MRO Delay Line

Delay Line Pipes and Supports Design Description

Document No. INT-406-VEN-0115

The Cambridge Delay Line Team

rev 1.0

7 Feb 2008

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Change Record

Revision	Date	Authors	Changes
0.1	2008-01-10	MF, XS	First released version
0.2	2008-01-31	MF, XS	Incorporated analyses in appendix
1.0	2008-02-07	MF	Minor corrections and released

Objective

The objective of this document is to describe the principal design features of the pipe and supports to be used for the Magdalena Ridge Observatory Interferometer delay lines.

Scope

This document provides a description of the design features which are specific to the actual supports to be used for the delay lines which will be up to 190m in length. The rational for the scheme was presented, together with test results, in RD1 and will not be discussed at length here.

Reference Documents

RD1 Results of the Risk Reduction Experiments (Rev 1.0 6th December 2005)

RD2 Top-level requirements INT-406-TSP-0002

RD3 Pipe Specification (Rev 8.0 25th August 2006)

Applicable Documents

AD01 MRO Delay Line Derived Requirements INT-406-VEN-0107

AD02 Pipe and Supports Drawing set

AD03 Risk and hazard Document INT-406-VEN-0121

AD04 MRO Delay Line Documentation Plan INT-406-VEN-0120

AD05 Limits Design Description INT-406-VEN-0116

AD06 ICD: Delay line to BCF infrastructure (building) INT-406-VEN-0009

AD07 ICD: Delay line to Beam Relay system INT-406-VEN-0008

AD08 ICD: Delay line to metrology system INT-406-VEN-0010

AD09 ICD: Delay line to vacuum system INT-406-VEN-0011

AD10 Proposed Delay Line Tools, Jigs and Handling Procedures INT-406-VEN-0119

Acronyms and Abbreviations

BCA Beam Combining Area

BCF Beam Combining Facility

BRS Beam Relay System

DL Delay Line

DLA Delay Line Area

ICD Interface Control Document

ICS Interferometer Control System (now SCS)

MROI Magdalena Ridge Observatory Interferometer

MRAO Mullard Radio Astronomy Observatory

NMT New Mexico Tech

OPD Optical Path Delay

SCS Supervisory Control System

TBC To be confirmed

TBD To be determined

Contents

1 Introduction

The MROI BCF is designed to accommodate up to ten delay lines. The delay lines are mounted side by side on a separate slab foundation housed in a long narrow building (called the Delay Line Area) projecting out from the Beam Combining Area. Two walls separate the DLA from the Inner BCA and so the delay lines project through these walls to connect with the beam relay pipes but otherwise do not contact the floor slab in that area.

The maximum required length of a delay line is 190m. The distance between the centres of adjacent delay lines is 2 feet; this is the minimum practical distance and is chosen to minimise the span of the building housing them. The floor slab in the DLA is 194m (~636.5 feet) long, 6.1m (20 feet) wide and 6 inches thick for most of its length. The slab thickness is increased to 24 inches in the area where the anchors for each delay line are to be installed to resist the large moment that would be imparted on it during an earthquake.

To aid in installation and maintenance a gantry crane spans the delay lines and can be moved the whole length of the building. A walkway is provided down one side of the delay lines to an area at the far end where it is expected that the electronics and power supplies necessary to run the delay line will be housed.

The delay line pipes are mounted on flexure legs to allow for expansion or contraction of the delay line longitudinally over the environmental temperature range. For each delay line there is one anchor support near to the BCA end of the delay line which restrains the delay line longitudinally. A depiction of the pipes and supports at the BCA end of the delay line is shown in Figure 1.

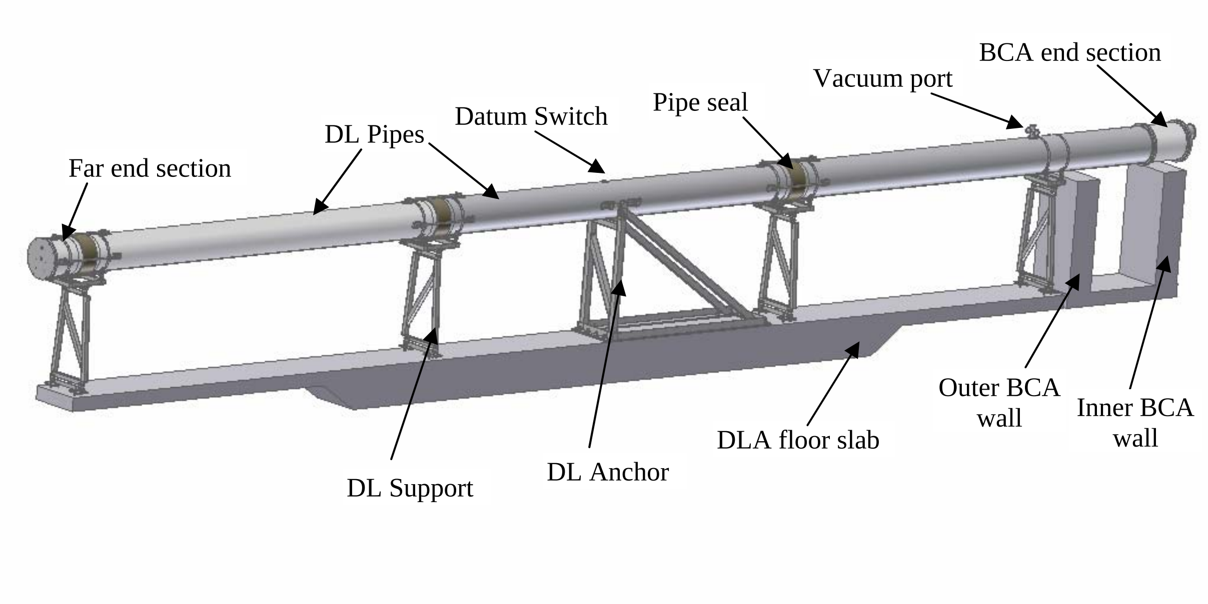


Figure 1 A 3-D view of the delay line nearest to the BCA. The wall between the DLA and the outer BCA and the wall of the inner BCA are shown. The anchor and the supports either side are positioned over the thickened floor slab. The end of the pipe at the left shows the end section that would be at the far end of the delay line. The locations of the datum switch and the vacuum port are also shown

The following sections describe the design of the delay lines, their pipes and supports, the safety and hazard issues. Analysis and design calculations are provided in the appendices.

2 Design of Pipe and supports

The design of the pipe and supports was undertaken prior to the risk reduction experiments and is described in RD1. This design has been modified somewhat to take into account the small increase in height between the test rig that has been used for the risk reduction experiments (and more recently the prototype tests) and the required beam height at MROI. Because of the much higher loading that would be placed on the anchor (due to the increased mass of the long delay line) during an earthquake a much stronger anchor design has been developed. Attention is drawn to other minor modifications in the design descriptions which follow. The design drawings for the pipes and supports are given in AD02 but note that pipe designs are based on standard 5m lengths: whilst this is the case at the anchor location it is unlikely to be the case for most of the delay line as shorter pipes are more likely to meet geometric specifications.

2.1 Delay Line Pipe

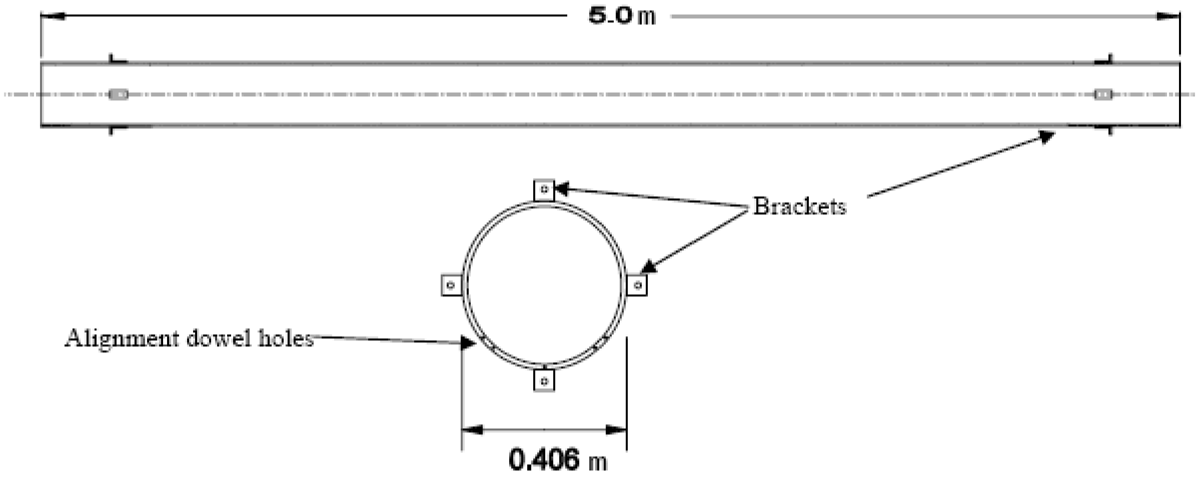
The delay line comprises a number of lengths of pipe which are joined together and supported at the correct height at each joint. To achieve vacuum integrity a standard industrial flexible pipe seal is positioned over each join and held in place by band clamps. These seals allow sufficient flexibility to account for variations in the size and shape of the pipes to be joined and also for alignment of the pipe with the desired delay line axis. The pipe is based on standard aluminium extrusions, the length of which is determined by the availability of sections which meet the required geometrical specifications.

For convenience in handling and for minimising the number of supports required the preferred length of pipe was chosen to be 5m but it is likely that manufacturers will prefer to deliver lengths of 12 feet.

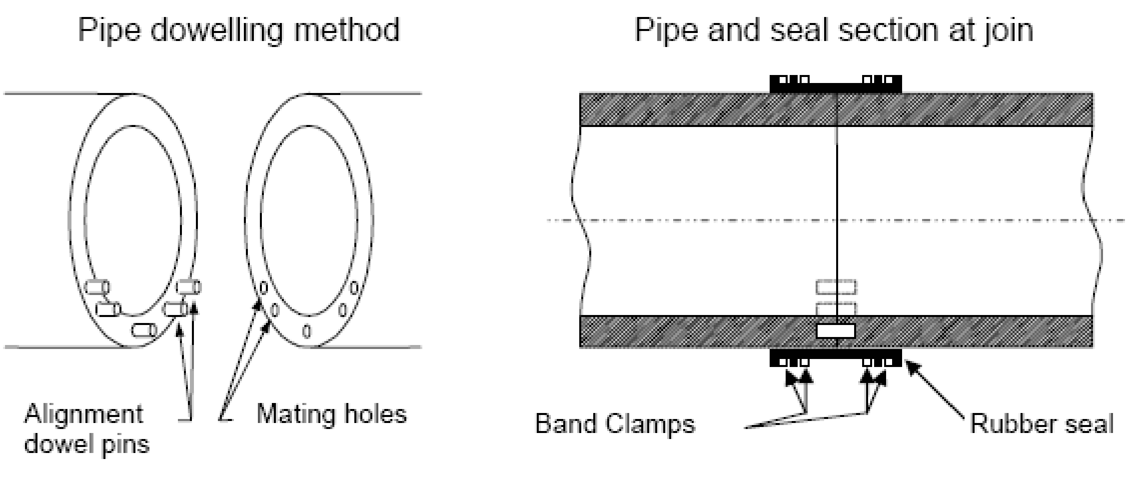
The pipe sections are machined to the required length and then prepared for being joined accurately. The specification for production of the pipes is contained in RD3.

2.1.1 Standard Pipe Sections

According to the preferred specification, each pipe section is of extruded aluminium and is nominally 5 m or 16.4 feet long and 406 mm (16 inches) in outer diameter. Four brackets are attached (welded) near each end of the pipe to assist in drawing the pipes together or pushing them apart. The pipe sections are held in alignment by two pairs of sprung steel dowel pins which are inserted into accurately placed holes in each end of the pipe. A schematic of the pipe section showing the bracket locations, dowel holes and nominal dimensions is provided below together with a description of the pipe joint details.



The alignment dowel holes are positioned so that the inner surfaces of the pipes to be joined align accurately at the region where the delay line carriage wheels run (45° from the vertical). These holes are positioned with respect to the inner surface of the pipe at those locations using a specially prepared jig. A fifth dowel hole is located at the bottom of the pipe between, and referenced to, the two pairs. This dowel provides assured local electrical conductivity for the return path of the inductive power transfer loop and also supports a prepared shim to define the point of contact when the pipes are drawn together. It is important that the pattern of dowel holes drilled at each end of a pipe have little or no rotational offset about the axis of the pipe. The dowel scheme is illustrated below.



2.1.2 Seals

Once the pipes are drawn together the vacuum seal is positioned over the join and the band clamps tightened. To ensure a good seal the outer ends of the pipes are prepared by grinding or a fine abrasive process to remove any deep handling or die marks, particularly those that run along the pipe.

2.1.3 Specific Pipe Sections

There are four other types of pipe section that are required to complete a delay line. These are:

- The anchor section
- The vacuum interface and flange section
- The BCA end section
- The far end section

2.1.3.1 Anchor Section

The anchor section is a 5m length section selected for straightness from 5m lengths which are acquired for manufacture of the beam turning cans. Two pairs of brackets are welded to this pipe to form the connection points for the anchor itself. These brackets have horizontally elongated holes, to allow for lateral deviation of the pipe, through which a large diameter threaded stud is passed and secured on either side by nuts. The threaded stud passes though a vertically elongated hole in the anchor upright to allow for adjustment of the pipe to the correct height.

The anchor section also contains a hole in the top near to the anchor fixing position into which the datum switch assembly can be fitted. This provides the most stable location for the reference position for each delay line.

2.1.3.2 Vacuum interface section

This section of pipe is another 5m length which connects between the anchor section and the BCA end section. It has a flange at one end for the connection to the BCA end section and a standard dowelled joint at the other. The flanged end carries the cantilevered weight of the end section and the vacuum seal is achieved using an O-ring. An interface to the vacuum system is incorporated near to the point where this pipe passes through the DLA wall into the outer BCA area. The details of this vacuum connection are given in AD09.

2.1.3.3 The BCA end section

This section (see Figure 2) connects by a flange coupling to the vacuum interface section and provides a flange for connection of the BCA end plate. The end section supports the limits target plate which provides the pre-limit and final limit positions for the trolley. The target plate is steel so as to actuate the magnetic limit switches mounted on the trolley and is attached to the end section at locations which are counter-bored into the flanges at either end.

2.1.3.4 The far end section

The far end section (see Figure 3) has a standard doweled interface at one end and a flange on which the far end plate is mounted. Vacuum integrity at the flange is provided by an O-ring seal. This end section also supports the limits target plate in the same way as the BCA end section.

