Insertion Device Alignment for the Diamond Light Source

A. Mariani
Diamond Light Source, Chilton, Didcot, Oxon. OX11 0DE, UK

This paper covers the survey and alignment techniques selected for the build & pre-alignment of the Insertion Devices, together with the alignment of the integrated 3-axis Hall probe bench magnetic measurement system, currently situated at Diamond Light Source. Insertion Device assembly consists of a main sub frame, upper and lower magnet arrays and two horizontal beams, which are currently assembled and surveyed prior to their magnetic field alignment. Instrument selection and measurement uncertainty is also covered on the assembly of the Insertion Devices and survey monument positions, prior to their installation within the storage ring.

1. COMPANY BACKGROUND

Diamond is a new synchrotron radiation source in the final stages of construction in Oxfordshire, UK. Diamond is the largest scientific research facility to be built in the UK for 30 years and will produce ultra-violet and X-ray beams of exceptional brightness, allowing pioneering experiments to be carried out which probe deep into the basic structure of matter and materials. The facility comprises of a 3GeV electron storage ring, injected from a 100 MeV linac through a full energy booster synchrotron. For day 1 operation 7 beamlines will be available with subsequent beamlines being added at a rate of 4-5 per year.

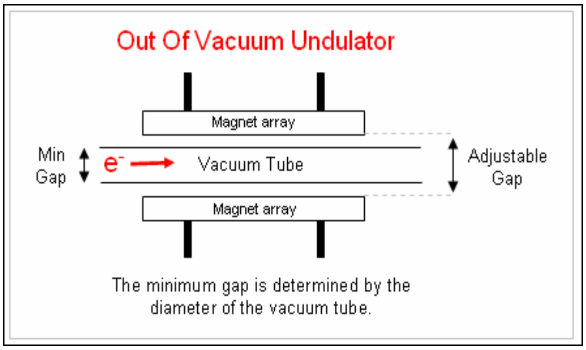
Figure 1: The Diamond site, July 2006

The facility is owned and operated by Diamond Light Source Ltd. (DLS), a private company formed under a Joint Venture Agreement between the UK Government and the Welcome Trust.

2. INTRODUCTION TO INSERTION DEVICES

DLS are in the process of producing long permanent magnet arrays for use in the electron storage ring. These structures, known as Insertion Devices (IDs), consist of two magnet array assemblies made up of a sequence of permanent magnet blocks which together produce a sinusoidal field, intensifying the synchrotron radiation supplied to the beamline. The two magnet arrays are fixed to upper and lower rectangular beams by adjustable columns which in turn are attached to the main support structure.

This paper covers the processes carried out by DLS to pre-align and subsequently install the in-vacuum and out-of-vacuum undulater IDs for the Diamond Project. Figures 1 & 2 identify the configuration for each type; the out of vacuum ID can accommodate larger magnets where as the in-vacuum ID can accommodate a narrow gap between the magnet arrays.



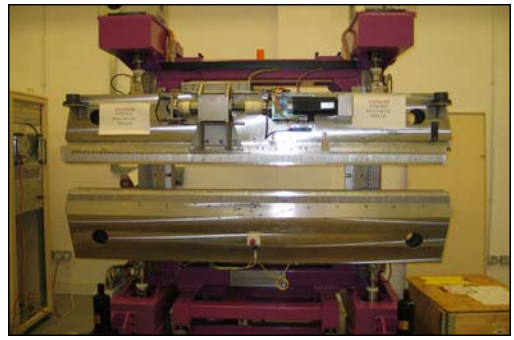
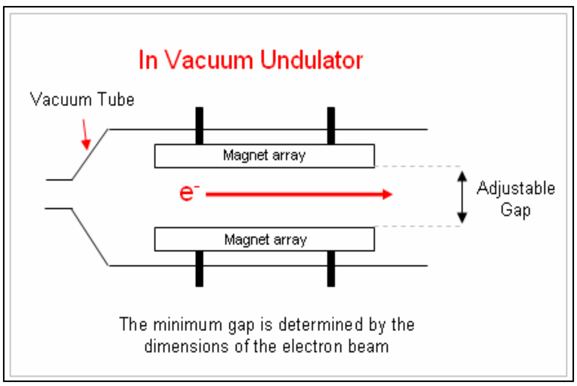


