Hiromi Iinuma：飯沼裕美

Iinuma Hiromi

Living in Tokai Village (J-PARC within 15 minutes by car)
Associate professor at Ibaraki University (nearest University from J-PARC)

お茶の水女子大学賞（湯浅年子賞）

https://www.ocha.ac.jp/news/20230221_1.html

Yuasa Toshiko prize

I have been learning from these experts very much, too

https://www.kek.jp/ja/newsroom/2016/04/28/1000/

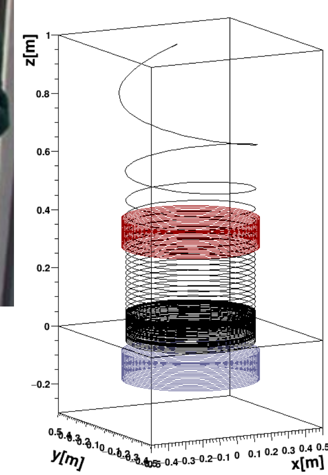
Prof. A. Yamamoto

Do it more than 20 years!

https://www2.kek.jp/accl/legacy/topics/topics140310.html

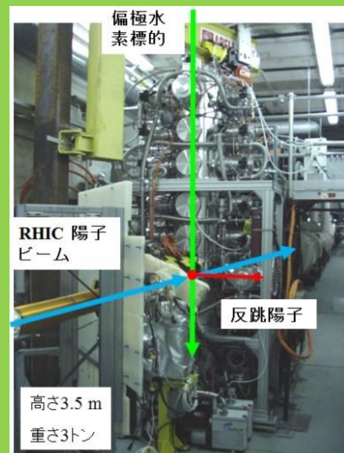
Prof. K. Oide

Why don't you inject 3-D way?



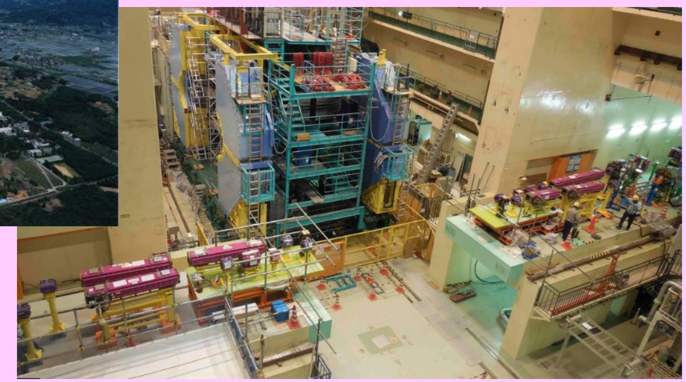
I have been around accelerator

BNL Spin physics (2002~2008)
Polarized proton beam
I was a polarimeter group

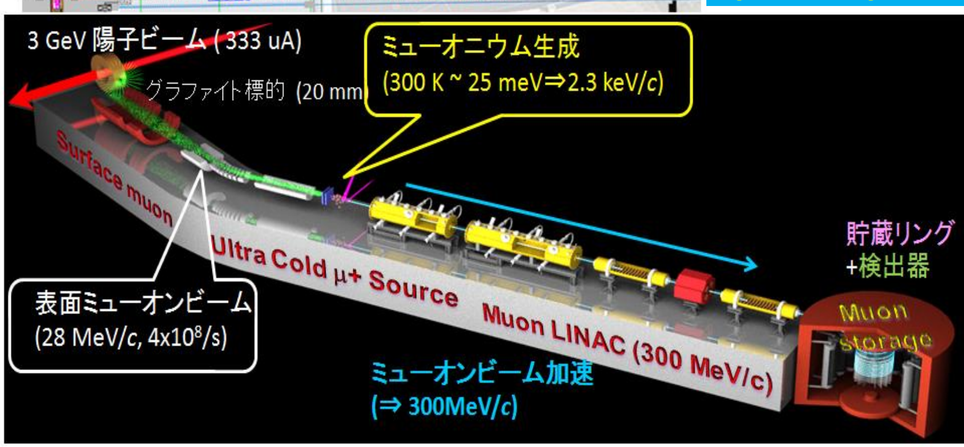


KEK tukuba (2008~2016)
SuperKEKB Mika's group (2011~2016)

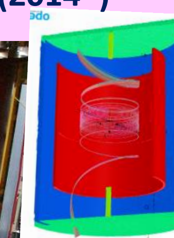
e^+ e^-



J-PARC/MLF
Muon experiment
(2016~)

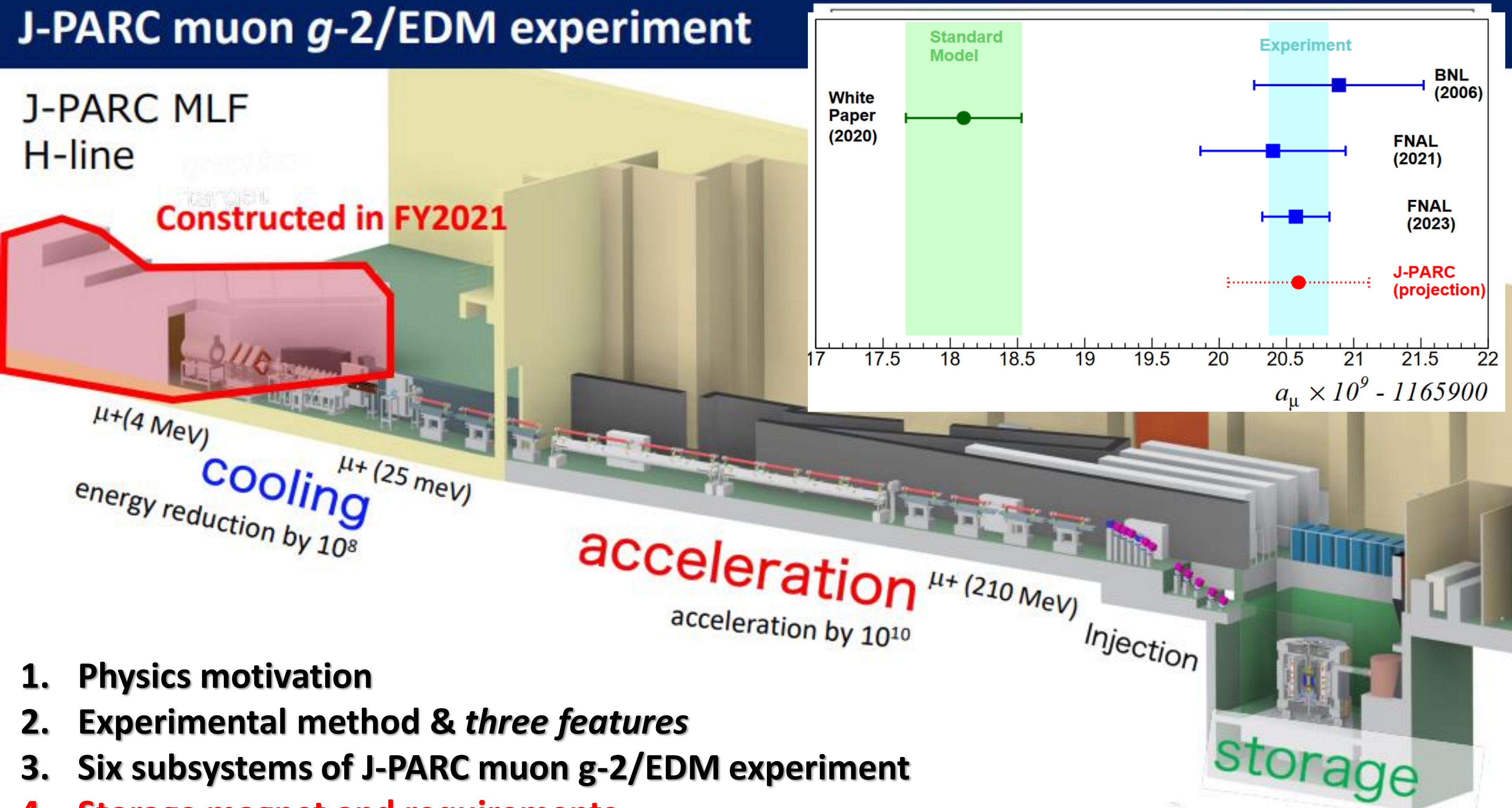


Grant-in-aid Kakenhi ：My own topics (2014~)



I was in BNL to get ph.D for 3 years + 2 years (post doc)

Three-dimensional beam injection scheme for the new J-PARC muon *g*-2/EDM experiment

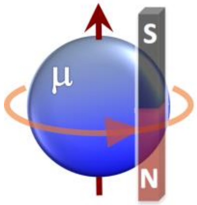


1. **Physics motivation**
2. **Experimental method & *three features***
3. **Six subsystems of J-PARC muon g-2/EDM experiment**
4. **Storage magnet and requirements**
5. **3-D spiral injection and demonstration experiment**
6. **Schedule and summary**

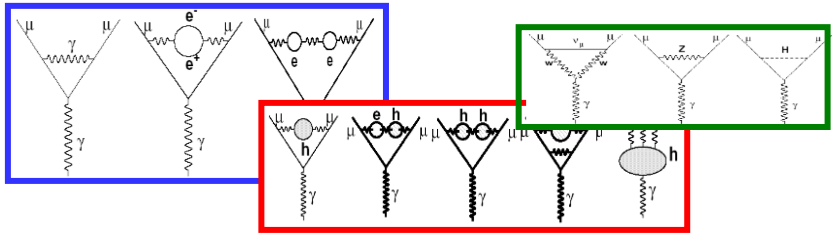
H.Iinuma (Ibaraki Univ.)
on behalf of the injection team/J-PARC muon g-2/EDM collaboration
茨城大学
Ibaraki University

Muon spin presession tells what ?

Anomalous magnetic moment



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



+?

Exp. a_μ(Exp) = 116 592 059(22) × 10^{-11} (0.19 ppm), arXiv:2308.06230v1 [hep-ex] 11 Aug 2023

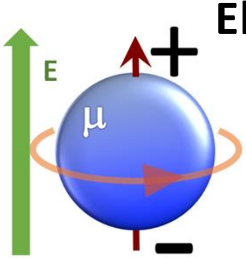
The. a_μ(The) =116 591 810(43) × 10^{-11} (0.37 ppm), Phys. Rept. 887 (2020) 1-166.

https://muon-gm2-theory.illinois.edu/

Differ by 5 standard deviation

https://www.nature.com/articles/d41586-021-00833-2

Electric **D**ipole **M**oment



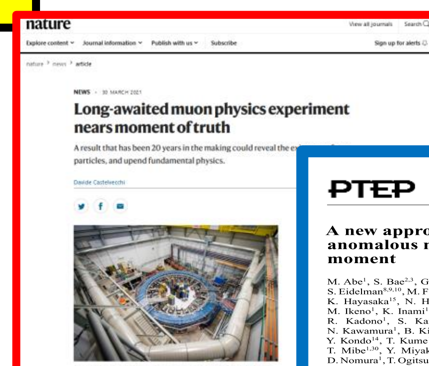
Direct evidence of new physics

The SM ～ 2 x 10^{-38} e・cm

Upper limit (E821) < 1.9 x 10^{-19} e・cm (90% CL)

- **FNAL E989's first and second results are consistent with BNL E821 (20 years ago)**
- **Different view by independent experimental method does help to judge these questions.**

2021 March


nature

NEWS · 30 MARCH 2021

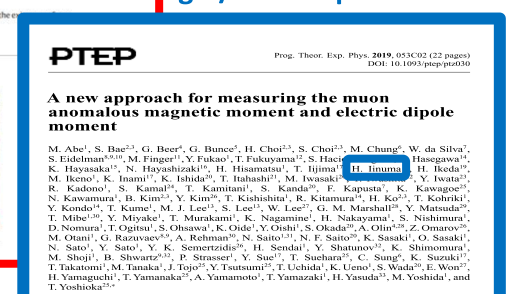
Long-awaited muon physics experiment nears moment of truth

A result that has been 20 years in the making could reveal the e... particles, and upend fundamental physics.

Davide Castelvecchi

BNL E821, FNAL E989 (20 years later)

2019 Proposal of J-PARC new g-2/EDM experiment


PTEP

Prog. Theor. Exp. Phys. **2019**, 053C02 (22 pages)
DOI: 10.1093/ptep/ptz030

A new approach for measuring the muon anomalous magnetic moment and electric dipole moment

M. Abe[1], S. Bae[2,3], G. Beer[4], G. Bunce[5], H. Choi[2,3], S. Choi[2,3], M. Chung[6], W. da Silva[7], S. Eidelman[8,9,10], M. Finger[11], Y. Fukao[1], T. Fukuyama[12], S. Haci... Hasegawa[14], K. Hayasaka[15], N. Hayashizaki[16], H. Hisamatsu[1], T. Iijima[17], H. Iinuma..., H. Ikeda[19], M. Ikeno[1], K. Inami[17], K. Ishida[20], T. Itahashi[21], M. Iwasaki..., Y. Iwata[23], R. Kadono[1], S. Kamal[24], T. Kamitani[1], S. Kanda[20], F. Kapusta[7], K. Kawagoe[25], N. Kawamura[1], B. Kim[2,3], Y. Kim[26], T. Kishishita[1], R. Kitamura[14], H. Ko[2,3], T. Kohriki[1], Y. Kondo[14], T. Kume[1], M. J. Lee[13], S. Lee[13], W. Lee[27], G. M. Marshall[28], Y. Matsuda[29], T. Mibe[1,30], Y. Miyake[1], T. Murakami[1], K. Nagamine[1], H. Nakayama[1], S. Nishimura[1], D. Nomura[1], T. Ogitsu[1], S. Ohsawa[1], K. Oide[1], Y. Oishi[1], S. Okada[20], A. Olin[4,28], Z. Omarov[26], M. Otani[1], G. Razuvaev[8,9], A. Rehman[30], N. Saito[1,31], N. F. Saito[20], K. Sasaki[1], O. Sasaki[1], N. Sato[1], Y. Sato[1], Y. K. Semertzidis[26], H. Sendai[1], Y. Shatunov[32], K. Shimomura[1], M. Shoji[1], B. Shwartz[9,32], P. Strasser[1], Y. Sue[17], T. Suehara[25], C. Sung[6], K. Suzuki[17], T. Takatomi[1], M. Tanaka[1], J. Tojo[25], Y. Tsutsumi[25], T. Uchida[1], K. Ueno[1], S. Wada[20], E. Won[27], H. Yamaguchi[1], T. Yamanaka[25], A. Yamamoto[1], T. Yamazaki[1], H. Yasuda[33], M. Yoshida[1], and T. Yoshioka[25,*]

1.EDM(d_μ) vs. a_μ (model independent relation)

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

P,C,T-even   P,T-odd (CP-odd)

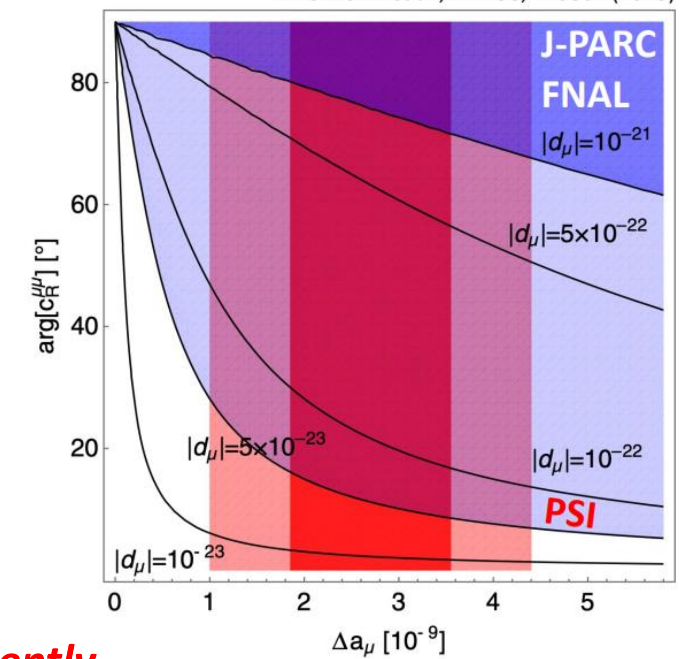
$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}$$

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

g-2 and EDM are defined as a single complex number.

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

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



In general, g-2 anomaly suggests a large EDM unless the complex phase is unnaturally small.

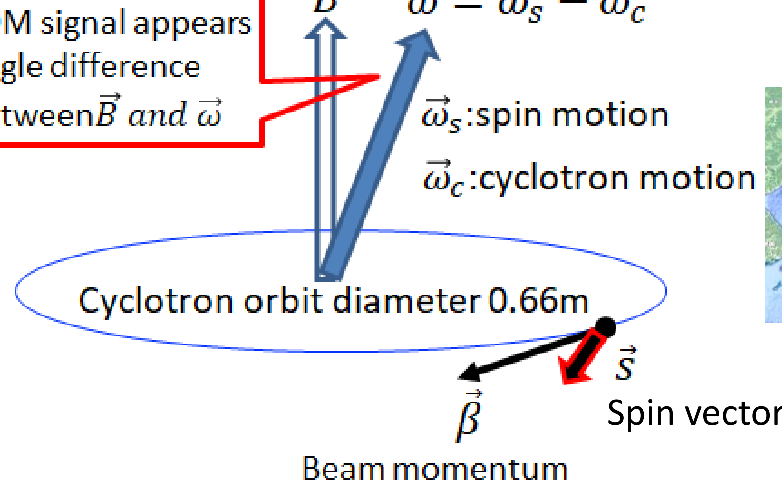
Want to measure both quantities at a time but independently

EDM signal appears angle difference between $\vec{B}$ and $\vec{\omega}$

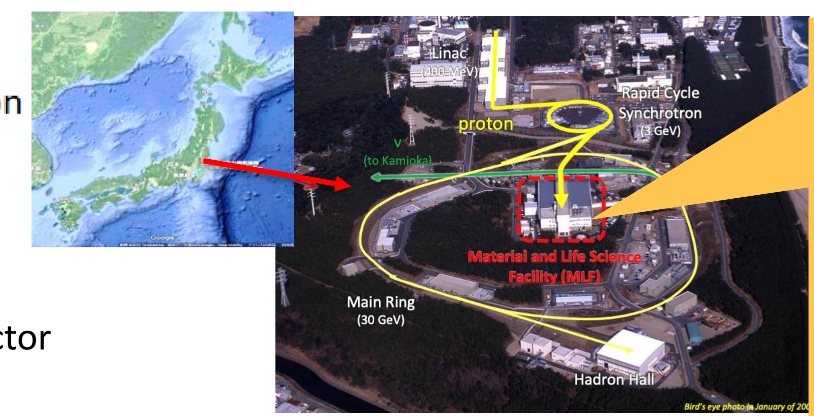
$$\vec{\omega} = \vec{\omega}_s - \vec{\omega}_c$$

