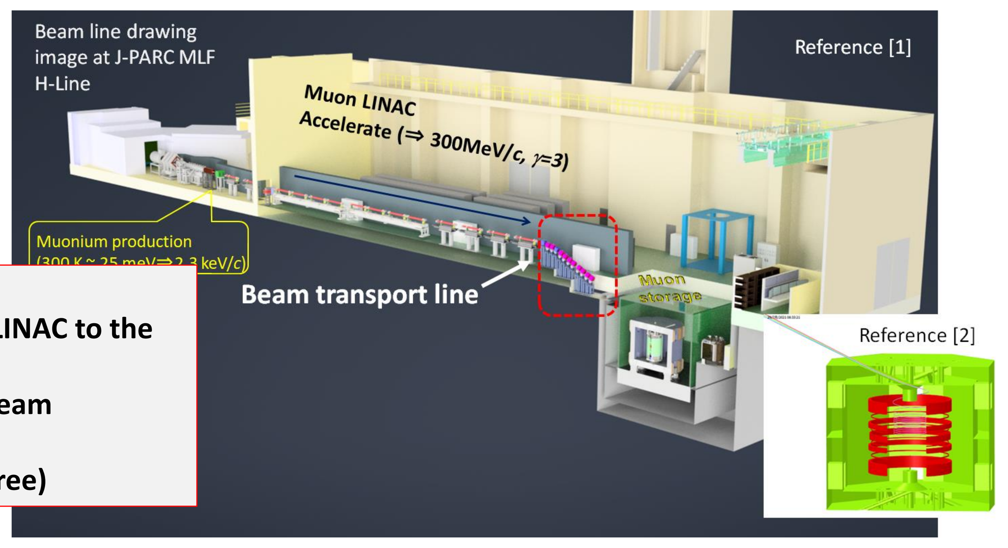


$$\vec{\omega}_{SPIN} = \frac{e}{m_\mu}\frac{g-2}{2}\vec{B} + \frac{2c}{\hbar}\eta_{EDM}\left(\vec{\beta}\times\vec{B}\right)$$

Super precise adjustment for muon storage magnetic field is a KEY

Typical size of circumference length of storage ring:
3km(KEKB) ~ 27km(LHC)

Muon g-2
BNL, FNAL : 44m (D=14m)
J-PARC:2.1m (D=0.7m)



