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

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Motivation

- Objective: Monitor vertical position of LBNF components (also tilt motion)
- 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

Requirements

- Looking at a slow time scale, not at fast vibrations
- Need relative measurements
- Not dependent on the absolute calibrations of these sensors
- Desired height accuracy ~ **0.2 mm** (tolerance of position is 0.5 mm, we want to see changes even smaller than that)

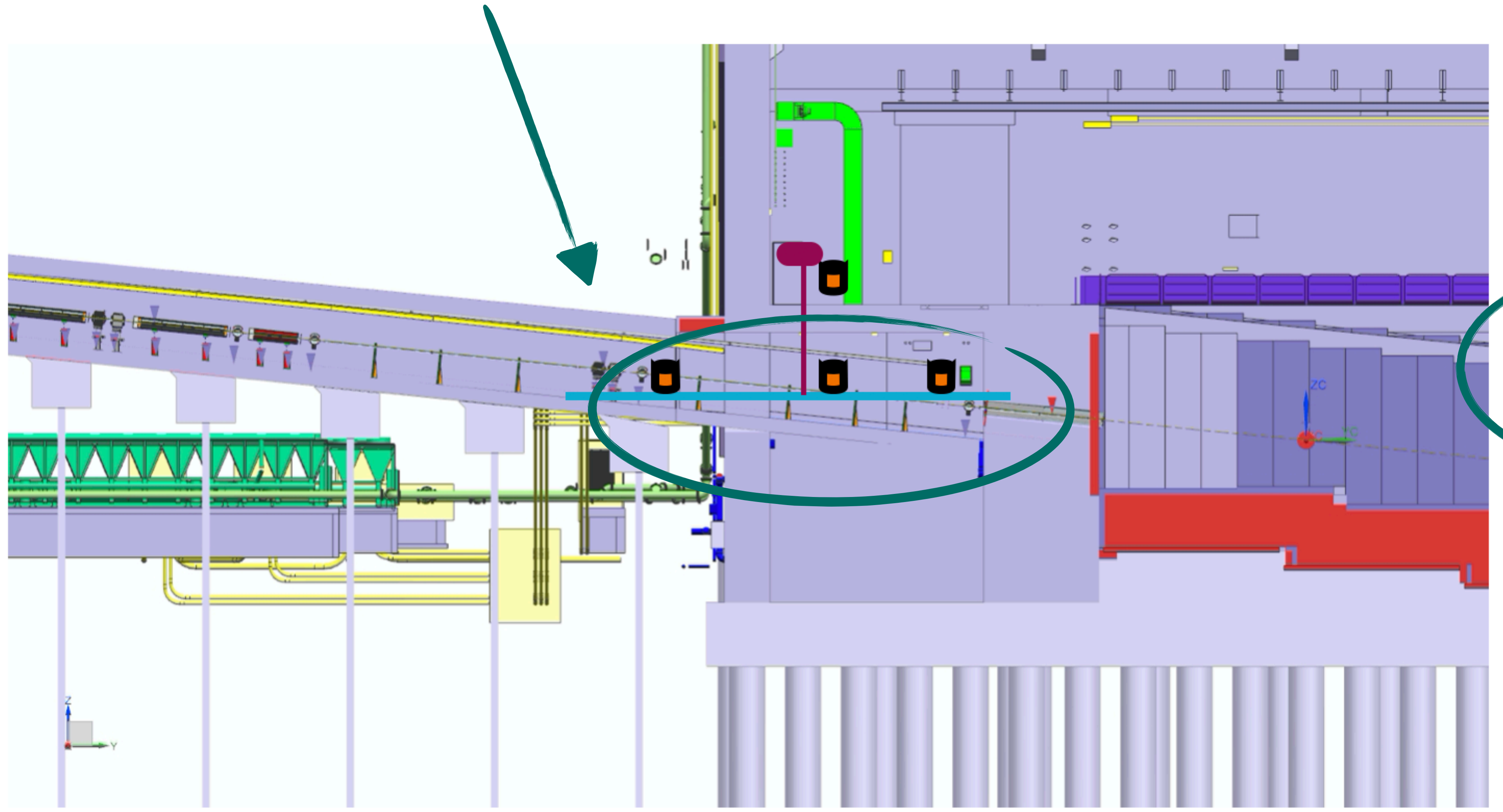
Quantity	1-sigma Shift	Notes	In TDR
Horn A Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	Y
Horn A Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N
Horn B Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	Y
Horn B Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N
Horn C Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	N
Horn C Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N
Target Transverse Displacement	0.5 mm	X and Y shifted separately, added in quadrature	N
Target Transverse Tilt	0.5 mm	X and Y shifted separately, added in quadrature; upstream and downstream ends shifted in different directions	N
Horn A Longitudinal Displacement	2 mm		N
Horn B Longitudinal Displacement	3 mm		N
Horn C Longitudinal Displacement	3 mm		N
Proton Beam Transverse Position	0.5 mm	X and Y shifted separately; added in quadrature	Y
Proton Beam Radius	10%	Updated from 0.1 mm for NuMI	Y
Proton angle on target	70μ rad	X and Y shifted separately; added in quadrature	Y
Decay Pipe Radius	0.1 m		Y
Horn Currents	1%	Changed in all three horns simultaneously	Y
Baffle Scraping	0.25%	To Be Updated	N
Bafflet Scraping	0.25%	To Be Updated	N
Target Density	2%		Y
Horn Water Layer Thickness	0.5 mm	Changed in all three horns simultaneously	Y
Upstream Target Degradation			N
# Protons on Target	2%		Y
Near Detector Position			N
Far Detector Position			N
Field in Horn Necks			N
Decay Pipe Position	20 mm		N

Table 1: Sources of alignment and focusing uncertainties in the neutrino fluxes at DUNE. Sources that were considered in physics studies in the TDR are marked with a 'Y' in the 'In TDR' column.

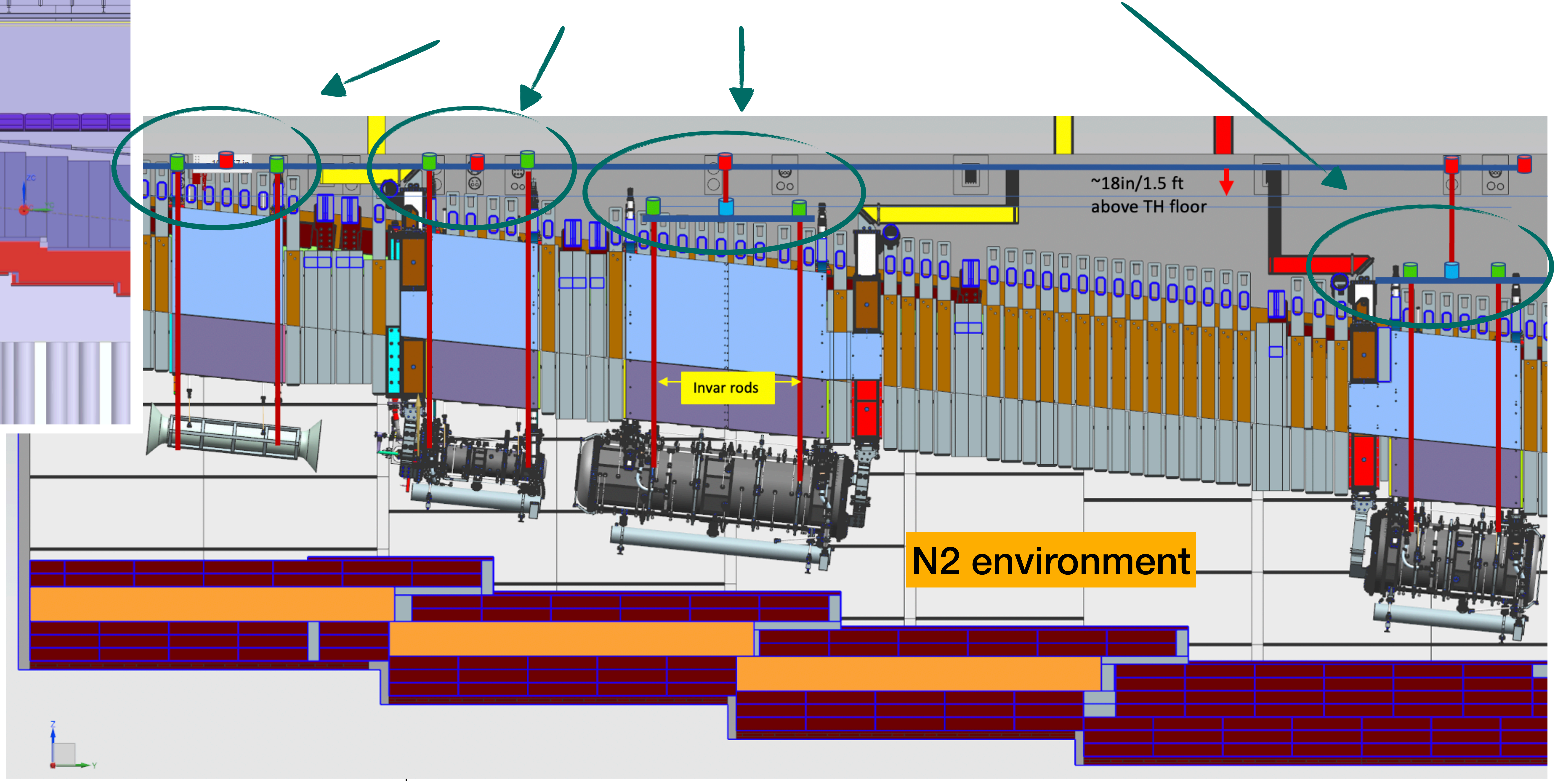
Beamline Components that need to be monitored

- 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

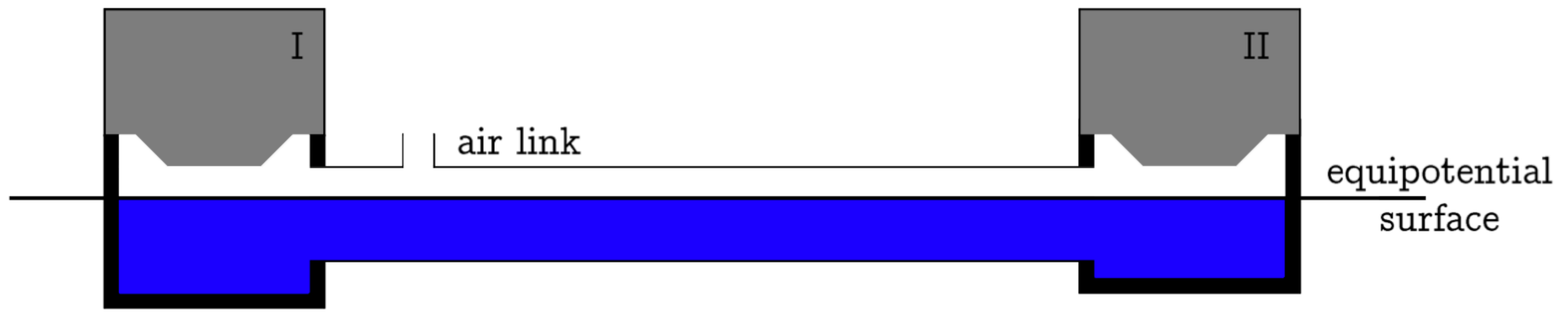


Requirements

- 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)
- Maximum optical fiber length ~ **238 ft (72 m)** (b/w laser and HLS sensor)
- Maximum height transfer need ~ **11 ft** (~**3.5 m**)

Horn Leveling System (HLS)

