Fine-Grained Tracking Detectors for Neutrino Physics: Part I

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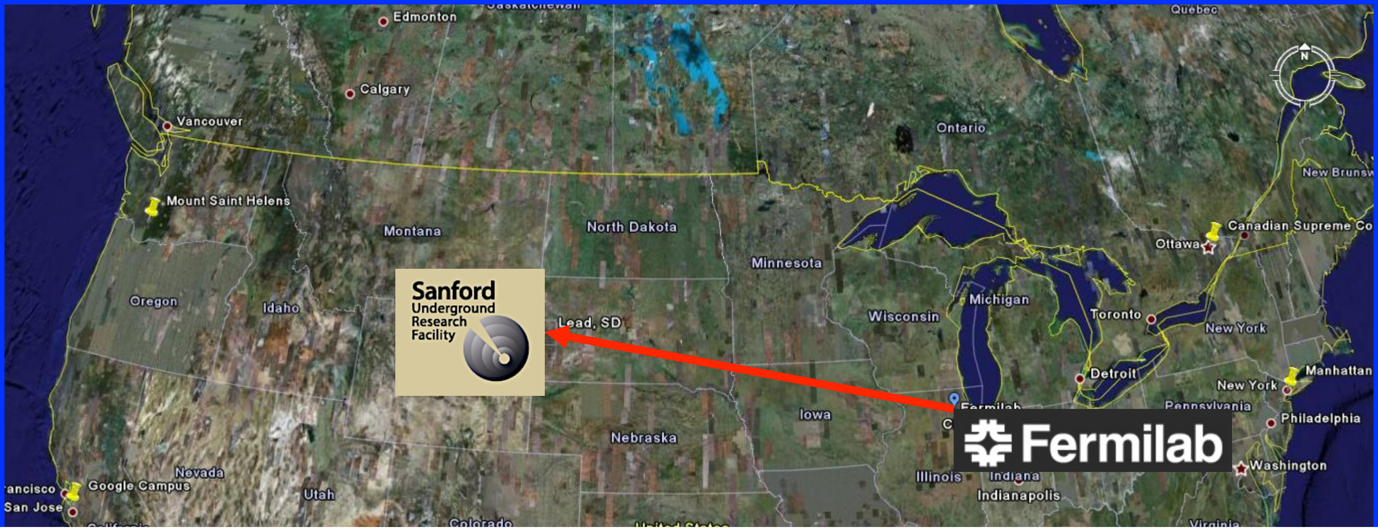
Outline

- What are we trying to measure?
  - Characteristics of typical neutrino beams
  - Event signatures
- What are the characteristics of a fine-grained tracking detector?
  - Monolithic vs. tracking detectors
  - Characteristics of neutrino targets
- Examples of fine-grained tracking detectors
- Basic Principles of tracking elements
  - Scintillator/Fiber Bars
  - Straw Tubes
  - Resistive Plate Chambers
- Gross Design Features
  - Tracking detector assembly
  - Magnet Issues
  - Nuclear targets
- Advantages/Disadvantages
- Conclusions

Long-Baseline Neutrino Oscillation Experiments

- The study of oscillation physics provides the opportunity to study interaction physics with the near detector

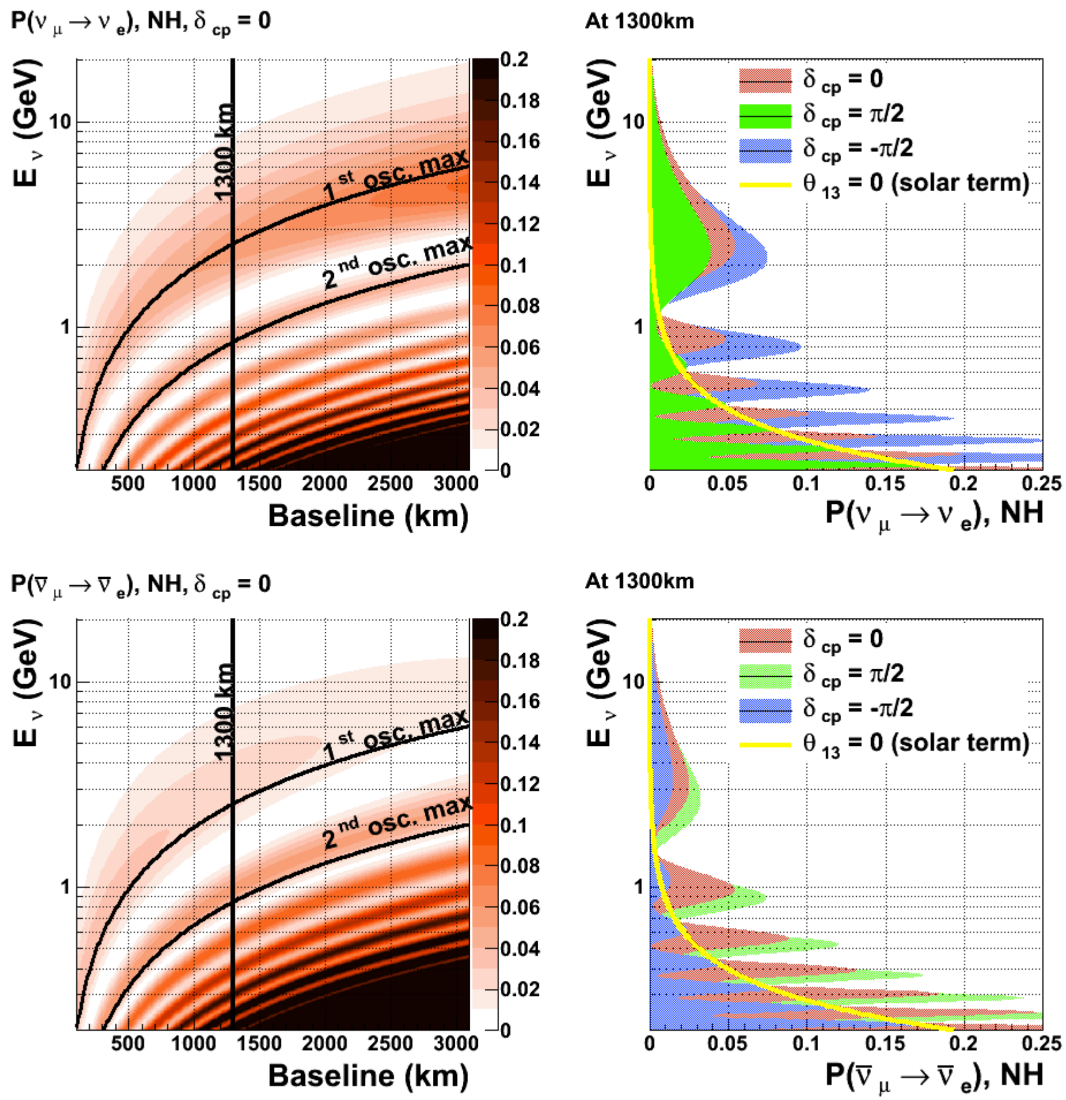
The Long-Baseline Neutrino Experiment



- LBNE consists of
  - an intense neutrino beam at Fermilab
  - near detector systems at Fermilab
  - a 34 kt liquid argon time-projection chamber (TPC) at Sanford Laboratory at 4850 foot depth – 1300 km from Fermilab
- When constructed, LBNE will have the longest manmade baseline of any neutrino experiment

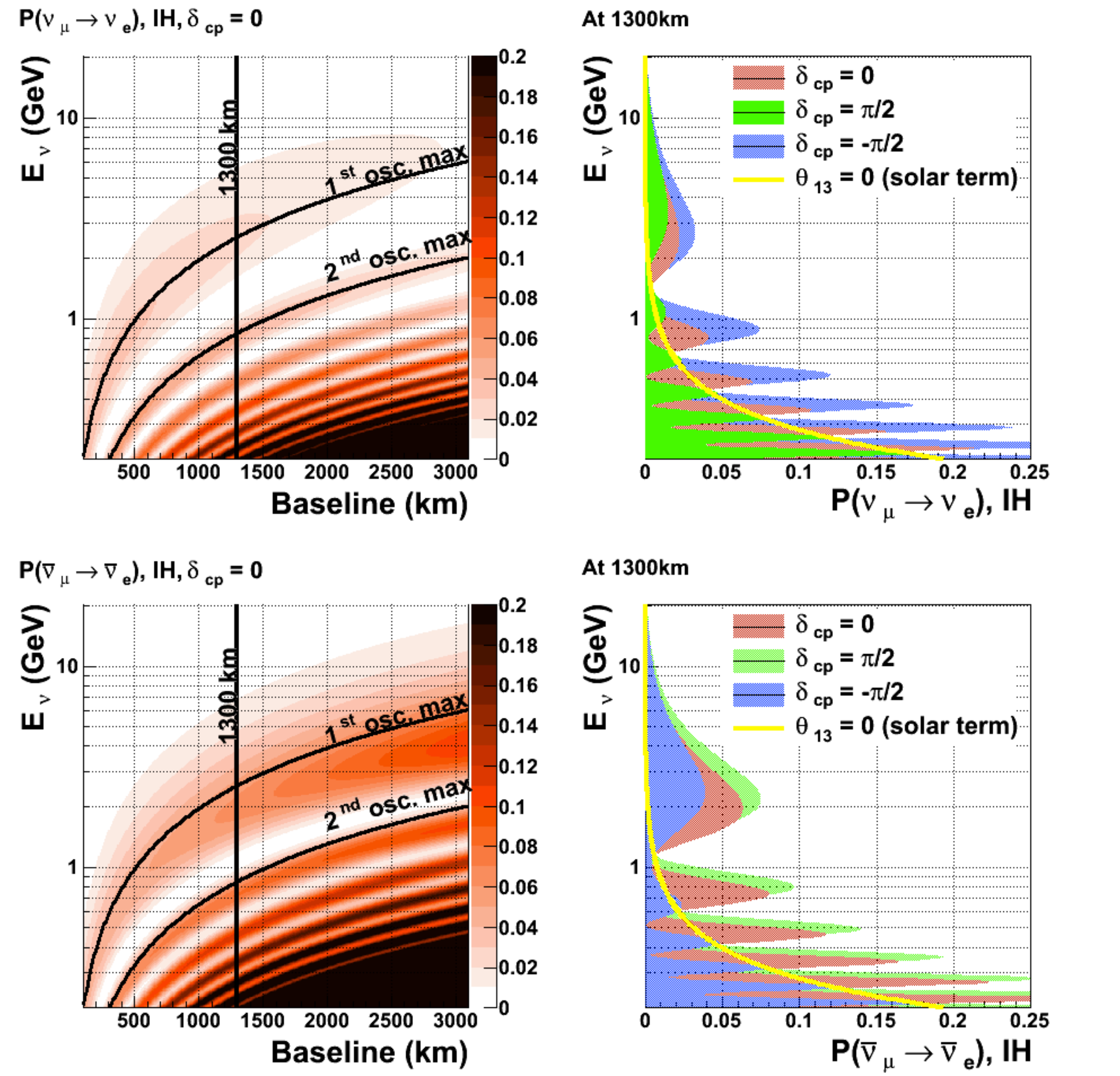
Appearance Oscillograms (Normal Hierarchy)

- Left plots: Neutrino oscillations vs energy and baseline for neutrinos (top) and antineutrinos (bottom) for $\delta_{CP} = 0$
- Right: Neutrino oscillations as a function of neutrino energy for different values of δ_{CP} for neutrinos (top) and antineutrinos (bottom) – solar term shown in yellow
- All plots assume Normal Hierarchy



Appearance Oscillograms (Inverted Hierarchy)

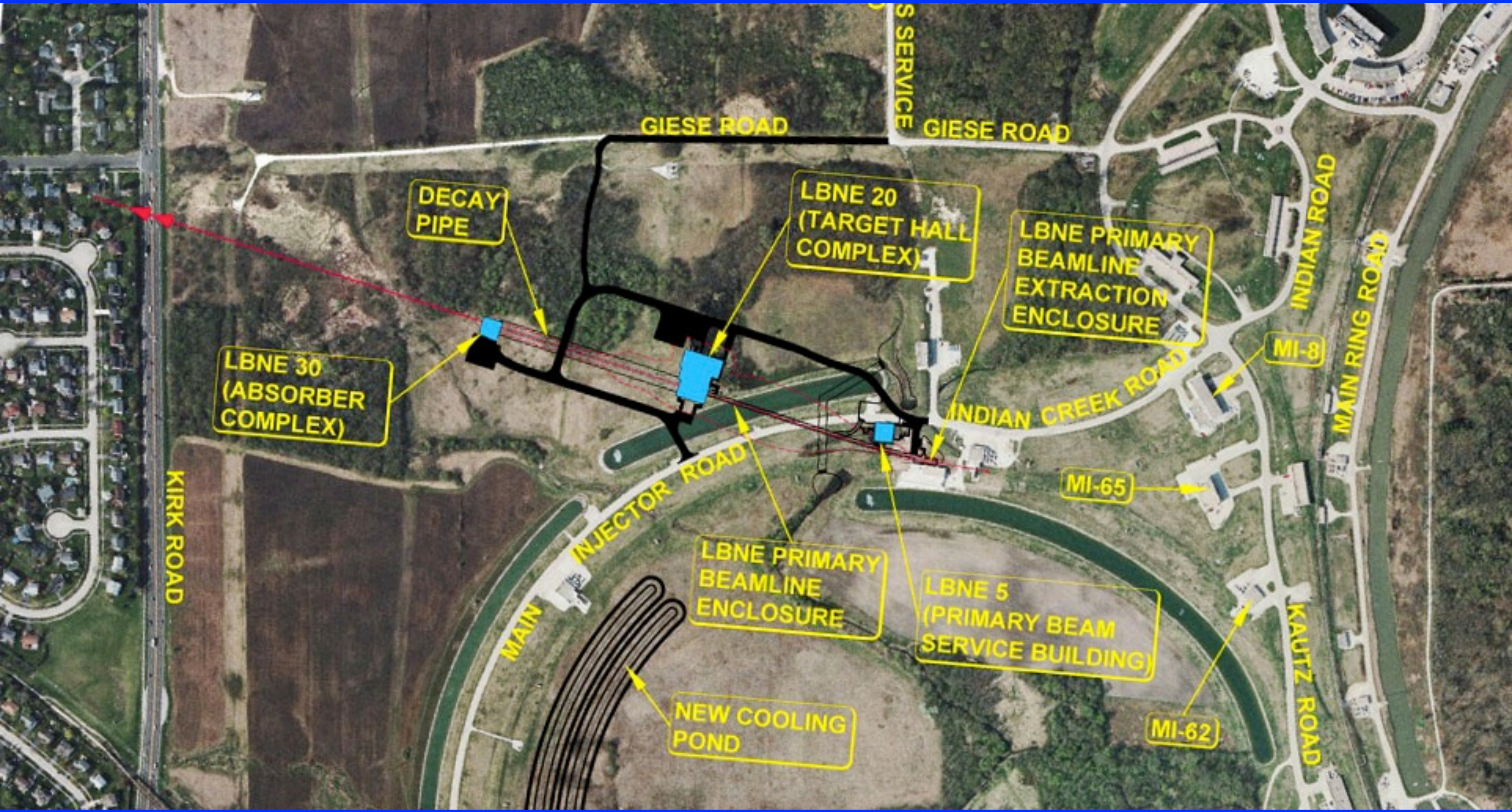
- Left plots: Neutrino oscillations vs energy and baseline for neutrinos (top) and antineutrinos (bottom) for $\delta_{CP} = 0$
- Right: Neutrino oscillations as a function of neutrino energy for different values of δ_{CP} for neutrinos (top) and antineutrinos (bottom) – solar term shown in yellow
- All plots assume Inverted Hierarchy



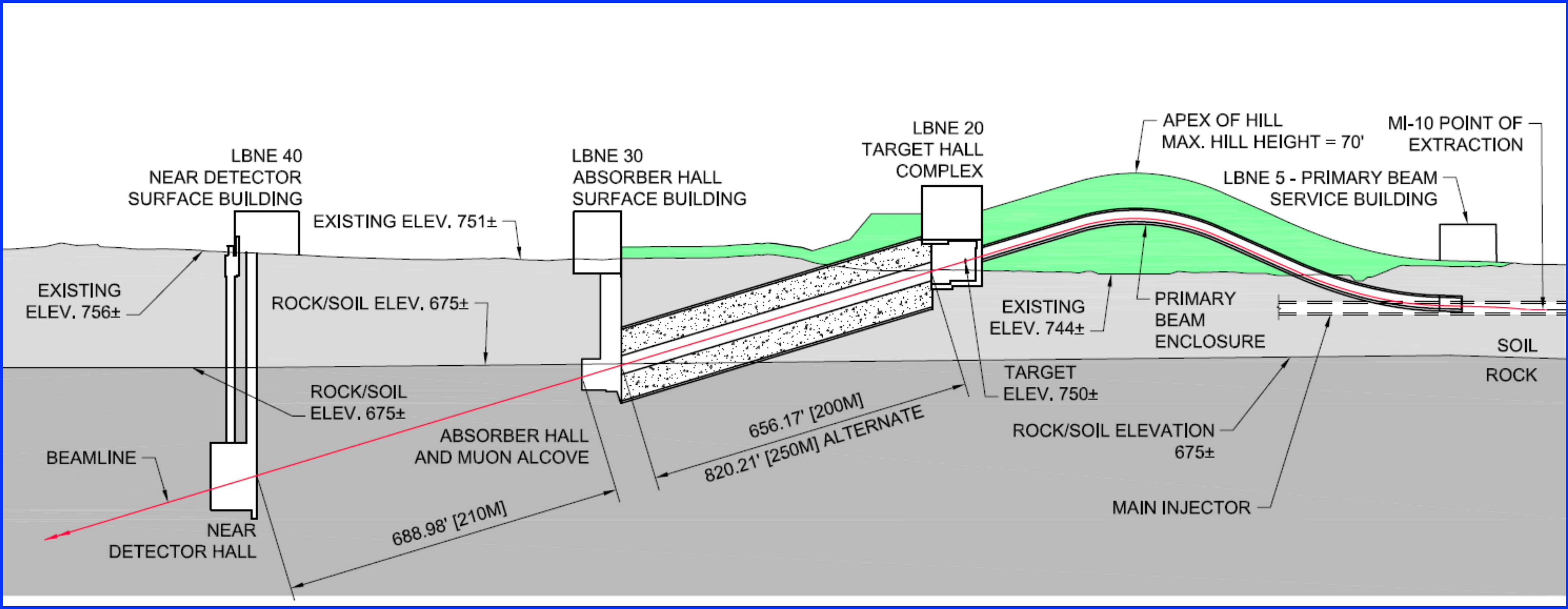
Long-Baseline Neutrino Oscillation Experiments

- The study of oscillation physics *requires* the study of interaction physics with the near detector

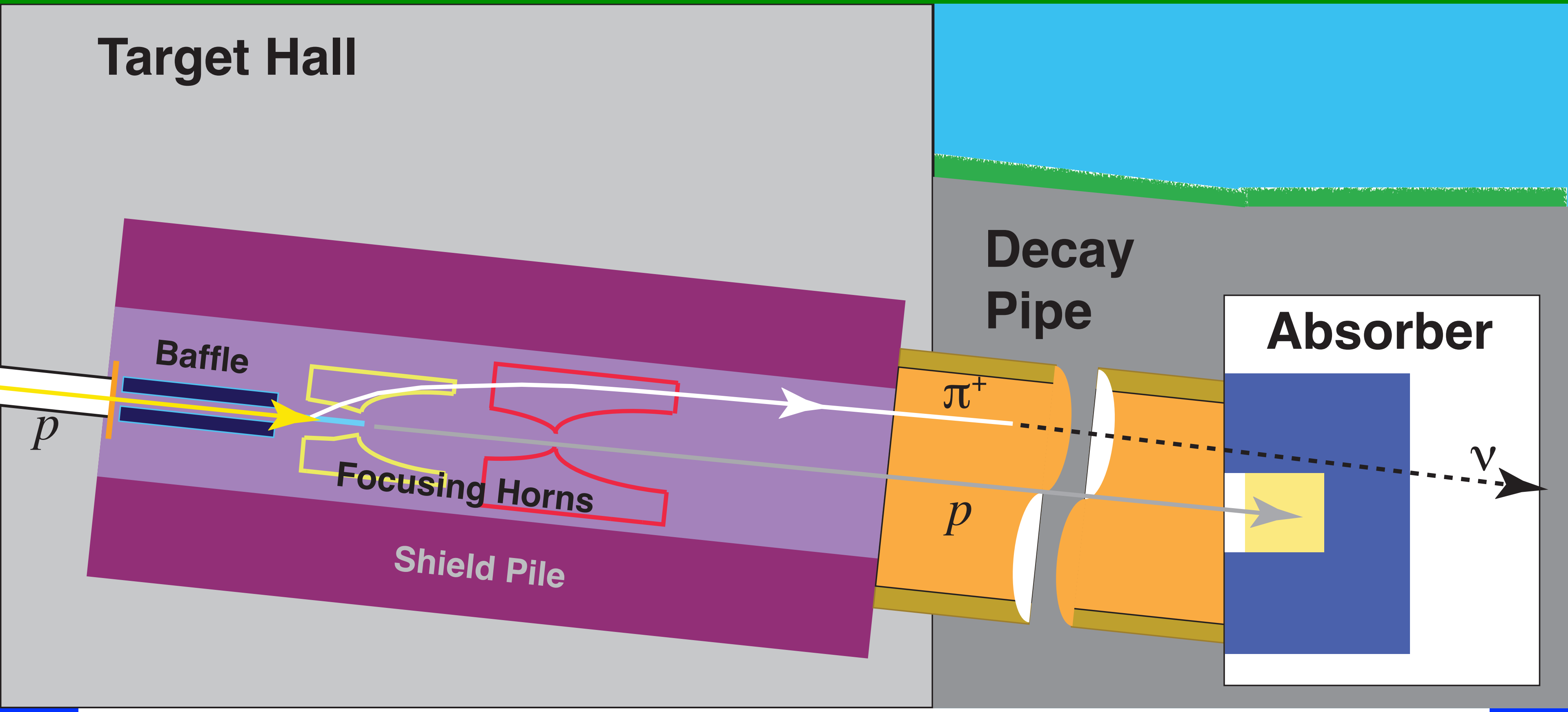
Layout on the Fermilab site



Cross-section of LBNE Near Site

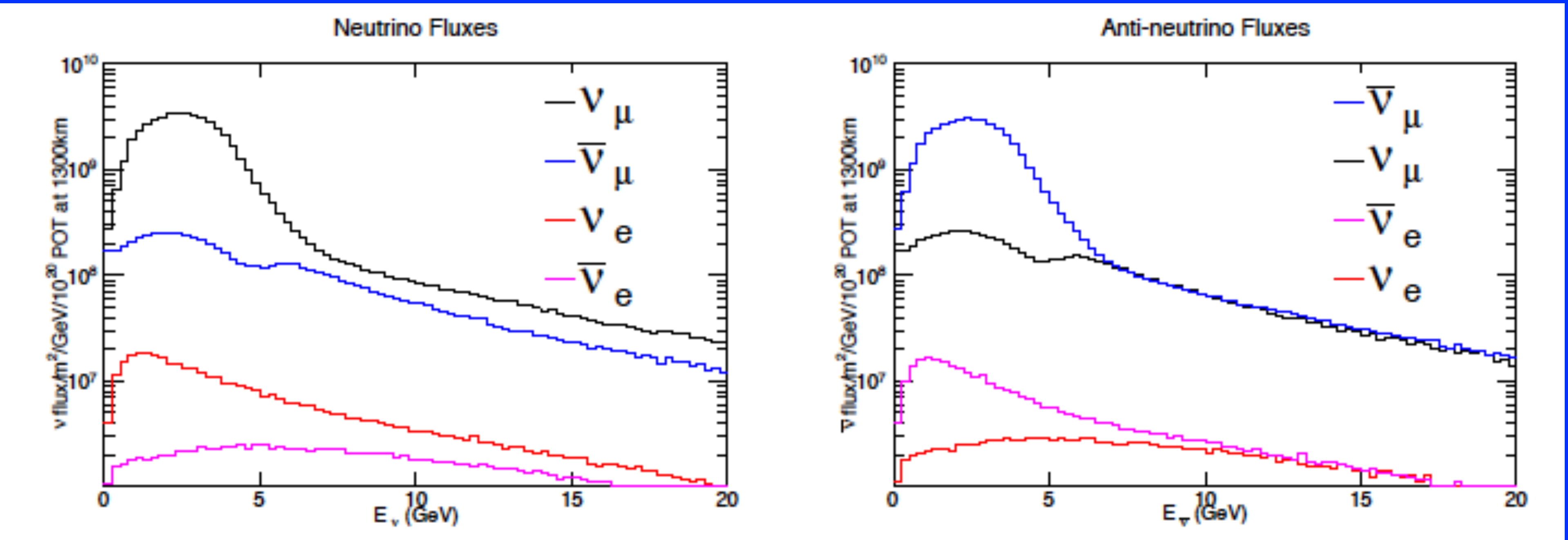


Layout of LBNE: Neutrino Beam



- $\pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

Characteristics of the Neutrino Beam



- Resultant Neutrino Beam (LBNE case)
- Neutrinos from few hundred MeV to 10's of GeV
- Predominantly muon (anti)neutrinos, but enough electron (anti)neutrinos to carry out studies in high-flux environments – it's a good thing, since LBL experiments are searching for electron neutrino appearance!

