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PW Blatchford et al.

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Diversification of the position sensing instrumentation for the JET neutral beam calorimeters

Peter Blatchford, Julian Hawes, and Simon Warder

***Abstract*— The JET neutral beam injection system incorporates a copper panel calorimeter in each beamline, instrumented with thermocouples to provide diagnosis of the beam shape and alignment. The panels are rotated out of the beam path to allow the beam to enter the torus; they are inertially cooled and can only sustain full beam power for a fraction of a second, hence must be fully withdrawn during plasma operation. Calorimeter position is monitored with in-vacuum micro-switches close to the limits of travel, but these have proved unreliable in the past. Along with various other weaknesses in the mechanism, this has led to periods of operation where the bottom of the panel has unknowingly scraped the edge of the beam and in 2013 this resulted in melting of the edge of one panel and a large water leak. A procedure has been implemented to check the calorimeter position and thus avoid a repeat of the melting incident; however in 2015 an independent review panel examined NBI reliability and recommended that a diversity of methods should be used to detect the positions of the calorimeters. This paper summarises the methods considered and details the option selected for installation during the 2017 shutdown.**

***Index Terms*— Calorimeter, JET, position sensing**

I. INTRODUCTION

EACH of the 2 JET neutral beam injectors (NBIs) incorporates 2 calorimeters – water cooled copper panels approximately 2m tall by 1.5m wide, which can be independently rotated so as to intercept the beamlines at a shallow angle. They are instrumented with rows of thermocouples and act as a beam dump to allow conditioning of the beam sources as well as providing alignment and beam profile information. The panels are water cooled but are not designed for steady state operation and can only withstand full beam power for a fraction of a second. Hence when injecting beams into the torus, it is essential that the calorimeters are fully rotated out of their path.

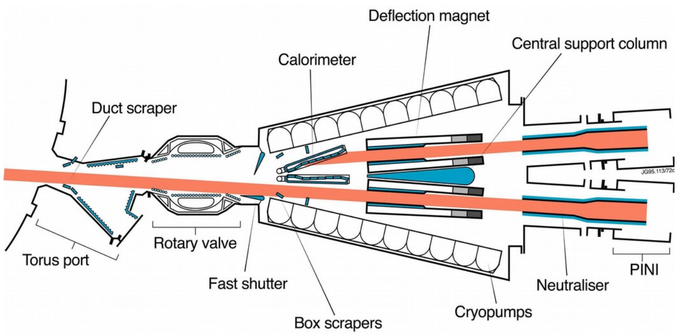

Fig. 1. Plan view of a neutral beam injector, showing one calorimeter panel intercepting a beam and one rotated for injection into the torus.

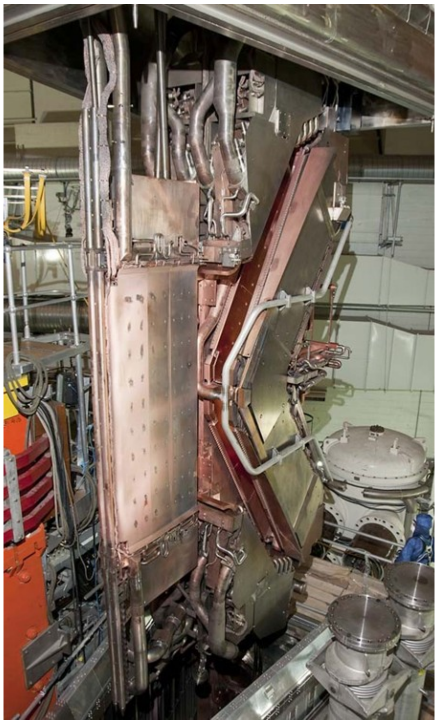

Fig. 2. Neutral beam components being lifted, calorimeter is the tall copper panel on the left.

Confirmation of calorimeter position is provided by micro-switches at the top and bottom of each panel. These are arranged such that a first switch indicates when the calorimeter is 10mm from its end stop and a second indicates when it reaches the end stop. However various weaknesses in the components have led to incomplete or unreliable position feedback being available. These have included:

- A tendency for the switch mechanisms to stick, thus rendering the switches useless;
- Twisting of the calorimeter structure, as they are

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To obtain further information on the data and models underlying this paper please contact publicationsmanager@ccfe.ac.uk.

Peter Blatchford is with Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK (email: peter.blatchford@ukaea.uk).

