Updates on Detector Beam Pipe Modeling in Geant4/DD4Hep

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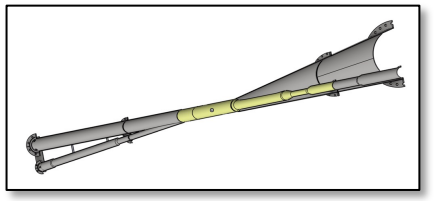
Acknowledgements:

Many thanks to Charles Hetzel (EIC Vacuum Group) for provided materials and discussions

Summary



Status Update: Beam Pipe Modeling in DD4hep

- Until recently, we were using an outdated beam pipe model in DD4hep (developed pre-2023).
  - This model did **not match** the vacuum geometry used for gas pressure and synchrotron radiation (SR) studies in the EIC.
- In Dec. 2023, the first realistic SR simulations revealed discrepancies between the beam pipe models, leading to:
  - **Incorrect detector background estimates**
  - **Geometry overlaps**, especially near the **hadron outgoing cone**.
- In Mar. 2025, the EIC Vacuum Group released an **updated IR6 beam pipe design**, driven by:
  - SR background constraints
  - Machine impedance requirements
  - Engineering feasibility

New Implementation (Dev Branch)

- New DD4hep beam pipe includes:
  - Vacuum region
  - Copper coating (critical for SR absorption)
  - Stainless-steel wall
- The **electron beam pipe** contains a **racetrack-to-circular transition**, which:
  - Cannot be constructed using standard DD4hep solids
  - Is modeled with **tessellated volumes**, which may still require refinement
  - A cutout in the **hadron cone** introduces geometry artifacts:
    - The Boolean subtraction is unstable and may lead to overlaps
- **Complex Boolean combinations** in the hadron/electron pipe cause occasional geometry creation failures

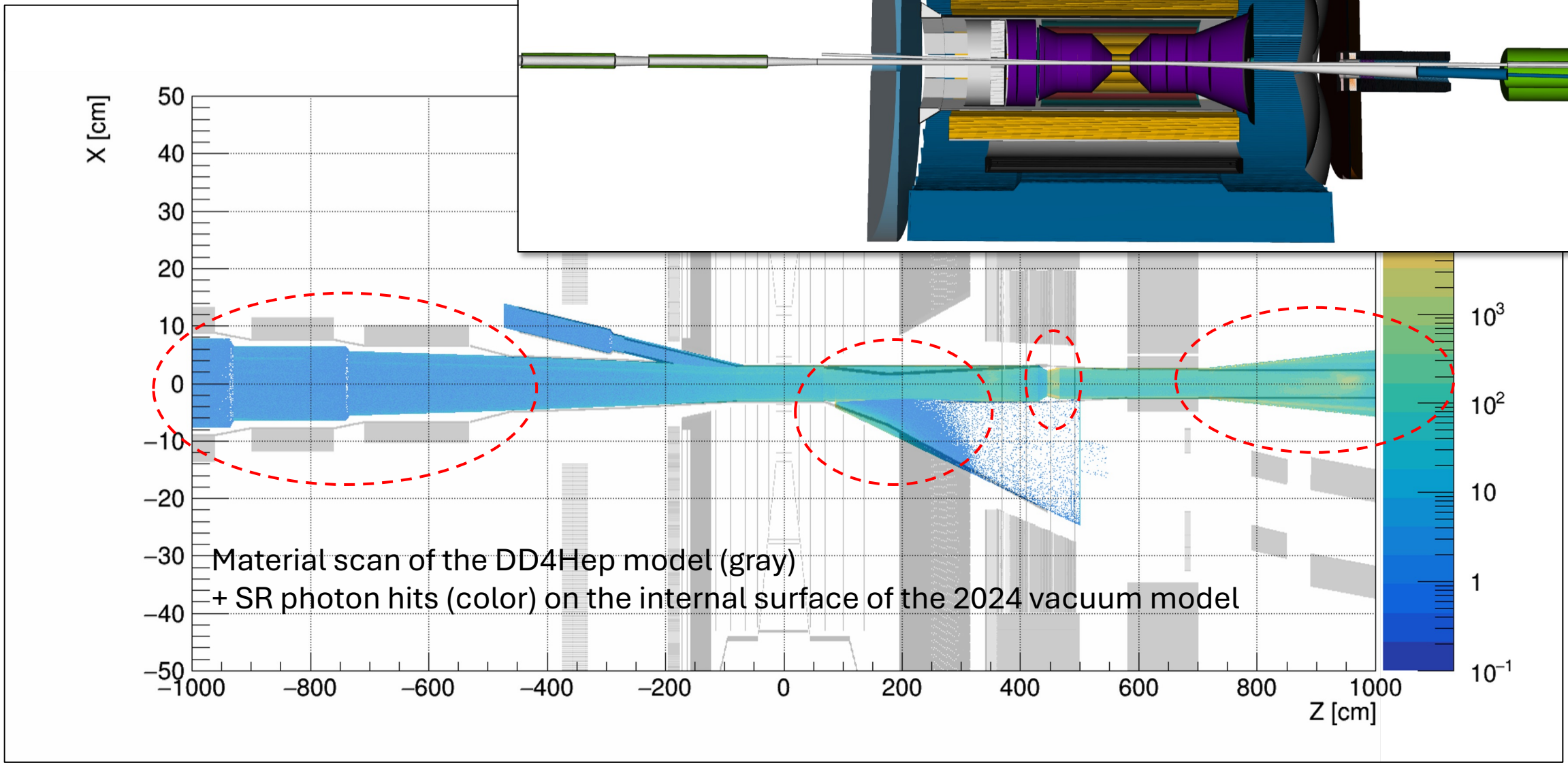
Overlaps & Prospects

- Only **one overlap** is currently detected near the racetrack-circular transition
- **Next Steps**:
  - Finalize vacuum geometry and check overlaps
  - Explore **GDML export/import** for racetrack transitions
  - Reduce Boolean complexity for stability
  - Submit a PR, polish the code, and merge with the main branch

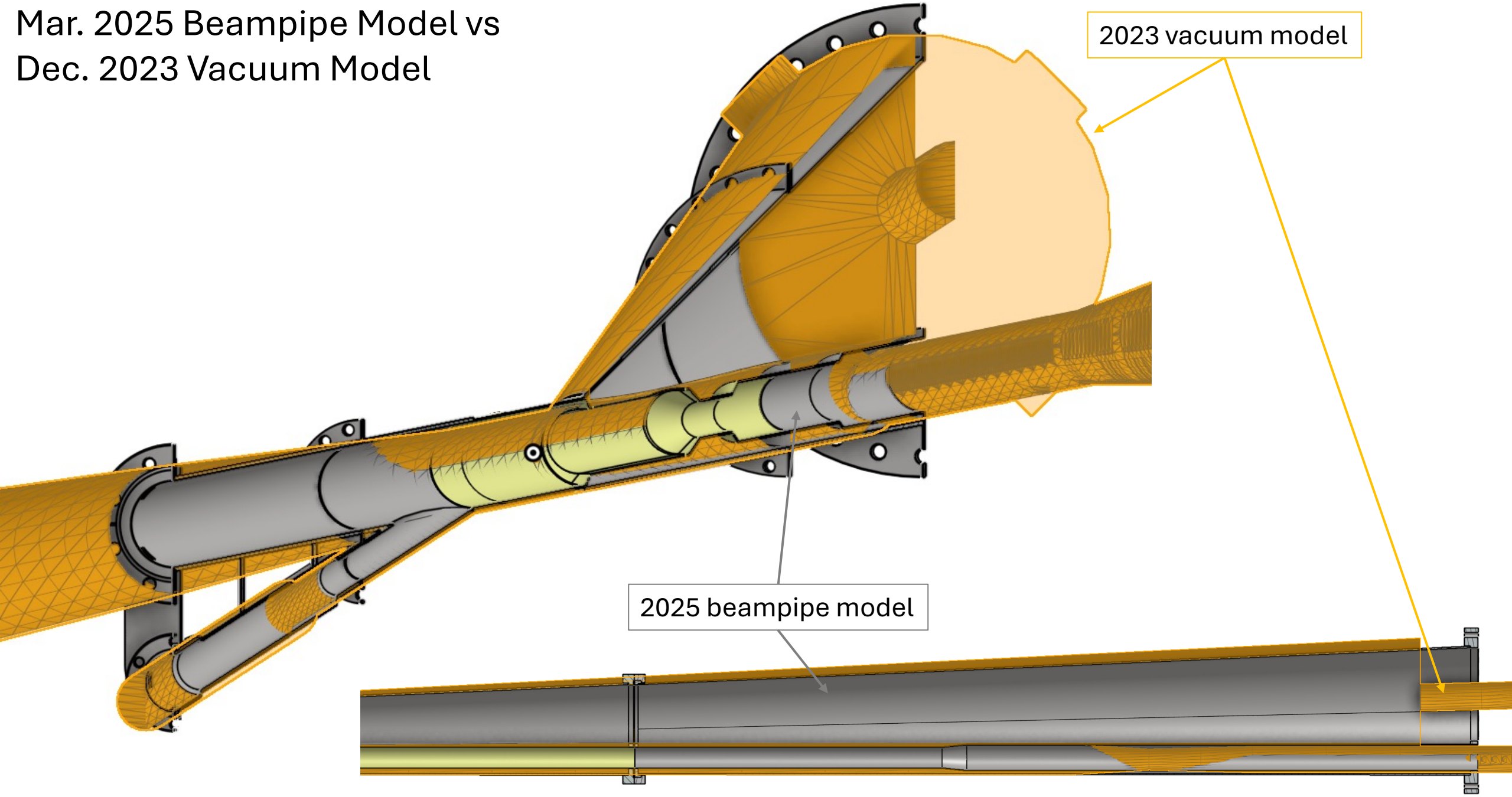
Please note that **updating the ePIC model** in parallel with the beam pipe is **crucial** for accurate detector radiation and background estimation.

