Camera System

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Purpose

Cameras are useful for the following reasons:

- While the detector is being filled, the cameras can be used to determine and verify the status of the fill, in collaboration with other devices (temperature monitors, etc).
- While the detector is operating, the cameras can be used to monitor for HV breakdowns, potentially determining where an arc occurs.
- The cameras (along with an interior light source) provide the only means for visually inspecting the cryostat and detector after the cryostat is sealed and filled with liquid argon. They are in this sense a final line of defense, but are limited in that they can only be placed in regions with low electric fields (to prevent arcing) and cannot be placed inside of the TPC field cage.

Hardware

The cameras proposed for use in protoDUNE SP were originally supplied by ETH Zurich / CERN for use in the high voltage field cage test being that is presently being conducted in the PC4 hall at Fermilab (HV@PC4). These cameras are closely related to those being used in the WA105 3x1x1 test, and (presumably) to the camera system planned for protoDUNE DP. There are a total of 6 cameras. Aspects of the camera system design were redesigned to pass Fermilab's operational readiness requirements and to introduce heaters which we found were needed to operate at cryogenic temperatures.

Camera construction

Each camera consists of a Raspberry PI v1.3 camera mini-board embedded in a stainless steel cryogenic vessel. The vessel has a window which allows the camera to photograph its environment. The rear of the assembly consists of a vacuum flange with a 15 PIN D-sub connector that connects the camera mini-board to a Raspberry PI single board computer (SBC). The SBC is located outside the cryostat. Inside the vessel the camera is connected to the flange with a 15 line ribbon cable that is a few inches long. The vessel connects to the SBC via a different 15 line cable that goes from the vessel to a flange at the top of the cryostat. In the HV@PC4 test the flanges have 50 pin connectors that serve 3 cameras. For protoDUNE it preferable to use individual 15 pin connectors if possible.

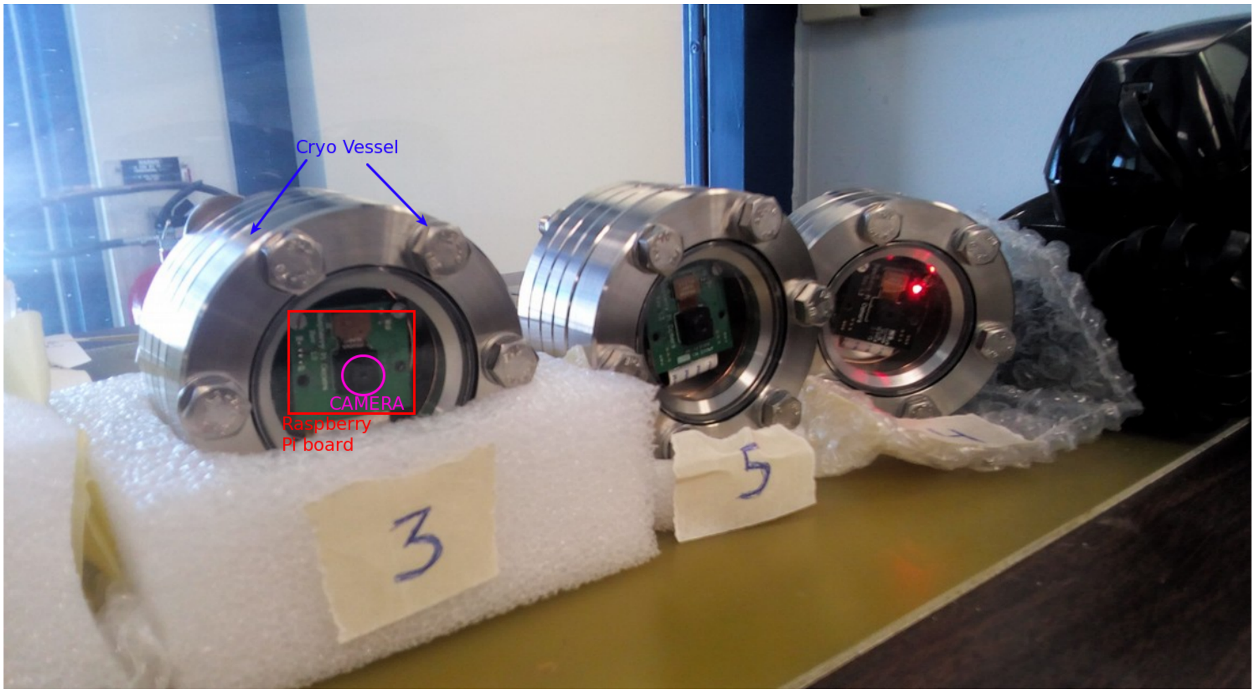

Figure 1: Three camera assemblies used in the HV@PC4 test.

Camera readout

The SBCs run a UNIX operating system and the cameras are readout as a normal peripheral. Code for camera control and image processing is readily available on the internet. The HV@PC4 test is operating without a "trigger". The data rate is 150MB per camera per day when running with a resolution of 640x480 at 90 fps (frames per second). This is for cameras in the dark (the image stream is compressed). A lower data rate could be achieved by implementing a circular buffer and trigger condition, such as a sufficiently large change in the image, as is done for security cameras. This is a few day day task. The camera system is also capable of taking higher resolutions, up to 1920x1080 at 30fps.

