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学位(専攻分野)	博士(理学)
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(Form 3)

Summary of Doctoral Thesis

Name in full Muhammad Abdul Rehman

Title A Validation Study on the Novel Three-Dimensional Spiral Injection Scheme with the Electron Beam for Muon g - 2/EDM Experiment

The muon anomalous magnetic moment $(g - 2)_{\mu}$ is one of the most important measurements in elementary particle physics. The most recent measurement of $(g - 2)_{\mu}$ at Brookhaven National Laboratory (BNL) results in more than 3σ discrepancy compared with the equally precise Standard Model prediction. This disparity could be indicative of new physics beyond the standard model. To resolve this discrepancy, a new muon's g - 2/EDM (E34) experiment at J-PARC aims to measure $(g - 2)_{\mu}$ to a precision of 0.1 ppm and electric dipole moment (EDM) down to the sensitivity of 1.5×10^{-21} e.cm. The key objective of measuring $(g - 2)_{\mu}$ is to store spin polarized μ^{+} beam in a magnetic field and evaluate the evolution of the spin precession vector. In the E34 experiment, a muon beam with an emittance less than 0.5π mm·mrad and a momentum of 300 MeV/c from a muon accelerator will be injected into a compact 3-T solenoid magnet. The muon beam will be stored on a 0.66 m diameter orbit. The solenoid magnet will provide an unprecedented local field uniformity of 0.1 ppm (peak to peak).

A new three-dimensional spiral injection scheme has been invented to inject the beam into a compact solenoid magnet. This new injection scheme will enhance injection efficiency and overcome technical challenges related to the small storage orbit diameter. In the spiral injection scheme, the beam will be injected at a vertical angle into the storage magnet. The radial component of the fringe field of the solenoid magnet will decrease the vertical angle of the beam as it approaches the midplane of the magnet. Finally, a magnetic pulsed kicker will guide the beam to the storage volume where the beam will be stored under a weak focusing field. However, the injection of the accelerated beam into such a small storage orbit is unprecedented; therefore, a demonstration experiment to establish the feasibility of this new injection scheme is inevitable.

The purpose of this research was to develop a scale down Spiral Injection Test Experiment (SITE) with an electron beam to demonstrate the ideology behind this new injection scheme.

An electron beamline of a length of 2 m has been designed and constructed for the SITE. The beamline consists of a triode-type thermionic electron gun with a LaB_6 cathode to generate a DC electron beam of 80 keV with a beam current of approximately 100 μA. Subsequently, a magnetic lens was placed to prevent the growth of the beam. A collimator with a diameter of 3 mm and a length of 5 mm was placed at a distance of 0.7 m from the exit of the electron gun. A pair of air-core steering coils has been installed to control the transverse position of the 80 keV electron beam. Next, three rotation quadrupole magnets were installed to control the beam phase space for the spiral injection. An electron beam in a straight beam line was successfully commissioned and confirmed at several locations via fluorescent screen monitors. The emittance of the electron beam after collimation was measured by the quadrupole scan method. The emittance value in the horizontal direction was estimated 0.61±0.05 mm·mrad and in the vertical direction, it was 0.41±0.04 mm·mrad. In order to estimate the beam transverse coupling strength a simple procedure was developed. The coupling strength of the beam after the collimator was estimated to 0.2±0.6. This small value of coupling means decoupled beam after the collimator.

A normal conducting solenoid-type storage magnet of field strength 82.5 Gauss was designed and constructed to store the electron beam in an orbit with a diameter of 0.24 m. In the case of SITE, the field index value "n" (strength of weak focusing: $0<n<1$) of 1.65×10^{-2} was set. This higher value of the field index relaxes the phase space requirement and vertical kicker parameters for SITE.

A non-invasive gas monitor was used to detect the electron beam track in the storage magnet. A charge-coupled device (CCD) camera was used to observe fluorescent light originating from the gas monitor. An electron beam track of four turns in the vacuum chamber of the storage magnet was confirmed by this gas monitor, which is a good qualitative tool to efficiently verify the electron beam track inside the storage magnet. However, a gas monitor lacks the ability to provide quantitative information about the position of the beam and the profile in the storage magnet. Therefore, a special type of a wire scanner for determining the beam position and measuring the profile in the solenoid magnet was designed, constructed and successfully commissioned for SITE. Two wire scanners were installed on the storage magnet to measure the beam profile and beam evolution in the storage magnet.

Due to the axial symmetric field of the solenoid magnet, a strongly XY-coupled beam is required. To produce the required phase space for the solenoid-type storage magnet, a beam transport line consisting of three rotatable quadrupole magnets has been designed and built for SITE. The vertical beam size reduction by means of phase space matching and other geometrical information have been successfully measured by the wire scanners and confirmed by the simulation. The vertical beam size had been reduced to 25.68±0.31 mm with the phase matching as compared to vertical beam growth of 78.41±0.83 mm without any rotatable quadrupole magnets.