Julian Hawes is with Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK (email: julian.hawes@ukaea.uk).

Simon Warder is with Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK (email: simon.warder@ukaea.uk).

actuated from the top but have considerable resistance to motion at the bottom from bearing friction and water bellows reaction forces;

- Cumulative damage to bearings, resulting in poor positional control of the entire structure.

These problems have led to periods of operation where the bottom of the calorimeter panels have unknowingly scraped the edge of the beam and in 2013 this resulted in melting of the edge of one panel and a large water leak. A procedure has been implemented to check the calorimeter position and thus avoid a repeat of the melting incident; however in 2015 an independent review panel examined NBI reliability and recommended that a diversity of methods should be used to detect the positions of the calorimeters.

Fig. 3. Melt damage of a calorimeter panel

A project was hence initiated to develop an alternative position sensing mechanism to supplement the existing micro-switches, for installation during the 2016/17 shutdown. The following sections describe the requirements and constraints defined for the system; sensing technologies considered; laboratory investigations undertaken on the most promising technologies; final selection and detailed design.

II. REQUIREMENTS AND CONSTRAINTS

The key requirements and constraints are summarised as follows:

- *Detect the position of the bottom of the panels, over at least the final 20mm when approaching the closed position*; ideally the sensors would operate over the full travel of the panels, but the most critical part is close to the closed (out of beam) position. The bottom of the panels is more important than the top, since the position of the bottom is less well controlled.
- *Measurement accuracy better than 5mm, ideally 2mm*; a number of discrete position signals (e.g. from multiple switches) would be acceptable, but continuous measurement is preferred.
- *Compatibility with ultra-high vacuum*.
- *Operating temperature range of -10ºC to +30ºC*; the temperature of the calorimeter structure is known to remain close to ambient, due to the large flow of water through the cooled components.
- *Presence of sputtered copper*; copper is sputtered by the beams impacting the calorimeter panels and the nearby ion dumps; careful shielding would be required for devices sensitive to this.
- *High neutron level (particularly during the planned D-T operation)*; this means that no active electronics could be located close to the sensor; to be confident of survival, such components must be outside of the torus hall biological shield. Spare twisted pair cables were already available between the neutral injection box (NIB) and diagnostic cubicles, the total distance being about 60 m.
- *Magnetic fields during pulsing (though sensor need not operate when pulsing)*; magnetic fields generated by the torus coils may affect some sensors.
- *High levels of vibration due to water flow*; flow induced vibration is an unquantified effect, but it is thought to have contributed to poor reliability of the micro-switches.
- *Limited number of electrical feedthroughs;* a maximum of 10 signal pairs were available in each NIB (with 2 calorimeters) in existing spare feedthroughs, installing new feedthroughs was not considered viable.

III. TECHNOLOGIES CONSIDERED

The following technologies were considered but rejected at an early stage, due to either being incompatible with the requirements or needing more development than was considered feasible in the time available:

Optical sensing

Optical sensors typically incorporate electronics close to the sensing location, which would be vulnerable to neutron damage. It may be feasible to utilise an optical fibre with remote electronics but this would require an optical feedthrough which was not available. Any optical sensor would also be vulnerable to sputtered copper.

Capacitive sensing

Capacitive sensors have similar limitations to optical, in requiring electronics close to the sensing location and being vulnerable to sputtered copper. Development of a bespoke sensor with remote electronics was considered to be too high risk.

Reed switches

A number of concepts utilising reed switches were considered. For example, a row of switches with a permanent magnet attached to the calorimeter, switching them as it moves past them. This would require multiple signal paths but this could be reduced to a single pair by connecting the switches to a series of resistors – the number of switches energised could be detected by measuring the resistance.

Alternatively, an electro-magnet could be used to activate a single reed switch (with one fixed and one moving) and the current required to do so would be a function of distance.

These concepts were more promising but were considered to be high risk, with uncertainties over robustness to vibration, repeatability, hysteresis and susceptibility to background magnetic fields.

Two technologies however were thought to be viable and were investigated further: an inductive eddy current sensor and use of strain gauges to detect deflection of a flexible element. These are described in more detail in the following sections.

IV. INDUCTIVE EDDY CURRENT SENSOR

Various techniques based on electro-magnetic induction were considered. An obvious candidate is an LVDT (Linear Variable Differential Transformer) but it was not thought that an off the shelf device could be obtained that would meet the environmental requirements. Development of a bespoke LVDT would be possible and would have the potential to be a good solution but was considered to be too large and risky an undertaking given the limited time available; hence a simpler, lower risk approach was preferred.

