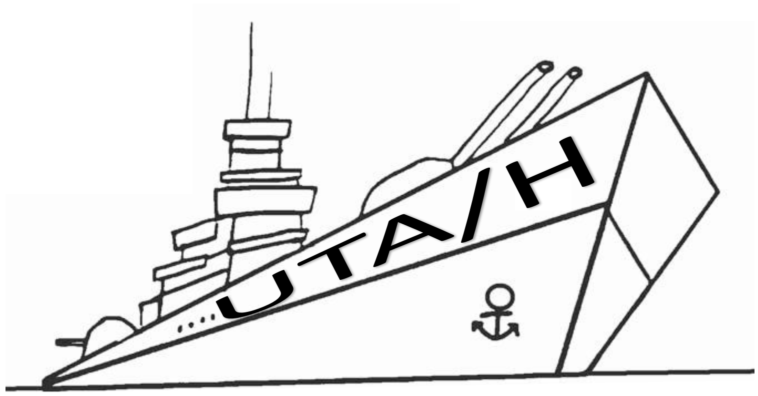
Design Considerations for the UTA/H Liquid Argon Time Projection Chambers



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Abstract

Development of a true pixelated readout to enhance the detection performance of large-scale, single-phase liquid argon (LAr) detectors is of particular interest since development of such a technology could improve tracking capabilities through an enhancement in spatial resolution. This could potentially lower the operational energy threshold and allow for exploration of more low-energy physical processes. Q-Pix is a technology of interest for pixelizing such large-scale detectors due to the comparatively low output rate which is inherent to the technique of sampling charge quanta instead of time. Presented here is the design of a time projection chamber (TPC) which will be duplicated at The University of Texas at Arlington (UTA) and Harvard University. These sister TPCs will be used for the calibration and small-scale physics studies required for the demonstration of Q-Pix technology.

Contents

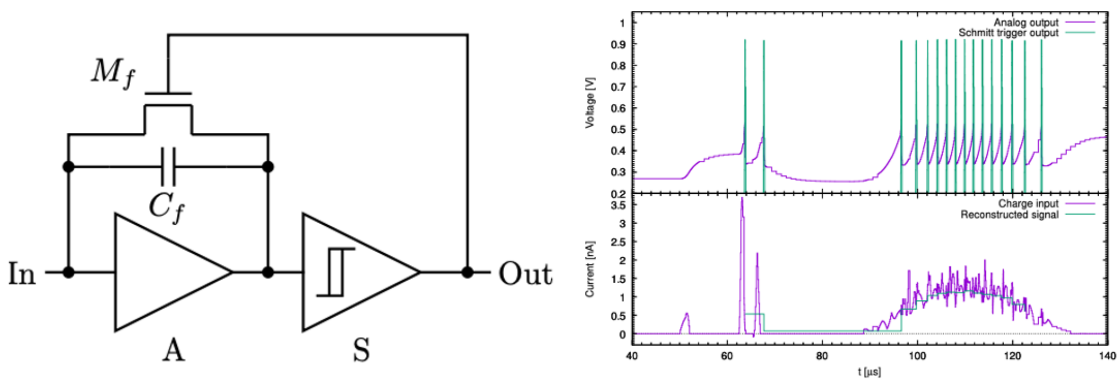


Figure 1: Left: Schematic diagram of the Q-Pix chip. Right: Example of how a current waveform is reconstructed from resets. Taken from [4].

1 Motivation

Q-Pix is a proposed a novel readout solution for large, rare-event detectors [4] where the detector is mostly inactive, such as DUNE. The notion of Q-Pix is to be active when it is needed and in a low-power quiescent state otherwise. This is done in a non-traditional manner by sampling when a set amount of charge arrives instead of when a set amount of time elapses. An overview of how such a system works can be seen in Fig. 1 (left). Here, the charge on the “In” line is integrated via “A” and “C_f”. Once the integrated charge reaches a set value determined by the comparator/Schmitt trigger (“S”), an output pulse is sent. The output pulse is logged and triggers a reset which drains the charge that has been integrated on “In” through “M_f”. Such an arrangement produces logic pulses whose reset time difference (RTD) is related to the current profile as $Q(t) \propto 1/\mathrm{R}TD$. This is further illustrated in Fig. 1 (right) where an example current profile and Q-Pix response can be seen.

A large Q-Pix array could greatly reduce the data rate of a large detector, such as DUNE, while providing a true pixelated readout. Such a technique has yet to be demonstrated and characterized, and is the focus of this document. The following sections will focus on the design aspects of a small-scale time projection chamber and the measurements that are expected for demonstration and calibration of a moderate-sized Q-Pix board.

2 Overview

The primary goal of the sister TPCs, to be constructed at UTA and Harvard (UTA/H), is to operate and calibrate a moderately sized Q-Pix board $\mathcal{O}(10)$ cm^2. The UTA/H TPCs presented here are designed to have flexibility to be general purpose test stands which can fully characterize and calibrate a Q-Pix board as well as perform a broader class of general measurements relevant to the liquid argon neutrino detector community. The TPCs are designed to efficiently transport electron to the cathode under a uniform drift field as well as collect the majority of the light via a reflector tube coated in a wavelength shifter (WLS) which guides the light to a photomultiplier tube (PMT). Such a design requires a buffer region in order to reduce the potential on the anode to ground so that light detectors can utilized. Moreover, the components of these TPCs are designed to be easily adaptable for testing of new charge and/or light readouts, including a multi-modal $Q{+}L$ sensor that is currently under development.

2.1 Measurements & Calibration

The Q-Pix boards are expected to be calibrated using a series of standard radioactive sources and through-going muons from cosmic rays that will be externally triggered (either via the PMT or external scintillator paddles). A list of the sources and their associated energies are summarized in table 1. Muons are expected to be highest energy deposited that can be achieved, producing $\sim$ 30 MeV of deposited energy (2 MeV/cm over $\sim$ 15cm) and likely spanning the detector diameter. The muon rate is estimated by assuming a flux of $\sim$ 1muon/(cm^{2}min), which gives a rate between 10 and 0.16 Hz. This translates to a data collection time for 100k muons to be between 3 hours and a week depending.

Source	Energy (MeV)	Electrons	Photons	P.E.
Muon	∼30	∼1,270,000	∼1,570,000	∼85,000
^{210}Po	5.3	∼225,000	∼279,000	∼15,100
^{60}Co	1.3 & 1.1	∼55,000	∼69,000	∼3,730
^{137}Cs	0.662	∼28,000	∼35,000	∼1,890

Table 1: Expected calibration sources and energies. The number of electrons and photons are calculated using $W_e = 23.6$ eV/pair and $W_p = 19.5$ eV/photon. Photo-electron yields are estimated assuming a 5.415% photon detection efficiency.

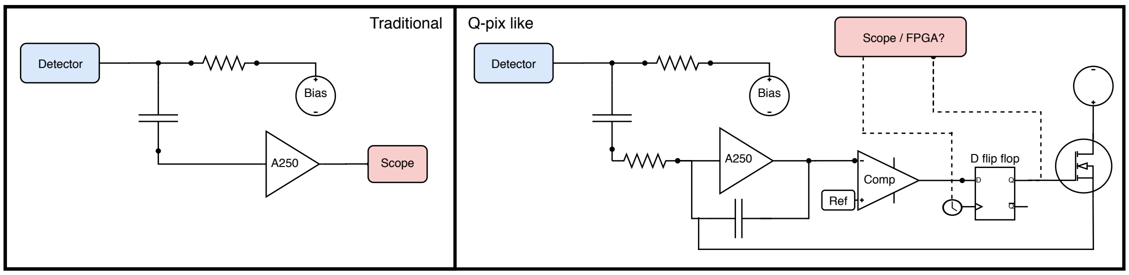


Figure 2: Left: A traditional CSA detector. Right: A CSA that has been modified to a Q-Pix style readout.

The radiological sources are anticipated to be ordered as needle sources and can be mounted inside the drift region and may be placed at various drift distances. These sources can have a much higher rate ∼1000 Hz (less than a 0.1μCi).

We anticipate the data buffer to be a generous 500μs. The max electron drift time will be 120μs if the electron drifts the whole 18 cm length of the drift region. Ordering a source of 100 Hz should result in a decay every 10 ms, which should give sufficient time between events in order to decrease the chance of overlapping events.

The Q-Pix board should be able to map out the muon angular dependence as a calibration of how well it can reconstruct the tracks. This is, however, dependent on the actual rate which needs further study. The radiological sources will be used to test the limit of the Q-Pix low-energy threshold since the ^{137}Cs photopeak should induce ∼3 resets at a 1 fC threshold (6125 electrons). For such calibrations the light will be used for an absolute energy measurement to be compared to the energy measurement from the RTDs.

The event trigger is expected to be from the light signal. This is based off a nominal photon detection efficiency of ∼5%, which was derived from a factor of 50% due to the photon direction, 60% for the WLS efficiency, 95% for each mesh, and finally 20% for the PMT efficiency, which equates to ∼280 photo-electron (P.E.) per 100 keV of energy.

2.2 Fundamental Measurements

Typical liquid argon-based neutrino experiments lack large-area photo coverage due to their large sizes and limited PMT/SiPM surface area. This gives the UTA/H TPCs a somewhat unique advantage as a test stand, which can allow for further fundamental LAr measurements. Such as mapping out the charge and light yields similar to [3], which is complementary to measuring the energy resolution form charge, light, and the anti-correlation between them as from charge in [2]. A measurement similar to these, shown in Fig. 3, will be performed to demonstrate the TPC's functionality.

A compelling first measurement will be to measure the energy resolution with both light and charge readouts. This would be done without Q-Pix and likely use a Charge Sensitive Amplifier (CSA) to directly read the charge. An example of a traditional CSA readout can be seen in figure 2 (left). Such a measurement would provide a traditional limit to compare the performance of Q-Pix to.

