J-PARC Muon g-2/EDM実験用 ビーム蓄積磁石内部の強いX-Y結合をもつビーム位相空間調整装置の仕様と設計検討

THP04

Specification and design study of beam phase space with strong X-Y coupled beam in the storage magnet for J-PARC Muon g-2/EDM experiment

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1. Physics goal : Explore the beyond standard model

g-2

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

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

g-2: 0.35ppm (exp.*)
4.2σ discrepancy from the standard model
(*) combined two experiments; E989@FNAL, Phys. Rev. Lett. 126, 141801(2021) & E821@BNL, Phys. Rev. D73 072003, 2006

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

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

EDM

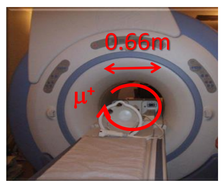
Non-zero observation = new physics

Standard Model expects ～ 2 x 10^{-38} e･cm

Upper limit (E821) < 1.9 x 10^{-19} e･cm (90% CL)
E821@BNL, Phys. Rev. D 80, 052008, 2009

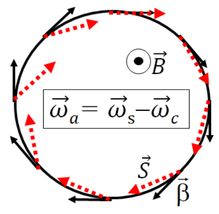
BNL E821/FNAL E989

J-PARC E34 ring size image



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

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

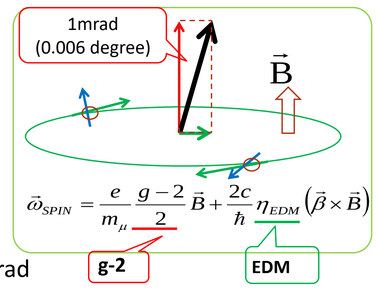


We measure $\vec{\omega}_a$ =Spin motion – cyclotron motion

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

g-2 EDM

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

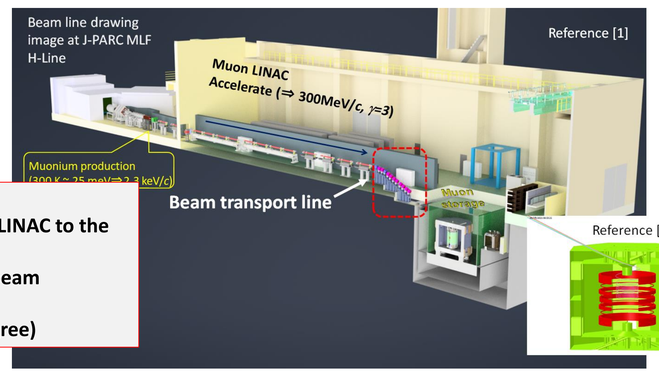


◆Electric field $\vec{E}$=0
◆Store muon beam in the uniform magnetic field (<0.1ppm)
◆Very precise control of the muon storage orbit
◆Angle between $\vec{\omega}_a$ and magnetic field $\vec{B}$ is estimated to be 1mrad assuming EDM upper limit from the previous experiment.
◆If we measure such angle with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

Super precise adjustment for muon storage magnetic field is a KEY

加速器の蓄積リング
1周 3km(KEKB) ~ 27km(LHC)

ミュオン実験
米国 リング1周：44m
日本 2.1m（入射できるのか？）



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

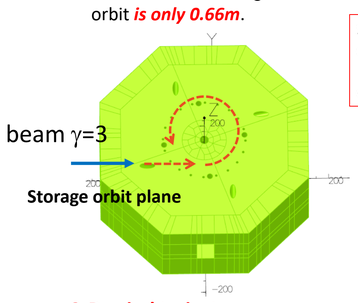
Beauties:
◆ **Smooth connection between injection and storage sections without any sources of error field**
◆ **A unit of magnet does work for this method and decrease sources of error field**

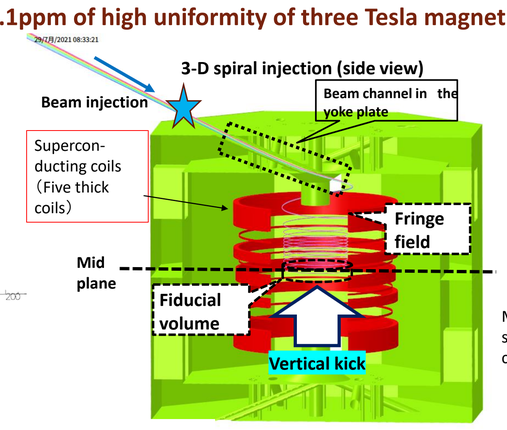
3. Compact storage ring applying medical MRI type superconducting magnet technology, requires newly developing 3-D spiral injection scheme!