Dec. 2023 DD4Hep vs Dec. 2023 Vacuum Model

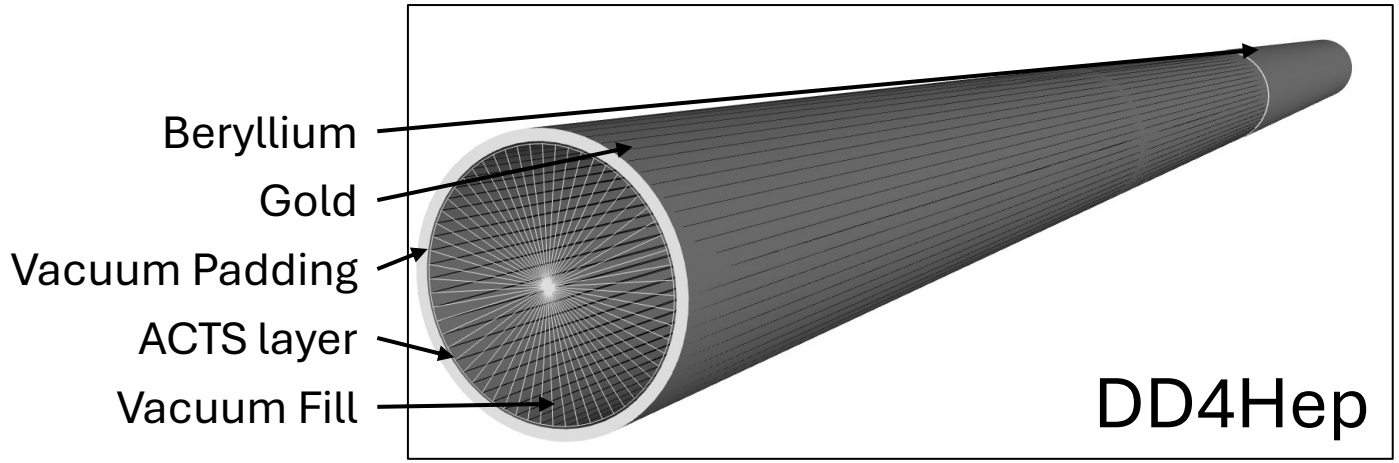
Overlaps

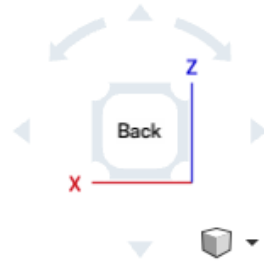


Mar. 2025 Beampipe Model vs Dec. 2023 Vacuum Model

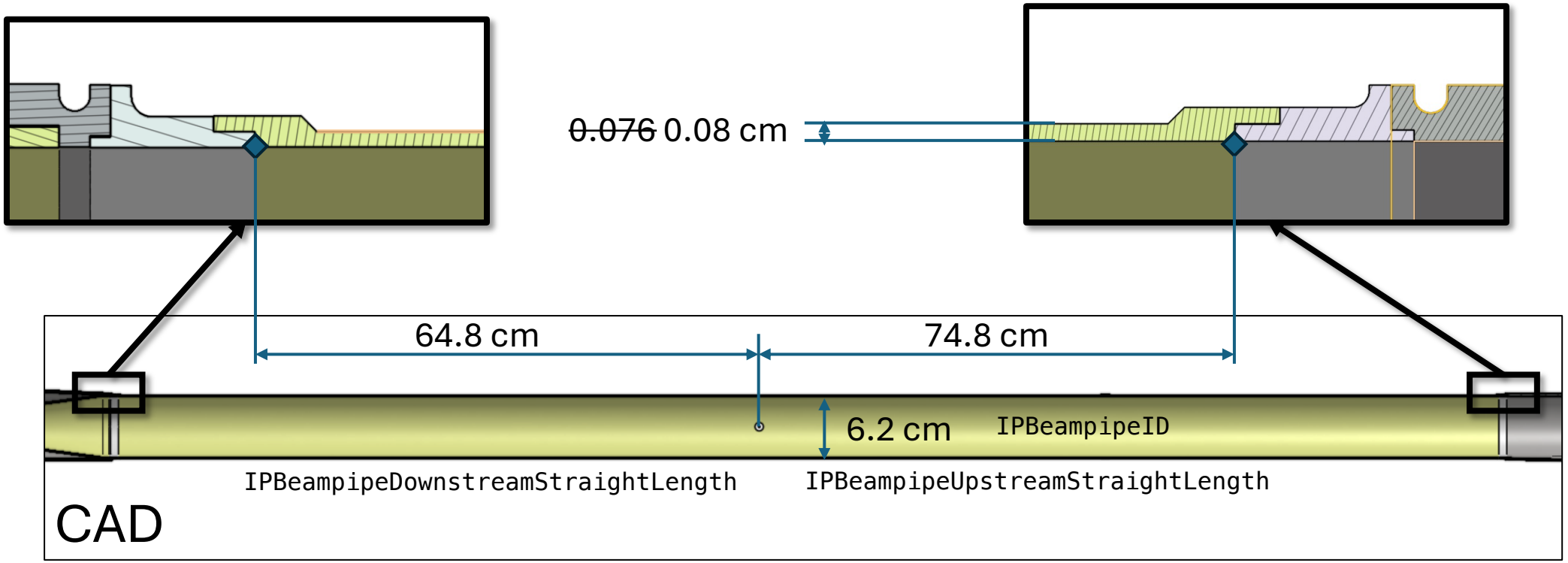


IP6 Beam Pipe

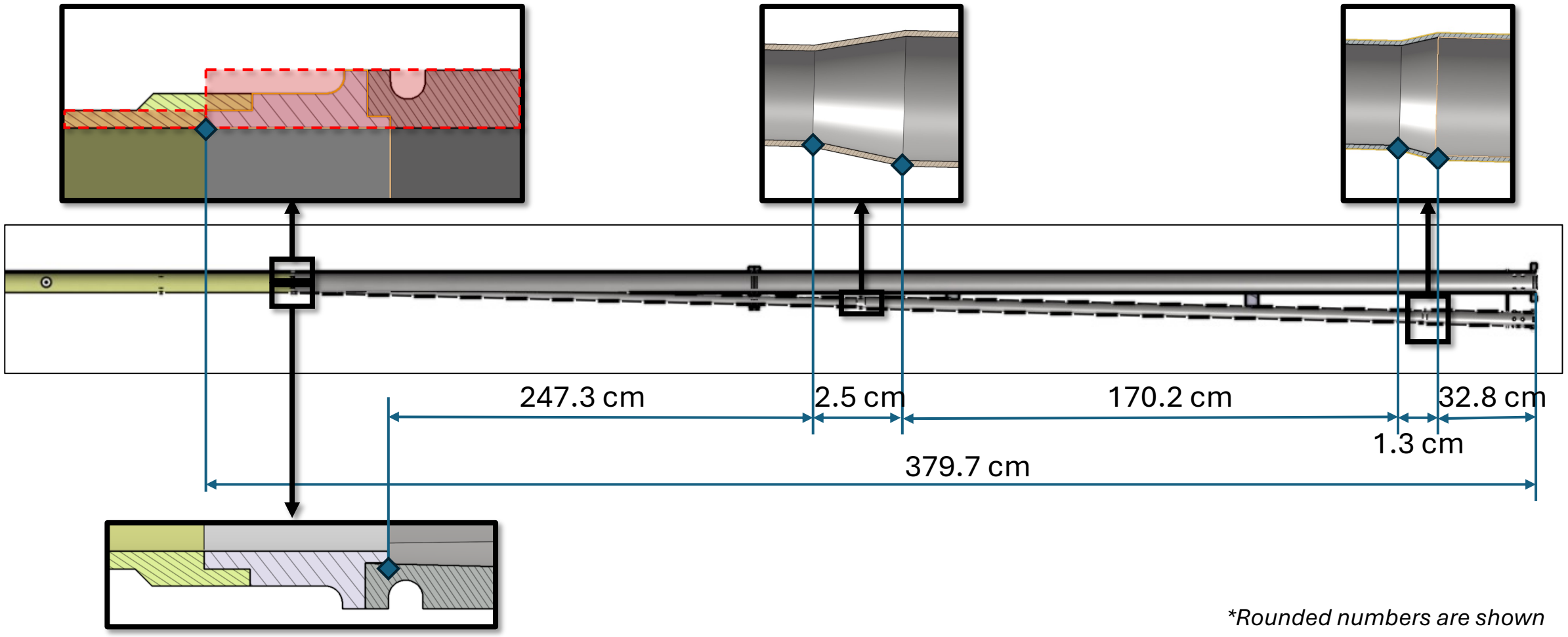




e- beam

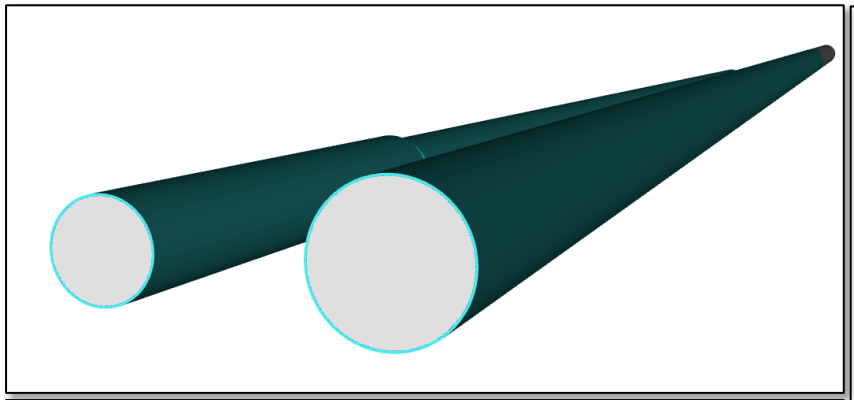


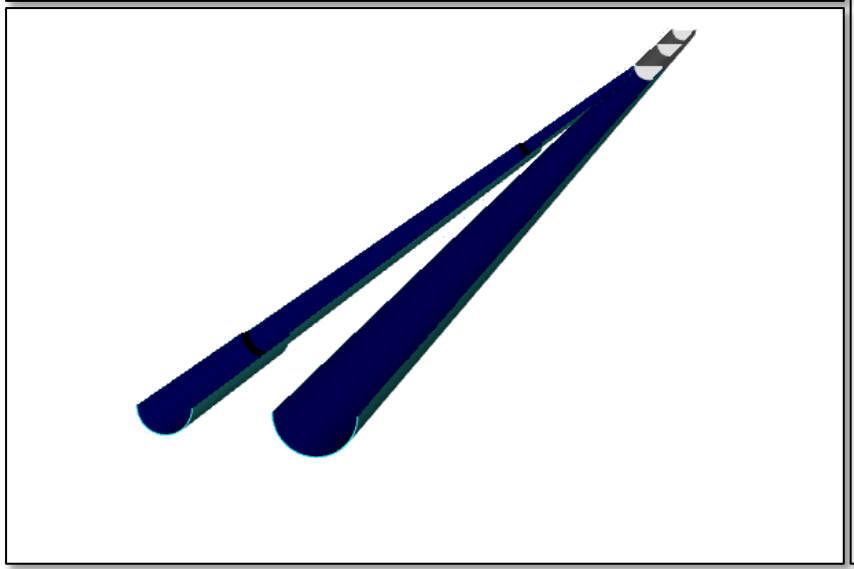
Rear Side Central Beam Pipe: CAD

