Development of three-dimensional Spiral Injection by Using Electron Beam for Muon *g* – 2/EDM Experiment

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1.Introduction

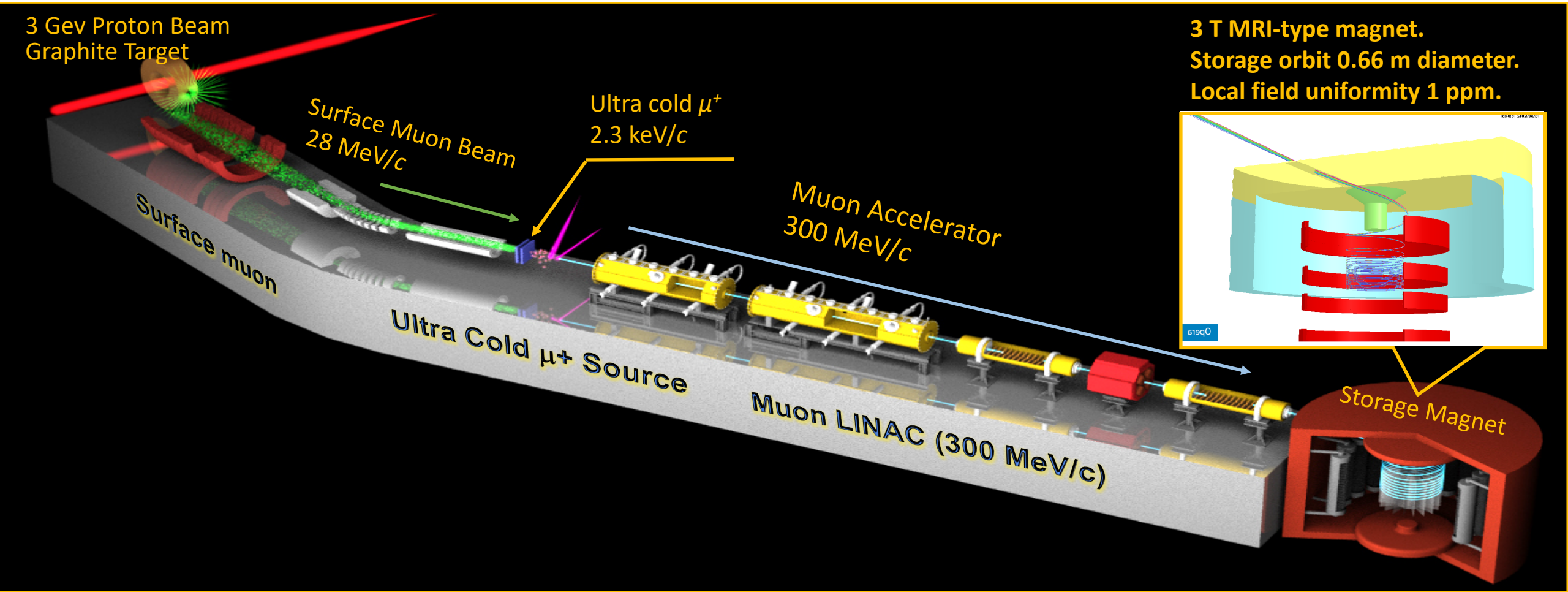
Muon *g* -2/EDM Experiment at the J-PARC (E34)

BNL E821

$(g-2)_\mu$: 0.54 ppm
EDM: 0.9×10^{-19} e.cm

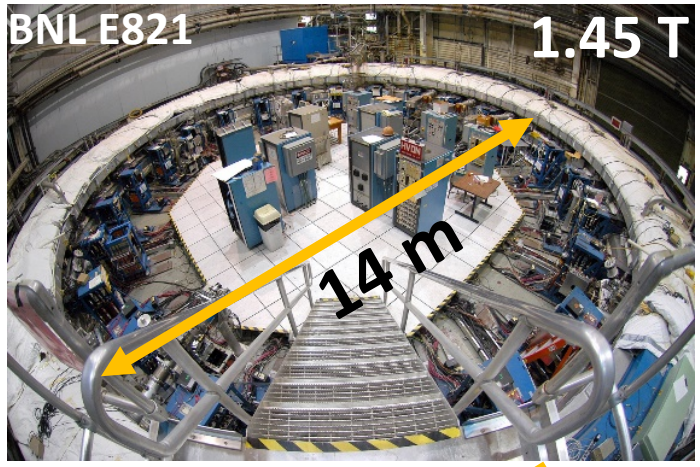
Target of J-PARC E34

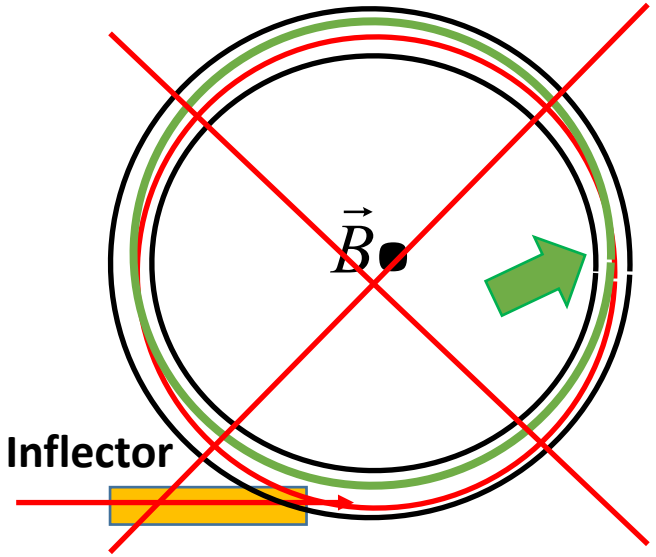
$(g-2)_\mu$: 0.1 ppm
EDM: 1.3×10^{-21} e.cm



Why inject beam spirally?

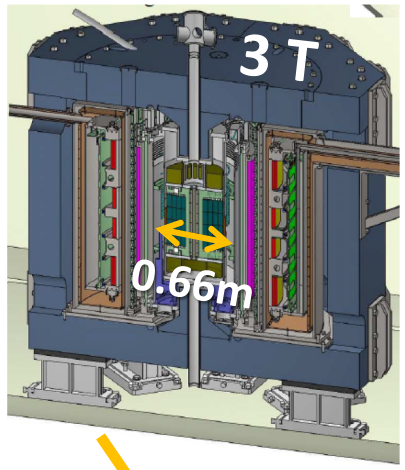
Conventional 2 D injection





In case of 14 m orbit, kick angle was **1.5 mrad** within **149 ns**.

