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Developments of a Pulse Kicker System for the Three-Dimensional Spiral Beam Injection of the J-PARC Muon g-2/EDM Experiment

K. Oda[1], H. Iinuma[1], H. Hirayama[1], M. Abe[2], K. Sasaki[2], S. Ohsawa[2], H. Nakayama[2], N. Saito[2,4,5], K. Furukawa[2], T. Mibe[2], T. Takayanagi[3,5], M.A. Rehman[2], R. Matsushita[4]

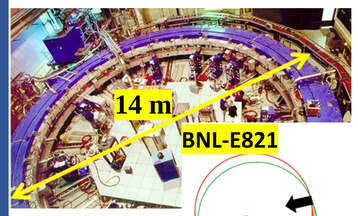
[1]Ibaraki-University, Ibaraki, Japan [2]KEK, Ibaraki, Japan [3]JAEA, Ibaraki, Japan [4]University of Tokyo, Tokyo, Japan [5]J-PARC, Ibaraki, Japan

茨城大学 Ibaraki University

Introduction

• The 3-D Spiral Injection

The J-PARC muon g-2/EDM experiment (E34) will use an unprecedented technique, **the Three-Dimensional Spiral Injection Scheme**, to inject the beam into a 66 cm diameter storage orbit, which is about 1/20th of the previous experiment (BNL-E821).



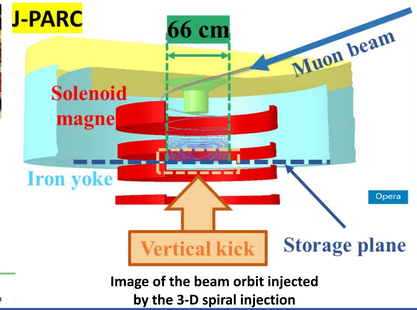
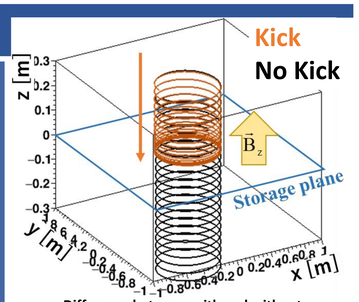


Image of the beam orbit injected by the 3-D spiral injection

How do we store the beam?

1. The beam is injected into the storage solenoid magnet moves in a spiral motion using the fringe field of the solenoid magnet.
2. Create a radial kicker magnetic field to give a vertical kick(Vertical force according to Fleming's left-hand rule).
3. This vertical kick guides the beam near the storage plane.
4. A weak focusing magnetic field holds the beam in Betatron oscillation and stores it in an almost two-dimensional plane without using an electric field.



Difference between with and without kicker when a single particle is injected.

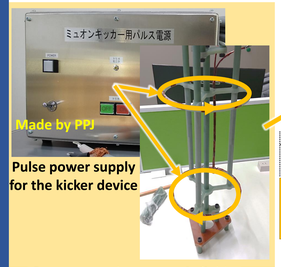
→For the success of this injection, the generation of the kicker field that gives this vertical kick is essential and giving the accurate kick and holding it in the weak focusing magnetic field is directly related to the high injection efficiency of the beam.

→The tuning of the parameters of the weak focusing magnetic field (static field) and the kicker magnetic field (dynamic field) is very coupled, and the mutual adjustment of these parameters is essential for the stable beam storage.

Demonstration of the 3-D spiral injection using the electron beam

In order to establish the injection scheme, **we will demonstrate the 3-D spiral injection on an electron gun test bench** which is a scaled-down version of the production experiment.

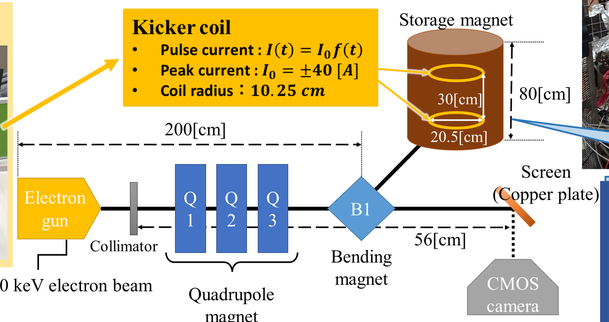
In the future, we will install the pulse magnetic field kicker device in the storage magnet.