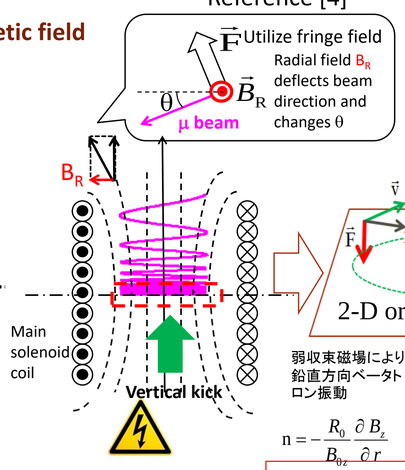
Reference [3]
Reference [4]

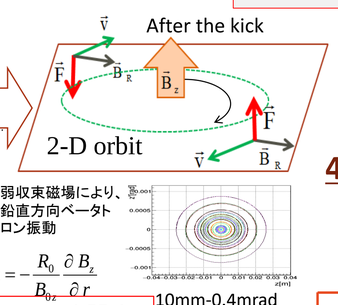
Expect to perform +/-0.1ppm of high uniformity of three Tesla magnetic field

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









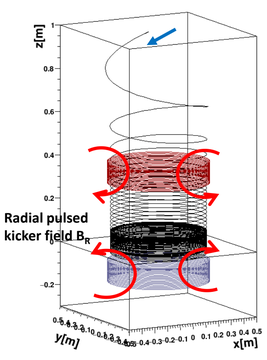
弱収束磁場により、鉛直方向ベータトロン振動

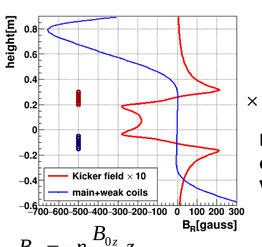
$n = -\frac{R_0}{B_{0z}}\frac{\partial B_z}{\partial r}$

Target :n=1.5E-4

10mm-0.4mrad

3-D spiral trajectory





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

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

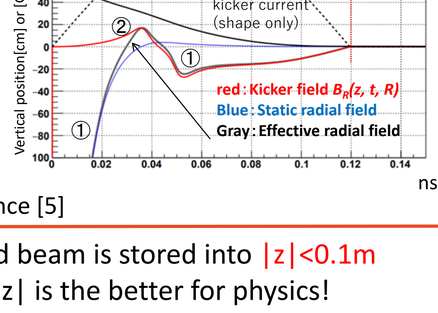
Weak Focus both direction

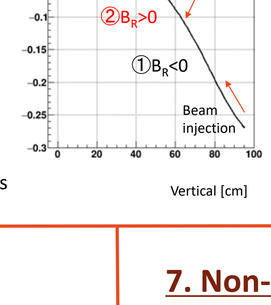
$I(t) = I_0 sin\left(\frac{\pi}{T_K}(t-t0)\right), : (t-t_0) < T_K$
$= 0, : (t-t_0) > T_K$

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

Half-sin shape current for Vertical kick

Effective radial kicker field
$= B_{R0}(r,z) + B_R(z) sin\frac{2\pi}{T_{kick}}(t-t_0)$

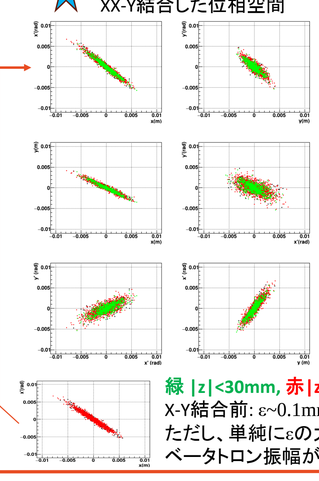


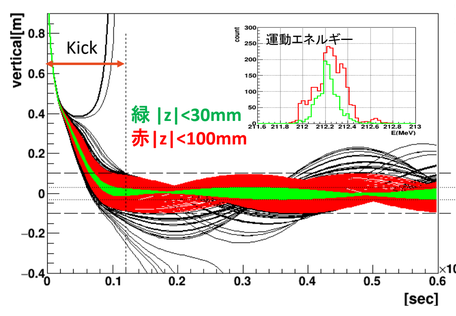


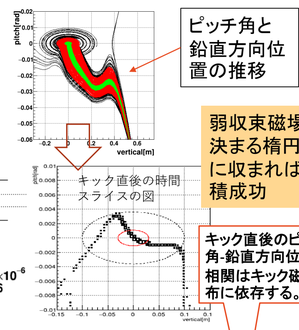
0<n<1: focus radially and vertically Reference [5]