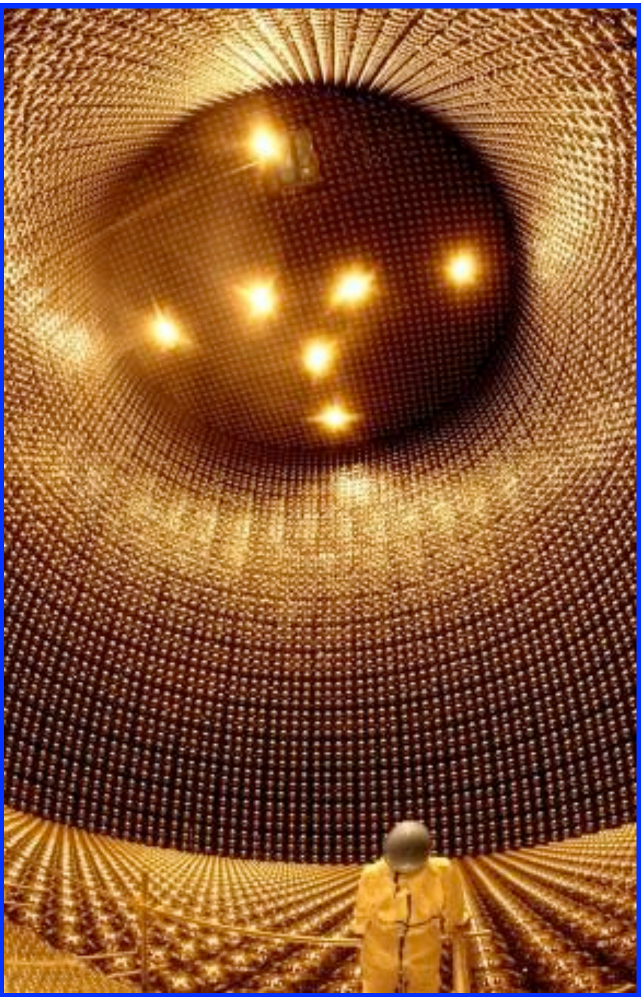
Event signatures of these beams

Signature label	Charged Current	Neutral Current
Quasi-elastic	Charged lepton + proton or neutron	Neutrino + proton or neutron
Resonance	Charged lepton + proton or neutron + a few other hadrons	Neutrino + several hadrons
DIS	Charged lepton + hadronic shower	Neutrino + hadronic shower

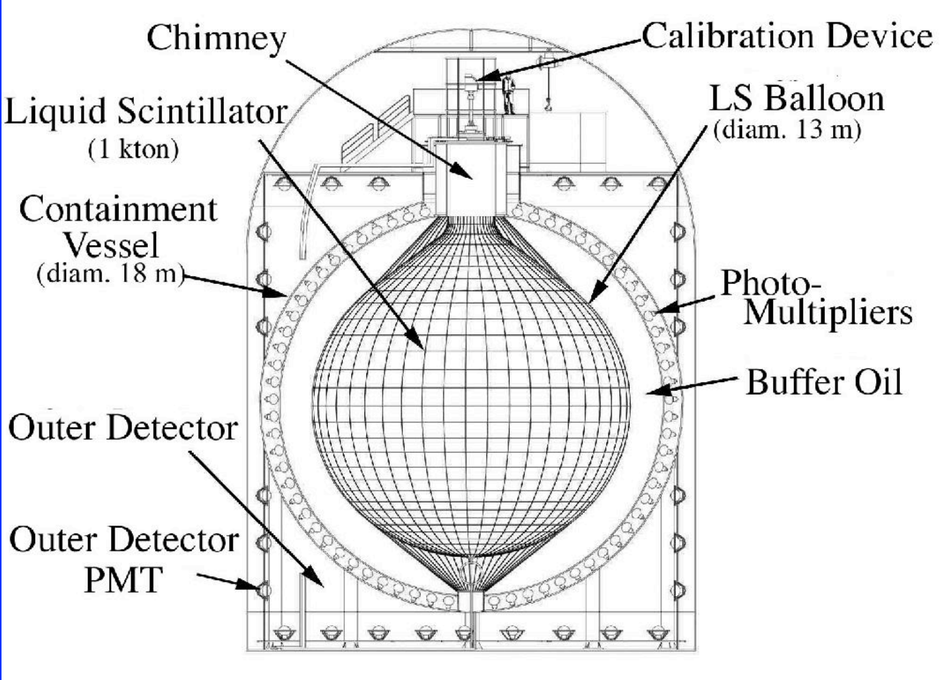
- Particle type: electron, gamma, muon, charged and neutral mesons, protons, neutrons (not usually done well
- Particle sign
- Momentum: Range of 10's MeV/c to multi-GeV
- Direction: Mostly forward-going, but some high-angle and backward-going

Tracking Detectors vs Monolithic

Super-Kamiokande: water Cherenkov

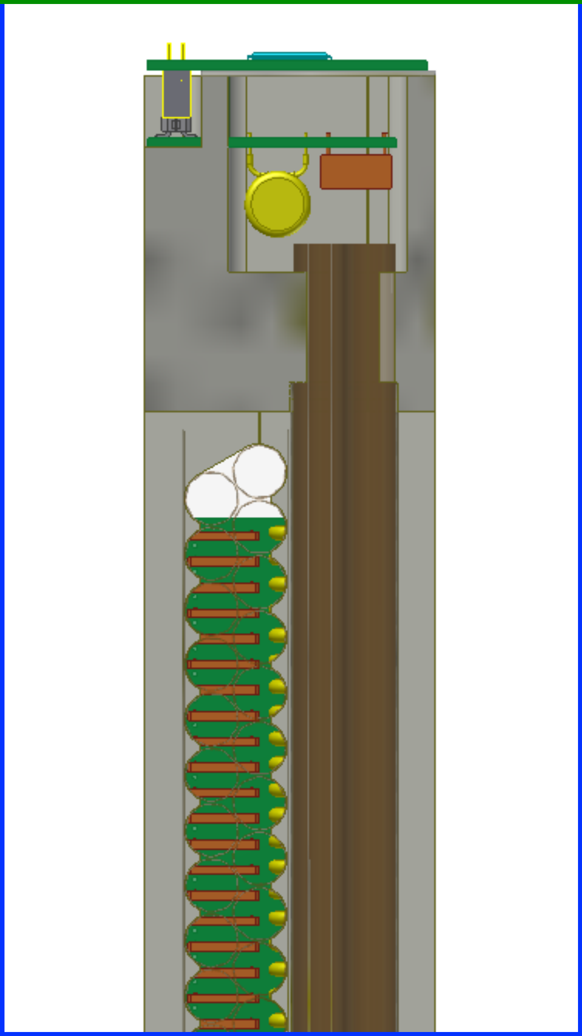


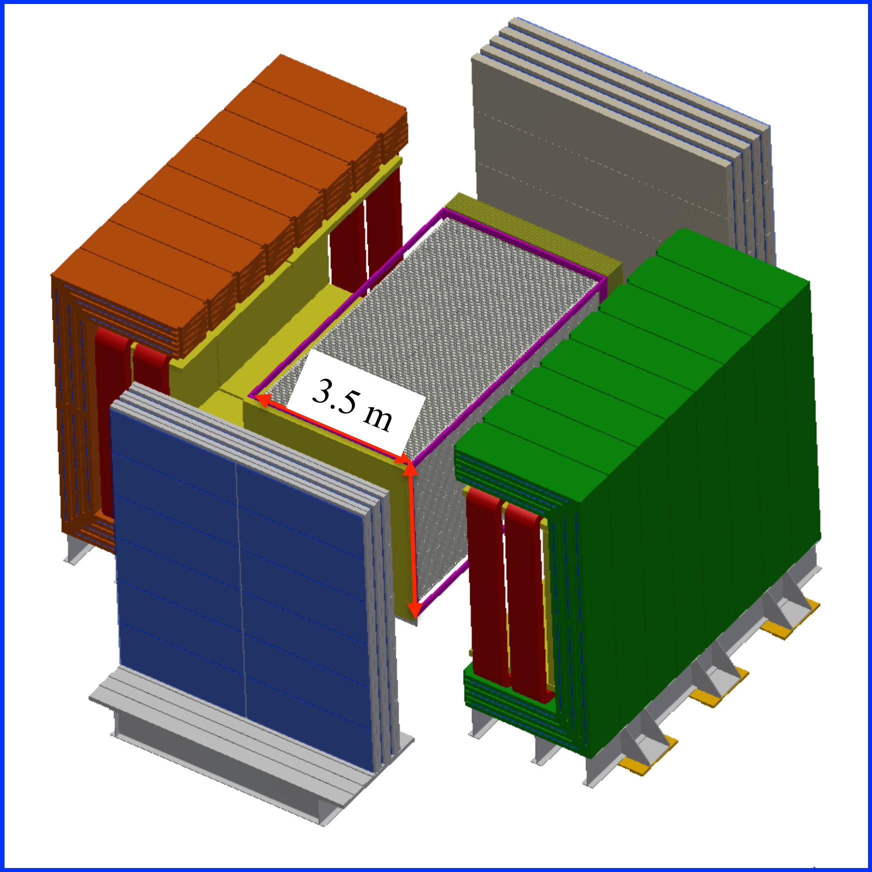
KamLAND: organic liquid scintillator



- Monolithic detectors have large uniform volume of neutrino target
- Target material is active – creates light, ionization, phonons, etc.
- Detectors positioned on the outer surface
- Good isotropic capabilities

Tracking Detectors vs Monolithic Detectors

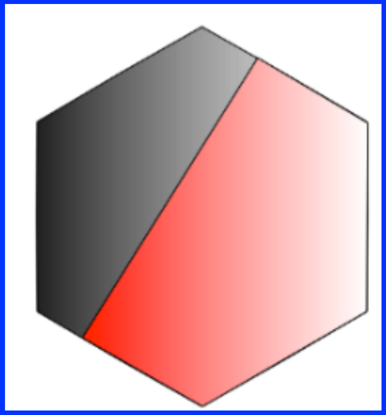


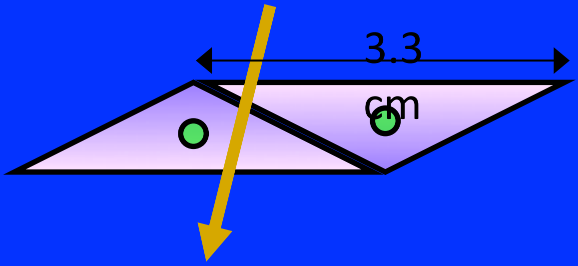


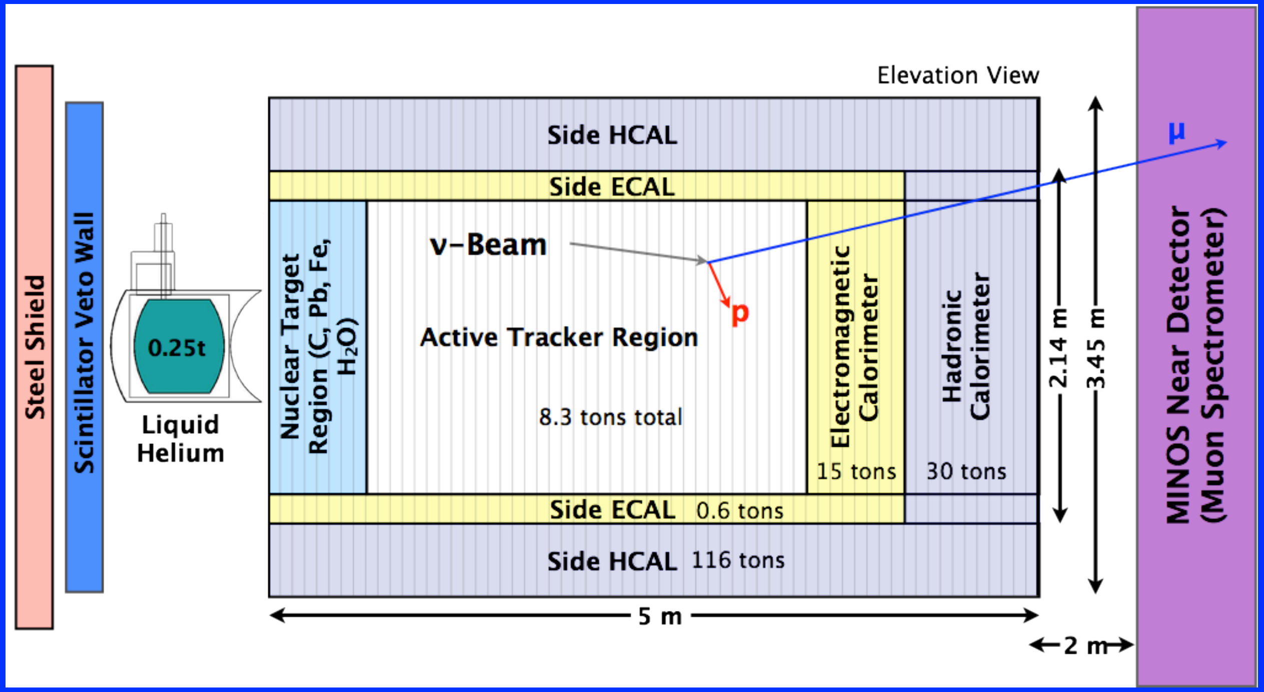
- Localization of particles by deploying many low-profile detector elements
- Detector elements throughout the volume
- Anisotropic distribution of elements
- Elements can be the target or targets can be separate from the elements

Fine-grained trackers and targets

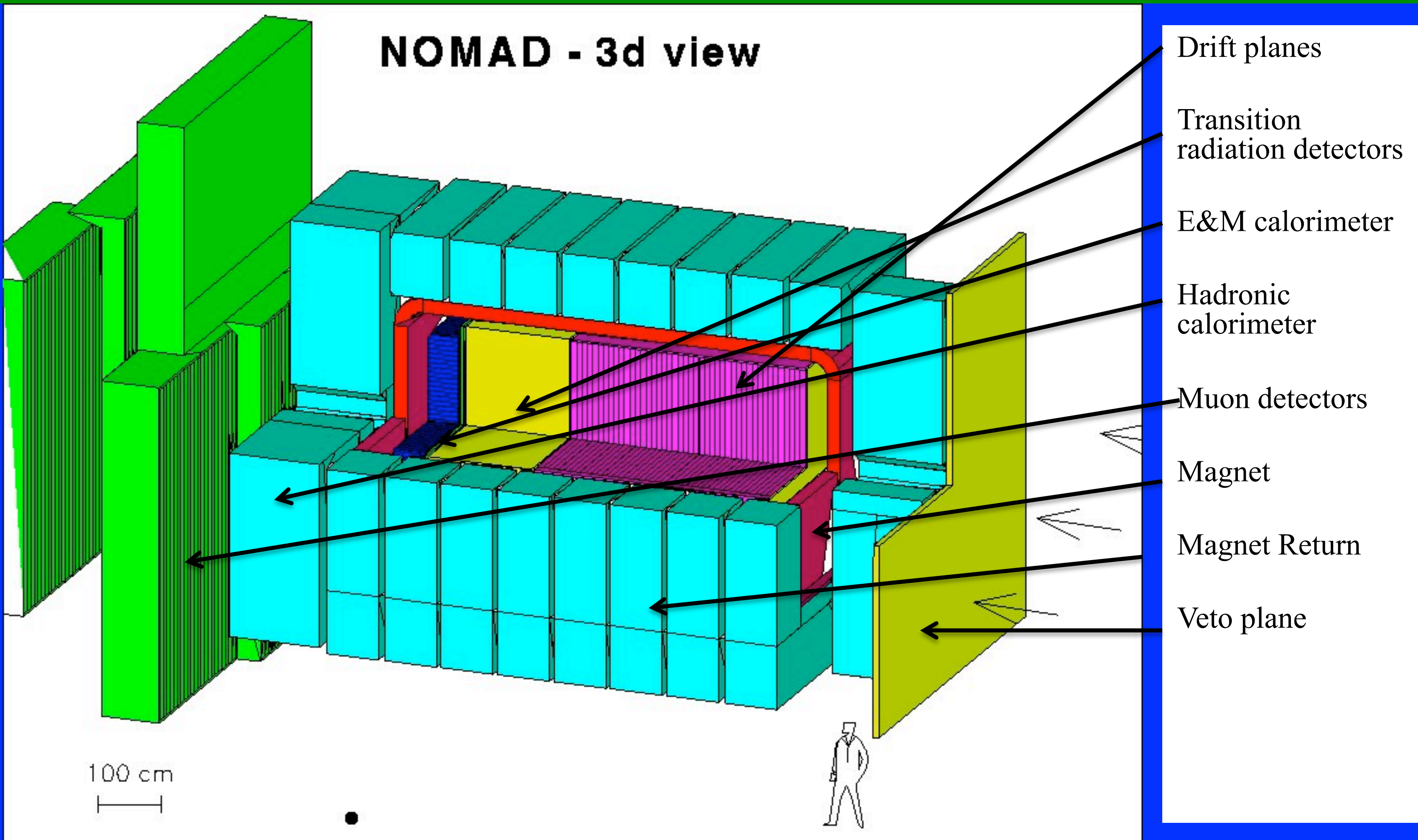
- Fine-grained trackers mean high pixelization of the detector – many detector elements
- The neutrino target can be active or passive
- Passive targets allow for the study of any nucleus
- Active targets in principle give better signal efficiency