J-PARC 3 T MRI type storage magnet

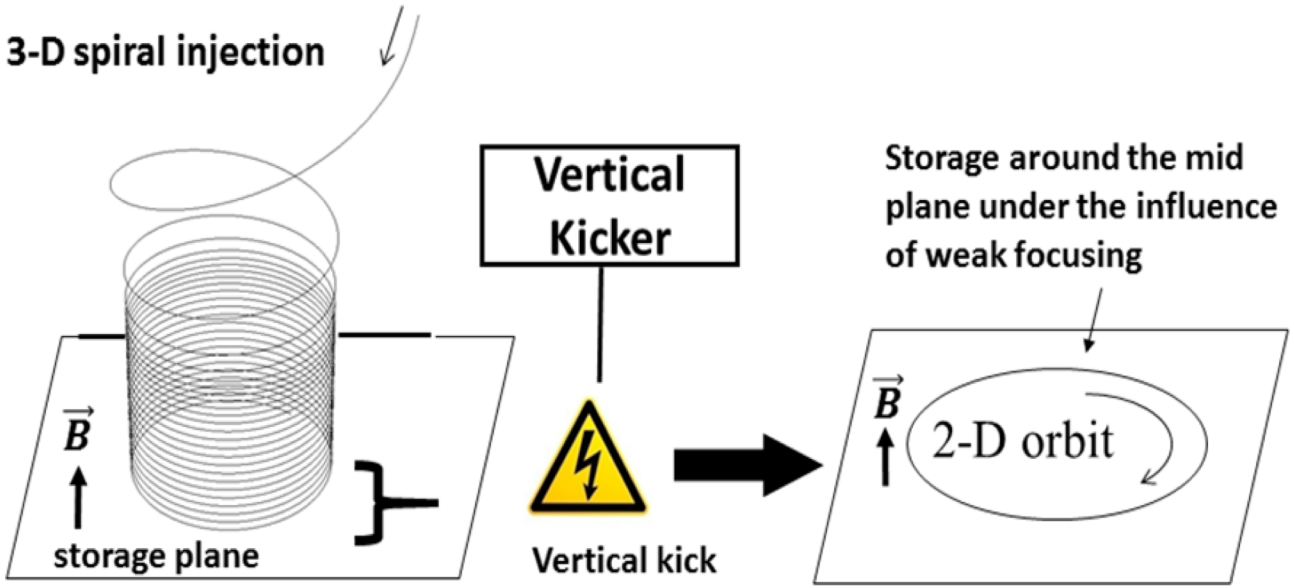


In case of 0.66 m orbit kick angle is **30 mrad** within **7.4 ns**. Which is not possible by any existent technology.
3 T is too high to be canceled by inflector.

G.W. Bennet, et al., Final Report of the muon E821 anomalous magnetic moment measurement at BNL, Phy. Rev D 73 (2006) 072003

Why inject beam spirally?

A new three-dimensional spiral injection scheme has been developed in order to solve all technical challenges related to the small storage orbit.



The Elegance and Advantages of this new scheme

- Smooth connection between injection and storage section
- All in one storage magnet, which reduce source of error fields
- No need to kick within a single turn.

However?

- **Unprecedented**

Therefore, it is indispensable to prove the feasibility of this new scheme.

H. Iinuma, H. Nakayama et. al, "Three-dimensional spiral injection scheme for the g-2/EDM experiment at J-PARC", Nucl. Instrum. Meth, Vol. A832, pp. 51-62 (2016).

2.Spiral Injection Test Experiment by Using Electron Beam (SITE)

2.Spiral Injection Test Experiment (SITE) by Using Electron Beam

We decided to establish new spiral injection scheme by using electron beam.

Advantages of SITE:

- **Both E34 storage magnet (3 T) and for SITE (0.0083 T) are using solenoidal storage magnet. (Weak focusing and magnetic kicker are included as in the E34.)**
- **SITE will provide freedom to perform experiment with e^- beam without any stringent time constraint of μ beam time availability.**

Goals of SITE are divided in two stages

First Stage

- ☑ Build DC electron beam line and storage magnet
- ☑ Observe electron beam track as fluorescent light due to the de excitation of nitrogen gas.

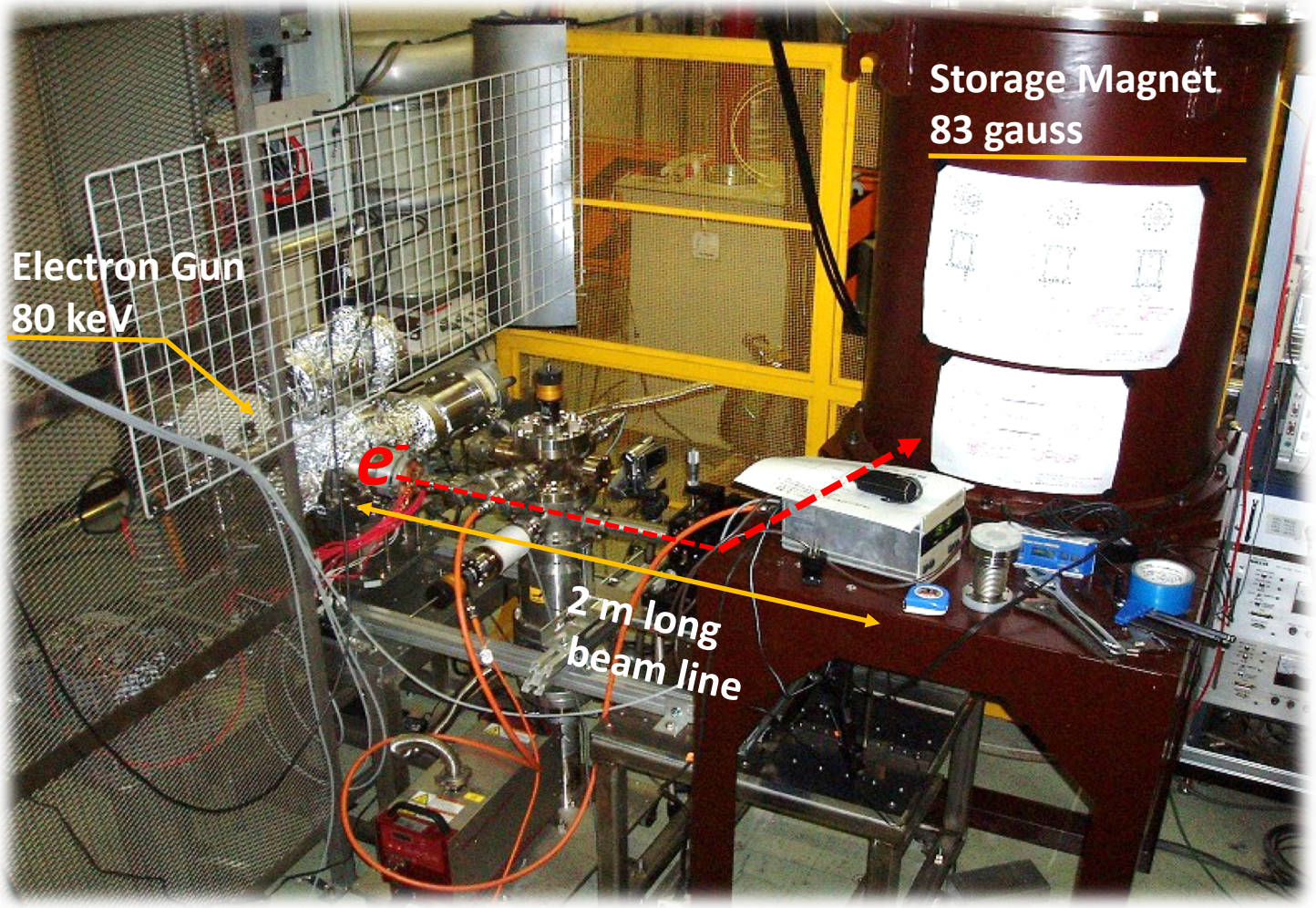
Second Stage

- ☑ Pulsed electron beam (In preparation)
- ☐ Magnetic kicker to guide electron beam to the very center of the storage region
- ☐ Improvement of beam monitors in the storage magnet
- ☐ Store the electron beam for the order of milliseconds

