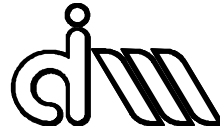UNIVERSITAT POLITÈCNICA DE VALÈNCIA

Departamento de Ingeniería Mecánica y de Materiales

Trabajo Fin de Máster en Ingeniería Mecánica

# DESIGN & DEVELOPMENT OF A HYDRAULIC TEST BENCH FOR AN EROSION & CORROSION TEST

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*Dirigido por*: Dr. Francisco David Denia Guzmán
*Supervisor del CERN*: Oliver Aberle

Valencia, Septiembre de 2017

*Never walk on the travelled path*
*because it only leads where others have been.*

Alexander Graham Bell

# *Abstract*

The neutron time-of-flight (n_TOF) facility at CERN is a source of high flux of neutrons obtained by the spallation process of 20 GeV/c protons onto a high purity (99.99 %) lead target. In 2008 the facility, that suffered severe corrosion after few years of operation, was completely upgraded. It includes now an aluminium alloy vessel and a cooling circuit with monitored oxygen content, and conductivity of the demineralized water used as coolant and moderator. During Long Shutdown (LS2) a third spallation target (target #3) will be installed in the facility, in order to substitute the present target which will have reached its end of life. The target is presently under design. Various materials are being investigated for both the core and the contact part with the cooling water.

In the framework of the target upgrade activities, a new water erosion/corrosion test bench is required, in order to evaluate the compatibility of various materials in the n_TOF target regime.

The new test bench is intended to be capable of being used to carry out erosion and corrosion tests, and check the changes of the materials to validate the design of the new target. This test bench has been designed in a way that will be versatile and adaptable to different types of tests and targets in the future.

The idea is that the design can modify variables such as the circuit flow, temperature, fluid conductivity and pressure for different tests with good reading out and logging values.

The project of the test bench comprises the conceptual to the detailed design and manufacture the device. This work has carried out in collaboration with several groups across CERN, involved in the technical specification, analysis, design, manufacture and security.

## *Key Words*

CERN, physics, particles, spallation, proton synchrotron, design hydraulic, test bench, erosion, corrosion, demineralized water, conductivity, heat, flow, manufacturing.

# Resumen

La instalación de neutrones de tiempo de vuelo (n_TOF) en el CERN es una fuente de alto flujo de neutrones obtenida por el proceso de espalación de 20 GeV/c de protones sobre un objetivo de plomo de alta pureza (99,99 %). En 2008, la instalación sufrió una corrosión severa después de pocos años de operación, ésta fue completamente mejorada. Incluye ahora un recipiente de aleación de aluminio y un circuito de refrigeración con contenido de oxígeno y conductividad del agua desmineralizada, utilizada como refrigerante y moderador, controlados. Durante la parada larga (LS2) se instalará un tercer objetivo de espalación (objetivo #3) en la instalación, para sustituir al objetivo actual que habrá alcanzado su fin de vida útil. El objetivo está actualmente bajo diseño. Se están investigando varios materiales para el núcleo y la parte en contacto con el agua del sistema de refrigeración.

En el marco de las actividades de mejora de objetivos, se requiere un nuevo banco de pruebas de erosión / corrosión, con el fin de evaluar la compatibilidad de diversos materiales en el régimen del objetivo n_TOF.

El nuevo banco de pruebas está destinado a ser capaz de realizar pruebas de erosión y corrosión, y verificar los cambios de los materiales para validar el diseño del nuevo objetivo. Este banco de pruebas ha sido diseñado de una manera que será versátil y adaptable a diferentes tipos de pruebas y objetivos en el futuro.

La idea es que el diseño puede modificar variables tales como el flujo del circuito, la temperatura, la conductividad del fluido y la presión para diferentes pruebas con buenos valores de lectura y registro.

El proyecto del banco de pruebas comprende del diseño conceptual al diseño detallado y la fabricación del dispositivo. Este trabajo se ha llevado a cabo en colaboración con varios grupos del CERN, involucrados en la especificación técnica, análisis, diseño, fabricación y seguridad.

## *Palabras Clave*

CERN, física, partículas, espalación, proton synchrotron, diseño hidráulico, banco de pruebas, erosión, corrosión, agua desmineralizada, conductividad, calor, caudal, fabricación.

# *Resum*

La instal·lació de neutrons de temps de vol (n_TOF) al CERN és una font d'alt flux de neutrons obtinguda pel procés d'espal·lació de 20 GeV/c de protons sobre un objectiu de plom d'alta puresa (99,99 %). El 2008, la instal·lació va patir una corrosió severa després de pocs anys d'operació, aquesta va ser completament millorada. Inclou ara un recipient d'aliatge d'alumini i un circuit de refrigeració amb contingut d'oxigen i conductivitat de l'aigua desmineralitzada, utilitzada com a refrigerant i moderador, controlats. Durant la parada llarga (LS2) s'instal·larà un tercer objectiu de espal·lació (objectiu #3) en la instal·lació, per substituir l'objectiu actual que hi haurà arribat al seu fi de vida útil. L'objectiu està actualment sota disseny. S'estan investigant diversos materials per al nucli i la part en contacte amb l'aigua del sistema de refrigeració.

En el marc de les activitats de millora d'objectius, es requereix un nou banc de proves d'erosió / corrosió, per tal d'avaluar la compatibilitat de diversos materials en el règim de l'objectiu n_TOF.

El nou banc de proves està destinat per a ser capaç de realitzar proves d'erosió i corrosió, i verificar els canvis dels materials per validar el disseny del nou objectiu. Aquest banc de proves ha estat dissenyat d'una manera que serà versàtil i adaptable a diferents tipus de proves i objectius en el futur.

La idea és que el disseny pot modificar variables com ara el flux del circuit, la temperatura, la conductivitat del fluid i la pressió per a diferents proves amb bons valors de lectura i registre.

El projecte del banc de proves comprèn del disseny conceptual al disseny detallat i la fabricació del dispositiu. Aquest treball s'ha dut a terme en col·laboració amb diversos grups del CERN, involucrats en l'especificació tècnica, anàlisi, disseny, fabricació i seguretat.

## Paraules Clau

CERN, física, partícules, espal·lació, proton synchrotron, disseny hidràulic, banc de proves, erosió, corrosió, aigua desmineralitzada, conductivitat, calor, cabal, fabricació.
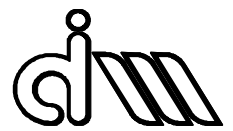
# *Acknowledgements*

The period of this thesis brought me valuable new experiences in both a scientific and personal perspective. This thesis would not have been possible without the constant support and motivation of many people.

Firstly, I would like to express my sincere gratitude to my supervisor, Oliver Aberle. His wide knowledge and his experience have been a great value for me. His encouraging and personal guidance have provided a good background for the present thesis.
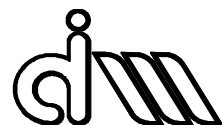
Many thanks to the professor Francisco David Denia Guzmán and Maria Papamichali, for accepting to review my work. Their constructive suggestions on the thesis are really appreciated for me. I am grateful that in the midst of their activities, they accepted these tasks.

During this period, I have collaborated with many colleagues, from different departments, the section workshop and suppliers for whom I have great regard, and I wish to extend my warmest thanks to all those who have helped me from a professional and personal point of view. Especially to Marco Calviani, Damien Grenier, Christophe Claude Mitifiot, Hubert Reymond, Domingo Gomez Dominguez, Yannic Body, Yann Lupkins, Ramon Folch, Pierre Broussart, Edouard Grenier-Boley, Abdelhabib Majbour, Edmundo Lopez Sola, Raffaele Esposito, Tomasz Kazimierz Strzalka.

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# Glossary

*CERN: Conseil Européen pour la Recherche Nucléaire*

*LHC: Large Hadron Collider*

*LS: Long Shutdown*

*PS: Proton Synchrotron*

*PSB: Proton Synchrotron Booster*

*SPS: Super Proton Synchrotron*

*ALICE: A Large Ion Collider Experiment*

*ATLAS: A Toroidal LHC ApparatuS*

*CMS: Compact Muon Solenoid*

*LHCb: Large Hadron Collider beauty experiment*

*AD: Antiproton Decelerator*

*N_TOF: Neutron Time-Of-Flight*

*ECR: Electron Cyclotron Resonance*

*RFQ: Radio Frequency Quadrupole*

*LEIR: Low Energy Ion Ring*

*RF: Radio Frequency*

*HV: High Voltage*
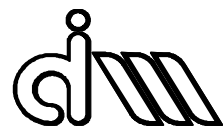
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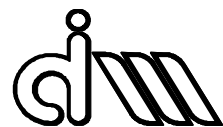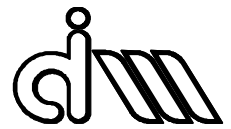
# Chapter 1

# 1. Introduction

## 1.1. CERN

The European Organization for Nuclear Research is the world's largest particle physics laboratory [1]. It is situated at Geneva across the border between France and Switzerland. The origin of the name comes from the French acronyms "Conseil Européen pour la Recherche Nucléaire".

It was founded in 1954 by 12 member states and nowadays the members are 22, but it gathers physicists and engineers from more than 100 countries in the world.

13.7 billion of years ago the Universe started with an explosion. The energy, concentrated in an infinitely small space, coagulated in equal part of matter and antimatter. At CERN physicists and engineers work to push more and more in the research boundaries probing the fundamental structure of the Universe.

In order to attain this main goal, particle physics studies the finest object of Nature. Looking into the very small and fundamental is also looking far back into time, just a few moments after the Big Bang [2].
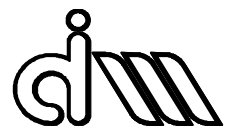
The investigation of the fundamental particle, the basic constituent of the matter, is made by the collision of two particle beams in the LHC (Large Hadron Collider), the most powerful accelerator in the world.

The temperature and energy density in the collision are similar to those that existed a few moments after the Bing Bang, in this way physicists hope to discover how the Universe evolved.

The CERN activity is regulated by an alternation of two periods: the "Run", when the beams circulate in the tunnel and the experiments can collect the data, and the "LS: Long Shutdown" when the beams are stopped and it is possible to make the maintenance and the upgrades of the devices inside the machines.

From the beginning of the LHC operation, in 2008, CERN has had two periods: the "Run1" and the "LS1". The energy reached in the collision of Run1 was 8 TeV and, thanks to this, the experiments have made the very important discovery of the Higgs Boson, which improves our current understanding of the Universe, confirming the Standard Model Theory.

During the two years of the LS1 the power of the machine was increased up to an energy of collision of 14 TeV.

Nowadays, we are in the Run2, that is going to be concluded in the middle of 2018, the LS2 will follow and then, the Run3 is foreseen for 2020.

## 1.1.1. The CERN's accelerator complex.

Before their collision, the particles are accelerated to a speed very close to the speed of light. This is made by a succession of machines that, step by step brings the particles to higher energies and speed, as the Figure 1 shows.
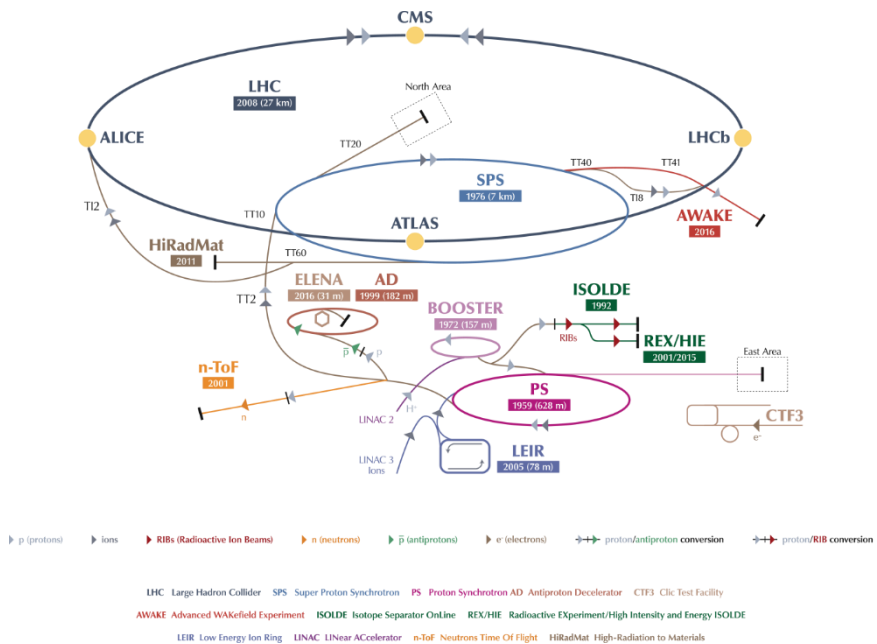


*Figure 1: Schematic accelerator complex.*

Each machine injects the beam into the next one, which takes over to bring the beam to an even higher energy, and so on. The LHC is the last element of the chain, there the particle beams are accelerated in order to reach the energy of 13 TeV.

The LHC stands for Large Hadron Collider. Large is due to its size about 27 km in circumference, Hadron is because it accelerates protons or lead ions, which are hadrons, and Collider because the particles travel into two beams in opposite direction and in four points of the ring they collide.

The accelerators inside the machine are normally circular tunnels in which the particles are bent to follow a circular trajectory by the dipole magnets.

The quadrupole magnets are used to focus the beam down to the smallest possible size before the collision point, in order to maximize the chance of two protons to smash with each other. In the LHC the superconductive magnets use a cryogenic system with a pumping of superfluid helium that permits to operate at a temperature of -273.1 °C, which makes it one of the coldest places on Earth. The Figure 2 shows a quadrupole in the LHC.

*Figure 2: LHC.*

The acceleration, instead, is made by the transfer of the beam inside the radiofrequency cavities. The electric field, created within the cavities, changes polarity with high frequency. The incoming protons are attracted inside the cavity when the positive sign of the electric field is in the same direction of the beam, while when the sign is in the opposite direction, the particles are pushed with higher speed.

All of the physics starts from a little bottle of hydrogen, the protons of which are taken by stripping orbiting electrons. These protons are accelerated to an energy of 50 MeV with a rise of the mass of the 5 % in the Linac2, one of the only two linear accelerators of the chain.

The protons are then injected into the PS Booster (PSB) that accelerates them to 1.4 GeV and 91.6 % of the speed of light. After, the beam is going through the Proton Synchrotron (PS) where it is accelerated to 25 GeV and 99.93 % of the speed of light. The Super Proton Synchrotron (SPS) follows, where the energy reaches 450 GeV.

Finally, after five accelerators that increase the mass of the protons of 7000 times and their velocity till 99.9999991 % of the speed of light, the beam is transferred to the LHC in both directions, clockwise and anticlockwise. In the LHC they are accelerated for 20 minutes to their nominal energy of 13 TeV. Beams will circulate for many hours inside the ultra-high vacuum beam pipes under normal operating conditions.

The two beams of the LHC collide only at four specific points in correspondence of the detectors. The detectors are machines that recognize and measure properties of the particles during the collisions, trying to understand their nature. Each detector is related to the one of the main experiments at CERN: ALICE [3], ATLAS [4], CMS [5] and LHCb [6].

