Updates on Detector Beam Pipe Modeling in Geant4/DD4Hep

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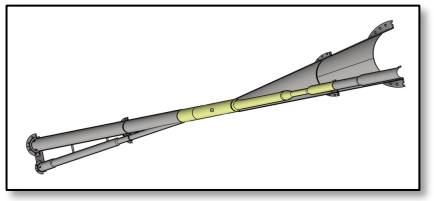
UPDATED

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- Until recently, we were using an outdated beam pipe model in DD4hep (developed pre-2023).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

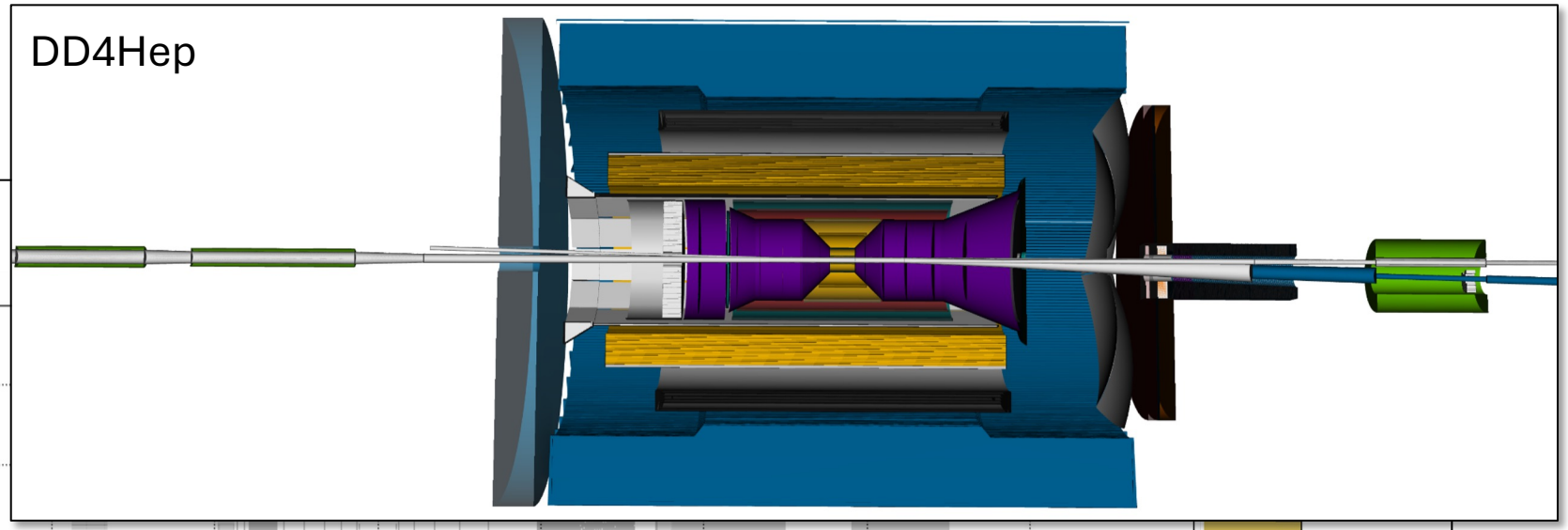
Overlaps & Prospects

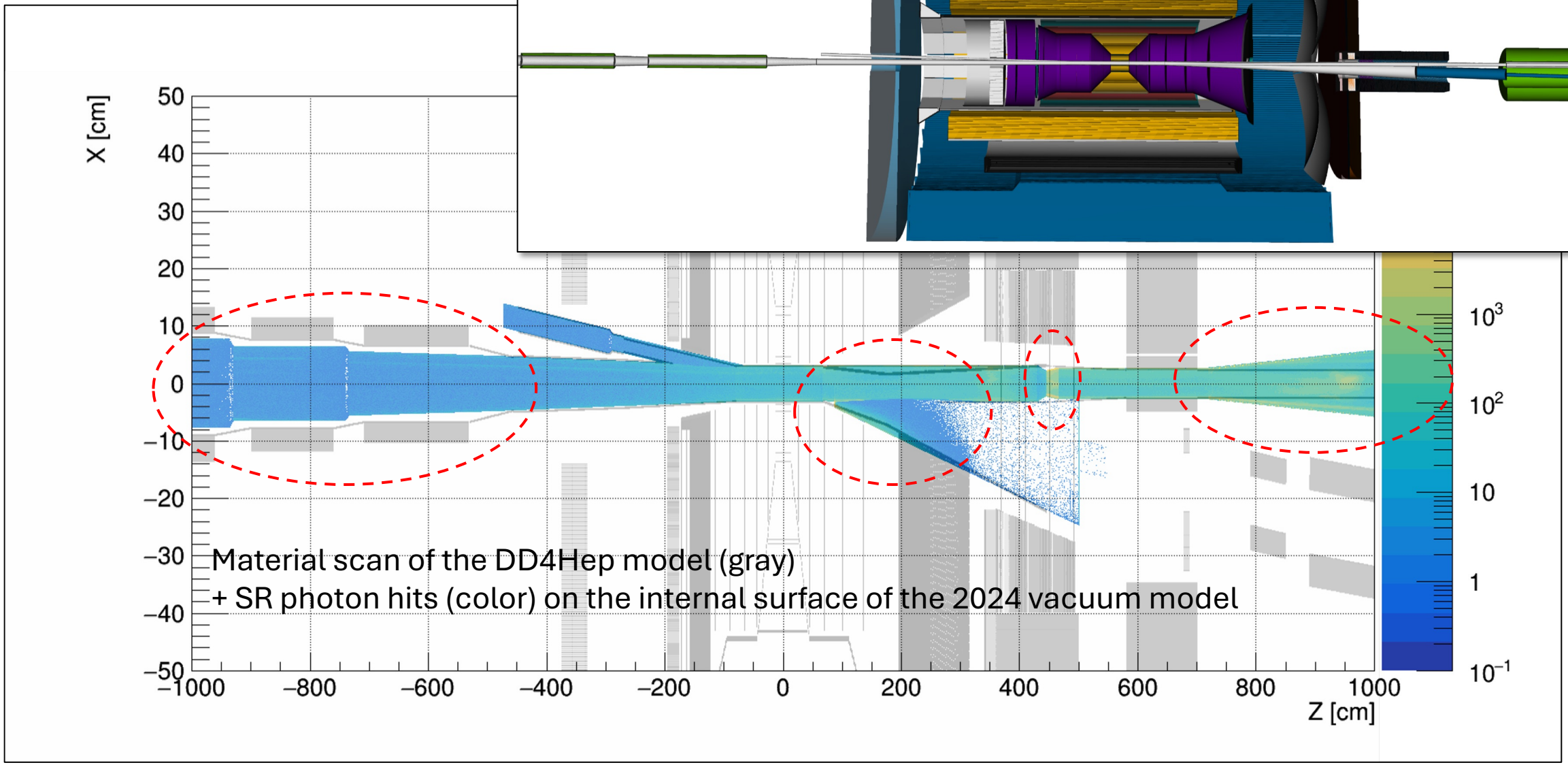
- Only **one overlap** is currently detected near the racetrack-circular transition
- **Next Steps**:
  - Finalize vacuum geometry and check overlaps
  - Explore **GDML export/import** for racetrack transitions
  - Reduce Boolean complexity for stability
  - Submit a PR, polish the code, and merge with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

