Monitoring LBNF beamline component heights with HLS (Horn Leveling System)

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Presenter Background

- Associate Scientist in TSD (November 2020 - Present)
    - Horn Leveling System for LBNF
    - NuMI beam simulation
    - DUNE LArSoft
    - Run-Coordinator for FY2022 accelerator operations
- Previously served as a run-coordinator and operations manager for Muon g-2 & developed lost muon detection techniques for the experiment (2015 - 2020)

Motivation

- Objective: Monitor vertical position of LBNF components
- Why vertical movements?
  - Mechanical failures
  - Placement of shielding
  - Heat expansion and building/enclosure settlement
- Beam based alignment is used to set position

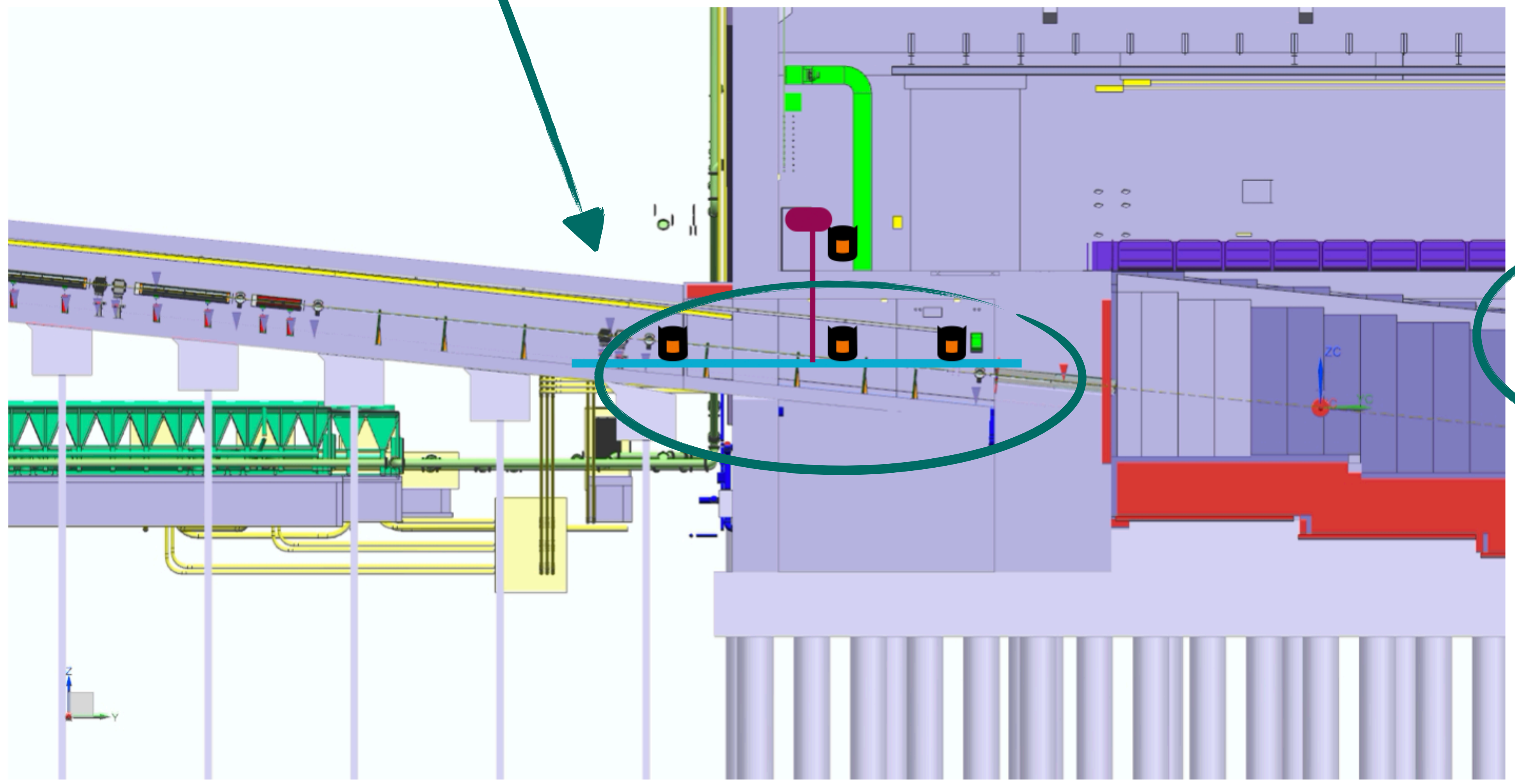
- Without HLS what we have currently
  - ➡BPMs in PBE (Primary Beam Enclosure)
  - ➡Target Vertical Position Thermometer (TVPT) on upstream face of target
  - ➡Beam scans of target/baffle (at low beam power)
  - Challenges
    - ➡After surveyors aligned target/horns
    - - no direct way to measure component movements
    - ➡No direct measurement of thermal expansion
    - ➡NUMI Horn movement not diagnosed until 1 year later
    - ➡BPM calibration drift - faking target movement
    - ➡LBNF PBE and parts of TH (Target hall) will settle differently than NuMI

Requires continuous monitoring of component positions

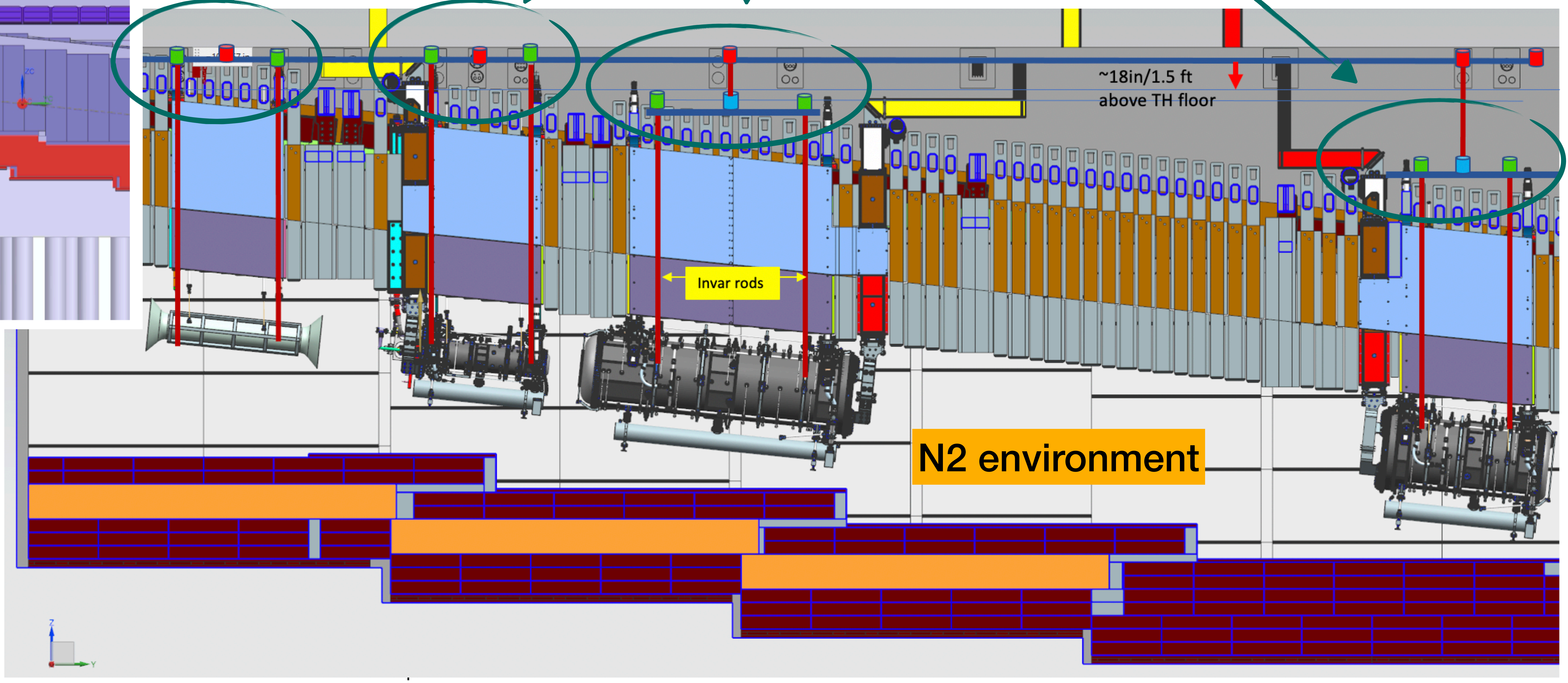
Beamline Components that need to be monitored

- Want to monitor vertical position of a horn/baffle/BPM → Observation of a change
- Locations where height transfer needed, e.g. b/w PBE and target hall

Next to BPMs in Primary Beamline (PBE)



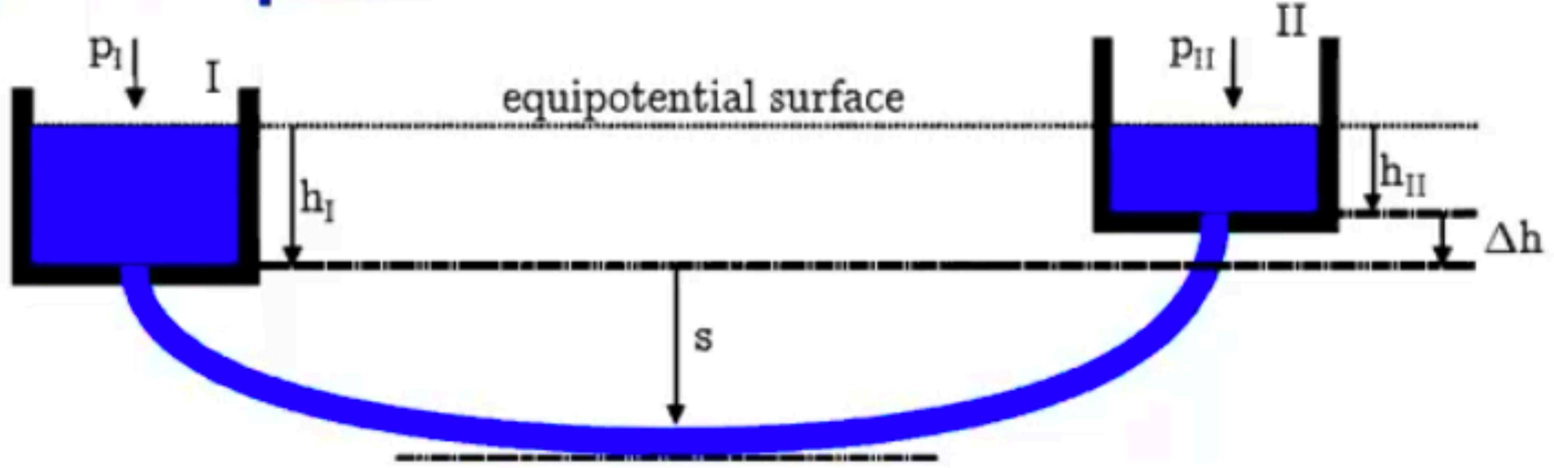
Above baffle and horns inside target chase

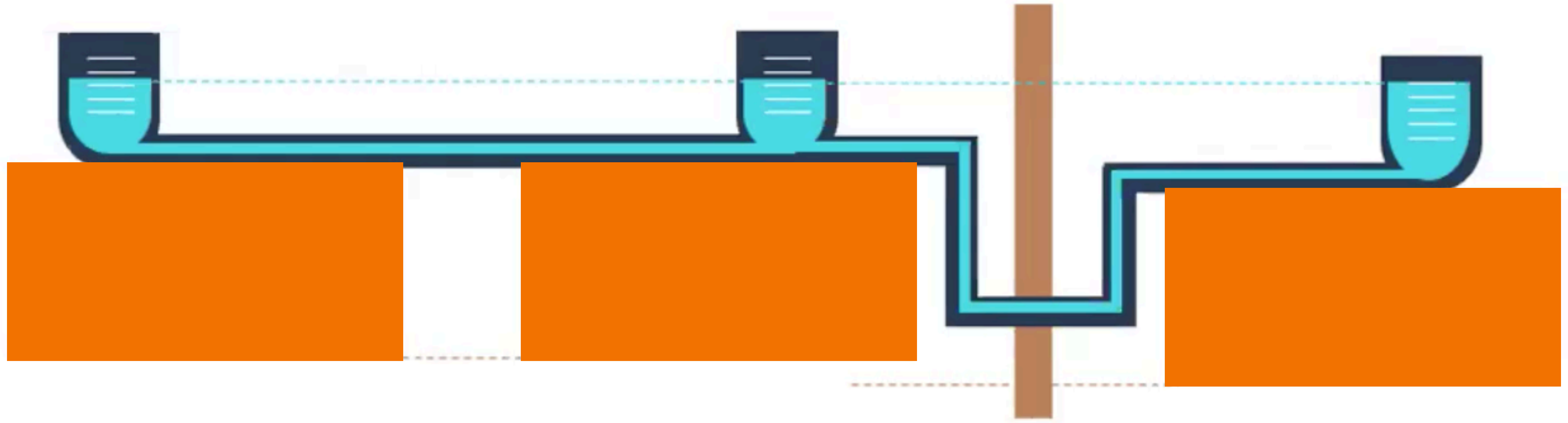


Horn Leveling System (HLS)

What is HLS?

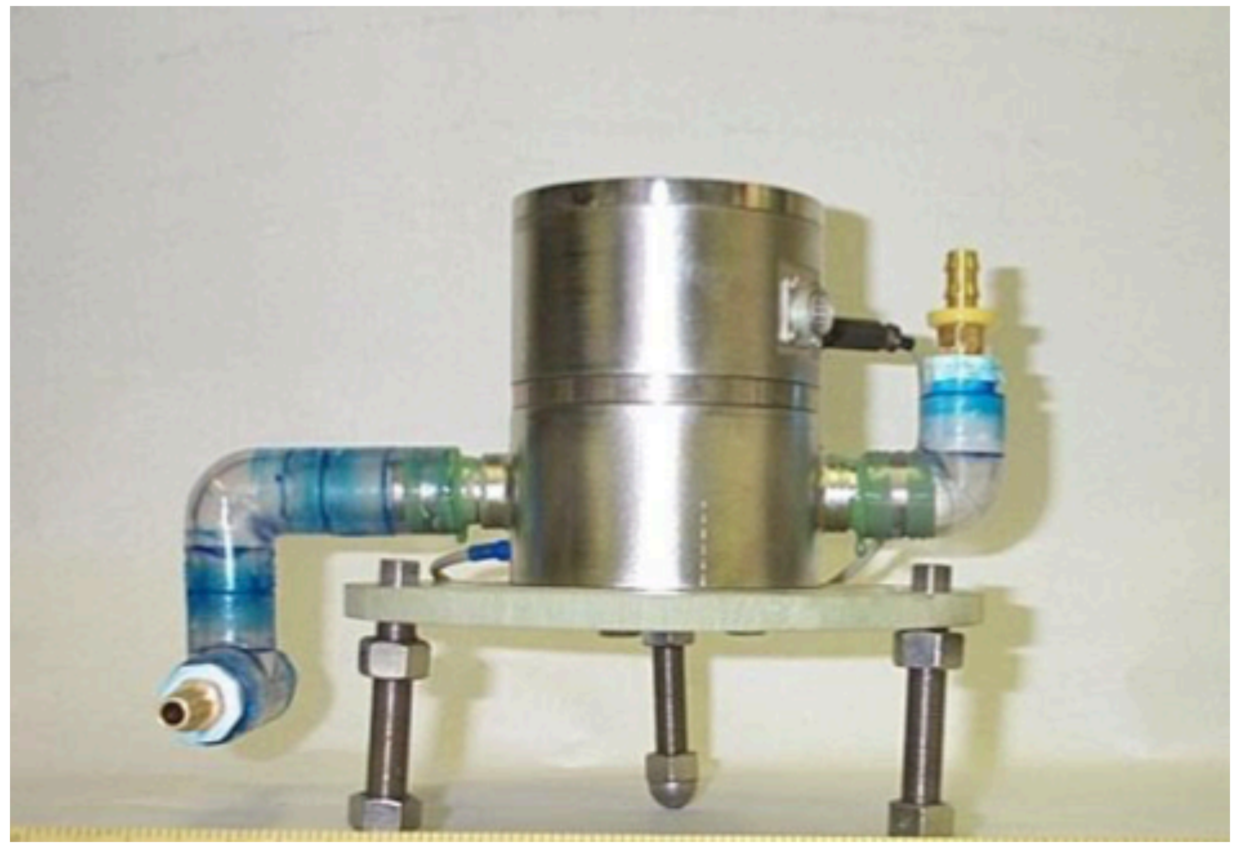
Principle





- Given a reference point, relative level of fluid varies as sensor moves up/down w.r.t other sensor

Older systems with capacitive sensors used in Fermilab



New CERN sensors based on Frequency Scanning Interferometry (FSI)

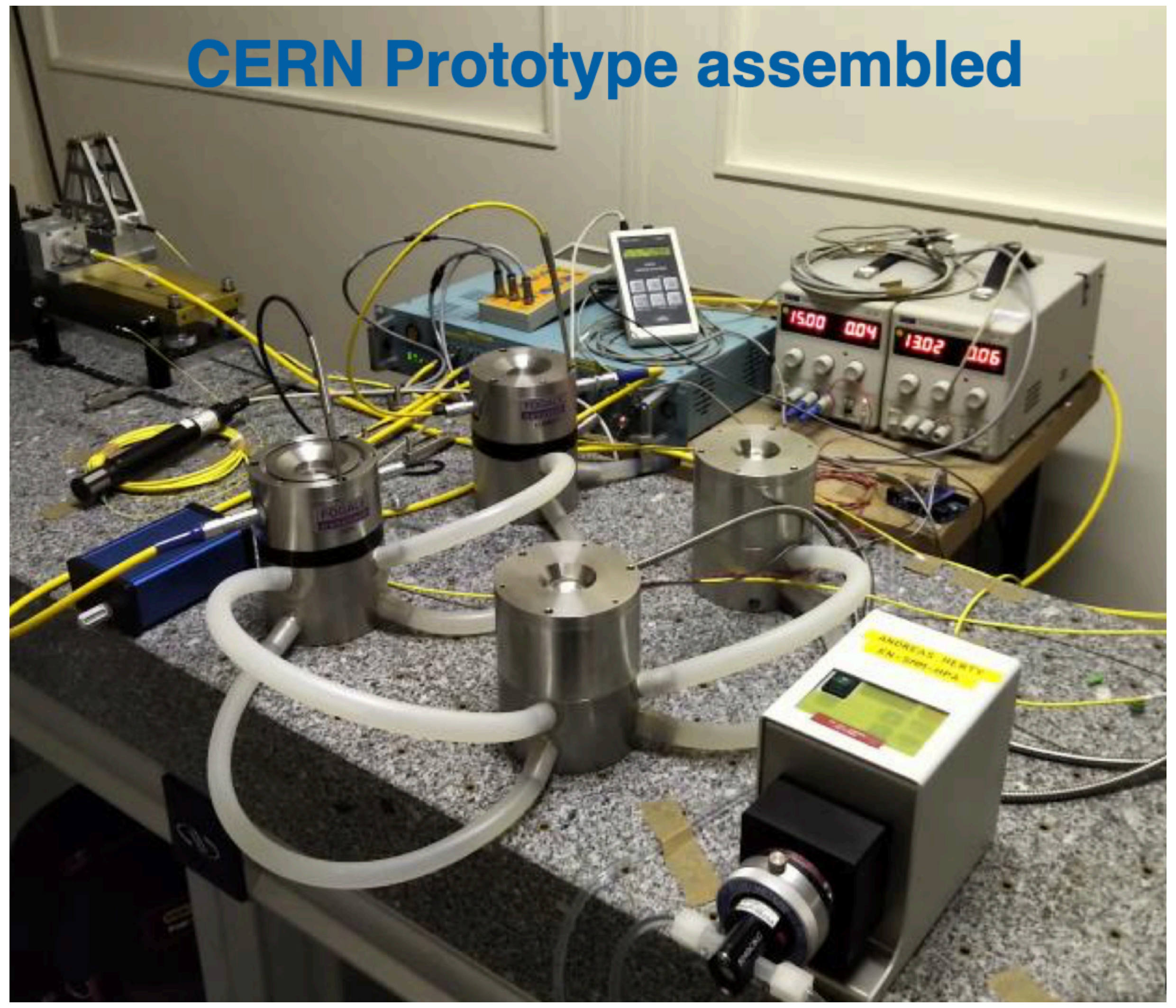
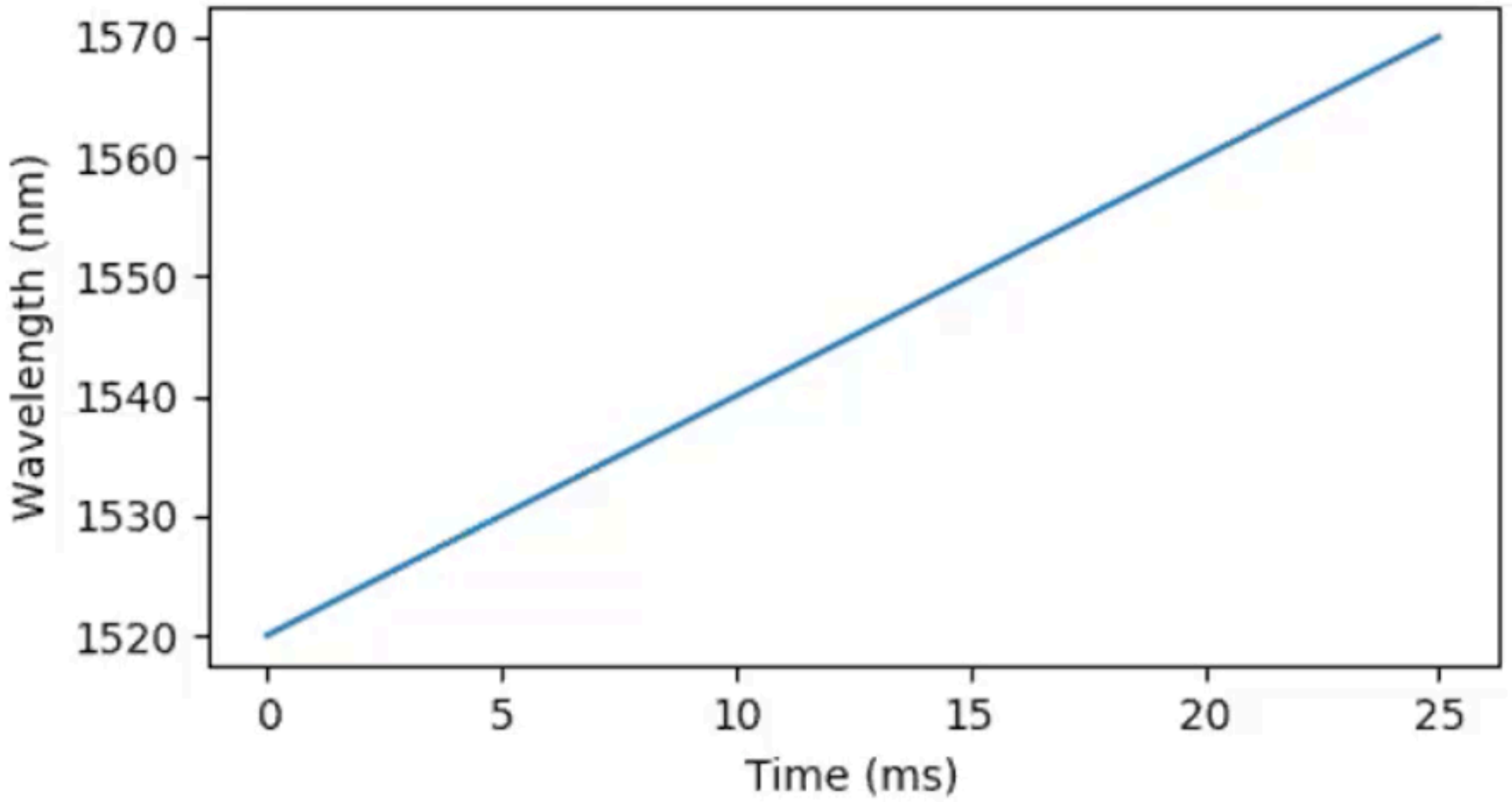


