HIE ISOLDE ALIGNMENT AND MONITORING SYSTEM TECHNICAL DESIGN AND PROJECT STATUS

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Abstract

In the frame of the HIE ISOLDE project most of the existing ISOLDE REX line will be replaced by a superconducting linac in order to upgrade the energy and intensity of the REX ISOLDE facility at CERN. Beam-physics simulations show that the optimum linac working conditions are obtained when the main axes of the active components, RF cavities and solenoid placed 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. This paper presents the proposed adjustment and alignment system based on opto-electronic sensors, optics and precise mechanic elements which are used, for some of them, in various non-standard environmental conditions such as high vacuum, cryogenic temperatures.

INTRODUCTION

The High Intensity and Energy (HIE)-ISOLDE project [1] aims at important upgrades of the current ISOLDE radioactive beam facility at CERN. The HIE linac goal is to increase the energy and quality of post-accelerated Radioactive Ion Beams (RIBs), delivered by the facility to the experiments. It will be made of two sections, one for low and one for high energy. The high energy section will be built first and will increase the energy of the existing facility from 3 MeV/u to 10 MeV/u. The low energy section will provide the full energy variability of the RIB.

The accelerator elements are superconducting copper RF cavities sputtered with a thin film of niobium. Superconducting RF Cavities and Solenoid(s) will be placed in six cryomodules [2]. The cryomodules will share the insulation vacuum with the beam vacuum.

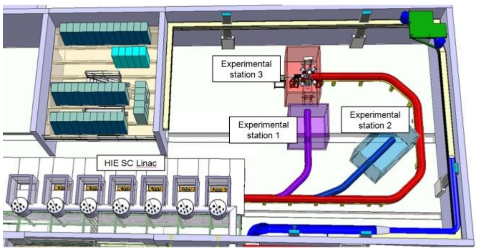

Figure 1: Layout of the HIE-ISOLDE facility

Beam-physics simulations [3] show that the optimum linac working conditions are obtained when the main axes of the active components, RF cavities and solenoid, are aligned on the ISOLDE REX Nominal Beam Line (NBL) within a precision, recently updated, of 0.3 mm and 0.15 mm respectively at one sigma level along directions perpendicular to the beam axis.

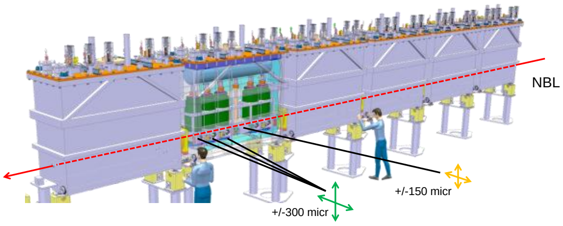

Figure 2 : The HIE-ISOLDE Linac

This precision will be obtained by the integration of the built-in alignment and permanent monitoring system described below that is able to measure the geometry of the linac active components with respect to a common axis representing the NBL at any moment.

The environmental conditions will change drastically along the linac from standard temperature and atmospheric pressure conditions in the inter-module space to high vacuum and cryogenic conditions inside the cryomodules where the RF cavities and solenoids will work at a temperature of 4.5 K.

THE ALIGNMENT SYSTEM CONCEPT

The basic concept of the alignment system is the creation of a closed geometrical network continuously measured using a set of opto-electronic sensors, optics and precise mechanical elements, all linked to external references defined in the NBL coordinate system.

The positions of the cryomodule RF cavities and solenoids are measured in this geometrical frame. Double sided Brandeis CCD Angle Monitor (BCAM) [4] cameras installed on precise metrological tables inserted in the inter-module space look at each other and at four end-pillars fixed to the floor. The locations of the pillars, determined via survey in the NBL coordinate system, are used as datum points. In such a way two external lines of sight are created, one on each side of the linac, allowing the reconstruction of the position of the inter-module tables. In case of lack of space the two end pillars could be suppressed and the end tables could be used as the datum.

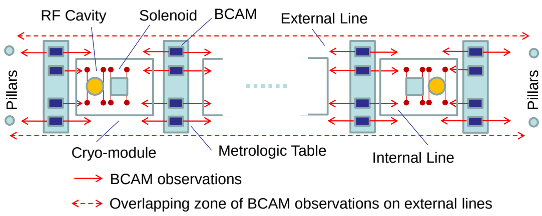

Figure 3 : Sketch of the alignment system - Top view

The double sided BCAMs of the external lines are placed in such a way that overlapping observations are possible (Figure 4).

