VISUAL INSPECTION OF A COPPER COLLIMATOR IRRADIATED BY 590 MeV PROTONS AT PSI

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Abstract

In March 2010 one of the most exposed collimators of the 590 MeV proton beam line at the Paul Scherrer Institut, was visually inspected after 20 years of operation without failure and a total beam charge of 120 Ah. Two samples of pieces peeling off the surface were taken and analyzed with a HPGe detector. The (relative) activity was compared to calculations (MCNPX and Cinder'90). Due to the high dose rate of the collimator, radiological precautions had to be taken when removing it from the beam line.

INTRODUCTION

The High Intensity Proton Accelerator (HIPA) facility at the Paul Scherrer Institut (PSI) uses a 4 cm thick graphite wheel, called Target E, to produce mesons. When the 590 MeV protons pass Target E, the beam diverges mainly due to multiple scattering by about 6 mrad. To protect the magnets and to reduce the beam losses along the beam line, collimator KHE2 is used to shape the defocused proton beam after Target E. It is located 4.7 m behind Target E. With a current of 2 mA on Target E, ~150 kW is deposited as heat in the collimator. KHE2 is made out of copper and actively cooled by water tubes placed on the outer surface of the collimator.

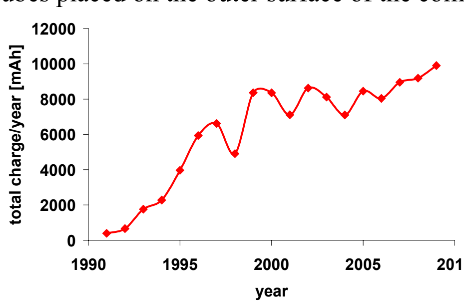

Figure 1: Charge per year in mAh on KHE2 during the last 20 years. The integrated charge today is ~120Ah.

The total beam charge today is 120 Ah after 20 years of operation. At the time the collimator was designed, the total charge per year was much smaller than today (Figure 1) and it was not expected that KHE2 would be exposed to such high thermal stress and accumulated charge. It is known that this can cause defects in the lattice, which can lead to a change of material properties, like its strength or the thermal conductivity. For thermal neutrons, considerable swelling of the material (change of geometry) would already have occurred. For high energetic protons much less is known about their effect on radiation damage. In general, the amount of damage is not really quantifiable and many factors play a role like e.g. the operating temperature.

Therefore, to keep the reliability of the facility, also in view of the upgrade plans to 3 mA, which require a new design of the collimator, it was decided to perform a visual inspection of the collimator and to remove KHE2 from the beam line for the first time after 20 years of operation.

Design and Temperature Distribution

The design of the collimator is not only driven by the needs of the beam shape but also by cooling demands. The 30 cm long collimator is segmented into six parts, each having an inner conical "teeth"-design for better thermal power distribution (Figure 2). The copper collimator is cooled by water flowing with 8 m/s in tubes of 9 mm inner diameter. The steel tubes are brazed to the outer surface of the copper body.

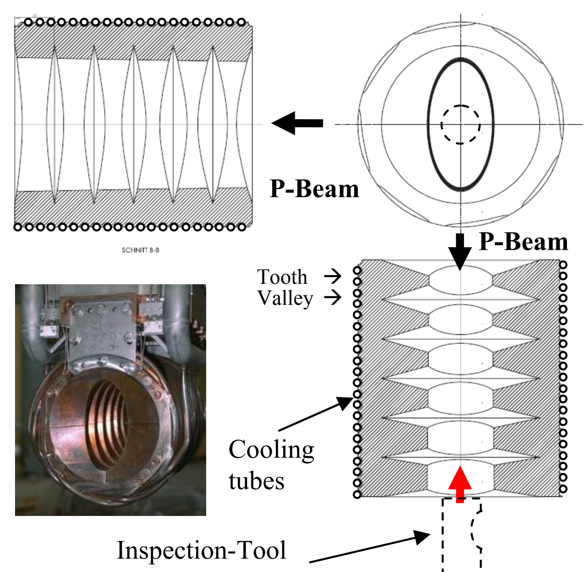

Figure 2: Photo and sketch of collimator KHE2. The insertion of the inspection tool is shown at the bottom (dashed line).