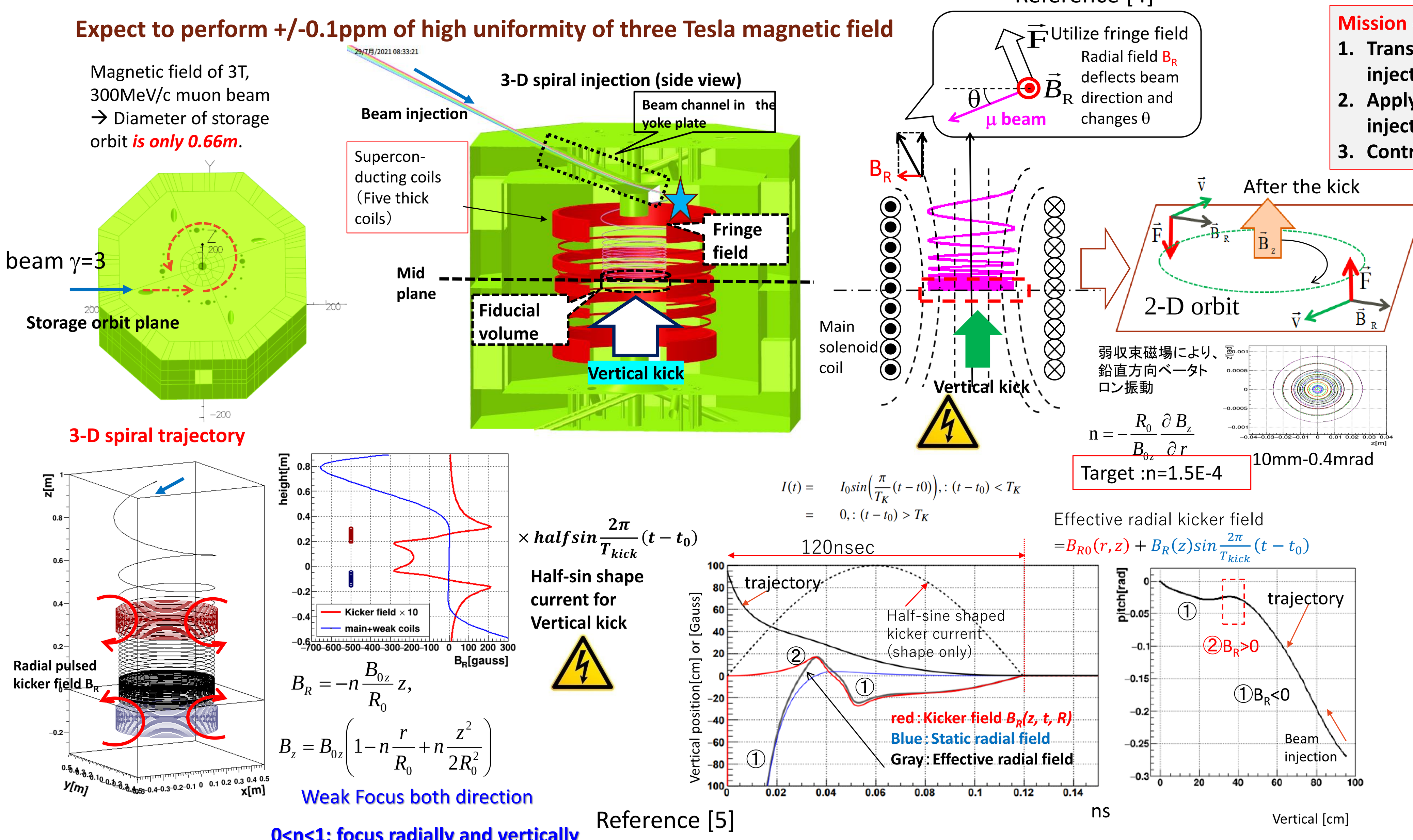
Mission of the beam transport line :
1. Transport muon beam from the exit of the muon LINAC to the injection point of the storage magnet
2. Apply appropriate "X-Y coupling" for "3-D spiral beam injection"
3. Control injection angle (beam line slope of 26 degree)

3. Compact storage ring applying medical MRI type superconducting magnet technology, requires newly developing 3-D spiral injection scheme!

Reference [3]
Reference [4]

Expect to perform +/-0.1ppm of high uniformity of three Tesla magnetic field

Magnetic field of 3T, 300MeV/c muon beam
→ Diameter of storage orbit *is only 0.66m*.



$$\times\, half\,sin\frac{2\pi}{T_{kick}}(t-t_0)$$

$$B_R = -n\frac{B_{0z}}{R_0}z, \qquad B_z = B_{0z}\left(1 - n\frac{r}{R_0} + n\frac{z^2}{2R_0^2}\right)$$