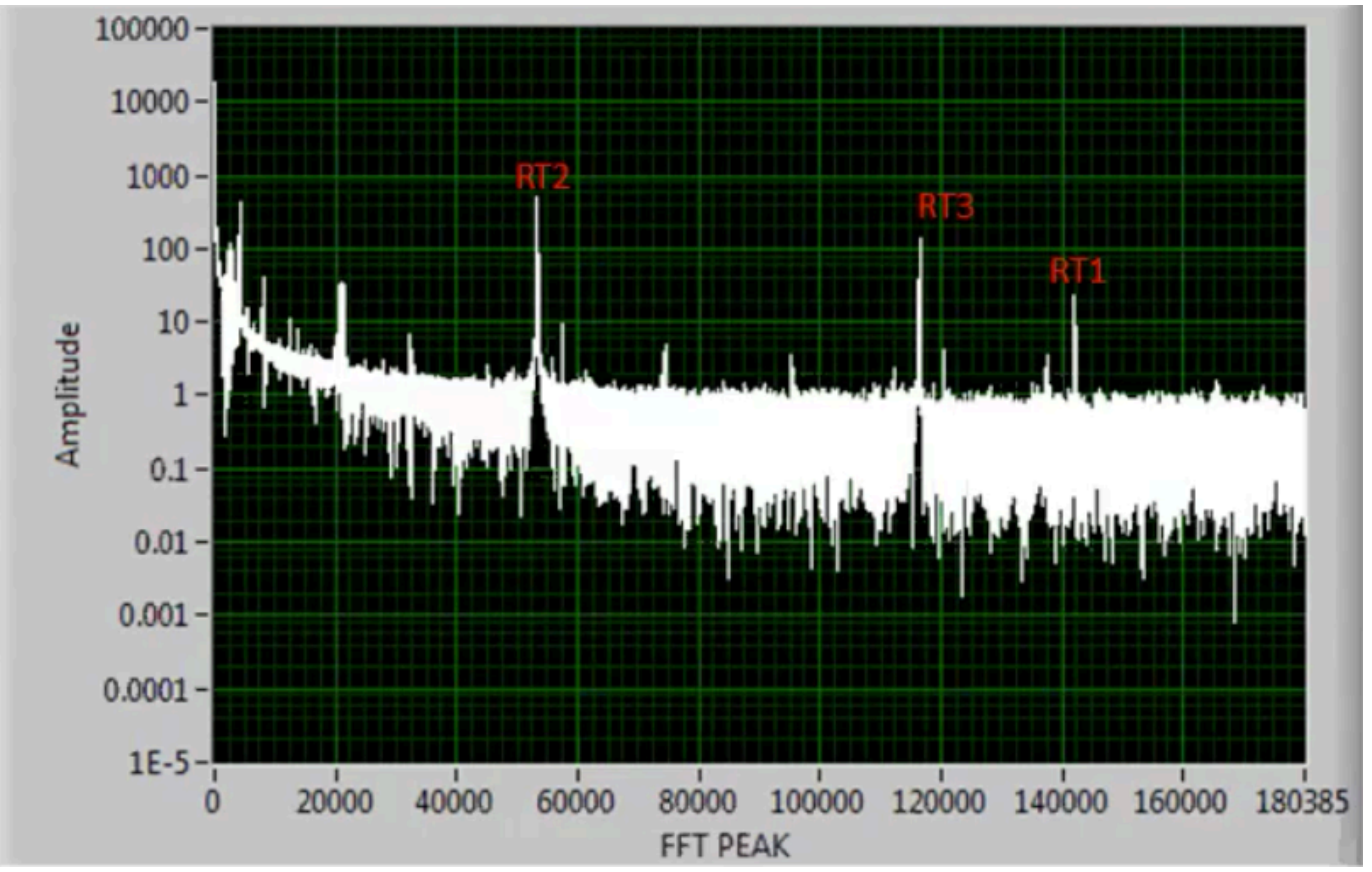
Photo Courtesy: M. Sosin, CERN

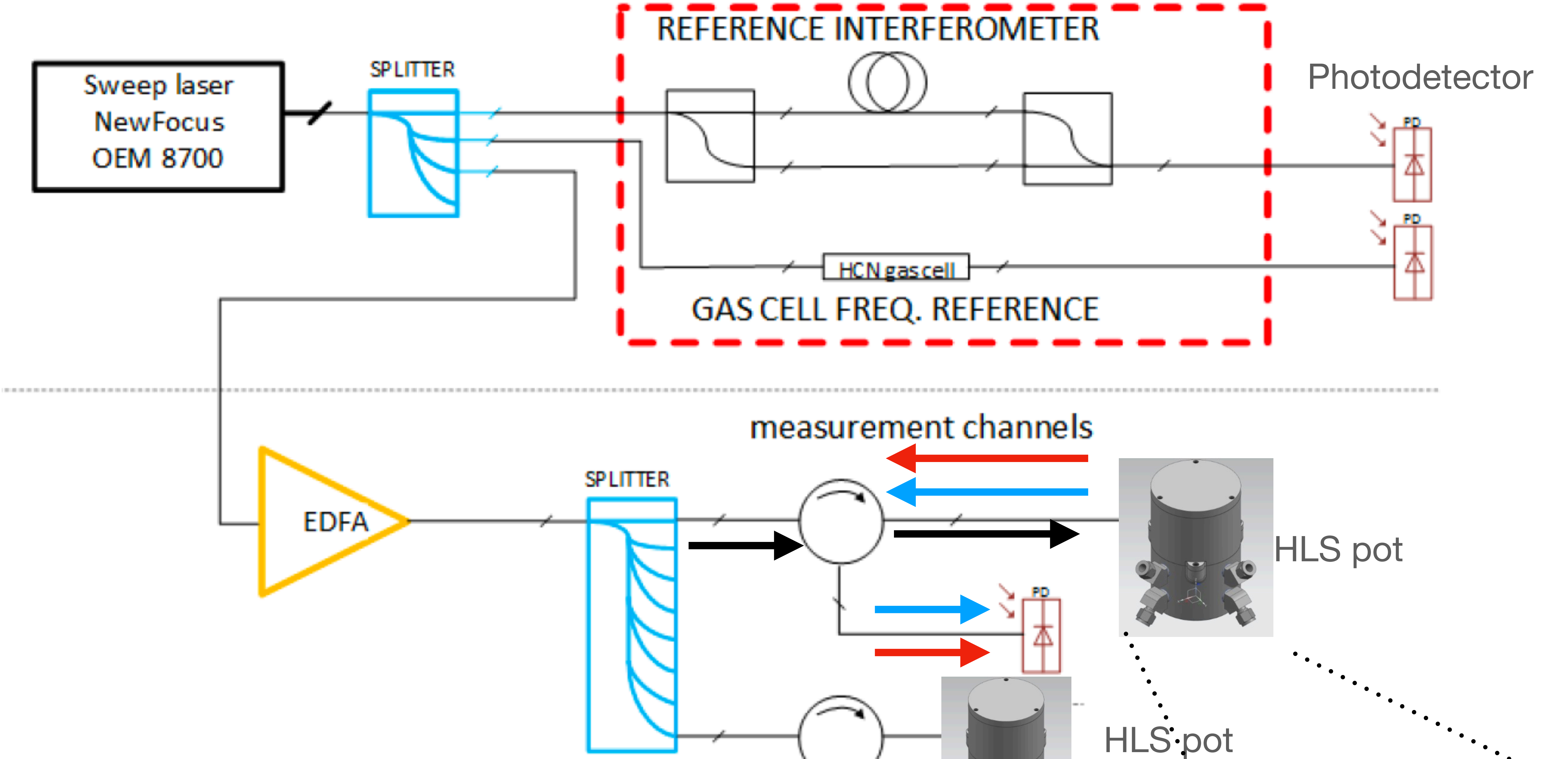
Horn Leveling System (HLS)

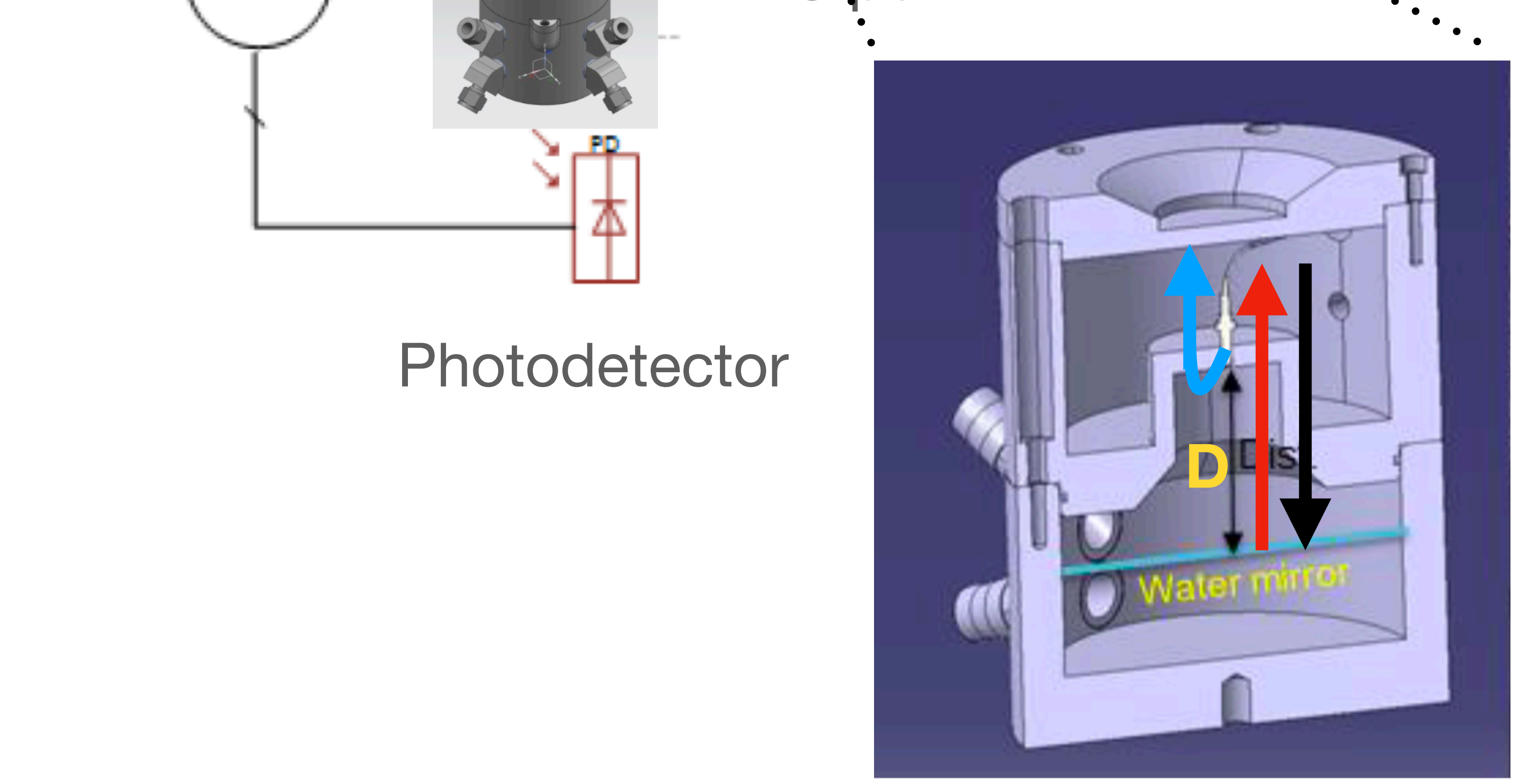
HLS based on FSI

Laser wavelength sweep









- Distance b/w ferrule tip & water surface $D = c\frac{f_{beat}}{2\frac{d\nu}{dt}} = c\frac{N}{2(\Delta\nu)n}$

No. of cycles of signal measured during sweep

change of laser frequency during scan

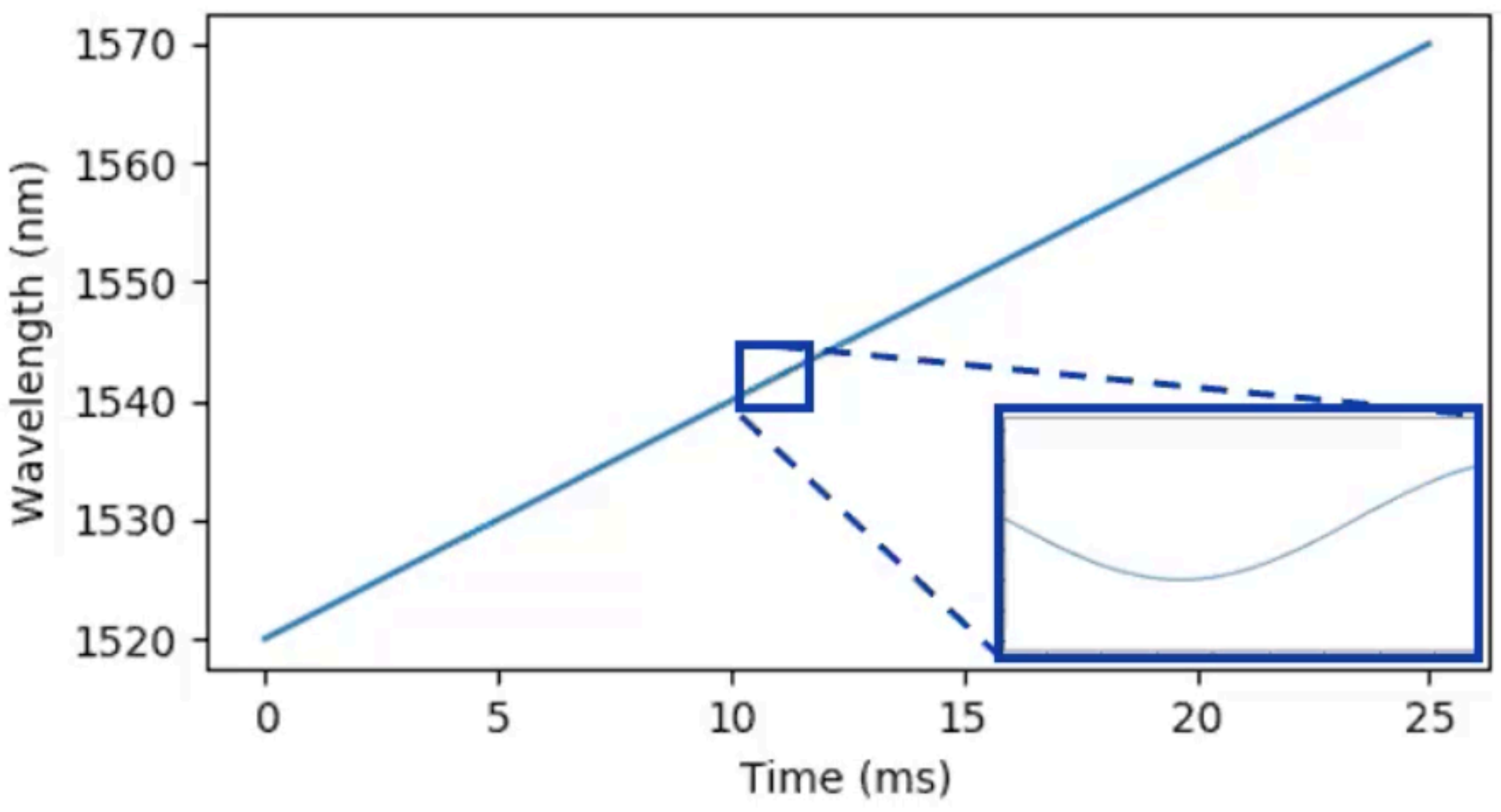
Refractive index of medium

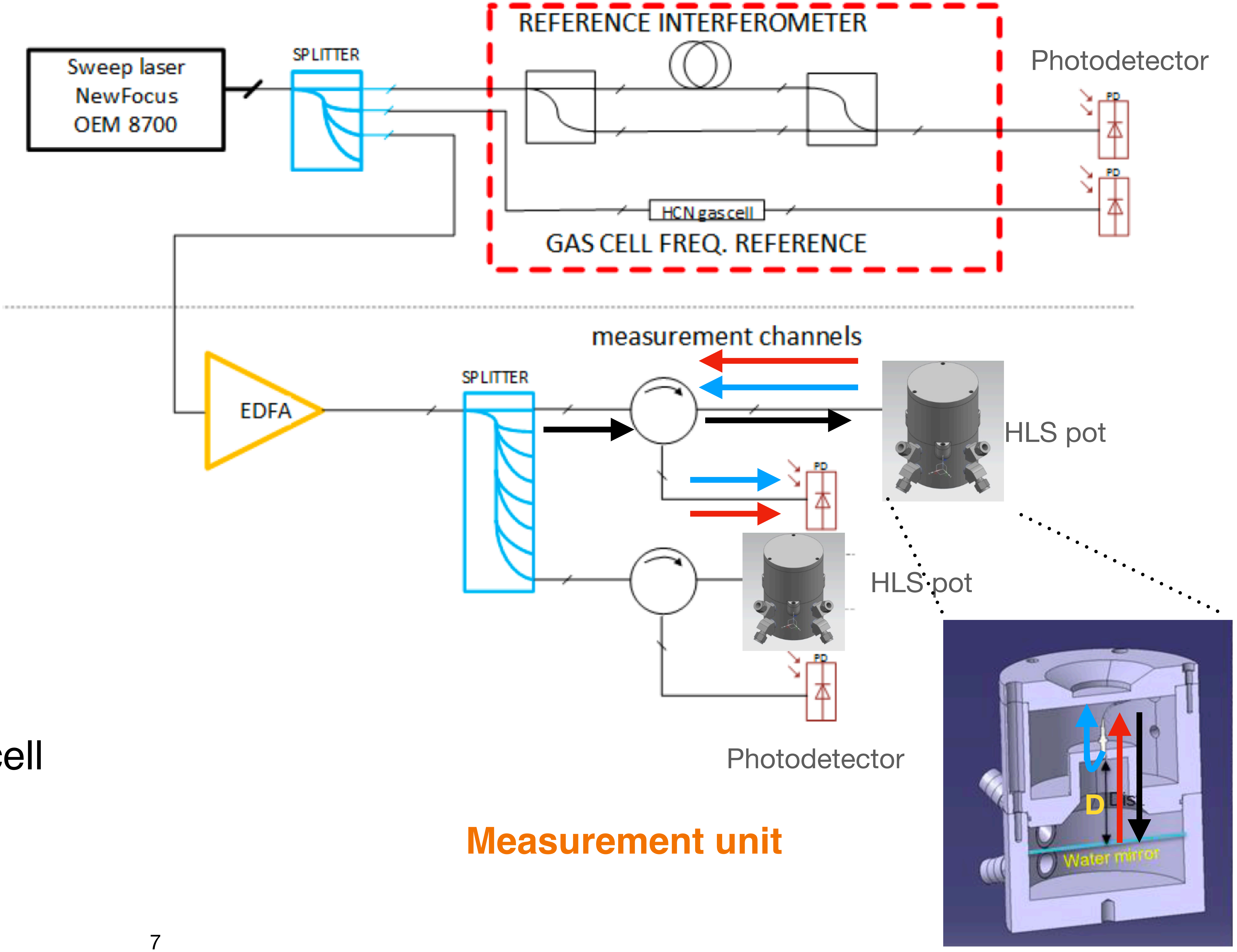
Horn Leveling System (HLS)

