ID #25

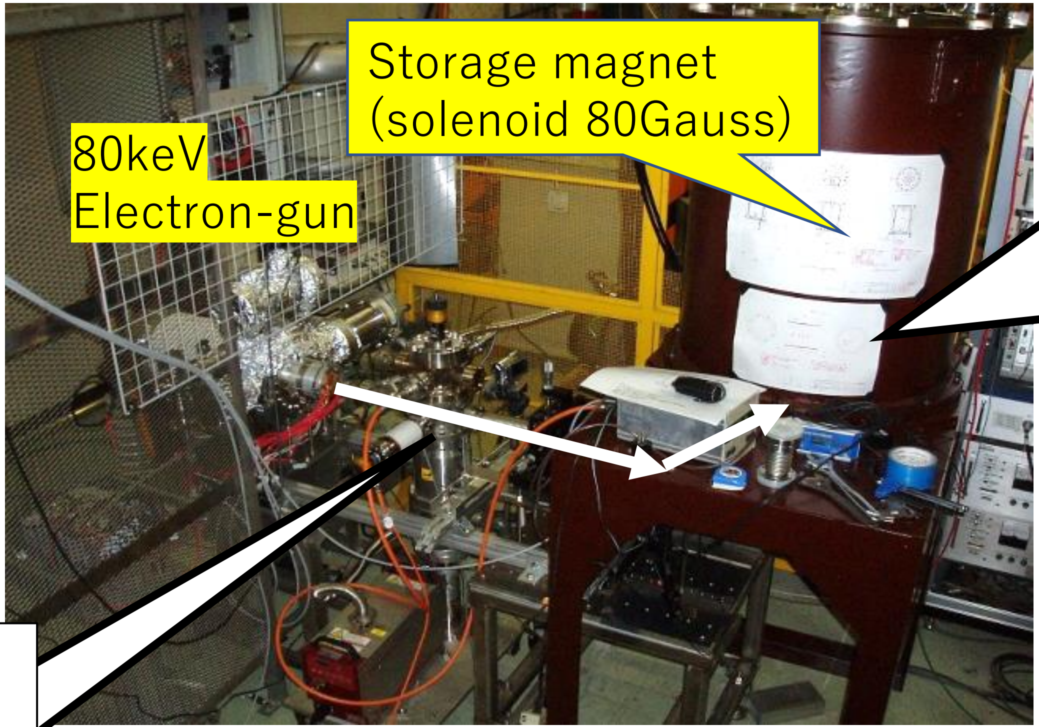
Development for 3-D spiral injection scheme by use of electron gun

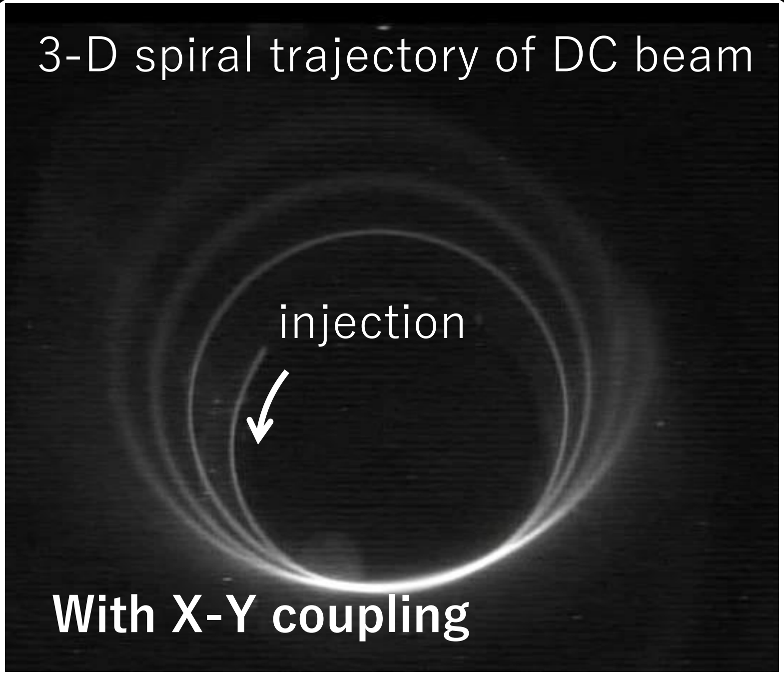
茨城大学
Ibaraki University

H. Iinuma

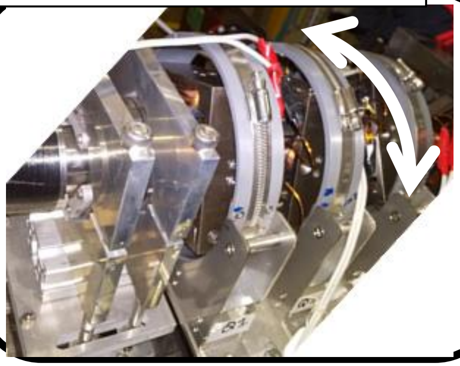
On behalf of ***SITE***

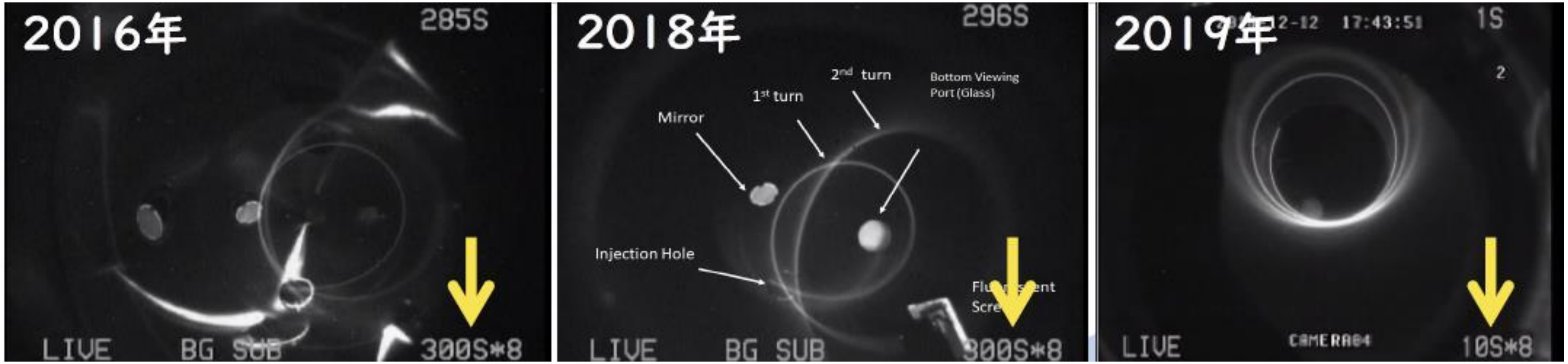
Spiral **I**njection **T**est **E**xperiment





Rotating Quads for X-Y coupling

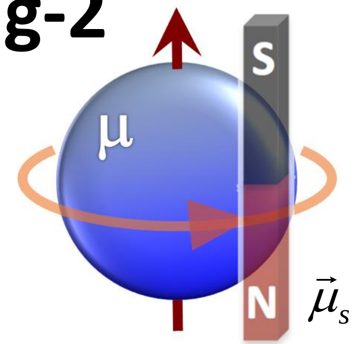




Why 3-D spiral injection?

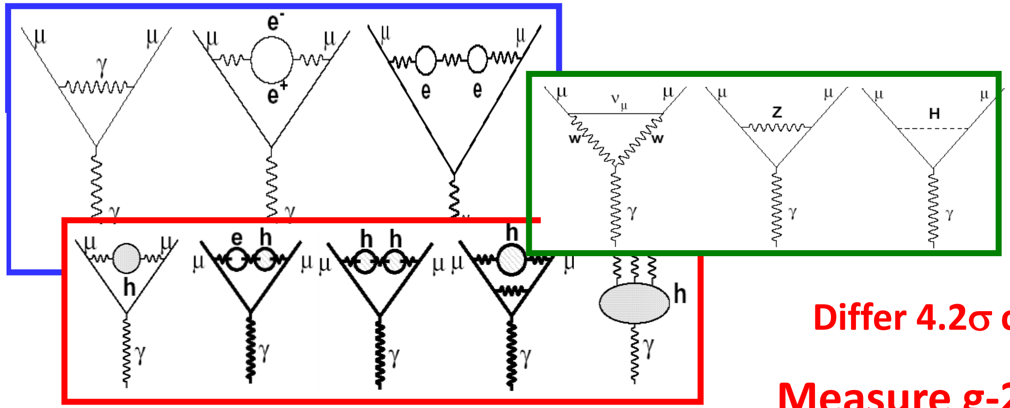
To accomplish Very precise measurement of muon g−2 and EDM

g-2



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

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



+?

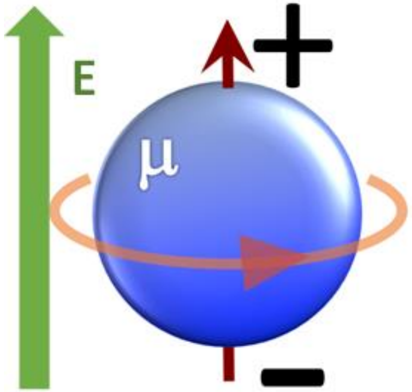
Differ 4.2σ compared with the SM standard model

Measure g-2: 0.35ppm accuracy

E989@FNAL, Phys. Rev. Lett. 126, 141801(2021)
E821@BNL, Phys. Rev. D73 072003, 2006

EDM

A direct evidence of 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

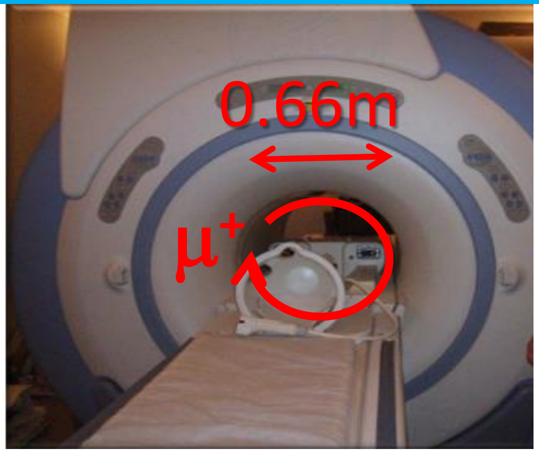
We aim sensitivity of $\sigma(d_\mu) < 1 \times 10^{-21} ecm$

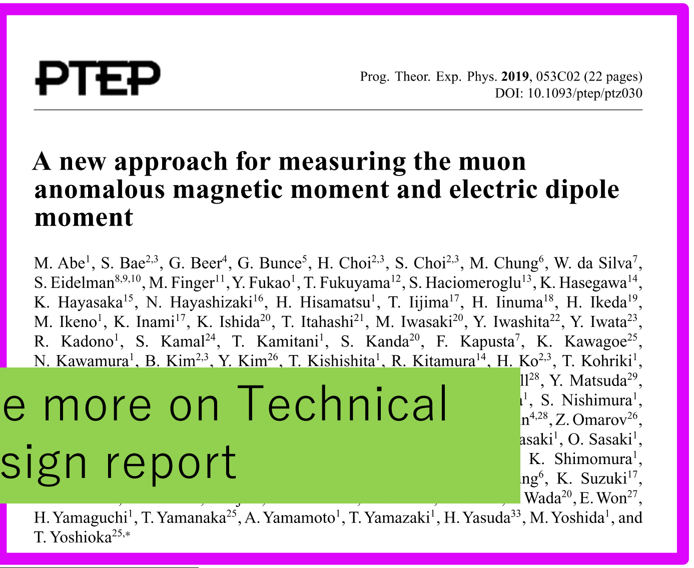
New experiment at J-PARC from 2026~(?)