The SBCs need 5VDC@2A power supplied by a micro-USB connector. They talk to the outside world via Ethernet.

Camera modifications for HV@PC4

1. Testing of the cameras in liquid nitrogen at Fermilab showed that they were unable to reliably operate at cryogenic temperatures and would have to be heated. Two 75Ω metal film resistors were connected in parallel and fixed to the camera board with a Kapton film in between. An external DC power supply was used to run current (0.2 A) through the resistors by repurposing two of four redundant ground lines running in the 15 line connector from the SBC to the camera mini-board. Three cameras shared one power supply in the HV@PC4 test. For protoDUNE it would be advisable to have a dedicated power source for each board. This could be an individual power supply or a multiplexing "power box" with potentiometer voltage dividers so that each camera can be independently tuned.

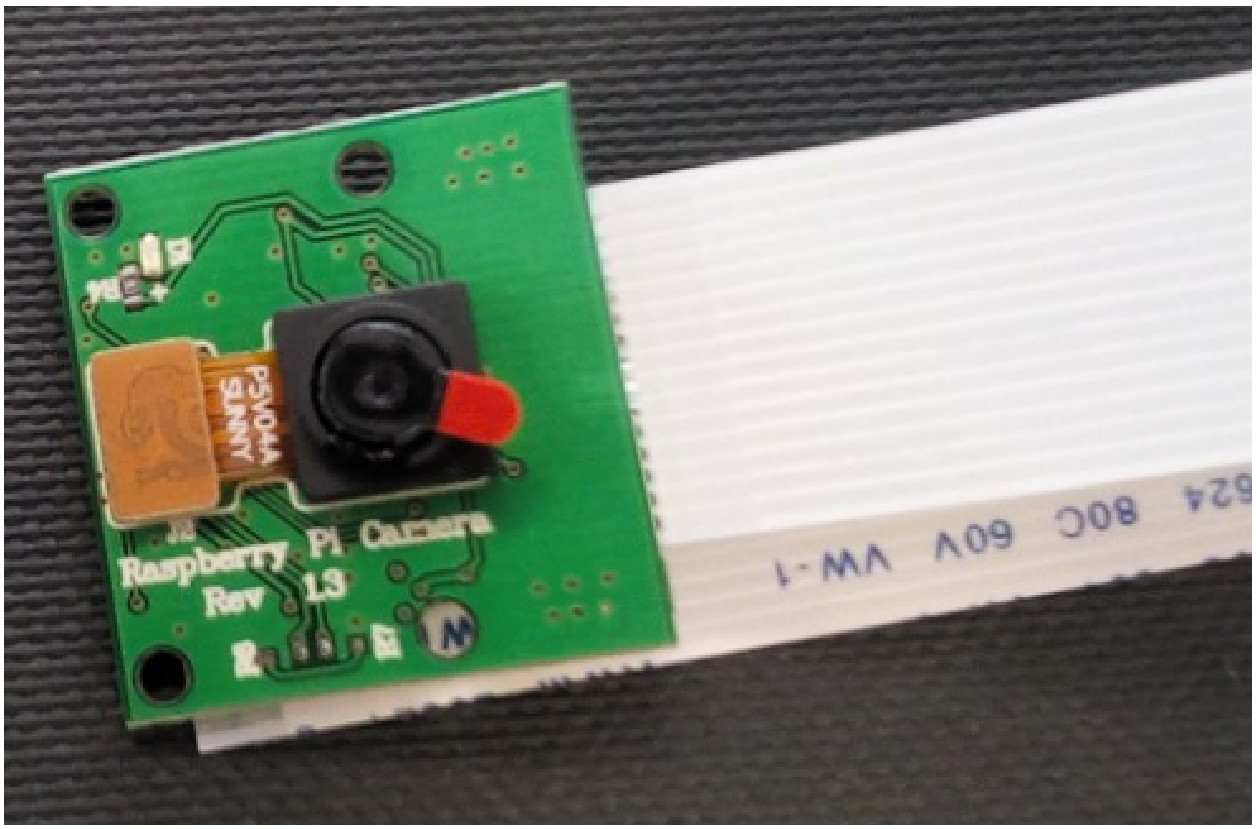

Figure 2: A Raspberry PI camera board and the flat flex ribbon cable used to connect it to the Raspberry PI single board computer. This cable was provided by the manufacturer but is not intended for runs longer than a meter or so and was replaced for the HV@PC4 test as described in the text.