In addition, most of the accelerators in the chain have their own experimental halls with a beam of lower energy. For example the SPS supplies several experiments, among them fix target experiments are the North Area NA62 [7] or the COMPASS [8] experiments. SPS also

provides the particles to the HiRadMat [9] for experiments on materials hit by the beam; instead, the PS injects the particles to the Antiproton Decelerator (AD) [10] or to n_TOF [11]. In Figure 3, two pictures of the CMS and ATLAS colliding beam particle detectors can be seen.
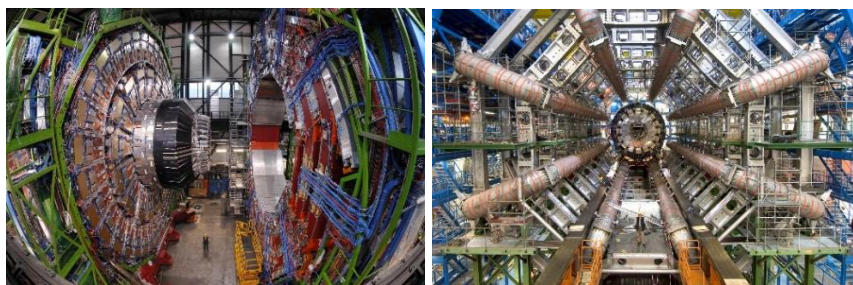


*Figure 3: CMS and ATLAS experiment at CERN*

Moreover, the accelerator complex also accelerates lead ions. The production of the lead ions comes from a highly purified lead sample, the ECR (Electron Cyclotron Resonance) [12] source, which is heated to a temperature of about 500 °C.

The lead vapour is ionized by an electron current; the source provides many different charge states, a spectrum from Pb22+ to Pb32+, with a maximum around Pb29+, which is the only of the charged states selected immediately by a spectrometer. Now, the travel of these ions starts from the linear structures which accelerates the ions to 4,2 MeV/u (energy per nucleon): A Radio Frequency Quadrupole (RFQ) and then an inter-digital Linear Accelerator, the Linac3, play this role.

Afterwards, the ions proceed and pass through a carbon foil, which strips most of them to Pb54+. These last are then accumulated and accelerated to 72 MeV/u in the LEIR [13]. From this, they are injected in the PS that accelerates to 5.9 GeV/u and transfers them through another foil of aluminium that fully strips to Pb84+ towards the SPS. Here, the beam reaches the energy of 177 GeV/u and goes to the last transfers into the LHC, which accelerates it to 2.76 TeV/u.

## 1.1.2. Neutron Time-Of-Flight Facility

The neutron time-of-flight facility (n_TOF), has been operating at CERN since 2001. N_TOF is a pulsed neutron source coupled to a 200 m flight path. It is designed to study neutron-nucleus interactions for neutron energies ranging from a few meV to several GeV. The wide energy range and high-intensity neutron beams produced at n_TOF are used to make precise measurements of neutron-related processes.

To produce neutrons, a pulsed beam of protons from the Proton Synchrotron (PS) is directed at a lead target. When the beam hits, every proton yields about 300 neutrons. The initially fast neutrons are slowed down, first by a lead target, and then by a slab containing water. Some neutrons slow more than others as they pass through the targets, which creates a range of neutron energies (a "neutron spectrum") from the meV region up to the GeV region.

These neutrons are guided through an evacuated beam pipe to an experimental area 185 metres from the target. In a typical experiment, a sample is placed in the neutron beam and the reaction products detected. This allows the team to reconstruct the reaction probability as a function of the incident neutron energy.

The current spallation target used in the n_TOF target area was installed during 2008. It generates neutrons for the Experimental Area1 (EAR1) about 185 m downstream the target. During 2014 a new Experimental Area2 (EAR2) was built about 20 m vertically above the target (see Figure 4).
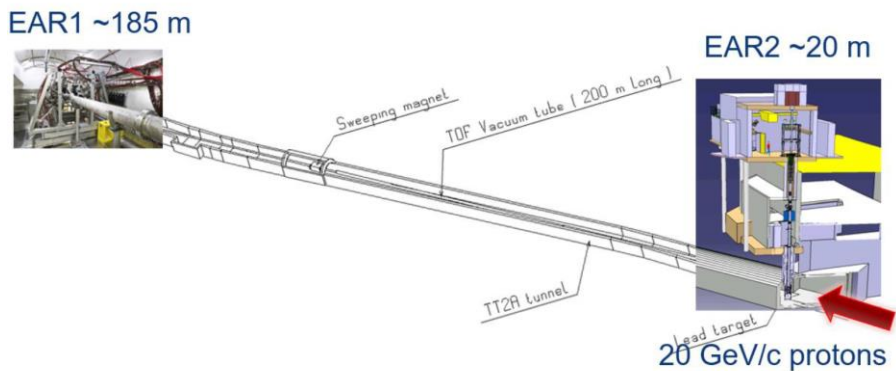


*Figure 4: schematic n_TOF experimental area*

Neutron time-of-flight measurements contribute in an important way to understanding nuclear data. Only a few time-of-flight facilities

exist worldwide, each with its own characteristics. The strength of n_TOF is the large energy range it can cover, and the high number of neutrons per pulse.

Data produced by n_TOF are used in astrophysics to study stellar evolution and supernovae. Intense neutron beams are also important in hadrontherapy (the treatment of tumors with beams of hadrons) and studies of how to incinerate radioactive nuclear waste.

A first facility, operational since 2001, was based on a non-monolithic lead target, an open cooling circuit of demineralized water and absence of control on the water chemistry. It suffered severe corrosion and extensive deformation of the central part of the target, as a consequence of the local energy deposition and insufficient cooling. Excessive temperature at the beam interaction point induced creep in the lead blocks and activated severe pitting corrosion.

The present n_TOF target was designed, built and installed in 2008 to overcome the serious problems of pitting corrosion of the previous target. In fact, because of the presence of metallic residuals from corrosion in the cooling water, the dose rate levels coming from the cooling circuit increased by a tenfold the last year of operation of the target in 2004, causing a three years stop of the facility.

This target consists of a monolithic lead cylindrical target with a diameter of 0.6 m, a height of 0.4 m and a total weight of 1.3 t (Figure 5). The target is cooled by a pressurized water cooling system, including an all welded aluminium alloy vessel and a cooling circuit with monitored and controlled oxygen content and conductivity of the demineralized water used as coolant and moderator.
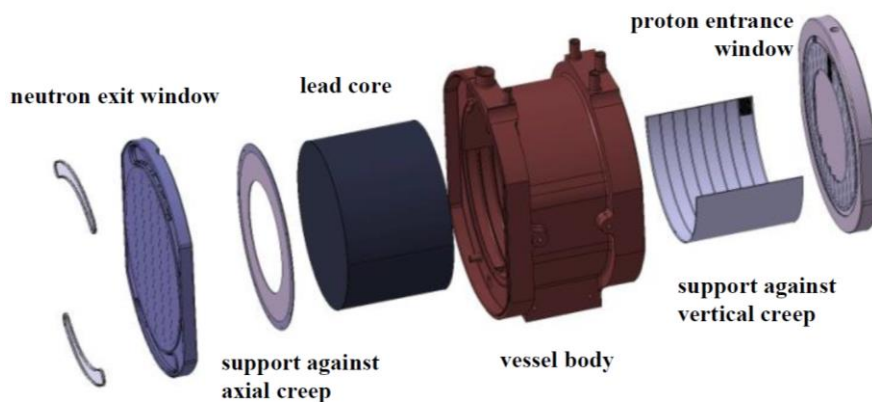


*Figure 5: Design of the target*

During LS2 a third spallation target (target #3) will be installed in the facility, in order to substitute the present target which will have reached its end of life. The target is presently under design. Various materials are being investigated for both the core and the contact part with the cooling water.

Careful attention has been paid during the course of the years in the operation of the present n_TOF target (target #2), in order to not exceed

the maximum acceptable number of protons/second on target and to make sure that the water chemistry was always respecting the very tight operational constraints, defined at the early stage of the project [14] [15]. It is important to note that conditioning and control of the water chemistry is required to maintain a chemically stable lead surface and avoid the problems encountered during the operation of target #1.
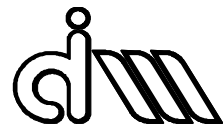
# Chapter 2

## 2. Description of the installation

In the framework of the target upgrade activities, a new water erosion/corrosion test bench is required, in order to evaluate the compatibility of various materials in the n_TOF target regime.

The new test bench is intended to be capable of being used to carry out erosion and corrosion tests, and check the changes in the microstructure of different materials to validate the design of the new target. The test bench is designed to be as most automatic as possible, only required from the operator the set-up of the materials inside the chamber, some manual valves and the manual start of the test, it is designed in a way that it will be versatile and adaptable to different types of tests and targets.

The experiment is carried out inside a stainless steel chamber, where the target is installed. To get all the special conditions is needed different devices for it. The demineralized water is used in the real experiment to avoid any material oxidation in the target or in the circuit components. In this case is going to be used an Ion exchange equipment in stainless steel that fulfil all the requirements needed. The mixed bed ion exchangers work according to the ion exchange principle.
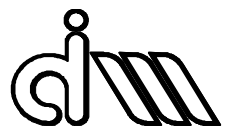
The idea of the test bench is the design can modify variables such as the circuit flow, temperature, fluid conductivity, and pressure for different tests with good reading out and logging values. To get all of these options a full market research has been done to find the best commercial components that can achieve all the requirements. The circuit is composed by a hydraulic pump that gives the flow, a heater that gives the temperature, flowmeters and valves to control the flow and different sensors to control the conductivity and the pressure.

Everything is placed on aluminium structure, in order to reduce the weight, with four wheels to make easier the placement and to find a water tap connection. A rectangular design with two aluminium sheets of 10mm thickness have been chosen to make easier the design, the assembly itself, and the assembly of all the components, also, the space for the electronic devices has been taken into account.

The Figure 6 presents the schematic target and flow impact inside the chamber:



10 mm

10 mm
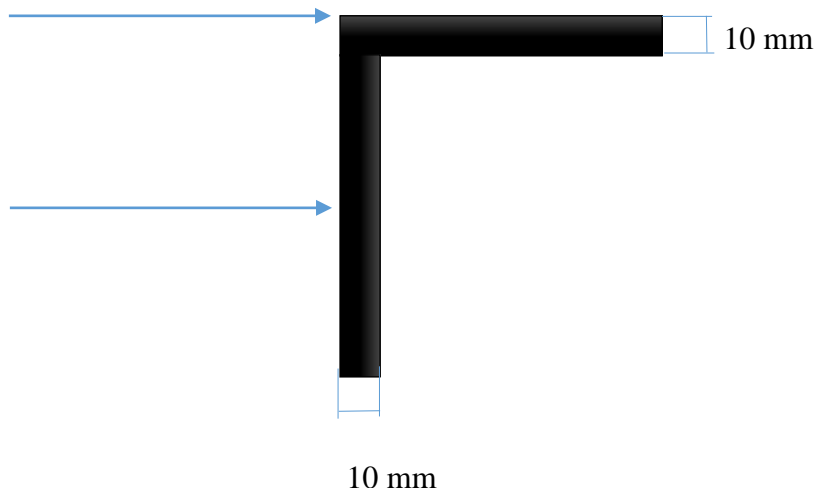
*Figure 6: Scheme of the target.*

## 2.1. Test procedure

In order to simulate as close as possible the conditions prevailing in the real n_TOF experiment, a test loop using demineralized water as process fluid was specially developed and connected on metal based loop circuit available at CERN. The test loop is shown and described in Figure 7.

The Test-Bench must be installed in a location with access to normal tap water, sewer to discharge used water, 380 V triphasic electric connection and Ethernet connection for internet access.

As in the real circuit, water passes through a mixed-bed resin cartridge in order to keep conductivity as low as possible. With a flow regulator valve, placed on the inlet cartridge, is possible to control the flow once the conductivity is suitable. The water is heated up to 80 °C to simulate the water temperature at the surface of the test material, where the beam hits the target. There are two temperature sensor that will control the heater operation.

The water circuit is split in two main branches, one as a by-pass in order to adapt the fluid to the experiment requirements and the other branch has two different injections points in a mock-up container.

Once the water is prepared with all requirements for the test (pressure, temperature, oxygen and conductivity), the valves V1 and V2 will be opened manually to allow the fluid to pass through the second branch to start the process. This is the most important branch because all the experiment depend on to maintain the flow conditions in these pipes. The valves VR2 and VR3 will be in charge of adjusting the proper flow through the test chamber. VR3 is a manual regulator flow valve that will be set up at the beginning and VR2 will control the flow during all the experiment as an automatic flow regulator valve (see Figure 7).

The Test-Bench was designed to send automatically the reports, warnings/alerts over email to the person in charge. Also, several interlock systems were implemented to prevent and alert CERN about test bench incorrect use or malfunctions.
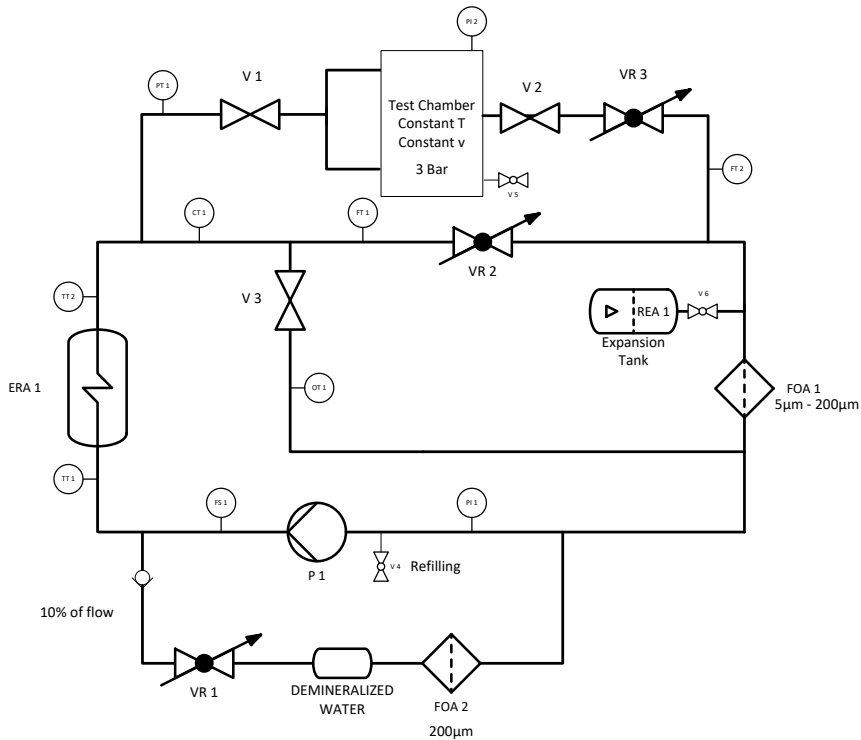


*Figure 7: Scheme of the hydraulic system.*

The duration of the test is expected to be three months for each material. The amount of erosion/corrosion will be verified at the end of the test by different processes such as dimensional verification or microscopy. The most adapted material will be chosen after evaluation of the results.

# Chapter 3

## 3. Ambit of the project.

The present project includes the design and manufacturing of the mechanical part of a hydraulic test bench to check the erosion and corrosion of different materials and thus validate the next target of the n_TOF experiment at CERN.

The test samples and the installation of them inside the chamber are not considered part of the project.

Parts of the electronic design, software design, and design of the wiring, protection and control elements are not considered part of the project. However, these elements must comply with the IEC Standards.

The limits of each section are specified in the points described below.

## 3.1. Test bench links.

Only the mechanical links of the bench test to the outside will be considered as belonging to the present project. In this case it would be the standard water inlet / outlet connection and the extraction valve in the chamber.

The design of the input electrical connection and its safety features are not considered as belonging to the project.

## 4. Design of the installation

The design of the hydraulic test bench began in February 2016 with the objective to determinate the best material option for the new target in terms of erosion and corrosion. The test bench should recreate, as close as possible, the conditions in the real n_TOF experiment.