$$n = -\frac{R_0}{B_{0z}}\frac{\partial B_z}{\partial r}$$

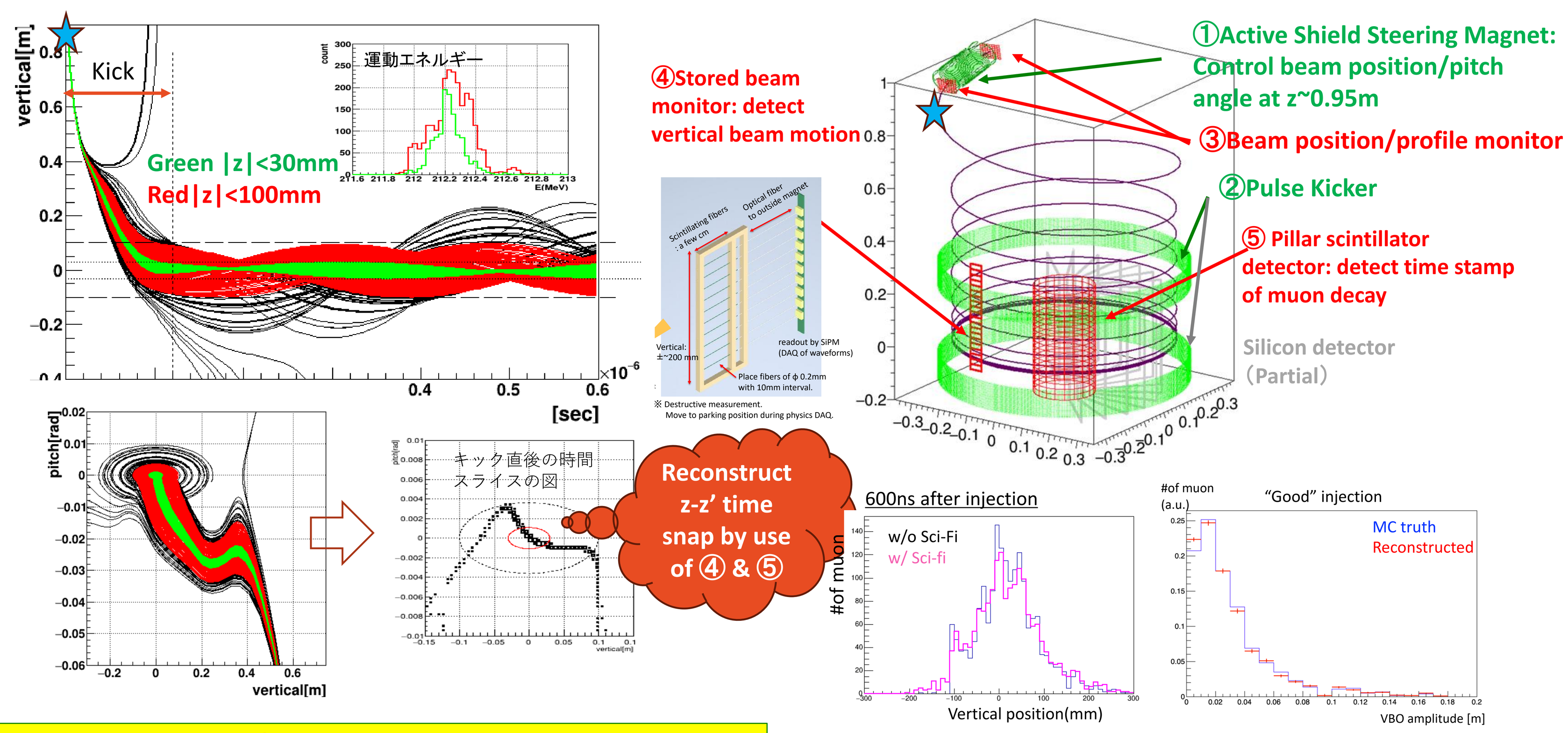
Weak Focus both direction

0<n<1: focus radially and vertically

Reference [5]