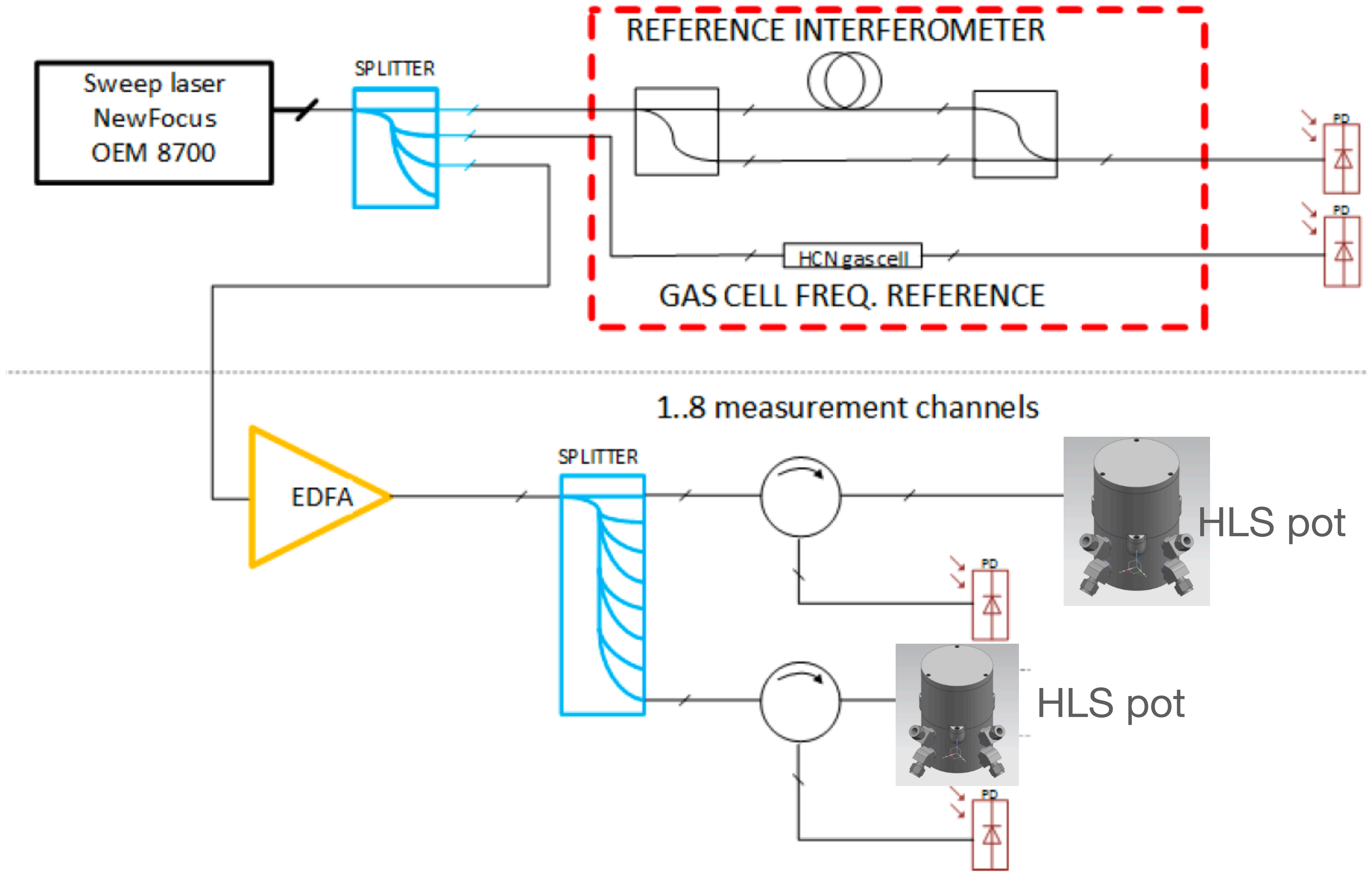
What is HLS?



Follows principle of communicating vessels:

- System of containers filled with a homogeneous fluid, connected at base and subjected to same atmospheric pressure
- Partially filled with water, allowing water and air to circulate freely
- Fluid seeks it's own level

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



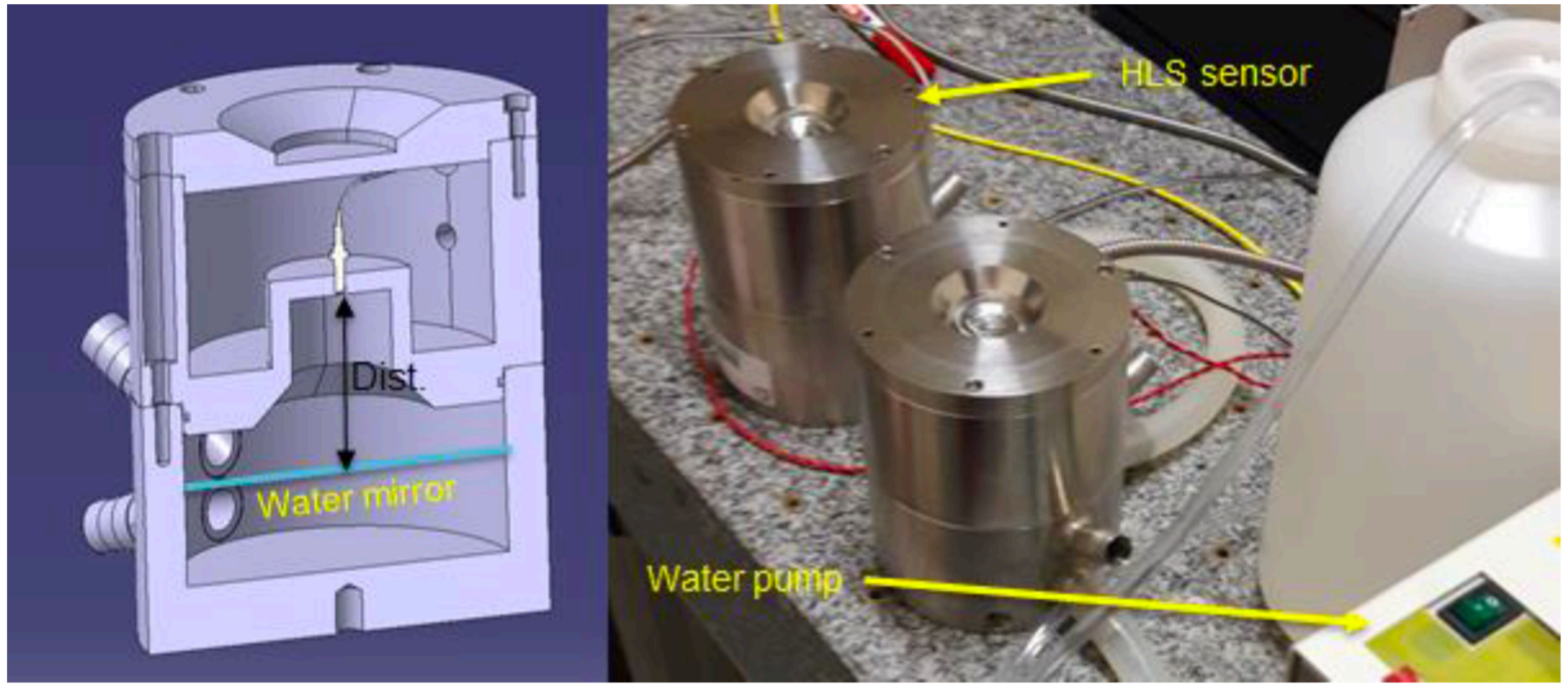
Will use HLS based on Frequency Scanning Interferometry (FSI)

Horn Leveling System (HLS)

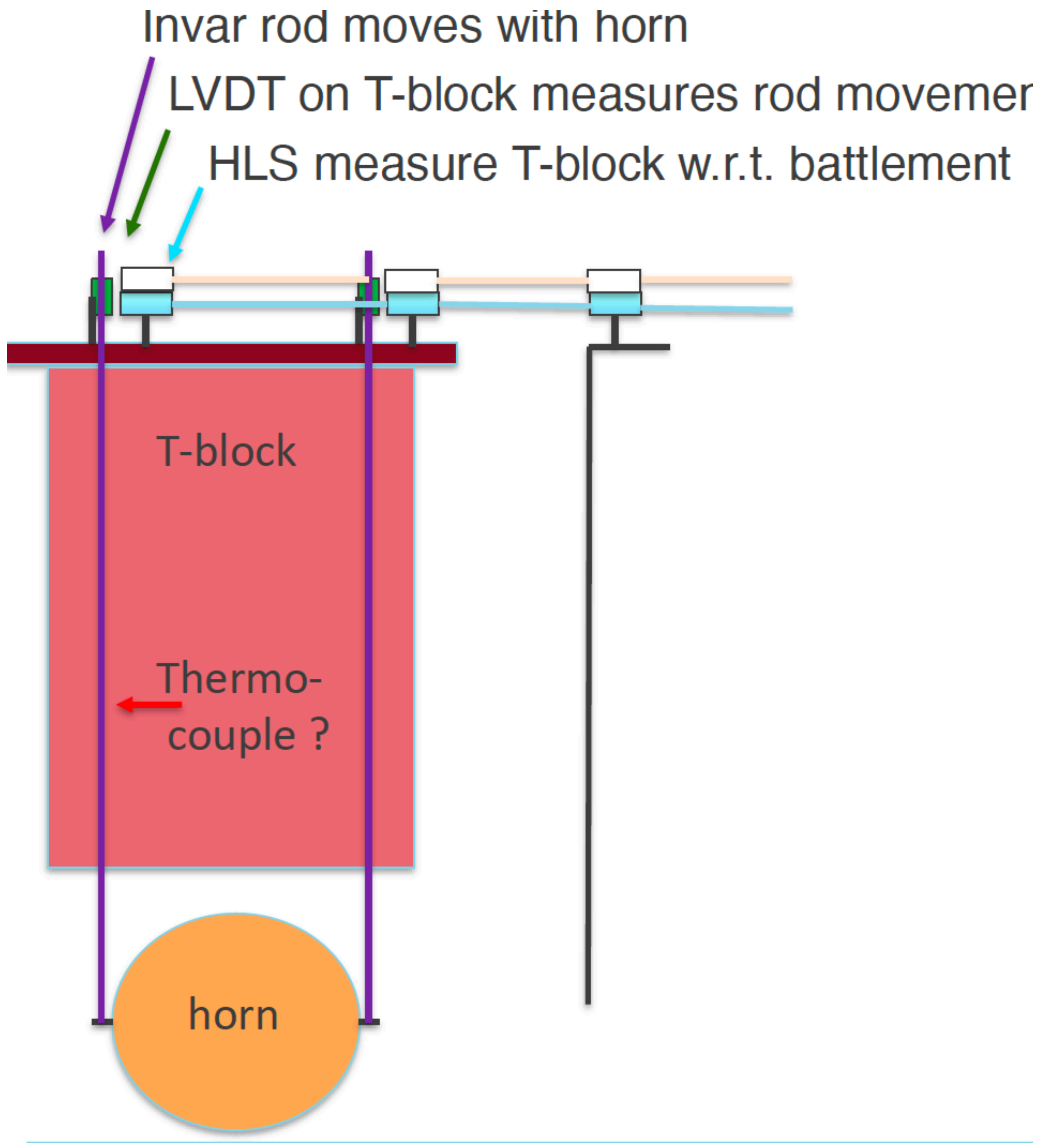
- Place HLS pots on Horns/Baffle, pots connected to each other via water & air lines
- Optical component: single fiber ferrule within each pot
- Part of light is reflected back from water surface, creating "beat" frequency signal in interferometer FFT spectrum
- Distance b/w ferrule tip & water surface $D = c\frac{f_{beat}}{2\frac{d\nu}{dt}}$