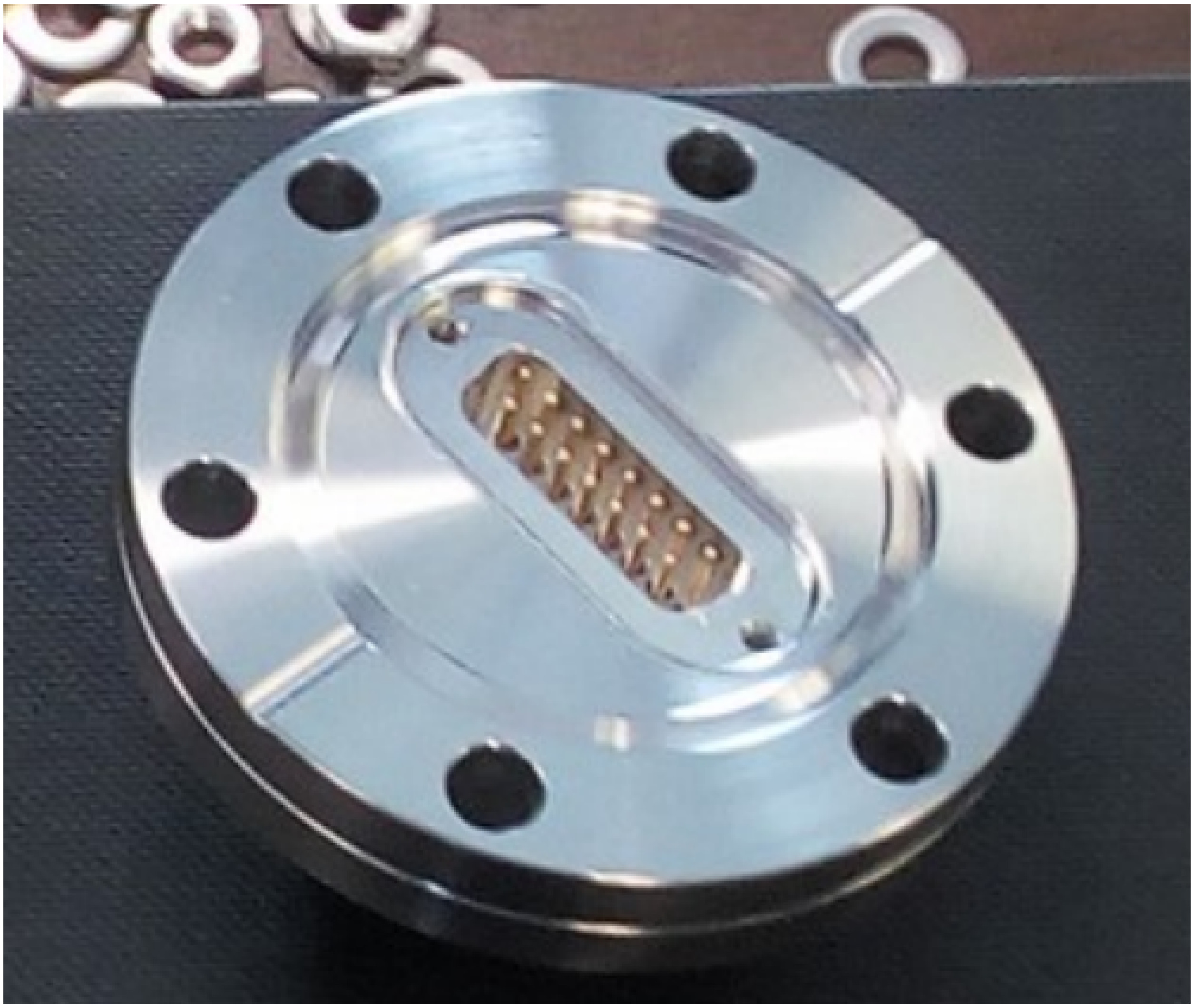

Figure 3: The 15 pin connector on the back of each camera vessel.