SITE Experimental Setup

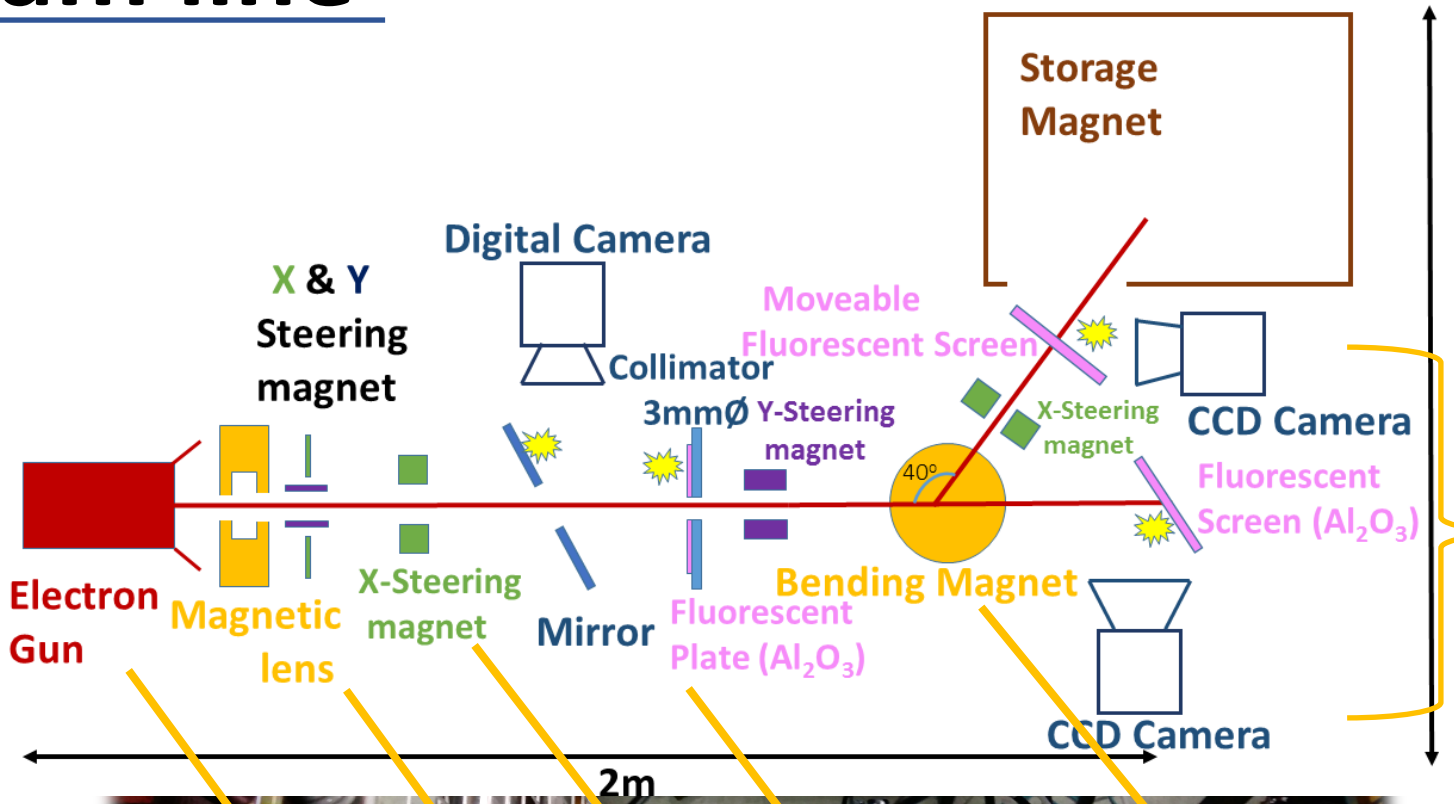
Comparison of Parameters between E34 and SITE

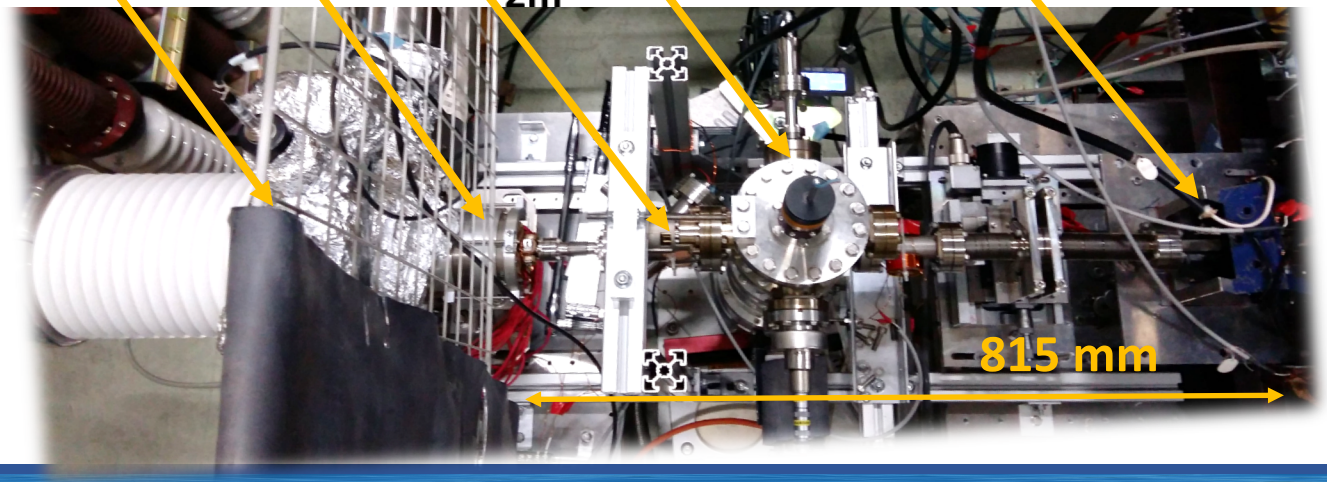
Parameters	E34	SITE
Storage magnet field strength	3-T	0.0083 T
Field uniformity	1 ppm	100 ppm
Magnet type	Super conducting	Normal conducting
Particle specie	μ^+	e^-
Momentum	300 [MeV/*c*]	0.296 [MeV/*c*]
Cyclotron period	7.4 nsec	5.0 nsec
Storage orbit diameter	0.66 m	0.24 m

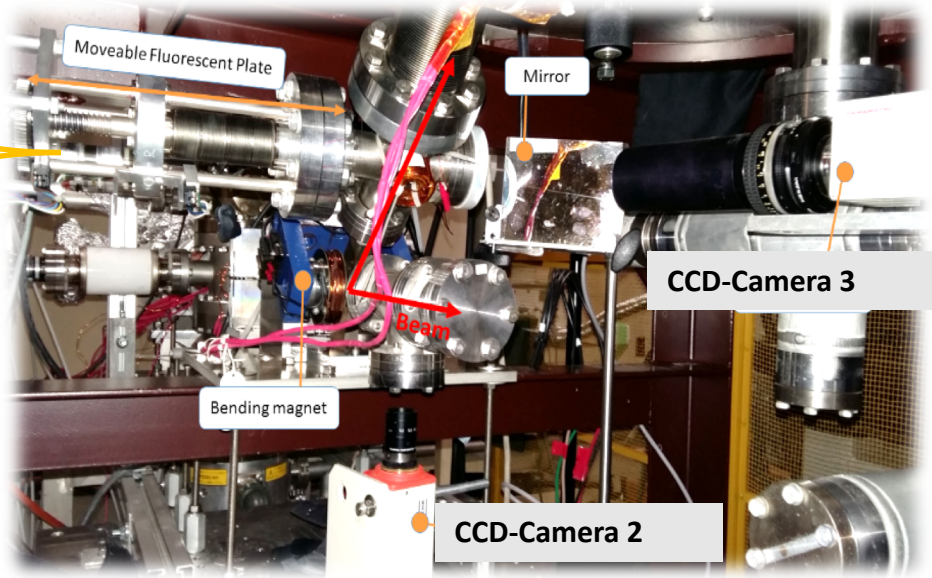


KEK LINAC klystron gallery, north end of sector 5

Beam line


Storage Magnet
Digital Camera
X & Y Steering magnet
Moveable Fluorescent Screen
Collimator
3mmØ Y-Steering magnet
X-Steering magnet
CCD Camera
40°
Fluorescent Screen (Al_2O_3)
Electron Gun
Magnetic lens
X-Steering magnet
Mirror
Fluorescent Plate (Al_2O_3)
Bending Magnet
CCD Camera
2m
1.9m