Figure 2: Out-of-Vacuum Undulator



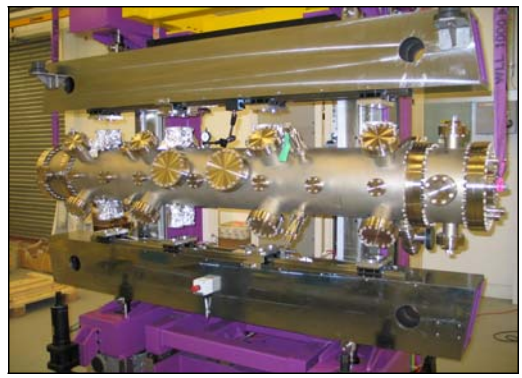


Figure 3: In-Vacuum Undulator

3. ID MAGNET ASSEMBLY

The magnet alignment process was carried out in 2 operations and was common to both types of undulator. Firstly, the magnet arrays were aligned parallel to the undulator's main frame beams, and at a required height. Secondary, to determine the magnet arrays transverse position through the centre of the Undulator.

3.1. Magnet array alignment – Gap and Parallelism

The lower beam of the assembly was set level to gravity using a Hamar laser alignment system. The system generates 3 mutually perpendicular laser planes square to 2 arc seconds. When the laser intersects with a dedicated sensor the offset to the base of the sensor is calculated perpendicular with respect to the plane(s). For this application only the offset perpendicular to the horizontal plane was required.

The upper magnet array was aligned parallel to the reference datum at a pre-defined height above it using the same system. For the lower magnet array however, the sensor was too large and so an alternative method had to be used. A Faro Gage Plus was used to generate a reference plain from measured points on the lower beam. The lower array was then set parallel to and at a pre-defined height above the reference plane.

3.2. Magnet array alignment – Transverse Position

To establish the transverse alignment reference for the ID installation the average position of the upper and lower magnet arrays were used. Points were measured on each of the arrays using a Faro laser tracker; these were then projected onto a common plane perpendicular to the gravity vector. A line of best fit through the 2 data sets was then constructed to define the beam axis for installation. Figure 4 details measured data and figure 5 details the best-fit line generated.

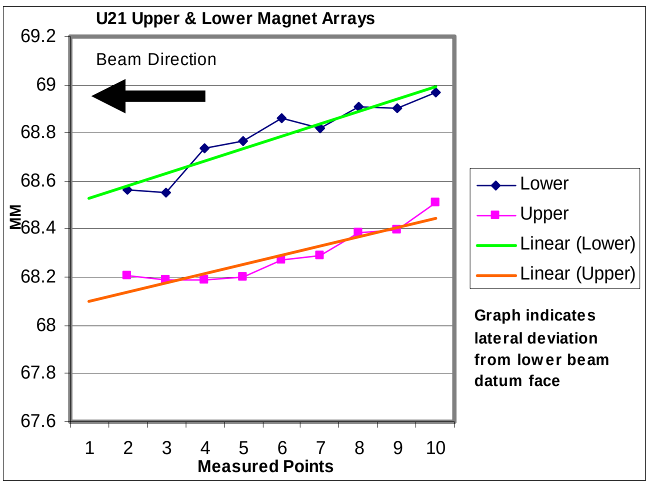


Figure 4: Measured data

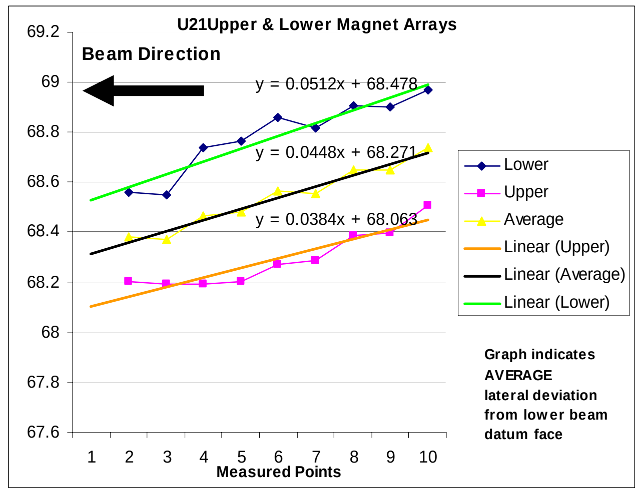


Figure 5: Best-fit line

4. MAGNETIC FIELD MEASUREMENT

To optimise the performance of the ID, the magnets which make up the arrays have to be sorted and shimmed. To enable this operation, a series of magnetic measurements in the gap between the arrays are performed using a hall probe magnetic field transducer and an Integrated Coil 2 axis XZ positioning system.