An eddy current sensor is inherently simpler and works using a single coil supplied with a high frequency current so as to generate a magnetic field. If the coil is close to a conductive material, the field will induce eddy currents in the material, which in turn will generate a field which opposes the field from the coil. This has the effect of increasing the inductance of the coil, and this change in inductance can be used to determine the proximity of the conductive object.

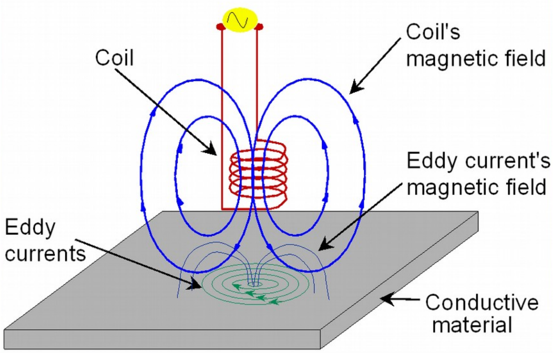

Image courtesy of Microwave Soft

Fig. 4. Eddy current sensor principle of operation

The concept was appealing because of its simplicity and the lack of moving parts, hence it should be straightforward to design a sensor to be robust. It also only requires a single pair of wires per sensor, which is advantageous given the limited number of feedthroughs. However initially it was felt that it would be unlikely to work well with the electronic components such a long distance from the sensing coil (60m). This was an easy thing to assess in the laboratory though so a number of test coils were trialled with a 60m long cable connecting the coil to the driving electronics.

Initial results were promising and by adjusting the dimensions and number of turns on the coil it was found that a sensing range of 40mm could be obtained with a 120mm diameter coil. The optimum geometry was found to be a flat profile - 105 turns were wound into a profile of 2mm high and 20mm radially, as illustrated in Fig. 5. The test coil is shown in Fig. 6.

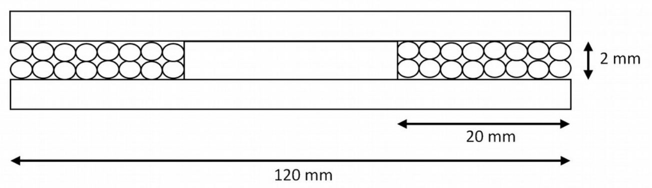

Fig. 5. Optimised coil geometry

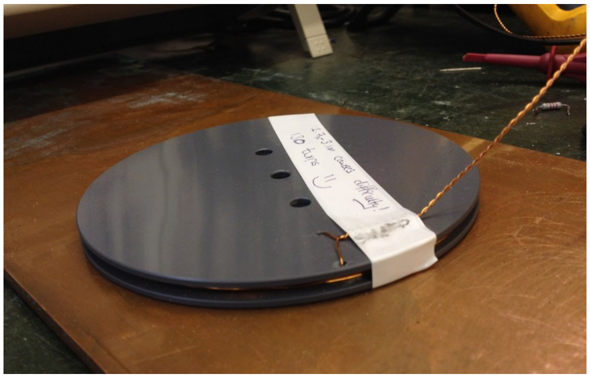

Fig. 6. Test coil

The coil had an inductance in free space of 1.8mH and was energised with an oscillator at a frequency of 46kHz. When it was placed in contact with a copper plate the oscillator frequency increased to 84kHz. The frequency response of the circuit with changes in distance to the copper plate is shown in Fig. 7.

One of the concerns with using such a long cable was that its capacitance makes a significant contribution to the overall circuit capacitance and hence affects the natural frequency. Any changes to either the capacitance or resistance of the cable would therefore have a direct effect on the circuit response and limit the overall sensor accuracy. However the cable would be fixed i.e. it would not change in length and the only variable likely to have any effect on its electrical properties is temperature. The cable in the laboratory test was therefore heated to about 50°C and this was found to have no measurable effect on the sensor response. In reality, the ambient temperature in the torus hall where the cable would be installed does not change by more than a few degrees during operational periods.