1/20 smaller muon storage ring than BNL-E821/FNAL-E989

BNL E821/FNAL E989

J-PARC E34 ring size image



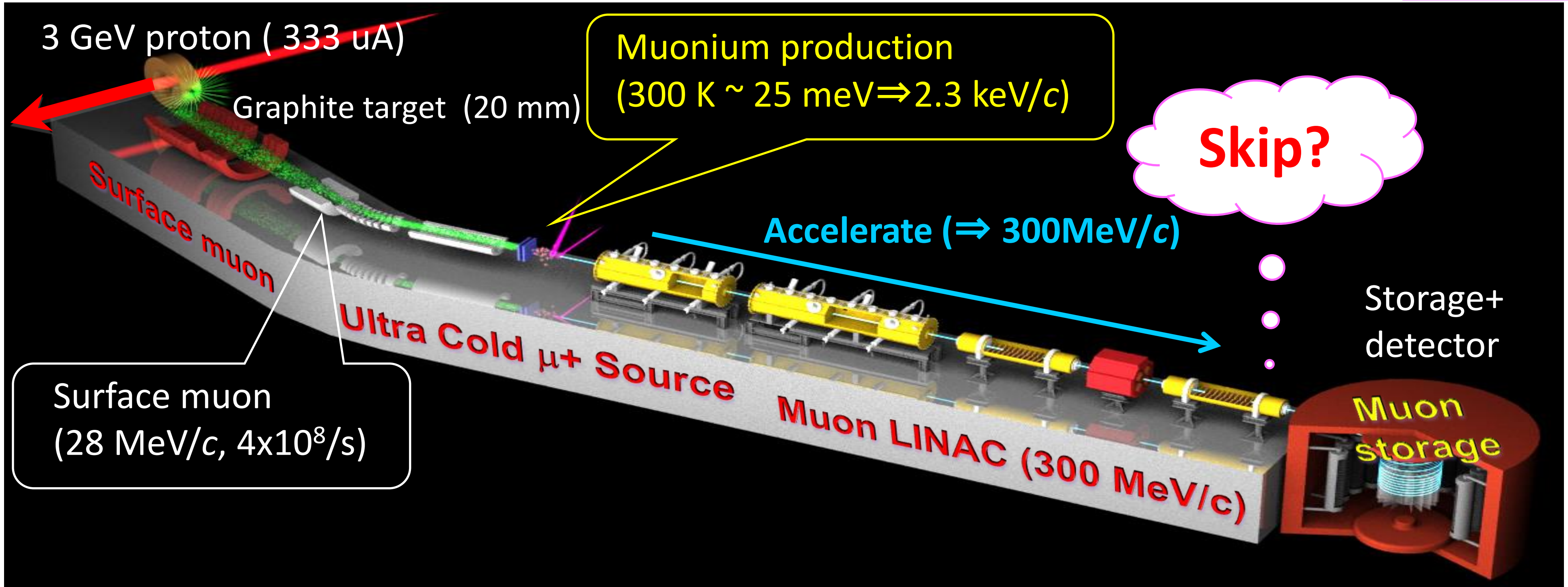

PTEP

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. Haciomeroglu[13], K. Hasegawa[14], K. Hayasaka[15], N. Hayashizaki[16], H. Hisamatsu[1], T. Iijima[17], H. Iinuma[18], H. Ikeda[19], M. Ikeno[1], K. Inami[17], K. Ishida[20], T. Itahashi[21], M. Iwasaki[20], Y. Iwashita[22], 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], ... ll[28], Y. Matsuda[29], ... [1], S. Nishimura[1], ... n[4,28], Z. Omarov[26], ... asaki[1], O. Sasaki[1], ... K. Shimomura[1], ... ng[6], K. Suzuki[17], ... 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,*]

See more on Technical design report

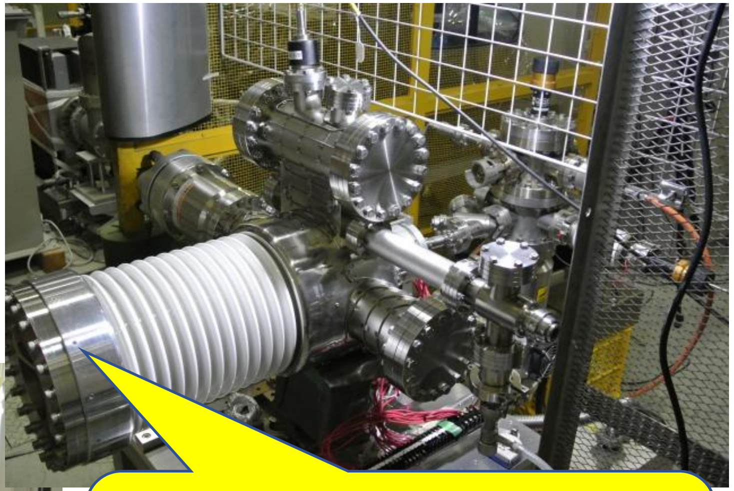


How do you inject 300MeV/c muon beam into 3T storage magnet with 0.66m diameter orbit?

SITE started from 2014!
Spiral **I**njection **T**est **E**xperiment

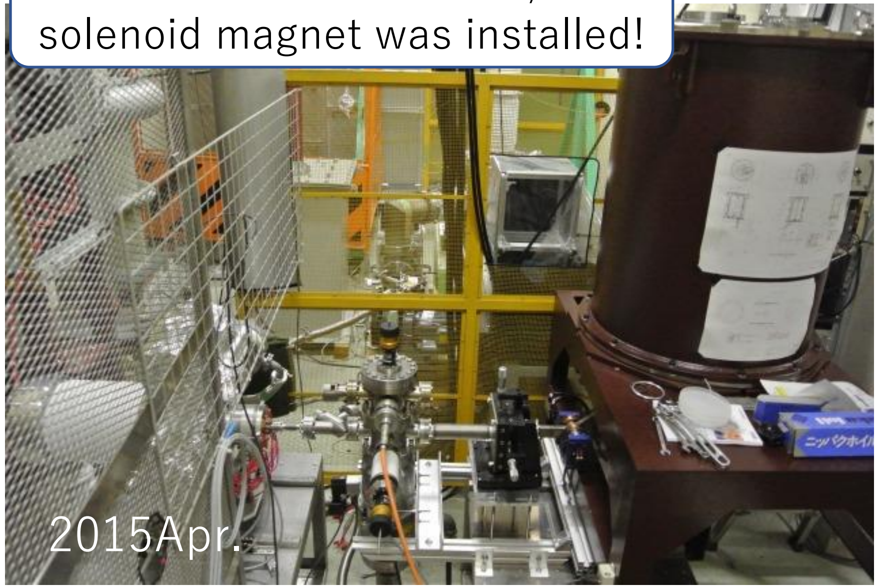
Brief history of SITE#1 (construction:2014 – 2015)

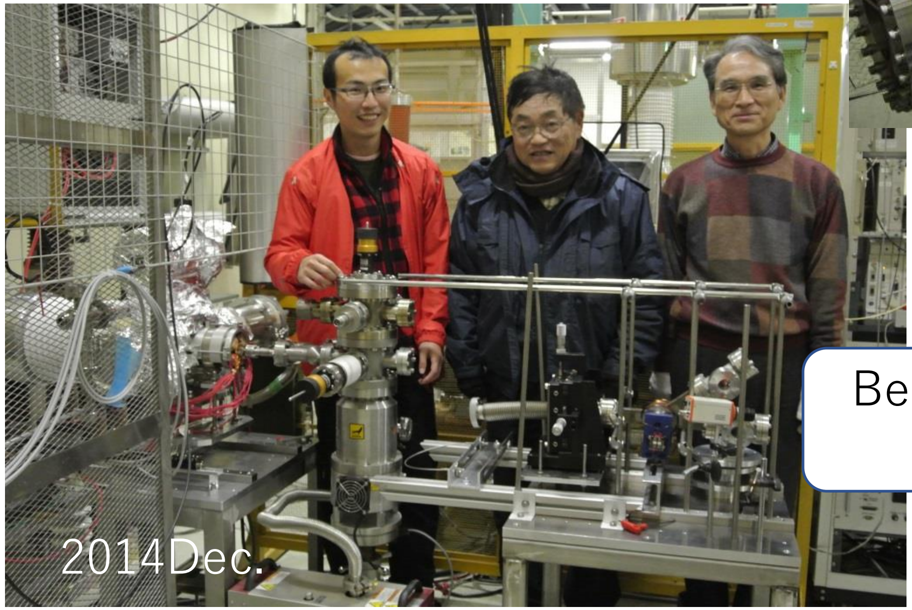
E-gun HV commissioning is done.
Stable operation at 115kV for several hours!



Negative High V
-100kV-2kV
Beam pipe is GND.

After field measurement, mini solenoid magnet was installed!

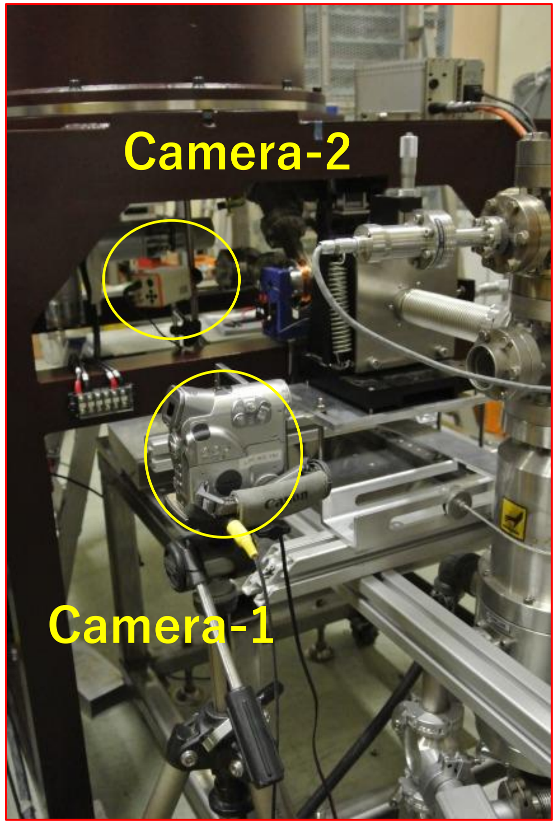


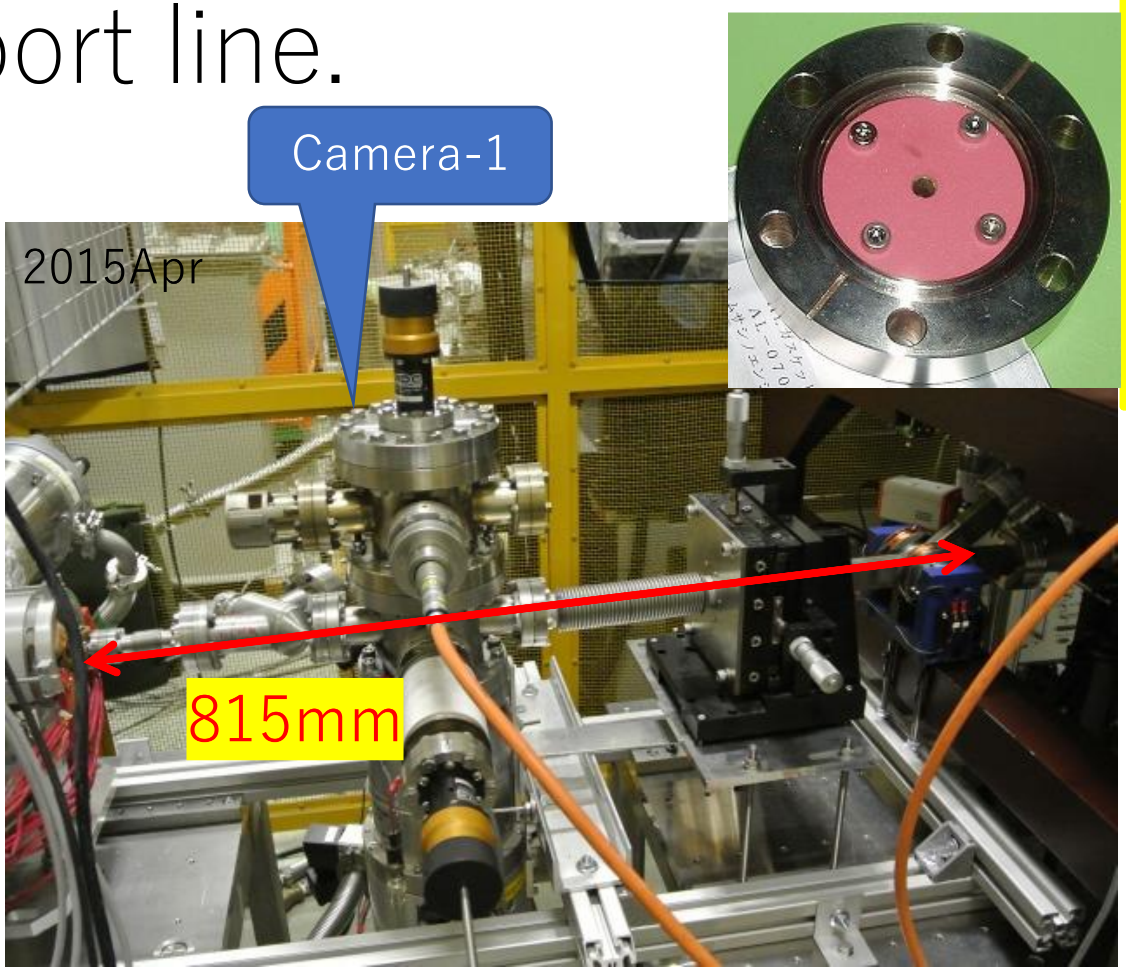


Beam line components are installed

Supported by Grant-in-aid
KIBAN-B 26287055 2014-2018
KIBAN-A 19H00673 2019-2022

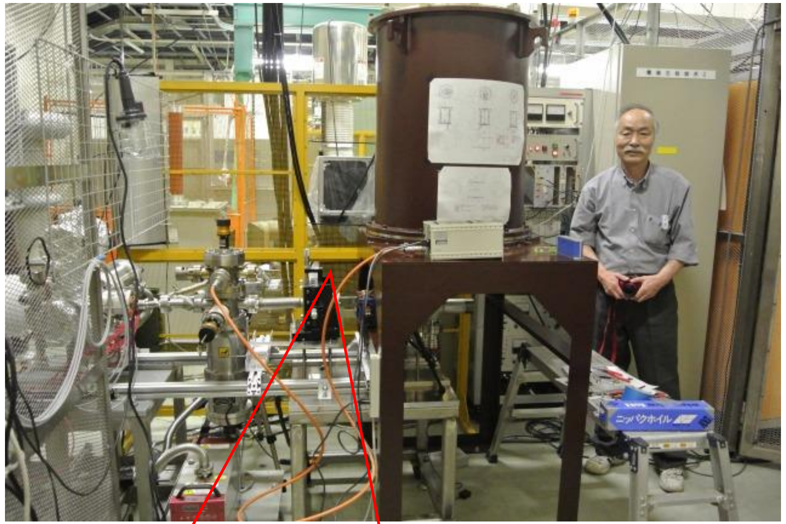
Less than 1m length, but 80keV electron beam transport is so tough. We put fluorescent plates along the beam transport line.

