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Lead shutter for the IFMIF LIPAc accelerator

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Abstract

The International Fusion Materials Irradiation Facility (IFMIF) aims to provide an accelerator-based, D-Li neutron source to produce high energy neutrons at sufficient intensity and irradiation volume for DEMO (Demonstration Fusion Power Plant) materials qualification. As part of the Broader Approach agreement between Japan and EURATOM, the goal of the IFMIF/EVEDA project is to work on the engineering design of IFMIF and to validate the main technological challenges which, among a wide diversity of hardware includes the LIPAc (Linear IFMIF Prototype Accelerator), a 125 mA continuous wave deuteron accelerator up to 9 MeV mainly designed and manufactured in Europe.

The LIPAc beam is stopped in a copper cone involving a high production of neutron and gamma radiation and activation of its surface. A lead shutter has been designed to shield against the gamma radiation coming from the copper cone through the beam tube when the beam is off, in order to allow access inside the accelerator vault. The lead shutter is located in a multipurpose chamber that also contains a scraper and two vacuum ports. The function of the scraper is to protect the last part of the beam tube in case of abnormal beams.

The requirements imposed on the lead shutter chamber include the motion of the lead shutter to locate it in open (beam on) and closed position (beam off), resistance to the radiation environment, vacuum and leak tightness, alignment capabilities of the scraper and leak tightness of its cooling circuit. In this article the radioprotection calculations demonstrating the shutter performance are presented and the mechanical system of the lead shutter and the layout of the different elements contained in the chamber are described, along with their functions.

Keywords:

IFMIF LIPAc; Lead shutter; Radiation shielding; Mechanical design; Radiological design

1. Introduction

The International Fusion Materials Irradiation Facility, also known as IFMIF, will be a test facility for the qualification of fusion reactors candidate materials [1]. The LIPAc (Linear IFMIF Prototype Accelerator) [[2], [3]] is a accelerator (9 MeV, 125 mA of D+ beam in continuous wave), identical to the low energy part of one of the two IFMIF accelerators.

The LIPAc will not have a target and hence a dump is needed to stop the deuteron beam [[4], [5]]. The beam will be stopped by a copper cone (2.5 m long, 6.8º angle), cooled by water flowing at high velocity along its outer surface.

Due to the interaction of the 9 MeV deuterons with the copper, both neutrons and gammas are generated. In this environment, all existing materials become activated by neutrons, and beam-facing materials are activated by deuterons as well. The copper cone is surrounded by a shield which has been designed to attenuate both the radiation produced during accelerator operation and the residual radiation [[6], [7]]. This shield (see Fig. 2) is made of an inner layer of polyethylene to moderate neutrons and an outer layer of iron (to attenuate gammas produced by deuteron interactions with Cu but also those generated by neutrons in the polyethylene).

LIPAc is a prototype whose objective is to validate the design of the IFMIF accelerator. The exact operation plan is not known, but for the purpose of radioprotection analysis and licensing it has been assumed conservatively a maximum operation time at full power of 6 months (24 h per day).

At the front side (towards the accelerator), the shielding is closed with a 700 mm thick, 3 m high concrete wall which separates the space where the beam dump is located (called beam dump cell) from the rest of the vault. This wall will have a cylindrical hole for the passage of the beam tube, through which radiation escapes during operation towards the accelerator. To minimize the radiation leakage the tube has been designed to be conical (adjusting its diameter to the increasing diameter of the beam), and the space between wall and tube has been filled with polyethylene and lead pieces (Fig. 2).

A lead shutter [7] (Fig. 8) will be inserted in the beam tube when the accelerator is switched-off to close the hole in the shield needed for the beam tube, shielding against the gamma radiation coming from the activated copper cone and reducing the dose rates in the vault to values that permit hands-on maintenance of the accelerator elements upstream this shutter. An actuator (Fig. 1) is in charge of the movement of the shutter.

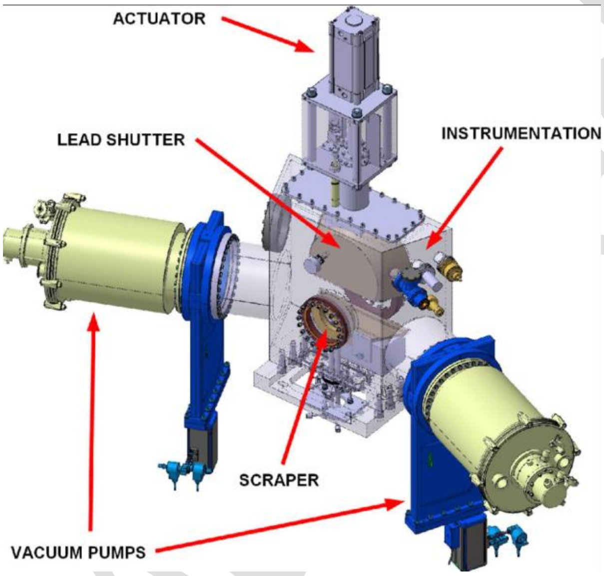

Figure 1 Lead shutter and vacuum chamber containing it.