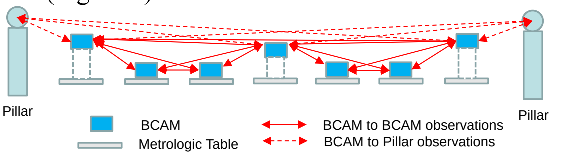

Figure 4 : Overlapping external line - Side view

Two internal lines of sight are formed by a second set of double sided BCAMs symmetrically placed on the same inter-module tables (Figure 3). They are used to observe the reference targets on the active components through precise glass viewports. Each RF cavity and each solenoid is equipped with four reference targets fixed at precisely known positions with respect to the component geometry. Their positions measured with the alignment system will determine the principal axis location and orientation of each active component with respect to the beam axis.

The geometrical frame and the position of each active component will be calculated from the redundant observations using a specific 3D compensation software [5-7] and taking into account BCAM to BCAM observations, the image coordinates of the targets on the BCAMs, the mechanical dimensions of supports and links, the BCAMs calibration parameters, the thermal effects and the distortions of the optical ports situated between atmosphere and high-vacuum.

THE KEY ELEMENTS OF THE SYSTEM

The BCAMs

The BCAMs (Brandeis CCD Angle Monitor) [4] are fixed focus simple and robust CCD cameras originally developed by Brandeis University and OSI for the Muon alignment system of the ATLAS LHC experiment at CERN. About 1000 of these devices are installed and have operated for years in this detector. Symmetrically placed on both sides of the camera lens, 2 laser diodes allow BCAM to BCAM observations. Double sided BCAMs equipped with 2 CCDs, lenses and diode systems also exist and allow a chain these devices to be created. All is included in a rigid body and an isostatic plug-in mount system consisting of a plane, a slot and a cone is located under the box base. The BCAMs are delivered calibrated taking into account the focal length, the CCD, lens and diode positions, and the geometrical relationship between optical axis and plug-in system. The BCAMs are connected to a LWDAQ (Long Wire DAQ) driver for camera control, power supply and data acquisition.

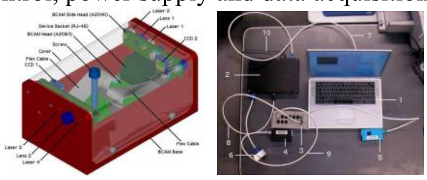

Figure 5 : BCAM and acquisition system

Several applications based on this device have been developed at CERN for BCAM to corner cube reflector or BCAM to target observations.

In the case of HIE ISOLDE a new BCAM so called HBCAM is under development. The CCD size will be increased from 336x243 10 microns pixels to 659×494 7.4 microns pixels and the focal length will be reduced from 74 to 50 mm in order to increase the field of view from 30x40 to 70x100 $mrad^2$. A synchronized illumination ring will also be integrated to allow observations of retro-reflective targets for which tests have been successfully done using an external light source.

The BCAM is a well proved system. The precision announced by the provider is better than 5 micro-radians for relative positions confirmed by different tests and 50 micro-radians for absolute position.

The Metrological Tables

The support of the BCAMs at the linac ends and between the cryomodules will be materialised by metrological tables. Each of them will be equipped with four sets of three balls receiving the plug-in mount system of 4 BCAMs and fixing the relative translations and rotations between these. In addition, fiducial marks placed at the corners of the plates will allow additional controls of the table position using survey tools such as laser trackers.

Each table fiducial mark and BCAM ball position will be measured with a precision of some microns using a Coordinate Measurement Machine (CMM). Even if the relative translation parameters between these elements will be very well defined, the precision of the knowledge of the relative angles between the BCAMs on a common table has to be improved due to the lever arm between the mounting balls inter distances of about 72 mm and the BCAM observation distances. Therefore a second calibration round of each equipped table will be performed observing common distant targets with its BCAMs. The relative angle of the cameras of each individual metrological table will be then known at the level of the BCAM performance.

Each table will finally be considered in the alignment system as a floating rigid body. Their position and orientation will be recalculated in the main reference frame every time an iteration of BCAM observations is performed.