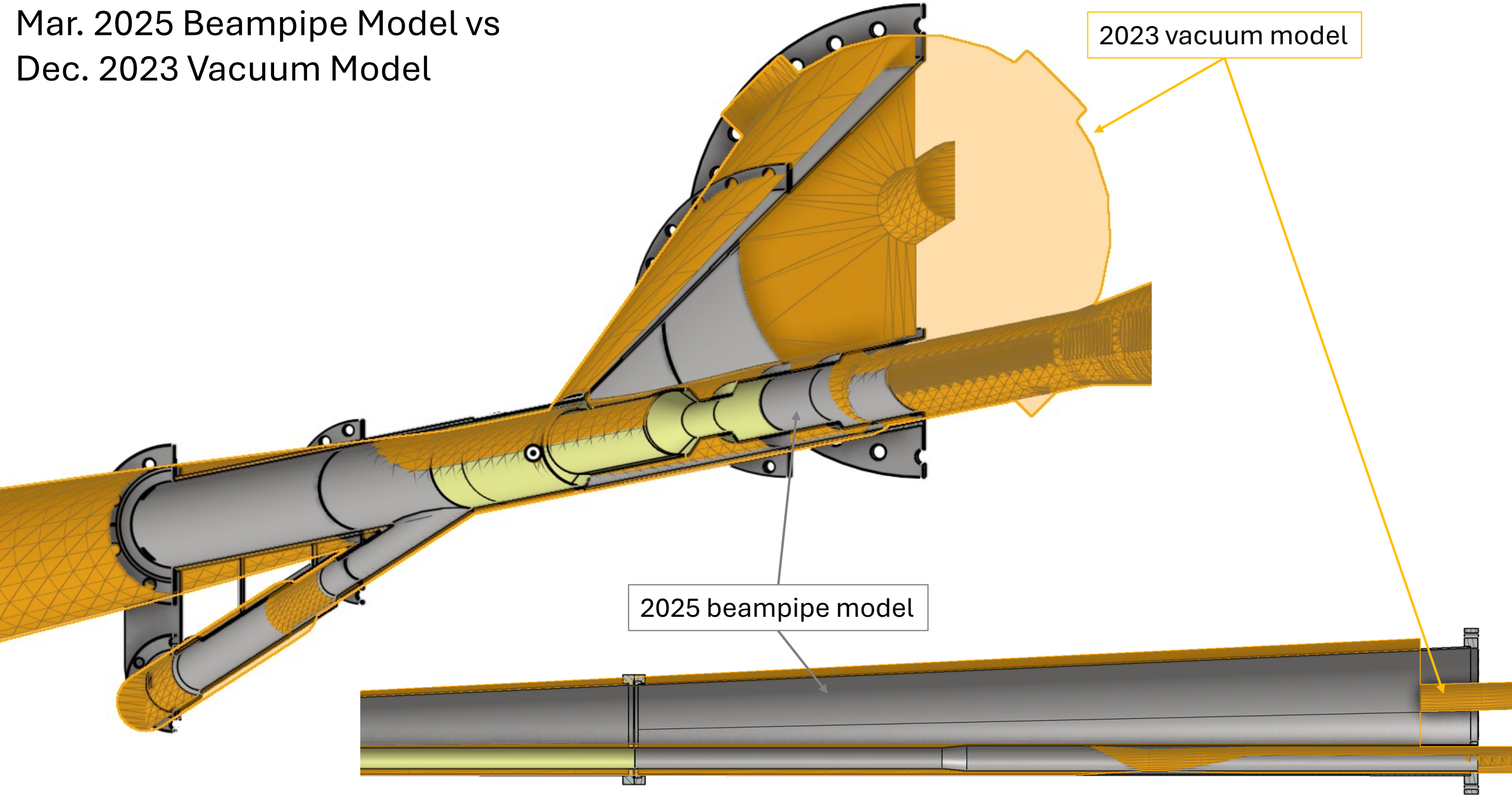
Dec. 2023 DD4Hep vs Dec. 2023 Vacuum Model

