# THE HIE-ISOLDE ALIGNMENT AND MONITORING SYSTEM SOFTWARE AND TEST MOCK UP 

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#### Abstract

For the HIE Isolde project a superconducting linac will be built at CERN in the Isolde facility area. The linac will be based on the creation and installation of 2 high- $\beta$ and 4 low- $\beta$ cryomodules containing respectively 5 high- $\beta$ superconducting cavities and 1 superconducting solenoid for the two first ones, 6 low- $\beta$ superconducting cavities and 2 superconducting solenoids for the four other ones. An alignment and monitoring system of the RF cavities and solenoids placed inside the cryomodules is needed to reach the optimum linac working conditions. The alignment system is based on opto-electronics, optics and precise mechanical instrumentation. The geometrical frame configuration, the data acquisition and the 3D adjustment will be managed using a dedicated software application. In parallel to the software development, an alignment system test mock-up has been built for software validation and dimensional tests. This paper will present the software concept and the development status, and then will describe the test mock-up and the obtained results.


## INTRODUCTION

The High Intensity and Energy (HIE)-ISOLDE project is a major update of the ISOLDE REX facility that aims to increase the energy and quality of post-accelerated Radioactive Ion Beams (RIBs) [1], delivered to experiments. The beam will be accelerated by 6 cryomodules [2] containing active components, i.e. RF cavities and solenoids, which will be in cold conditions $(4.5 \mathrm{~K})$ and share the insulation vacuum with the beam vacuum.

To run the linac in the optimum conditions, the main axes of the active components, cavities and solenoid, must be aligned on the REX Nominal Beam Line (NBL) within a precision of 0.3 and 0.15 mm respectively at one sigma level along directions perpendicular to the beam axis.


Figure 1: Sketch of the alignment system - Top view.
As sketched in Figure 1, the proposed alignment and monitoring system [4] uses a set of double-sided Brandeis CCD Angle Monitor (BCAM) [5] fixed to metrological
tables in order to create a close geometrical network link to the NBL by reference pillars. Two external lines of sight, one on each side of the cryomodule, are created and act like a frame. The BCAM from the internal lines are placed in front of viewports and allows the observation of targets attached to the active elements and of the BCAMs situated on the previous and next table.

The project requires the study and development of the acquisition and calculation chain. Parameters such as the effects of measuring through the cryomodule viewports, thermal contraction and the dimensions of the mechanical pieces will also have to be included in observation corrections and the global 3D-adjustment.
The software developed [6] especially for the project and the results of a test bench constructed to validate the different part of the software and hardware are presented.

## SOFTWARE

## Mathematical Concepts

The alignment system for HIE-Isolde acts on many different coordinate systems during the geometrical adjustment and the monitoring of targets. All systems are of Cartesian type and have the same scale factor. This reduces the problem of transition between the individual systems to 6-parameter transformations. The definition of the coordinate systems is rather pragmatic: Each rigid body with calibration data has its own coordinate system in which the constants are given and all systems are attached to a single common system for the definition of the adjustment frame.


Figure 2: Overview of the coordinate systems.
All systems are defined in hierarchical order and, as shown in Figure 2, the main systems are:

- "HIE System" linked to the NBL. Its datum is basically arbitrary but will be defined by pillars in the ISOLDE building or by the first and last datum tables. All the studies have been made with this last solution because of possible pillar integration issues with the Linac enclosed in a tunnel.
- "Table system", one for each metrological table. These systems contain the coordinates of the corner reference points and of the mounting balls
supporting the BCAMs. Thanks to the balls: the cone, plane and slot recess in the BCAM body subsequently fix a point, a line and a plane. This isostatic connection allows the calibration results to be reproduced.
- "Mount system", one for each BCAM.

The nature of image coordinates implies that there is a 2D-system in which the observations are made. Using calibration constants, the observations are transformed into the mount system by the known position of the CCD plane in it.