### 4.1. Limitations of the system

- Fluid to use: Demineralized water
- Flow rate: 1-90 L/min
- Fluid temperature: 20 °C / 80 °C
- Water speed inside the chamber: 0.1 to 5 m/s
- Pressure inside the chamber: 1-3 bar
- O2 content: ppm (1/10 of ppm)
- Conductivity: 0.175 µS/cm
- Tow impact angles: 90 deg. 0 deg.
- 10 mm jet diameter
- Container sealed capable of reaching up to 100 °C
- Test container: X: 30-40 cm; Y: 30-40 cm; Z: 15-30 cm
- Structure: X: 150-200 cm; Y: 80-100 cm; Z: 60-110 cm

Based on the general limitations posed by the system, a conceptual design is carried out. The commercial devices necessary to achieve the requirements are agreed upon, through discussions with other sections that will contribute their experience and work.

All the equipment is mounted on a rectangular structure, able to move easily. The selection of the equipment is determined by the established requirements from the beginning, the requirements that the components themselves require and the amount of water to be moved.

The hydraulic test bench consists of a hydraulic pump, a heater, electrical resistances, control and protection elements (manometers, thermometers, filters, compensators, electro-valve, thermostats, resistors and flow switch), and spherical closing valves for flow adjustment and also the pipes.

The circuit consists of pipes in charge of providing the required pressure to the chamber. The user is responsible to make the pipe connection. The entrance to the test bench circuit is made by a quick connection of 1".

To design all the system, the temperature, pressure and flow must be determined in a general way, taking into account that the most critical element is the chamber where the tests will be carry out.

## 4.2. Description of the elements of the installation

This chapter will describe the process for the design of each component, the calculations developed, the components selected and the solutions that have been adopted. In the Figure 8 one may visualize the components of the installation to be designed.
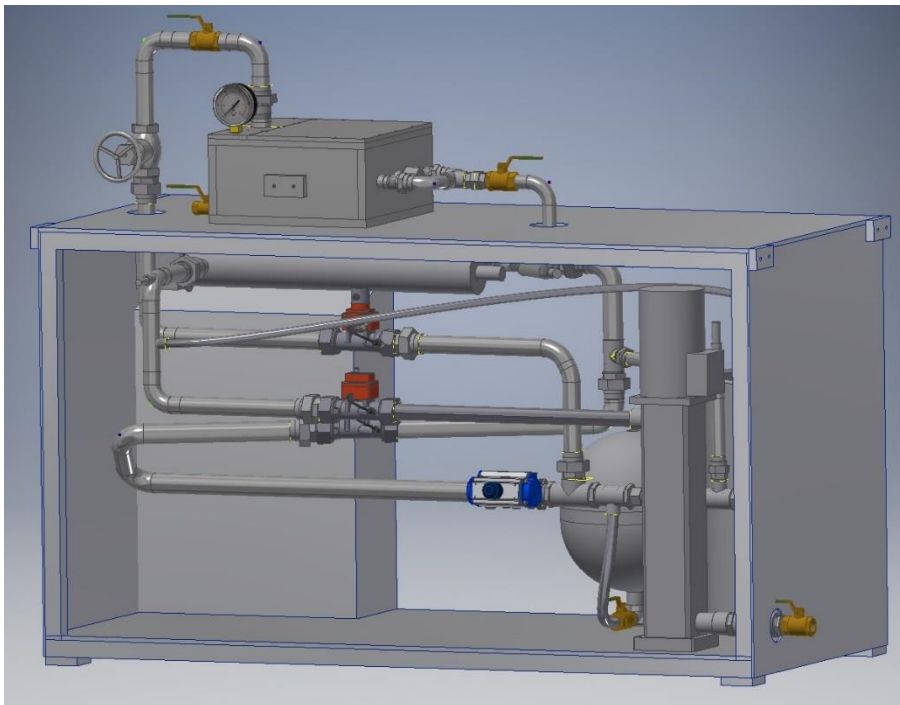


*Figure 8: Test bench design.*

### 4.2.1. Structure

Aluminium has been considered for the structure in order to reduce the weight of the test bench. A rectangular design with two aluminium sheets of 10 mm thickness have been chosen to make easier the design, the assembly itself, and the assembly of all the components. The dimensions are 1810 x 800 x 1030 mm, which were decided by the iteration of the rest of the design.

The space for the electronic devices has been taken into account. It consists of three aluminium sheets creating a water isolated space to assembly everything related to the electricity. Also, there are installed four aluminium parts, with two M10 threated holes, on the structure sides for the lift. All the structure is showed in the Figure 9.
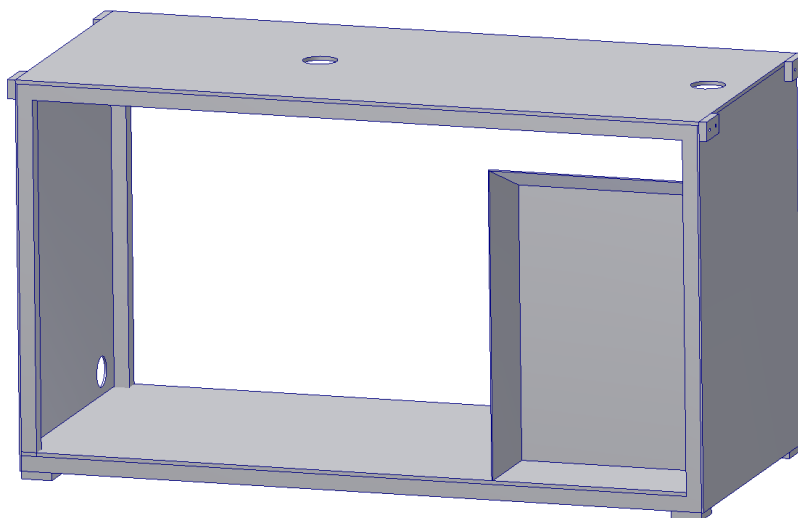


*Figure 9: Aluminium structure.*

### 4.2.2. Demineralized water

Demineralised water is specially purified water that has had most or all of its mineral and salt ions removed, such as Calcium, Magnesium, Sodium, Chloride, Sulphate, Nitrate and Bicarbonate. It is also known as Deionised water, DI or Demin water.

Demineralised water is generally considered distinct from distilled water, which is purified in a still for example by being boiled and re-condensed, a process which also removes salt ions.

The major differences are that demineralised water is usually freer of mineral ions, depending on the number of processes used to make it, and distilled water may have less organic contaminants, as deionisation does not remove uncharged molecules such as viruses or bacteria. However, deionisation also leaves behind less 'scale' than distillation, and so has a cleaner production.

There are two main ways of producing demineralised water. A Demineralisation Plant that uses Ion-exchange Resins. The cation exchange resins exchange the positive ions (e.g. Calcium) for hydrogen ions, and the anion resins exchange negative ions (e.g. Chlorine) for

hydroxide ions. The final water consists primarily of hydrogen and hydroxide ions, which is the chemical composition of pure water.

Electro-Deionisation Plants also use Ion-exchange Resins but pass an electric current through the resins to keep the resin regenerated for example the mineral ions migrate away from the resin toward an anode or a cathode.

Often, several stages of demineralisation occur to obtain the required quality of the final product, and some of these stages may also include reverse osmosis (RO) systems, where water is pressurised and forced through semi-permeable membranes which retain the mineral ions and other impurities, as well as distillation and filtration. [16]

In this case, after taking account all the requirements of the system, performing a market research taking into account different companies and their commercial equipment and exchanging views with experienced colleagues in this topic from the Cooling and Ventilation section at CERN, there were limited number of candidates, mainly due to the high temperature in use.

ASD (Aqua Service Distribution), based in France, has Ion exchange equipment in stainless steel that fulfil all the requirements

needed. The mixed bed ion exchangers work according to the ion exchange principle. The dissolved salts that are present in the water are in form of ions. Demineralisers are mixed bed ion exchangers with a constant quality of the resins ensuring you irreproachable and reliable results. The result is pure, demineralised water. The Table 1 represents all the device features and the Figure 10 shows the device.

| | |
|---|---|
| *Stakpure mixed bed ion exchanger* | *DS 7000* |
| *Water demineraliser* | *pressure resistant* |
| *Stainless-steel cartridge* | *pressure resistant up to 10 bar* |
| *Flow rate* | *2000 l/h* |
| *Capacity for 10° dH total dissolved solids* | *7000 l* |
| *Pure water quality* | *0.1 – 20 µS/cm* |
| *Max. water temperature* | *30 °C* |
| *Material* | *Stainless steel – AISI 316* |
| *Dimensions mm (Ø x height)* | *363 x 600* |
| *Connection* | *R ¾* |
| *Weight, approx.* | *55 kg* |

*Table 1: Ion exchange device features.*

*Figure 10: Ion exchange system.*

### 4.2.3. Flow rate

In the following chapter, the selection procedure of components in charge to control the flow rate is described. First, a suitable hydraulic pump for operation of the circuit, based on the requirements of the system, is selected. From the several valid options available, the final decision is made after the selection of different elements, such as pipes section, flowmeters or heater because they give other dimensional requirements to consider.

#### 4.2.3.1. Hydraulic pump

Hydraulic pumps are used to drive the water of the circuit to the rest of the elements of which the test bench is composed. For these purposes mainly two types or models of pumps are used, horizontal and vertical. Their differences, in addition to the constructive form, are the work curves; the horizontal ones have a flat curve while the curve of the vertical one curve is more pronounced.

Going through the catalogue of a company, a pump can be chosen taking into consideration the flow and working pressure data. The efficiency diagrams, based on flow and pressure, are taken as the main information in order to choose the device, as much in the middle is the pump, better will work in the conditions presented before. A 20 % increase of the total flow is considered as a security factor for the selection of the pump.

The requirements for the selection of the hydraulic pump are:

- Flow rate: 1-90 L/min

- Fluid temperature: 20 °C / 80 °C

- Pressure inside the chamber: 1-3 bar

- Material: stainless steel

For the design we chose the vertical pump, because of the inherent limited space of the structure. The temperature and material requirements are quite restrictive and leave us few options in the market. The brand DAB is chosen, because its reliability, based on previous experience, the short delivery time and the price.

There are two suitable options for the design of the test bench available in the DAB catalogue; KV 3/12 T and KV 3/15 T. The chosen pump for this project is KV 3/12 T because it works properly for the design demands and it is the cheapest option. The Table 2 represents the pump features.

## SELECTION TABLE - KV 3

| MODEL | | P2 NOMINAL | | Q=m³/h | 0 | 1.8 | 3.6 | 5.4 | 7.2 |
|-------|-------|------|------|------|------|------|------|------|------|
| SINGLE-PHASE | THREE-PHASE | kW | HP | Q=l/min | 0 | 30 | 60 | 90 | 120 |
| KV 3/10 M | KV 3/10 T | 1.1 | 1.5 | | 88 | 77 | 63.5 | 45.7 | 21 |
| KV 3/12 M | KV 3/12 T | 1.5 | 2 | H (m) | 105.6 | 92.4 | 76.2 | 54.8 | 25.2 |
| KV 3/15 M | KV 3/15 T | 1.85 | 2.5 | | 132 | 115.5 | 95.3 | 68.6 | 31.5 |
| – | KV 3/18 T | 2.2 | 3 | | 158.4 | 138.6 | 114.3 | 82.3 | 37.8 |

*Table 2: Hydraulic pump features.*

### 4.2.3.2.    *Water circulation heater*

Circulation heaters are compact heating systems for fluids and gases, generally have multiple elements mounted on a screw plug or flange fitting and placed in an insulated vessel through which liquids passes. The medium is heated as it flows past the heating elements.

These heaters are ideal for applications such as purified and inert gases, supercritical fluids and liquids like de-ionized water for use in semiconductor and electronics industries as well as for general liquid and gas heating applications.

Electric heaters work on the principle of resistive heating in which an electrical current passing through a conductor creates heat. According to Joule's First Law, the heat produced by an electric current is equal to the product of the resistance of the conductor, the square of the current, and the time for which it flows.

Heating systems generally require precise instruments to reach and maintain appropriate temperatures and to control the large current load need to create heat from electricity. [17]

Circulation heaters are made of a steel or stainless steel vessel equipped with 3 nozzles (input-output) and with an immersion heater

(generally threaded) equipped with space to add a control device temperature. In our case, a stainless steel vessel was used in order to avoid changes in the composition of the demineralized water.

In this application, after determining the amount of heat required, 4.5 kW, and taking into account the target temperature to be reached, the needs for the circulation heater are defined and, considering also the suppliers' knowledge, the most appropriate device is the CETAL RPM-C-045 (detailed information in the Water circulation heater calculations chapter). The Figure 11 shows the heater 3D model.
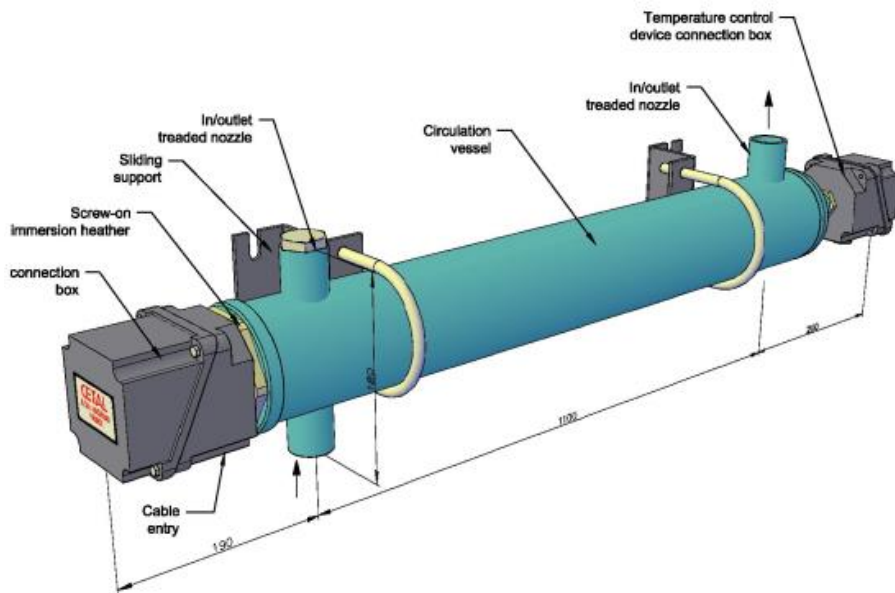


*Figure 11: Scheme of the heater.*

### 4.2.3.3. Flow security

It is a control element that is used to verify that the pump is pushing water, otherwise it sends a signal to the equipment and stops it immediately. For these flow control devices, the KOBOLD brand has been chosen for its reliability and in this case the DUK-12G8H S300L.

### 4.2.3.4. Flowmeter

It is a measuring instrument for the flow or volumetric flow of a fluid or the mass flow. These devices are usually placed in line with the pipe that carries the fluid. There are mechanical and electrical versions.

The large number of theories and models of flowmeters that exist confirm us that there is no ideal formula to measure flow. The final decision must be made based on the flow rate, viscosity, temperature, chemical composition and pressure of the fluid we wish to measure. Each application has a flowmeter that best suits your needs. In this case we have decided to use the ultrasonic flowmeter for its adaptability to the temperature, as well as because of the flow rate and viscosity of the fluid to be used.

KOBOLD DUK Series compact ultrasonic flowmeters are the devices chosen for our test bench and are used for measuring, monitoring, and batching of low viscosity (water-based) fluids. These

compact ultrasonic flowmeters with no moving parts work on the principle of run-time difference. Ultrasonic waves in the media are influenced by the rate of flow. It features two sensors mounted opposite one another in the pipeline, which function simultaneously as transmitter and receiver of ultrasonic signals. If no flow is present, the run-times of both signals are identical. If the media is flowing, the run-time of the signal against the flow will be longer than the signal with the flow. This run-time difference, determined by the KOBOLD DUK Series compact ultrasonic flowmeter's microprocessor, is proportional to flow rate. [18]

For the design two ultrasonic flowmeters are needed because of the fact that we want to monitor, mainly, the input flow to the chamber, and then to control the rest of the flow.