Overlaps

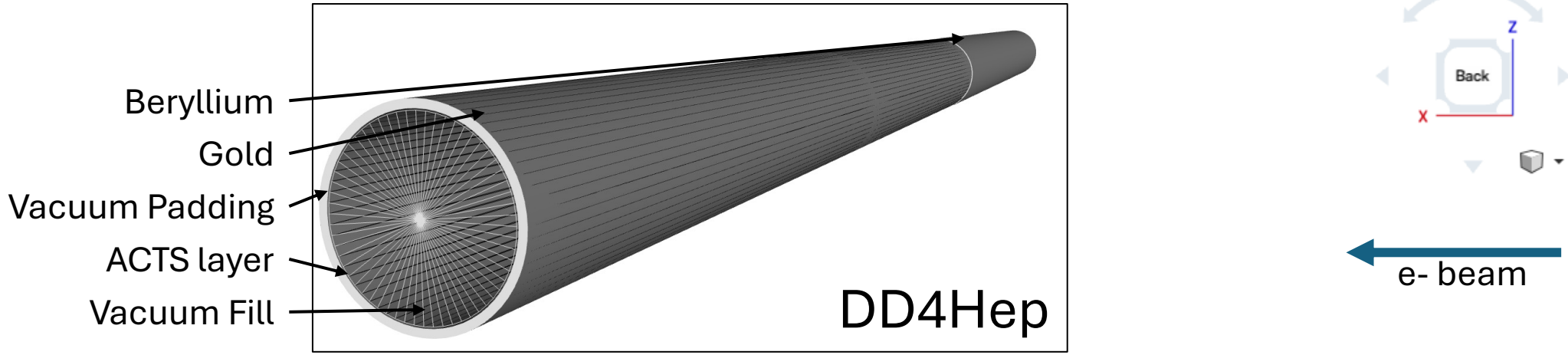


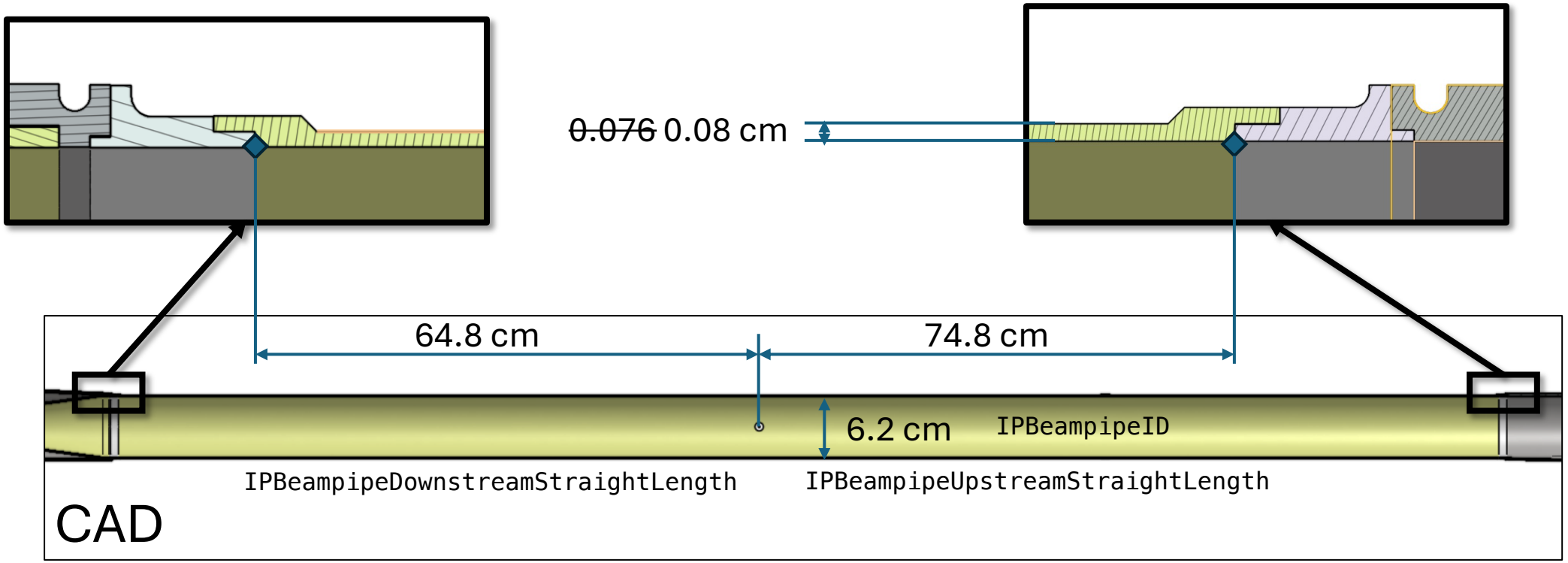


Mar. 2025 Beampipe Model vs Dec. 2023 Vacuum Model

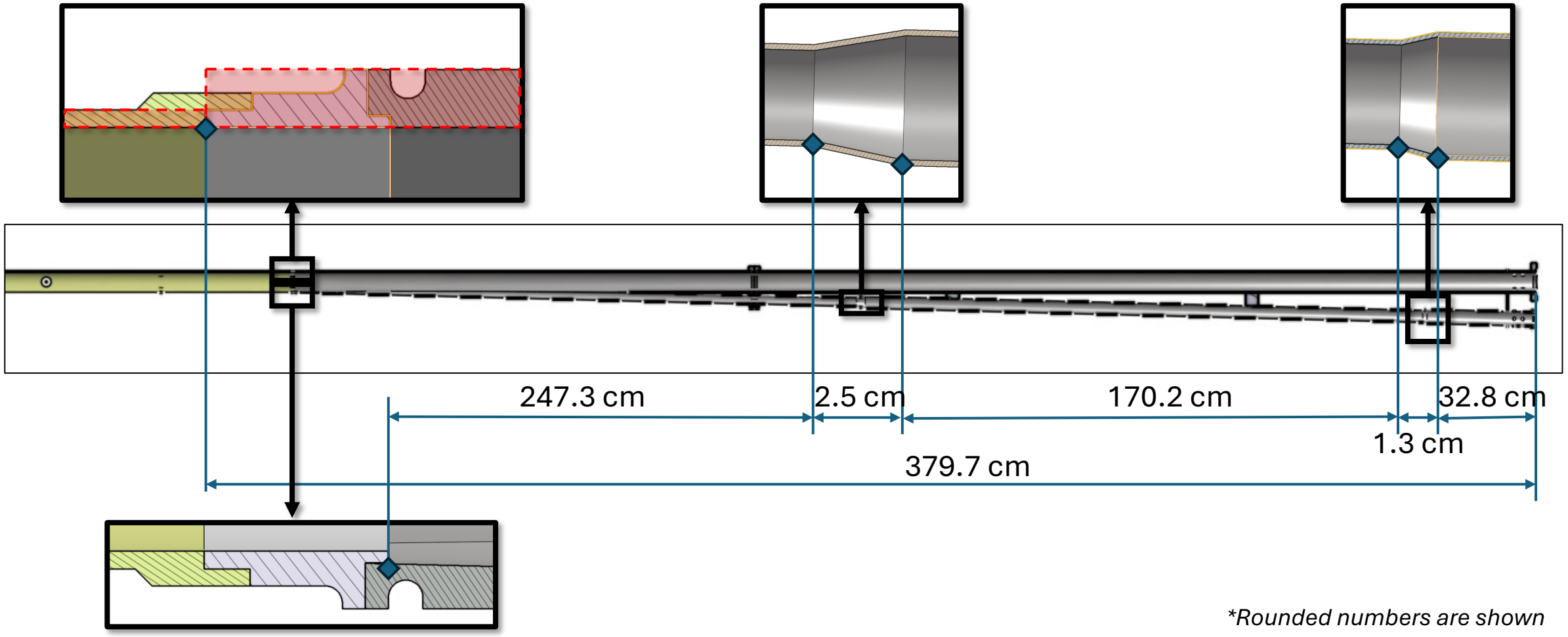


IP6 Beam Pipe



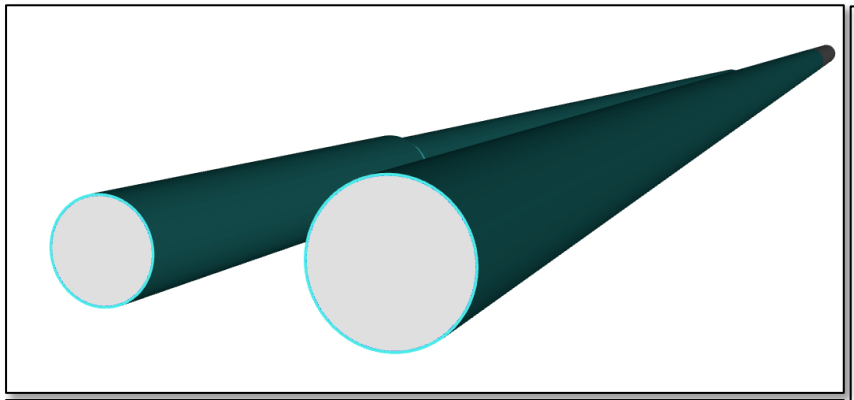


