STATUS AND EXPERIENCE WITH THE ALIGNMENT OF LINAC4

Jean-Frederic FUCHS - CERN, Geneva, Switzerland

Abstract

LINAC4 (L4) is an H- linear accelerator that will deliver, for the High Luminosity LHC (HL-LHC) project requirements, a beam of protons at 160 MeV energy to the PS complex and then to the LHC. Its connection to the PS booster will take place during the Long Shutdown 2 (LS2) in 2019-2020 or earlier if any major failure of the LINAC2. The Linac4 project requires the precise alignment with a tolerance of about +/- 0.2 mm in both the horizontal and vertical planes, of elements along approximately 150 m beam line.

This paper will give a status, an overview of the challenges of the alignment, the issues solved by the survey section, the techniques and methodology used to realise the survey activities over the last five years.

INTRODUCTION

The linear accelerator is the first stage of any hadron accelerator complex that generates the initial transverse and longitudinal beam emittances and defines the beam quality for the next stages of acceleration. Linac4 is presently under construction at CERN and will replace the present 50 MeV proton Linac2 as injector of the CERN PS Booster, as a first step of the LHC Injector Upgrade (LIU).

LINAC 4 OVERVIEW

Linac4 is located in a new underground tunnel connected to the Linac4-PSB transfer line. A surface building houses RF equipment, power supplies, electronics and other infrastructure.

General Layout

The overall architecture of Linac4 is shown in Figure 1. The chosen sequence of accelerating sections is quite standard : the ion source is followed by a Radio Frequency Quadrupole (RFQ), a chopping line and accelerating structures. [1]

A L4 transfer line (L4T) connects Linac4 to the existing Linac2. Before the complete installation of the L4T, temporary components will be tested as part of the Half-Sector Test (HST) project.

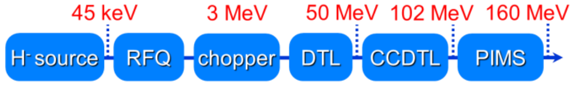

Figure 1 : LINAC 4 – General Overview

L4 – LINAC 4

Linac4 is composed of an ion source, a Low Energy Beam Transport (LEBT), a Radio Frequency Quadrupole (RFQ) and Medium Energy Beam Transport (MEBT).

The linac front-end is followed by a sequence of accelerating structures that bring the energy up to 160 MeV: 50 MeV Drift Tube Linac (DTL), a 102 MeV Cell-Coupled DTL (CCDTL) and a 160 MeV PI-mode structure (PIMS), for an overall length of 86 metres.

L4T – LINAC4 Transfer Line

The L4 transfer line (L4T) starts after the last PIMS. A first horizontal bending (MBH) is used to deviate the beam: the H- particles either can go straight to the main L4 dump, or thanks to three MBH be deviated by 35 degrees in order to meet the L2.BHZ.20 in the L2 tunnel before the injection line going to the Proton Synchrotron Booster (PSB).

The main components of the L4T beam line are five bendings, seventeen quadrupoles, a debuncher and additional components such as beam current transformers, beam stopper, steerers, bean and energy monitoring instruments.

L4H – L4 Half Sector test

The Half-Sector Test (HST) is a project incorporated within the LHC Injector Upgrade (LIU) for the Proton Synchrotron Booster (PSB) in order to increase the PSB extraction energy. The PSB injection section will undergo a complete exchange once Linac 4 will inject H- ions at 160 MeV instead of protons at 50 MeV.

As CERN has no experience with H- injection and in order to mitigate this risks it has been proposed to install half of the future PSB injection section in the L4T. [2]

STATUS – SEPTEMBER 2016

The present status is the following: all the L4 components have been installed and smoothed. The L4T beam line is installed and smoothed including the L4H section. Some components of the L4T located after the first vertical bending magnet (MBV) are already installed and pre-aligned.

Linac4 is presently being commissioned, with the aim of achieving the final energy of 160 MeV at the end of the year and a seven month long reliability run will take place during 2017. [3]

Figure 2 gives an overview of the L4 tunnel from the source side going to the main dump and the starting sector of the L4T line with the first horizontal bending.