$\vec{\omega}_s$:spin motion

$\vec{\omega}_c$:cyclotron motion

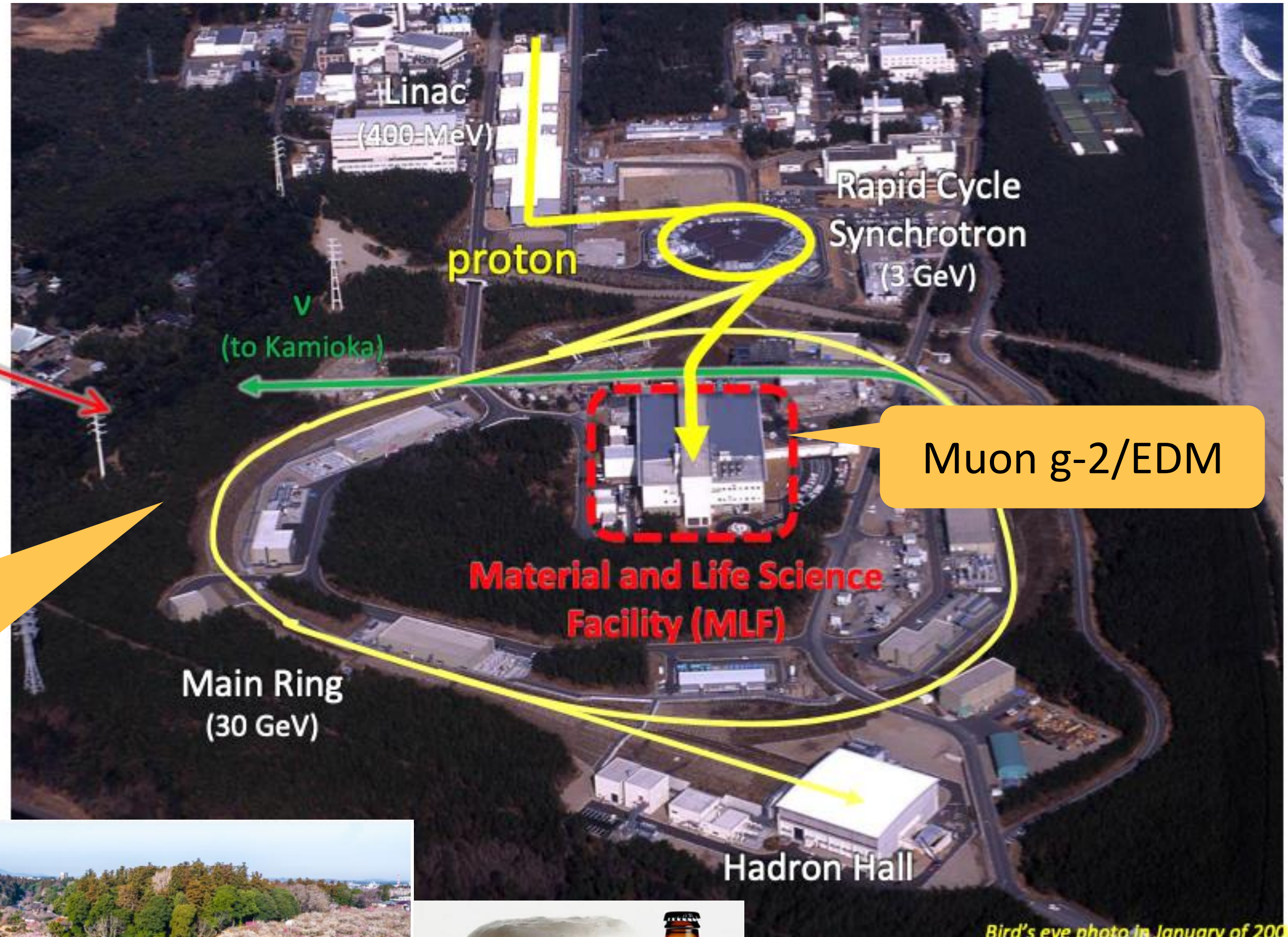


$$\vec{\omega} = -\frac{q}{m}\left[\frac{g-2}{2}\vec{B} + \frac{\eta_{\mathrm{EDM}}}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$



Super precise compact ring
B=3[T], γ=3

New g-2/EDM experiment (E34) at J-PARC MLF



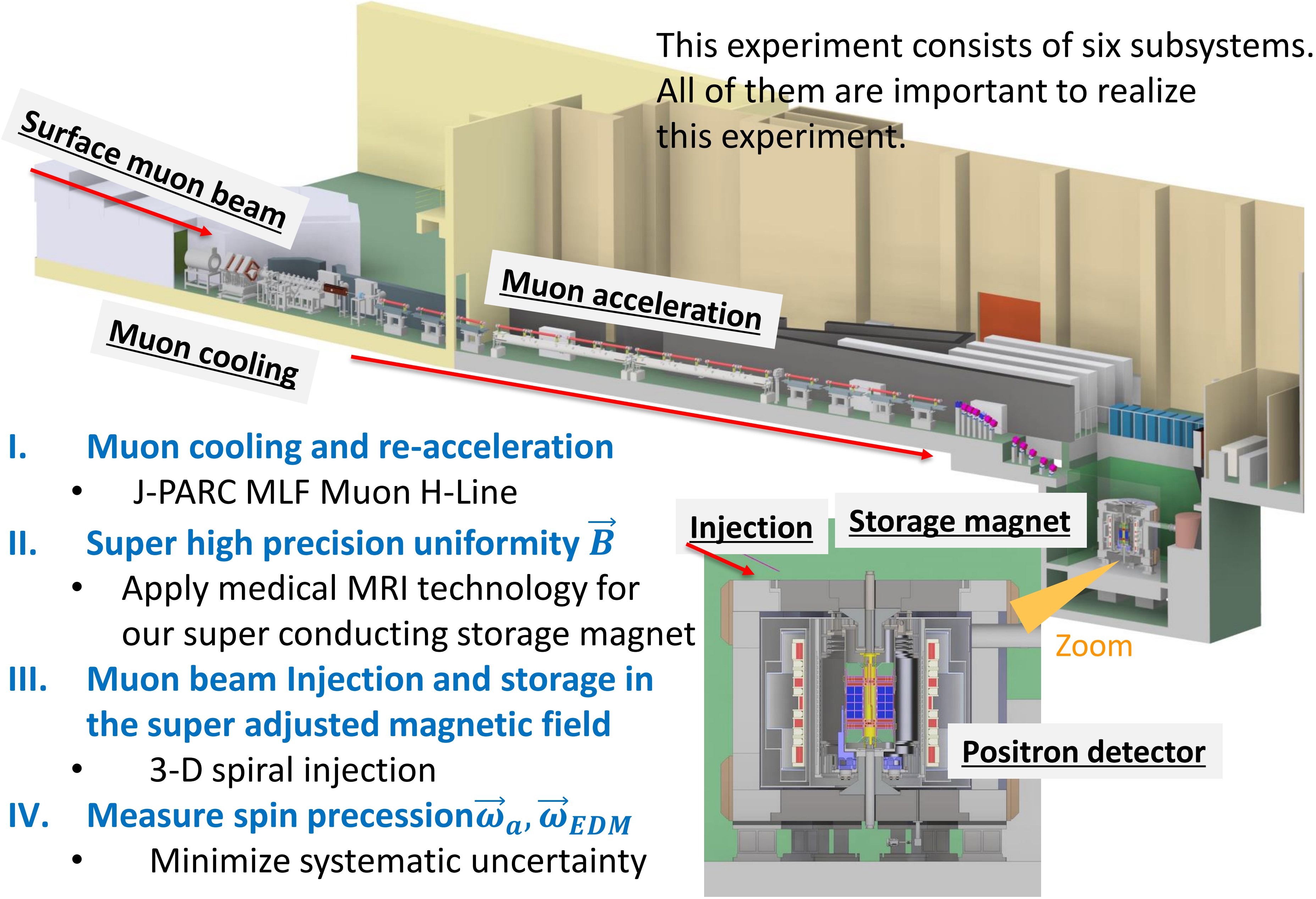
Satellite-campus of Ibaraki Univ. is just next to the J-PARC site.
university
(Main campus is at Mito)

Famous for a plum garden (Kairakuen)

Good sake and beer

3. Six subsystems of J-PARC muon g-2/EDM experiment

This experiment consists of six subsystems.
All of them are important to realize this experiment.



I. Muon cooling and re-acceleration
- J-PARC MLF Muon H-Line

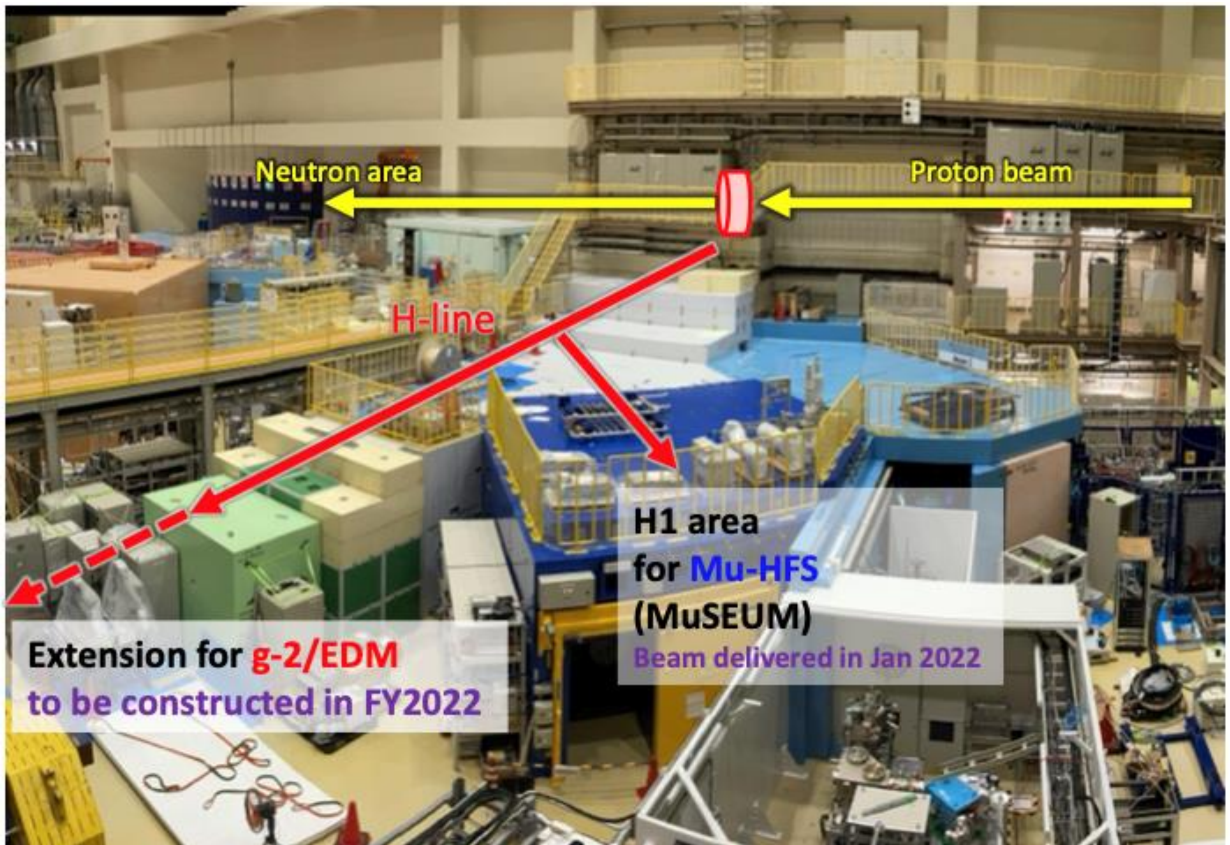
II. Super high precision uniformity $\vec{B}$
- Apply medical MRI technology for our super conducting storage magnet

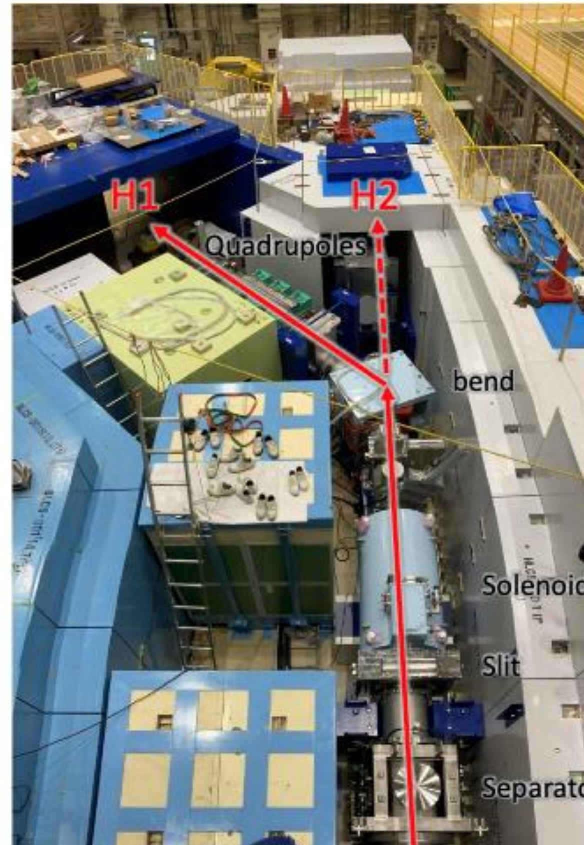
III. Muon beam Injection and storage in the super adjusted magnetic field
- 3-D spiral injection

IV. Measure spin precession $\vec{\omega}_a, \vec{\omega}_{EDM}$
- Minimize systematic uncertainty

Surface μ⁺ beam

- MLF H2 beam line.
  - Surface μ^+ beam: 4MeV, 10^8 μ+/s with 25Hz rep
  - Beam line extension inside the (existing) MLF bldg. in this fiscal year.
  - Construction of extension bldg. is also ready.

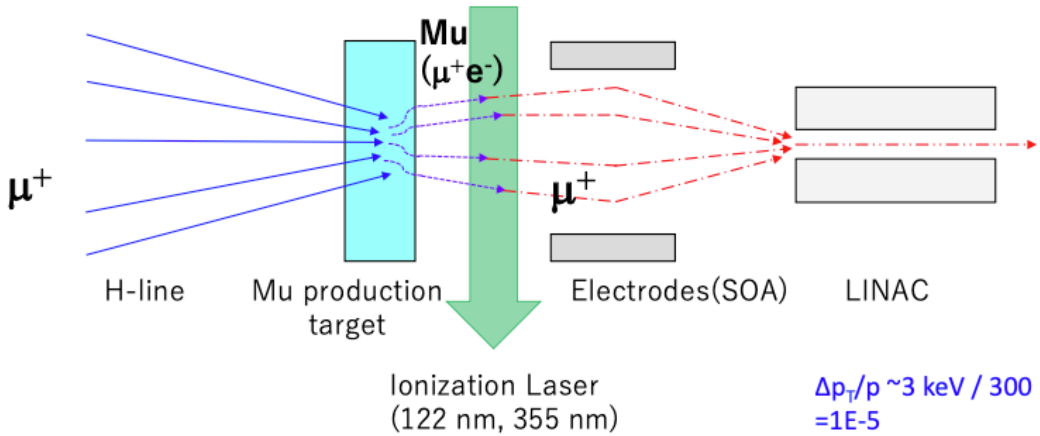




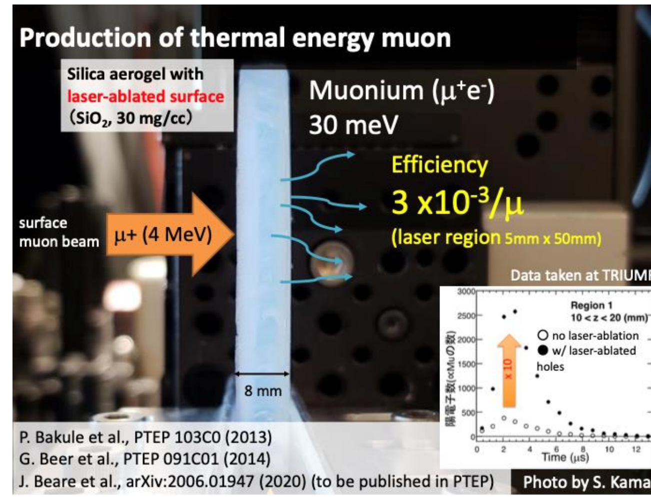
Muon cooling

- Low emittance muon beam by reacceleration of thermal muon.
  - Silica aerogel target : Surface muons stopped, and thermal muoniums emitted.
  - Laser ablated aerogel to increase the efficiency.

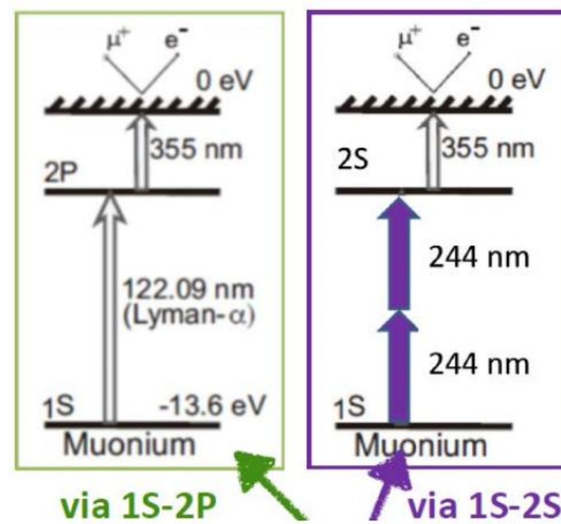
	surface muon	thermal muon	accelerated muon
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
Δ p/p	0.05	0.4	4×10^{-4}



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



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



Muon acceleration

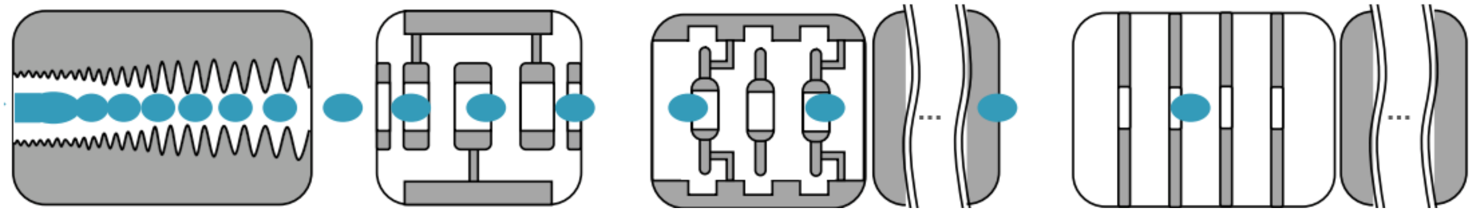
- Muon reacceleration to 300MeV/c by muon LINAC.
  - Series of 4 types of cavities depending on the muon β of each stage.

Low-β	Middle-β	High-β
$\beta = 0.01 \rightarrow 0.3$	$\beta = 0.3 \rightarrow 0.7$	$\beta = 0.7 \rightarrow 0.94$

RFQ IH-DTL DAW-CCL **DLS**

(Kinetic energy)

5.6 keV → 340 keV → 4.3 MeV → 40 MeV → 212 MeV

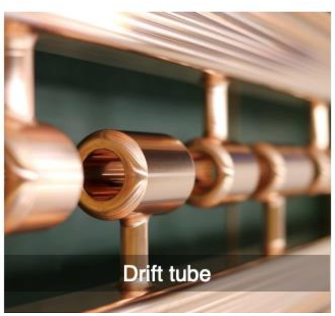


Acceleration test with thermal μ planned in 2023

Fabrication completed

1st tank under fabrication

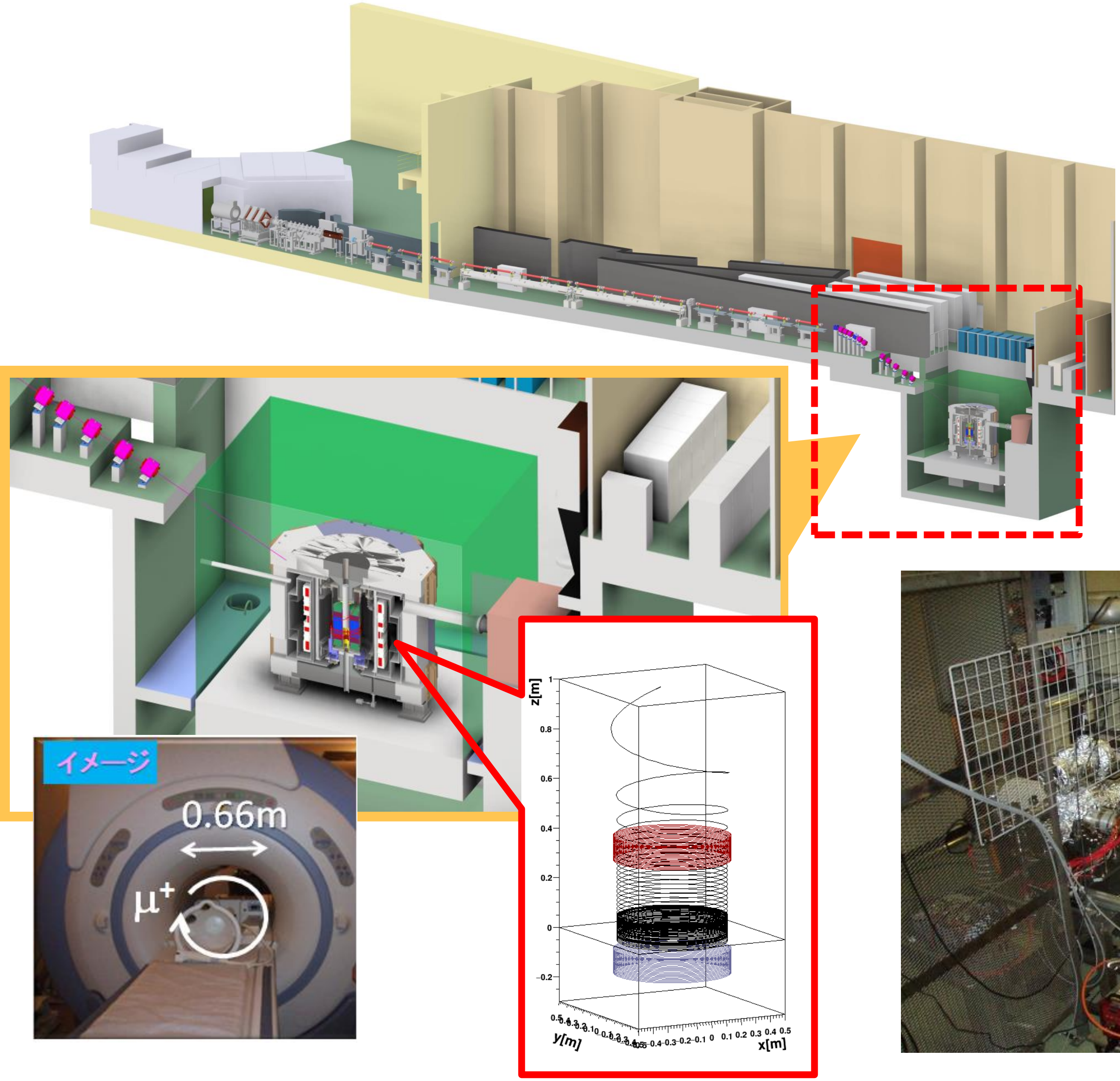
Prototype fabrication in JFY2022



Washer 1,2 (×2)

