HIE-ISOLDE: COMMISIONING AND FIRST RESULTS OF THE MATHILDE SYSTEM MONITORING THE POSITIONS OF CAVITIES AND SOLENOIDS INSIDE CRYOMODULES

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Abstract

The new superconducting HIE-ISOLDE Linac extends and will replace in its final phase most of the pre-existing REX post-accelerator at CERN-ISOLDE facility. This upgrade involves the design, construction, installation and commissioning of 4 high-β cryomodules. Each high-β cryomodule houses five superconducting cavities and one superconducting solenoid. Beam-physics simulations show that the optimum linac working conditions are obtained when the main axes of the active components, located inside the cryostats, are aligned and permanently monitored on the REX Nominal Beam Line (NBL) within a precision of 0.3 mm for the cavities and 0.15 mm for the solenoids at one sigma level along directions perpendicular to the beam axis.

The Monitoring and Alignment Tracking for HIE-ISOLDE (MATHILDE) system has been developed to fulfil the alignment and monitoring needs for components exposed to non-standard environmental conditions such as high vacuum or cryogenic temperatures. MATHILDE is based on opto-electronic sensors (HBCAM) observing, through high quality viewports, spherical retroreflectors made of high index (~2) glass. Precise mechanical parts, metrological tables and the, so called, MATHIS software were designed to be able to reconstruct the position of the active elements within a precision of 0.1 mm.

The commissioning of MATHILDE and its first results to monitor the cavity and solenoid positions, especially during the installation and tests of the two first cryomodules on the HIE-ISOLDE Linac, are reviewed in this contribution.

INTRODUCTION

The HIE-ISOLDE project is an upgrade of the REX post-accelerator at CERN-ISOLDE facility and involves design, construction, installation and commissioning of 2 low-β and 4 high-β cryomodules. The linac installation is staged in 3 phases. The first one, involving 2 high-β cryomodules, took place from the beginning to mid-2016. They will be joined by 2 other high-β cryomodules in a second phase (2017-2018) and, eventually, 2 low-β cryomodules at a third stage. Each high-β cryomodule houses five high-β RF cavities (6 for the low-β version) and one superconducting solenoid (2 for the low-β version). To run the linac in the optimum conditions, the active components, cavities and solenoid, must be aligned and monitored on the REX Nominal Beam Line (NBL) within a precision of 0.3 mm and 0.15 mm respectively at one sigma level along the directions perpendicular to the beam [1]. The active elements are operating under cryogenic (4.5K) and vacuum (10^{-11} mbar level) conditions.

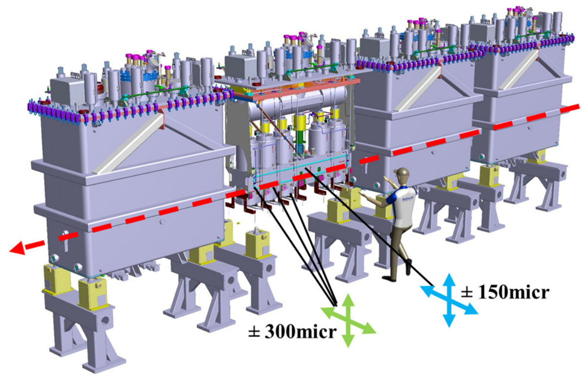

Figure 1: HIE-ISOLDE linac phase 2 configuration

The Monitoring and Alignment Tracking for HIE-ISOLDE (MATHILDE) system was designed and installed to fulfil these requirements. As sketched in Figure 2, MATHILDE uses a set of newly developed double-sided HIE-ISOLDE Brandeis CCD Angle Monitor (HBCAM) [2] fixed to metrological tables in order to create a close geometrical network linked to the Nominal Beam Line by reference pillars. The HBCAM from the internal lines are placed in front of viewports and allows the observation of targets associated to the active elements and of the HBCAMs situated on the previous and next table. The ones from the external lines link the metrological tables between them and to the datum.

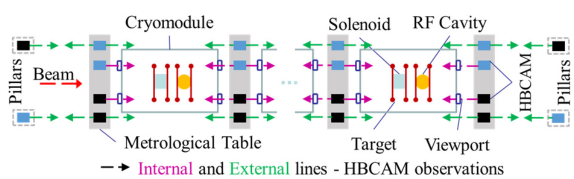

Figure 2: Sketch of the alignment system - Top view

The project required the study of the optical effect of measurements through precise viewports [3], the creation of a dedicated 3D-Reconstruction Software [4,5,6], of precise mechanical parts [3,7], an upgrade of the foreseen BCAM devices [7] and the development of a new type of targets based on high index (~2) glass ball properties [7]. The MATHILDE system is described in the reference documents [3] to [7].