2.1.4 End Sections and End Plates

There are two end plates, the BCA end plate through which the science and metrology beams pass, and the far end plate which supports the aerials for radio communication links with the trolley.

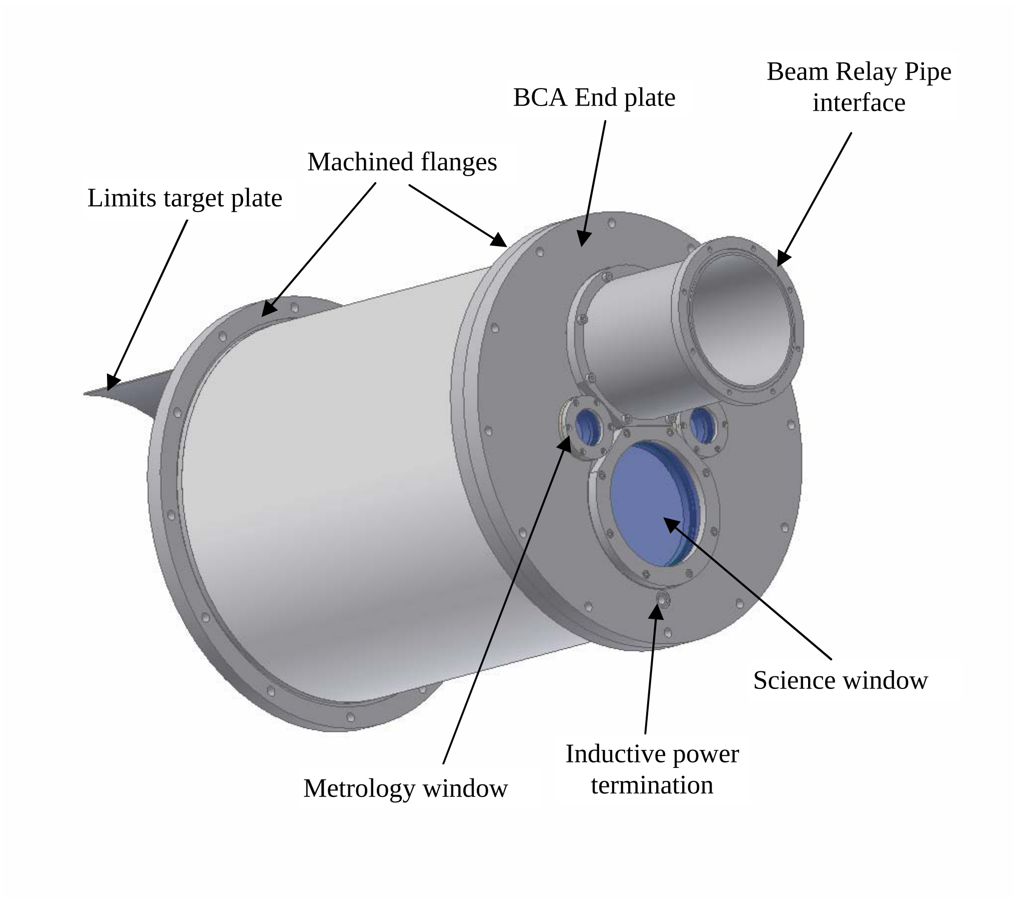


Figure 2 The BCA end section with the end plate carrying the metrology windows, the science window and the connection to the beam relay pipe. The end of the limits target plate is just visible at the left hand side.

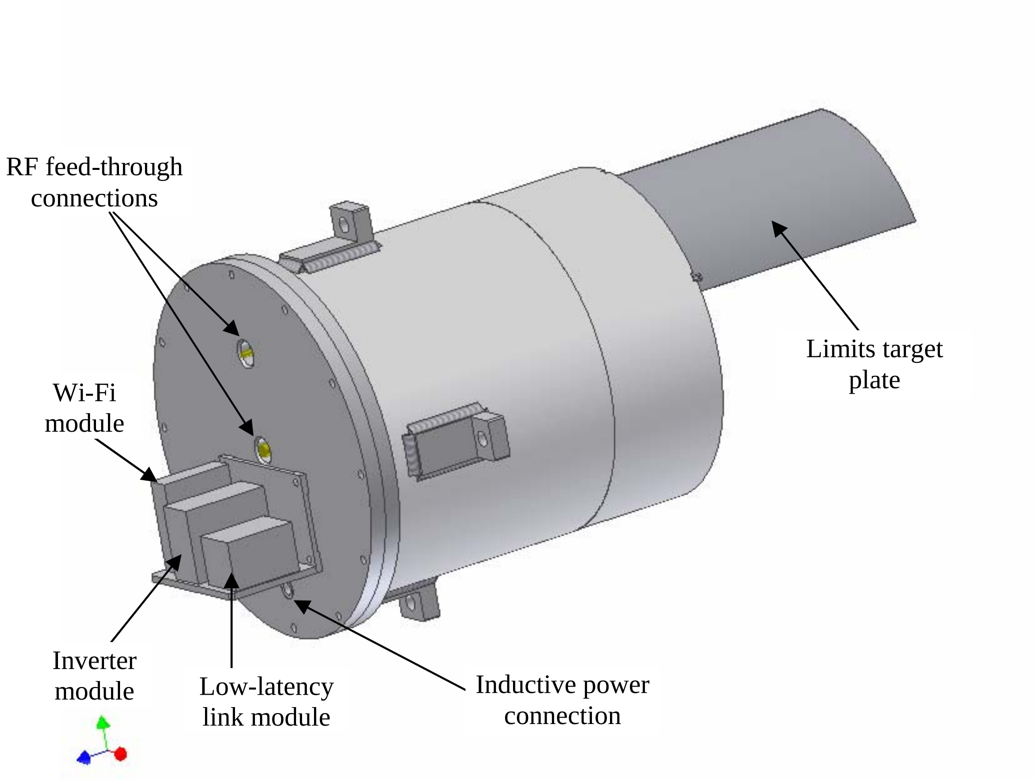


Figure 3: The Far End Section, showing the support for the electronics modules, the feed-through connections for the communications aerials and inductive power, and the limits target plate.

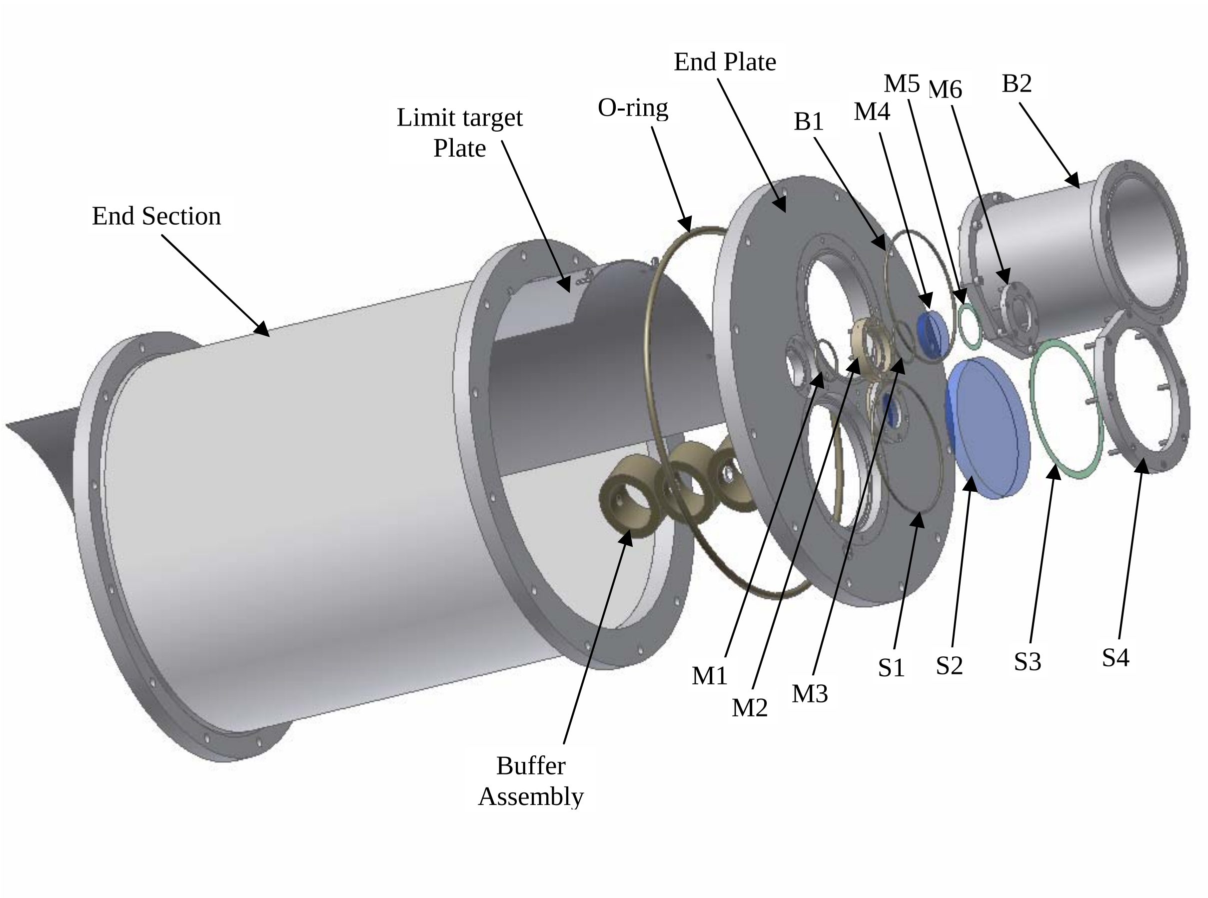


Figure 4 BCA End Plate. Components marked with a number prefixed by M are metrology window components, those prefixed by S are science window components and those prefixed by B are beam relay interface components. See text for a descriptive key to these components.

Key to Figure 4:

M1 O-ring	S1 O-ring
M2 Window holder	S2 Science window
M3 O-ring	S3 Rubber spacer
M4 Metrology window	S4 Clamp ring
M5 Rubber spacer	B1 O-ring
M6 Clamp ring	B2 Beam Relay Interface

2.1.4.1 BCA end plate

This end plate interfaces to the beam relay pipe and houses the metrology beam windows and the science window for the returning science beam. In addition the plate supports the buffer assembly and a port in which the restraining plug for the inductive power transfer cable termination is housed.

The end plate has a precision groove machined in it to accept an O-ring while the mating flange of the end section is machined flat. This arrangement produces a stable vacuum seal when the end plate is bolted in position.

The science window (S2) fits into a recess machined into the end plate which also provides a precision groove for the O-ring (S1). The rubber spacer (S3) protects the window from glass to metal contact with the clamp ring (S4). The window is held in position and a vacuum seal produced when the clamp ring is screwed into the end plate. The components are toleranced such that the science window compresses the O-ring sufficiently but does not contact the bottom of the recess in the end plate.

Both metrology windows are fitted in a similar fashion but have an added complication. To prevent metrology light reflecting back into the interferometer the metrology window is tilted slightly from the normal to the beam axis. To achieve this, a window holder (M2) is inserted into a recess machined into the end plate, which also has an O-ring groove and O-ring (M1) to form a vacuum seal, and is screwed in place. The rear face of the window holder is machined at a slight angle so that the window, when fitted will not be normal to the metrology beam axis. The window (M4) is inserted in the window holder together with the O-ring seal (M3), the rubber spacer (M5) and is held by the clamp ring (M6).

The Beam Relay Interface is a short stub of pipe which attaches to the upper window of the end plate and presents an appropriate flange to which the beam relay pipe can be bolted. The beam relay pipe incorporates a bellows coupling to help alignment and prevent undue forces being coupled to the delay line. The Beam Relay Interface can be removed and replaced with a window assembly very similar to the science window already described. This enables the delay line to be operated in vacuum while introducing alignment aids into the beam relay path.

The buffer assembly (see Figure 5) is a stack of three industrial buffers made of rings of composite plastic which provide linear compression characteristics until almost flattened. The stiffness and operating length of the buffers are chosen to protect the trolley and cat's eye by limiting the deceleration to 1g even if the trolley has passed the through the position limits at one metre per second. The trolley rebounds but will not necessarily drive back into the buffer depending on the failure conditions. See the operation of the limits described in AD05.

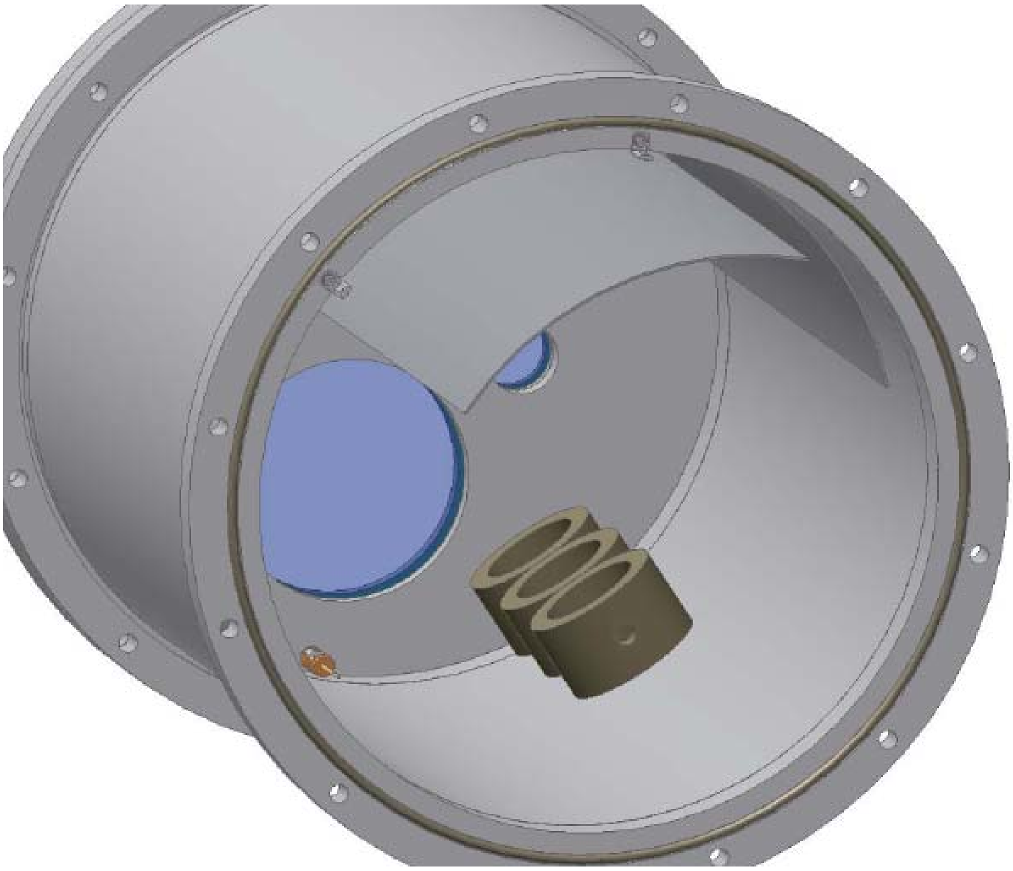


Figure 5: Internal view of the BCA end section showing the target plate, the buffer stack and the termination for the inductive power cable.