### 4.2.3.5.    *Flow regulator valve*

They are devices that regulate to a fixed flow, independent of the fluctuation of the working pressures and start flow rates. They control the operation of pumps or regulate the performance of all systems and installations. With them one can control the pressure and speed in each branch of the installation.

For the test bench three flow regulators have been installed, one electronic that will be located at the end of the circuit and two manuals,

one of them will remain fixed once the system has been set up and another will control the flow of fluid that enters the deionizer to maintain the same level of conductivity in the water. The computer program will control the electronic valve to decide the speed of the fluid impacting against the targets of the experiment.

### 4.2.3.6.    Sensors

As the idea of the design is that it should modify variables such as flow, temperature, conductivity, oxygen content and pressure (the flow is already controlled by the flowmeters), different sensors are required in order to obtain good readings and logging values.

For the temperature, two sensors are chosen to be placed; one before the input and the other after the output of the heater. The sensor before the input of the heater will be the M12TXC-PT100-3MM-24MM-G1/8 from OMEGA brand, because in this point it is not needed a lot of accuracy and this sensor is just a cheap transmitter that it is possible to log the values by the computer. For the output position more accuracy and visual logging are needed, this point will be the primary information about the temperature, the KOBOLD TDA15H2R4 0 L3M has been chosen.

After a deep market research, considering all the high requirements of the test bench, the conductivity and oxygen sensors have been

chosen in one external transmitter, because it was the only option in the market that fulfilled all the requirements. These are Dissolved Oxygen Sensor HX438-01, Conductivity Sensor 400VP-11 and Intelligent Dual Input Analyser 1056-03-20-35-HT from EMERSON brand.

The pressure sensor is a transducer that converts pressure into an analogue electrical signal. Although there are various types of pressure transducers, one of the most common is the strain gauge based transducer.

The conversion of pressure into an electrical signal is achieved by the physical deformation of strain gauges which are bonded into the diaphragm of the pressure transducer and wired into a Wheatstone bridge configuration. Pressure applied to the pressure transducer produces a deflection of the diaphragm which introduces strain to the gauges. The strain will produce an electrical resistance change proportional to the pressure. The PXM309-007GI from OMEGA has been chosen. Also, there are two manometers installed on the test bench to give an easier visual control of the pressure.

### 4.2.3.7.   Filter

Their function is to avoid particles in the circuits, which could obstruct the circuit or damage the hydraulic pump. In this case, two filters are used, one at the end of the circuit to collect the particles that can arrive from the erosion of the materials to be tested and another to control the fluid after the outlet in the deionizer.

The one that is installed at the end of the circuit consists of a stainless steel container in which there is a cartridge of cellulose fiber that allows a filtration of 50 μm. The following is a special Y-filter for demineralised water consisting of an inner 0.5 mm mesh.

### 4.2.3.8.   Piping and fitting

The design has been made based on the necessary requirements in the chamber, the minimum pipe section with which the system can operate was calculated and each pipe branch was studied separately in order to obtain the optimal design. The size of the fittings is obtained by the pipe size.

### *4.2.4. Chamber*

The chamber is a stainless steel pressured vessel where the test with the materials will be performed. It will be placed on the top of the aluminium structure, between the two holes because they are the access of the pipes.

Two fluid inlets will perform the jets which will allow the fluid impact on the materials wall.

In the upper part two covers have been designed, one of which will always remain closed by its fixed connection with the outlet pipe and the other cover will be in charge of facilitating access to the parts to be tested.

## 4.3. Components calculations

In this chapter, the design decisions taken and calculations performed in the design process are going to be described. In the Figure 12 is possible to see all the components of the test bench.
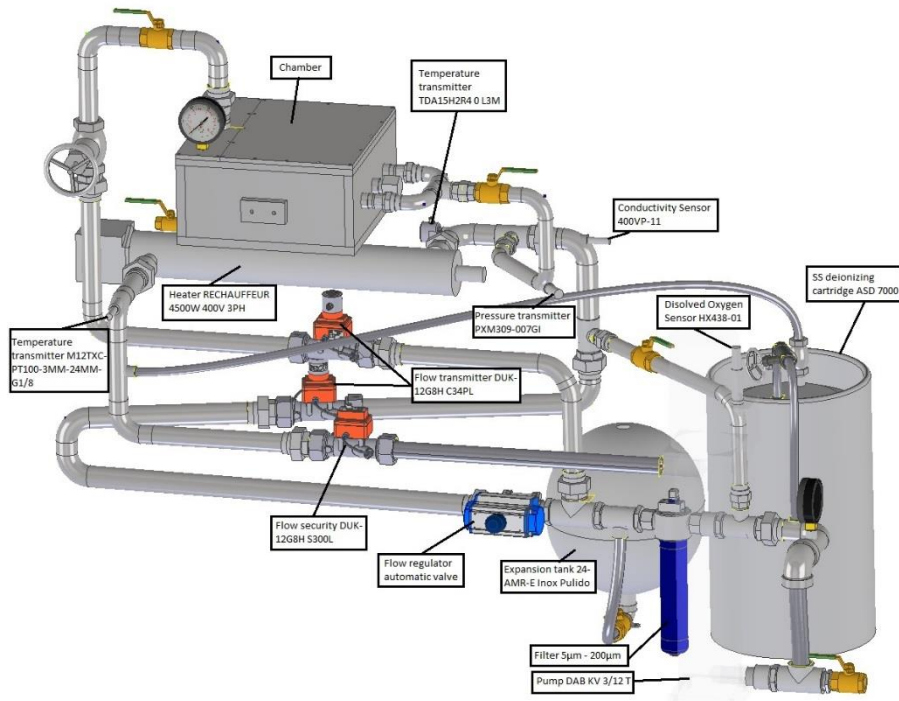
*Figure 12: Test bench components.*

### 4.3.1. Calculation of the hydraulic pump

The pump is responsible for providing the necessary pressure for the circulation of the demineralized water in the closed circuit of the bench test. The pressure to be supplied is at least 4 bar as mentioned in the Limitations of the System The flow to be driven is the minimum required by the system requirements plus 20 % for oversize, 110 L/min.

With these data and taking into account that the electrical connections available are 400 V and 50 Hz, considering the DAB

catalogue, the appropriate pump is selected. In this case, these two models are considered:
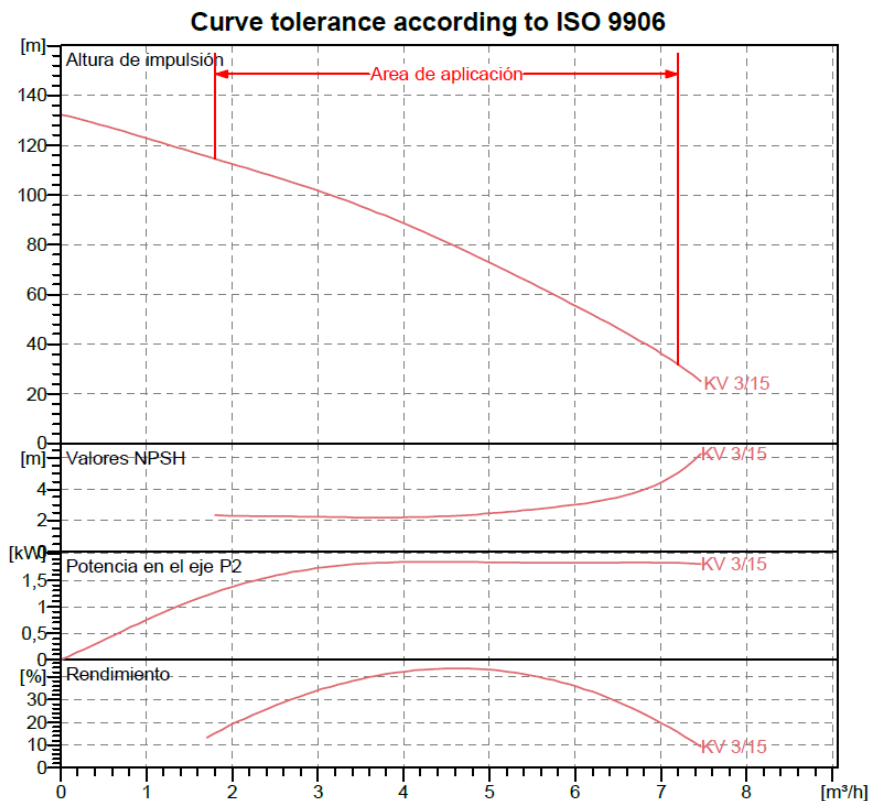


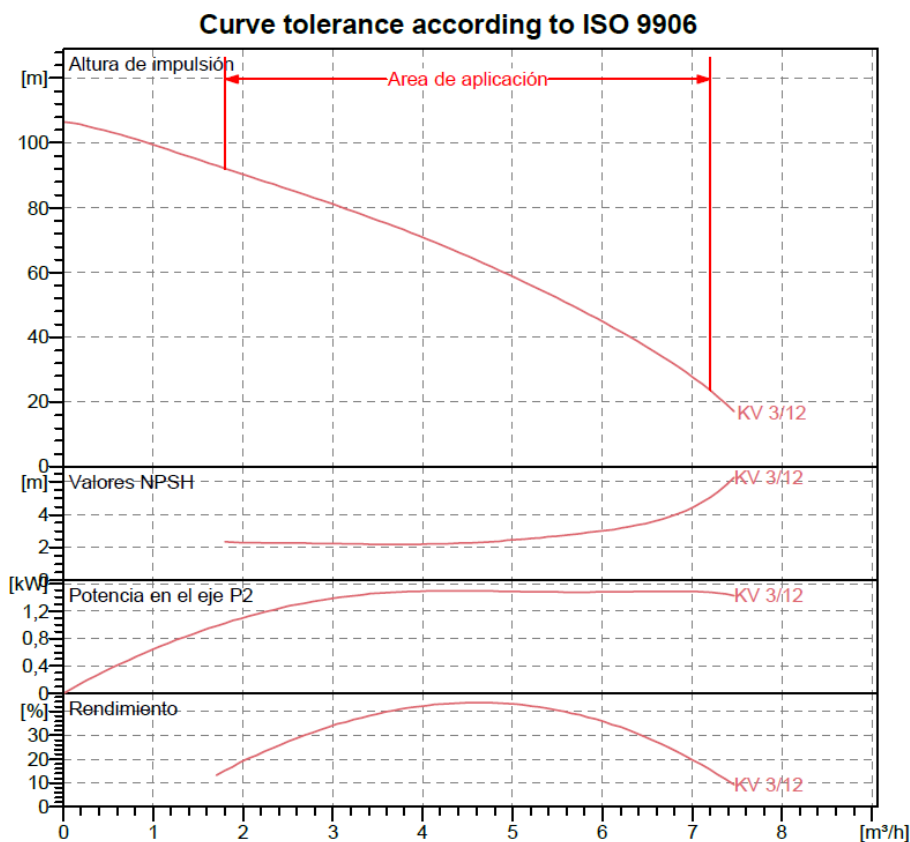*Figure 13: KV 3/15 T pump.*

*Figure 14: KV 3/12 T pump.*

The pumps meeting the requirements are the Vertical multistage centrifugal pump KV 3/15 T which for a flow rate of 110 L/min provides a height of 55 m which is equivalent to 5.5 bar and the Vertical multistage centrifugal pump KV 3/12 T A flow rate of 110 L/min provides a height of 45 m which equals 4.5 bar.

The Figures 13 and 14 show the performance curves of the pumps. It can be seen that the operating point of the pump is practically in the central part of the curve.

### 4.3.2.  Water circulation heater calculations

The first step in selecting an electric heater is determining the amount of heat required by the application. The total heat power in kW required to satisfy the system needs is calculated by the following formula based on the supplier instructions:

$$P = \frac{Q}{t} = \frac{m \times Cp \times \Delta T}{3600 \times t} \times 1.2 \ (Eq.1)$$

Where:

| | |
|---|---|
| *P: Power (kW).* | |
| *m: Mass heating (kg).* | *V: heating volume (L).* |
| | *ρ: density (kg/dm³).* |
| *Cp: Specific heat (kJ/kg °C).* | |
| *ΔT: Temperature difference (°C).* | |
| *Q: Heat quantity.* | |
| *t: Time (h).* | |
| *1.2: Security coefficient.* | |

The result of this formula is 4.3 kW, so the chosen power for the commercial heater will be the immediately above, that is 4.5 kW.

Other requirements considered for the selection of proper heater device are the material – which has to be stainless steel to avoid any change on the conductivity of the water – the dimensions, and the connexions. After the supplier's advices, the chosen heater has been Heater 4500 W 400 V 3 PH. The Figure 15 shows the heater placed on the structure.



*Figure 15: Heater 4500W 400V 3PH*

### 4.3.3. Pipe calculations

Since the maximum speed needed in the jets for the crash with the target wall is 5 m/s and the diameter of the jets is 10 mm, we obtain the necessary flow to reach that speed by the formula:

$$Q = v \times S \text{ (Eq.2)}$$

Where:

| |
|---|
| Q: Flow |
| V: Speed |
| S: Section |

The result shows that a flow of 23.5 L/min on each jet is needed. The pipe connected to the jets is divided in two symmetrical parts, so that the same flow rate of fluid at each moment reaches the two impellers. Therefore, the piping before the bifurcation should have a flow rate of 47 L/min ≈ 50 L/min.

Taking this information into account and that the flow rate to be obtained from the hydraulic pump is 90 L/min, it is possible to obtain the minimum section of the pipes.

In order to carry out the design of the pipes that make up the different process lines, these will be divided into sections, each of which will be formed by the portion of the line between two consecutive equipment. In this way the different aspects to calculate

(optimum diameter of the conduction, pressure drop, etc.) will be evaluated independently for each one of these sections.

A very important aspect to take into account for the design of the piping system is the speed that the fluid reaches inside the pipes. This velocity, in the case of isothermal flow of incompressible fluids, is determined by the flow rate and the diameter of the internal section of the line, and for each fluid it has a maximum value that must not be exceeded, otherwise the product would be deteriorated due to improper mechanical treatment. The approximate values used in practice depend on the type of fluid being treated, but the most common ones are listed in Table 3.

| Fluid | Type of Fluid | Speed m/s |
|---|---|---|
| low viscosity liquids | Gravity flow | 0.15 – 0.30 |
| | Pump inlet | 0.3 – 0.9 |
| | Pump outlet | 1.2 – 3 |
| | Driving Line | 1.2 – 2.4 |
| viscosity liquids | Pump inlet | 0.06 – 0. 15 |
| | Pump outlet | 0.15 – 0.6 |
| Stream water | | 9 – 15 |
| Air or gas | | 9 – 30 |

*Table 3: Recommended rates for piping fluids.*

Thus, for the flow rate of 90 L/min to be pumped, by imposing the maximum speed thereof, the minimum diameter of the pipe is determined immediately, which in this case corresponds to a nominal diameter of DN25 mm or 1 in:

$$S = \frac{v}{Q} = \pi \times \left(\frac{D}{2}\right)^2 \text{ (Eq.3)}$$

Where:

| |
| --- |
| *Q: Flow* |
| **v**: *Speed* |
| *S: Section* |
| *D: Diameter* |

In any case, the normalized diameter should be chosen immediately above the minimum value. This value is what is known as the optimum diameter of the pipe, because it represents the lowest possible cost, meeting the requirements as to the maximum speed of circulation of the fluid through it.