A version of the MATHILDE system is set up and measures the active elements (i.e. cavity and solenoid) inside the two cryomodules installed and commissioned in 2016. The monitoring performed during the cool down and the adjustments accomplished are summarized in this paper, together with some feedback and future development of the MATHILDE System.

CRYOMODULE ADJUSTMENT POSSIBILITIES

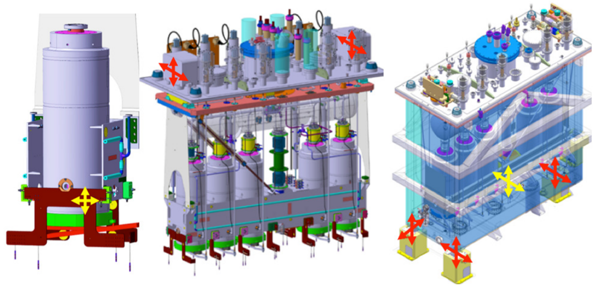

Figure 3: Omega plate supporting a cavity (left), frame hanging from the top plate (centre), complete cryomodule sitting on its 3 jacks (right)

Each cavity or solenoid is equipped with hollow half-sphere mounted and centred on its beam entry and exit point. The spheres (beam ports) are supported by a V-shaped groove machined on an, so-called, omega plate. An omega plate is equipped with two MATHILDE targets [7] each containing 2 high index glass balls observable by the HBCAMs. The omega plates are enclosed into a supporting frame. The whole frame is attached to the top plate by two stainless-steel sheets, one downstream and one upstream of the active elements. The top plate is lying on top of the vacuum vessel, which is sitting on three adjustable jacks. The alignment of the omega plates into the frame, and therefore the relative position of the cavity and solenoid beam port centres, is only possible during assembly. Subsequently, the frame is mechanically adjusted to nominal under the top plate. Those operations are performed with the help of a Leica AT401 laser tracker while the cryomodule is open into the ISO5 clean room dedicated to the project. Once the cryomodule is complete, MATHILDE is the only way to measure the internal active elements.

To adjust the line of cavities and solenoid onto the accelerator nominal beam line, 3 methods are available:

1. Acting on the cryomodule supporting jacks. All the cryomodule components are moving.
2. Motors moving the stainless-steel sheets supporting the frame. Two sets of motors, one upstream and one downstream, allow the frame to move in two perpendicular directions transverse to the beam. They act on the liaison between the top plate and the steel sheets holding the frame and can move the frame position by ±5 mm with 50 microns steps.
3. The omega plates allocated to the solenoid can be moved independently into the frame.

Method 1 is carried out on the installation of the cryomodule onto the experimental line and is also possible once cryogenic (4.5K) conditions are reached and stabilized for the entire linac. Moving the whole cryomodule presents some integration and safety risks, especially at cold. For instance, the bellows connecting the cryomodule to the previous and next element on the linac are rather short. Therefore a movement can damage or break them. The decision to do this operation is taken in collaboration with, and must be validated by a panel of experts (vacuum, cryogenics, safety, etc).

Method 2 is only used for the "vertical" direction where the relation between the movements applied by the motors is consistent with the one observed on the active elements. The "horizontal" adjustment does not offer that consistency but shows what can appear to be a stick slip effect. Hence, further studies and tests are necessary to use this possibility.

Method 3 allows an independent movement of the solenoid. The system is not installed and is an option "if needed". The technology to achieve this movement calls for additional analysis to cope with the cleanliness requirements of the cavities.

To summarize, methods 1 and 2 ("vertical") move the whole frame in where the cavities and solenoid are installed. The relative alignment between the active elements is a crucial and definitive operation done throughout the assembly into the clean room.

MATHILDE CONFIGURATION

All next results are expressed in the local coordinate system of HIE-ISOLDE shown in Figure 5. Its origin is situated in the mass-separator magnet. The Y-axis is along the beam and Z-axis follows the local vertical and is positive to the top.