4. Multi tracks study with expected beam phase space from upstream beam line

鉄ヨーク上、入射点のXX-Y結合した位相空間





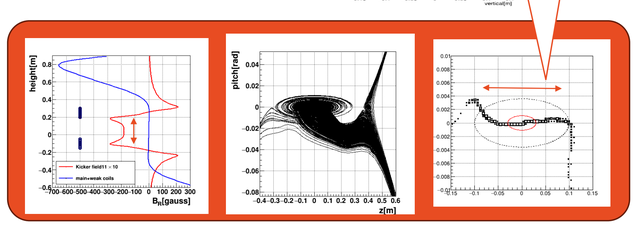


ピッチ角と鉛直方向位置の推移

弱収束磁場で決まる楕円内に収まれば蓄積成功

キック直後のピッチ角-鉛直方向位置の相関はキック磁場分布に依存する。

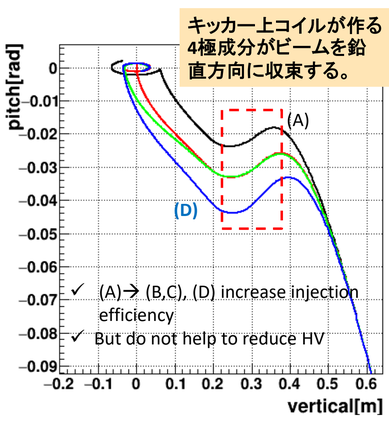
緑 |z|<30mm, 赤|z|<100mm
X-Y結合前: ε~0.1mm-mrad
ただし、単純にεの大小で蓄積後のベータトロン振幅が決まる訳ではない。

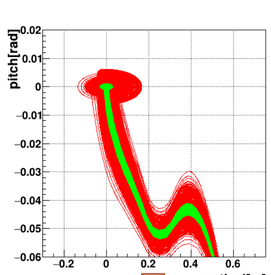


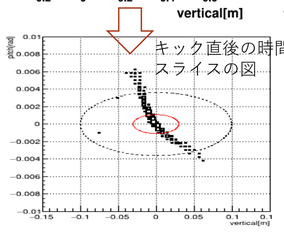
- ✓ Current kicker design with appropriate X-Y coupled beam is stored into |z|<0.1m region with 85% efficiency. However, the smaller |z| is the better for physics!

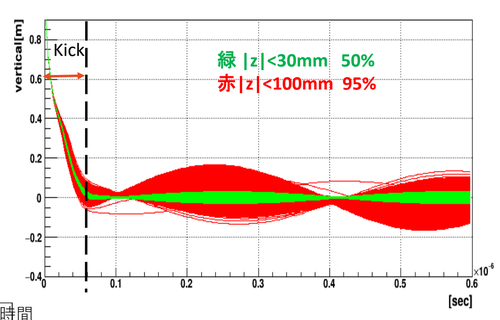
5.Squeeze beam phase space by super strong kicker field (effective vertical focus)

キッカー上コイルが作る4極成分がビームを鉛直方向に収束する。



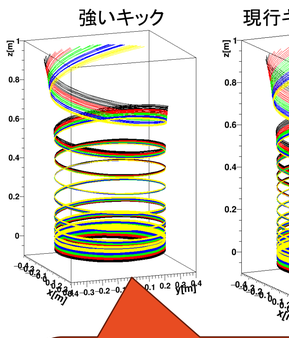


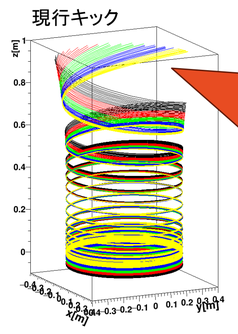




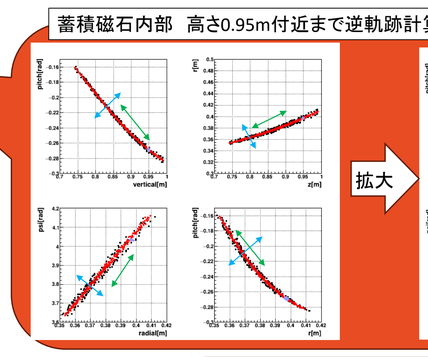
課題1:
キッカーは
短い時間に強いパルス磁場
が理想だが、技術的困難との妥協点を検討中