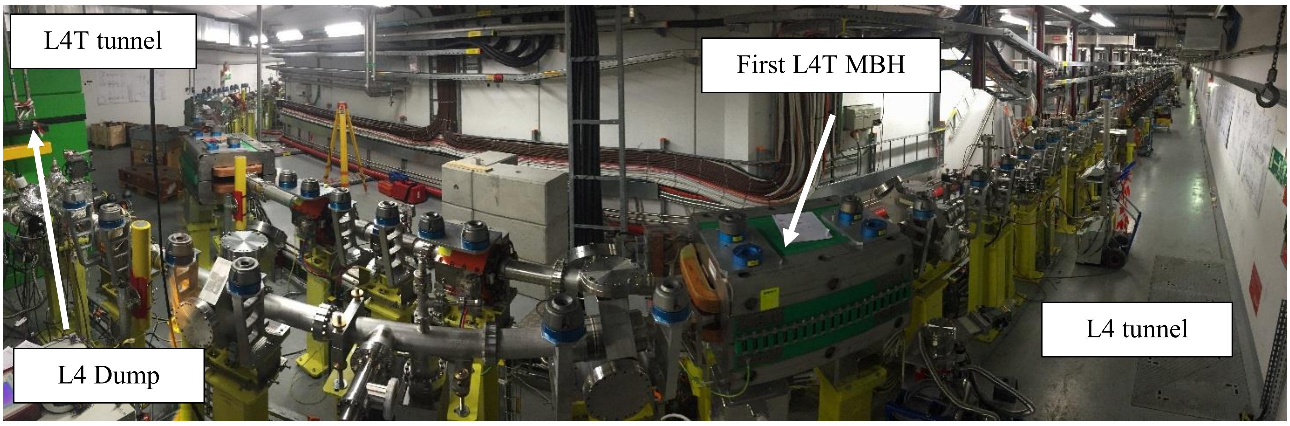

Figure 2 : L4 and L4T general view

NETWORK AND BUILDING STABILIZATION

Introduction

The L4 network is composed by survey reference targets inserted under the tunnel floor (GGPSO), five removable pillars (GPP) along the L4 beam line and more than thirty 3D nests that are fixed on the walls. The GGPSO and pillars can be measured and also used as reference points as the model of socket used in both cases allows the forced centring of the instruments. [4]

All the 3D coordinates are known in the CERN Coordinate System (CCS) thanks to measurements link to others beam components of PS BOOSTER, LINAC2 and PS that have been achieved in 2012, see Figure 3.

The X- and Y-Coordinates in the CERN Coordinate System (CCS) of the reference points were determined with distance and angle measurements using TDA5005 total station / AT40x tracker and a vertical descent into the tunnel using a nadir optical plummet directly onto points in the tunnel (ZL optical plummet from WILD.). The permanent pillars equipped with CERN standard survey reference sockets have been measured using total station, wire offsets and direct levelling. The data have been completed by gyro-theodolite acquisitions in April 2012. A global direct levelling has been performed with the automatic optical levels DNA03 from Leica for the determination of the altitude of the points.

Figure 3 gives details about the measurements done outside and inside the PS/PSB tunnels in order to determine the L4 network with respect to other CERN complexes.

Periodical control measurements are carried out to monitor the possible deformations of the floor of the tunnel and to maintain the accuracy of the network during the installation.

Floor movements

The L4 is installed in a new dedicated underground tunnel built underneath the "Mont Citron" and connected to the existing Linac2 transfer line.