The MATHILDE configuration (Figure 5) for the first phase of the HIE-ISOLDE project with two high-β cryomodule consists of: four references pillars and three fully equipped metrological tables. A HBCAM is installed on every pillar; their lasers serve as reference. Those device observations are also kept and included into the computation. Each metrological table is equipped with 4 HBCAMs, the two internal one measure inside the cryomodule and the two external ones observe the HBCAM on different metrological tables or pillars [7].

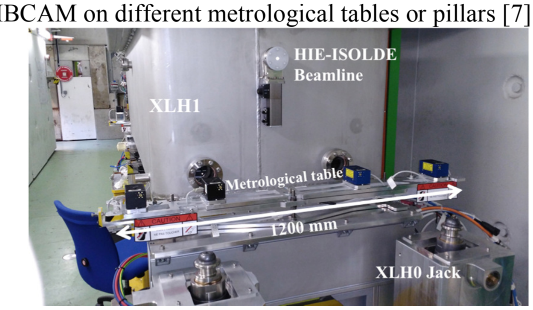

Figure 4: Upstream view of a metrological table on the beam line during installation. XLH0 and the XLH1 surrounding accelerator elements are not installed

The control of the devices is done through the CERN intranet network. A LWDAQ Driver is installed outside the linac shielding and connected to the CERN network. The LWDAQ driver connects to seven LWDAQ multiplexer situated nearby the metrological tables. Each HBCAM is linked to the LWDAQ Multiplexer attributed to the corresponding metrological table.

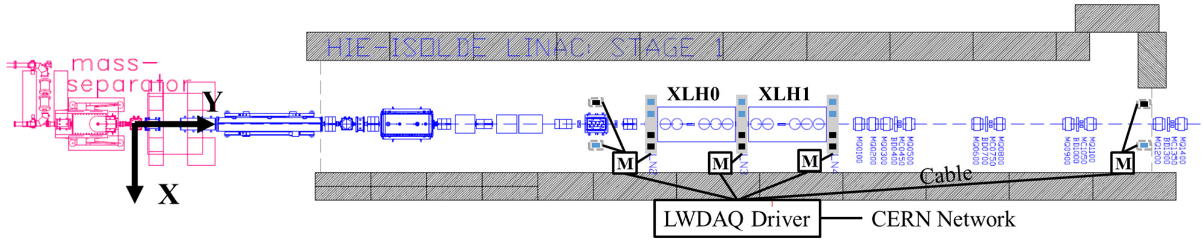

Figure 5: Definition of the local HIE-ISOLDE coordinate system and of the MATHILDE Configuration installed for the phase 1 with the two cryomodule XLH0 and 1. HBCAM control is done through LWAQ Multiplexer (M) and a LWDAQ Driver [2] connected to the CERN network

The installation and adjustment of the different MATHILDE elements to their nominal position is done by AT401 laser tracker observations. The measurements rely on the nearby geodetic network and on the metrology of the different mechanical parts. The accuracy needed for the different MATHILDE elements is not demanding, but is typically within some tenth of mm. The HBCAM field of view can deal with several millimetres of offsets of the metrological table or target positions. In addition, the metrological table position and orientation are reconstructed by the MATHILDE computation with respect to the datum defined by the pillars. All the MATHILDE elements are re-measured by AT401 before the start of the cool down in order to determine the initial geometrical parameters for the MATHILDE configuration. The specially developed Monitoring and Alignment Tracking for HIE-ISOLDE Software (MATHIS) manages acquisition, computation and link to the different databases [5]. To sum up its philosophy, every element, even a point, has a coordinate system (or frame) attached to it. All the frames are placed in a hierarchical order where one frame can only have one parent but several child systems. The geometrical link between frames is described by 6 transformation parameters (3 translations, 3 rotations), each of them can be constrained or not and can be parameterized by a formula depending on temperature and pressure in order to cope with the thermal expansion of the mechanical pieces. Each frame can have some options depending on their allocated type (active/passive targets, viewport, etc). The goal is to recalculate each free parameter by a 3-D adjustment taking into account the HBCAM observations. This highly versatile and flexible principle allows virtually to create any kind of system configuration using BCAM or HBCAM.