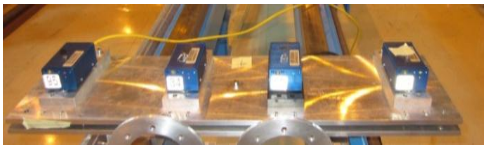

Figure 6 : Example of metrological table prototype

In order to give robustness to the system the BCAMs of external lines which are not constrained by the cryomodule crossing will be placed at different levels on top of the tables to allow overlaps in the table to table observations as shown in Figure **4**.

The Viewports

The interfaces between the inter-module BCAMs at atmospheric pressure and the RF cavities and Solenoid reference targets placed in the high vacuum of the cryomodules will be materialised by 6.5 mm thick glass viewports. The influence on the line of sight due to window wedge angle, uniformity of the plate, parallel plate effect and deformation of the windows due to high vacuum on one side have been studied [6].

Calculations and tests show that the ray deviation due to the wedge angle induced by the non-perfect parallelism of the window faces becomes negligible as soon as high quality windows are used. Measured wedge angles of the chosen viewports are in a range of 5 to 10 micro-radians creating observation changes of half these values that remain at the level of BCAM performance.

To evaluate the line of sight shift due to parallel plate crossing, BCAM observations were performed through a viewport mounted on top of a theodolite telescope at different well controlled incidence angles. The different test results fit very well with the theory and show that the incidence angles have to be known within 1°. The angles between each inner line BCAM optical axis and the closest crossed viewports will be measured once the cryomodules are under vacuum, their stability being good enough to maintain the orientation within the desired precision. In order to minimize the corrections implemented in the alignment software the viewports will be mounted on an adjustable system to set them perpendicular to the closest observing BCAM axis.

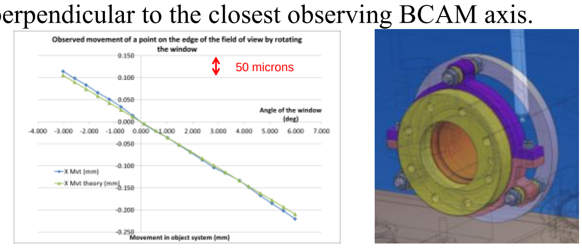

Figure 7 : Parallel plate effect – Adjustable viewport

To assess the homogeneity of the window, a series of measurements were done by translating the window in front of a BCAM observing a fix target. For the quality of viewports chosen, no noticeable effect above the BCAM performance level was detected.

BCAM to BCAM observations are also possible through a cryomodule. In this case the lines of sight will cross two windows. The study shows that these two can be modelled as a single thicker equivalent window, its angle with respect to each observing BCAM optical axis being calculated from each [BCAM to Close Window] pair angle combined with the reconstructed relative orientation of the supporting metrological tables.

The window deformations due to vacuum loads have been evaluated using ANSYS calculations done at CERN and have been validated by laboratory measurements performed by the Liberec University (CZ). Experimental results match the calculation and confirm that the faces parallelism is maintained, the deformation being the same on both sides. With a 6.5 mm thick viewport the expected deformation is at a level of 7 microns at the centre and the largest angular deformation due to the change of shape is of 15 micro-radians. These values are negligible for the application.

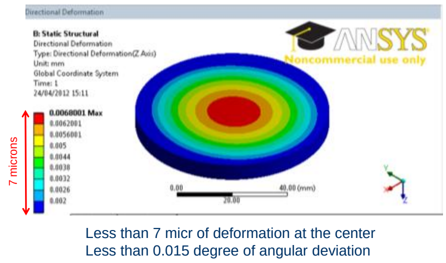

Figure 8 : 6.5 mm thick window deformation with vacuum - Calculation Y. Leclercq - CERN

The targets

Due to mechanical and integration constraints the fiducial marks of the RF cavities and Solenoid will be attached under the support cross-bars as described in the mechanical supporting system chapter.

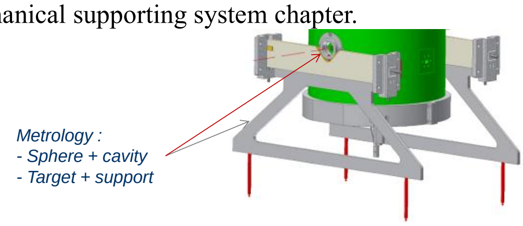

Figure 9: Cavity adjustable support and alignment targets

Three different target types have been studied, two of them are actively illuminated and one is passive.

The targets of the first type are materialised by the bright end point of silica-silica optical fibres. Vacuum-tight feedthrough flanges are used to run the fibres into the cryomodule. The target illumination are devices controlled by the BCAM driver.