Figure 3 : Definition of the BCAM mounting system by the balls on the table. [5]

There is an important difference between the BCAM mounting system and the other local systems: It is directly defined by the coordinates of the mounting balls. A drawing in Figure 3 shows the principle of the mounting system definition. The basic mathematical definition of the mounting system's unit axes (with the index u for unrotated) reads:

$$
\begin{aligned}
& \vec{M}_{z u}=-\left(\overrightarrow{P_{\text {slot }}}-\overrightarrow{P_{\text {cone }}}\right) \\
& \vec{M}_{y}=\left(\overrightarrow{P_{\text {slot }}}-\overrightarrow{P_{\text {cone }}}\right) \times\left(\overrightarrow{P_{\text {plane }}}-\overrightarrow{P_{\text {cone }}}\right) \\
& \vec{M}_{x u}=\vec{M}_{y} \times \vec{M}_{z u}
\end{aligned}
$$

The X and Z axis are afterwards rotated by a constant angle around the Y axis. After this rotation, the Z axis of the mounting system is mostly parallel to the optical axis of the BCAM. The unit vectors of the mounting system are used as columns to create the rotation matrix from table to mounting system:

$$
R_{\text {Table }}^{\text {Mount }}=\left(\begin{array}{lll}
M_{x_{x}} & M_{y_{x}} & M_{z_{x}} \\
M_{x_{y}} & M_{y_{y}} & M_{z_{y}} \\
M_{x_{z}} & M_{y_{z}} & M_{z_{z}}
\end{array}\right)
$$

As the transformation parameters between the table and the mounting system are considered constant, only the three translations and three rotations of the tables with respect to the HIE system are estimated for each table.

The estimation of the parameters is made by a standard Gauss-Markov weighted least squares adjustment. Therefore, observation equations are needed that relate the unknown parameters to the observations. Two basic types of observations exist: Observations made by BCAMs and external observations.

BCAM measurements can be done frequently since the sensors are statically installed at the accelerator and connected to their controlling device which is reachable
via a network connection. Although the acronym BCAM suggests using it as an angle monitor, the observations should be taken as raw as possible. Therefore, the image coordinates are included in the observation equations without calculating explicit angles first. Relating the unknown parameters to the image coordinates is done by a projection of the observed light source onto the CCD, first with these two steps:

1) The image coordinates are transformed into 3 D coordinates by calculating the pixel position on the CCD in the mounting system.
2) The position of the observed light source is transformed from the observed mounting system into the HIE system and afterwards into the observing mounting system.
These transitions use all parameters for the observing and the observed table. Now, with the light source and its projection being in the same system, the intersection of the ray of light running from the observed BCAM light source through the pivot point with the CCD can be calculated by a line-plane intersection. These formulations require a normal N on the plane, a point Pp in the plane and two points Li and Li ' that define the line. An ideal candidate for the required normal is the optical axis from the BCAM calibration data. The pivot point PP can be moved along the optical axis by the calibration constant c that describes the distance between pivot point and CCD to create point Pp. A point $P$ lies in the plane described by N and Pp when the equation 1 is fulfilled.

$$
\begin{equation*}
N \cdot(P-(P P+N \cdot-c))=0 \tag{1}
\end{equation*}
$$

Substituting the equation for a line defined by two points into the above formula for P leads to

$$
\begin{aligned}
& 0=N \cdot\left(L_{i}+t\left(L_{i}^{\prime}-L_{i}\right)-P P+(N \cdot-c)\right) \\
& \Rightarrow t=\frac{N \cdot\left((P P+N \cdot-c)-L_{i}\right)}{N \cdot\left(L_{i}^{\prime}-L_{i}\right)}
\end{aligned}
$$

Accordingly, the desired intersection point can be calculated using the line equation with the above equation substituted for the parameter t :

$$
P=L_{i}+\left(\frac{N \cdot\left((P P+N \cdot-c)-L_{i}\right)}{N \cdot\left(L_{i}^{\prime}-L_{i}\right)}\right)\left(L_{i}^{\prime}-L_{i}\right)
$$

After these calculations, the observation and the function value calculated with the transformation parameters can be compared by the adjustment. In addition to the BCAM observations, external distance measurements between all the tables are also introduced into the adjustment.