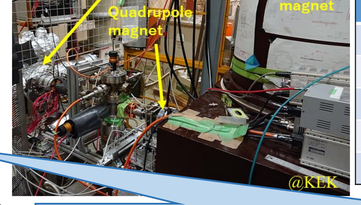
Pulse power supply for the kicker device

Prototype pulse magnetic field kicker device for our test bench

Kicker coil
- Pulse current : $I(t) = I_0 f(t)$
- Peak current : $I_0 = \pm 40\ [A]$
- Coil radius : $10.25\ cm$



Schematic diagram of the electron gun test bench at KEK



Differences Between Production and Demonstration Experiments

	J-PARC(E34)	Electron gun test bench
Particle	μ^+	e^-
Diameter of the storage orbit	66 cm	24 cm
Storage field flux	3 T	82.5 Gauss
Momentum	300 MeV/c	296.9 keV/c
Cyclotron period	7.4 ns	5.0 ns

Pulse magnetic field kicker device

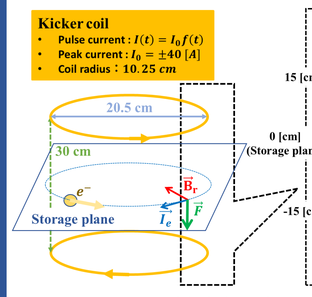
• Principle of Operation

Create a radial magnetic field by applying a pulse current in the reverse direction to one turn coils symmetrical above and below the storage plane.

• Advantages

- **The pulse magnetic field generation time can span multiple cyclotron cycles.**
- **The solenoid axial magnetic field is a canceling magnetic field distribution.**
- **Vertical kick can be given without disturbing the orbital center because the kick field is axisymmetric.**

Kicker coil
- Pulse current : $I(t) = I_0 f(t)$
- Peak current : $I_0 = \pm 40\ [A]$
- Coil radius : $10.25\ cm$



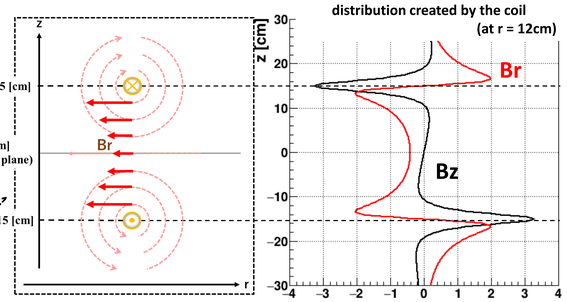


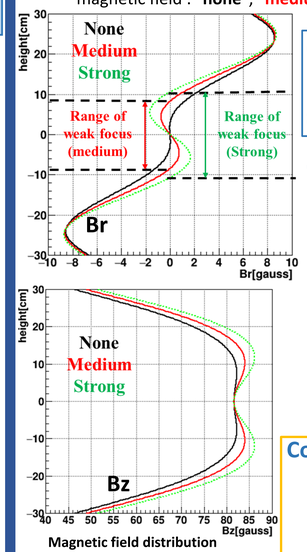
Image of the kicker coil creating the magnetic field Br

Calculation result of the magnetic field distribution created by the coil (at r = 12cm)

Weak focusing magnetic field

Our storage solenoid magnet can create **the weak focusing magnetic field** around the storage plane by changing the current balance between the main coil and the auxiliary coil.

- **The beam can be held by betatron oscillation near the storage plane without using an electric field.**
- In this study, we consider three different models of weak focusing magnetic field : "**none**", "**medium**", and "**strong**".



Magnetic field distribution of the weak focusing field

Current balance

None・・・Main:8.14 A, Aux:4.40 A
Medium・・Main:8.76 A, Aux:6.84 A
Strong・・・Main:9.35 A, Aux:9.16 A

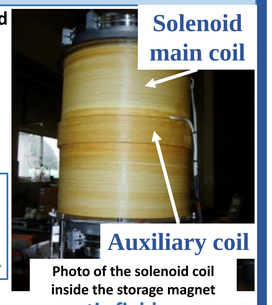
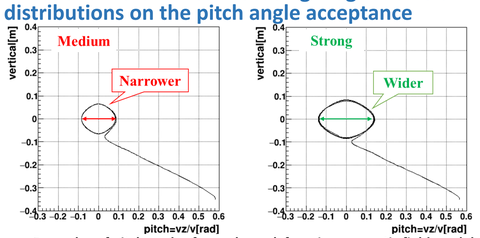


Photo of the solenoid coil inside the storage magnet

• Effect of different weak focusing magnetic field distributions on the pitch angle acceptance



Examples of pitch angles for each weak focusing magnetic field model

Consideration

- **The stronger the weak focusing magnetic field is the larger the pitch angle acceptance that can be stored.**
- **For the multi-particle model, the pitch angle alignment of the stored particles can be changed by tuning the weak focusing magnetic field. →The balance of injection efficiency needs to be considered.**