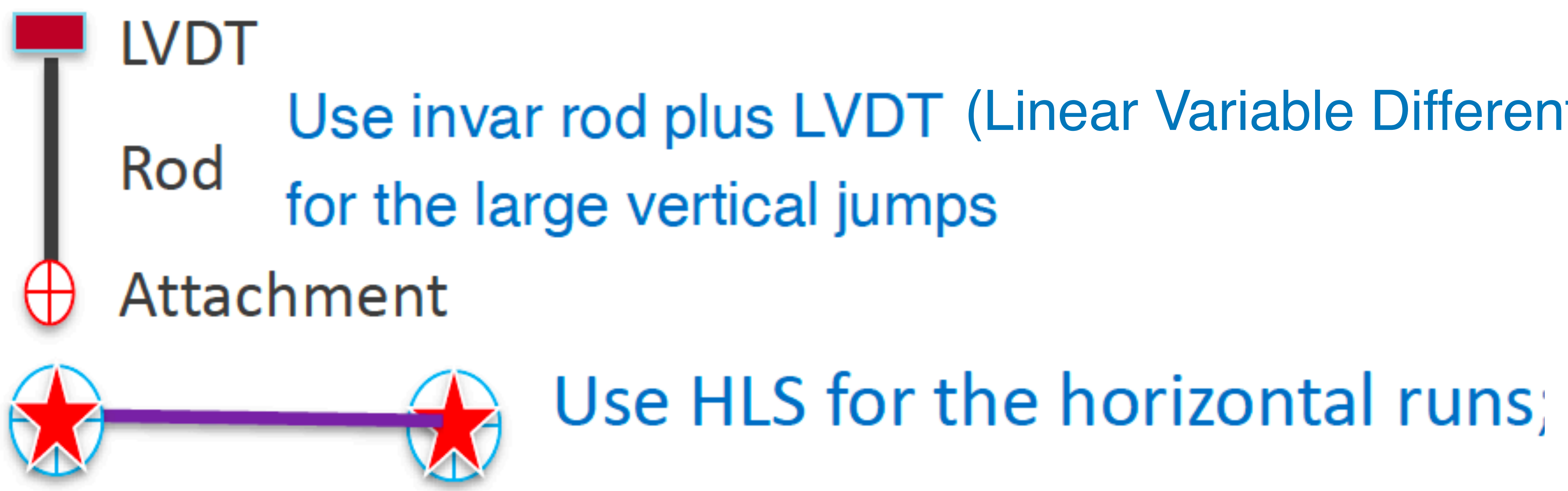
change of laser frequency during scan

Photo Courtesy: M. Sosin, CERN



Horn Leveling System (HLS)





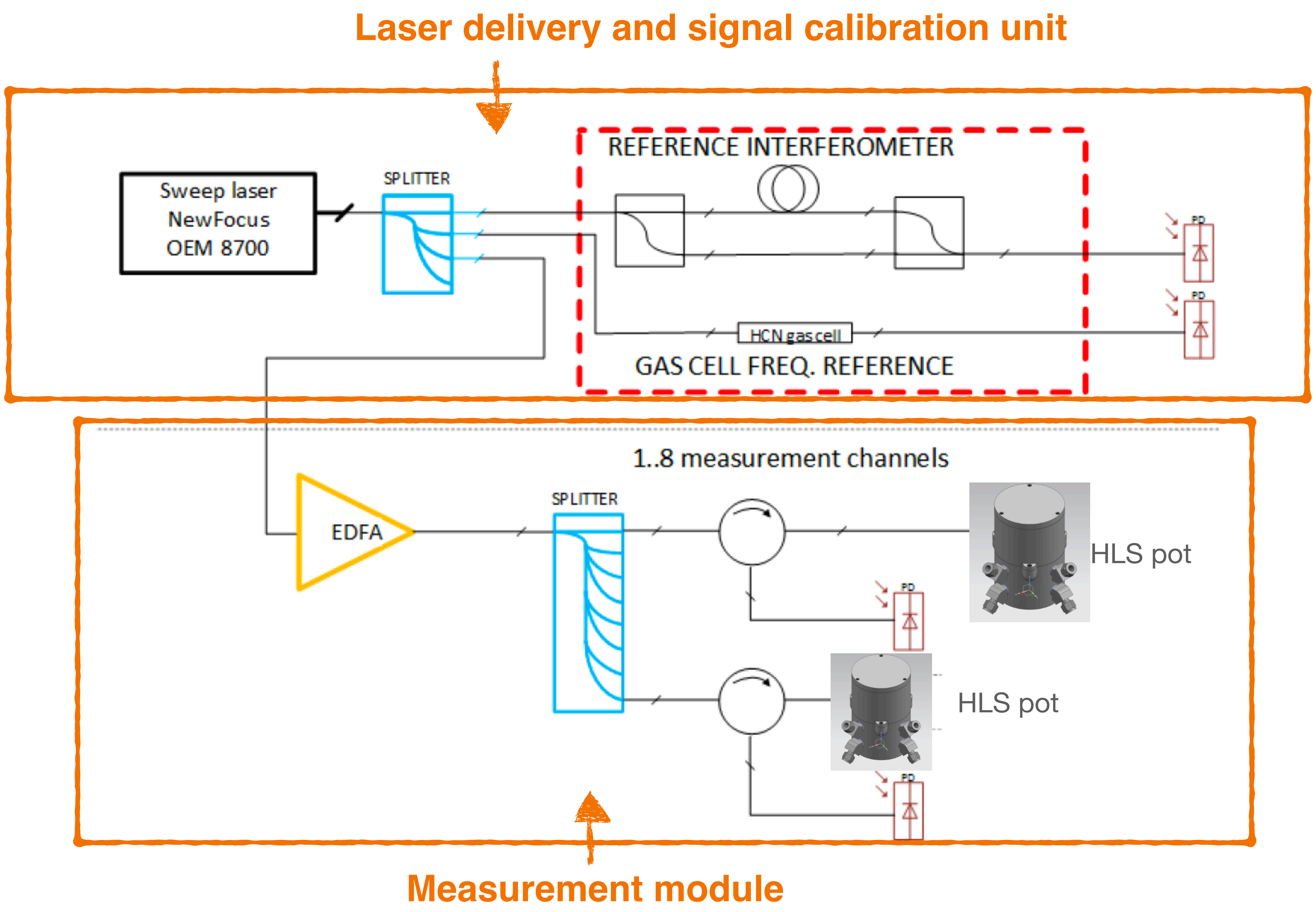
(Linear Variable Differential Transformer)

LVDT monitors distance b/w HLS & top of module

→if mis-alignment

- due to shift b/w module & component
- due to shift in target pile/building

Conceptual Design of the System



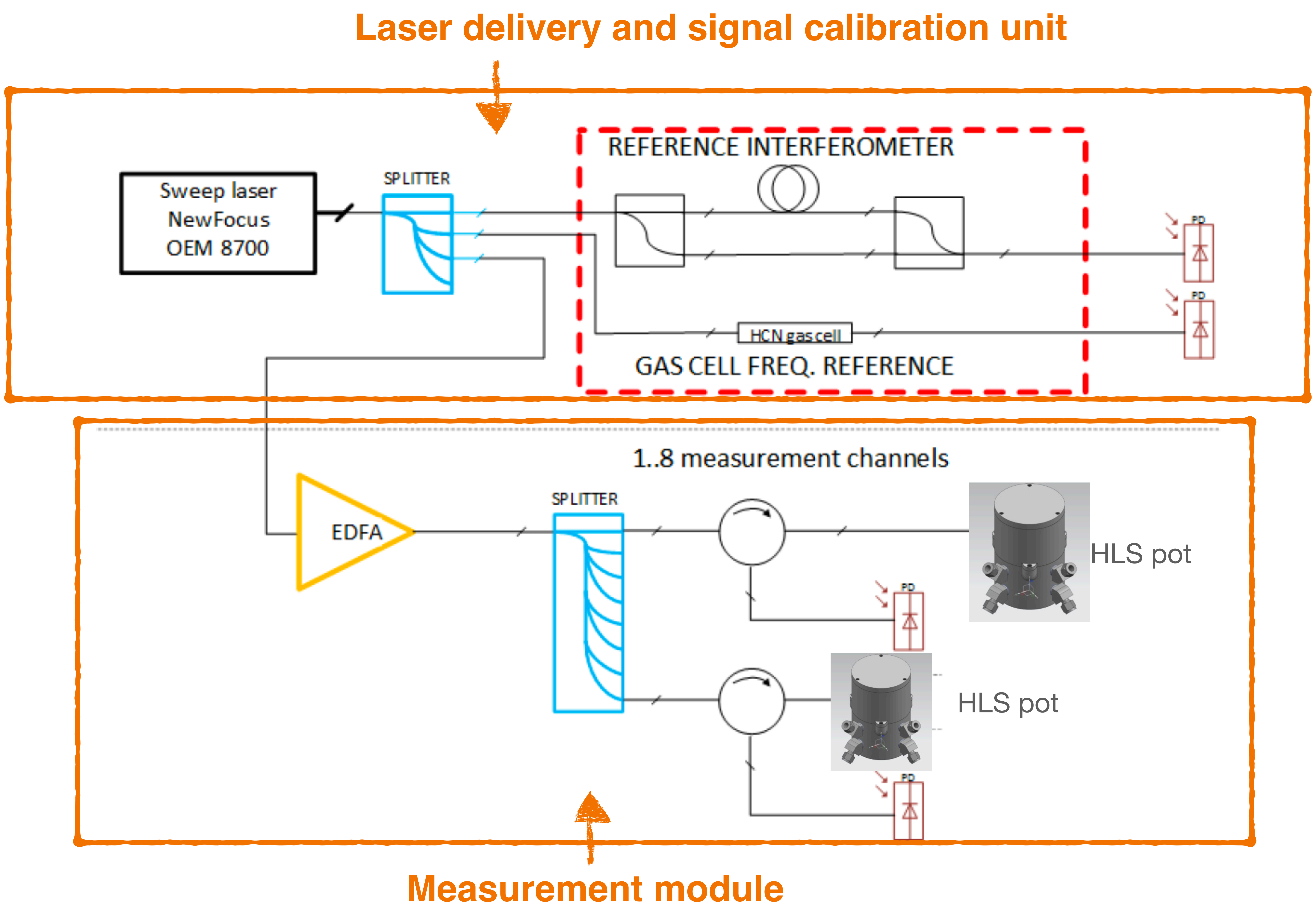
Main components:

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

Measurement steps:

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

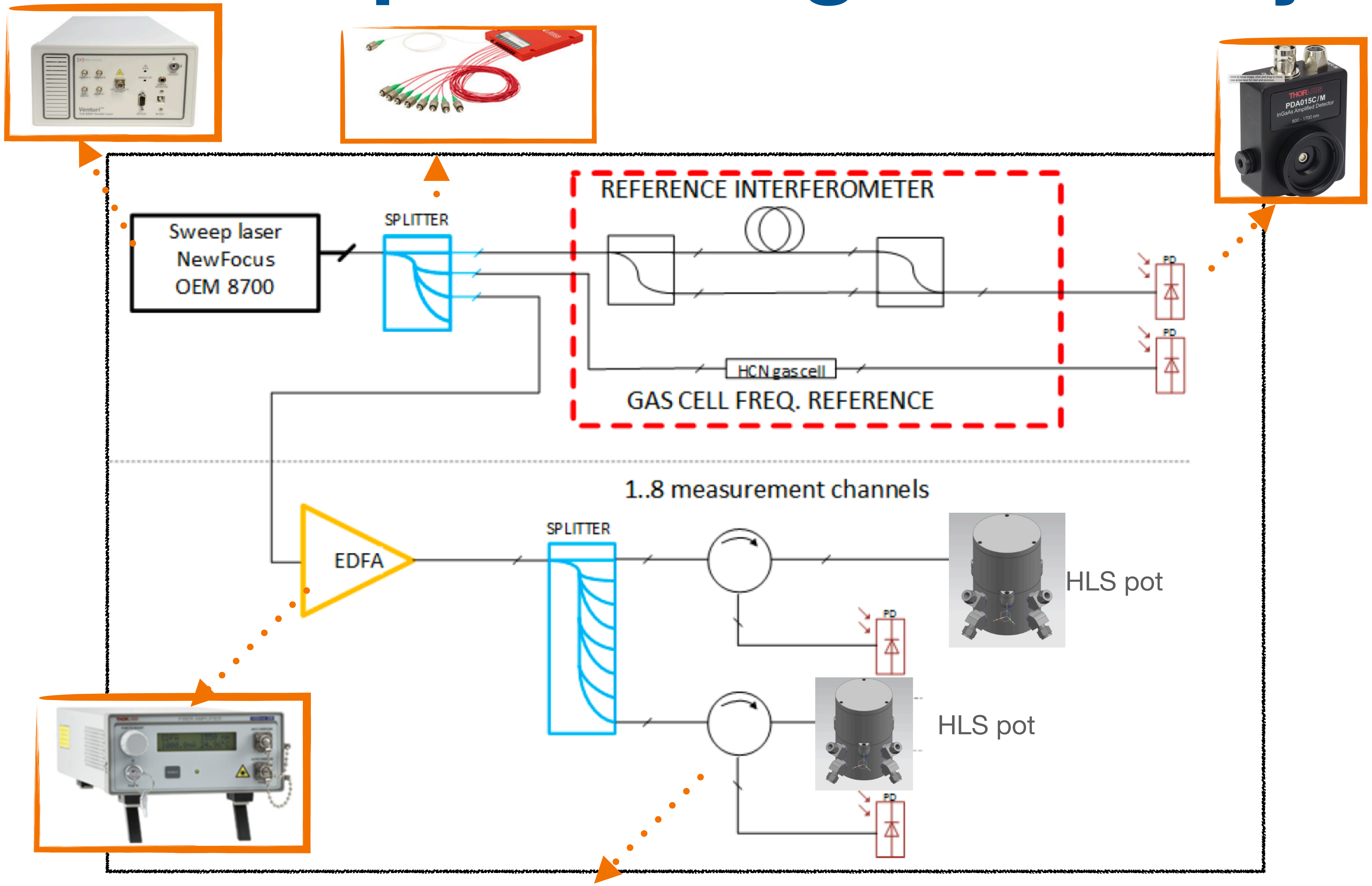
Conceptual Design of the System

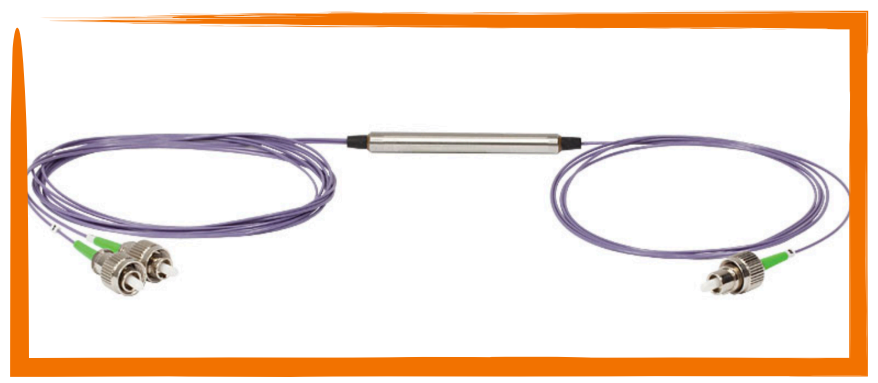


Components needed:

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

Conceptual Design of the System





Components needed:

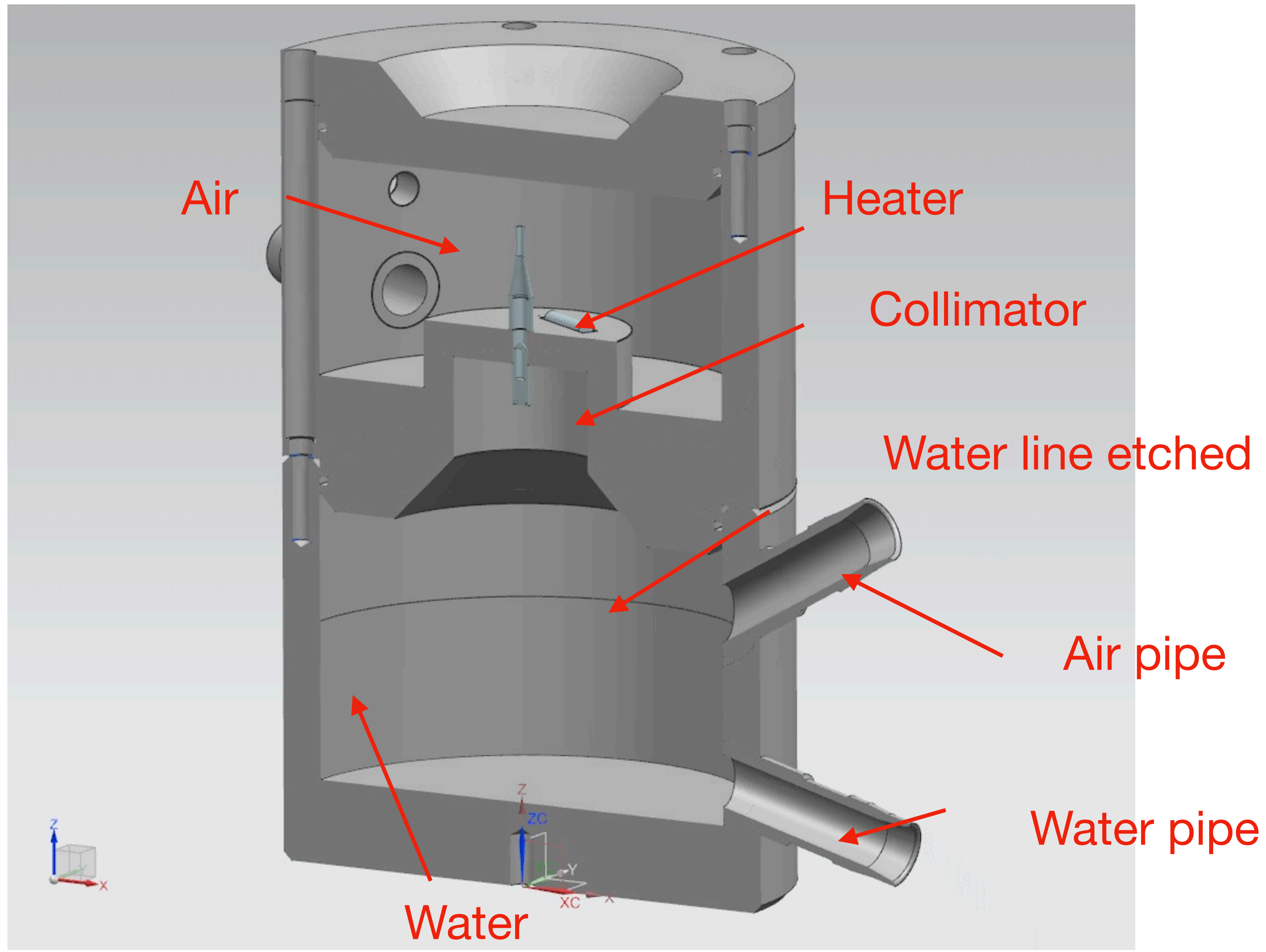
- ✓ Laser
- Reference interferometer
- ✓ HCN gas cell
- ✓ Amplifier
- ✓ Splitters
- ✓ Optical circulators
- ✓ Photodetectors
- Pots
- Water lines
- Air lines
- ✓ Heaters
- ✓ Fiber collimator
- ✓ Optical fibers
- Mechanical stands for pots
- Invar rods
- LVDTs
- Thermocouples

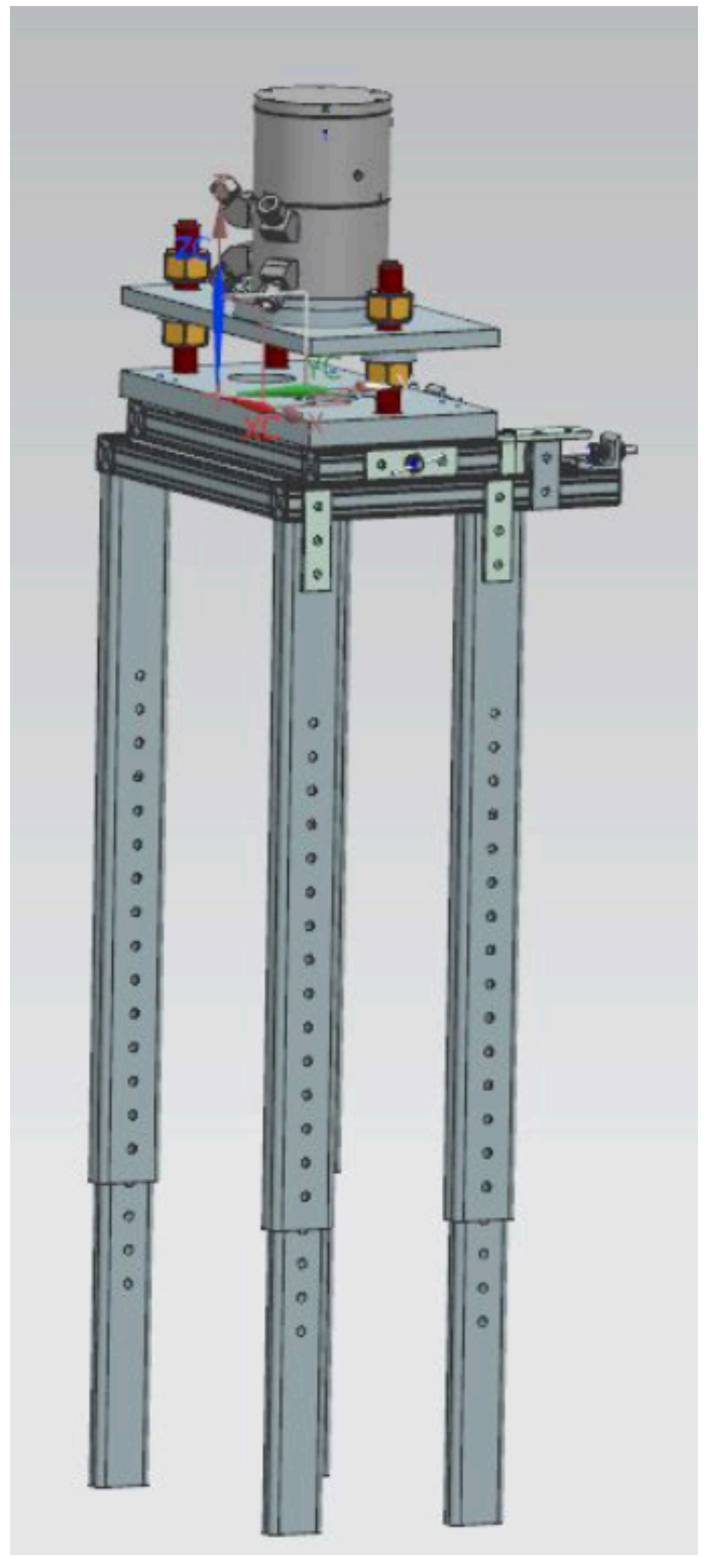
Needs designing (Pots, Mechanical stands for pots)

Checked items available off the shelf

Conceptual Design of the System

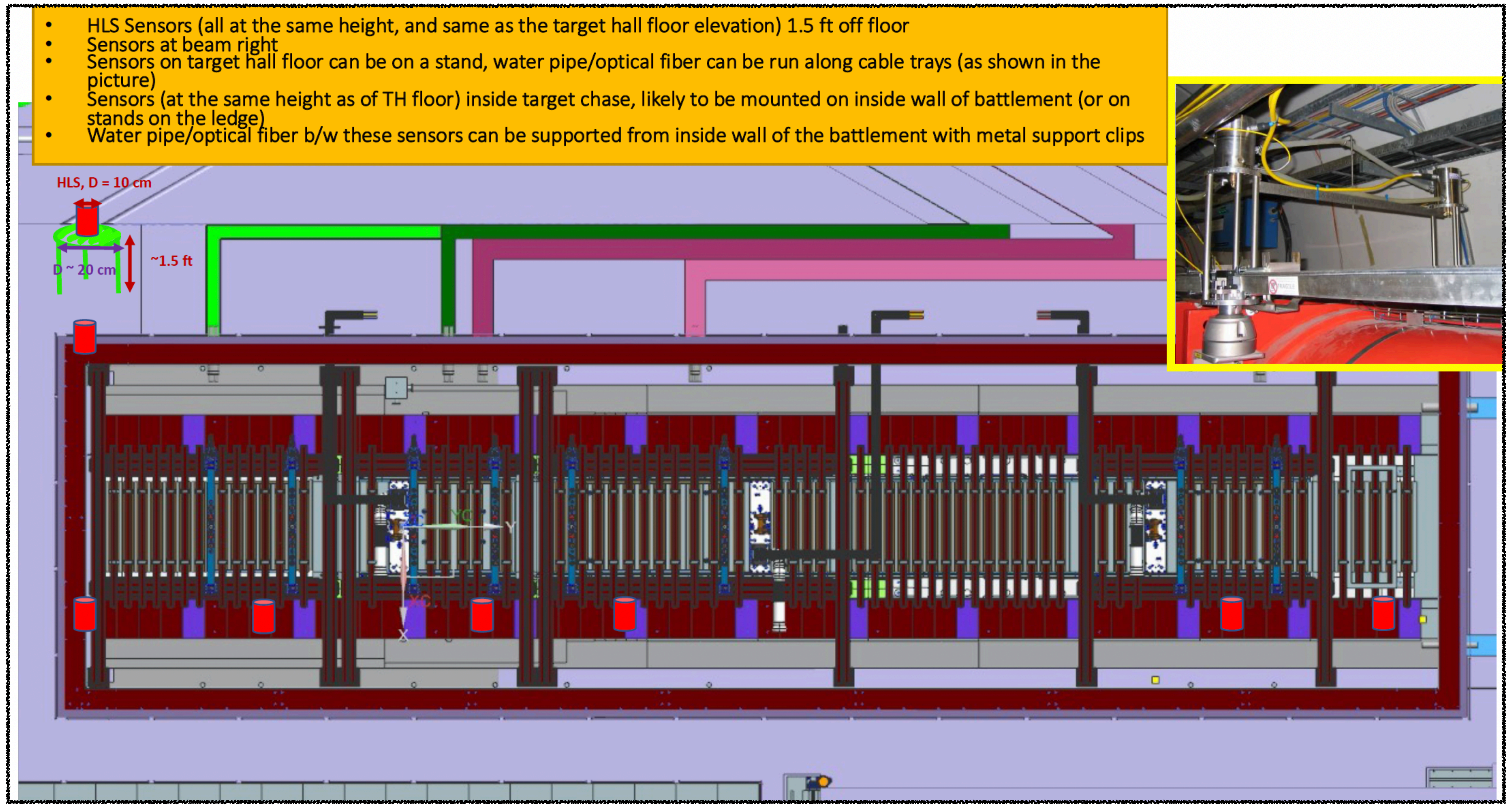
- Conceptual design of “pot” by Matt Sawtell : 26OCT21 Latest Drawing Package for LBNF HLS 2 and 4 Nozzle Pots
- Conceptual design of stand by Hannah Magoon