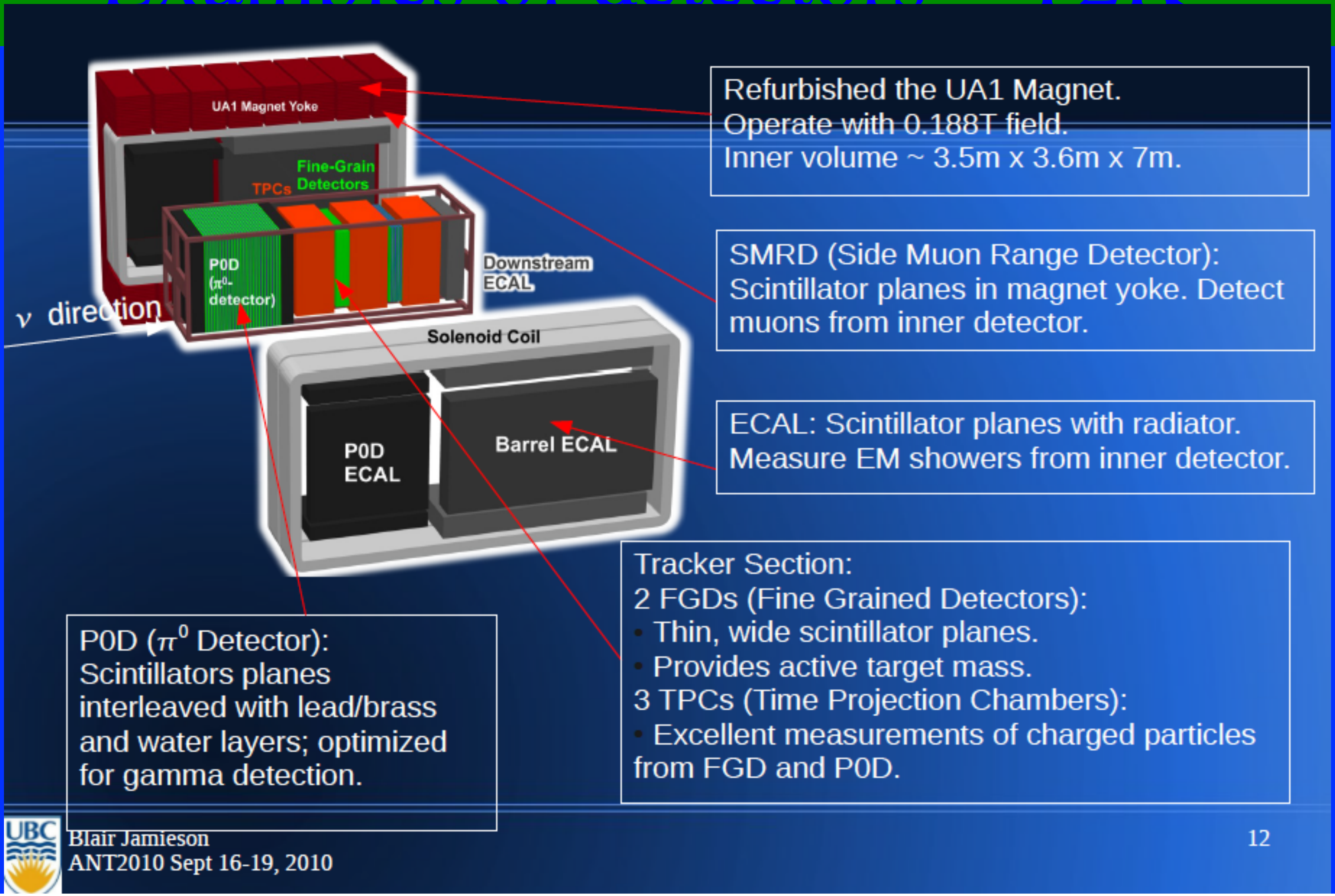


Examples of detectors - NOMAD



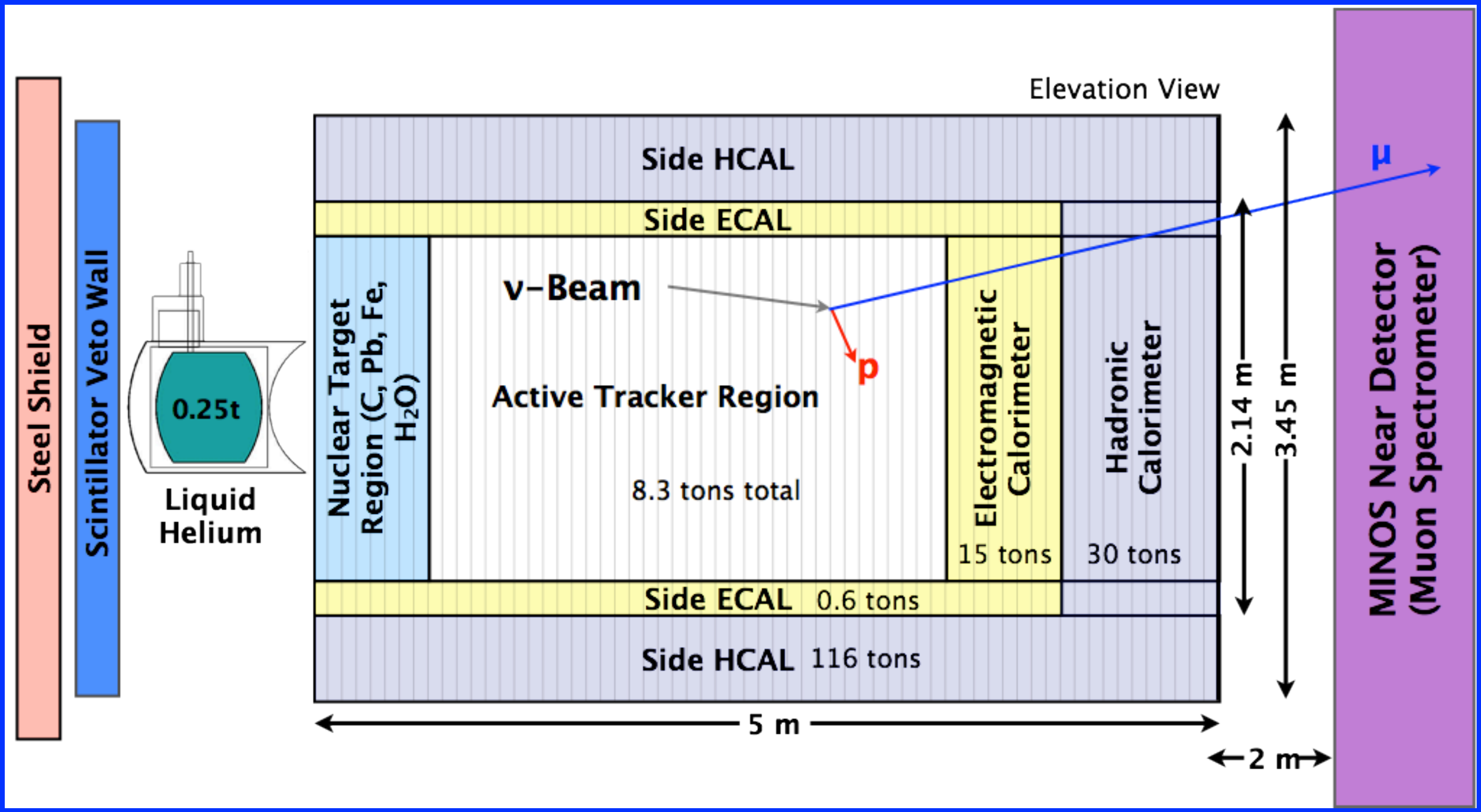
Examples of detectors - NOMAD

Examples of detectors – T2K



- See Professor Kendall Mahn's talk for more details

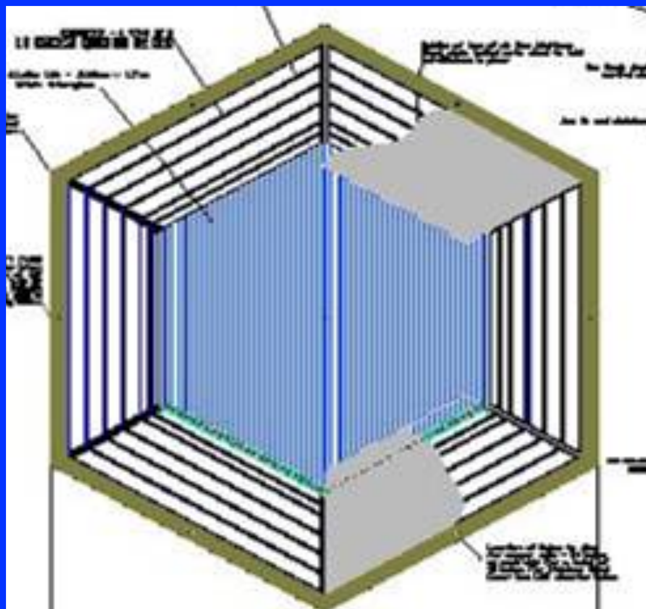
Examples of detectors – Minerva

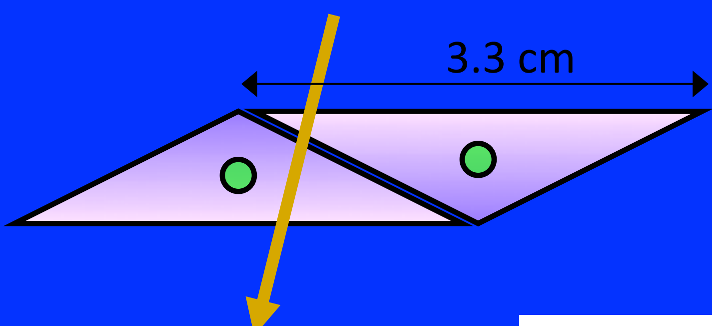


- 120 modules for tracking and calorimetry
- Magnetized MINOS near detector for downstream muon tracking/sign selection

From: Brian Tice

Examples of detectors – Minerva active target modules



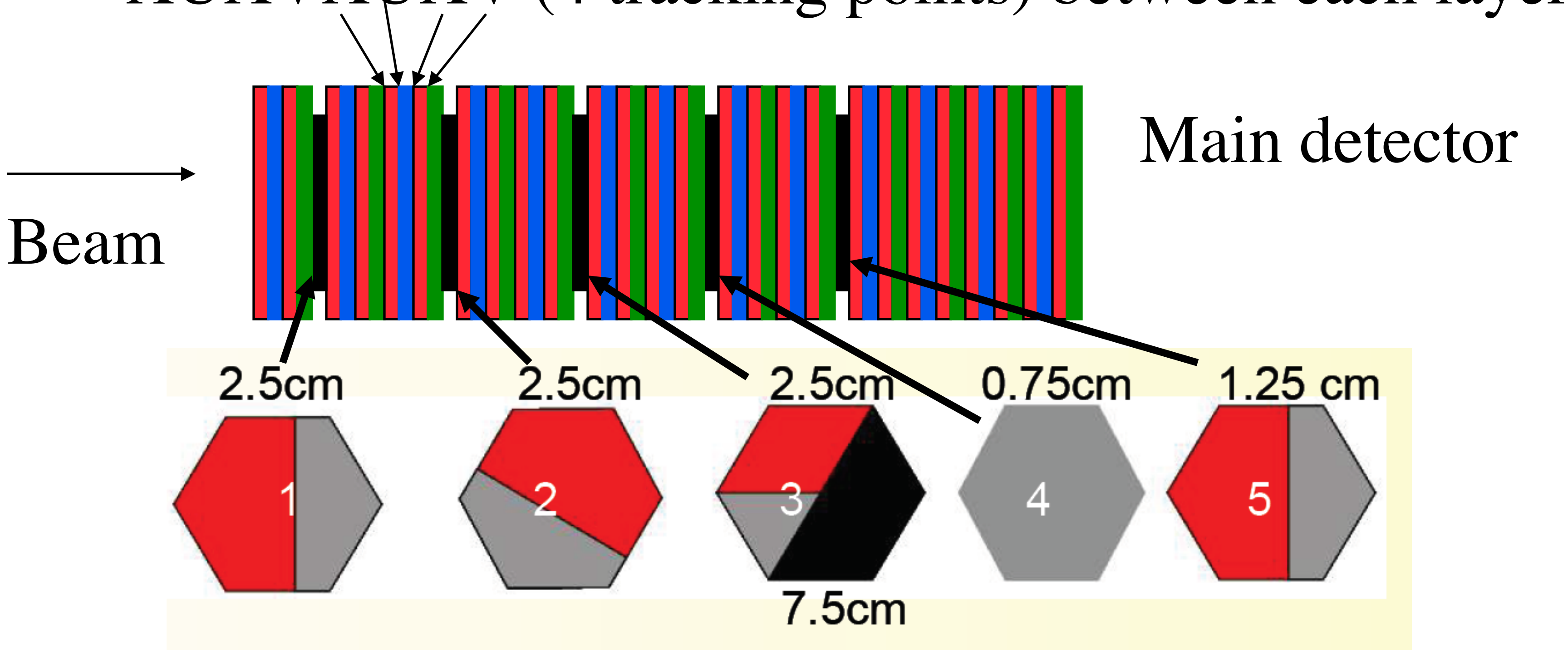


From: Jorge Morfin

- Inner detector: active scintillator strip tracker – triangular extrusions using charge sharing rotated by 60 degrees for stereo views
- Lead pieces on outer 15cm of active target for side electromagnetic calorimeter
- Outer frame provides side hadronic calorimeter/muon identifier

Solid Nuclear Target Region

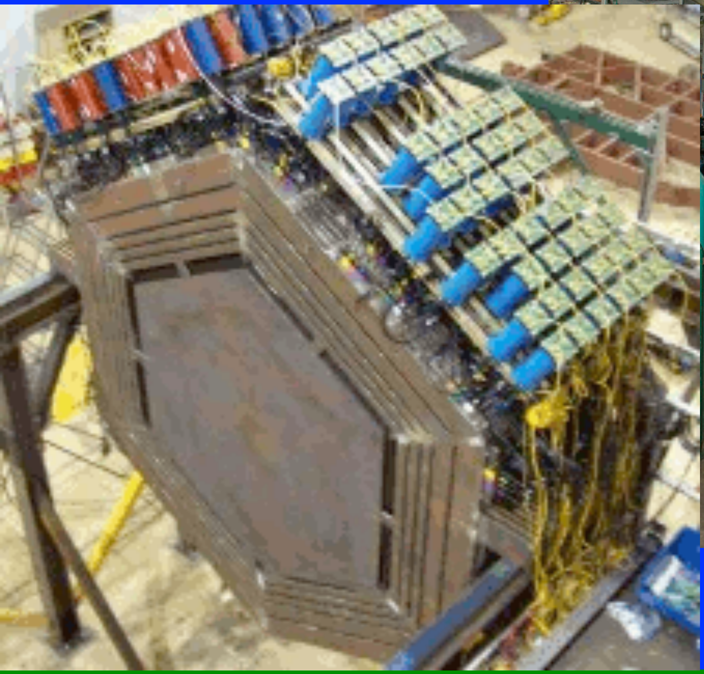
XUXVXUXV (4 tracking points) between each layer



Carbon, **Iron**, **Lead – mixed elements in layers to give similar systematics**

From: Jorge Morfin

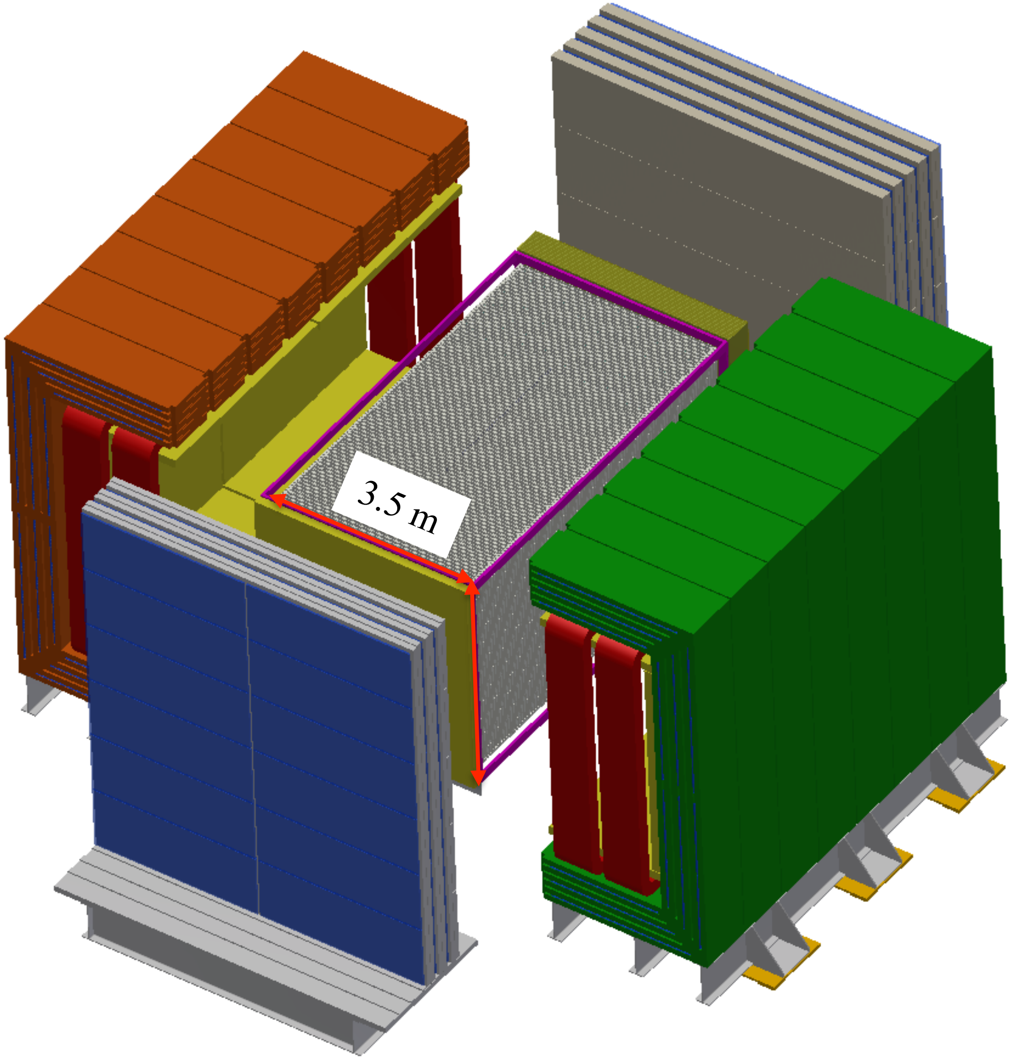
Examples of detectors - Minerva



From Minerva website

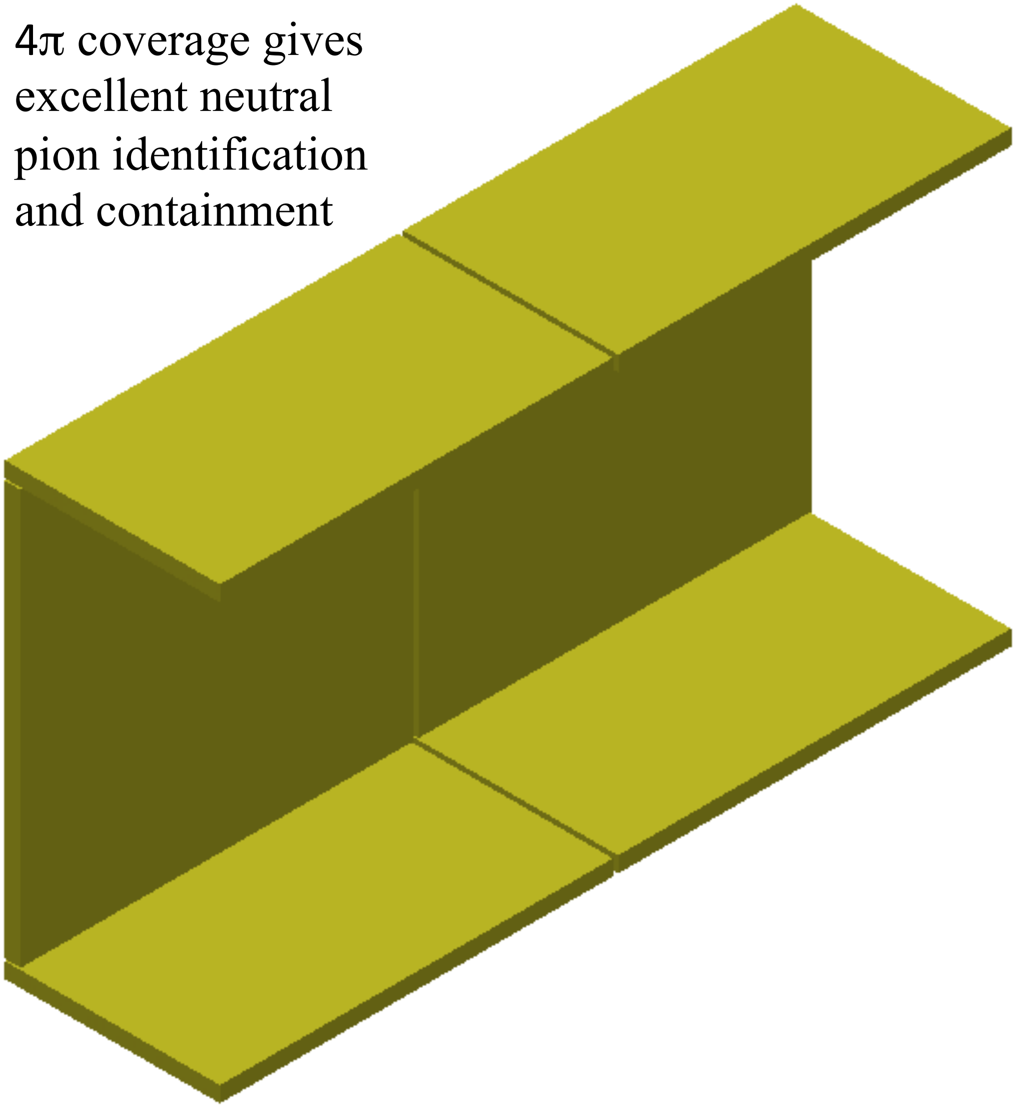
LBNE Near Neutrino Detector

- High precision straw-tube tracker with embedded high-pressure argon gas targets
- 4π electromagnetic calorimeter and muon identification systems
- Large-aperture dipole magnet
- Philosophy
  - make high-precision, high-statistics measurements of neutrino interactions with argon (far detector nucleus)
  - measure inclusive and exclusive cross-sections to build and constrain models to predict the event signatures at the far site *and correlate them with the true neutrino energy*
  - make detailed studies of electron (and muon) neutrinos and anti-neutrinos separately



Electromagnetic Calorimeter

4π coverage gives excellent neutral pion identification and containment



ECal designed to identify electrons and photons – critical for measuring neutral pion background

Sandwich of lead and plastic scintillator

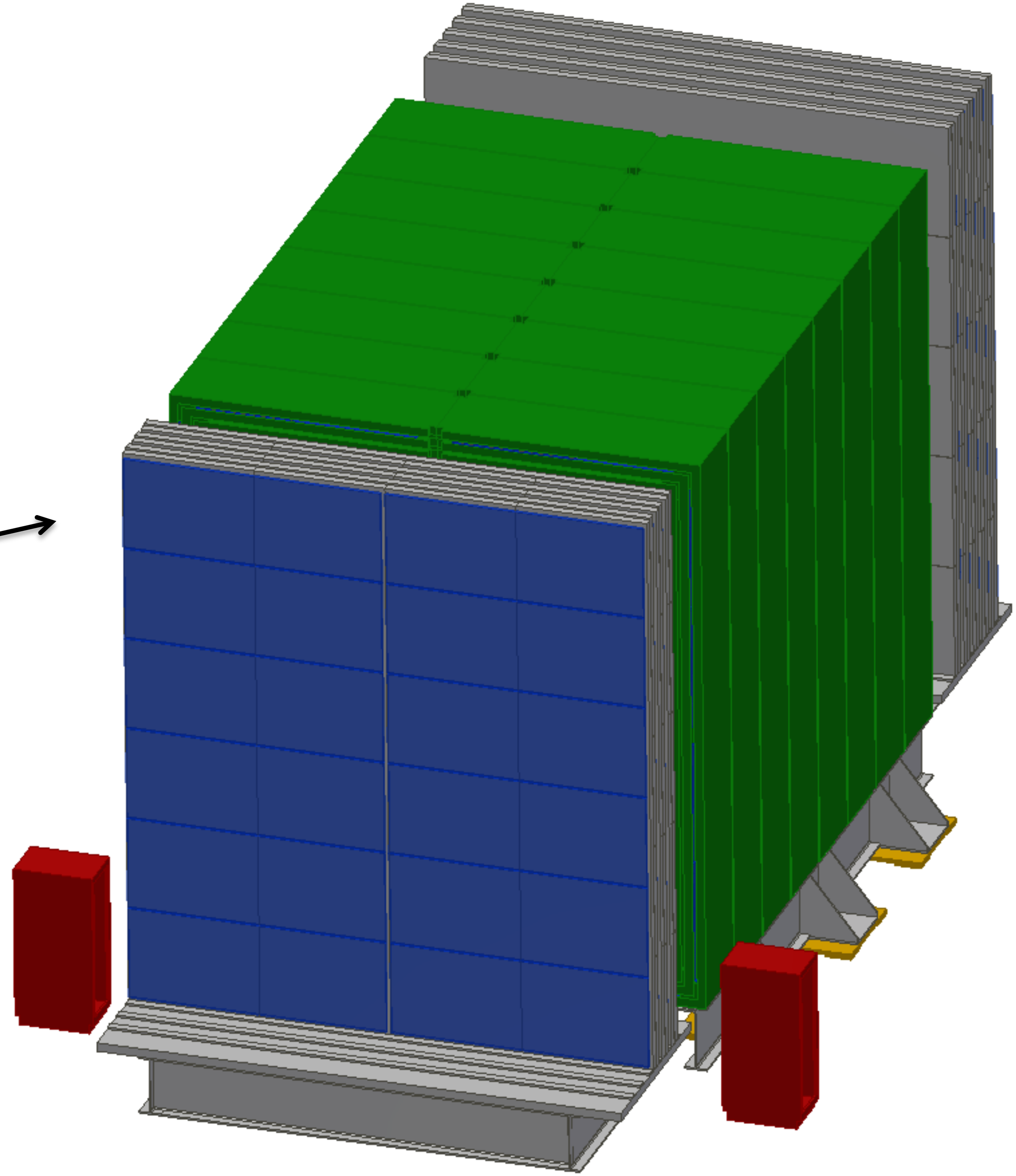
Downstream ECal has 58 layers of 1.75mm lead with scintillator bars of 2.5cmx0.5cm profile (4m long)