HLS based on FSI

Laser delivery and signal calibration unit

Laser wavelength sweep



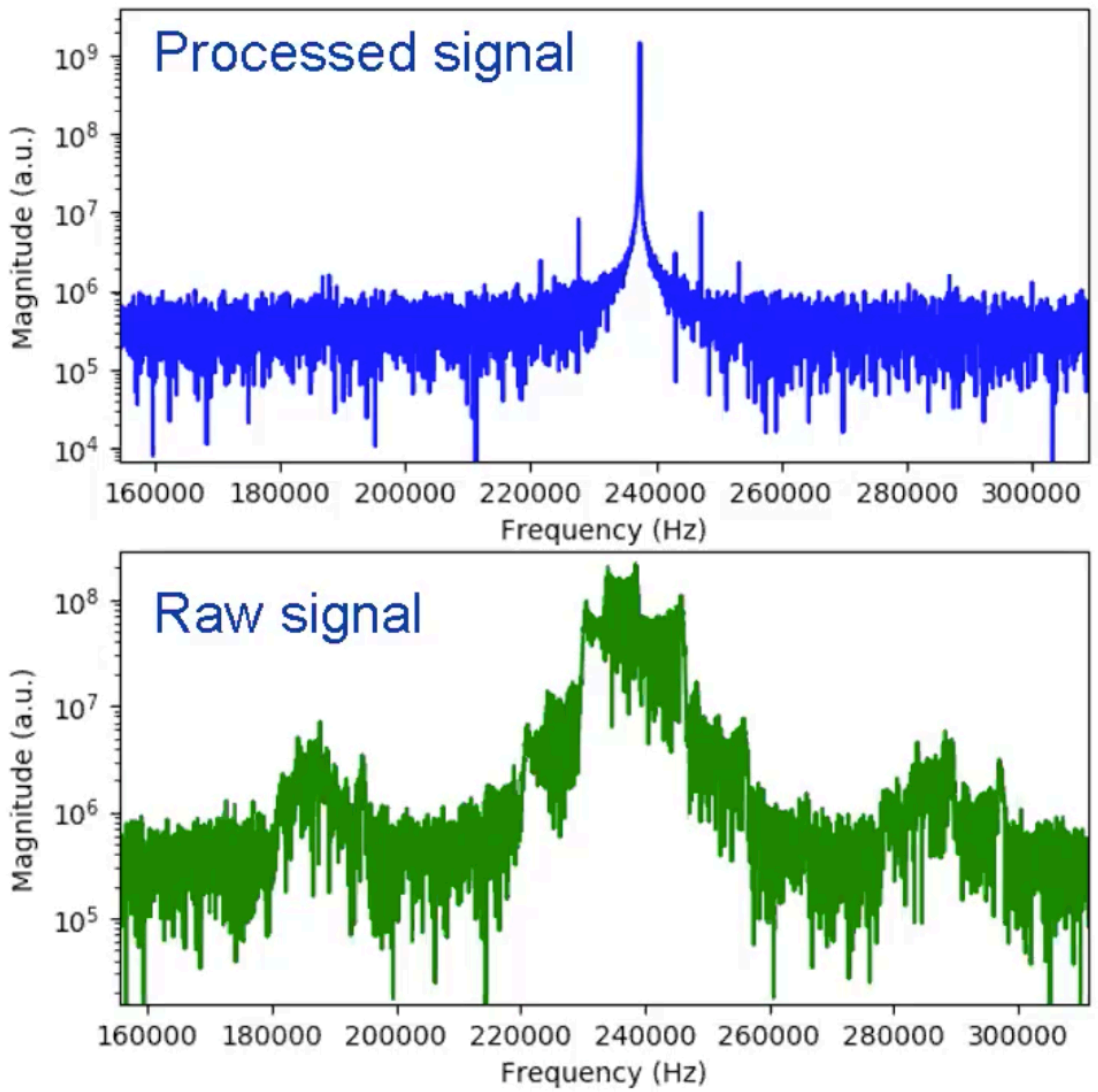


- Signal processing:
  - Linearization of measured signal
  - Wavelength correction - HCN gas reference cell

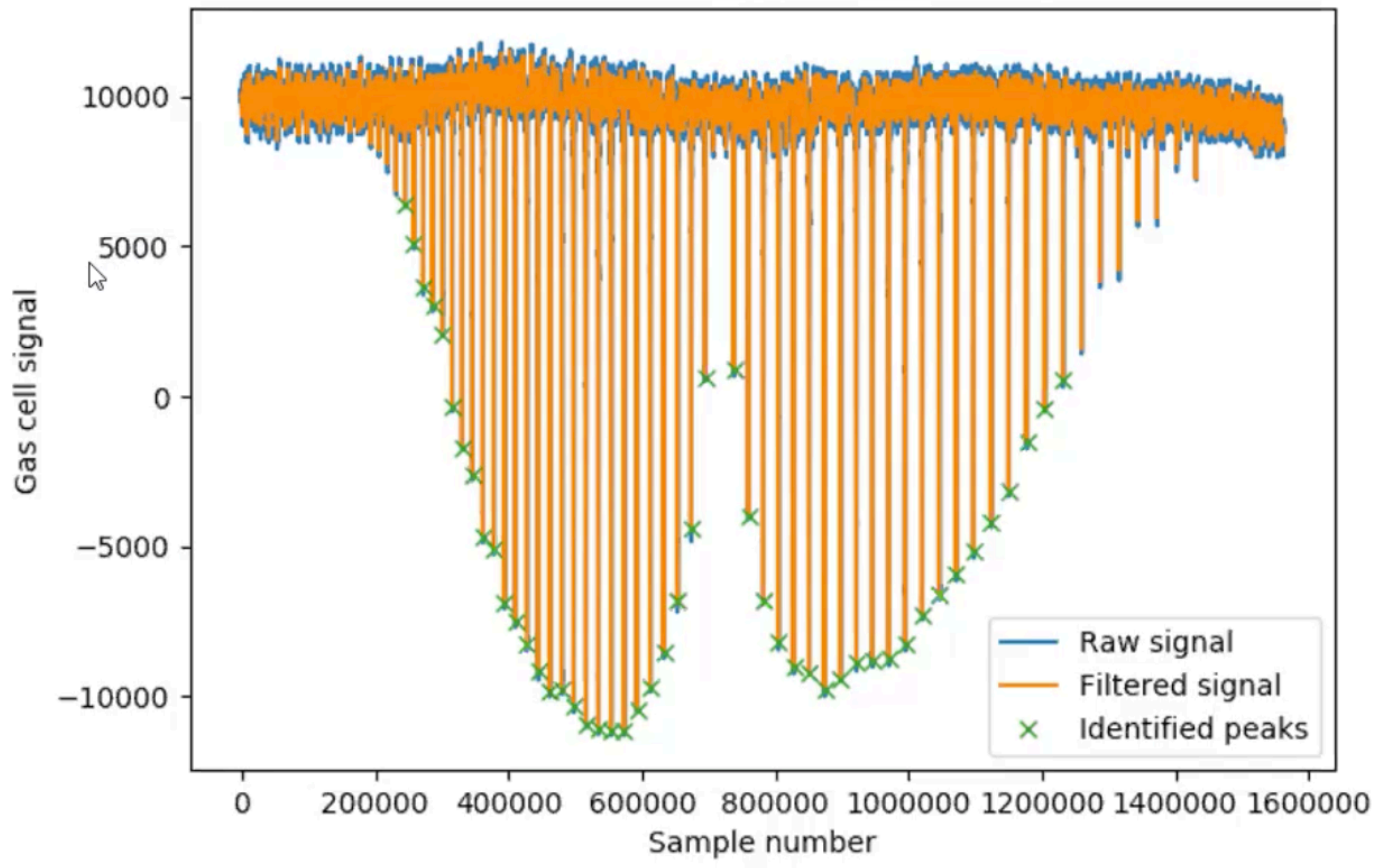
Measurement unit

Horn Leveling System (HLS)

Linearization - precision

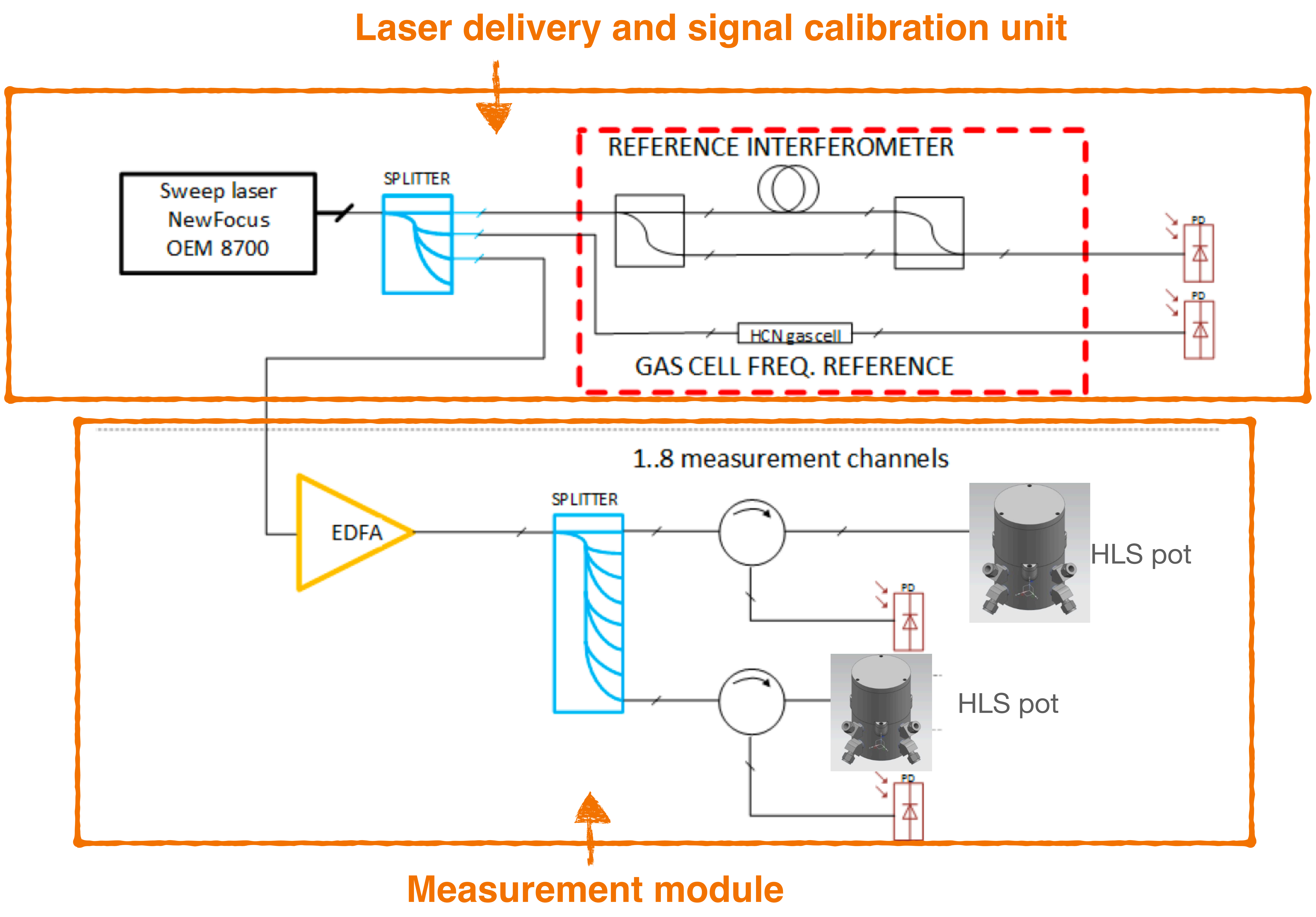


Sweep speed calculation - Accuracy, traceability



Courtesy: CERN Talk by Jaroslaw Rutkowski

Conceptual Design of the System



Main components:

- Tunable laser source with range: 1530 – 1625 nm;
- Reference interferometer → constant length interferometer of 2 fibers.
- Hydrogen Cyanide (HCN) absorption gas cell → track "true" frequency of sweeping laser
- Erbium-Doped Fibre Amplifier (EDFA)→ amplify laser signal before transmitting it to measurement channels
- Measurement channels → each consists of C-band optical circulator, measurement optics with a pot, photodetector.

Measurement steps:

- Photodetectors data linearization
- Sweep speed calculation
- Detection of the "beat" frequency peaks representing distances to measured targets

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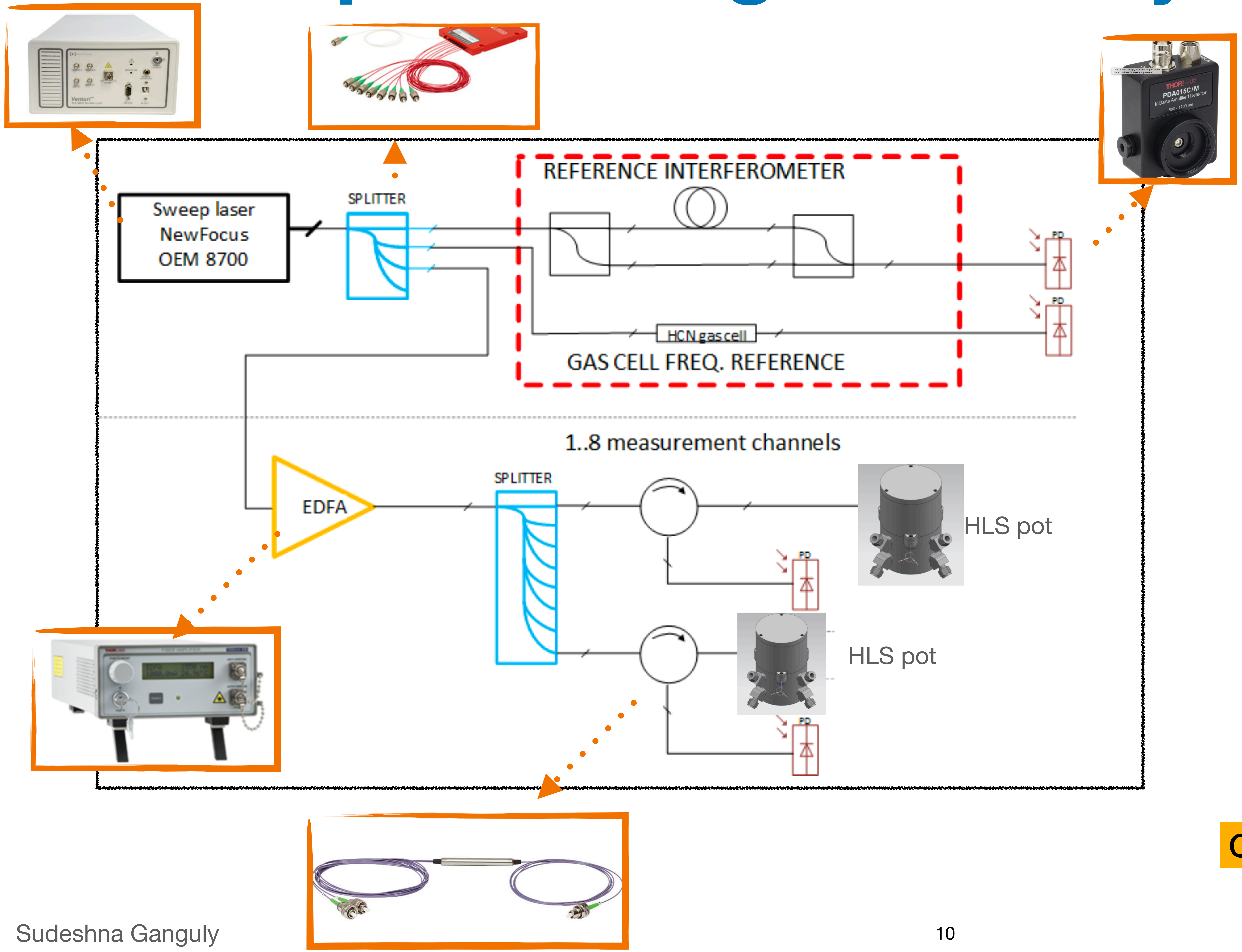

Components needed:

- Laser
- Reference interferometer
- HCN gas cell
- Amplifier
- Splitters
- Optical circulators
- Photodetectors
- Pots
- Water lines
- Air lines
- Heaters
- Fiber collimator
- Optical fibers
- Mechanical stands for pots
- Invar rods
- LVDTs
- Thermocouples

Needs designing

Checked items available off the shelf

Requirements

- Looking at slow time scale, not fast vibrations
- Need relative measurements ~ 0.5 cm
- Not dependent on the absolute calibrations of sensors
- Desired height resolution ~ 0.2 mm
- Desired height accuracy ~ 0.1 mm (tolerance of position is 0.5 mm, we want to see changes even smaller than that)
- Desired dynamic range ~ ± 5 mm
- Shall allow for ±5 mrad angular misalignment of sensor w.r.t. water surface
- Expected Invar rod movement due to thermal expansion ~ 0.1 mm
- Maximum optical fiber length ~ 238 ft (72 m) (b/w laser and HLS sensor)
- Maximum height transfer need ~ 11 ft (~3.5 m)

1. Does the NBI preliminary design meet the functional requirements identified?

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8. Are there any issues concerning the schedule for the NBI?

- Radiation:
    - Top of LBNF modules ~ 5 to 50 Kilo-rad (50 to 500 gray)/year (suitable for HLS installation)
    - Bottom of modules ~ 100 Giga-rad (10^9 gray)/year (not suitable for HLS)

1. Does Preliminary Design Meet Requirements Identified?

- Looking at slow time scale, not fast vibrations
  - Vibration in single laser FSI →degradation could be seen at ~ 20 μm movement
  - What amplitude vibration one might get on T-block when horns are pulsing?
    - T-blocks are supported on target pile shielding, uncoupled from horn support module
    - Would not expect any vibration spectrum coupled into T-blocks from horn pulsing
    - Since these structures are also very large and heavy, any potentially higher frequency ringing from adjacent stripline structures should be negligible
    - Lower frequency usually means relatively larger displacement, and these large structures will have essentially no low frequency movement.

- Desired height accuracy ~ 0.1 mm, is that achievable with the FSI optical HLS sensors?
    - In LHC, For 140 m, alignment better than 0.1 mm
    - In low vibration with single laser, uncertainty is 3.5 μm

- Desired dynamic range ~ ± 5 mm
    - With water based device, typically ferrules of fibers start at 4 cm up to 6/7 cm from water level, **dynamic range of sensors can be 20 mm**
    - For LHC, 10-15 mm max dynamic range used

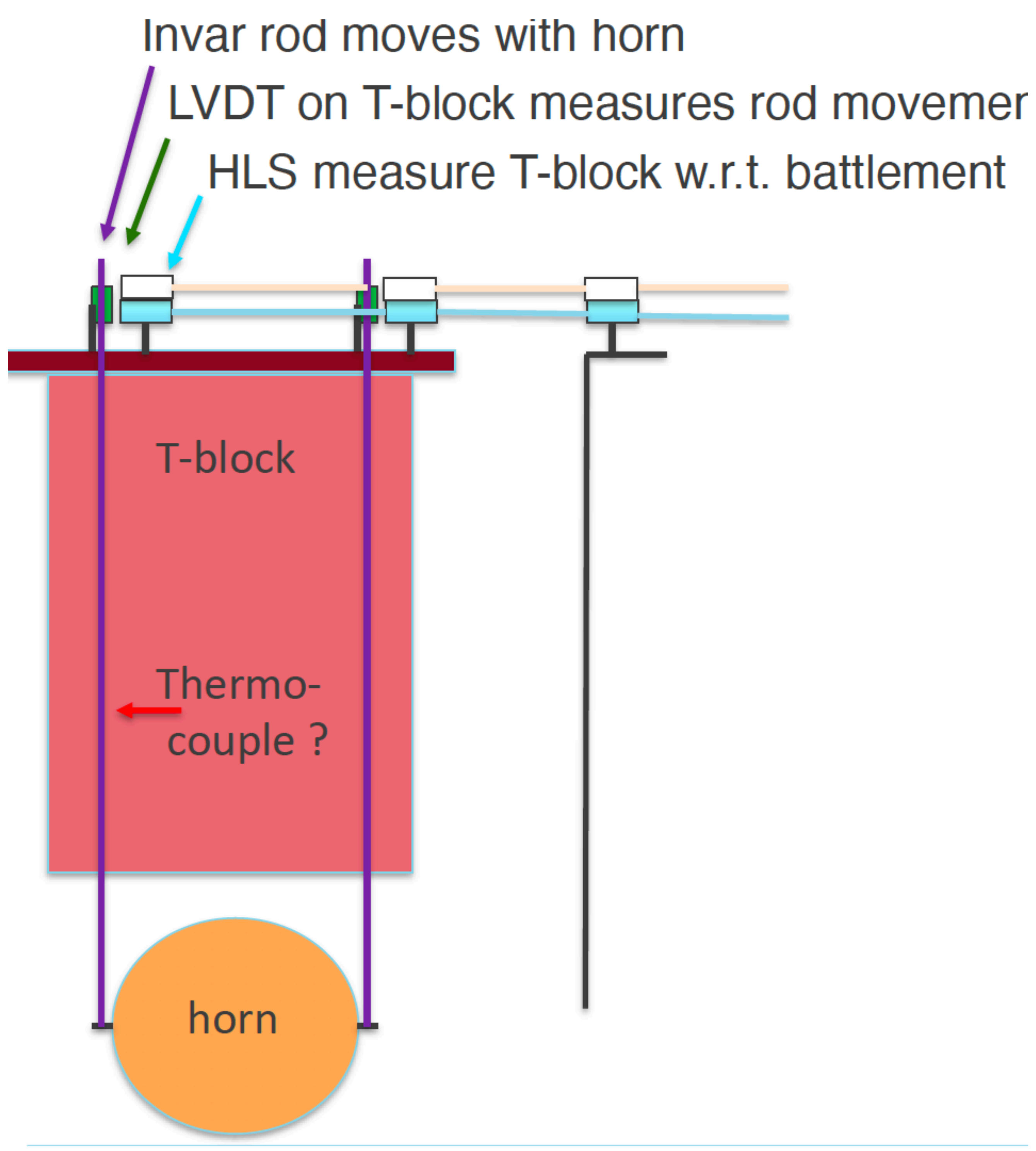
- How well does a sensor need to be aligned?
  - Install devices within 1-2 mm relative to each other, can be achieved via optical survey
  - In vertical?
    - Measure incident light perpendicular to water surface, vertical misaligned in vessel acceptable

1. Does Preliminary Design Meet Requirements Identified?

- Can HLS pot and optics survive many mega-rad(10^4 gray) radiation?
  - 30 years*500 gray << 1 mega gray
  - At LHC, tested same optics upto 10 mega gray
- How far away can we keep electronics & laser?
  - At CERN, tested over 1/2 km, can serve upto 1 km
- Laser power?
  - At CERN, Typically using 1 mW, can use upto 10 mW
  - Venturi8800 output power 10 mW
- Settle time of liquid inside pot?
  - Longer the network, longer settle time
- How many HLS pots with same laser?
  - At LHC, 2 lasers covered 500 channels
- How often data taken?
  - At LHC single measurement takes ~16 ms, sample as fast as possible to reduce impact of vibrations of HLS pots
- For longer distance, need high DAQ rate
  - Longer distance generate higher beat frequency
  - 250kH sampling rate, 16 bit resolution PXIe DAQ for prototype test
  - Expect 84kHz beat frequency from ~5 cm b/w ferrule tip and water
  - For actual LBNF system, possibly switch to python
- Dissociation of water into H2 and O2 into the system?
  - Volume of water within each HLS unit ~ 360-400 mL
  - For target He water cooler radio analysis with ~12000 mL water, <4cc H2 gas/year
  - Top of module, dissociation small