Schematically, the following frame hierarchy can describe the full MATHILDE system:

Root → Pillar (4) → HBCAM (1)
Root → Metrological Table (3) → HBCAM (4)
Root → Cryomodule (2) → Ω Plate (12) → Target (4)
Cryomodule → Viewports (4)

Each arrow represents a 6 parameter (freed or constrained) transformation with the formalism Parent → Child(s) frame. The number in brackets is the number of frames existing for one instance of the parent frame. For example, 3 metrological table frames are linked to the root one. In each metrological table frame, 4 HBCAM frames are defined. The definition of this hierarchy and their fixed/free parameters plays a key role to determine the appropriate values of interest. For instance, all the omega plates are constrained in their pitch rotation (around X-axis in Figure 5) with respect to the beam. The precision of the 3-D reconstruction of the glass ball targets along the beam (Y axis in Figure 5) is within a few mm. Therefore, having the pitch freed can lead to millimetric errors in the determination of the Z-coordinate of cavity and solenoid beam port centres.

INSTALLATION AND COOL DOWN

The two cryomodules were installed on the HIE-ISOLDE Beamline in 2016, XLH1 in March and XLH0 in May. Their fiducialisation happened at the end of the assembly using a laser tracker and a MATHILDE set up based on two metrological tables.

The plots in Figure 7 show the cool down of cryomodule XLH1 from May 23rd 2016 9:00 CEST to July 2nd 2016 23:30 CEST (41 days). They display the movement with respect to the first observation plotted of the entry and exit beam port centres for each cavity and solenoid embedded into the XLH1 cryomodule. The naming rule is the following, first 3 digits are the cryomodule name, the next ones are designating the entry or exit beam port centre of the concerned active element (Figure 6).

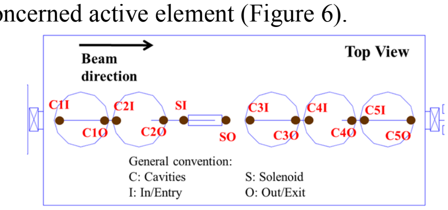

Figure 6: Naming convention of the cavity and solenoid beam port centres

The cavity and solenoid beam port centres went up along Z by about 4.3 mm for XLH0 and 4.2 mm for XLH1, all in agreement with the thermo-mechanical calculations [8]. The cooldown introduced a displacement along X-axis, of about 0.8 mm for XLH0 and 0.5 mm for XLH1. As the frame supporting the active element is hanging from the top plate, a lateral movement was expected and can be reasonably limited to ± 1mm by experimental feedback. The full line of cavities and solenoid is moving together along both axes, the outliers are explained later.

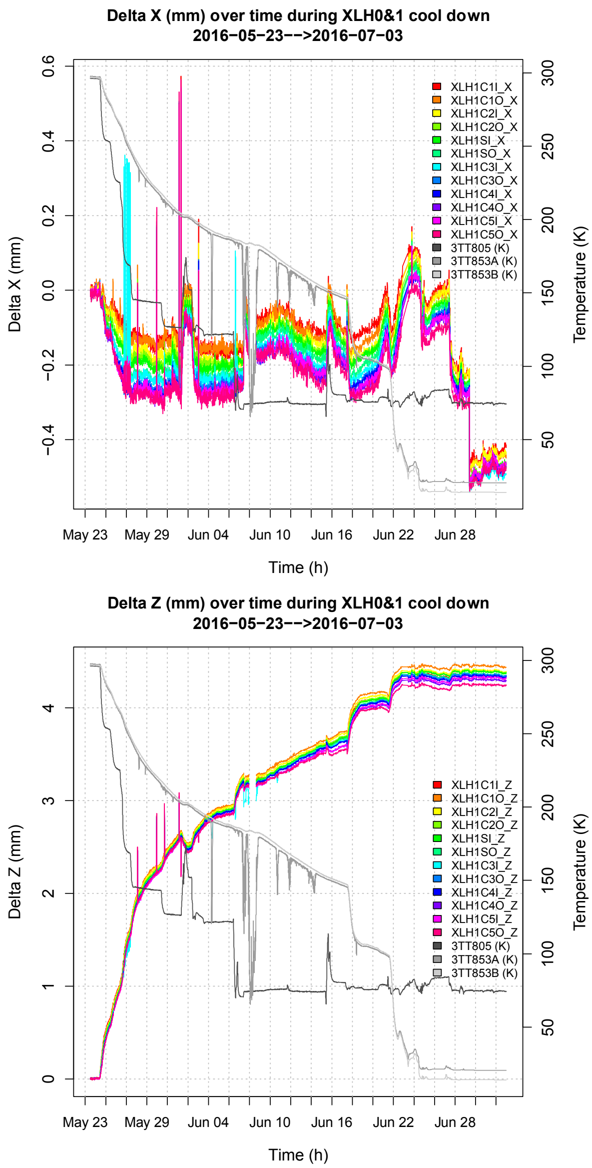

Figure 7: Movement during cool down of the active element beam ports of XLH1 in mm (rainbow colours) with respect to a reference measurement along X (Top) and Z (Bottom). In greyscale, temperature of different element inside the cryomodule