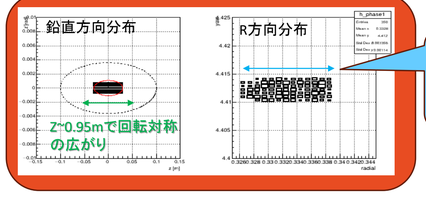
6.Track-back study to compare z-z' phase space at the storage vs. kick point



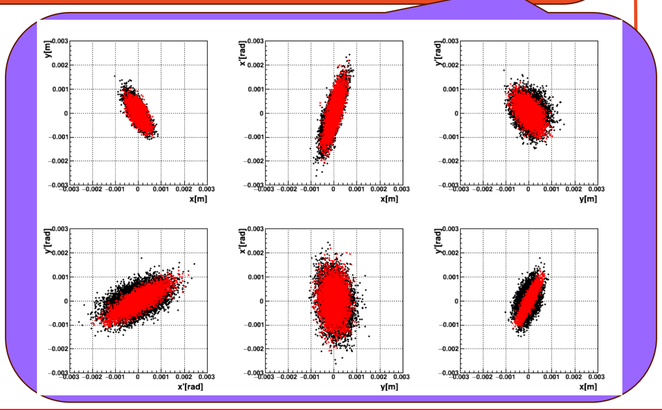


蓄積磁石内部 高さ0.95m付近まで逆軌跡計算したときの位相空間例





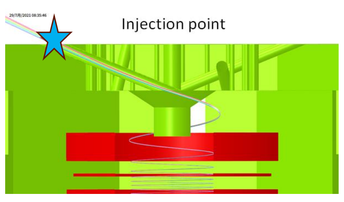
逆軌跡始点のr方向(径方向)分布を広げると高さ0.95m点での分布の幅が太くなる。

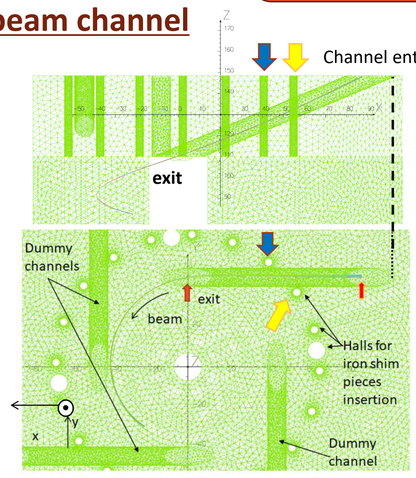


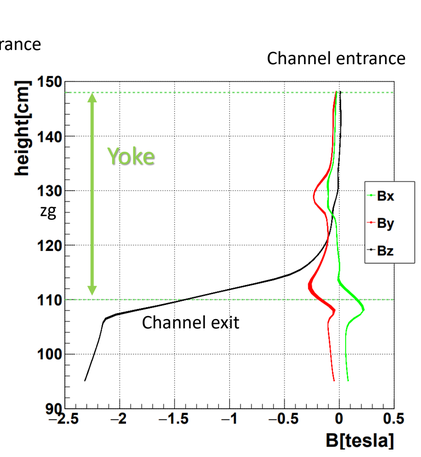
◆ 蓄積領域：ピッチ角-鉛直位置が|z|<30mmの領域を始点とし、逆方向の軌跡計算を行う。強いキック、現行キックの場合で、キックポイントでのビーム位相空間の広がり形状を確認する。
◆ 鉛直方向の位相空間をずらすと、軌道は回転対称にずれた形になる。
◆ 軸対称なソレノイド磁場中の軌道の特徴といえるが、鉄ヨーク外からの入射で、このような形にビームを成形するのは無理。
◆ 実際は、紫の分布に示すように、許容位相空間のごく一部にビームを入射する形になる。

課題3: Besides strong X-Y coupling, five-parameter phase space correlation should be considered to control precise vertical beam motion in the storage volume. Design work for magnetic shield tube at the injection channel ,which control distribution $\vec{d}$ of to be narrower, is ongoing. And additional multipole magnet at the injection point is also under considering.