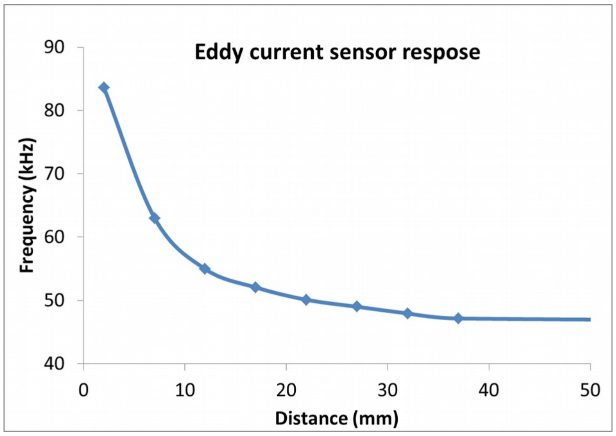

Fig. 7. Eddy current sensor response with distance from a copper plate

The laboratory tests demonstrated that an eddy current sensor was electrically viable, but environmental constraints had to be considered as well. Ultra-high vacuum compatibility could be achieved using polyimide (Kapton) insulated wire and mounting the coil on an insulating material such as PEEK or machine-able ceramic. Fig. 8 illustrates a conceptual installation and design of a single piece coil former; at the bottom of each calorimeter is a large copper shielding panel which would make an ideal target for an eddy current sensor. However the figure shows an additional small panel acting as the target, mounted on a threaded stud as this would make initial set up much simpler (the target panel would need to be set up as close as possible to the coil with the calorimeter closed, without actually touching it).

The remaining concern with this concept was its vulnerability to sputtered copper. It is clear that deposition of a conducting layer on the surface of the coil would have an impact on its performance, though it was hoped that the likely thickness of a sputtered copper layer would be sufficiently below the skin depth of the eddy currents at the frequency of operation as to have only a small effect. This could not be proven easily though, as the rate of build-up of deposited copper is not easy to predict. Tests on the laboratory coil showed that a sheet of aluminium foil approximately 10 micrometres thick had a dramatic effect on its performance, even when only covering a small portion of the coil, so it was felt that the only way to be sure of immunity from sputtered copper would be to shield the coil from it completely. Such shielding would have to be positioned a suitable distance from the coil to ensure it would have no effect on its performance and various arrangements were considered, though none were able to provide good confidence of complete protection. This was not considered an insurmountable problem, but overall it was felt that the level of development required to produce a robust device was rather greater than for the other technology being investigated at the same time, as described in the next section.

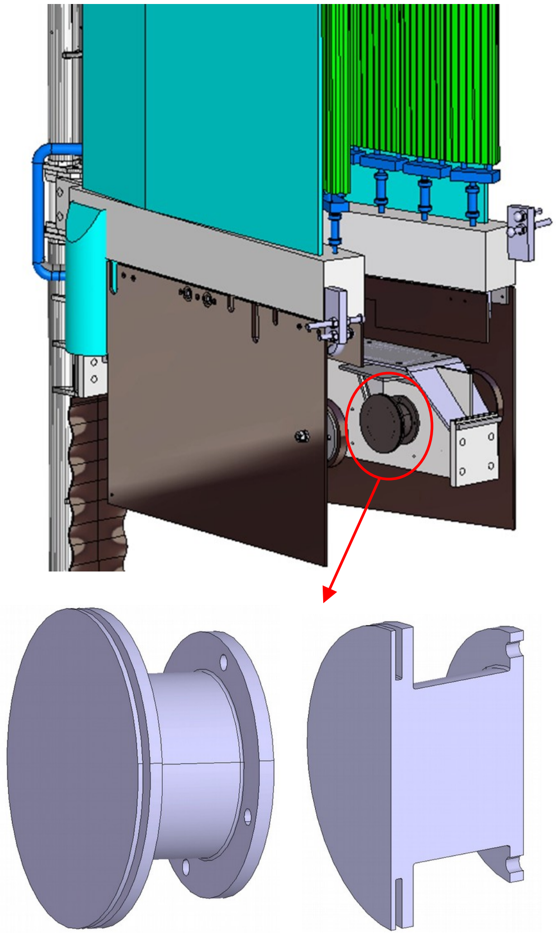

Fig. 8. Conceptual installation of eddy current sensor

V. STRAIN GAUGE SENSOR

This concept was based on using a spring element which is deflected by the movement of the calorimeter panel and is instrumented with strain gauges to detect its deflection. This had appeal in that it should be possible to eliminate any sliding or rotating parts, which are inherently problematic in vacuum (and had caused reliability problems with the micro-switch assemblies), and is fundamentally simple both mechanically and electrically. The approach taken was to design a sensor that would be pushed by the panel over the last part of its travel as it approaches fully closed rather than over its full travel, to give maximum sensitivity in this most critical position.