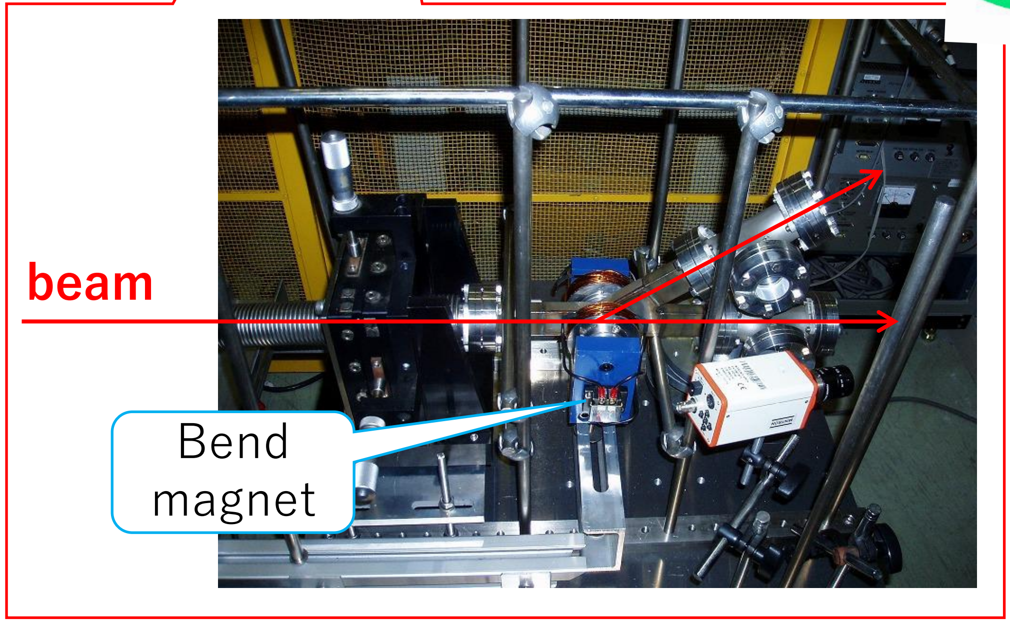


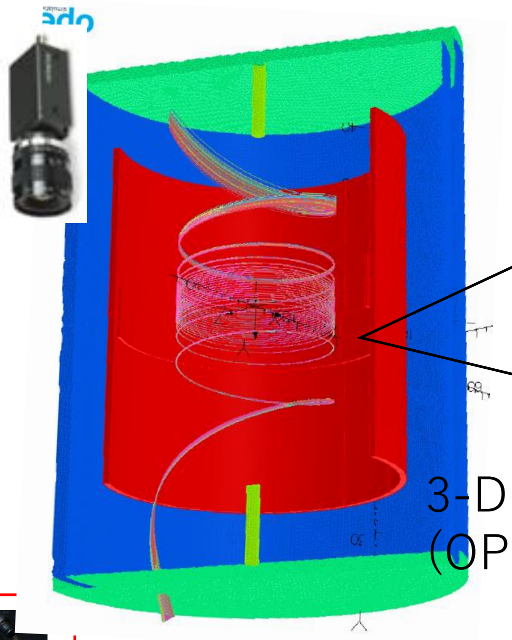


Brief history of SITE#2 (Beam injection:2016 –2019)

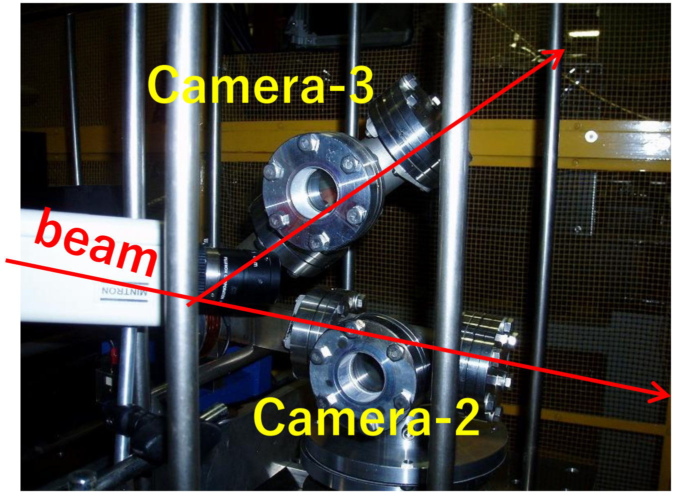
ID #25

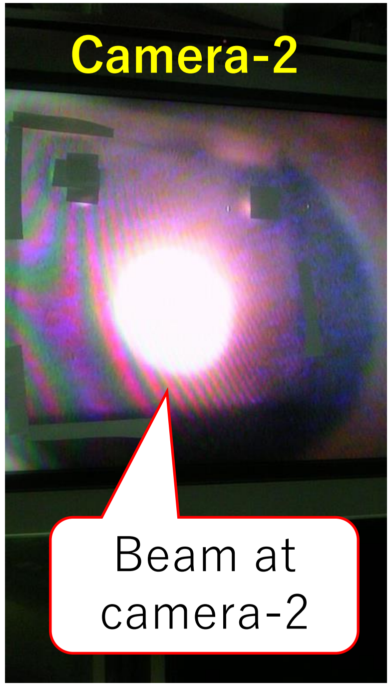


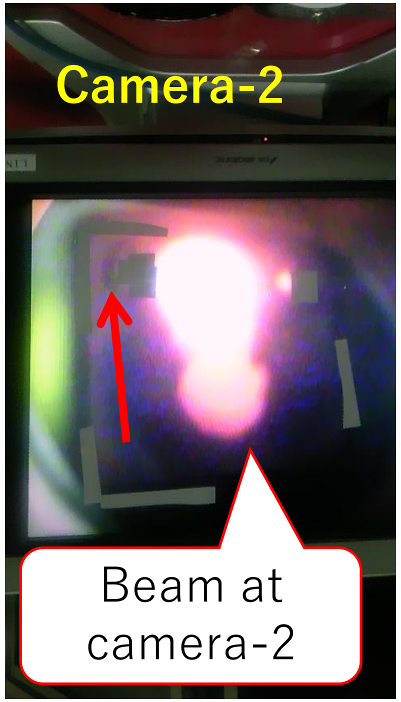




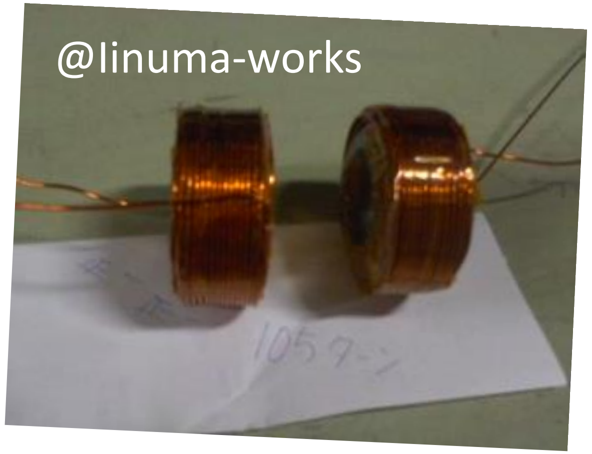
3-D trajectory
(OPERA-3D)

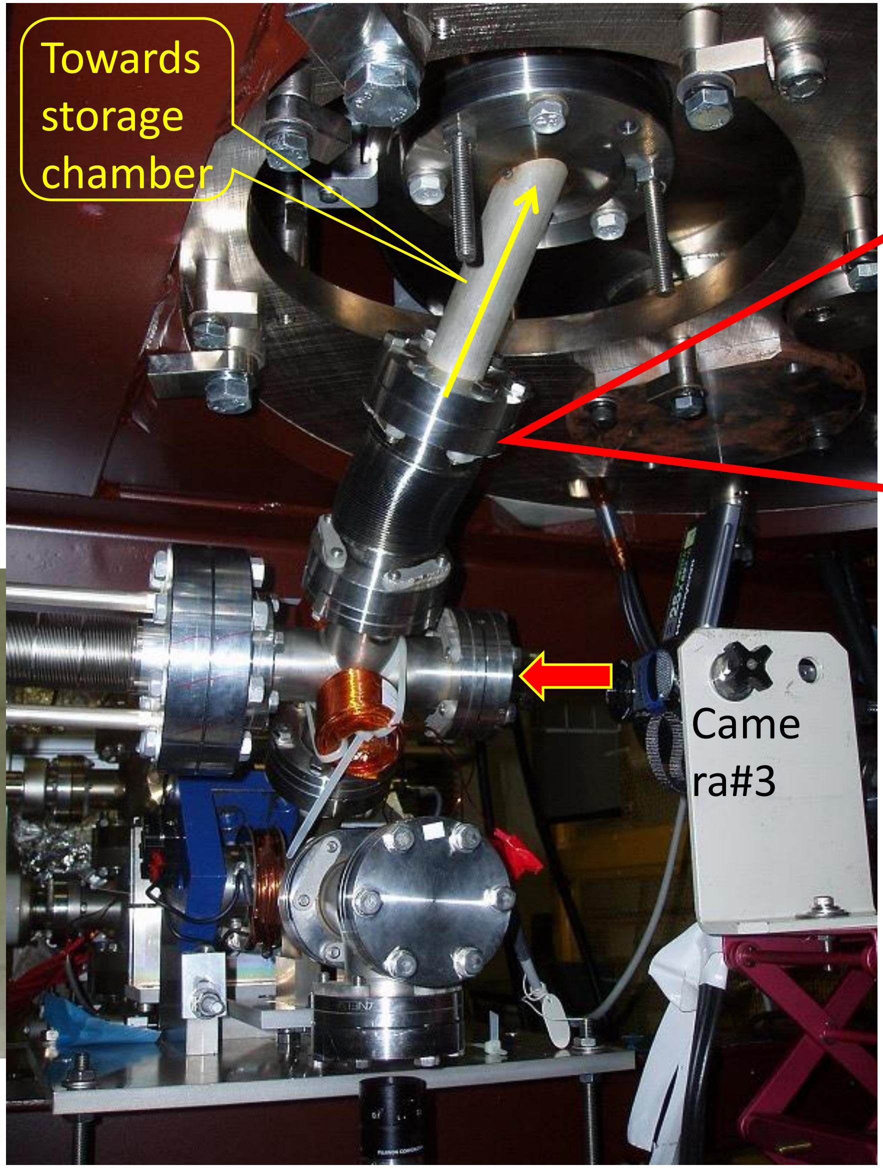


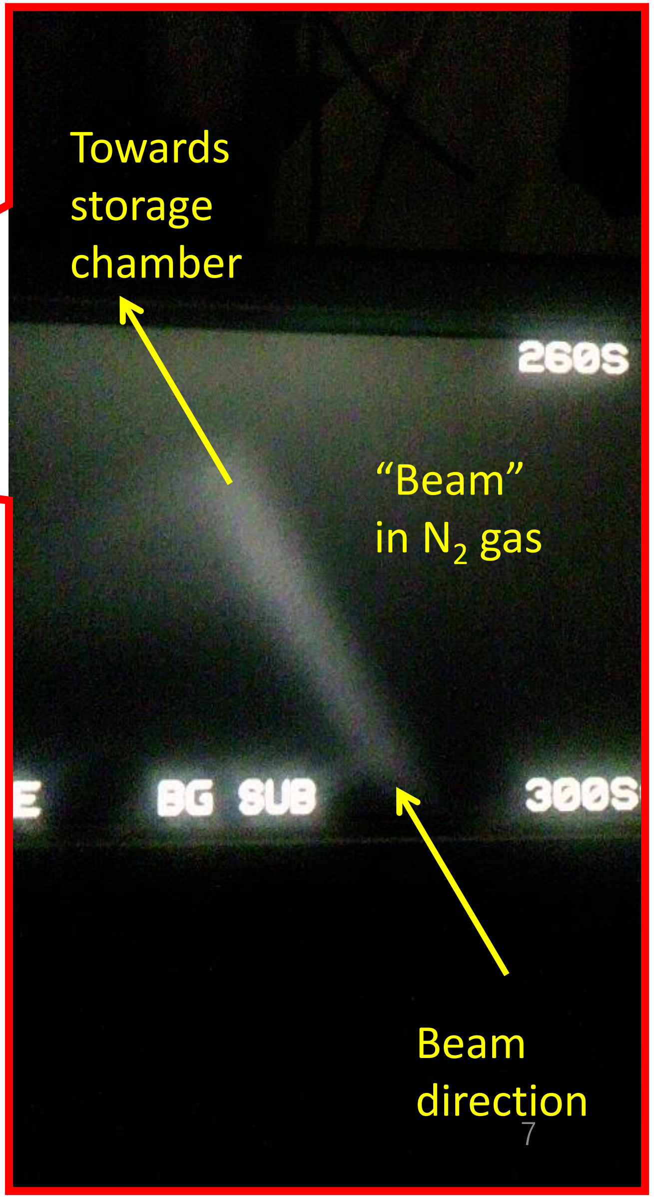




Less than 1m length, but 80keV electron beam transport is so tough.
We put steering coil magnets along the beam transport line.