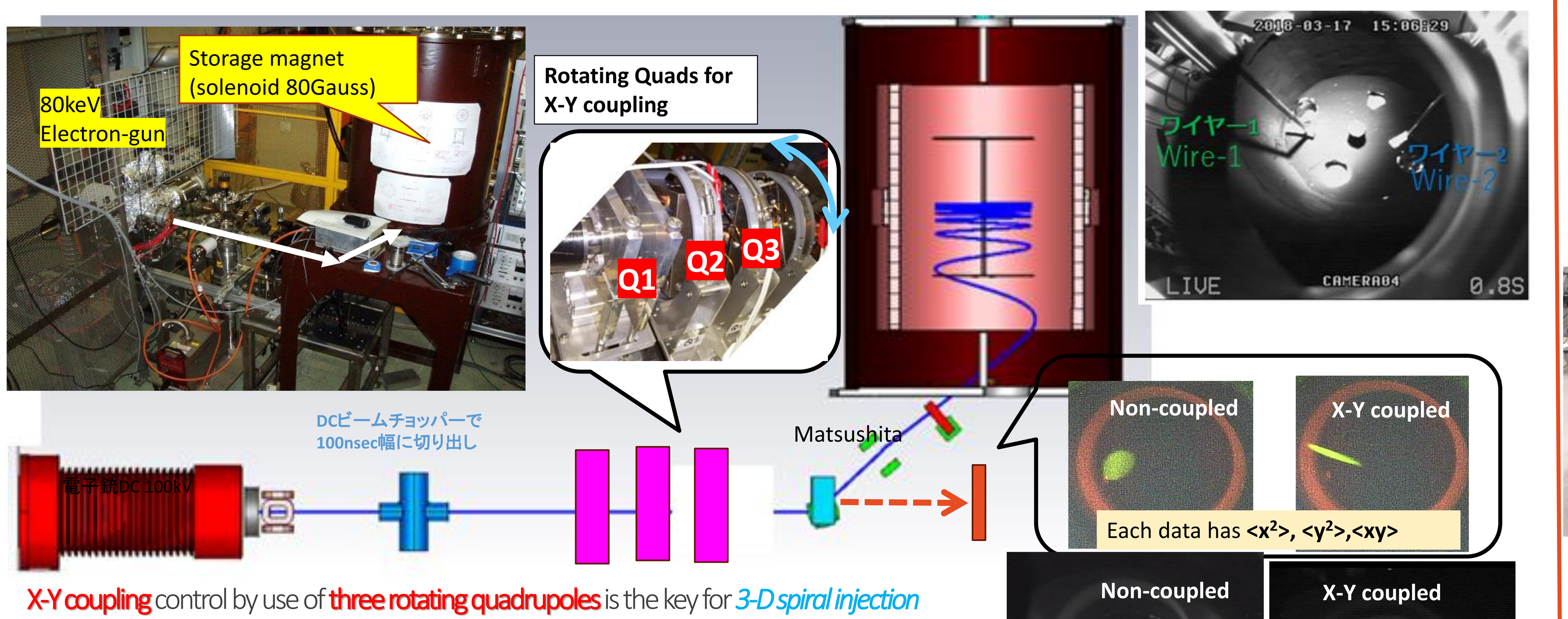
Beauties:
- ◆ Smooth connection between injection and storage sections without any sources of error field
- ◆ A unit of magnet does work for this method and decrease sources of error field

4. Beam monitor inside the storage magnet: How do we control the beam?



5. Development for 3-D spiral injection scheme by use of 80 keV electron gun

preparation-1:X-Ycouplued beam by rotating Quads.



X-Y coupling control by use of **three rotating quadrupoles** is the key for *3-D spiral injection*

- ☐ Q-scan by use of single quadrupole (Q1 or Q2 or Q3)
  - ☐ Change K-vale of Q1 (or Q2 or Q3) to measure focus and defocus beam shape
  - ☐ Reconstruct σ_0 (at initial point)
- ☐ Estimate σ_1 at the end of the transport line