The principle of operation is illustrated in Fig. 9. A spring strip has strain gauges attached to both sides, when it flexes the gauges on one side are in tension and those on the other side are in compression. By using 4 gauges (2 on each side), a full Wheatstone bridge arrangement can be used as shown in Fig. 10. This maximises the output of the bridge (compared to using only one or two gauges) and also provides automatic temperature compensation. Any change of gauge resistance due to temperature is the same in all gauges, so the output of the bridge is unaffected.

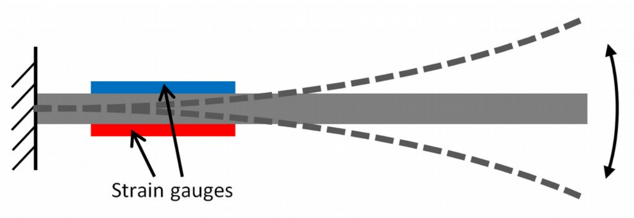

Fig. 9. Principle of operation of the strain gauge sensor

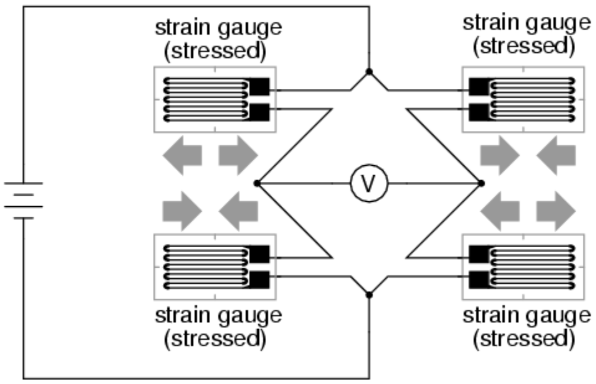

Image courtesy of EETech Media & Marketing

Fig. 10. Full Wheatstone bridge arrangement of strain gauges

A fundamental requirement is vacuum compatibility so it was essential that suitable strain gauges and adhesives could be identified. Fortunately it is commonplace for strain gauges to be encapsulated in polyimide, which is a low out-gassing polymer commonly used in vacuum. Bonding of strain gauges is normally done with either cyanoacrylate type adhesives or epoxy; use of epoxies in vacuum is quite widespread and a number have been developed specifically for low out-gassing. A substantial amount of data has been compiled by NASA in assessing materials suitable for use in space, including adhesives and is publically available [1].

The adhesive selected was EPO-TEK 353ND two-part epoxy, manufactured by Epoxy Technology Inc. A sample was obtained and cured at the recommended 150°C for 1 hour and assessed in a vacuum chamber with a residual gas analyser at ambient temperature, which indicated no outgassing products of concern. Strain gauges were obtained from Omega Engineering Inc, from their Karma gauge range. These are polyimide encapsulated and use Karma alloy for the resistance grid rather than the more usual Constantan. This gives them a longer fatigue life and they are more stable over time and are recommended for transducer applications. The gauges were also checked for outgassing and again no products of concern were detected.

One concern raised when assessing this concept was whether the adhesive bond would have a sufficient fatigue life, and in order to assess this a laboratory test was set up. Strain gauges were bonded to both sides of a 0.5mm thick 301 stainless steel strip. This was mounted in a test rig comprising a motor and gearbox driving a profiled wheel, which pushed a rod up and down; the rod in turn deflected the steel strip. The position of the strip could be adjusted so as to vary the deflection (and hence strain at the bond).