Each omega plate shape is corrected for the thermal expansion before the least square adjustment. To do so, the omega plates are equipped with thermal sensors. The temperature is retrieved simultaneously by the MATHILDE acquisition and serves as input for a correction formula. The position, especially along the Z-axis, of the active element beam ports is highly dependent on those values. Some erratic behaviour was observed for the sensor 3TT853A associated with XLH1C3I. It can be seen in the Z plot in Figure 7 between June 6th and 10th. The position of XLH1C3I beam port centre is altered by 0.15 mm in this specific case and for a temperature misreading of 100K. Mitigation to those effects needs to be implemented.

The time interval between two measurements is 15 min for the first two weeks and 30 min after. The time needed to acquire and process the data is about 4min 30s with each HBCAM image repeated twice. This rather long time is mainly driven by the image acquisition. Two minutes are needed to gather all the images without any repetition. The computation by LGC2 [6] takes about 20-30 seconds depending on the number of iterations done during the least square adjustment. For a six cryomodule linac, the data-acquisition time is estimated to last around 6 minutes and the LGC2 computation below 1 minute. No need for a faster computation has been expressed yet. If so, the system can be upgraded acting on the acquisition or the computation. The HBCAMs are measuring one after the other; it would be possible for several devices to be activated on the same time without interfering each other. The upgrade would include the installation of several HBCAM drivers and a modification of the current MATHIS Software. On the computation side, LGC2 is new and could be subject to optimization (use more than one processor core, etc.).

Out of the 2686 computations done during the cool down period: 2583 are considered good, 90 failed to compute (<3,5%) and 13 contained errors.

For one computation, 364 HBCAM images are acquired resulting in 227 observations on either glass balls or device reference laser diodes. A number of 157 unknowns, i.e. free transformation parameters, needs to be determined by the least square adjustment.

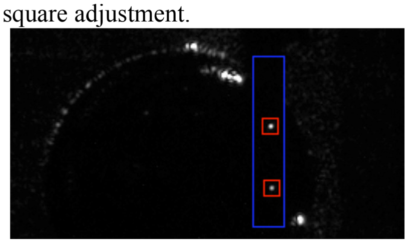

Figure 8: LWDAQ acquisition picture detail, blue rectangle is the analysed part of the image, the red squares are centred onto the detected targets, the rest of the white spots are parasitic reflections

The failed and erroneous computations, as well as the missing observations, appeared mostly during the cool down of the thermal shield contained in the cryomodule vacuum vessel. The failure source is the misdetection of the target into the HBCAM image.

The thermal shield is the first element to be actively cooled down by helium gas until it reaches a stable temperature of 80K. The temperature of the thermal shield is represented by the 3TT805 curve in Figure 7. The thermal shield possesses two so-called alignment corridors [7] where the targets are observed. They are designed to minimize the parasitic reflections of the HBCAM flashes appearing on the thermal shield surfaces. The anti-reflection scheme is mostly effective. It has a couple of defaults caused mainly by the assembly tolerance of the thermal shield leaving some holes in the reflection defence.

As shown in Figure 8, only a part of the image is analysed (blue rectangle), the targets are detected in this area. The analysed zones are manually configured into an observation file before the acquisition and are avoiding the parasitic reflections positions. With the cryomodule at ambient or steady cryogenic temperature, the positions of the defaults are stable and easily excluded by configuration from the analysed areas of the images. Once the observation configuration file is set for those cryomodule statuses, there is no need to change it. In the cooldown process, the thermal shield alignment corridors are moving up by about 6 mm due to their thermal expansion and expose new holes or change their positions. Some defaults can, sometimes, alter the detection of the spot into the analysed part of the HBCAM images. The relative movement between the alignment corridors and the MATHILDE targets amplifies these effects. Indeed, the targets are refrigerated later, mostly during the frame and cavity cool down. The need for a change of observation configuration file can take time to be detected and no "on call" person strategy is applied or is foreseen.

