1 Introduction

The PMT enclosure and support system is designed to:

- position the energy plane PMTs inside the detector for best light collection,
- to protect them from the high pressure xenon,
- to provide the signal and power interfacing.
- be as radiopure as reasonably possible.

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

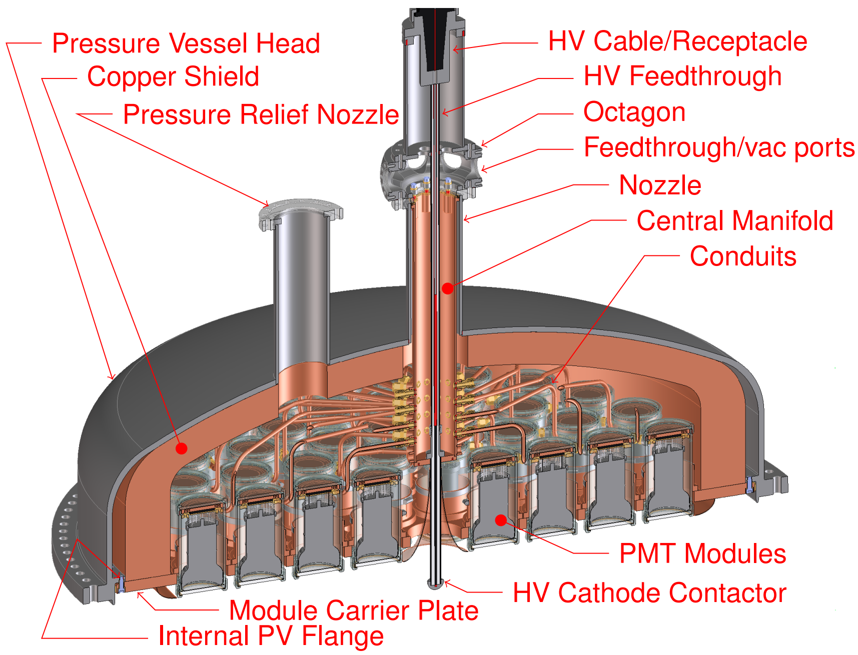

Figure 1: NEXT100, PMT Enclosure and Support System

2 Description

A brief system overview is as follows:

- PMTs are sealed into individual pressure resistant, vacuum tight titanium enclosures (PMT Module).
- The PMT modules are all mounted to a common carrier plate that attaches to an internal flange of the pressure vessel head.
- Sapphire windows are secured with titanium screw-down rings and O-ring sealed to the front end of the enclosure. A similar backcap of titanium seals the back side of the enclosure
- PMT bases are potted with heat conducting epoxy to flexible copper heat spreaders which connect to the enclosures.

- PMT cables are enclosed in individual pressure resistant,vacuum tight tubing conduits.
- Conduits all lead to a central manifold. The central manifold is cantilevered from the nozzle flange.
- PMT cables route through central manifold to 41 pin CF feedthroughs on a CF octagon, outside the lead shielding.
- High vacuum($< 10^{-6}$ torr) is applied at octagon port; good vacuum ($< 10^{-4}$ torr) is maintained inside enclosures through conduits, well below Paschen minimum, avoiding sparkover or glow discharge across PMT pins.
- A large vacuum tank buffer volume exists to limit pressure build in central manifold in case of sapphire window failure (avoids Super-K chain reaction failure mode). Xenon permeation through seals is recovered with a cold trap.
- 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.
- Carrier plate and central manifold can be electrically (but not thermally) isolated from the pressure vessel, to allow the PMTs to be operated with cathodes at full negative voltage, with anodes and signals at low voltage
- Alternately, the cathodes can be grounded, and the anodes and signal run at high positive voltage using only the central 21 pins of each 41 pin feedthrough, to avoid flashover.

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).

We considered the alternative of backfilling the enclosure with inert gas such as CO2 or N2, but this could be a source of contamination for xenon, and complicates both recovery of xenon, and PMT to PMT pressure isolation. We also considered the alternative of fully potting bases to PMTs but concluded this would reduce serviceability and possibly increase background radiation. We also considered the possibility of hermetically sealing each PMT and base into the enclosure, as this might be possible using niobium enclosures which can be diffusion bonded to sapphire. This option entails significant R&D to assure window seal integrity from pressure cycling. It also requires the development of a radiopure electrical feedthrough, possibly also using niobium and sapphire, since commercial feedthroughs with brazed alumina insulators typically show high background radioactivity.

