DESIGN AND PERFORMANCE OF THE MICE TARGET*

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Abstract

The MICE experiment [1], uses a beam of low energy muons to study ionisation cooling. This beam is derived parasitically from the ISIS synchrotron at the Rutherford Appleton Laboratory. A mechanical drive has been developed which rapidly inserts a small titanium target into the beam after acceleration and immediately prior to extraction, with minimal disturbance to the circulating protons. One mechanism has operated in ISIS for over half a million pulses, and its performance is summarised. Upgrades to this design have been tested in parallel with MICE operation; the improvements in performance and reliability are presented, together with a discussion of further future enhancements.

THE MICE EXPERIMENT

The goal of the international Muon Ionisation Cooling 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%. A set of particle detectors will be used to measure the cooling effect particle by particle with high precision, to achieve an absolute accuracy on the measurement of emittance of 0.1% or better. The emittance will be measured with muon beams of various momenta within the range of 140 to 240 MeV/*c* and a variety of beam optics and absorber materials will be employed. The primary beam-line 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, at which MICE is housed, is located at the Rutherford Appleton Laboratory in the UK. 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 ms 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 show some variation, the insertion depth of the target must be 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 operated for over 550,000 actuations until summer 2011, when damage occurred apparently due to a control fault.

THE TARGET DRIVE

The target drive is a brushless DC permanent magnet linear motor, consisting of a moving magnetic assembly which operates inside a set of 24 flat coils contained within the stator body. The magnetic assembly is attached to a long cylindrical titanium shaft mounted vertically, the bottom end of which acts as the particle production target. This shaft is normally held magnetically levitated out of the beam. On receipt of a trigger, it is magnetically propelled in and out of the beam by the interaction of the magnets with the stator coils. The shaft is supported by two sliding bearings, one at each end of the stator. This is a demanding application; the target must accelerate at ~800 m s^{-2} and the components of the target system must remain compatible with the ultra high vacuum of the ISIS system, while operation must be maintained in a high-radiation environment.

Further information on the initial hardware design and control of the first target device that was installed in ISIS can be found in the conference proceedings presented at PAC 09 [2]. This paper presents some aspects of the performance of the target operating in ISIS, together with details of recent upgrades to the target mechanism which have been tested in parallel with ISIS operation and plans for further enhancements.

THE TARGET ON ISIS

The target installed in ISIS has a diamond-like carbon (DLC) coated titanium shaft sliding through DLC-coated stainless steel bearings. The bearings serve to keep the target on the axis of the coils in the stator, and also prevent rotation of the shaft. The latter constraint is important, as the optical position measurement system

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(used for both control and monitoring) requires that a slotted vane is maintained perpendicular to the laser beams which detect its location. The DLC provides a very hard, low-friction surface which was hoped to have a low susceptibility to wear. Off-line tests, however, have showed that the lifetime of such DLC-on-DLC bearings has been highly variable. Some tests have involved targets which have operated for millions of cycles with negligible wear, while in other cases patches of DLC coating have transferred between shaft and bearing, resulting in metal-on-metal contact, rapid wear and the production of dust. (This behaviour is believed to be a consequence of operating the bearings in vacuum, though the reason for the variability in performance is not fully understood.)

In order to demonstrate the integrity of the bearing surfaces for the device operating in the accelerator, regular calibration runs have been performed. The target was operated under standard drive conditions (corresponding to a nominal depth of strike of about 44 mm) and the variability in the position of maximum depth was analysed. Figure 1 shows such calibrations for the full running period, from November 2009 to July 2011. As can be seen, there has been negligible deterioration in target performance.

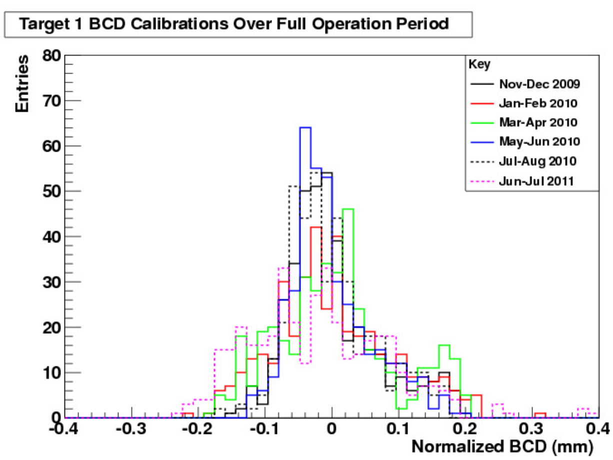

Figure 1: The spread of beam-centre distance (BCD) at maximum depth for target calibrations throughout running of the present target in ISIS.