To store the beam at the center of the storage magnet, a pulsed magnetic kicker was designed and simulated. From simulation studies, the best design parameters for the magnetic kicker have been determined. As explained earlier in the case of SITE, the field index value of 1.65×10^{-2} was used. This value of the field index allowed to use pulse width of 50 ns for the kicker. In addition, it also provides a weak focusing trap of ±50 mm at storage region. A tracking simulation with the best beam phase space that can achieved by the three rotatable quadrupole magnets has been performed. And it was estimated that injection efficiency of 81% can be achieved for SITE.

The purpose of this study was to prove the ideology of 3-D spiral injection scheme with the electron beam. The qualitative and quantitative details of the vertical and horizontal beam profiles and positions inside the solenoid storage magnet are one of the most important requisites for the successful 3-D spiral injection. Therefore, a wire scanner type beam position and profile monitor was developed for the SITE. The knowledge and experience of wire scanner development to extract the beam profile and position for the SITE storage magnet greatly helped to understand the beam behavior inside the solenoid storage magnet. Moreover, it paved the way for the development of a similar quantitative monitor for the successful 3-D spiral injection in the case of E34. The method to measure the transverse beam coupling developed at the SITE will also be implanted at E34 to estimate the coupling strength at the matching point.

Hence, evidence from this study concludes that the novel 3-D spiral injection scheme can be applied to the E34 storage magnet with the appropriate phase space matching and a quantitative monitor for the solenoid type storage magnet.

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Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏 名　　Muhammad Abdul Rehman

Title
論文題目　　A Validation Study on the Novel Three-Dimensional Spiral Injection Scheme with the Electron Beam for Muon g - 2/EDM Experiment

J-PARC 加速器の E34 実験において計画されているミューオンの異常磁気モーメントの超高精度での測定は標準理論を超える物理現象の発見につながる可能性のある重要な実験である。実験の精度を飛躍的に向上させるためには磁場の一様性が極めて優れた 3T 磁場強度の超伝導 MRI 型ソレノイドを用いるが、そこにミューオンビームを蓄積するためには従来のような蓄積ビーム旋回軌道面内での入射方式を適用することが不可能であり、世界で初めて開発された三次元螺旋軌道入射方式を採用することになった。この方式ではビームの水平方向と垂直方向の運動の結合（XY 結合）が強いためにビームサイズの増大を引き起こすので、入射前のビームにこの影響を相殺するような相関を持ったビーム光学的な整合を取っておくことが重要であることがこれまでに明らかになっている。

Rehman 氏はこの新しい入射方式の原理検証を行うために、事前の試験には使用することが困難なミューオンの代わりに熱電子銃からの電子ビームを常伝導ソレノイドに三次元螺旋軌道で入射しそのビーム特性を測定するためのテストスタンドを構築した。そこでは、電子銃からの DC ビームをパルス化するための静電チョッパー、XY 結合のあるビーム整合を取るために中心軸の周りに回転することのできる四極電磁石のシステム、ビームの Twiss パラメータを測定するためのスクリーンモニター、入射したソレノイド内の三次元軌道を観測するための N2 ガスモニター、三次元軌道上でのビームサイズをより定量的に測定するための 3D ワイヤースキャナーシステムなどの開発を行った。そして測定された初期ビームの Twiss パラメータを基にした計算により、必要とされる XY 結合を作るような四極電磁石の磁場強度と回転角のパラメータを限られた数の自由度の中で求めた。こうして得られたパラメータに基づいてビーム入射試験を行い、ワイヤースキャナーによる測定により、シミュレーションで予測される程度までソレノイド内でのビームサイズを小さくすることができることが確認された。

この Rehman 氏の研究により、適切な XY 結合ビーム整合を取ることによりソレノイド内の三次元軌道でのビームサイズを必要な程度に小さくすることができることが確認されたこととこのビームサイズを定量的に測定する方法が確立されたことはミューオンによる E34 実験における三次元螺旋軌道入射方式の実現に向けて重要な示唆を与えている。

本審査会ではこれまでの研究の手法と結果についての発表を行い、質疑応答でも質問に対する的確な回答を行なっており、本研究に関する深い理解を有していると判断できる。また論文は英語で書かれており、本審査におけるプレゼン及び質疑応答も全て英語で行われ英語能力も十分であることが確認できた。またこの研究に関しては IPAC の国際会議等（peer review 付き）で発表し、別途投稿論文を準備中である。以上のことから本論文は十

分に学位授与に値すると認められ、審査員全員一致で合格とした。