DESIGN AND DEVELOPMENT OF THE T2K PION PRODUCTION TARGET

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Abstract

The T2K experiment will utilise the highest pulsed power proton beam ever built to generate an intense beam of neutrinos. This uses the conventional technique of colliding the 0.75 MW 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 system required to meet the demanding requirements of the T2K facility. Challenges include radiation damage, shock waves resulting from a 100 K temperature rise in the graphite material during each beam spill, 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 and could also be replaced remotely in the event of a target failure.

T2K ν FACILITY AT J-PARC

The Tokai-to-Kamioka (T2K) [1] experiment currently being commissioned in Japan will direct the world's most intense conventional neutrino beam from Tokai to the Super-Kamiokande far detector [2] some 295 km distant, in the study of $\nu_\mu \rightarrow \nu_e$ oscillations. The neutrino beam is directed at a small off-axis angle to the detector in order to generate a quasi-monochromatic ν_μ beam tuned to the oscillation maximum at 0.5 – 1 GeV. The ν_μ beam is a tertiary beam produced from the decay of pions, which are themselves generated by the interaction of a 30 GeV proton beam with a two interaction length graphite target. A system of three magnetic horns focuses the required sign of pions in a forward direction. Consequently the ν_μ beam generated by the decay of pions as they traverse a decay volume is also well focussed. In order to maximise the capture of forward momentum pions, the target is supported directly inside the bore of the first magnetic horn.

The proton beam enters the target station through a proton beam window which separates the beamline vacuum from the target station and decay volume 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 target and horn in the event of a miss-steered beam. The remnant proton beam is deposited in a hadron absorber or beam dump situated 100m downstream of the target 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 required. The components 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. Consequently there is a need to begin the design of replacements for these components for higher power operation. 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.

BEAM EFFECTS ON GRAPHITE TARGET

Table 1: 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
Pulse width	4.2 µs
Bunch structure	8 bunches
Bunch length / spacing	58 ns / 598 ns
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
Cooling medium	Helium (g), 32 g/s

Table 1 lists key beam and target parameters used for Phase I operation. The target is a polycrystalline graphite rod, a commonly used low-Z target material as it has a low thermal expansion coefficient and sufficient strength to make it resilient to thermal shock. Graphite also retains its mechanical properties at high temperature. It does however have a relatively low strength compared with metals and care has to be taken with implementation of the engineering design.

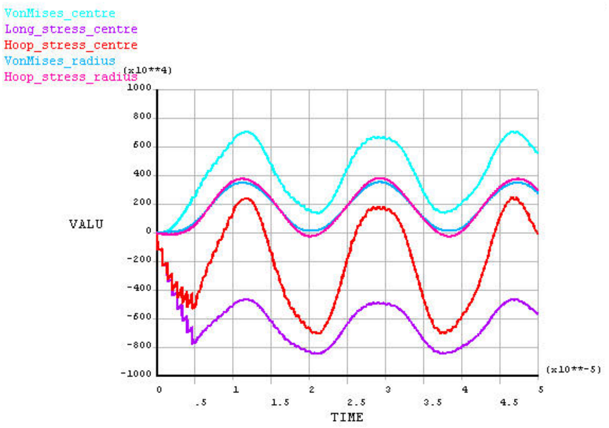

Figure 1: Stress wave development in graphite target rod during 8-bunch pulse and subsequent resonance.

A simple calculation of the expected stress wave magnitude generated in the graphite from the beam pulse is $\sigma = E\alpha\Delta T = 8.3$ MPa, where E = Young's Modulus, α = linear expansion coefficient and ΔT the temperature rise. The ANSYS FE code was used to calculate the effect of the multi-bunch pulse structure. Figure 1 shows the radial and Von Mises equivalent stress wave profile at the target centreline as it develops during the beam spill and the subsequent oscillations. The maximum Von Mises stress developed was calculated to be 7 MPa giving a safety factor of 5 against tensile strength.