The second type of active targets is similar to the first, but the fibre end is equipped with a ceramic ball used as a diffuser. These targets, of which a prototype was developed for LHC experiment survey applications 20 years ago and the concept re-used for CLIC alignment tests, give a well-defined circular target image pattern and present the advantage of being observable from both sides of the cryomodules.

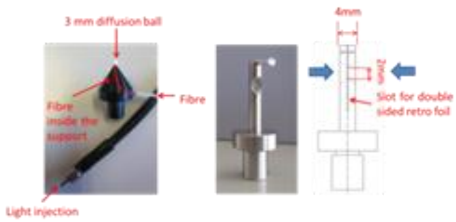

Figure 10 : Optical fibre terminated with a ceramic ball diffuser (left) - Double sided retro-reflective target (right)

The passively illuminated target type is made of retro-reflective targets. In order to allow double observations of references and increase the system redundancy, double sided targets observable from both sides have been developed. The centre points of both sides can be considered the same along radial and vertical directions as soon as the target is oriented perpendicular within a few degrees to the optical axis of the opposite observing BCAMs. To highlight the retro-reflective targets the HBCAM under development will be equipped with an illumination ring controlled by the driver.

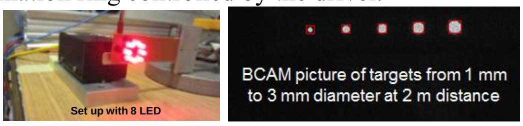

Figure 11 : BCAM to retro-reflective targets test with ring shape illumination system

Displacements using the different types of targets have been monitored. The comparisons show an average difference of 7 microns at 1.4 m, compatible with the BCAM performance.

Cryogenic conditions have also been simulated by placing the different targets in a bath of liquid nitrogen. No cracks were detected on fibres, ceramic balls or retro-reflective coating. Even if a 10% reduction of the light transmission in the fibres was noticed the observed position of the fibre end light spot was not changed significantly.

Outgassing tests [M. Hermann – CERN TE/VSC] show the compatibility of most of the targets with high vacuum conditions. After 10 hours the outgassing is at the level of the background except for the retro-reflective photogrammetric ball target for which the level is higher but still acceptable. The full compatibility of retro-reflective tape with high vacuum is under investigation.

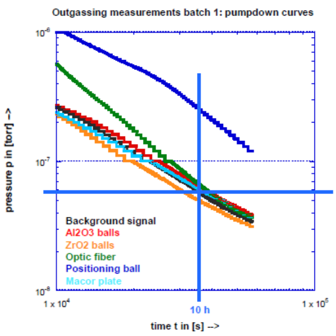

Figure 12 : Targets outgassing tests results - M. Herrmann – CERN

Among the advantages of the passive targets are their robustness and their low cost compared to the fibre solution that is more fragile and for which expensive feedthrough flanges are needed. The main drawback being that individual lighting is not possible and the image processing must discriminate the different targets in a single image.

The target distribution

A symmetrical radial distribution was chosen to limit the influence of the thermal contraction on the calculation of the beam hole centre position. Along the vertical direction it was not possible to install the targets at the beam level and the contraction in this direction will have to be introduced carefully in the adjustment.

In each cryomodule the target distribution in the BCAM field of view overlapping volumes has been studied in order to keep all of them visible from the BCAMs placed at the cryomodule ends. The targets and their support feet must not overshadow others. An envelope of 10 x 25 mm^2 around each of them was defined according to expected movements and to thermal contractions. Note that BCAM to BCAM observations across the cryomodules must be kept possible and that the BCAMs cannot observe the closest targets. The targets of the central part have to stay visible from both sides as shown in figure 12.

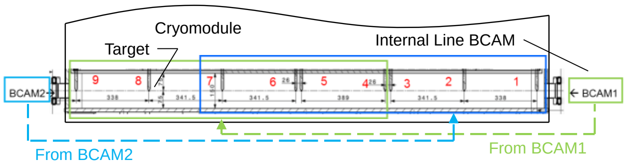

Figure 13 : Side view sketch of BCAMs observations from both sides of a cryomodule

In the blue rectangles the BCAM2 and the relative observed targets from positions 1 to 7. In the green rectangles the BCAM1 and the relative observed targets from positions 4 to 9.

Simulations of the targets positions were done for High and Low Beta cryomodules and have been then checked on a test bench. Possible arrangements were found and will define the position of the fiducial marks on each cross-bar.