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. 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 utilize the standard push-on connectors, however they will be potted using a thermally conductive, electrically insulating epoxy to a heat spreader. This is a flexible disk of copper that is clamped on its periphery between the backside cap and the retaining ring for the PMT spring, as described in Enclosures below. There are several possible designs for these heat spreaders, we will test for the best design. PMT resistor heat is then dissipated through thermal conduction into the enclosures out 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

These enclosures are similar to those shown in the CDR (pg 36) which were welded into the torispheric head; however the welded-in option appears too difficult to fabricate, so both the pressure vessel and the PMT system are simplified by moving the enclosures fully inside the vessel. This allows the PMT system to be developed independently of the vessel. These PMT/enclosure modules are now mounted to a single carrier plate which itself is then attached to an inside flange of one head of the pressure vessel.

An option to house all PMT's in a single large pressure tight housing was investigated, but discarded due to the difficulty of providing adequate pressure isolation in case of window failure, which could lead to a catastrophic Super-K style PMT implosion scenario. The modular approach we have taken here allows us to develop the enclosure PMT/enclosure subsystem independent of the support system. This comes at the expense of having a large number of conduit connections which are potential leak sources. However the full system is easily leaked checked before assembly into the pressure vessel head. The PMT's and windows may be serviced or replaced without disturbing the conduit connections.

The enclosures are fabricated from grade 1 titanium pipe, having 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. The ends of the enclosure are threaded and a screw-down ring (similar to a Mason canning jar) is used to apply the sealing force.

Special spanner wrenches are used, and the threads on each ring are PTFE anodized to prevent galling. This has the advantage of maintaining a smaller profile and may allow use of Titanium pipe instead of bar stock. 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 will be advantageous. Grade 1 titanium shows potentially good radiopurity and samples will be screened for low background. Copper enclosures are an option, should radiopure Ti not be available in pipe. Required wall thickness for pressure (external) is 2mm; the actual wall thickness is 5mm.

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 on the backside; this spring (with PEEK interface collars) bears against a circlip held in a groove machined into the ID of the enclosure. Thus the PMT can be installed independently from the base, and the base can be serviced or replaced without disturbing the optical coupling of the PMT to the window.

Cables from the PMT exit through a vacuum tight fitting into a copper tube that serves as both a cable conduit and a vacuum port for the interior. Conduit fittings screw into a welded-on boss in the side of the enclosure, this location allows the back cap to be removed for PMT and base access without disturbing the conduit fitting. these bosses are shown welded in at right angles to the enclosure axis, however use of Swagelok fittings (to be determined) may require an angled weld.

2.3 Sapphire Windows

The sapphire windows will first be coated on one side with indium tin oxide to form a transparent (410nm and above) conductive coating. The conductivity is required to prevent electric field penetration into the PMT. 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 radiopure 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. 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. Also 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.

2.3.2 Test pressure ratio

LEFM defines a material quantity called stress intensity K that is a function of material, applied stress σ and crack length a. When this quantity reaches a critical value K_{Ic} (from either increased crack length, or increased stress) a previously stable, but slow growing crack of associated length a_{cr} will undergo rapid uncontrolled propagation. Single crystal sapphire (C-plane parallel to window plane; strongest orientation) has a well measured K_{Ic} [?]. In addition single crystal sapphire also has a threshold stress intensity K_{TH} where crack growth is so slow as to be unmeasurable [?]; this is our desired maximum operating point. The formula for stress intensity is:

$$K = Y\sigma\sqrt{\pi a}$$

Critical stress intensity, in air, from [?]:

$$K_{Ic} = 2.5 \text{ MPa}\sqrt{m}$$

Threshold stress intensity [?]:

$$K_{TH} = 1.64 \text{ MPa}\sqrt{m}$$

Y is a geometric factor which will cancel out below. We want the (maximum) critical stress intensity at the test pressure to fall off to the threshold stress intensity at our operating pressure, so our desired test-to-actual pressure ratio R_p is simply:

$$R_p = \frac{K_{Ic}}{K_{TH}} = \frac{2.5}{1.64} = 1.52$$

2.3.3 Minimum Window Thickness

Typical strength testing results, where specimens are stressed to failure (short term loading), can be characterized by a two-parameter Weibull distribution, where the probability of survival (for any successive identical test specimen) as a function of stress σ is given.

