THE MICE TARGET*

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Abstract

The MICE experiment [1] uses a beam of low energy muons to test the feasibility of ionization cooling. This beam is derived parasitically from the ISIS accelerator at the Rutherford Appleton Laboratory. A target mechanism has been developed and deployed that rapidly inserts a small titanium target into the circulating proton beam immediately prior to extraction without undue disturbance of the primary ISIS beam. The first target drive was installed in ISIS during 2008 and operated successfully for over 100,000 pulses. A second upgraded design was installed in 2009 and after more than half a million actuations is still in operation. Further upgrades to the target design are now being tried in a separate test rig at the Rutherford Appleton Laboratory. The technical specifications for these upgraded designs are given and the motivations for the improvements are discussed. Additionally, further future improvements to the current design are discussed.

THE MICE EXPERIMENT

The goal of the MICE experiment is to construct a section of cooling channel long enough to demonstrate a measurable cooling effect. This is achieved by reducing the transverse emittance of a muon beam by the order of 10%. Several different particle detectors will be used to measure the cooling effect particle by particle with high precision, the aim being to achieve an absolute accuracy on the measurement of emittance of 0.1% or better. The emittance measurements will be performed with muon beams of different momenta within the range of 140 to 240 MeV/*c* and a variety of beam optics and absorber materials will be tried. Much of the primary beamline for the experiment has been constructed and commissioned and work is now focussing on installing the major components of the cooling channel.

MUON SOURCE

The ISIS accelerator based at the Rutherford Appleton Laboratory in the UK is a high power neutron spallation source. It accelerates protons from a kinetic energy of 70 MeV at injection to 800 MeV at extraction, over a period of 10 ms. The next injection follows 10 ms later. The MICE target has been designed to operate parasitically on the accelerator, inserting a small titanium shaft into the proton beam during the last 2 ms prior to beam extraction. Pions created by the interaction are collected, their subsequent decay providing the source of muons for the MICE experiment. The MICE target must be completely outside the beam during injection and acceleration, being driven to overtake and enter the beam in the 1-2 milliseconds before extraction when the protons are close to their maximum energy. The target must then be outside the beam envelope again before the next injection. To achieve this, the acceleration required of the target is of the order of 800 ms^{-2}.

During the 10 millisecond acceleration period the beam at the target location shrinks from a radius of ~48 mm to ~37 mm. Since the exact position of the edge of the beam and the intensity of the halo shows some variation, the insertion depth of the target is adjustable. MICE will only sample the beam up to a rate of a few Hz, so actuation is on demand, synchronised to trigger on signals from both MICE and ISIS.

Two targets have operated on ISIS since the experiment started. The first target drive was installed in ISIS during 2008 and operated successfully for over 100,000 pulses. A second upgraded design was installed in 2009 and after 550,000 actuations is still in operation.

THE TARGET DRIVE

The target drive is a brushless DC permanent magnet linear motor. This motor consists of a moving magnetic assembly that operates inside a set of 24 flat coils that are contained within the stator body. The magnetic assembly is attached to a long cylindrical titanium shaft coated with Diamond Like Carbon (DLC) [2]. This shaft is magnetically propelled by the interaction of the magnets with the stator coils. The shaft is supported by two plain bearings, one at each end of the stator. This is a demanding application; the target must accelerate at ~800 ms^{-2} and the components of the target system must remain compatible with the ultra high vacuum of the ISIS system.

As this paper focuses upon the details of the recent upgrades to the target mechanism, further information on the initial hardware design and control of the first target device that was installed onto ISIS can be found in the conference proceedings presented at PAC 09 [3].

MONITORING

The target drive is monitored continually during operation. The target's position - obtained optically, total beam-loss signal produced by ISIS, beam intensity and the beam-loss produced in the vicinity of the target mechanism are currently recorded by a local PC.

The target Data Acquisition (DAQ) system therefore provides a record of the trajectory of the target and also allows the calculation of its velocity and acceleration.