This section of the paper describes how these 2 pieces of equipment were aligned in the ID assembly & Test area within DLS.

Figure 6: Measurement Bench Layout

4.1. General Layout

The magnetic field transducer’s Hall probe is mounted on an XZ positioning unit which allows a 250mm travel in the vertical and horizontal direction. The XZ unit is in turn mounted on a carriage which can be moved up and down a 6m long granite block via a linear motor guide system. This allows field measurements to be made at any point in a 250 x 250 x 6000 mm volume, and is used to map the field distribution of the DLS undulators. The integrating coil is a stretched rectangular loop coil which spans the length of the granite block. At each end of the coil is a rotation stage which is fixed to an XZ positioning unit, allowing the whole coil to be moved horizontally and vertically and also rotated. The coil measurements allow the total integral of the field along the axis of the undulator to be evaluated in one measurement. As a result, having the two measuring devices aligned relative to each other, greatly speeds up the process of aligning the permanent magnets.

4.2. Hall probe transducer alignment

The first alignment performed on the Hall Probe Bench was to align its main axis (S) perpendicular to gravity and the other two remaining axis (X & Z) mutually perpendicular to this axis. An alignment frame clocked vertical with respect to gravity was established using the internal gyro within a Faro laser Tracker. Using the watch window function within Spatial Analyzer (SA) software live measured data from the laser tracker was utilised during the alignment process.

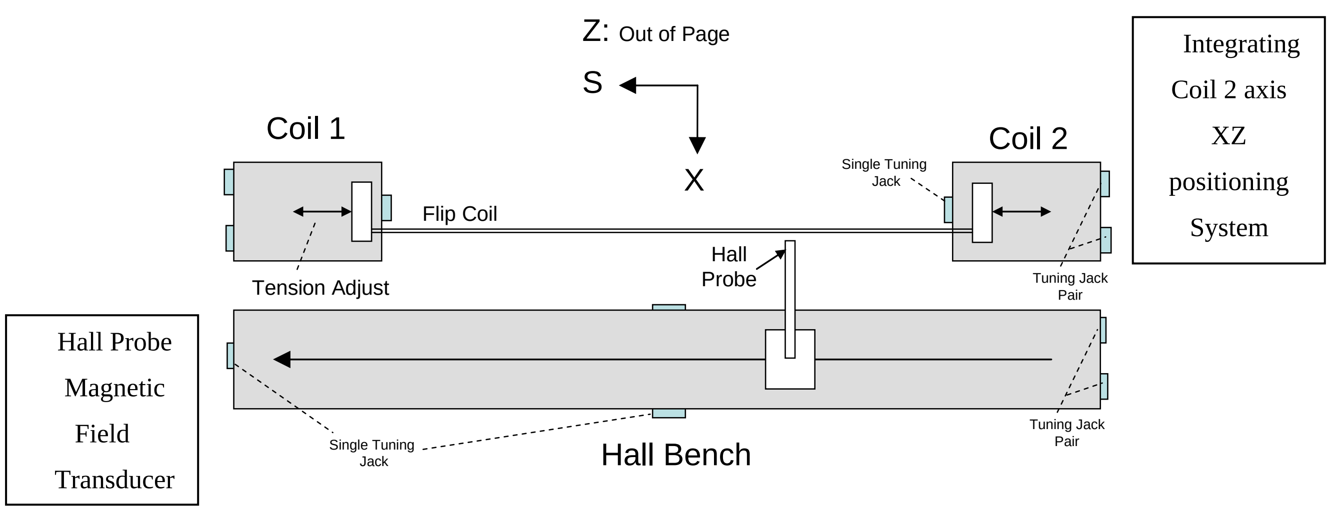


Figure 7: Hall & Flipping Coil Layout and Co-ordinate Frame

To align the hall bench, a target nest was carefully mounted to the arm of the hall probe, this provided the interface for a spherical mounted reflector (SMR), the target to which the laser tracker measures. The hall probe was driven through its full operating range and its path relative to nominal was dynamically mapped with the laser tracker. Using jacking feet positioned as shown in figure 7, careful adjustments were made to correct the pitch and roll of the assembly. The method was repeated for the Hall Probe’s X and Z axes perpendicular to the S axis, which were used to define the laser trackers co-ordinate frame.