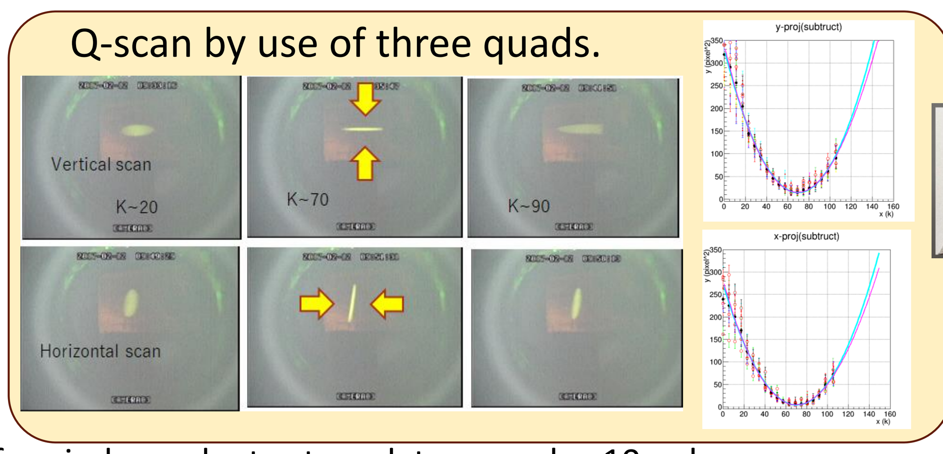
$$\sigma_1 = M\sigma_0(M)^t$$

Q-scan can measure

$$\sigma_0 = \begin{pmatrix} \langle x^2\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle & \langle x'y\rangle & \langle x'y'\rangle \\ \langle xy\rangle & \langle x'y\rangle & \langle y^2\rangle & \langle yy'\rangle \\ \langle xy'\rangle & \langle x'y'\rangle & \langle yy'\rangle & \langle y'^2\rangle \end{pmatrix}$$

X-Y coupling component

Q-scan by use of three quads.



20 different Q settings for σ_0 measurement

Every set-up has different m_{11}~m_{44} and three measurements:<x²>,<y²> and <xy>

Copper Collimator

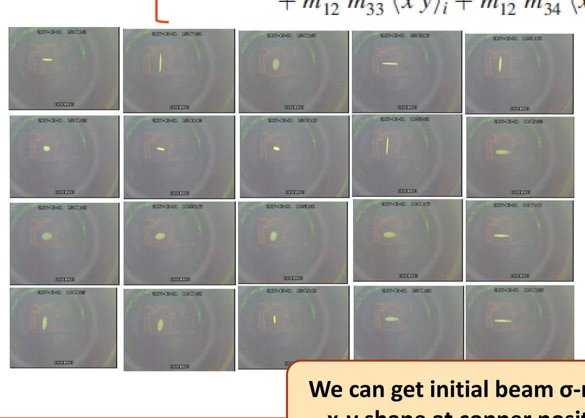
$$\begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_f = \begin{bmatrix} m_{11} & m_{12} & 0 & 0 \\ m_{21} & m_{22} & 0 & 0 \\ 0 & 0 & m_{33} & m_{34} \\ 0 & 0 & m_{43} & m_{44} \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \end{bmatrix}_i$$

3 data for each set-up

$$x_f = m_{11}x_i + m_{12}x'_i$$
$$y_f = m_{33}y_i + m_{34}y'_i$$
$$\langle xy\rangle_f = m_{11}m_{33}\langle xy\rangle_i + m_{11}m_{34}\langle xy'\rangle_i + m_{12}m_{33}\langle x'y\rangle_i + m_{12}m_{34}\langle x'y'\rangle_i$$

- ☐ At least four independent set-up data can solve 10 unknown parameters, in principle.
- ☐ Q-scan data is a kind of special data set

$$\langle x^2\rangle_1 = m_{11}^1m_{11}^1\langle x^2\rangle_i + 2m_{11}^1m_{12}^1\langle xx'\rangle_i + m_{12}^1m_{12}^1\langle x'x'\rangle_i$$
$$\langle y^2\rangle_1 = m_{33}^1m_{33}^1\langle y^2\rangle_i + 2m_{33}^1m_{34}^1\langle yy'\rangle_i + m_{34}^1m_{34}^1\langle y'y'\rangle_i$$
$$\langle xy\rangle_1 = m_{11}^1m_{33}^1\langle xy\rangle_i + m_{11}^1m_{34}^1\langle xy'\rangle_i + m_{12}^1m_{33}^1\langle x'y\rangle_i + m_{12}^1m_{34}^1\langle x'y'\rangle_i$$
$$\langle xy\rangle_{20} = m_{11}^{20}m_{33}^{20}\langle xy\rangle_i + m_{11}^{20}m_{34}^{20}\langle xy'\rangle_i + m_{12}^{20}m_{33}^{20}\langle x'y\rangle_i + m_{12}^{20}m_{34}^{20}\langle x'y'\rangle_i$$