$$P_s = e^{-\left(\frac{\sigma}{\sigma_0}\right)^m}$$

The two parameters refer to the quantities σ_0 which is the called the characteristic stress and represents the stress at which 63% of specimens will fail, and the exponent m, which is called the Weibull modulus and is a measure of the stress spread, from low to high failure (or survival) probability; a low number indicates a wide range of stresses over which there are significant failure/survival probabilities, which is characteristic of brittle materials where there is a random distribution of surface or volume flaws which are difficult to eliminate. A high number is characteristic of ductile metals (>10), and a modulus of 1 indicates completely random failure. The modulus may even be negative which is an indication of infant mortality failure modes.

The characteristic stress is only applicable to parts that are the same size, surface condition, and loading distribution of the test specimen. Furthermore it is often normalized to a standard test area and stress distribution, which is typically a circular 1 cm^2 area loaded in a ring-on-ring fixture which produces a uniform biaxial bending stress distribution. To account for the difference in area between the test specimen an actual part and the different stress distribution (pressure loading produces a nonuniform stress) the following formula results:

$$P_s = e^{-k\left(\frac{A}{A_0}\right)^m\left(\frac{\sigma}{\sigma_0}\right)^m}$$

The factor k is a function of m and represents a weighting factor derived from integrating the probability function over the stress distribution and normalizing it to the uniform stress distribution of the characteristic strength. The area ratio $\frac{A}{A_0}$ relates actual stressed area to characteristic area.

Klein [?] gives a Weibull modulus $m = 3.4$ and characteristic strength $\sigma_0 = 975$ MPa for a 1 cm^2 uniform biaxial stress, for c-plane oriented specimens of 60/40 scratch/dig polish specification. Salem [?] gives a formula for an effective area, as a function of m from which $k(m = 3.4) = .332$ is readily computed, and is applied to the area ratio of actual to characteristic areas, A_w (= 45 for our window size). We then solve for a maximum stress at the test pressure of:

$$\sigma_t = \sigma_0 \left(\frac{ln(P_s)}{-kA_w} \right)^{\frac{1}{m}} = 975 \text{ MPa} \left(\frac{ln(.95)}{-.332 * 45} \right)^{\frac{1}{3.4}} = 186 \text{ MPa}$$

and our design stress for actual pressure $p = 15$ bar is:

$$\sigma_d = \frac{\sigma_t}{R_p} = \frac{186 \text{ MPa}}{1.52} = 120 \text{ MPa}$$

and a resulting window minimum thickness, using a simple formula for a circular plate loaded in bending, with simple edge supports [?](table 24, case 10a), ($\nu = 2.9$ is Poisson's ratio for sapphire) is then:

$$t = \sqrt{\frac{3}{8}(3 + \nu)\frac{p}{\sigma_d}r^2} = \sqrt{\frac{3}{8}(3 + 0.29)\frac{1.5 \text{ MPa}}{120 \text{ MPa}}r^2} = 4.9mm$$

Prototype windows have been ordered at 5mm thickness.

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 screwdown lid 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 screwdown 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 screwdown 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 triax cable which will provide an acceptable pumping speed, so as to maintain good vacuum inside the enclosure.

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 1.5 cm thick to which the modules are attached. It is 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

This is an OFHC copper pipe with brazed in threaded bosses for conduit fittings. Torr-seal vacuum grade adhesive will be used for the fitting pipe threads. It is attached only to the nozzle flange, using a clamping ring inside the octagon and seals with an O-ring. The lower end is cantilevered,except for servicing, where a temporary support attaches it to the carrier plate. It has a threaded hole in the base to which the HV feed through screws into and also seals with an O-ring. the HV feedthrough is grounded on the outside where it is inside the cabled sectionof the central manifold. If the carrier plate is electrically isolated from the pressure vessel, an interface flange of PEEK will be used between it and the nozzle flange.

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 atm 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 1000V 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 (and we are planning to test soon) 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 800V 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.

2.8 R&D Plan

Several sapphire windows 5mm thick have been ordered and due Jan 2012. The following activities remain:

* Build prototype enclosure.
* Design and build window pressure test cell.
* Scope, design and build PMT module pressure test chamber.
* Test PMT module/conduit/cable assembly for vacuum level inside enclosure.
* Test 41 pin feedthroughs for 1750 V voltage capability, as a function of vacuum.
* 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.

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