4.3. Integrating coil alignment

Having generated a co-ordinate frame from the hall probe assembly, this was used to align the integrating coil system. The loop coil is attached at each end to bi-directional translation stages facilitating independent adjustment in vertical and transverse directions. It was necessary to orientate these stages with respect to the hall probe co-ordinate system. To do this, each stage was driven through its full travel and adjusted so that its axis was perpendicular to that of the hall probe, Figure 9. The measurements were taken dynamically using a laser tracker.

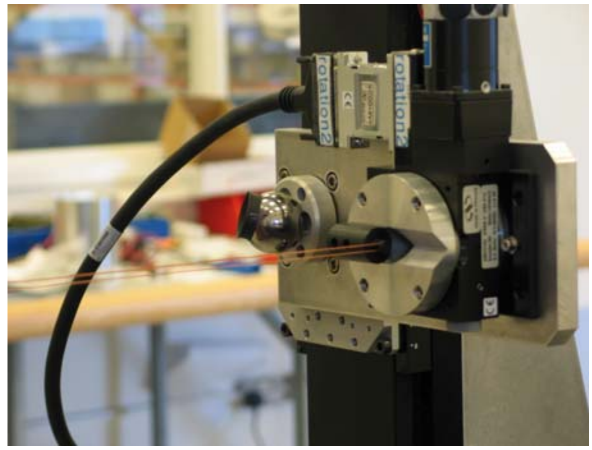


Figure 8: Integrating Coil Arm

During the alignment process it became evident that there was play in the slides of the stages causing deflection either side of the central position. This produced a maximum variation of about 100μm from the straight path of each slide. The most important measure of alignment was taken as the variation of the coil length over the full XZ travel range of the coil (X, Z ±120mm). The alignment achieved produced a maximum variation of 0.5mm for the coil length over the full travel range.

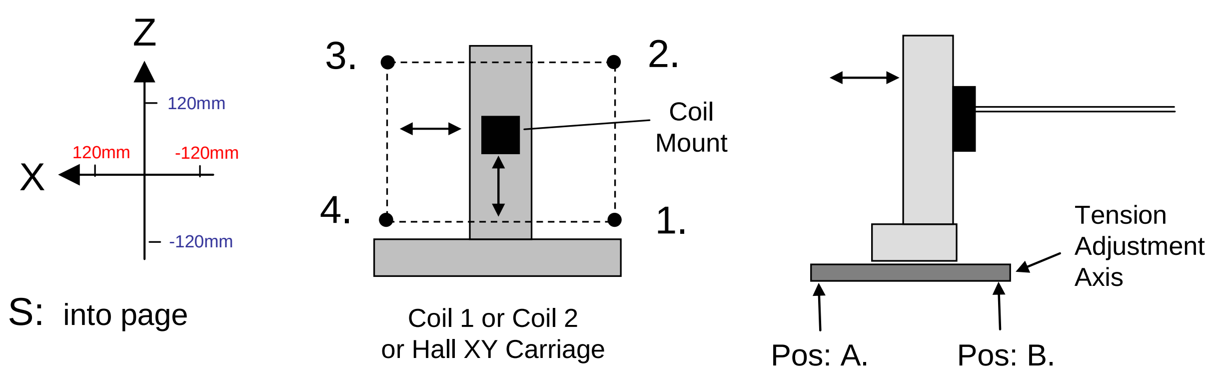


Figure 9: Coil Unit Measurement Procedure

5. ID PRE-ALIGNMENT

Survey Monuments are positioned at each end of the ID to provide the alignment reference for the ID within the storage ring. Each ID assembly was surveyed to ensure the local alignment between the magnet arrays had been achieved. The survey was carried out using a Faro Laser Tracker running SA software. To optimise survey accuracy multi-station measurements were employed. Once all measurements were taken SA's Unified Spatial Metrology Network (USMN) was used to best fit and then solve the network. An uncertainty analyses was then carried out for each point within the network.