Installation Plan & Interfaces

Installation in each location: HLS Pots, Invar Rods, LVDTs



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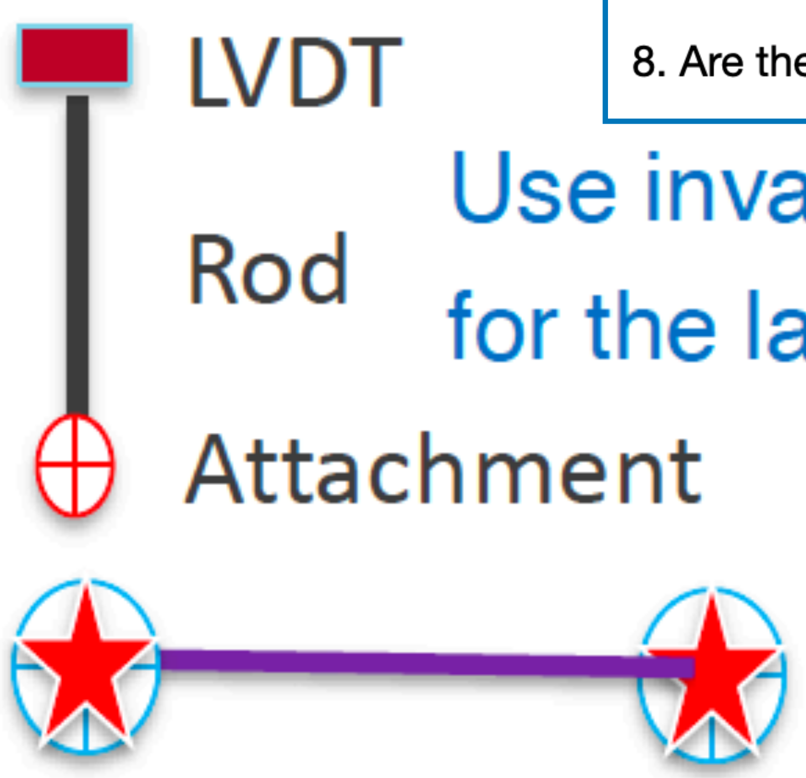
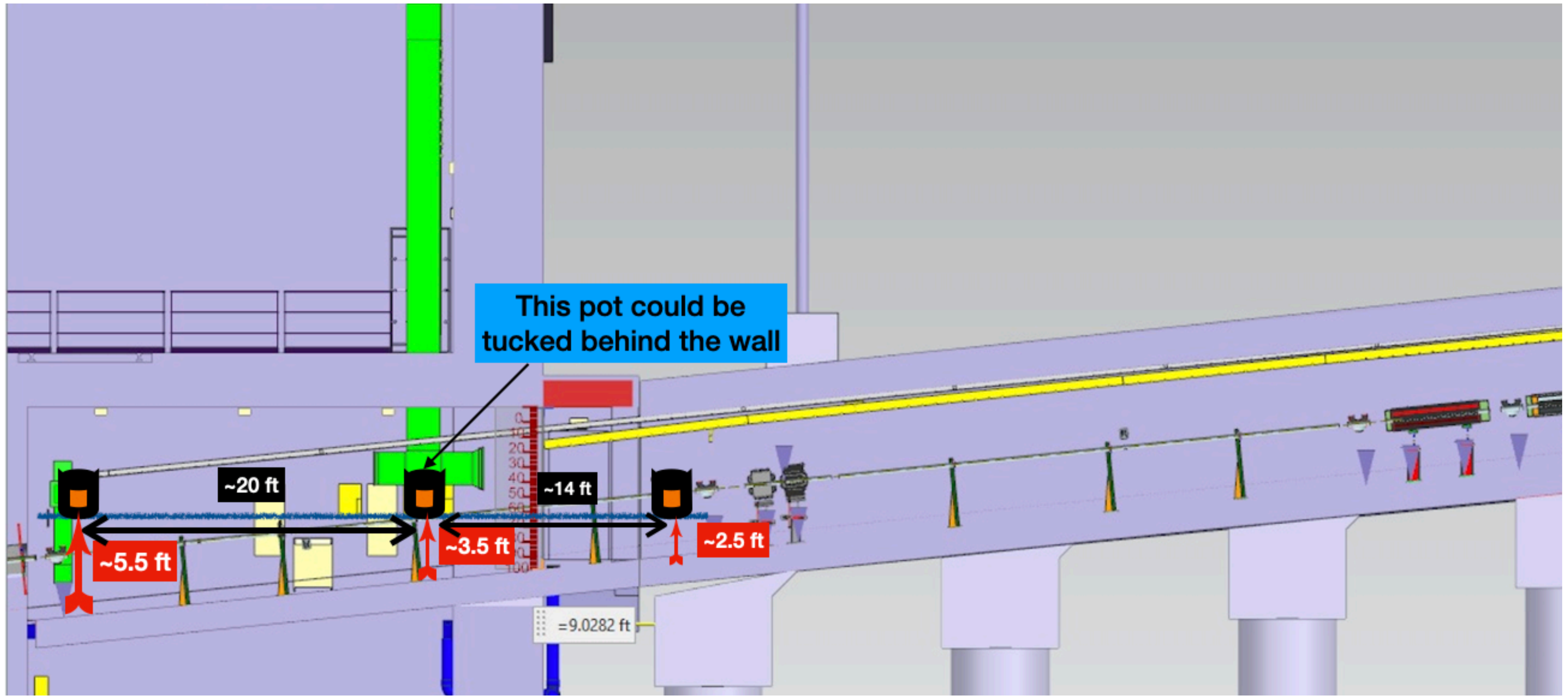


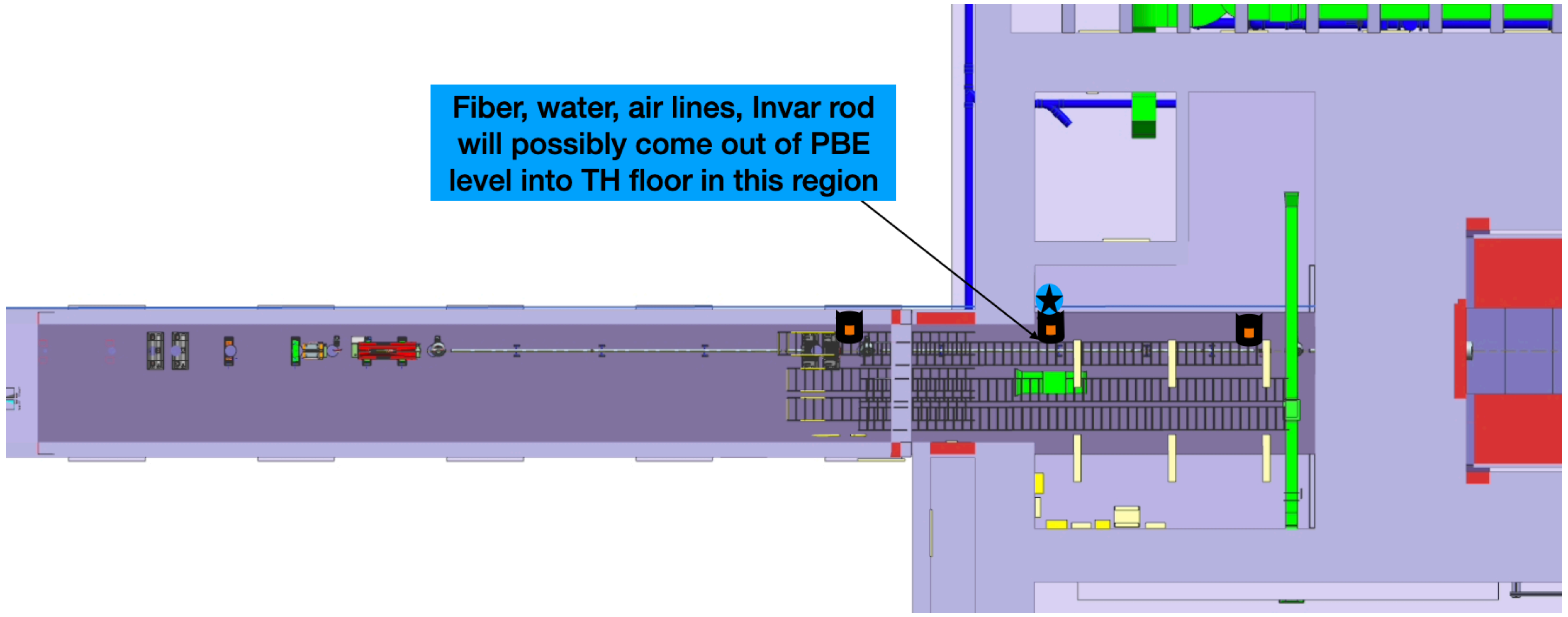
Use invar rod plus LVDT (Linear Variable Differential Transformer) for the large vertical jumps

Use HLS for the horizontal runs;

- LVDT attached to T-block will measure rod movement (rod is actually moving with horns/baffle)
- HLS will measure movement of T-block w.r.t battlement
- LVDT will give distance b/w HLS & top of module

Preliminary Plan of Installations in PBE



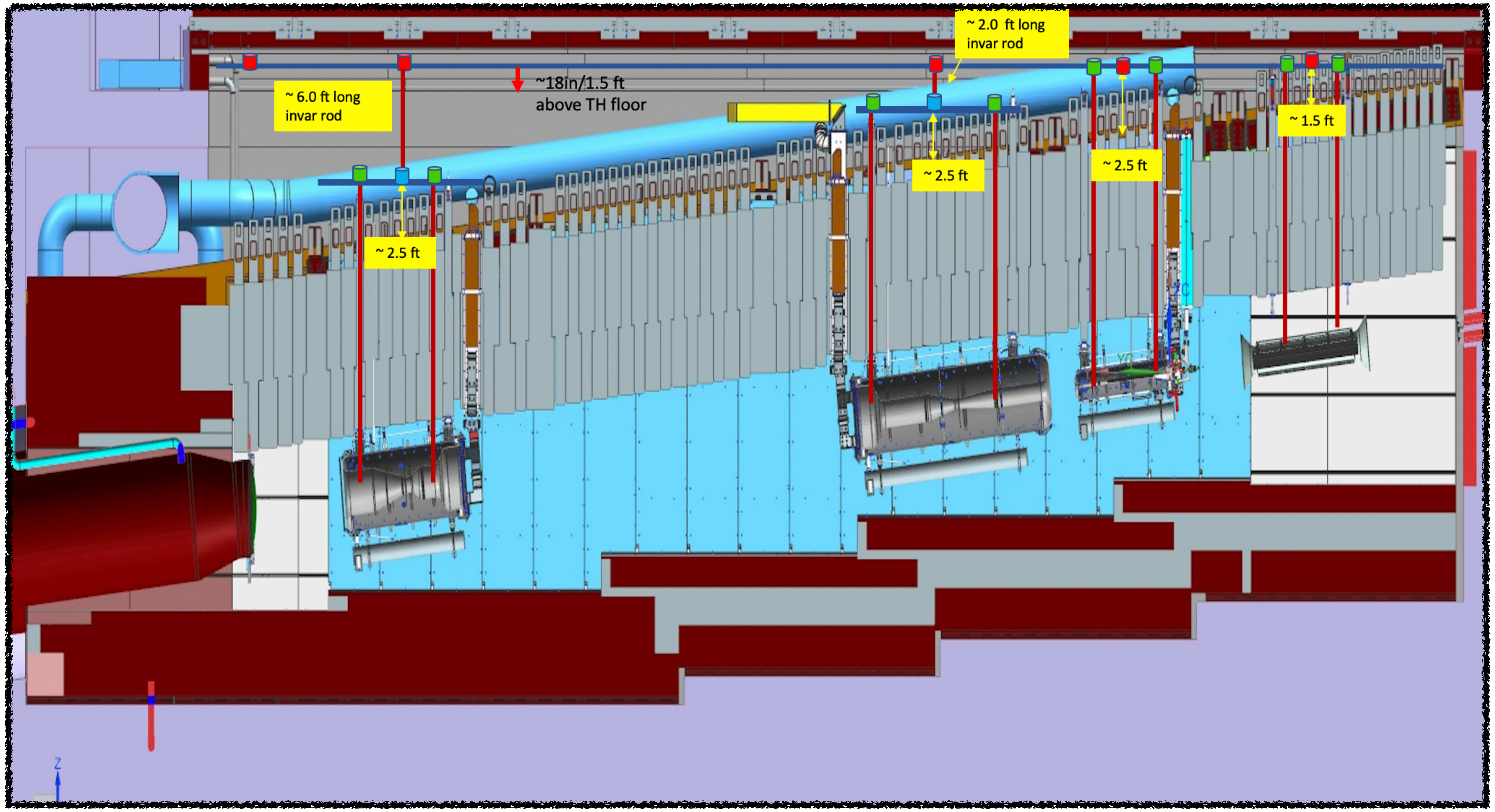


- Put system in beam left as much as possible
- Could put in plexiglass cover around them on beam side and on top
- Run Invar rod from PBE to TH floor level, could tuck Invar rod as far out of way behind wall
- Run some steel rods from ceiling down to floor and bolt them onto floor, to prevent bumping into Invar rod
- Fibers could be brought up in through same area, through some cage
- HLS fiber, water, air lines can be strung from a hook on ceiling
- Water tank can be placed in dead space b/w magnet and trims, but tank should be below pot at each location

Preliminary Plan of Installations in Target Chase

- Where to place HLS pots in different locations
- How to run fiber optics - through patch panels
  - Add panels at battlement walls & run several meters of fiber on each side

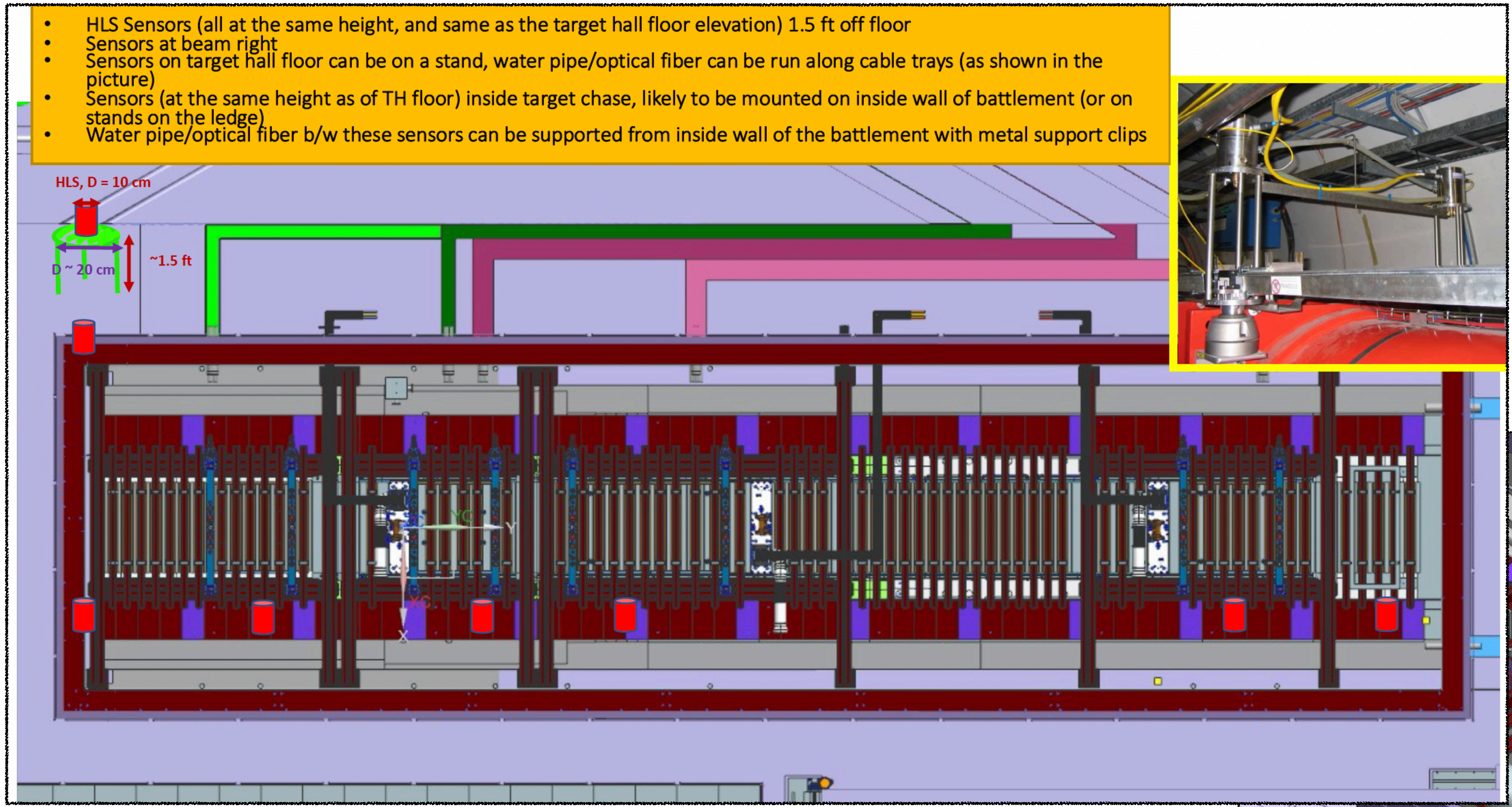
- Installation order:
  - HLS pots, fiber optics, water/air pipes installed on
    - bunker wall
    - baffle module
    - horns C, B, A
    - utility corridor
  - HLS pots filled with water and air
  - Test system



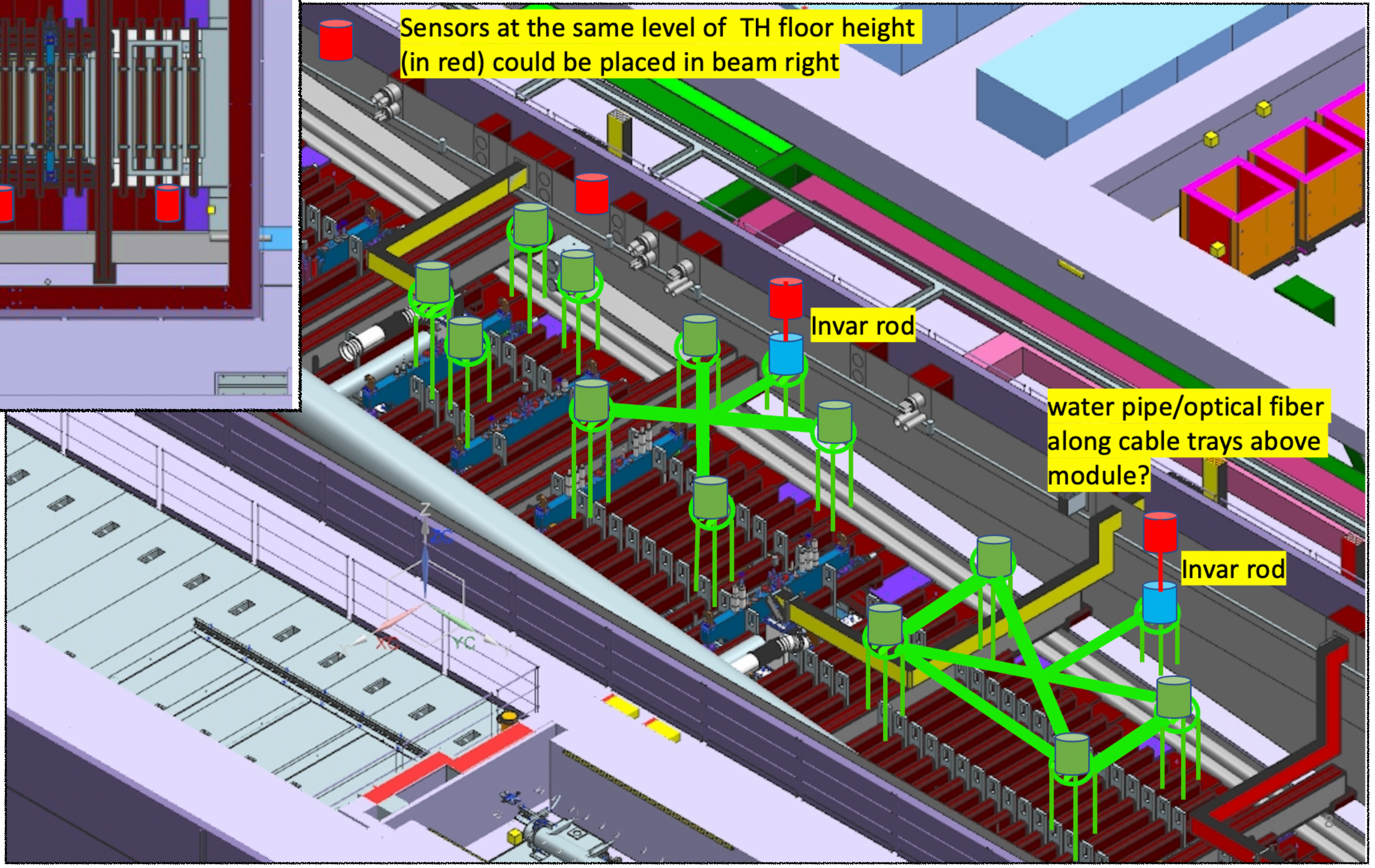
To-do:

- Plan installation of Invar rods, LVDTs & thermocouples
- Design paths for water/air lines for pots: design/modeling phase, make sure invar rods not going through water lines
- Running LVDT cables
- Run fibers and put connectors on fiber optics, connectors should fit with patch panels

Preliminary Plan of Installations in Target Chase



- Pots stay on same height above each module
- Air lines: at a higher level than pot
- Water lines: lower than pot