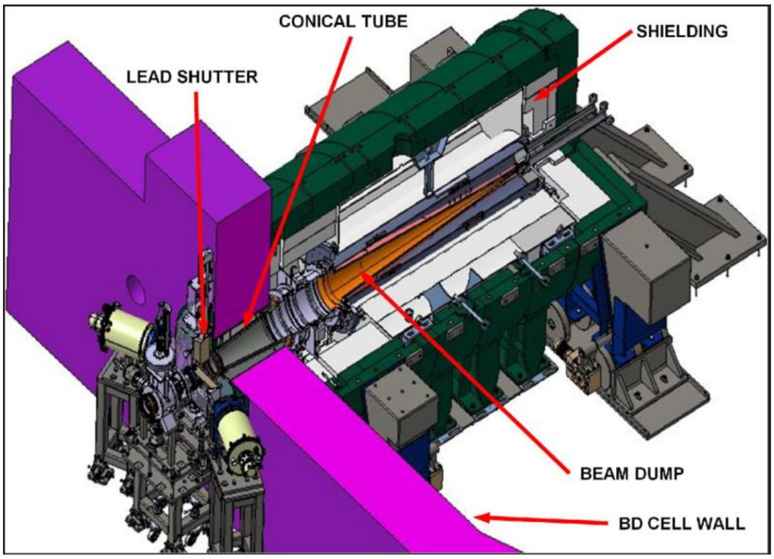

Figure 2 Quarter section of the beam dump showing all shielding elements.

The lead shutter is placed in a multipurpose vacuum chamber (Fig. 1), containing vacuum pumps, a scraper to protect the last part of the tube from abnormal beams and vacuum instrumentation. The maximum allowed length for this vacuum chamber in the direction of the beam is only 293 mm, resulting in a challenging design and integration.

Similar systems have been used in SLS (Swiss Light Source) [8] and LANSCE (Los Alamos Neutron Science Center) [9]. The SLS shutter was designed to keep the guidance of the shutter out of the vacuum, making the material selection more flexible. This concept has been used in the LIPAc lead shutter too.

The SLS shutter is a beam intercepting component with an inner water cooling circuit and thermocouples to monitor its temperature. On the other hand, the LANSCE and LIPAc shutters are conceived as components which do not intercept the beam, with limit switches to monitor their positions in order to prevent the accelerator operation if the shutters are not in opened position.

In contrast with the multiple components included in the LIPAc lead shutter chamber, the other shutter chambers designs were conceived with the only aim of accommodating their shutters.

2. Requirements

The main requirement of the lead shutter is to shield against the gamma radiation coming from the copper cone through the beam tube when the beam is off, in order to allow access inside the accelerator vault and, hence, enable hands-on maintenance of the accelerator components located upstream this shutter. The lead shutter geometry has been chosen to obtain values of residual dose rates upstream lower than the dose rate limit in the accelerator vault established by the project (12.5 μSv/h). The system includes an actuator to locate the lead shutter in open (beam on) or closed (beam off) positions and means to monitor its position.

The color dose rate map around the accelerator during full power operation – Fig. 3–, shows that, as a reference, the absorbed dose rates in polyethylene in the lead shutter area are near 10 Gy/h, mainly by neutrons. For the mentioned assumed operation of 0.5 full-power years, these radiation levels result in estimated maximum absorbed doses over 10^5 Gy, forcing a careful selection of materials in the lead shutter chamber, where components must be metallic if possible or radiation resistant plastics.

