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Design and Operational Experience of the MICE Target

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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 has been developed that inserts a small titanium target into the proton beam on demand. The target remains outside the beam envelope during acceleration and then overtakes the shrinking beam envelope to enter the proton beam during the last 2 ms before beam extraction.

The technical specifications are demanding, requiring large accelerations and precise and reproducible location of the target each cycle. The mechanism operates in a high radiation environment, and the moving parts are compatible with the stringent requirements of the accelerator's vacuum system. The first operational linear electromagnetic drive was installed onto ISIS in January 2008 and has since been operated for several tens of thousands of actuations.

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[1] Speaker

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1. Accelerator Requirements

The ISIS accelerator at the Rutherford Appleton Laboratory operates at 50 Hz, accelerating 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 ~48 mm to ~37 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 and enter the beam in the 1-2 ms before extraction where the protons are close to their maximum energy. The target 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 to achieve this is of the order of 830 ms^{-2}, or ~85 g. MICE will only sample the beam at less than one up to a few Hz, so actuation must be on demand, synchronised to both MICE and ISIS.

2. The Target Drive

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

The stator, illustrated in Figure 1, consists of 24 flat coils mounted around a steel tube. Individual coils consist of 36 turns of copper wire and have an axial thickness of 2.85 mm. After winding, each coil is impregnated with insulating varnish to form a stable compact unit. Six thin copper shims are placed between each pair of coils to facilitate heat conduction out of the coil stack. This gives a coil pitch of 3mm. Three thermocouples inserted between pairs of coils enable the temperature to be monitored. A coiled copper tube soldered to a solid copper jacket around the coils in contact with the copper shims carries cooling water. The entire assembly is inserted into an aluminium outer cylinder, the stator body, with the insulated copper wires and the cooling pipes emerging through a slit in the side.

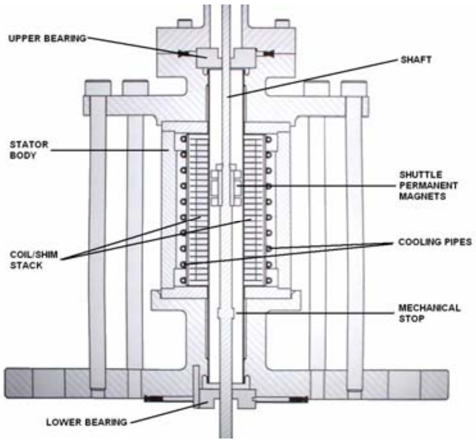

Figure 1: The stator mounted in its supporting flanges. (Note that the full length of the target shaft and the optical readout block are not illustrated.).

The shuttle consists of a magnet assembly mounted on a long shaft, which also carries the target at the bottom and a readout vane at the top. To prevent the magnets from falling out of the coils in the absence of power, a larger diameter section of the shaft acts as a stop that can rest on a lower 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 and carries the magnet. It is held in place with a stop clamped to the shaft. The final 94 mm of the shaft has a slot to carry the readout vane. The sections of the shaft that are in contact with the bearings are coated with Diamond Like Carbon (DLC) to minimise friction and to give a hard wearing surface. The magnet assembly consists of three radial iron-neodymium-boron magnets, as shown in figure 2.

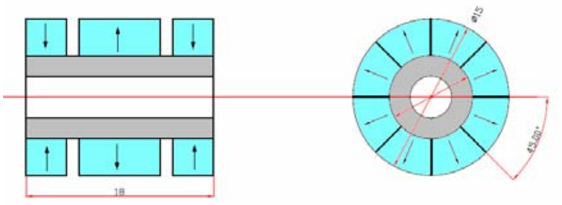

Figure 2: The shuttle magnet assembly.

The shaft passes through two steel bearings, one above and one below the stator assembly which maintain the magnet unit on the axis of the stator while allowing longitudinal (vertical) movement with minimal friction. The bearings, like the shaft, are coated with diamond like carbon to give a hard wear resistant surface.

Position sensing is performed using a quadrature system viewing an optical vane mounted in the slot at the top of the shaft. The vane is a wire-eroded double-sided "comb", 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 side.

3. 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 and jacking system is 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 stepper motor. A set of thin-walled UHV bellows connects the two assemblies allowing the lowest position of the target to be lifted above a gate valve. Closure of the valve separates the vacuum space surrounding the target from the ISIS beam.

4. Position Sensing and Control

Knowledge of the position of the target is required for 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 track the exact position of the magnets. The depth of insertion of the target into the beam must also be monitored, to be correlated with particle production. Future cycles of target insertion can then be adapted accordingly.

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 determines 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.

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 six IGBTs powered by a capacitor bank.

The movement between power-off and the shuttle's holding position is done passively without feedback from the optical system. These movements and levitation of the shuttle at its holding point can be done at a relatively low coil current of approximately 3 Amps.

Target insertion is synchronised to the ISIS machine start signal. After a programmed delay, the current through the coils is increased to 60 Amps to drive the shuttle through its trajectory 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 levitated at its hold point until another actuation signal is received from ISIS.

5. Monitoring

The target drive is monitored continually during operation. The position information provided by the optical readout is recorded in addition to being used for the control of the driver electronics. Time and position are read at a rate of up to 60 kHz, and written to a file. Also recorded is the total beam loss signal produced by ISIS and one-bit digitisation of the beam current. The record of the trajectory also allows the calculation of velocity and acceleration. 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 will be used to optimise target insertion parameters.

Monitoring will also allow surveying of the long term behaviour of the drive. It is possible that gradual degradation, e.g. due to radiation damage, can be diagnosed, and operating parameters adjusted to compensate. As the MICE experiment enters the next phase, the system will be modified to allow parameters such as the target insertion depth and time to be passed to the central MICE monitoring system.

6. Performance

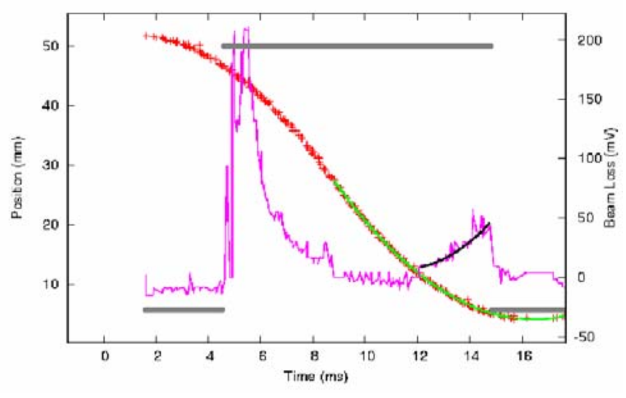

Figure 3: The target trajectory (curved line - mm) and its relationship to beam loss (noisy line - mV). The large spikes on the LHS of the beam loss are due to ISIS injection losses. Losses caused by the target can be seen as the rise in the beam loss signal on the RHS of this signal (fitted). The" top hat" signal (solid line) shows when the beam was on in ISIS (10ms).

The target system installed on ISIS has demonstrated particle production for MICE. It has run at an insertion rate of ~0.5 Hz whist ISIS has operated at its normal operating frequency of 50 Hz, so demonstrating that the target can operate parasitically. Figure 3 illustrates beam loss production by the target. Beam loss has so far been limited so that an understanding of the target's performance with respect to ISIS operation, particle production and irradiation of the target area can be studied. A significant increase in particle production will be required in the future for optimum running of the MICE experiment.

References

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