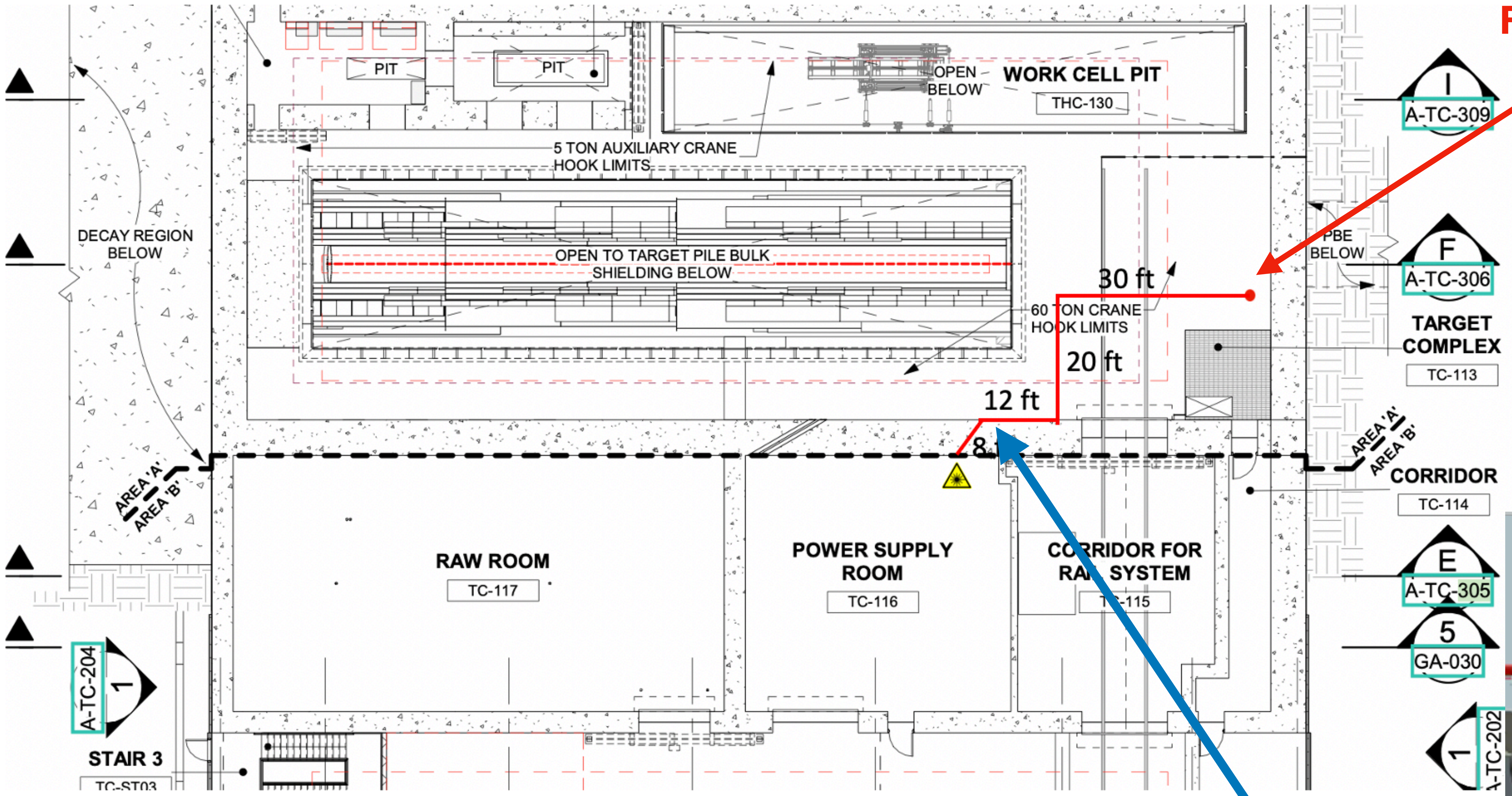


- X-pattern above horn B is a low point w.r.t 4 green pots
- Another line run over to reservoir which is even lower
- Another X-pattern at a high point with a common vent for air lines
- Very painful to get air out of water lines
- Getting all pipes at an angle makes that easier

Maximum Optical Fiber Length Required

Primary Beam Enclosure to the Power Supply room

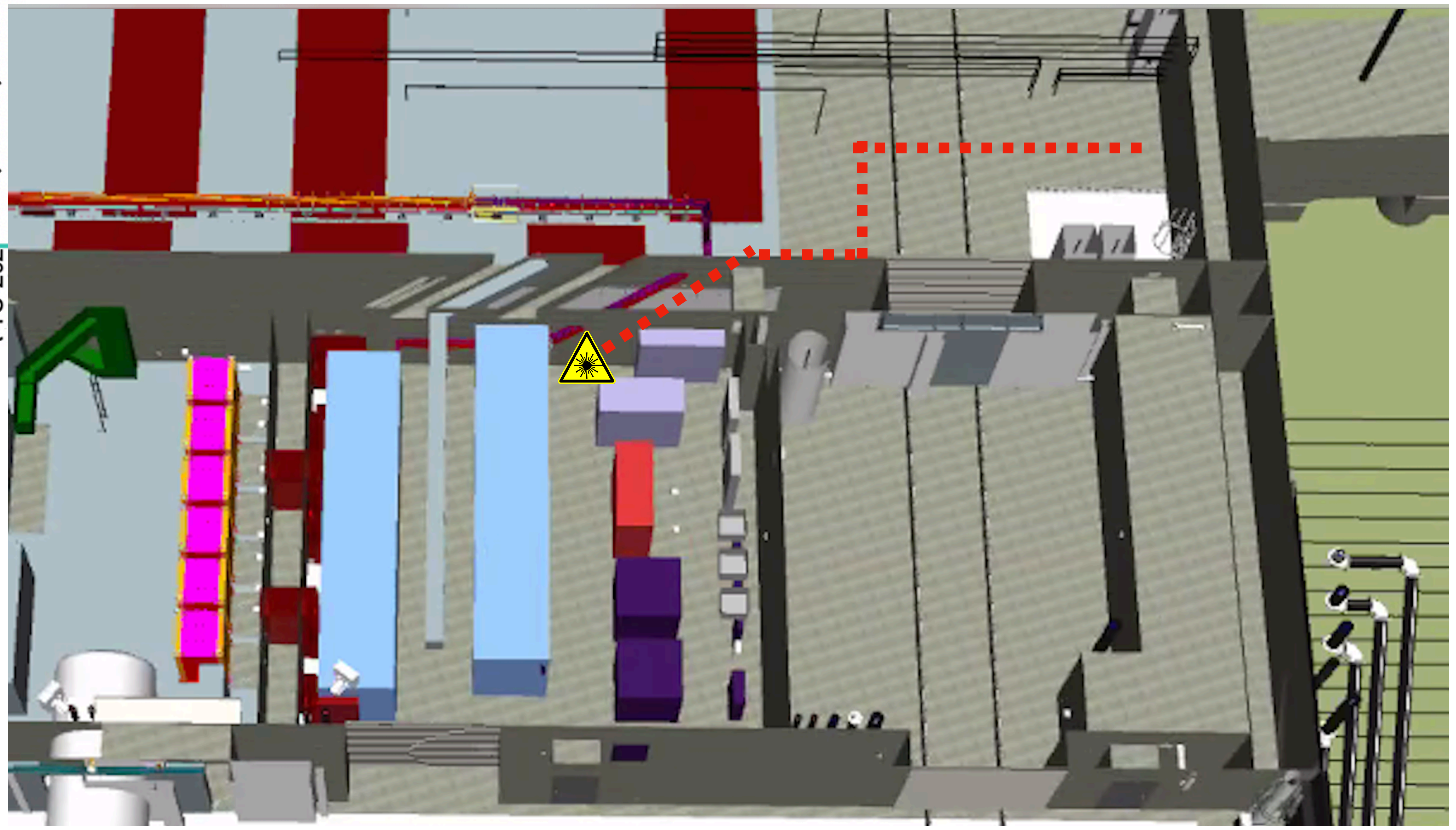
Fiber comes out to main level through here



Fiber climbs from floor

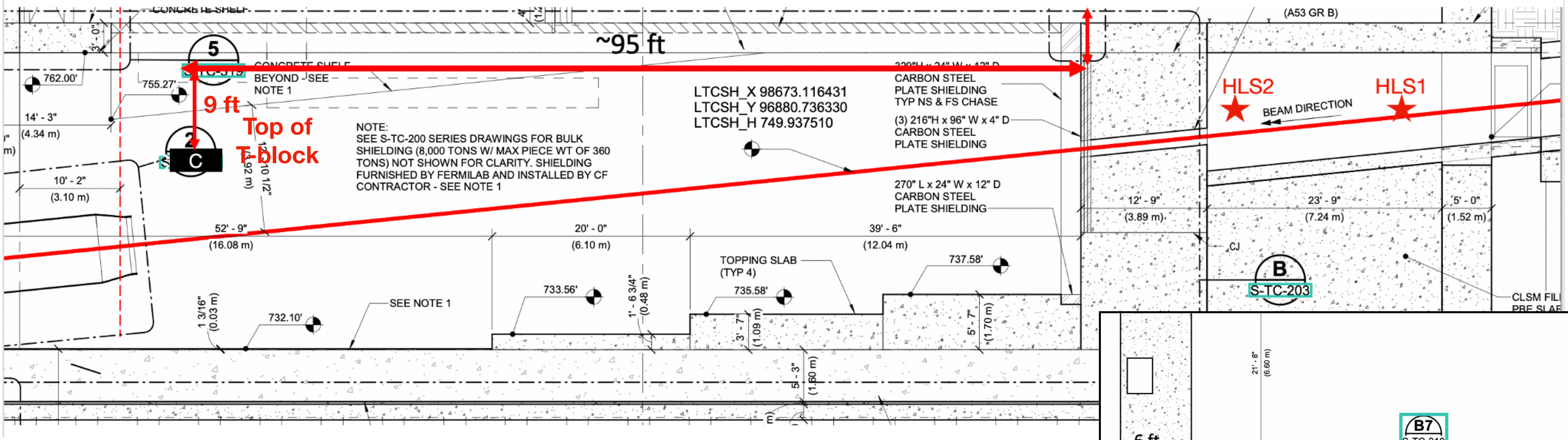
Path below rail system

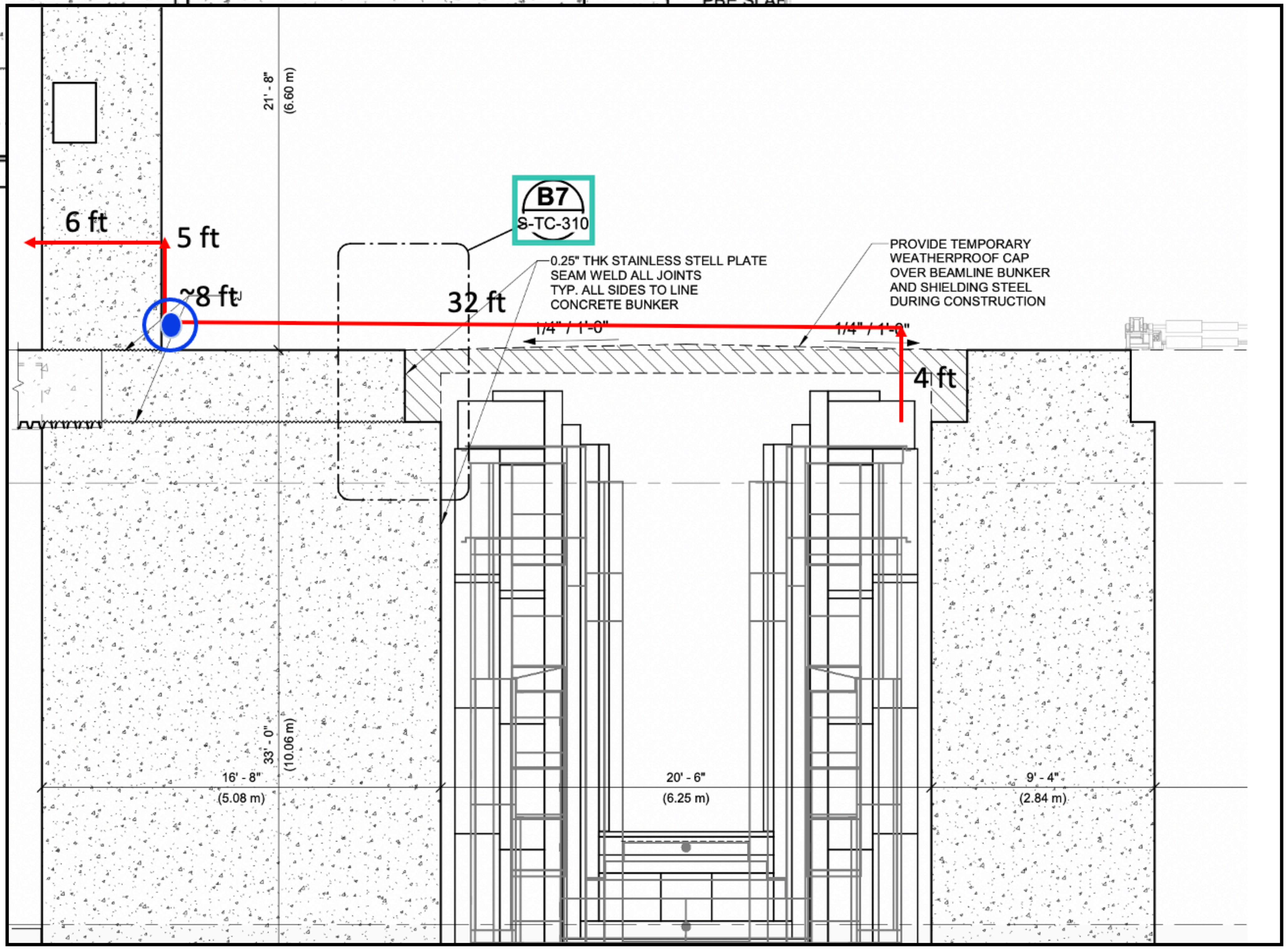
Main Level to Power Supply Room fiber length = 30 ft+ 20 ft +12 ft+ (8 ft from floor) + 8 ft = 78 ft + 15% ~ 90 ft



Maximum Optical Fiber Length Required

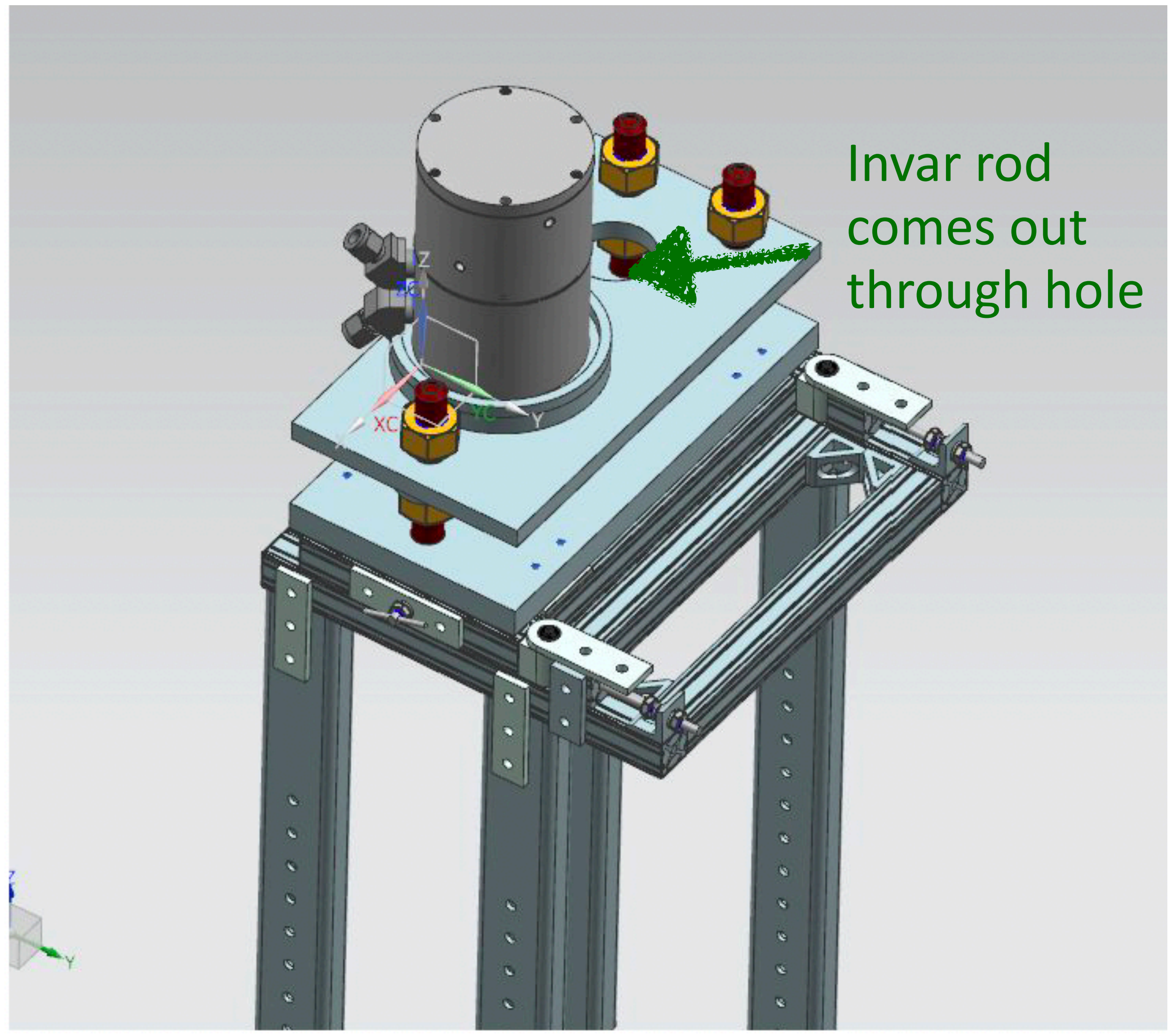
Target Chase to Power Supply Room

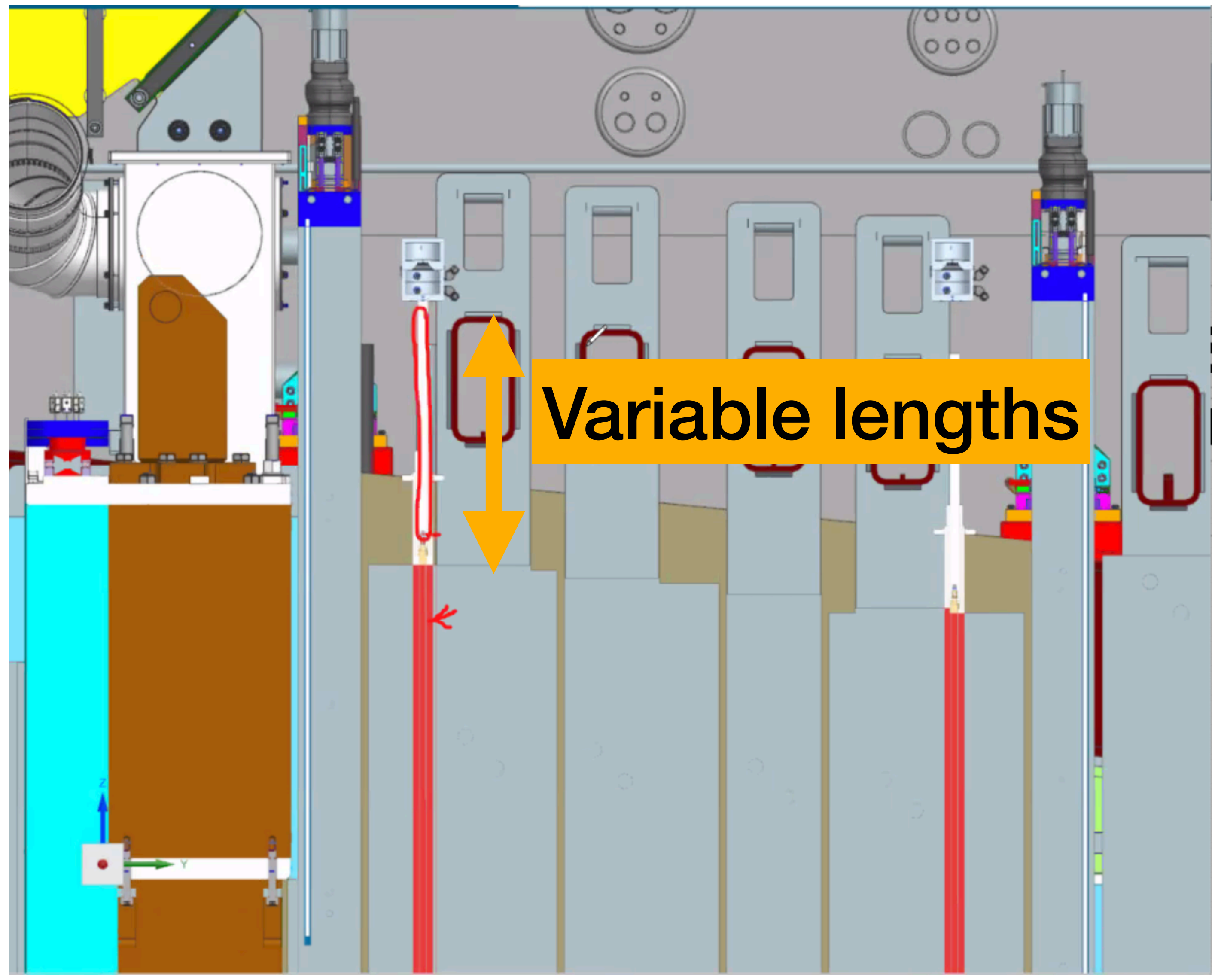




Horn C to Power Supply Room fiber length =
9ft + 95 ft+ 4 ft+32 ft+8 ft+5 ft+6 ft+
8ft (through penetration) = 167 ft
+ 15% ~ 192 ft

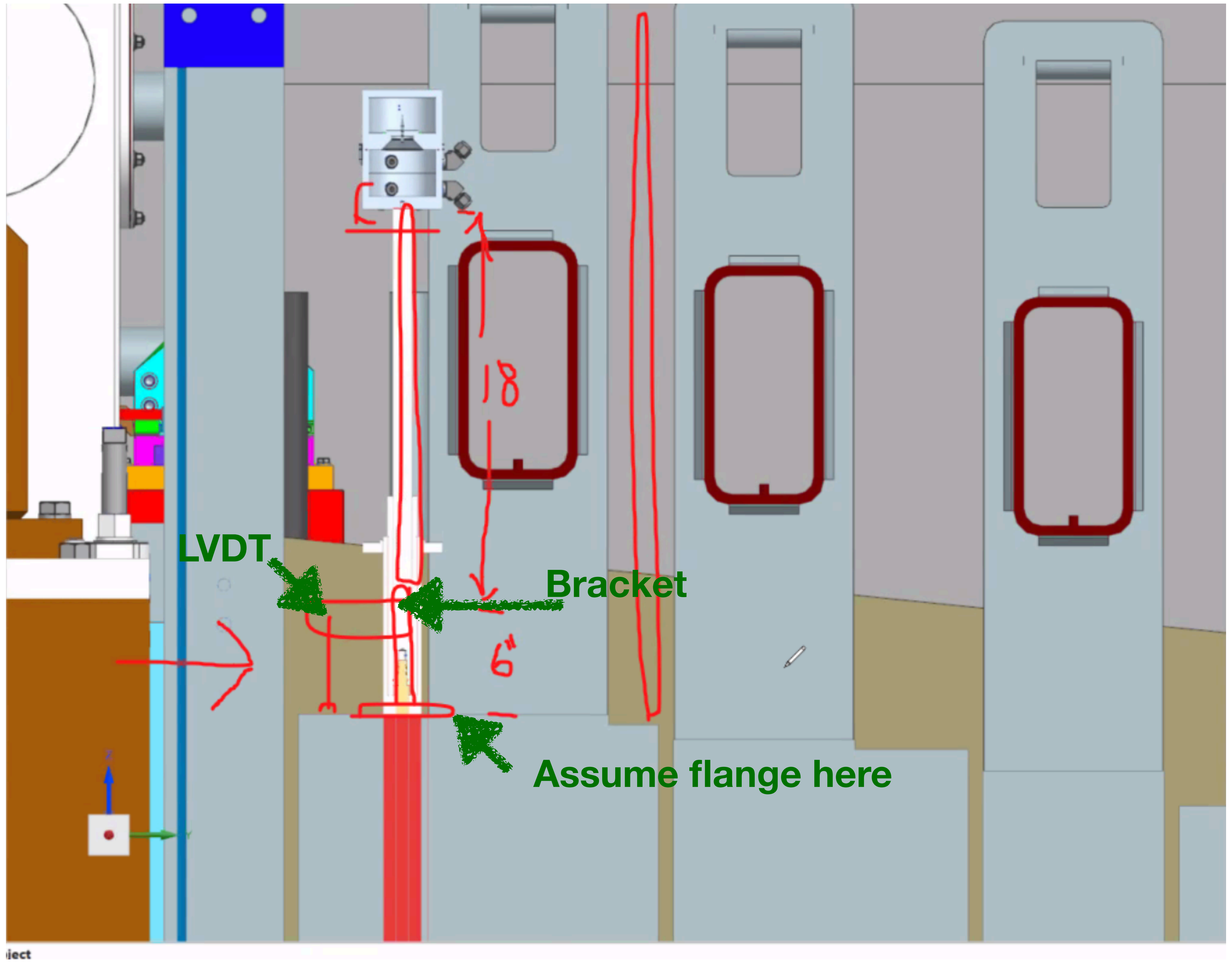
HLS interface between Invar Rods through T-Blocks