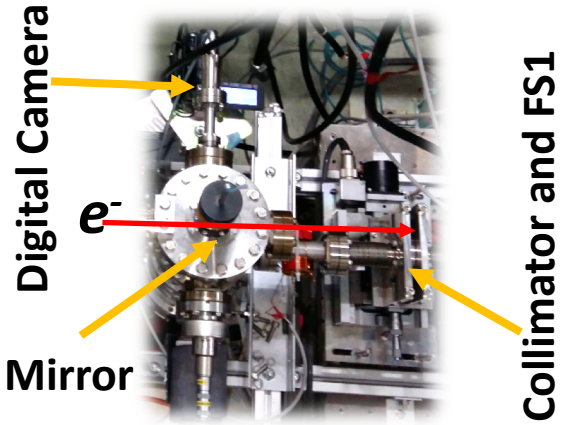

815 mm

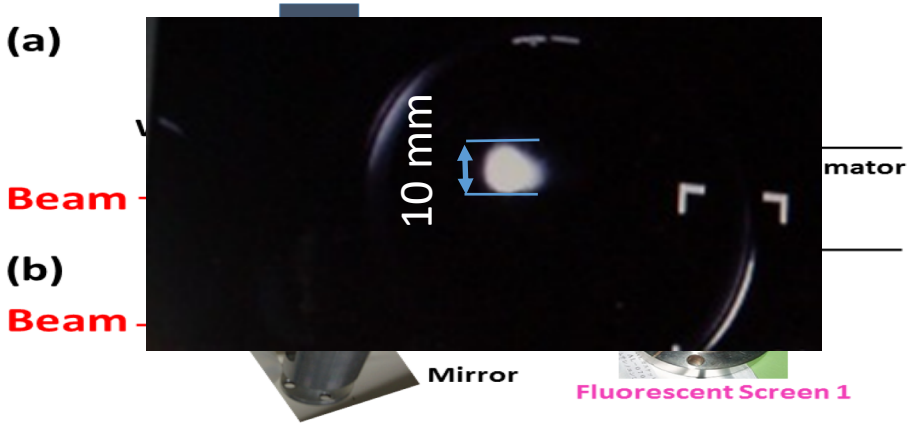

Moveable Fluorescent Plate
Mirror
Beam
Bending magnet
CCD-Camera 3
CCD-Camera 2

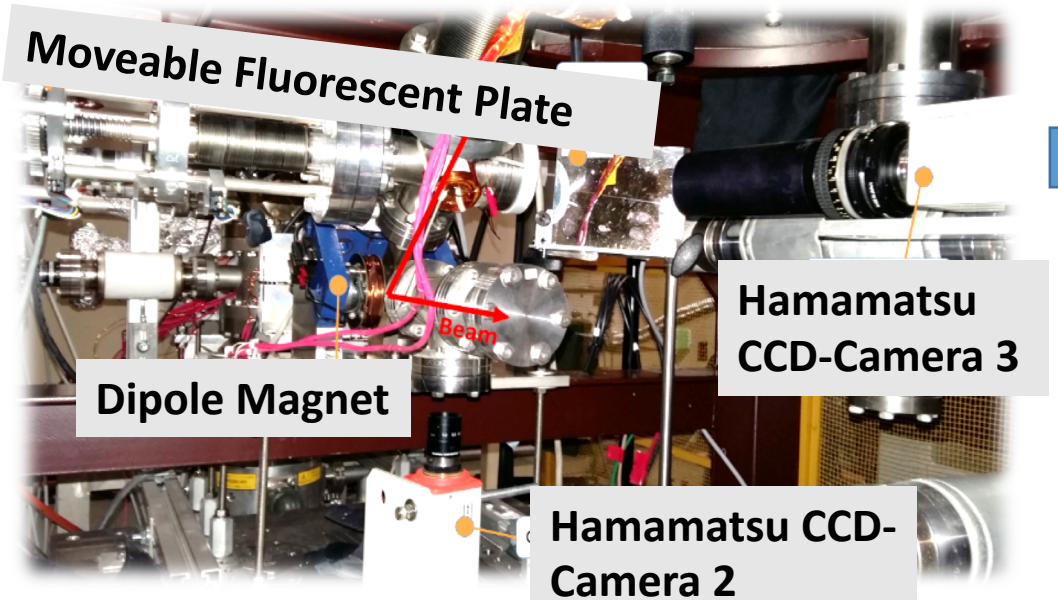
3.Beam Commissioning

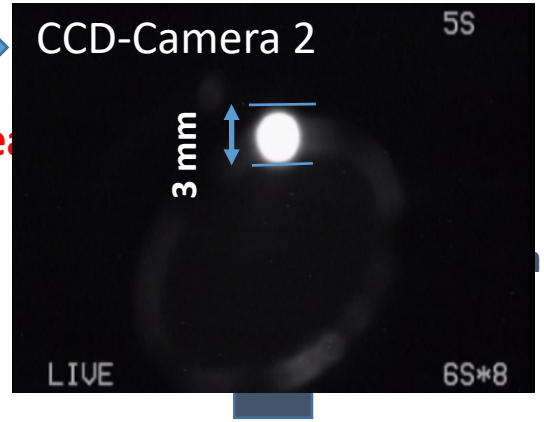
3. Beam commissioning

Three fluorescent screen (FS) monitors are installed to detect DC electron beam profile along the beam line.









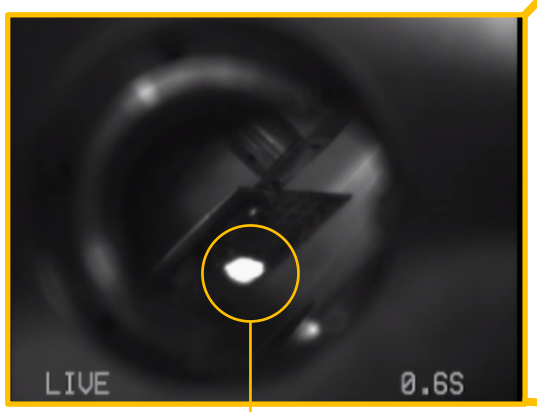
Beam commissioning (cont'd)