The Barrel ECal (shown at left) and Upstream ECal have 3.5mm of lead

Total lead mass is 110 tons, scintillator mass is 35 tons

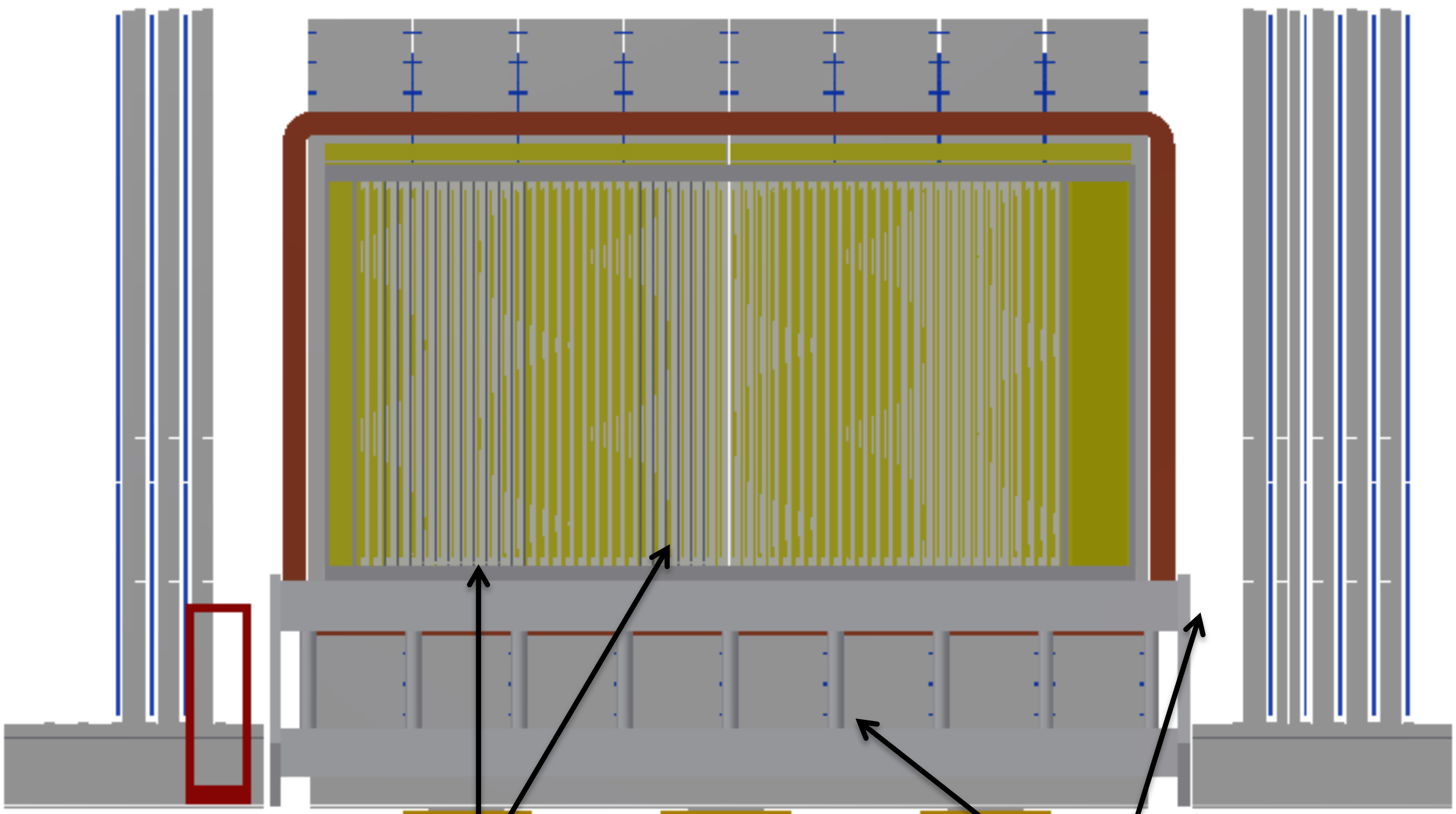
External Muon Identifier

Steel interleaved with Resistive Plate Chambers



Identifies muons – separates muons and charged hadron (e.g. pions)

LBNE Near Neutrino Detector



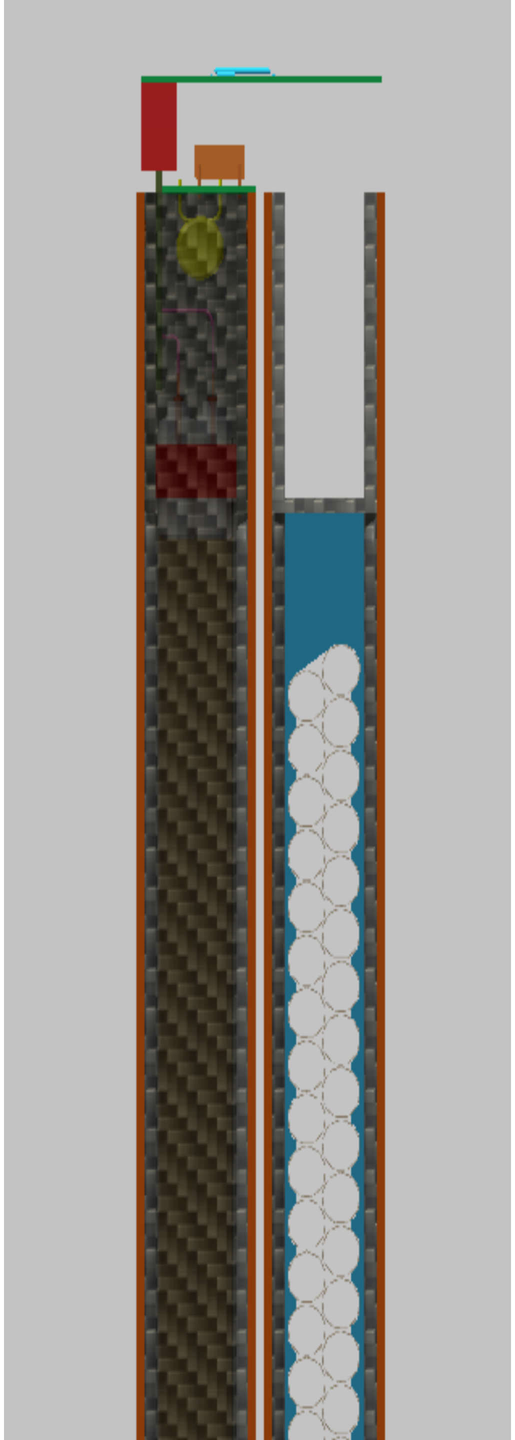
Transition Radiation Detector
Radiator foils, argon gas targets, other nuclear targets

Average density ~ 0.1 g/cm^3

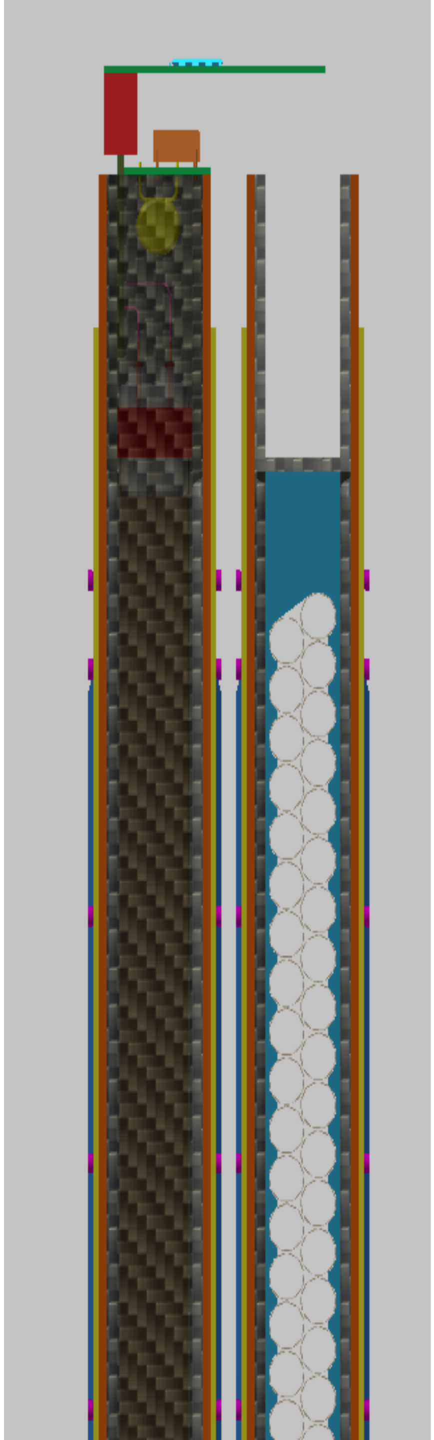
UA1-style dipole magnet – 0.4 T

Muon identifier – also interleaved in magnet

Strawtube Tracker Module



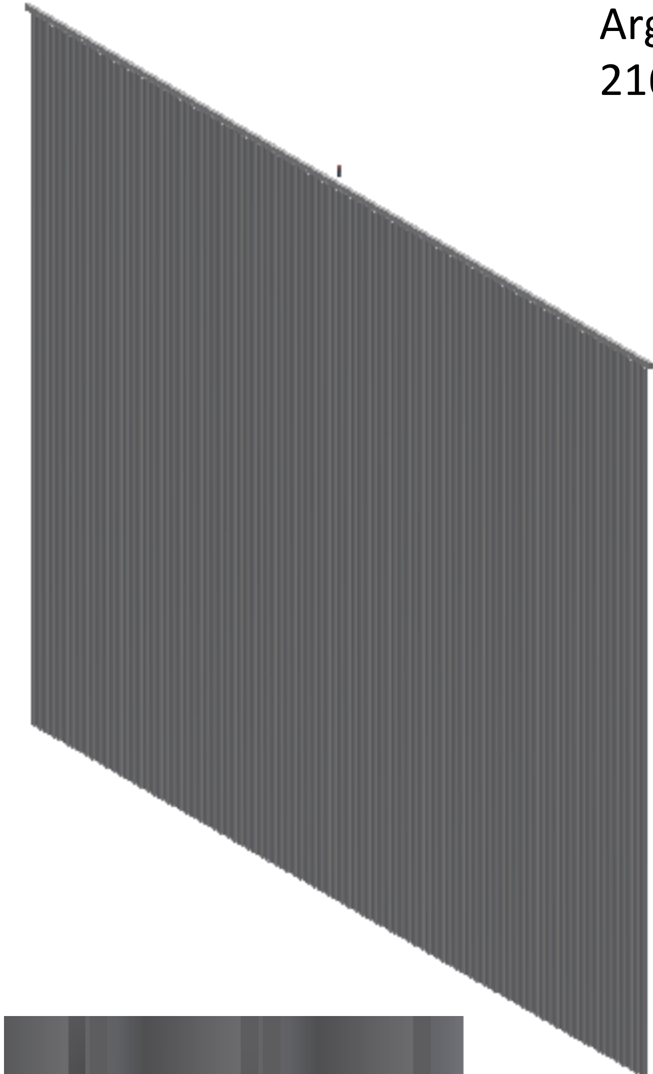
XX YY Module
62mm thick
leaving 18mm for
a nuclear target
module

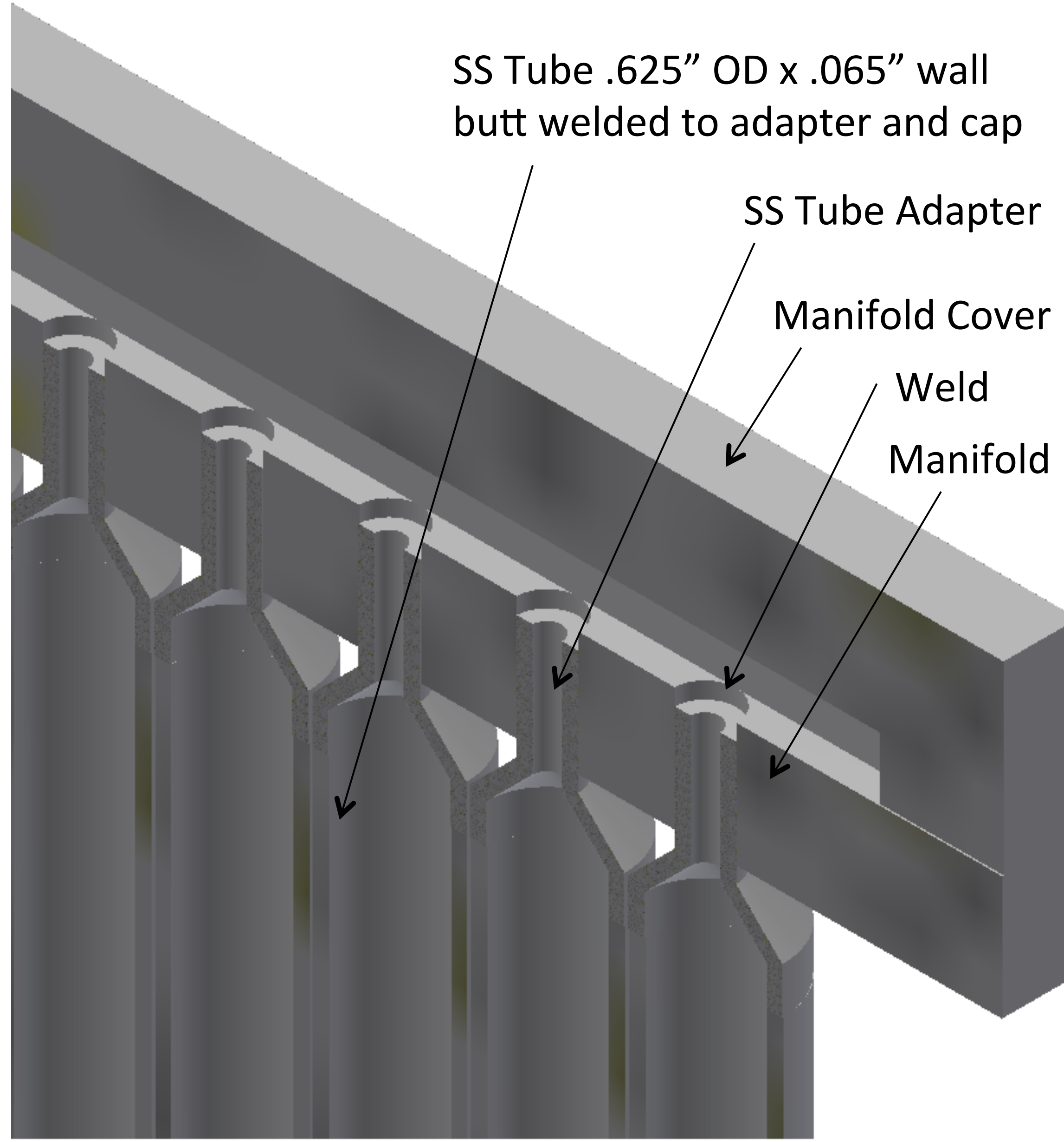


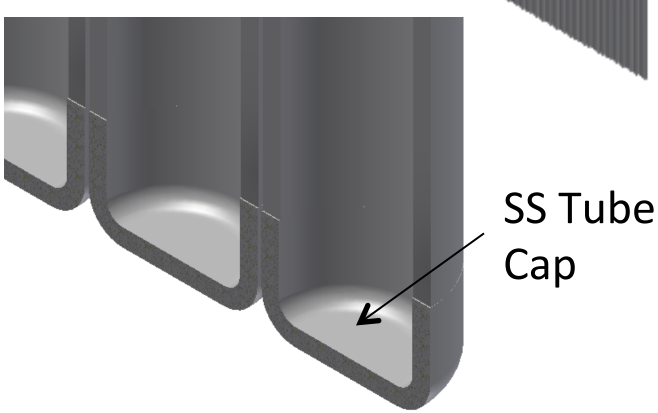
TRD XX YY
Module
76mm thick

Argon Gas Target Assembly – SS Version

216 tu

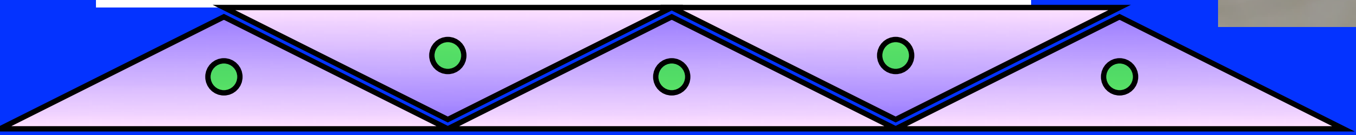






Basic Elements – Scintillator Bars

- Scintillation peaks at 420nm, cuts off at 400nm
- Collect scintillation light with wavelength shifting fiber – emission peak at 476 nm (green) – total internal reflection to end of bar
- Maximize collection efficiency with a reflector around the outside of the bar
- TO_2 reflecting material co-extruded with scintillator at FNAL
- Wavelength shifter attenuation length > 3m, so long bars are possible
- Versatile – used for tracking, ECal, Hcal
- Useful in moderate density applications

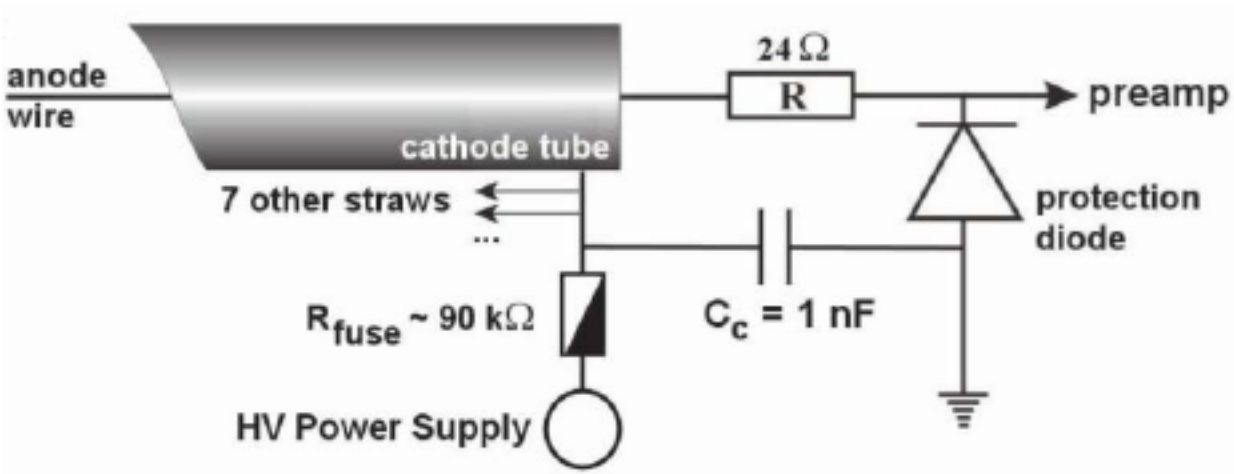


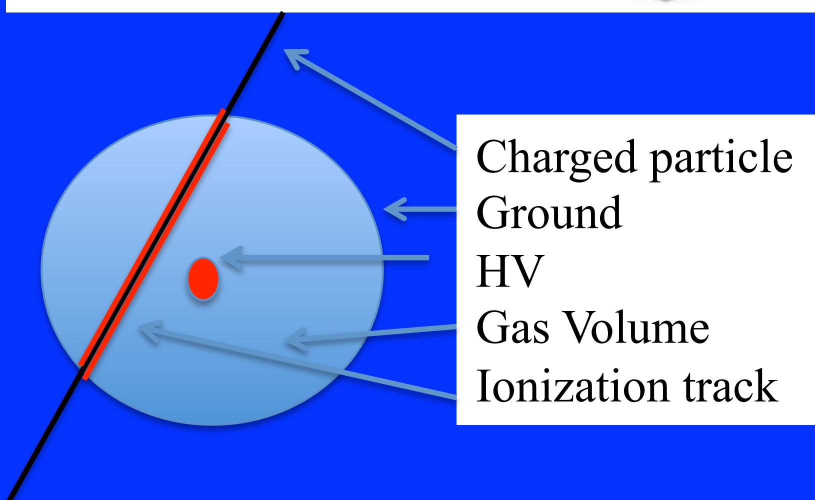
Basic Elements – Scintillator Bars

- Lab 5 at FNAL, polystyrene scintillator extrusion
- Co-extrusion with titanium dioxide successful, R&D on wavelength-shifting fiber co-extrusion