The temperature distribution inside the collimator (Figure 3) was calculated with the CFD-ACE+ [4] code for 2 mA on Target E. Due to is elliptical aperture, the collimator cuts the beam symmetrically at one and two standard deviations, respectively. The resulting temperature is much higher on the sides than at the top or bottom. The maximum temperature inside the collimator for a 2 mA beam current is about 380 °C (Figure 3).

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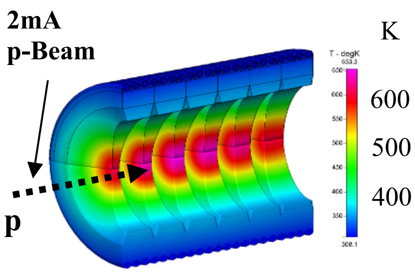

Figure 3: Temperature distribution in K along KHE2 at 2 mA. The calculated maximum temperature is 653 K (380°C).

INSPECTION

This inspection was initiated to investigate the current condition of the collimator and to answer the following questions:

- Can one recognize radiation damage on the surface of the collimator?
- Is there any swelling? The relative volume increase of 0.5% per DPA[1] is known for thermal neutrons in reactors. This would predict large swelling for the current conditions. Data for protons are rare and much less precisely known. Depending on the calculation program used, DPA values between 40 and 80 DPA were estimated for the inner sides of the collimator.

Inspection Tool

A tool for the inspection was designed to meet the following requirements:

- Inspection at the outside and inside of the collimator, including all details of the "teeth" and the "valleys" (Figure 2), that is to view and to make photos with a high quality camera.
- Inspection of the aperture diaphragm.
- Since no replacement of the collimator is currently available, the collimator has to be kept intact.
- Measurements of the collimator aperture and structure elevation.

In addition, the tool has to be operated remotely, since the dose rate of several hundred Sv/h requires the use of a closed hot cell.

The expected dose rate of the collimator was estimated with MCNPX [1] and Cinder'90 [2]. As a consequence of these results, MicroShield [3] was used to design the shielding of the camera and electronics. Investigations have shown that a digital camera will operate correctly in a radioactive field of about 100 mSv/h. Therefore, three lead bricks, each 5 cm thick, were attached directly on the tool housing, to protect the electronic. An additional 5 cm thick lead shielding was mounted at the rear side of the support frame holding the collimator in the hot cell. For pictures taken around the collimator, it had to be removed.

To take pictures of the inside of the collimator, the tool uses a long tube and two surface mirrors, which work like in a periscope and which fits into the opening of the collimator (mode S1, one of four setup configurations). It was inserted via a guiding tube from the rear side of the KHE2 (Figure 2) to avoid damage of the collimator and the diaphragm (a 127 μm Ni foil). The first mirror in the periscope avoids the camera being on the beam axis where the dose rate is highest. The second mirror is placed at the end of the tube (Figure 4 right) to view the inner structure and the details. In order to get good lighting conditions and to minimize reflections we installed three different and dimmable systems with several lamps each, which could be individually lighted if needed. Because of the very high radiation, only filament lamps where used.

The camera was operated in the so called live view mode where the viewed scenes are displayed online on a PC through an USB cable. With this setting, the camera was also controlled and photos and videos stored directly on the PC.

Another system was integrated in the tool housing to measure the horizontal opening of the collimator aperture (mode S2). Two commercial laser distance meters were placed on each side near to the camera. The tube with one mirror for photos inside, was replaced by a tube containing a double mirror (two mirrors at 45°, Figure 4 left) such that the distance between the left and the right inner collimator wall was measured. The exchange of the tubes, which are fastened to the housing by manual clamps, is performed by the manipulators in the hot cell. The measurement of the opening is not absolute but was calibrated beforehand with tubes of known sizes. The accuracy of the measurement was estimated to be better than ±0.5 mm.