Monitors in the storage magnet

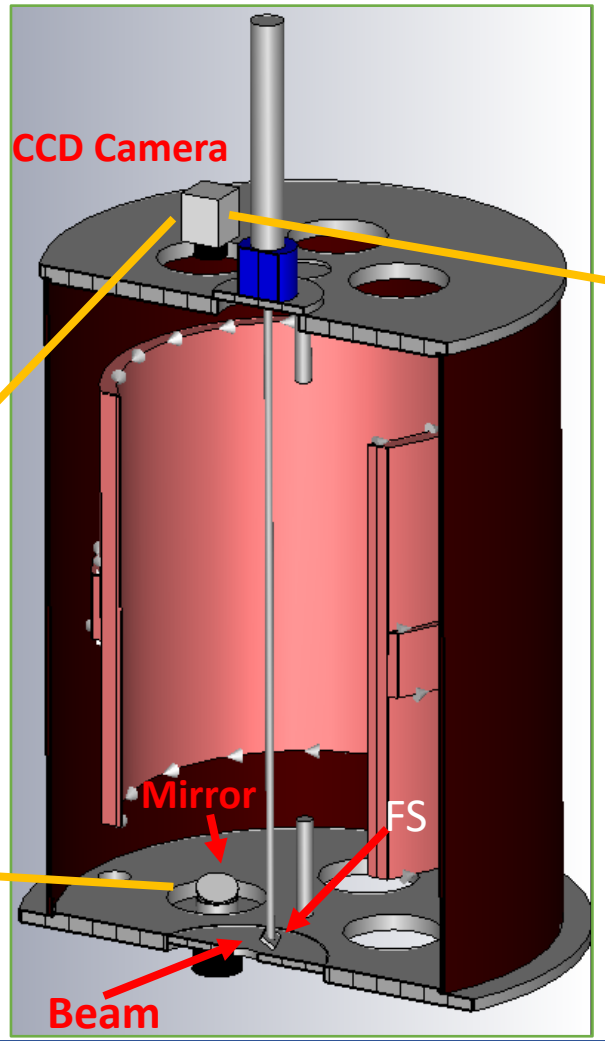
Beam monitors in the storage magnet

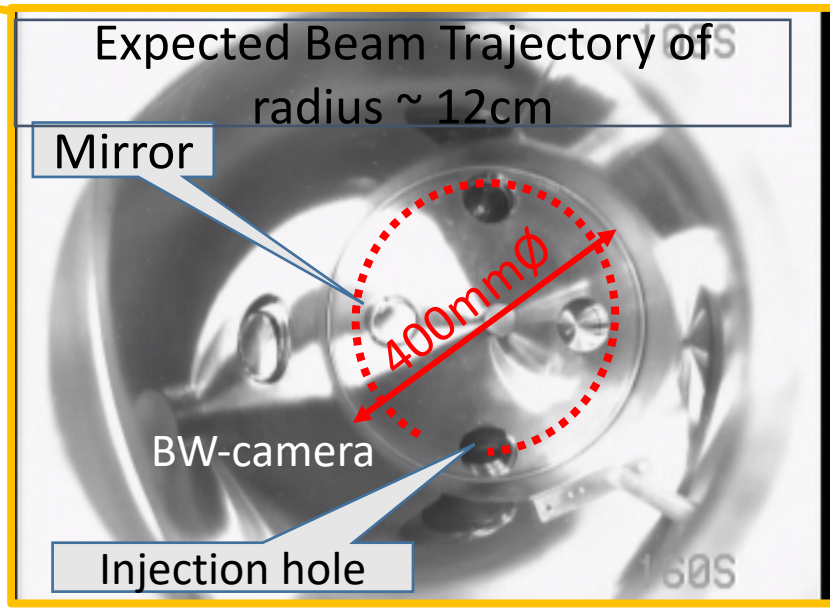
Two kinds of monitors are used in the storage magnet

1) **Invasive fluorescent screen monitor**
2) **Non-invasive nitrogen gas monitor in storage magnet.**



Beam spot at the FS

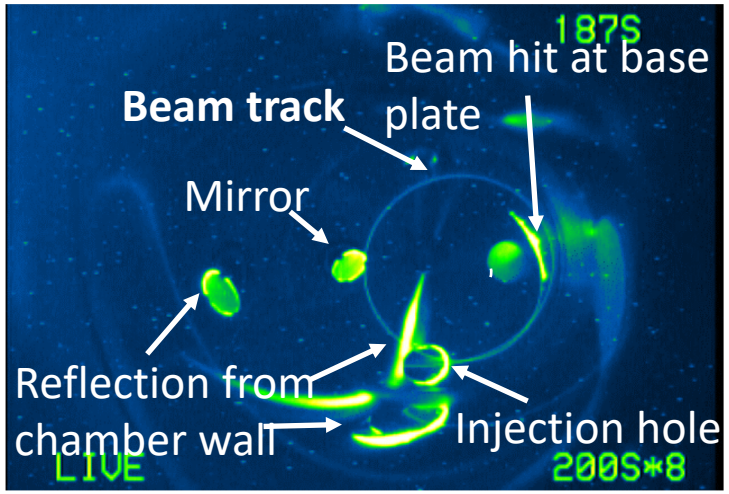


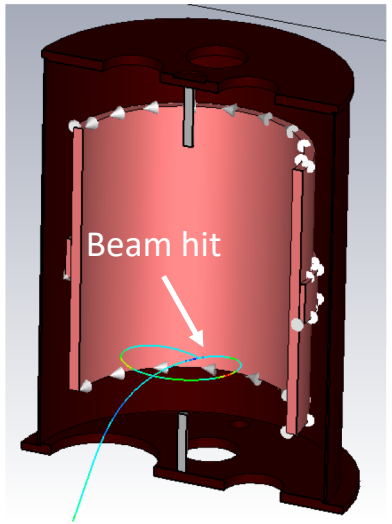


Injection of beam into the storage magnet

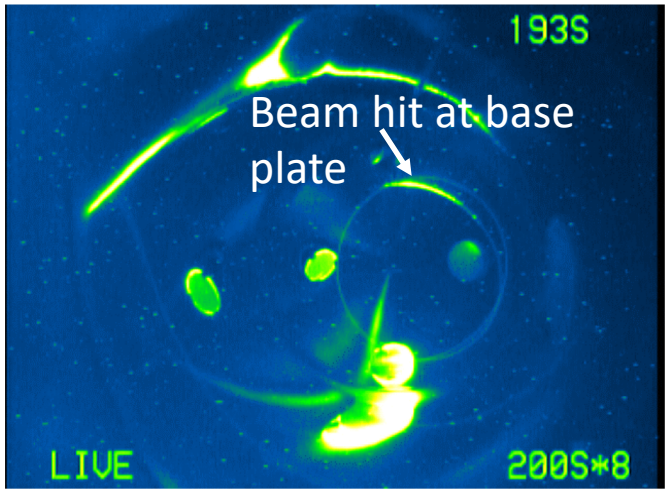
Injection at the lower angle

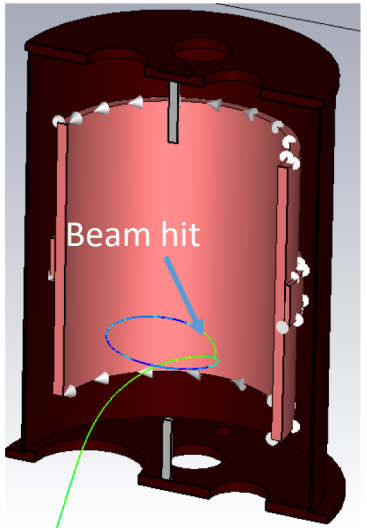
Beam injection into the storage magnet at 42°