Basic Elements – Straw Tubes

STT Readout

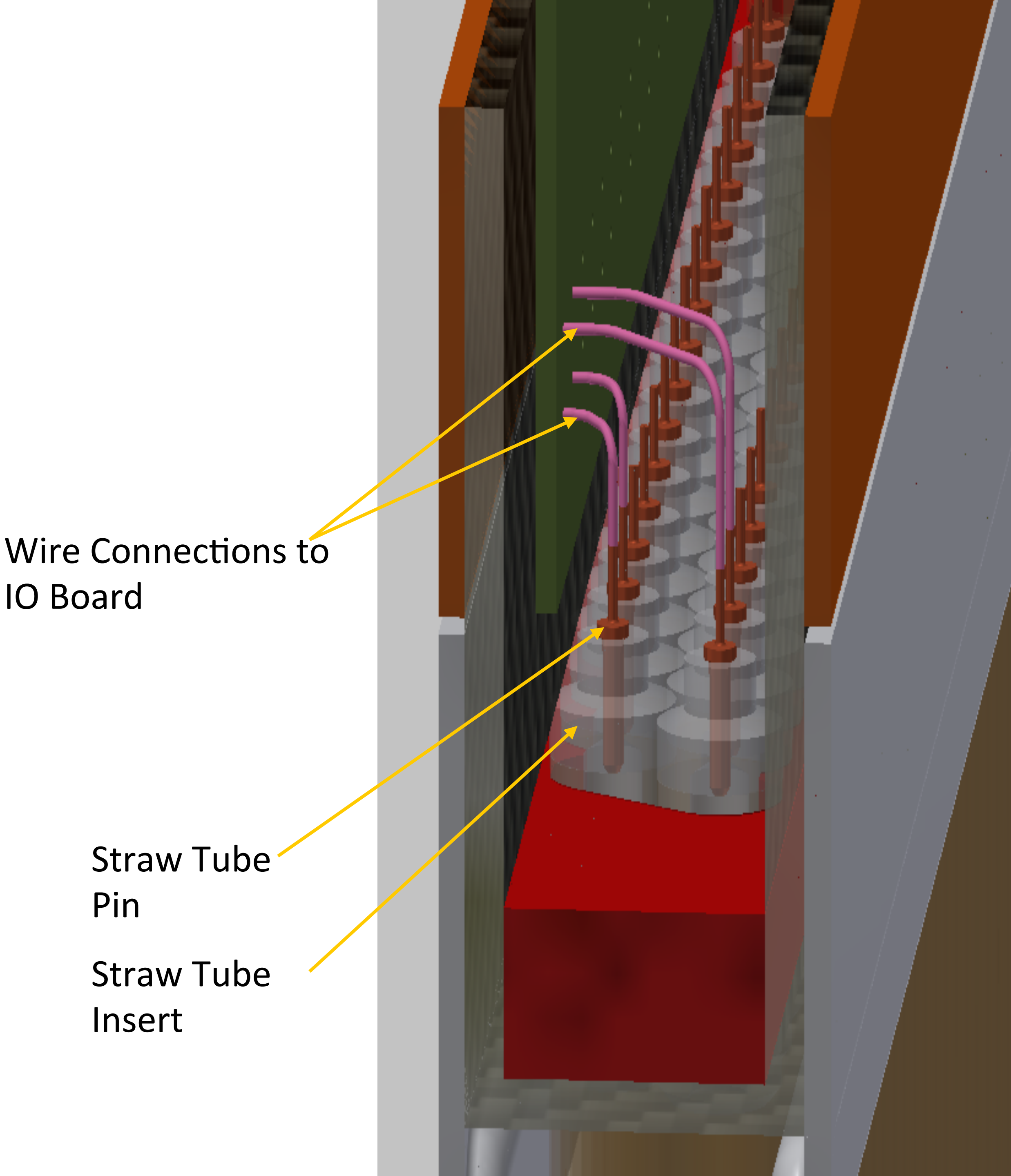


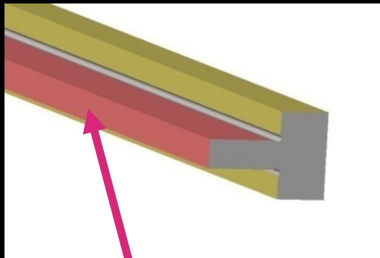


- Straws fabricated with conducting material (or coated with conducting material)
- Anode wire threaded through the straw (which can be a few meters in length)
- High electric field – especially near the anode results in electron multiplication
- Excellent response to charged particles
- Excellent in low-density applications

Straw Tubes

- Anode wire: strong, good conductor, thin (gold-plated tungsten 30 microns)
- Straw: kapton, coated with conducting material
- Gas mixture: usually noble gas (argon) and damping gas (hydrocarbon)
- Straw material can be the neutrino target



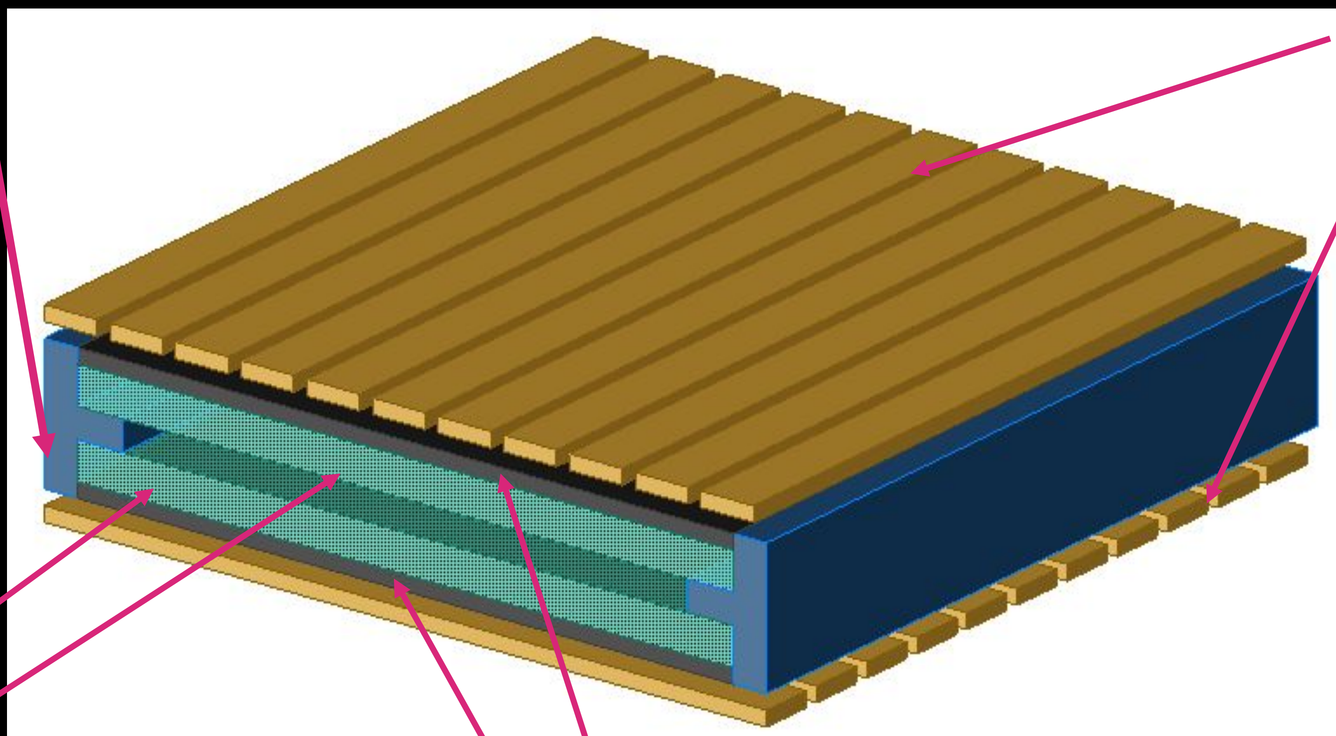


Construction of RPC

Two 2 mm thick float Glass
Separated by 2 mm spacer

2 mm thick spacer

Pickup strips



Glass plates

Resistive coating on the outer surfaces of glass

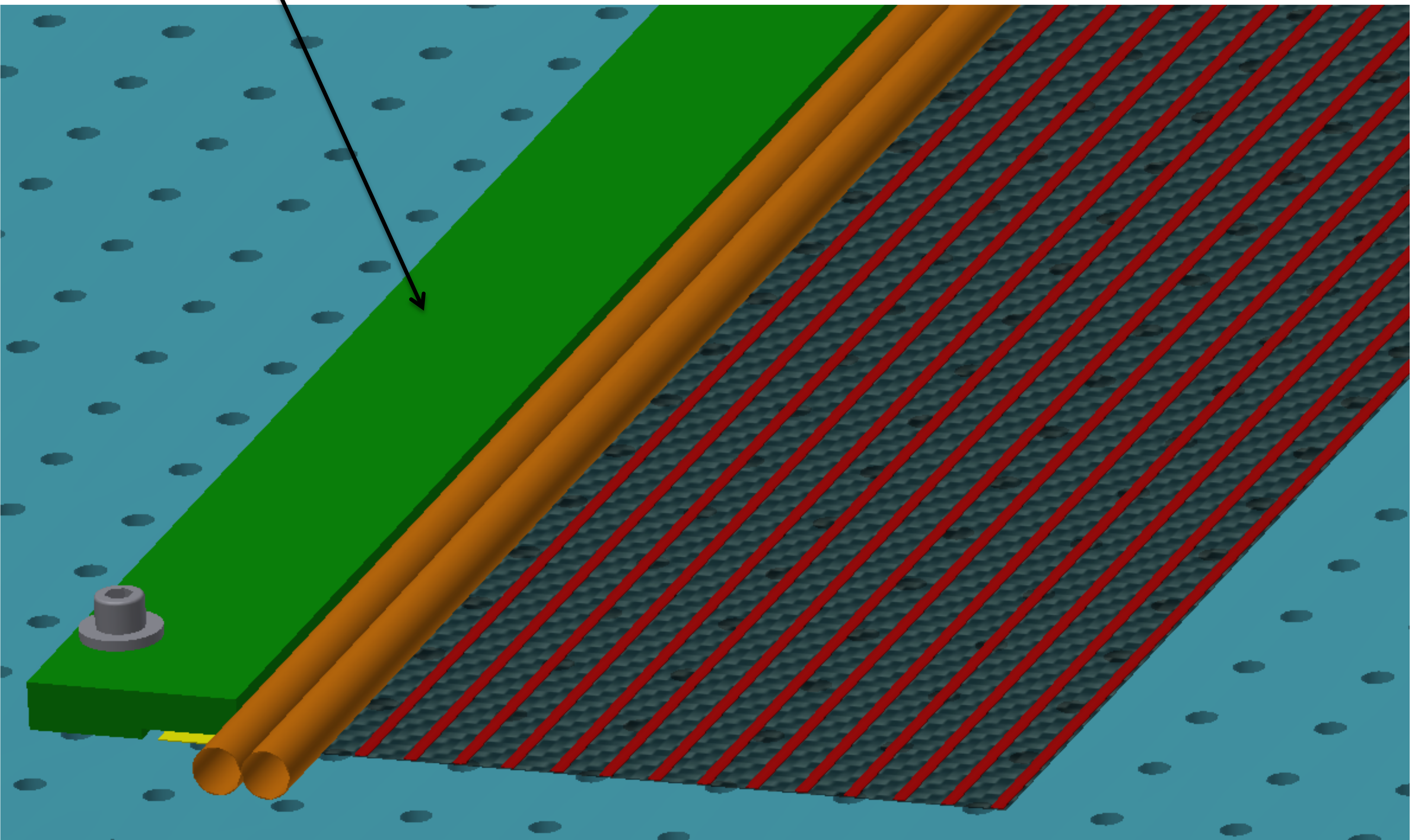
Basic Elements – Resistive Plate Chambers

- RPCs can be built with glass or plastic (bakelite)
- Voltage drop across the plates (several kV)
- Spacers used to keep the plates separated (few mm thick)
- Charged particles induce a localized discharge
- Good timing resolution (25 ns)
- Enables inexpensive readout over a broad area

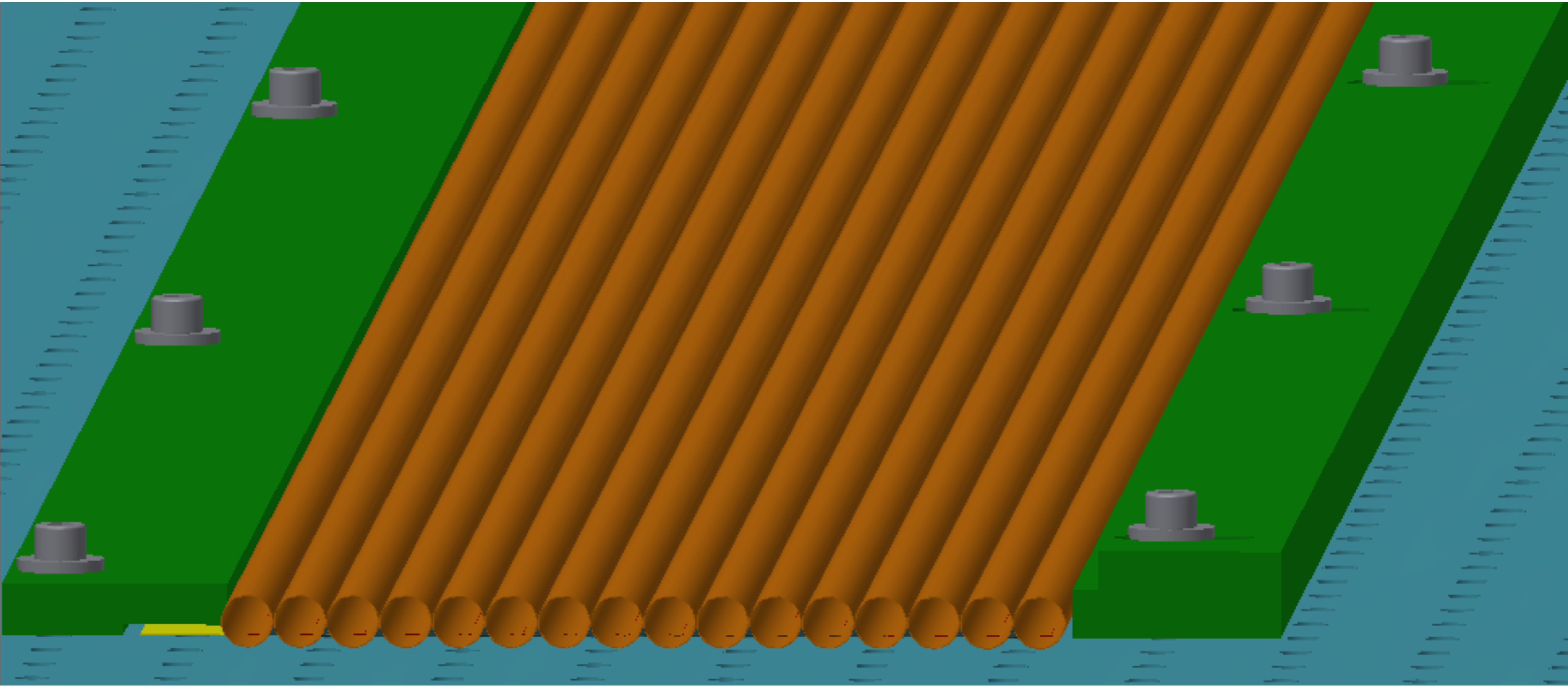
Gross Design Features - Tracking

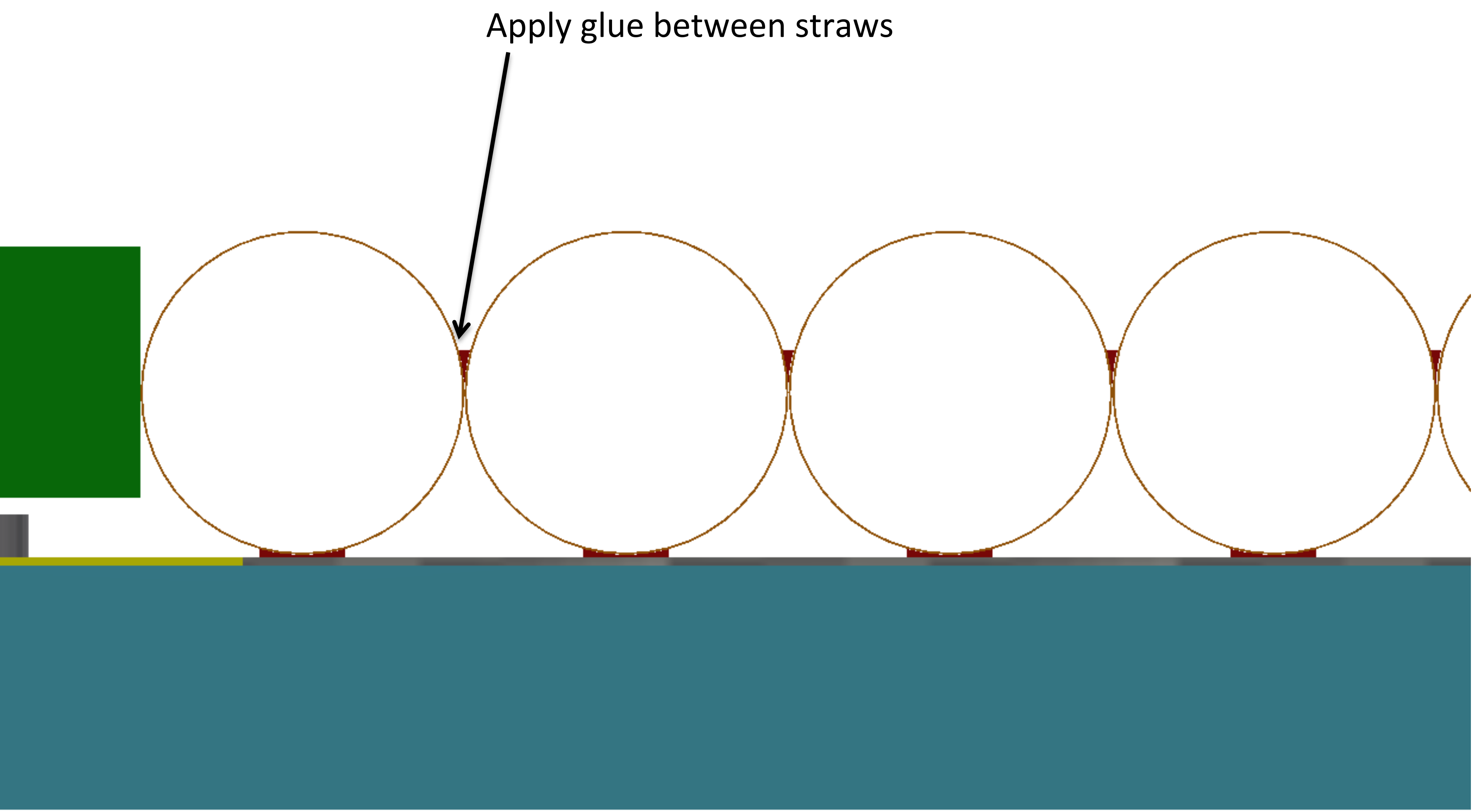
- How do we fit these together?
- Next slides by Jan Boissevain (LBNE engineer)

Place straws and fill with precision steel balls (.375”)

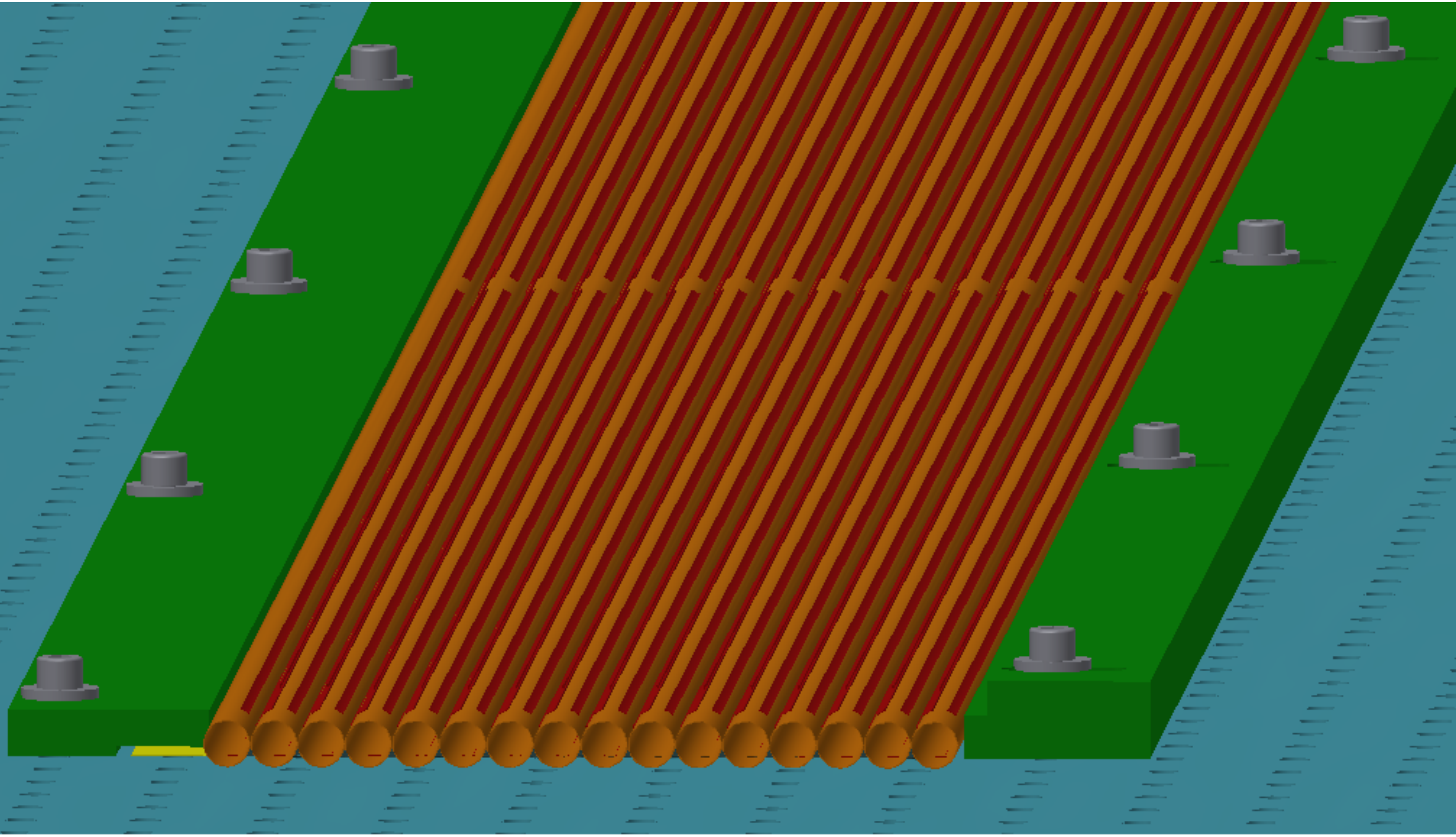


Complete straw placement for first row, add straw locator – all straws filled with precision steel balls