- **Interface on top of Invar rod where it attaches to LVDT**
- Pots will stay on same height above each module, stand legs will be adjustable
- Need adjustable lengths of invar rods on top of T-blocks
- If rod comes through hole, LVDT is at same location as pot
- **Need special length rods, downstream ones will have to be longer**
- For a module/beamline component change out:
  - Pots and all tubes will need to be removed, dissembled
  - Invar rods and stands will have to be removed & stored so as to lift out T-block separately

HLS interface between Invar Rods through T-Blocks



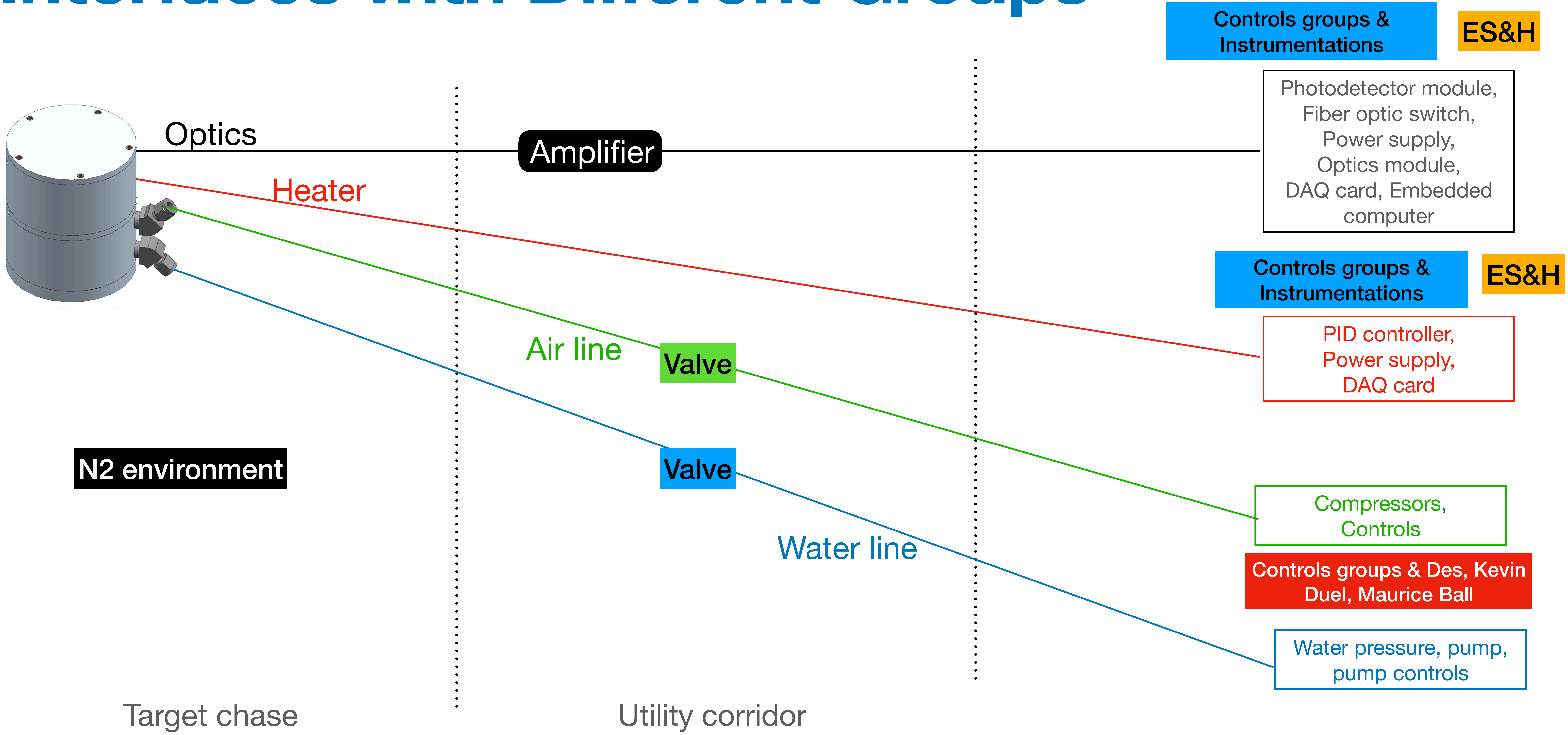
Alternative:

- Fixed invar rod length
- LVDT sitting on T-block instead of on stand - need a connection to T-block that has LVDT connected to rod
- Only error in the system is whenever height changes are occurring between LVDT itself and HLS pot - should be minimal, stable region
- Bring invar rod up, attach lift eye on top of rod, have a bracket, attach to LVDT
- LVDTs sit on the same surface where the legs of the stand touches
- **Cleaner from design, cost and reliability perspective, but harder from worker stand point, worry about ALARA**

Other Interfaces

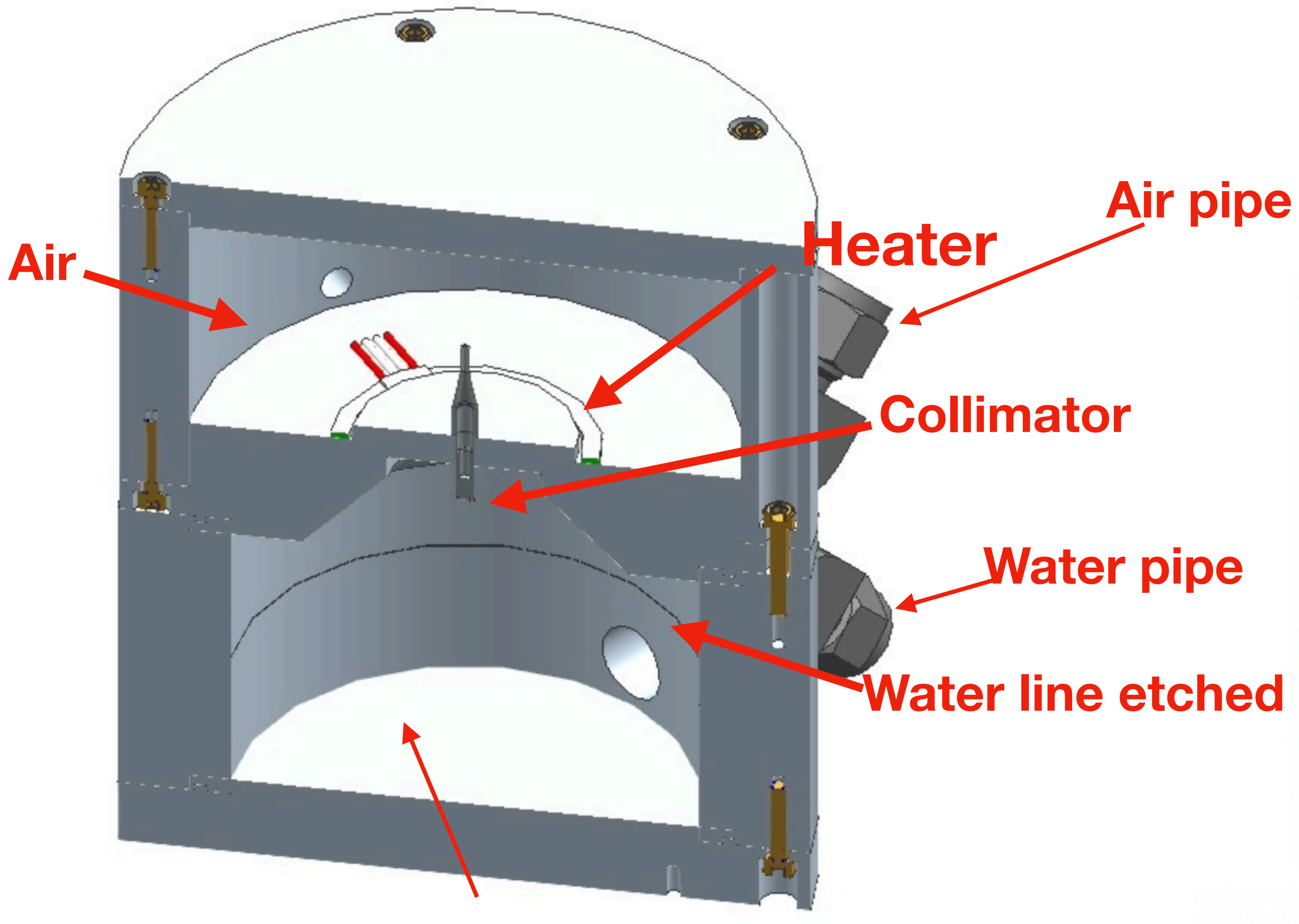
- These interfaces have been identified, details need to be worked out
  - Run Fiber optic cables, from different installation locations i.e. target chase, PBE to laser
  - Run Water, Air pipes
  - Run heater cables
  - Checking out cables
  - Optical and electric feed throughs
  - Controls for lasers and heaters

Interfaces with Different Groups

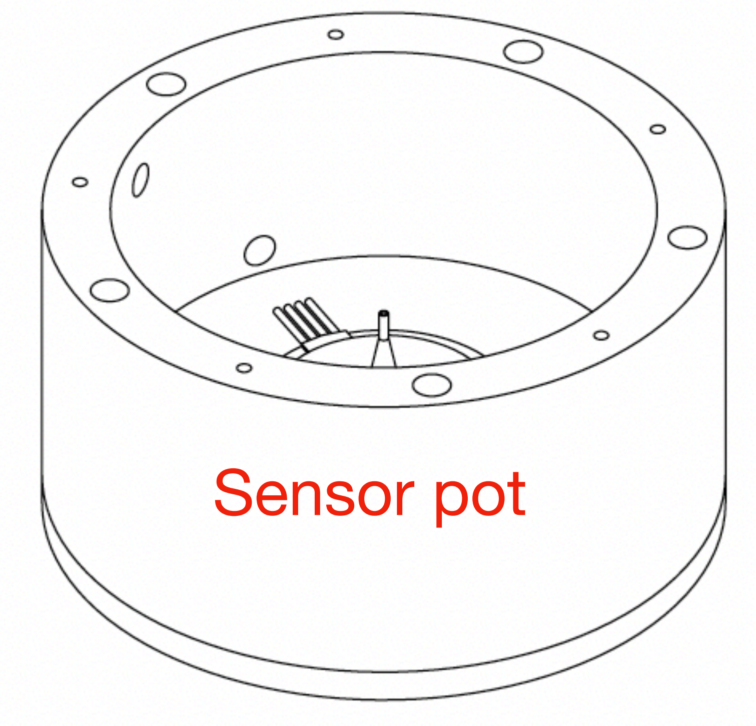


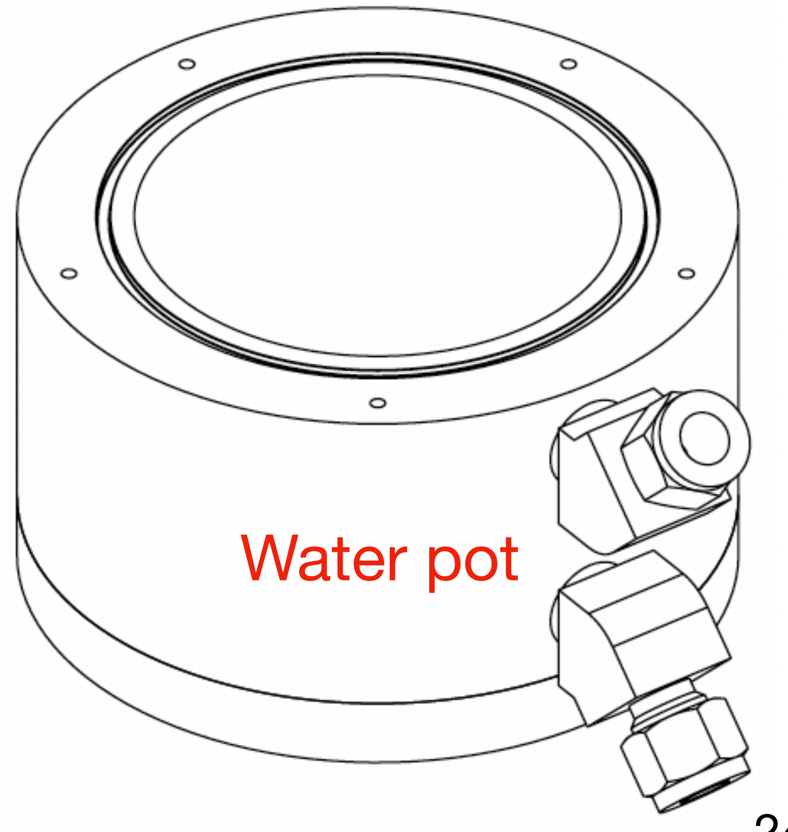
Conceptual Design of Pots

- Conceptual design of “pot” by Matt Sawtell, reviewed by Salman Tariq and Dakota Krokosz
- Rough estimated cost for :
  - 1 assembly (bottom cavity + top cavity + cap) Al pot ~ 2.2K
  - 45 of 1 assembly SS304L pot ~ 40K



6061-T6 ALUMINUM





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8. Are there any issues concerning the schedule for the NBI?

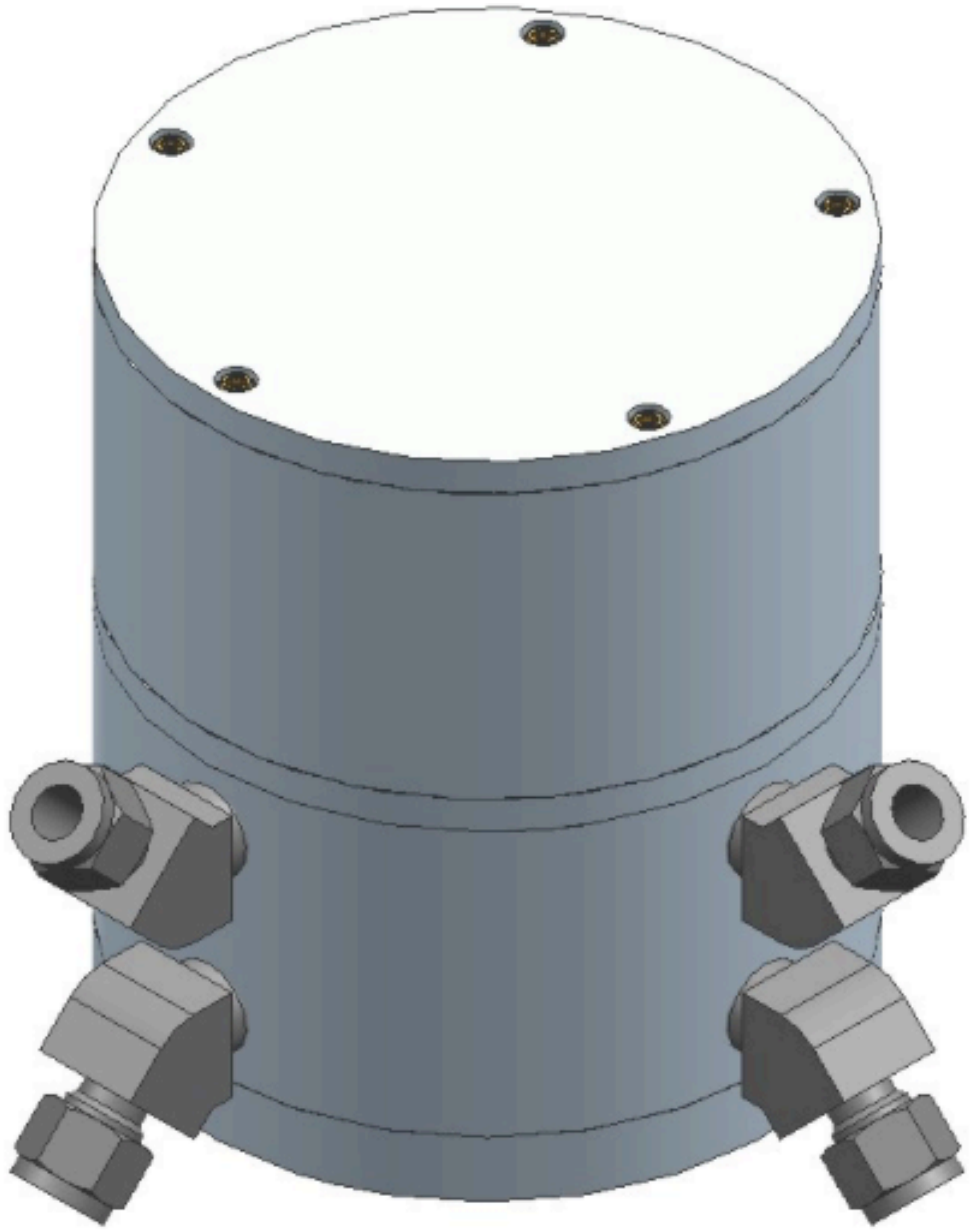
- **Issues addressed as design evolved:**

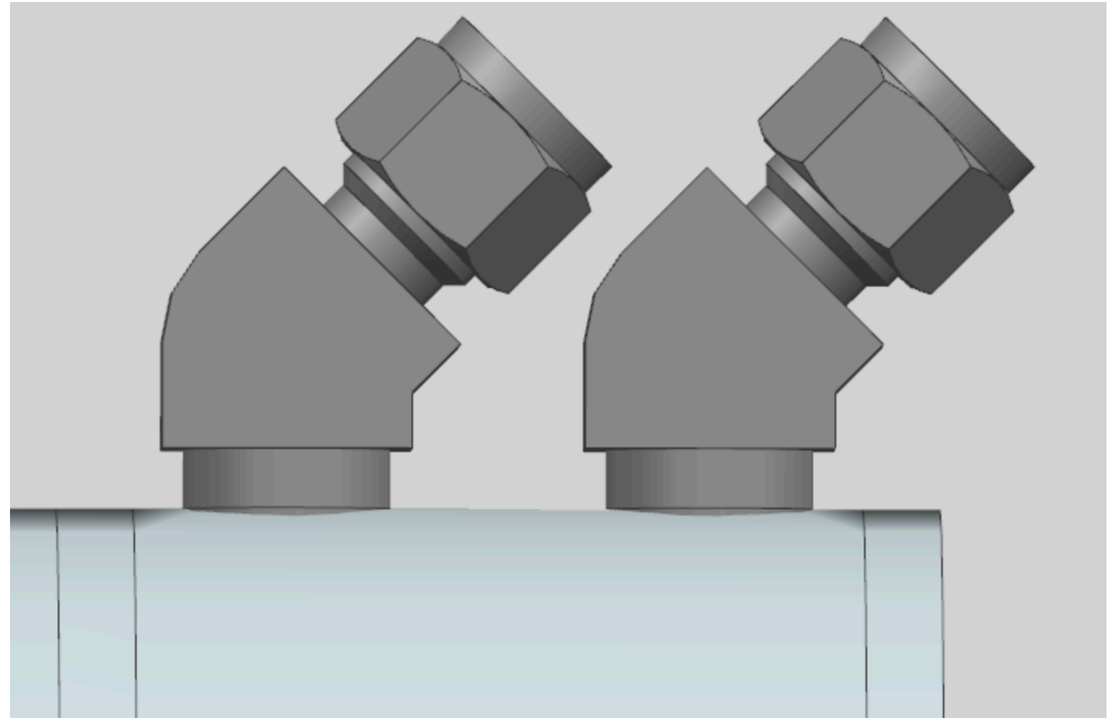
  - Screws to connect top and bottom pots with cap
  - Wall thickness
  - Units sitting on top of horn inside N2 vessel, N2 vessel will be run at 2-3 psig over pressure
  - Significant differential pressure b/w unit inside vessel and outside vessel
  - Worry about O-ring will leak over time - EPDM seal
  - Add raised surface / nub on plates for alignment to stop them from sliding around during assembly

- Sensor pot can be a Nitrogen environment
- Water pot has to be in air, O-ring seal – ferrule glued to sensor pot & air tight is required