Beam injection into the storage magnet at 42.5°





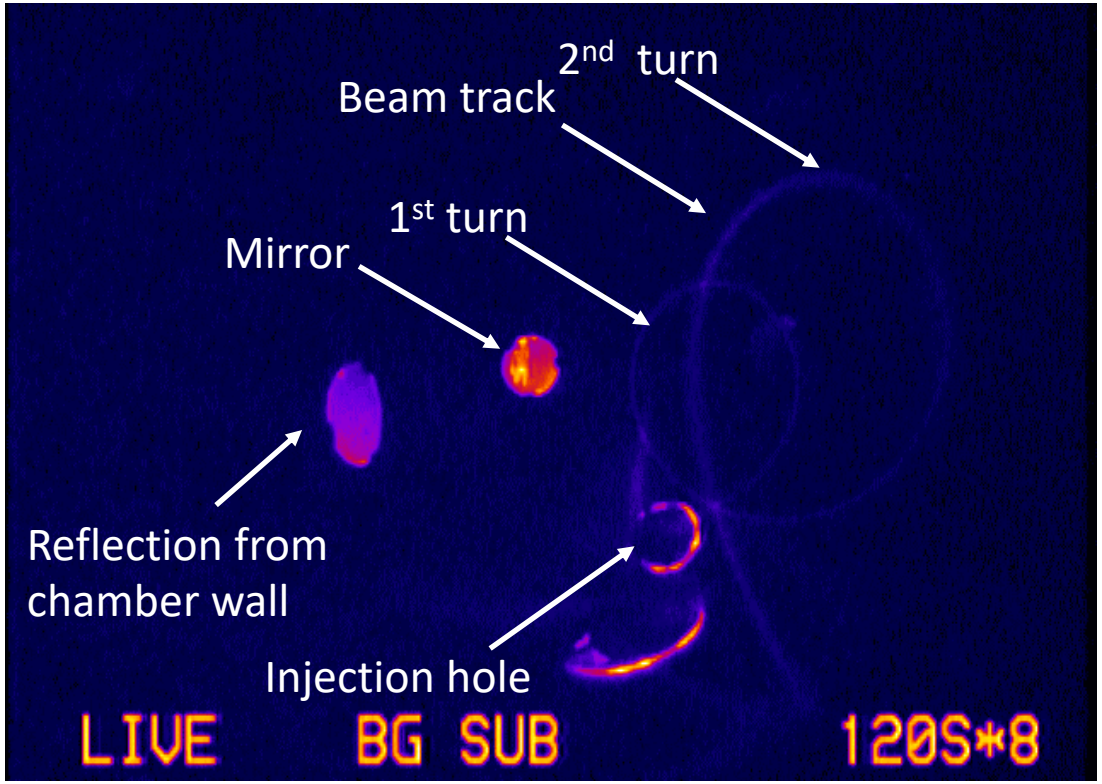
Reflection from the chamber wall cause background.

- **We will blackened chamber with graphite paint.**

Injection of beam into the storage magnet (cont'd)

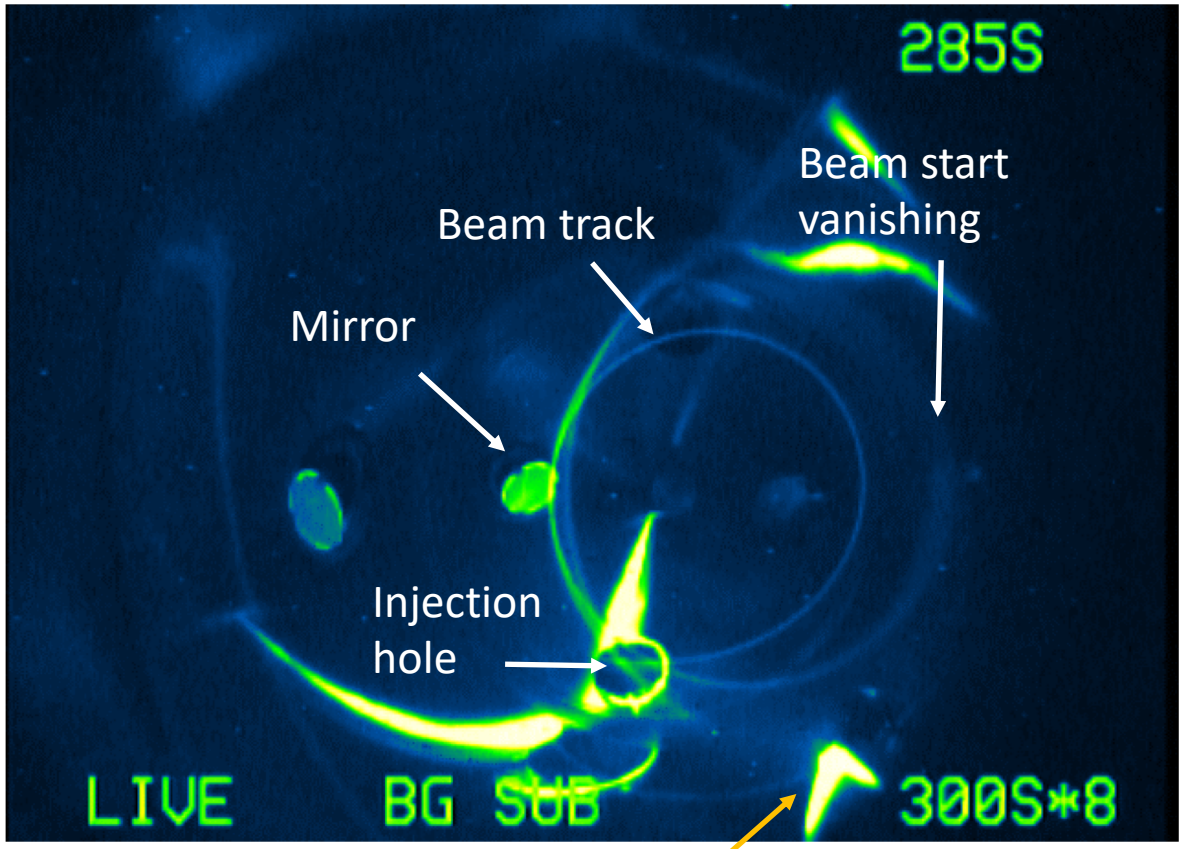
Injection at the higher angle

Beam injection into the storage magnet at 47^{o} to the 44^{o} in steps of 0.5^{o}



Injection of beam into the storage magnet (cont'd)

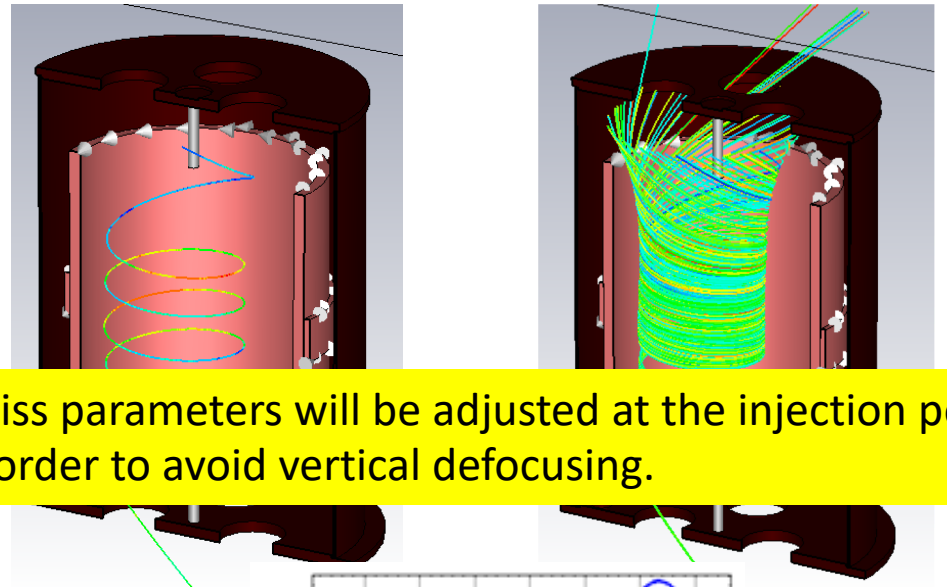
For the injection angle range (43.5° < injection angle < 44°) Multi turns should appear. But we didn't observe them. After one complete turn beam track vanish away.