The Inductive Power Transfer Termination is a specially developed mechanical ‘plug’ to which the inductive power wire is anchored. It serves two purposes: (i) it provides the electrical connection to the delay line pipe for the return path of the inductive power and (ii) it provides the means with which the trolley can be withdrawn from the pipe in the event of failure. The plug is mounted on the inside of the end plate against an O-ring seal and is held in position by a screwed thread and nut on the outside of the plate. This arrangement enables the plug to be released from the outside of the pipe after the pipe has been brought up to atmospheric pressure. A pull-back chord is attached to the outside of the plug before it is released because the inductive power chord is tensioned from the far end. After releasing the plug the inductive power cable is pulled from the far end so that the plug is drawn towards the trolley and engages against a ‘fairlead’ plate (a cable guide) mounted on the front of the trolley. This ensures that the trolley can be pulled back using the inductive power transfer wire without damage to the trolley or the wire.

2.1.4.2 Limits target plate

The Limits Target Plate is a one-piece steel plate which is rolled to a radius approximately 3mm smaller than the pipe radius. One half of the width of the plate is 800mm long while the other half is 400mm long. It is fitted inside the pipe, centred at the top, so that each half of the plate covers an arc 67.5˚ either side of vertical. The plate is attached at both ends of the end section using small brackets which screw into recesses in the face of the flange (see Figure 6).

A pair of magnetic switches is mounted at each end of the trolley at 45˚ from the vertical, on either side. When the trolley reaches the limit target one switch will activate when it reaches the longer half of the target plate causing the trolley to undergo a controlled deceleration. If this action fails the second limit switch reaches the shorter half of the target plate and the trolley is brought to an emergency stop. The trolley roll angle would have to reach 22.5˚ before either one of the switches would miss the target plate but at least one of the switches would always be activated.

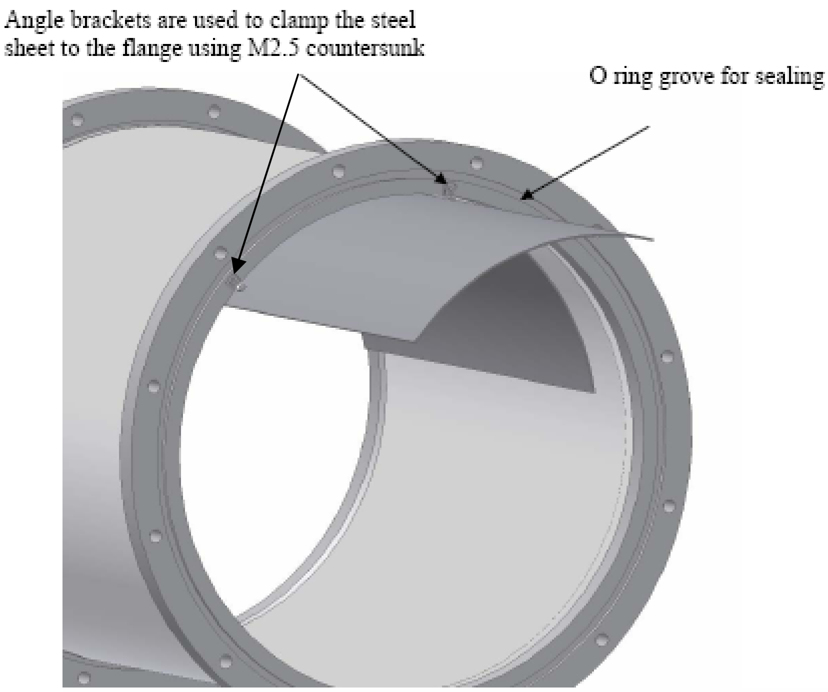


Figure 6: End section with target plate fitted.

2.1.4.3 The vacuum safety device

The vacuum safety device is a passive mechanism which is mounted to the science window to protect the delay line from catastrophic re-pressurisation in the event that the window should be completely ruptured. A similar device is used to protect the delay line from a rupture of the beam relay pipe and so the design will be based on a common mechanism. Such a device has been developed before in the nuclear research industry and relies on the inrush of air to tilt a cantilevered flap into the airflow whereupon the valve becomes self-closing. Such a device reacts in a few tens of milliseconds and is quite capable of protecting the delay line.

2.1.4.4 Far End plate

This end plate attaches to the flange at far end section of the delay line, using an inset O-ring to achieve the vacuum seal in the same way as the BCA end plate (see Figure 7).

Internally this end plate supports a buffer assembly identical to that on the BCA end plate. In addition the plate supports the connectors, aerials and ground plane for radio communication with the trolley and a connector for the inductive power cable. A covering of ‘echosorb’ material about the ground plane reduces unwanted reflections of the radio waves from the trolley. The plate also supports a tensioning mechanism for the inductive power cable and sufficient cable storage (not shown) to allow the end plate to be removed for access to the trolley and removing it from the pipe.

Externally the plate supports a shelf on which the inductive power inverter module, the Wi-fi network link and the special low-latency receiver module are mounted. The RF signals are connected to the internal aerials through sealed connectors as is the inductive power.

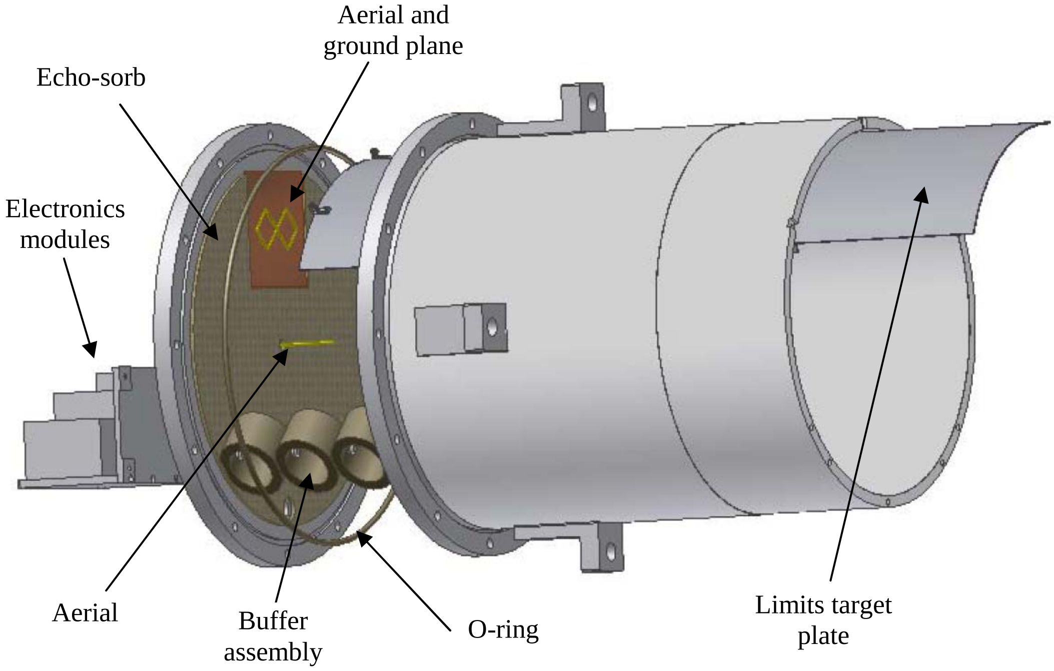


Figure 7 Exploded view of the Far End Plate showing the buffer assembly, the O-ring seal, the aerials, the ground plane and the echo-sorb arrangement.

2.1.5 Special features

Apart from the end plates there are two other ‘ports’ in the delay line which have been mentioned. These are the vacuum port and the window for the datum switch. These are described in more detail below.

2.1.5.1 Vacuum port

The vacuum port is based on a 2 inch feed and connects to a four way cross adaptor specified in the vacuum subsystem. The interface is defined at the pipe which is machined to receive a 2 inch centring O-ring seal which is held in position by a specially designed sectional clamp. The arrangement is depicted in Figure 8. A flat surface is machined into the top of the pipe and a hole is bored to receive the centring seal. Blind holes are drilled into the pipe at places where the pipe thickness is preserved and are tapped to receive ‘heli-coil’ inserts. The sectional clamp, which fits around the conical stub of the four-way cross is held in place by three screws on each part and these are tightened so that the centring ring seal is seated and clamped to the pipe. This interface is defined in the ICD (AD09).

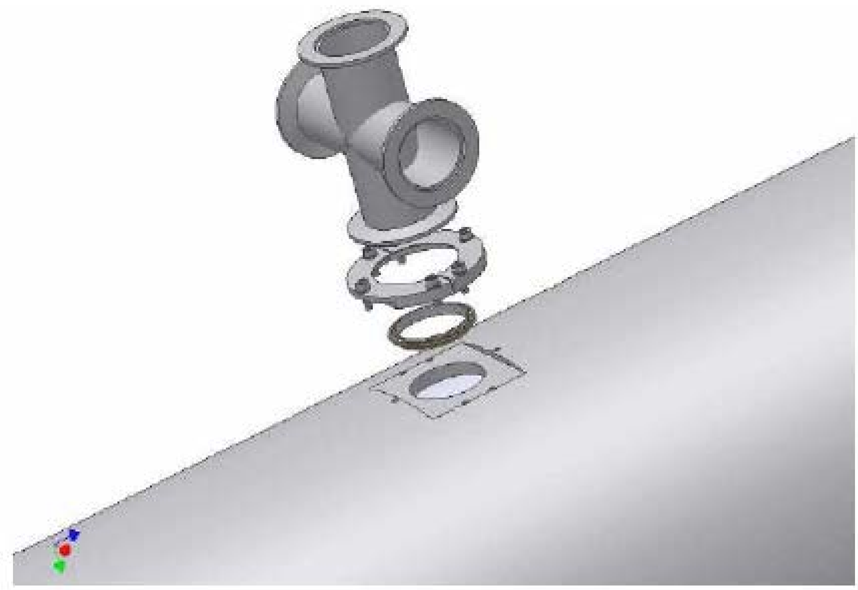


Figure 8: The vacuum port arrangement.

2.1.5.2 Datum facility

The datum switch is a ‘Nano-spot’ sensor which uses an optical beam to accurately sense the presence of a reflective target. The sensor is mounted externally on the delay line pipe near to the location where the anchor attaches (see Figure 9). The sensor can view the trolley through a window set into the pipe to maintain a vacuum seal. For short distances a target is often not required but because the sensor is mounted further away target tape provided for the sensor is affixed to the top of the trolley.

An exploded view of the datum assembly is shown in Figure 10. The Nano-spot sensor is mounted to a bracket supported by the datum base-plate. A flat area is machined on the top of the pipe and a set of four holes, fitted with heli-coil inserts is provided to attach the datum switch plate. A hole is bored through the pipe with a larger counter-bore to provide a seating for the window. An O-ring and centring/spacer ring are inserted into the counter-bore followed by the window and a further O-ring. These components and the counter-bore are toleranced so that a vacuum seal is produced when the datum plate is screwed down. A cover keeps stray light and dust from the datum window.

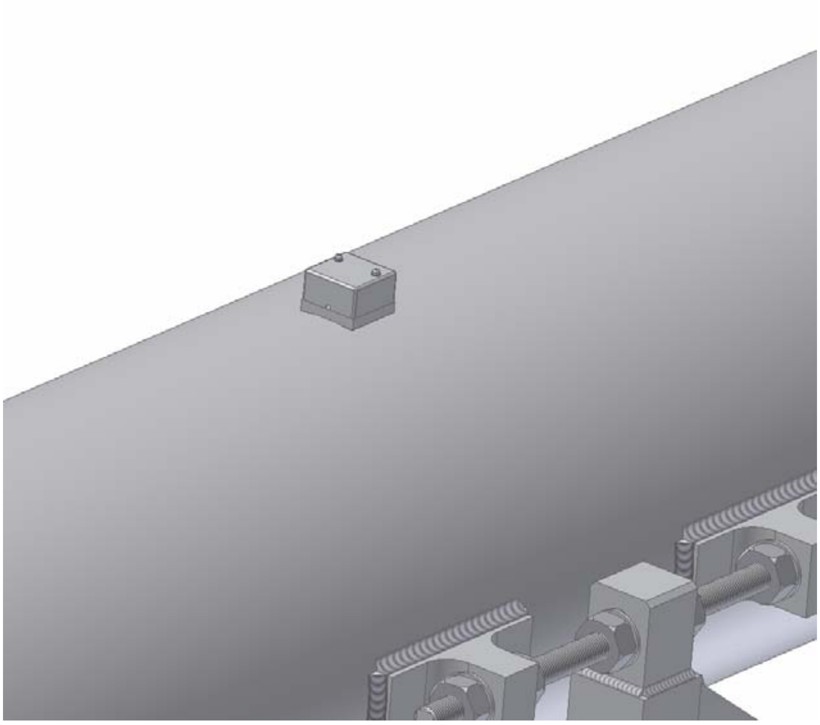


Figure 9: The position of the datum switch near to the anchor connections of the delay line pipe.