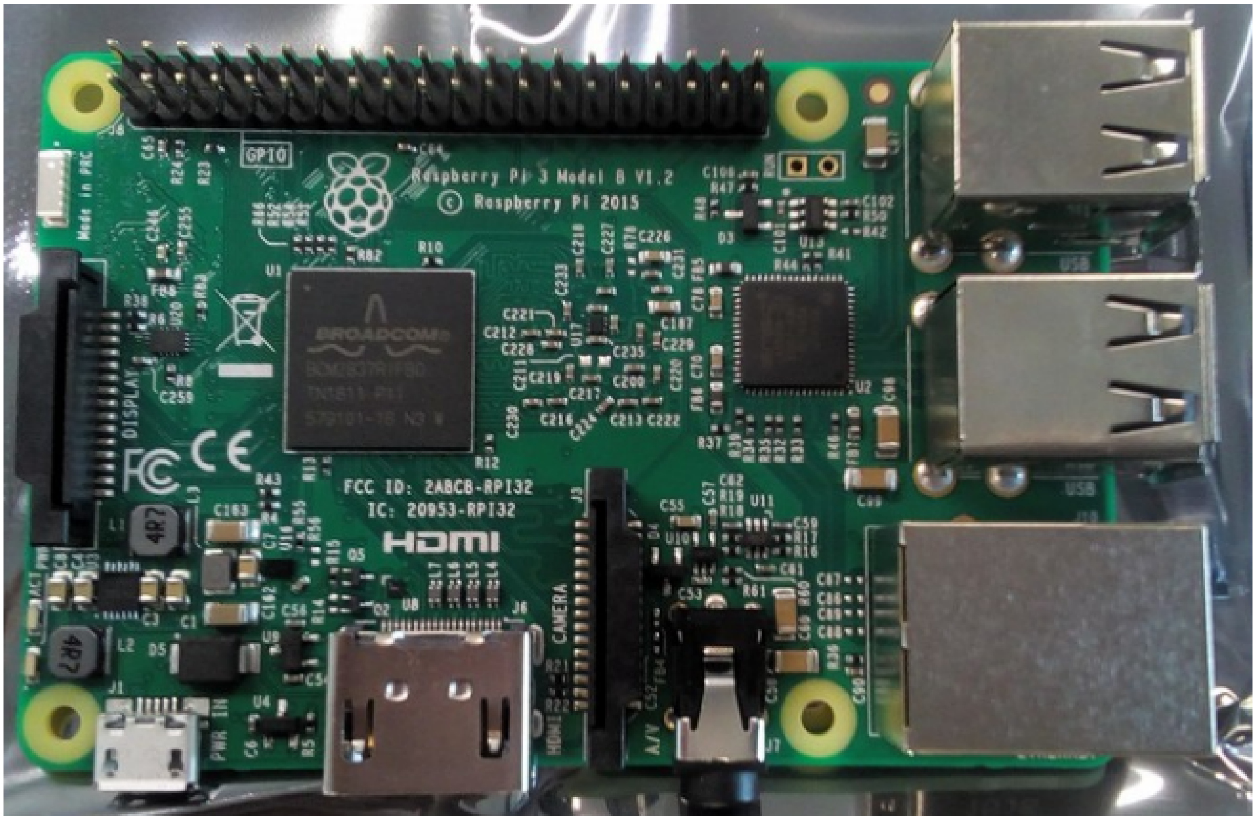

Figure 4: The Raspberry PI single board computer.

2. The flat flex ribbon cables provided with the Raspberry PIs are not suitable for runs over a meter or so. Inside the cryostat these were replaced with multi-pair 24 AWG solid core cables made by Gore. These have enabled camera to flange runs of 3-8m, though there is some confusion associated with a non-functional camera with a run of 5m. It is not yet clear that the problems are associated with the cable length, but they may be.
3. Outside the cryostat the connection from the flange to the Raspberry PI SBCs was initially made with a 50 line ribbon cable. This cable was replaced with three 15 line 18 AWG multi-core twisted cables.
4. There were nine modifications needed to adapt the system to Fermilab operational regulations. This is mentioned because a similar set of modifications might be needed when the cameras return to CERN. Obviously it would be good to determine this in advance if possible, though some on-site inspection will presumably be needed.

Proposed use in ProtoDUNE SP

An overview of ProtoDUNE SP is shown in Figure 6. The most relevant areas for high voltage monitoring are the HV cup, the beam plug, and the cathode plane (CPA). The beam plug seems especially important to monitor since it connects the cryostat wall (0V)