Due to the design requirements of some devices that have been previously selected, the pipes of DN40 mm or 1-1/2 in must be chosen in some sections. The Table 4 shows the connections of each element of the installation.

| Component | Connexion |
|---|---|
| *Pressure indicator* | *G 1/2 Male* |
| *Pressure transmitter PXM309-007GI* | *G 1/4 Male* |
| *Temperature transmitter M12TXC-PT100-3MM-24MM-G1/8* | *G1/8 Male* |
| *Temperature transmitterM12TXSS-PT100-24MM-G1/8* | *G1/8 Male* |
| *Temperature transmitter TDA15H2R4 0 L3M* | *G 1/2 Male* |
| *Flow transmitter DUK-12G8H C34PL* | *G 1" 1/2 Female* |
| *Flow security DUK-12G8H S300L* | *G 1" 1/2 Female* |
| *Oxygen transmitter* | *G1/8 Male* |
| *Conductivity* | *3/4" NPT Male* |
| *Pump* | *G 1" ¼ Female* |
| *Filters 5 μm – 200 μm* | *1" NPT Female* |
| *Heater* | *G 1" Female* |
| *Expansion tank* | *G 1" Male* |
| *Water deionizer* | *G 1/2 Male* |
| *Flow regulator automatic valve* | *G 1" 1/2 Female* |

*Table 4: Connexion of the components.*

Due to space limitations, the entire circuit must be inserted into the aluminium structure and this means that there are some changes of direction with their consequent losses being will be studied later.

At this point, each section of pipeline of the installation will be studied. The Figure 16 shows the final layout of the bench test.
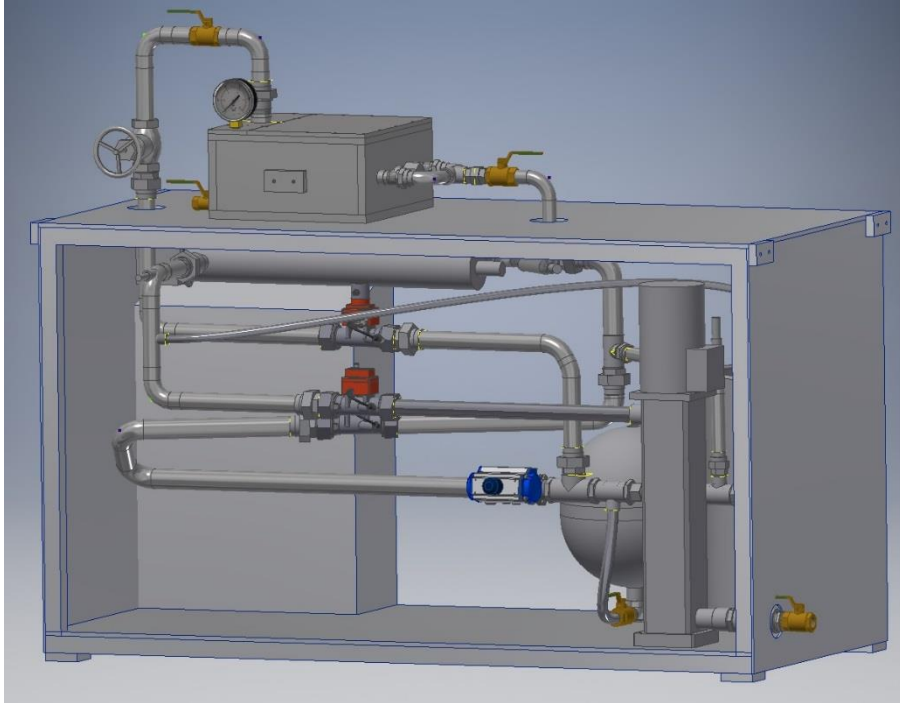


*Figure 16: Test Bench design.*

The first section, showed in the Figure 17, consists of the pump output to the heater inlet. The sections will always be designed as straight as possible. In this section, the flow security device DUK-12G8H S300L is installed with which the flow passage is controlled for safety, thus avoiding a possible failure of the pump when it is in operation and there is no flow.

Due to the design restrictions that the safety device gives us, we will have to use a pipe with a diameter of 1-1/2 in and at least 500 mm of pipe length before and after this for its correct operation. Then, we have that the output of the pipe is 1-1/4 in, we will use a reduction fitting from 1-1/2 in to 1-1/4 in. Afterwards a flexible stainless steel pipe will be used to absorb the possible vibrations of the pump, then the safety flowmeter is installed and finally a stainless steel pipe fixed to the heater. For the connection to the heater, a reduction ratio of 1-1/2 in to 1 in will be used. The temperature transmitter M12TXC-PT100-3MM-24MM-G1/8 is also installed in this section.
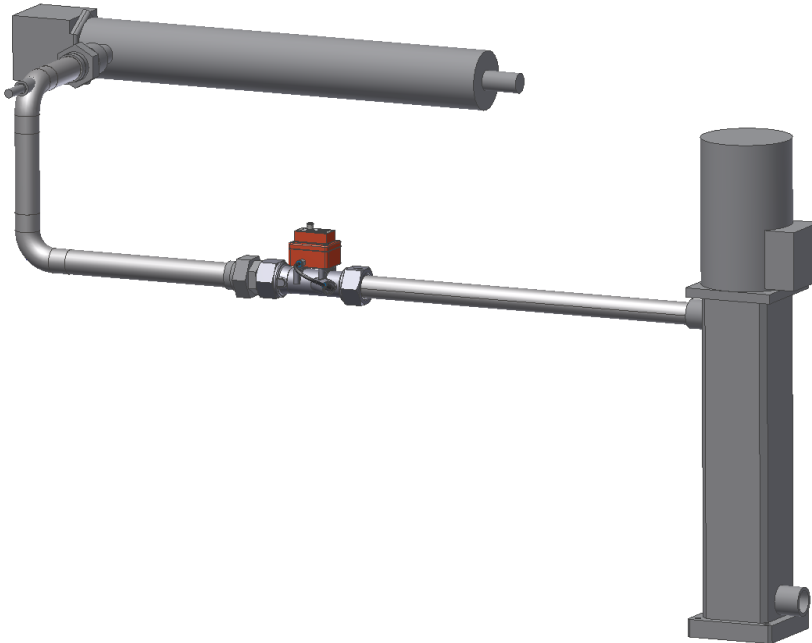


*Figure 17: First section.*

The second section, showed in the Figure 18, of piping would be provided from the heater outlet to the pump inlet. In this section one of the flow transmitter DUK-12G8H C34PL is to be installed, so that the same restrictions of section 1 have been re-established, the pipe has to be 1-1/2 in and 500 mm before and after the flowmeter.

At the outlet of the heater, a 1-1/2 in to 1 in reduction fitting will be used to connect the pipe to the device, then the temperature transmitter TDA15H2R4 0 L3M will be installed and then a T-connection will be added, with an output of 1 in which will be addressed in section 3. Continuing with section 2, the conductivity sensor will be installed in the next corner and then a T-connection will be added, with an output of 1 in, to be explained in the section 5.

Now the 500 mm input to the flowmeter is considered, then the same at the output and the direction is taken to the pump with a slight inclination. In the last part of this section, the following devices will be installed in this order: flow regulator automatic valve, 1-1/2 in T, 1-1/2 in to 1 in T, filter, 1-1/2 in to 1 in T and manometer. The connection with the pump will be done by a flexible pipe to avoid the pump vibrations.
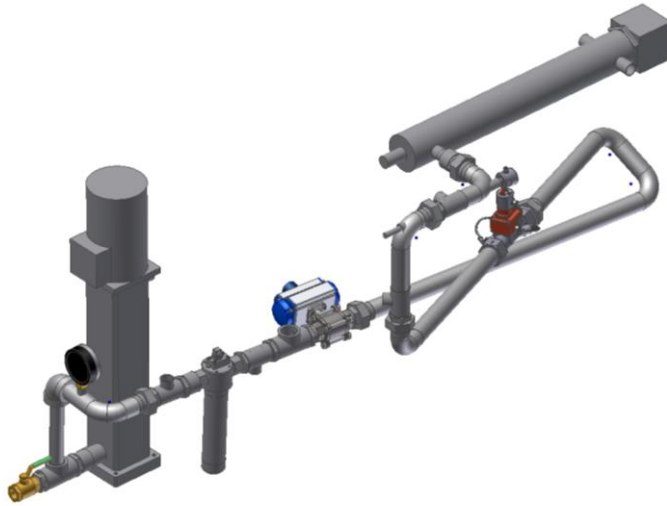
*Figure 18: Second section.*

The third section, showed in the Figure 19, starts from the first T after the heater to the entrance to the chamber of the test bench. In this case a 1-n pipeline will be used since we have no restrictions due to the equipment installed and as previously estimated, the flow necessary to reach 5 m/s in the jets will be 50 L/min, so it is on the side of security. The pressure transmitter PXM309-007GI is installed in this line to log the pressure at the chamber inlet. A 1-in valve is also installed to isolate the chamber once the test is complete.
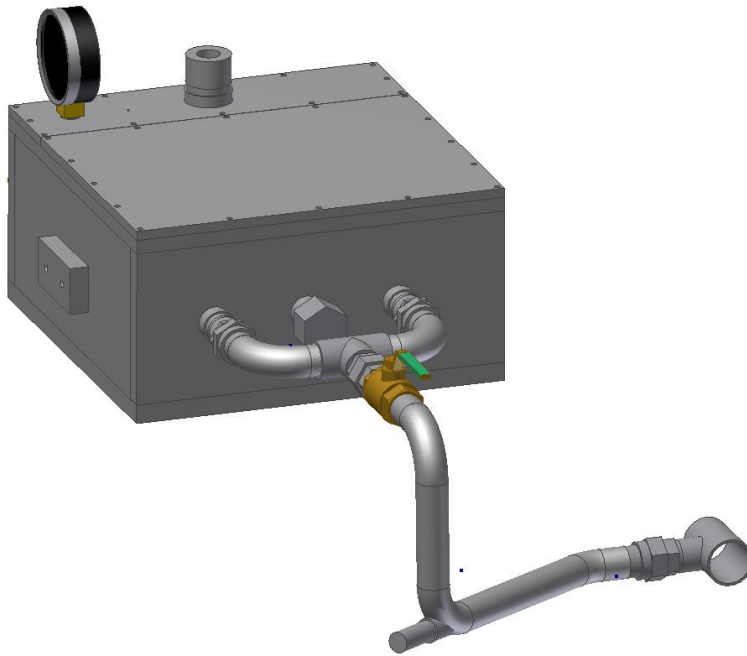
*Figure 19: Third section.*

Section four, showed in the Figure 20, consists of the pipe connecting the chamber outlet to the third T-joint of section 2. In this section, a valve to isolate the chamber once the test is complete is installed, a manually flow regulator valve is set up at the beginning of the process, the electro valve controls the flow. The second flow transmitter DUK-12G8H C34PL is installed to control the flow through the chamber. Following the requirements of the flowmeter design, it has to be considered a pipe of 1-1/2 in and 500 mm before and after the flowmeter.
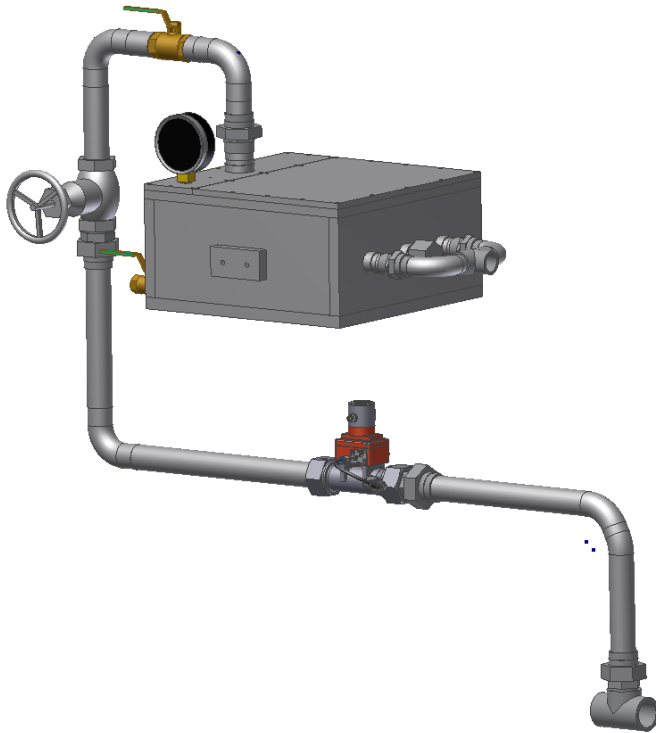
*Figure 20: Forth section.*

The last section consists of a 1-in pipe that connects the second T-connection of section 2 with the fourth of it. This bypass has been made to avoid, as far as possible, that the oxygen sensor supports too much pressure since its limit is 4 bar (Figure 21).
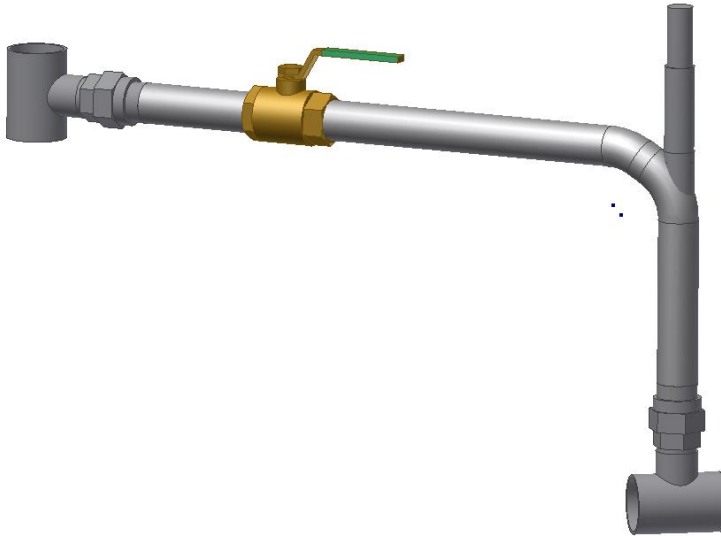
*Figure 21: Fifth section.*

### 4.3.3.1. *Stainless steel pipe thickness*

In this chapter, the calculations of the pipe thickness are demonstrated base on the internal pressure using the ASME Code B31.3 norms.

The material selected for the pipes is determined by the experiment because the fluid used is demineralized water and stainless steel is not going to modify the water characteristics.

The basic formula for determining pipe wall thickness is the general hoop stress formula for thin-wall cylinders, which is stated as:

$$t = \frac{Pd_o}{2(SE+PY)} \quad (Eq.4)$$

Where:

| | |
|---|---|
| t: pipe wall thickness, in. | |
| P: internal pressure of the pipe, psi. | |
| $d_O$: outside diameter of pipe, in. | |
| S: allowable stress for pipe, psi. | |
| E: longitudinal weld-joint factor. | |
| Y: derating factor. | |

Once the thickness results are obtained with Equation 4, one may determine the minimum thickness considering the corrosion and erosion allowance. This is an extra thickness called "corrosion allowance" and it is added to the wall thickness to compensate the metal expected to be lost over the life of the equipment. In this case, since stainless steel and demineralized water are used, the corrosion is really low.

Comparing the minimum thickness obtained by the design with the commercial thickness of the pipes from the suppliers, the safety factor of 6.46 is safe enough. The calculations are performed in the Table 5.

