THE TARGET DRIVE FOR THE MICE EXPERIMENT

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Abstract

The MICE Experiment [1] requires a beam of low energy muons to test muon cooling. This beam will be derived parasitically from the ISIS accelerator. A novel target mechanism is being developed which will allow the insertion of a small titanium target into the proton beam halo on demand. The target must remain outside the beam envelope during acceleration, and then overtake the shrinking beam envelope to enter up to 5 mm into the beam during the last 2 ms before extraction. The technical specifications are demanding, requiring large accelerations and precise and reproducible location of the target each cycle. The mechanism must operate in a high radiation environment, and the moving parts must be compatible with the stringent requirements of the accelerator's vacuum system. A prototype linear electromagnetic drive has been built, and the performance is being measured and improved to meet design specifications.

ACCELERATOR REQUIREMENTS

The ISIS accelerator at the Rutherford Appleton Laboratory operates at 50 Hz. It accelerates protons from a kinetic energy of 70 MeV at injection to 800 MeV at extraction, over a period of 10 ms. During this time, the beam (at the target location) shrinks from a radius of 67 mm to 48 mm. The next injection follows 10 ms later. The MICE target must be completely outside the beam during injection and acceleration, being driven to overtake the beam and enter up to 5 mm in the 1-2 ms before extraction, when the protons are close to their maximum energy; it must then be outside the beam envelope again before the next injection. Since the exact position of the edge of the beam and the intensity of the halo may show long-term variations, the insertion depth must be adjustable. The acceleration required of the target is of the order of 1000 ms^{-2}, or 100 g. MICE will only sample the beam at one or a few Hz, so actuation must be on demand, synchronised to ISIS.

THE TARGET DRIVE

The linear motor required to drive the target into and out of the beam consists of a moving magnet assembly on a long shaft carrying the target (the shuttle) inside a series of coils (the stator).

The Stator

The stator, illustrated in Figure 1, consists of a cylinder containing 24 flat coils mounted around a ceramic tube, in a manner to facilitate the removal of heat generated by current flow. Individual coils, with an inner diameter of 18.3 mm, consist of 36 turns of copper wire and have an axial thickness of 2.85 mm. After winding, coils are impregnated with insulating varnish to form a stable compact unit and to facilitate conduction of heat. They are assembled onto a temporary aluminium former (previously coated with release agent) with paper spacers to give a pitch of 3 mm. Connecting leads are led radially outwards. Thermocouples inserted close to the inner and outer radii of the coils monitor the temperature. A coiled copper tube placed around the coils carries cooling water, and the assembly is inserted into an aluminium outer cylinder with the insulated copper wires and cooling pipes emerging through holes in the outer cylinder. Spacers at each end of the coil assembly, inside stainless steel endplates screwed to the outer cylinder, compress the coils to their correct locations. The unit is vacuum-impregnated with a thermally conductive but electrically insulating potting compound.

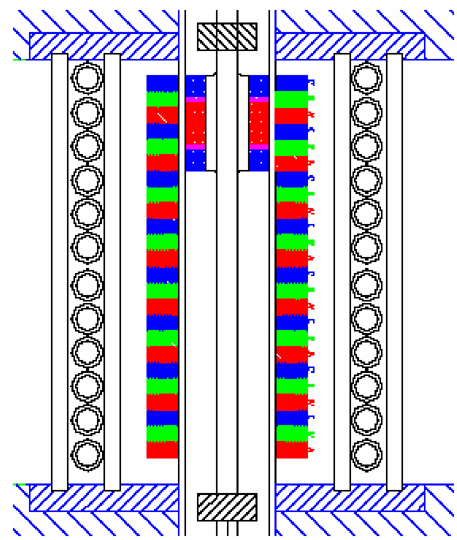

Figure 1: The stator, also showing the shuttle magnets.

The Shuttle

The shuttle consists of a magnet assembly mounted on a long shaft, which also carries the target at the bottom and position sensing equipment at the top. To prevent the magnets from falling out of the coils in the absence of power, a larger diameter disc acts as a stop that can rest on a lower ceramic bearing. The target, shaft and stop are machined from a single piece of titanium. The target, at the lower end of the shaft, consists of a blade of titanium 1 mm thick, 10 mm wide and 35 mm high. The shaft, for most of its length of 530 mm, has a cross-shaped cross-section, with material thickness of 1 mm and a total width of 6 mm. The cross-shaped form not only provides mechanical rigidity but also, by passing through a similarly shaped aperture in the lower bearing, maintains the orientation of target and readout vane. The upper third of the shaft is circular in cross-section, of diameter

4 mm. The magnet assembly slides onto the shaft from above, resting on the top of the cross-shaped section. It is held in place with a disc which is riveted to the shaft. The final 94 mm of the shaft has a flat to carry the readout vane.