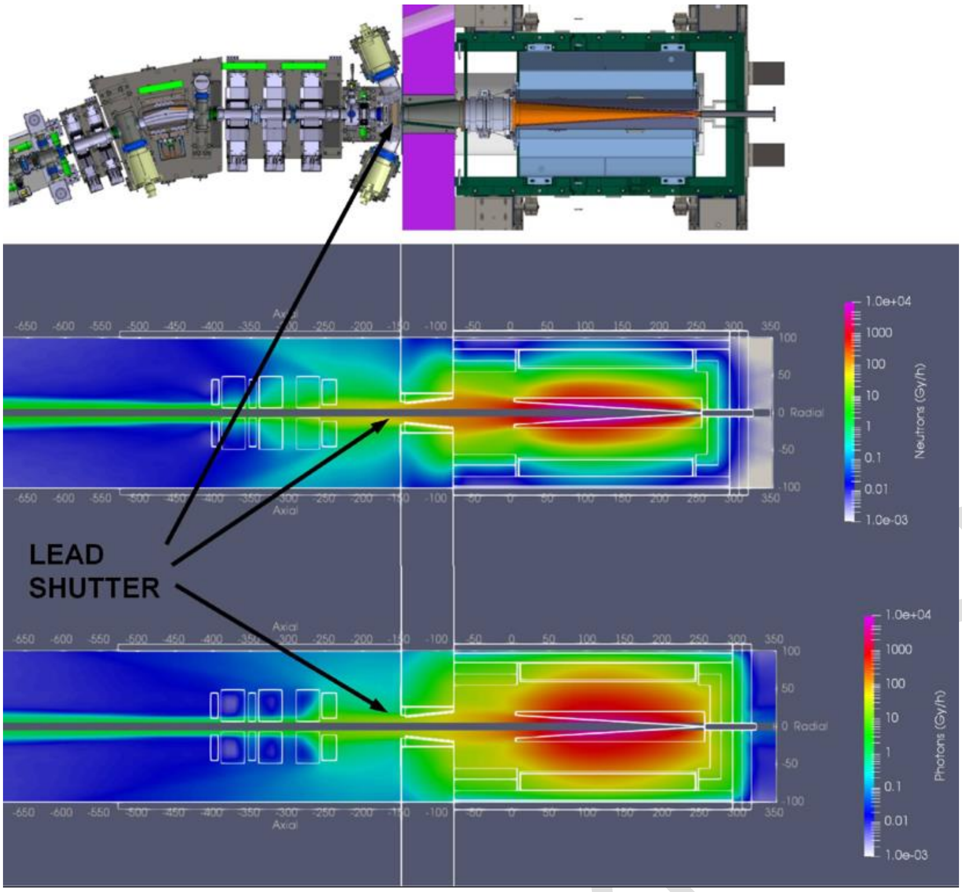

Figure 3 Up: 2D cross section of the HEBT and BD components. Middle: Neutron absorbed dose rate map during operation for polyethylene. Down: Photon absorbed dose rate map during operation for polyethylene.

Lead is a relatively low activation material for the radiation environment created during operation of the accelerator. Impurities that can contribute to residual radiation if activated must be controlled, especially antimony and silver, which are commonly found in commercially available lead. Calculations show that these elements must not be found in more than 20 ppm. Impurities in the material procurement of the vacuum chamber must be controlled too; a cobalt content in the stainless steel 316 of less than 1000 ppm has been specified.

Pressure values in the lead shutter chamber during operation will be in the order of 5×10^{-6} to 1×10^{-5} mbar. The lead shutter chamber must achieve and withstand a pressure value of 1×10^{-8} mbar and the maximum allowable He leak rate is 5×10^{-12} mbar·l/s.

Tolerance requirements have been imposed to the beam line flanges of the vacuum chamber (Fig. 4) to ensure the assembly of the chamber and the surrounding components in the beam line.

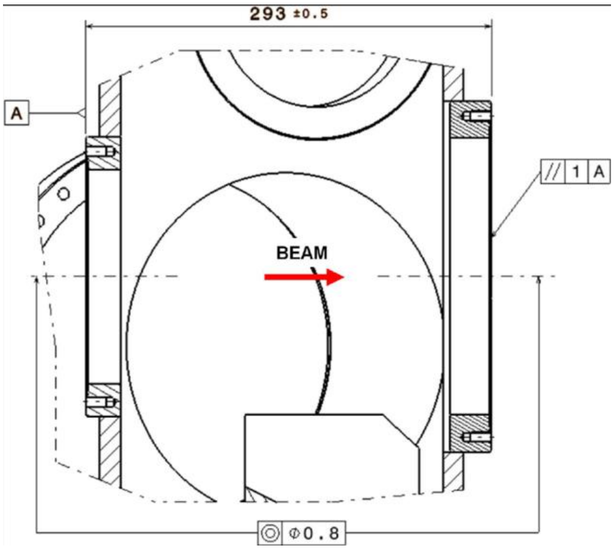

Figure 4 Tolerance requirements in the vacuum chamber.

Regarding safety requirements, the chamber must allow the restart of the shutter motion in case of failure of the actuator. So, the motion system has been designed in such a way that if there is a lack of compressed air supply the shutter closes, and in addition, a system that enables the release of the shutter from its actuator has been provided, so that the actuator could be replaced if damaged. As already mentioned above, the actuator system must include means to monitor the position of the shutter in order to stop the beam if the shutter is not in opened position. The elements that monitor this position must include redundancy. Thermocouples will be installed in the scraper in order to monitor its temperature.

