DESIGN OF THE T2K TARGET FOR A 0.75-MW PROTON BEAM*

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Abstract

The T2K experiment began operation in April 2009 [1]. It utilises what is projected to become the world's highest pulsed power proton beam at 0.75 MW to generate an intense neutrino beam. T2K uses the conventional technique of interacting a 30 GeV proton beam with a graphite target and using a magnetic horn system to collect pions of one charge and focus them into a decay volume where the neutrino beam is produced. The target is a two interaction length (900 mm long) graphite target supported directly within the bore of the first magnetic horn which generates the required field with a pulsed current of 320 kA. This paper describes the design and development of the target required to meet the demanding requirements of the T2K facility. Challenges include radiation damage, stress waves, design and optimisation of the helium coolant flow, and integration with the pulsed magnetic horn. Conceptual and detailed engineering studies were required to develop a target system that could satisfy these requirements.

T2K SECONDARY BEAMLINE

A primary 30 GeV proton beam is used to generate a secondary beam of pions by interaction with a two interaction length graphite target [2]. The target station houses the target and three magnetic horns as shown in Figure 1. The proton beam enters the target station through a proton beam window which separates the beamline vacuum from the target station and decay volume which is filled with helium at atmospheric pressure. Between the window and the first horn assembly containing the target is a graphite baffle/collimator to protect the downstream components in the event of a miss-steered beam. The target is supported directly inside the bore of the first magnetic horn, which directs pions of the required sign in a forward direction. The second and third horns further focus the pion beam which decays to generate the ν_μ beam as the pions traverse a 96 m long decay volume. The remnant hadron beam is deposited in a hadron absorber or beam dump situated at the far end of the decay volume. Approximately one third of the beam power is transmitted into the kinetic energy of secondary particles including pions, another third is deposited in the beam dump and the remainder into the decay volume walls and target station shielding. Less than 5% of the proton beam power is deposited in the target itself as heat.

The beam window, baffle, target and magnetic horns are supported beneath shielding modules to permit replacement and to accommodate a potential change in off-axis angle for the facility if desired for a future upgrade. Each support module assembly is contained within the helium vessel. The building is equipped with a remotely operated crane to enable these highly activated components to be lifted from the beam line and lowered into a Remote Maintenance Area adjacent to the beam line.

The beam window, target and horns installed for Phase I have been designed for operation at an average beam power of 750 kW. The T2K roadmap foresees an upgrade to 1.66 MW by 2014 and there is an ambition to achieve 3-4 MW within the lifetime of the facility. Since the target station, decay volume and hadron absorber are fixed installations and cannot be maintained or replaced after activation, they were all designed for operation at the highest envisaged beam power of 4 MW.

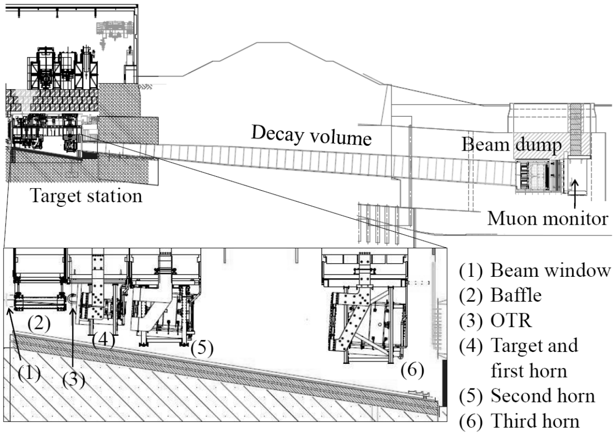

Figure 1: T2K secondary beam line.

TARGET DESIGN ISSUES

Nuclear grade IG430 [3] graphite was chosen as the pion production target material for T2K since it is able to withstand the stress waves generated in it by the pulsed proton beam. The power density generated by the pulsed proton beam is approximately proportional to the atomic number, consequently a low-Z material is favoured for the pion production target. Graphite has an attractive combination of high thermal conductivity, high heat capacity, low expansion coefficient, low modulus and a sufficiently high strength which is retained at high temperatures. The main disadvantage of graphite compared with e.g. beryllium is that it suffers

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significantly more from radiation damage, undergoing dimensional changes and a reduction in thermal conductivity [4]. However, both of these effects have been shown to be reduced at an elevated irradiation temperature, with minimum dimensional change occurring at around 800°C [3]. Helium cooling was chosen since a gaseous coolant both minimises the absorption of pions and avoids shock waves that would be generated by secondary particle interactions with a liquid coolant, e.g. water. Gas cooling at moderate pressures and velocities typically generates a lower heat transfer coefficient than water, and the helium cooling flow can be tuned to some extent to permit the graphite to operate at the desired elevated temperature; this requires low oxygen contamination of the helium to minimise oxidation [5]. Another advantage of helium cooling is low activation. Some key beam and target parameters are listed in Table 1.