Disk1

Beam injection and storage



Demonstration experiment @ KEK

2. Experimental method & 3 features of new experiment ：

$\vec{E} = 0$ ・off-γ_{magic} ・sub-meter ring

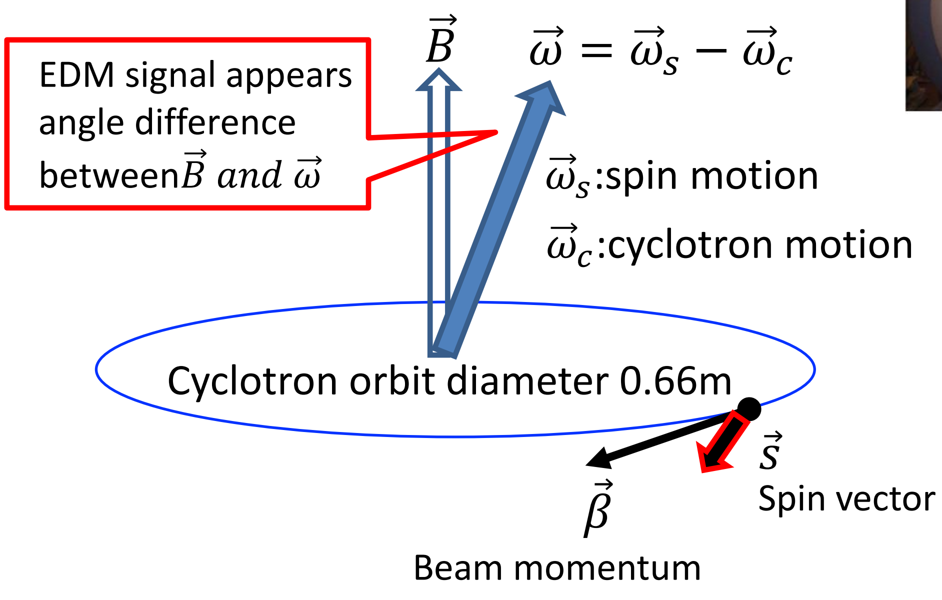
B=1.45[T]

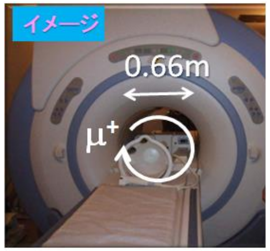
γ_{magic}=29.3

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

- **Cooled low-emittance beam (1/1000) → No need for $\vec{E}$**
- **No need to stay with magic momentum γ_{magic}=29.3**

$$\vec{\omega} = -\frac{q}{m}\left[\frac{g-2}{2}\vec{B} + \frac{\eta_{\rm EDM}}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$



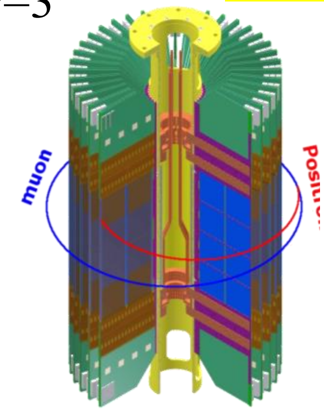


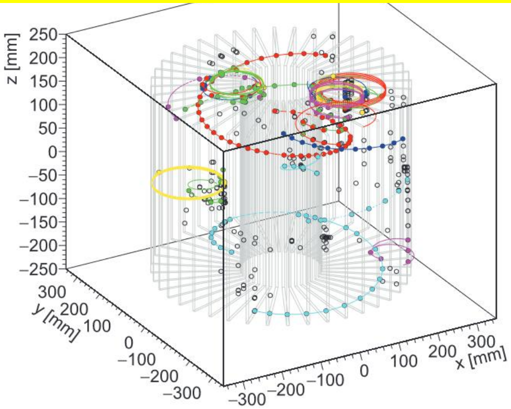
- **Storage beam in compact orbit diameter =0.66m (1/20)**
- **Very precise control of stored beam**
- **Good injection efficiency (>80%)**

Measure g-2 and EDM at a time, with the same setup but independently!

B=3[T]

γ=3





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- **Storage beam in compact orbit diameter =0.66m (1/20)**
- **Very precise control of stored beam**
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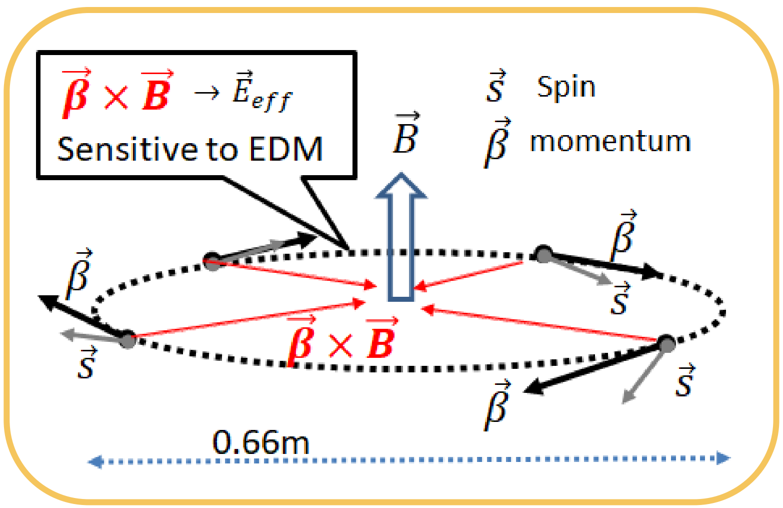
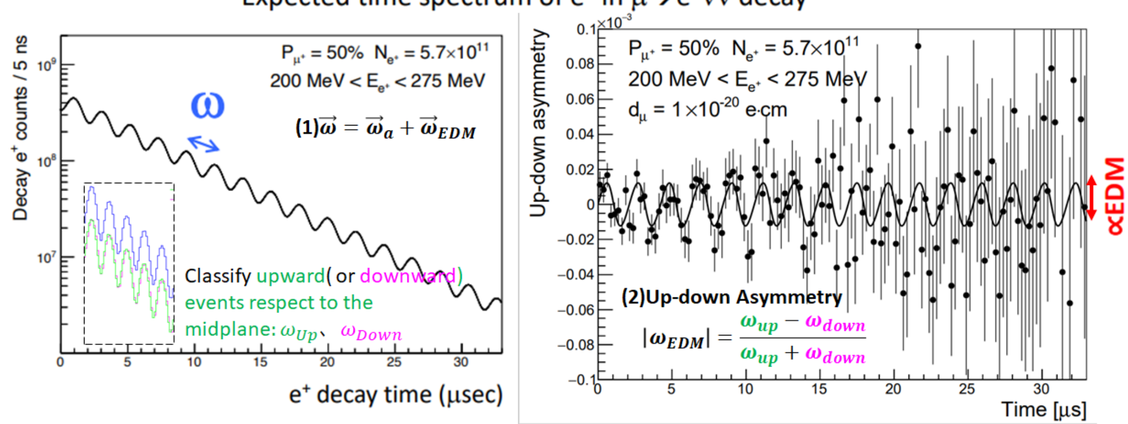
B=3[T], γ=3,
$\omega_{g-2} = 2.11\mu s$



Expected time spectrum of e⁺ in μ→e⁺νν decay

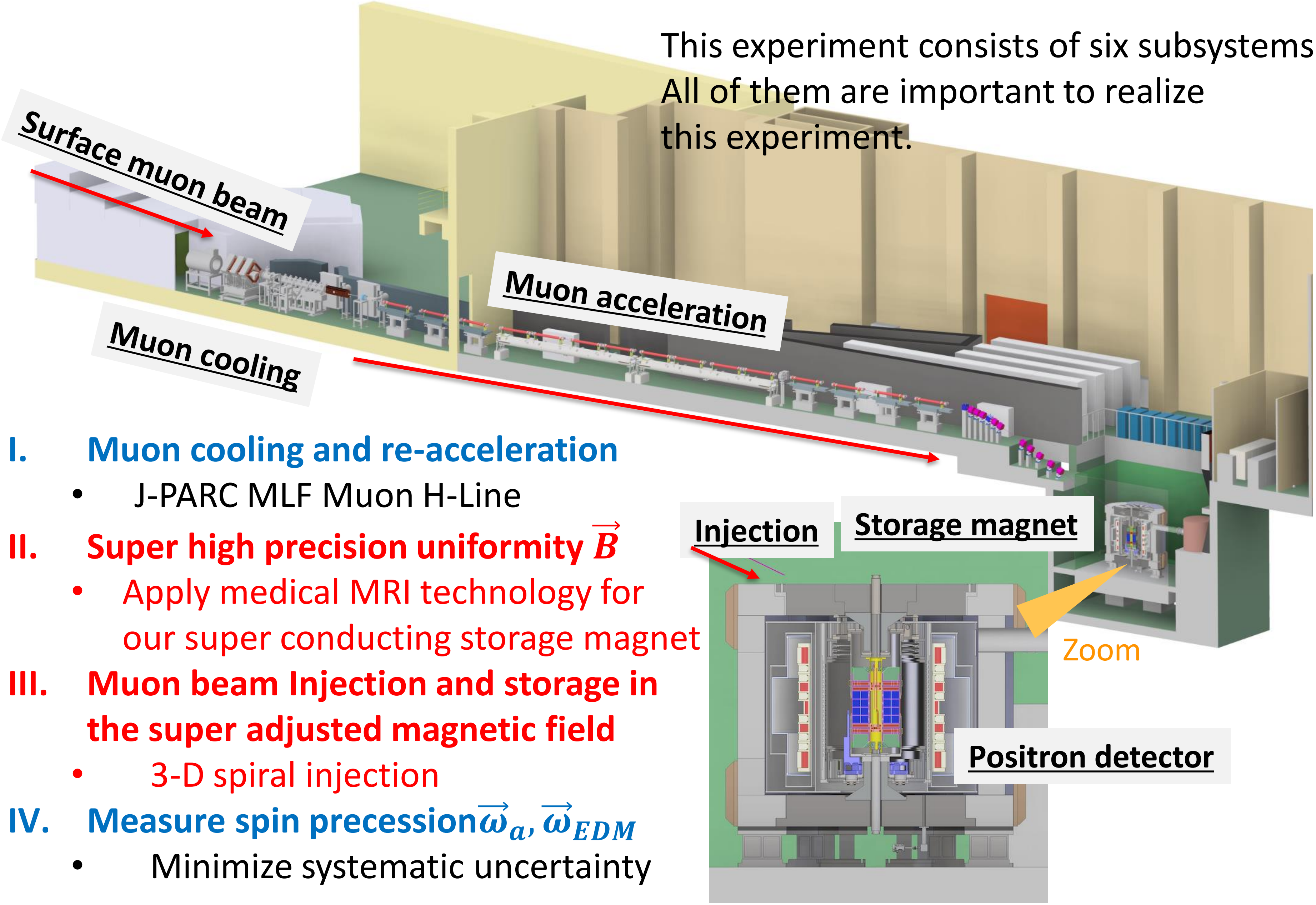


Measure g-2 and EDM at a time, with the same setup but independently!

3. Today :magnet & Injection

$$\vec{\omega} = -\frac{q}{m}\left[\frac{g-2}{2}\vec{B} + \frac{\eta_{EDM}}{2}\left(\vec{\beta}\times\vec{B}\right)\right]$$

This experiment consists of six subsystems. All of them are important to realize this experiment.



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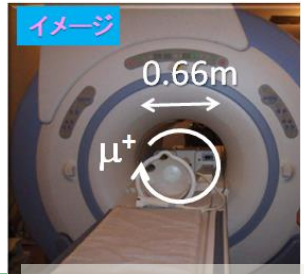
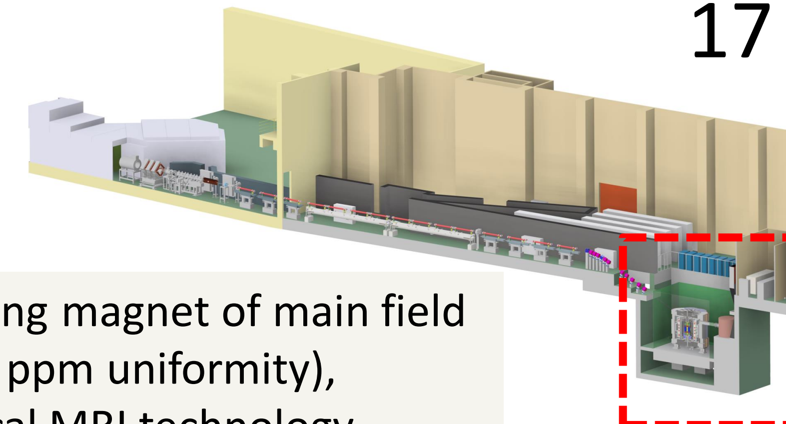
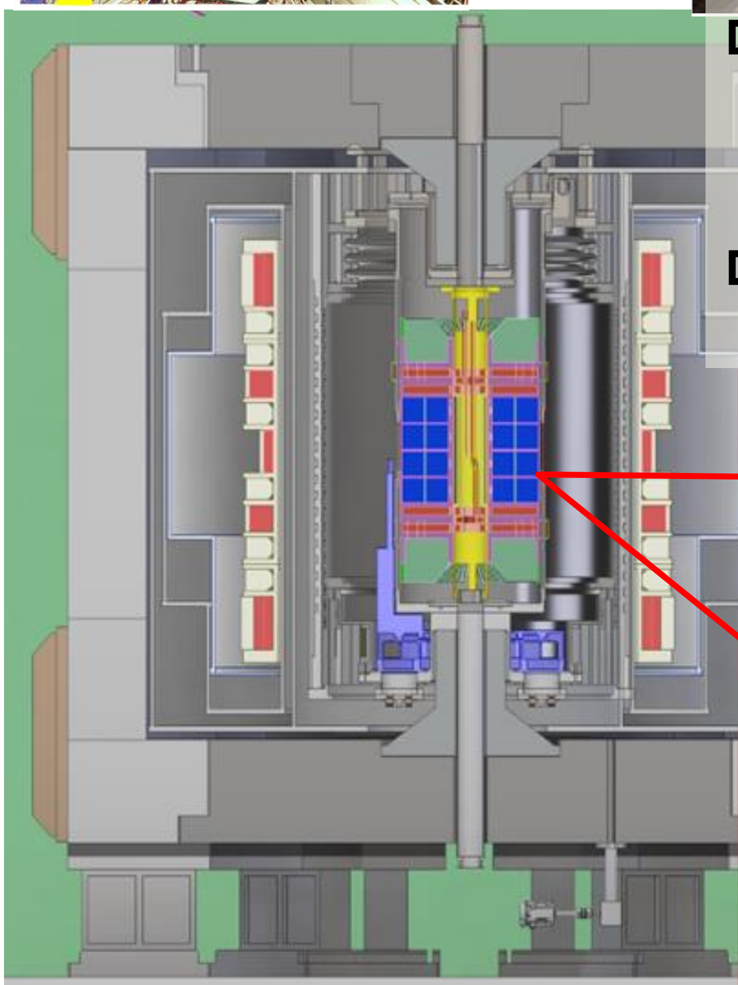
   - Minimize systematic uncertainty

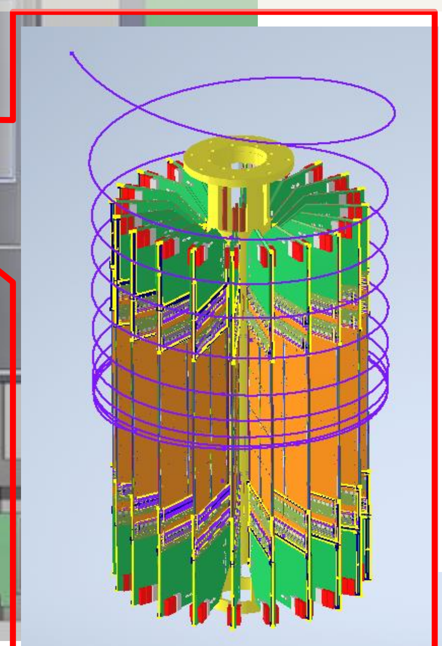
3-D tracking of decayed positron in compact storage ring

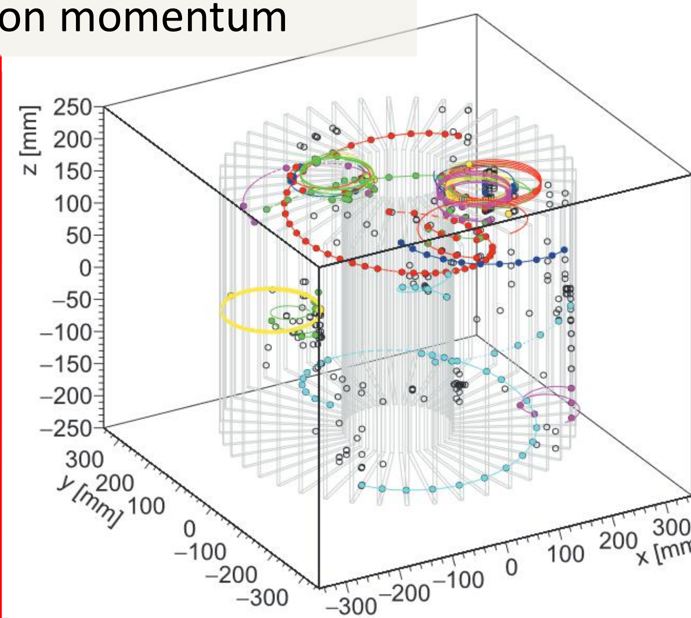




- Super conducting magnet of main field flux = 3T (< 0.1 ppm uniformity), applying medical MRI technology
- Spin precession vector is available by track-back of positron momentum







3-D tracking of decayed positrons

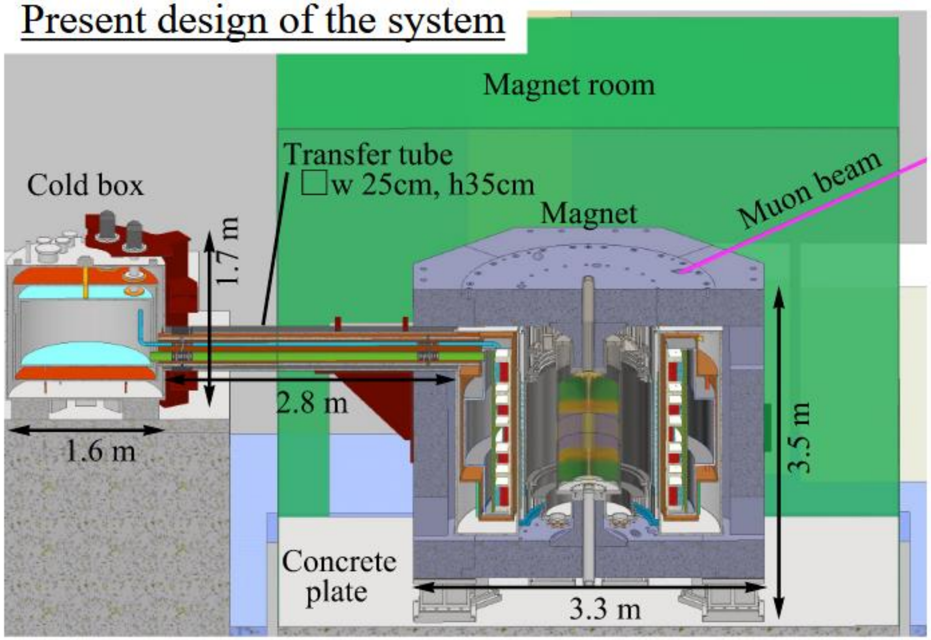
Overall Design

Studied magnet design since 2010.