TARGET UPGRADE RESULTS

As indicated above, the DLC-on-DLC bearings have not proved to be sufficiently reliable for long-term use in the inaccessible environment of a synchrotron. We have therefore embarked on a programme of improvements to the bearings, backed up by systematic tests on a dedicated rig which replicates the section of beam-pipe in ISIS on which the target is installed. Targets are run under identical conditions to those in ISIS, including UHV, except that there is no particle beam and so no induced radiation. This means that the target is accessible at all times for inspection or modification.

The goal was to minimise bearing wear, in order both to maintain target lifetime and to eliminate any possibility of abraded material migrating into the synchrotron. This has been achieved by a number of modifications [3]. The DLC-coated titanium shaft has been maintained, but the steel bearings have been fitted with inserts made of high-density polyimide plastic known as VESPEL®, as shown in figure 2.

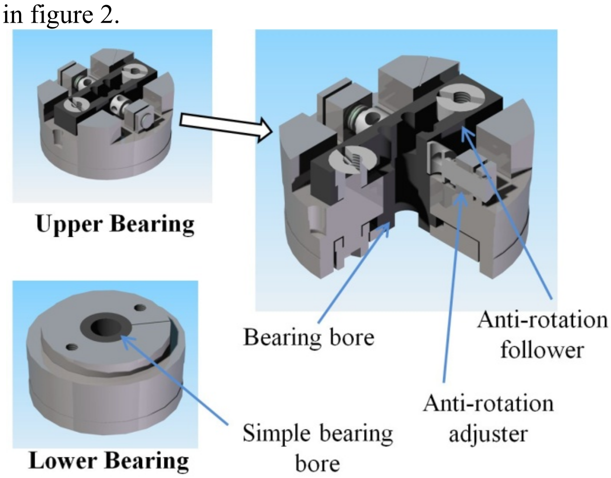

Figure 2: Upper and lower bearings, showing the VESPEL® inserts.

The lower shaft and bearing are cylindrical, while the upper shaft has two carefully polished flats. Similarly polished, adjustable VESPEL® followers make contact with the flats, and ensure the correct alignment of the target. Precise tolerances are maintained, to ensure that there is minimal play in the bearings, and so guarantee that the target is well aligned at all times. Tests of revised bearings with this design showed a high degree of reliability and a long lifetime. There was, however, noticeable wear on the anti-rotation followers where they had been rubbed by the edges of the flats on the shaft. This produced a small amount of abraded material, which was found mainly to adhere to the shaft and bearing mounts. Subsequent bearings have been constructed with semi-circular cut-outs in the followers (as illustrated) to prevent the edges of the flats cutting into the bearing surfaces.

As a precaution, a set of traps are fitted beneath the bottom bearing. These comprise a series of concave “shelves” with a small aperture for the target shaft, and are designed to catch any abraded material from the bearings. Even with the first anti-rotation flats (without cut-outs), when the drive was dismantled and inspected after a million actuations, no evidence of any material was found outside the target actuator.

Several bearing sets have now been assessed on the test rig, with minor variations in clearances and operating regimes. These have operated for between 1 and 4 million cycles, at the end of which in each case a visual inspection revealed very little wear. The performance was monitored throughout the tests, and as shown in figure 3 some change in behaviour is observed. When driven in a nominally identical fashion through ~44 mm, the actual position reached showed an increasing spread and a slight shift in mean. This is attributed to a small increase in friction with wear. Also after about 1 M pulses, the target did not always return to exactly the correct starting position for the next actuation. It should be noted that this spread in positions is small compared with natural fluctuations in the ISIS beam size, and that more sophisticated use of the controller can compensate for the drift in position, and correct the start point.