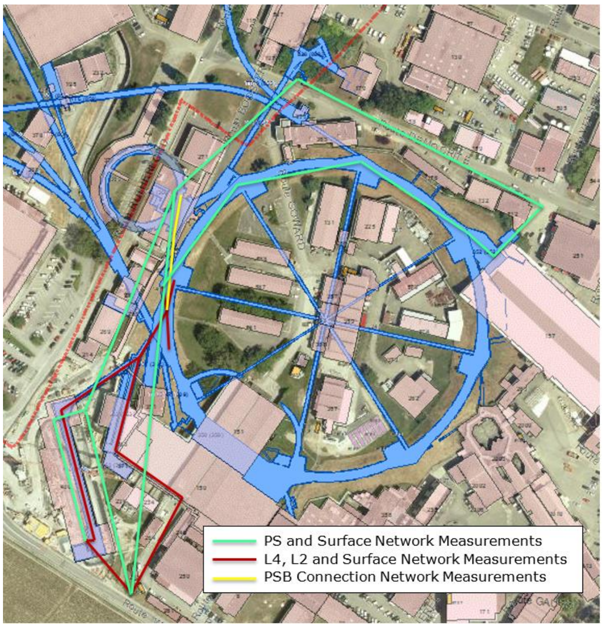

Figure 3 : L4 network measurements

The levelling campaigns showed a very good stability of the concrete floor closed to the L2 building and a linear vertical displacement towards the top direction following the L4 tunnel up to +1.5 mm / year at the extremity in the source area. Floor movements were expected by the civil engineers but they were not able to give values and time limit.

The RFQ is impacted by the floor movement but as it is very complex component to re-align, it has been decided in 2015 to use the RFQ as the main reference for the vertical position. Therefore, all the L4/L4T components have been pre-aligned in a horizontal plane at +3.4 mm from their nominal position.

This + 3.4 mm vertical offset will be compensated through the sector between the two vertical bending magnets located few meters before the connection on the Linac2 transfer line, so L4T will be connected at its nominal vertical position.

The last measurements showed a decreasing of the floor movement even if the source and DTL area is still under the civil engineering effects. If the same strategy is kept, the survey section should ask for a new MAD-X with the nominal vertical values defined by the RFQ vertical position.

METROLOGY AND FIDUCIALISATION

All the components that need to be aligned on the L4 beam have been measured before installation in surface using a laser tracker.

The survey section did many quality control measurements in order to validate the assembly and the manufacturing of the cavities. On the other hand as external reference marks are used in the tunnel to perform the alignment, laser tracker measurements are needed in order to determine a local frame for each element that gives the position of the new "fiducials" with respect to the roll surface and beam axis of the component.

RFQ, DTL, CCDTL, PIMS

The instrumentations and processes used for the several cavities measurements such as RFQ, DTL (x3), CCDTL (x7) and PIMS (x12) are very similar.

The most difficult element to align are considered to be quadrupoles of the DTL which are positioned inside a tank and are not visible at the time of alignment. Figure 4 shows the DTL3 axis defined by the drift tubes within ±0.1 mm.

The survey section enforces the fiducialisaiton measurements with a laser tracker LDT500 and Axyz as the acquisition software. Spatial Analyser was also used for the post-processing of the data, all the geometrical validations and best-fit calculation.

As the cavities are composed by several sections, the first quality control has been done piece by piece. Some 8H7 or 10H7 holes have been integrated on the outside surface during the design process in order to determine the axis of the object and also add external points that are used during best-fit calculations. During this first step, internal reference marks such as drift tubes or permanent quadrupoles were measured in order to validate the radio-frequency (RF) specifications and their positions as showed in Figure 5.

Thanks to this first stage, the components located inside the tank were known with respect to the external mechanical references. In addition, planes such as the roll surface, start and end reference planes, flanges, ….were measured and taken in account for the component geometry definition.

Following the segments acceptance, the cavities were assembled and equipped with their fiducials (= external survey reference marks) before a final laser tracker measurement that was performed in order to validate the final geometry of the object and determine the position of the fiducials.

In some cases the cavities was out of specification : so it was re-opened, corrected and then re-measured before the final acceptance.

At this stage, the measurements in surface are finished and the position of the fiducials are stored in the survey data base named GEODE before the alignments in the tunnel.