Once the as-built position of the survey monuments had been determined, a local co-ordinate system or frame used with SA will be established co-incident with the best-fit magnetic axis of the upper and lower magnet arrays, which represented beam centre position through the ID (figure 11), in return a 3 dimensional value is generated for the position of the survey monuments from the mechanical beam axis. These monuments will become the alignment reference for the storage ring installation.

5.1. Spatial Analyzer (SA)

For all data collection through the Faro Laser trackers on the Insertion Devices SA software was used.

SA is a 3-D metrology software platform created by engineering software development company, New River Kinematics. NRK are not affiliated to any specific instrument manufacturer as illustrated in figure 10. SA is designed to provide a common interface for the majority of portable measurement Technologies (Laser Trackers, Local GPS, Portable CMMs, Theodolites, and Laser Scanners) **[4].**

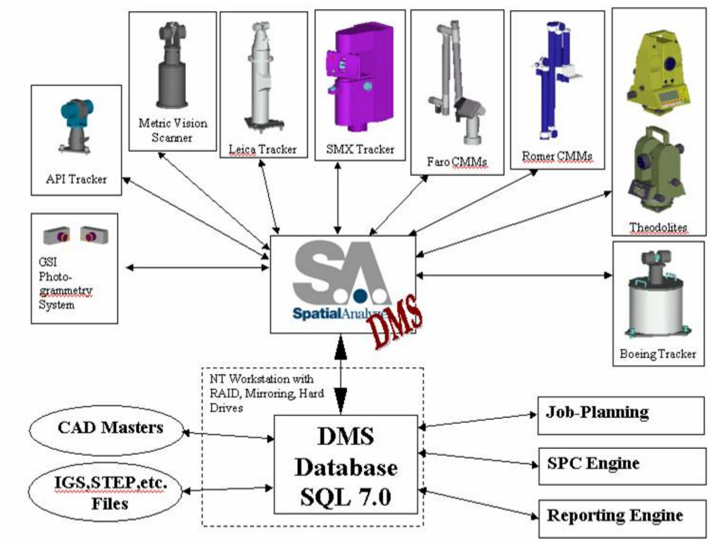


Figure 10: Spatial Analyzer

The main advantage for using SA is that it can carry out bundle adjustments through its own Unified Spatial Metrology Network (USMN) software. This is an important function where multiple instrument stations are introduced around a specific job, within a common co-ordinate system or frame as known in SA. A bundle adjustment is a least squares technique, which optimises a network orientation. The adjustment takes the bundle of measured points to identified targets and processes them through a best fit of angle and distance measurements. By measuring points from many station setups the estimation of the true co-ordinate value is considerably improved.

SA is a traceable metrology 3D graphical software platform that can simultaneously communicate to virtually any number and type of dimensional measurement systems and perform complex analysis tasks. It has a simulation function, which allows instrument station geometries to be qualified detailing uncertainty values for station placement and observed targets.

The viewing of SA's display allows the user to download solid models from CAD in standard STEP format or any other standard formats within today's industry, from this, all measurements can be analysis including Geometric Dimensioning & Tolerancing within all workshops, also complete suites of analysis and alignment/transformation routines are available.

5.2. Constructed network

Measured points were taken on the ID to enable the co-ordinate system frame to be constructed. Previous checks had been made on the ID's lower beam to confirm its flatness within the manufacture's specification of +/- 25µm, therefore the use of the surface was used as a Bestfit plane within the constructed co-ordinate system. Prior to all measurements fixed targets with known offsets are positioned at each corner of the lower beam's top and front surfaces and at various positions around the ID. Having these fixed targets this would then allow measurement shots from various station positions, giving a lesser uncertainty on each target position.

ID's are set in **roll** & **pitch**, using an engineer's level positioned upstream at the end of the lower beam, this operation is repeated for roll only when finally positioned in the global network situated in the storage ring.

Note! Setting the ID in pitch as well as in roll with the engineer's level at the pre-alignment stage, was only necessary if the Laser tracker internal gyro level was used as the Bestfit plane, otherwise measured points on the lower beam plane was used to determine the ID's Best-fit plane. The advantage of using the gyro's level plane, would be to generate a greater area comparing it with the cross surface area of the lower beam, which only measured 250mm in width.