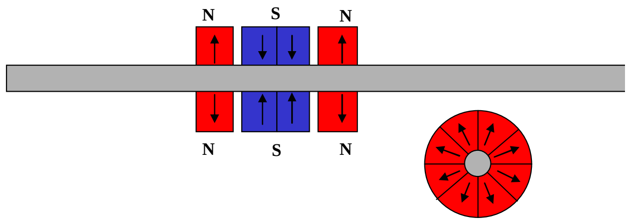

Figure 2: The shuttle magnet assembly.

The magnet assembly consists of three radial magnets, as shown in figure 2. Each of the magnets is produced in octants. The magnet material – sintered iron-neodymium-boron – is cut into the required shapes by wire-erosion. The pieces are then appropriately magnetised, before being assembled on a mild-steel former, separated longitudinally by ceramic washers and held in place in a jig for gluing with a two-component aircraft adhesive. Once the glue is cured, the magnet unit is lightly machined to the precise outer radius required. The unit is then attached to the shaft, as described above. The shaft passes through two ceramic bearings, one above and one below the coil assembly, which maintain the magnet unit on the axis of the stator while allowing longitudinal (vertical) movement with minimal friction.

Position sensing is performed using a quadrature system viewing an optical vane (figure 3) mounted at the top of the shaft. The vane is a wire-eroded double-sided "comb" of 0.2 mm thick steel, having 157 teeth 0.3 mm wide (with 0.3 mm gaps) and 3 mm long on one side of a 6 mm wide spine, and a single similar tooth two-thirds of the way down the vane on the other.

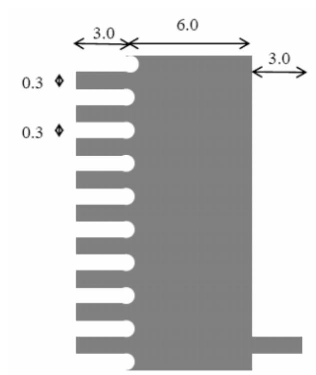

Figure 3: Section of the readout vane.

Vacuum Seals

A ceramic tube passes through the centre of the stator, forming the wall of the vacuum chamber. It is 18 mm exterior diameter and 1 mm thick zirconia, with a length of 130 mm. There is sufficient clearance between stator coils and ceramic tube to prevent stresses on the tube. A pair of steel flanges, above and below the stator, clamps it firmly in place and also contains recesses for indium seals. A further pair of flanges, above and below the first pair, mates with these and provides the pressure on the indium wire to form vacuum seals between the ceramic tube and flanges. This second set of flanges contains the recesses which carry the ceramic bearings with (for the lower bearing) a pin to locate in the bearing and maintain it in its correct orientation. A third pair of flanges completes the assembly, holding the bearings in place and forming vacuum seals with Conflat fittings. The uppermost flange carries the tube with windows for optical readout, while the lower flange is welded to a set of bellows.

SUPPORT & ISOLATION MECHANISM

The target must be actively levitated to keep it out of the beam. Any mechanical or electrical failure would result in an obstruction to ISIS. An isolation system is therefore incorporated to allow the drive to be removed. The drive is supported from a steel plate below a heavy frame, accurately located in the ISIS vault. Between the two is a screw jack, driven by a linear motor (or hand crank in case of failure of the motor). Thin-walled, edge-welded bellows connect the bottom of the target drive to the beam pipe, via a gate valve. The bellows compress to a length of 44 mm in normal use, but extend to 244 mm allowing the lowest position of the target to be lifted above the valve. Closure of the valve separates the vacuum space surrounding the target from the ISIS beam.

POSITION SENSING AND DRIVE CONTROL

Knowledge of the position of the target is required for both control and monitoring purposes. The stator coils are driven from a 3-phase supply, and to achieve maximum shuttle acceleration the phase of the current through the coils must be adapted to the exact position of the magnets. It is also necessary to monitor the depth of insertion of the target into the beam, so that this can be correlated with particle production, and future cycles of target insertion can be adapted accordingly.

Optical Readout

The position of the shuttle is measured with an optical quadrature system. As described above, the top of the shaft carries a readout vane in the form of a comb with a pitch of 0.6 mm. The teeth on the comb interrupt laser beams, and the modulation of two of these beams is used to determine the change in the shuttle's position. A third beam fixes the absolute position. As the target assembly is in a high radiation environment, all active optical and electronic components are situated remotely, and signals are delivered to and from the readout via optical fibres.