The corners of the datum end tables have to be measured by existing external solutions, such as laser tracker or total station measurements. These points will be introduced as direct coordinate observations with a weight based on their precision. The stability can be controlled by remeasuring these points occasionally in networks that include reference points [5]. Including these points as direct observations with the accuracy information from their measurement determines the position and orientation of the end tables by a simple linear relationship to the observation that also takes the precision of the measurement into account (Figure 4).

Consequently, the network receives a "dynamic datum" with known stochastic information for the control points.


Figure 4: External observations that support the BCAM observations.

The weights of the observations in the adjustment are derived from their standard deviations. For the corner observations, the standard deviations are given by the result of their calculation. In the current implementation, there is no stochastic information for the image coordinates that are calculated by the BCAM acquisition software, LWDAQ [5]. Thus the specification of the software which identifies the spot centers with an accuracy of $1 / 10$ pixel is used, which is equivalent to $1 \mu \mathrm{~m}$ for the CCD of the current BCAMs. This value has been tested and validated by the feedback on other experiments.

## Software architecture

During the early stages, the mathematical and utility functionality was developed separately from userinterface implementations. Portability of the developed software is a serious concern in order to be adaptable to several operating systems and interfaces. Since portability and good performance for large matrices are both needed, a mix of C and $\mathrm{C}++$ was chosen to implement the calculation and configuration backend. The C++ open source matrix library Eigen is used for all linear algebra problems. The configuration of the program is done by INI-style configuration files. An additional benefit of a native implementation is the possibility to incorporate C libraries virtually into any popular script or programming language through native interfaces. Modularity and loose coupling between the parts of the software is another important design aspect. This can be achieved by programming against interfaces instead of objects. This means that only a rather small set of high-level public functions is known by objects that use a certain object, thus no knowledge about the implementation details is available to the calling object. This approach works very well with C-interfaces.


Figure 5: Block overview of the alignment library.
The developed library is flexible enough to allow changes to the BCAM types, observations and number of tables just by changing the configuration file. Besides the
configuration file, the calibration constants of the BCAMs are also needed by the software. An independent part of the library reads the file with the BCAM calibration data that can be downloaded from the web sites of OSI [5]. Access to the BCAM observations is provided by another software part that acts as a flexible front end for either stored image coordinates from a file to test the influence of software modifications or to an LWDAQ instance that accesses the BCAMs and calculates the spot coordinates.


Figure 6: Communication chain between the software and the BCAMs

## Simulations

It is possible to generate image coordinates from given table positions and orientations. Based on the projection code that was explained with the observation equations, the projected spot on the CCD in the mount system is transformed into a sub-pixel observation. The result of this computation can be used to validate the adjustment model: With the generated observations, a setup must reconstruct to the positions that generated the observations. Another possibility is the simulation of the stability and accuracy of a bigger setup or new observations. For this purpose, the calculated image coordinates are randomized by a Gaussian noise to simulate random observation errors. Simulations have been carried out for a configuration close to the whole final set-up, i.e 6 cryomodules and 7 inter-tank tables, with randomizing the observations by one tenth of a pixel ( 1 micron on the CCD) and with the two end tables fixed. The direct coordinate system is defined with the X axis in the direction of the beam, Z axis vertical to the top and the zero point at the middle of the first table. So the radial components that we are more interested in are Y (horizontal) and Z (vertical). The differences between the simulation results and the reference table theoretical coordinates are within $\pm 20$ microns. The following table presents the standard deviations for each transformation parameter between HIE-System and every table.
Table 1: Rotation (R) and Translation (T) precisions without overlapping