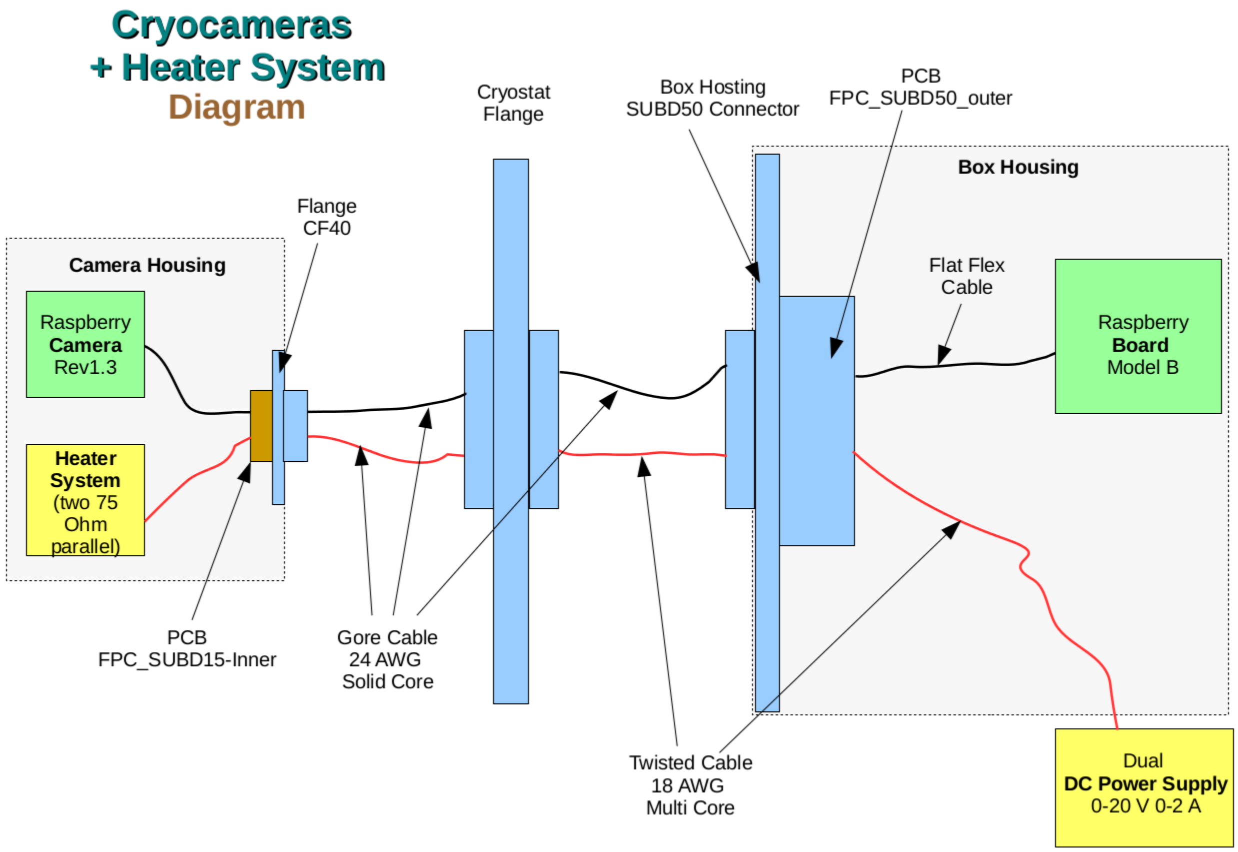

Figure 5: An overview of the HV@PC4 camera system.

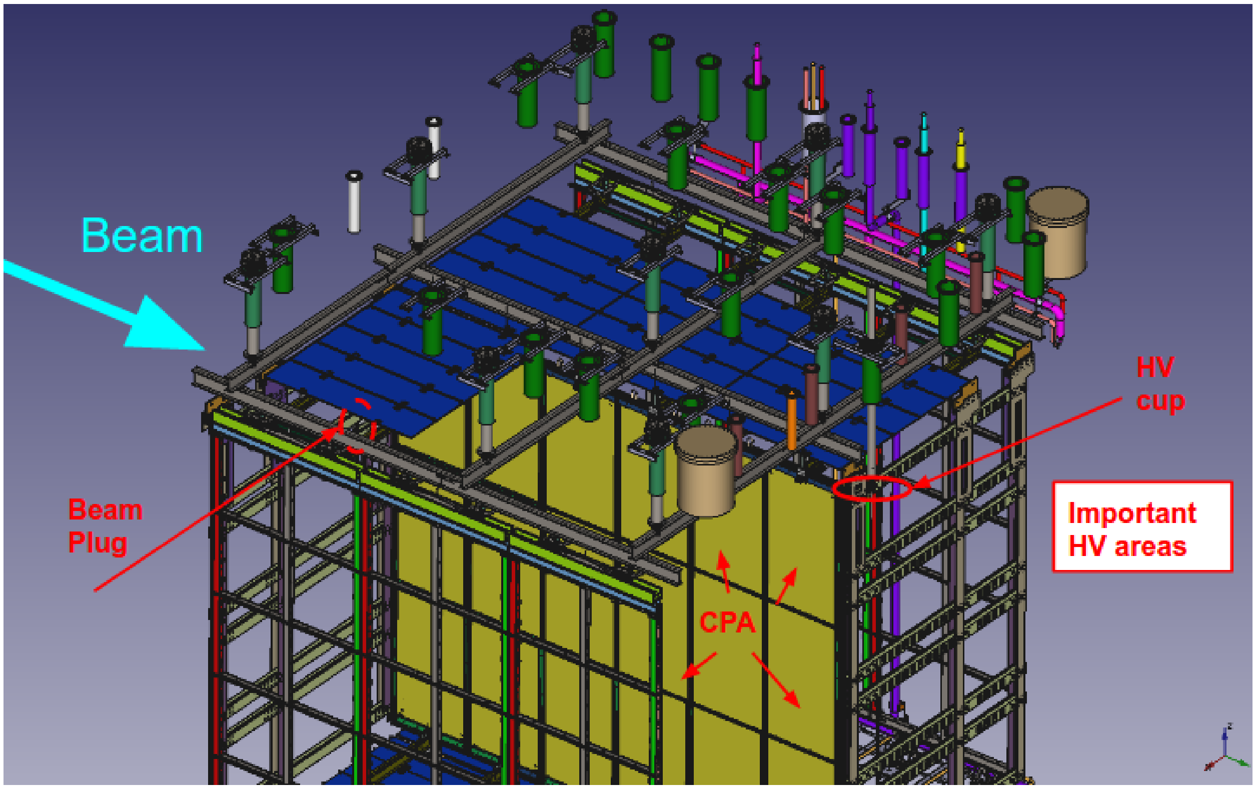

Figure 6: An overview of protoDUNE SP showing areas that we would like to monitor.

to the field cage ($\sim$ 150 kV) and could be a source of breakdown. The HV cup and HV feedthrough are also at the highest voltage and could be locations of HV breakdown. We may also want to monitor the cryogenic piping on the far side of the detector in Figure 6, or the readout electronics for the anode planes, located along the vertical corners of the cube.

The cameras cannot be installed in regions with a large electric field for fear that they will provide a path to ground for discharges. Figure 7 shows the areas that are safest for camera installation. These are essentially locations above the ground plane at the top of the detector and along the vertical corners, where the potential difference between the detector and cryostat wall is no more than a few kV. We assume that the cameras will be fixed to the cryostat wall or potentially to the field cage support structure.

Figure 8 shows proposed locations for three cameras to monitor the HV cup. One camera would sit above the cup looking down on it, while the other two would be located to give side-on views of the cup. This scheme could potentially be reduced to have only the two secondary cameras. The laser ports could be used as feedthroughs.