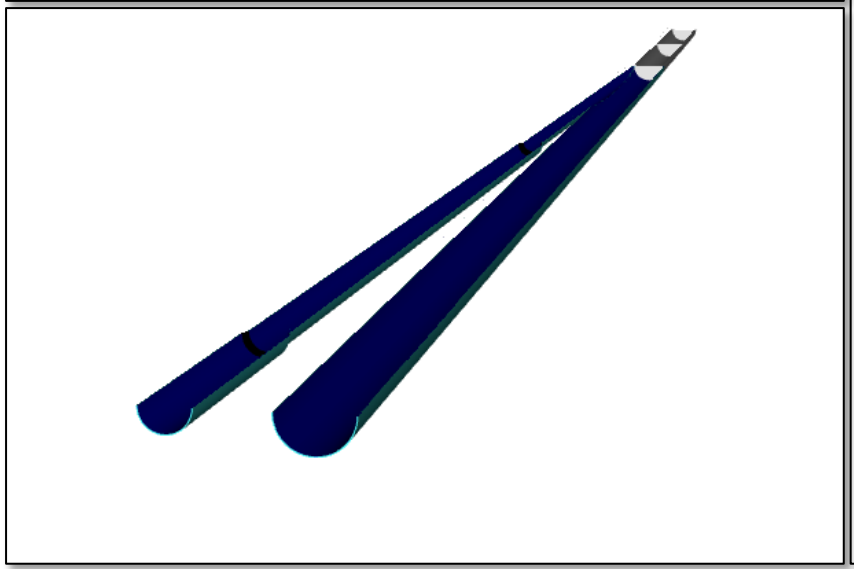
Rear Side Central Beam Pipe: CAD

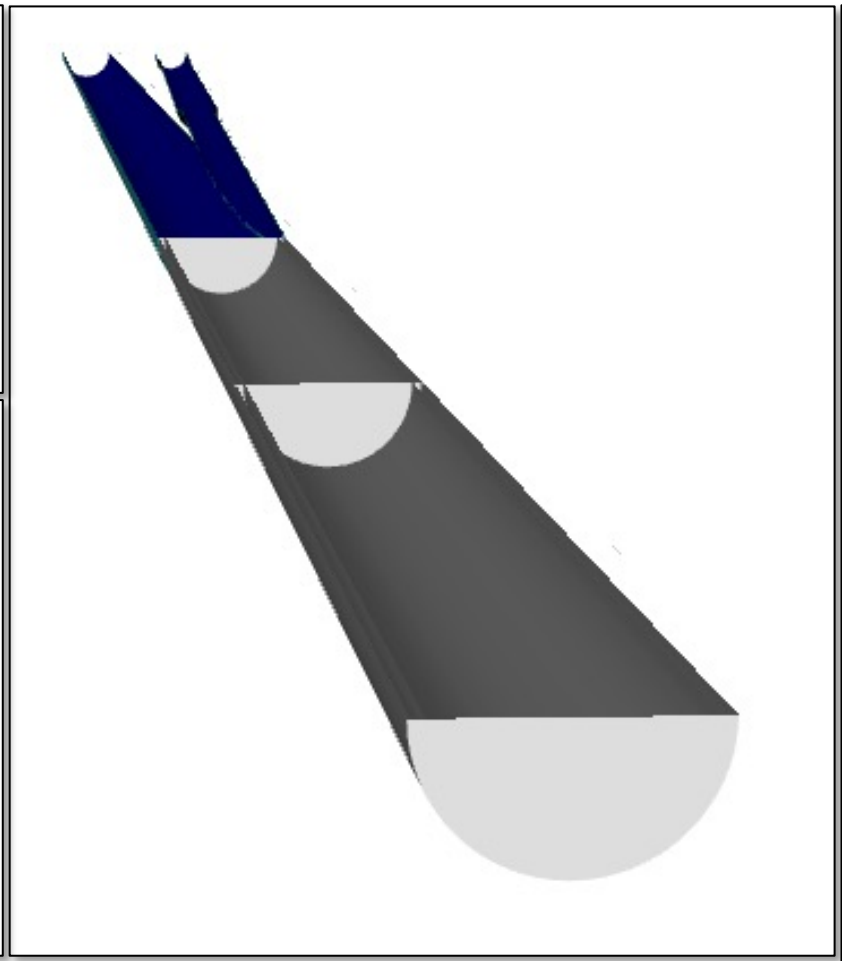


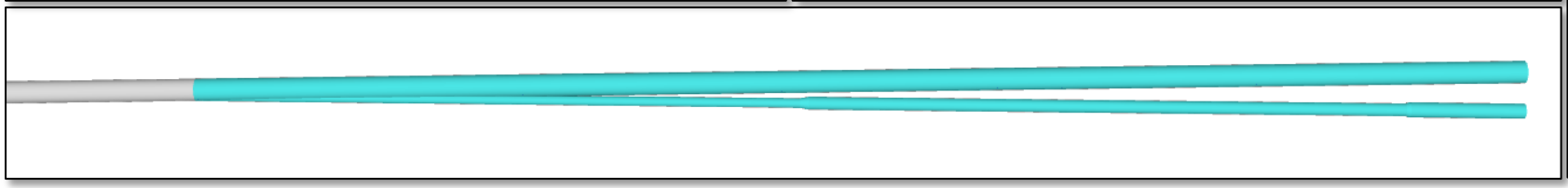
*Rounded numbers are shown

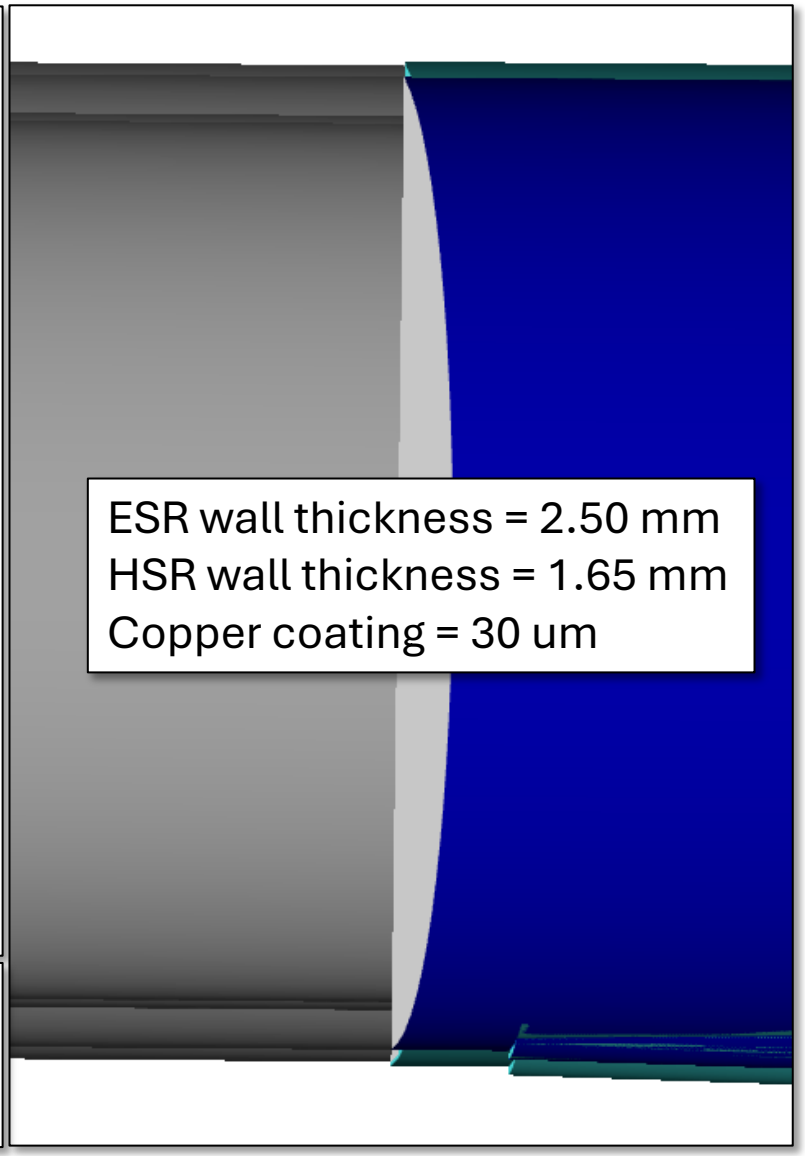