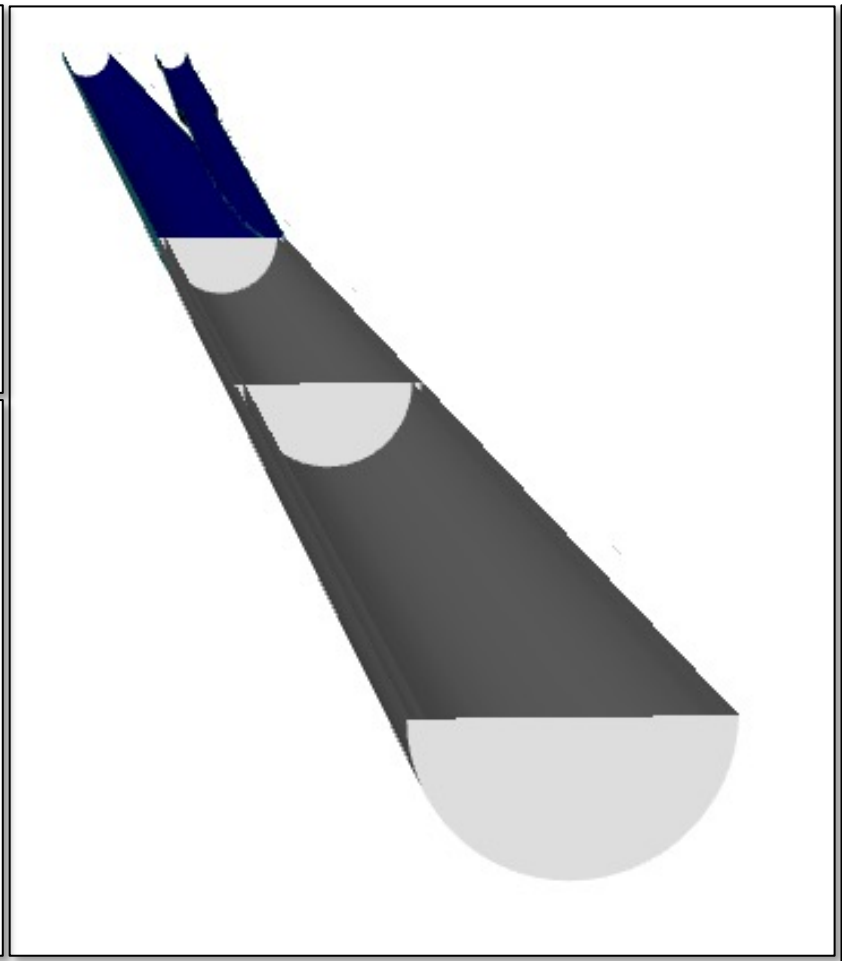


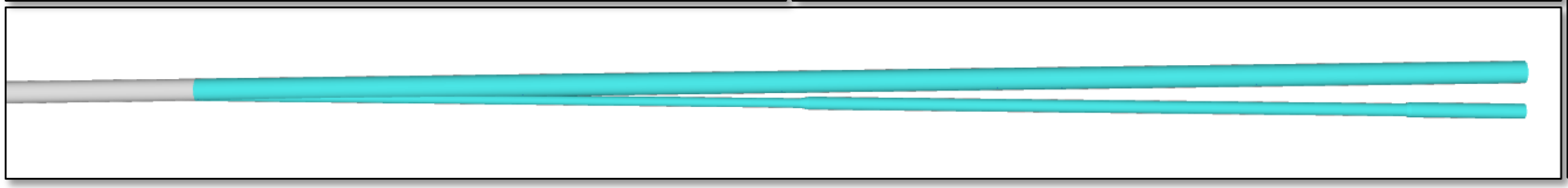
*Rounded numbers are shown

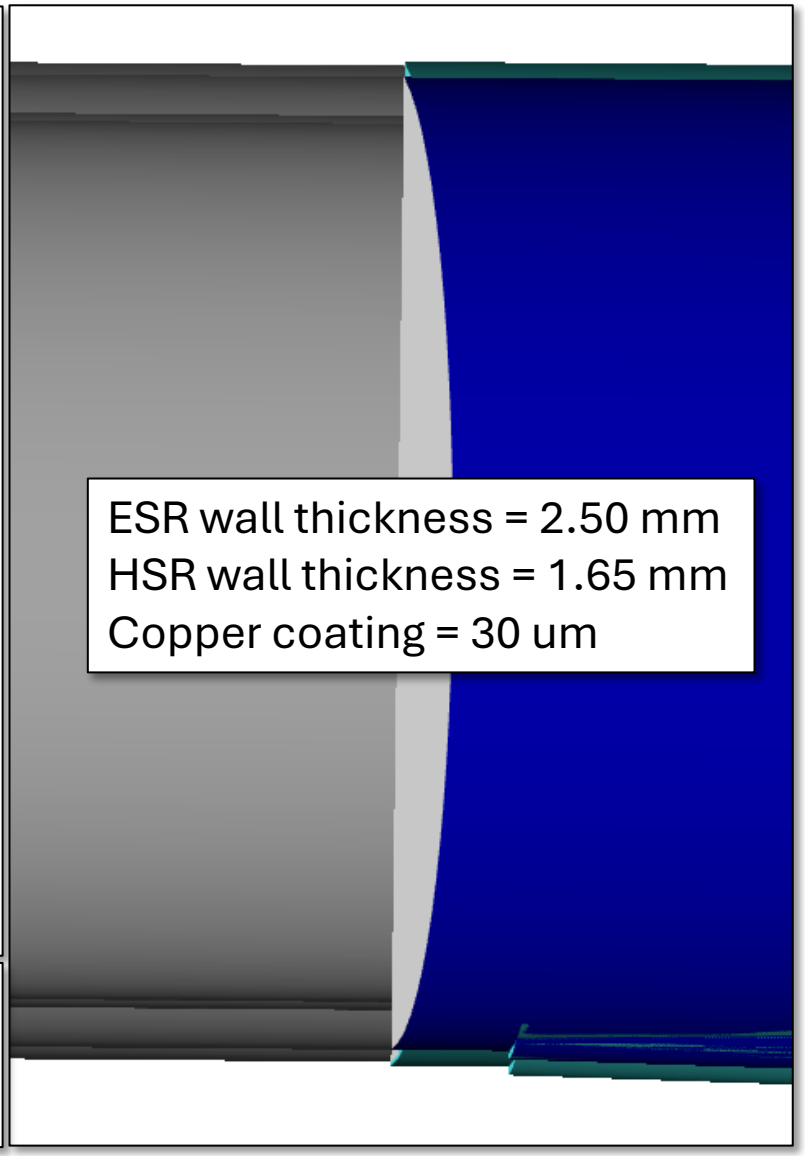
Rear Side Central Beam Pipe: DD4Hep



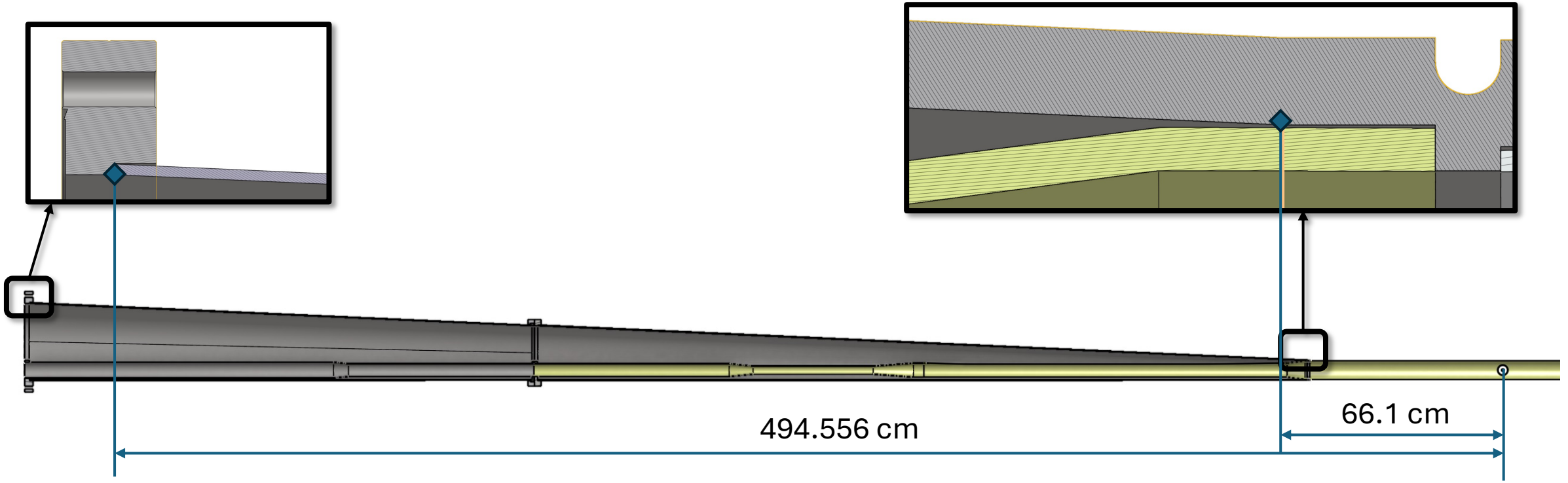


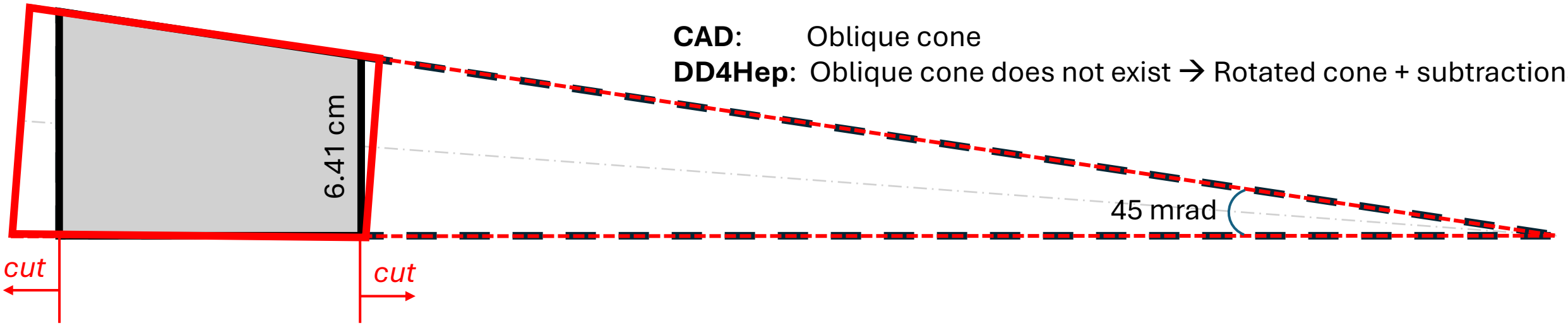






FWD Side Central Beam Pipe: CAD

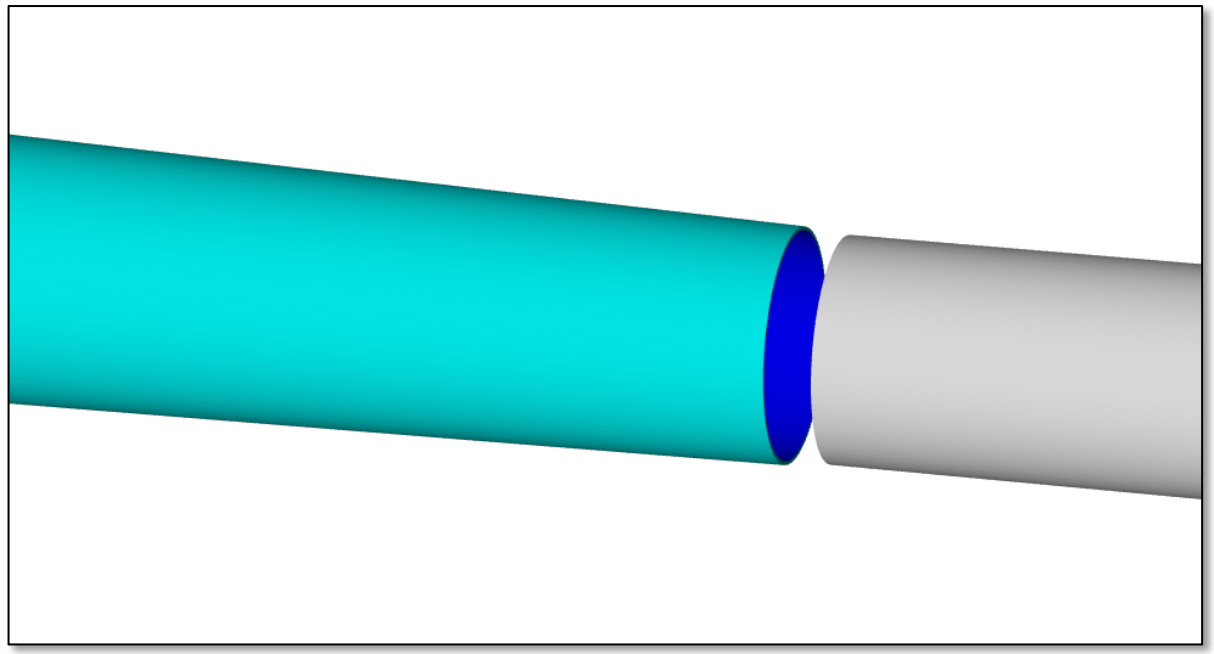


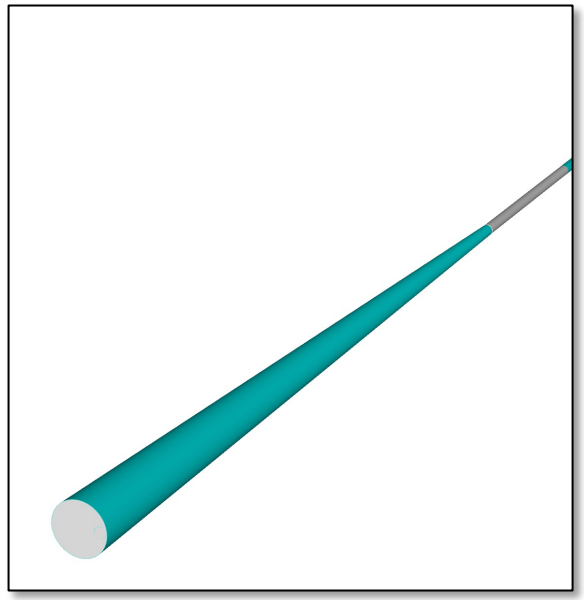


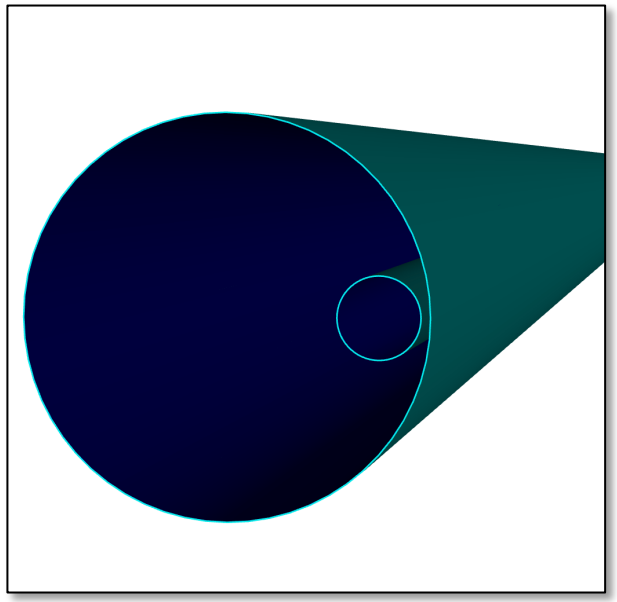