Figure 9 shows the proposed location of three cameras used to view the beam plug region. Two cameras sit above each side of the plug while a third views the bottom of the plug from further away. That third camera could potentially mount to the field cage support structure. There are multiple ports above the camera locations which could be used to carry signals to and from the cameras.

The potential location of a camera (or cameras) optimized for viewing the top of the CPA is shown in Figure 10. It is unclear that such cameras are needed.

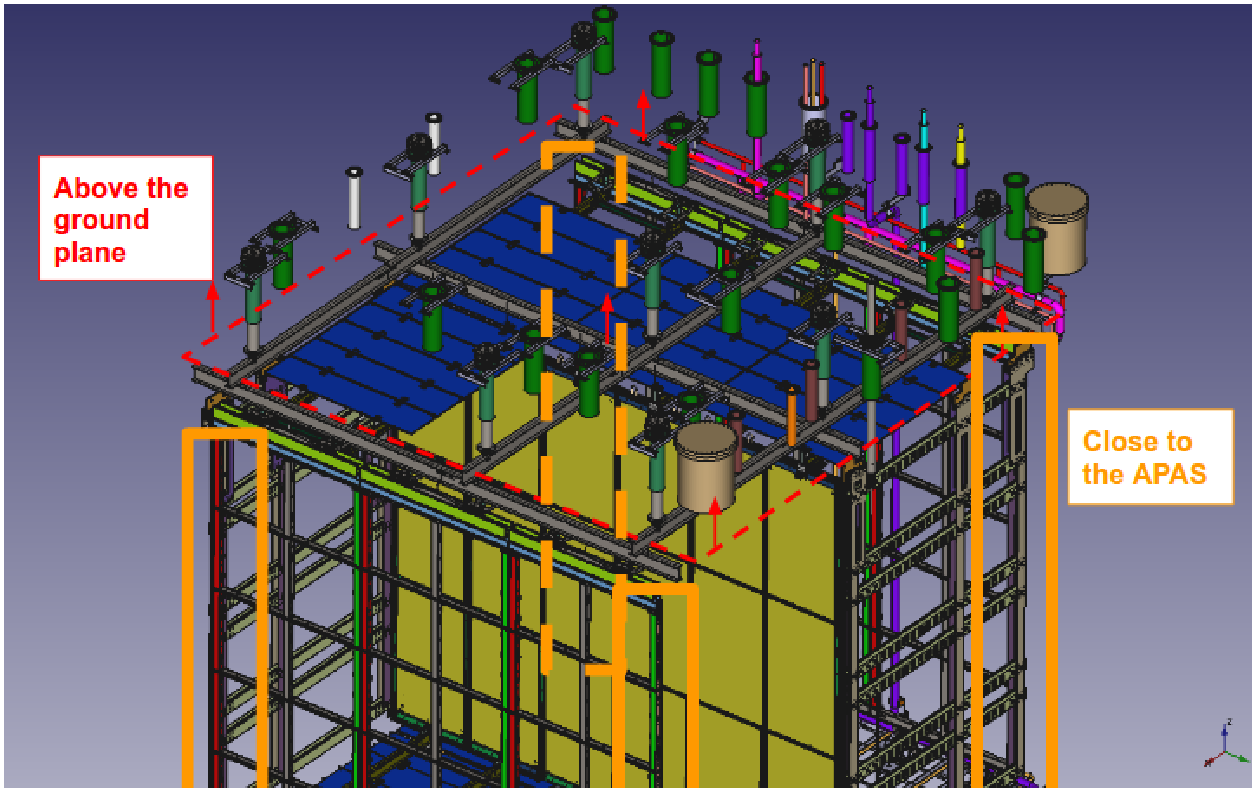

Figure 7: Areas in which cameras could be placed.

Additional concerns for camera placement

- The liquid argon causes a substantial pressure gradient between the top and bottom of the cryostat. Bo Yu mentioned that this reduces the chance of high voltage breakdown near the bottom. This had caused us to focus on the top half of the cryostat and TPC.
- The performance of the cameras decreases with cable length. The HV@PC4 test partially addressed this, but it seems wise to design for lengths that are as short as possible. This has a few ramifications:
  - We should keep the cable lengths outside the cryostat as short as possible. From this standpoint it would be best if we could place the SBCs inside small boxes (which can be bought commercially) and mount them to the feedthroughs. Connections to the rest of the world would be DC power (which could be located far away) and ethernet.
  - Cable length concerns are particularly relevant if we would like to place a camera near the bottom of the cryostat so as to observe the cryogenic piping.
  - We should consider designing a repeater board that would sit outside the cryostat and boost signals going in and out. This would provide some insurance and perhaps improve performance.
- I would like to have a conversation about grounding with someone knowledgeable. I think the current system references the camera ground to the power supply and the