KEK Prof. Sasaki and Dr. Abe

- Superconducting coils : NbTi
  - Main solenoid coil
    - Persistent current operation
  - Weak focusing coil
    - Power supply operation
  - Shim coils
    - Power supply operation
- Field tuning system using iron pieces
- Iron yoke
  - Adjust field shape
- Cooled by liquid Helium
  - Cryocoolers to recondense LHe
- Separated cold box from magnet cryostat
  - Isolate vibration
- Vibration isolation/control system

Present design of the system



Main parameters

Item	Unit	Value
Nominal central field	T	3.0
Nominal current	A	417.5
Stored energy	MJ	14.6
Inductance	H	166.9
Peak field on strand	T	5.4

4

Development of a Superconducting Solenoid for Hyperfine Structure Measurement of Muonium at the J-PARC
Ken-Ichi Sasaki, Michinaka Sugano, Ryuji Ohkubo, Hiromi Iinuma, Toru Ogitsu, Naohito Saito, Koichiro Shimomura, Akira Yamamoto. 2012. 4 pp. Published in IEEE Trans.Appl.Supercond. 22 (2012) 3, 4500904

Parameters

KEK Prof. Sasaki and Dr. Abe

- Requirements for the magnetic field of the muon storage magnet
  - Storage region :
    - radius : 33.3±1.5 cm
    - height : ±5 cm
    - Field strength : 3T
    - Uniformity : ± 0.1 ppm (Azimuthal integral)
  - Injection region :
    - Smooth field for beam injection
  - Weak focus field:

$$B_r = -n \frac{B_{0z}}{R} z \quad n: 1.0\times10^{-4} - 2.0\times10^{-4}$$

Adopt MRI technology

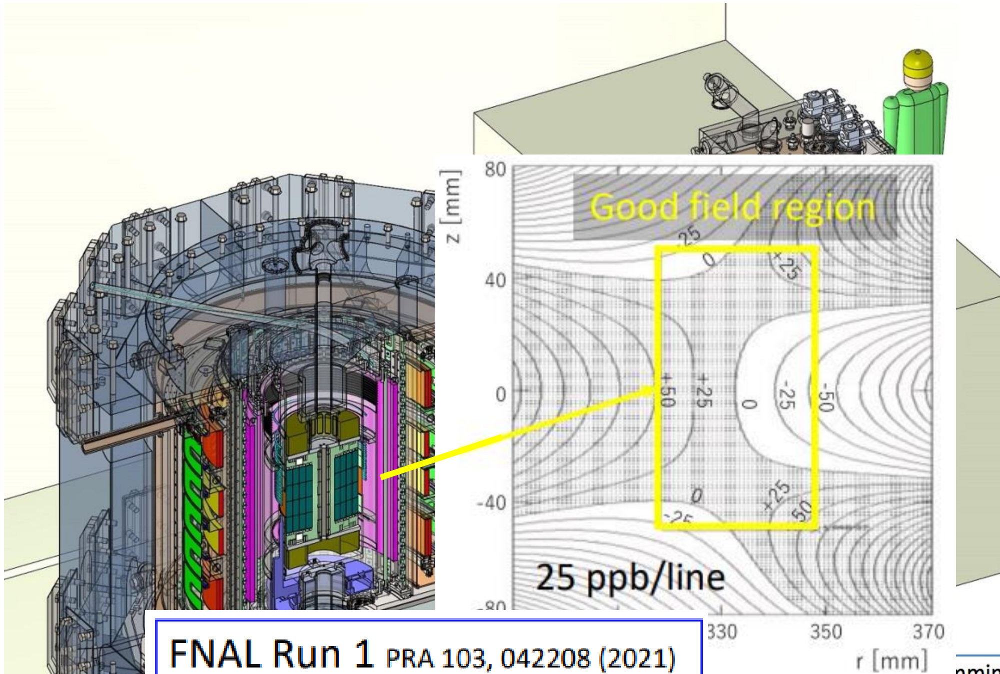
- *Developing superconducting solenoid system*

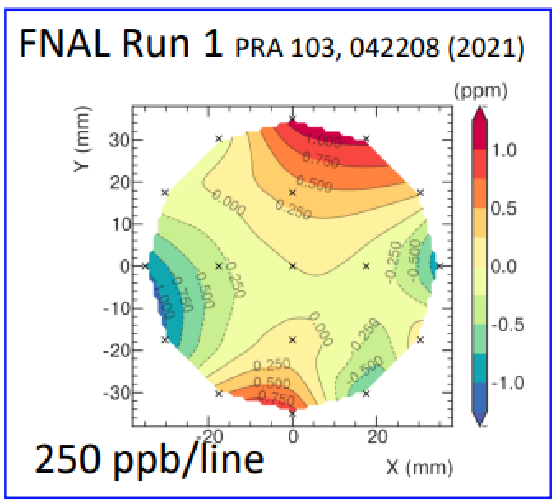
History

Date	Events
July, 2009	**LOI** submitted to PAC8
Jan, 2010	**Proposal** submitted to PAC9
Jan, 2012	**CDR** submitted to PAC13, **Milestones defined.**
July, 2012	**Stage-1** status recommended by PAC15, granted by the IPNS
May, 2015	**TDR** submitted to PAC
Oct, 2016	**Revised TDR** submitted to PAC and FRC
June, 2016	Selected as a KEK-PIP priority project
Nov, 2016	**Focused review on technical design**
Dec, 2017	Responses and Revised TDR submitted to PAC
Nov, 2018	**Stage-2 status granted by the IPNS director**
Jan, 2019 Mar, 2019	**Stage-2 status granted by the IMSS director** KEK-SAC endorsed the E34 for the near-term priority
June, 2020	Grant-in-aid “specially prompted research” (2020-2025)
2019-2023 **Jan. 2024**	**KEK allocated preparatory budget for construction** **MEXT allocated partial construction budget**

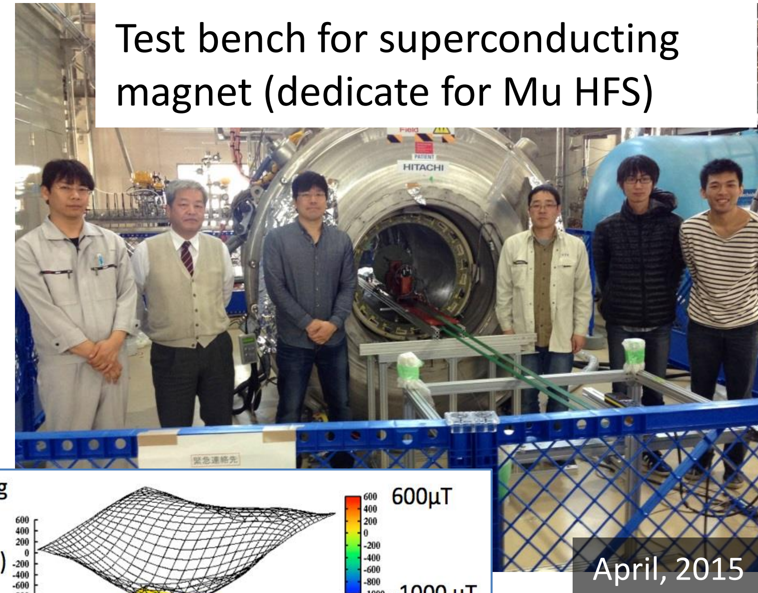
Super precisely adjusted $\vec{B}$

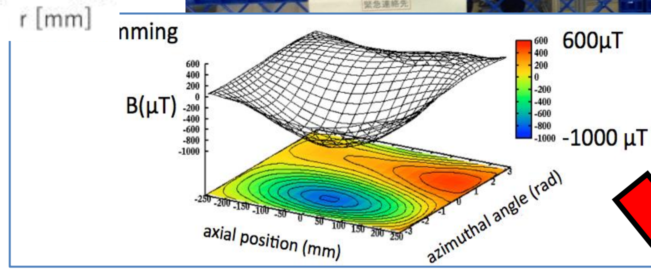
Design work of superconducting magnet for muon storage is ongoing applying medical MRI technology





Test bench for superconducting magnet (dedicate for Mu HFS)





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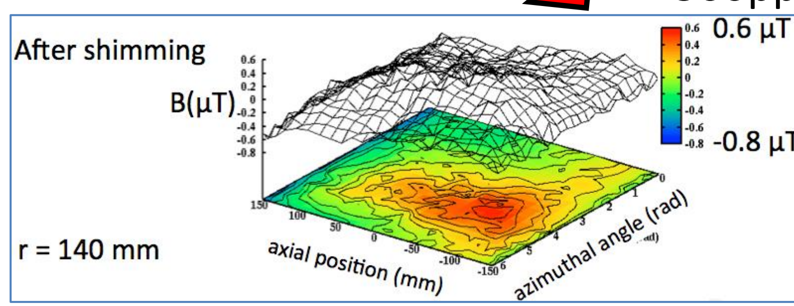


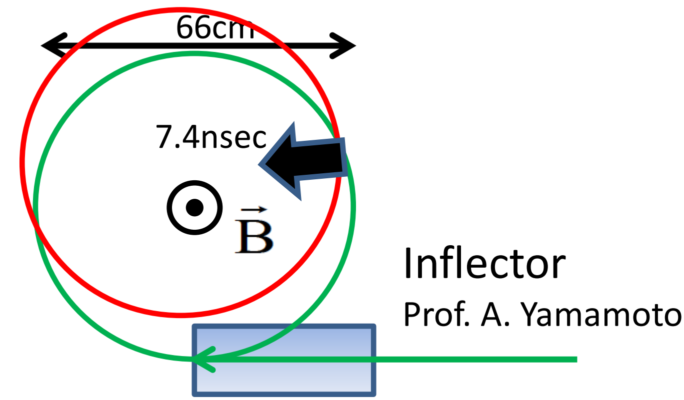
[1] M. Abe, K. Shibata, “Consideration on Current and Coil Block Placements with Good Homogeneity for MRI Magnets using Truncated SVD”, IEEE Trans. Magn., vol. 49, no. 6, pp. 2873-2880, June. 2013.
[2]阿部充志　他、特許第４９０２７８７号、「MRI装置用磁場調整」、
平成24年１月13日登録、日本国特許庁

M. Abe et. al., NIM A 890, 51 (2018)

Why 3-D spiral injection and kicker?

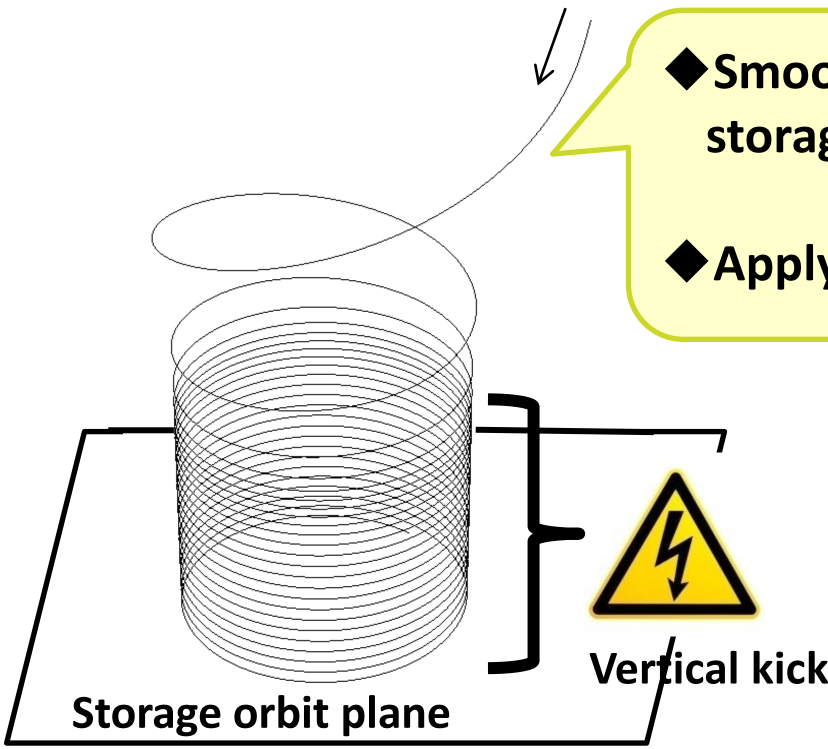
Technical difficulties for compact 2-D injection:

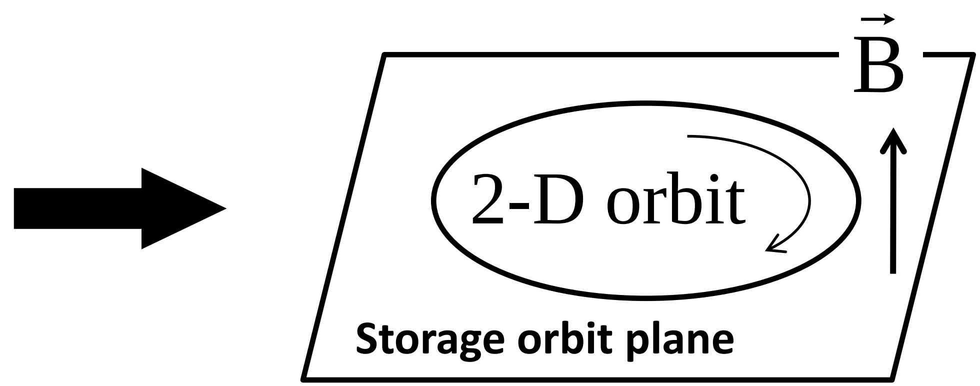
- ✓ 3T is too high to cancel fringe field by inflector,
- ✓ Required kick angle within a single turn is too fast and big.



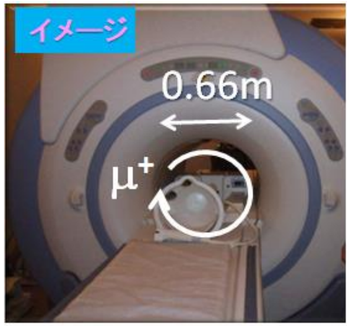
3-D spiral beam injection does help:

- ◆ **Smooth connection between injection and storage sections without any sources of error field**
- ◆ **Apply vertical kick during *"several turns"***





Outline of 3-D spiral beam injection

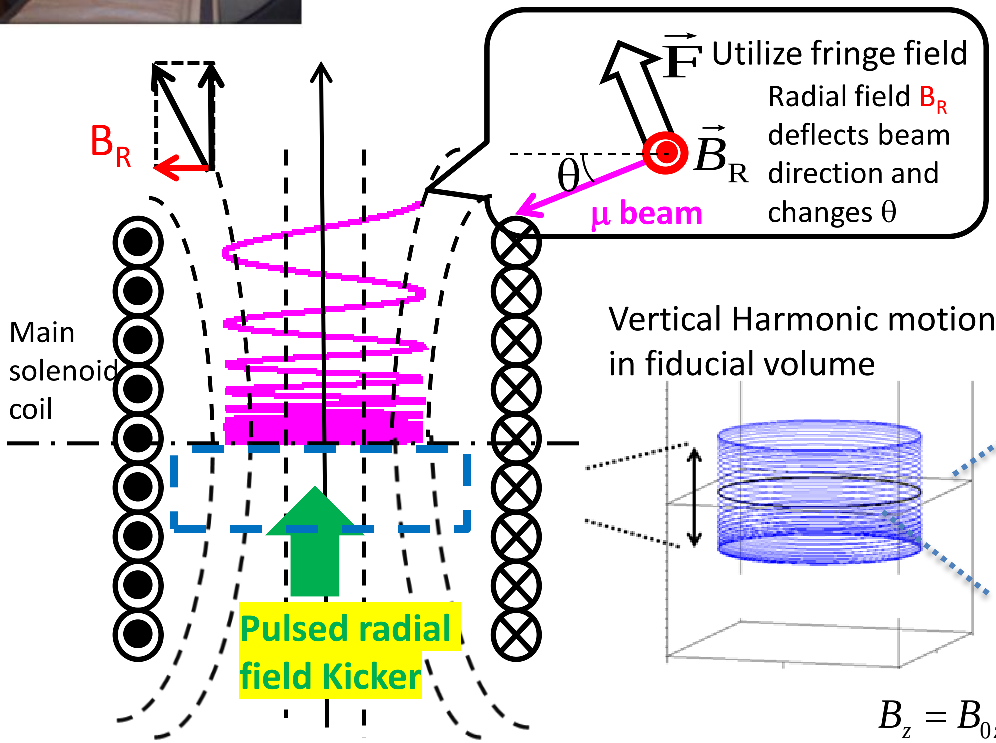


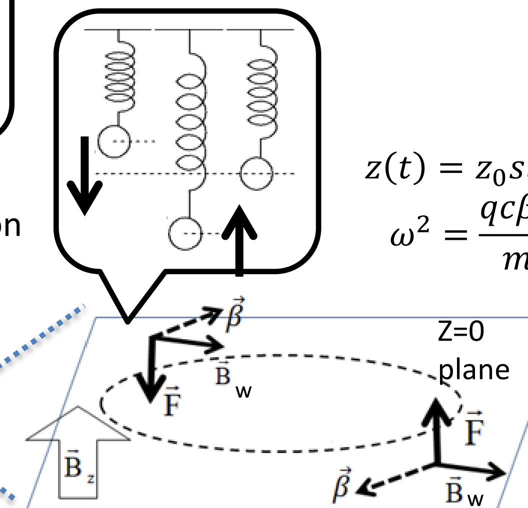
All-in-one solenoid magnet is suitable for super compact storage ring

NIM.A 832 (2016) 51-62.
https://doi.org/10.1016/j.nima.2016.05.126

Beauties :

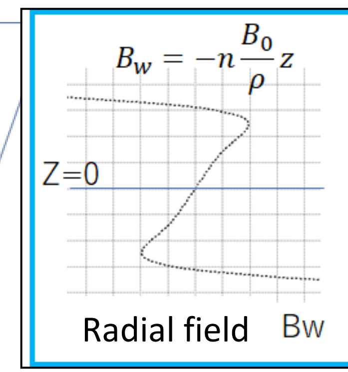
- **Smooth connection between injection and storage sections,**
- **A unit of magnet does work for this method and decrease sources of error field,**
- **Vertical motion is controlled by pulsed radial field kicker**
- **No electric field is required to control muon beam!**





$$z(t) = z_0 sin(\omega t)$$

$$\omega^2 = \frac{qc\beta B_0}{m\rho} n$$



$$B_R = -n \frac{B_{0z}}{R_0} z,$$

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

New idea and unprecedented scheme!
Three major keys to be discussed today.

0<n<1: Focus both vertical and horizontal direction at a time!!

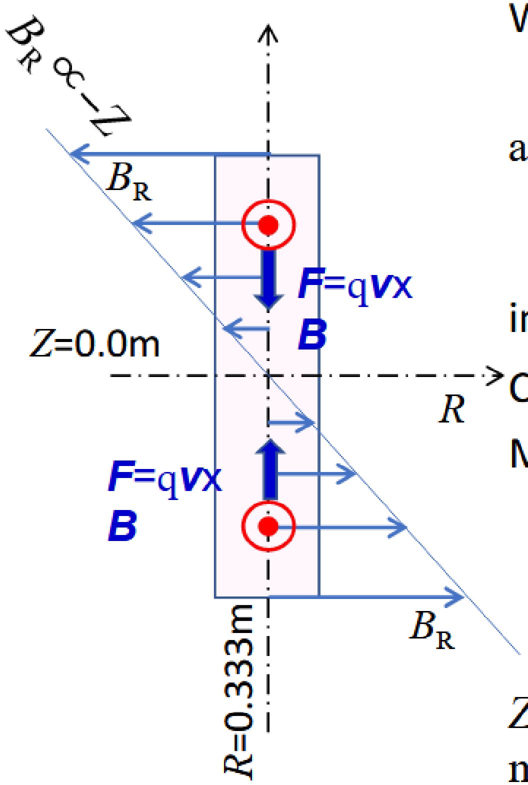
Target :n=1.5E-4 →0.6μs betatron period, well away from g-2 of 2.11μs

Technical Challenge-1

M. Abe, CM27,

Weak Focus magnetic Field

B_R distribution is important for WFF, but we can only measure B_Z strength.
Following equations are discussed and we will make attention on Z^2 term.



WFF & EM force on muon in storage volume

WFF coil generates magnetic field of,

$$B_Z(R) \propto R^{n-index},$$

and a parameter

$$n\text{-index} = -\frac{R_0}{B_{Z0}}\frac{\partial B_Z}{\partial R} \quad (=1.5\text{E-}4)$$

indicates the WFF strength.