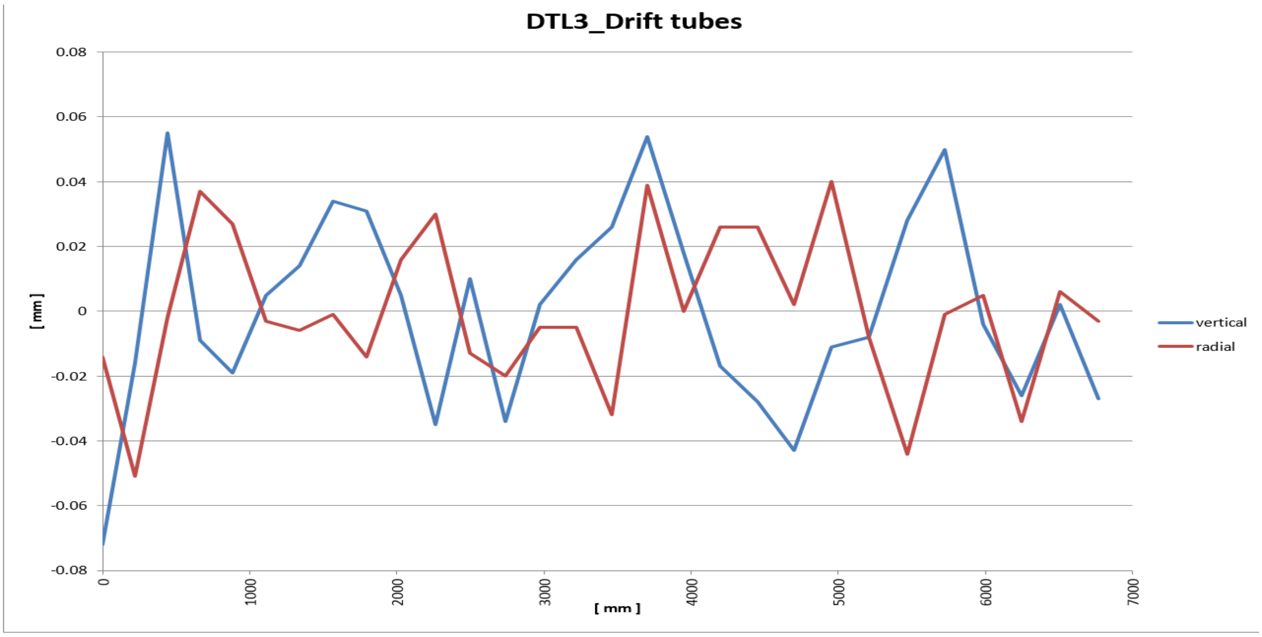

Figure 4 : The axis of the DTL3 is given by the internal drift tube centres that are all aligned within ±0.1 mm

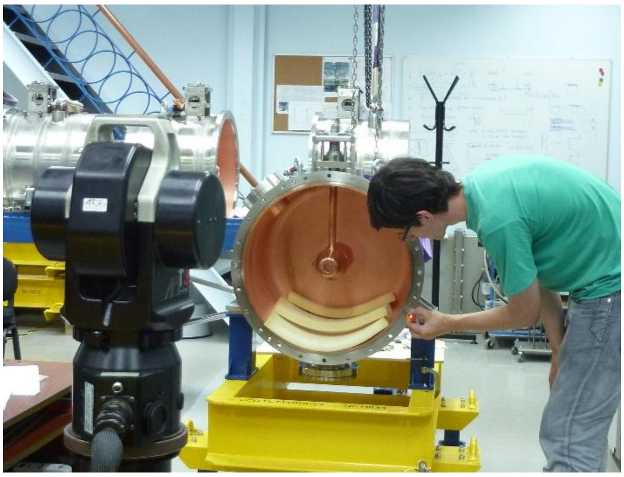

Figure 5 : Measurements of a CCDTL cavitiy constructed at the Budker Institute of Nuclear Physics (BINF) with an API laser tracker.

PMQ and EMQ alignment

Another challenging task was the alignment of the Permanent Magnet Quadrupoles (PMQ) and Electromagnetic Magnet Quadrupoles (EMQ) that have to be positioned on the cavity girders.