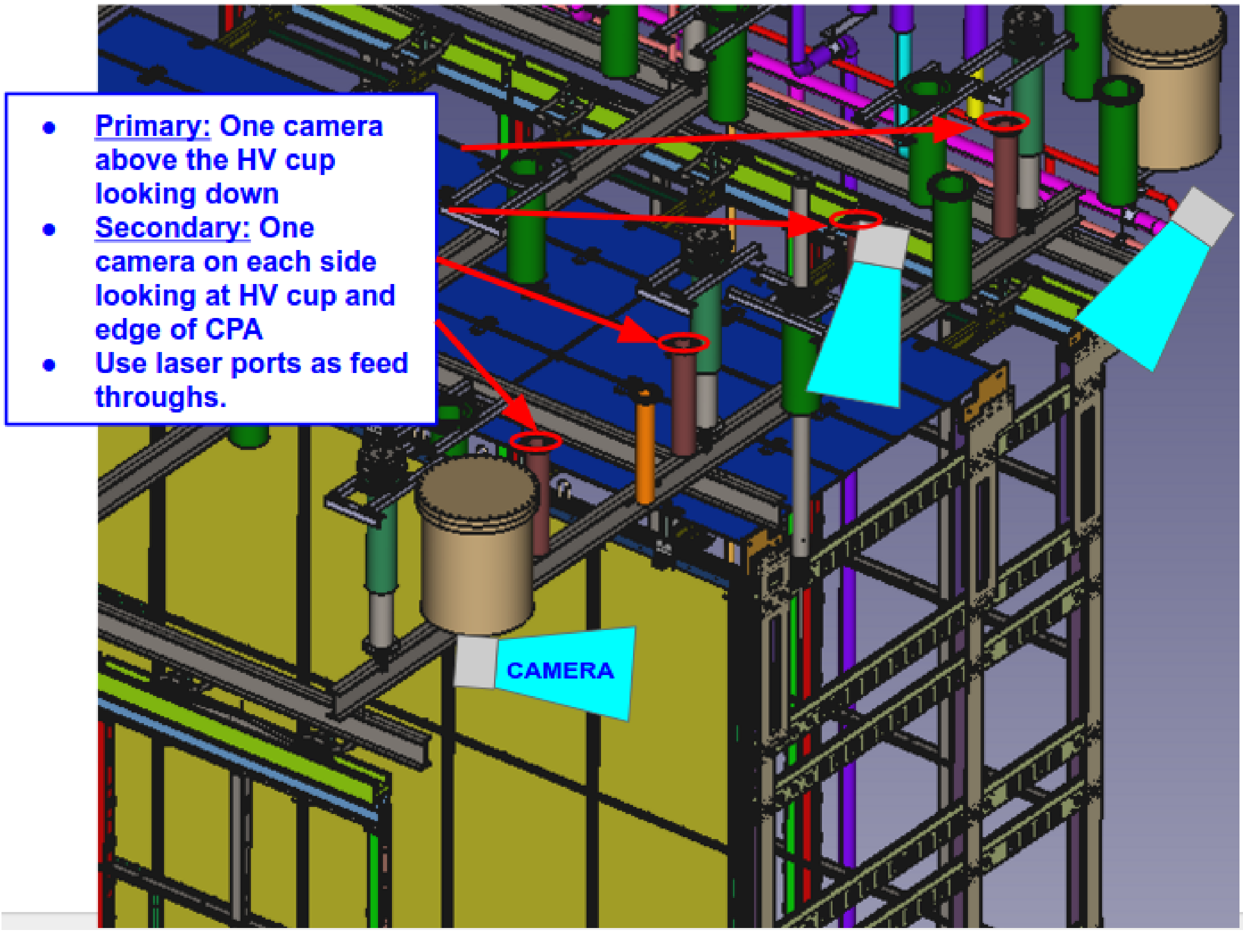

Figure 8: Possible camera locations for viewing the HV cup.