A MARS simulation calculated the radiation damage of the graphite to be 0.15-0.2 displacements per atom (dpa) per year. The fluence is around 10^{21} protons/cm^2 per year, a level at which this grade of graphite has disintegrated in tests carried out at BNL [3] at room temperature, although lifetimes of polycrystalline graphite targets at fluences of 10^{22} p/cm^2 have been reported at LAMPF and PSI. Data on radiation damage in graphite generated by thermal neutrons [4] reports shrinkage and a reduction in thermal conductivity which would result in an increase in thermal stress. The data shows that shrinkage can be minimised by maintaining the graphite at a temperature of around 700-800°C, a temperature which also significantly reduces the reduction in thermal conductivity.

OUTLINE OF TARGET DESIGN

The heat load deposited in the target is sufficiently low that cooling by gaseous helium is possible. Helium cooling is preferable to water for several reasons:

- gas cooling permits targets to run at higher temperatures than would be possible with water cooling.
- the strongly pulsed proton beam would generate secondary heating in cooling water, resulting in high pressure shock waves. It is thought this mechanism has caused target failures in some facilities [7].
- minimal activation of coolant

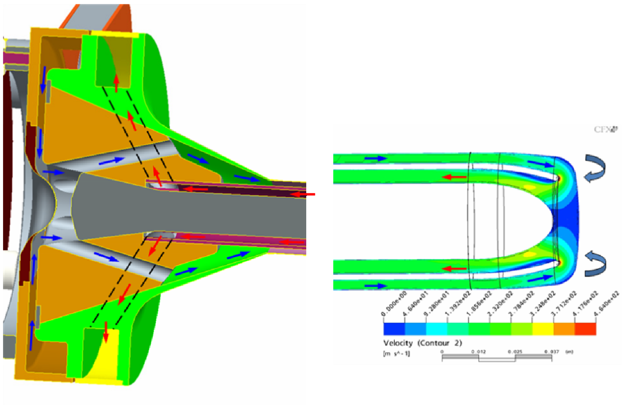

Figure 2: Upstream target design (L) and velocity contours from CFD analysis at downstream window (R).

A difficulty with operating the graphite at high temperature is that if it were to come into contact with the helium atmosphere of the target station and decay volume, the trace quantity of air present would oxidise the graphite and reduce the target lifetime [5]. To avoid this, the graphite is sealed within a thin titanium alloy container which includes thin single skin entry and exit windows. The target and its container walls are cooled by a single circuit of high purity, high velocity helium. The alloy Ti-6Al-4V is used for the container and windows since it has a relatively high strength, low Z and low thermal expansion coefficient making it one of the few materials able to withstand the shock wave stresses generated within it by the pulsed proton beam. It is also known to retain its mechanical properties albeit with a reduction of ductility at proton fluences up to 10^{20} p/cm^2 [3]. However as with all metals, titanium loses strength at elevated temperatures and it is necessary for the helium to cool both the entry and exit windows before cooling the target rod. It was also necessary to achieve a pressure drop across the target within a budget of 0.8 bar at 32 g/s at a nominal outlet pressure of 0.9 bar, including a 30% cooling margin. A cooling flow path has been devised and optimised to achieve this.