When both tubes were demounted, photos from the outside of the collimator were taken (mode S3).

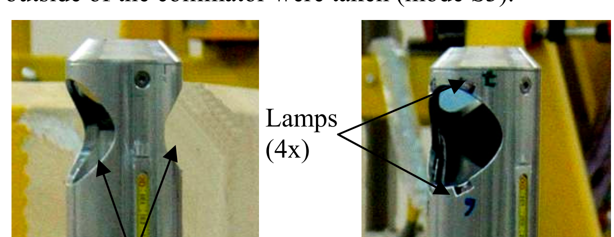

Figure 4: End caps of both mirror tubes (diameter 50 mm). The tube on the right used for the pictures at the inside, has four xenon lamps placed symmetrically around the mirror.

In combination with this inspection tool, a third external system was provided to measure the height of the surface structure (roughness) or of pieces at the surface (mode S4). With a remote-controlled mirror device, a laser beam was guided into the collimator and moved

[1] DPA = Displacements Per Atom. It is a measure used to quantify the radiation damage and to compare different irradiation conditions.

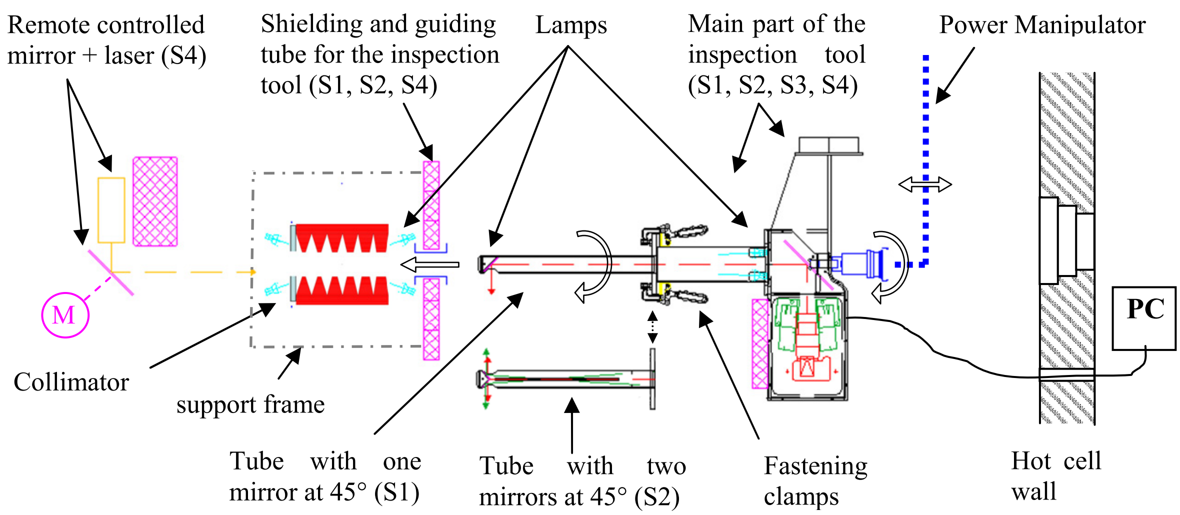

Figure 5: Schematic view of the inspection tool with the collimator in the hot cell. The tool was used in four setup configurations S1, S2, S3 and S4 (modes) combining different equipments.

along a specific object. The distance between the mirror and the object was known and the deflection angle of the mirror was measured. From this the height of the object was obtained. This operation was observed and controlled through the camera.The housing of the inspection tool was held by the power manipulator in the hot cell so it can be moved, rotated and firmly held in any position. An overview of the four different setup configurations as well as a sketch of the inspection tool is shown in Figure 5.

Procedure

The collimator was taken out of the beam line by a remote-controlled exchange flask and transported to the hot cell via crane. The shielding of the flask consists of 40 cm of steel. The dose rate on its surface was at maximum 1 mSv/h.