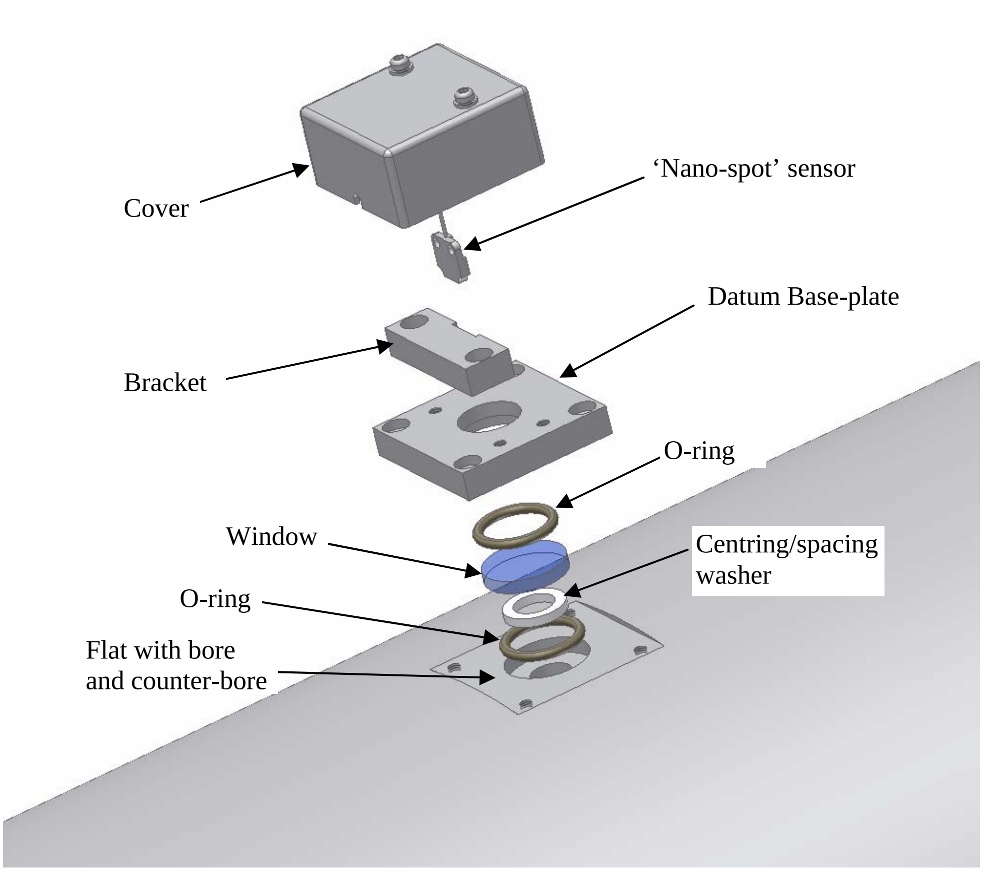


Figure 10: An exploded view of the datum switch assembly.

2.2 Delay Line Supports

There are two types of delay line support: (i) a pipe support and (ii) an anchor which stabilises the pipe providing a fixed reference point for the delay line and.

The pipe support is a single stand with top and bottom flexures which will allow for thermal expansion and contraction of the delay line in the longitudinal direction but is stiff in the lateral direction, orthogonal to the axis of the delay line. It is used to support the pipe ends at every pipe join so there will be 40 or more pipe supports in a 190m delay line depending on the length of standard pipe sections.

The anchor is a fixed frame which restrains the delay line in the longitudinal direction at one point, near the BCA end, preventing longitudinal motion with a sufficiently rigid structure to withstand earthquake forces and providing a stable reference point for the datum facility.

For a fully complemented facility of ten 190m delay lines there will be ten anchors and 400 pipe supports (approximately 550 if 12 foot pipes are used).

2.2.1 Pipe supports

The pipe support is a flexure leg and consists of a cradle connected by two steel flexures to an ‘A-frame’ which in turn is connected by another two flexures to a base plate. The length of the leg between the flexures must be 1m or more to avoid excessive height changes at the far end of the delay line where the legs will flex most due to temperature changes in the DLA. The flexures are intentionally made soft to reduce the force required to deflect the large number of legs on each pipe and to reduce the shear load on the pipe alignment dowels necessary to bend the upper flexures. No grout is used under the leg base plates so that the height can be adjusted both up and down as required when aligning the delay line.

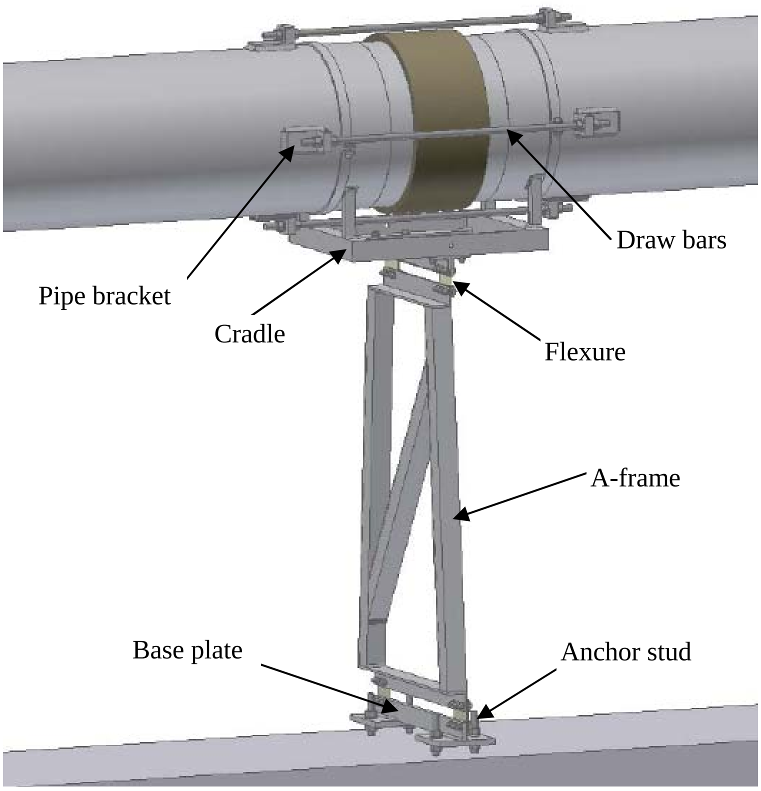


Figure 11: Pipe support

2.2.1.1 Frame

The A-frame (Figure 12) is made of hot-rolled mild steel square tube (50x50x2.5mm) with L-section (50x50x6mm) at the top and bottom. The frame is approximately 560mm wide at the base and 406mm wide at the top. Holes are provided in the L-sections where the flexures are attached and clamped using M8 bolts. The flexures, two at the top and two at the bottom of each leg are made of steel plate bolted between clamping plates of bright mild steel so they can be changed easily if need be. The length between top and bottom flexure centres is approximately 1.05m.

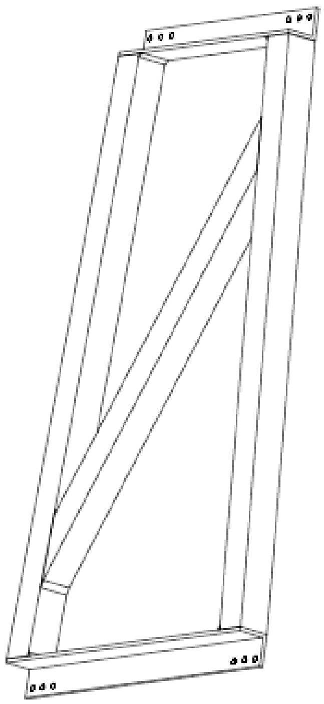


Figure 12: A-frame

2.2.1.2 Cradle

The pipe support cradle (Figure 13) is also made of hot-rolled mild steel square tube with L-section forming the sides. The cradle bolts on to two inverted L-sections using M10 bolts but with oversize bolt holes so that it is able to rotate slightly in azimuth if need be when the pipe sections are installed, allowing the cradle to align to the pipes.

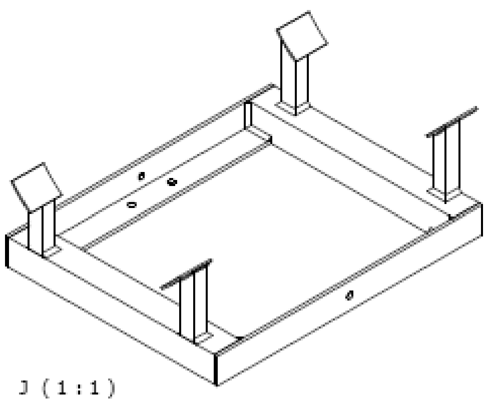


Figure 13: Cradle

A stub projects upward from each corner of the cradle to provide a pair of supports for each pipe, with a specially angled and shaped tab so that the pipe nestles between them at the correct height. The tabs also provide points where the pipes can be strapped down onto the support cradles to make sure that there is no creep between the pipes and the legs (Figure 14).

No specific provision is made for lateral adjustment of the cradle because small sideways movements of the top of the legs can be accommodated by elongating the mounting holes in the base plate or made by small differential adjustments of the vertical setting of the legs at the base plate.

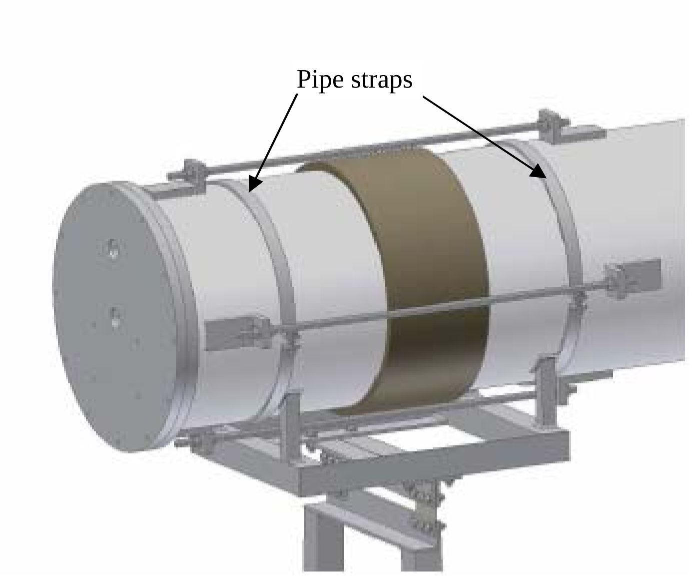


Figure 14: A pipe joint showing the cradle and the straps holding the pipe to it.

2.2.1.3 Base plate

The base plate, shown in Figure 15, is formed by welding two sub-plates to a cross piece onto which the bottom flexures of the A-frame can be attached. Each sub-plate provides two holes through which the studs of the chemical anchors set into the DLA slab pass. These holes are over-sized to allow for error in setting the chemical anchors and also some lateral adjustment of the whole support leg. Washers and nuts are positioned either side of the sub-plates to provide height adjustment of the leg for alignment of the delay line pipes.

Figure 15 Delay line support base plate.

To accommodate deviations in DLA floor slab height the studs are sufficiently long to provide ±20mm of height adjustment. In the event that the floor slab varies by more than this amount, due to a slope for example, there is another version of the base plate which is reduced in height by 20mm, see Figure 16.

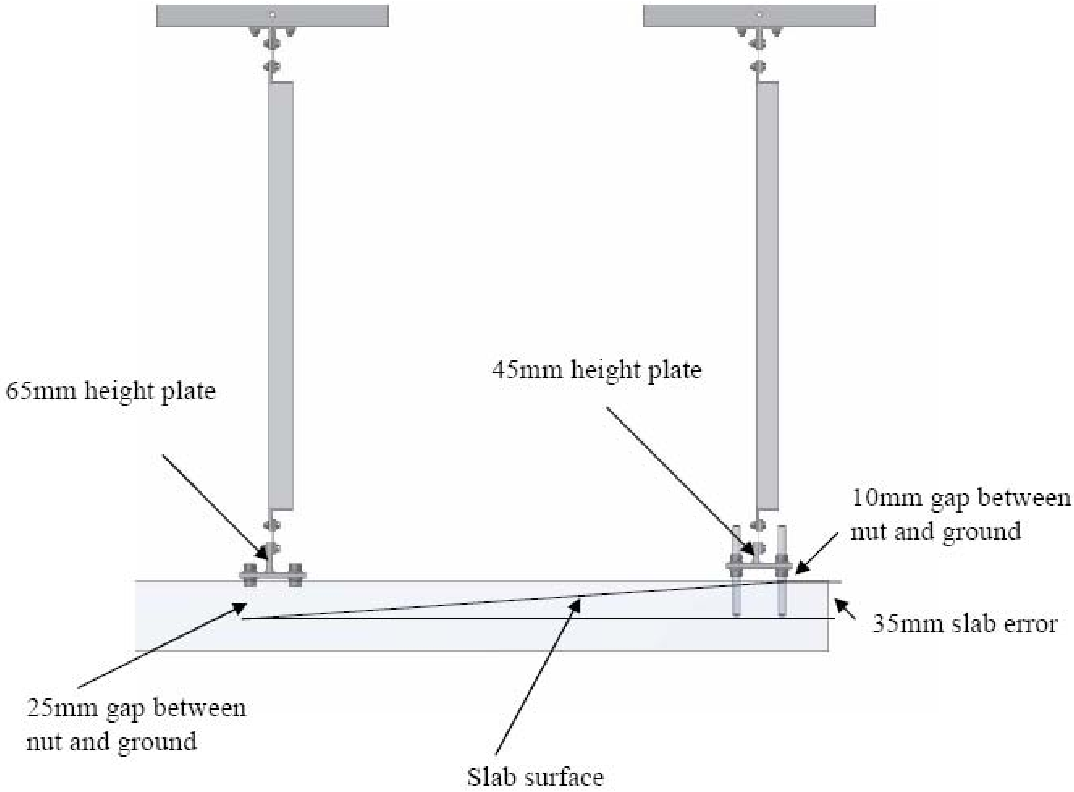


Figure 16: Base plate versions allow for deviations in the height of the DLA floor slab which cannot be accommodated by a single size.

2.2.1.4 Design calculations and analysis

The supports must be able to withstand the forces that may be produced during a 0.3g earthquake. The anchor studs must be able to withstand the lateral shear and moment forces placed on them during a lateral shock without pulling out of the slab and do this in the presence of axial forces and displacements as well as vertical forces due to simultaneous shocks in those directions. The flexures must be capable of withstanding increased vertical loading without buckling and the pipe brackets must be capable of withstanding forces which would otherwise separate the pipes.

An FEA analysis, described in Appendix A, supplemented by the dynamic response spectrum methodology has determined what dynamic forces will be present on the delay line structure and these are used in simple calculations to show that the design has sufficient safety margin. The analyses, calculations and selection of the appropriate chemical anchors are presented in Appendix B.

2.2.2 Anchor

A 3D view of the full set of delay line anchors is shown in Figure 17. This shows that there is very little space between delay lines and therefore the anchor design and in particular the connection to the pipe must be compact yet still accessible.

Two further views, Figure 18 and Figure 19, show the anchor and its connection to the DLA slab in rather more detail. The frame is fixed to the DLA slab using twelve chemical anchors, six at each end, but with a layer of high pressure grout to provide a flat surface for clamping.

Slotted holes, to allow for height adjustment of the pipe, are machined into the uprights for the threaded anchor bars to pass through. These bars connect to pairs of brackets welded onto either side of the pipe. Nuts and washers are used to clamp the bar on either side of each upright and then to clamp the ends at each bracket. This forms a very strong and stable connection of the delay line pipe to the anchor.