Figure 2 shows a cross-section of the upstream target assembly with a plot from a CFD model showing velocity contours of the flow around the downstream window. The graphite target rod is bonded to a graphite head using Nissinbo ST-201 adhesive in a conical joint. The graphite head is diffusion bonded to a titanium manifold block using a thin interface layer of pure aluminium, a technique developed at Culham Laboratory, UK. The first target prototype used for operation on day 1 was manufactured in Japan by Toshiba using screwed and bolted joints in place of these bonded joints, but otherwise with a similar geometry. The titanium alloy manifold block, tube and windows are fully welded. The helium inlet enters an annular buffer volume before flowing through a 5 mm gap across the entry window. The window profile minimises the combination of stresses resulting from the differential gas pressure across the window, the transient thermal stress and the shock wave stress. The dominant requirement is for destructive (rather than constructive) interference between consecutive bunch-to-bunch stress waves in the window material, resulting in an optimal thickness of 0.3 mm within the beam footprint [6]. The curved profile tapers out to an 8 mm thick plate to accommodate the pressure load while the inverted shape improves cooling and directs the helium flow. The helium then flows through 6 angled holes in the graphite head to an outer annular coaxial channel. The helium cools the titanium outer tube before it performs a 180° turn at the downstream window as shown in Figure 2. The geometry here has been carefully optimised to minimise the pressure drop while maintaining adequate cooling of the downstream window. The helium returns along an inner annular coaxial channel separated from the outer channel by a 2 mm thick graphite tube bonded into the graphite head. The helium cools the target rod then flows to an outlet annular manifold through 6 angled holes in the graphite head which are interspaced between the 6 inlet holes. The pressure drop across the entire target flow path was 0.85 bar compared with the CFD simulation of 0.79 bar. The maximum target temperature is calculated at 736°C assuming a degradation in thermal conductivity of 75%.

Figure 3 shows a photograph of the target being installed into the horn. The target is supported as a cantilever from a plate mounted upstream from the horn 1 support frame, with a nominal 3 mm radial separation between the target outer tube and the inner bore of the magnetic horn. The clearance minimises the transmission of transient mechanical loads to the target generated by the pulsed horn current of 320 kA. A high resistance electrical connection to the support prevents voltage breakdown from capacitive coupling between the target and horn. The helium pipes are isolated using thick walled alumina tubes where the joint to metal is achieved by diffusion bonding with a thin aluminium intermediate layer, a similar technique to that used for the target graphite-to-titanium joint. Commercially available brazed ceramic-to-metal joints were avoided as failures with these have been reported [7]. The target assembly is sufficiently rigid that the end deflection resulting from the cantilever support is less than 1 mm which is deemed acceptable for uniformity of pion production. The maximum deflection resulting from a beam misaligned to the target was calculated at less than 1 mm with low stresses generated.

The target supports and helium pipe connections have been designed to permit failed targets to be replaced. The target support plate was accurately aligned and normal to the horn axis so that replacement targets are automatically installed on the horn centreline. Also mounted on the target support plate are helium quick-connectors in which the hubs on the replacement target helium pipes locate. A bellows and concentric pipe support on the target side accommodates thermal expansion and tolerances of the helium pipes while also supporting the hubs sufficiently for location in the mating fixed parts. When operating at 750 kW a cool-down period of 1 month is required before the shield plug supporting the horn 1 module with a failed target can be lifted from the beamline and lowered into a remote maintenance area in the Target Station. This is equipped with manipulators and a shield window. Specially designed remote handling equipment is offered up to the target support to remove the failed target, place it in a shielded flask, and install a replacement target into the horn so that it can be installed back in the target station.

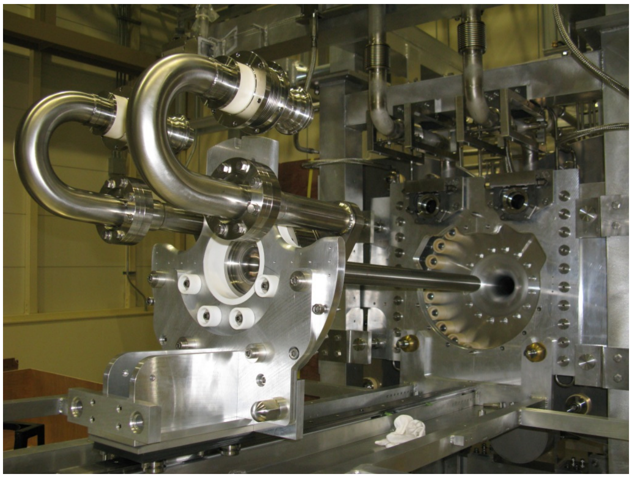

Figure 3: Target assembly being installed in horn.

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