An analogous measurement which could demonstrate the Q-Pix technique without requiring a full pixel board would be to modify the output of the CSA such that it resembles the Q-Pix Charge-Integrate / Reset (CIR) circuit. This can be done by changing the CSA into an integrator whose out-

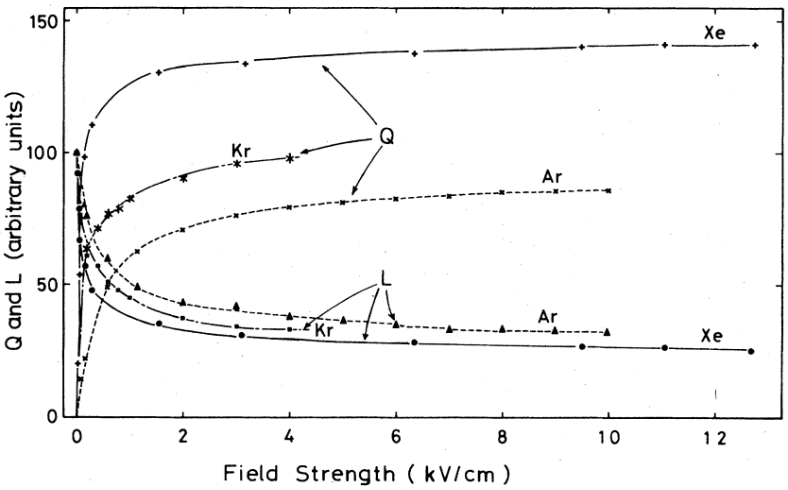


Figure 3: Famous light and charge dependence in noble elements as a function of external electric field from [3]. A similar measurement will be performed in the UTA/H TPC.

put is compared to a reference. Once the signal is integrated to the reference, a flip-flop is triggered which sends a logic pulse to the data collection system. The logic pulse also serves as a trigger to an NMOS which will drain the charge on the integrator.

This simplified Q-Pix-style readout could provide a validation of this method before a full Q-Pix array is produced. This measurement could also provide a robust comparison to the traditional limit and give insight to the overall performance.

Furthermore, the TPC's large photo coverage allows it to be an exceptional test bed for testing a multi-mode pixel readout that collects both charge and light. Such a measurement would greatly benefit from a known light detection system. In this case the PMT would serve as a comparison to the light seen by the multi-mode sensor.

3 Cryostat & Vessel

The methodology employed here is a standard in the LAr community, where a large cryostat is filled with a lesser grade purity LAr and an inner vessel is submerged in the bath and filled with ultra-high purity (UHP) grade LAr (typically further purified in a single-pass filter system). The overall scheme here is to support the inner vessel from the cryostat lid which will need to be removed via crane and placed on a platform in order to work on the inner vessel. All connections to the inner vessel will also need to penetrate the outer cryostat.

The inner vessel is expected to be pumped to 1 mBar prior to filling. Given the relatively small volume of the inner vessel, this should be easy to do, but the argon gas "piston-purge" method could also be employed. While the materials chosen are not optimal for ultra-high vacuum (UVH), ∼ 1 mBar vacuum is still expected to be easy to achieve. Once evacuated the inner vessel can be filled with LAr and measurements can begin. The filling will be done through a 1/2 in swagelok pipe that will extend to the bottom on the inner vessel. Since the TPC hangs vertically the liquid fill from the bottom to the top, in order to not trap gas inside the active volume the top plate has slots where it mounts to the Q-Pix board so the gas can escape. The measurements with radiological sources is expected to takes less than 8 hours, which should not be prohibitively difficult to maintain both the LAr level and the necessary purity. However, measuring the muons could take much longer depending on the rate and there are no previsions for cleaning the LAr in the inner vessel. Instead, a periodic boil-off and refilling of purified argon will be done to maintain the argon level and keep the purity high over the extended cosmic ray data-taking period. A similar technique has been successfully used in the LArIAT experiment [1] and will be replicated here given the extensive experience the group has from LArIAT.

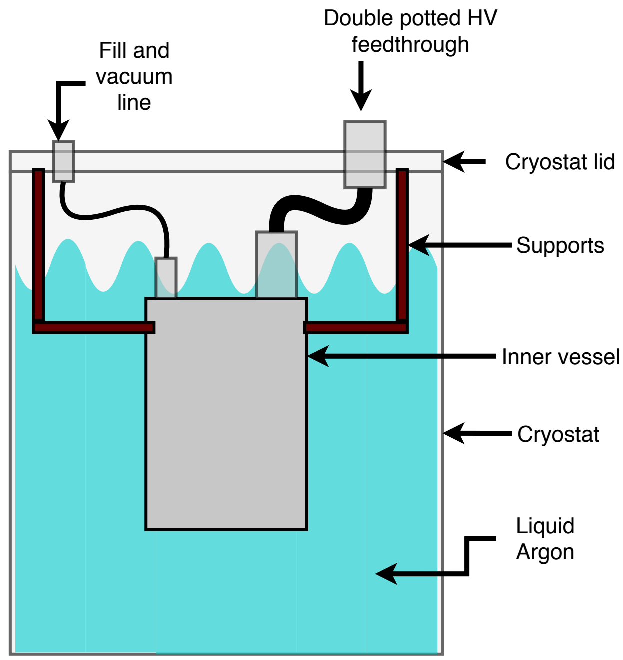


Figure 4: Schematic diagram of the vessel inside the cryostat.

4 Inside the Vessel

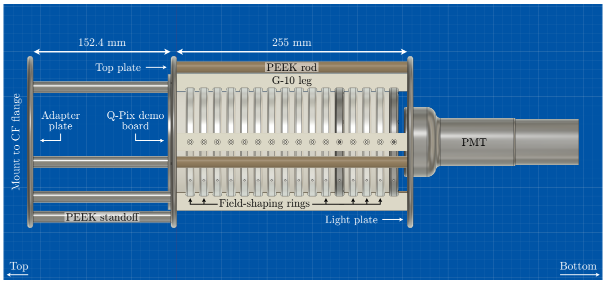
The inner vessel will be a 254 mm (10 in) outer diameter ConFlat (CF) full nipple with a nominal tube outer diameter (OD) of 203.2 mm (8 in) and inner diameter (ID) of 197.104 mm (7.76 in); the length of the vessel will be 660.4 to 762 mm (26 to 30 in) to be determined. An adapter plate made of 304 or 316L stainless steel (SS) will be mounted to the vacuum side of a CF flange at the top of the vessel. A top plate made of aluminum 6061-T6 will stand off 152.4 mm (6 in) from the adapter plate in which the Q-Pix demonstrator chip will be mounted onto on the top side. This large standoff distance is to allow for the liquid level to remain several inches above the Q-Pix board to reduce the chance of bubbling and provide a gas gap for connectors. The TPC field cage will be mounted onto the under side of the top plate and will be supported by 3 polyether ether ketone (PEEK) rods that are secured to the light plate at the bottom of the field cage; nylon 1/4"-20 screws will be used to fasten the PEEK rods to the aluminum plates. The field cage structure will be supported by 4 G-10 legs that are fastened to the aluminum plates with nylon M5 screws. CAD images of the TPC field cage assembly are shown in Fig. 5.

4.1 Field cage

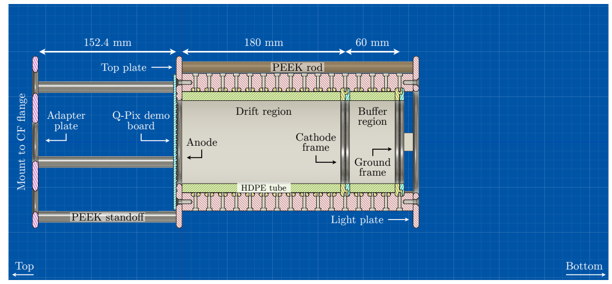
The TPC field cage is 255 mm in length and 120 mm in diameter, and consists of two distinct regions (Fig. 5b):

- a 180 mm long drift region, and
- a 60 mm long buffer region.

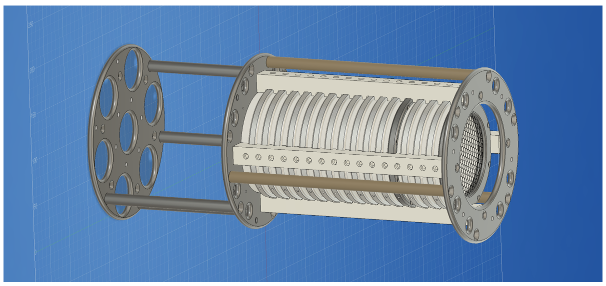
The drift region consists of 11 field-shaping rings and a cathode frame that holds a mesh with hexagonal holes; the buffer region extends from the cathode frame to a ground frame that also holds a mesh with hexagonal holes and consists of 3 field-shaping rings. The field cage rings have an outer diameter (OD) of 120 mm, an inner diameter (ID) of 112 mm, and a height of 10 mm. The hexagonal holes allow light to pass through and be collected by a 76 mm (3 in) diameter PMT that will be mounted to the light plate at the end of the buffer region; the transparency of a mesh is estimated to be 95% [6]. The pitch of the field-shaping rings and mesh frames is 1.5 mm; the rings and frames are held in place by 4 G-10 legs that are equally spaced around the field cage. The field-shaping rings and mesh frames have 4 threaded holes so that they can be secured to the G-10 legs with nylon M3 screws. There is



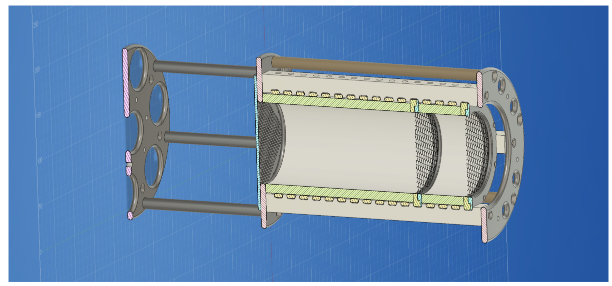
(a) Field cage with PMT



(b) Section view of the field cage



(c) Alternate view of the field cage



(d) Alternate section view of the field cage

Figure 5: CAD images of the field cage.

also an additional hole on each ring and frame for mounting the resistor board (Fig. 10) with nylon M3 screws.

Each mesh frame consists of two different rings of OD 120 mm and ID 92 mm that will clamp down on the mesh (Fig. 7). The mesh will be secured to the frames by eight ⌀2.5-mm dowel pins. Two high-density polyethylene (HDPE) tubes of OD 111.51 mm and ID 92 mm will be placed inside the drift and buffer regions. The inner walls of the HDPE tubes will be coated with tetraphenyl butadiene (TPB) to allow the 128 nm vacuum ultraviolet (VUV) scintillation light to be wavelength-shifted into the optical range for detection in the PMT. The clearing between the field cage rings and the inner wall of the vessel will be 41.6 mm (Fig. 6).