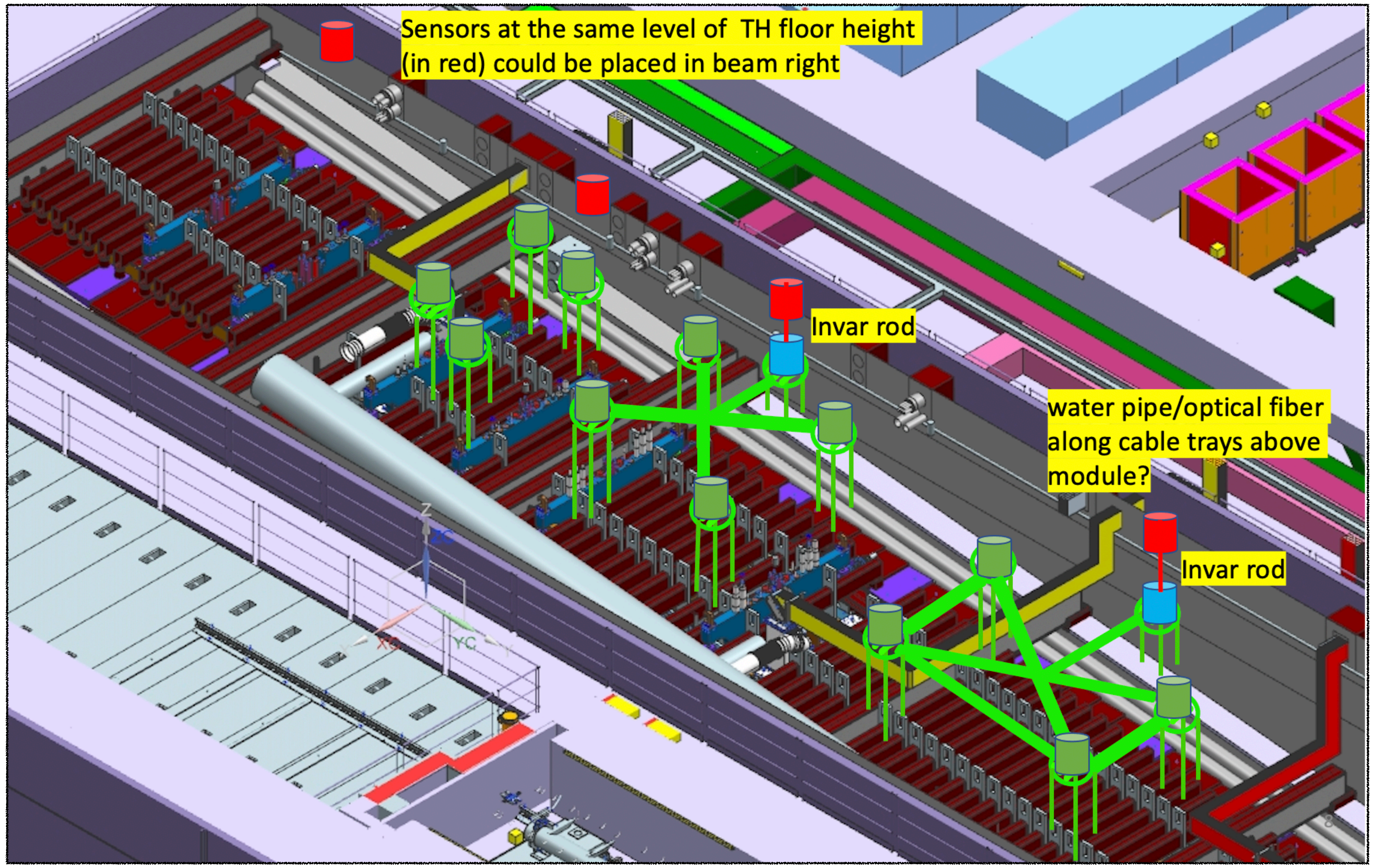




Preliminary Plan of Installations

- Preliminary discussions on where to place HLS pots in different locations, connect to water+air lines
- Preliminary discussions on how to run fiber optics, use of patch panels





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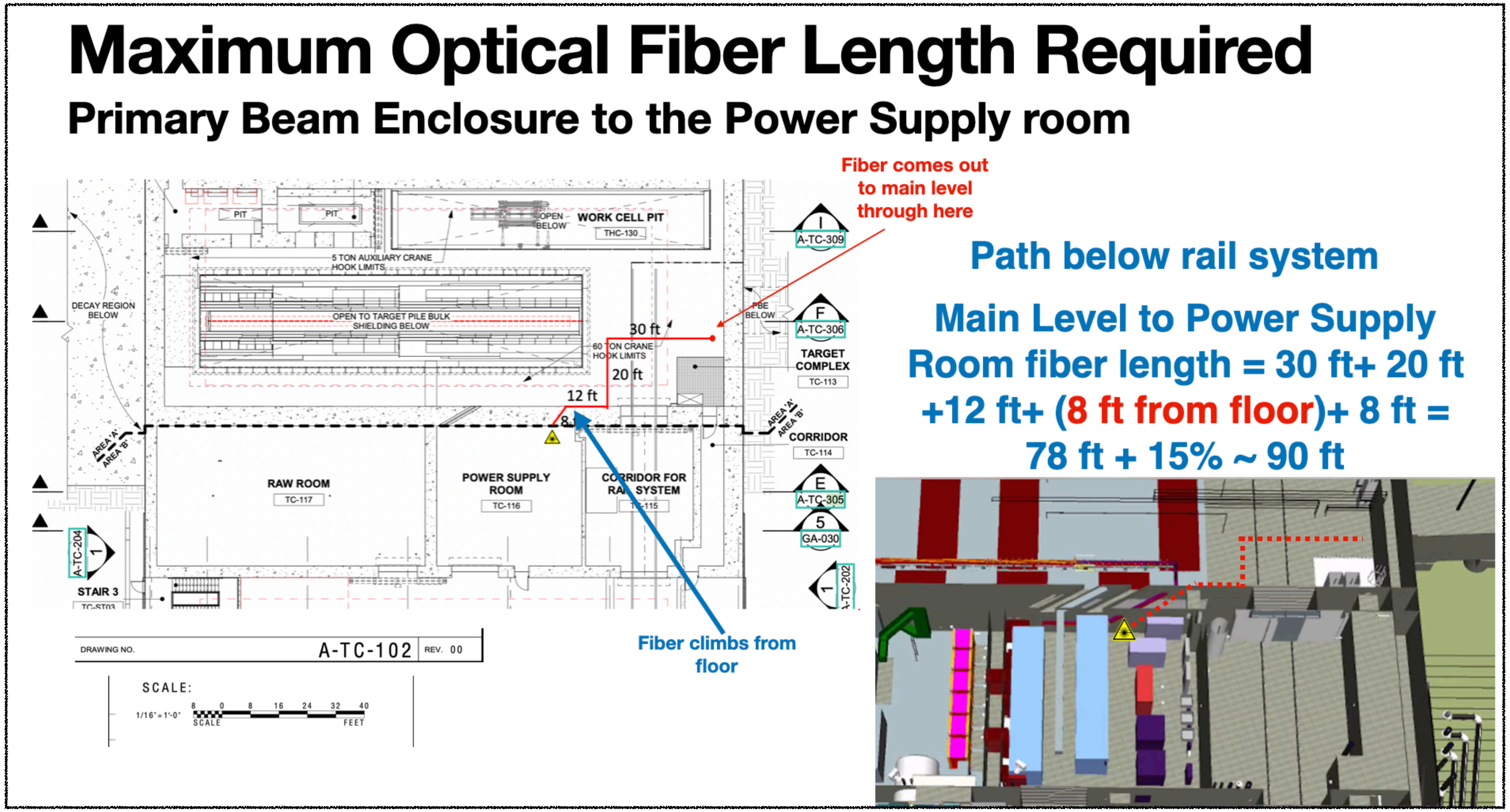


Preparation for Prototype Test

- **Prototype test likely next summer**

- **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 temperature of temperature
  9. Test rate of gas leakage through HLS pot

- **Location to be determined** - EDFA has a laser source which is class 3B, requires putting system in an enclosed space, without windows and interlocked

- **Requirement document in place**

Preparation for Prototype Test

- **Measurement accuracy depends on:**
  - frequency resolution of FFT spectrum (depends on no. of samples gathered during one laser scan)
  - sampling rate of interferometric signal
  - proper determination of center frequency

- **Performed preliminary study**
  - to decide what sampling frequency needed
  - how higher frequencies impact sampling frequency

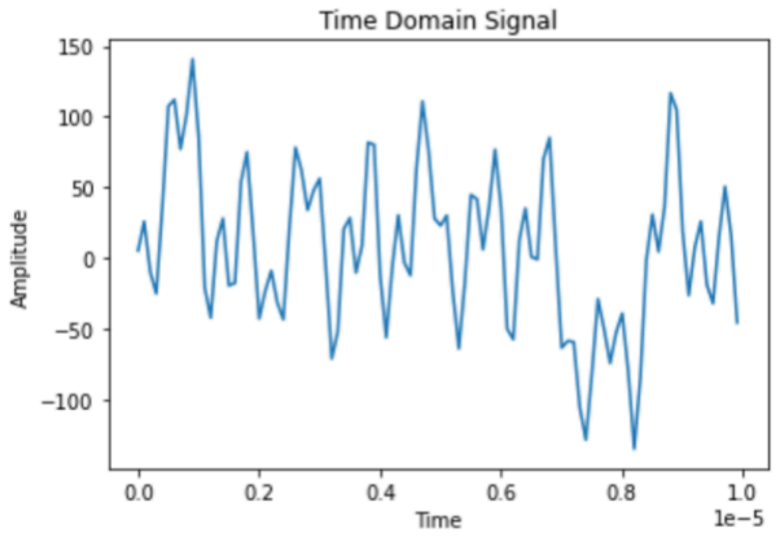
- Calculated Beat Frequencies for long fibers from Horn A, B, C and some smaller fiber lengths

0.05	1527	1559	1	1344.20289	0.016	84012.6809	0.084012681	B/w ferrule tip and water surface
0.1	1527	1559	1.45	3898.18839	0.016	243636.775	0.243636775	
0.15	1527	1559	1.45	5847.28259	0.016	365455.162	0.365455162	
0.2	1527	1559	1.45	7796.37679	0.016	487273.549	0.487273549	
0.25	1527	1559	1.45	9745.47098	0.016	609091.936	0.609091936	
36	1527	1559	1.45	1403347.82	0.016	87709238.8	87.70923883	Horn C
12	1527	1559	1.45	467782.607	0.016	29236412.9	29.23641294	Horn B
6	1527	1559	1.45	233891.304	0.016	14618206.5	14.61820647	Horn A
24	1527	1559	1.45	935565.214	0.016	58472825.9	58.47282589	
1	1527	1559	1.45	38981.8839	0.016	2436367.75	2.436367745	
(meter)	(nm)	(nm)		beats (N)	ms	N/s	MHz(beat rate)	Locations

