Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: Naja de la Cour *et al* 2018 *J. Phys.: Conf. Ser.* **1021** 012082

IOP Conf. Series: Journal of Physics: Conf. Series **1021** (2018) 012082 doi:10.1088/1742-6596/1021/1/012082

Implementation of the proton beam instrumentation into the proton beam instrumentation plug

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Abstract. The 5 MW proton beam to be delivered to the ESS spallation target must be tuned to its nominal value and controlled at all times. To achieve this, a suite of beam diagnostics has been proposed and is currently been designed. It is located in two plugs, the Proton Beam Window (PBW) plug and the Proton Beam Instrumentation Plug (PBIP). Here we present the design concept for the PBIP imposed by the beam physics requirements as well as by the high power target environment, i.e. material lifetime, remote handling and waste management.

1. Introduction

The ESS accelerator delivers to the target a 125 MW peak power, 2.86 ms pulsed proton beam with a low emittance of 1 mm mrad. Even a fraction of this beam is capable of inducing damage in material it intersects. The chosen beam delivery strategy is to raster the beam in order to reduce the high current density below the permanent damage threshold of the target materials. Simultaneously, the transverse beam extent can be constrained to limit energy deposition outside of the aperture[1, 2]. The required beam control is enabled by a suite of diagnostics, located mainly in the target area[3], and composed of two imaging systems, one multi-wire grid and three aperture monitoring systems. They permit measurement of the beam transverse profile, the beam divergence, the position of the beam with respect to the Target Wheel (TW), and the fraction of the beam outside the nominal aperture that could potentially cause damage, or pollute the neutron flux delivered to the neutron instruments. The two imaging systems are both supported by the PBIP and they provide images of the beam intersecting the PBW at the entrance of the target monolith area and the target wheel. The image analysis provides the location of the beam at the PBW and at the TW in the general ESS coordinate system, and also the current density distribution on both PBW and TW from which a measurement of the raster beam pattern can be compared with the defined nominal distribution of the beam on the TW. The accuracy of the measurement should provide the position of the beam to within ± 1 mm and the flatness of the density to within 20% of the mean peak current density. The optical system design is highly constrained by the required performance of the imaging system, and also by geometric and shield integrity requirements in the target area[4].

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The multi-wire grid, also supported by the PBIP, provides two 1-D profiles of the beam distribution. It is based on the reading of the current generated by the interaction of the beam with the wires[5]. The analysis of the profiles provides the projected current density, the position of the beam and the extent of the beam along each axis. This system provides redundancy to the imaging systems, but these two systems are not equivalent. Although the grid may be more sensitive than the imaging systems, it does not detect some errant beam conditions that could damage the target. Similar to the imaging system, the grid has to be positioned with ±0.5 mm accuracy. It can be interlocked to the machine protection system (MPS).

The aperture monitoring systems are located in three positions along the beam path: the first one is at the pivot point of the beam raster optics where the beam has to be in a fixed position and highly focused; the second one is in the PBW plug; and the third one is supported by the PBIP. These systems are based on two techniques to measure the current intersecting the defined aperture: metallic blades and thermocouples. The metallic blades measure the current induced by the intersecting beam. It is a fast response detector that can detect errant beam condition in the μs timescale. The thermocouples measure the current outside the defined aperture at the *s* time scale. The system detects errant beam conditions within a pulse, and also accumulation of small beam losses at the aperture. Errant beam conditions detected by these monitors can trigger the MPS.

In the following, we will focus on the design of the PBIP which supports the integration and the operation of the diagnostics suite.

2. Target environment

The PBIP is situated inside the Monolith in the ESS Target station (Fig. 1 and 2). It is positioned between the TW and the PBW, where it supports the beam instrumentation. The PBIP, and thus part of the instrumentation it supports, is situated in a high radiation environment. The PBIP and its components will receive high doses of secondary particles produced by the proton beam on the PBW, the target and the aperture. Therefore, materials of the PBIP and its components will be heated by energy deposited from these particles, and also degraded by accumulated radiation damage. The PBIP is located in the monolith shielding 1.5 m from the target and as a result, it will receive a higher dose at its bottom. Thus it will be experiencing a high temperature gradient, which will have to be controlled to manage the resulting mechanical deformation that could misalign the instrumentation components.

3. Design concept

The design of the plug should satisfy requirements issued from the diagnostics and from the target environment. The design should allow the diagnostics to be positioned with a typical accuracy of 0.5 mm, should minimize distortion and movement during operation, and should maintain the shielding integrity. The instrumentation lifetime is expected to be 55GWh [1]. However, in case of failure, instruments should be independently replaceable. Figure 2 shows a model of the PBIP. In the figure, one can see a solid base in which slices can be inserted. Each of these slices support a diagnostic instrument. The concept of slices permits each instrument to be maintained independently of the other ones. It is a single independent slice, so the alignment precision of the slice depends on the instrument it supports. For instance, for the optics, the precision should be in the range of 1 mm in position, but 1 mrad or less in angle. To achieve this, the mirrors are mounted on specially developed mounts that can maintain the mirror alignment. The slice is assembled horizontally in the loading bay before it is installed in the PBIP. The alignment precision at this stage is within the μm and μrad range. During lifting and installation of the slice into the PBIP, the rigidity of the mounts guarantee the that the pre-alignment is maintained. While being slowly lowered by the robotized crane above the PBIP, the solid base guides the slice into its position with 6 mrad accuracy.

[1] 2 years of operation at full power, 5500 h at 5 MW

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In addition, the rigidity of the PBIP structure guarantees good alignment repeatability. This applies for the other slices too, where the grid and aperture monitors should be positioned to within 0.5 mm from the nominal beam axis.