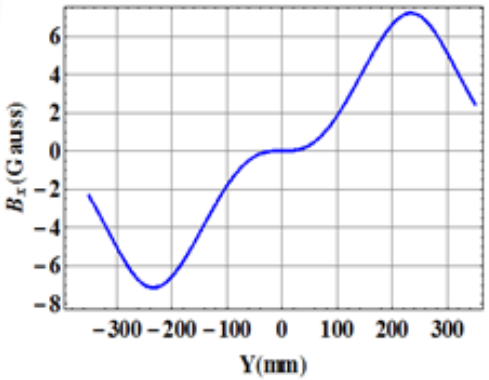
Fluorescent screen at height 39 cm.

Single particle tracking At injection angle (43.5° < injection angle < 44°) Multi turns appear.

Multi particle tracking shows beam start vertical defocusing due to the radial field of storage magnet.



Twiss parameters will be adjusted at the injection point in order to avoid vertical defocusing.

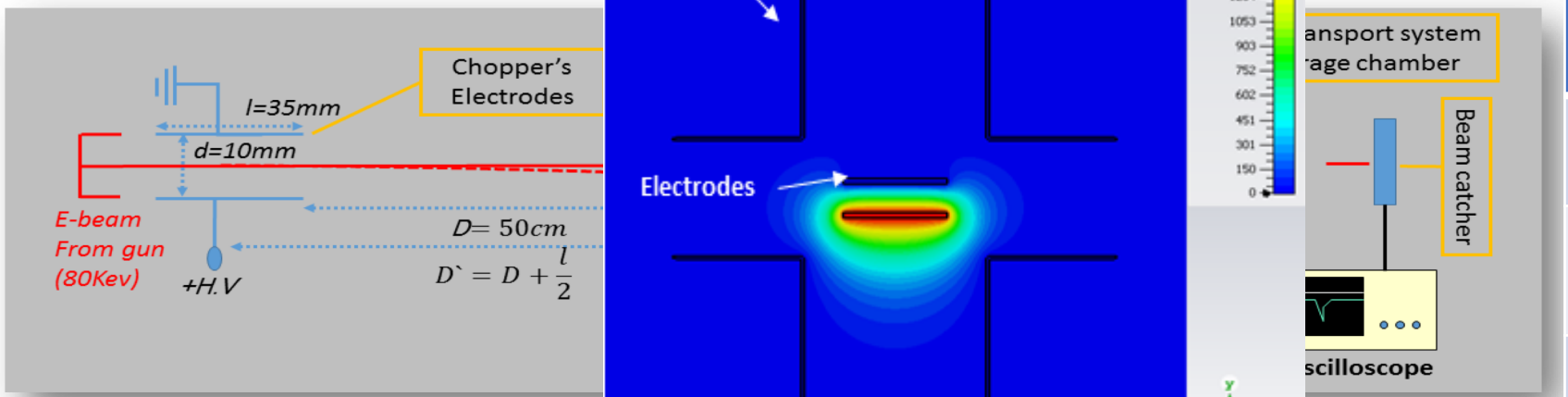


4.Electric chopper system

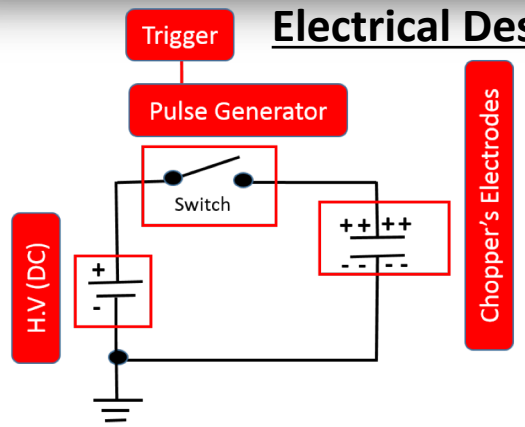
Electric chopper system

Electric chopper is the best choice for the generation of the pulsed beam (low energy)

- **Fast response**
- **Simple structure**
- **Low cost**



Electrical Design



CST-EM Simulation

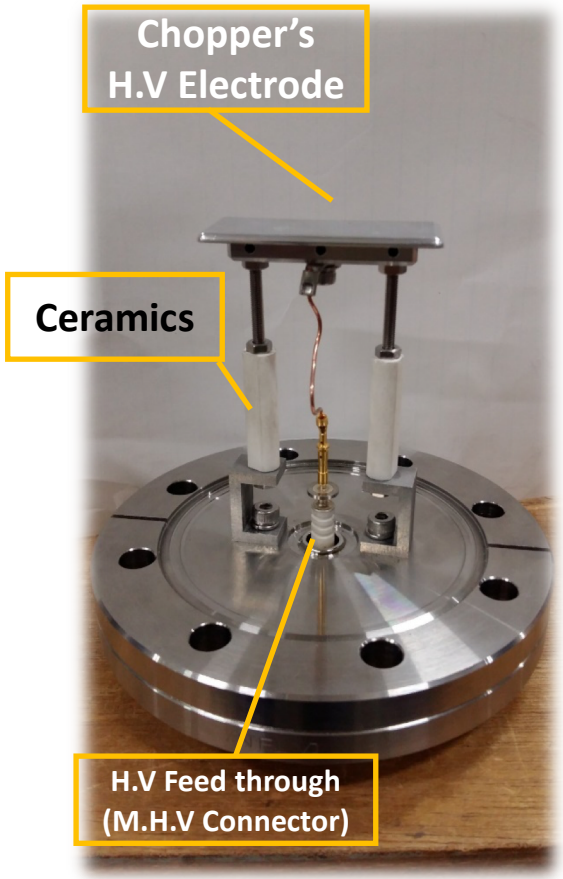
Parameters for the electric chopper system

Parameters	Values
Injected beam energy	80 keV
Chopper deflecting voltages	1.2 kV
Electrode length	50 mm
Pulse rise and fall time	< 25 ns
Pulse width	50 ns
Frequency	50 Hz

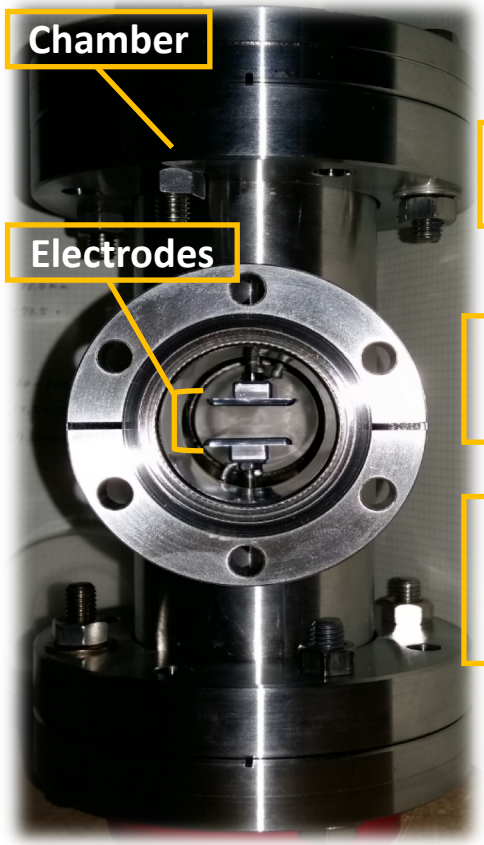
Electric chopper system (cont'd)