Table 1: Key Beam and Target Parameters

Proton beam kinetic energy	30 GeV
Average beam power	750 kW
Protons per pulse	3.3×10^{14}
Beam cycle	2.1 s
Beam size at target (1σ)	4.24 mm
Target material	Graphite (Toyo Tanso IG43)
Target radius	13 mm
Target length	900 mm (2λ)
Heat load on target	23.4 kW
Peak temperature rise per beam pulse	180 K
Helium flow rate	32 g/s
Helium outlet pressure	0.9 bar

TARGET OPTIMISATION

The graphite target rod is supported within an outer titanium alloy Ti-6Al-4V canister, with an intermediate graphite tube to separate the helium flow and return. The ANSYS Mechanical and CFX [6] finite element packages were used to optimise the target design. This was necessary to achieve the required cooling path while keeping the overall pressure drop of the system within the available limit of 0.8 bar. A cross section of the optimised target design is shown in Figure 2. The temperature distribution of the target calculated by the CFX code using the K-epsilon turbulence model is shown in Figure 3. This was calculated using a thermal conductivity reduced by a factor of 4 from the value for new material, equating to material than has experienced a radiation damage of 0.25 displacements-per-atom, the value calculated using the MARS code for 1 year of operation. The helium cools the entry window which deflects the flow to pass through six angled holes in the graphite target head block to then flow between the titanium outer tube and the intermediate graphite tube. At the downstream end the flow turns through 180°, cooling the downstream window before being heated by the graphite rod on its return. Thus all the thin titanium alloy components are maintained at a low temperature in order to maximise their mechanical properties. The beam window thickness and profile was optimised to minimise the combined stresses resulting from the pressure stress, the thermally induced bending stresses and the pulsed beam microstructure induced stress waves [7]. Figure 4 shows the optimized profile of the beam window, tapering out from a 0. 3mm thick dome within the beam footprint to a 7 mm thick plate. The inverted profile serves to increase the cooling of the surface and to direct the helium flow downstream, thereby reducing the pressure drop of the system. Figure 5 shows the flow lines and velocities generated by CFX and Figure 6 shows the associated pressures.

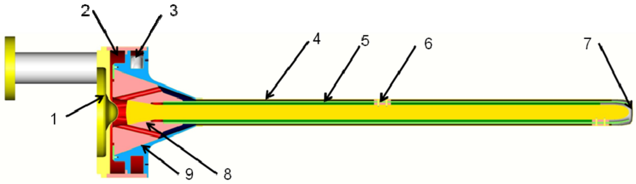

Figure 2: Cross-section of optimized target design showing 1) beam entry window, 2) helium inlet annulus, 3) helium outlet annulus, 4) titanium outer canister, 5) intermediate graphite tube, 6) streamlined separator, 7) downstream window, 8) bonded graphite joint, 9) diffusion bonded graphite-to-titanium joint.

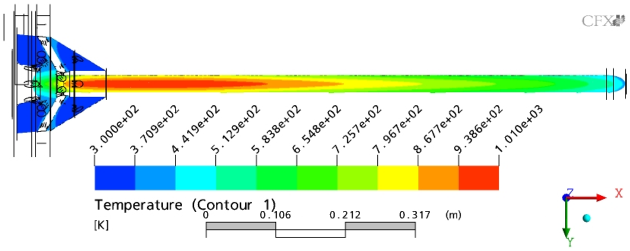

Figure 3: Temperature distribution in target graphite for 750 kW beam power acting on radiation damaged graphite with a thermal conductivity of 20 W/mK. Maximum temperature in graphite 1010K (737°C).