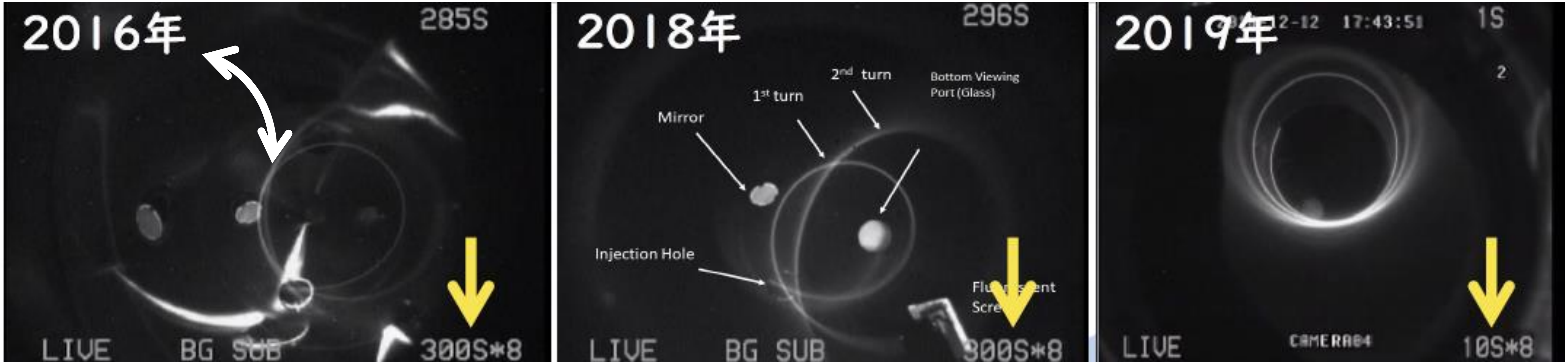




Struggled for three years to get 3-D trajectory within reasonable waiting time

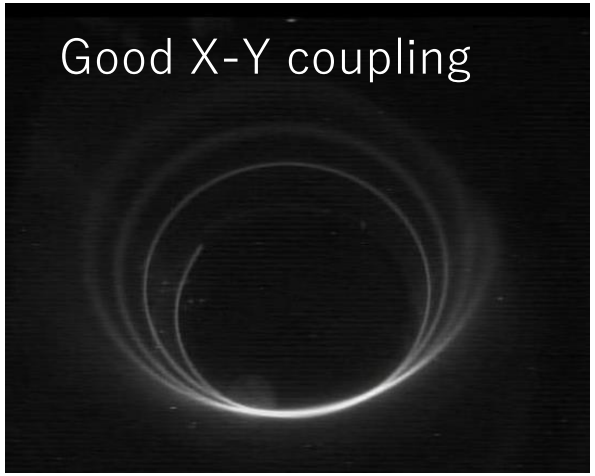
- ◆ We have two cameras above and below storage chamber to see injected beam.
- ◆ Nitrogen gas allow us to visualize DC electron beam, but it took three years to get a well fulfilled view.

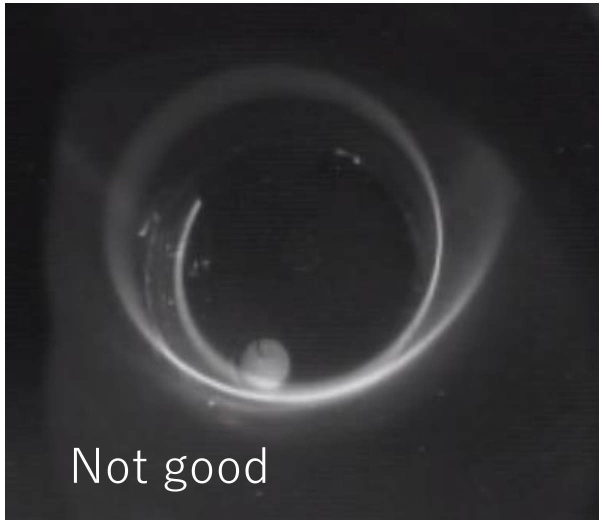
- ◆ We also insert wire-scan monitor to get more quantitative information.

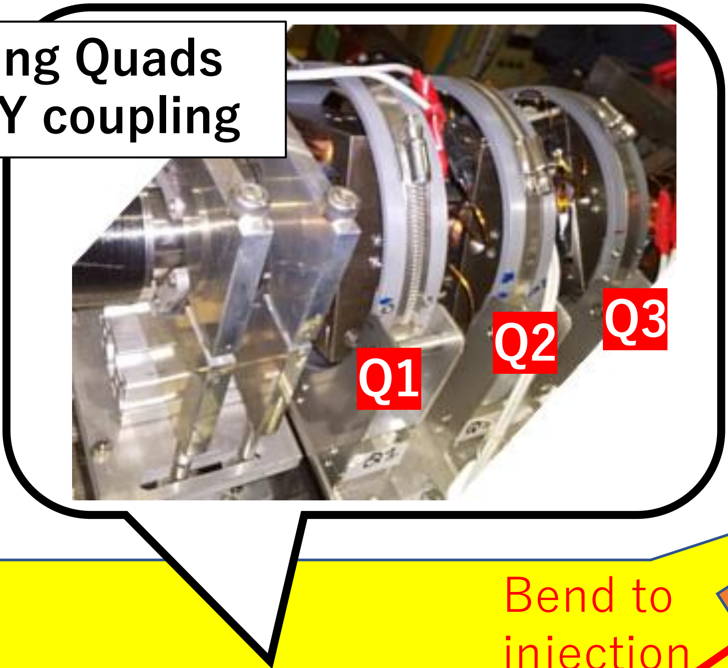


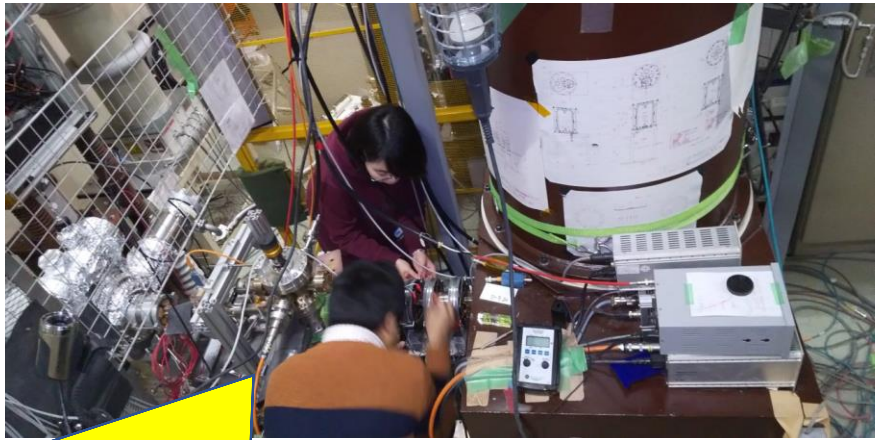
Brief history of SITE#3
(Beam control in the storage chamber:2020 –2021)

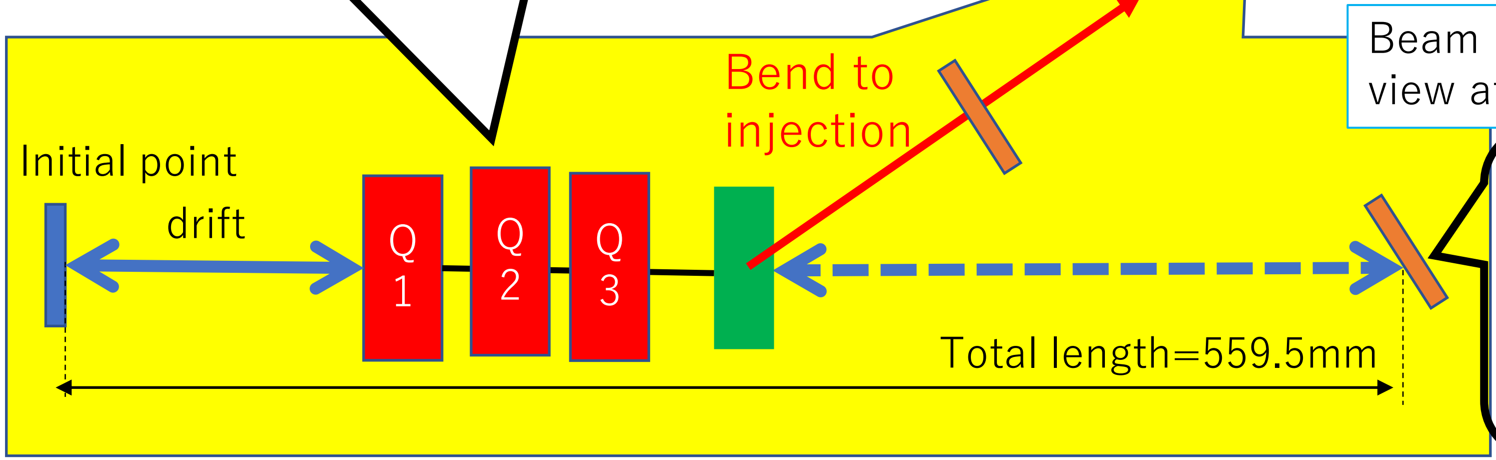
X-Y coupling control by use of **three rotating quadrupoles** is the key for *3-D spiral injection*



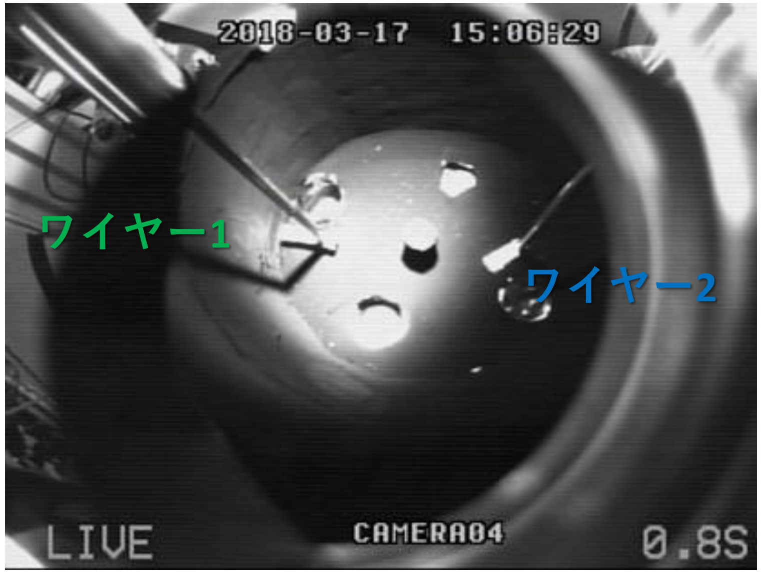


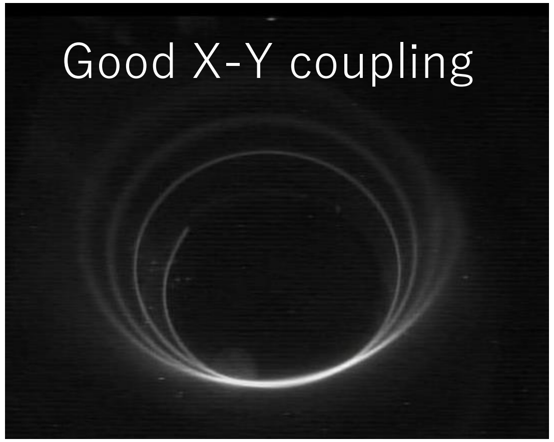


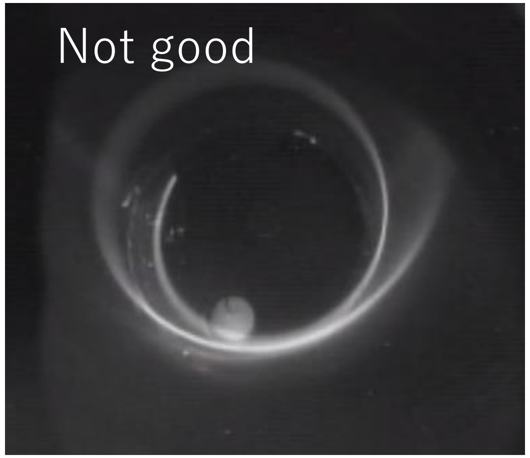


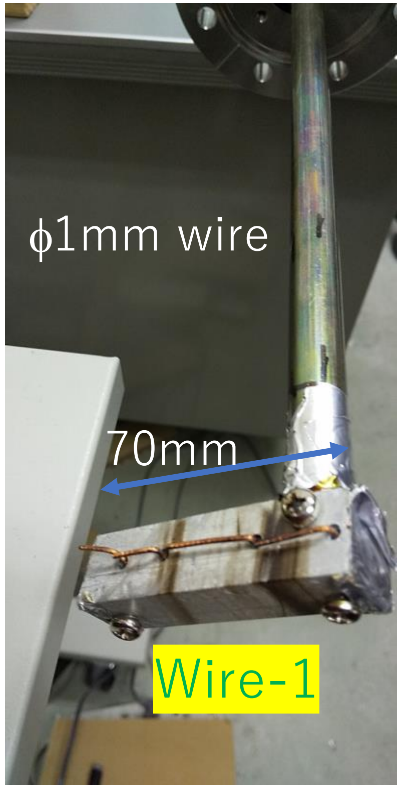


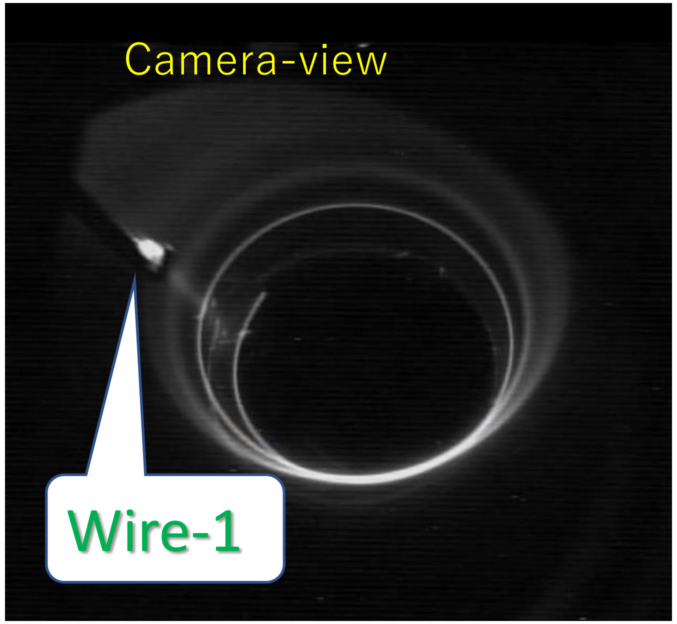
Measure vertical beam size in the storage chamber by use of wire monitor and compare with visualized trajectory