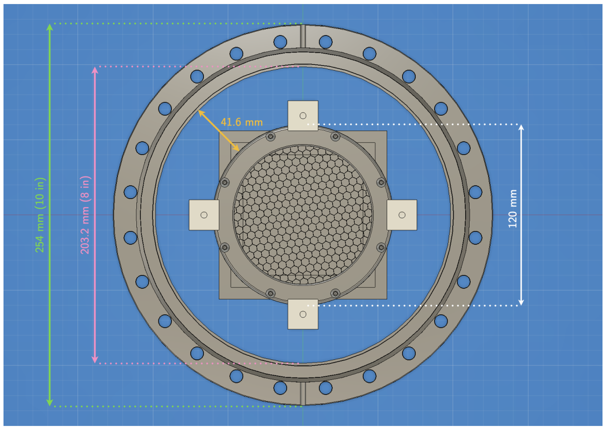
Table 2 lists the number of parts along with the material to be used for the field cage. We expect the relative linear thermal contraction between the materials to be no more than 2% in LAr (Fig. 8); there is no available data on HDPE or polyethylene, however, we expect it to be similar to PTFE.

The electric field was simulated using COMSOL Multiphysics® (Fig. 9) with a nominal drift field magnitude of 500 V/cm. According to the simulation, the field uniformity is better than 99% up to a radial distance of 5 mm from the HDPE walls and sufficiently far from the cathode mesh (at least 20 mm away); the variation in the radial* component of the electric field can be up to 4% near the anode at a this radial distance, and up to 23% near the cathode mesh.

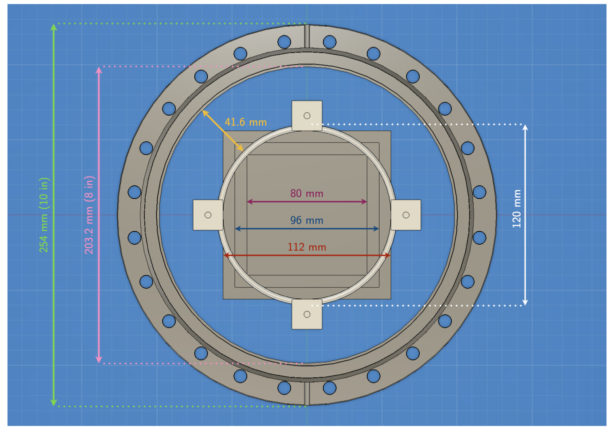
5 High Voltage

The high voltage for the drift field will be generated from Glassman high voltage (HV) supplies that are ∼40 kV rated. The supplies will be connected to a 60 kV HV cable provided by Dielectric Sciences, Inc. (2149SJ), and is similar to the one used in LArIAT [1]. The HV cable will be potted with Stycast 2850 in a 2.75 CF nipple that will penetrate the cryostat. The HV cable will need to be potted again for entry into the inner vessel. The HV cable inside the vessel will be striped to the bare polyethylene. The cable will pass though one of the six 0.5 in holes located on the otter of the top plate and secured to the nearest PEEK support. The cable will be cut to the length of the cathode and will be bridged to the resistor chain board via another piece of cable.

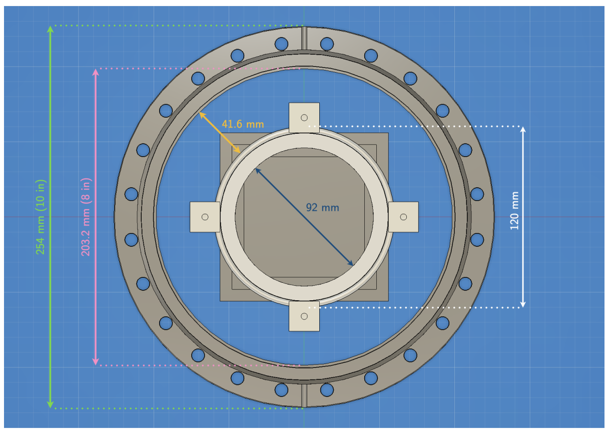
*Here, *radial* is defined to be $\rho \cos\phi$ in the cylindrical coordinate system. The $\rho \sin\phi$ components are negligible due to symmetry.



(a) Top-down view of the TPC with visible mesh frames



(b) Top-down view of the TPC with visible field-shaping rings (mesh frames and HDPE tubes hidden)



(c) Top-down view of the TPC with visible TPB-coated HDPE tubes and field-shaping rings (mesh frames hidden)

Figure 6: Top-down views of the TPC field cage inside the inner vessel. There is a 41.6 mm clearing between the field cage rings and inner wall of the vessel. The squares represent 3 different configurations of active pixel area for the Q-Pix demonstrator chips.

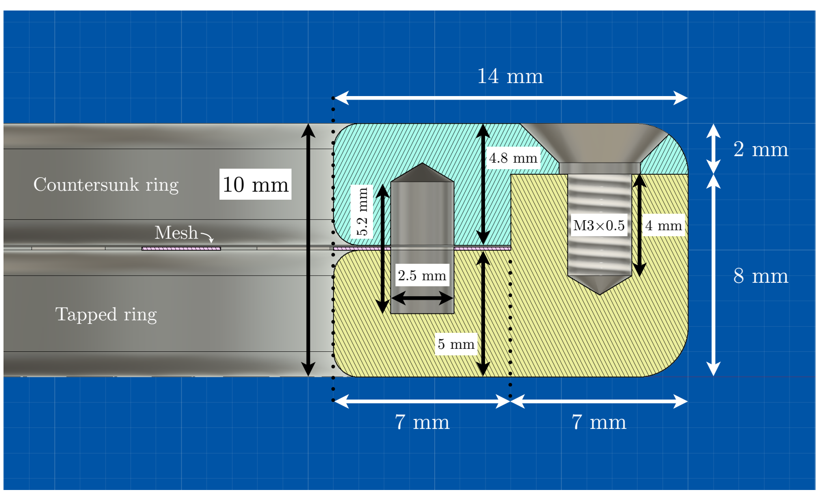


Figure 7: Section view of the mesh frame.

Quantity	Part	Material
1	Adapter plate	304/316L stainless steel
1	Top plate	Aluminum 6061-T6
1	Light plate	Aluminum 6061-T6
14	Field-shaping ring	Aluminum 6061-T6
2	Countersunk ring	Aluminum 6061-T6
2	Tapped ring	Aluminum 6061-T6
2	Hexagonal mesh	316L stainless steel
16	⌀ 2.5 mm dowel pin	316 stainless steel
4	G-10 leg	G-10
6	Standoff	PEEK
3	Support rod	PEEK
1	Buffer region light tube	HDPE
1	Drift region light tube	HDPE
80	M3 screw	Nylon
8	M5 screw	Nylon
6	1/4”-20 screw	Nylon

Table 2: Materials of the field cage parts.

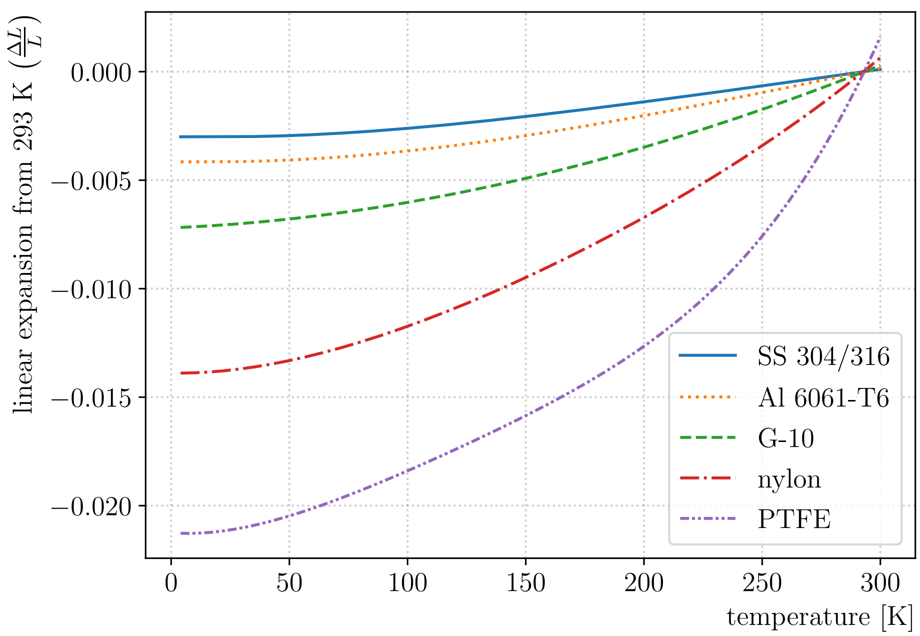
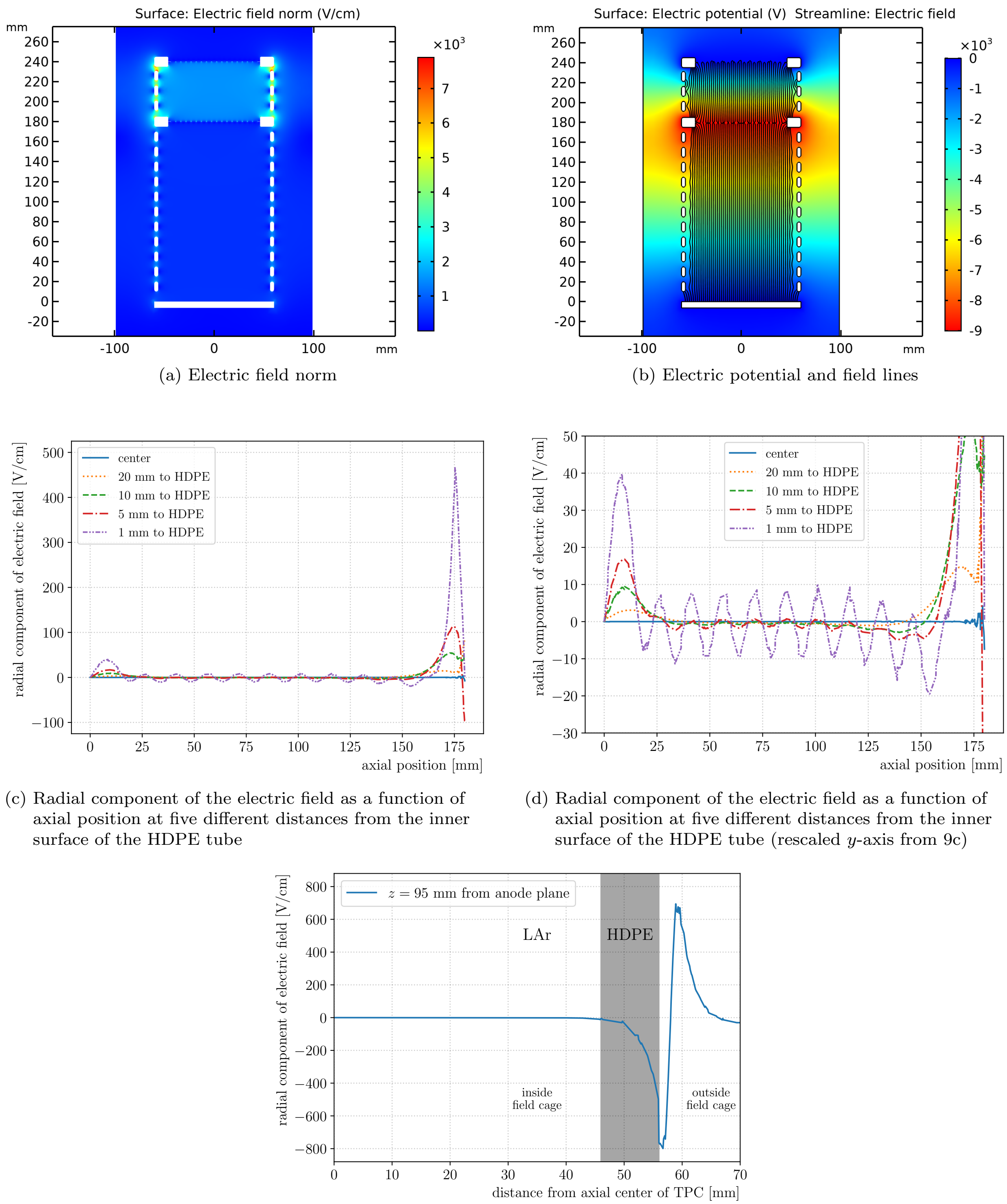