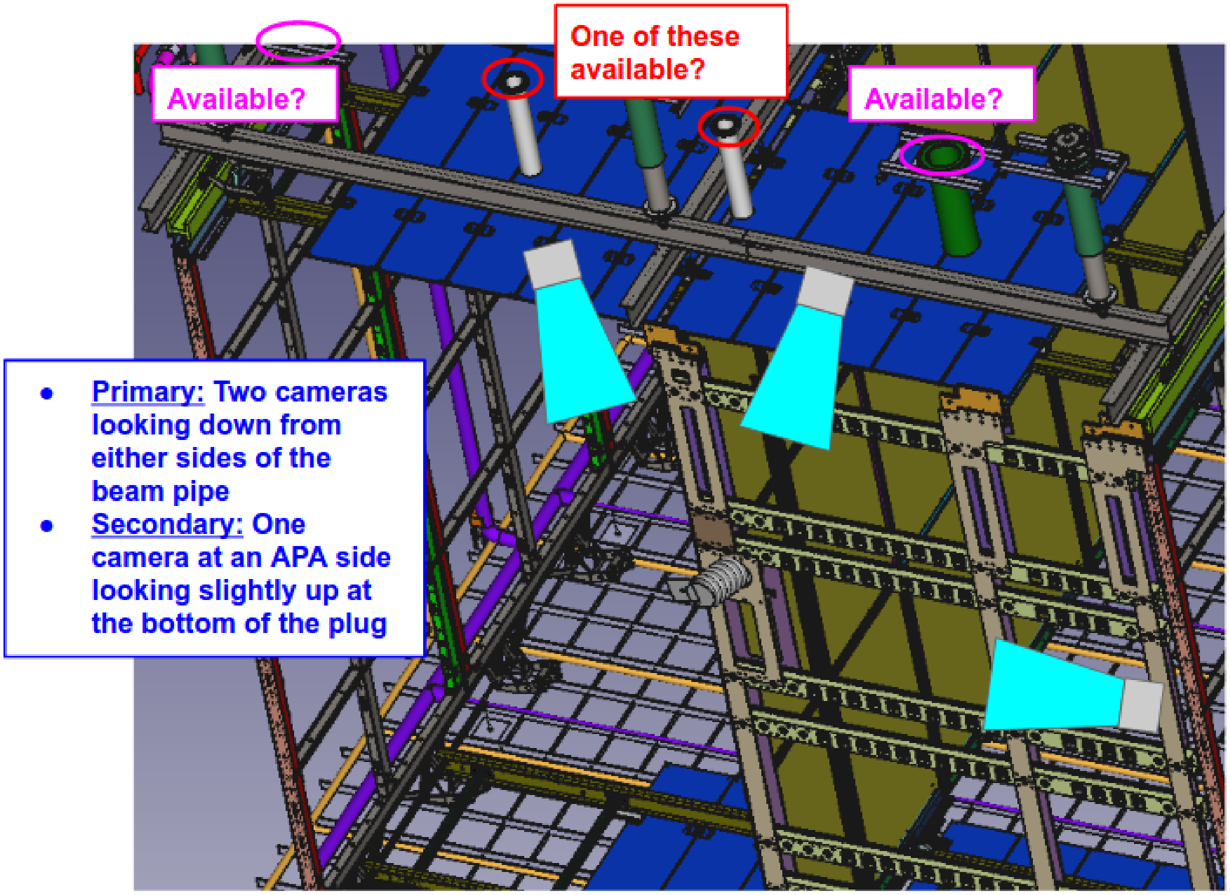

Figure 9: Possible camera locations for viewing the beam plug.

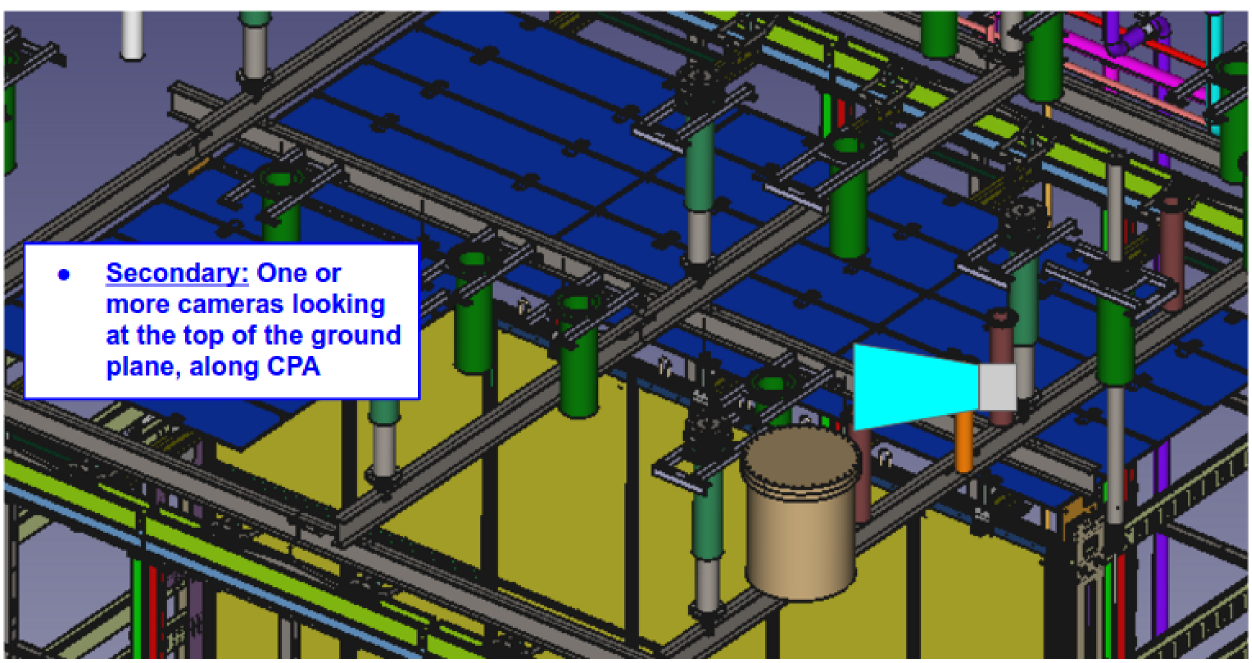

Figure 10: Possible camera location for viewing the ground plane. It is not clear this is necessary, but it is an easy region to monitor if desired.

vessel ground to the mounting point (e.g., cryostat wall), but I do not know if that is the right choice.

- We should explore augmenting each camera with a lens so as to better focus on the region of interest (HV cup and beam plug). More space for a lens could be obtained by adding additional rings to the camera vessels (see Fig. 1).
- We need to have a conversation about the details of mounting the cameras. The 35t prototype had numerous mounting points but I do not understand what will be available in protoDUNE.