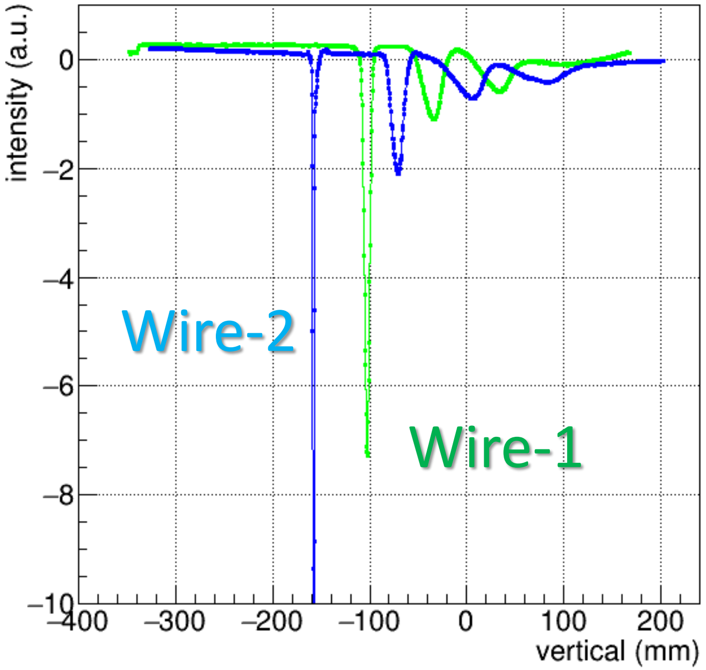


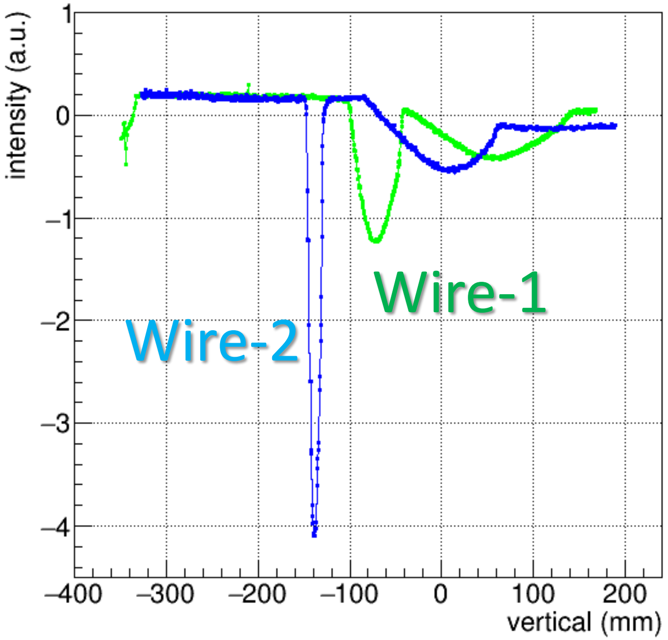






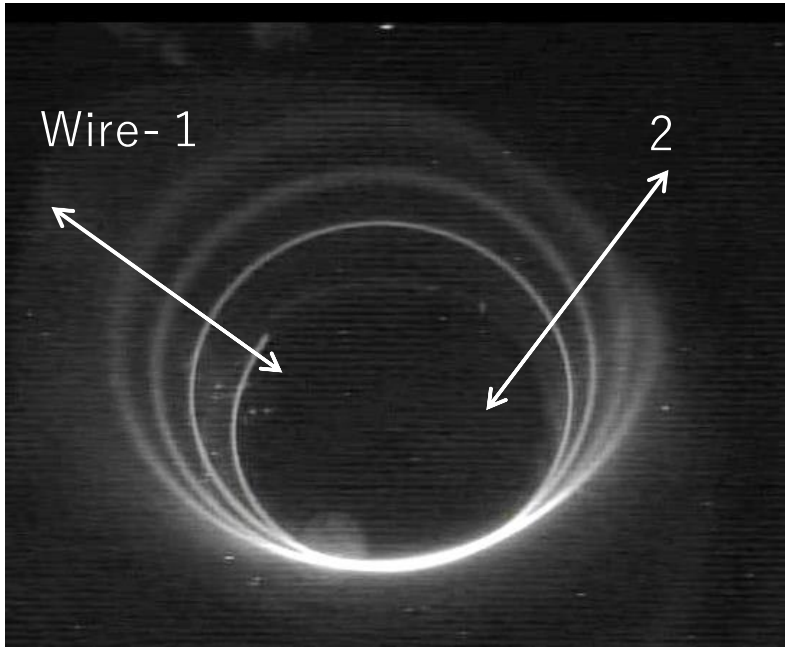


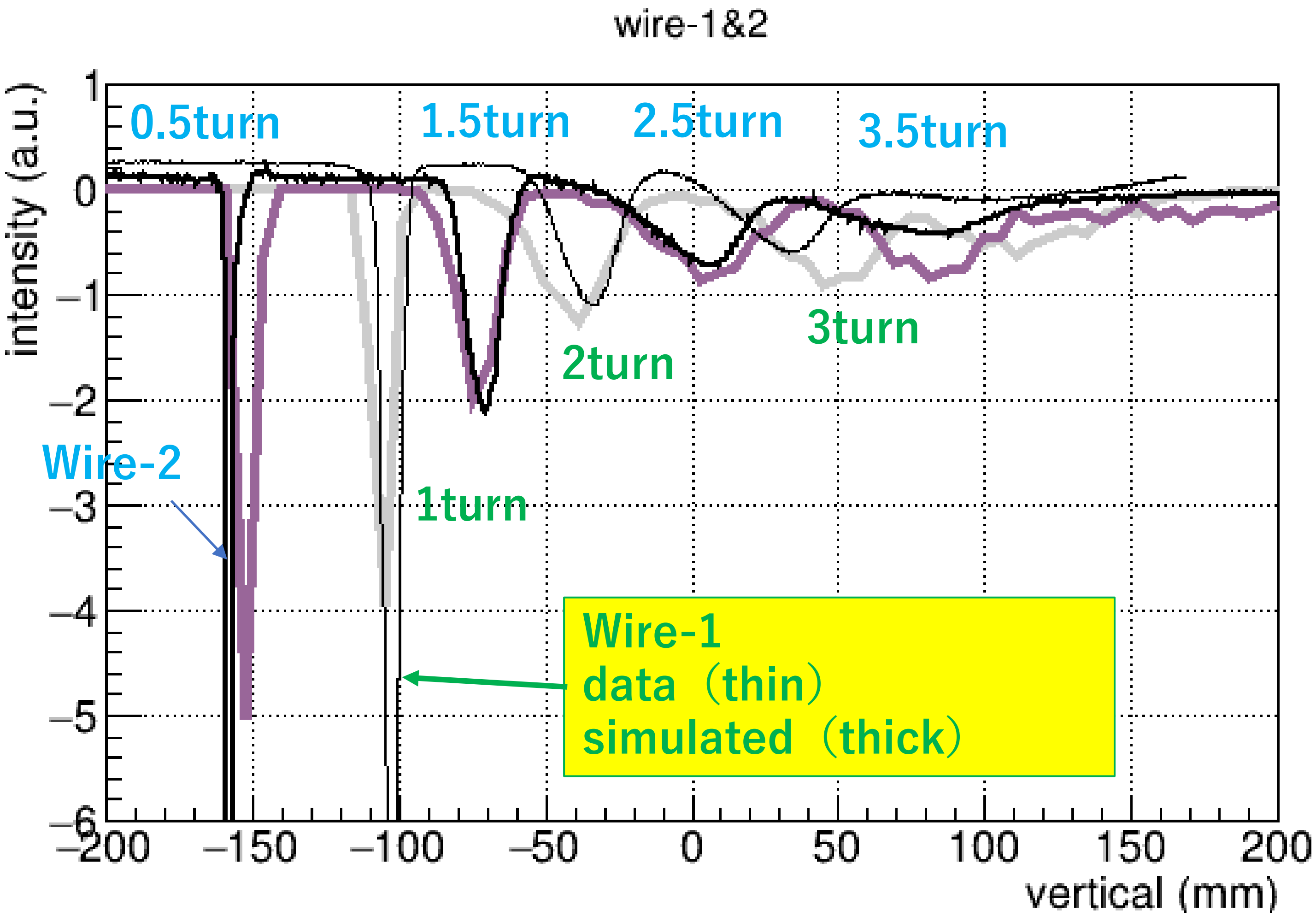




Measure vertical beam size in the storage chamber by use of wire monitor and compare with visualized trajectory,

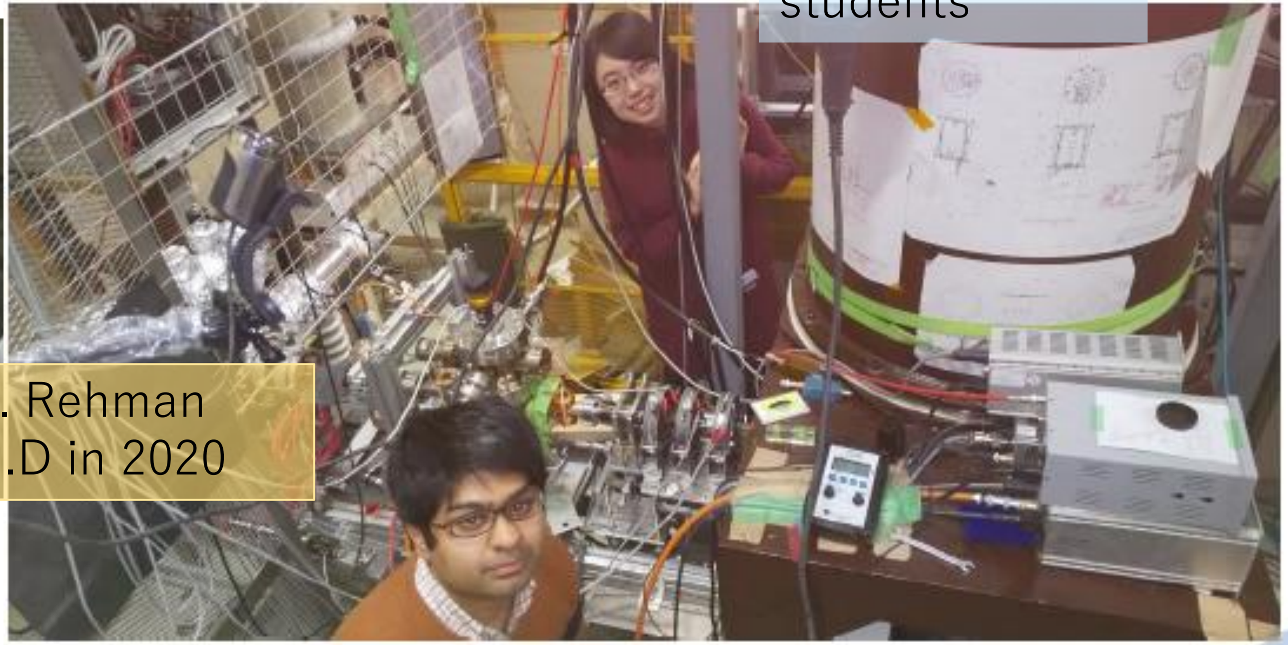
And, also compared with simulation results