So, the misdetections of targets in the HBCAM images happen during the thermal shield cool down and can have three different effects. Firstly, it can lead to a failed computation, for instance, if one or several spots are not or wrongly detected resulting into an ambiguous estimation of a frame free-parameter during the LGC2 computation. Secondly, one or several targets are not detected but the computation can run. For example, if only one target is not measured on an omega plate, the computation will run anyway with only a marginal impact on the computation. For the cool down and those two first cases, 152 observations on glass balls failed out of ~380 000. They are spread over 134 measurement runs (~5%). Thirdly, one of the parasitic reflections is misinterpreted as a target but is close enough to the expected position for the computation to run. This situation leads to a computation giving a wrong results either on the whole system or on a few active elements depending on the location of the errors. The effect can be seen with the 13 outliers to the general trend in Figure 7 for XLH1C3I (X) and XLH1C5I (Z) between May 25th and June 2nd.

The spot detection and the error detection can be improved by acting on three levers:

- Implement special function into the image analysing routines to detect and suppress some patterns. Indeed, those parasitic reflections often follow the default into the assembly; either a line or part of a circle in the MATHILDE case.
- Change the spot detection routine to be more robust. The actual one using the partly analysed images was the fastest to implement for the first cool down.
- Have a consistency control of the LGC2 input to ensure the computation success even without some observations. For instance, checking that an object has enough observations in order to determine its associated free translation/rotation parameters. If not, remove the object and the corresponding observations.

CRYOMODULE COLD ADJUSTMENT

At the end of the cool down, the positions of the cavity and solenoid were adjusted to the Nominal Beam Line. This operation took into account the smoothing measurement carried out a couple of days before where every element of the HIE-ISOLDE linac, transfer lines and MATHILDE system were measured.

The adjustment in cryogenic condition was performed within two days early August 2016. The operation itself was done in two steps: vertical alignment followed by the horizontal alignment.

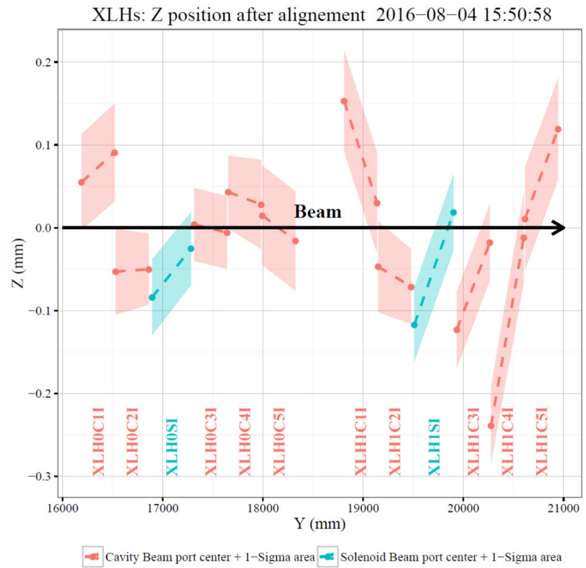

Figure 9: Position along Z (mm) after final alignment of the cavity and solenoid beam port centres

The vertical alignment operation has been done using the remote motors moving the frame inside the cryomodule and described earlier. No access to the tunnel where the linac is partially enclosed was requested. The movement was followed by MATHILDE only. Along Z-axis, the active elements of XLH0 and XLH1 cryomodules were moved respectively by +0.35 mm / -1.15 mm on the upstream side and +0.05 mm / -0.75 mm on the downstream side. Figure 9 shows the final position along Z of the active elements in two cryomodules. The 1-Sigma precision with respect to the datum defined by the pillars is about 0.05 mm (case A) and 0.07 mm (case B). This difference is due to the observation scheme. The targets used to determine C2O to C4I beam port centres are seen from the upstream and downstream metrological table HBCAMs of the corresponding cryomodule (case A). The others (case B) are only seen from one side [3]. The precisions expressed do not consider the uncertainties on the fixed parameters of the geometrical configuration, i.e. internal metrology of the omega plate, HBCAM, metrological table and pillars. Monte Carlo simulations show that the precision with respect to the datum is below 0.1 mm and 0.15 mm at 1-Sigma respectively for the active element beam port centre with targets seen twice and once.