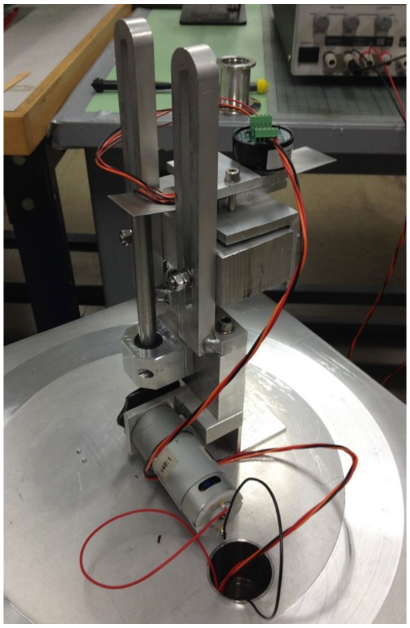

Fig. 11. Fatigue test rig

Initially the rig was set up to give a strain range at the gauge bond of 0 to 1700 microstrain (0.17%) and was operated for 2×10^6 cycles in air and a further 1×10^6 cycles under rough vacuum. The gauges were wired to an amplifier and the linearity of its output with deflection was checked before and after the test. No significant change in output was seen, indicating that the bonds were still performing consistently. The fatigue life of the strain gauges is specified as $> 10^7$ cycles at 1800 microstrain but it was intended to operate well below this level to ensure fatigue of both the gauges and the spring strip would not be a concern. A peak strain of 1000 microstrain was proposed.

It is possible that when the calorimeters are closed, the entire panel could be subjected to water flow induced vibration, thus transferring small movements at high frequency into the sensor. Hence further tests were carried out using the test rig to assess high cycle, low amplitude fatigue. In this case it was set for a strain range of 500 to 1000 microstrain and operated for 10^7 cycles; again no change in the output of the bridge was observed.

The testing concluded that this sensor concept is viable and compatible with all the defined requirements. It was considered to be lower risk than the eddy current sensor and so was selected to be taken forward to detailed design.

VI. DETAILED SENSOR DESIGN

One of the desirable requirements of the sensor was that any predicted failure should be detectable – so for example if a wire should break, this should be distinguishable from a normal operating state. When the strain gauge bridge is unstressed this will give a zero output, so it was decided that the sensor should be designed such that the spring is deflected in both directions so that it only passes through the unstressed position when moving. The output of the bridge will thus swing from positive to negative and a constant zero output will indicate a break.

One way to achieve this would be to pre-deform the spring strip into a curve and bond the strain gauges to it whilst it is clamped flat. The strain gauges will thus be stressed when the spring relaxes to its natural shape, and as the spring is pushed straight and then deformed in the opposite direction, the strain gauge stress will fall to zero and then reverse. This is a simple arrangement with a minimal number of parts, but it has the disadvantage that the peak stress in the spring strip is high since it is only deformed in one direction. So for the strain gauges to have an operating range of -1000 to +1000 microstrain, the strain range for the spring strip will be 0 to 2000 microstrain. This is high even for the highest strength metals, when considering that an unknown level of vibration might be superimposed on this static strain. For confidence in an effectively infinite fatigue life, the static strain level needs to be lower.

Of course this could be achieved simply by reducing the working strain range, but this also reduces the bridge output and hence the overall signal to noise ratio. This may not be a problem, but the sensitivity of the overall system to bridge output level can only fully be assessed when it is installed and all potential sources of noise and interference are present. It was decided that maximising the bridge output should be a priority.

The arrangement selected was to retain a flat spring strip but bias it in one direction with a separate spring. This way the peak strain on both the strain gauges and the spring strip is limited to 1000 microstrain. A torsion spring was designed to provide the biasing force and positioned so as to eliminate any sliding motion. Fig. 12 shows the final design and Fig. 13 shows a section through it, illustrating the two extremes.