Considering $\frac{\partial B_R}{\partial Z} = \frac{\partial B_Z}{\partial R}$, and $\frac{1}{R}\frac{\partial}{\partial R}(RB_R) + \frac{\partial B_Z}{\partial Z}=0$,

Magnetic field (B_R, B_Z) distributions are

$$B_R = -\frac{B_{Z0}}{R_0}Z(n\text{-index}) \quad \text{(difficult to measure)}$$

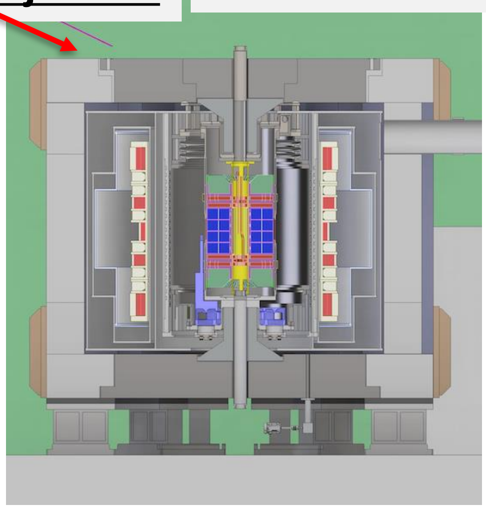
$$B_Z = (n - index)\{\frac{B_Z^0}{R^0}(R^0 - R) + \frac{B_Z^0}{R^0}\frac{Z^2}{2R^0}\}.$$

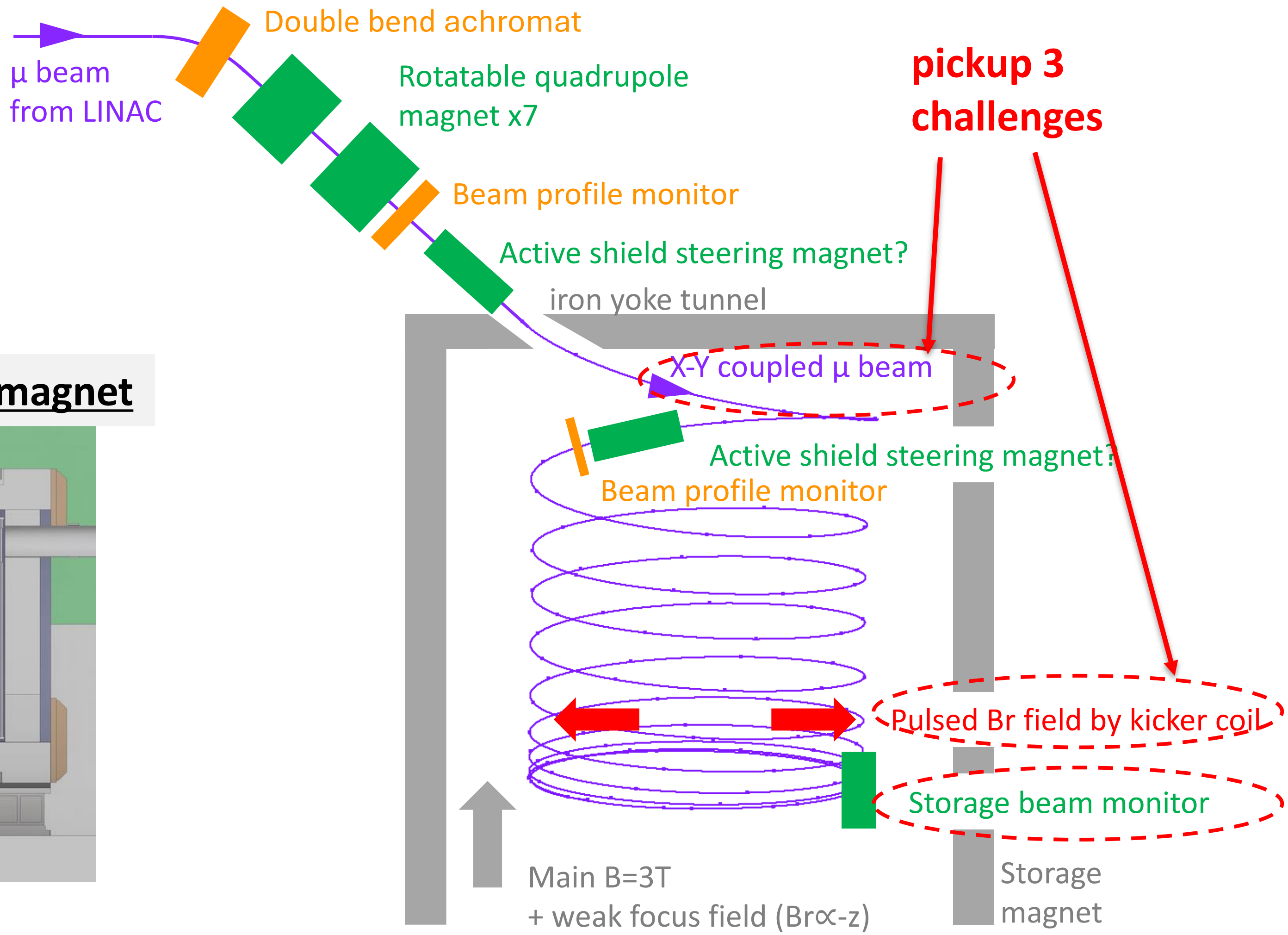
Z-square term in B_Z equation is available to determine midplane from measured magnetic field distribution through the reconstruction. The discussion above is in R-Z cylindrical coordinate, but the reconstruction is in 3D coordinate and search dB_Z/dZ position.

3-D spiral beam injection

(Dr. Ogawa/Kyushu-Univ.)

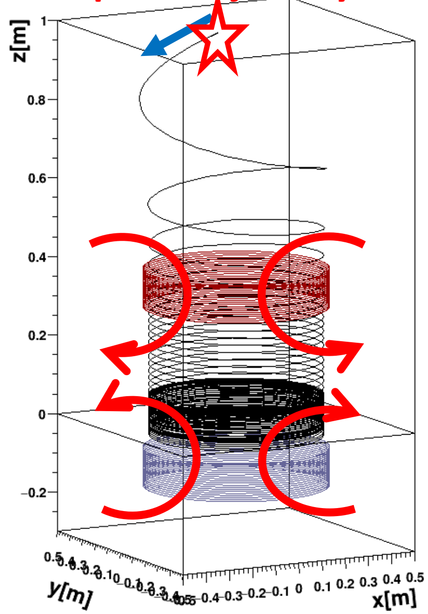
Injection **Storage magnet**

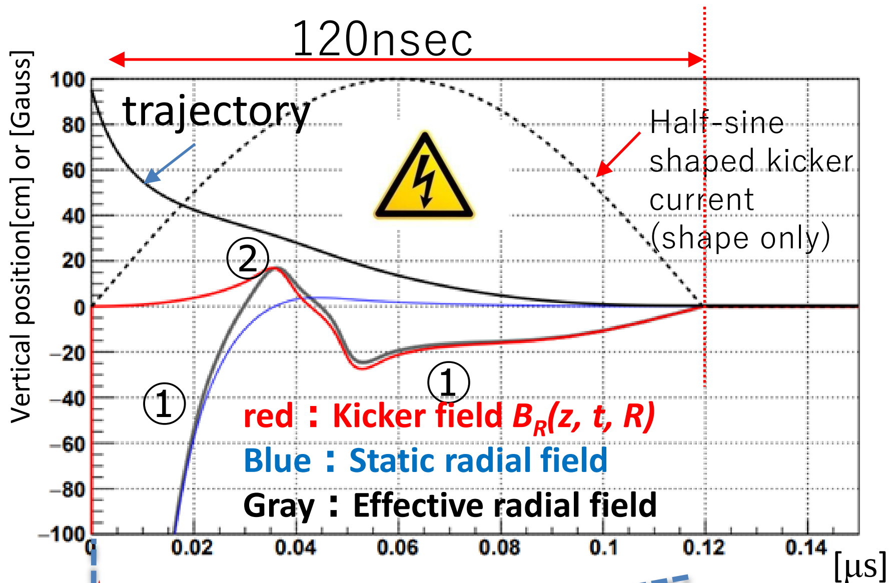


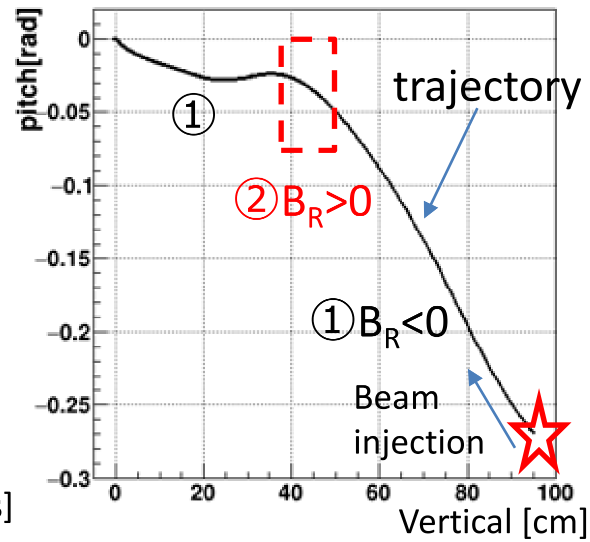


Technical Challenge-2: Vertical kicker to control *vertical beam phase space* in the storage region

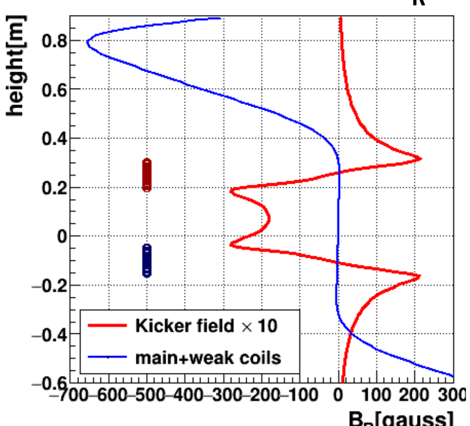
3-D spiral trajectory



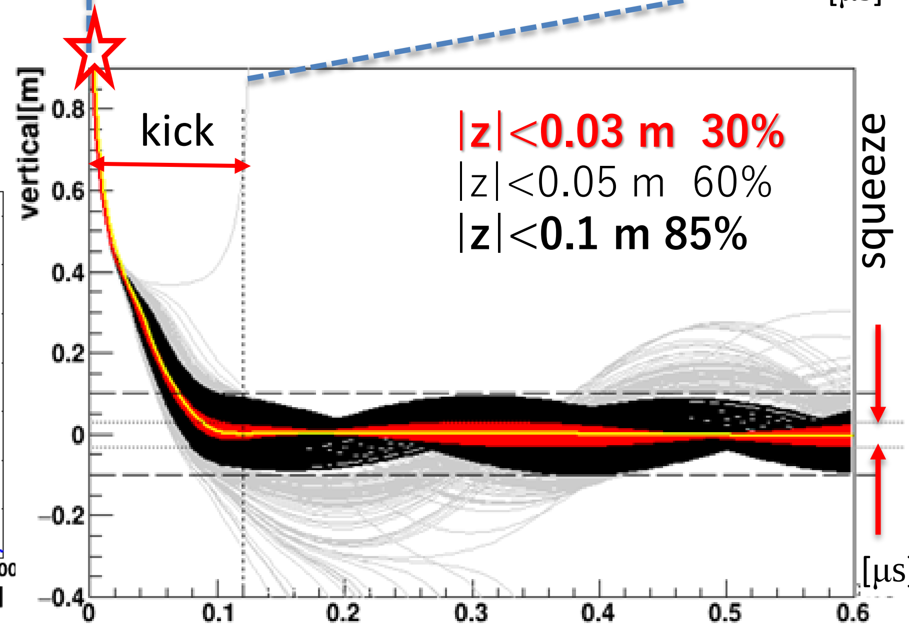


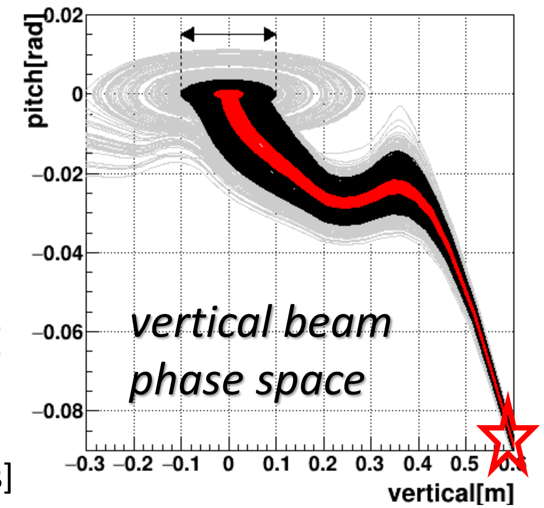


A pair of up/down kicker coil forms Radial field B_R



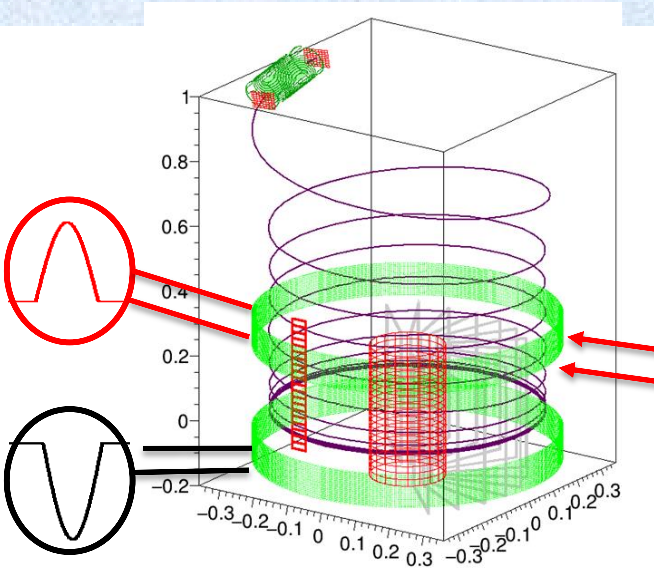
$$\times\, half sin \frac{2\pi}{T_{kick}}(t - t_0)$$

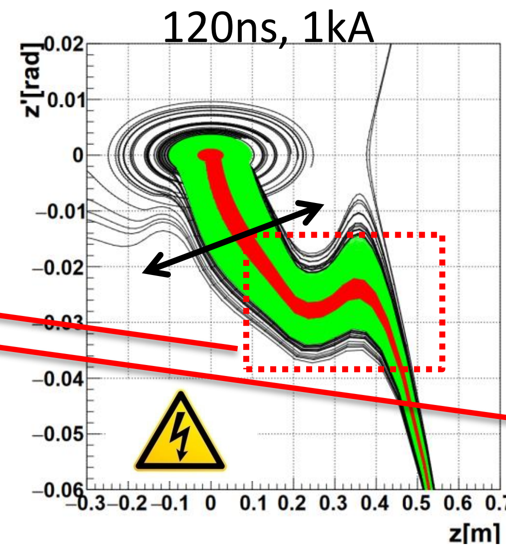


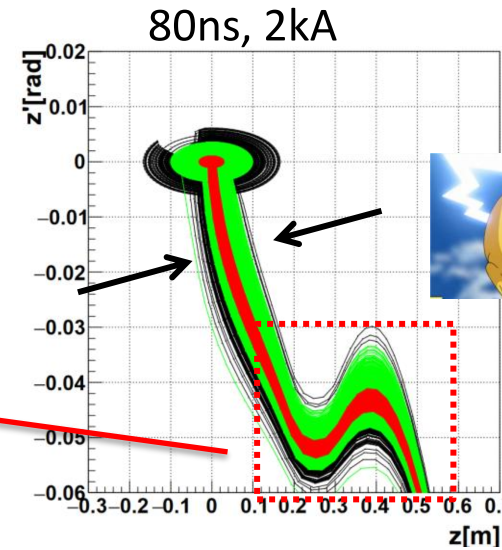


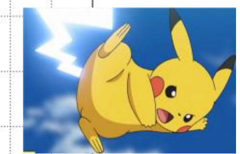
Current kicker design with appropriate X-Y coupled beam is stored into |z|<0.1m region (e^+ detector acceptance) with 85% efficiency. However, the smaller |z| is better for physics!

Shorter and stronger kick is better but,: *Technical challenges* to realize kicker









Simple LC circuit

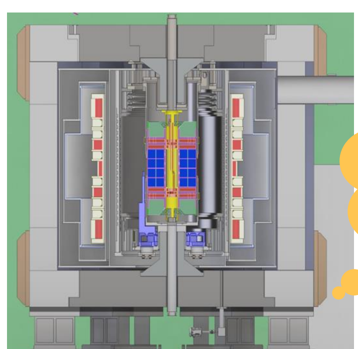
A charged capacitor stores energy

= a coil carrying current stores energy

$$\frac{1}{2}CV^2 = \frac{1}{2}LI^2 \quad I_c$$

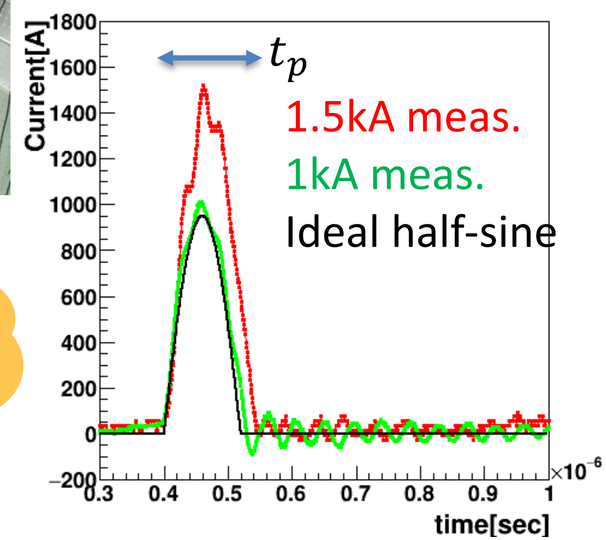
$$t_p = \frac{T}{2} = \pi\sqrt{LC} = 120ns$$

Capacitor charging voltage $$V_c = \frac{L \cdot I \cdot \pi}{t_p}$$



Inside of the magnet, High voltage <30kV

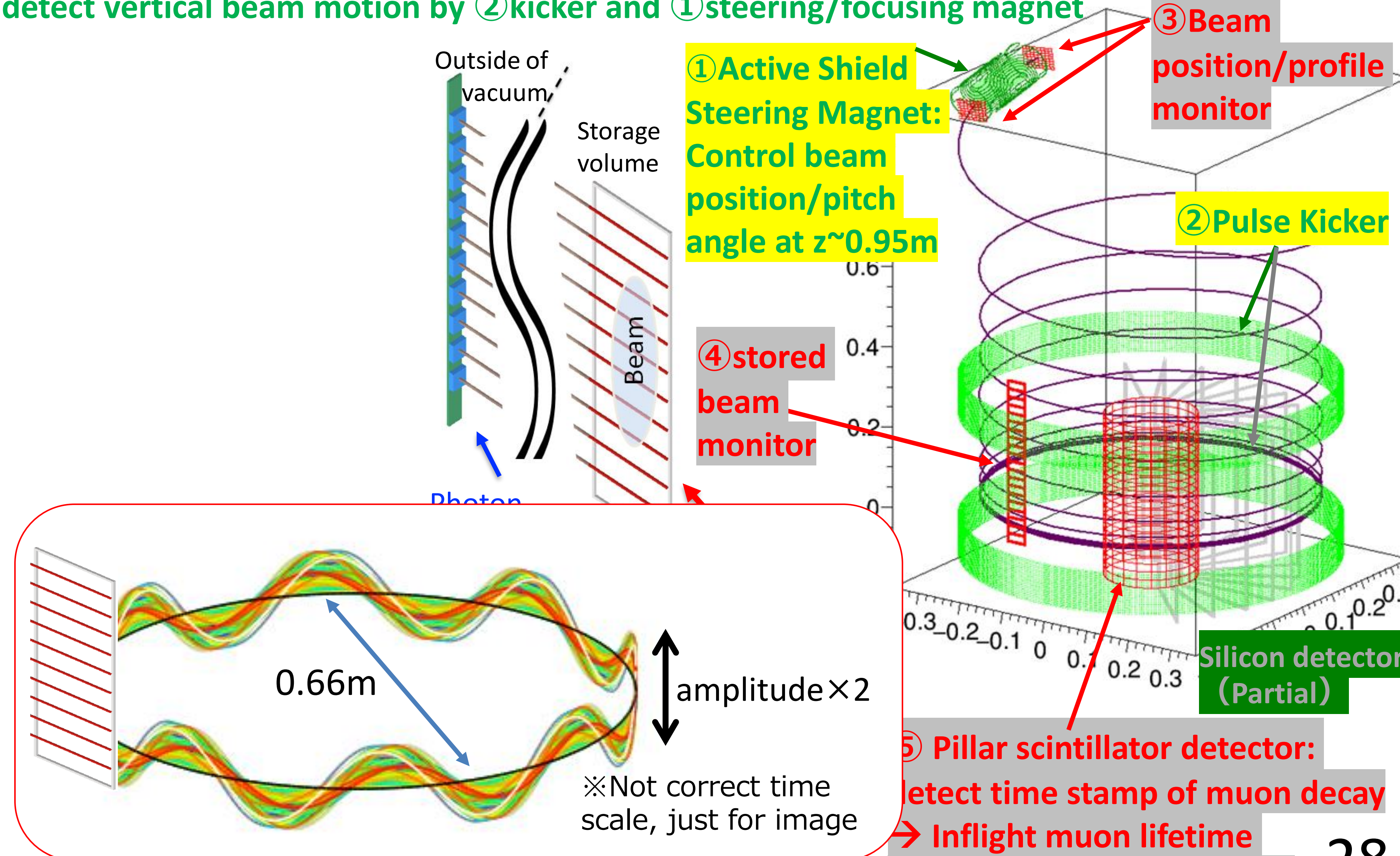
Realistic kicker with stable operation is crucial



Technical challenge-3: Beam stearing magnet and monitor ***inside*** the storage magnet: How do we control the beam?