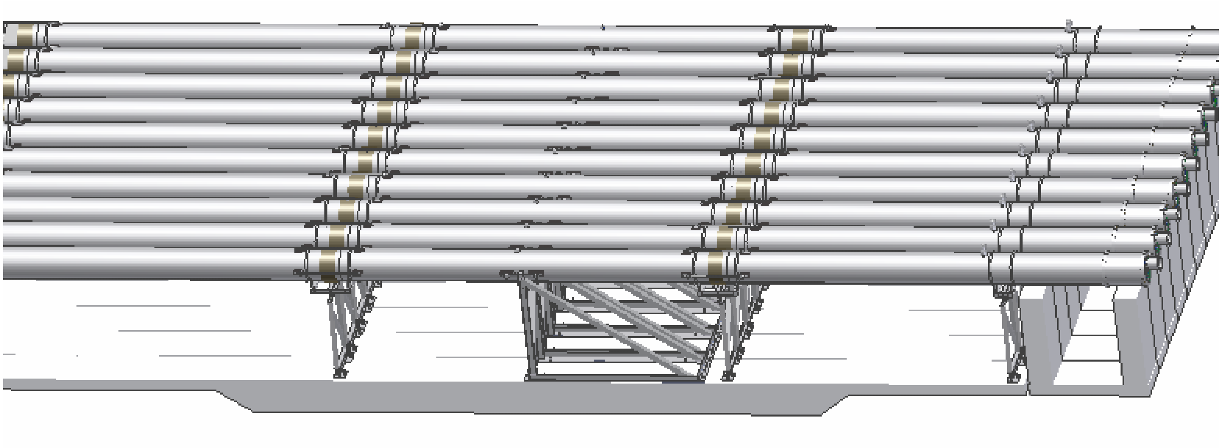


Figure 17: The full complement of delay line anchors reveals how little space there is between delay lines.

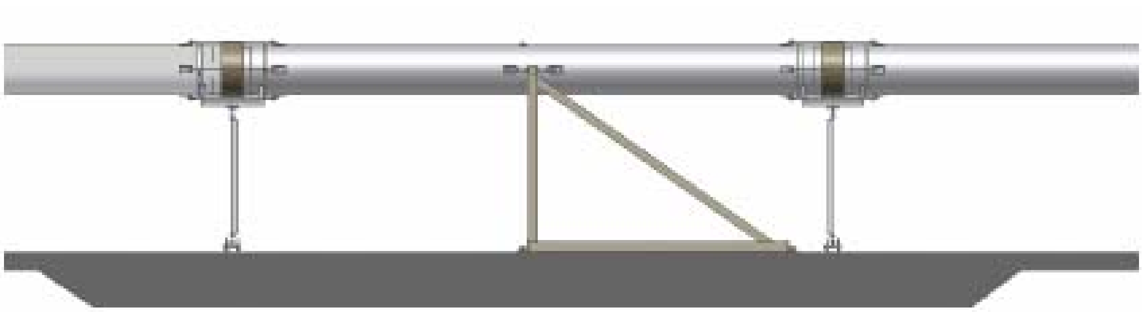


Figure 18: Elevation of the delay line anchor.

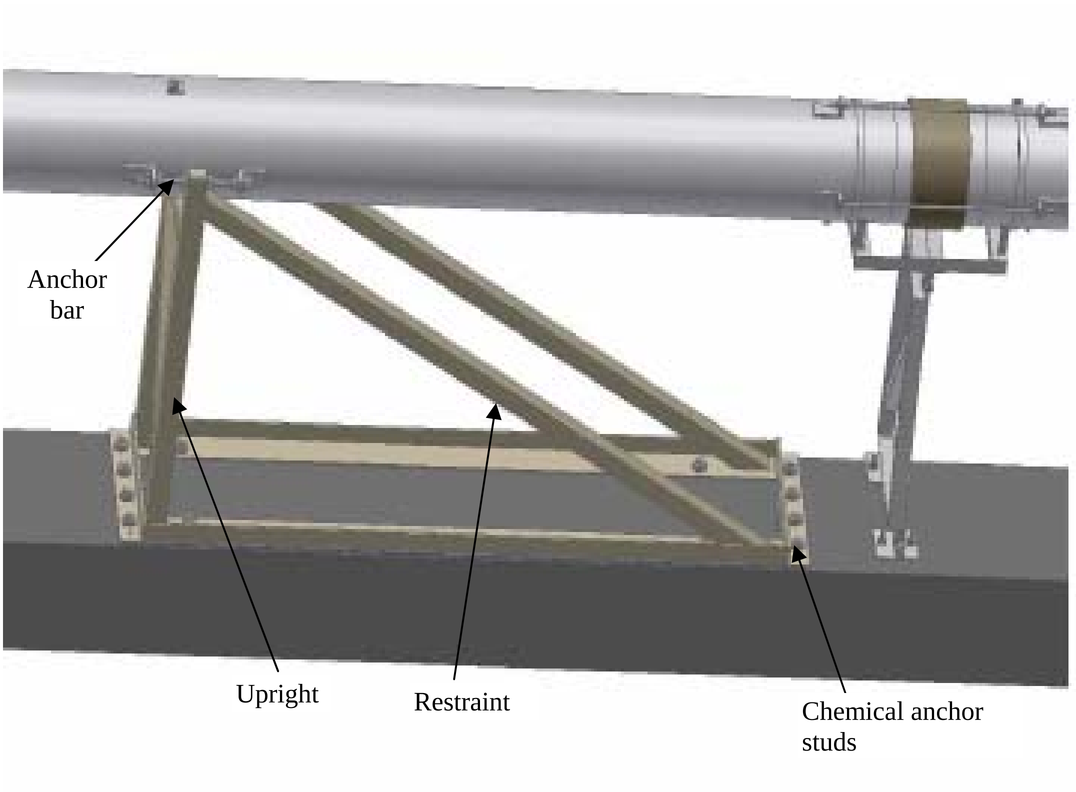


Figure 19: A 3D view of the delay line anchor showing the connections to the floor.

2.2.2.1 Frame

The anchor frame (see Figure 20) is a welded fabrication using hot rolled mild steel. SHS 70mm x 70mm x 6mm square tube is used for the uprights and cross-members. The diagonal restraint members are SHS 70mm x 70mm x 8mm. The base is made up of L-sections of 125mm x 75mm x 10mm for the sides and 80mm x 80mm x 10mm for the ends. Six holes, oversized to allow for chemical anchor positioning errors, are provided at each end of the frame for the chemical anchor studding to pass through. Load-spreading washers and nuts to suite the anchor stud are used to clamp the structure to the DLA floor. The connection points to the pipe are made of solid bar welded into the open tube ends.

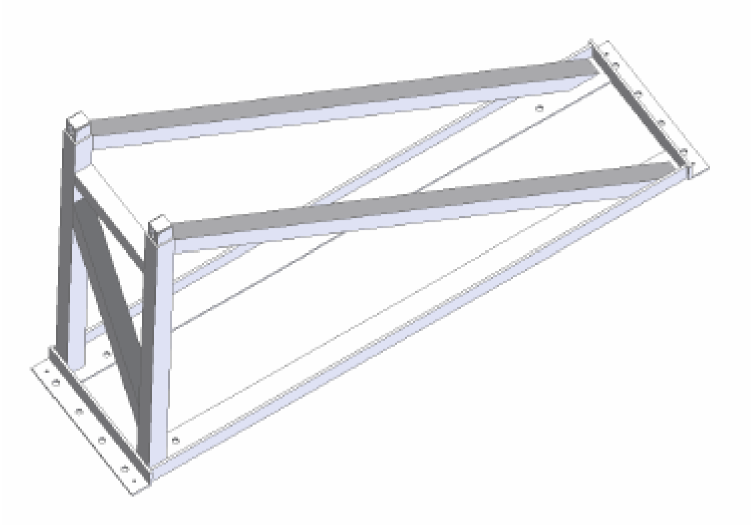


Figure 20: The anchor frame

2.2.2.2 Pipe connection

The connection between the pipe and the anchor uprights is made through 7/8” diameter threaded bars on either side of the pipe. With the delay line pipe at the correct height these bars are passed through the pipe brackets and the vertically elongated hole in the anchor upright and clamped using nuts tightened on either side of the upright (see Figure 21). The holes in the pipe brackets are elongated horizontally to allow for lateral pipe adjustments.

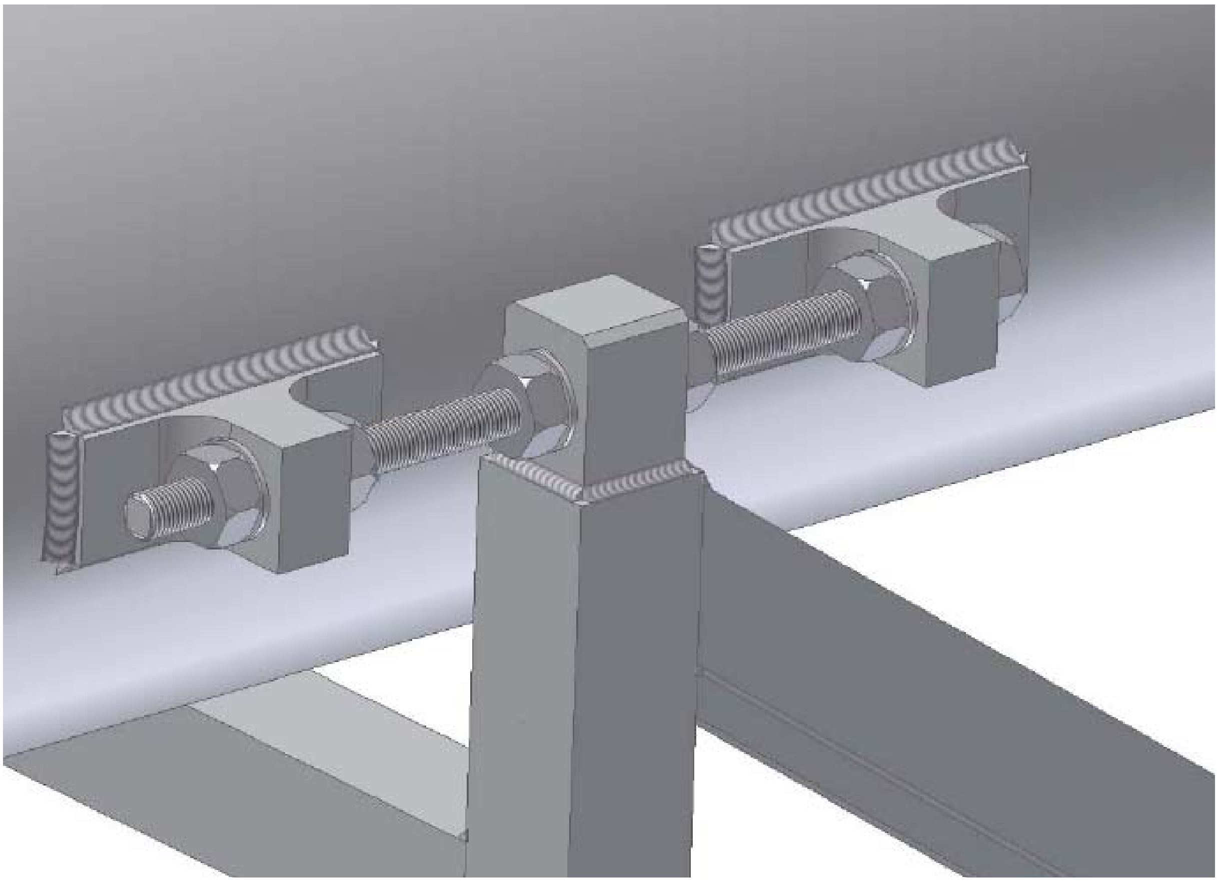


Figure 21: Close-up of threaded bars used in clamping the pipe to the anchor.

2.2.2.3 Base connection

The frame is fixed to the DLA slab using twelve ¾” ASTM A193 B7 chemical anchors with an embedment depth of 6-3/4”. To ensure that undue stresses are not placed upon the anchor during the bolting down process the anchor is spaced off from the DLA slab and then grouted with a high pressure grout. Once set the anchor is tightened down with a specific torque on each bolt. The expected grout thickness is 10mm to 15mm and depends on the DLA slab height. Once set the anchor is tightened down with a specific torque on each bolt. The expected grout thickness is 10mm to 15mm and depends on the DLA slab height.

2.2.2.4 Design calculations and analysis

The anchor must be able to withstand the axial forces that may be produced during a 0.3g earthquake. The anchor studs must be able to withstand the shear and moment forces placed on them during an axial shock without pulling out of or breaking the slab. The anchor bars and pipe brackets must be capable of transmitting the load from the delay line pipe to the anchor frame without buckling. The analyses, calculations and selection of chemical anchor size and embedment depth are presented in Appendix B.

3 Delay Line Interfaces

The interfaces between the delay line and other components or areas are addressed in interface control documents. These interfaces are described briefly here and the relevant ICD should be referred to for more detail.

3.1.1.1 AD07 Delay line to Beam Relay system INT-406-VEN-0008

This ICD describes the connection of the beam relay pipe to the top science beam port of the end plate at the BCA end of the delay line. It is essentially a simple flanged connection since any longitudinal displacements are absorbed by a flexible coupling in the beam relay pipe.

3.1.1.2 AD06 Delay line to BCF infrastructure (building) INT-406-VEN-0009

This ICD describes the interfaces between the delay line and the BCF area. These include the fixing of the delay line anchor and supports, the apertures in the outer and inner BCA walls through which the delay line passes, the power and network connections and other cable requirements.

3.1.1.3 AD08 Delay line to metrology system INT-406-VEN-0010

This ICD describes the axis and space envelope requirements between the delay line end plate science and metrology windows and the metrology system. Although there is no physical connection involved the axes of the metrology beam expanders must coincide with the metrology windows in the pipe end plate and the returning science beam must pass through without vignetting. In addition there must be clear space between the delay line pipe and the metrology system to allow access to the pipe end plates and to clear any protective mechanism covering the science window.

3.1.1.4 AD09 Delay line to vacuum system INT-406-VEN-0011

This ICD describes the interface between the vacuum system and the delay line pipes. There will be a vacuum pipe brought down to each delay line from a manifold above the delay lines close to the outer BCA wall, i.e. just inside the DLA. The ICD details a compatible vacuum connection and the distance of this from the BCA wall.

4 Installation and Maintenance of delay line pipes

Descriptions of how the delay lines are installed and what special tools and jigs are needed are given in AD10. Detailed instructions on how to install the delay line pipes are provided as part of the documentation package which is outlined in the documentation plan AD04.

