1 Introduction

The PMT enclosure and support system is designed to:

- Position the energy plane PMTs inside the detector for best light collection,
- Protect them from the high pressure xenon,
- Provide the PMT signal and power interfacing,
- Be as radiopure as reasonably possible,
- Accommodate a movable radioactive source for calibration.

Fig. **??** shows the PMT enclosure and support system:

Figure 1: NEXT100, PMT Enclosure and Support System

2 Description

A brief system overview is as follows:

- PMTs are sealed into individual pressure resistant, vacuum tight, radiopure OFE copper enclosures (PMT Module).
- The PMT modules are all mounted onto a single OFE copper carrier plate that attaches to the internal copper shielding bars (ICS) lining the main cylindrical vessel.
- Sapphire windows are clamped by copper rings to the front end of the enclosure, with an O-ring, or a metal C-ring seal. A similar backplate of copper seals the back side of the enclosure.
- The PMT is optically coupled to the sapphire window backside via a silicone optical pad; springs are used to provide contact force.
- The sapphire window is coated with indium tin-oxide (ITO) on the entire front surface, for electrical conduction, this is overcoated with tetraphenyl butadiene (TPB) wavelength shifter, over the exposed window surface, to shift VUV light to blue. Electrical connection of the ITO to the enclosure is made by using a conductive polyethylene (UHMW) pressure ring between the clamp and the window.
- PMT bases are potted with heat conducting epoxy to flexible copper cables which then connect to the enclosure backplate.
- PMT cables are enclosed in individual pressure resistant, vacuum tight tubing conduits of copper or stainless steel which attach to each enclosure using a compression fitting. This fitting attaches to the enclosure with pipe threads, epoxied with Torr-seal
- Cable conduits all lead to a central manifold fabricated from copper pipe, connecting with a compression fitting (also pipe thread /Torr-seal).
- PMT cables route through central manifold to 32 or 41 pin CF feedthroughs on a CF stainless steel octagon, outside the lead shielding.

- High vacuum(p< 10^{-6} torr) is applied at octagon port; good vacuum (p< 10^{-4} torr) is maintained inside enclosures through conduits, well below Paschen minimum, avoiding sparkover or glow discharge across PMT pins.
- Vacuum source is a large vacuum tank of 20-30m^3; in case of sapphire window failure, this limits pressure buildup in central manifold, avoiding a Super-K chain reaction implosion scenario. It also retains EXe, as a fast vacuum gate valve is installed on the opposite side of the vacuum tank. Xenon permeation through seals is recovered with a cold trap inside the tank, ahead of the vacuum pump.
- Vacuum inside enclosure requires good thermal management, base cooling is by conduction into enclosure through a special low force heat spreader plate.
- PMT Modules are clamped into copper heat conduction flanges attached to the copper carrier plate.
- Heat is carried to pressure vessel flange by conduction through copper carrier plate; 7 C total temp rise.
- PMT is operated in +HV mode with photocathodes grounded; using a differential mode between anode and first dynode.

Figure 2: PMT Module

This design requires a vacuum inside the enclosure, so as to detect the presence of any Xe leakage. Without vacuum the enclosure would eventually pressurize and destroy the PMT. Xenon leakage through seals will be recovered in a cold trap in the vacuum system. The primary concern with vacuum is possible flashover across the PMT pins; this is avoided by maintaining enough conductance through each conduit (with cable inside) in conjunction with a high vacuum in the central manifold to keep enclosure pressure several orders of magnitude below the Paschen minimum (for Xe).

2.1 PMTs and Bases

A range of PMT solutions were presented in the CDR; we have now found the R11410-10 low background PMT from Hamamatsu to be available (fig 3.2 pg 33), and have chosen to use them. These PMTs require up to 1750V for operation. They can only withstand 2 barg external pressure, and so may not be exposed to the xenon. These larger PMTs do not appear suitable for pressure hardening, unlike the smaller 1 inch cube PMTs (Hamamatsu 8560).

The PMTs may be operated with (either) the cathode at full negative voltage, or at ground; to run at negative voltage the PMT can itself must run also at negative voltage. We have designed and fabricated a prototype insulator from polyetherimide (PEI, Ultem-1000) that may be sufficient to provide insulation, however, our baseline approach is to leave the PMT and photocathode at ground, If this latter option is chosen the the PMT body must either be insulated from the enclosure or the entire enclosure/carrier plate/conduit/central manifold system must be insulated from the vessel. Both options appear feasible, by either installing heat shrink PVC insulation around the wide part of the PMT body, or by using PEEK and Kapton insulation sheets at the two flange interfaces on the pressure vessel. Drawings and illustrations show both options simultaneously.