Concerning alignment requirements, the chamber and the shutter only require the precision to allow the installation of the beam line components, while the scraper must be aligned to the beam axis with an accuracy lower than 0.1 mm in order to ensure the protection of the beam tube downstream the lead shutter.

The design has been done so that during operation the lead shutter is opened up to a radial distance from the beam axis of 80 mm, which guarantees that no beam deposition is expected on it. Beam transport simulations confirm this.

3. Radiological design

3.1. Radiation sources

Beam deuterons are deposited onto the beam dump copper cone. Having 9 MeV of energy, some of these deuterons induce nuclear reactions on the copper, liberating neutrons among other secondary radiation. The combined activation by deuterons and neutrons results in generation of significant radioactive inventory. The beam dump cone becomes the most activated element, with 25 TBq of Zn65 ($T_{1/2}$ = 244 days) and 13 TBq of more rapidly decaying Cu64 ($T_{1/2}$ = 12.7 h) after six months of continuous irradiation and one-day cooling time [10]. Such strong radioactive source would produce at one meter distance dose rates over 2 Sv/h, which explains the necessity of a strong shield around the activated material.

Zinc 65 is a positron and gamma emitter with the main emission line at 1.1 MeV. Lead is an efficient shielding material for this radiation and for this reason it has been chosen for the beam shutter.

3.2. Calculation methodology

In order to compute radiological magnitudes during maintenance scenario, it is very important to perform accurate neutronics and activation calculations. The MCUNED code [11], an enhanced variant of MCNPX [12] for light ion transport, was used with nuclear data from TENDL2010 [13] for interactions with deuterons and

ENDF7 for neutrons. TENDL2010 was proven to be accurate for these deuteron interactions with copper [14]. Material activation was computed with the ACAB [15] code and EAF2007 [16] data libraries.

Ambient dose equivalent has been computed as an estimation of the effective dose, using flux-to-dose coefficients from the ICRP74 standard [17].

The computation of residual doses from activation by deuterons is done in a different manner than that of the activation by neutrons, since deuterons are deposited in a very thin superficial layer, and nuclear data libraries for deuterons are not always accurate. Activation by deuterons was first determined with ACAB and EAF2007 to have Zn65 as main radioisotope after 1 day cooling, produced by direct reaction.

Using experimental cross section data [18] for this reaction pathway as a flux tally modifier, the reaction rate and concentration of radioisotope was computed with MCUNED, dividing the irradiation volume longitudinally to obtain spatial resolution. The resulting radioisotope activity was then assigned to a source in the internal surface of the cone, and with the proper longitudinal intensity, and energy spectrum of Zn65. Residual doses by deuterons were computed transporting this source.

Residual doses from neutron activation were computed first with ACAB and EAF2007 using average neutron fluxes in the cone, with longitudinal resolution in different conical sectors. The residual gamma source was assumed volumetrically homogeneous in each of those longitudinal sectors, with the energy spectrum from Cu64.

3.3. Shielding efficiency

To allow the installation and alignment of the beam tube the final design considers that the conical beam tube is introduced through a cylindrical hole in the wall. To minimize the radiation leakage, the space between the cylindrical hole and the tube is filled with polyethylene and lead pieces (see Fig. 5) leaving a 20 mm thick annular space around the tube to allow its precise alignment.

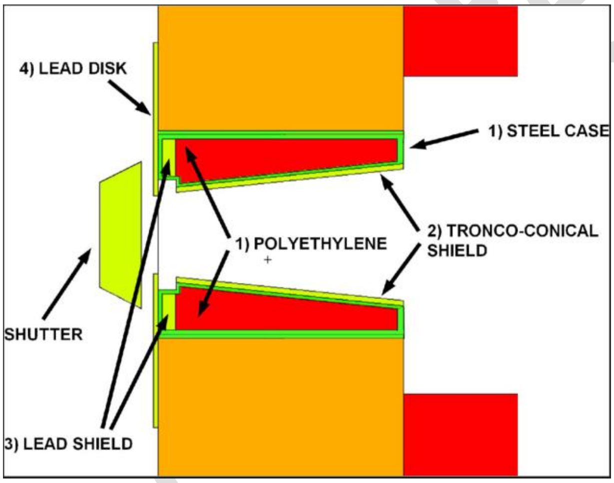

Figure 5 Frontal beam dump shielding design, where lead is represented in yellow, polyethylene in red, steel in green and concrete in orange. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The shutter has been designed using the methodology mentioned above taking into consideration all the constructive details and necessary space between shielding elements, obtaining a required lead thickness of 12 cm. An optimization was performed minimizing the weight while keeping the shielding efficiency, leading to a final cone trunk geometry with diameters 15 cm and 21 cm.