(3*N) × 1 (Ex. N=20)

$$X = TX_0$$

(3*N) × 10, 10 × 1

$$\begin{bmatrix} \langle x^2\rangle_1 \\ \langle y^2\rangle_1 \\ \langle xy\rangle_1 \\ \langle x^2\rangle_2 \\ \vdots \\ \langle xy\rangle_{20} \end{bmatrix} = \begin{bmatrix} m_{11}^1m_{11}^1 & m_{11}^1m_{12}^1 & 2m_{11}^1m_{12}^1 & \cdots \\ \vdots & \ddots & & \vdots \\ \cdots & & & m_{12}^{20}m_{34}^{20} \end{bmatrix} \begin{bmatrix} \langle x^2\rangle_i \\ \langle x'^2\rangle_i \\ \langle xx'\rangle_i \\ \langle y^2\rangle_i \\ \langle y'^2\rangle_i \\ \langle yy'\rangle_i \\ \langle xy\rangle_i \\ \langle xy'\rangle_i \\ \langle x'y\rangle_i \\ \langle x'y'\rangle_i \end{bmatrix}$$

$$X_0 = [T^tT]^{-1}T^tX$$

We can get initial beam σ-matrix from beam x-y shape at copper position, in principle

$$\sigma^{4D} = \begin{pmatrix} \langle x^2\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle & \langle x'y\rangle & \langle x'y'\rangle \\ \langle xy\rangle & \langle x'y\rangle & \langle y^2\rangle & \langle yy'\rangle \\ \langle xy'\rangle & \langle x'y'\rangle & \langle yy'\rangle & \langle y'^2\rangle \end{pmatrix}$$

$$\varepsilon_x = \sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle xp_x\rangle^2}$$