|  | $\boldsymbol{\sigma} \mathbf{R X}$ <br> $[\boldsymbol{\mu r a d}]$ | $\boldsymbol{\sigma} \mathbf{R Y}$ <br> $[\boldsymbol{\mu r a d}]$ | $\boldsymbol{\sigma} \mathbf{R Z}$ <br> $[\boldsymbol{\mu r a d}]$ | $\boldsymbol{\sigma} \mathbf{~ T Y}$ <br> $[\boldsymbol{\mu} \mathbf{m}]$ | $\boldsymbol{\sigma} \mathbf{~ T Z}$ <br> $[\boldsymbol{\mu} \mathbf{~ m}$ |
| :--- | :--- | :--- | :--- | :--- | :--- |
| Table 0 | 1.9 | 6.8 | 1.6 | 0.6 | 0.7 |
| Table 1 | 48.4 | 7.6 | 6.1 | 13.7 | 19.1 |
| Table 2 | 61.1 | 6.9 | 6.0 | 23.2 | 31.6 |
| Table 3 | 64.8 | 6.3 | 5.7 | 26.8 | 37.1 |
| Table 4 | 61.1 | 6.6 | 6.0 | 23.2 | 34.1 |
| Table 5 | 48.3 | 8.0 | 6.1 | 13.7 | 22.2 |
| Table 6 | 4.0 | 9.5 | 1.6 | 1.1 | 1.3 |

In addition, overlapping the BCAM observations is also considered (Figure 7). It consists in observing not only the BCAMs on the previous and next metrological tables, but several others in order to increase relations and therefore redundancy. This operation is only possible on BCAMs situated on the outer lines because it will be made by offsetting the instrument principally in height.


Figure 7: Side view of the overlapping observations simulation without observing reference pillars linked to the NBL.

The differences between the simulation results and the reference table theoretical coordinates are within $\pm 10$ microns. The following table presents the standard deviations for each transformation parameter between HIE-System and every table.
Table 2: Rotation (R) and Translation (T) precisions with overlapping

|  | $\boldsymbol{\sigma} \mathbf{R X}$ <br> $[\boldsymbol{\mu r a d}]$ | $\boldsymbol{\sigma} \mathbf{R Y}$ <br> $[\boldsymbol{\mu r a d}]$ | $\boldsymbol{\sigma} \mathbf{R Z}$ <br> $[\boldsymbol{\mu r a d}]$ | $\boldsymbol{\sigma}$ TY <br> $[\boldsymbol{\mu m}]$ | $\boldsymbol{\sigma}$ TZ <br> $[\boldsymbol{\mu m}]$ |
| :--- | :--- | :--- | :--- | :--- | :--- |
| Table 0 | 1.5 | 3.5 | 1.2 | 0.5 | 0.5 |
| Table 1 | 34.5 | 4.2 | 3.8 | 9.2 | 10.7 |
| Table 2 | 38.2 | 3.6 | 3.4 | 12.7 | 15.4 |
| Table 3 | 38.0 | 2.8 | 2.7 | 13.7 | 16.9 |
| Table 4 | 38.3 | 3.6 | 3.4 | 12.7 | 15.6 |
| Table 5 | 34.5 | 4.2 | 3.8 | 9.2 | 11.0 |
| Table 6 | 3.2 | 3.9 | 1.2 | 0.9 | 1.1 |

The overlapping increases the results of:

- The coordinate reconstruction and the precision of the translation by a factor 2 .
- The rotation precisions by a factor 1.5.


## TEST BENCH

## Introduction and Goals

A test bench was designed and built in order to reproduce, test and validate the monitoring concepts and the software.


Figure 8: Concept, dimensions and coordinate system.

The test bench is designed to be close to the final configuration (Figure 8), to be adjustable and adaptable to a previous mock-up of the cavities/solenoid adjustable support and was installed on precise rails. The coordinate system is the same as the one used in the simulations.
The test bench is composed of three main objects:

1) The pre-existing adjustable support, which simulates the support for cavities and the solenoid.
2) Two tables that support a system to fix and adjust the viewport position and orientation.


Figure 9: Picture of cavities support mock-up (left) and the viewport support (right).
3) Four metrological tables (Figure 10) including three elements: One base plate screwed onto the rails by U-shaped plates. One adjustable plate equipped with fiducial points in every corner that when located on the base plate by three cone point screws allows leveling. The system is fixed down by a central screw to the base plate. Four BCAM supports screwed to the adjustable plate. These supports contain three fiducials and three ceramic balls to ensure the isostatic position of the BCAM.