The shielding of the beam dump radiation in its frontal part is performed by the lead shutter, the concrete wall and the following elements, as shown in Fig. 5:

(1) Shielding plug encased in steel with polyethylene filling for neutron shielding during operation. To allow the assembly its outer cylindrical surface has a diameter 10 mm lower than that of the receiving penetration.
(2) 15 mm thick, internal tronco-conical lining for the plug, made of lead.
(3) 50 mm thick, ring shaped lead shield adjacent to the shutter in order to shield against radiation escaping around it. The ring covers radial positions between 15 and 25 cm.
(4) 15mm annular disk of lead, placed on the left side of the concrete wall, covering radius from 9 to 55 cm.

The simulations performed for this design, following the methodology described in Section 3.2, show acceptable doses during maintenance periods. Color map in Fig. 6 shows residual dose rates in the neighborhood of the lead shutter for the most conservative conditions (after 6 months continuous irradiation of the beam dump).

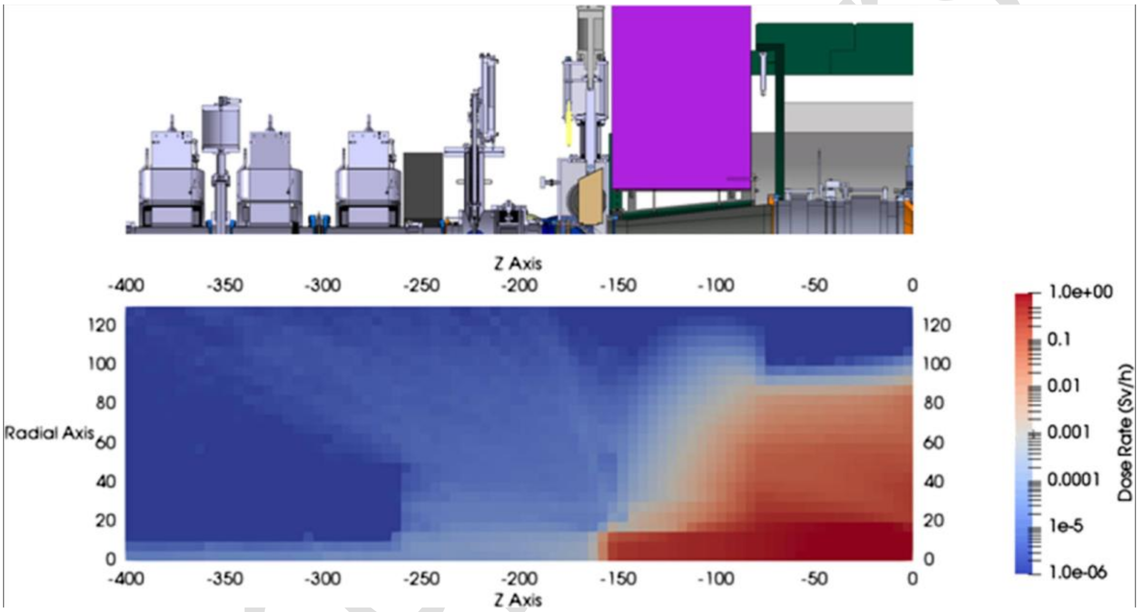

Figure 6 Up: Vertical cross section of the elements in the vicinity of the shutter. Down: Dose rates during maintenance periods according to the vertical cross section. (For interpretation of the references to color in this figure legend, the reader is referred

The plot in Fig. 7 shows, at an axial coordinate of −185 cm in Fig. 6, which corresponds to a position right before the lead shutter, the dose rate in accessible radial values from 20 cm apart from the beam line, and up to 130 cm. The peak value at 27 cm corresponds to the gap between the shielding plug and the penetration in the concrete wall. Values beyond 30 cm fulfill the dose rate requirement of the project.