CAD: Oblique cone

DD4Hep: Oblique cone does not exist → Rotated cone + subtractions

FWD Side Central Beam Pipe: DD4Hep



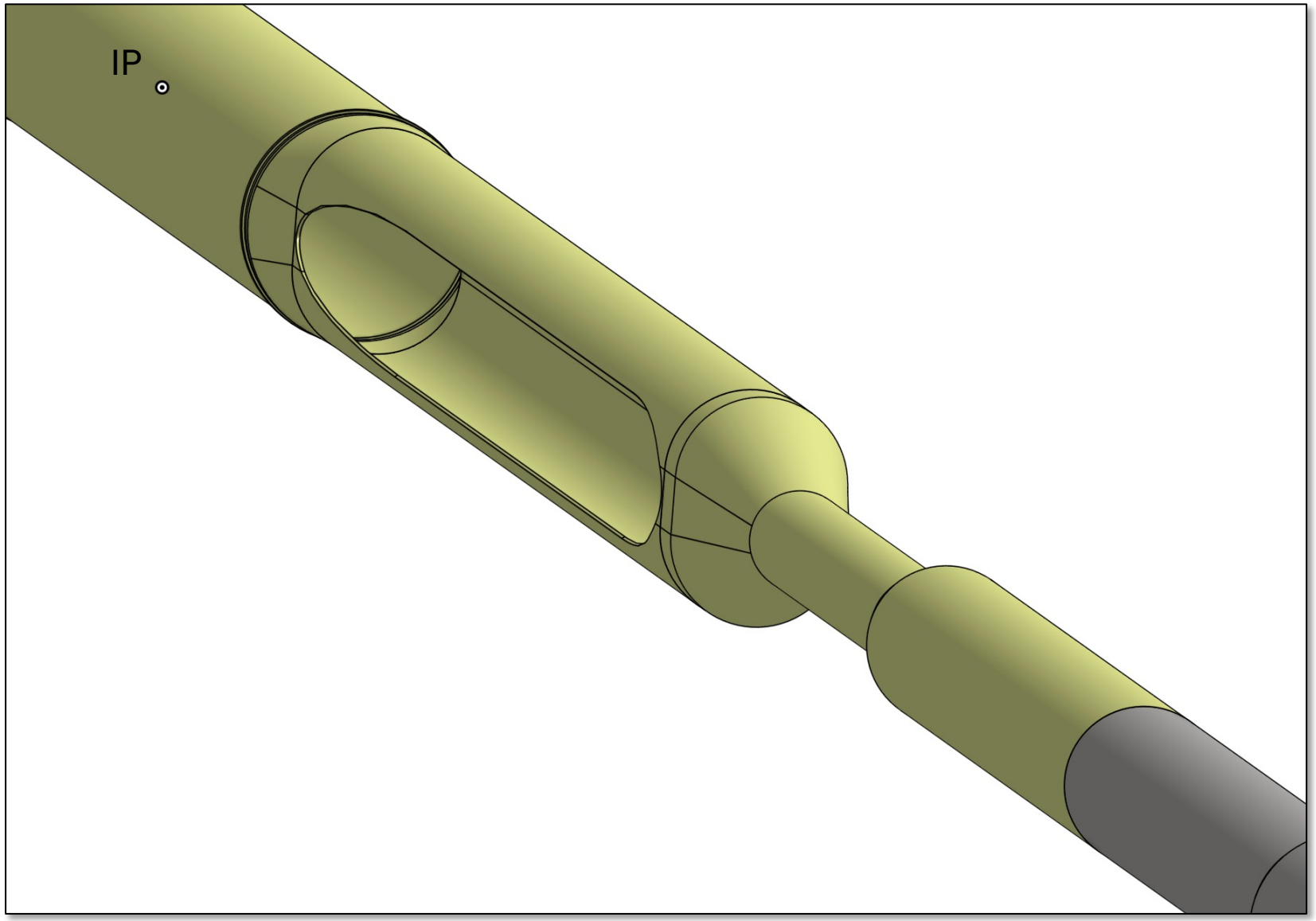




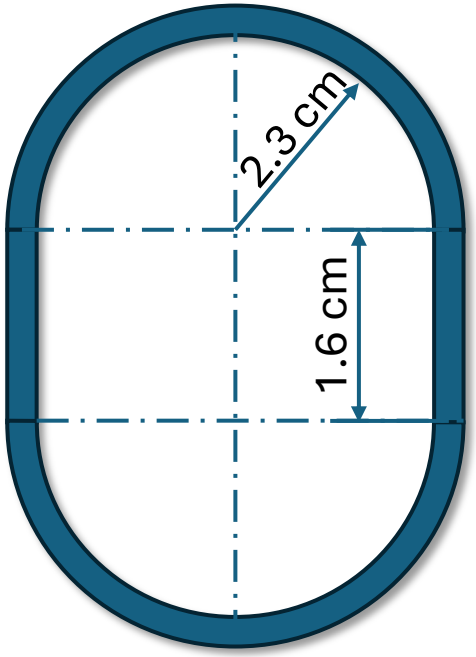
FWD Side Electron Beam Pipe - Racetrack: CAD

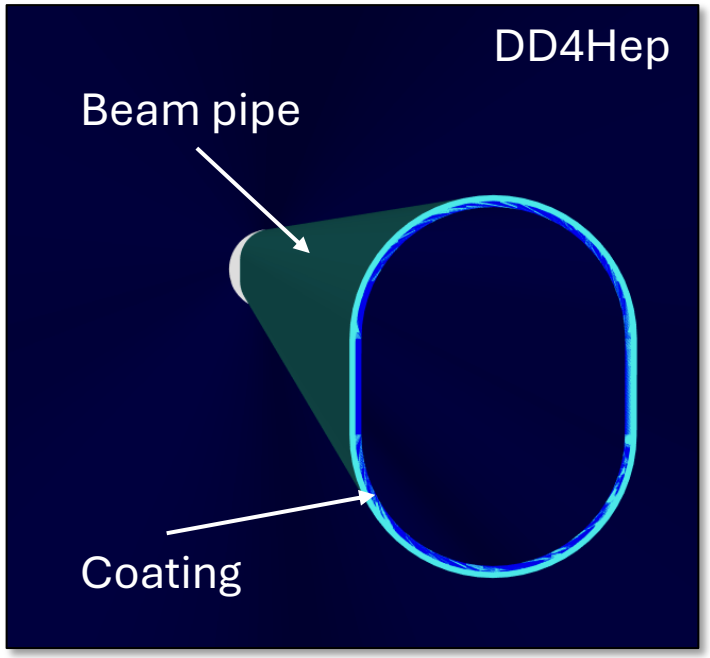
While DD4hep (and ROOT/Geant4) does not have a built-in racetrack primitive, it can be built using **Boolean operations** (i.e., UnionSolid) between:

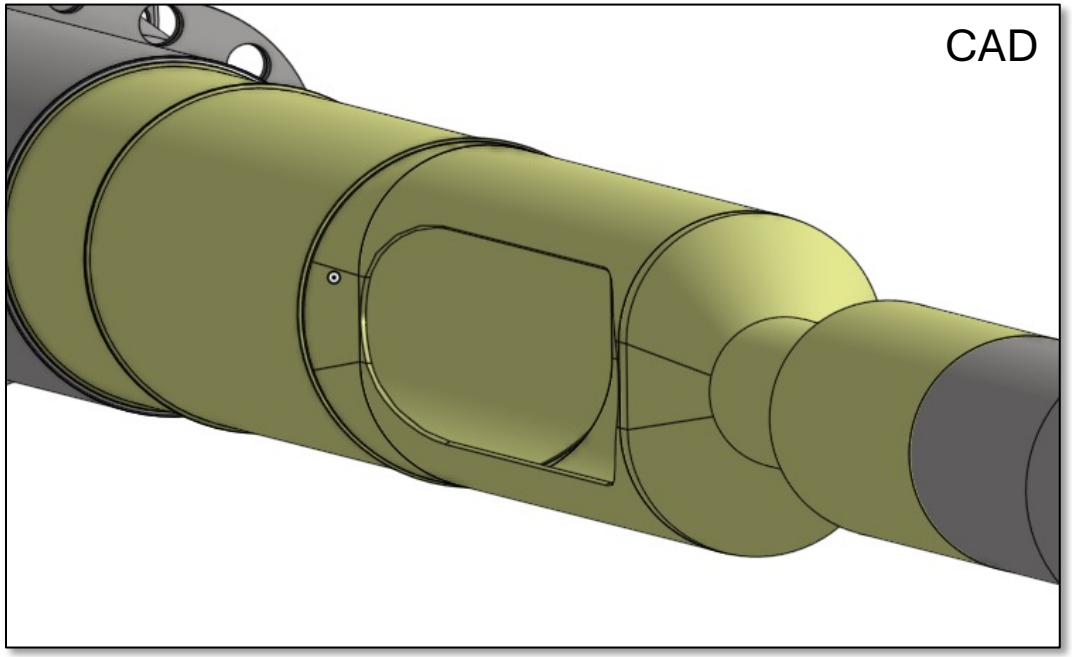
- A **box** (for the straight section)
- Two **cylinders** (for the semicircular ends)



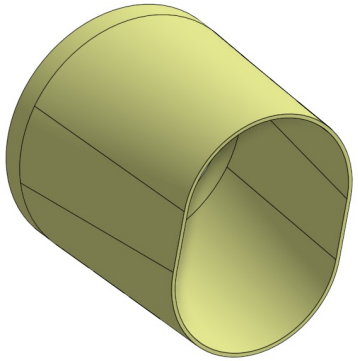
FWD Side Electron Beam Pipe - Racetrack: DD4Hep vs CAD





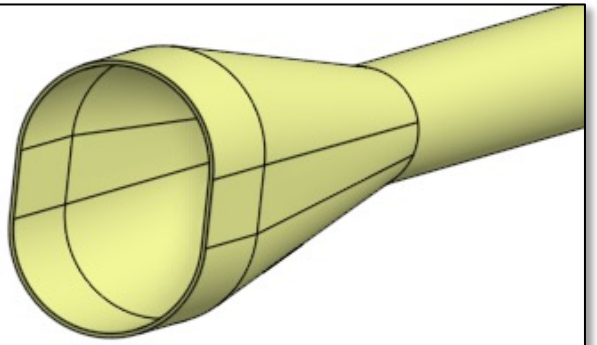


FWD Side Electron Beam Pipe – Racetrack-Cylinder Interface: DD4Hep vs CAD

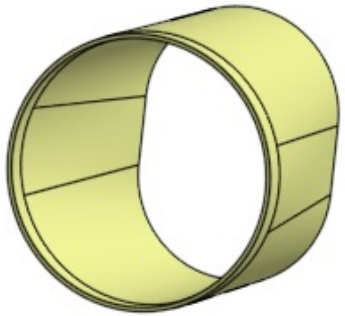


Assumptions:

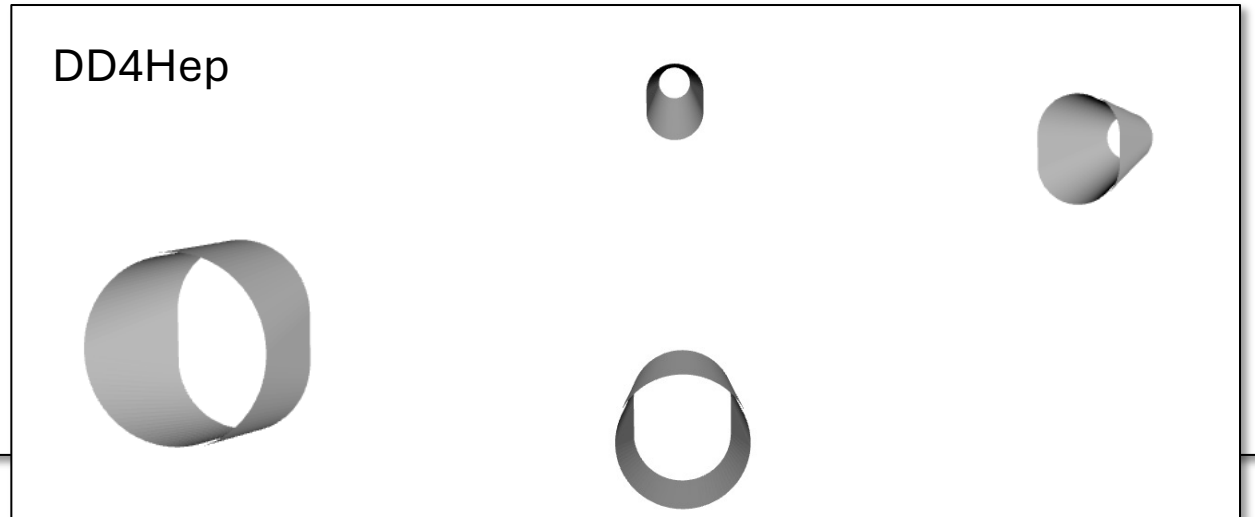
- The **cylinder** has a circular cross-section.
- The **racetrack** has a flat section + semicircles.
- The interface region is a **short transition piece** where the circular face morphs into the racetrack shape.
- Approximate both ends using **tessellated solids** without coating to avoid overlaps.