The horizontal alignment could not be done with the motors and needed a manual intervention to move the full cryomodule inside the linac shielding using its supporting jacks. The cryomodules were in steady state with all the cavities at 4.5K and not in any transient phase. The external vessel position has been followed by an AT401 Laser Tracker and the internal element positions were checked by the MATHILDE System. Along X-axis, the active elements of XLH0 and XLH1 cryomodules were moved respectively by -0.58 mm / +0.55 mm on the upstream side and -0.66 mm / +1.00 mm on the downstream side. Experts in vacuum and cryogenics assisted the operation, monitoring the vacuum/cryogenic sensors of the linac and checking the bellows bridging the cryomodules to surrounding element vacuum tubes,

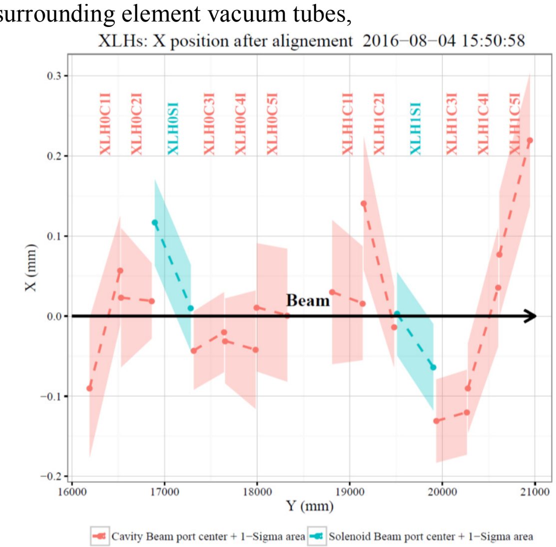

Figure 10: Position along X (mm) after final alignment of the cavity and solenoid beam port centres

Figure 10 shows the final position along X of the active elements in the two cryomodules. The 1-Sigma precision with respect to the datum defined by the pillars is about 0.06 mm and 0.09 mm respectively for the active element beam port centre with targets seen twice and once. Monte Carlo simulations considering the fixed parameter uncertainties show that their precision against the datum is below 0.12 mm and 0.18 mm at 1-Sigma.

For both cryomodules, the alignment of the cavities and solenoid in their supporting frame is kept during the cool down and with respect to the fiducialisation done by AT401 laser tracker during assembly in the clean room. Differences are staying below 0.1 mm except for an outlier (<0.2 mm) on an exit beam port of a cavity.

STABILITY OVER TIME

The hall containing the HIE-ISOLDE project is not temperature regulated and is situated on the surface with the roof exposed directly to the atmospheric conditions. Therefore there is a seasonal expansion of the slab and the supports of the accelerator elements, by ~0.3 mm / 10 m and 0.2 mm respectively. The one of the supports may have an effect due to the different supporting schemes of the cryomodule, the other accelerator elements and the MATHILDE reference pillars. Corrections for these effects are not implemented in the MATHILDE system yet.

Over a span of a month after the commissioning ended in the beginning of august 2016, the movement of the active element beam port centres with stable cryogenic and vacuum conditions is staying within ±0.1 mm with respect to the final alignment, with a an average of 0.015 mm (s=0.03 mm) along X and -0.005 mm (s=0.02 mm) along Z. No deviating trend is observed on the stability results, which is suggesting a relative stability of the linac, comprising the pillars. The stability of the system, and especially of the pillars, is under evaluation.

CONCLUSION

After 5 years of R&D, a MATHILDE system was successfully installed in 2016 for the first phase of the HIE-ISOLDE project. MATHILDE is giving good results in accordance with the needed precisions for the cavity and solenoid beam port centres enclosed into the two first HIE-ISOLDE high-β cryomodules. The system has proven to be reliable and robust, even though some possible improvement for the software and the measurement strategy are identified. The system works in any type of vacuum and cryogenic conditions foreseen for the cryomodules. The study of long-term stability of the datum and potential seasonal change influencing MATHILDE requires data taken all along the year.

The first beam was delivered on September 12th, 2016 to an experiment by the HIE-ISOLDE linac and transfer line. The monitoring of the position of the active elements will continue during the accelerator operation. The installation of two additional cryomodules will happen in the upcoming years, the MATHILDE system will, then, welcome two new metrological tables already procured and integrated.

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