### Straight Pipe Section

| | Variable | Units | Value | Notes | Source |
|---|---|---|---|---|---|
| Design Pressure | $P$ | bar | 4 | Maximum pressure in the piping system | |
| | | Psi | 58 | | |
| Design Temperature | $T$ | C | 80 | Maximum fluid temperature | |
| | | F | 176 | | |
| Allowable Stress at Design Temperature | $S$ | Psi | 20000 | | Appendix A – Table A-1 – Code B31.3 |
| | | Mpa | 137.9 | | |
| Pipe Outside Diameter | $d_o$ | mm | 48.3 | | Supplier info |
| | | inch | 1.9 | | |
| Commercial Pipe Thickness | $t_c$ | mm | 3.68 | | Supplier info |
| | | inch | 0.145 | | |
| Longitudinal-joint Quality Factor | $E$ | | 1 | | Appendix A – Table A-1B – Code B31.3 |
| Wall Thickness Correction Factor | $Y$ | | 0.4 | | Table 304.1.1 – Code B31.3 |
| Corrosion and Erosion Allowance | $CA$ | mm | 0.5 | | |
| | | inch | 0.019 | | |
| Pressure Design Thickness | $t$ | mm | 0.069 | $t = \dfrac{Pd_o}{2(SE + PY)}$ | Equ. (3a) – Code B31.3 |
| | | inch | 0.003 | | |
| Minimum Thickness | $t_m$ | mm | 0.570 | $t_m = t + CA$ | |
| | | inch | 0.022 | | |
| Design Safety Factor | $Sf$ | | 6.46 | $Sf = \dfrac{t_c}{t_m}$ | |

*Table 5: Calculation Note for pipe thickness.*

### 4.3.4. Chamber calculations

Due to the requirements imposed from the beginning, the material of the chamber must be of stainless steel to avoid changes in the conductivity of the demineralized water and because it has a highly corrosion resistant grade.

On the other hand, it has as limit pressure 3 bar, although it is designed for a higher pressure for possible uses in the future. In this case, 10bar is used as the calculation basis.

We have opted for a rectangular shape because of its ease of insertion of the materials to be treated and as the dimensions are given as a requirement as well. Calculations are performed in order to validate the pressure design. ANSYS software is used in order to obtain the pressure results with a static structural analysis.

The original test bench target box design, is reduced to a simpler and symmetric model for the simulations, as can be seen in the Figure 22.
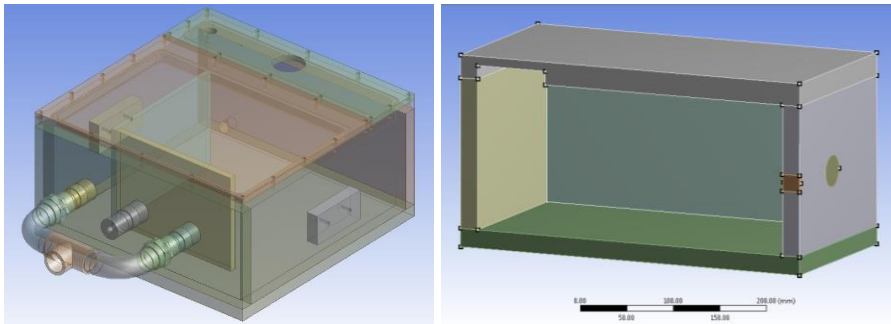
*Figure 22: Test bench target box original (left) and reduced model (right).*

The analysis process has been done considering an equal pressure inside the chamber of 10 bar.

The fluid body is meshed with tetrahedral elements, because this geometry provides better mesh quality, and several inflation layers in the interface with the solid bodies for an accurate near-wall treatment.

The pressure calculations, showed in the Figure 23, performed allowed to define the deformation of the chamber walls showing the maximum in the section change on the tapes and the result is 0.2 mm. As a conclusion, this design is able to carry out the test.
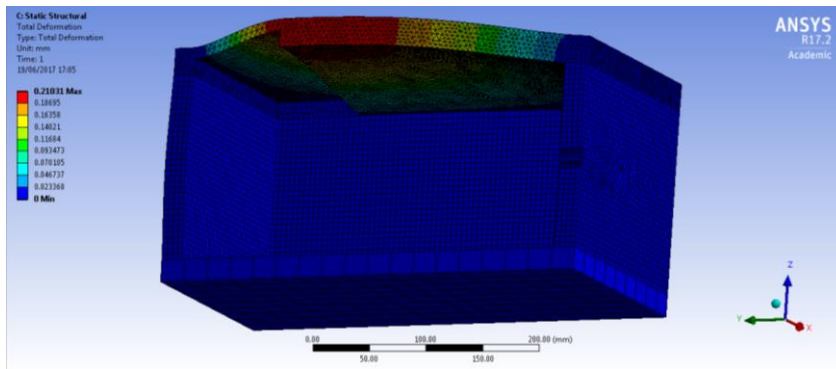
*Figure 23: Pressure analysis results.*

On the other hand, due to the design of the pipes, the two fluid inlets are determined by the dimensions of the pipes, so that two male connections of 1 in each and the diameter of the 10 mm jets must be machined. The fluid outlet from the chamber is also determined by the pipe and will be 1-1/2 in.

In the upper part two covers have been designed, one of which always remains closed by its fixed connection with the outlet pipe and the other cover is in charge of facilitating the access of the parts to be tested.

### 4.3.4.1.    Water speed inside the chamber

This paragraph describes the calculations of the pipe diameter and the flow required to achieve the speed inside the chamber based on the CFD calculations.

*CFD simulation setup*

The original test bench target box design, is reduced to a simpler model for the CFD simulations, as can be seen in Figure 24.
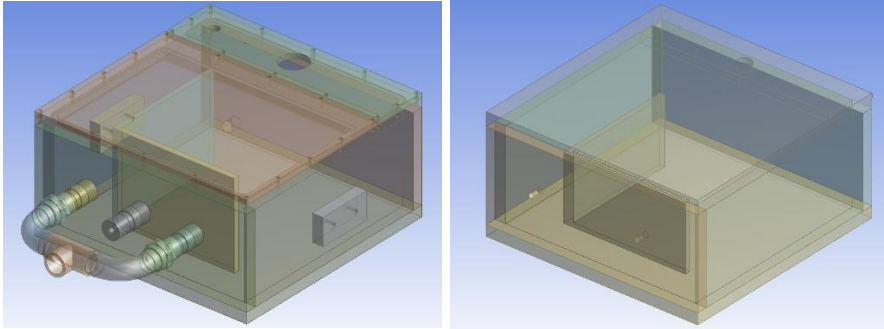


*Figure 24: Test bench target box original (left) and reduced model (right).*

The system has two inlets in the side of the box, allowing the water to impact the target in two different ways: one water jet impacts the target wall directly, and the other one hits the corner of the target. The box is entirely filled with water, and an outlet is placed on the top part of the box.

The fluid body is meshed with tetrahedral elements and several inflation layers in the interface with the solid bodies for an accurate near-wall treatment.

The pressure of the water is set to 3 bar, which is the pressure planned to be used in the test bench operation. The fluid turbulence model used is Shear Stress Transport (SST), which is a robust model for the near-wall region and the far field.

In a first step, the target wall is placed 55 mm from the water flow inlet and the water volumetric flow is set to 80 L/min. Therefore, the mass flow specified in each one of the two inlets is 0.6667 kg/s.

*First iteration results*

Taking into account the boundary conditions presented, CFD calculations are performed with ANSYS CFX®. The Picture 25 shows the velocity distribution of the water in a XY plane coincident with the water inlets, the maximum speed reached by the water in the circuit being 8.8 m/s.
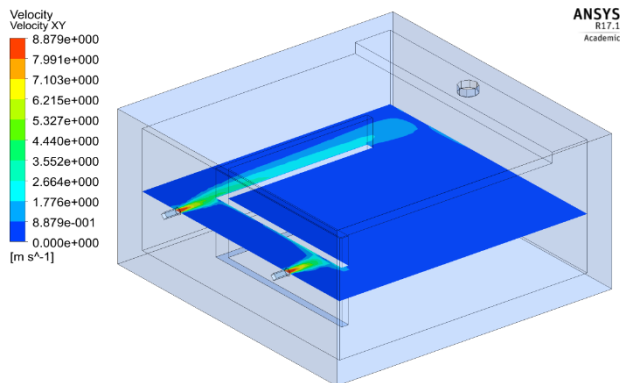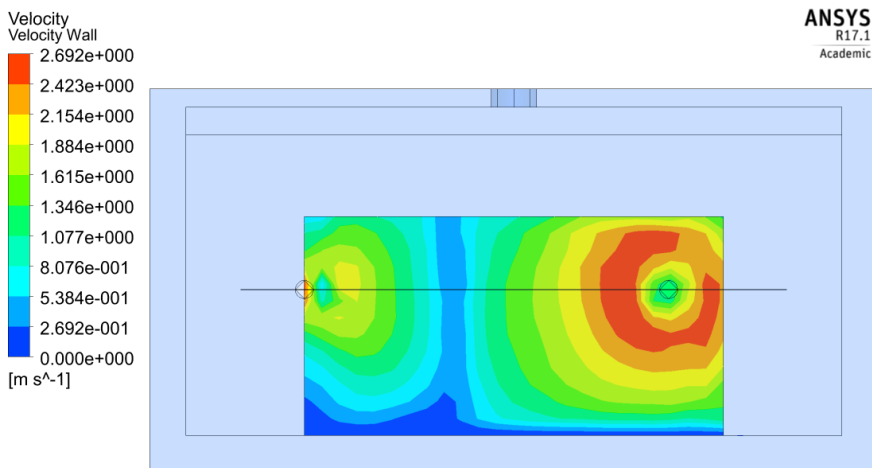


*Figure 25: XY-plane velocity distribution, target placed 55 mm far from the box wall 80 L/min water flow.*

This result could be also approximated analytically taking into account the area of the inlets, $7.85 \cdot 10^{-5}$ m$^2$, and the volumetric flow, $6.66 \cdot 10^{-4}$ m$^3$/s, then:

$$v = \dot{V}/_A = 8.5 \ m/s. \ (Eq.5)$$

As can be seen in the Picture 26, where the velocity distribution in the target wall is shown, the maximum speed reached is 2.7 m/s, which is lower than the desired maximum value of 5 m/s.
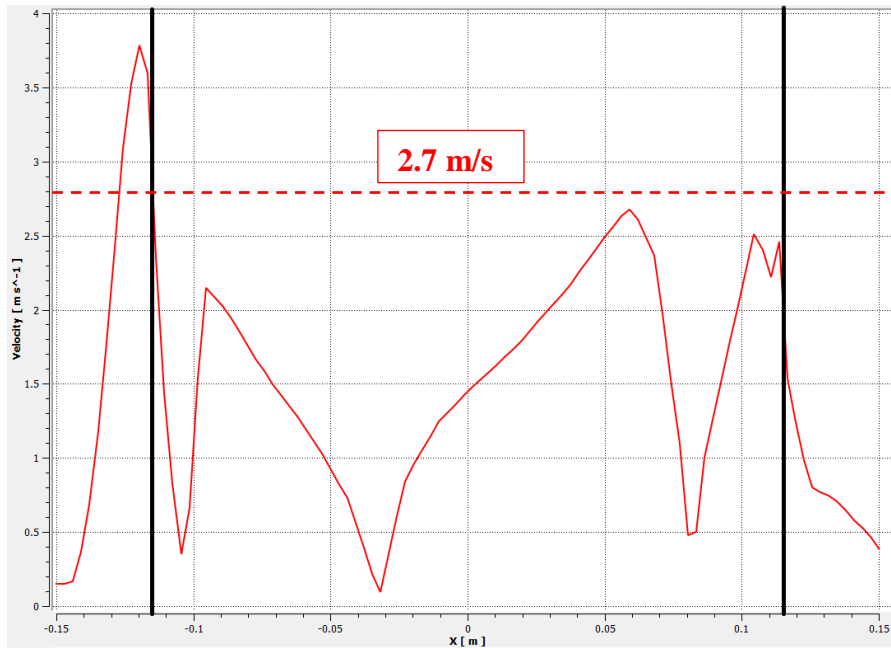


*Figure 26: Velocity distribution in the target wall, first iteration configuration.*

The velocity distribution along the wall can be also appreciated in the following graph, where the water speed is displayed along a

horizontal line located in the target wall plane at the water inlets height (shown in figure 27). The target wall is delimited by two lines, and it can be seen once again that the maximum velocity reached by the water impacting the wall is around 2.7 m/s.



*Figure 27: Velocity distribution along a horizontal line placed in the target wall. Maximum speed = 2.7 m/s.*

These calculations are done considering a water flow of 80 L/min, which is already close to the maximum values that will be used in operation. Therefore, the next step for the analysis is to estimate the necessary distance between the target wall and the box in order to obtain the required 5 m/s velocity.

It is possible to obtain the velocity evolution along a horizontal line starting in each one of the water inlets and finishing in the target wall, one right in the corner and the other in the wall itself, as shown in figure 28.
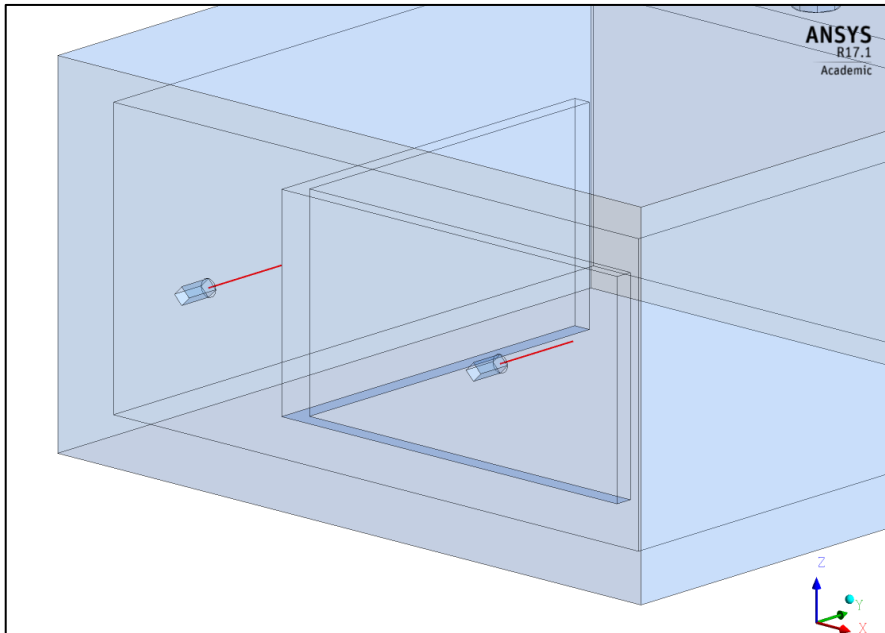


*Figure 28: Horizontal lines along water trajectory used to obtain the velocity evolution.*

The Figures 29 and 30 represent the velocity evolution of the water flow along the two lines. The velocity of the water at Y=-0.15 m is approximately 5 m/s in both cases, which represents a distance of 20 mm between the target and the box wall.