(Dr. Ogawa/Kyushu-Univ.)

Detect vertical phase space by ④Stored beam monitor, and then control detect vertical beam motion by ②kicker and ①steering/focusing magnet



⑤ Pillar scintillator detector: detect time stamp of muon decay → Inflight muon lifetime measurement as byproduct

More details of 3-D spiral injection are discussed in these papers

New approach to the Muon g-2 and EDM experiment at J-PARC

Hiromi Iinuma for J-PARC New g-2/EDM experiment collaboration
KEK, High Energy Accelerator Research Organization, 1-1, Oho, Tsukuba, 305-0301, Japan

19th International Spin Physics Symposium (SPIN 2010)

•27 September-2 October 2010. Juelich, Germany (C10-09-27)

DOI 10.1088/1742-6596/295/1/012032

Three-dimensional spiral injection scheme for the g−2/EDM experiment at J-PARC

Nuclear Instruments and Methods in Physics Research A

Idea of 3-D spiral injection

DOI: 10.1016/j.nima.2016.05.126

Design of a strong X-Y coupling beam transport line for J-PARC muon g-2/EDM experiment

H. Iinuma, H. Nakayama, M. Abe, K. Sasaki and T. Mibe

Conceptual design for beam transport line

DOI: 10.1109/TASC.2022.3162810

PRECISE CONTROL OF A STRONG X-Y COUPLING BEAM TRANSPORTATION FOR J-PARC Muon g-2/EDM EXPERIMENT

Vertical kicker design

DOI:10.18429/JACoW-PAC2023-MOPA110

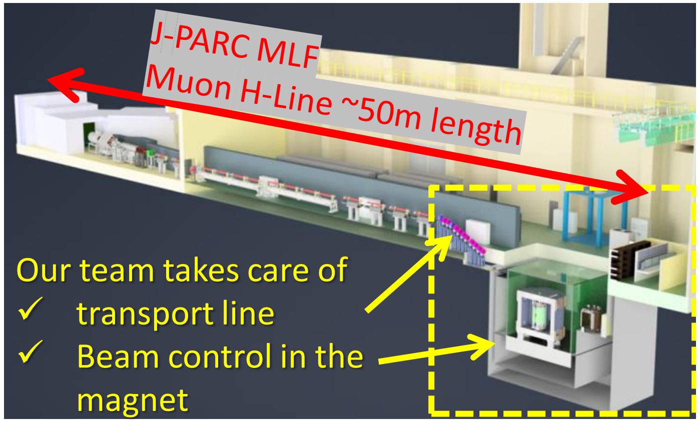
J-PARC muon g-2/EDM 実験における
精密な三次元ビーム入射のための蓄積ビームモニター

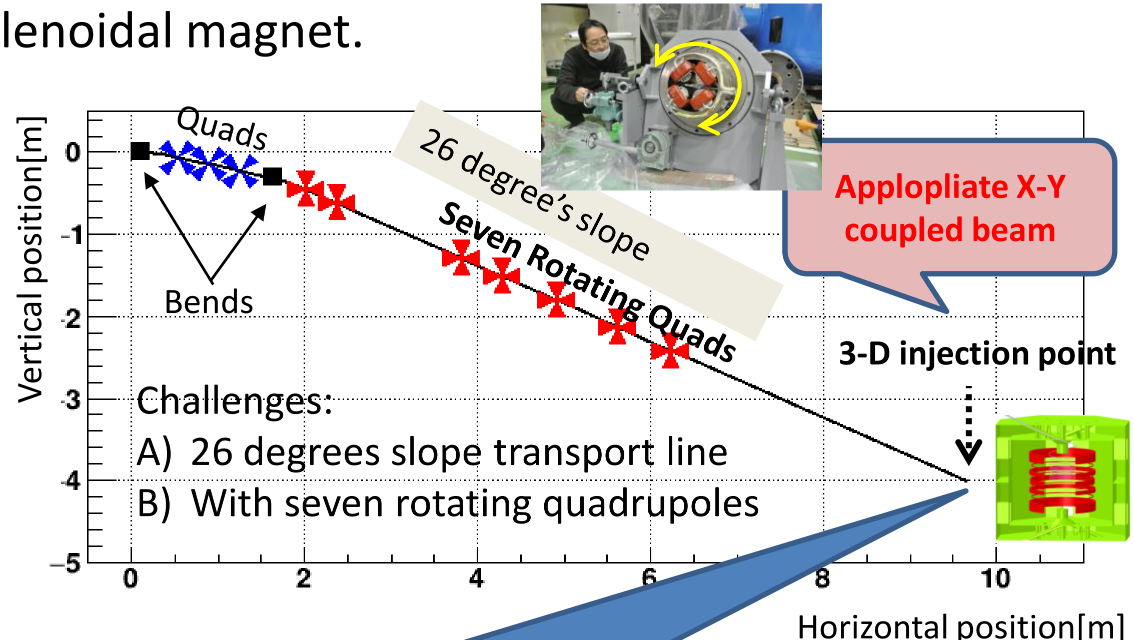
STORAGE BEAM MONITOR FOR PRECISE THREE-DIMENSIONAL BEAM INJECTION AT J-PARC MUON G-2/EDM EXPERIMENT

Details of beam monitor (Japanese) will be published (Ogawa/Kyushu-Univ.)

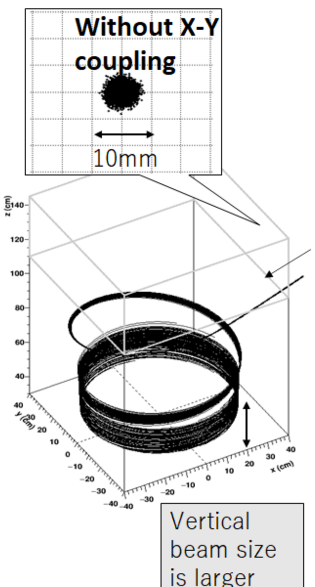
key: Strongly X-Y coupled beam at the beam transport line

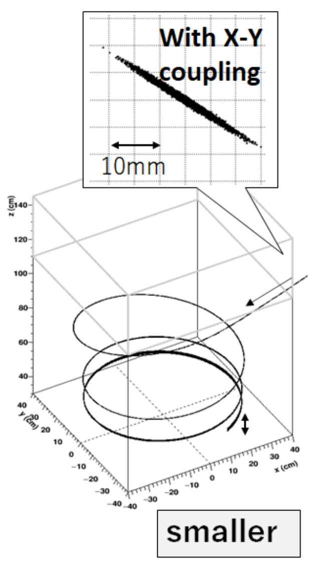
To realize high injection efficiency (~80%), a strong X-Y coupled beam is required due to axial-symmetric field of solenoidal magnet.

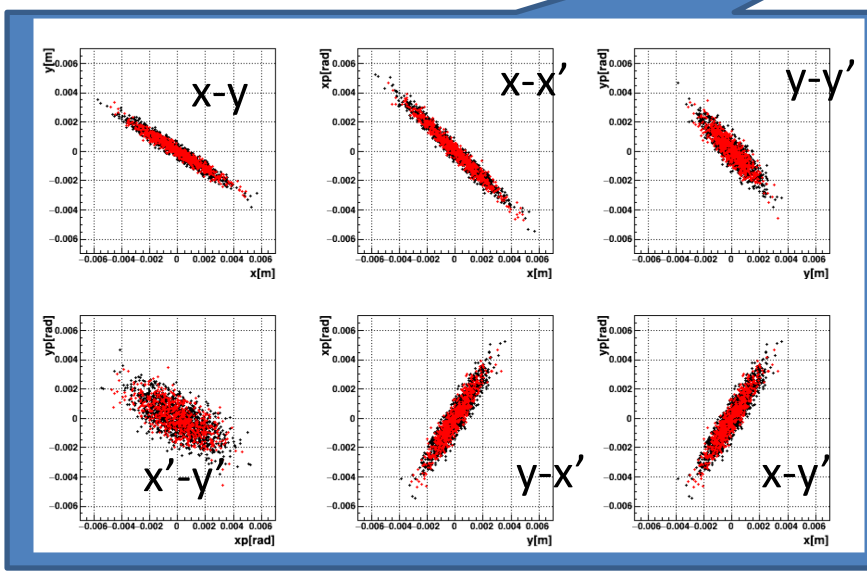




Seven rotating quadrupole magnets in the transport line control X-Y coupling at the injection point.

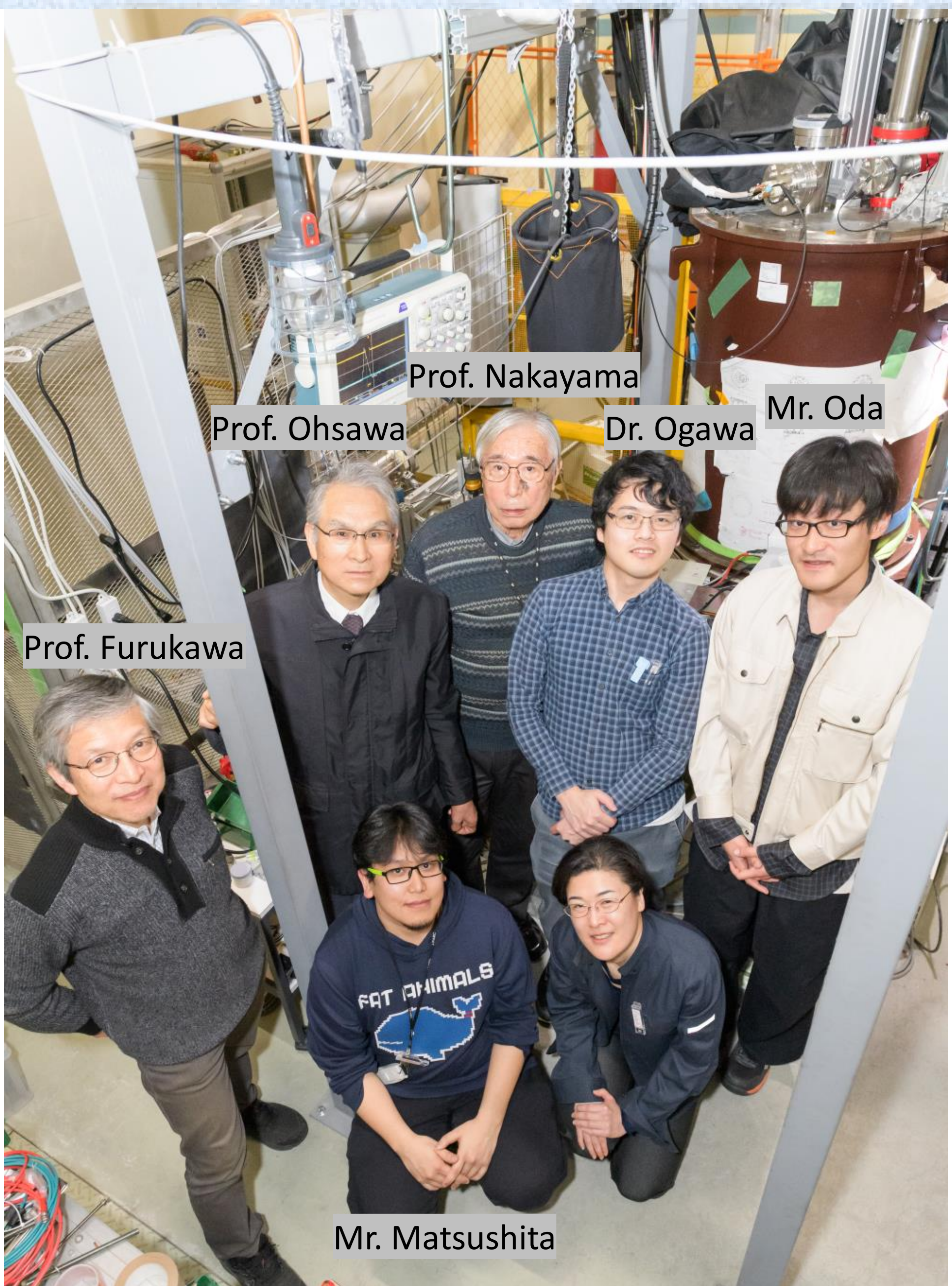






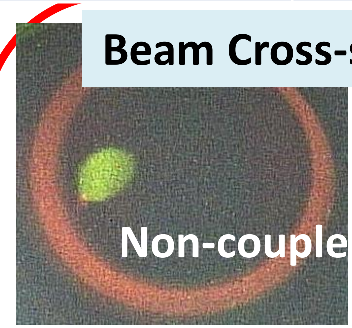
ID	angle	K-value
Q3	45.0	16.449
Q4	45.0	-0.278
Q5	60.0	2.091
Q6	-60.0	0.063
Q7	-60.0	0.814
Q8	45.0	-0.041
Q9	-60.0	-1.825

Demonstration experiment: 3-D injection and storage

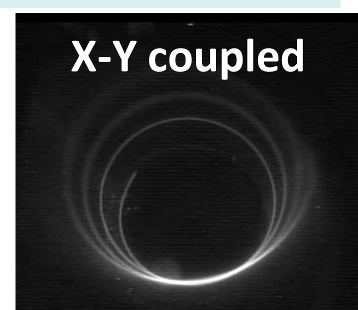


	J-PARC	
Main field beam momentum	3T (0.1ppm), 300MeV/c muon	0.008 T (~100ppm), 80keV Electron
Radius, cycrotron period	0.33m, 7.4ns	0.11m, 5ns
Kicker period/current	120ns, 1kA	50ns, 40A
# of rotating Quads.	7	3

Beam Cross-section monitor



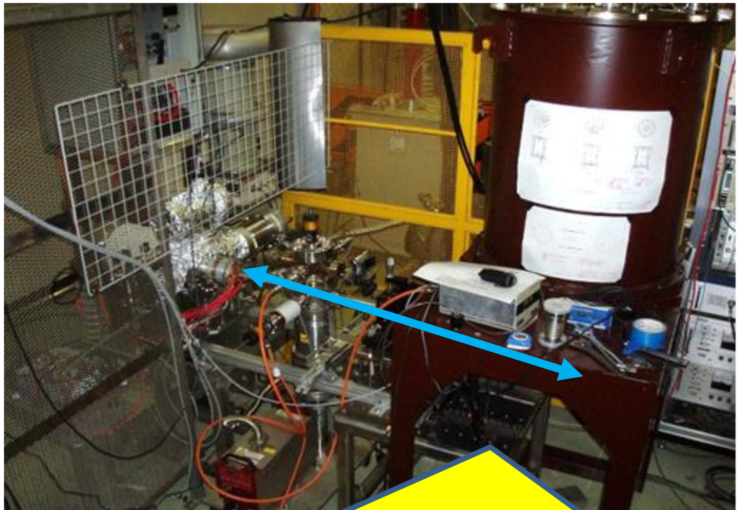
ionization luminescence signal



Understand our beam line :Q-scan

Beam phase space analysis ＝4-D beam matrix (σ-matrix) reconstruction

E-gun testbench for 3-D spiral injection



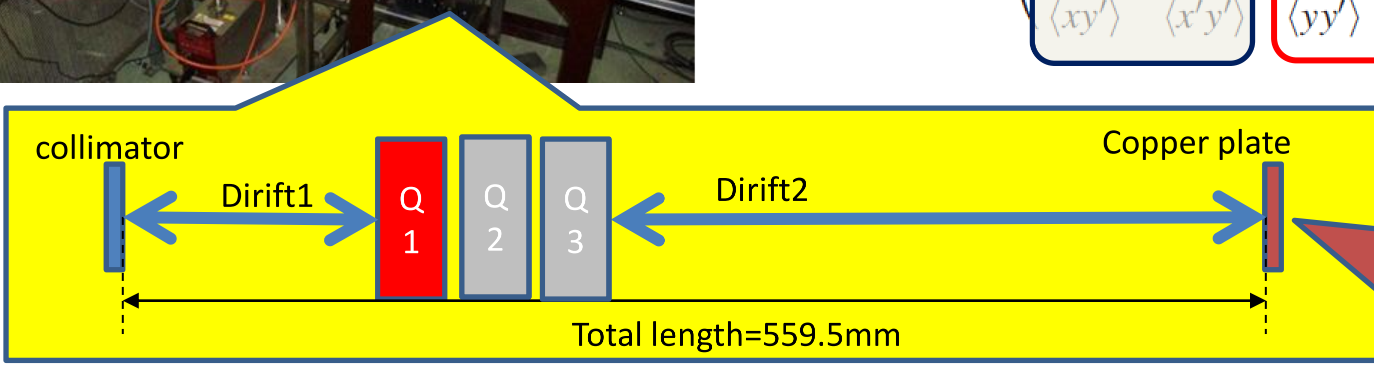
- ☐ Q-scan by use of single quadrupole (Q1 or Q2 or Q3)
  - ☐ Change K-vale of Q1 (or Q2 or Q3) to measure focus and defocus beam shape
  - ☐ **Reconstruct σ_0 (at initial point)**
- ☐ **Estimate σ_1** at the end of the transport line

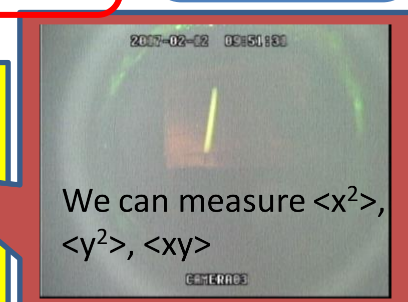
$$\sigma_1 = M\sigma_0(M)^t$$

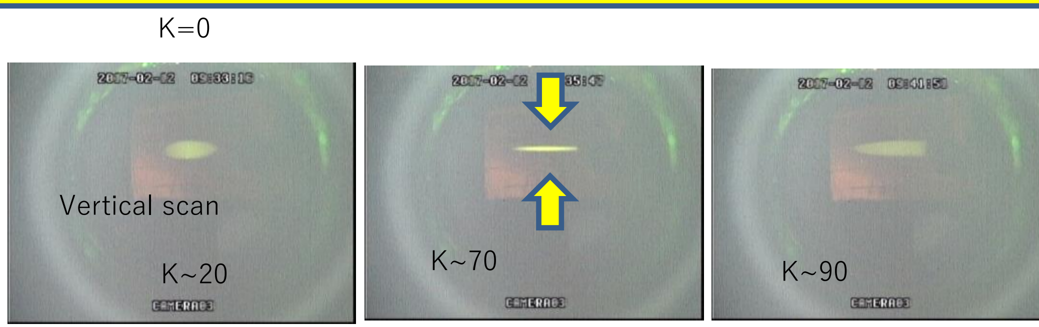
Q-scan can measure

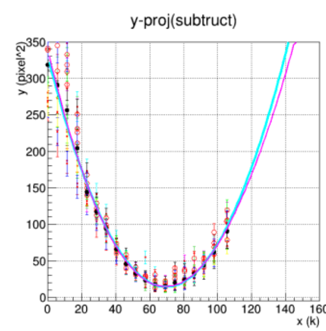
$$\sigma_0=\begin{pmatrix} \langle x^2\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle & \langle x'y\rangle & \langle x'y'\rangle \\ \langle xy\rangle & \langle x'y\rangle & \langle y^2\rangle & \langle yy'\rangle \\ \langle xy'\rangle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