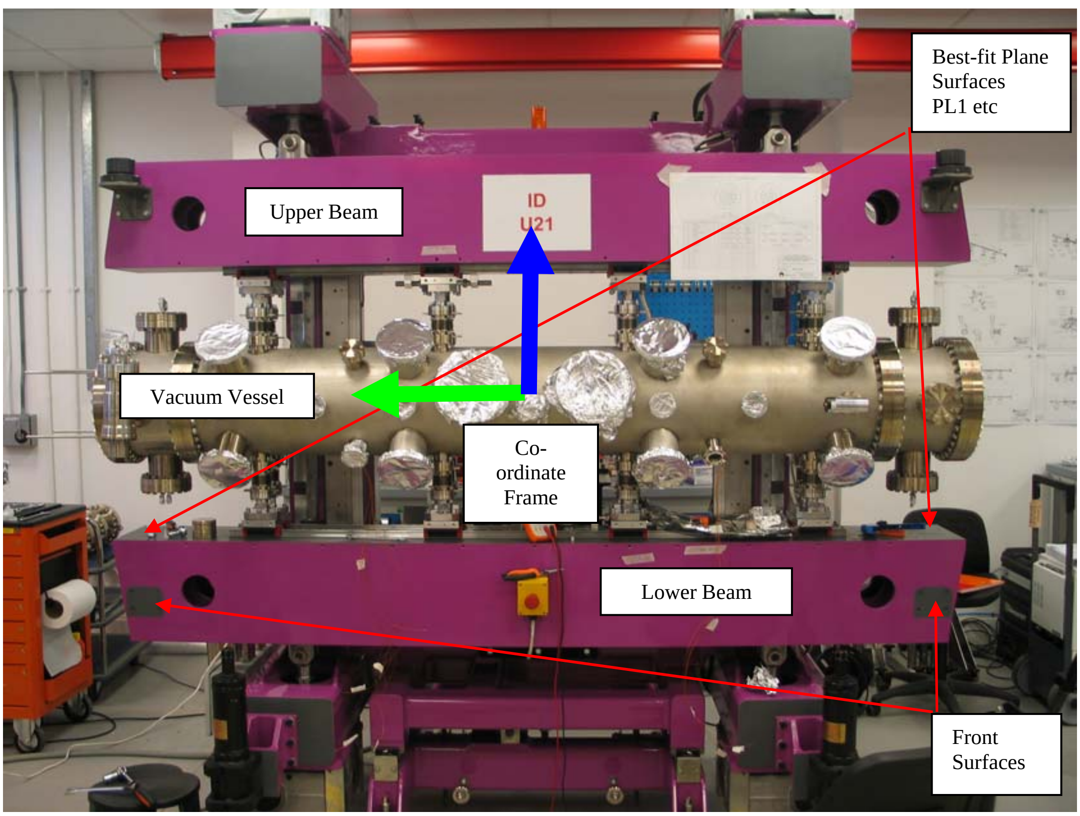


Figure 11: ID pre-alignment frame location

From the multi positions of the instruments around the ID, measurements were taken of the Upper & Lower beams surfaces, magnet arrays **[3.2]**, survey monument positions at the rear of the ID (SM1 & SM2) and the controlled network situated around the ID.

Having measured fixed targets from various positions, SA's USMN was used to determine the uncertainty value for each survey target position, illustrated graphically as a point cloud within the software.

Figure 12 illustrates a plan view of the survey geometry using multi laser tracker positions situated around U21 ID forming its own control network.