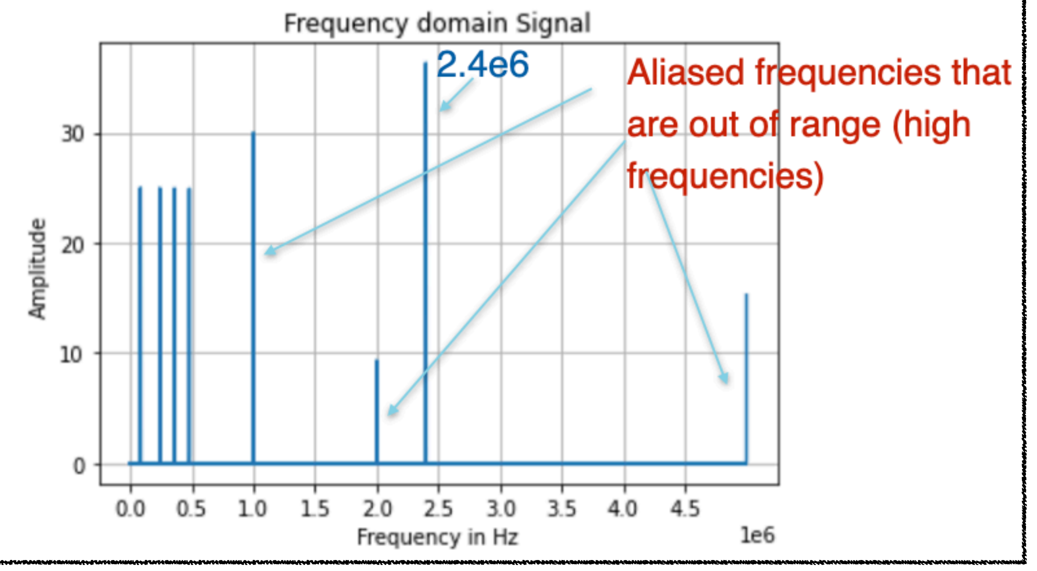
10 MHz Sampling Frequency

- **Nyquist-Shannon Sampling theorem, we can only analyze frequency components up to half of the sampling rate**

```
plt.plot (time [0:100], time_data [0:100])
plt.title ('Time Domain Signal')
plt.xlabel ('Time')
plt.ylabel ('Amplitude')
plt.show ()
```



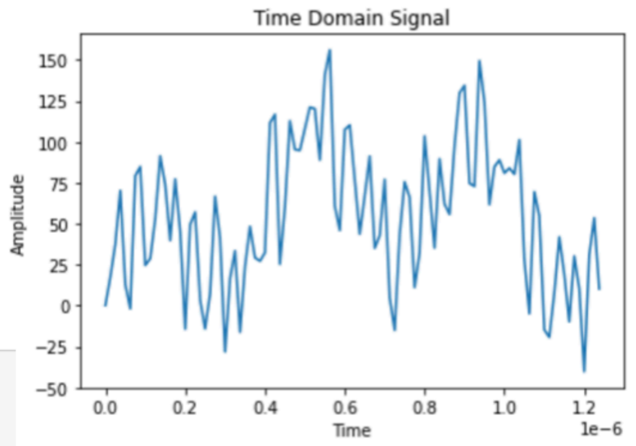

```
In [48]: frequency = np.linspace (0.0, 5000000, int (N/2))

freq_data = fft(time_data)
y = 2/N * np.abs (freq_data [0:np.int (N/2)])
fig = plt.figure()
ax = fig.gca()
ax.set_xticks(np.arange(0, 5000000, 500000))
ax.set_yticks(np.arange(0, 200, 10))
plt.plot(frequency, y)
plt.title('Frequency domain Signal')
plt.xlabel('Frequency in Hz')
plt.ylabel('Amplitude')
plt.grid()
plt.show()
```



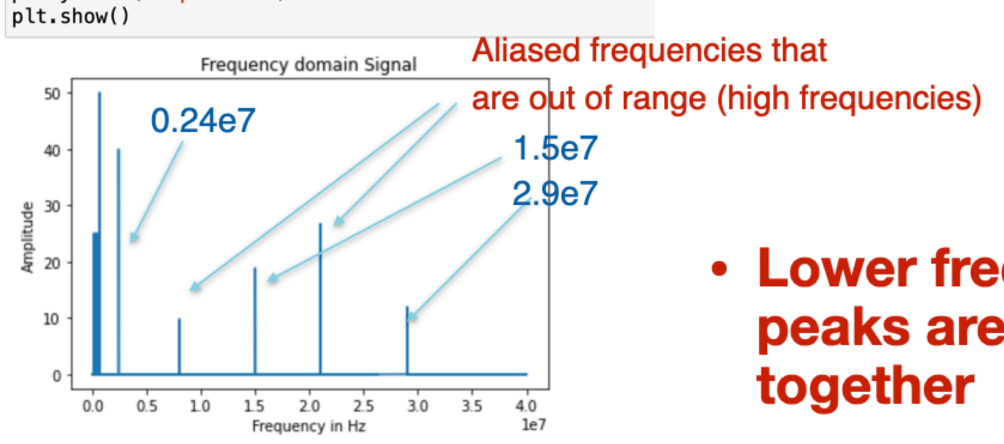
80 MHz Sampling Frequency

```
import numpy as np
import matplotlib.pyplot as plt
from scipy import pi
from scipy.fftpack import fft
sample_rate = 80000000 #sample rate 80MHz, scan duration = 16 ms
N = (2 - 0) * sample_rate #collecting 2sec worth data
time = np.linspace(0, 2, N)
freq1 = 84000 #5cm
magnitude1 = 25
freq2 = 240000 #10cm
magnitude2 = 25
freq3 = 360000 #15cm
magnitude3 = 25
freq4 = 480000 #20cm
magnitude4 = 25
freq5 = 88000000 #36m, HornC
magnitude5 = 10
freq6 = 29000000 #12m, HornB
magnitude6 = 15
freq7 = 15000000 #6m, HornA
magnitude7 = 20
freq8 = 59000000 #24m
magnitude8 = 30
freq9 = 2400000 #1m
magnitude9 = 40


waveform1 = magnitude1 * np.sin (2 * pi * freq1 * time)
waveform2 = magnitude2 * np.sin (2 * pi * freq2 * time)
waveform3 = magnitude3 * np.sin (2 * pi * freq3 * time)
waveform4 = magnitude4 * np.sin (2 * pi * freq4 * time)
waveform5 = magnitude5 * np.sin (2 * pi * freq5 * time)
waveform6 = magnitude6 * np.sin (2 * pi * freq6 * time)
waveform7 = magnitude7 * np.sin (2 * pi * freq7 * time)
waveform8 = magnitude8 * np.sin (2 * pi * freq8 * time)
waveform9 = magnitude9 * np.sin (2 * pi * freq9 * time)

noise = np.random.normal (0, 3, N)
time_data = waveform1 + waveform2 + waveform3 + waveform4 + waveform5 + waveform6 + waveform7 + waveform8 + waveform9 + noise
```

- Sampling rate = 80 MHz
- Collecting data for 2 sec




```
In [49]: frequency = np.linspace (0.0, 40000000, int (N/2))

freq_data = fft(time_data)
y = 2/N * np.abs (freq_data [0:np.int (N/2)])
plt.plot(frequency, y)
plt.title('Frequency domain Signal')
plt.xlabel('Frequency in Hz')
plt.ylabel('Amplitude')
plt.show()
```



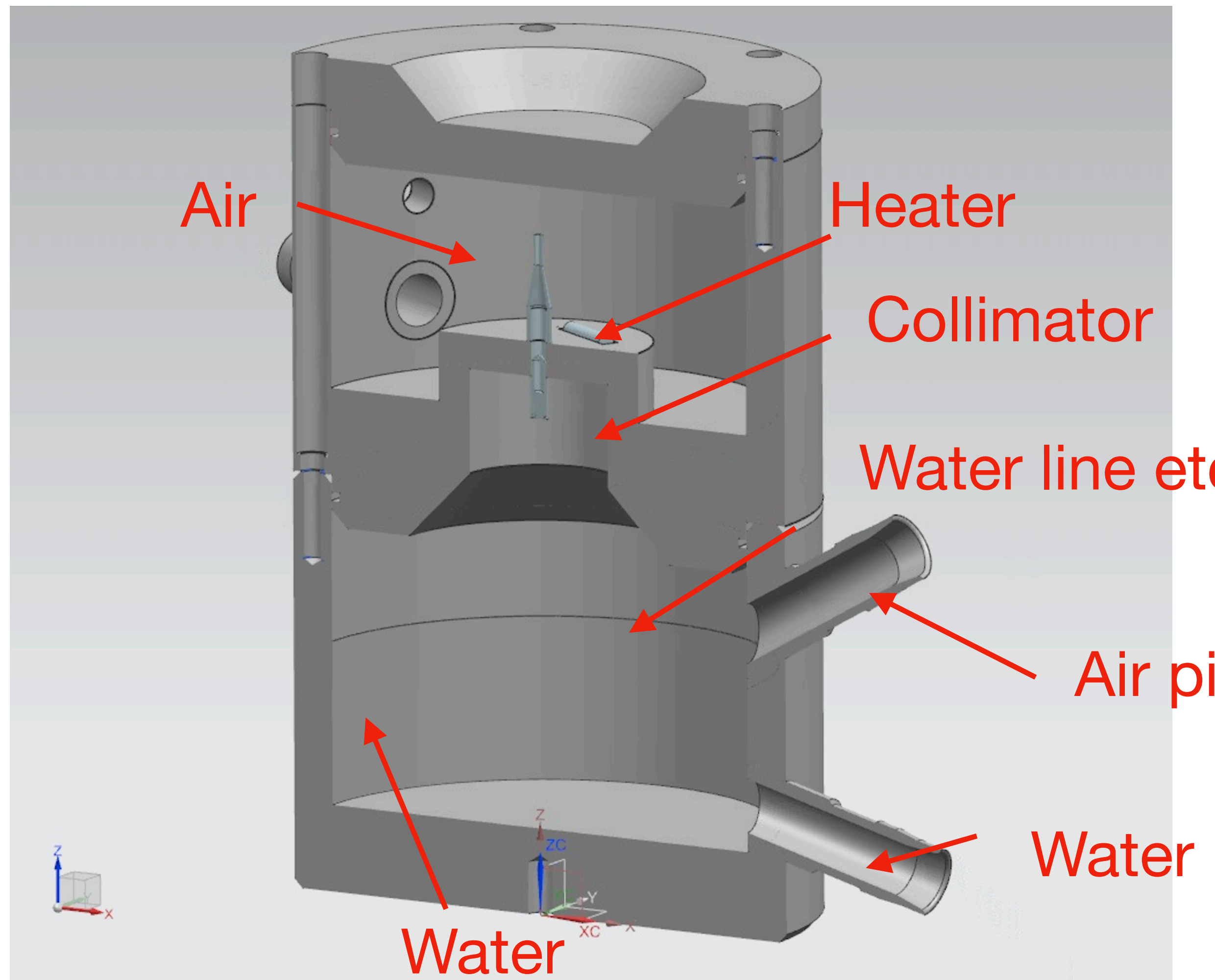
- **Lower frequency peaks are too close together**