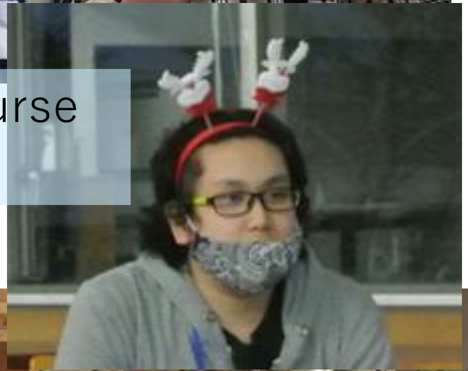


SITE core members

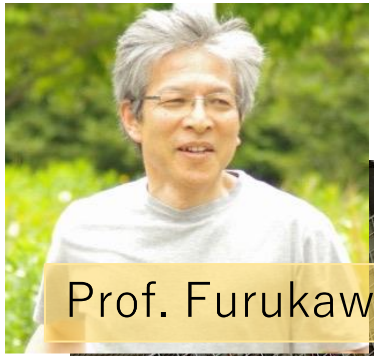
Dr. Rehman
Ph.D in 2020



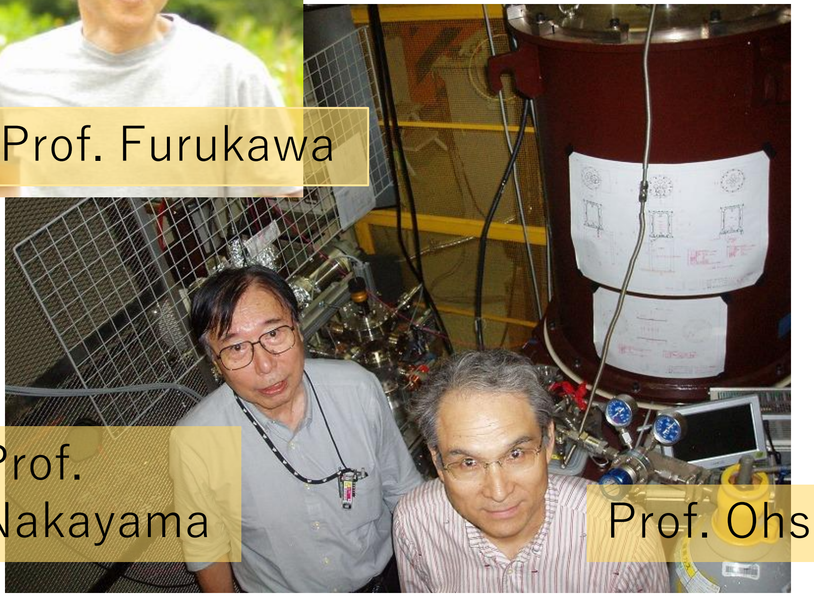
Master course students



Master course students

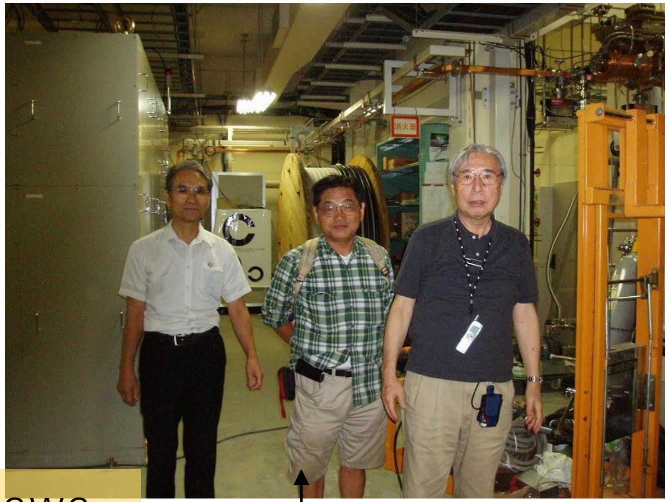


Prof. Furukawa

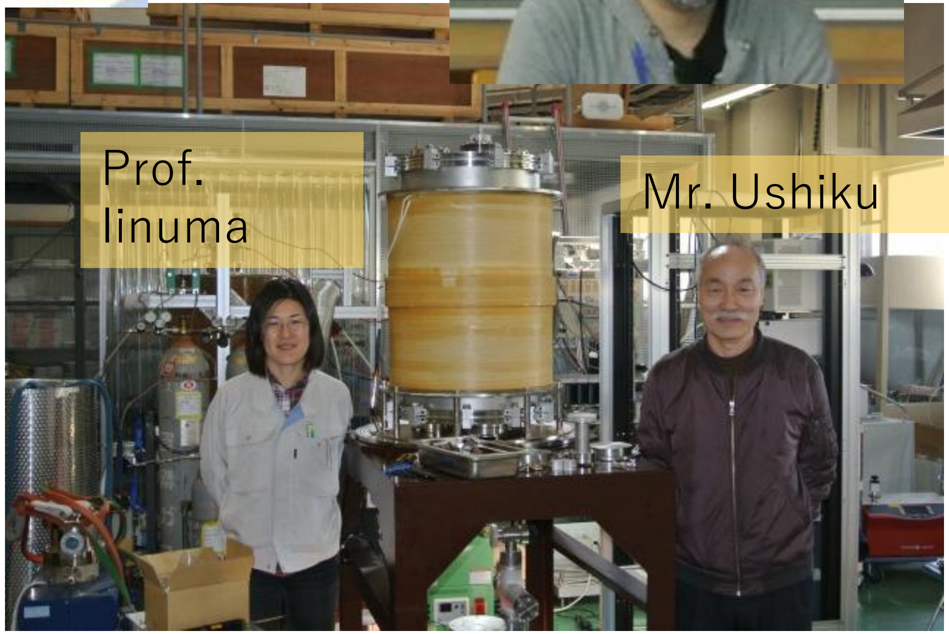


Prof. Nakayama

Prof. Ohsawa



Mr. Hisamatsu



Prof. Iinuma

Mr. Ushiku

Detailed beam study at straight line

- Q-scan to measure emittance and Twiss parameters
- Sigma matrix measurement by use of three quadrupoles and X-Y cross-section views

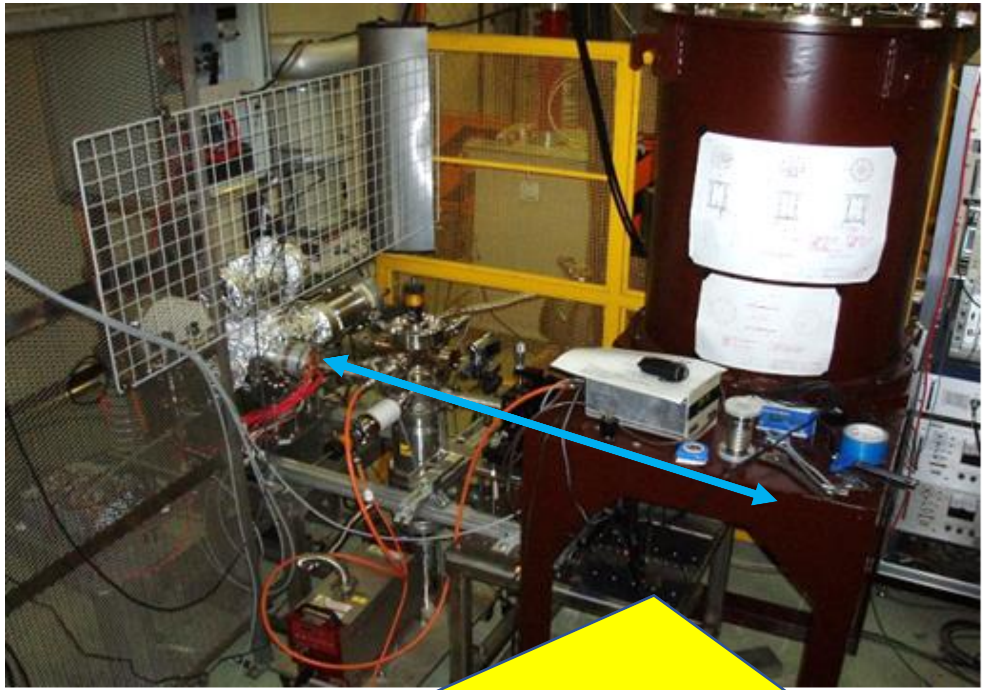
For details about SITE, please find Dr. Rehman's thesis at the link below:
http://id.nii.ac.jp/1013/00006023/

To contact with Hiromi Iinuma: hiromi.Iinuma.spin@vc.ibaraki.ac.jp
http://muonspin.sci.ibaraki.ac.jp/

Brief history of SITE#4 (Beam study at Straight line 2020~)

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

E-gun testbench for 3-D spiral injection



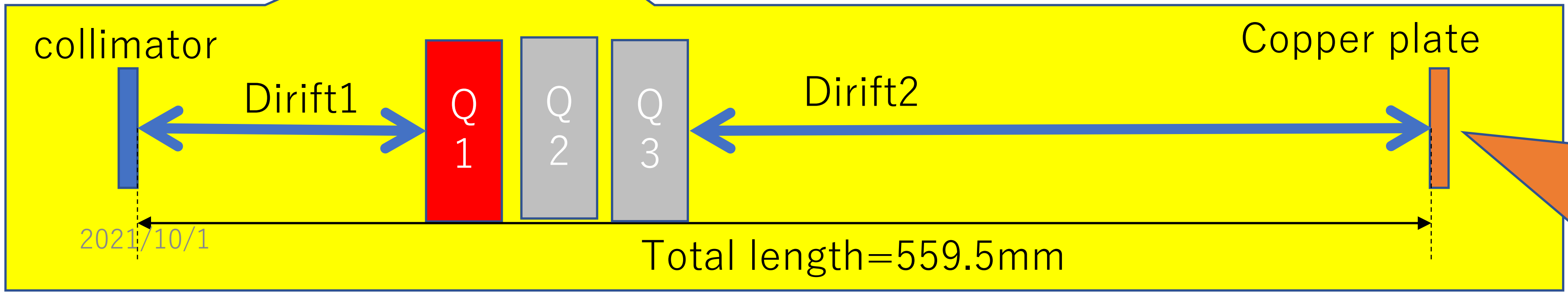
- Q-scan by use of single quadrupole (Q1 or Q2 or Q3)
  - Change K-vale of Q1 (or Q2 or Q3) to measure focus and defocus beam shape
  - **Reconstruct σ_0 (at initial point)**
- **Estimate σ_1** at the end of the transport line