5 Safety and Hazards

Safety and hazards are identified and addressed in the Safety and Hazards Document AD03 but there are two specific safety concerns that should be described here: (i) the prevention of harm to personnel working in the DLA and the survival of the delay line in the event of an earthquake and (ii) the prevention of harm to personnel working in the DLA in the event of a catastrophic re-pressurisation of the delay line.

In addition to the analysis in the safety and hazards document a risk analysis should be undertaken at the actual facility before installation, taking into account installation hazards as well as future operational hazards.

5.1 Earthquake

The environmental specification for the site includes a maximum earthquake magnitude of 0.3g in any direction with a response up to 100Hz. The principal requirement is that the delay lines should survive a 0.3g level earthquake without collapse or serious damage. This places structural requirements on the design of the supports and on the anchor frame of the delay line. In particular the anchor bolts which are used to connect the delay lines to the concrete slab of the DLA must be appropriately sized. The requirements for the structural design are established through an FEA model of the complete delay line and validated by simple calculations.

5.1.1 Earthquake Analysis

The FEA model was developed at an early stage in the design and presented in the document 'Provisional Anchor Requirements for Delay Line Supports v1.0' which was produced in May 2006 to provide initial confirmation of the requirements for anchoring the delay line and for assessing the depth of concrete required for the anchors to be effective. A revision of the FEA model has been undertaken to reflect the current design and the results from this model have been obtained using an earthquake spectrum generated from the USGS on-line design facility for the MROI area. The FEA model and the results of the analysis are briefly presented in Appendix A but the principal characteristics are summarised here.

- Total mass of delay line is 9317kg
- Total mass of pipe is 195m at 206kg per 5m = 8034kg
- Mass of each support = 30kg
- The top level requirement for earthquake loading is 0.3g in each coordinate.
- The design ground acceleration for MROI site is 0.332g over frequency range of interest.
- The amplification factor for 2% damping is 3.66 giving an equivalent shock loading of 1.2g

5.2 Vacuum Safety

It is necessary to consider vacuum failure modes of the delay line and analyse the potential for damage or harm. Rupture of a seal is not likely to cause any damage as the airflow is restricted by the narrow gap between pipes. Similarly failure of an O-ring or a feed-through connector is not likely to produce dangerous airflow. Apertures up to and including the size of the metrology windows do not present a significant danger to the trolley if they should suddenly be open to atmosphere.

5.2.1 Catastrophic re-pressurisation

There are two scenarios in which damage to the trolley, the delay line or personnel at the far end of the delay line may be caused by a catastrophic failure of the vacuum integrity of the delay line. A catastrophic failure is judged to be an event in which a substantial area at one end of the delay line becomes open to atmosphere. In such an event the trolley may experience a pressure difference from front to back which is close to atmospheric pressure for a short period and hence be pushed down the pipe with a substantial acceleration before sufficient air is able to escape beyond it.

The only substantial areas that need to be considered are the science beam apertures at the BCA end of the delay line. The cases that should be considered are:

- A severe rupture of the beam relay pipe
- The complete failure of the science window

Rupture of the beam relay pipe is much more likely than complete failure of the science window but it either case the trolley, if positioned towards the BCA end of the delay line, will be accelerated to a velocity in excess of 50m/s within one second and can be smashed into the far end of the delay line, possibly bursting the end plate off.

5.2.2 Analysis of catastrophic re-pressurisation

There are two forces that will eventually limit the velocity of the trolley and decelerate it. One is the friction that would caused as the trolley is pushed down the pipe and the other is pressurisation of the air in the far end of the pipe as it flows past the trolley and becomes compressed by motion of the trolley in the same direction. Although it is quite a complex dynamic situation it is amenable to modelling if some assumptions can be made about airflow past the trolley. A model based analysis of the science window case has been undertaken and is summarised in the safety and hazard document AD03.

5.2.3 Mitigation of risk of catastrophic re-pressurisation

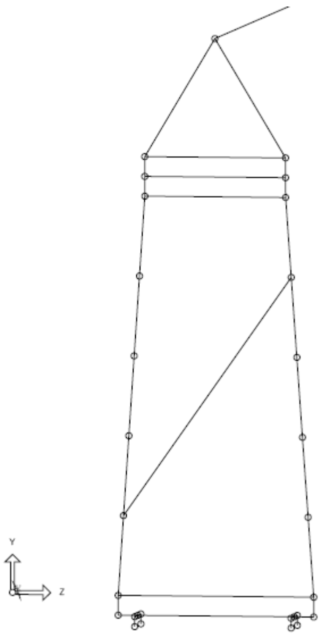
Although the risk of catastrophic re-pressurisation is very small the consequences could be very serious and it is judged that some precautions are necessary, particularly in the case of the beam relay pipe. A fast-acting valve placed in-line in the beam relay pipe which can close in a few tens of milliseconds will protect the trolley and the delay line. The passage of the air itself can act as the mechanism by which the valve starts to close and then rapidly shuts as the pressure differential increases. Such a valve has been developed[1] and it is intended that a similar valve be designed and incorporated not only into the beam relay pipe but also into a cover over the science window.

1. Fast acting valve. IEEE Transactions on Nuclear Science 1967, John S. Moenich, Argonne National Lab

2. Appendix A

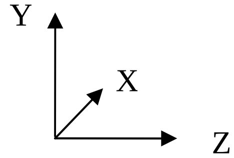
1 FEA representation

The simplified FEA model of a pipe support is a beam structure using the appropriate section elements based on the design. The FEA model of the delay line consists of 40 such supports linked by 40 beam sections representing the pipe. These models are shown in Figure 22.



The support stand model reproduces the current stand features but replaces the cradle with a triangular frame which supports the pipe element at its apex which is 1.45 m from floor level. The natural mode results agree sufficiently well with the detailed FEA model developed previously and validated by tests carried out on the first test rig developed for the risk reduction experiments.

The assembled delay line consists of 40 supports and 39 5m pipe sections. The first support at the far end of the delay line is assigned number 1 and the anchor is located between supports 38 and 39.



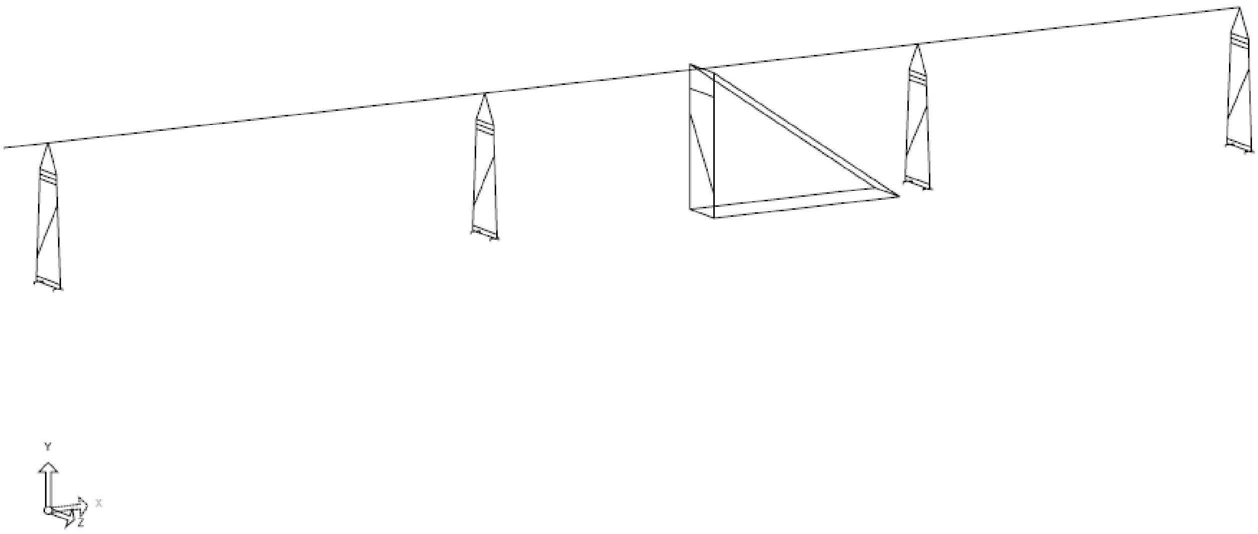


Figure 22: FEA model of anchor structure within delay line.

1.1 Modal results

The most significant modes out of the first 250 which accounts for the range 0 to 140Hz are shown in Table 1. There is, as expected only one significant axial mode, accounting for 83% of the mass. There are a number of vertical modes around 92 Hz accounting for 90% of the mass. There is one significant lateral mode and three minor modes which together account for 91% of the mass. Any resonances in Y above 100Hz is outside the band of excitation, resulting in very low displacement and load levels.

Table 1: This shows the most significant modes from the first 100 based on participation factor.

X - Axial			Y - Vertical			Z - Lateral		
Mode number	Freq. (Hz)	Particip’n (%)	Mode number	Freq. (Hz)	Particip’n (%)	Mode number	Freq. (Hz)	Particip’n (%)
1	6.2	83	130	92.95	78	2	15.9	81
18	18.4	9.7	132	92.96	8.3	4	16.0	6.3
34	30.4	1.6	134	92.97	1.8	6	16.1	1.7
35	30.5	1.7	136	92.99	1.1	29	23.0	1.9
44	42.2	1.7	207	111.6	1.1			
			209	122.4	2.9			
			211	129.1	1.4			

1.2 Shock Analysis

For the preliminary analysis a shock spectrum of 0.3g magnitude ($3ms^{-2}$) over 0.5 Hz to 100 Hz with linearly decreasing acceleration outside of that band was defined. For this revised analysis data have been obtained for a Design Response Spectrum for Site Class B based on IBC code 2006 and generated from the USGS on-line design facility for the MROI area. The spectrum generated produces 0.33g which is rather more than that specified in RD1 but is used as a conservative value.

The design response spectrum is applied to the modal results from the FEA analysis in the X, Y and Z directions individually. A spectral response modification factor of 3.66 for 2% damping is applied which amplifies the ground response to produce a shock loading of approximately 1.2g in the X and Z directions and 0.53g in the Y direction (vertical).

The shock analysis uses the ‘Complete Quadratic Combination’ (CQC) method produces the conservative sum of the individual modal responses while preserving the sign of the most significant mode. This procedure works well even where significant modes are closely spaced so that the peak response is not underestimated. Modes in the vertical direction at a much higher frequency (>100 Hz) and have little influence on the response spectrum (shown later) and so can be ignored.

1.2.1 Delay Line parameters

Total mass of delay line is 9317kg
Total mass of pipe is 195m at 206kg per 5m = 8034kg
Mass of a single support is 30kg
Design ground acceleration for MROI site is 0.332g over frequency range of interest. The amplification factor for 2% damping is 3.66 giving an approximate pseudo acceleration of 1.2g for lateral and axial shocks and 0.52g for vertical shock.

1.2.2 Lateral shock analysis

The results of the lateral shock analysis do not include the dead weight load. The reactions at the anchor studs associated with lateral shock are shown in Table 2 for support number 4 which experiences the highest dynamic loading. The maximum anchor stud axial load is 5.1kN. The static load contributes 600N compression to each anchor stud. Hence the maximum anchor stud load is modified to 4.5kN tension or 5.7kN compression. The lateral shear load sums to 2.92kN and the maximum shear load on a stud is 1.12kN.

Table 2 Reactions at the anchor studs on support number 4

Node	Description	X	Y	Z
121	Anchor bolt	3.911E+03	5.111E+03	-1.120E+03
122	Anchor bolt	-3.911E+03	5.111E+03	-1.121E+03
125	Anchor bolt	-3.902E+03	-5.099E+03	-3.400E+02
126	Anchor bolt	3.901E+03	-5.098E+03	-3.407E+02

The displacement associated with lateral shock is shown in Table 3. The lateral displacement of the delay line is a maximum at the top of support 4 and is just greater than 1.3mm.

Table 3 Displacement associated with lateral shock.

NODE	Description	X	Y	Z	Xrot	Yrot	Zrot
110	Top of support 4	9.585E-05	-4.050E-05	1.336E-03	5.524E-04	-5.683E-06	-1.168E-07

The axial loading of the flexure elements is given in Table 4 and is 9.6kN. The critical Euler buckling load given by Pcry is 40.8kN but the static load and also any vertical shock load must be taken into account.

Table 4 Axial loading of the flexure elements

Element	Group	Axial load	Length	Pcry @ c=1	Pcrz@ c=1
S105*101*98	Flexures	-9.614E+03	5.000E-02	-4.086E+04	-5.746E+07

The loading due to a vertical shock applied to the FEA model is 406N per anchor stud. When combined with the static load of 600N the additional compressive force on the flexures is approximately 1kN. Hence the maximum axial compressive force on the flexure is 9.6kN plus 1kN, i.e. 10.6kN. The safety factor for buckling is then 40.8/10.6, i.e. greater than four, which is satisfactory.

1.2.2.1 Forces at support 4 for a 1.2g lateral shock

Results from FEA model at the support with the maximum lateral displacement are shown in Figure 23 . The static gravity load is not included in these results.

The maximum tensile load on an anchor stud including the vertical shock loading and the static load is 5.1kN + 406N - 600N = 4.9kN hence the anchor studs must be capable of a much higher load.

A safety factor of between 3 and 4 is usual for such loading of chemical anchors hence each anchor should be capable of 15kN to 20kN tensile force and 3.5kN to 4.5kN in shear. Additional allowance must also be made for the stand-off distance of the base-plate from the DLA floor. These factors are taken into account in anchor selection tables. The sizing of the chemical anchors is addressed later.