7. Non-linear effect in the beam channel







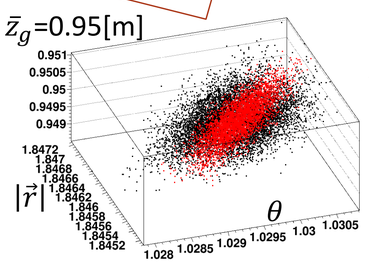
There is a non-linear magnetic distribution at the exit and some point in the middle of the channel.

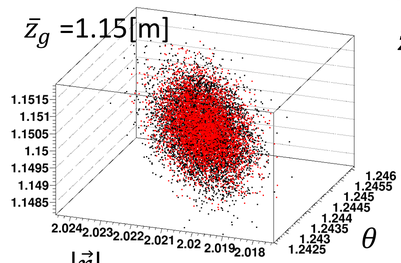
課題2:
鉄ヨーク外の入射点のおけるビームの位相空間を、磁石内部のビーム位相空間に関連付けるには、トラッキングを行うしかない。

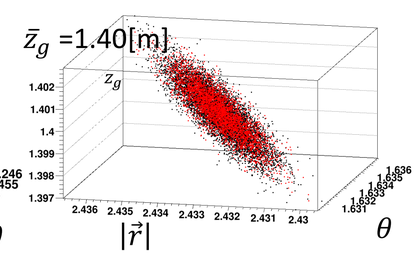
8. Phase space study in the channel

$|r| - z_g - \theta$ correlation is not clear above the channel because of non-linear magnetic field.

$\vec{r} = (x_g, y_g, z_g),\ \vec{p} = (p_x, p_y, p_z)$
$|r| = \sqrt{x_g^2 + y_g^2 + z_g^2},\ cos(\theta) = \frac{\vec{r}\cdot\vec{p}}{|r||p|}$







Now we invite another two angles:

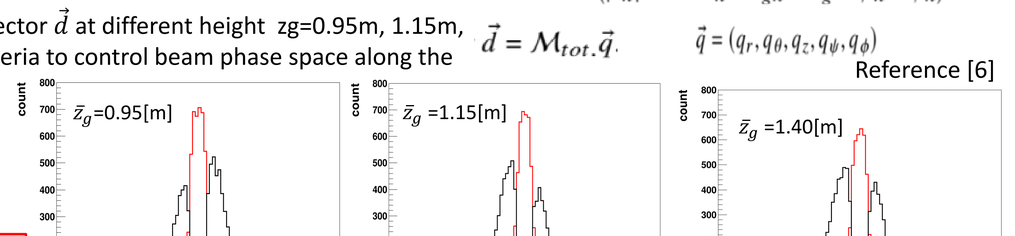
$sin(\psi) = \frac{p_z}{|p|},\ cos(\phi) = \frac{p_x}{\sqrt{p_x{}^2 + p_y{}^2}}.$

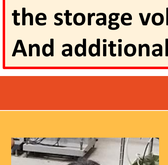
- ✓ We have 5-phase space parameters. Try to find a correlation to judge beam phase acceptance for |z|<3cm storage.
- ✓ Find a five-dimensional eigen vector $\vec{q}$ of red points phase-space.
- ✓ We define total particles' (N=red + black) matrix M_{tot} and evaluate residues $\vec{d}$.
- ✓ Components of $\vec{d}$ indicates how differ red and black sub-groups as in below histograms.
- ✓ Obtained residue vector $\vec{d}$ at different height zg=0.95m, 1.15m, 1.40m indicates criteria to control beam phase space along the beam channel.

$$\mathcal{M}_{red} = \begin{pmatrix} |\vec{r}_0| - \bar{r} & \theta_0 & z_{g0} - \bar{z}_g & \psi_0 & \phi_0 \\ |\vec{r}_1| - \bar{r} & \theta_1 & z_{g1} - \bar{z}_g & \psi_1 & \phi_1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ |\vec{r}_n| - \bar{r} & \theta_n & z_{gn} - \bar{z}_g & \psi_n & \phi_n \end{pmatrix}$$

$\vec{d} = \mathcal{M}_{tot}.\vec{q}.$ $\quad \vec{q} = (q_r, q_\theta, q_z, q_\psi, q_\phi)$

Reference [6]





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

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