The thermo-mechanical deformation of the PBIP structure has been studied, using MCNPx[2] and ANSYS[3] codes. The energy deposited into the structure, obtained from MCNPx, is used for the thermo-mechanical simulation studies with ANSYS. The initial results showed several degrees distortion to the structure. The induced angular motion to the first mirror of the optics assembly would reduce image intensity, degrade resolution, and add distortion beyond acceptable limits. With the addition of cooling in the PBIP, more acceptable results were achieved, which can be seen in Fig. 3. With an angular distortion of the order of 3 mrad, the degradation of the imaging system performance reaches its limit. More cooling can solve the problem.

3.1. Shielding integrity

The apertures in the plugs, from the point of view of the shielding, represent a hole in the shield and increase the environmental radiation level. As a result, the tendency in practice is to reduce the apertures, and add chicanes. This presents serious challenges to the optics design. To ensure the performance of the imaging system, a large aperture is needed, and the traditional 90 degree chicane with the rule of a 1:7 offset[4] is not easily achievable. In the current design, a large 100 mm aperture is provided in the PBIP optics slices[4]. Figure 4 depicts the element of the optics assembly in the PBIP that looks toward the TW. The other assembly that looks toward the PBW is similar. The MCNPx shielding calculation with the optics in the configuration shown here proved that the concept is acceptable. The additional radiation coming through the optics slices is attenuated by a passively cooled shielding block placed on the top of the PBIP. It is removable so the slices can be replaced.

3.2. Remote handling and waste management

In each extraction arm of the PBIP slices, remote handling features are included to be able to extract the component into a cask and transfer it to the Active Cells facility. Components are vertically extracted and can be exchanged individually. The whole slice is considered to be expendable after it has been removed from the PBIP. However, a possibility to design the slice in pieces is under study. The Monte Carlo simulation on the target model has shown that only the bottom part of the assembly needs to be considered as radioactive waste. Having the top part of the slices re-used could reduce the waste production by more than 50%. The radioactive waste management drives some aspect of the design of the PBIP. The immediate impact is a reduction of the overall cost, as long as the specifications for the instrumentation performance can be achieved. Also, the parts of the plug with the instrumentation and the cables should follow a recycling path. This includes the radioactive cooling time. The cost of storing these radioactive elements will be studied so that the real benefit can be evaluated – optimum waste management is included in the global performance of the facility.

4. Concluding remarks

The design for the PBIP has seen significant progress. The design of the plug which supports critical diagnostics for tuning and monitoring the beam on target has addressed most of the requirements driven by from the instruments' performance and by the radiation environment. Technical solutions are under evaluation to enable required performance of the instrumentation, and the large 100 mm aperture for the optics assembly has been shown to be compatible with the shielding requirements. The rigid structure of the plug and the alignment procedure is still under design consideration. However, critical alignment tolerances are well defined and drive the design.

[2] https://mcnpx.lanl.gov
[3] http://www.ansys.com
[4] 1 for the aperture 7 for the length after a 90 degree chicane

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The waste management is also considered in the design. Producing less waste is one of the objectives. It reduces the running cost of the facility. At the same time, a recycling circuit for the upper parts of the plug, including the instruments and cables should be studied to fully evaluate the real benefit.

The design of the PBIP is mature, and it continues with few remaining issues to be addressed.

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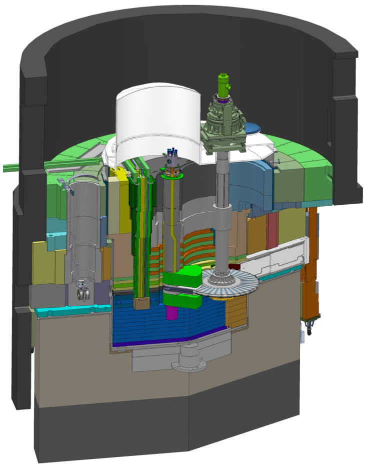

Figure 1. Cut through the Target Monolith.

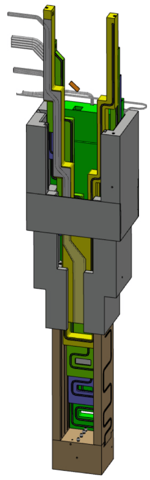

Figure 2. . PBIP design showing the slices supporting the instruments

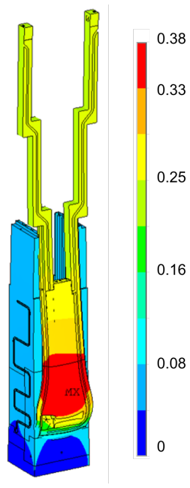

Figure 3. . PBIP thermal deformation at 5MW beam on target. Color scale is in mm

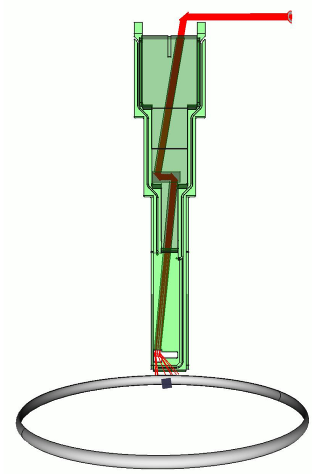

Figure 4. Part of the optics assembly supported by the PBIP.

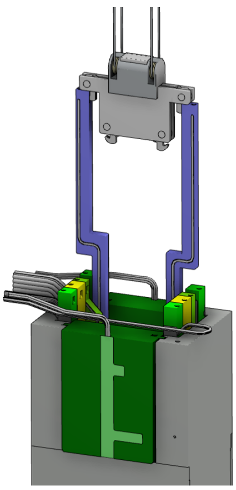

Figure 5. Handling tool crane to install or remove a PBIP slice.