Therefore, the next step for the analysis is to repeat the calculations with the target placed at a distance of 20 mm from the inlets, so that the water impacts the target wall with the required speed of 5 m/s.
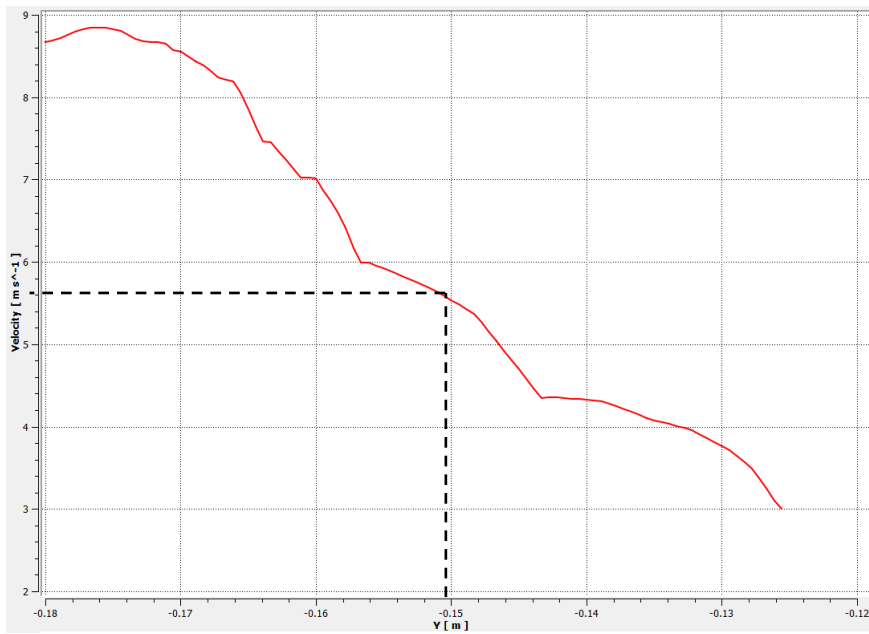


*Figure 29: Water flow velocity evolution along Y axis, from the inlet to the target corner.*
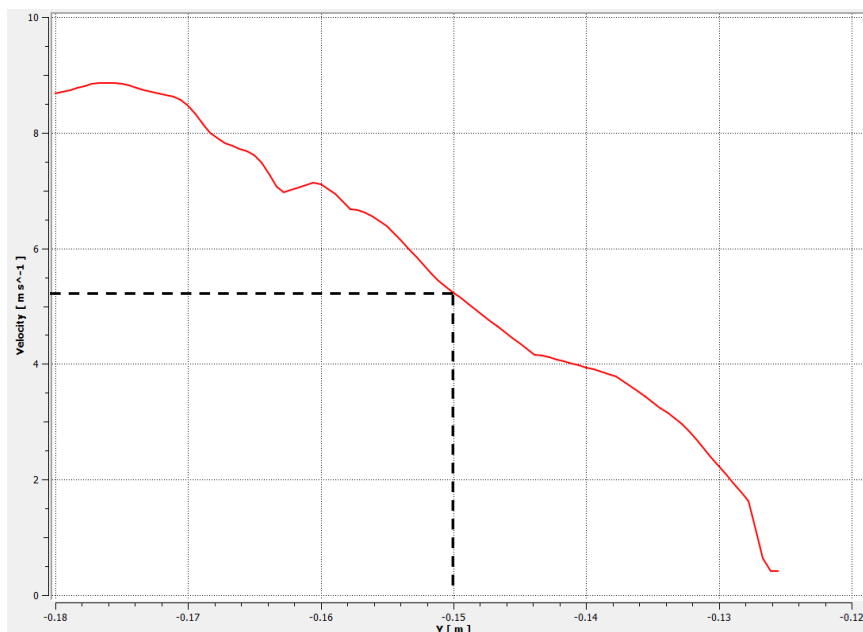
*Figure 30: Water flow velocity evolution along Y axis, from the inlet to the target centre.*

### *Final configuration results*

New CFD calculations are performed with this configuration, with a distance between the target wall and the box inlets of 20 mm.

The water speed distribution in a XY plane coincident with the water inlets is shown in figure 31. The maximum speed reached by the water in the circuit is around 10 m/s in this case. The reason is that even if the inlet area and the volumetric flow are the same, the proximity of the target induces higher velocities of the water jet coming from the inlets.
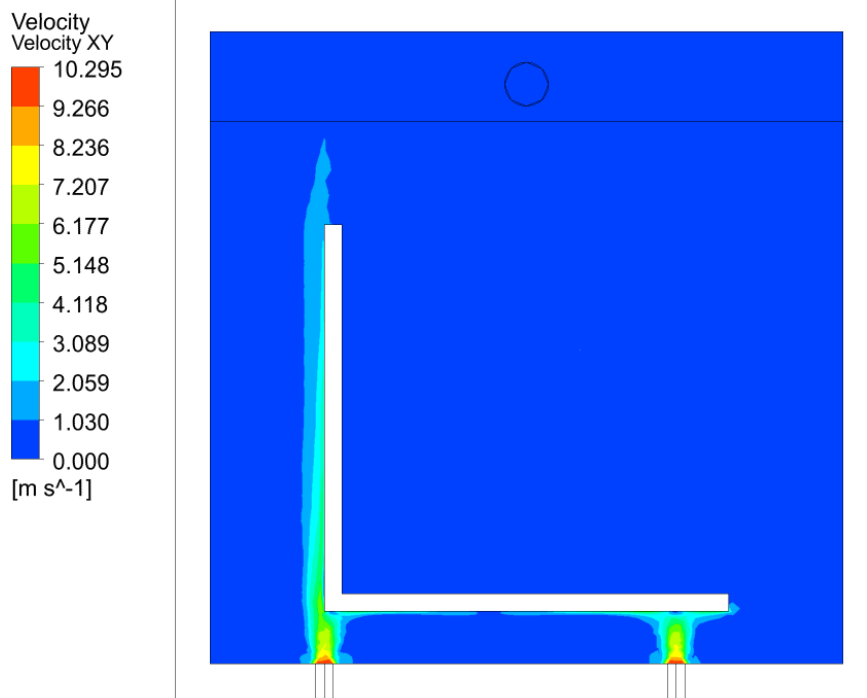
*Figure 31: XY-plane velocity distribution, target placed 20 mm far from the box wall. 80 L/min water flow.*

With this configuration, the maximum velocity reached in the target wall is around 5 m/s as desired, which is shown in the Picture 32 and 33, whereas previously the water velocity distribution along the target wall is displayed.
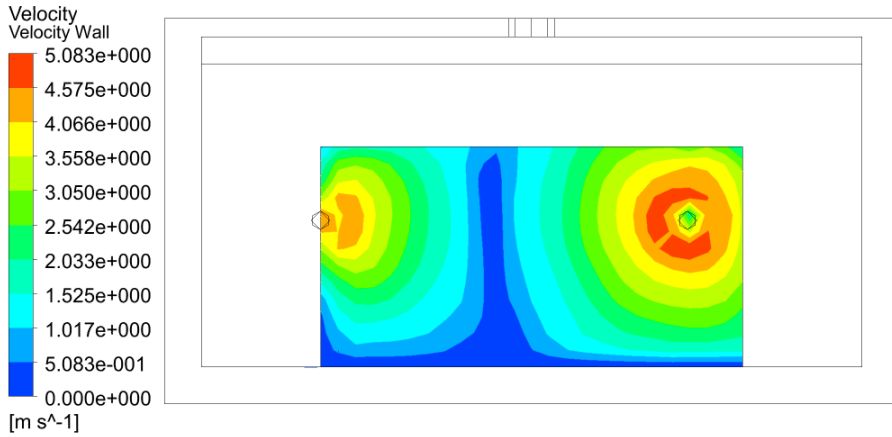
*Figure 32: Velocity distribution in the target wall, final configuration.*
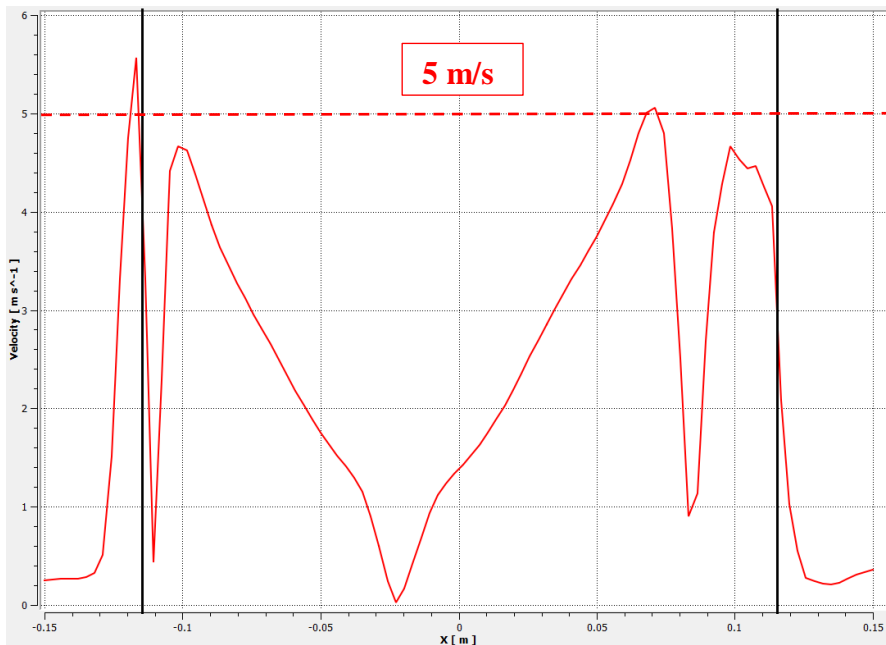


*Figure 33: Velocity distribution along a horizontal line placed in the target wall. 80 L/min. Maximum speed ~ 5 m/s.*

As a first conclusion of this calculations, with a water flow of 80 L/min and a distance between the target and the box wall of 20 mm, the required 5 m/s velocity of the water impacting the target wall can be reached. The velocity of the water impacting the corner of the target is slightly lower than 5 m/s, however a higher value could be reached by increasing the water flow.

These calculations are repeated with a water flow of 50 L/min and 25 L/min to have an idea about the velocities that would be reached in the target wall for lower water flows.

At 50 L/min the maximum velocities are around 3 m/s, and at 25 L/min they reach 1.5 m/s, which is the minimum water speed considered for the operation of the test bench.
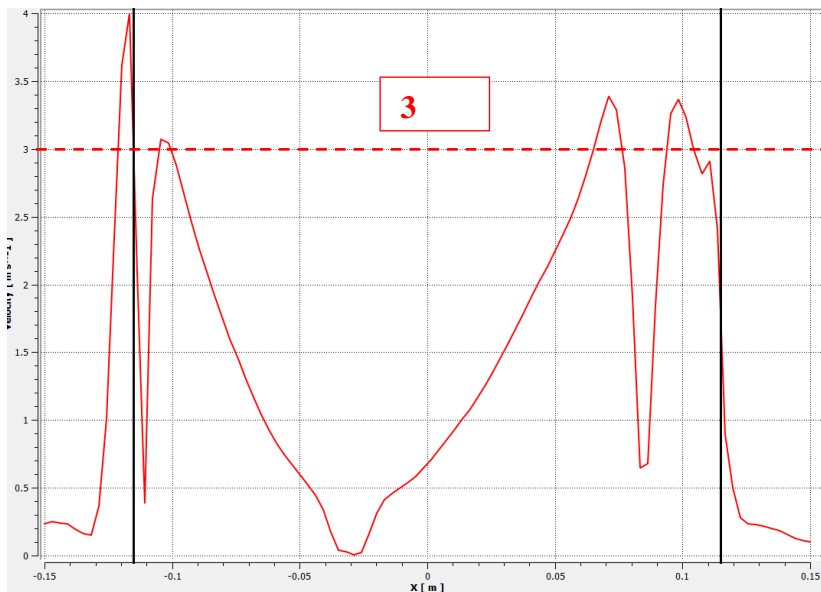


*Figure 34: Velocity distribution along a horizontal line placed in the target wall. 50 L/min. Maximum speed ~ 3 m/s.*

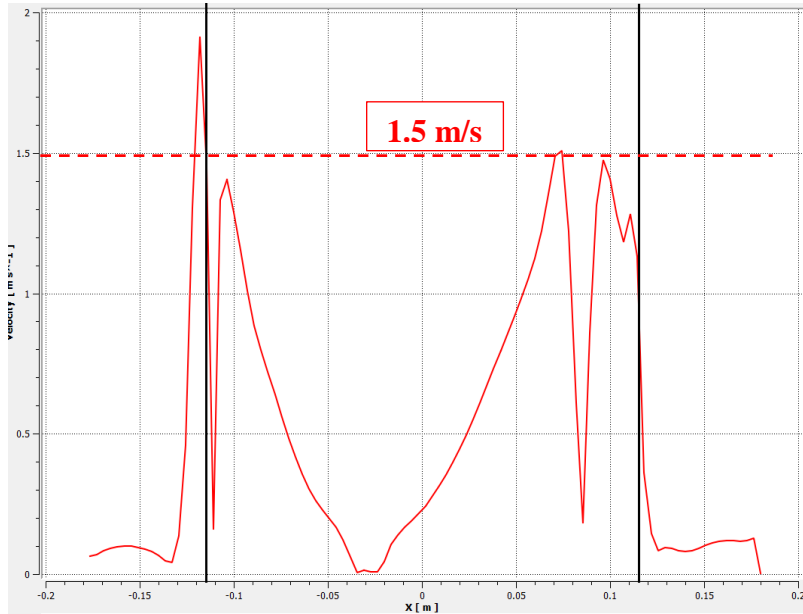*Figure 35: Velocity distribution along a horizontal line placed in the target wall. 25 L/min. Maximum speed ~ 1.5 m/s.*

*Conclusions*

The CFD calculations performed allowed to define the necessary target distance to the target box wall (20 mm) in order to obtain the required water velocities impacting the target. These velocities can be obtained by variating the water flow from 25 L/min to 80 L/min.

## 4.4. System requirements.

The system formed by the hydraulic bench test, object of this project, presents the following conditions required for its correct operation:

### 4.4.1. Power supply of the system.

For the design of the power supply of the test bench it must be taken into account that the power absorbed by the main devices is showed in the Table 6.

| | |
|---|---|
| *Hydraulic pump* | *1.5 kW* |
| *Heater* | *4.5 kW* |
| *Total Power* | *6 kW* |

*Table 6: Power supply components.*

There are other devices that work with electric current although its consumption is negligible in this case. Following the instructions of ICE Standard this consumption is covered.

The system will be connected to a distribution board, which according to the IEC 62305 instructions, must have a general omnipolar safety switch, as well as short-circuit protection, overload

and indirect contacts, which establish the said instructions according to the type of installation.

The system will be connected via the general omnipolar cut-off switch to a three-phase alternating current system of 380 V between phases. This switch must isolate the entire system from the three-phase electrical network.

## 4.5. Risk assessment

The utilization of the Test bench is not free of safety risks and the operator should be aware of them. CERN does not take responsibility for the wrong usage of the test bench or for non-specified use of test bench as presented in the instructions manual.

There are two possible main risks to the integrity of the operator:

- Possibility of burning due to leaks between the connection fittings and the chamber (if it is removed) or if the chamber tape is not properly fitted as presented in the Instruction Manual. Periodical replacement of the O-Rings will be done by CERN to minimize the risk of leaks.

- Danger of electric shock if a major leak appears and the electric sector of the test Bench is flooded.

Therefore, some compensatory measurements were adopted in order to minimize these risks and alert the operator for the zones of potential risk:

- Every element of the electric circuit is protected against short-circuits by a breaker, as presented in the drawing "Power Line" that can be found in the Appendix. This assures that the power of the test bench should be cut in case of short-circuit.

- The doors that give access to the hydraulic and electric sector must be locked in normal operation and can be only opened by staff of CERN for maintenance proposes. This will minimize the risk of injury to the operator, in case a leak or short circuit happens.

- Zones with an elevated potential risk of burning and electrical shock are identified using explicit symbols. This will alert/remind the operator for the risks involved in the operation of the Test Bench.

- Software interlocks were designed to disconnect the pumps, water heaters in case of leak (pressure drop in the circuit), excessive temperature of the water and if there is any valve in the wrong position (which means no flow). This will potentially minimize the risk of leak or electrical shock for the operator.

## 4.6. Corrective maintenance

During the normal operation of the Test bench and between CERN maintenance periods some small issues may appear. The next paragraphs show the operations that can be performed.