Figure 8: Linear thermal expansion as a function of temperature for several materials. Taken from [5].



(a) Electric field norm

(b) Electric potential and field lines

(c) Radial component of the electric field as a function of axial position at five different distances from the inner surface of the HDPE tube

(d) Radial component of the electric field as a function of axial position at five different distances from the inner surface of the HDPE tube (rescaled y-axis from 9c)

(e) Radial component of the electric field at a fixed axial position; the shaded region indicates where the HDPE is located

Figure 9: Electrostatics simulation from COMSOL for a drift field of 500 V/cm.

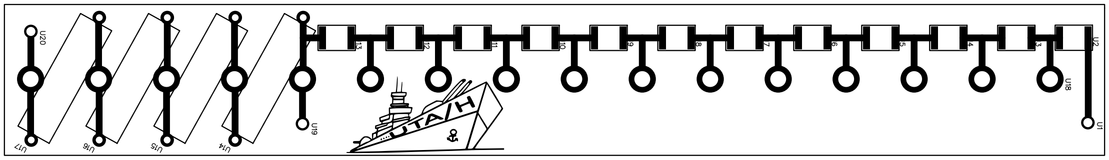


Figure 10: Field cage resistor board.

The drift field is established via a chain of 1 GΩ resistors. The resistors are mounted to a printed circuit board (PCB) that can be seen in Fig. 10. The connection between he PCB and the field cage rings is made with M3 screws. The surface mount resistors are able to withstand a 3 kV potential with a 36 kV bias limit (2000 V/cm), the 4 resistors the make up the buffer are rated for 10 kV. While we expect most running time to be 500 V/cm (1500 V/cm buffer, 9 kV bias) or below, operation at 1500 V/cm drift (4500V/cm buffer) is possible and would require a bias of 27 kV which is within the operating parameters.

Another source of HV will be the PMT which is expected to be a Hamamatsu R11065 (3 in). However, this should not exceed 2 kV and should be routed on the opposite side of the vessel as the field cage bias.

References

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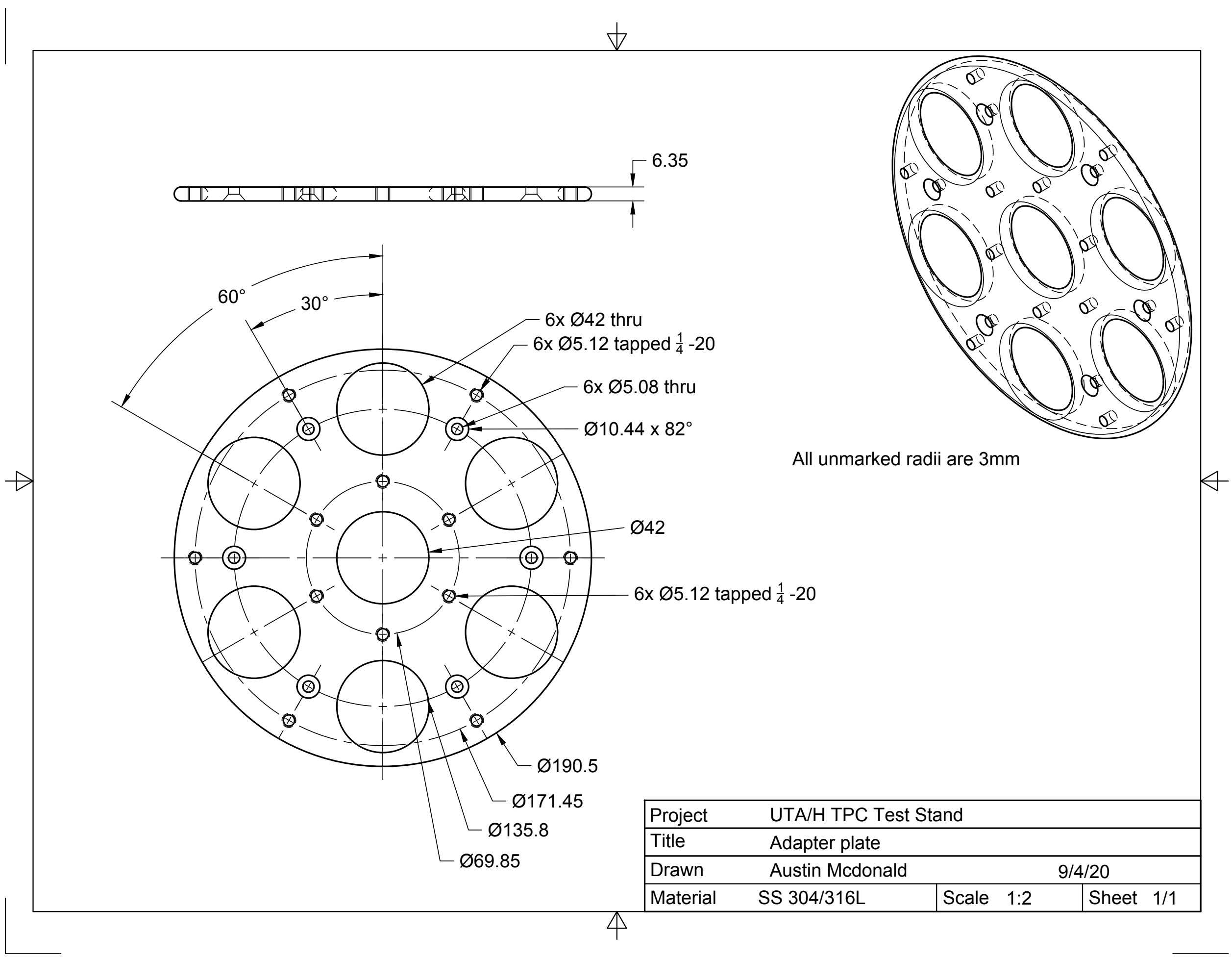
A 2D drawings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30°
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All unmarked radii are 3mm
Ø42
6x Ø5.12 tapped $\frac{1}{4}$-20
Ø190.5
Ø171.45
Ø135.8
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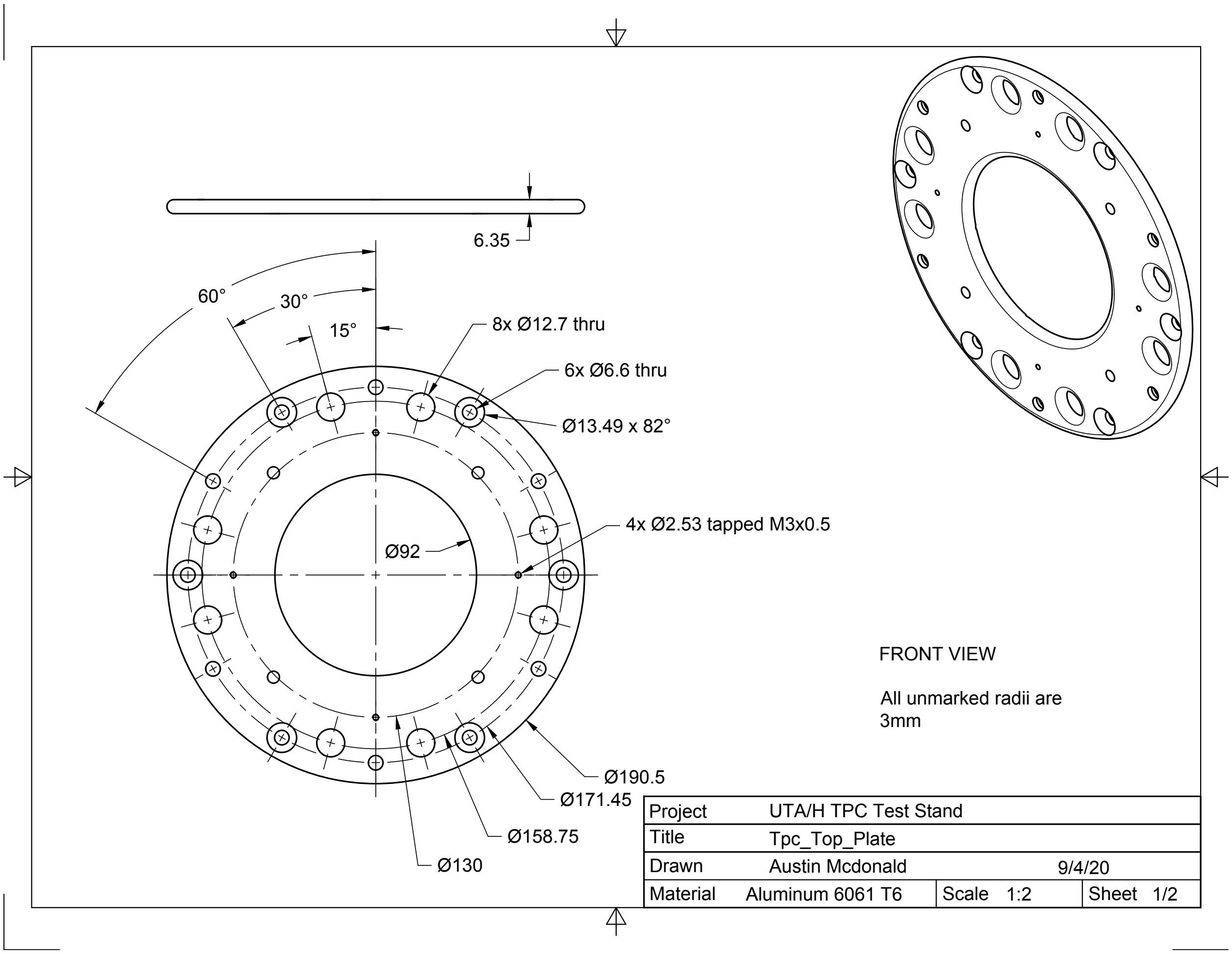