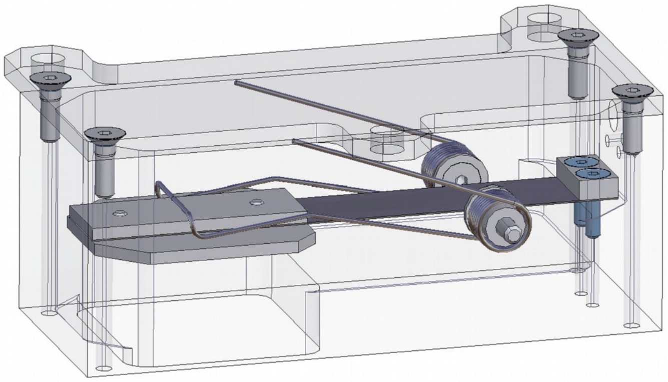

Fig. 12. Final design of strain gauge sensor

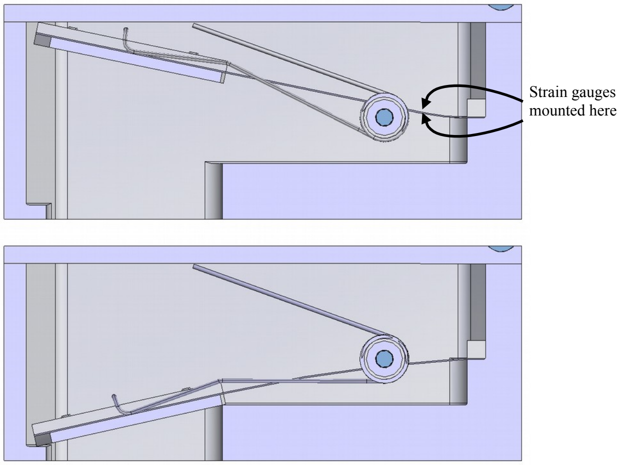

Fig. 13. Strain gauge sensor limits of travel

The installation of the sensor on the calorimeter is shown in Fig. 14. It is actuated by an adjustable ball ended rod mounted to the bottom of the moving panel. The housing provides a high level of mechanical protection for the sensing components and ensures they are well shielded from sputtered copper. The opening for the actuating rod to enter becomes closed off when the rod withdraws, so the risk of anything entering the enclosure is minimal.

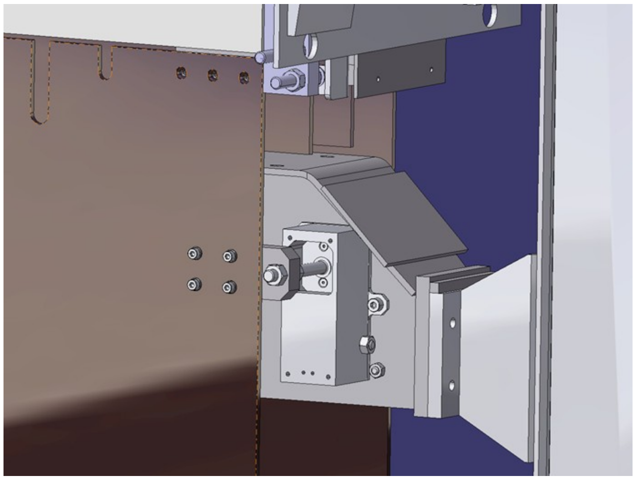

Fig. 14. Installation of strain gauge sensor

On initial installation, the calorimeter panel will be positioned against its closed end stop and the sensor actuator rod adjusted until the sensor is at its maximum travel (i.e. it touches the inside of the housing). The rod will then be backed off by a few millimetres to ensure the sensor does not quite reach its limit i.e. it does not become the end stop.

Table 1 summarises the materials selected. Other materials could be used in applications where environmental requirements are more demanding.

TABLE I
COMPONENT SUMMARY

Component	Material/specification
Spring strip	0.38mm thick 1.4310 stainless steel (301 C1300 temper)
Torsion spring	1.4319 stainless steel (302S26)
All machined parts	1.4301 stainless steel (304)
Strain gauges	Omega Engineering SGK-D6A-1000S-PC11-E, polyimide encapsulated
Strain gauge adhesive	Epoxy Technologies EPO-TEK 353ND epoxy

Strain gauges are available with a range of resistance values and for this application a relatively high resistance of 1000Ω was selected. There are a number of reasons why a high resistance was preferred:

1) The maximum allowed voltage supply to the bridge is higher, resulting in a higher voltage output;
2) The heat generated in the individual strain gauges is reduced; this may be significant in vacuum, as the only path for heat to be removed from the gauges is conduction through the very thin spring strip;
3) The resistance of the long cables between the bridge and the electronics becomes a less significant proportion of the overall resistance. The total cable resistance (i.e. per pair of wires) has been calculated to be about 10Ω.

The in-vacuum cabling is polyimide insulated copper twisted pairs. It is anticipated that the interfacing electronics will be commercial strain gauge amplifiers. If noise is found to be a particular problem then custom filtering could be incorporated, potentially along with the use of AC excitation.

VII. CONCLUSIONS

A sensor has been designed for detecting the position of the JET neutral beam calorimeters as they approach their closed positions, to supplement the existing micro-switches. It is based on the use of strain gauges sensing the deflection of a spring strip over a travel of 30mm. An alternative concept of a bespoke eddy current sensor has also been investigated and demonstrated to be viable for this application in laboratory tests. Either technique may be applicable to the sensing of position of components in other applications where more conventional sensors are not suitable.

REFERENCES

[1] https://outgassing.nasa.gov/index.cgi.