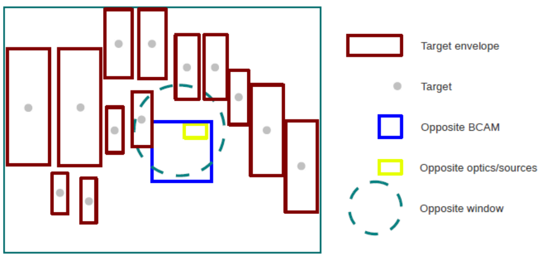

Figure 14 : An example of target distribution simulation - Targets and envelopes projection on the BCAM CCD

The reconstruction software

The mathematical model of the alignment system has been described. Portable software [5-7], designed as a library and allowing simulations as well as real calculations, is being developed. Its modularity, combined with a description of the alignment system configuration in a separate file, makes the reconstruction program adaptable to the evolution of the project over time.

The calculation tools for the 3D reconstruction of the closed geometrical network, materialised by the metrological table equipped with BCAMs, is available.

Simulations indicate precisions at the level of 30 microns for table translations along radial and vertical axes and 4 micro-radians for rotation parameters. The first validation tests done on a bench using table prototypes and standard BCAMs observations confirm these numbers. Differences at the level of 50 microns were found in the comparison to laser tracker measurements.

The modules to include the target observations, the window corrections are ready but are not yet included in the full package for the first tests. In addition an improved image processing is under development.

THE MECHANICAL SUPPORTING AND ADJUSTMENT SYSTEM

The common beam and insulation vacuum adopted for the HIE-ISOLDE cryomodules, obliges for their assembly, the use of a purpose built ISO class 5 clean-room. A vertical, top-down cryomodule assembly sequence has been adopted. The facility will be equipped with geodetic references to measure the position of components and sub-assemblies of each cryomodule at stages during its assembly using standard survey methods such as laser tracker. For this the top plate is furnished with machined references materialised by 2 reference dowel pin holes and with respect to these, by 4 emplacements for Taylor Hobson type targets as shown in Figure **15**.

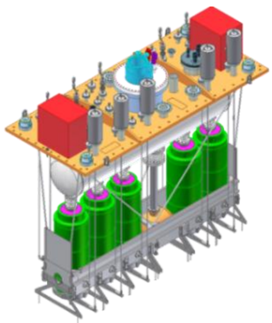

Figure 15 : The HIE-ISOLDE Cryomodule Top Plate Assembly and Suspended Internal Equipment

Two mechanisms for the vertical and lateral alignment of the support frame are assembled one onto each extremity of the top plate.

Four suspension tie-rods, two at each end link these mechanisms via end plates to the support frame. Four more tie-rods triangulate and rigidify the suspension and the length of two of these rods may be changed slightly to permit adjustment of the position of the suspended frame with respect to the top plate references.

Around the beam ports on each side of the RF cavities and on both extremities of the solenoid, are assembled spherical supports as shown in Figure **16**. These, are lowered into V-shaped details in cross-bars that are located in adjustment mechanisms on both sides of the support frame. Precise triangular target supports assembled beneath each cross-bar, hold illuminated ball or reflective targets positioned on the lower ends of the vertical pins.

This constitutes a fundamental design feature of these cryomodules, locating the RF cavities and the solenoid as close as possible to the beam-line and optimising the accuracy of their positional adjustments with respect to the beam.

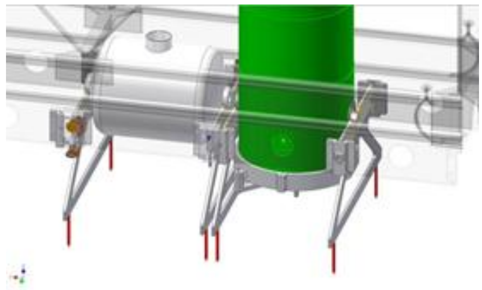

Figure 16 : Support and adjustment of the RF cavities and Solenoid in their support frame

After their assembly into their support frame, and the support frame then suspended from the tie-rods under the top plate, the beam-port positions of the RF cavities and the solenoid are all adjusted, through controlled differential vertical movements of the cross-bars, onto a common axis.

This achieved, the cross-bars of the RF cavities are locked to the support frame, whereas the solenoid cross-bars are left moveable to allow later, fine adjustments of the solenoid in operational conditions.