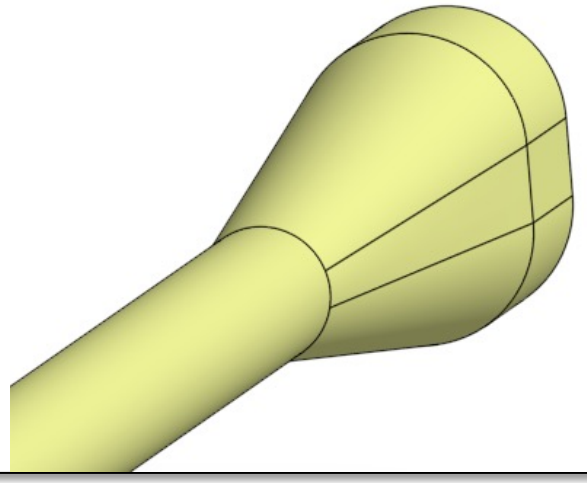


CAD

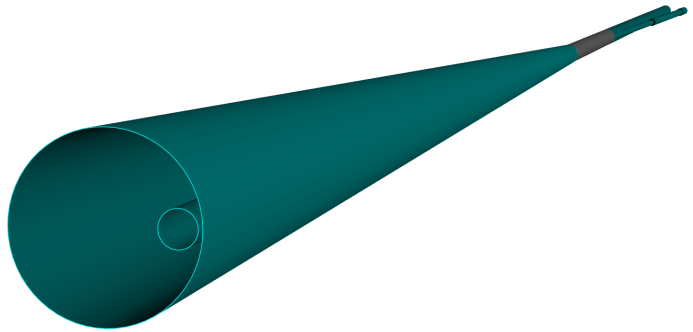


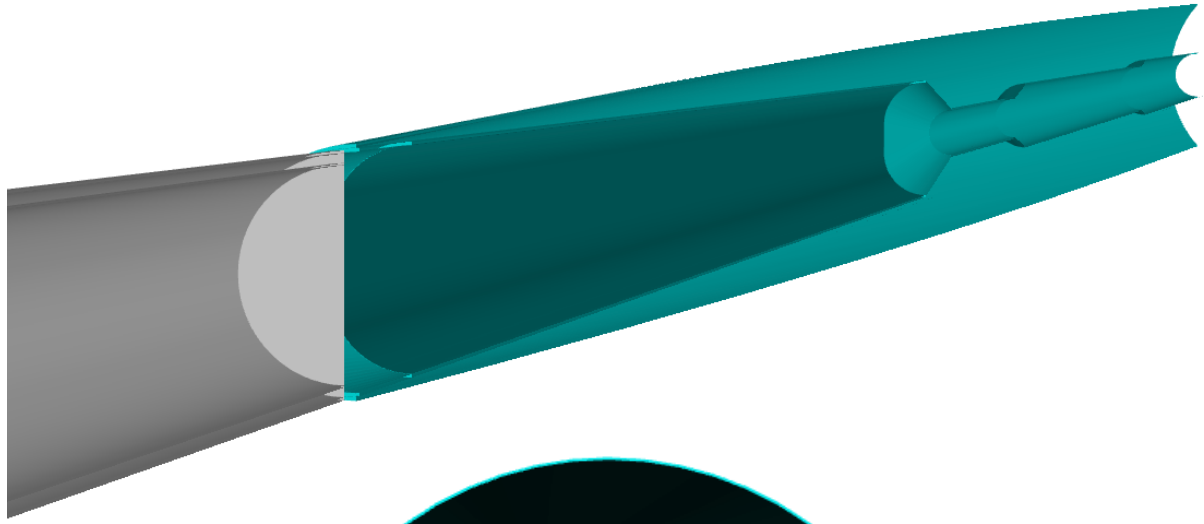
DD4Hep

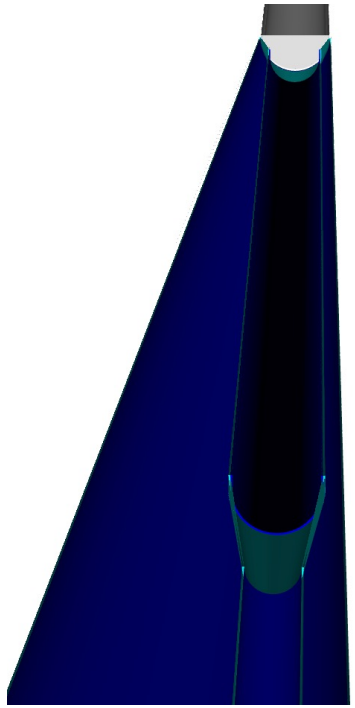


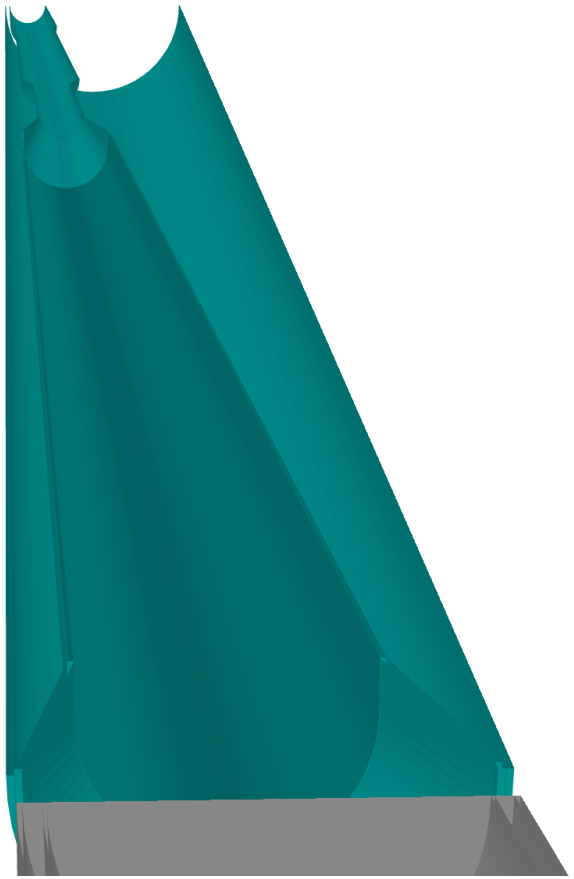


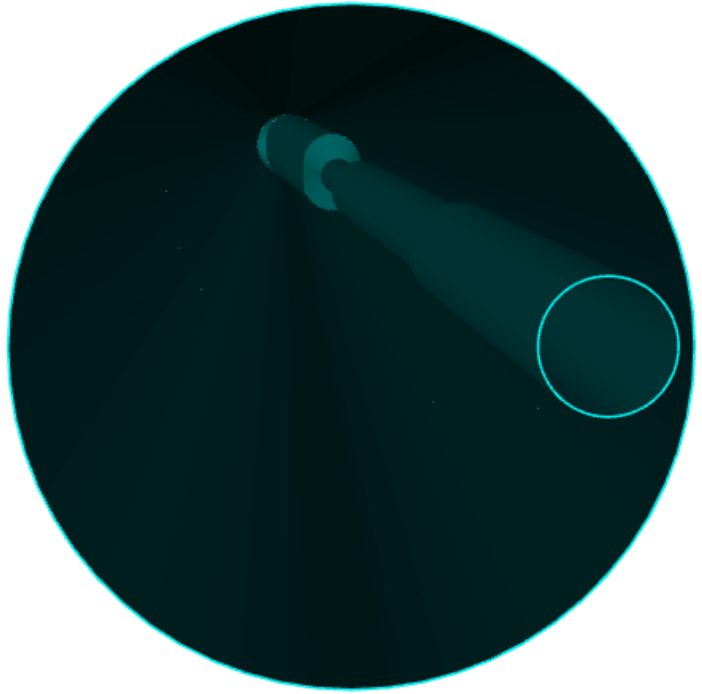
FWD Side Electron Beam Pipe: DD4Hep

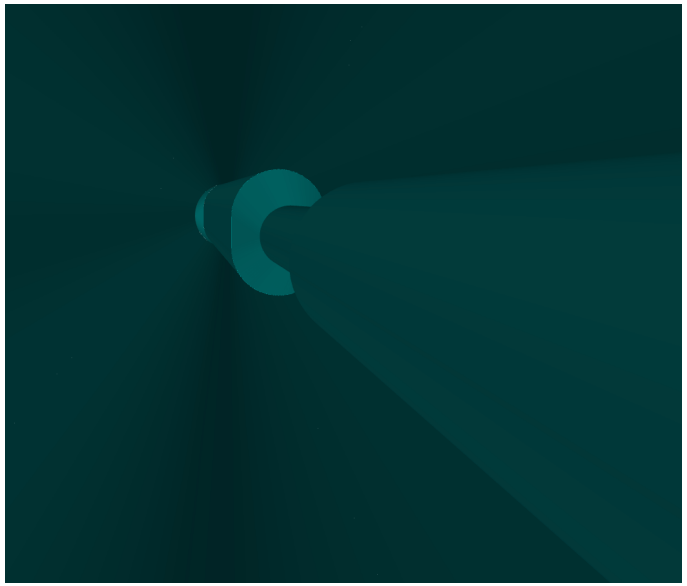






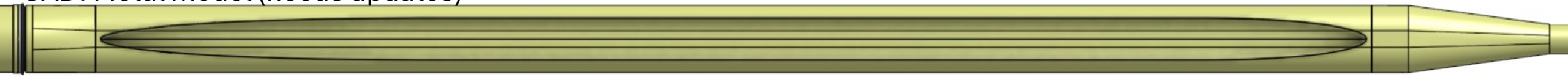




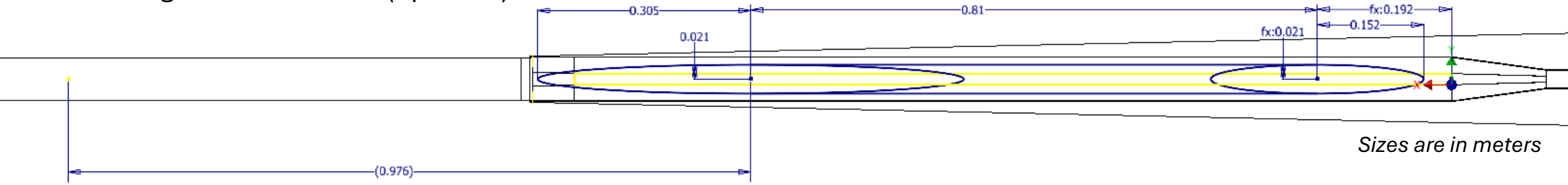


FWD Side Electron Beam Pipe: Hadron Beam Opening

CAD: Metal model (needs updates)

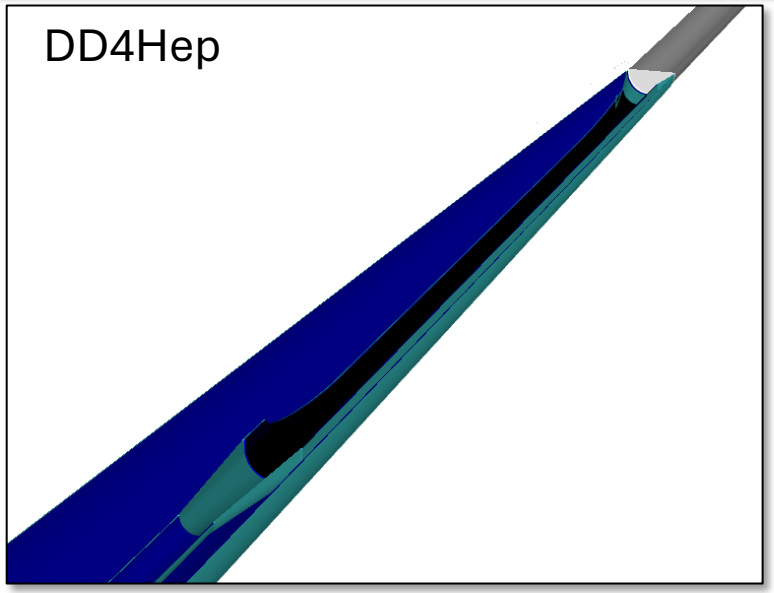


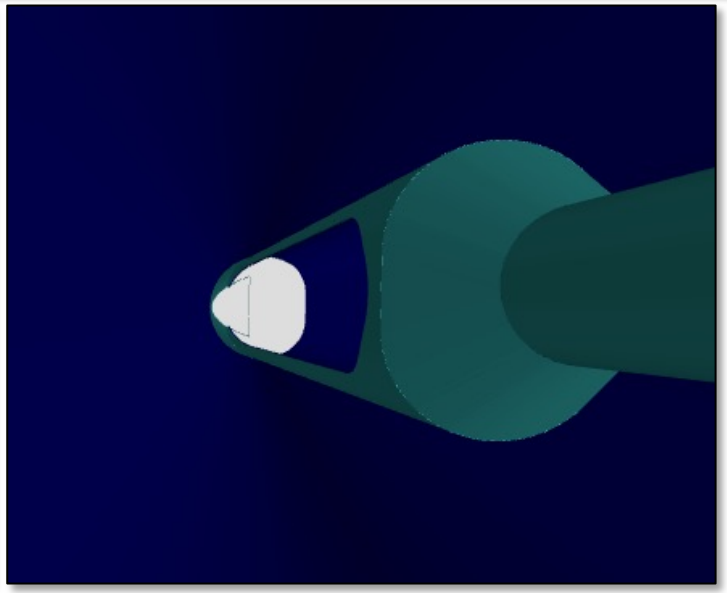
TechDrawing: Vacuum model (updated)