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The record of ISIS beam-loss allows correlation of target behaviour with the rate of particles being lost from the ISIS beam. Measurements of the number of useful muons down the MICE beam-line by other instrumentation is used to optimise the target insertion parameters.

MOTIVATION FOR TARGET UPGRADES

The two targets that have been installed and operated on ISIS have functioned successfully for an extended period of time; however the strict requirement that all components must be compatible with the UHV of ISIS has meant that the sliding bearing mechanism has had to remain un-lubricated. As access to operational targets is limited, special attention has had to be paid to both the design and construction of these bearings to ensure that the target has a long and reliable service life.

To aid development work on the target a test rig that replicates the section of beampipe on ISIS on which the target is installed was built at the Rutherford Labs. This test rig runs under UHV and allows a target mechanism to be run and inspected under conditions that closely replicate those observed on ISIS. This permits a variety of hardware configurations to be tried without the constraint of limited access.

Historically the lifetime of the bearings on individual targets has varied markedly from stator to stator. To ensure that only good targets are installed onto ISIS it has been necessary to demonstrate a period of successful running on this rig before installation.

The variability in the bearing lifetime has led to a development program of which the primary aims are to both increase the lifetime of, and minimise the variability in the lifetimes of, the target's bearings. In order to achieve these goals the program has initially concentrated on two objectives; firstly to improve the mechanical construction of the stator and secondly to try alternative bearing designs and materials. As will be described, this has been a successful approach; good progress has been made improving the lifetime of the bearings.

A third objective, to improve the electromagnetic performance of the target through development of the coil design, is now being investigated. An improvement in the electromagnetic design should improve the wear rate of the bearings [4].

MECHANICAL REDESIGN

During the period that the first stator was operating on ISIS in 2008 the target underwent some significant design changes to improve its mechanical stability. The aspiration was to improve the mechanical tolerances between the target components and to stiffen the shaft. This would ensure that there was less mechanical variability between stators, improving the alignment and reducing the stress on the bearings.

To this end the stator encapsulation was redesigned as was the interface between the stator body and the connecting flanges. The geometry of the shaft was changed from a cruciform cross section to a tubular cross section, significantly stiffening the shaft for the same mass due to the increase in the second moment of area.

The bearings were redesigned so that the active surfaces were continuous, allowing a tighter shaft/bearing tolerance to be achieved. The bearings were DLC coated so that the bearing shaft interface was DLC on DLC, identical to the first target installed on ISIS.

Two redesigned targets were constructed and tested on the target test rig. One of these targets demonstrated a significant improvement in operational stability and no observable wear was seen on the bearings during a running-in period of 50,000 actuations. This target was installed on ISIS during the summer of 2009. Since then this target has operated admirably; regular inspections along with DAQ analysis has not shown any indication of significant bearing wear.

The second stator did not perform as well and showed visible bearing wear during its running in period on the test rig. Given the fine mechanical tolerances achieved with the stator construction this has suggested that there may be another factor influencing the rate of bearing wear. As will be discussed there is some indication that this factor could be an electromagnetic asymmetry.

BEARING DESIGN AND INTERFACE

Since the original tests in 2009 on the two mechanically improved targets a series of additional bearing tests have been performed using the second target from the pair (the one that was not installed onto ISIS). After several tests demonstrated that a DLC shaft on DLC bearing could not be made to work consistently with this particular stator a new bearing material was sought.

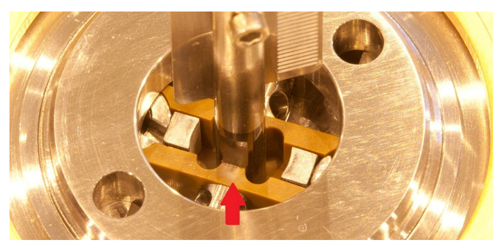

Figure 1: Photograph showing the detail of the top bearing in the target mechanism. The active part of the bearing is made from a plastic called VESPEL® (red arrow). Two separate cylindrical sections of the shaft bear on cylindrical bores in the top and bottom bearings. The top bearing also prevents rotation; this is achieved via flats on the shaft that bear against isolated flats on the bearing - as shown above. The bottom bearing is also made from VESPEL® but is of a simpler circular design.