Once the completed cryomodule has been installed, and all its external services have been connected, it will be pre-aligned onto the HIE-ISOLDE beam line using the 4 Taylor-Hobson targets on its top plate as references.

The insulation vacuum will be pumped and the internal active components will all be cooled from ambient, temperature to 4.5K.

Positional movements of the internal active components will be monitored during cooling using the BCAM Alignment System.

Of particular importance is the nature of the dimensional changes during cooling of the support frame. Normal behaviour is defined as a prismatic change in all its dimensions, however, due to internal stresses not all removed by thorough heat treatment during its manufacturing process, it is possible that the support frame also twists to some degree.

On the first cryomodule, targets are attached to all the cross-bar supports in order to thoroughly determine the extent of any tendency of the support frame to twist.

Once cooling is complete and steady state operational conditions have been attained it will be possible to align the complete support frame together with its RF cavities and the solenoid as a single unit onto the beam-line.

Controlled and measured motorized movements will be provided in independent vertical and lateral directions by the adjustment mechanisms situated at each end of the top plate. These mechanisms will be capable of a range of +/- 5 mm with resolution (step size) of 0.05 mm in each direction.

The BCAM system will monitor the movements of the illuminated or reflective targets to determine the effect of these adjustments.

With the support frame well aligned it will be possible, with respect to the frame, to make small adjustments to the position of the solenoid by differential movements in vertical and lateral directions applied to its two cross-bars. A range of +/- 3 mm with a resolution (step size) of 0.02 mm in each direction is intended.

HIE PROJECT SCHEDULE

A tight and carefully planned schedule is established in order to minimise disturbance to the experiments presently receiving beams from ISOLDE due to the upgrade work. Civil engineering work and main services installation will take place while the ISOLDE facility is running.

Civil Engineering work inside the experimental area, Linac tunnel construction, main services connections or modifications will happen during the CERN Long Shutdown (From beginning 2013 to September 2014).

The cryomodule assembly clean room will be ready in February 2013 and the first cryomodule will be installed on the beam line at the beginning of 2014.

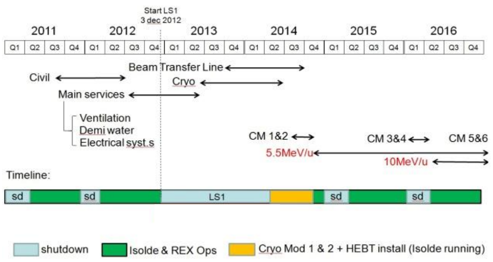

Figure 17 : Simplified HIE-ISOLDE planning

Start-up of the low energy (60keV/u) part of the ISOLDE facility excluding the REX post-accelerator is foreseen for April 2014. At that moment the HIE-ISOLDE Linac and high-energy beam transfer line will still be under construction with the installation of the first two high-beta cryomodules and the beam transfer line elements into the summer of 2014. Beam commissioning at 5.5MeV/u is planned for the end of the 2014 run and physics at 5.5MeV/u for the start of 2015.

The remaining two high-beta cryomodules will be installed in a second stage in 2016, increasing the beam energy to 10MeV together with an additional bend to the high energy beam transfer line providing the users with a third experimental station. The low-beta cryomodules completing the HIE-ISOLDE linac are foreseen for a later stage after 2017.

The alignment System developments will end on 2012 to get a system ready on 2013. Its installation will follow the different steps of the linac construction.

CONCLUSION

The HIE ISOLDE Alignment System technological options are now almost all fixed. The concept is mainly based on well-proven elements such as the BCAMs. The various key elements such as the viewports, which could have been the main concern, and the possible target types have been studied and tested successfully in different situations, incorporating the constraints due to vacuum or cryogenic conditions. A HBCAM camera based on the existing BCAM is under development. The new CCD is already tested and gives very promising results. The other developments foreseen are mechanical adaptation changes, the focal length upgrade and the addition of a ring illumination system and no serious problems are expected.

The software development is well advanced. The mathematical model is ready and the main software modules for the reference frame reconstruction are written. The validation started successfully on a partial but almost full size model equipped with metrological table prototypes and existing BCAMs. In the near future the test bench will be extended and will be equipped with HBCAMs, viewports and with targets held by crossbar prototypes.

The goal is to be ready to install the first alignment system once the first cryomodule will be assembled and ready for vacuum and cryogenic tests.

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