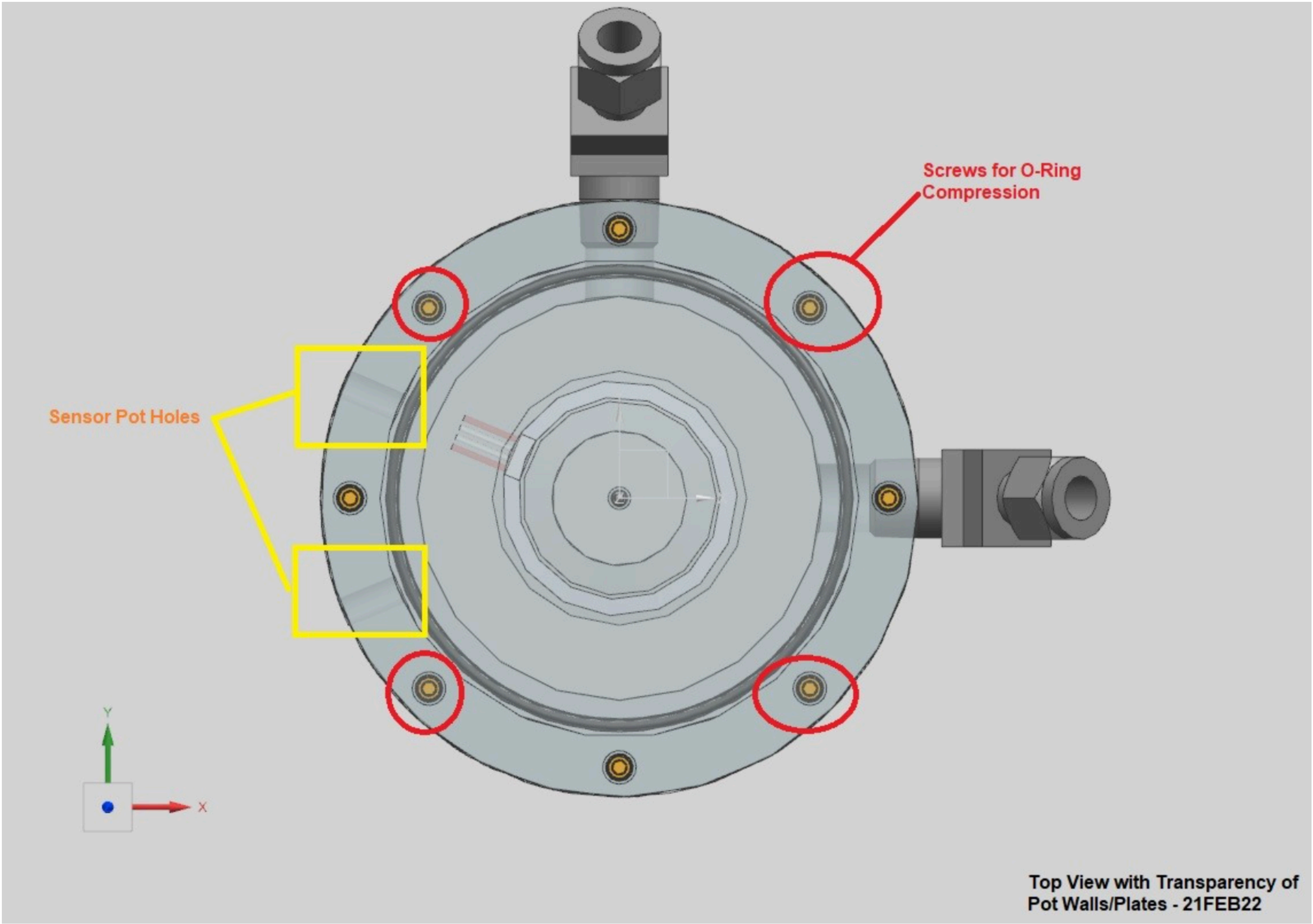
Conceptual Design of Pots

- Some locations will need 4-nozzle pots
- 2-Nozzle & 4-Nozzle pots will be tested at prototype





- Swageloks to be screwed into Water Pots
- Swageloks can rotate



Conceptual Design of Mechanical Stands

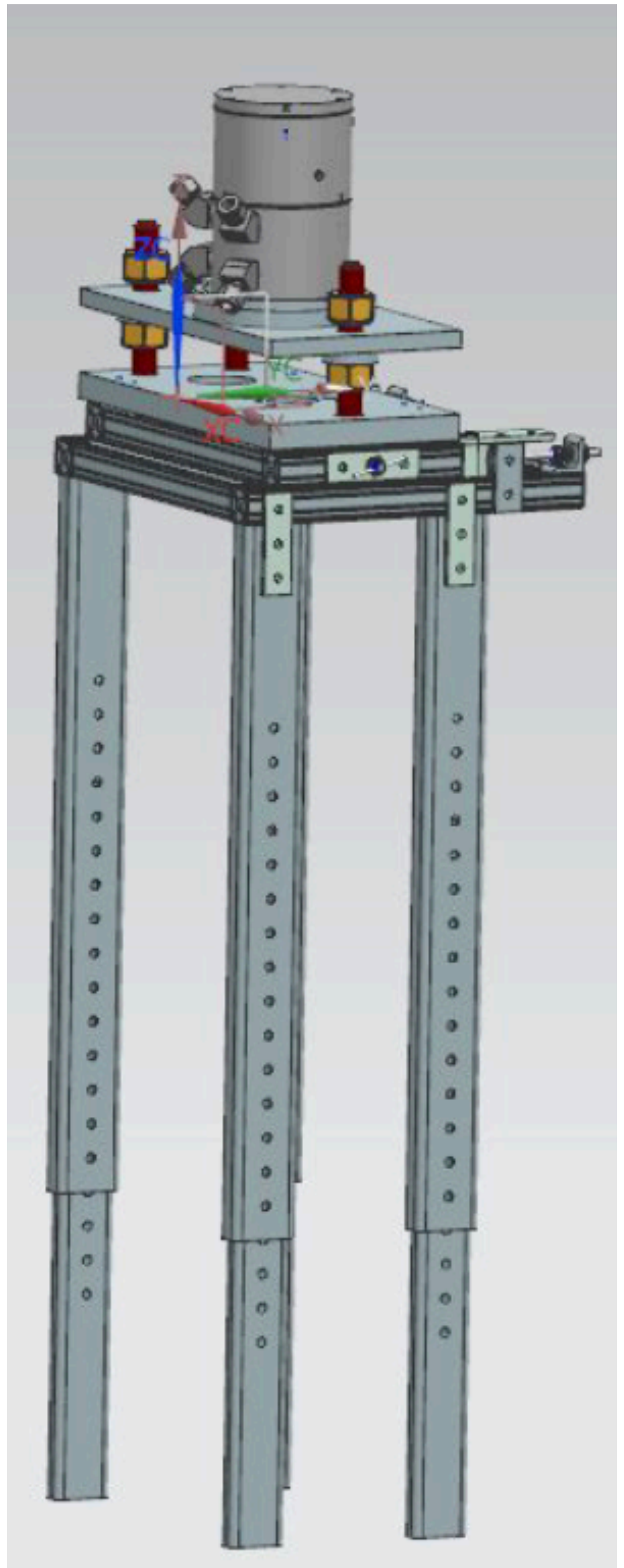
Conceptual design of stand by Hannah Magoon

- Above each of the Horns, two different stand heights because of slopes, heights will have to be adjustable
  - Course height adjustment, fine kinematic adjustment
- Is a single t-block wide enough for a stand to sit on it?
  - One stand can sit on one t-block
- How high can we go with stand?
  - ~8.5 ft above horn C

- **Technical requirements addressed:**
  - Size and Position
  - Strength and stability
  - Adjustability
  - Vibration
  - Installation
- **To-do:**
  - Horizontal support frame for legs
  - Tipping analysis
  - Interface with horn
  - Cable routing
  - Connection to HLS pot

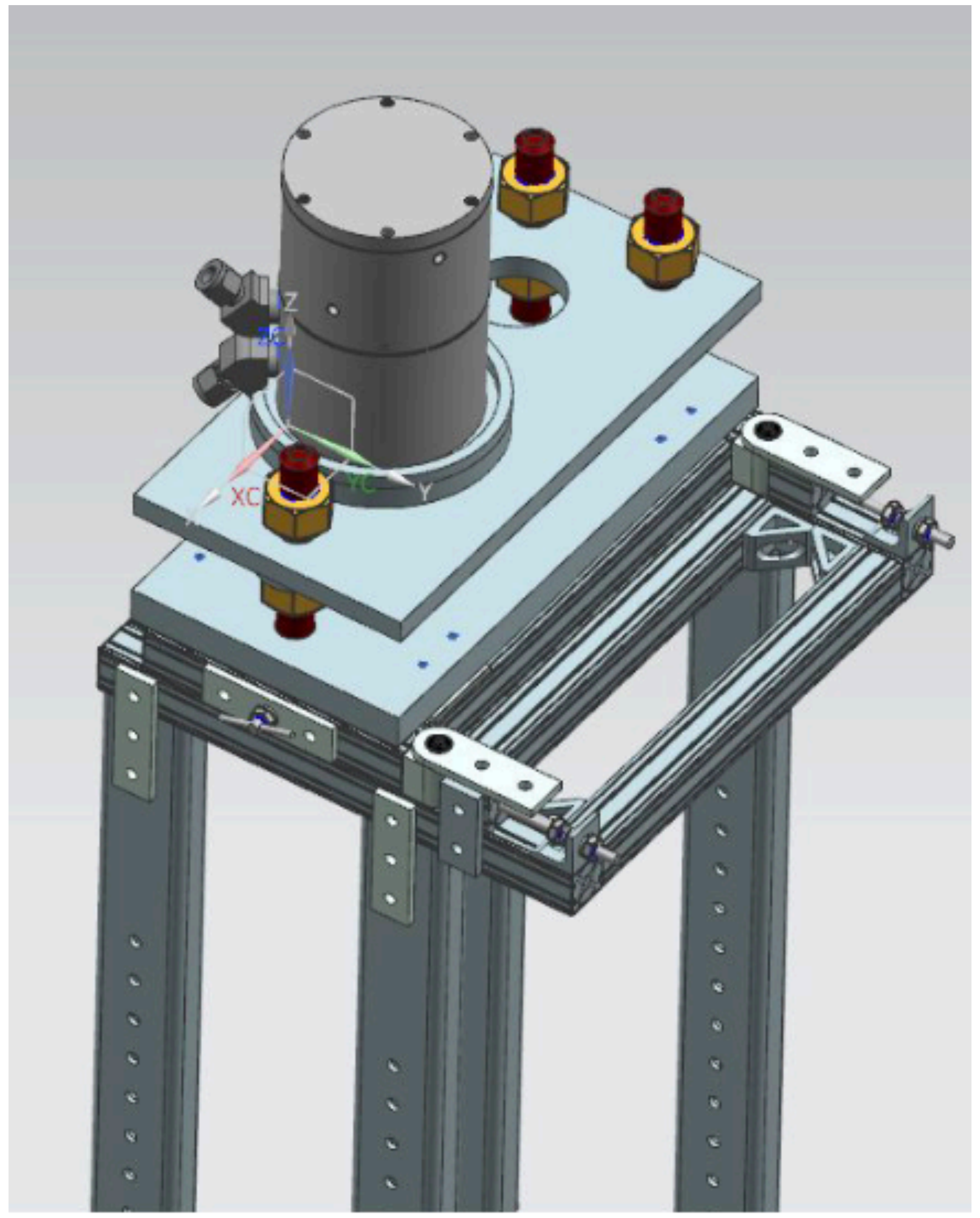
Adjustability

- Kinematic alignment system allows for adjustments in all degrees of freedom
- Since the HLS pot needs to be completely level, the stand should offer both coarse and fine height adjustments
- Adjustment either by hand or hand tool



Conceptual Design of Mechanical Stands

Conceptual design of stand by Hannah Magoon

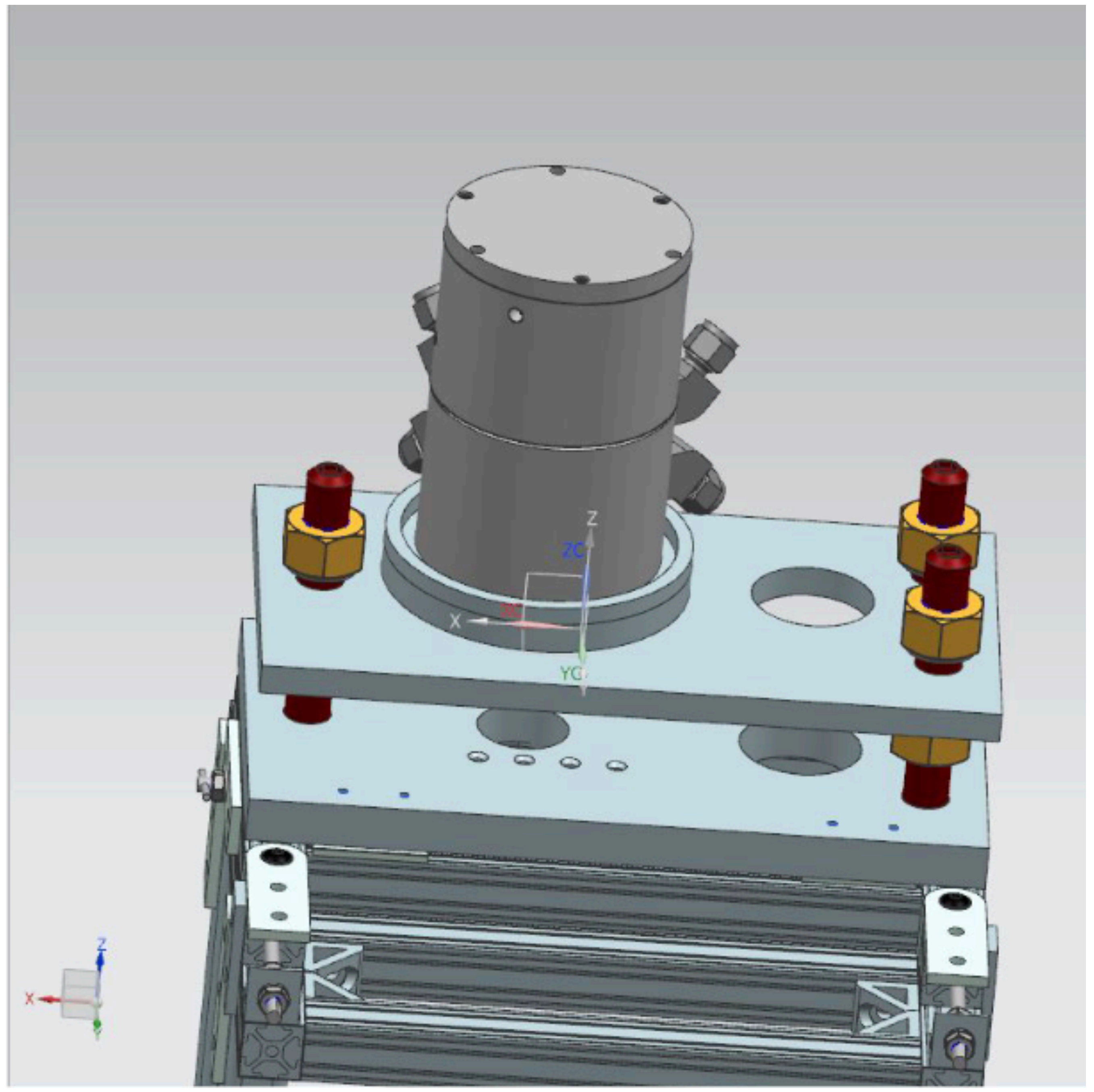


Strength Requirements

- Needs to support approximately 2.68 kg
  - Based on the CERN model, the HLS pot is expected to have a mass of approximately 2.28kg, and it will be filled with 400 mL of water

Vibration

- The stand should have a low natural frequency less than 100 kHz
- The natural resonance of the structure should not be similar to the frequency of pulses in the stripline (625 Hz and its multiplicities)
- The natural resonance of the structure should not be near any of the standing wave frequencies of the water in the HLS pots, as this would interfere with the leveling system



Routing

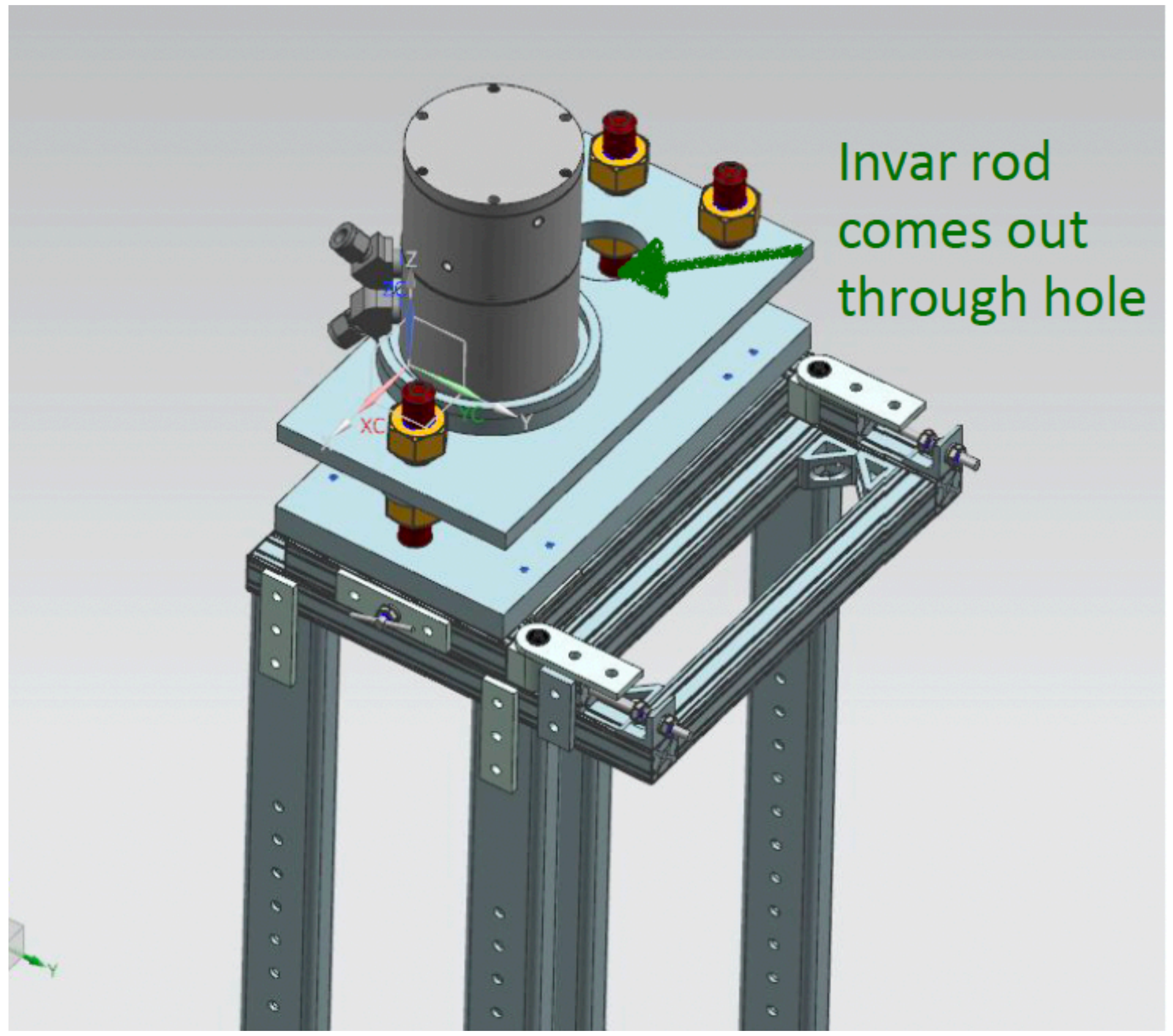
- The stand will be modified to support routing for water, air, heating, and fiber optics
- The stand has a 1.5" diameter cutout at the bottom of the HLS pot to accommodate the potential drainage pipe

- Bottom hole removed, potential leak
- have a drain for the entire system at one level through reservoir

Conceptual Design of Mechanical Stands

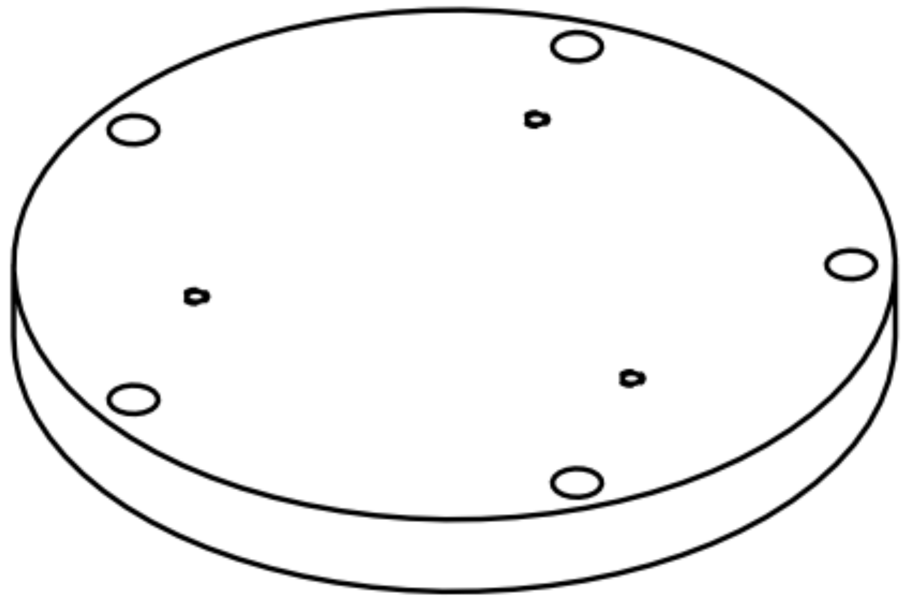
New ideas to consider:

- T-blocks/beams move with thermal expansion of pile ~ a few mm
- Clamp stands to t-block beam, reduce stand leg height
- Adjustable stand above clamp
- Have something that clamps to beam, a slab for pots and Invar rods to come through - reduce necessity of stand, can be modular