Figure 10: Top: Schematic view with point numbers, the fiducials (Black), the adjustable plate (dark grey), the BCAM Support (light grey) and the Ceramic balls (White). Bottom: Picture of the system as installed.

## Measurements done

## Calibration of the plates

Each metrological table was measured in a temperature controlled laboratory using a Romer Multi-Gage, measurements included the ficucials on the adjustable plate, the balls and three fiducials on the BCAM support. The measurements were carried-out with a torque of 1 Nm on the central fixing screw; the flexion due to this torque was reproducible within 50 microns at the center. The precision of determination of these points is evaluated at 10 microns at one $\sigma$.

## In-situ, first iteration

The calibrated tables were installed on the rails and a measurement of the fiducial points on the adjustable plate was done by a laser tracker (Leica Ltd 500). The network was calculated using a Spatial Analyzer "Unified Spatial Metrology Network" option and includes six stations. The achieved precision at one $\sigma$ is about 20 microns. BCAM observations were made at the same time. After analysis of the data, the adjustable plate flexure at its center was slightly different than in laboratory conditions. The result is still valid as this first-iteration aims to validate the software theoretical foundations and implementation. In addition, the observations by BCAM and Laser Tracker were carried out with one table turned.

## In-situ, second iteration

After the first, a second iteration was made, but this time by measuring all the fiducials on the adjustable plates and the BCAM support plates. In addition: one table was turned, overlapping and through-viewport BCAM measurements were carried-out. The network was calculated using a Spatial Analyzer "Unified Spatial Metrology Network" option and includes eight stations over two days. The achieved precision at one $\sigma$ is about 20 microns. For this iteration, the calibration of the plate is planned only to be used partially in the computation. All fiducials on each BCAM support were measured in order to reconstruct the whole table and then be independent from the flexure of the adjustable plate.

## Results

## Introduction

Only the first iteration measurements were analyzed so far. This set of observations was made in order to evaluate the software parts. The second set should increase the reconstruction result quality.

Since all corners of all tables were measured, the end tables are stabilized and given a datum by four direct observations per table, this leads to 24 observation vector entries for direct coordinate observations (Figure 11). Six distances were calculated by corner distances from the laser tracker results, they directly add six observations. Finally each BCAM observes two 2D-coordinates which lead to four observations per BCAM. This sums up to 94 observations to adjust: 12 parameters for the central moving tables and 12 parameters for the fixed end table.


Figure 11: Observations without overlap of the test bench. The end tables each receive 12 direct observations (four 3D-coordinates each). Additionally, six length measurements are added. A minimum three translations and rotations per table have to be estimated.

## Comparison with Laser tracker



Figure 12: Differences between the corner coordinates reconstructed by the software and the reference Laser tracker measurements. The point IDs match the point numbers in Figure 11.

The position along the X -axis is only influenced by the reference measurements. As shown in Figure 12, the distance differences between the reconstructed corner positions to the Laser-Tracker measured points for the Zdirection (height) are below 40 microns for almost all points. The differences for observable horizontal movements seem to have a systematic error; the variations within one table are barely noticeable. Despite the systematic offset, all differences remain below 80 microns for the radial positioning along the beam. Further research and comparison with different test measurements is needed to identify the source of the systematic error in the Y-direction.

## Parameter precisions

The standard deviations of the translation and rotation parameters are presented in the following table.