### 4.6.1. Water leaks

During the setup of the test bench some issues regarding the water leaks appeared. All the screwed connections are exposed to leaks and the procedure to fix them is to empty the hydraulic circuit, focus on the connections with problems and restart the procedure described in the Hardware Manual.

### 4.6.2. Deionizer system

The mixed bed ion exchangers work according to the ion exchange principle. The dissolved salts present in the water are in the form of ions. The result is pure, demineralised water. The resins used have a certain ion exchange capacity, whereby the volume of raw water that can be processed depends on the total salt content of the raw water. A conductivity meter that is fitted to the outlet of the cartridge containing the resins shows the degree of resin exhaustion. When the reading reaches the limiting value, the ion exchange capacity has been reached. The cartridge containing the ion exchange resins is then to be sent to a central regeneration station for appropriate regeneration treatment and return.

*Figure 36: Ion exchange system.*

After six months of usage, ion exchange resins have to be replaced for new ones. The process to be following can be found in the datasheet of the equipment. The ion exchange resin used has to be sent back to the supplier for regeneration.

### 4.6.3. Filters

The filters cartridge, showed in the Figure 37, must be changed after the three months experiment.
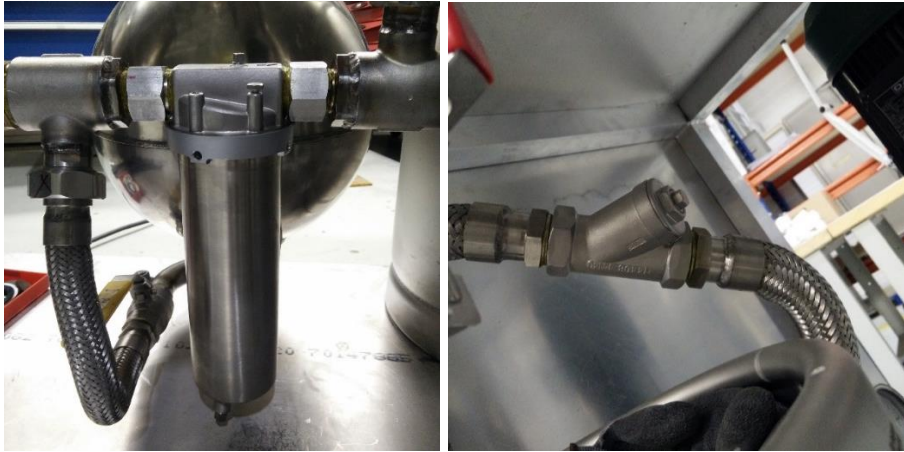
*Figure 37: Filters.*

## 4.7. Lifting system

In order to move the test bench there are two different ways, the first one is by hand because the structure is provided with four directional wheels with brakes that make the transfer easy.

The other way is with the lifting system. By using a crank in the workshop, it is possible to lift it by the four aluminium plates welded on the structure sides, the Picture 38 show the system.
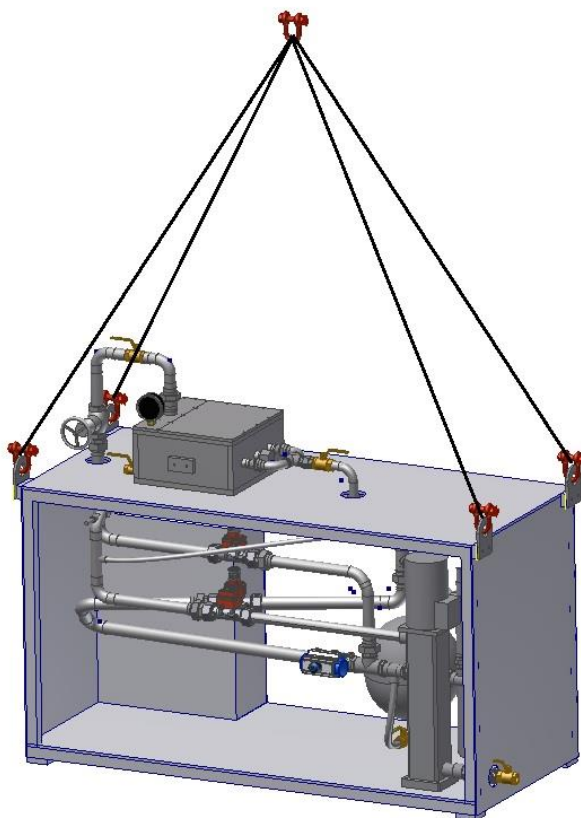
*Figure 38: Lifting system.*

### 4.8. Legal scope of the machine.

This installation is designed and manufactured taking into account the following standards:

- EN 13480 Standard. Metallic industrial piping

- EN 13445: 2002 - Unfired Pressure Vessels

- BS EN 286: 1991 Simple Unfired Pressure Vessels

- EN ISO 12100 – Safety of machinery – General principles for design – Risk assessment and risk reduction (Europe).

- DIRECTIVE 2014/68/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL (http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0068&from=ES)

Regardless of what is established in this specification, all provisions on working conditions, safety measures, production and manufacturing procedures etc, fully comply with the Regulations, Ordinances and Laws in force.
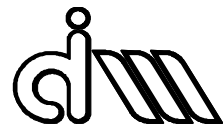
# Chapter 4

## 5. Conclusions

The work of this thesis focuses on the design of the hydraulic test bench for the erosion and corrosion test in order to evaluate the compatibility of various materials in the n_TOF target regime.

At present, the target is under design and various materials are being investigated for both the core and the contact part with the cooling water, in order to substitute the present target which will have reached its end of life.

The project of the test bench, from the conceptual to the detailed design and manufacture the device, has been developed in approximately one year.

The work has carried out in collaboration with several groups across CERN, involved in the technical specification, analysis, design and manufacture.

The main phases of the project can be summarized in the following steps:

- Analysis of the technical specification and a consequently careful material choice;

- Conceptual design with Autodesk Inventor;

- Numerical study, based on the Finite Element Method, for the implementation of the problem in ANSYS;

- Selection of all the equipment used;

- Discussion with the suppliers for the best options;

- Detailed design for manufacture;

- Preparing the technical drawings for manufacture;

- In contact with the technical employees for the proper assembly.

The final proposal of this project is a hydraulic test bench based on stainless steel any device in contact with the fluid to not modify the conductivity of this. All this mounted on an easily moving aluminium structure.

The circuit has a total volume of 96 L, distributed in 50 L the ion exchanger, 21 L the chamber, 24 L the expansion tank, 1 L the piping system. All this with a maximum pressure of 4bar due to the restriction of the oxygen sensor.
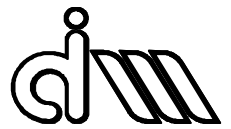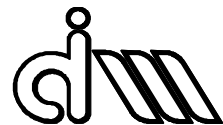
After different tests of the set-up, it is possible to say that everything works perfectly and that, also, it is possible to get the data needed to carry out the necessary experiments successfully.

In the future, it could be a good idea to install a heat exchanger to control the low temperatures, at this moment the heater is installed and it is possible to heat up the fluid but not cool down (just spending time with the heater turned off). Also, the pump generates heat so the fluid has a temperature established by the device.

# Chapter 5

## 6. Appendix

### 6.1. Hardware manual.

This manual is a quick guide to the installation and use of the Test bench hardware for the validation of the erosion and corrosion for the new n_TOF target. For additional information/doubts the responsible person for the Test bench at CERN must be contacted.

#### 6.1.1. Important notes

It is important to stress that the Test bench is a prototype and is on an early stage of development.

During operation it does not require permanent vigilance of the operator but a periodic check is strongly advised.

The Test bench was designed to automatically send the reports, warnings/alerts over e-mail to the person in charge. Also, several interlock systems were implemented in order to prevent and alert CERN about Test bench incorrect use or malfunctions.

#### 6.1.2. Test bench installation and setup

The Test bench must be installed in a location with access to normal tap water, sewer to discharge used water, 380V triphasic electric connection and Ethernet connection for internet access.

Before using the Test bench the operator must perform several operations and verifications. These operations are described in the next list. Detailed explanations of all the steps are presented in the subsections bellow. If any doubt arises during the usage of the Test bench, the person in charge of the Test bench at CERN must be contacted.

1. Connect the chamber to the Test bench.

2. Install the target pieces inside the chamber.

3. Open the valves V1, V2, V3, V4, V6, V7, VR1, VR2 and VR3 and close V5

4. Connect and/or turn on the cooling tap water.

5. Fill the circuit with tap water until 3-4 bar.

6. Connect the power cable.

7. Turn on the test bench.

8. Run the program.

### 6.1.3. Connect the chamber

The chamber must be placed in position on the Test bench before filling all the hydraulic circuit:

1. Place the chamber in the Test bench according to Figure 39.

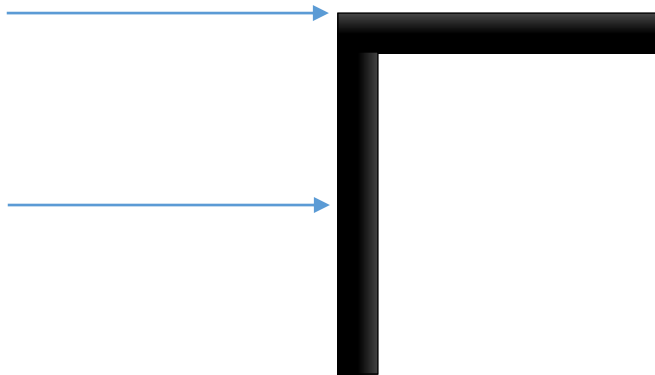2. Screw the two inner connections and the outer connection.



*Figure 39: Test chamber and connections.*

### 6.1.4. Install the target pieces

The targets will be installed inside the chamber as decided before the experiment, as shown in Figure 40.

*Figure 40: Schematic procedure of the test.*

Then, the chamber must be closed properly. You should be sure that the O-rings are properly inserted and screw all the bolts.

### 6.1.5. Valves

Make sure that the valves V1, V2, V3, V4, V6, VR1, VR2 and VR3 are open and the V5 valve is closed.



*Figure 41: Valve 1.*



*Figure 42: Valve 2.*

*Figure 43: Valve 3.*



*Figure 44: Valve 4.*



*Figure 45: Valve 5.*



*Figure 46: Valve 6.*



*Figure 47: Valve 7.*



*Figure 48: VR 1.*

*Figure 49: VR 2.*


*Figure 50: VR 3.*

### 6.1.6. Tap water connection

The Test bench must be connected to a normal tap water hose and the tap opened. Figure 44 presents the connection of the inlet of the tab water connection.

Once you fill the hydraulic circuit until **3-4 bars** you must close the V4 valve to keep the pressure inside the test bench. In the Figure 51 is possible to see the manometer where indicates the pressure.


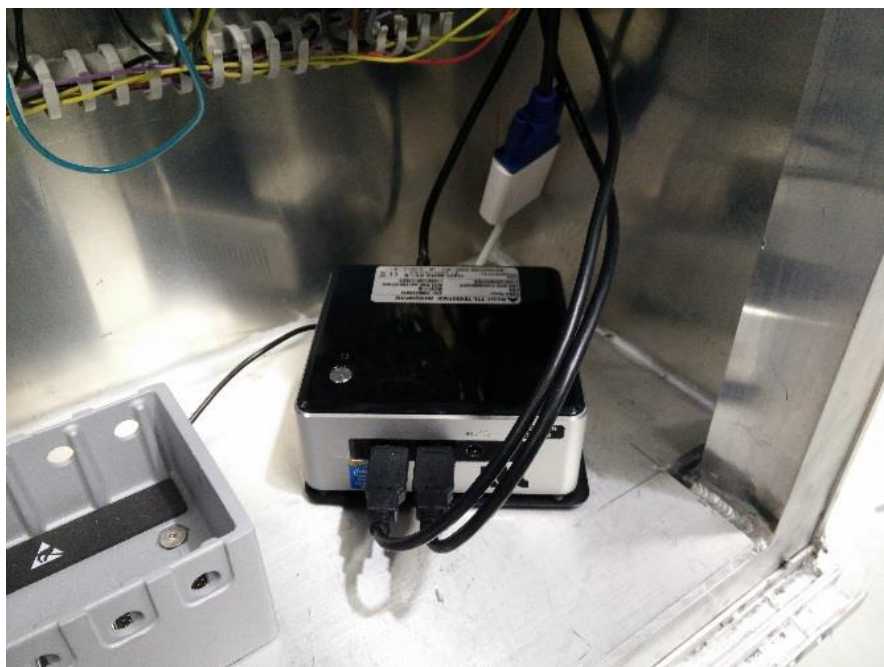*Figure 51: Manometer.*

### 6.1.7. Connecting the power cable

The power plug is presented in Figure 52.



*Figure 52: Power plug.*

### 6.1.8. Ethernet connection

In order to work properly the Test bench must have internet connection through an Ethernet connection. The plug for the Ethernet connection is behind the CPU shown in Figure 53.



*Figure 53: CPU.*

### 6.1.9. Turn the test bench on/off

The general electrical switch is presented in Figure 18 and must be turned on to start the Test bench. Afterwards, it is necessary to wait for the computer to initialize and load the Test bench program. To turn the Test bench off, it is necessary to first turn off the computer and then to

turn off the general electric switch. Please refer to the software manual for more information about the program.

### 6.1.10. Emergency stop

In case of emergency, the switch presented in Figure 54 must be pressed to cut the power of the 400 V circuit.
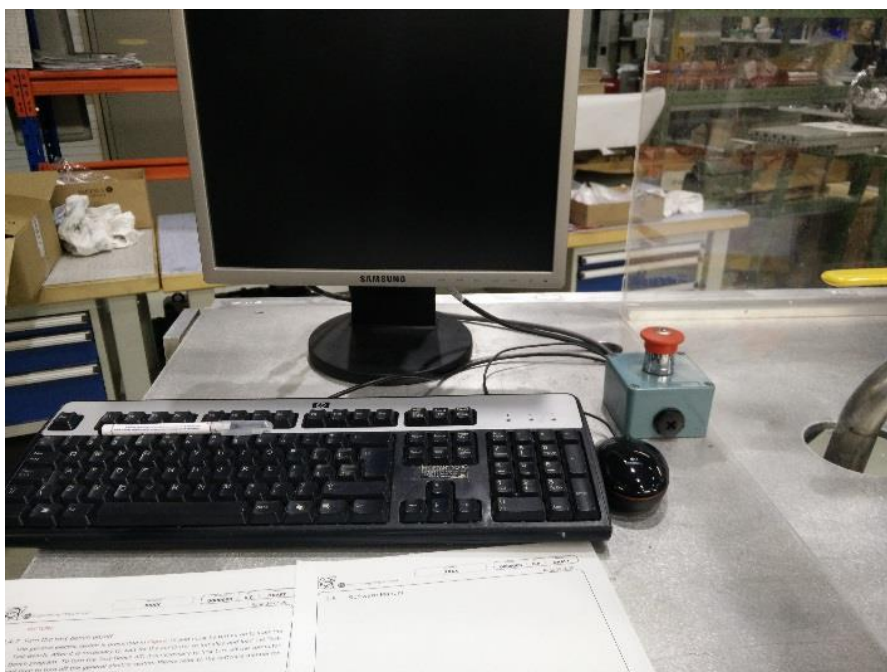


*Figure 54: Emergency stop.*

### *6.1.11.Installer's responsibility.*

It is the responsibility of the installer that the set-up and correct operation of the test bench made by him, is in line with what was written in this project.

Any mismatch over the wording must be modified on behalf of the installer and the possible consequences of this will be the sole responsibility of the installer.

The installer is responsible for requesting the material corresponding to the manufacturer that can offer the conditions of the identification of components.

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