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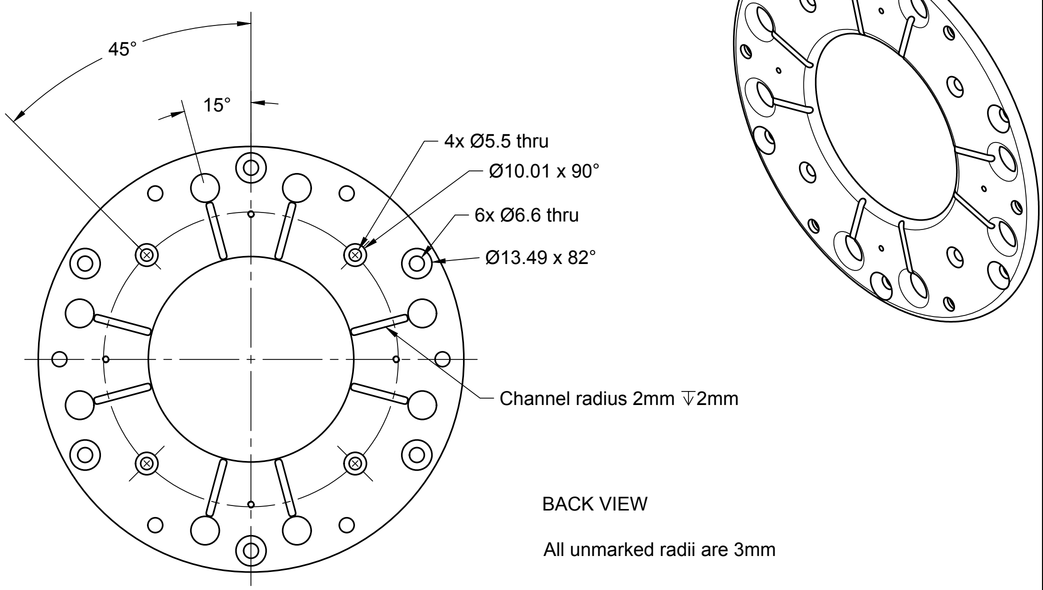

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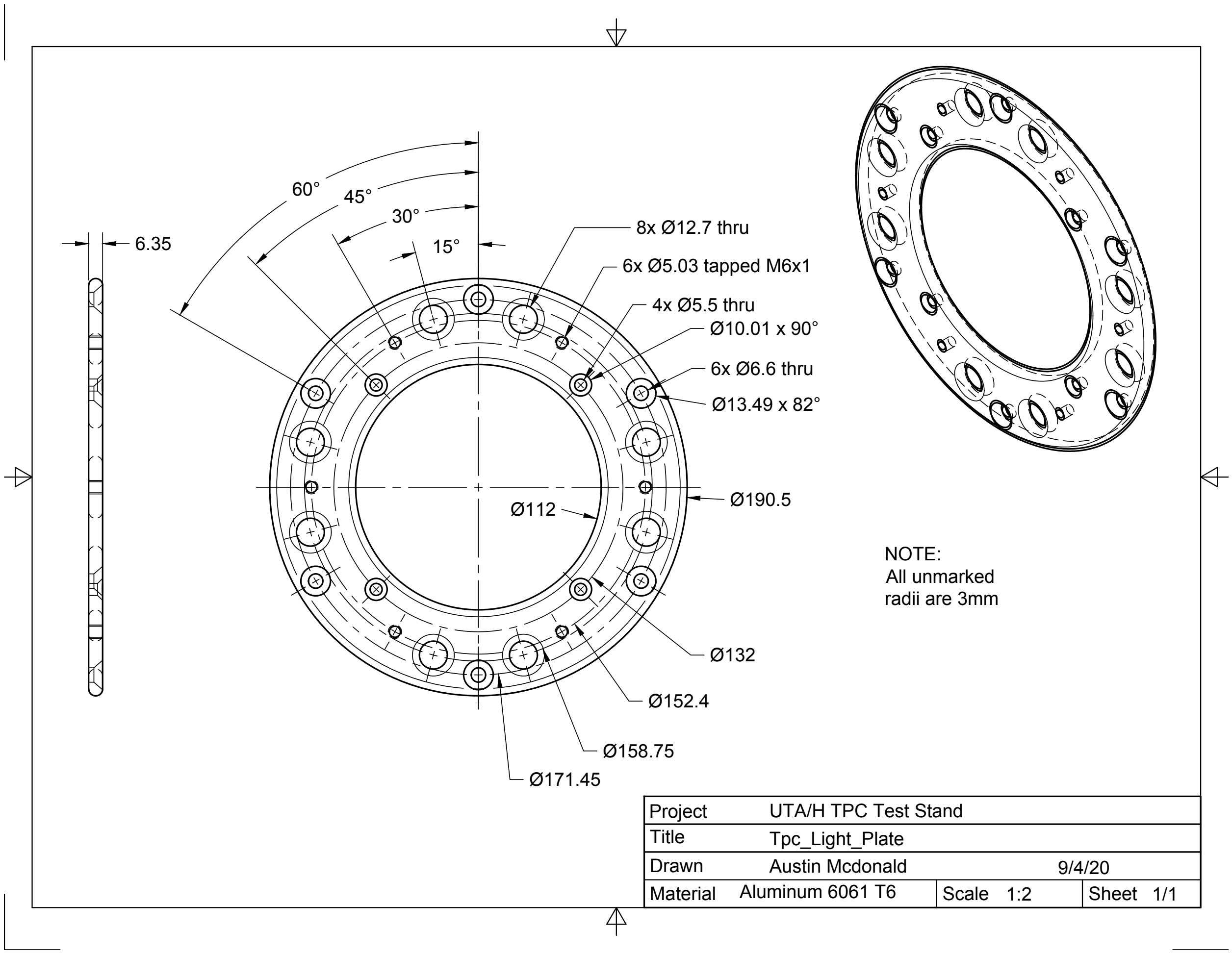
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60°
45°
30°
15°
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6x Ø5.03 tapped M6x1
4x Ø5.5 thru
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6x Ø6.6 thru
Ø13.49 x 82°
Ø190.5
Ø112
Ø132
Ø152.4
Ø158.75
Ø171.45
NOTE:
All unmarked
radii are 3mm
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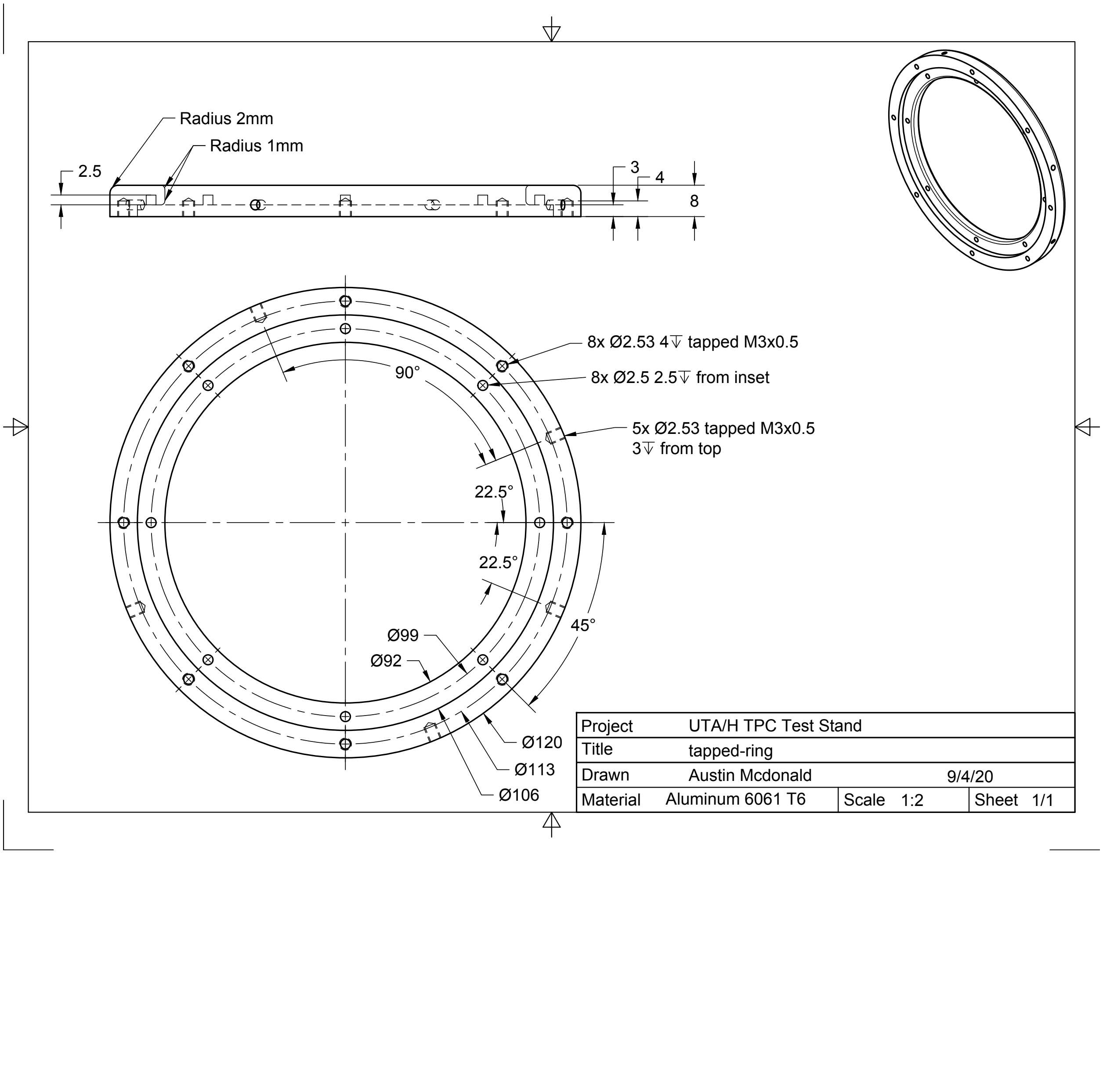
Radius 2mm
Radius 1mm
2.5
3
4
8
8x Ø2.53 4↧ tapped M3x0.5
8x Ø2.5 2.5↧ from inset
5x Ø2.53 tapped M3x0.5
3↧ from top
90°
22.5°
22.5°
45°
Ø99
Ø92
Ø120
Ø113
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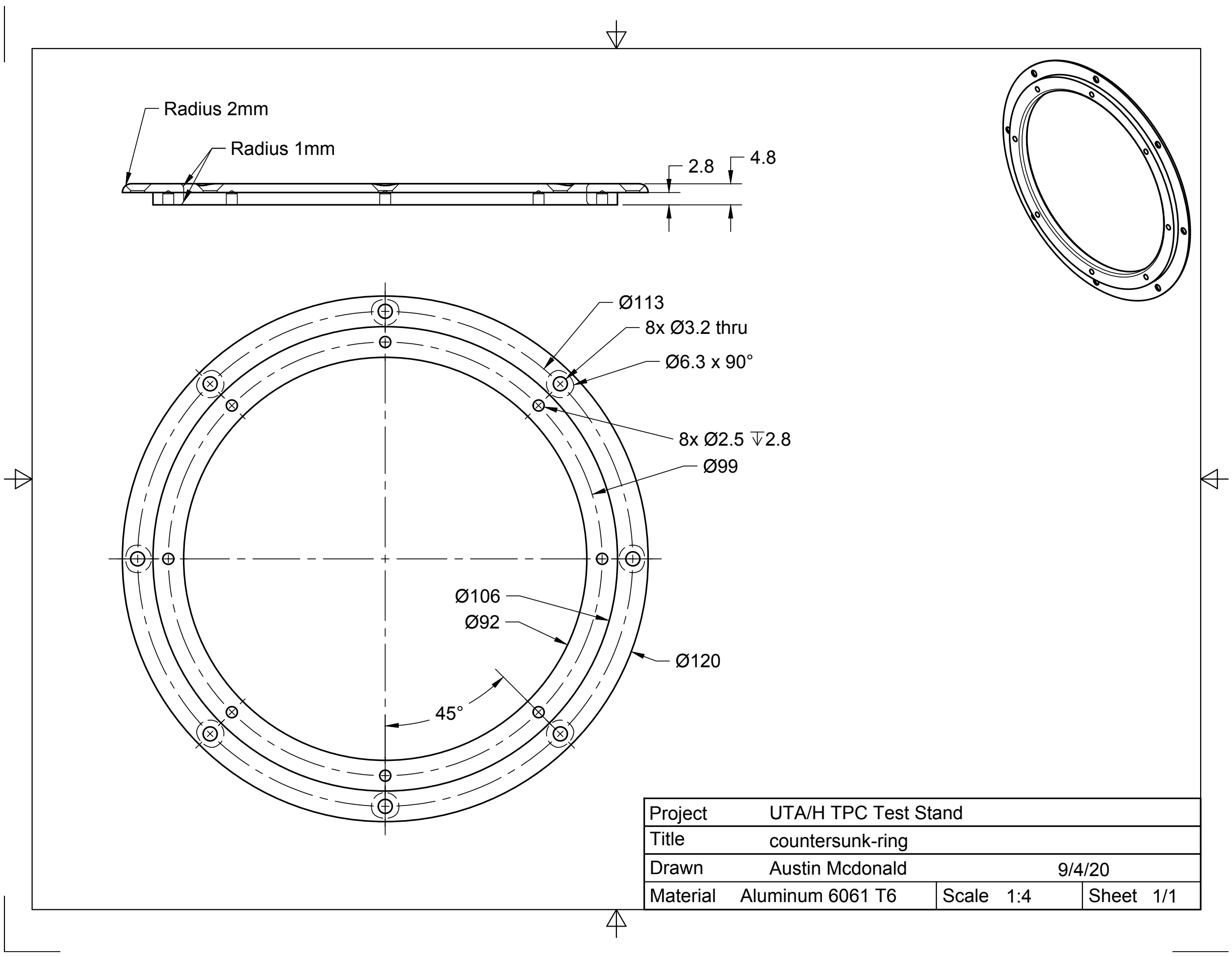
Sheet 1/1