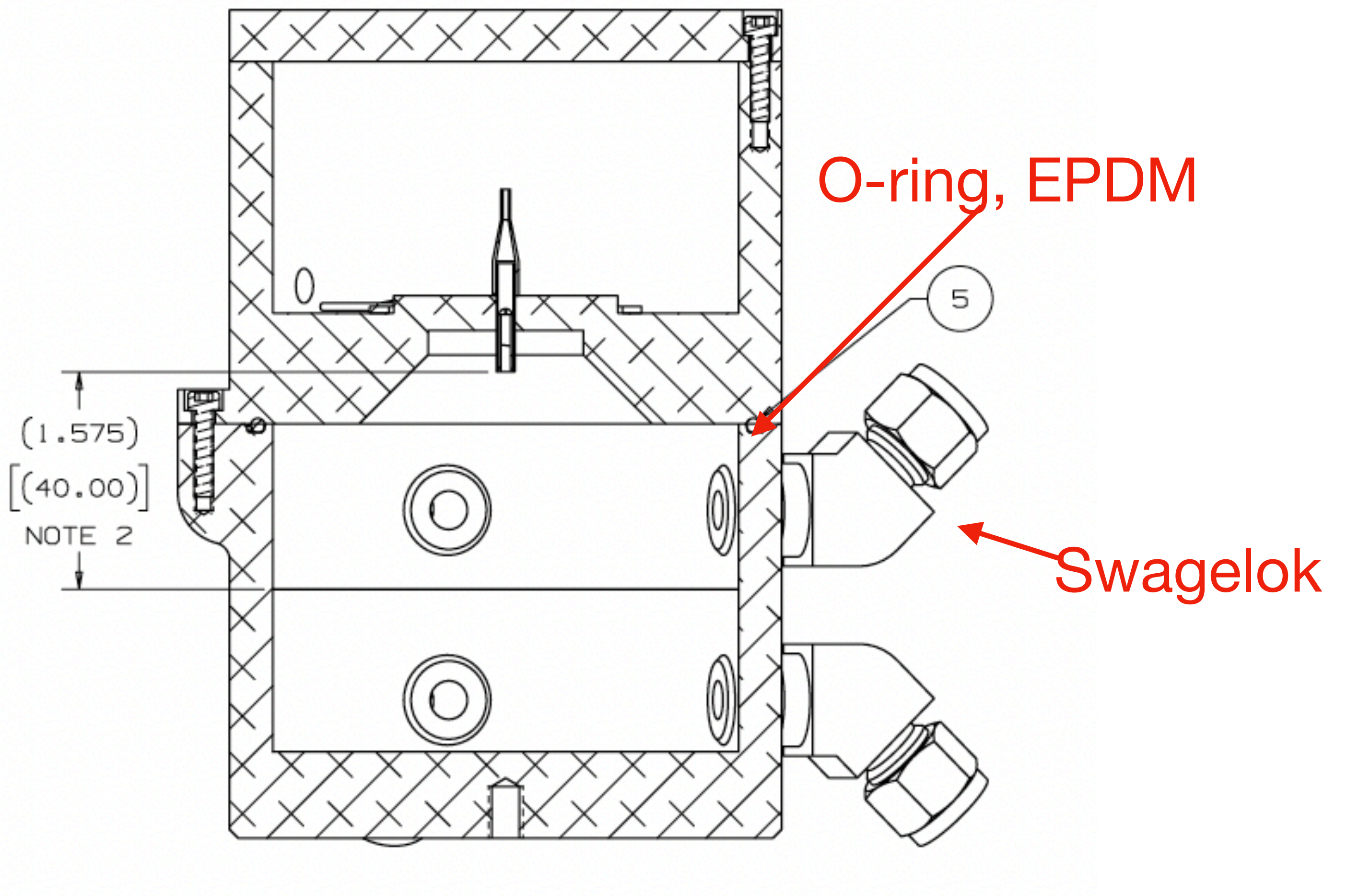
Backup

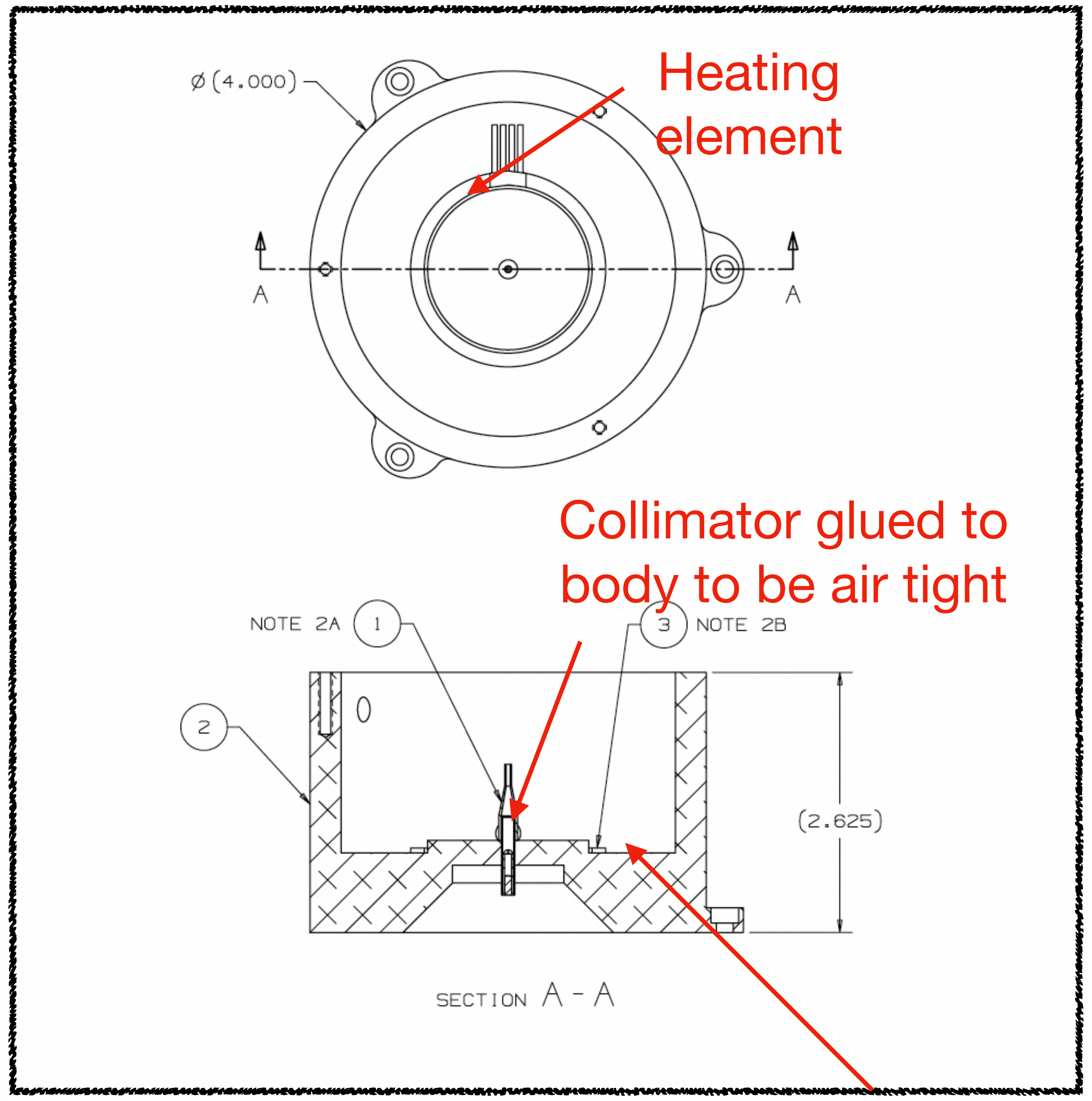
Conceptual Design of Pots

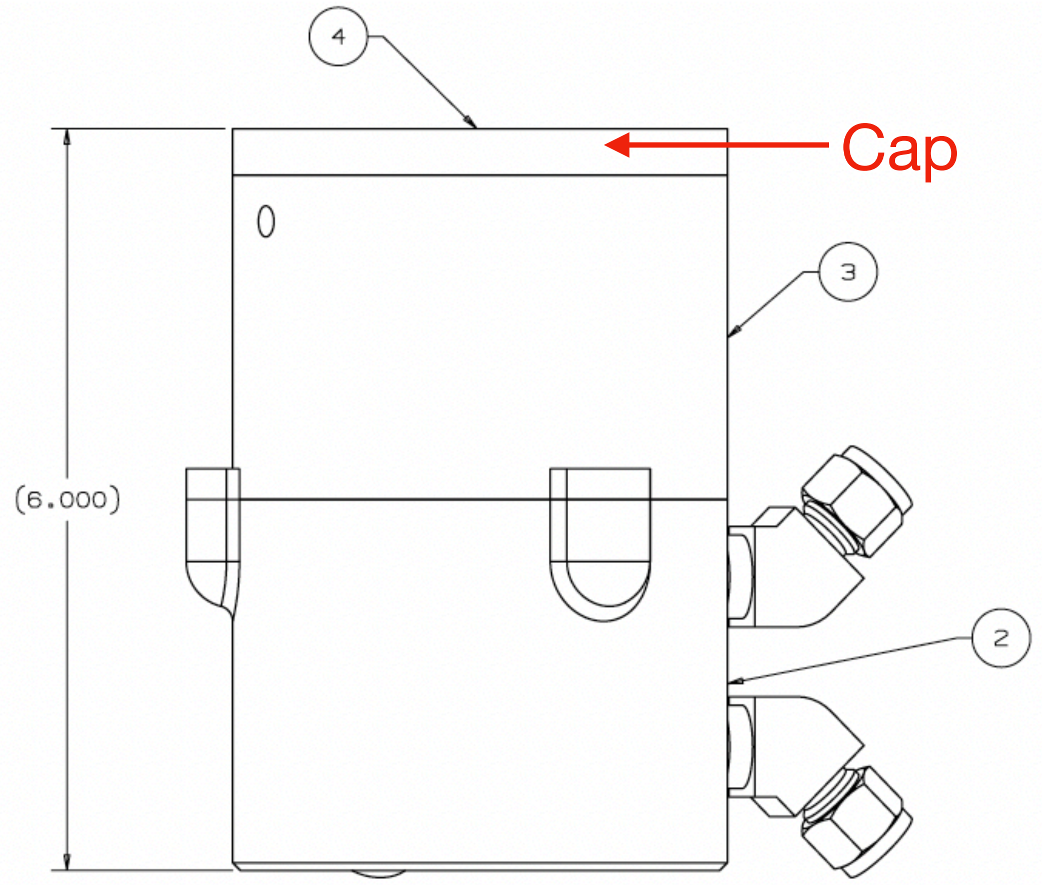
Conceptual design of “pot” by Matt Sawtell : 26OCT21 Latest Drawing Package for LBNF HLS 2 and 4 Nozzle Pots

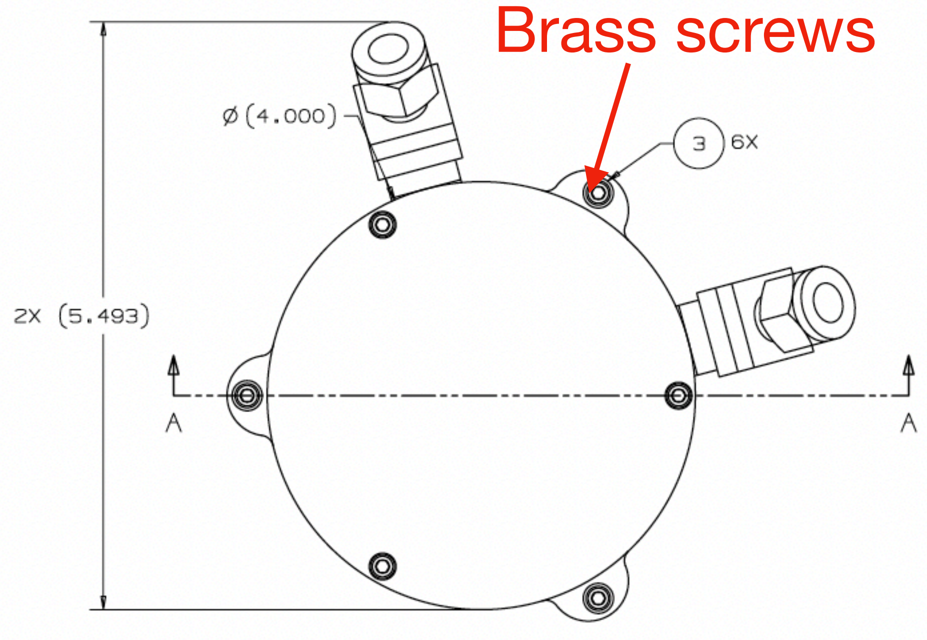
- Quotes from Xometry for Al pot ~ 2200 for 1 assembly (bottom + top cavities + cap)
- Quotes from Protolab for SS304L pot ~40k for 45 of 1 assembly (bottom + top cavities + cap)