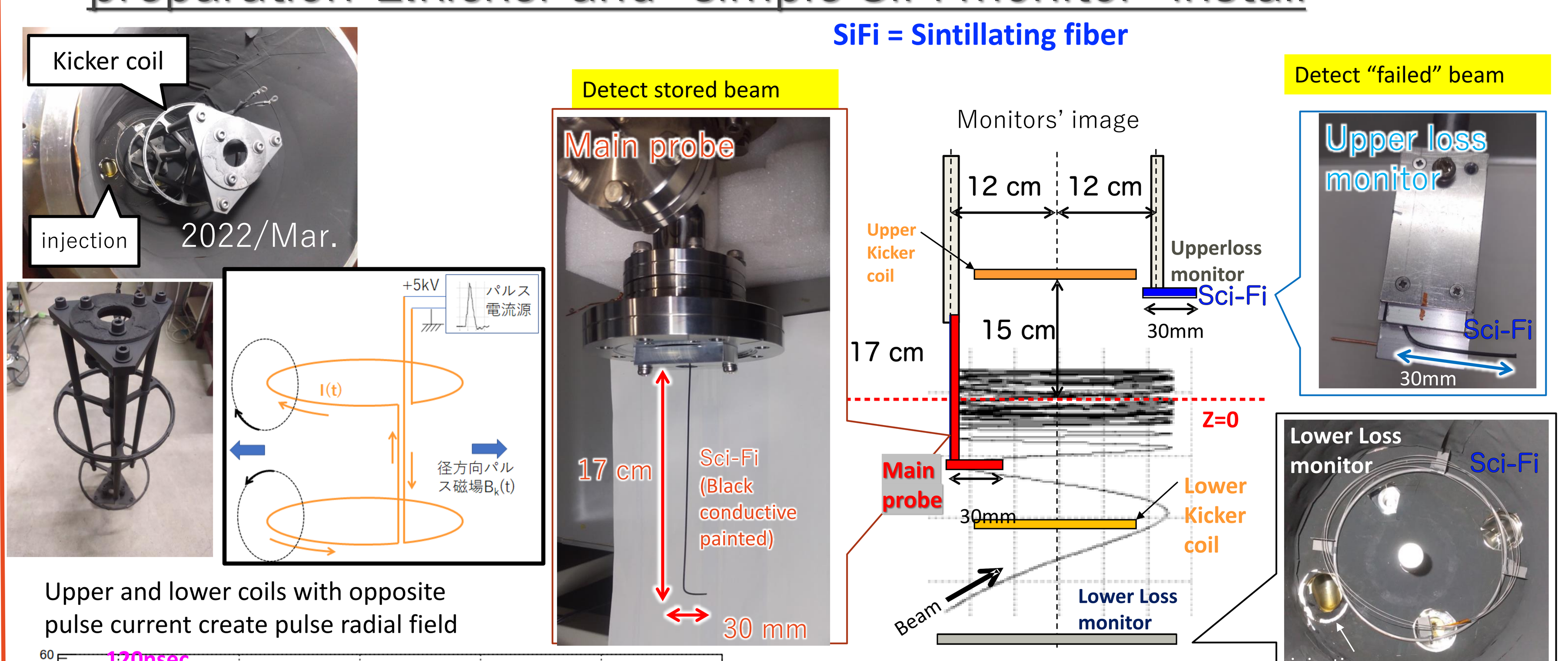
C=determinant of σ

$$t = \frac{\varepsilon_x\varepsilon_y}{\sqrt{C}} - 1$$

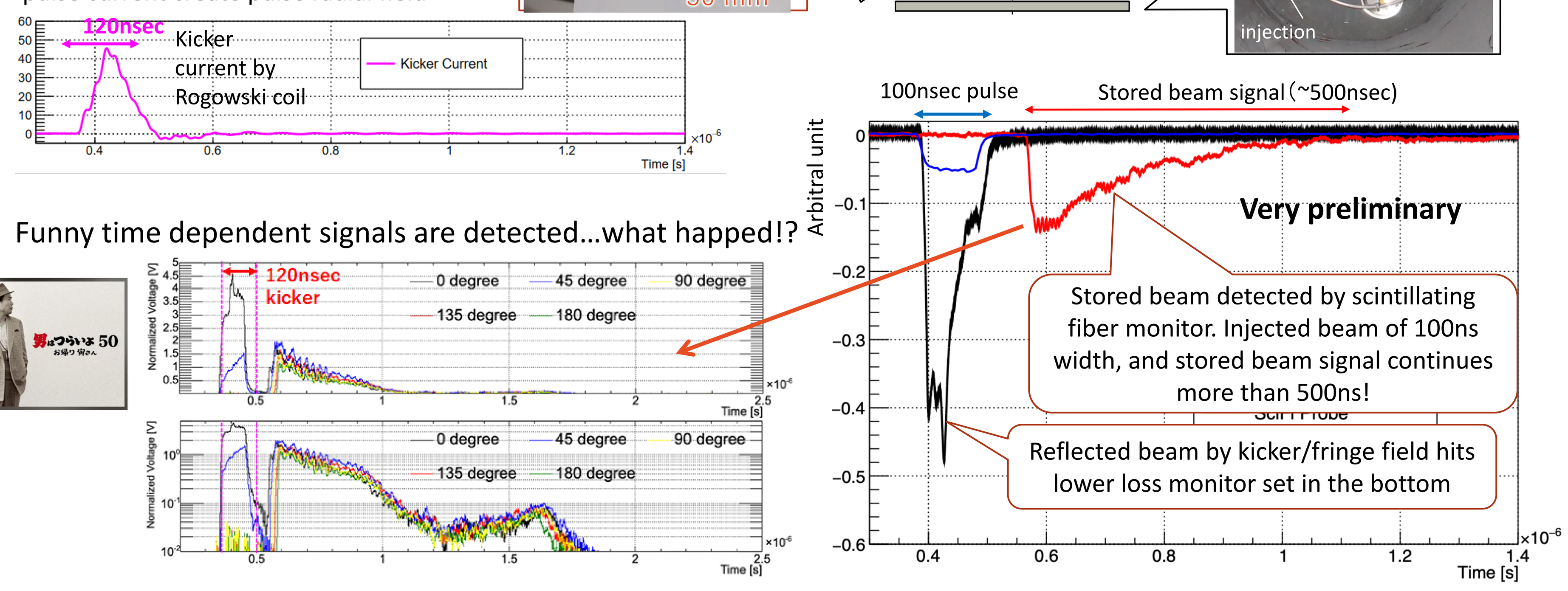
t>1 Huge X-Y coupling
t~0.1 enough small