Table 3: Rotation (R) and Translation (T) precisions

|  | $\boldsymbol{\sigma} \mathbf{R X}$ <br> $[\boldsymbol{\mu} \mathbf{r a d}]$ | $\boldsymbol{\sigma} \mathbf{R Y}$ <br> $[\boldsymbol{\mu} \mathbf{r a d}]$ | $\boldsymbol{\sigma} \mathbf{R Z}$ <br> $[\boldsymbol{\mu} \mathbf{r a d}]$ | $\boldsymbol{\sigma}$ TY <br> $[\boldsymbol{\mu} \mathbf{m}]$ | $\boldsymbol{\sigma} \mathbf{~ T Z}$ <br> $[\boldsymbol{\mu m}]$ |
| :--- | :--- | :--- | :--- | :--- | :--- |
| Table 0 | 18.4 | 59.0 | 15.0 | 5.8 | 6.4 |
| Table 1 | 355.6 | 52.0 | 222.3 | 140.1 | 111.7 |
| Table 2 | 397.5 | 47.8 | 222.3 | 157.0 | 132.9 |
| Table 3 | 37.9 | 72.0 | 15.4 | 10.8 | 12.7 |

The majority of the observations are image coordinates for which no stochastic information is available at the current state of development. Therefore, the standard deviation of the image coordinates was set to a constant value of $1 / 10$ pixel. The accuracies of the first and the last table's parameters are much better than the middle tables because they are held in place by the very precise direct observations of the laser tracker. This first test setup already delivers good accuracies that are promising. However, slight turn effects of the plates when compared to the reference values are still visible. This might be a result of the uncertainties of the mounting ball positions. The comparison to the reference measurements showed, that the mounting ball positions would be needed within a precision better than one micron. Consequently, a calibration of the mount relative rotation angles will be made by observing common distant targets with the 4 BCAMs fixed to their table.

## On-going activities and next steps

The second session of measurement is still under analysis. Indeed, BCAM-BCAM measurements were carried-out through precise viewports turned (approximately $\pm 5$ degrees with respect to the optical axis of the nearest BCAM) and each position was scanned by a Laser Tracker in order to reconstruct their orientation.

Only BCAM-BCAM observations were carried-out but the mock-up for cavities supports will allow us to attach targets to it. One of the main concerns is to ensure that they can be measured from both sides. As shown in Figure 13, two types are studied: illuminated targets and retro-reflective targets.


Figure 13: Optical fibre ended by a ceramic ball diffusor (left) - Double sided retro-reflective target (right).

New BCAMs, so called HBCAMs, are under development at Brandeis University. The two new main features are a wider field of view of about $30 \%$ in order to detect up to thirteen targets simultaneous with two BCAM spots and an illuminating system around the lenses controlled by LWDAQ Software in order to measure retro-reflective targets.

Several mandatory options need to be developed, implemented and/or tested on the software part:

1) Target position computation. At this time, the software only handles BCAM/BCAM observations and reconstructions.
2) Image analysis. With the possible use of retroreflective targets, this type of target cannot be illuminated individually.
3) Thermal expansion of the alignment elements inside and outside the cryomodules needs to be taken in account.
4) Viewport correction [7]. Studies have shown that this correction is controllable with the use of precise viewports (below 50 micro- rad of wedge angle) and by knowing the orientation of the viewport with respect to the BCAM optical axis. In theory and for the precise viewports chosen, for an orientation change of 1 degree, the observed radial displacement is about 30 microns in object space independently from the distance of the object. The value has been confirmed by a test and is at least valid for a viewport orientation between $\pm 5$ degrees with respect to the main optical axis of the BCAM.
5) Double - viewport correction [7]. BCAM-BCAM observations on the internal sight lines will go through two viewports. The theoretical formulas showed that the reconstruction of a specific
equivalent viewport is possible and needs to be confirmed by a mock-up.
6) Online reconstruction. The main aim of this project is to monitor the cavities and solenoids. Therefore, an automatized measurement and upload to databases is needed.
7) Watch window option that reconstructs quickly the offsets of the target to a nominal coordinates in order to adjust efficiently the cryomodules.

## CONCLUSION

Test measurements and calculations showed that the desired reconstruction precision can be reached at the current stage of development when four tables and 16 BCAMs are used. These results validate the theoretical foundations of the development and the software implementation.
Simulations have shown that the goal to align the RF cavities and the solenoids inside the cryomodule should be reachable within the desired precision.
The development is well advanced and most of the new features such as viewport correction are already coded. The modularity of the software will guarantee an easy implementation.

The extended test bench will be used to go further in the studies and tests, especially for the new HBCAMs.

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