The bearings were redesigned to take an insert of a high density polyimide plastic called VESPEL®. Initial tests in 2010 with this HD plastic were encouraging. Over 2 million actuations were achieved before the test was voluntarily terminated. Unfortunately one side of the top of the test shaft was rougher than the other side, (this was due to their having been a non contacting flat in the DLC bearing design) which resulted in the generation of a small amount of particulate matter as the shaft rubbed against the bearing surface during the test period. The total volume of wear over the test period was small; however the generation of a small amount of particulates would not be acceptable for use in ISIS.

Further tests were performed in 2010/2011 that utilised the same stator with a fully polished DLC shaft and new VESPEL® bearing inserts. A mechanical trap was added to the target to prevent the migration of any particulate matter into ISIS. After 4 million actuations virtually no bearing wear was observed and the mechanical trap has prevented any particulate matter from escaping the target device. These tests are being repeated.

ELECTROMAGNETIC DESIGN

The different rate of bearing wear observed in two mechanically identical stators indicated that there may be electromagnetic asymmetries within the second stator. A finite element model of the stator was built to understand the effect that field asymmetries have on the production of lateral forces on the target shaft [4]. This model indicated that the stator was very sensitive to field asymmetries, and that strong lateral forces during target operation could be expected for small deviations in the symmetry of the azimuthal magnetic field.

To support the finite element modelling the second stator was field mapped at Daresbury Laboratory (STFC). The resulting field map has indicated that minor field asymmetries do exist within this particular stator. However without access to the first stator that is currently operational on ISIS it is difficult to conclusively prove that these asymmetries are the cause of the discrepancy between the two stators, although the lack of any other known cause suggests that this is likely.

The coil construction and assembly of the coil stack now remains the largest mechanical uncertainty in the construction of the target mechanism and significant effort is being made to improve the construction of both the coils and the coil stack. To this end a test bobbin is being manufactured so that a set of coils can be counter wound onto this one fixed bobbin.

This represents a departure from the current method of constructing the coil stack where each coil is manufactured individually and then inserted onto a central former, and should give several advantages. The one-piece bobbin should ensure that all of the coils are accurately aligned with each other, and counter-winding the coils with square cross section wire will provide a more uniform coil construction as well as improving the packing density. It is hoped that if the test piece is successful, and that the associated FE modelling does not indicate any problems, that the next target will be constructed using this method.

The finite element model has also indicated that an increase in the diameter of the permanent magnets would be beneficial to the design as it improves the force to mass ratio of the target shaft, theoretically permitting larger accelerations to be achieved for the same coil current. As this is effectively a performance improvement for 'free' this change will be tried later this year.

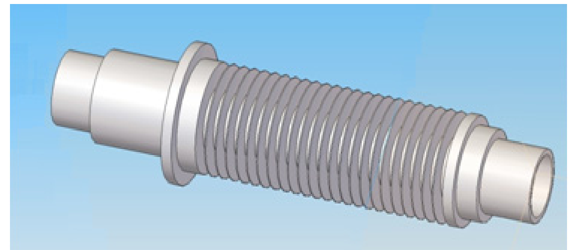

Figure 2: The new bobbin for the target will help to align the 24 flat coils. Each coil will be accurately counter-wound onto the bobbin. This should reduce any lateral forces and improve both the cooling and electromagnetic uniformity of the coils.

CONCLUSIONS

This paper has shown that a significant amount of development work has been and continues to be undertaken on the target mechanism. This work will ensure that the target will perform reliably for extended periods of time for the MICE experiment. With a reliable target, further development of the target controls would allow the target to be operated at higher accelerations, improving the rate at which muons can be produced for MICE whilst simultaneously reducing beam losses for ISIS.

REFERENCES

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