It was checked beforehand using MicroShield that the shielding of the exchange flask as well as the one of the hot cell is sufficient. During the dismounting, tritium monitors were installed but no increase of tritium was observed.

After the inspection of the collimator in the hot cell, it was transported back to the proton channel and mounted again.

RESULTS OF INSPECTION

General

The most important results of the inspection are now summarized and some conclusions are drawn. Due to the different temperature conditions in the collimator at the vertical and horizontal direction, as well as, due to the different appearance of its surface, the findings are grouped according to different locations inside and outside of the collimator. Further, the results of the analysis of two material samples regarding their radioisotope content as well as the comparison of the measured and calculated dose rates are shown.

Inside in Vertical Direction (Top and Bottom)

According to Figure 3, the temperatures of the upper and lower inner surfaces of the collimator are about 80 to 100°C at 2 mA. Some photos taken with the inspection tool in mode S1 and S3 are shown in Figure 6. The most important observations are:

→ The observed damage seems to be larger at the beam exit.
→ Some grey skinlike pieces are peeling off.
→ The surfaces between the vertical and horizontal direction (at ~45°) seem not to be affected.

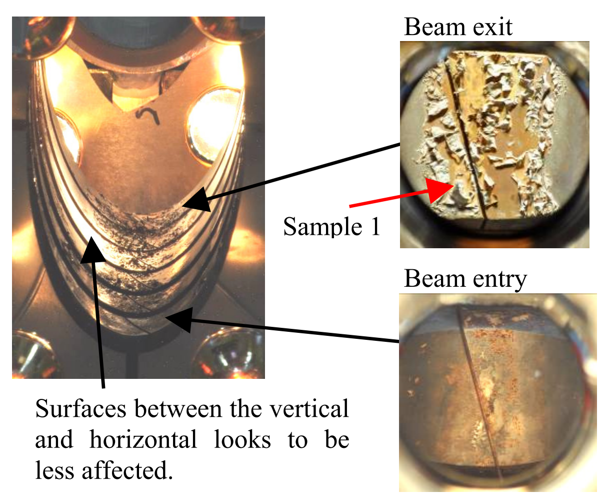

Figure 6: Picture of the lower collimator opening in beam direction. The upper part looks very similar. On the right, the pictures show the surfaces at the beam entry and exit.

Since the stopping range of 590 MeV protons is about 24 cm in a full block of copper, lower energetic protons and more secondary neutrons are hitting the last section of the collimator compared to the first one. It is known that low energetic particles are causing more damage to the bulk material. Further, the main damage seems to be concentrated at the coldest location. The grey surface and the pieces peeling off might be a result of erosion and dirt. Therefore, a material sample (No 1) was taken from the last section at the bottom using a tissue soaked with alcohol. The analysis and conclusions are presented below.

Inside in Horizontal Direction (Left and Right)

With the same setup, photos were taken from the vertical surfaces on the left and the right hand side (Figure 7), where the temperatures are above 350 °C. The main observations are:

→ The main surface modifications seem to be at the beam entry side.
→ Grey pieces (about 1 cm in diameter and larger) are peeling off.

Contrary to the vertical direction, the grey pieces are concentrated at the locations with the highest temperatures (left and right). It looks like they peel off along grain boundaries, whose size has grown considerably. The size of the grain boundaries in unirradiated and untreated OFHC copper is of the order of a few hundred microns, but exposed to temperature and irradiation, they are known to grow. Unfortunately, a sample piece could not be taken without the risk of damaging the collimator.