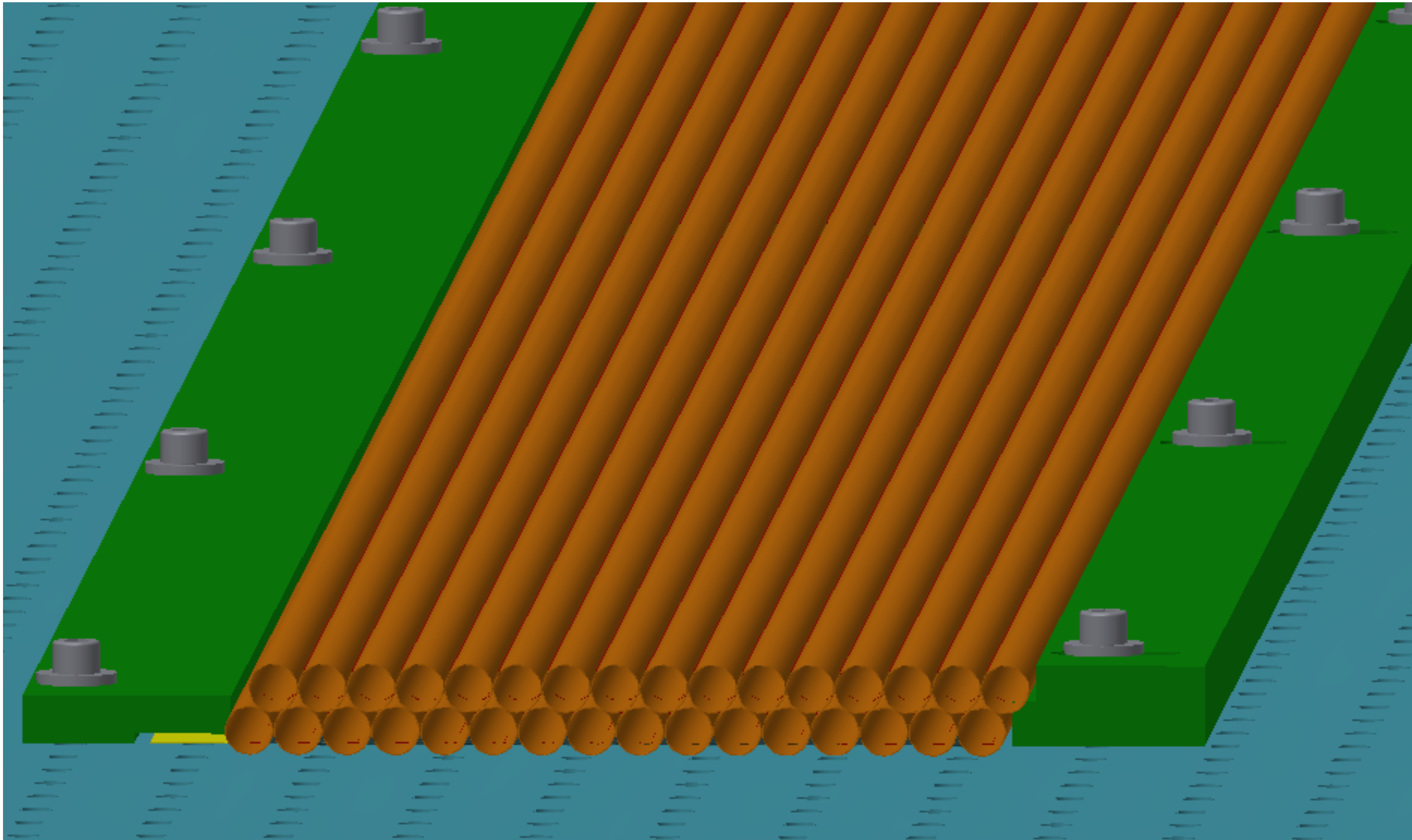



Apply glue between straws

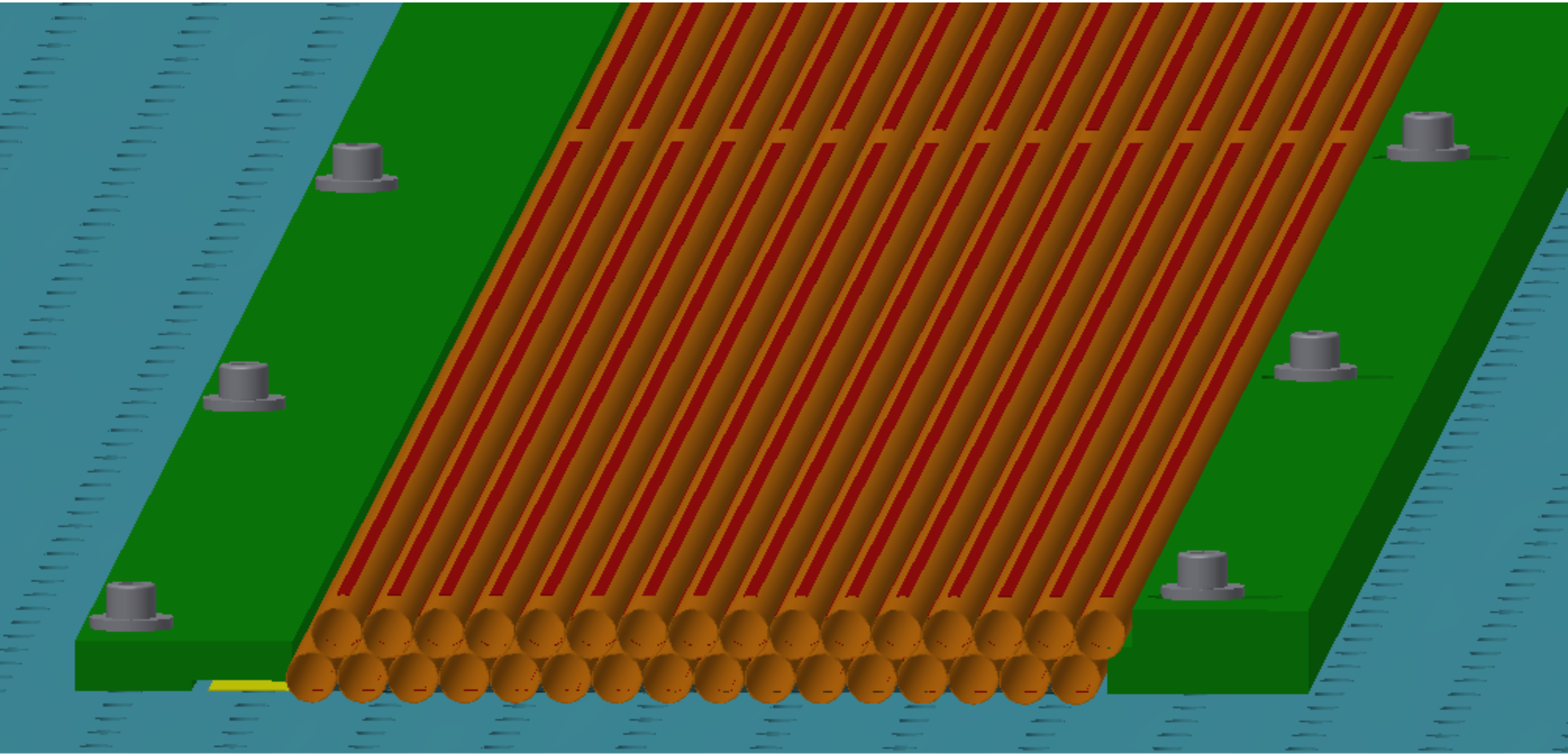
Apply glue in preparation for placement of 2nd row of straws



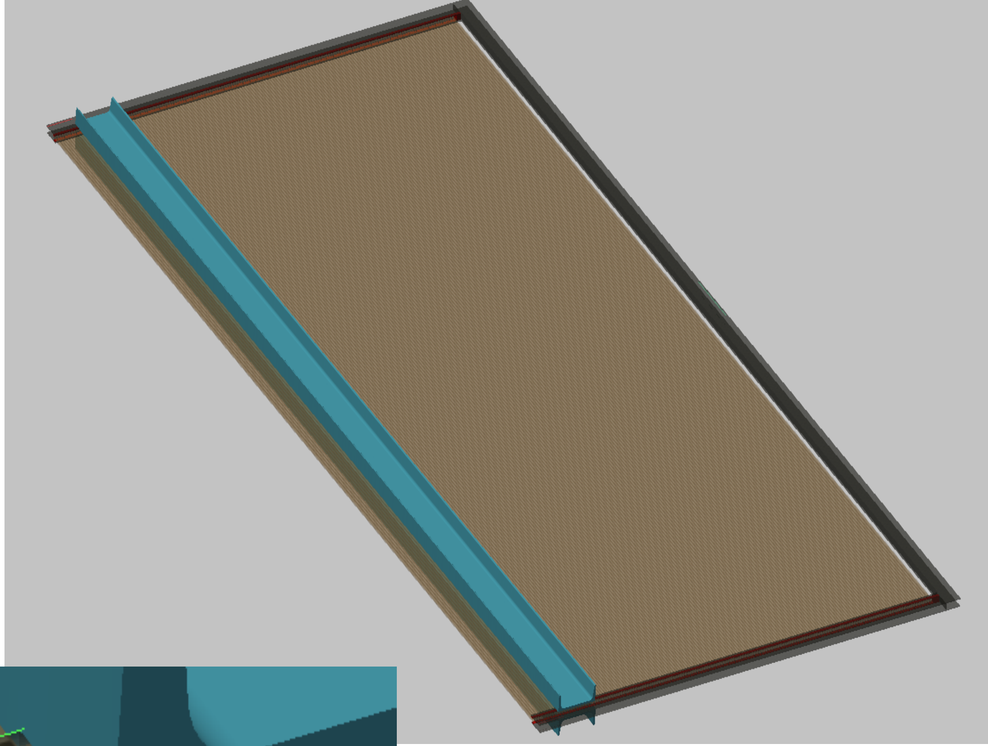
Add second row of straws, fill straws with precision steel balls – the bottom row of straws remain filled with steel balls



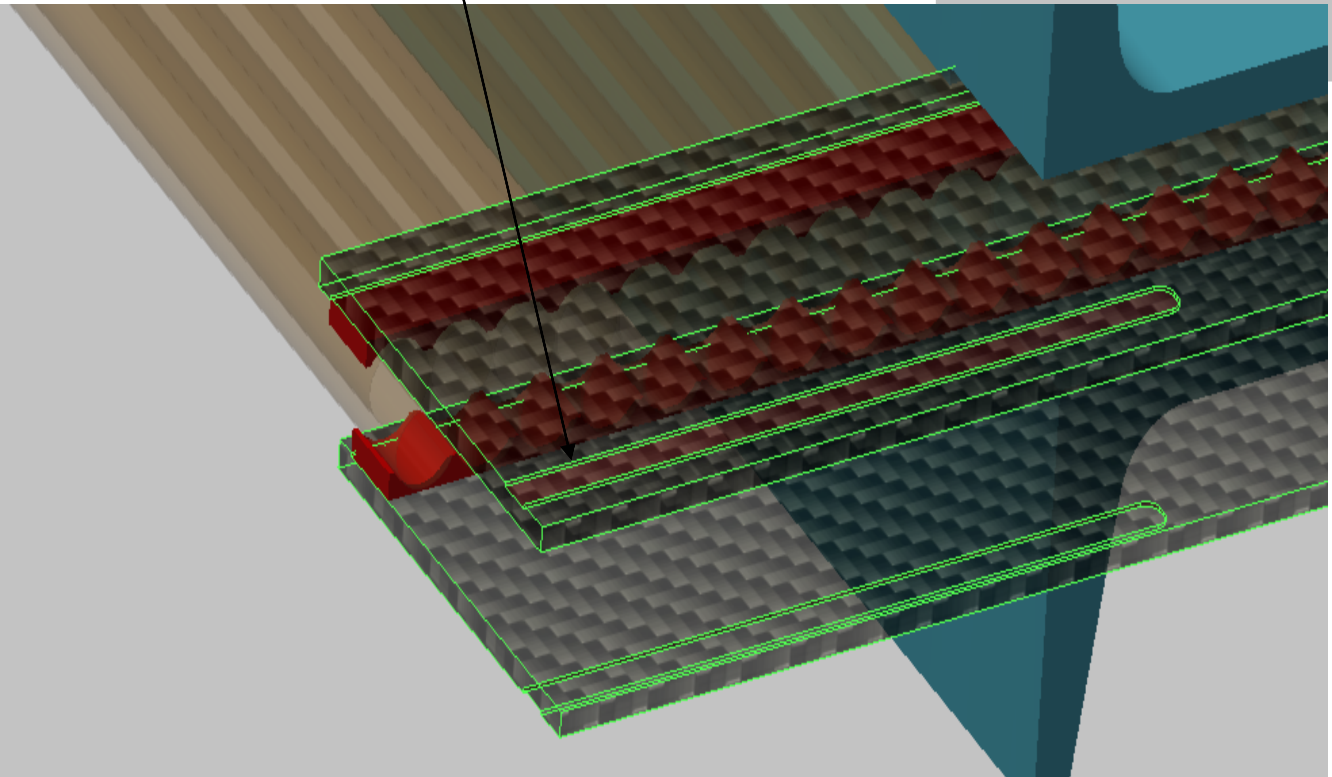
Add glue lines for top composite sheet



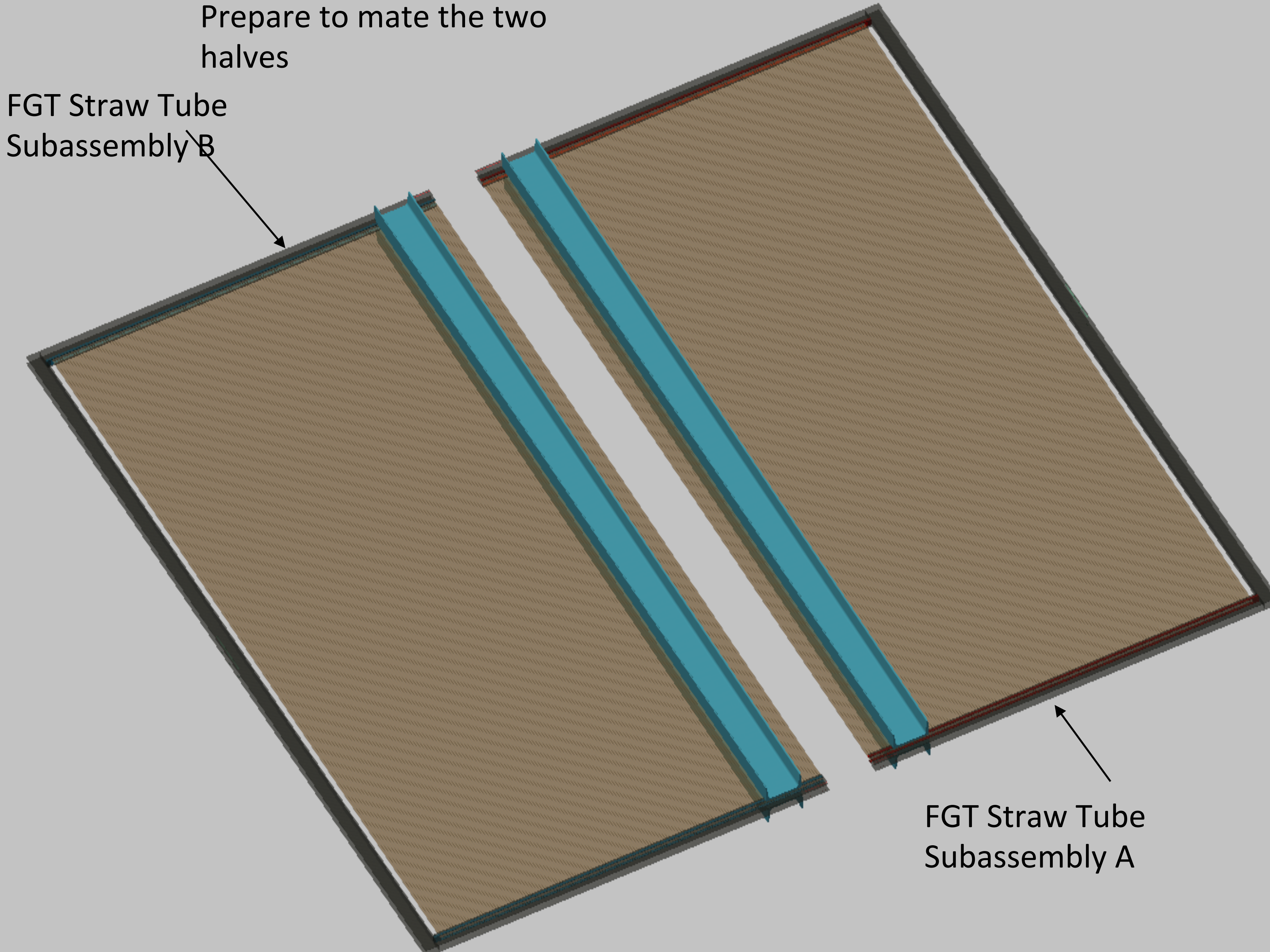
FGT Straw Tube Subassembly A with aluminum channels for shipping

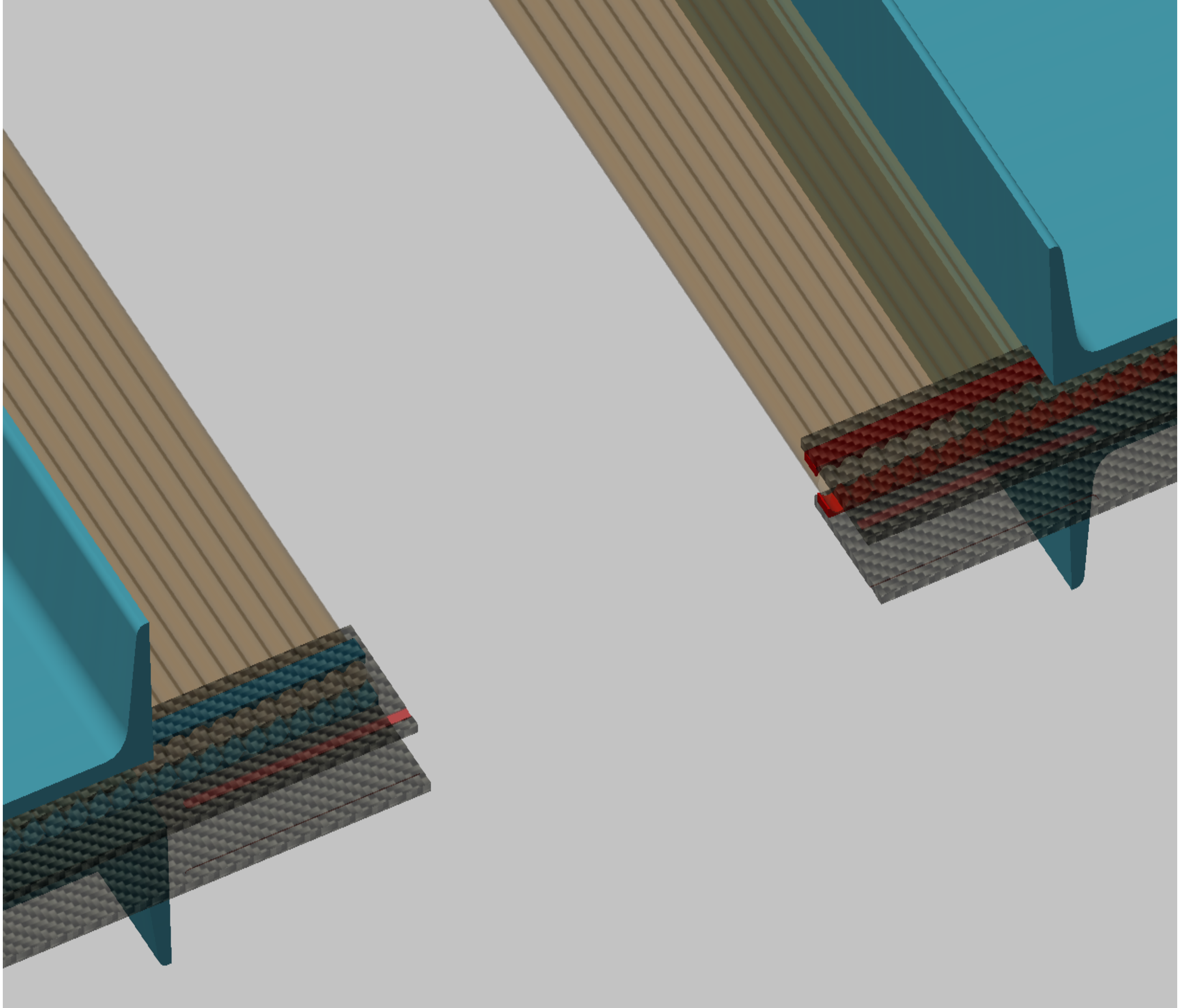


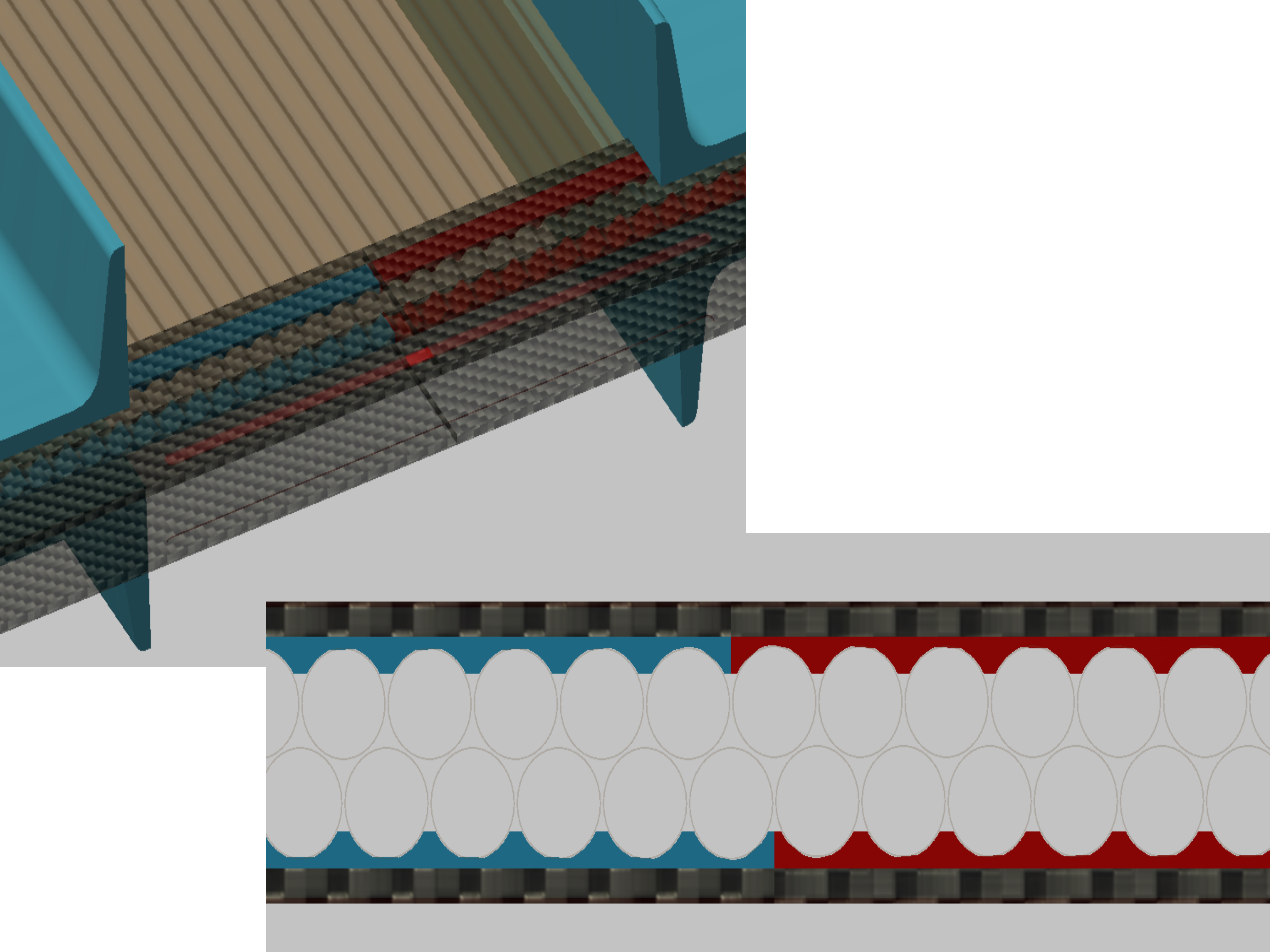
Groove Feature for Indexing the Outer Frame during a glue operation