The vane, moving inside the vacuum chamber, is viewed through a pair of flat glass windows. Optical alignment pieces outside the vacuum chamber allow the delivery and collection of the transmitted beam. Three lasers operating in the red are connected to silica monomode fibres which deliver the beams to the first alignment unit. Each fibre is connected to a collimator and converging glass lens. The focused beam passes through a window to a focal point in the plane of the readout vane. It then diverges again, passes through the second window and is collected by a second lens and collimator into a 200 µm silica multimode fibre. (A silica-clad multimode fibre is used from the alignment block to a local patch panel, with radiation-hard polymer-clad silica multimode fibre from there to the control area.). The pairs of collimators are accurately aligned to ensure maximum transmission of light. Two beams view the same optical comb, but are offset by the pitch multiplied by (n + ¼), hence giving signals in quadrature. The rate of pulsing of a beam as it is interrupted by the passing comb gives the speed of motion, while the phase of the two signals determines if the comb is moving up or down. The use of both signals allows a position resolution given by the pitch ÷ 4, i.e. 0.15 mm. The absolute position is determined by a third beam viewing the other side of the readout vane which carries a single tooth. The "index mark" arising from the interruption of this beam zeros the position counter which is incremented or decremented by the other beams.

Control and Power Electronics

There are a number of modes of operation of the target drive. These include movement from powered off "park" to raised "hold" position (outside the beam), "enabled", when the electronics is waiting for a trigger, "actuating", the triggered rapid insertion into the beam, and return from hold to park position. All require the appropriately phased application of currents through the stator coils, and are under microprocessor control. The three-phase, bi-directional supply to the coils is switched through a Hex-Bridge.

The movements between power-off and park positions are unsynchronised, and do not use the position sensing system. The coils are driven with a relatively low current (~3 A) and the pre-determined sequence of currents is advanced rather slowly so that the magnet assembly and shuttle move up or down in a series of steps until the required position is reached.

Target insertion is synchronised to the ISIS machine start signal. After a programmed delay, the current through the coils is increased significantly to drive the shuttle downwards at high acceleration. Feedback from the position sensing ensures that the correct coils are powered in sequence maintaining the maximum force on the shuttle magnets. When the target is halfway through its descent, the controller reverses the currents so that the shuttle experiences a decelerating (upward) force. This decelerates the shuttle until the target reaches its maximum insertion depth and then reaccelerates the shuttle and target back up the actuator. At a second preset point the currents are reversed again, decelerating the shuttle so that it comes to a halt at its intended holding position. At this point the microprocessor changes the mode to keep the shuttle at its hold point until another actuation signal is received from ISIS.

PERFORMANCE AND MONITORING

Monitoring serves a number of purposes. It allows correlation of target behaviour with the rate of useful muons down the MICE beam-line, and readings from the ISIS beam-line monitors. It is hoped that this will allow optimisation of the target insertion. Monitoring will also allow surveying of the long term behaviour of the drive. It is therefore possible that gradual degradation, e.g. due to radiation damage, can be diagnosed, and operating parameters adjusted to compensate. Monitoring will also provide fast feedback which can be used to quickly pick up any malfunction in the target operation.

The position information provided by the optical readout is recorded by a PC in addition to being used for the immediate control of the driver electronics. Electronics latches the time when a change in position occurs, and the time and position are read by the PC at a rate of 100 kHz, with each change being written to file. This system provides a record of the trajectory of the target (see figure 4), and will also allow the calculation of velocity and acceleration. The present prototype electronics is limited to a current of 10 A and actuates through 39 mm in 60 ms, with an acceleration of 15-20 g. It is expected that 80 A will be required to reach the required 24 mm stroke in 20 ms.

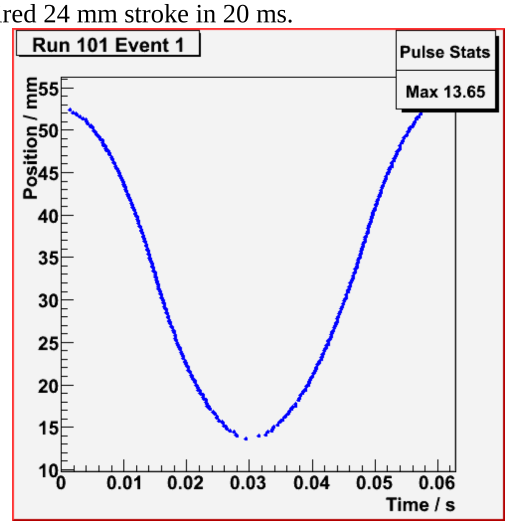

Figure 4: Example of the readout of target motion

Key parameters such as the target insertion depth and time will be passed to the central MICE monitoring system, along with parameters such as the coil temperatures. Full operational information including driver currents and coil sequences will also be recorded, giving a complete record of the target's operation during each pulse.

REFERENCES

[1] MICE, an international Muon Ionisation Cooling Experiment: proposal to the Rutherford Appleton Laboratory, submitted to CCLRC and PPARC on the 10th January 2003, http://mice.iit.edu/micenotes/public/pdf/MICE0021/MICE0021.pdf