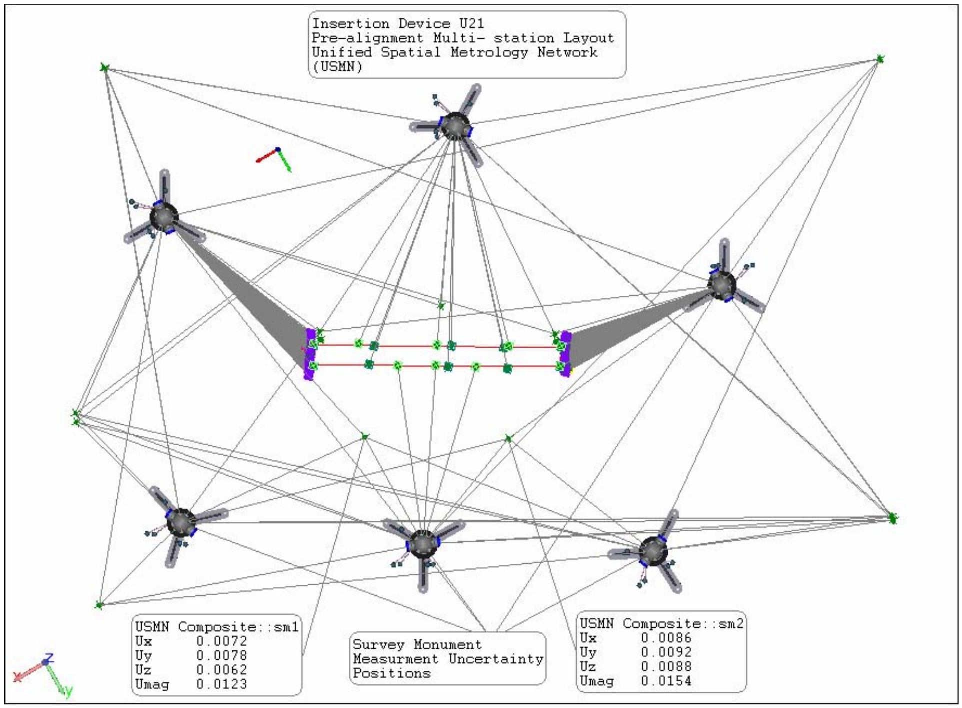


Figure 12: USMN Network

Uncertainty values of 12µm to 15µm were achieved through SA for the survey monuments positions within the controlled network. USMN Point error RMS = 0.0083mm, Average = .0062mm, Max = 0.0321mm (ERP4), Uncertainty Magnitude Average = 0.020, Max = 0.025 (ERP3), 95.46% Confidence Interval (2.0 sigma).

During the layout of the network process, consideration was given to the desired instrument locations. Since the instrument was moved around the ID, the majority of the target field should be visible from all instrument locations, as shown in figure 12, showing six instrument positions, all at varying heights and orientations. Care must also be taken during the process when measuring these targets; therefore all surveys had been performed in a temperature controlled laboratory to obtain a less uncertainty value.

5.3. SA Constructed Pre-alignment Co-ordinate system (frame)

Once all measurements were taken, the agreed co-ordinate system at the time of alignment was constructed with the following Plane, Line, and Point (3 point) method. Only measured points from the result of the USMN were used to generate the co-ordinate frame.

Constructing a right-handed Cartesian co-ordinate system as illustrated in figure 13, where Y-axis follows the direction of the beam aligned to the Best-fit magnet arrays cardinal points **[3.2]**, **Z-axis** is upwards, positioned equally between the upper & lower beams perpendicular to the Best-fit lower beam plane or Laser trackers gyro and **X-axis** pointing radially outwards. The position of the co-ordinate system's origin was situated at the mid point of the vacuum vessel as illustrated in figure 11.

Following the construction of the co-ordinate system, a 3 dimensional position was generated for the survey monuments position relative to the ID's beam centre. A further rotation and translation of the co-ordinate frame within SA, followed by a Bestfit to the network nominal was needed to proceed with the final installation within the storage ring as described in ID storage ring alignment.

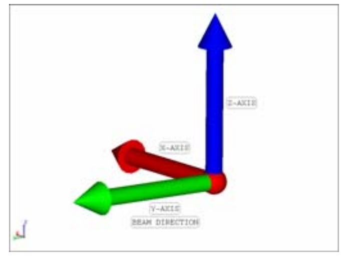


Figure 13: Right Hand Co-ordinate System (Frame)

6. ID STORAGE RING ALIGNMENT

As the ID's were installed they were locally aligned to the global survey network using a Faro Laser tracker and SA software. A relative alignment tolerance of each survey monument situated on the ID of +/- 50 µm was achieved by viewing through SA's watch window. This function enables the operator to continuously view the live data required to set the survey monuments.