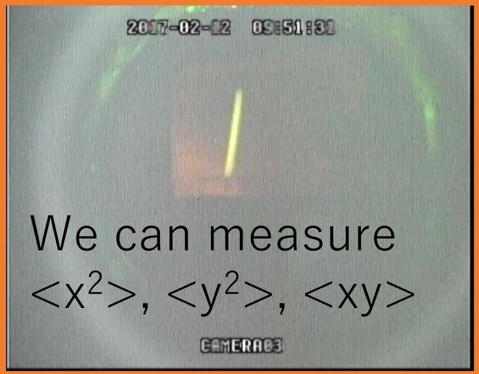
$$\sigma_1 = M\sigma_0(M)^t$$

Q-scan can measure

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

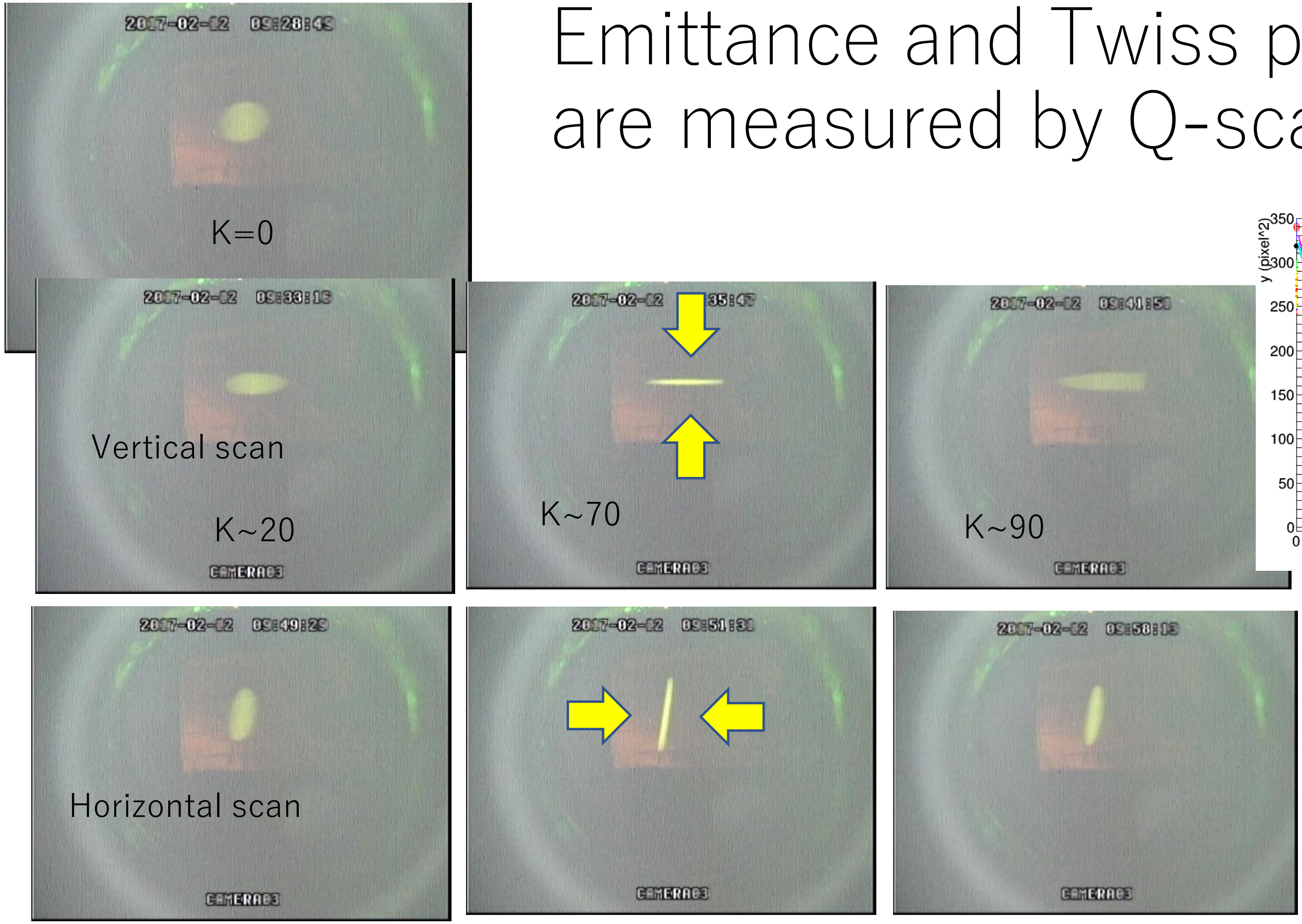
X-Y coupling component

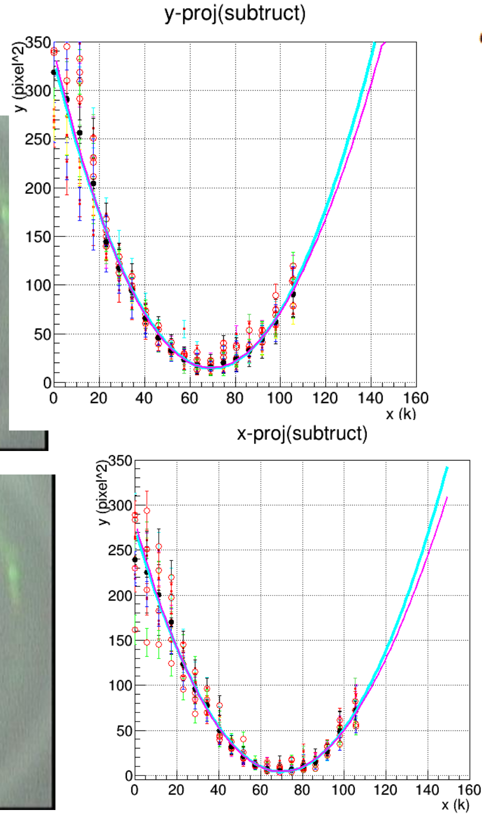




We can measure <x²>, <y²>, <xy>

Emittance and Twiss parameters are measured by Q-scan method



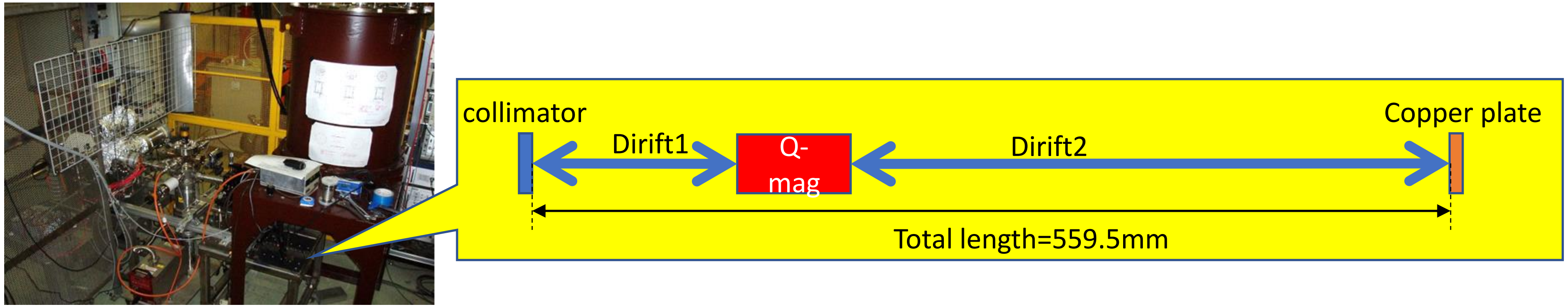


$$\sigma^{4D} = \begin{pmatrix} \langle x^2\rangle & \langle xx'\rangle & \langle xy\rangle & \langle xy'\rangle \\ \langle xx'\rangle & \langle x'^2\rangle & \langle x'y\rangle & \langle x'y'\rangle \\ \langle xy\rangle & \langle x'y\rangle & \langle y^2\rangle & \langle yy'\rangle \\ \langle xy'\rangle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

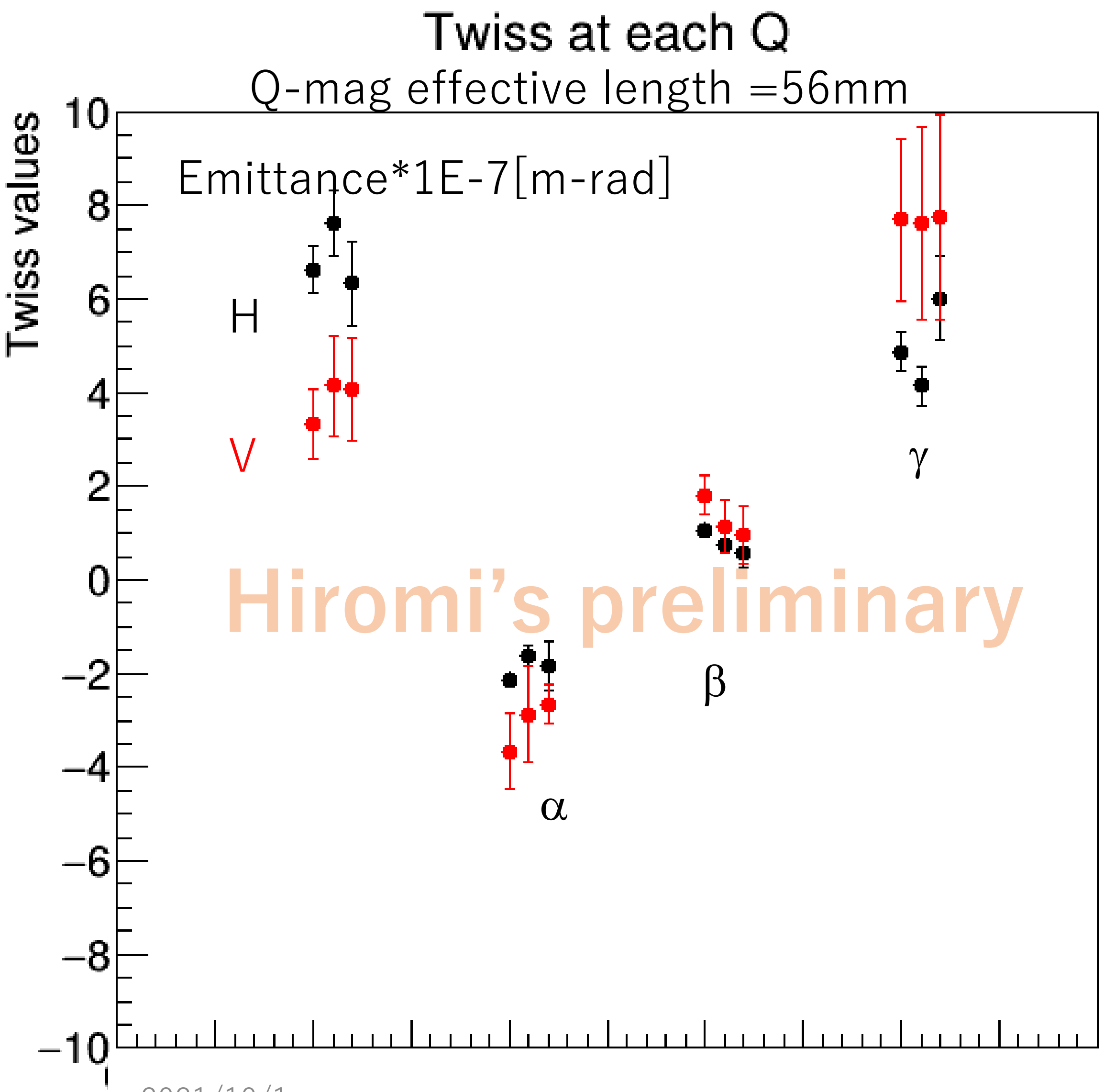
$$\begin{pmatrix} \sigma_{0,11} \\ \sigma_{0,12} \\ \sigma_{0,22} \end{pmatrix} = (\mathcal{M}_\sigma^T \mathcal{M}_\sigma)^{-1} \mathcal{M}_\sigma^T \begin{pmatrix} \sigma_{1,11} \\ \sigma_{2,11} \\ \sigma_{3,11} \end{pmatrix}$$

$$\sigma_{11} = \langle x_i^2 \rangle = \epsilon\beta,$$
$$\sigma_{22} = \langle x_i'^2 \rangle = \epsilon\gamma,$$
$$\sigma_{12} = \langle x_i x_i' \rangle = -\epsilon\alpha.$$

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \epsilon^2 \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}.$$



Twiss parameters at the collimator



Horizontal ------
ε_x=6.85e-07 +/-3.7e-08 [m-rad]
α_x=-1.93 +/-1.3e-01
β_x=0.945 +/-7.2e-02
γ_x=4.67 +/-2.8e-01

Vertical ---------
ε_y=3.69e-07 +/-5.3e-08 [m-rad]
α_y=-2.88 +/-3.6e-01
β_y =1.42 +/-2.9e-01
γ_y=7.68 +/-1.1e+00

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

$$\langle x^2 \rangle = \beta(s)\varepsilon$$

$$\langle x p_x \rangle = -\alpha(s)\varepsilon$$

$$\langle p_x^2 \rangle = \frac{1+\alpha(s)^2}{\beta(s)}\varepsilon$$

Q-scan can measure

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

Q-scan doesn't measure X-Y coupling component

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

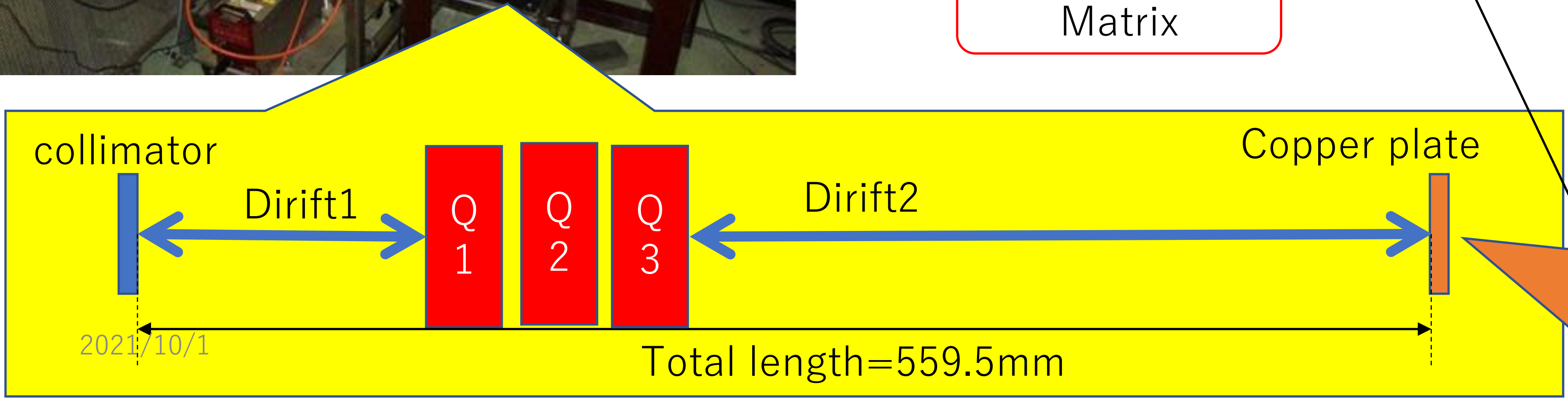
If we have N times different set-up data,