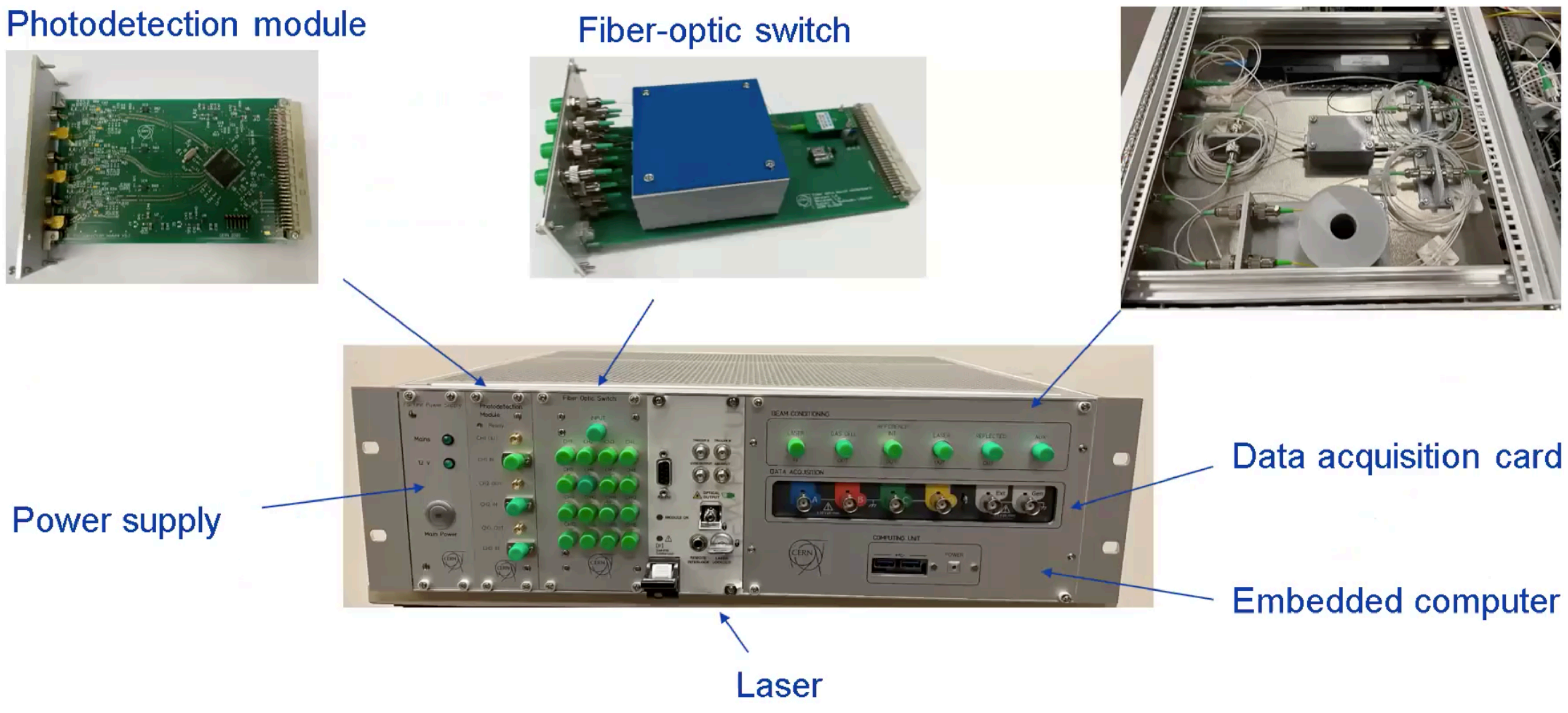
Interface between pot and stand:

3x120° pattern to prevent any unwanted rotation of pots after mounting



Readout and Data Access

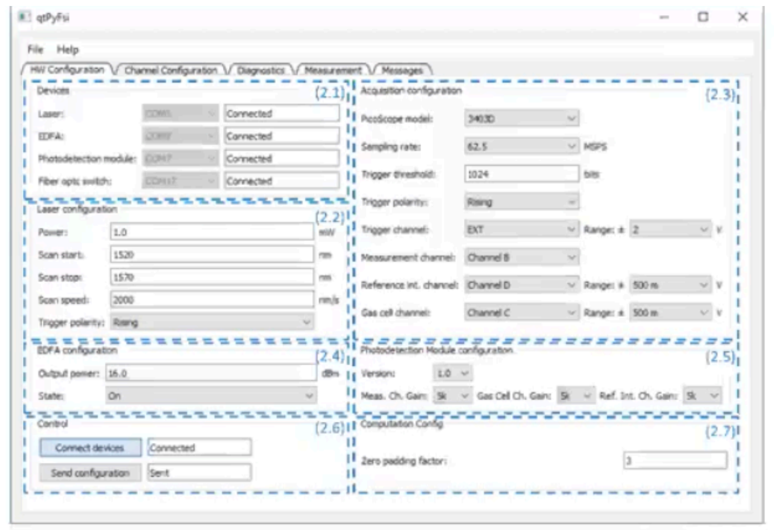
CERN Compact FSI setup



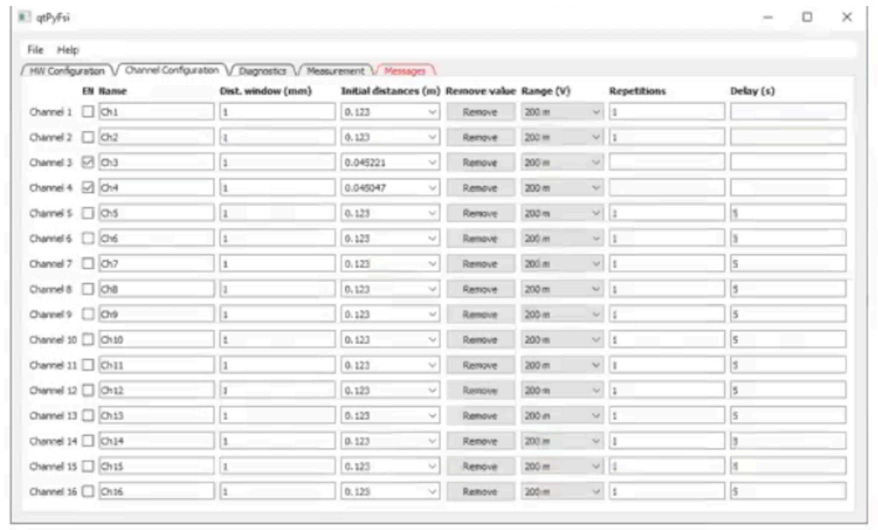
- System will be running continuously, continuous data writing, e.g. magnet data

CERN FSI Acquisition and processing software

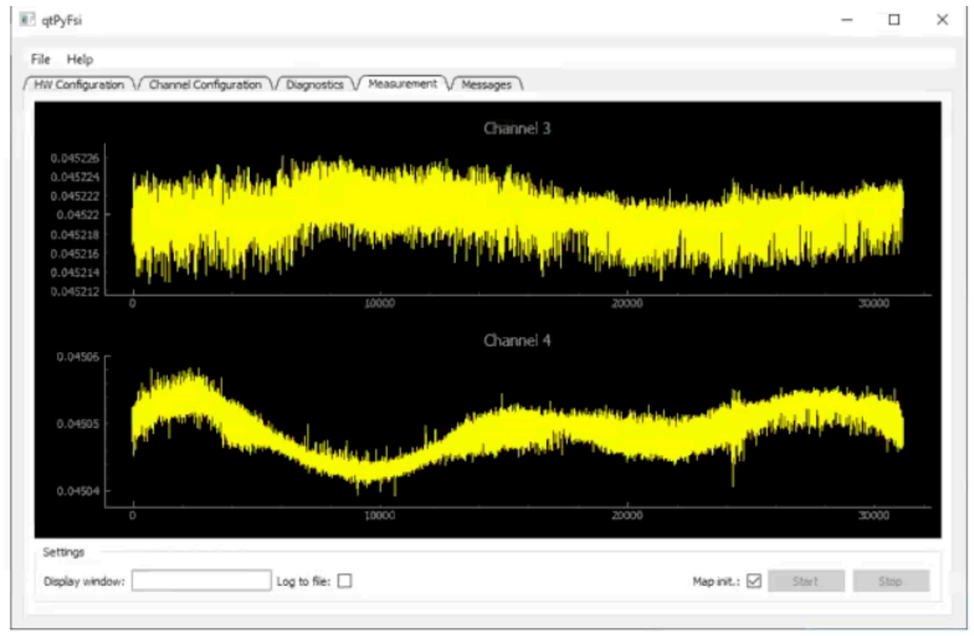
Controls hardware

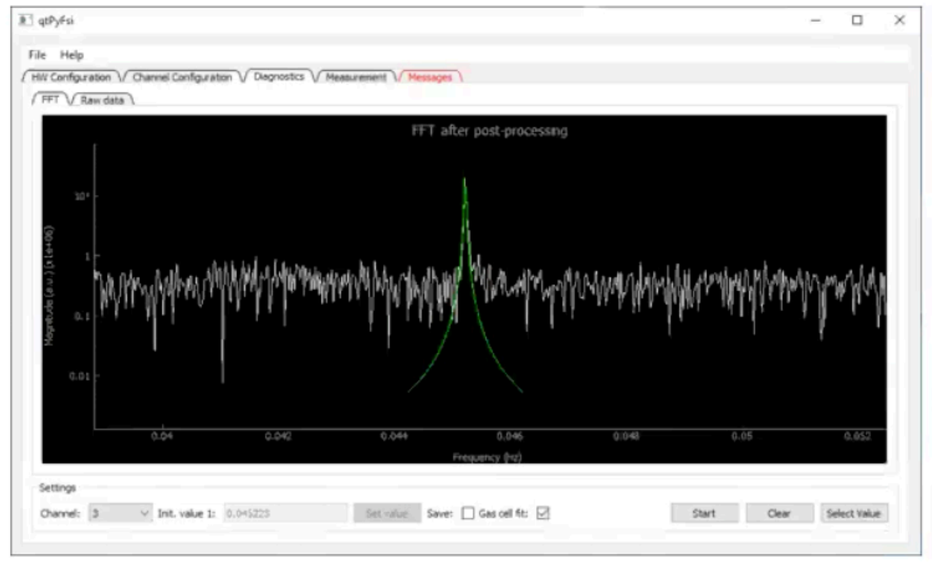


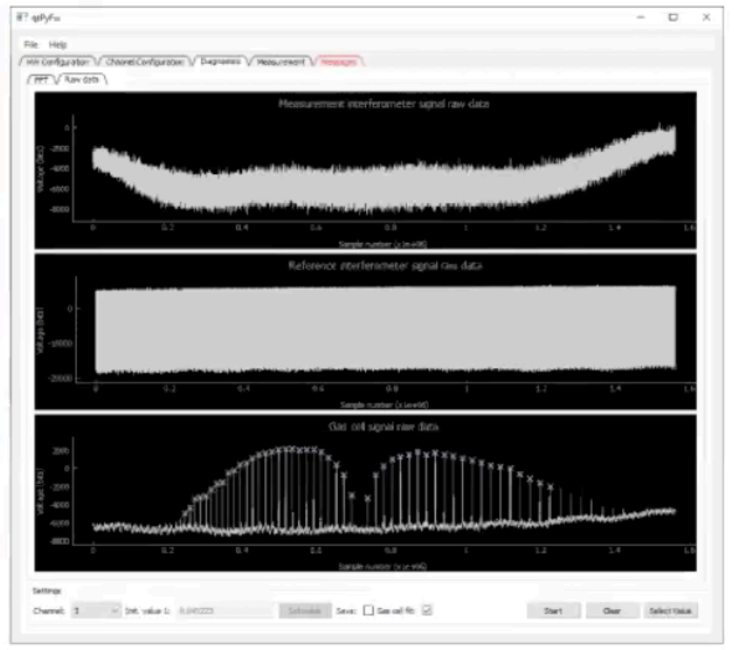
Controls parameters for each channel



Take measurements







Debug raw signal

Realized using:
- Python 3
- PyQt 5
- PyQtGraph
- NumPy, SciPy, lmfit …

- Q2.b.
- **HLS pot for prototype testing**
  - HLS pot drawing finalized, reviewed and approved by Salman Tariq
  - Updated drawings have been sent out to vendors for quote
  - HLS stand design
  - Work on stand design has began by Hannah Magoon and will continue this summer
  - New design ideas will be considered
- **Laser**
  - Laser for prototype testing: TLB-8800 Newport laser, delivery delayed due to global supply shortage of semiconductors
  - New estimated delivery: December 2022
  - Other options explored: nothing available with the required sweep speed
- Q3.
  - Preliminary pot design by Matt Sawtell, reviewed by Dakota Krokosz and Salman Tariq, approved by Salman Tariq
  - Preliminary stand design by Hannah Magoon
- Q4.
  - Prototype HLS pot work –
    - Drawings for components done to comply with ASME Y14.41 – policy of Fermilab
    - Assembly drawings done to comply with ASME Y14.5 – policy of Fermilab
    - Initial Engineering Risk Assessment has been performed ss per Fermilab Engineering manual
    - O-rings will be tested as per ASTM-D6147 to make sure it can provide sufficient sealing
    - O-rings radiation hardness will be tested

1. Does the NBI preliminary design meet the functional requirements identified?

2. Is the design maturity presented for the NBI, interfaces, and ancillary systems at a level appropriate for a Preliminary Design?

a. Based on acceptable progress for a Preliminary Design to be 50 to 70% complete, with 100% meaning ready for procurement.

b. Are areas where components are awaiting forthcoming development well understood?

3. Have suitable engineering analyses been performed and documented, and reviewed/peer reviewed and approved, where applicable?

4. Are the appropriate codes and standards adequately applied to the design?

5. Are there any significant ES&H issues been identified and analyzed appropriately?

6. Have potential design, manufacturing, and installation risks and challenges been identified within the scope of work, and has it been adequately planned to address these during the final design? Are difficult design features and possible prototyping issues identified?

7. Is the level of integration with other LBNF beamline entities appropriate for this stage of the work?

8. Are there any issues concerning the schedule for the NBI?

- Q5.
  - Fermilab Laser Standard Operating procedure has been approved by RSO
  - Will address electrical safety, fire hazard from cable deterioration
  - System will have water, effect of radiation is expected to be minimum
  - Will seek advice from fluid group to determine if tritium exposure is possible during maintenance and provide handling instruction
  - Will use HCN gas cell, safety protocol needs to be defined
- Q6.
  - Prototype testing planned for next summer - details next slide
  - Potential issues have been addressed during HLS pot design
- Q7.
  - Interfaces have been identified, some discussed
  - Work under progress to interface with other groups

Preparation for Prototype Test

- **Prototype test likely next summer - driven by laser delivery schedule from NewPort**

- **Objectives:**
  1. Test mechanical design and manufacturing feasibility of HLS pots
  2. Gain assembly, installation, and operational experience
  3. Test electronics and DAQ
  4. Measure precision of device
  5. Investigate possible effects of vibration
  6. Mockup battlement fiber optics setup by using patch panel and fiber optics patch cables of different lengths to see effects on FFT spectrum from different cable lengths
  7. Investigate impact of humidity
  8. Investigate effect of temperature
  9. Test rate of gas leakage through HLS pot

- **Location** - Room 32 in Lab 6 in Fermilab village
- Fermilab Class 3B/4 Laser Standard Operating Procedure prepared, submitted and approved by RSO to use class 3B laser
- TSW (Technical Scope of Work) form submitted and approved
- Preliminary run plan document available
- PXI DAQ and LabView as software application- support available at lab

Supporting Documents

- Pot and assembly drawings
- Engineering Risk Assessment
- Run plan document
- Hannah’s work on mechanical stand

Docdb link:https://docs.dunescience.org/cgi-bin/sso/ShowDocument?docid=25259

Thanks!

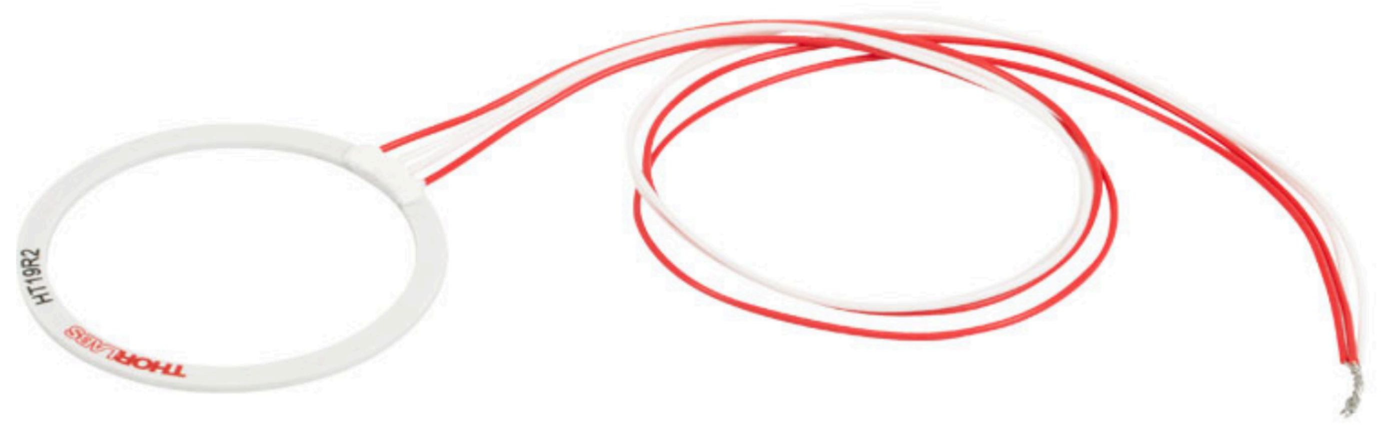
- Many thanks to Matt Sawtell, Dakota Krokosz, Salman Tariq, Hannah Magoon, Joe Angelo!

Backup

Prototype Test - Heater

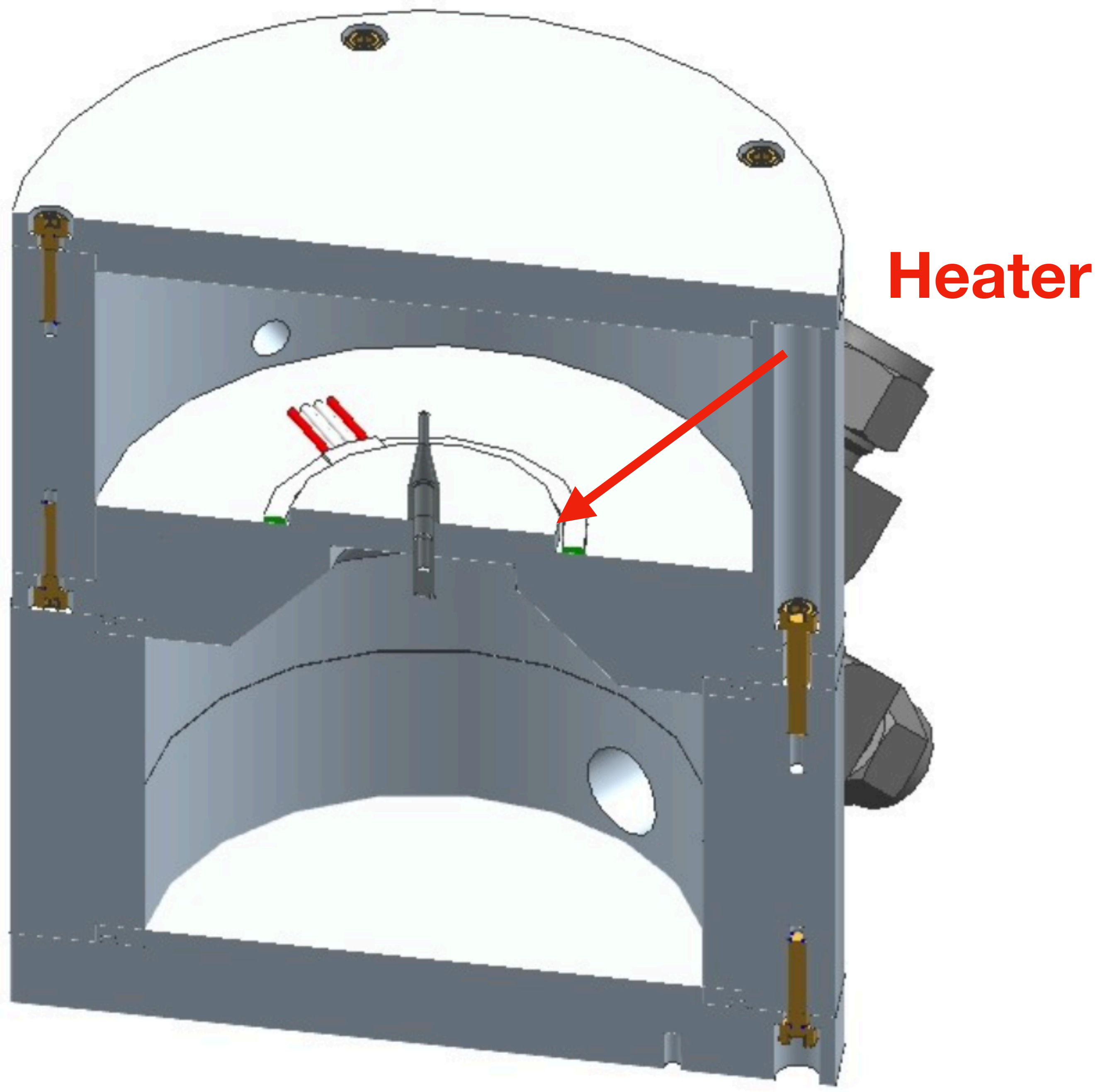
- Heater system will consist of three components; Thor Labs heater, a PID controller **(Brand TBD)**, a 60W single phase 2.5A Power Supply **(Brand and output TBD) - to test pots**

- Attached to pot body with radiation hard epoxy, Scotchcast 2123D: can take1E9 rads before showing signs of mechanical damage



HT19R2 - 19 W Metal Ceramic Ring Heater with 10 kΩ Thermistor

HT15W - 15 W Resistive Cartridge Heater



- Feed heater element cables through designated wire holes in sensor pot

Calculation for target helium heat exchanger

RAW system	Hydrogen gas production rate at 2.4 MW beam power					H_2O lost	Argon gas	Horn Argon
	(gal/sec)	(gal/hr)	(gal/day)	(gal/wk)	(gal/yr)	(gal/yr)	(sccm)	(Sccm)
Cooling Panels	3.83E-04	1.38	33.12	231.83	6773.98	5.44	8706	0.03
Horn_A	4.01E-04	1.44	34.63	242.42	7083.50	5.69	9128	**9128**
Horn_B	1.79E-04	0.64	15.45	108.17	3160.66	2.54	4155	**4155**
Horn_C	3.92E-05	0.14	3.38	23.68	692.03	0.56	973	**973**
T_blocks	7.05E-05	0.25	6.09	42.64	1245.91	1.00	1601	0.03
Modules	2.55E-06	0.01	0.22	1.54	45.05	0.04	58	0.03
Target Helium HX	5.24E-11	1.89E-07	4.53E-06	3.17E-05	9.26E-04	7.44E-07	0.0012	0.03
Totals	**1.08E-03**	**3.87**	**92.9**	**650**	**19001**	15	24621	**14256**
Hadron Absorber	7.61E-05	2.74E-01	6.57E+00	4.60E+01	1.34E+03	1.08E+00	1728	0.03

After 1 year operation	**Total Activity**	**Specific Activity**		**Total Activity**
	Bq	**Bq/cm3**	**(Ci/cc)**	**(Ci/Year)**
H3	7.26E+05	6.82E-01	1.84E-11	1.96E-05
Be7	6.98E+06	6.56E+00	1.77E-10	1.89E-04
C11	9.38E+06	8.81E+00	2.38E-10	2.53E-04
N13	4.69E+06	4.41E+00	1.19E-10	1.27E-04
O15	3.28E+07	3.09E+01	8.34E-10	8.87E-04
		Total=	1.387E-09	1.475E-03