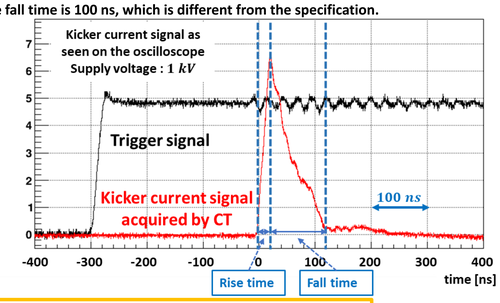
Study of appropriate kicker timing

• Actual pulse current waveform

- Based on the specifications of the pulse power supply, the actual kicker device's current waveform signal was acquired by CT. [1]
  - The pulse power supply alone → **Confirmed to meet the specification.**
  - The pulse power supply + kicker coil → **The fall time is 100 ns, which is different from the specification.**

Main specifications of pulse power supply for kicker for electron gun test bench

Item	Specification
Current rise time	25 ns
Current fall time	50 ns
Peak current	40 A(20 A+20 A)
Supply voltage	5 kV
Load inductance	1.5 μH
Repetition	50 Hz



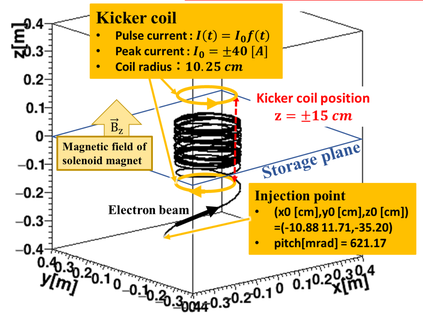
Duration time is long due to the pulse power supply limitations.
→How much does this change the kicker timing?

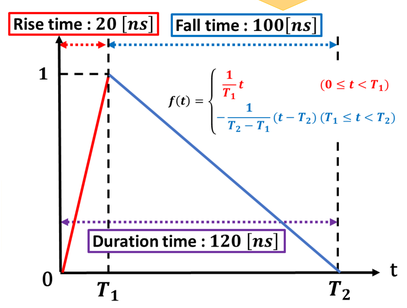
• Assume a triangular wave for beam orbit calculation

- Use the parameters in the figure as a "**base**" for discussion.
- **The time at the injection point is set to t0 = 0 ns.**
- Parameters that can be changed : **weak focusing magnetic field flux("Medium" ⇔ "Strong"), pitch angle**, peak current, kicker coil position

I defined a triangular wave that is close to the real waveform.

Change these parameters in this study and discuss.

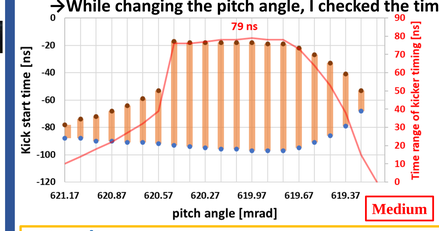


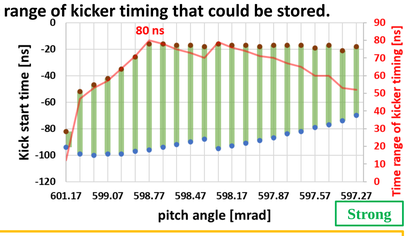


While changing the parameters from the "**base**", I checked the time range of kicker timing that could accumulate one electron with the assumed triangle wave.

• Change the weak focusing magnetic field flux

→While changing the pitch angle, I checked the time range of kicker timing that could be stored.





• Results

- **Kick in flying (t0<0) and use the falling time part of the waveform.**
- Changing the model of the weak focusing magnetic field requires changing the kick start timing and pitch angle accordingly, but **we were able to find the best solution with a bunch width acceptance of about 80 ns in each case.**

Future study

- We used peak current and kicker coil position as the "**base**", but we will also change these parameters to determine the best kicker parameters.
- It will be discussed in the **multi-particle model**, and **the balance between the weak focusing magnetic field flux and the injection efficiency** will be considered.
- **Install the kicker device on the electron gun test bench and run it as a system.**

References

[1] K. Oda *et al.*, "Developments of a Pulse Kicker System for the Three-Dimensional Spiral Beam Injection of the J-PARC Muon g-2/EDM Experiment", in *Proc. IPAC'21*, Campinas, SP, Brazil, May 2021, pp. 726-729. doi:10.18429/JACoW-IPAC2021-MOPAB221