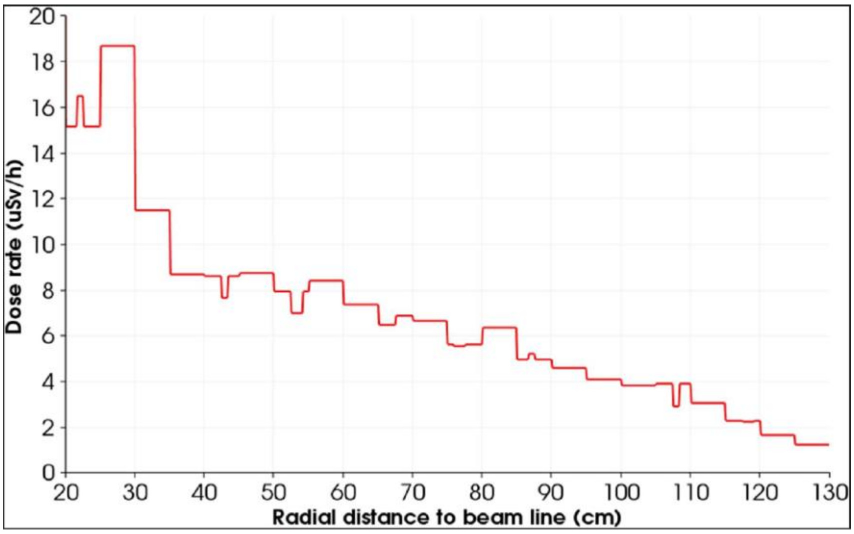

Figure 7 Radial dependence of the dose rate measured from the beam line, and at a distance of 35 cm outside the frontal concrete wall.

4. Mechanical design

The current design of the lead shutter chamber has been upgraded from the former design [7]. The changes are described in the next sections.

4.1. Shutter

The lead is covered by a 3 mm layer of stainless steel 316 to ensure the structural integrity of the piece and to avoid outgassing of the lead into vacuum.

As shown in Fig. 8, the shutter is divided in a moving and a fixed part. The division has been designed with a dogleg shape to avoid radiation streaming at the junction. The moving part contains the attachment to the actuator in its upper side, while the fixed part contains two plates with holes to connect by bolted joints the component to the vacuum chamber.

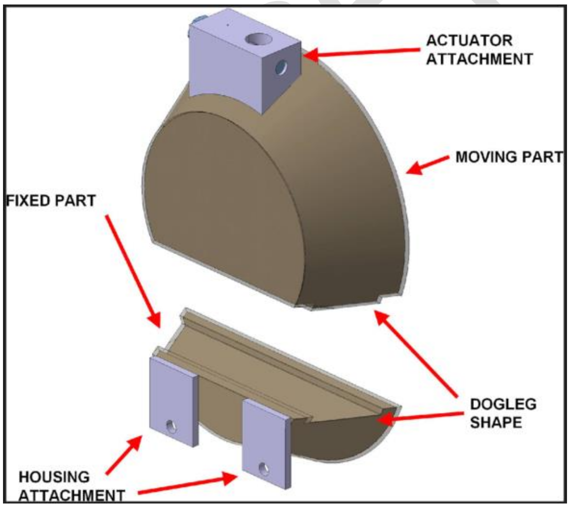

Figure 8 Lead shutter parts.

During beam operation the shutter will be in open position, at a minimum distance from the beam axis of 80 mm so that no beam losses can take place on it. Therefore no heat deposition is expected on the lead shutter.

4.2. Vacuum chamber

The lead shutter chamber has been designed with plates of austenitic stainless steel 316 with 10–15 mm thickness to guarantee the structural integrity under the vacuum level to be achieved.

The upgraded design adds new several vacuum ports for instrumentation and vacuum purposes, maintaining two beam line ports, the two vacuum pump ports, the actuator port, the scraper port and the shutter attachment port that enables to replace the actuator in case of failure, releasing it from the shutter (Fig. 9).

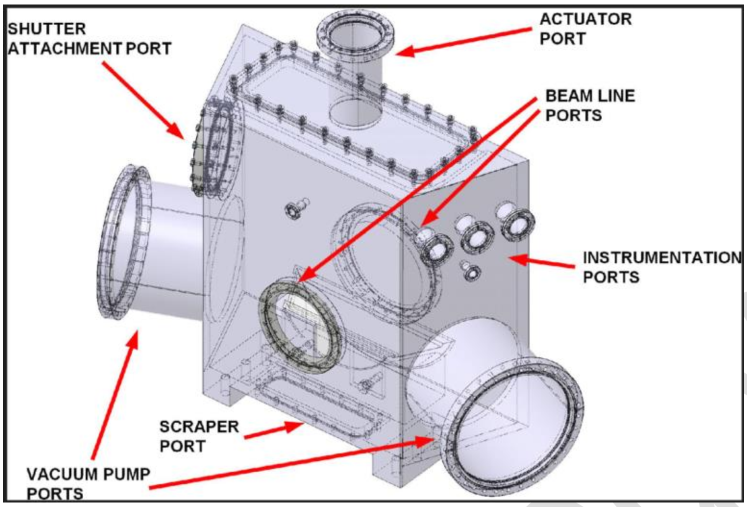

Figure 9 Vacuum chamber.