The PMT bases will be soldered to the pins, after shortening them. The backside of the base (with all resistors) will be potted using a thermally conductive, electrically insulating epoxy to a flexible heat conductor. This is a short section of braided copper cable (grounding strap) that attaches to the enclosure backplate with 4 screws. . PMT resistor heat is then dissipated through direct thermal conduction into the enclosures, proceeding out through the clamps and carrier plate to the pressure vessel flange. It is likely some heat will dissipate into the xenon as well, however maximum temperature rise from conduction alone is 5-10 C, which is acceptable.

2.2 Enclosures

The enclosures are fabricated from OFE (OFHC) extra heavy wall copper pipe; they have a sapphire window on one end, and a simple cap on the other end. The sapphire window and back cap are sealed to the enclosure using O-rings, or if feasible, Helicoflex metal C-rings. The ends of the enclosure are threaded and a screw-down ring is used to apply the sealing force. Leakage thorough O-rings (total for 60 enclosures) is calculated to be no more than 300 gm/yr, which will be recovered using a cold trap in the vacuum system. As an option, tests are underway to see if a Helicoflex metal gasket (C-ring) can seal against the sapphire without damage; if so, a lower leak rate may be advantageous.

The copper pipe wall thickness is left as thick as possible, 1 cm, so as to provide shielding; this is far in excess of that required for pressure resistance. The copper will be checked for radiopurity, if

The windows are inserted from the front side and the PMT is inserted from the backside. This is required in order to use pipe, as there is an internal flange for the window to bear against, containing the O ring groove. This apparent disadvantage has an advantage: the window may be replaced without affecting the PMT and vice versa. The alternative is to make the enclosure larger in diameter and machine it from bar stock, both are undesirable.

The PMT is optically coupled to the window backside using silicone optical pads of 2-3mm thickness; use of grease is not advisable since any type of grit between the window and the PMT face can scratch the window where tensile stress from pressure is highest, leading to premature window failure (see window section below).

The PMT is held against the optical pad by a spring assembly on the backside; these springs are captured with PEEK interface collars. bears against a retaining ring held in a groove machined into the ID of the enclosure. Thus the PMT can be installed independently from the window. If the base is not soldered to the pins (using spring connectors only) the base can be serviced or replaced without disturbing the optical coupling of the PMT to the window.

Cables from the base exit through a vacuum tight compression tube fitting into a copper tube that serves as both a cable conduit and a vacuum port for the interior. The enclosure has sufficient wall thickness to be tapped for 1/4 in. pipe threads, thus the tube fittings can be screwed in, using Torr-seal high vacuum compatible epoxy for a thread sealant. Locating these fitting on the side of the enclosure allows the back cap to be removed for PMT and base access without disturbing the conduit fitting. The fittings are nominally straight, so as to allow a larger bend radius in the conduit, however a 45 deg. fitting may be feasible. 90 degree fittings likely have too small a bend radius for the cable.

2.3 Sapphire Windows

The sapphire windows will first be coated on one side with indium tin oxide (ITO) to form a transparent (410nm and above) conductive coating. The conductivity is required to prevent electric field penetration into the PMT. The entire front surface will be coated so as to make electrical contact Over this coating a layer of TPB is evaporated, which will shift any direct light (EL or S1) to a wavelength that has high transmission through the sapphire window and the optical coupling pad. This coated side faces outward, and electrical contact of the ITO layer to the antirotation washer is provided by using a PEEK pressure ring that is either 30% carbon filled, or metalized unfilled PEEK. Alternatively, instead of ITO, a transparent mesh screen may be used (over a window coated only with TPB), this screen located between the PEEK ring and the antirotation washer.The antirotation washer has a "springy"tab that fits into a milled notch in the enclosure threads which provides metal to metal contact