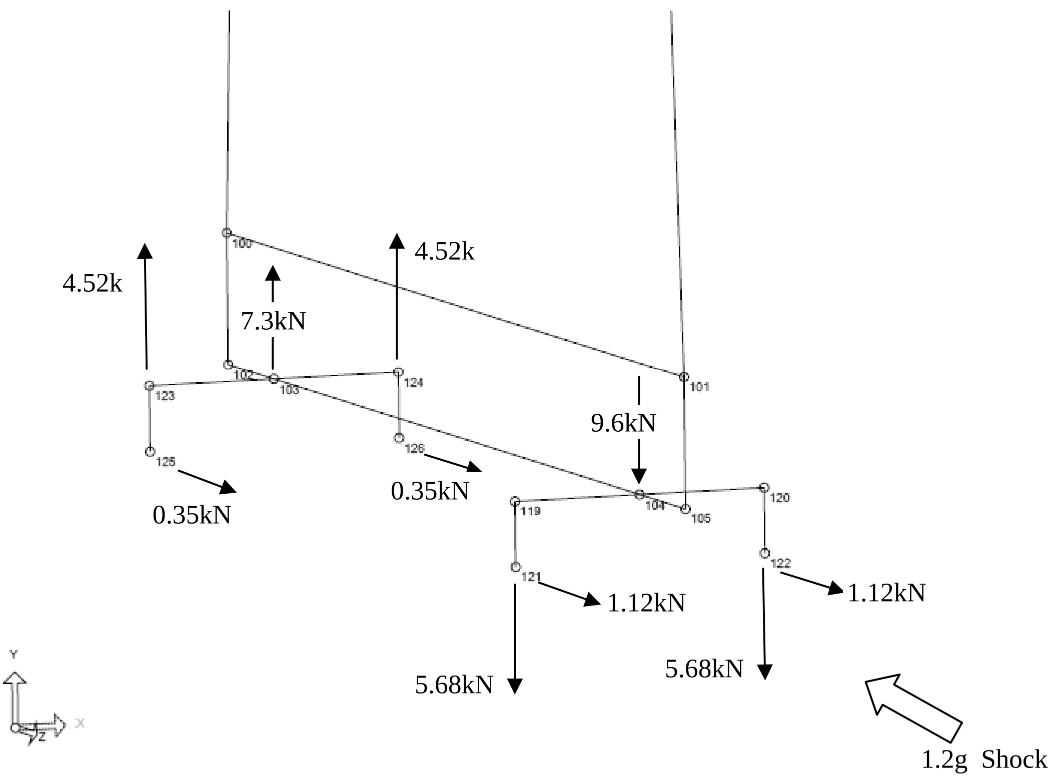


Figure 23: Maximum force at ground connection points and in members of support 4 due to a 1.2g lateral shock. Note: for axial loads compression is –ve.

1.2.3 Support force calculations

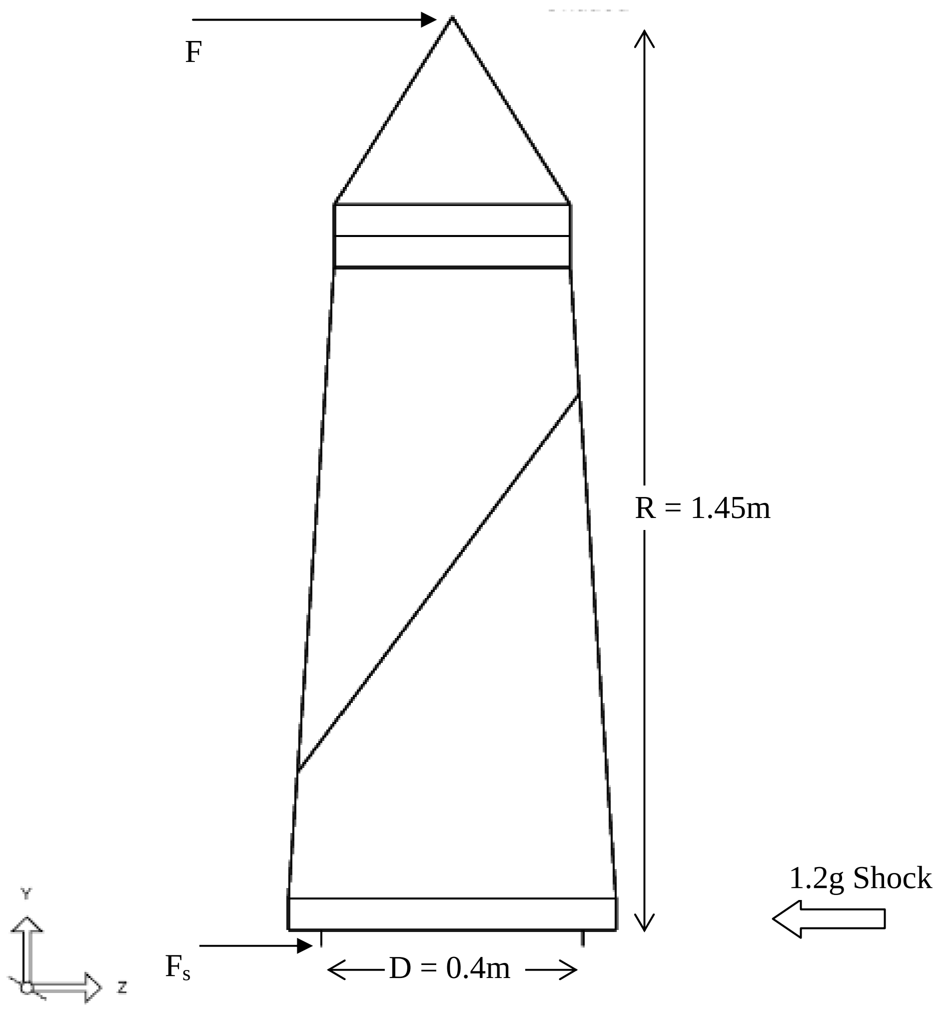


Figure 24 Calculation of forces acting on supports

The loads on the anchor studs are validated by the following calculations:

For a 1.2g shock the equivalent force acting on the pipe is F = ma.

For a pipe of mass 206kg and 50% of the 30kg support stand the force F is 2.6kN.

This produces a shear force at the base of 2.6kN and a moment about the base of approximately M = FR = 3.77kNm.

This moment introduces axial forces in the support legs of FR/D = ±9.4kN

These calculations are in very good agreement with the FEA results. There is a factor of greater than four between the highest expected axial loads in the flexures and the critical buckling load. The support stand design is acceptable and the requirements of the chemical anchor studs have been determined.

1.2.4 Axial Shock Analysis

The results of the axial shock analysis are shown in Table 5 where X,Y and Z direction reaction force is shown for the ground nodes of the anchor. Reaction forces at the ground nodes are less than a few tens of Newtons, as expected. The forces at the anchor restraint are approximately 47kN per side in shear and almost 33kN vertically.

Table 5 Reactions at ground connections of 0.3g shock loading in X (along the delay line).

Node	Description	X	Y	Z	Comments
1202	Anchor foot	-4.961E+02	3.235E+04	-3.489E+02	
1205	Anchor foot	-1.600E+02	3.098E+04	1.491E+02	
1204	Anchor restraint	-4.650E+04	-3.243E+04	6.369E+02	
1207	Anchor restraint	-4.670E+04	-3.257E+04	-6.019E+02	

The element axial loads occurring in selected elements during axial shock to the delay line are given in Table 6 where compression is indicated by a negative sign. The axial loading within the anchor restraint is about 57kN and there is a buckling safety factor of about 6.5 for these elements indicated by the values of critical buckling force Pcry and Pcrz.

Note that the static loading due to gravity is not required to be taken into account as the pipe is supported by the supports either side of the anchor.

Table 6 Element axial loads for the axial shock

Element	Group	Axial load	Length	Pcry @ c=1	Pcrz@ c=1
S1203*1204*1202	Anchor Restraints	5.669E+04	2.622E+00	-3.727E+05	-3.727E+05
S1206*1207*1202	Anchor Restraints	5.694E+04	2.622E+00	-3.727E+05	-3.727E+05
S1214*1202*1210	Anchor Leg	-3.235E+04	2.500E-01	-4.098E+07	-4.098E+07
S1215*1205*1202	Anchor Leg	-3.098E+04	2.500E-01	-4.098E+07	-4.098E+07

The displacement associated with axial shock is shown in Table 7. The axial displacement of the delay line seen at the top of the anchor where it connects to the pipe is approximately 0.54mm. The pipe will deflect a little more due to the limiting stiffness of the connecting rods and the brackets welded to the pipe.

Table 7 Displacements associated with axial shock.

NODE	Description	X	Y	Z
1203	Anchor top	5.378E-04	-1.188E-04	-1.016E-04
1206	Anchor top	5.391E-04	-1.178E-04	-1.004E-04

1.2.5 Forces at the anchor for a 1.2g longitudinal shock

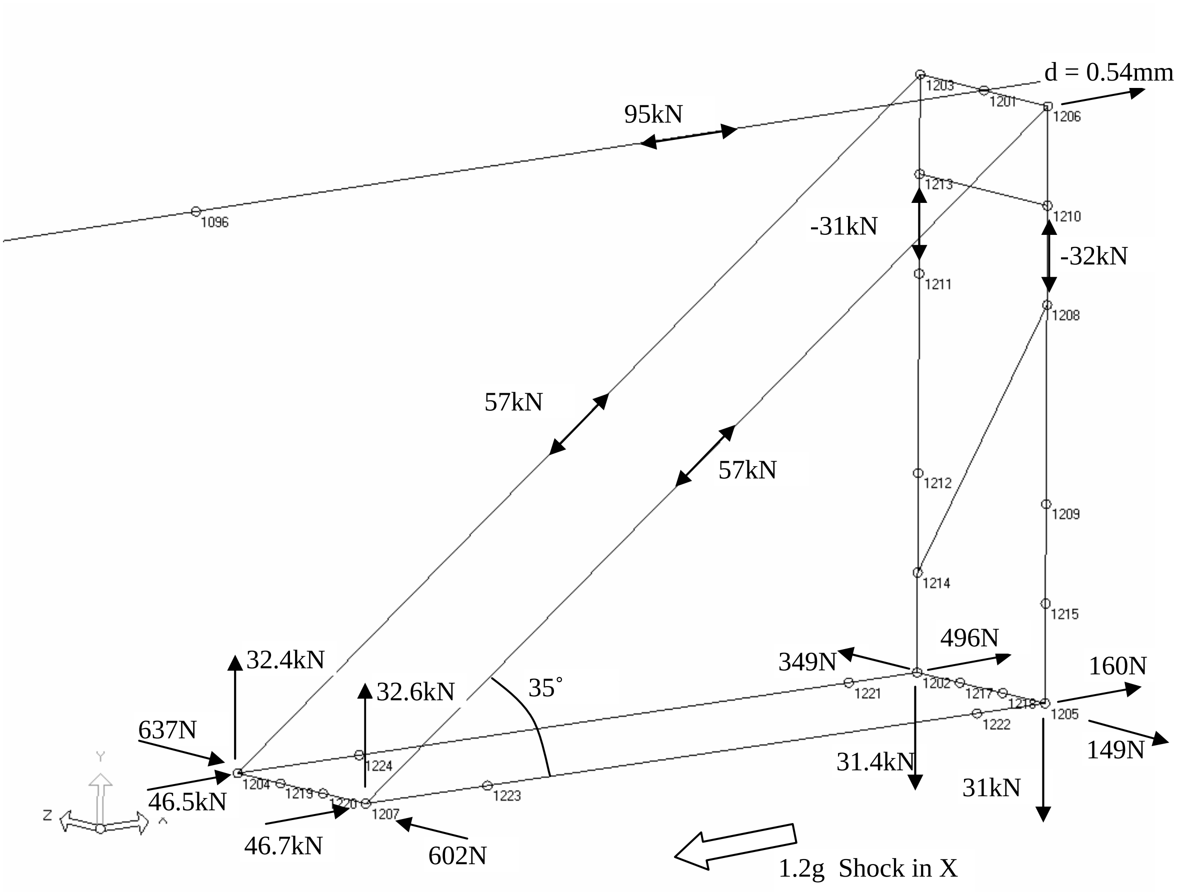


Figure 25: Maximum force at ground connection points and in members of anchor due to a 1.2g longitudinal shock. Note: for axial loads compression is –ve.

1.2.6 Anchor Force Calculations

The loads on the anchor members are validated by the following calculations:

Assume effective mass is 8034kg and is acted on by 1.2g shock. This produces an endwise force of 94.58kN (compared with 95kN from FEA).

The angle of the restraint members with the horizontal is 35º.

The expected forces in the restraints are then 94.58/(2*cos 35º) = 57.7kN

The resolved vertical member forces at the restraint are 57.7kN*sin35º = 33.1kN

The resolved horizontal shear forces at the restraint are 57.7kN*cos35º = 47.26kN

These calculations are in very good agreement with the FEA results. As there is a factor of greater than six between the highest expected axial loads in the members and the critical buckling load, the anchor design the anchor design is acceptable. Forces on the anchor due to lateral shock are small since they are shared with two adjacent supports.

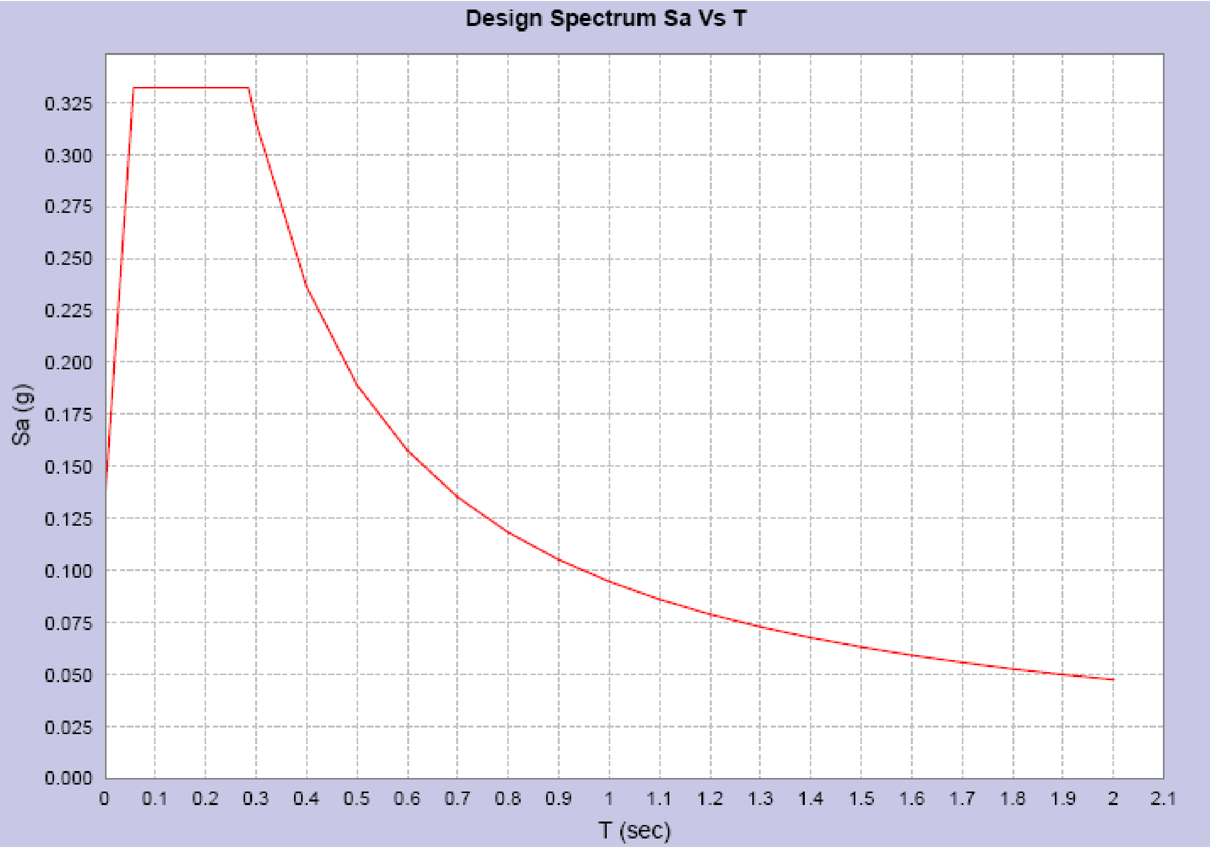
The high tensile and shear loads imparted to the anchor require that the number of chemical anchors used is increased. There are six anchors at each end of the frame and the choice of anchor is dealt with later in this document.