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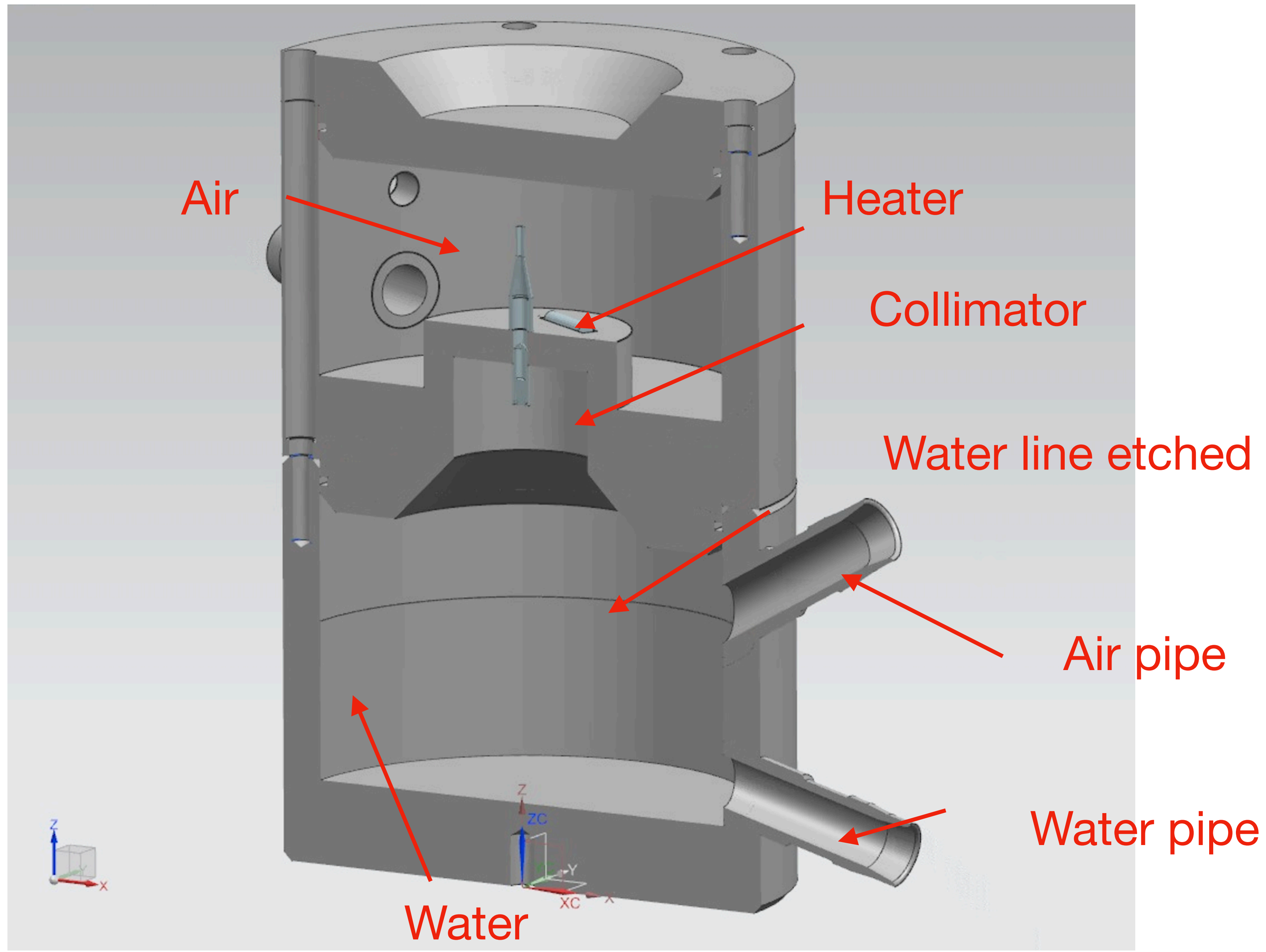


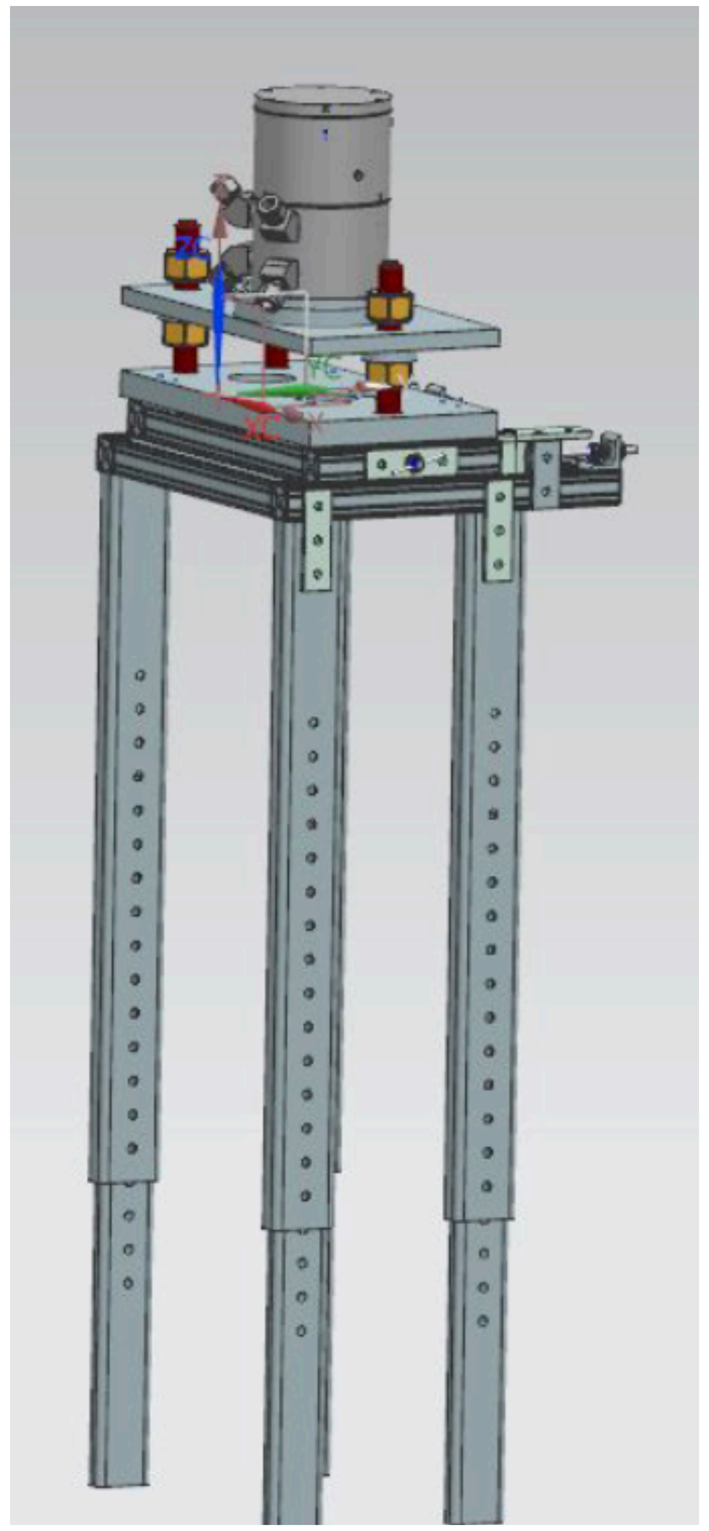
- **Issues addressed:**
  - Screws to connect top and bottom pots with cap
  - Wall thickness
  - Units sitting on top of horn inside N2 vessel, N2 vessel will be run at 2-3 psig over pressure
  - Significant differential pressure b/w unit inside vessel and outside vessel
  - Worry about O-ring will leak over time - EPDM seal

Conceptual Design of Mechanical Stands

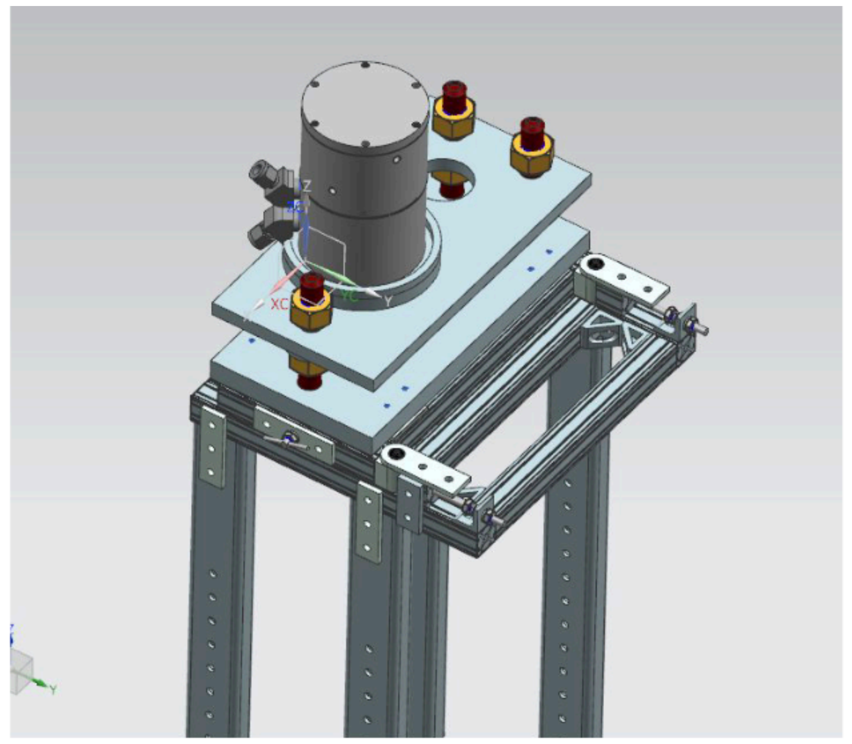
Conceptual design of stand by Hannah Magoon

- **Technical requirements addressed:**
  - Size and Position
  - Strength and stability
  - Adjustability
  - Vibration
  - Installation

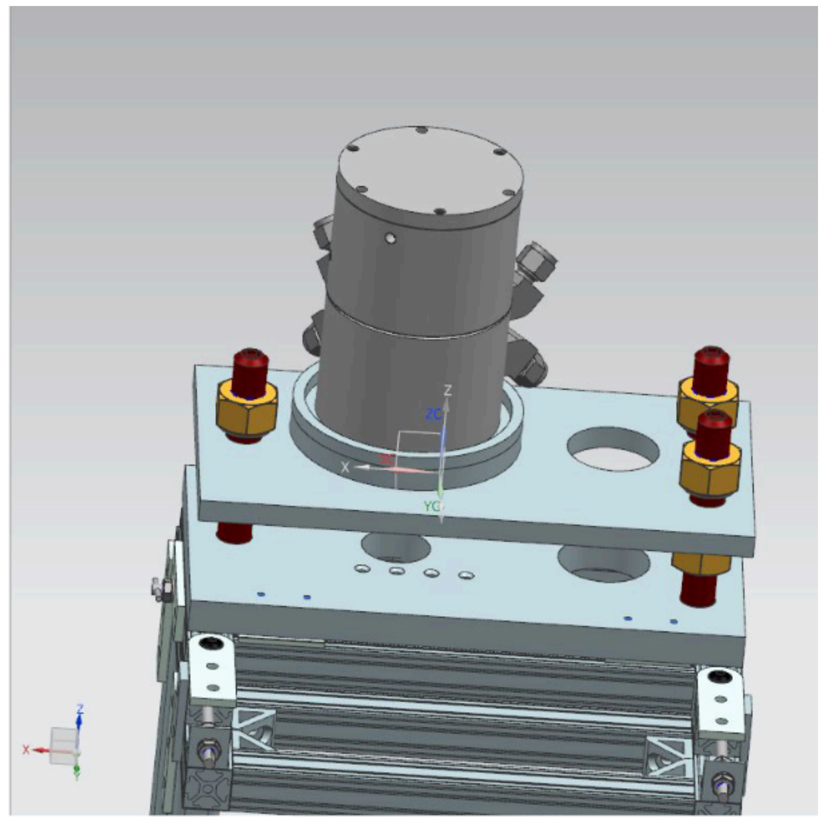
- **To-do:**
  - Horizontal support frame for legs
  - Tipping analysis
  - Interface with horn
  - Cable routing
  - Connection to HLS pot



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



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



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