Rear Side Central Beam Pipe: DD4Hep



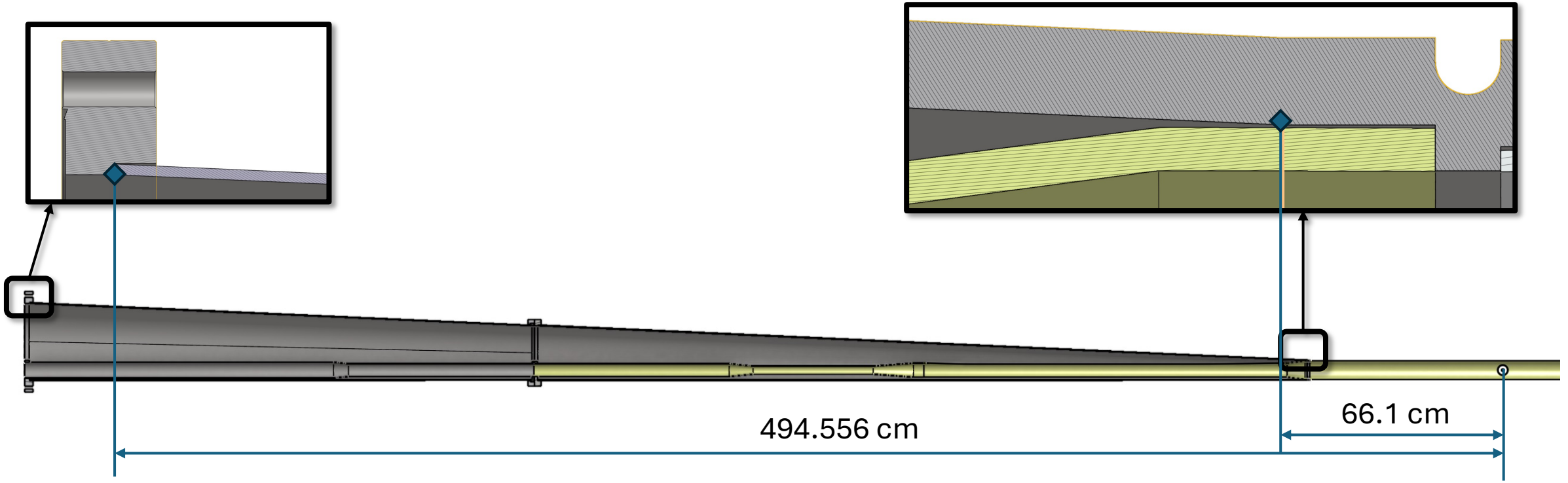


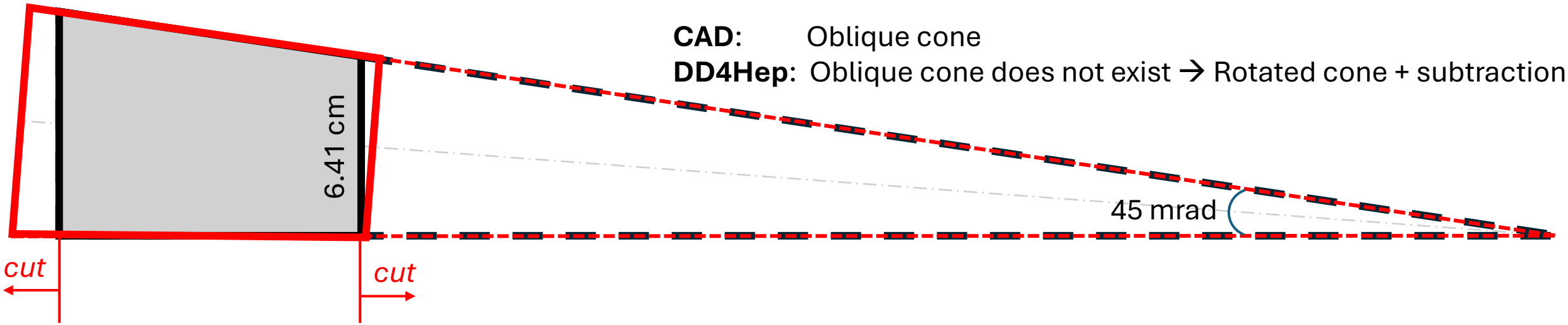






FWD Side Central Beam Pipe: CAD

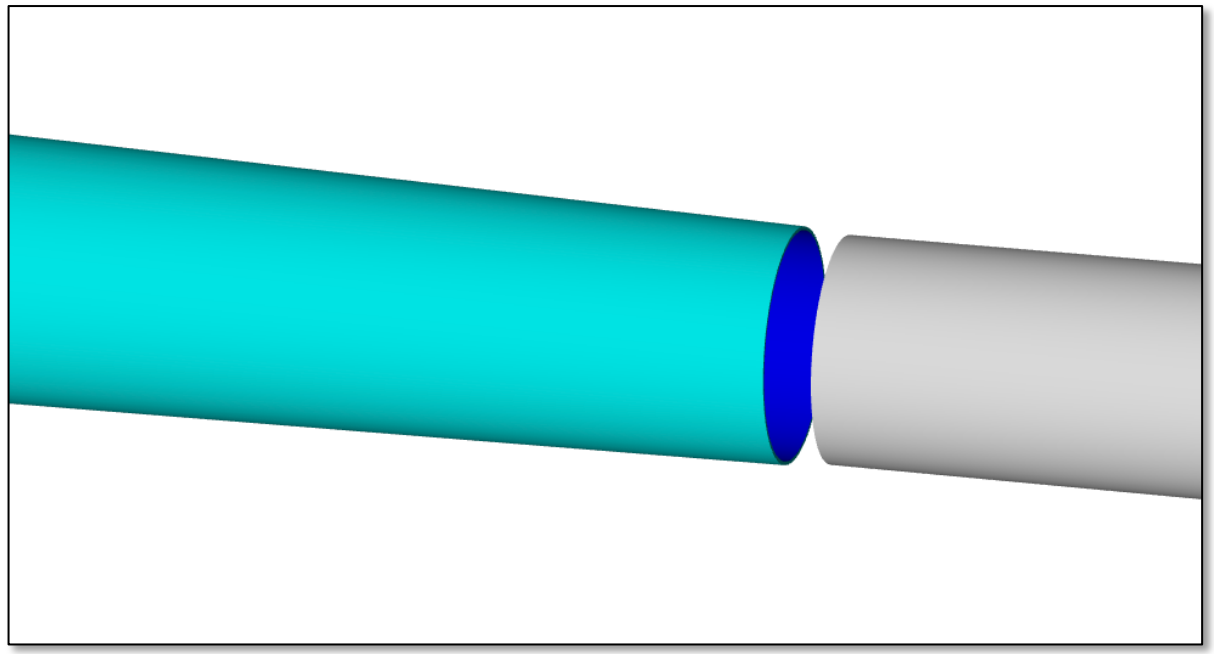


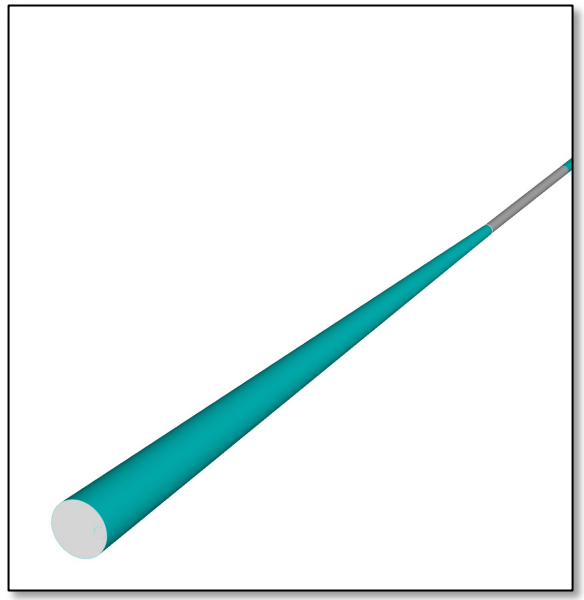