Radius 2mm
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Ø6.3 x 90°
8x Ø2.5 ⤓2.8
Ø99
Ø106
Ø92
Ø120
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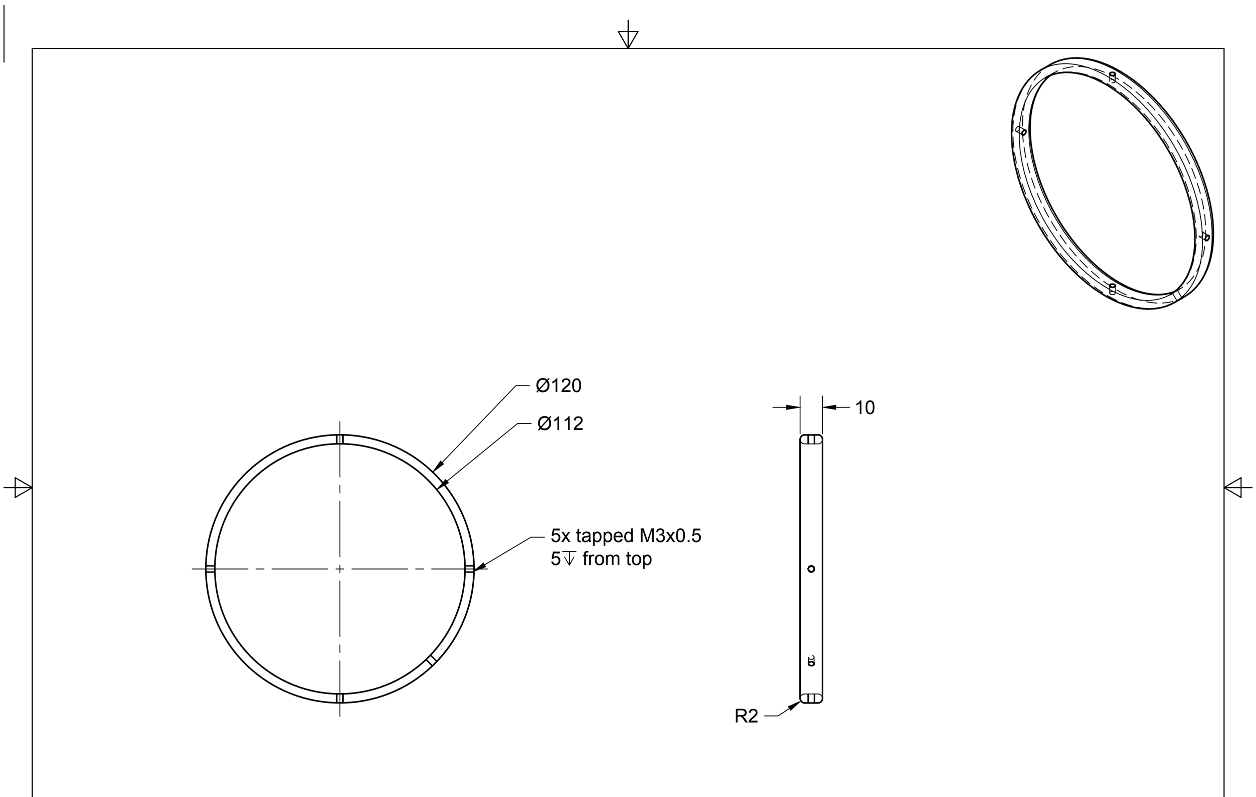