4.3. Actuator

The linear pneumatic actuator is connected to an extended rod that links with the moving part of the shutter by a captive bolt system that can be operated from the shutter attachment port.

This actuator system is designed to keep its guiding elements out of the vacuum by means of a bellows assembly acting as vacuum barrier, allowing an easier maintenance and materials selection of these guiding elements. It also has an anti rotation pivot preventing the whole system to rotate (Fig. 10).

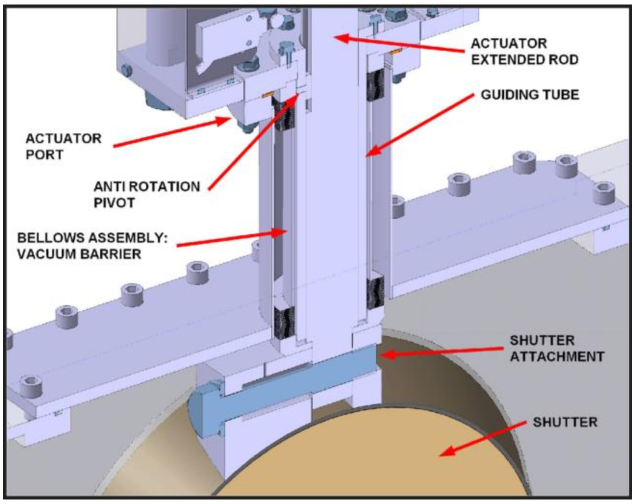

Figure 10 Attachment and guidance of the actuator system.

The position of the shutter is monitored by two pairs of redundant limit switches which are activated in the extreme positions of the shutter. A shock absorber is installed in the actuator system to cushion the fall of the shutter and its contact with the fixed part (Fig. 11).

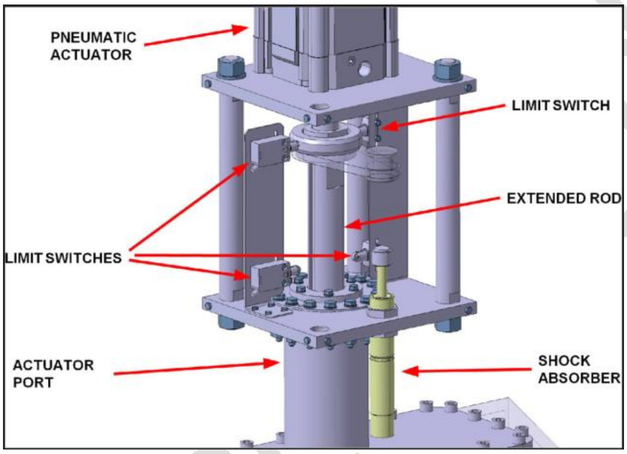

Figure 11 Monitoring of the actuator system. One of the four structural pillars has been removed from the figure to allow an easier understanding.

As a result of a loss of air in the actuator or a power outage, the shutter will fall closed, allowing the access to the accelerator building if needed to restore the air or power supply.

4.4. Scraper

The scraper has been designed of aluminum, since it gathers a good compromise among thermal conductivity, mechanical properties and moderate activation. The aluminum alloy finally chosen is UNS A91100 H12. The scraper is being designed to handle a maximum beam power of 900 W, although during operation in nominal conditions no power deposition is expected. It contains an annular front surface, where the abnormal beams will impinge, and an annular cooling channel of a rectangular section of 12 x 20 mm, through which the water will flow at a rate of 0.4 l/s with a pressure of 3 bars.

The low part of the scraper assembly which contains the water connections to the cooling skid and the alignment plate is made of stainless steel 316. The transition between aluminum and stainless steel 316 is made in the upper pipes with two compression tube fittings between the aluminum and the stainless steel 316 pipes.

Thermocouples will be installed in the back surface of the front plate of the scraper distributed in several radial positions to monitor its temperature (Fig. 12). The signal cables of the thermocouples are conducted out of the vacuum chamber by means of two feedthroughs in the scraper flange. Thermocouples and signal cables are not represented in Fig. 12.