As input data, the 3D coordinates of the two fiducial targets on the top of the magnet with respect to the magnetic axis were defined using a magnetic bench with a single stretched wire system.

The center of the magnet must be aligned within +/- 0.1 mm and the roll angle within +/- 1 mrad.The orientation of the magnetic axis in terms of pitch and yaw should be contained within +/- 2mrad. The position along the beam axis is not critical and must be better than +/- 1 mm.

The initial position of the magnets was measured with respect to the cavity frame by measuring point clouds on the roll reference plane, the 3D coordinates of the two targets and external reference on the cavity. As there is no adjustment system on the PMQs and EMQs, the only way to re-align the magnets is the machining of the shims and the wedge.

The offsets with the cavity axis and reference planes were calculated in terms of translation and rotations. The survey section was in charge of the calculation of the values that have been communicated to the workshop for the machining of the foot shims (Tz translation, Rx and Ry rotations) and the central wedge (Ty translation and Rz rotation).

Vacuum chamber alignment in the L4T MBH/MBV

Due to the L4 beam aperture, the free space for the vacuum chamber inside the L4T bendings was very tight. Therefore, in accordance with the design office, the following strategy was applied : survey target supports were added at the extremities of the “Y” and “V” chambers and an alignment system was implemented on each bending in order to move the chamber. The vacuum chambers were first measured by the metrology office and the position of the survey targets defined with respect to their axis following the survey section requests.

Then, the chambers were installed and the survey section took in charge their alignment with respect to the bending axis within +/- 0.2 mm.

Figure 6 : vacuum chamber alignment in a horizontal bending with a LTD 500

The alignment system dedicated to the vacuum chambers will not be used anymore as the bendings will be aligned with their own fiducials and jacks. So the alignment of the MBH/MBV will guarantee the correct positioning of the vacuum chambers with the neighbour vacuum elements.

ALIGNEMENT IN THE TUNNEL

Process

All the elements that need to be aligned are equipped with survey reference points and a mean to establish the roll of the element : this could be achieved by a third appropriately positioned fiducial or a flat surface used to measure the roll angle.

In order to achieve the alignment of the L4 and L4T component within the beam request at +/- 0.2 mm, several steps were needed.

The first stage, carried out with a total station, was the marking out of the beam line on the floor, the beam components (“entry” and “exit” points), the support and jack positions in order to help the cabling team and the first installations.

Afterward, all the jacks were pre-aligned before sealing using a 8H7 reference hole machined on the top surface : the foot reference plane was put horizontally and the jack positioned within +/- 3 mm.

Finally, the head of jack was aligned within +/- 1 mm before the component transportation : thanks to the well positioning of the jacks, the element was installed in the tunnel without more survey support.

Figure 7 : L4 jacks aligned waiting for a component installation

Then, all the component were pre-aligned before the vacuum connection. The initial positioning of the beam line elements has been carried out from the geodetic reference network using an AT40x, direct levelling and offsets measurements. The GGPSO and permanent pillars alongside the L4 and L4T were used as reference to maintain the overall geometry of the machine and the relative position of the L4 and L4T components.

A final smoothing to achieve the desired relative alignment of the components along the L4 and L4T line has been carried out before each beam commission steps at 12MeV, 50 MeV, 100 MeV and 160 MeV by using AT40x, wire offset measurements and direct levelling.

Linac4 vacuum and mechanical constraints

The survey section had to face with some new vacuum constraints. Due to the small diameter of the vacuum bellow the roll angle displacement is limited to 0.7 mrad. This value has been obtain after mechanical tests as at the initial decision no roll movement was allowed.

In addition no cavity can be moved (roll, vertical, radial) without the release of the wave guides and the ion pumps. Following all this mechanical interventions that should be done previously any displacement, the roll angle is not corrected before the vertical or radial initial measurements and the offsets are calculated at the beam level taking in account the roll angle of the components.