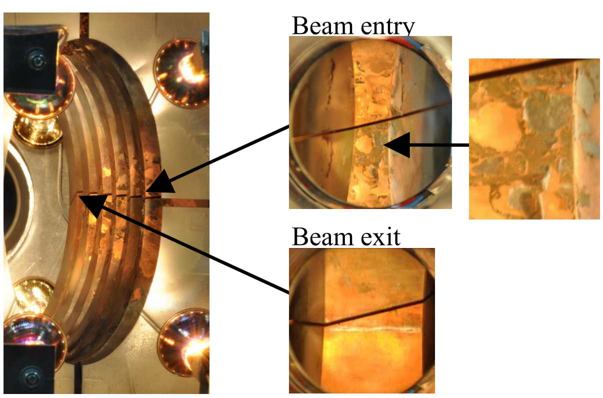

Figure 7: Picture of the right collimator side in beam direction. The left side looks quite similar. Two surface pictures at the beam entry and exit are also shown.

Inner Surface Structure and Aperture

Besides the visual examination of the surface, the aim was to determine if swelling had already occurred. Therefore, the horizontal opening was measured in mode S2. The measured distance agreed with the nominal value of about 80 mm within 0.2 mm, at an accuracy of the measurement system of ±0.5 mm. Another indication that no swelling occurred can be seen in Figure 7. The slits, which are 1 mm wide and serve the purpose of reducing thermal stress, have kept their dimension. In mode S4, the height of surface structure or salient particles was determined. It is between 1 and 3 mm for prominent pieces.

Front Side and Back Side of the Collimator

At the beam entry (front side) of the collimator, one can see the aperture diaphragm made out of 127 µm thick Ni foil (Figure 7). It is used for monitoring the beam position online and protecting the collimator and subsequent systems from damage, as it is a device in the run permit system of the accelerator. The Ni foil is in a very good shape and free of dirt. The maximum operating temperature is ~750°C at 2 mA. The slightly darker colour reveals the beam profile. Behind the diaphragm, some damage of the copper can be discerned.

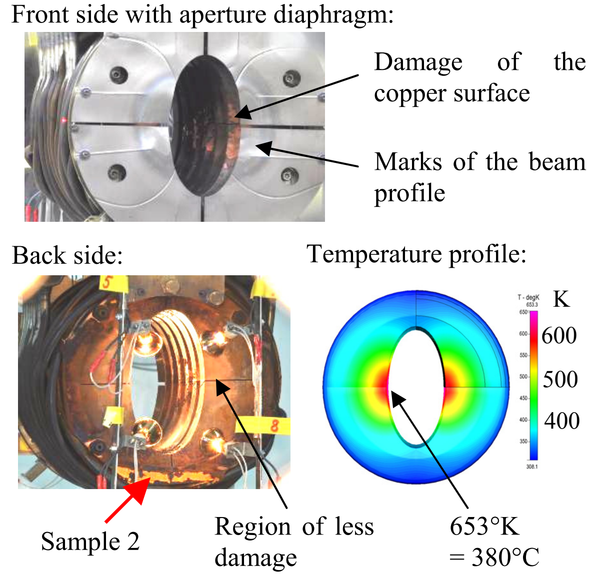

Figure 8: Pictures of the back and front side of KHE2. The calculated temperature profile on the back side is shown for comparison.

At the back side the damage to the collimator seems to be larger at the top and the bottom than in the horizontal direction where the temperature (~380°C) is much higher (Figure 7). It seems almost to reveal the temperature profile shown on the right of Figure 8. It is likely that the higher temperatures helped to heal the damage of the bulk material.

At the bottom, a stripe of golden colour can be seen. It is partly covered with black pieces; some of them are peeling off. One of them was taken as sample 2.

Analysis of the Samples

The aim of the analysis of the two samples was to clarify, if the pieces peeling off the collimator surface are from pure copper or contain other materials. To get an indication of the material composition a gamma spectroscopy of these samples was performed with a HPGe detector. In order to identify a possible source of these nuclides the nuclide inventory of the copper collimator was calculated for the same irradiation conditions. The calculation was performed with the Monte Carlo particle transport program MCNPX 2.5.0, which was coupled to the decay and build-up code Cinder'90. In the model of the beam line geometry, the protons start before Target E and are tracked through a system of four collimators (including KHE2) taking into account their nuclear reactions within the bulk material. As impurities in the material composition of OFHC Cu, 17 ppm Ag, 3 ppm O_2 and 1 ppm Na were assumed.