6.1. Storage Ring Tunnel Network

Diamonds storage ring tunnel network was installed in October 2004 and last re-measured in March 2006. The instruments used for the survey were two Leica TDA-5005 total stations both measuring a total of 1200 observations from all 48 instruments stations, onto the PEBPM'S and assembled girders survey monuments positions situated around the storage ring, acting as the network for the ID's installation.

Measurements were then post processed using a free network least squares adjustment, which in return gave Diamond its own 2D Planmetric control. Level data was then added using two Dini 12 digital levels to give a 3D co-ordinate for each of the control points.

6.2. Constructed ID Geometry

Three of the initial seven first phase ID's (in straights I02, I03, and I04) was installed at a canted angle of 0.25mrad away from the nominal electron beam axis (see fig.14). During the second phase of ID installation, an extra ID will be installed into each of these straight sections, this time installed with an angle of 0.75mrad in the opposite sense. The reason for this is to allow two independent beamlines to be fed from a single straight section.

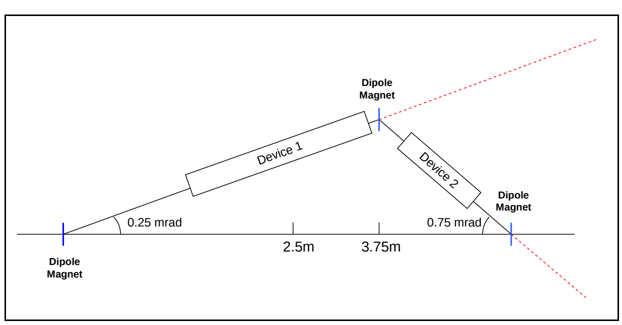


Figure 14: ID Configuration

Additional constructed geometry was therefore added to the existing pre-alignment SA survey of the ID. Nominal data of the Girder positions, along with the nominal data of the ID's straight was imported within the SA job. A second co-ordinate frame was constructed maintaining the current level of the pre-alignment frame situated on the ID which is situated on the direction of the straight at beam height.

If the canted ID is applied the following corrections were made to both of the co-ordinate frames:

- Frame is translated -1608 mm (upstream) in line with the direction of the straight positioned at the first chicane magnet.
- Frame is rotated 0.0143239 degrees towards the facet wall making the ID canted towards the ratchet wall.

Once the co-ordinate frames are in position on the nominal data, a **frame** to **frame** transformation can be applied within SA as follows:

- Source Frame – Pre-alignment co-ordinate frame on ID
- Destination Frame - Constructed Frame on nominal positions
- Objects to Transform - ID's Survey Monument positions.

By entering the command this transformed the frame of the pre-alignment ID onto the constructed frame situated on the nominal positions taking with it the survey monument positions of the ID. Making the new current frame active this generated 3D nominal data for the survey monuments in Diamond's control network. Once the ID was carefully lowered into the storage ring, final installation could commence.

The storage control network was finally imported into the current SA job file. A Faro laser tracker was leveled to gravity with its internal gyro. Measured points were taken of the control around the ID, then using the Bestfit transformation points to points; the measured data was best fitted to nominal data. By fixing the Rotation in x and y of the co-ordinate frame, enabled the laser trackers level to become active. Careful adjustments were made to finally locate the survey monument positions in position within a tolerance of +/-50µm against nominal data. Roll was set against an engineer's level positioned on its datum plane (lower beam) at the correct position stated in constructed network **[5.2]**; figure 15 illustrates the final installation taking place.

Figure 15: U21 Final Alignment

7. CONCLUSION

With the completed and final positioning surveys of all phase 1 ID's situated at Diamond, all have drastically benefited from the continuous use of the Faro 3D portable measuring system and SA software. The addition of the Faro Gage plus Arm had also benefited for small scale alignment tasks around the build of the ID's prior to the measuring of the magnetic fields situated at the measuring Hall Probe Bench.

Acknowledgments

I would like to thank David Wilson, Allen Baldwin, Jason Giles and Charles Thompson for their involvement, guidance and knowledge given.

References

[1] A.I. Baldwin, "ID Measurement Bench Survey Report", February 2005

[2] D. Wilson, "Survey & Alignment for the Diamond Light Source", IWAA2006, October 2004

[3] www.faro.com

[4] www. Kinematics.com