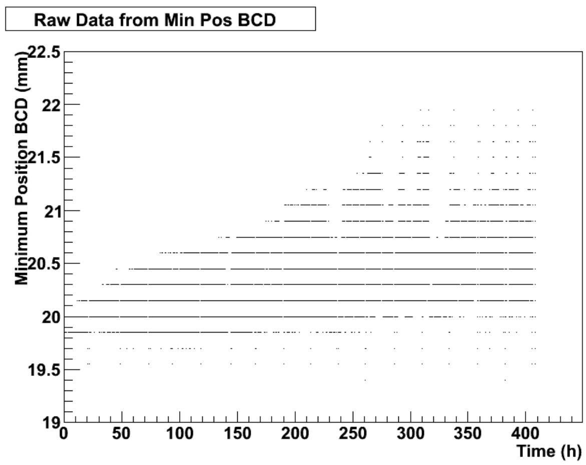

Figure 3: Minimum target distance from beam centre over a prolonged run. 420 hours corresponds to ~1.1 M cycles. Note the variation of ~1 mm is small compared with both the strike of ~44 mm and fluctuations in ISIS beam size.

FURTHER TARGET ENHANCEMENTS

Prior to the tests of VESPEL® bearings, different target drives, as noted above, have shown inconsistent lifetimes and amounts of wear. Magnetic field asymmetries will lead to off-axis forces, which would be expected to contribute to increased wear. After the early failure of a steel/DLC bearing, the stator in use (which is the same coil assembly as has been employed for all the VESPEL® tests reported in this paper) had its field mapped at Daresbury Laboratory (STFC). The resulting measurements do indicate some irregularities and offsets in the magnetic centre compared with the mechanical axis of the device. (It has not yet been possible to measure the field in the stator mounted on ISIS, which has showed a much longer lifetime with steel/DLC bearings, to prove that the offsets are the cause of the variation in lifetime.)

The present stators are constructed of 24 flat coils which are wound and potted individually. These are inserted onto a central former, separated by thin copper shims which make contact with an external cooling jacket. The pre-assembled coil stack is then slid onto the tube which forms the wall of the vacuum chamber, and through which the target shaft passes. Visual inspection of the coils shows significant non-uniformities in the windings, in particular where a wire from the outside connects to the innermost turns. This form of construction incurs an uncertainty in the lateral position of the coils of the order of 0.1 to 0.2 mm, of the same magnitude as the offsets observed in the field map.

A new method of stator construction will shortly be tested, where the coils are wound directly onto a slotted former as illustrated in figure 4. This is constructed in stainless steel, machined down to form the vacuum tube, with 24 slots 2.5 mm wide, separated by "fins" 0.5 mm thick. A groove in each fin will lead a wire to the centre, and coils will be wound using square-section silver wire with dimensions chosen to give a whole number of turns per layer. The fins will connect directly with a water-cooled aluminium cooling jacket, which should improve heat transfer.

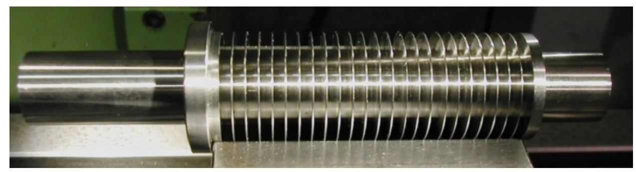

Figure 4: The new former for the target. Each coil will be wound directly onto the former, improving alignment and cooling of the magnetic assembly.

The inner diameter of the tube has been reduced, to bring the coils closer to the permanent magnets on the shaft and so increase electromagnetic coupling and the acceleration which can be imparted to the target. This, together with the improved cooling, which will allow larger currents to be used, should allow greater control in how the target intercepts the particle beam, and so more flexibility in the production of muons for MICE. The first stator employing the new construction will be tested in autumn 2011.

CONCLUSIONS

The Muon Ionisation Cooling Experiment has operated a target on ISIS allowing muons to be used for beam-line optimisation and detector commissioning. Its behaviour has been monitored and very little deterioration in performance was observed due to wear until failure occurred, believed to be caused by a control fault.

A programme of off-line tests has led to the production and optimisation of bearings using VESPEL®, with operational lifetimes in excess of 1 M actuations. Further improvements will involve winding coils in situ onto a special former, to achieve enhanced mechanical, electromagnetic and thermal performance.

REFERENCES

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[3] C. Booth et al. The MICE Target. Contribution TUP282 to Particle Accelerator Conference PAC'11 28 March – 1 April 2011, New York, USA. (Proceedings in press)