$$T X_0 = X$$

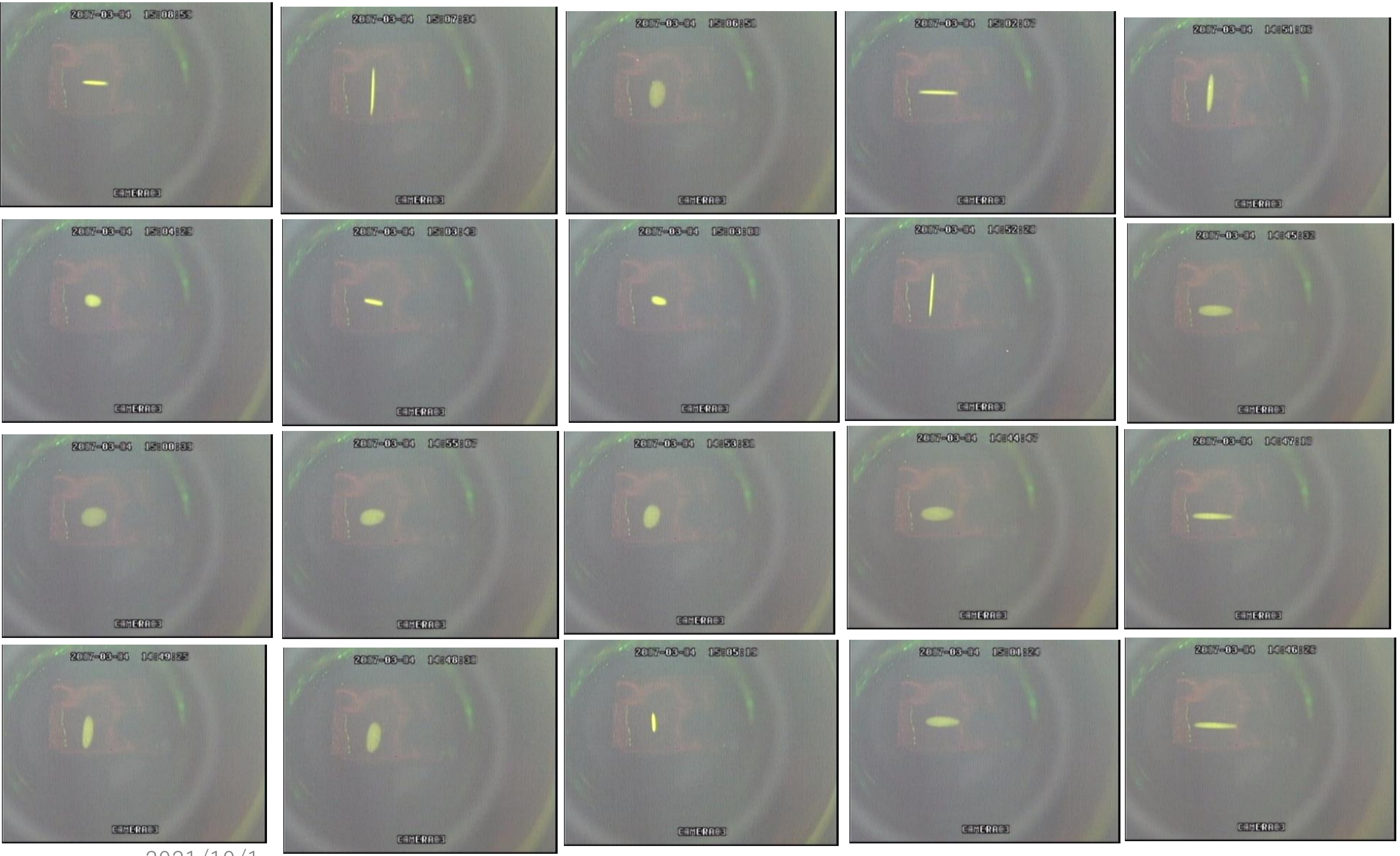
10×1 (for X_0), $(3*N)\times1$ (for X)

$(3*N)\times10$ Matrix (for T)

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



20 different Q settings for σ_0 measurement



We can simulate beam shape view and compare with measured data

10 unknown initial beam parameters

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

Every set-up has different $m_{11} \sim m_{44}$ and three measurements: $\langle x^2 \rangle$, $\langle y^2 \rangle$ and $\langle xy \rangle$

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

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

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

…………

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

$$X = T X_0$$

(3*N)×1 (Ex. N=20) ; (3*N)×10 ; 10×1

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

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

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

Although T is not regular matrix, it doesn't matter

Judge X-Y coupling of initial beam

To apply appropriate X-Y coupling, we need to confirm there is no initial X-Y coupling.

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

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

C=determinant of σ

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

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

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Rotating system for four-dimensional transverse rms-emittance measurements

C. Xiao, M. Maier, X. N. Du, P. Gerhard, L. Groening, S. Mickat, and H. Vormann
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(Received 1 February 2016; published 19 July 2016)

Knowledge of the transverse four-dimensional beam rms parameters is essential for applications that involve lattice elements that couple the two transverse degrees of freedom (planes). Of special interest is the elimination of interplane correlations to reduce the projected emittances. A dedicated rotating system for emittance measurements (ROSE) has been proposed, developed, and successfully commissioned to fully determine the four-dimensional beam matrix. This device has been used at the high charge injector (HLI) at GSI in a beam line which is composed of a skew quadrupole triplet, a normal quadrupole doublet, and ROSE. Mathematical algorithms, measurements, and the analysis of errors and the decoupling capability for ion beams of $^{83}Kr^{13+}$ at 1.4 MeV/u are reported in this paper.

DOI: 10.1103/PhysRevAccelBeams.19.072802

$$\varepsilon_{4d} = \varepsilon_1\varepsilon_2 = \sqrt{|C|} \le \varepsilon_x\varepsilon_y. \qquad (6)$$

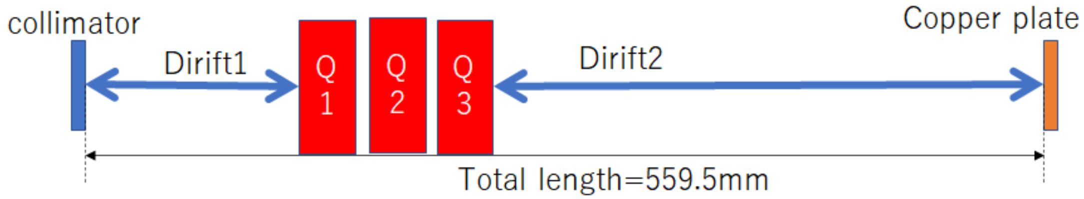
The coupling parameter t is introduced to quantify interplane coupling as

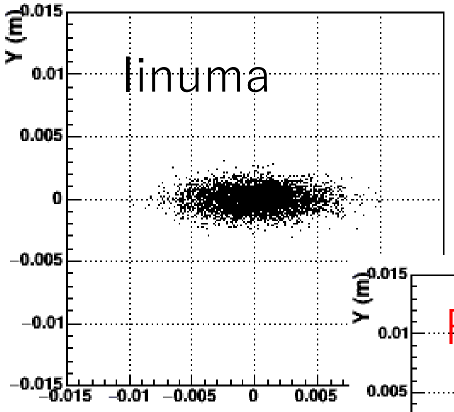
$$t := \frac{\varepsilon_x\varepsilon_y}{\varepsilon_1\varepsilon_2} - 1 \ge 0, \qquad (7)$$

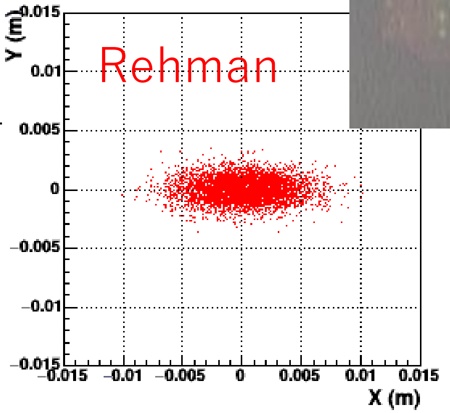
and if t is equal to zero, there are no interplane correlations and the projected rms emittances are equal to the eigen emittances.

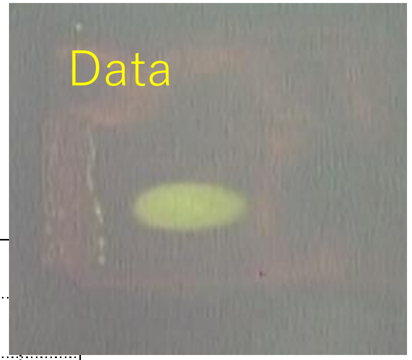
Compare 20 data set vs. simulation (σ_0 from Q-scan)

red：Rehman's Twiss parameter
black：Iinuma's Twiss parameter
green：Feb-4 data(from Rehman)

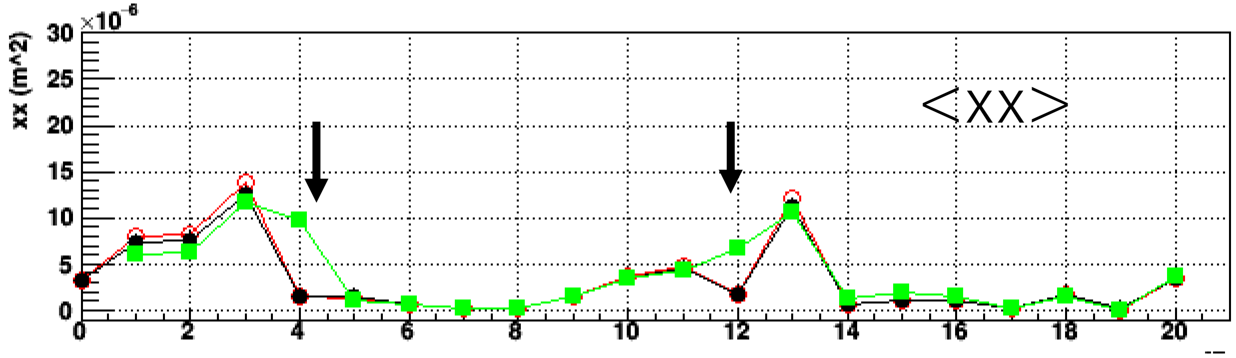


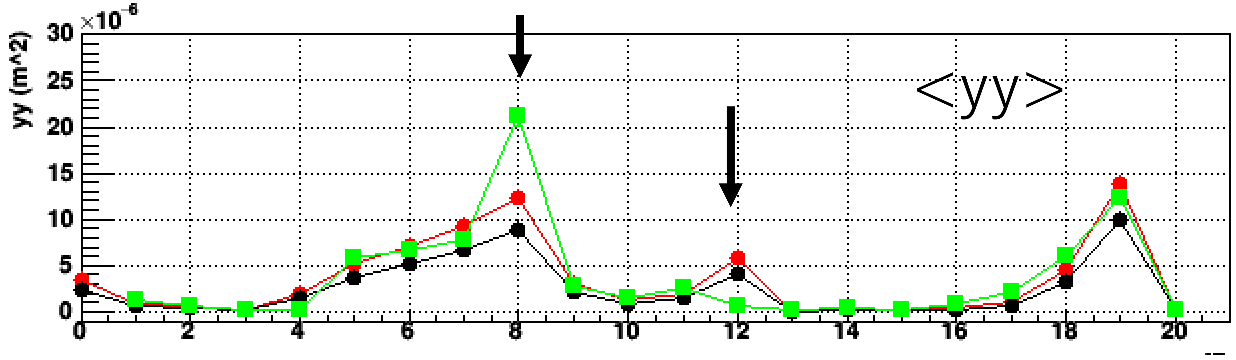


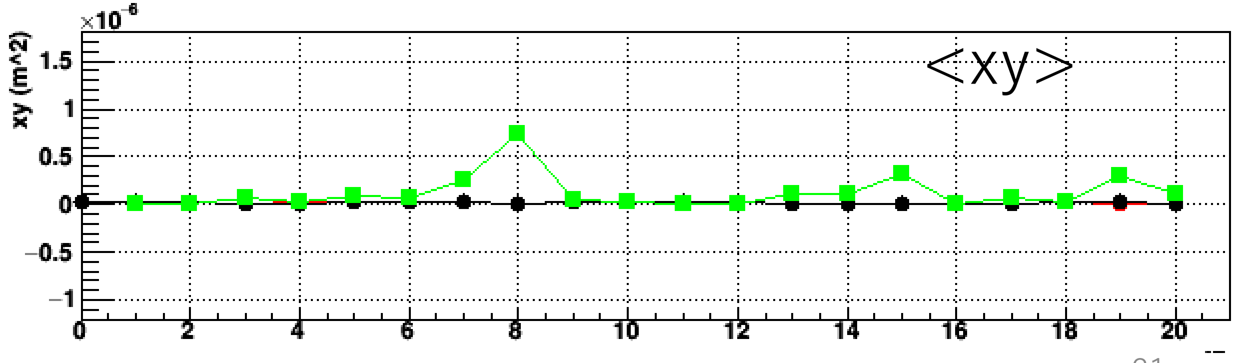




Still working on beam shape uncertainty







2017-prepared
2021Oct-1 modified

Global plan

note） items in gray box can be done with DC beam

①Modification of beam monitor system

2017 Jan.~Mar.
- 3-D imaging study
- Develop analysis scheme

FY2018
- ~~Camera upgrade~~ — No need

FY2019
Pulsed electron detector installation (Si, MCP etc.) for kicker operation — Working on beam monitor by 2021

②X-Y coupling control

- Install rotating Q magnet( ) for trial — 2019 done

- Fabricate rot… for Q-magnets — 2020 done
- Phase-space matching of X-Y coupling — 2020 done
Weak focus field

Mr. Someya and Ms. Hirayama are working on remote rotating Quads system by 2021Mar.

③Setup Kicker system

- Modification of pulsed current supply — 2020 done
- Field measurement

④Setup trigger system

- Base clock for the system
- Trigger system
  - Pulse shop… — done 2020
  - Kicker
  - Electron Detector — Will be done 2021Nov
- Overall test

- Fine tuning of kicker timing system

Mr. Matsushita and Mr. Oda will complete them by 2021Mar.

FY2020 (FY2021)

✓ **Quantitative analysis**
✓ **Optimization of injection efficiency**