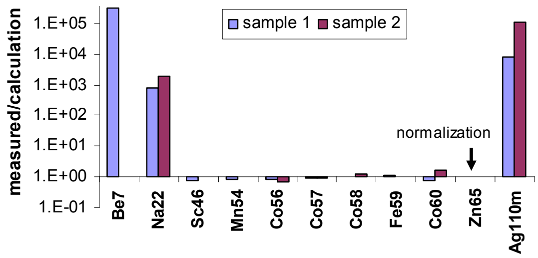

Figure 9: Ratio of the measured to calculated activities in the samples 1 and 2. Zn65 is used for normalisation of the measured nuclide inventory.

Because of the very small and fragile samples, their weight could not be measured. For the comparison of the measured and calculated activities, the nuclide inventory is normalised to the activity of Zn65. This was chosen because of its close neighbourhood to Cu. From the normalisation, one can estimate the weight of the samples to ~0.2 g.

Figure 9 shows the ratio of the measured to calculated activities. For the isotopes from Sc46 to Co60, both activities are in very good agreement. These isotopes are produced mainly from Cu. However, large deviations are observed for Be7 in sample 1. Be7 is produced in large quantities in the graphite of Target E. It is likely that the grey cover of the last teeth is a layer of graphite evaporated from Target E. The measured activity of both samples show a large excess of Ag110m. It is obvious that it comes from the silver solder used to fabricate the collimator; in particular, the sample from the back side contains even more Ag110. The golden shiny stripe at the back side (Figure 7) is probably due to the diffusion of Ag into Cu. The reason for the large amount of Na22 is not clear yet. It might come from surrounding materials.

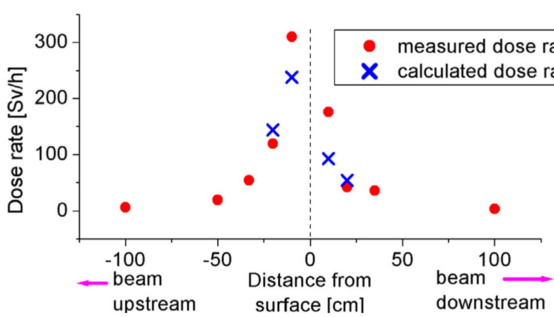

Figure 10: Comparison of calculated and measured dose rates at the collimator, measured along the beam axis.

Dose Rates

Dose rates at the collimator were obtained from the nuclide inventory calculated with MCNPX2.5.0 and Cinder'90 by applying dose conversion factors. The calculation was done beforehand, in order to plan the shielding for the camera and electronics in the hot cell. Later the dose rates were measured in the hot cell. Figure 10 shows the calculated and measured values. The agreement is better for larger distances from the collimator, because the calculated dose rate is an average over a larger region and cannot reproduce hot spots at the inner surface. The dose rate in 10 cm from the beam entry was 310 Sv/h.

SUMMARY

Despite of its high activation a detailed optical and geometrical inspection of the collimator KHE2 was performed within one week. Peak activation levels of ~500 Sv/h were measured close to the irradiated surface. Photos from the inside and outside of the collimator were taken and the horizontal opening was measured. No swelling was observed. The gamma spectroscopy of two samples compared to calculations revealed that the grey surface inside the collimator is probably graphite. In both samples, Ag110m from the silver solder was present in large amounts.

Besides the successful inspection, it was demonstrated that highly activated components can be safely handled in the facilities available at PSI. This is important in case of a failure of a component.

Even though the collimator looks intact from the outside, it was not possible to gain information about the mechanical stability (e.g. cracks) and the thermal conductivity. Since the thermal conductivity is known to decrease during irradiation, the actual temperature in the collimator might be higher than predicted. For 2012, we plan to replace KHE2 by a replica. This will allow detailed analysis of the irradiated item, taking larger material samples for measuring the thermal conductivity as well as its mechanical properties.

ACKNOWLEDGMENTS

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