preparation-2:kicker and "simple SiFi monitor" install

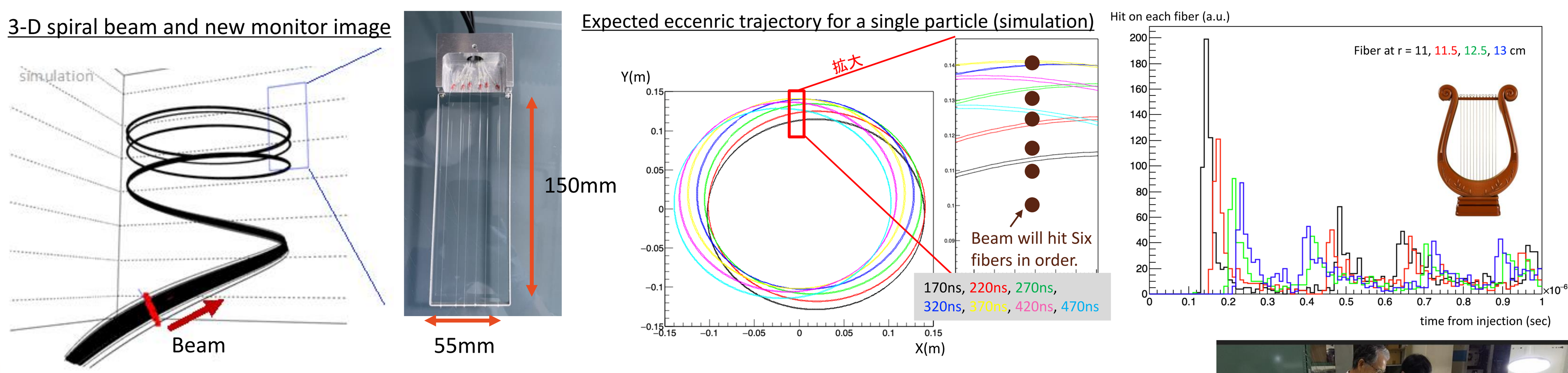
SiFi = Sintillating fiber



Upper and lower coils with opposite pulse current create pulse radial field



preparation-3: "lyre shaped SiFi monitor" install



Summary and Future
- Preparation for a new precise experiment for muon g-2 and EDM (E34) is ongoing. We expect the first beam in FY2028.
- 3-dimensional spiral injection is a key for new experiment, and feasibility studies shown here.
- X-Y coupled beam is controlled by rotating quadrupole magnets. Q-scan and sigma-matrix measurements are introduced.
- Stored beam guided by kicker is detected. New lyre shape SiFi monitor will strong tool to understand "eccentric trajectory".
- Feasibility study goes well and many knowledge will be reflected on the new J-PARC E34.

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http://muonspin.sci.ibaraki.ac.jp/
https://g-2.kek.jp/

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