1.3 Earthquake spectrum

The data for the design response spectrum was obtained from the USGS on line facility and is detailed below. The FEA software was configured with this design spectrum and the shock loading applied individually in each ordinate.

Design Spectrum:
Conterminous 48 States
2006 International Building Code
Zip Code = 87801
Design Response Spectra for Site Class Site Class B
SDs = 2/3 x SMs and SD1 = 2/3 x SM1
Site Class B - Fa = 1.0 ,Fv = 1.0

Period (sec)	Sa (g)	Sd (inches)	Period (sec)	Sa (g)	Sd (inches)
0.000	0.133	0.000	1.000	0.095	0.924
0.057	0.332	0.011	1.100	0.086	1.016
0.200	0.332	0.130	1.200	0.079	1.109
0.285	0.332	0.263	1.300	0.073	1.201
0.300	0.315	0.277	1.400	0.068	1.293
0.400	0.236	0.370	1.500	0.063	1.386
0.500	0.189	0.462	1.600	0.059	1.478
0.600	0.158	0.554	1.700	0.056	1.570
0.700	0.135	0.647	1.800	0.053	1.663
0.800	0.118	0.739	1.900	0.050	1.755
0.900	0.105	0.831	2.000	0.047	1.848



Appendix B

1 Support analysis and calculations

1.1 Chemical anchor selection

The selected chemical anchor stud is 5/8” ASTM A 193 B7 and is based on the following calculations:

The embedment depth of the anchor is 4” (101.6mm).

Considering the weakest anchor connection near to the edge of the DLA slab the calculation uses 3-3/4” (95.25mm) as the distance from the stud to the edge.

The load adjustment factor is f_A=0.3(c/h_{ef})+0.55= 0.83, where c is the actual edge distance (95.25mm) and h_{ef} is the actual embedment (101.6mm).

The full allowable tensile capacity for the stud in f_c=3000psi concrete is about 30.95kN at 143mm embedment depth and 10.5kN at 73mm embedment depth according to Hilti specifications. Interpolation between these two values produces an allowable tensile capacity of the stud of 18.8kN at an embedment depth of 101.6mm.

The tensile load under earthquake conditions calculated in section 1.2.2.1 is 4.9kN therefore the safety factor is approximately 3.8 and there is no problem under the tensile load for the stud and concrete bonding. The tensile capacity of the steel stud is 56.3kN for a 5/8” Hilti stud.

The shear load from FEA is 1.12kN. The shear capacity of the concrete for a stud at 101.6mm embedment in f_c=3000psi concrete is 36.23kN. The allowable shear load for the stud is 29kN from Hilti and allowing de-rating for the stand-off distance the safety factor is approximately 8 (TBC).

1.2 Pipe Bracket loading

The brackets welded to the ends of each pipe are 22mm thick, 50mm wide and 100mm long. The specified weld is all-around with a weld bead dimension a little less than 10mm.

The rod (draw-bar) dimension is 5/8” OD. The brackets under the worst case condition are the ones near to, but on the further side of the anchor from the BCA. The maximum axial load of 93.5kN from the longitudinal shock should be discounted to some extent due to the decrease of the effective mass but a load case of 40kN for each of the four brackets was used for the FEA of the bracket.

The FEA results is shown in Figure 26 where the max. Von Mises stress is 197N/mm^2 (71.6% of the yield strength).

Conclusion: The four brackets around the pipe will with stand the earthquake load even if it is very unevenly distributed.

1.3 Tie rods (draw bars)

The minor diameter of the 5/8" rod is about 0.51". Therefore, the minor area is 131.73mm^2. The stress generated by a 40kN load is 40/131.73 = 0.3036kN/mm2 = 303.6MPa. This is about 42% of the yield strength of the material and is therefore satisfactory.

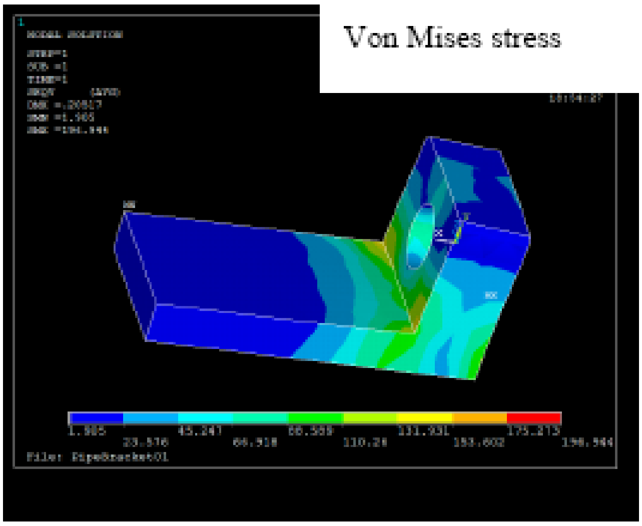


Figure 26: FEA of standard pipe bracket under 40kN load.

1.4 Anchor analysis and calculations

1.4.1 Chemical anchor selection

The selected chemical anchor stud is ¾” ASTM A193 B7 with an embedment depth of 6-3/4” (171.5mm). These anchors clamp the anchor frame to the DLA floor using a high pressure grout to distribute the load.

The tensile load on the anchor fixings under longitudinal shock load is similar for either direction of applied shock.

The weakest anchors are near to the edge of the DLA slab and the distance used is 3-3/4”. The load adjustment factor for this case using Hilti tables is 0.72. Considering the edge spacing factor, the tensile capacity of the studs is 0.72x43.2kN = 31.1kN.

Assuming the concrete strength is fc = 3000psi, the full tensile capacity for the ¾ inch anchor is about 43.2kN.

The maximum moment generated by the 93.5kN longitudinal load is 93.5kN (31.2kN+32.7kN) x 2063mm = 131825.7kNmm.

Based on the moment and the dimensions on the drawing in Figure 27, the force on stud 3, 4, 5, or 6 can be calculated as 15.22kN (compare with FEA results of 65kN/4 = 15.12kN)

The height of the pipe support is 1517.5mm. Assuming the anchor had to withstand all of the lateral shock (i.e. the load was not taken by or shared with the support stands at either end of the anchor) the moment from lateral shock is 2.42kNx1517.5mm= 3672.35kNmm.

At the anchor position, the moment applied on the anchor is estimated to be 3672.35/2 = 1836.2kNmm. Ignoring the contributions from studs 7 and 8, the load on the stud 1, 2, 3 or 6 due to the lateral shock is approximately 1.76kN. Therefore, the total load on stud 3 or 6 is 15.22 + 1.76 = 16.98kN. The capability of the studs is higher than the tensile load generated by the earthquake by a factor of almost 2. Hilti anchors have an inherent safety factor of 4 built in to their specifications and so the anchor stud is capable.

The maximum pre torque on the stud can be obtained by equation T=0.2DxF, where D is the nominal dimension of the stud (19.1mm) and F is the tensile load on the stud.

F = 31.1 - 16.98 = 14.12kN. Therefore, T = 0.2 x 19.1 x 14.12 = 53.93Nm. This means that the torque on the studs for clamping the nuts should not be larger than 54Nm.

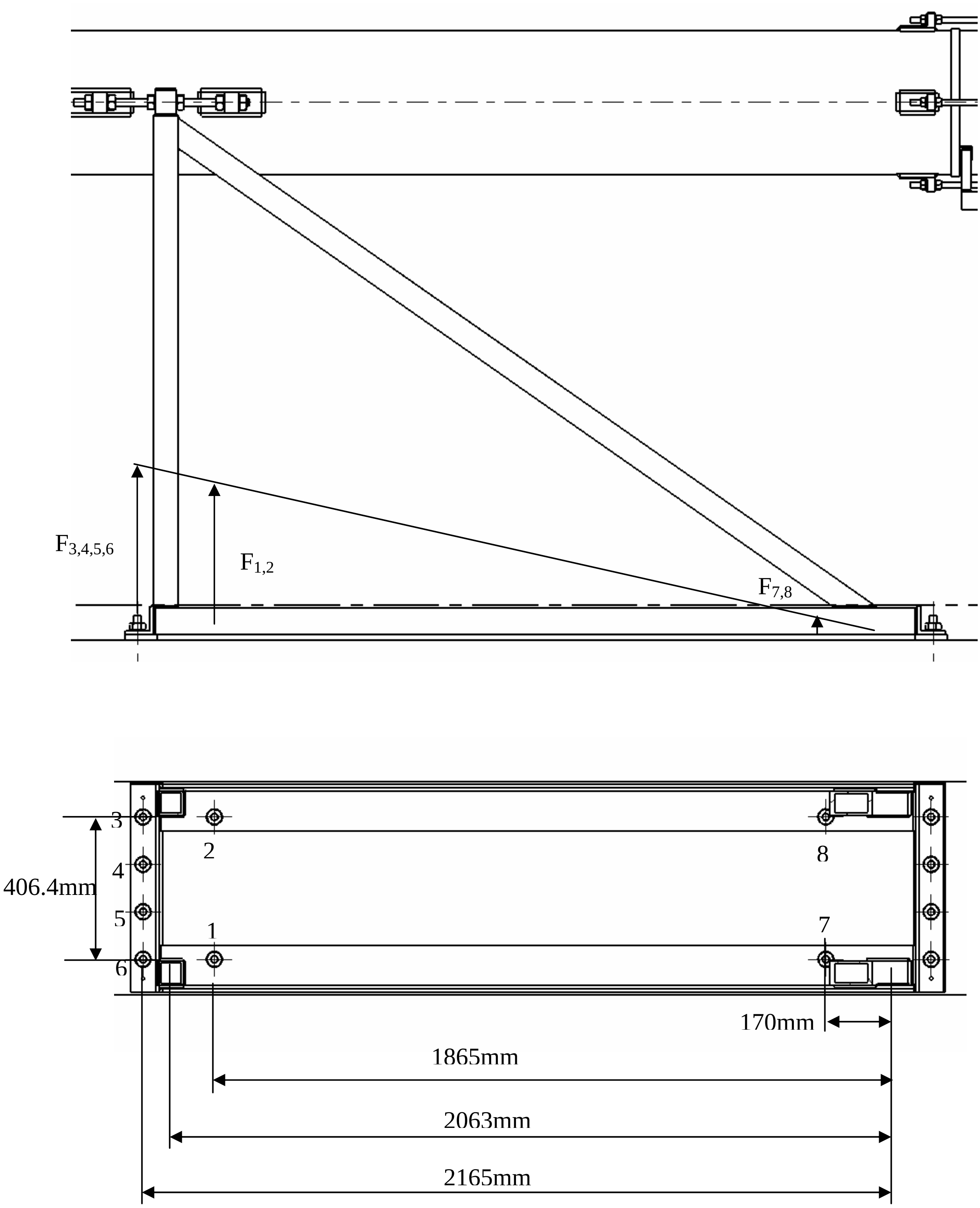


Figure 27 Anchor bolt down locations.

1.4.2 Loading of the anchor pipe brackets

1.4.2.1 Stress on the brackets of the anchor

There are two brackets welded on either side of the anchor section of pipe to which the anchor is bolted using two tie-bars.

The anchor pipe bracket is made of aluminium similar to the pipe material and is shown in Figure 28 and the FEA in Figure 29. The main block of the bracket is 60mm wide and 40mm thick; bevels are given for better weld-all-around welding.

The tie rods used are 7/8" OD rods (ASTM A 193 B7).

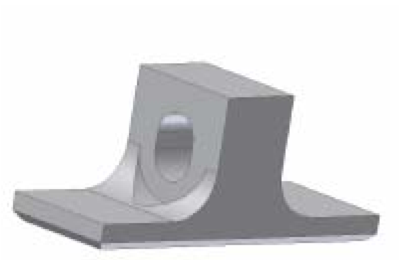


Figure 28 The anchor pipe bracket

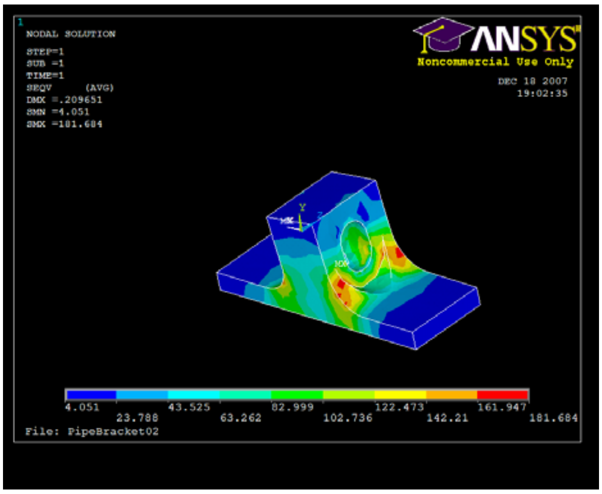


Figure 29: Von Mises stress for pipe bracket

The FEA was based on an applied load 90kN on one bracket.

The maximum stress 181N/mm^2 as shown above is 66% of the yield strength of the aluminium (275N/mm^2) hence the four brackets on each anchor pipe can withstand for the maximum earthquake load with a safety factor of at least 8 when equally loaded.

1.4.3 Tie rod analysis

The bars use 7/8" threaded bars. ASTM spec. number A193 B7 with yield strength of approximately 724N/mm^2.

A conservative value 90kN is applied on one threaded bar for the calculation.

The area of the minor diameter of the bar is $(0.3x25.4)^2$ x 3.14 = 182.32mm^2.

The stress on the bar equals 90/182.32 = 494N/mm^2. This is 68% of the yield strength and therefore, the bars are capable of withstanding the earthquake loading and have a safety factor better than 4 (given the conservative load case).