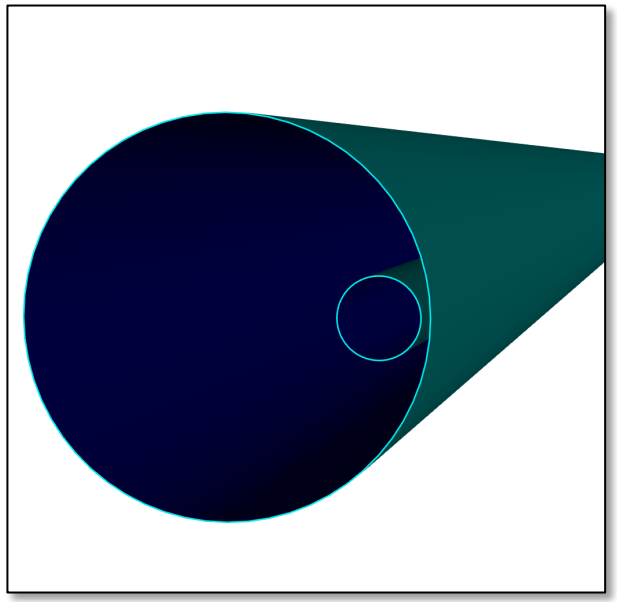
CAD: Oblique cone

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

FWD Side Central Beam Pipe: DD4Hep



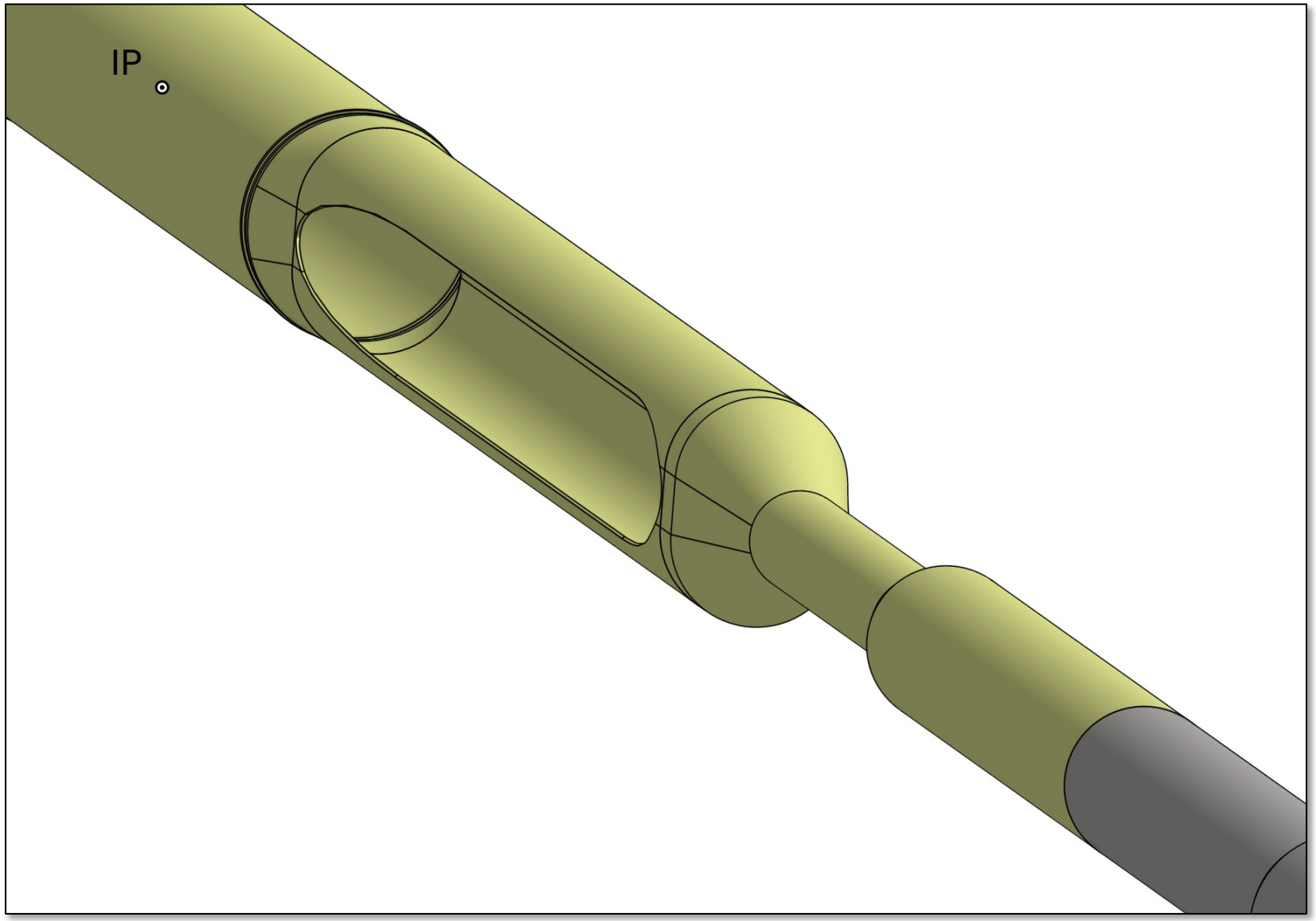




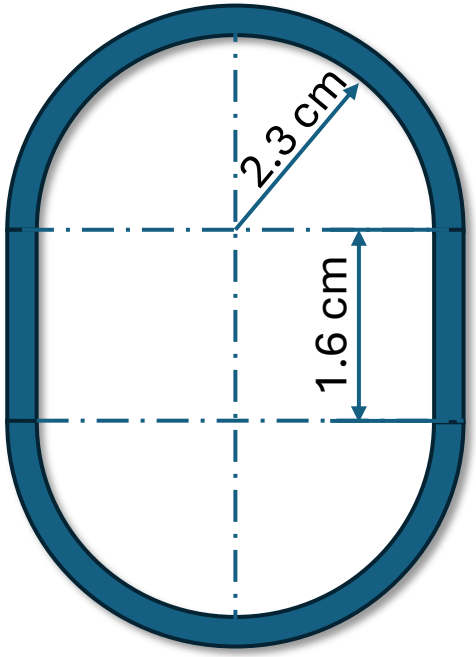