Experimental Setup

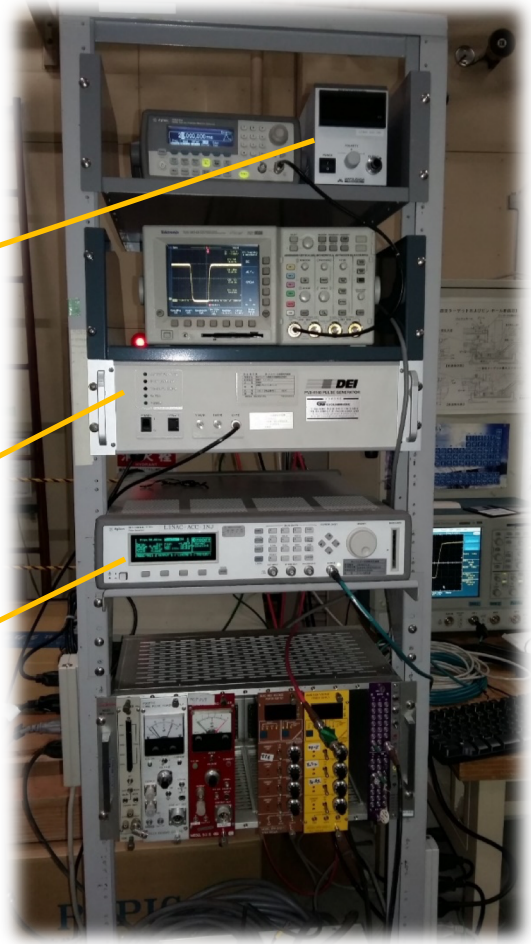
Chopper H.V Electrodes



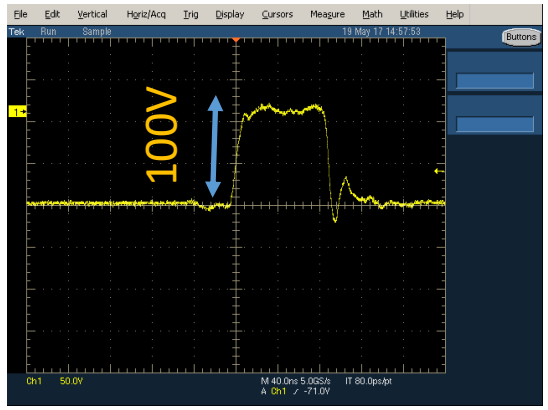
Chamber and Electrodes



Electrical components



Output from pulse generator



Conclusion:

Chopper is almost ready to install on the beam line.

5.Future plans and Conclusions

Future Plans

Stage I

- Overcome the vertical defocusing of the electron beam in the storage magnet
- Blackened chamber wall of the storage magnet

Stage II upgrades

- Electric chopper system to be installed at the beam line
- Magnetic kicker
- Beam monitors
- Final task is to store electron beam for the order of milliseconds

Conclusion

First Stage of SITE

- **Electron beam has been injected into the storage magnet successfully.**
- **Electron beam of 80 keV as fluorescent light from the nitrogen gas excitation has been observed.**

Second Stage of SITE

- **Development of the electric chopper system to produce pulsed electron beam has been started and soon it will be installed on the beam line.**


Thank you very much.
どうもありがとうございました

Backup

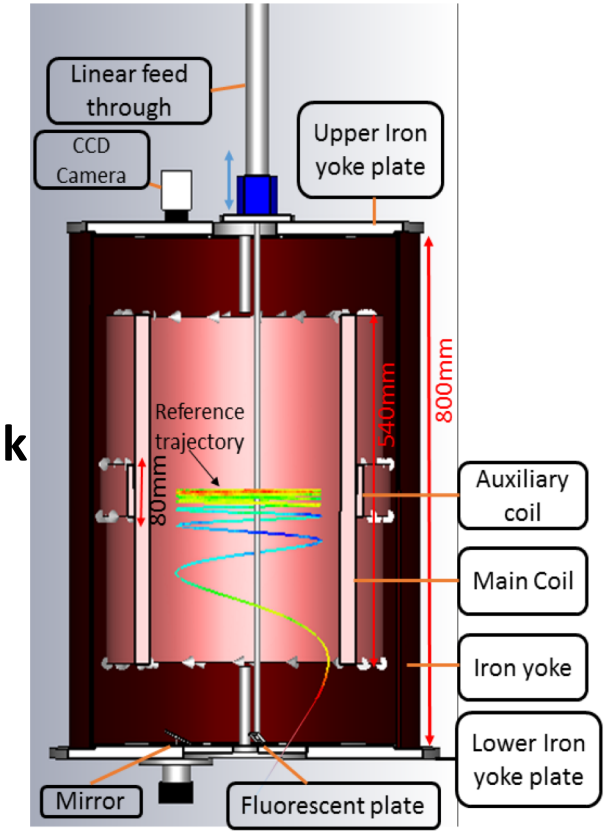
Storage Magnet

Storage magnet is a solenoidal electromagnet placed inside a cylindrical iron yoke.

Storage Magnet is consist of

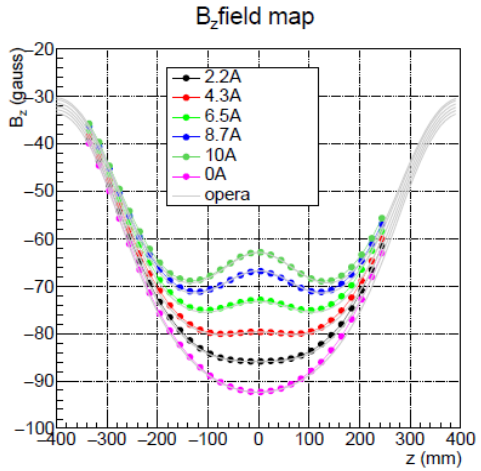
- **Iron yoke**
- **Main Coil**
- **Auxiliary coil to provide weak focusing.**

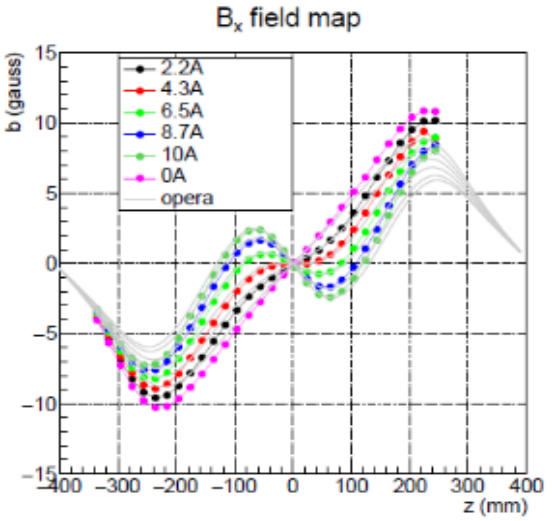
Model of the Storage Magnet



Storage Magnet and Vacuum Chamber

Axial and radial field profile of the storage magnet





Beam commissioning (cont'd)

Non-invasive Nitrogen gas monitor in the storage magnet

Working Principle

- When charged particle collides with the residual gas or specially introduced gas, some molecules are ionized and some undergoes the excitation. De excitation of molecules results in the emission of fluorescent light.
- In the case of Nitrogen de excitation, photon emits in the visible wavelength of the range (390 nm < λ < 470 nm).
- A CCD-camera is used to catch fluorescence light from the nitrogen gas de excitation.

Setup