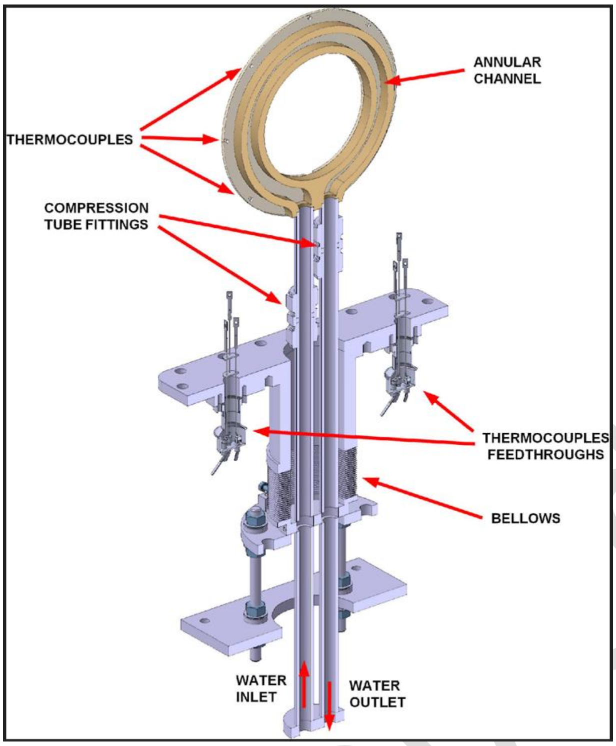

Figure 12 Cross section of the scraper.

A dedicated alignment support has been devised to reach an accuracy in the position of the scraper lower than 0.1 mm, in order to ensure the protection of the beam tube downstream the lead shutter chamber. It allows moving the scraper both in horizontal and vertical directions (Fig. 13). A bellows connects the alignment plate with the scraper flange in order to allow the relative movement of the scraper from the chamber and to ensure the vacuum barrier (Fig. 12, Fig. 13).

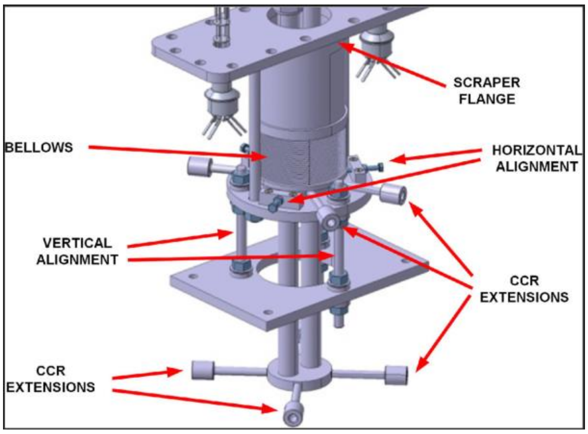

Figure 13 Alignment of the scraper.

CCR (Corner Cube Reflectors) extensions can be connected to the alignment support plates to align the scraper. First, the real positions of the CCR centers have to be measured in a CMM (Coordinate Measuring Machine) and relate them with the position of the axis and frontal surface of the scraper. After that, the CCR centers will be used to align the scraper during the final assembly with no direct vision of the scraper (Fig. 13).

5. Manufacturing and acceptance tests

In order to achieve the vacuum requirements, internal TIG welding has been used in the chamber to avoid virtual leaks, electro polishing has been applied in the inner surfaces to achieve the required roughness and TIG welding with full penetration has been adopted in the stainless steel 316 covers of the shutter.

These covers of stainless steel 316 have been employed as an enclosure to cast melted lead to the shutter final dimensions.

The beam line flanges have been machined after the welding construction of the chamber in order to meet the tolerance requirements imposed.

The annular channel of the scraper has been manufactured in two pieces joint by TIG welding. Welding is not allowed in the front surface, in charge of dealing with the power deposition of abnormal beams.

The selection of materials has been made in order to withstand the radiation environment, avoiding non-metallic pieces whenever possible. Radiation resistant plastics are used in the seals of the pneumatic actuator and the shock absorber and in the extension cables of the limit switches and thermocouples. In the case of the seals, the material used is NBR, able to tolerate up to 3×10^6 Gy with no compromise [19], and in the case of the extension cables, the material used is Kapton, able to tolerate up to more than 10^7 Gy with no compromise [19].

Acceptance tests include dimensional checking of the tolerances of the chamber and the scraper, an alignment test of the scraper with laser tracker, He leak tests of the whole chamber and the hydraulic cooling circuit of the scraper and a functional test of the motion of the shutter under vacuum conditions.

6. Conclusions

A shutter to shield against the gamma radiation coming from the beam dump allowing hands-on maintenance of the accelerator components upstream the shutter has been devised.

The shutter fulfills its main function, being in opened position during operation, allowing the passage of the beam, and moving to closed position when the accelerator is off. The lead shutter chamber contains several other components, fulfilling other purposes such as vacuum pumping, vacuum monitoring and beam tube protection downstream the shutter.

Radiation, vacuum, dimension, alignment and safety requirements have been taken into account.

Acknowledgment

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