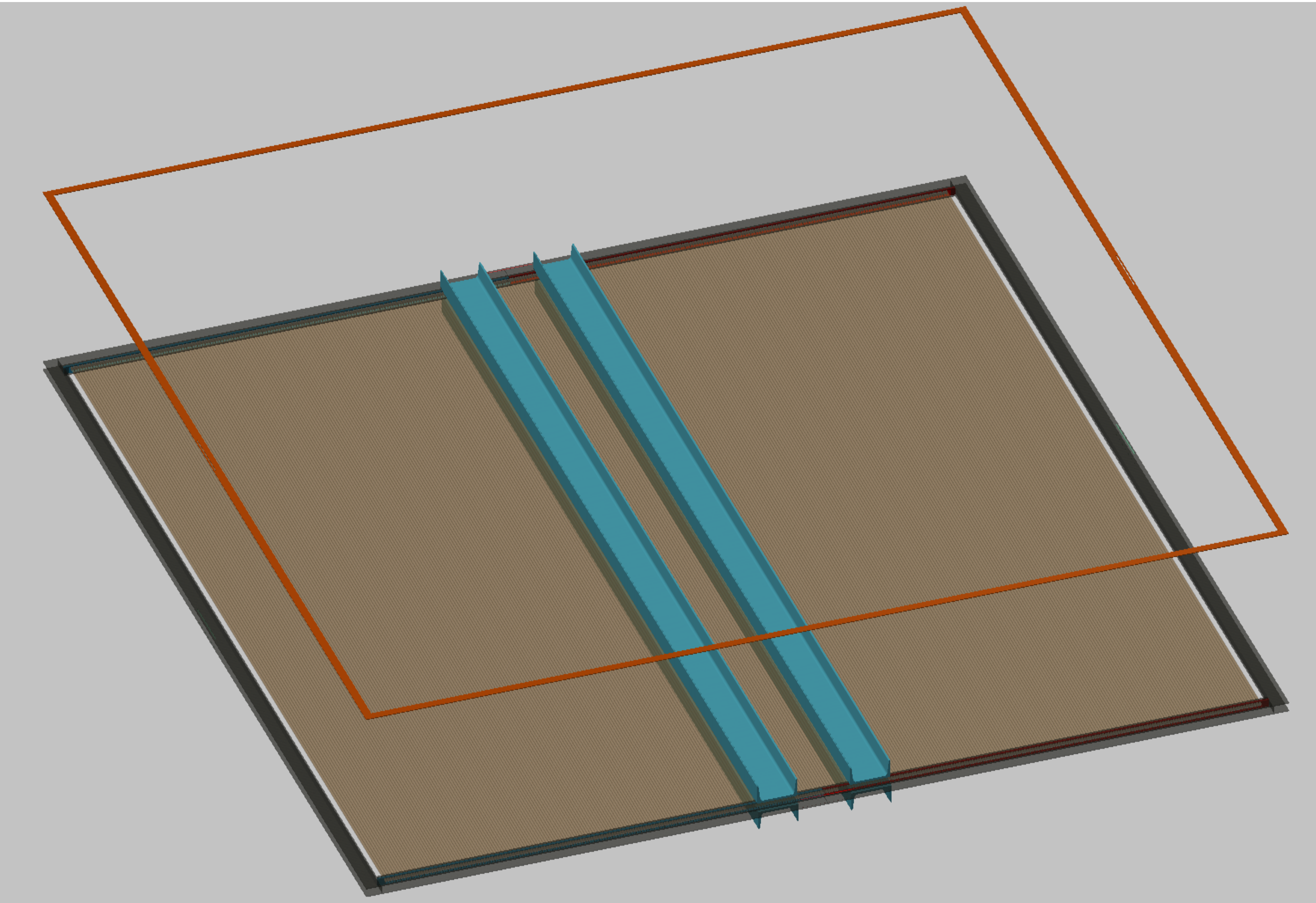
Prepare to mate the two halves



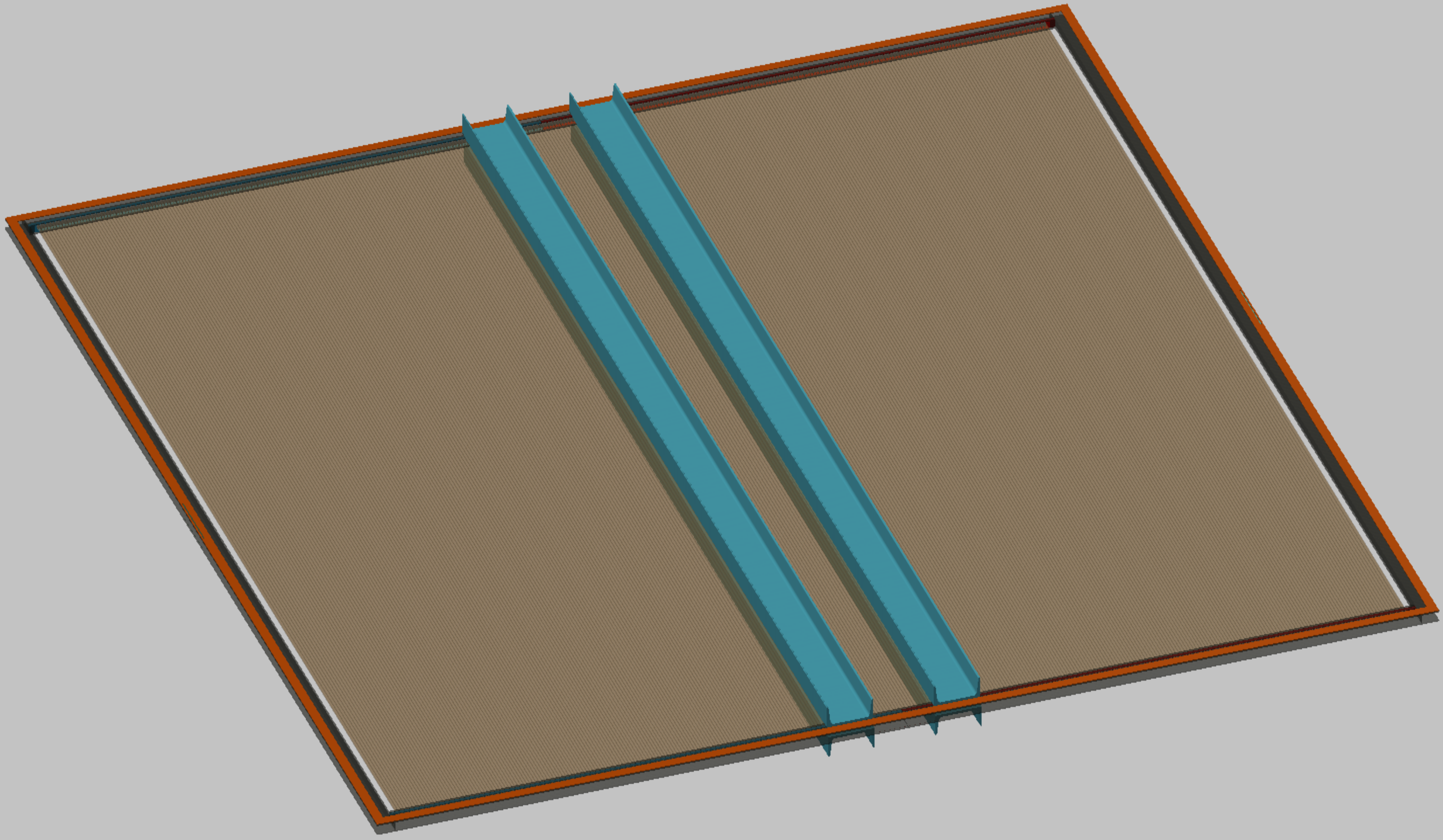




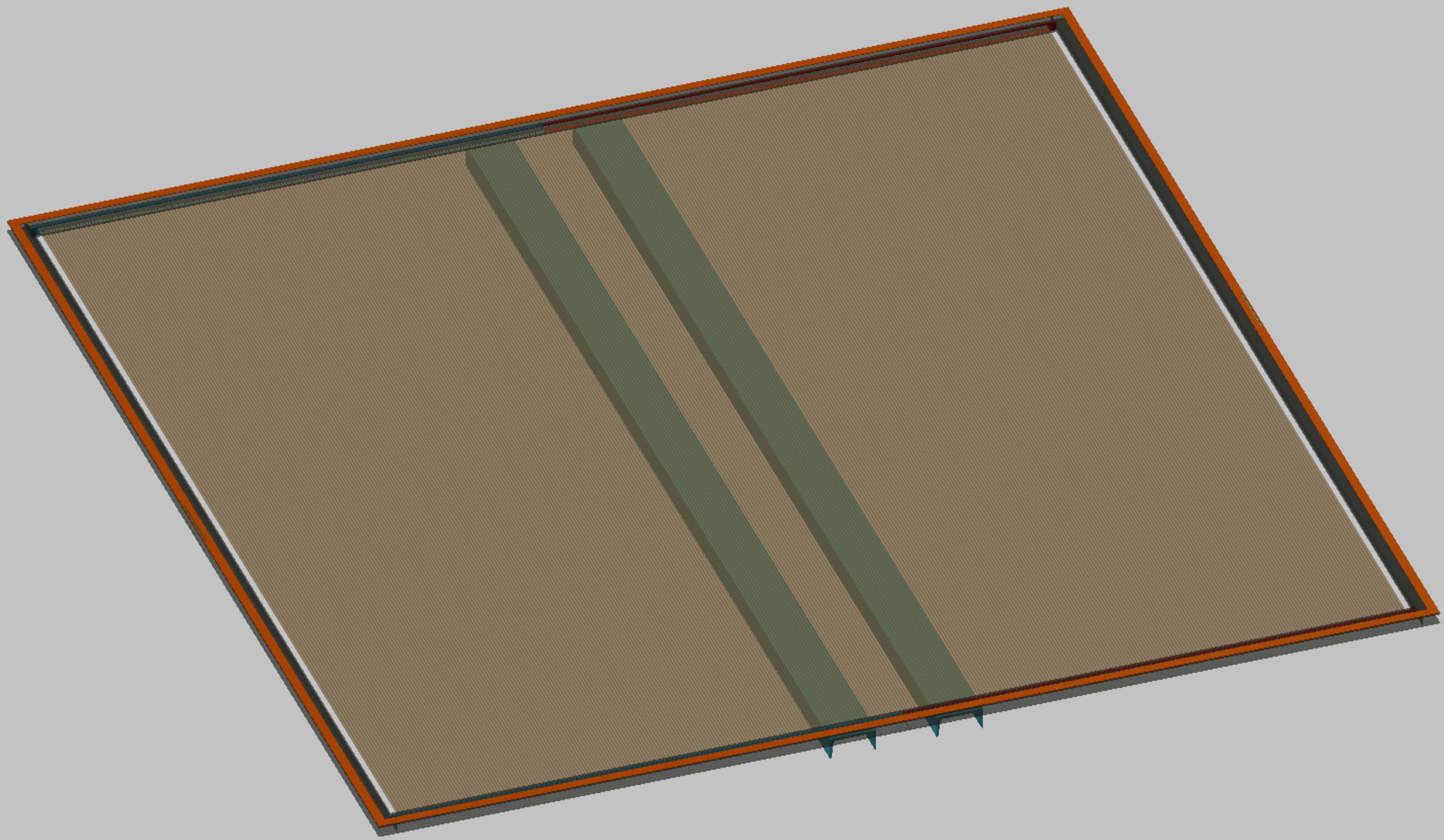
Position Outer Frame

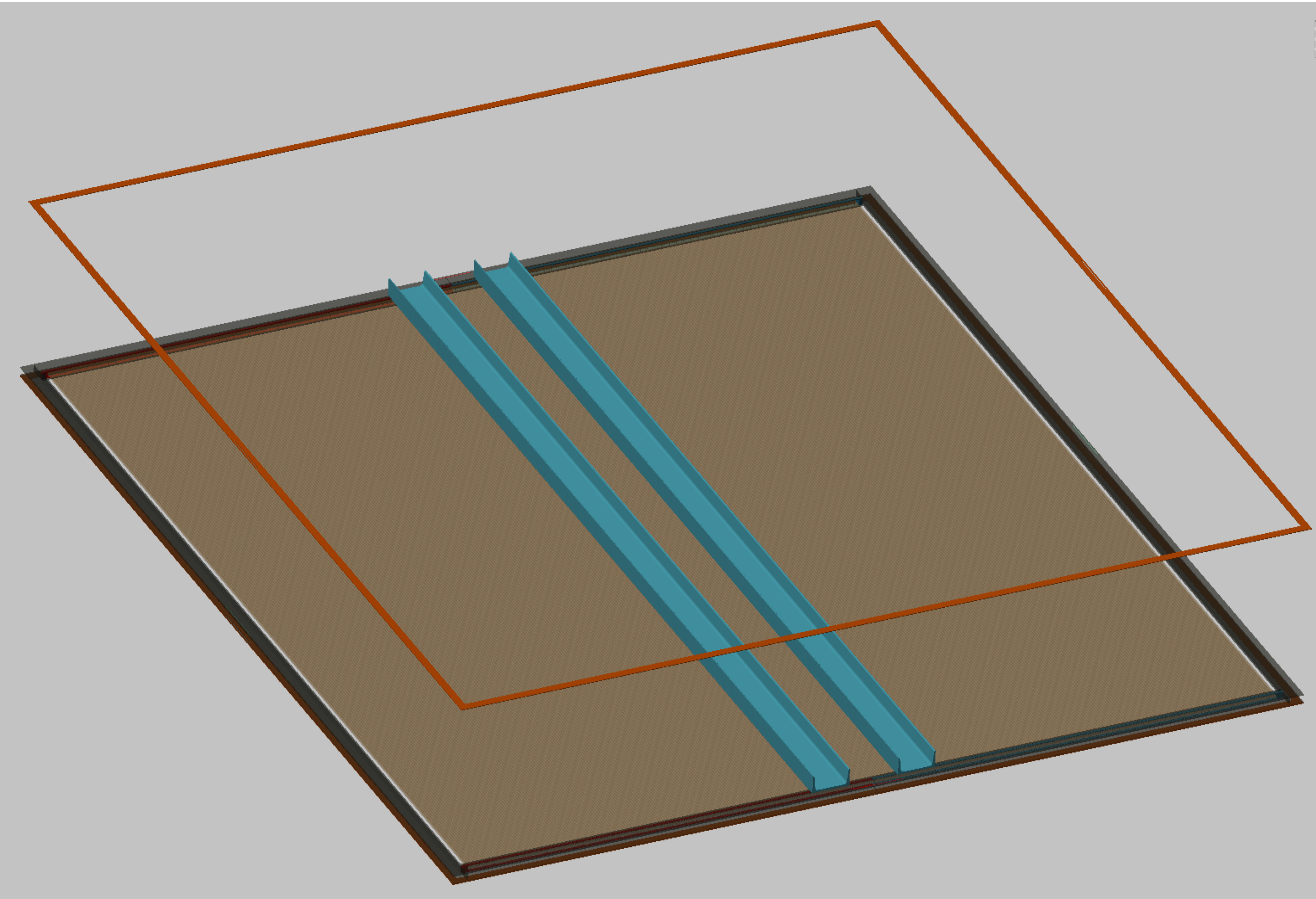


Glue Outer Frame In Place

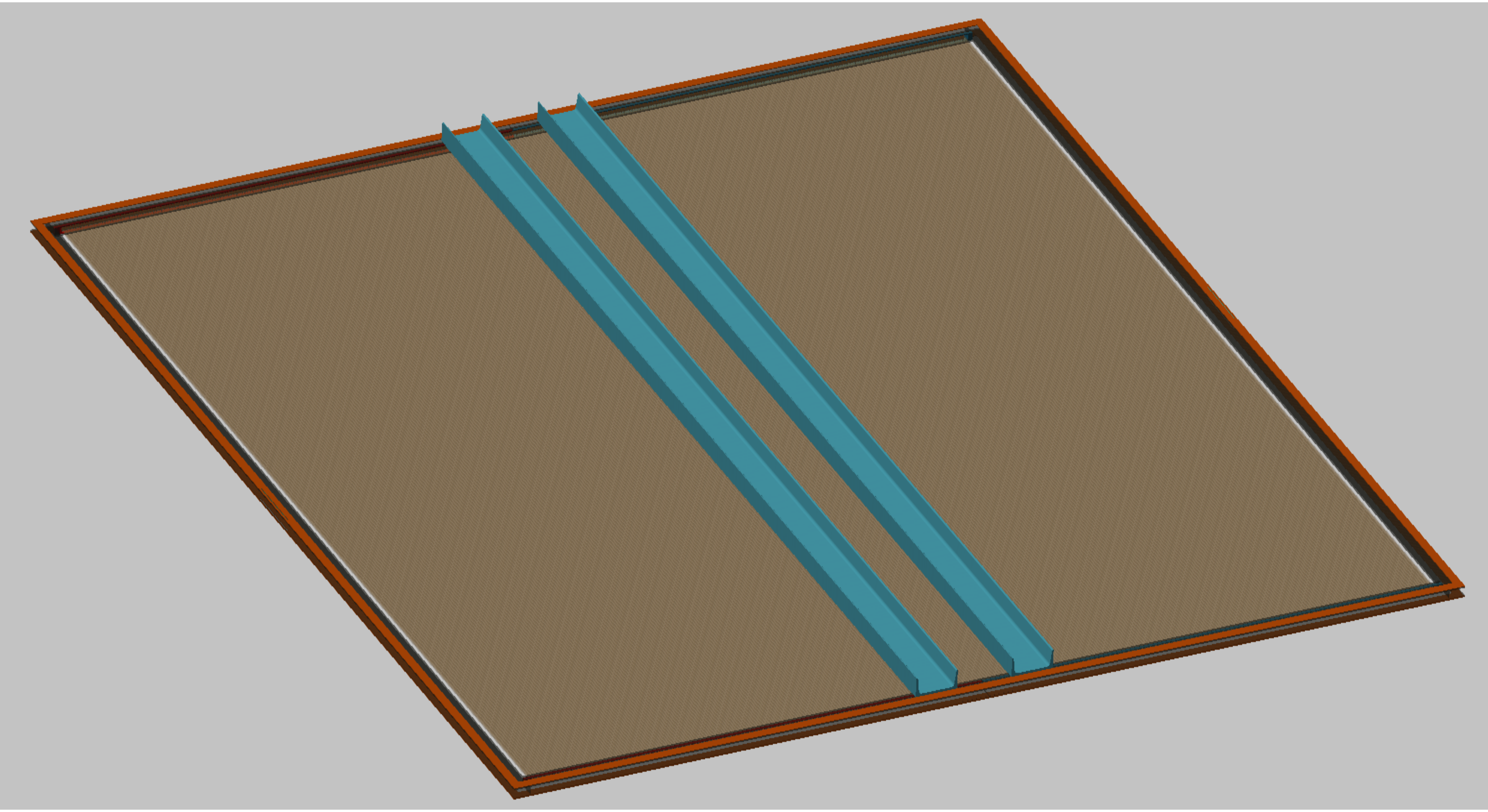


Glue Outer Frame to mated
subassemblies A & B
Remove shipping fixtures



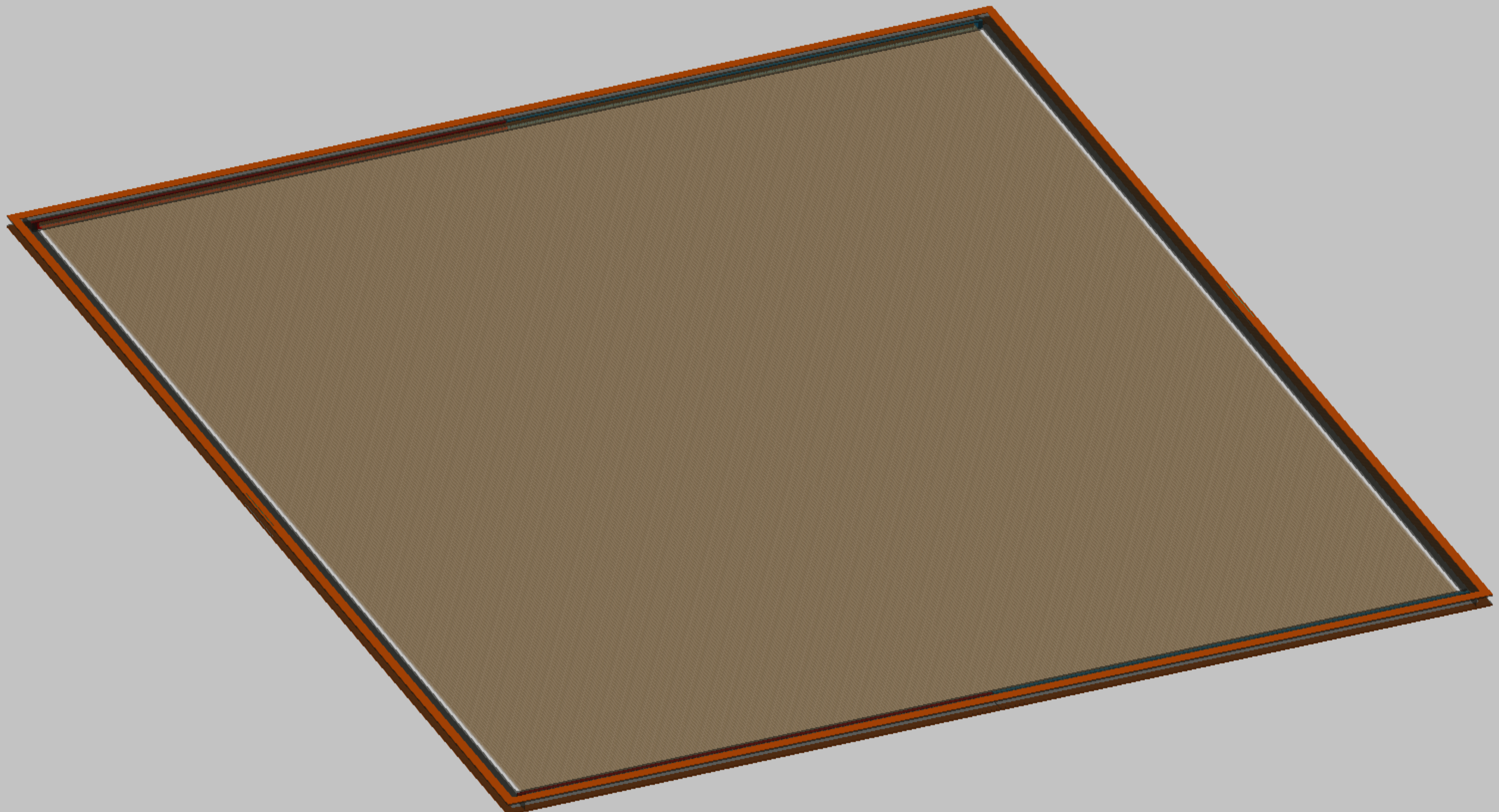


Turn assembly over and glue the second outer frame

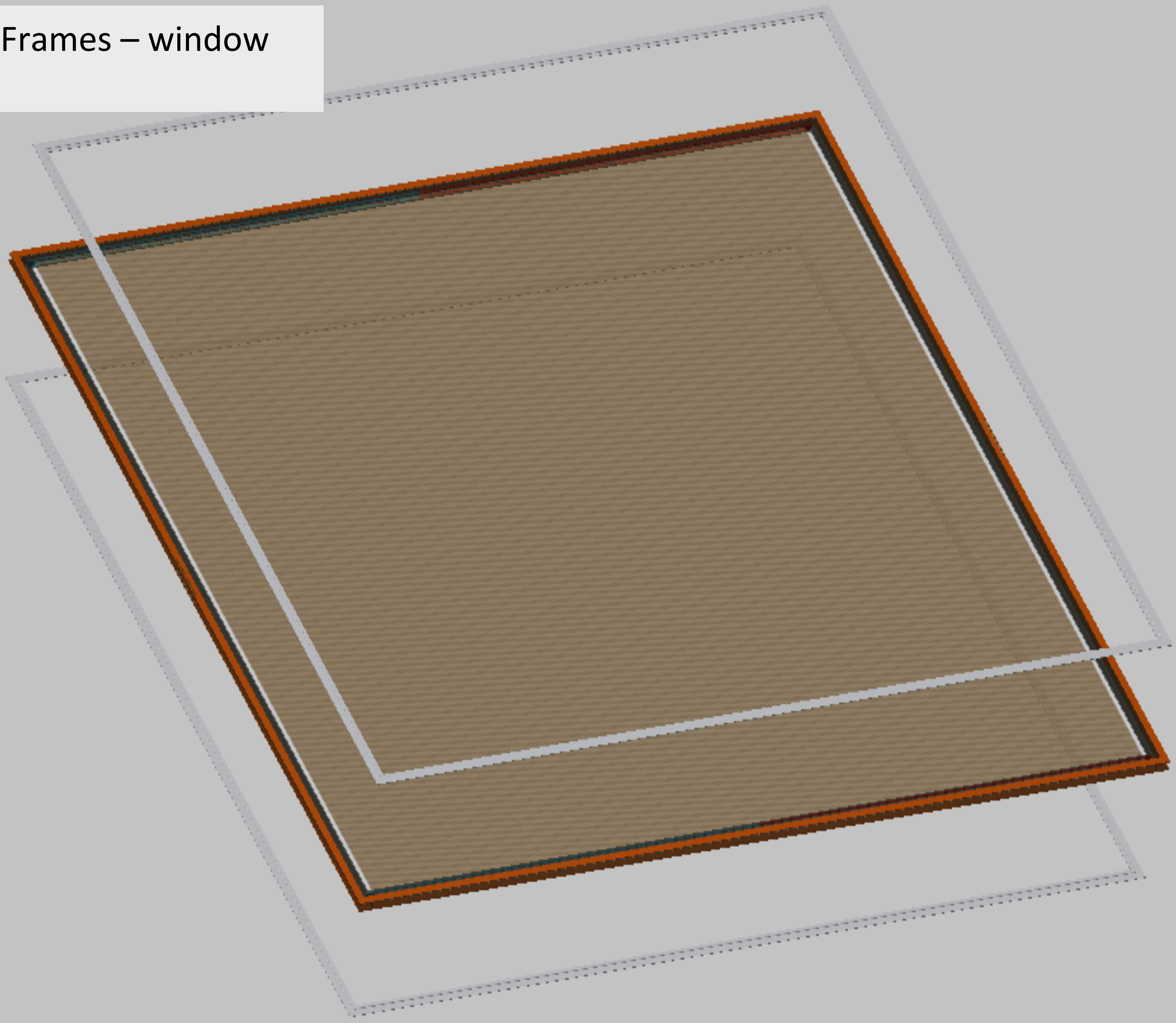


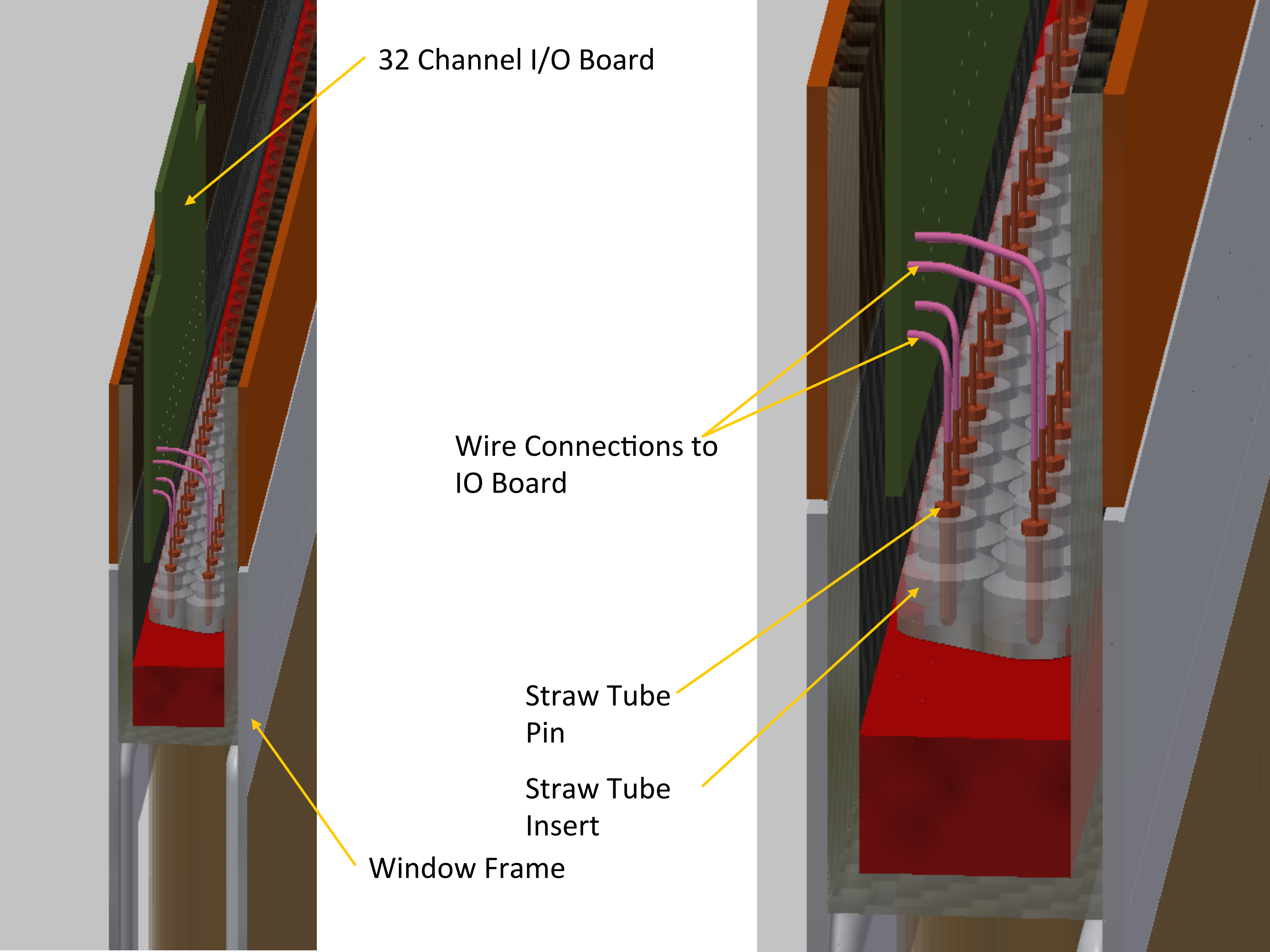
Remove shipping fixtures

Result: XX straw tube plane assembly with 672 straws
3500mm x 3500mm x 30mm outside dimensions



Install Window Frames – window foil not shown




32 Channel I/O Board
Wire Connections to IO Board
Straw Tube Pin
Straw Tube Insert
Window Frame

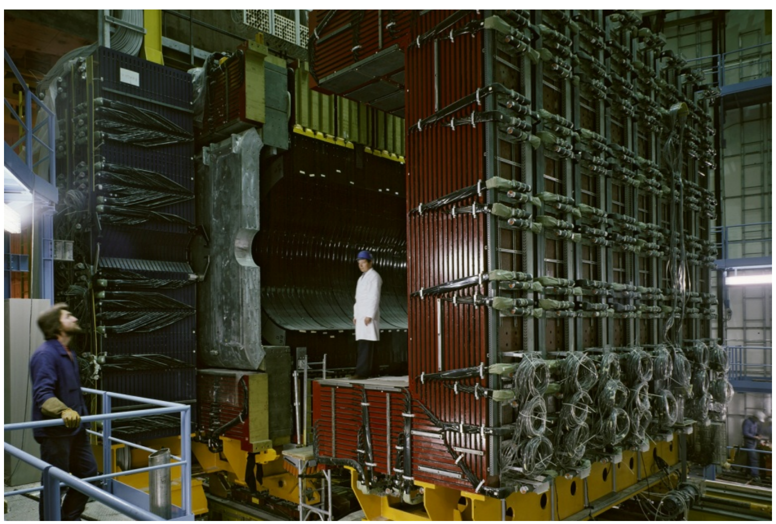
Gross Design Features - Magnets

- Magnetic field useful for charge separation and momentum measurements
- Geometry of typical neutrino beams favors dipole configuration
- Low-density trackers (e.g. straw tubes) can do electron-positron separation
- Requires significant power – especially for cooling (few Mwatts)

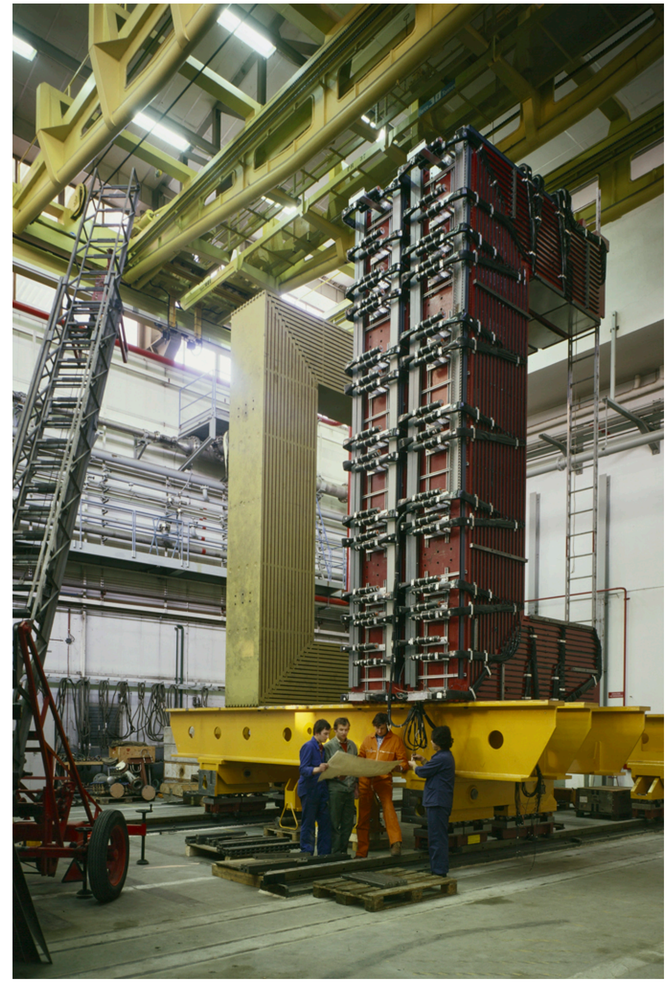
UA1 magnet at CERN:

Yoke material: EN S235JRG2, a European low Carbon steel

Yoke sections assembled, tested



Assembled magnet in hall



2 yoke sections on carriage, the total number of yoke sections is 16

UA1 magnet at CERN:

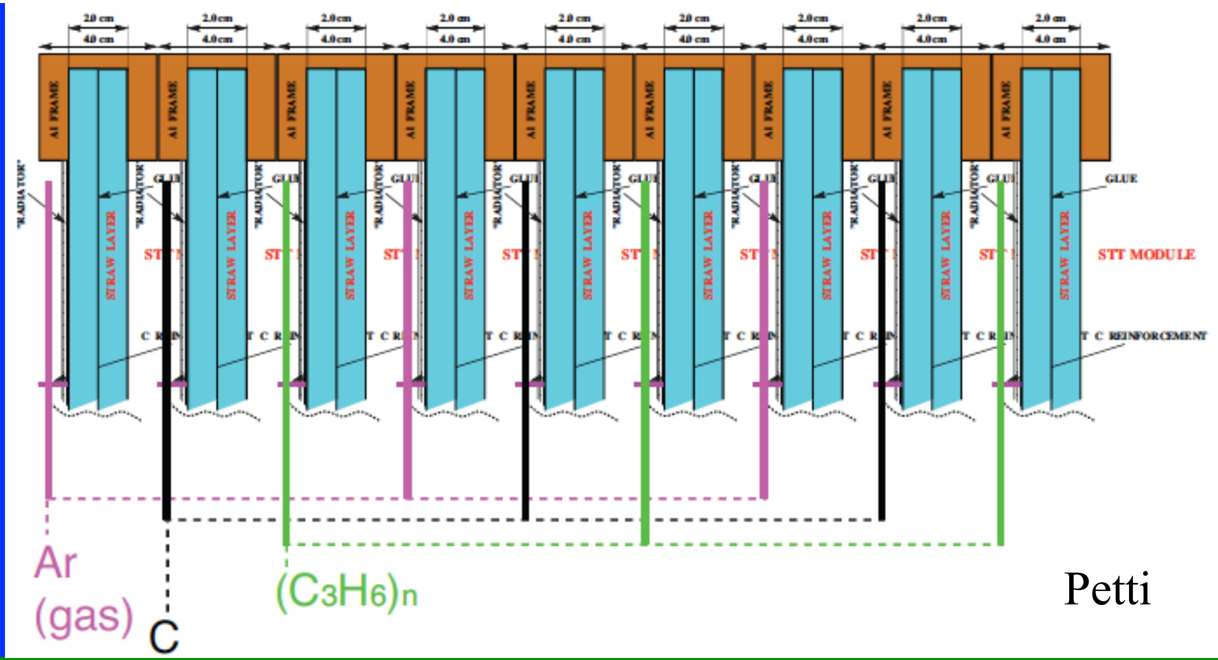
Essential to have a continuous magnetic circuit in steel yoke -

Assembled yoke sections on carriage in UA1 experimental hall at CERN. Total magnet weight 850. tons.
Data taking started in November, 1981.