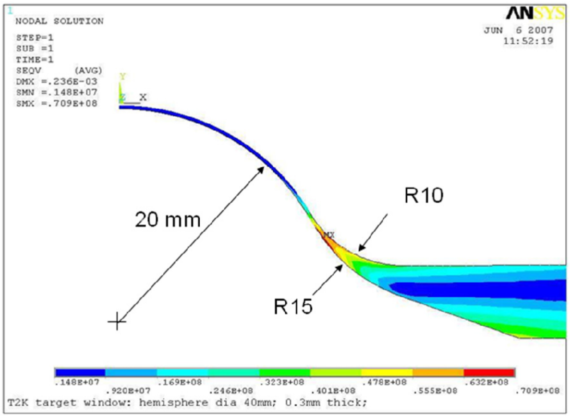

Figure 4: Axi-symmetric 2D ANSYS model of titanium alloy beam entry window showing stresses of 71 MPa generated by the helium pressure.

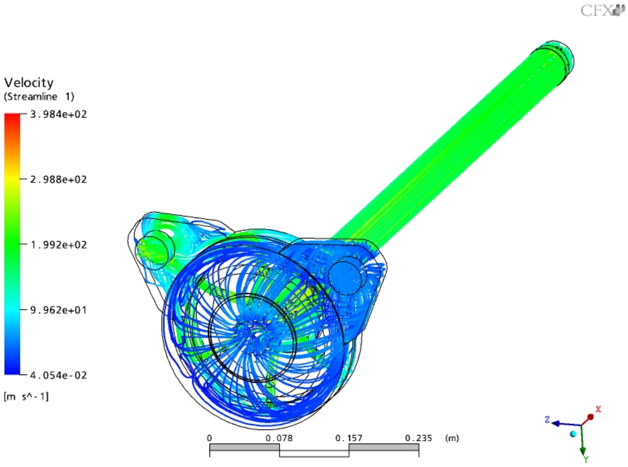

Figure 5: Helium flow lines within the target, showing a maximum velocity of 400 m/s.

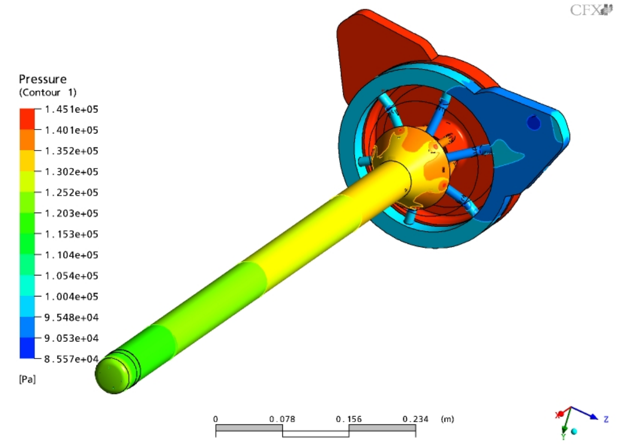

Figure 6: Calculated helium pressure contours (Pa) showing pressure drop of 0.792 bar from helium inlet to outlet.

TARGET MANUFACTURE

The first Mk 1.0 target installed in the T2K facility was manufactured in Japan by Toshiba Ltd following the above design but using a clamped metal seal rather than a bonded joint design. The second target was manufactured at RAL using the complete design described above. All critical stages of the manufacture were prototyped, for example the diffusion bonding process that was used to bond the graphite target head to the titanium housing. Figure 7 shows a sectional view of the graphite-to-titanium alloy diffusion bonding test piece carried out by the Special Techniques Group at Culham Laboratory. The completed Mk 2.0 target is shown in Figure 8.

By the end of its first year of operation in 2010, the target was operating successfully at beam powers of up to 100 kW.

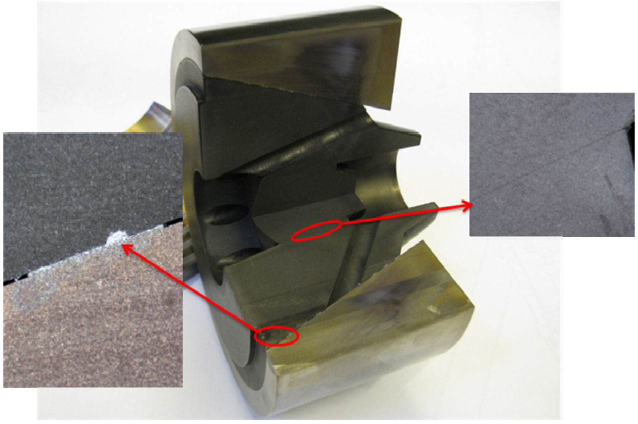

Figure 7: Diffusion bonding test piece of graphite-to-titanium joint using an intermediate aluminium layer, shown in the close-up on the left, with a graphite-to-graphite bonded joint shown in close-up on the right.

Figure 8: Completed target ready for integration with horn.

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