X-Y coupling component









Try to Estimate σ_0 by use of 20 data sets

E-gun testbench for 3-D spiral injection

initial

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

10 independent components in 4-by-4 matrix

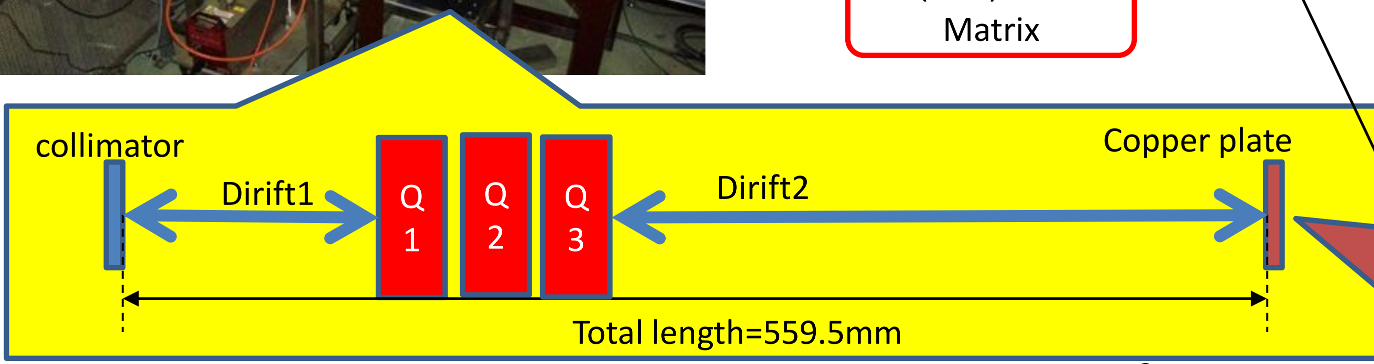
- **Measure X-Y view at transport line**
- **reconstruct σ_0 at the initial point**
- **Check emittance, Twiss parameters,**
- **X-Y Coupling parameters**

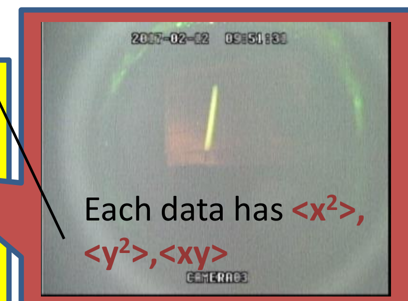
If we have N times different set-up data,

10×1 (3*N)×1

$$T X_0 = X$$

(3*N)×10 Matrix





$$X = TX_0$$

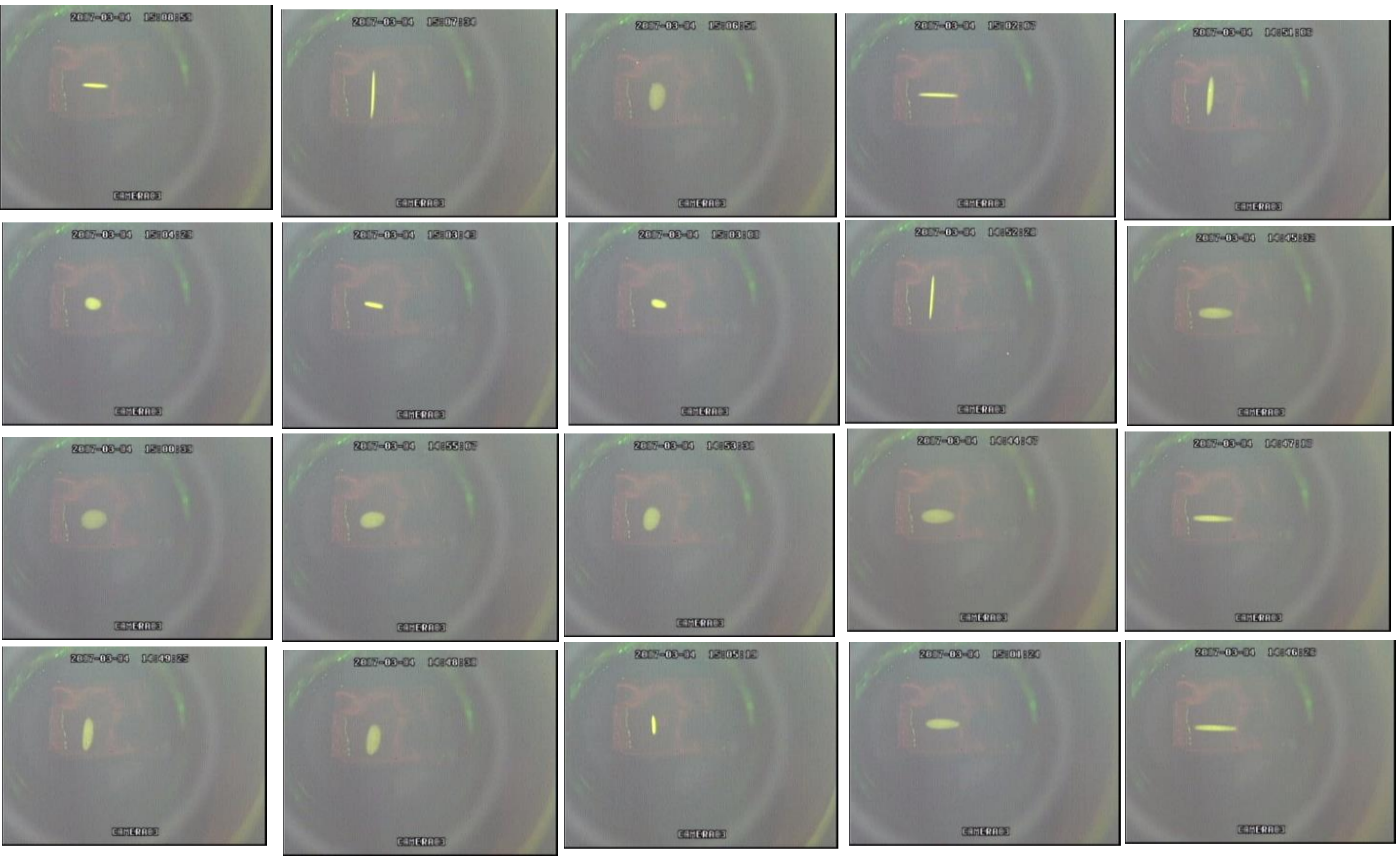
(3*N)×1 (Ex. N=20) 10×1

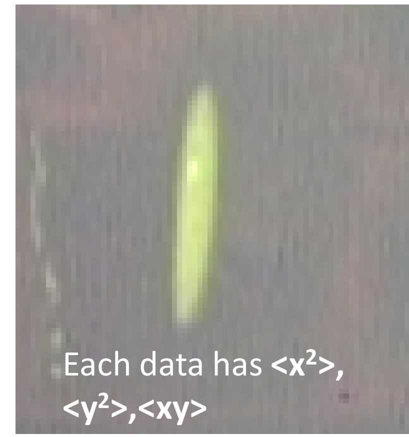
(3*N)×10

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

$$X_0 = [T^t T]^{-1} T^t X$$

20 different Q settings for σ_0 measurement

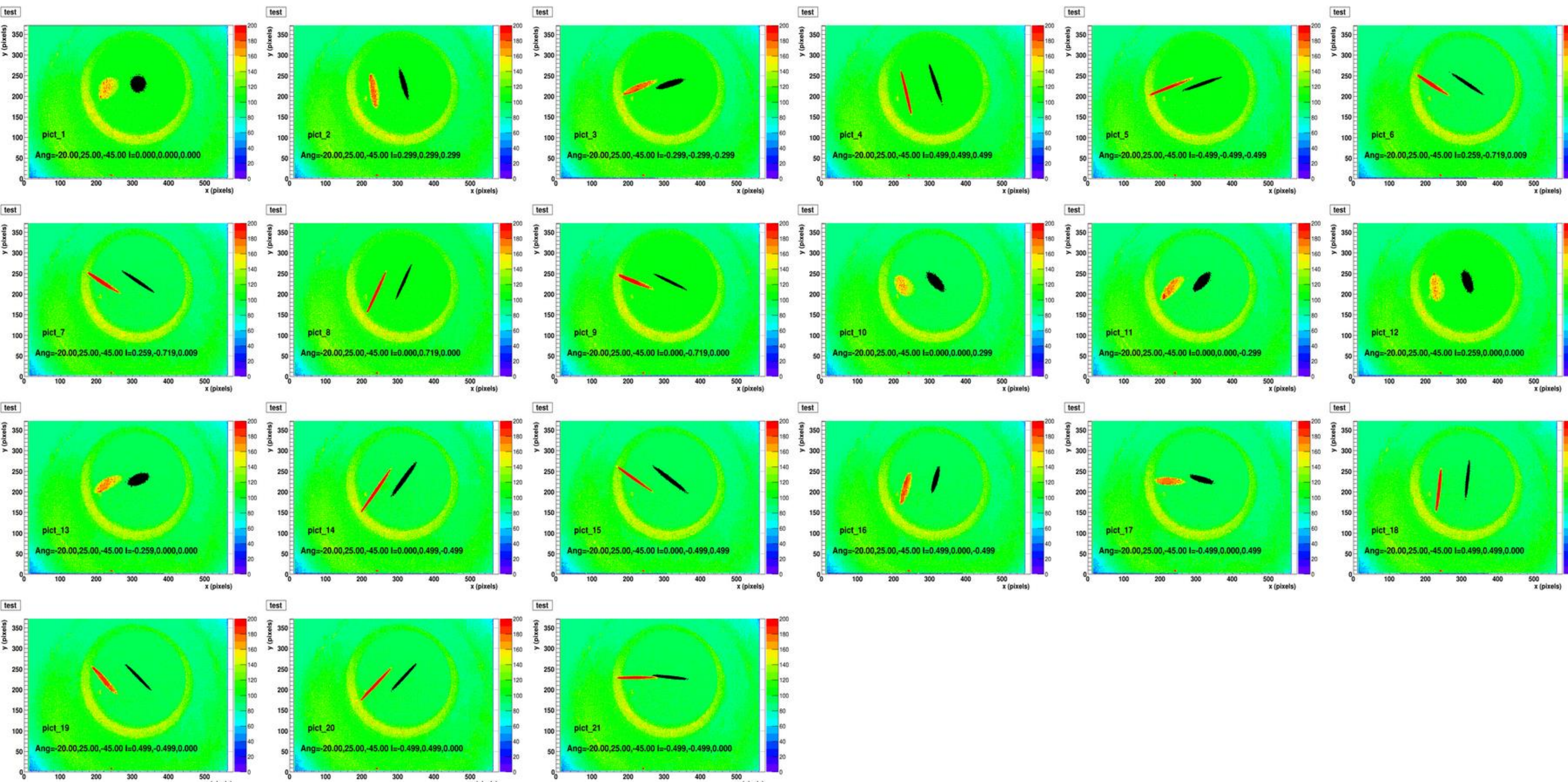




We can simulate beam shape view and compare with measured data

Compare estimated sigma-matrix vs. real

$$X = TX_0$$

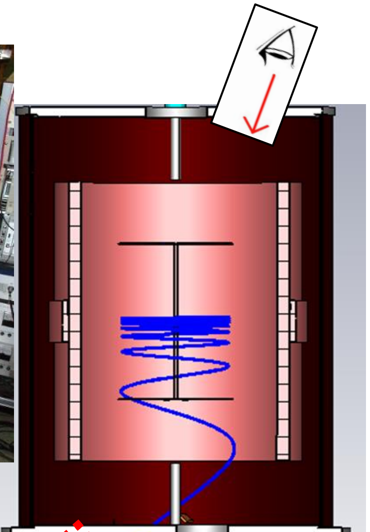


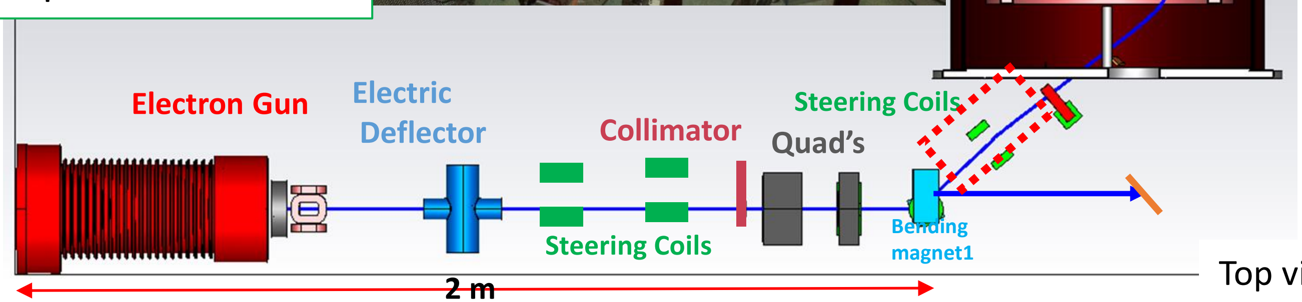
Demonstration feasibility of 3-D spiral injection

- 80keV Electron beam (β=0.5), instead of muon, is adjusted “X-Y coupling”, injected into ϕ0.24m orbit.
- Cyclotoron period is only 5nsec.

✓ Learn how to control beam of “X-Y coupling”

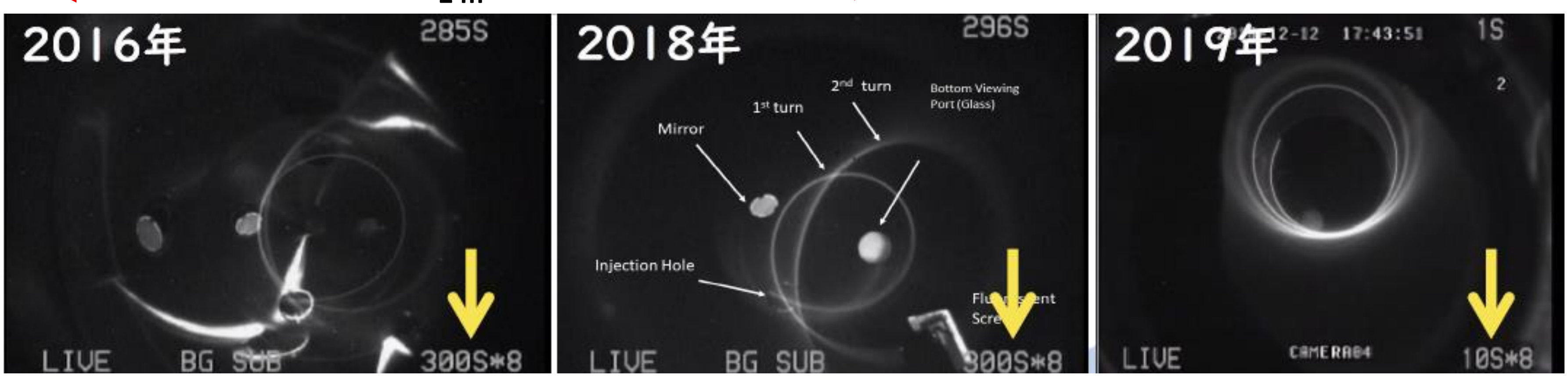
✓ Reflect studies on original experiment





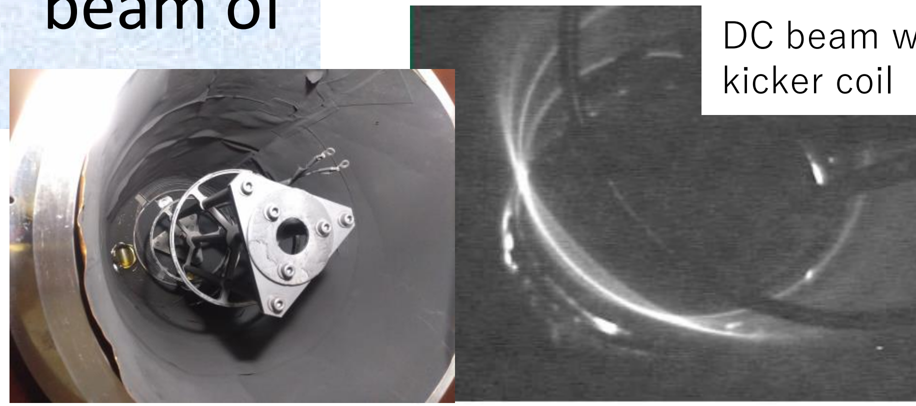
- Wakate B:2011～2013
- Kiban-B:2014～2018
- **Kiban- A 2019～2022**

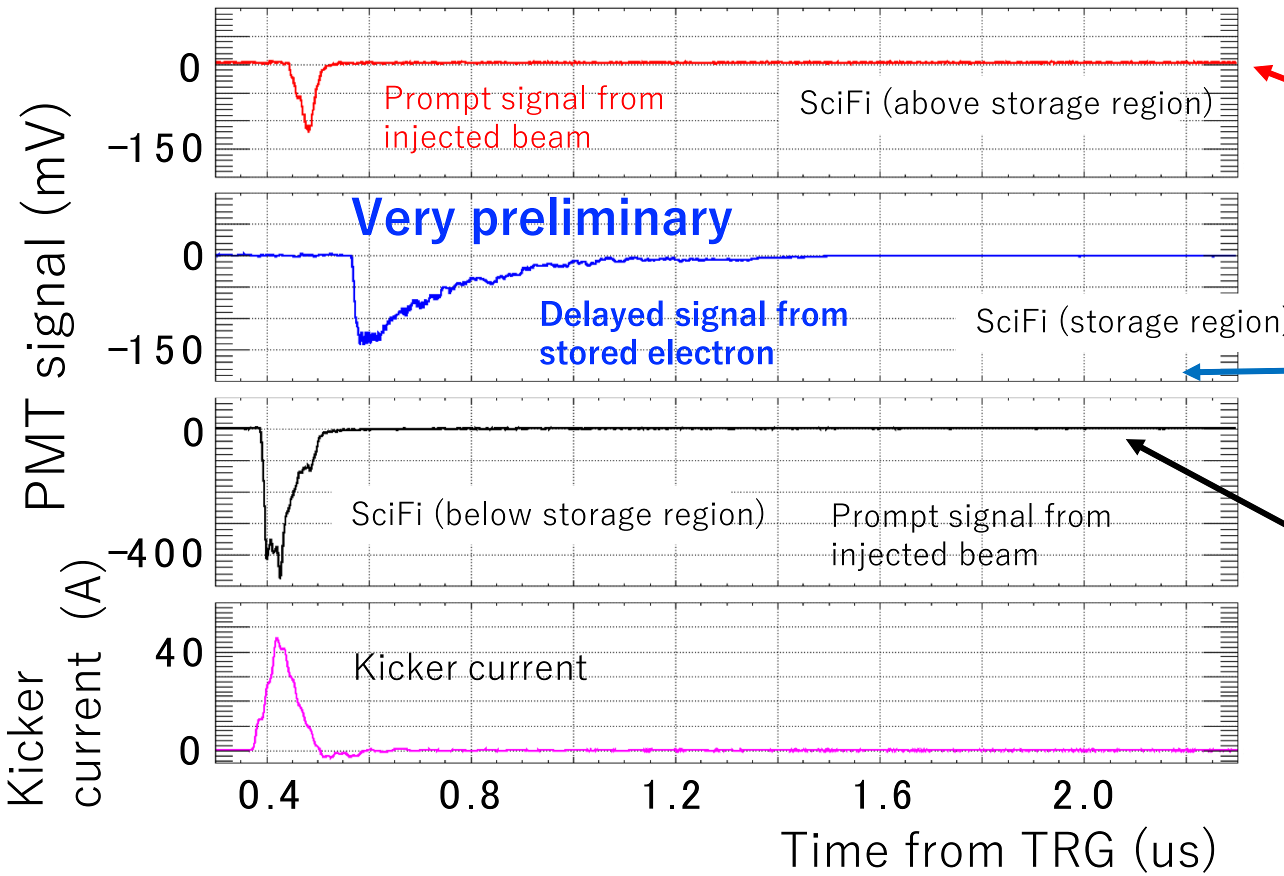
Top view of wide-angle camera

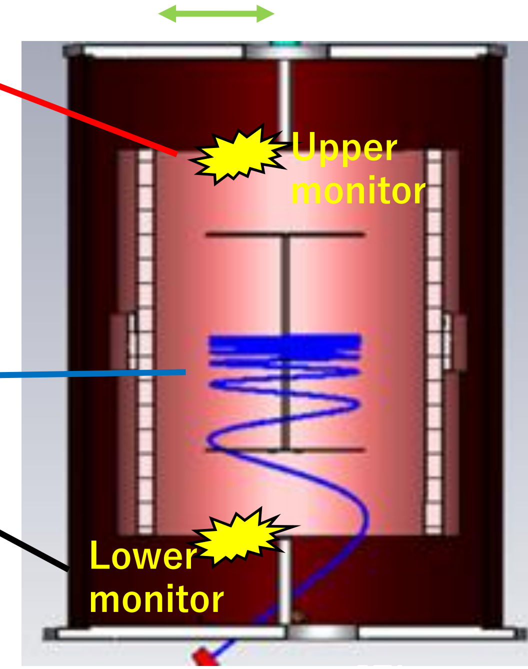


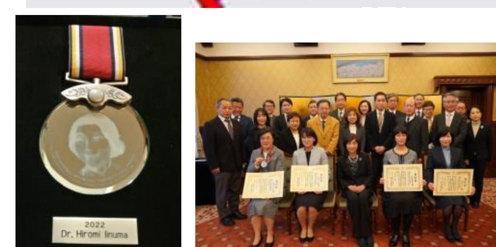
Preliminary result of "stored" beam of 3-D spiral injection