Operating properties: 10,000 amps, 576. V., resistance .0576Ω @ 40.^{o} C. Cooling water flow 50. liters/sec.
Original yoke costs – 2,000,000.00 *Euros* in 1978.

Sondheim

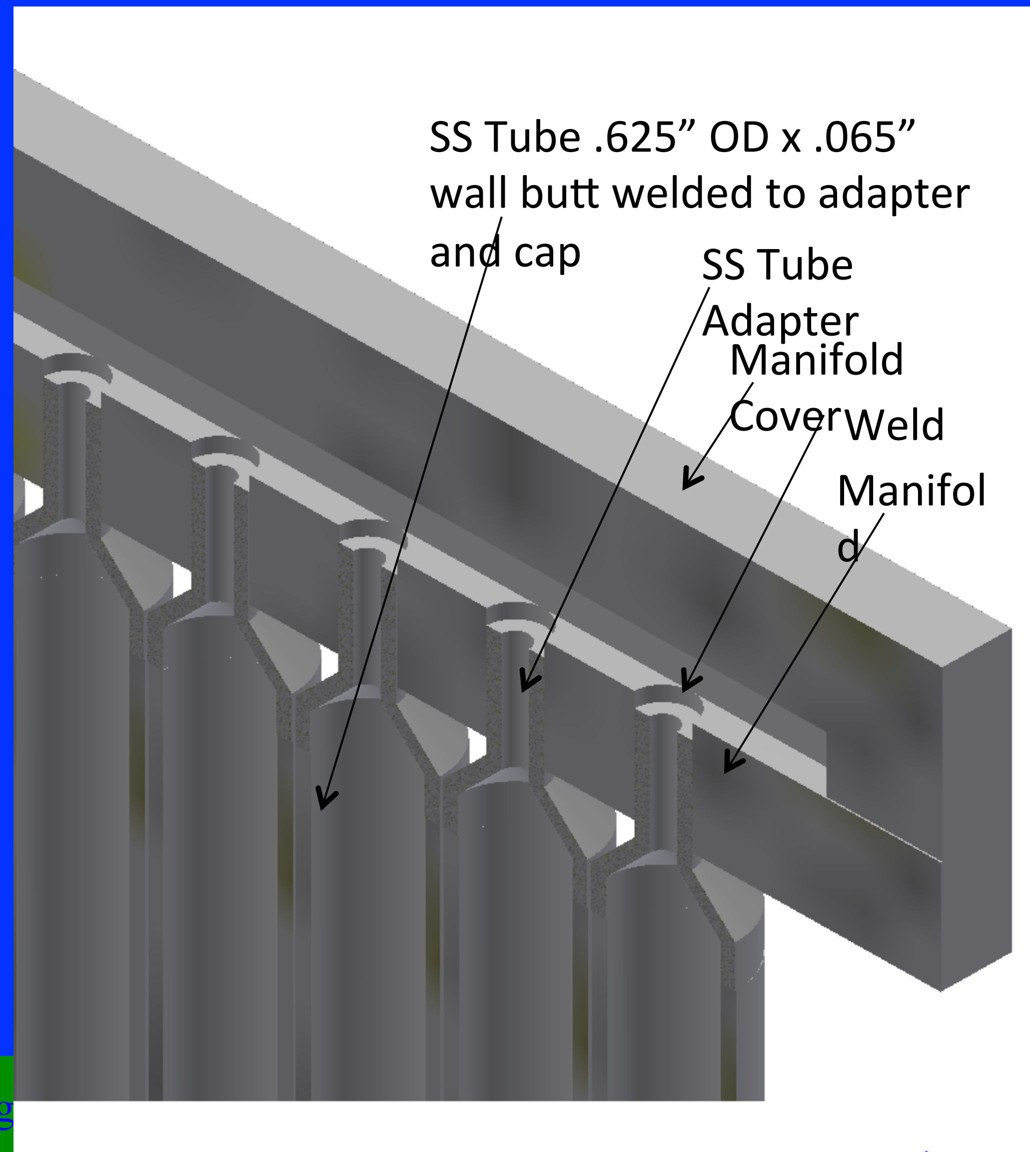
Gross Design Features – Nuclear Targets

- Geometry of typical fine-grained trackers such that planes of un-instrumented nuclear targets can be interspersed with tracking material
- This allows good possibilities for neutrino-nucleus interaction studies. Targets can even be swapped out.
- Care must be taken due to absorbed particles and side-going particles that will be missed.



Gross Design Features – Nuclear Targets

- Some materials require specialized target containment – gases, liquids
- In the case of liquid, liquid in, liquid out studies can be performed
- In the case of gas, can vary the pressure continuously to enable efficiency studies



Advantages and Disadvantages to Fine-Grained Trackers

- Advantages
  - exquisite reconstruction possible
  - similarities to collider physics detectors
    - share reconstruction tools, development costs, materials and component costs
  - non-uniform: design flexibility
- Disadvantages
  - non-uniform, need to study efficiencies carefully
  - dead space
  - Issues of non-uniformity/dead space different from collider detectors since vertices happen anywhere
  - cost scales like volume – not a problem for current and future experiments

Conclusions

- Fine-grained trackers have a long history in neutrino physics.
- FGTs benefit from similarities to detector systems in other communities (e.g. collider physics)
- FGT designs can be tuned to the event rate, energy regime and background environment of a particular experiment
- FGTs are optimal for high precision studies important for understanding neutrino interactions