Results of the 160 MeV smoothing

The network has been re-measured using total station, wire offsets and direct levelling in July 2016. The results showed the continuously vertical movement of the floor in the top direction inside the area from the source (+ 0.8 mm) to the DTL3 (+ 0.3 mm).

At the end of summer 2016, the L4, L4T and L4H components were ready for smoothing before 160 MeV beam. The roll angle position of all the element was measured before a direct levelling with a Na2. Angles and distances measurements (AT401), with a special care around the MBH area in order to well connect the L4 and L4T wire offset acquisitions.

Figure 8 shows the vertical deviations of the beam points for L4 and L4T components after 160 MeV smoothing.

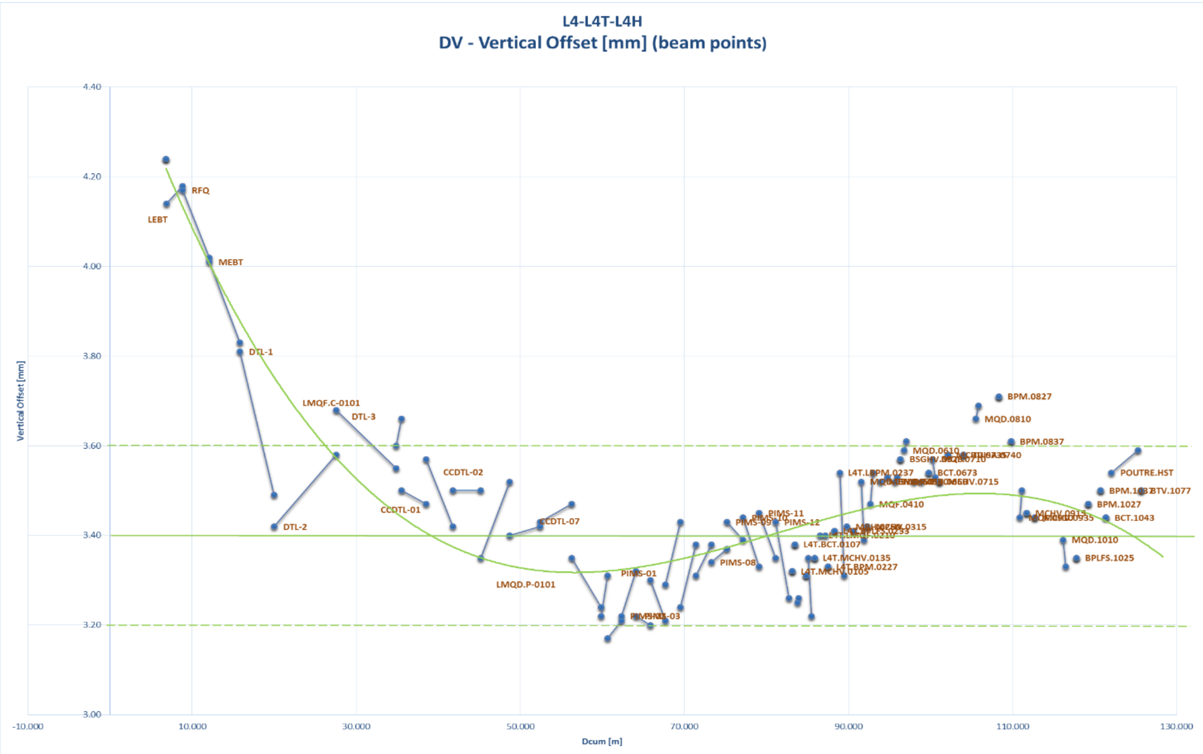

Figure 8 : Vertical deviations of the beam points (L4 / L4T)

SOME FEEDBACKS AND IMPROVEMENTS

L4T supports

There are more than 50 supports along L4T beam lines. The majority of them is dedicated to only one equipment. The rigidity of the arm supporting the survey sockets was so such that it was impossible to perform LTD 500 laser tracker measurement because of the vibrations. On the other hand the roll surface was unusable.

After many simulations, it has been decided to change all the survey arms supporting the sockets on the L4T feet. It was a difficult decision but essential for the future of the project !