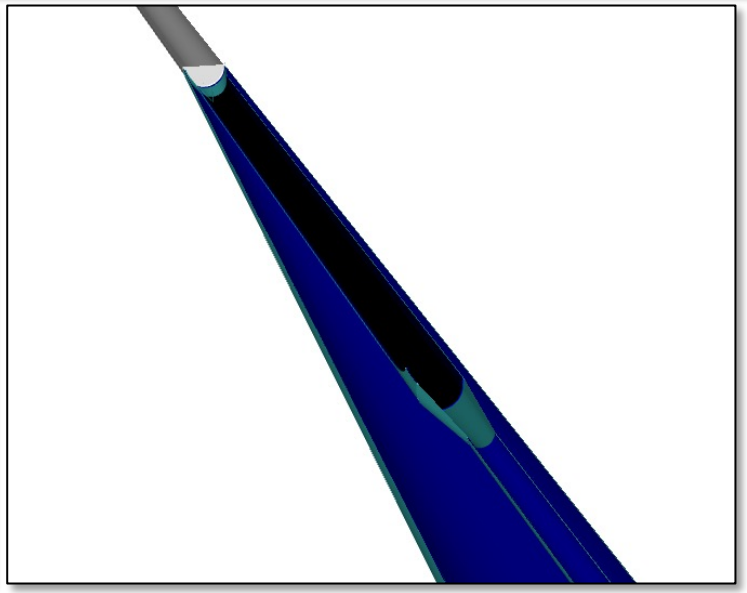


Sizes are in meters

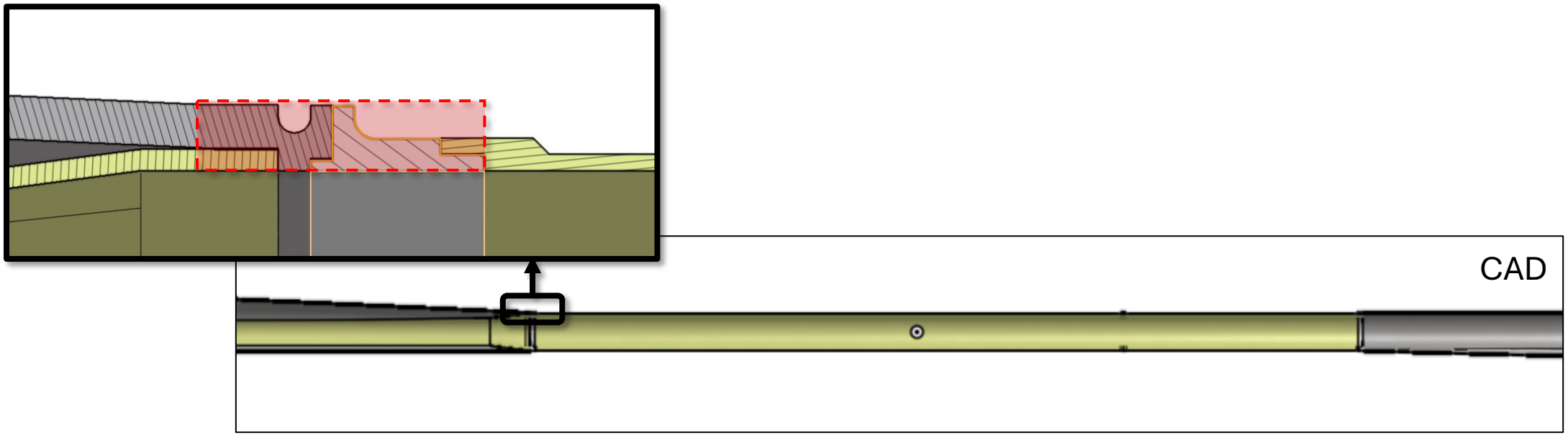
DD4Hep

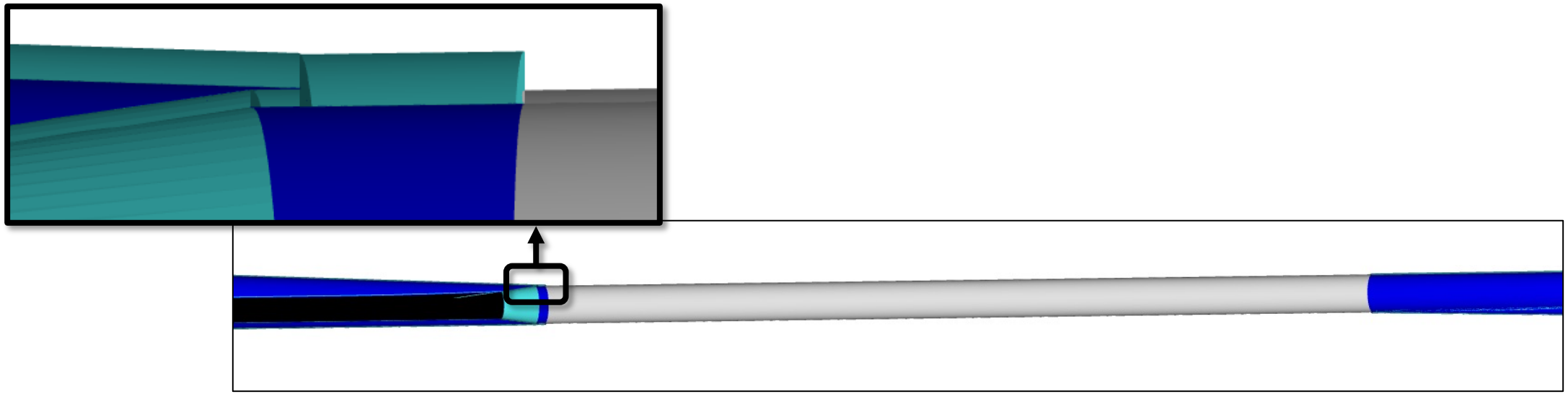






FWD IP Flange





ePIC and Beampipe Overlap: DD4Hep

```
INFO: +++================================================================================================================================
INFO: +++ Loading compact geometry:
INFO: +++ /Users/andriinatochii/eic/epic/install/share/epic/epic.xml
INFO: +++ tolerance: 0.100000, option:
INFO: +++================================================================================================================================


Info in <TGeoManager::TGeoManager>: Geometry default, Detector Geometry created
Info in <TGeoNavigator::BuildCache>: --- Maximum geometry depth set to 100
Info in <TGeoManager::SetTopVolume>: Top volume is world_volume. Master volume is world_volume
Info in <TGeoManager::CheckGeometry>: Fixing runtime shapes...
Info in <TGeoManager::CheckGeometry>: ...Nothing to fix
Info in <TGeoManager::CloseGeometry>: Counting nodes...
Info in <TGeoManager::Voxelize>: Voxelizing...
Error in <TGeoVoxelFinder::SortAll>: Volume EcalEndcapPInsert: Cannot make slices on any axis
Info in <TGeoManager::CloseGeometry>: Building cache...
Info in <TGeoManager::CountLevels>: max level = 7, max placements = 7714
Info in <TGeoManager::CloseGeometry>: 5385286 nodes/ 4727 volume UID's in Detector Geometry
Info in <TGeoManager::CloseGeometry>: ----------------modeler ready----------------
…
Info in <TGeoNodeMatrix::CheckOverlaps>: Checking overlaps for world_volume and daughters within 0.1
TGeoMatrix::dtor:0: RuntimeWarning: Registered matrix LumiPhotonChamber_placement was removed
TGeoMatrix::dtor:0: RuntimeWarning: Registered matrix AnalyzerMag_assembly_placement was removed
TGeoChecker::CheckOverlaps:0: RuntimeWarning: Volume EcalEndcapPInsert with 2 daughters but not voxelized
TGeoMatrix::dtor:0: RuntimeWarning: Registered matrix Station1Bottom_placement was removed
TGeoMatrix::dtor:0: RuntimeWarning: Registered matrix Station1Top_placement was removed
TGeoMatrix::dtor:0: RuntimeWarning: Registered matrix Station2Bottom_placement was removed
TGeoMatrix::dtor:0: RuntimeWarning: Registered matrix Station2Top_placement was removed
Check overlaps:      [==========] 5385286 [100.00 %]
Info in <TGeoNodeMatrix::CheckOverlaps>: Number of illegal overlaps/extrusions : 1


INFO: +++================================================================================================================================
INFO: +++ Printing overlaps of geometry:
INFO: +++ /Users/andriinatochii/eic/epic/install/share/epic/epic.xml
INFO: +++================================================================================================================================


=== Overlaps for Default ===
 = Overlap ov00000: world_volume/OuterSiTrackerSubAssembly_6/OuterTrackerEndcapP_1/OuterTrackerEndcapP_layer2_0 overlapping
world_volume/BeamPipe_assembly_27/v_downstream_wall_interface_13 ovlp=0.380756
INFO: +++ Execution finished...
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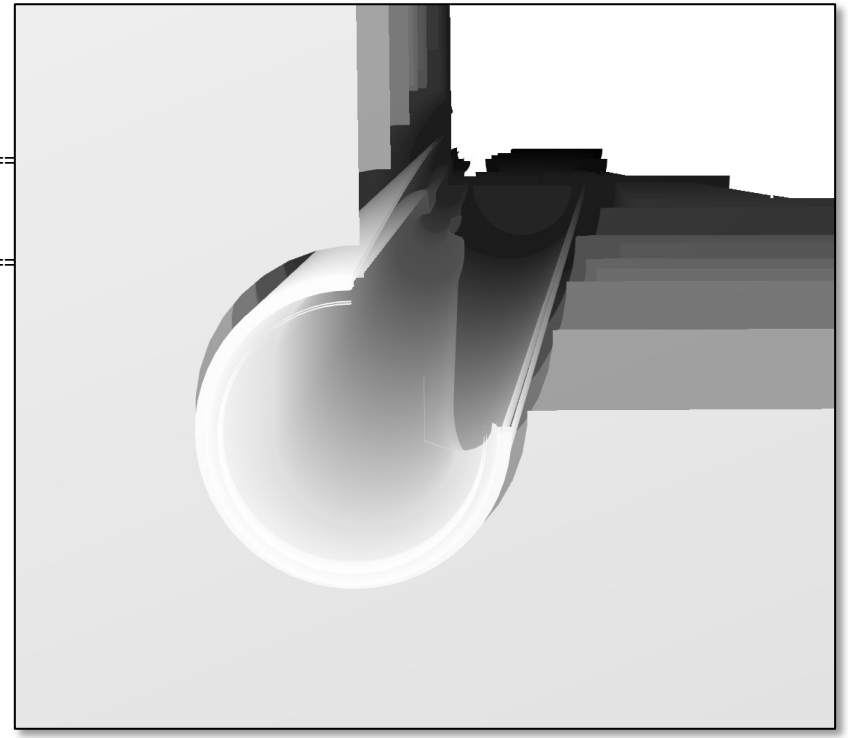

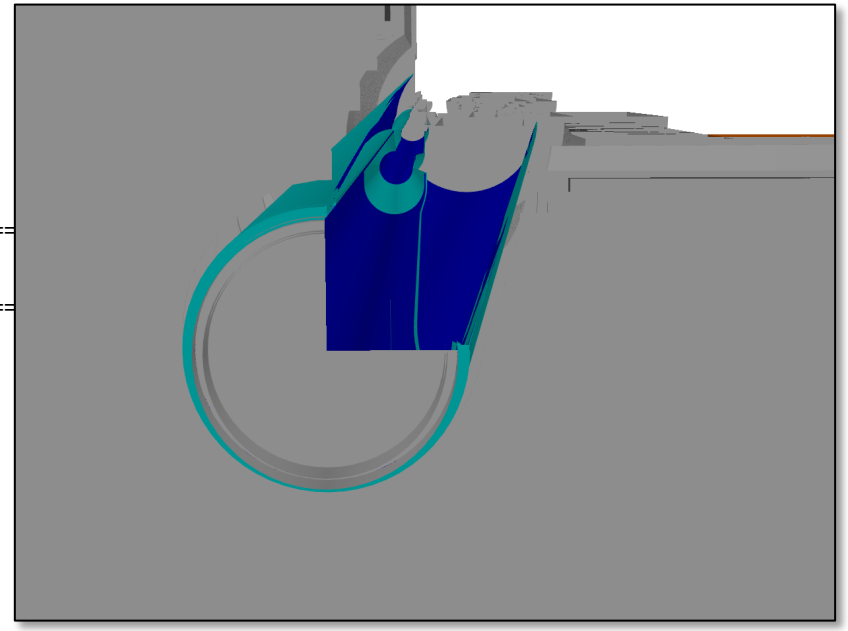

Presumably due to inaccurate tessellated interface description

ePIC and Beampipe Overlap: DD4Hep

There are no other overlaps seen by eye or detected by the framework