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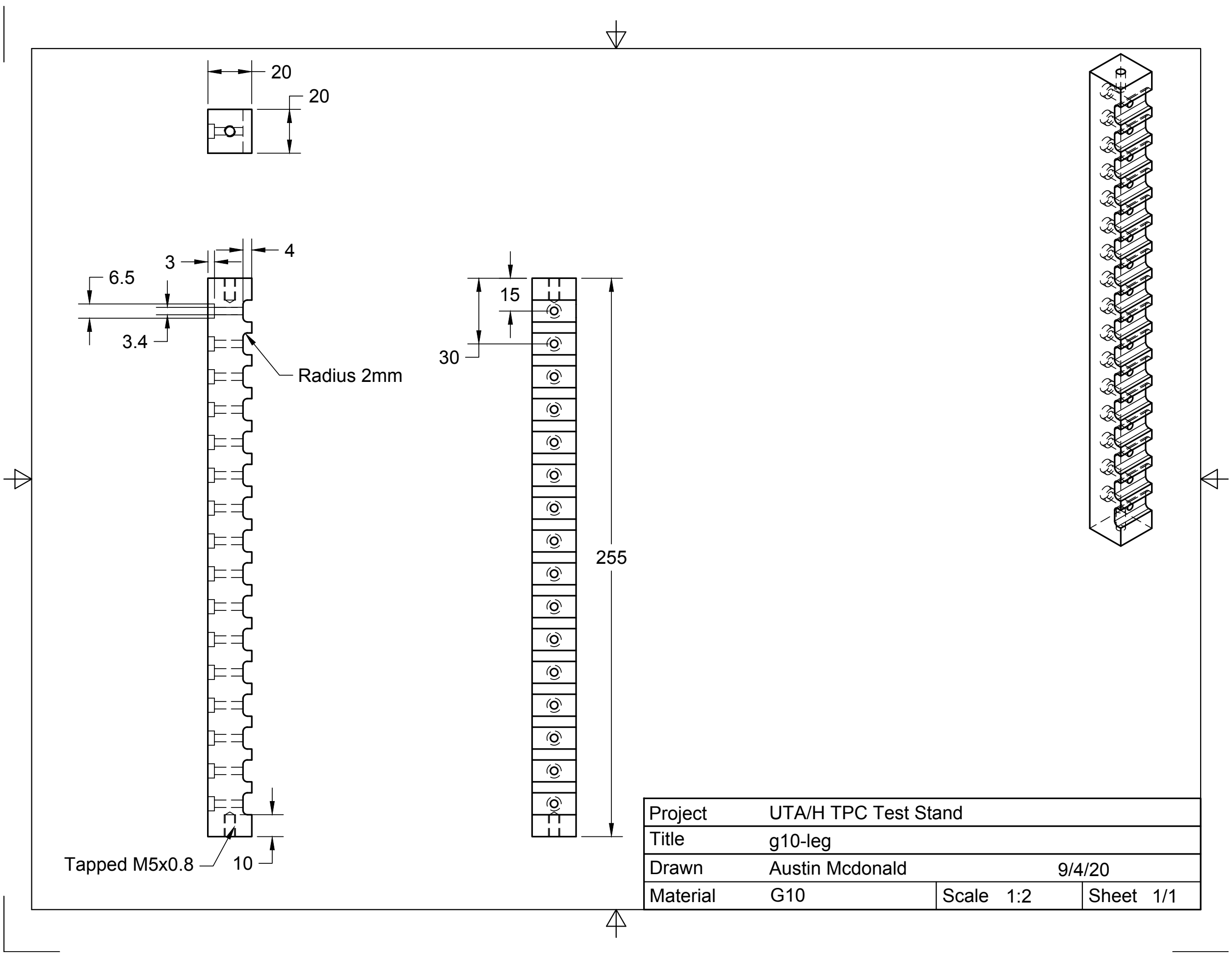
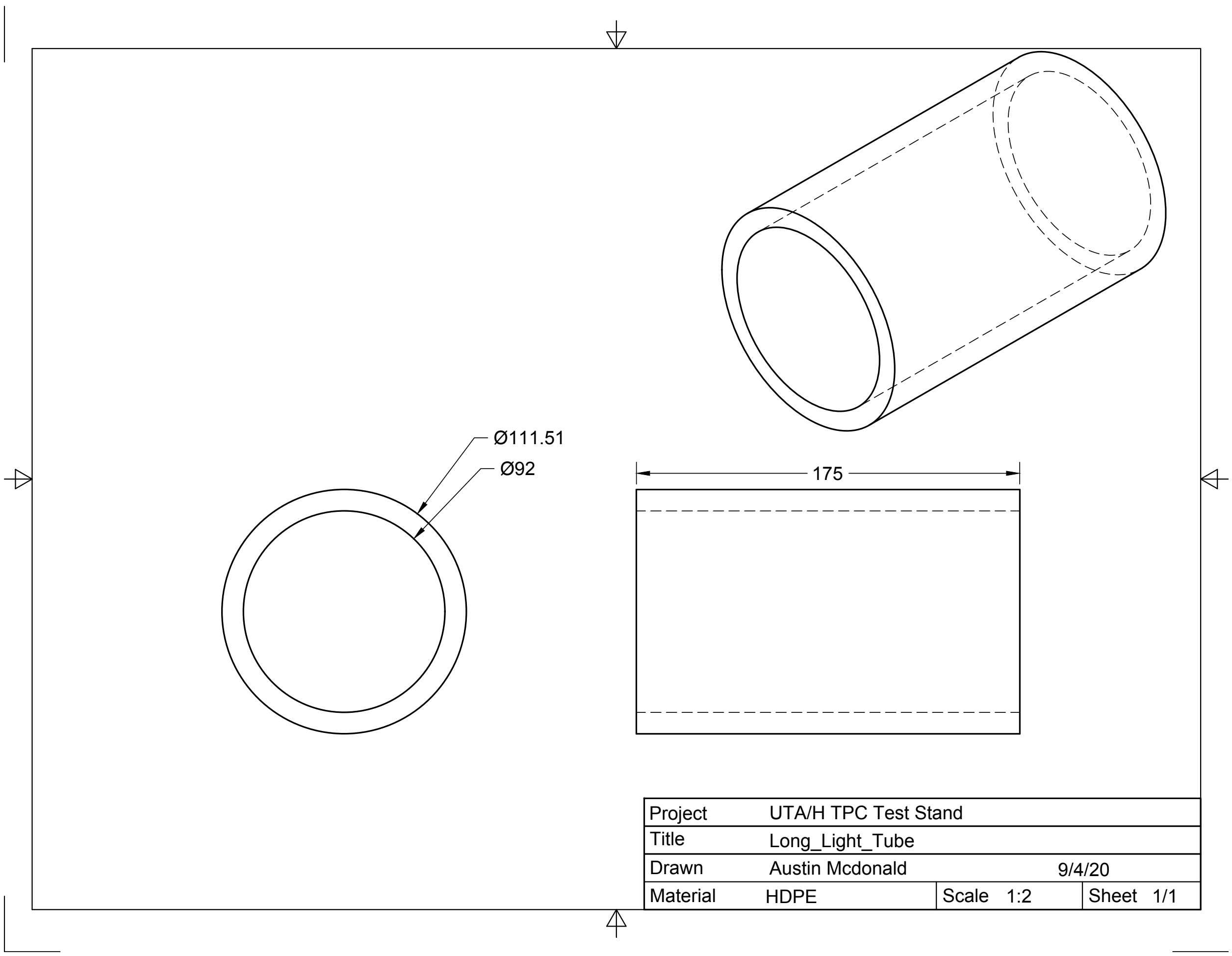
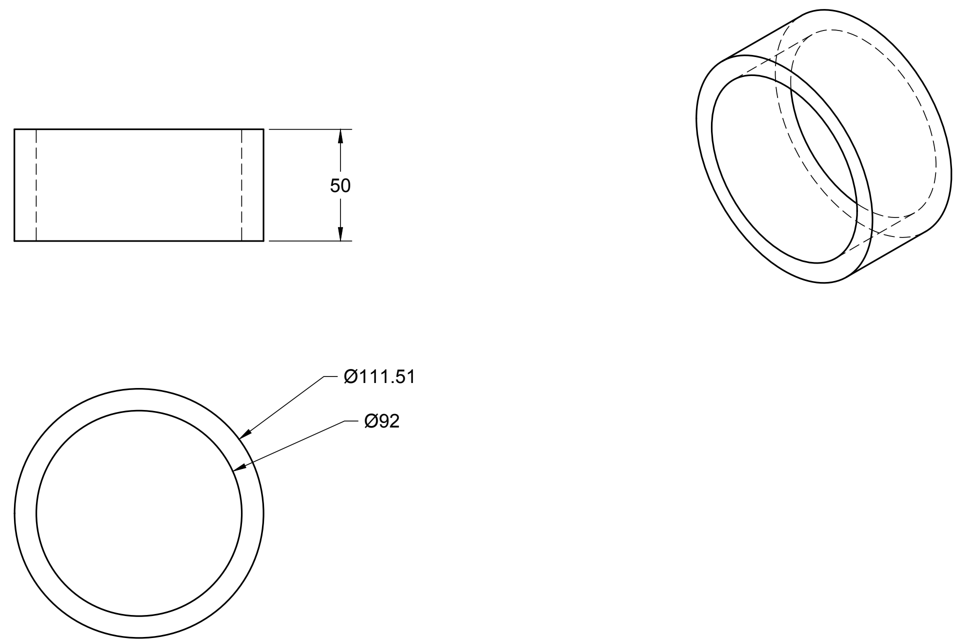
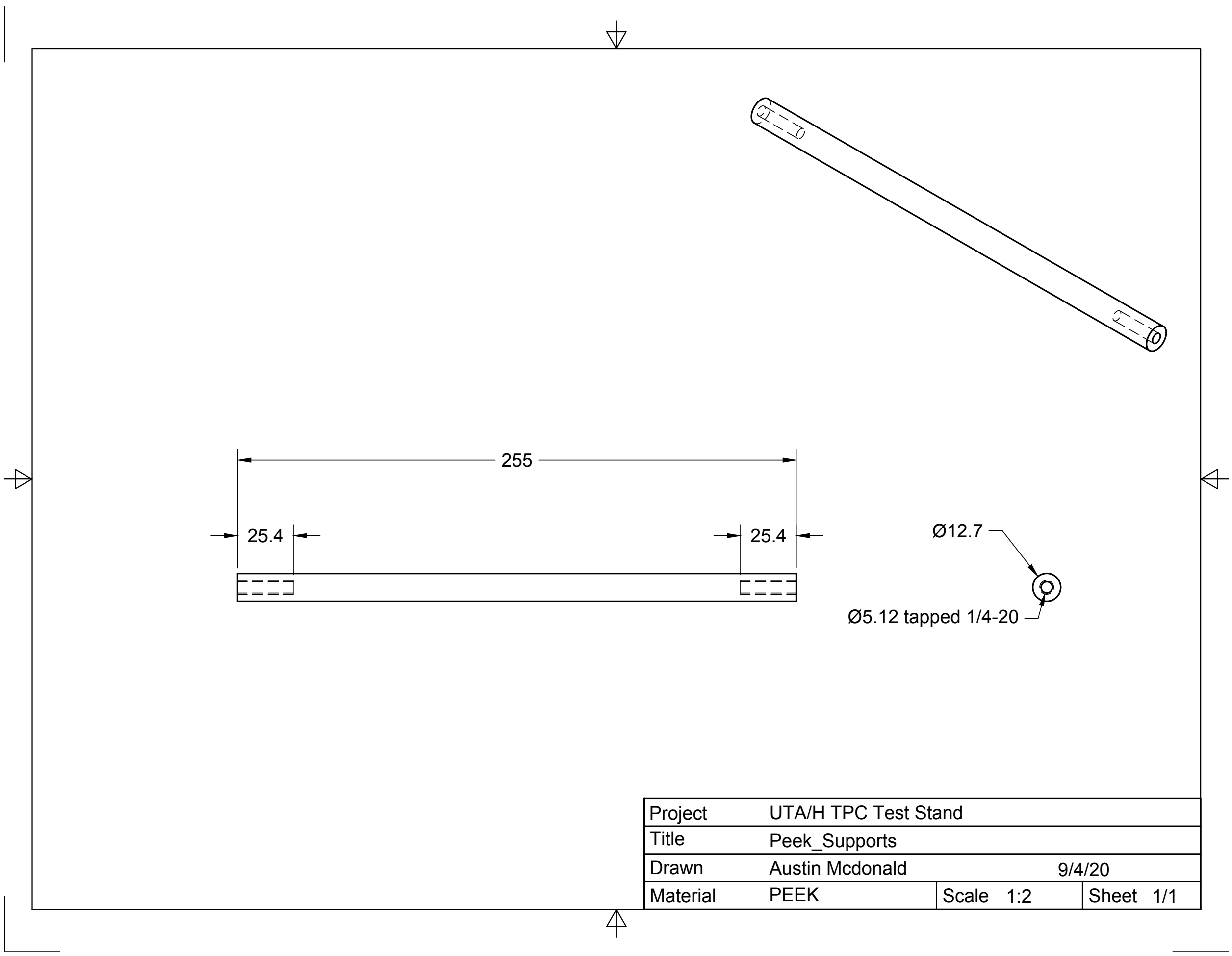
Drawn	Austin Mcdonald	9/4/20	
Material	Aluminum 6061 T6	Scale 1:2	Sheet 1/1