- Injected beam (100ns width) is kicked and then we detected "stored signal" for few μs









https://www.ocha.ac.jp/danjo/op/ytp/20230221_yuasa.html

https://www2.kek.jp/kokusai/AIL/TYL/index.html

Toshiko Yuasa Laboratory

Schedule and milestone (Mar. 2024)

JFY	2022	2023	2024	2025	2026	2027	2028 and beyond
KEK Budget							
Surface muon	✓ Beam at H1 area		Funding Secured!	★ Beam at H2 area			Commissioning, Data taking
Bldg. and facility		Final design ★				★ Completion	
Muon source	✓ Ionization test @S2			★ Ionization test at H2			
LINAC			★ 80keV acceleration@S2	★ 4.3 MeV@ H2	★ fabrication complete	★ 210 MeV	
Injection and storage			★ Completion of electron injection test			★ muon injection	
Storage magnet				★ B-field probe ready	★ Install	★ Shimming done	
Detector		✓ Quoter vane prototype	★ Mass production ready			★ Installation	
DAQ and computing		✓ grid service open ★ common computing resource usage start	★ small DAQ system operation test	★ Ready			
Analysis			★ Tracking software ready	★ Analysis software ready			

More detailed schedule at https://docs.google.com/spreadsheets/d/102lSO5MvxWnEjrqH4sJGOLmSlQUiPj9p/edit#gid=1381089061

Merci

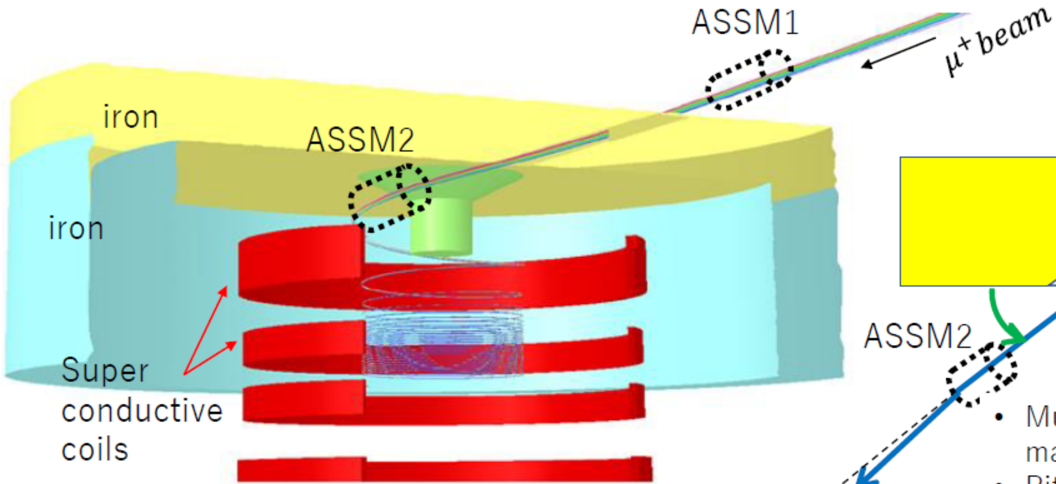
ご清聴ありがとうございました。

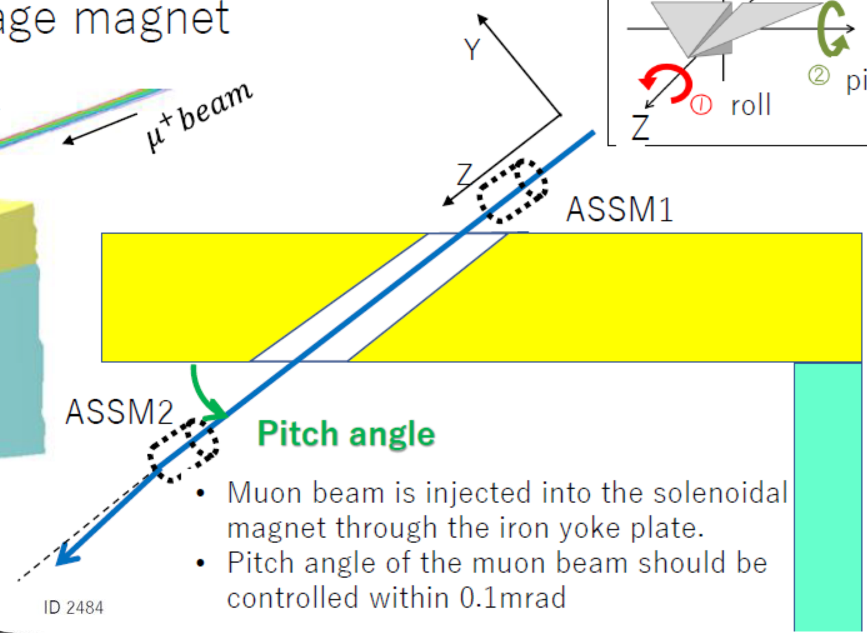
Thank you very much!

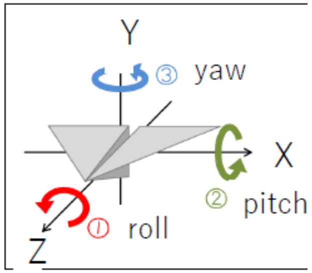
Backups

Precise Control of Three-Dimensional Beam Trajectory by an Active Shield Steering Magnet in the Solenoid Fringe Field

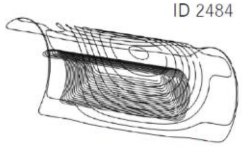
Purpose of ASSM:
Need to a tuning nob to control ±1mrad pitch angle at outside and inside of the 3-T storage magnet



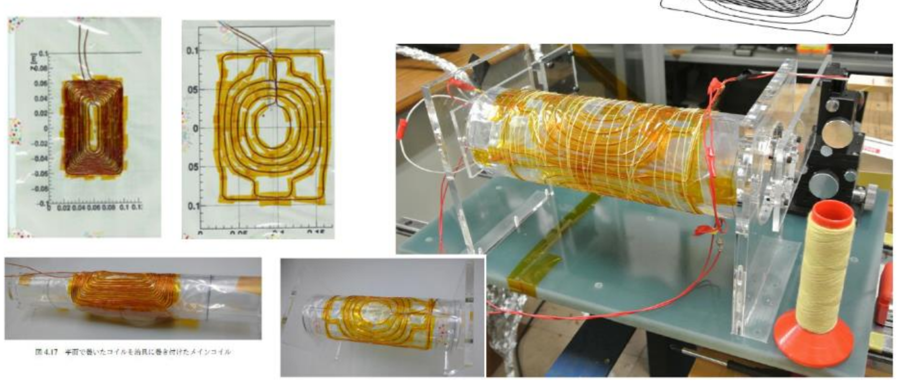


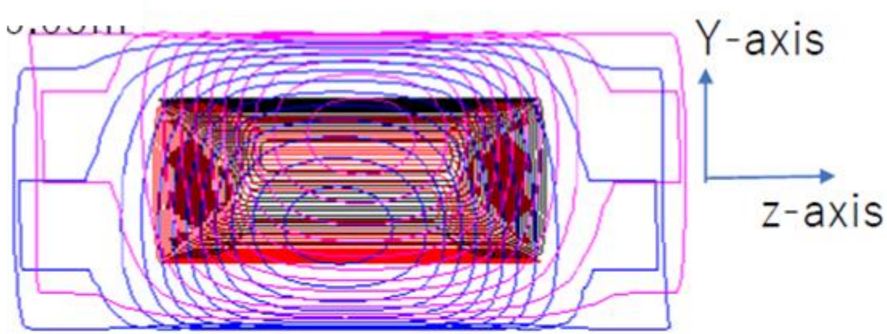


- Muon beam is injected into the solenoidal magnet through the iron yoke plate.
- Pitch angle of the muon beam should be controlled within 0.1mrad



Handmade proto-type magnet



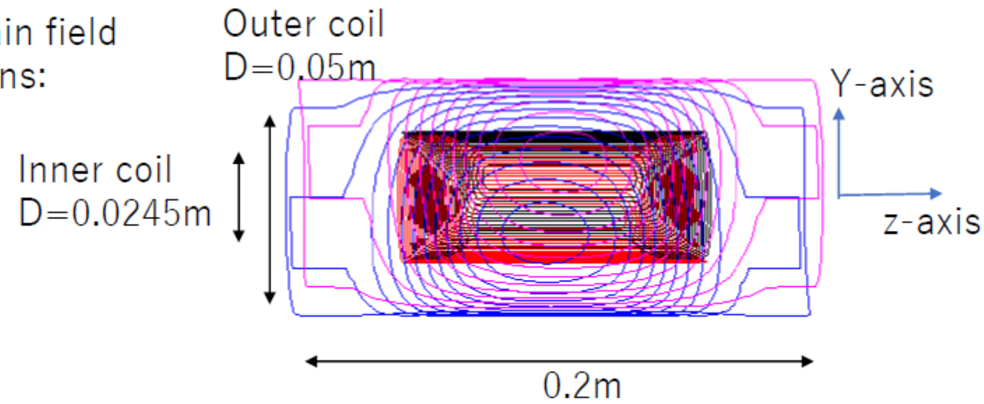


Specification of ASSM2

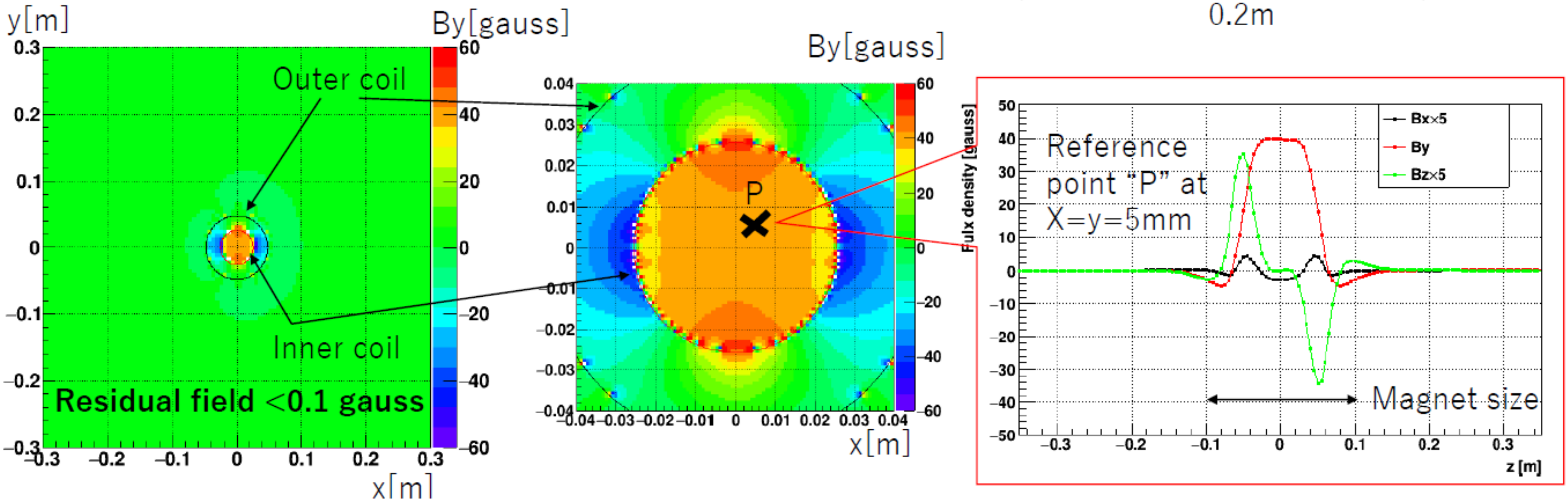
Because we install ASSM in the storage magnet: main field 3T and 0.1 ppm uniformity, we set three specifications:

- No iron yoke, coil current only
- Uniform dipole (By) field R<0.01m
- No residual field at R>0.2m, |z|>0.2m

→double layers coil magnet design is done.

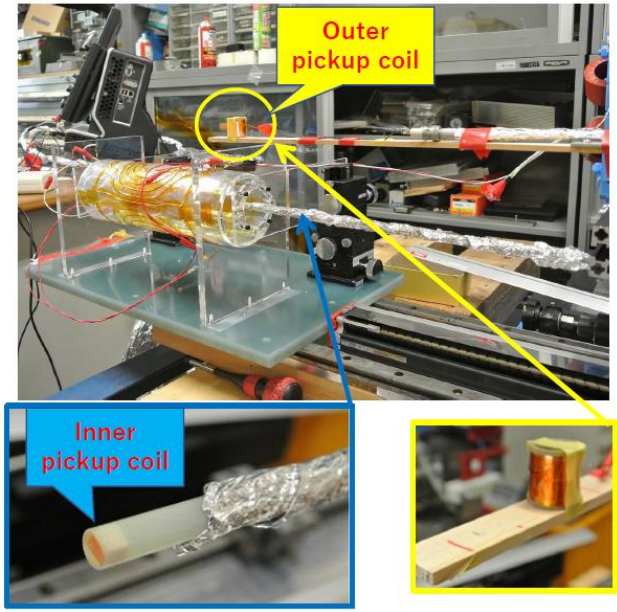


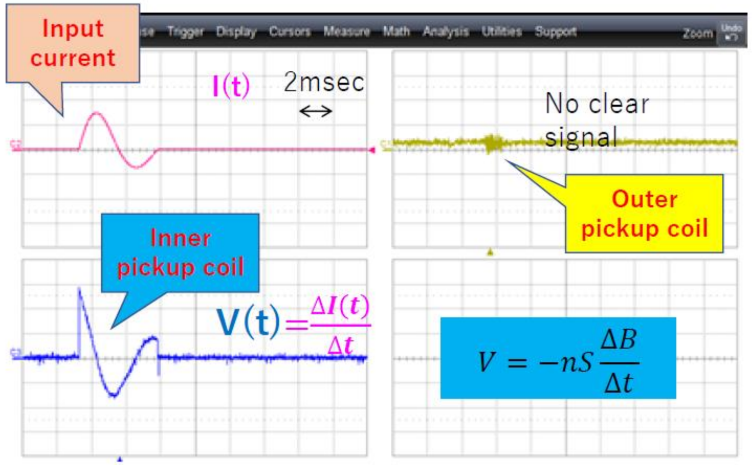
X-Y cross section views



M. Abe *et al*., "Design Method of Active Shield Steering Magnet for Fine Tuning of Muon Injection Orbit Into g-2/EDM Precision Measurements Magnet," in *IEEE Transactions on Applied Superconductivity*, vol. 32, no. 6, pp. 1-5, Sept. 2022, Art no. 4007505, doi: 10.1109/TASC.2022.3190247.

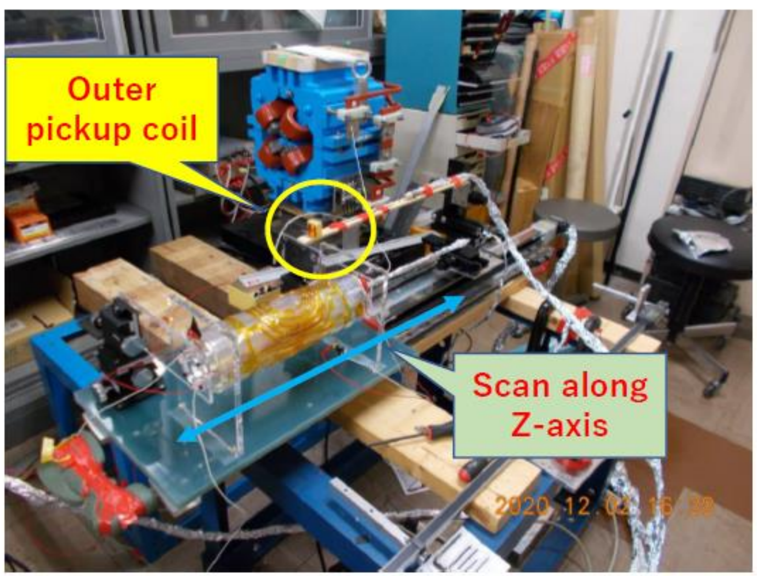
Pickup coil signals of inside and outside of the magnet

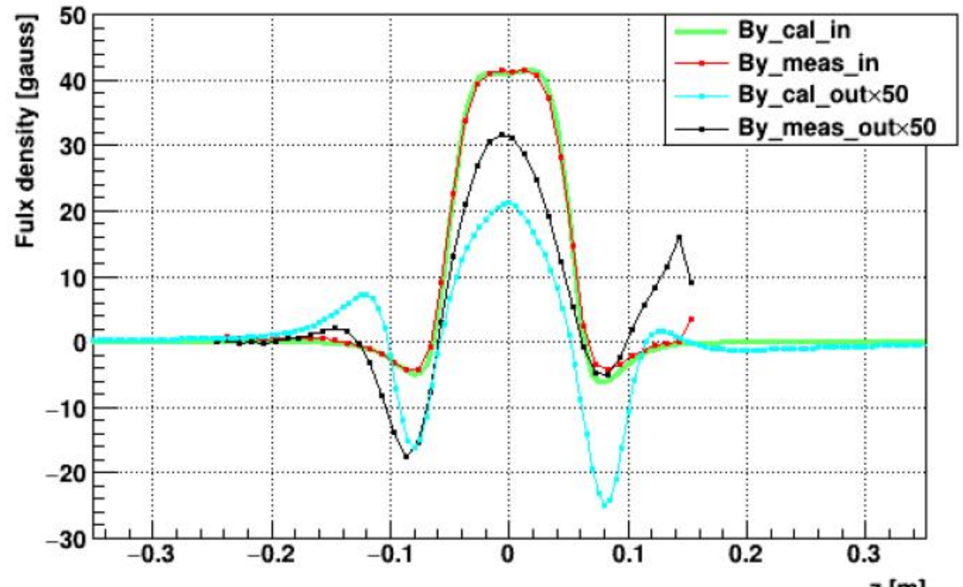




Proto-type Active Shield Steering Magnet is now at KEK-Tsukuba for field measurement.

- At the first-look, we confirm dipole inner volume and quite small residual field !

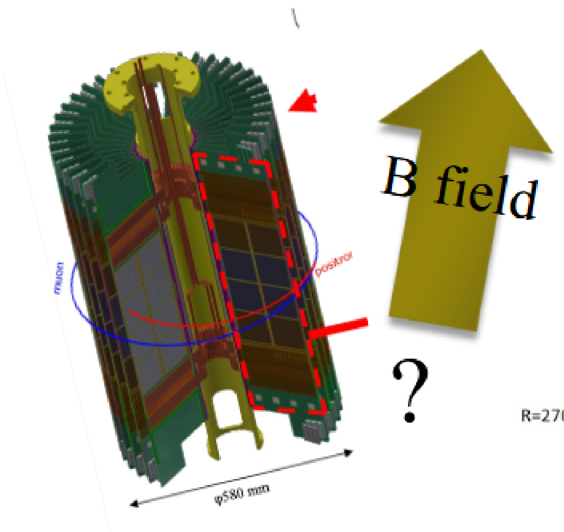




Many interesting challenges

Study of alignment method between detector and main magnetic field

- Detector and Magnetic field (Main coil, Weak focus field, Iron pieces for shimming) are mechanically aligned INDIVIDUALLY.



- Relative position between detector and magnetic field ??
  - ✓ Checking of alignment will help to understand the data taken by the detector

- Just started to study Detector-Magnetic field Alignment oil (DMA coil)