2.3.1 Window Strength and Reliability

Sapphire is chosen over other possible materials such as Suprasil synthetic quartz, due to its much higher strength; this allows a reasonable window thickness of several mm which improves light acceptance. Finished window cost is lower than Suprasil for equivalent strength and finish. Radiopurity is at present unknown and needs quantification. One can find typical strength numbers for sapphire in manufacturer's literature, however, sapphire, like other brittle materials, has an actual strength that is not only a function of the intrinsic material strength, but also a strong function of the flaw content present (unlike ductile materials, like metals, where intrinsic material strength is the primary determinant of actual strength). For windows stressed in bending, where maximum tensile stress is highest at the surface, surface flaws are more important than internal flaws, and the degree of polish has a strong effect on strength. Large windows show a reduced strength compared to smaller equivalents, since the chance of having a critical size flaw present goes up with increased (stressed) area. Crack growth is the failure mechanism, as no ductility is present which can act to blunt the crack tip. In ductile materials like metals, cracks primarily grow from cyclic stresses, but in ceramics, crack growth is primarily caused by the phenomenon of stress corrosion cracking wherein the presence of moisture, in conjunction with high stresses at the crack tip act to dissociate the atomic bonds, and cyclic stresses do not seem to have a significant effect [**?**]. The degree of polishing, and the size of the window, affect the resulting strength to a significant degree, as crack growth rates are a function of initial flaw sizes. Typically, the crack growth rate is slow until a critical size is reached (at the given stress level), then growth rate accelerates quickly to failure. This crack growth phenomenon is quantified using the methods of linear elastic fracture mechanics (LEFM).

Window reliability against breakage is assured by following a two step method:

First we use LEFM to determining a test-to-actual pressure ratio that will assure that any window which survives the test pressure for a short time, will not contain a flaw large enough to grow at a rate that will lead to failure at the operating pressure after a long time (10 years or more). We still need to determine an appropriate stress level for our window. This is done by using the methodology of Weibull distributions.

We use the Weibull distribution methodology [**?**], [**?**], giving the probability of failure as a function of applied stress and stressed area to determine a thickness whereby 95% of all windows purchased will not fail at the test pressure. We choose this initial survival probability as a balance between excessive test breakage and excessive window thickness. We do not have a strong requirement to minimize thickness for optical transmission, and window cost is dominated by polishing, not material cost. We gain further reliability by specifying a finer polish (20/10) than the typical (60/40) scratch/dig which was used as the basis of the published Weibull parameters. From calculations in the Appendix we find a thickness of 4.9mm is required to achieve this 95% testing survival rate. Prototype windows have been ordered at 5mm thickness. For added The enclosure is designed to accommodate a window thickness of 6mm, and

The O-ring requires a groove to seal correctly and a lip is provided on the enclosure ID for this purpose. As such, the window bears against this lip from both pressure and from clamp ring forces. To avoid high stress concentration at the edge of the lip, a polyimide or PEEK shim of 0.5mm thickness is placed between the window and the lip. Similarly, a PEEK washer is placed atop the window, followed by an metal anti-rotation washer which has a tab that fits into a milled slot in the enclosure threads, then the clamp ring is screwed onto the enclosure, with only enough force to fully compress the O-ring. The anti-rotation washer tab also serves the purpose of maintaining an electrical contact between the window and the enclosure if a mesh screen is used for electrical shielding; this mesh screen will be placed between the PEEK ring and the anti-rotation washer, if used. The clamp ring threads are PTFE anodized and cannot make a reliable electrical contact.

2.4 Conduits and Cables

Conduits are either copper tubing or titanium (grade 1), screened for radiopurity. Nominal OD is 1/4" (6.35mm) wall thickness of .031" (0.75mm). This is sized to give a clearance to the PMT triaxial cable which will provide an acceptable pumping speed, so as to maintain good vacuum inside the enclosure. 3/8" OD tubing is also feasible, and would give better gas conductance, if needed; both will be tested.

There are two failure modes for external pressure, buckling, and elastic limit. At 15 bar external pressure a wall thickness of only .005" is required to avoid collapse, safety factor goes as the cube of the thickness. Where the conduit is bent to an arc, it will deform to an ellipsoidal shape (keystoning). The tube will collapse if yield stress is exceeded. For a maximum aspect ratio of 0.8 (D_{min}/D_{maj}) maximum stress is 20 MPa, well below the yield strength of 1/4 hard OFHC = 180 MPa. Care must be taken to use proper bending tools and procedures.

The PMT cable is a copper conductor, Kapton Insulated Triaxial UHV compatible cable available from Accu-glass Products, Inc., in California, with 26 or 28 gauge center conductor and an OD of 2.5 or 3mm.