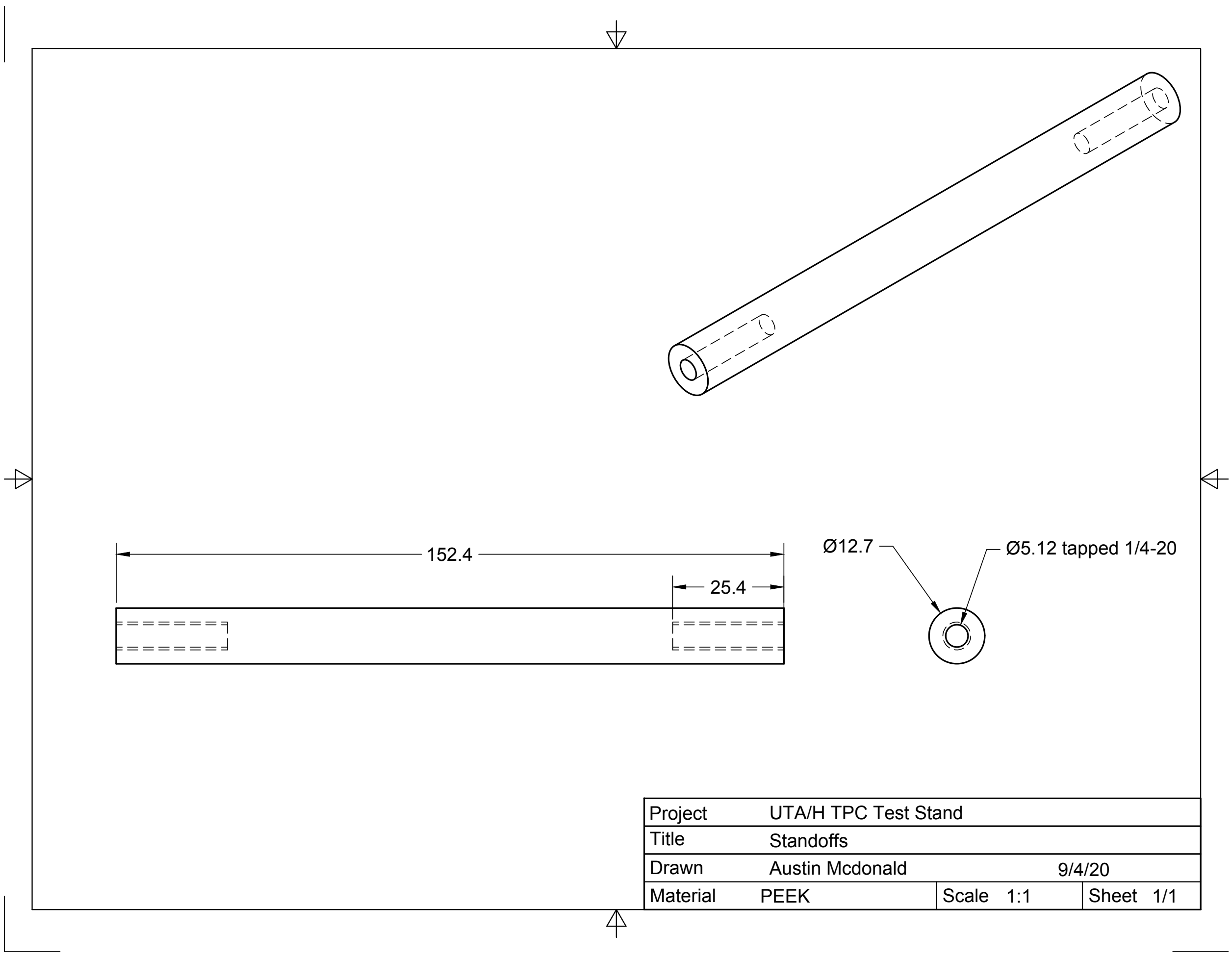

20
20
3
4
6.5
3.4
Radius 2mm
15
30
255
Tapped M5x0.8
10
Project
UTA/H TPC Test Stand
Title
g10-leg
Drawn
Austin Mcdonald
9/4/20
Material
G10
Scale 1:2
Sheet 1/1

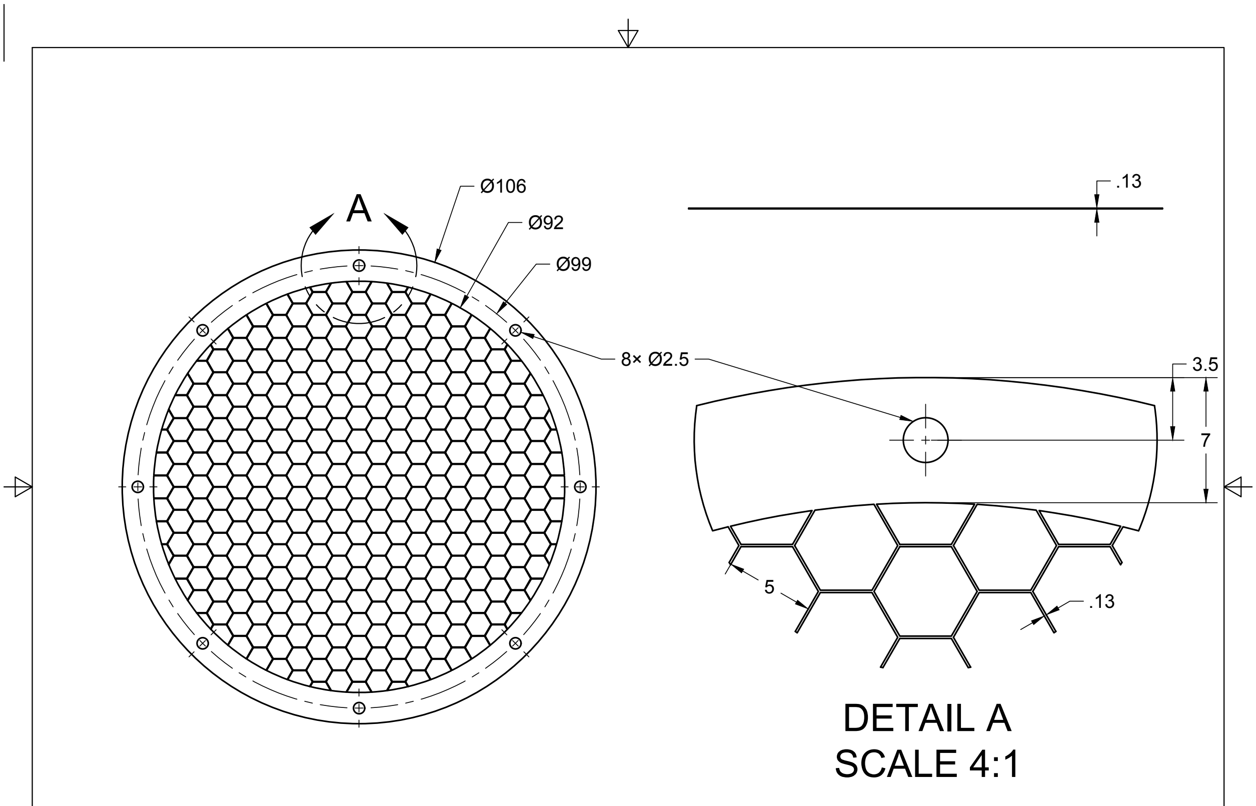

Ø111.51
Ø92
175
Project UTA/H TPC Test Stand
Title Long_Light_Tube
Drawn Austin Mcdonald 9/4/20
Material HDPE
Scale 1:2
Sheet 1/1



Project	UTA/H TPC Test Stand		
Title	Short_Light_Tube		
Drawn	Austin Mcdonald	9/4/20	
Material	HDPE	Scale 1:2	Sheet 1/1


255
25.4
25.4
Ø12.7
Ø5.12 tapped 1/4-20
Project
UTA/H TPC Test Stand
Title
Peek_Supports
Drawn
Austin Mcdonald
9/4/20
Material
PEEK
Scale 1:2
Sheet 1/1


152.4
25.4
Ø12.7
Ø5.12 tapped 1/4-20
Project
UTA/H TPC Test Stand
Title
Standoffs
Drawn
Austin Mcdonald
9/4/20
Material
PEEK
Scale 1:1
Sheet 1/1



ALL DIMENSIONS ARE IN MILLIMETERS

Project	UTA/H TPC Test Stand		
Title	mesh		
Drawn	Johnny Ho		9/11/20
Material	Stainless Steel 316L	Scale 1:1	Sheet 1/1