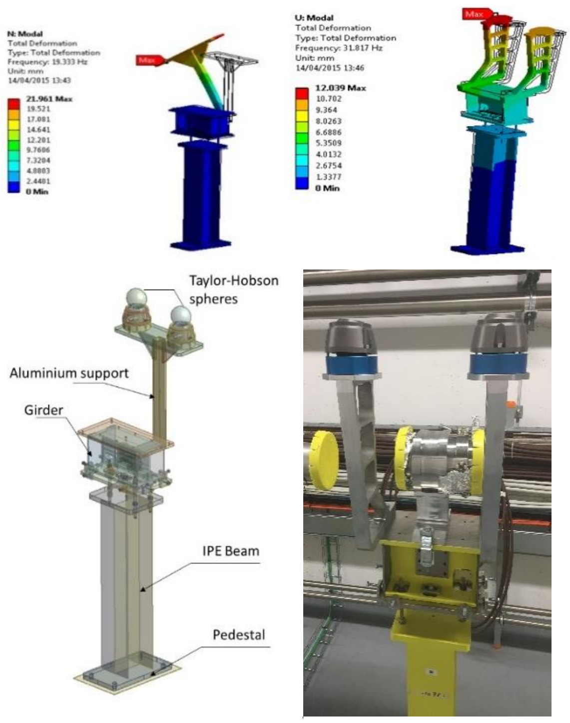

Figure 9 : Old and new model of the arm supporting the survey fiducials

A major improvement for L4T should be the replacement of all the single supports by several girders supporting L4T components. The excellent jacks designed for the L4 cavity could be used, the alignment process will be easiest while ensuring a better relative alignment.

RFQ

The RFQ consists of a 3 m long structure made of 3 brazed sections. The component is connected to a ridge line supporting the RF alimentation that should be free of constraint.

The RFQ has been monitored with and without vacuum conditions during several cycles : displacement of about 0.5 mm in the radial direction have been measured with the laser tracker. It has been supposed that the RFQ has an important flexibility due to the vacuum force coming from the ridge line. As the shape of the RFQ is a “banana” with vacuum condition the fiducialisation defined at the atmospherically pressure is not valid during beam condition better than +/- 0.5 mm as they fixed on outer surface of the tanks.. Nevertheless, it has been ask to the survey section to check the alignment of the RFQ under vacuum conditions.

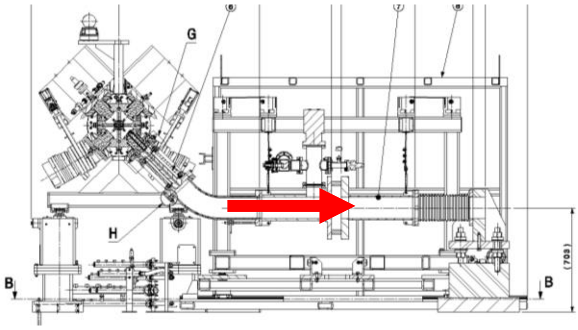

Figure 10 : RFQ with the ridge line force

An improvement should be additional fixation points along the tanks in order to avoid any RFQ deformation and install the survey sockets directly on the RFQ girder as it has been done for the CCDTL cavities.

CONCLUSION AND OUTLOOK

The survey section has smoothed all the components from L4, L4T and L4H beam lines in vertical and radial direction.

With the completion of the 160 MeV commissioning in the coming weeks, the Linac4 will enter a new phase during which its performances and reliability will be improved to meet the LIU requirements.

After the connection work in 2018 and 2019, the commissioning of the L4 transfer line, Linac4 will become the sole injector for the CERN proton accelerator complex.

ACKNOWLEDGEMENT

Since the Linac4 project was started, in 2008, it has involved more than 5 topographical colleagues for the geodetic studies, database management, scanning acquisition and computing, metrology and alignment operations.

The quality of the survey measurements taken over the last years are the direct result of their commitment and dedication. My sincere thanks go to all of them.

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