The fittings can be a flare fitting, VCR, or Swagelok; testing will be performed to determine the most reliable fitting type.

2.5 Carrier Plate

The PMT module carrier plate is a circular plate of copper 10 cm thick to which the modules are attached. It attaches to the ends of the internal copper shielding bars (ICS) screwed to an internal flange inside the pressure vessel head. The entire PMT system is contained in the head. It serves to carry heat to the pressure vessel flange. Cooling may be applied to the outside of the head flange, if desired. If electrical isolation is used, a thin polyimide gasket and PEEK bolt liners will be used between the plate and the head internal flange.

2.6 Central manifold

The central manifold comprises two sections of pipe, a conduit manifold section and a nozzle connection section; these two sections connected by a bellows type expansion joint section in the middle. This allows the conduit manifold section to be rigidly attached to the carrier plate, and the nozzle connection section to attach to the axial nozzle flange of the torispheric head without high stresses being transmitted to the nozzle. The conduit manifold section will contain, in addition to the cables, a calibration source and perhaps a collimator, located centrally in the manifold section. The conduit manifold section is currently an OFHC copper pipe (same as that for enclosures with threaded holes for conduit fittings. As on the enclosures, Torr-seal vacuum grade adhesive will be used for the fitting pipe threads.

2.7 Feedthroughs

These are 41 pin UHV feedthroughs on CF (DN40) flanges made by VACOM, in Germany. They are pressure rated to 21 bar pressure, however they will not see more than 1 bar pressure in case of window failure, due to the low conductance vacuum port leading to the large emergency vent tank, which is always open. The pin-to-pin, and pin-to-ground rated voltage is 1000 V for vacuum ($<10^{-4}$ torr) and air sides, however, we note that the pins are arranged with a ring of 20 pins in a circle closest to ground and the remaining 21 pins are clustered further inside. It should be possible to run all the inside pins at 1500-1750V and use the outside ring of pins as a shield by either letting them float, or by applying 800 V to them; With 6 feedthroughs (out of 7 possible), we have 6x21=122 pins available, which is sufficient for both operating schemes, however, if each PMT is required to have its own high voltage line, this will require splitting off HV conductors onto separate feedthroughs from signals. See PMT electrical section elsewhere for details. Should more pins be needed, we will add a spool and second octagon to the first octagon, and extend the HV feedthrough. Preliminary tests on a similar 32 pin feedthrough from Ceramtec show that as much as 2500 V pin-to-pin, and pin-to-ground can be withstood when vacuum is better than 0.1 millitorr. This test included a fully cabled air-side plug, but pins in vacuum side were bare. More and better testing is planned which will include realistic connections of triax cables to the vacuum side pins.

3 Plan for Completion of Energy Plane

At present there are some remaining design tasks and RD activities to pursue before full scale fabrication can take place:

3.1 Remaining Design Tasks

* Central manifold - design expansion joint, integrate source and collimator, design cable termination harness at feedthroughs
* Carrier plate - Detail design - Issues: finalize HV cable location, is there to be a ground mesh?
* Design and build window pressure test cell.

3.2 R&D Activities

Progress to date :

- 3 sapphire windows purchased and received, screened for gross radiopurity: Activity ¡ 10 mBq/kg
- prototype enclosure parts are designed, fabricated, ready for first assembly
- pressure vessel for testing enclosure is designed, fabricated and pressure tested, ready for use
- sample 41 pin feedthrough has been tested (preliminarily) for flashover as a function of vacuum The following activities remain:
- Design, fabricate and test base/front end for +HV operation (Nygren zener design).
- Assemble prototype enclosure, check parts for fit, function.
- Connect prototype enclosure to vacuum measuring system, initial test vacuum inside.
- Install enclosure module in pressure test chamber- test O-ring permeation (Ar, Ne, He)
- Test PMT module/conduit/cable assembly for vacuum level inside enclosure.
- Final test 32 pin feedthroughs for 1750 V voltage capability, as a function of vacuum, including pin connections.
- Test PMT base pin mockup for flashover resistance and glow discharge as a function of vacuum.
- Test various fittings (flare, VCR, Swagelok) for vacuum tightness repeatability.
- Further develop and test various heat spreader designs.

3.3 Fabrication and Assembly

References

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