FWD Side Electron Beam Pipe - Racetrack: CAD

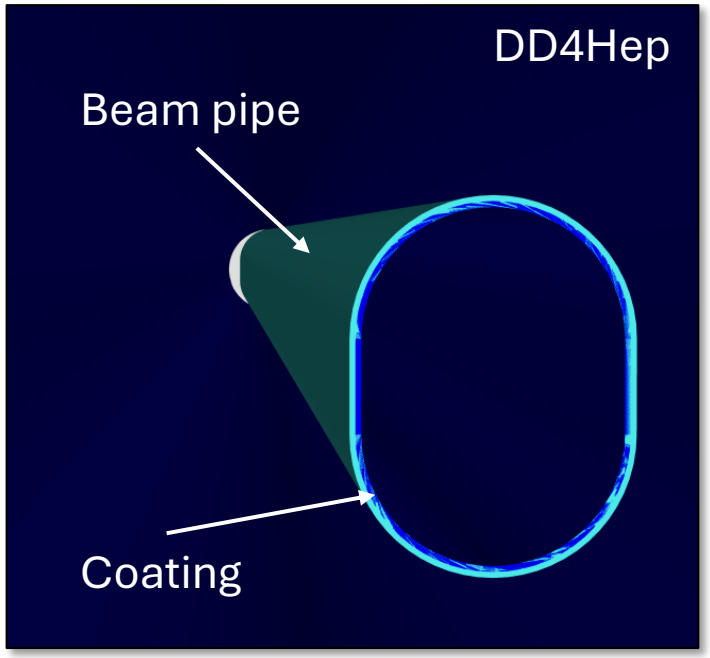
While DD4hep (and ROOT/Geant4) does not have a built-in racetrack primitive, it can be built using **Boolean operations** (i.e., UnionSolid) between:

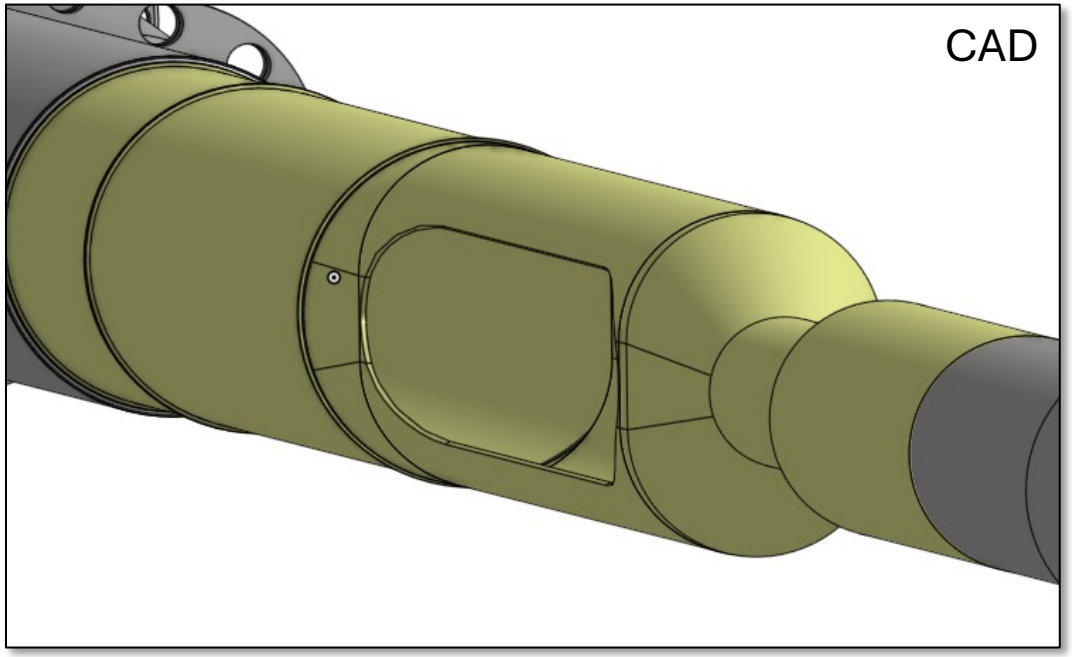
- A **box** (for the straight section)
- Two **cylinders** (for the semicircular ends)



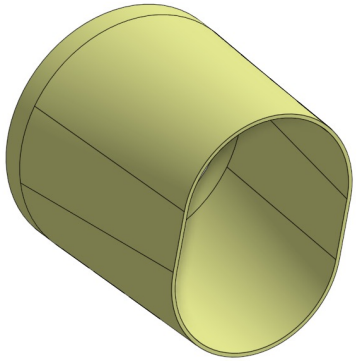
FWD Side Electron Beam Pipe - Racetrack: DD4Hep vs CAD



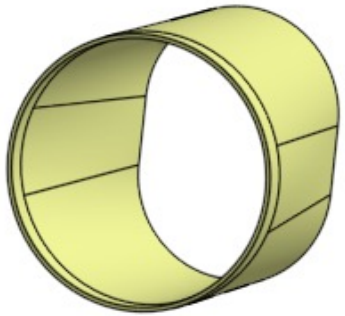




FWD Side Electron Beam Pipe – Racetrack-Cylinder Interface: DD4Hep vs CAD



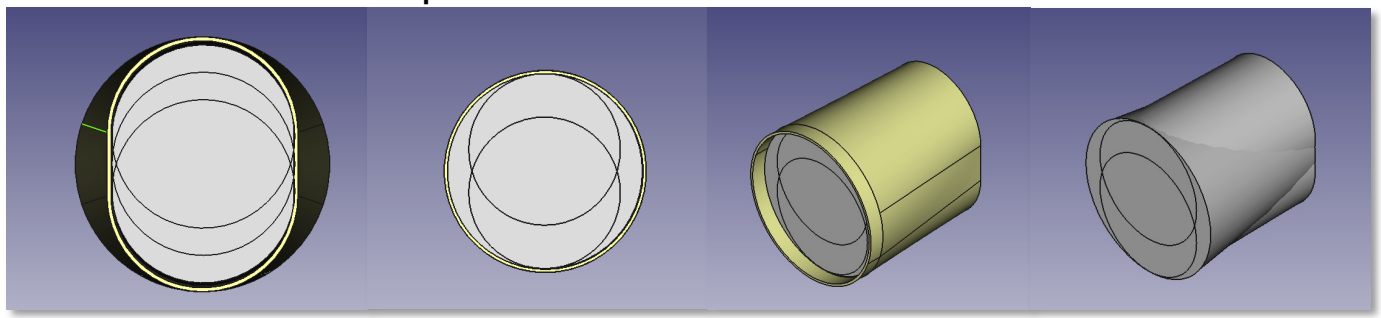
CAD



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 **a combination of a cone and two shifted cylinders**.

FreeCAD → DD4Hep



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

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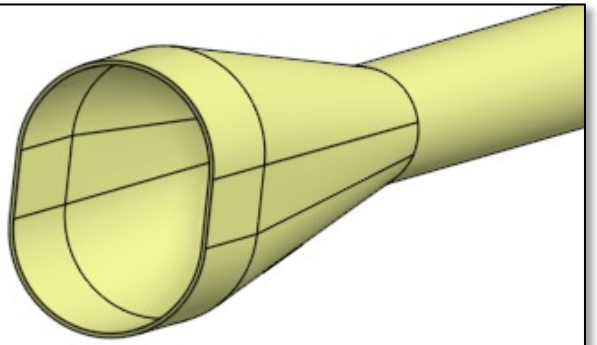
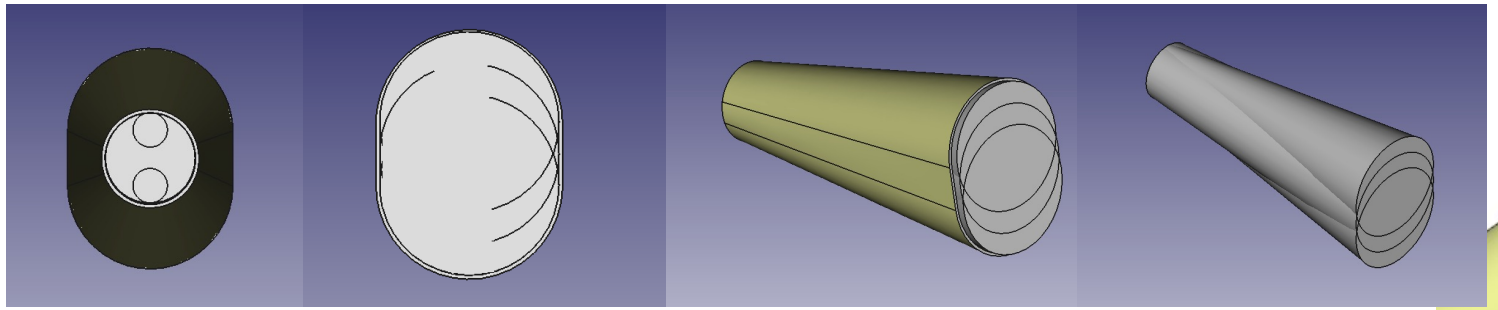
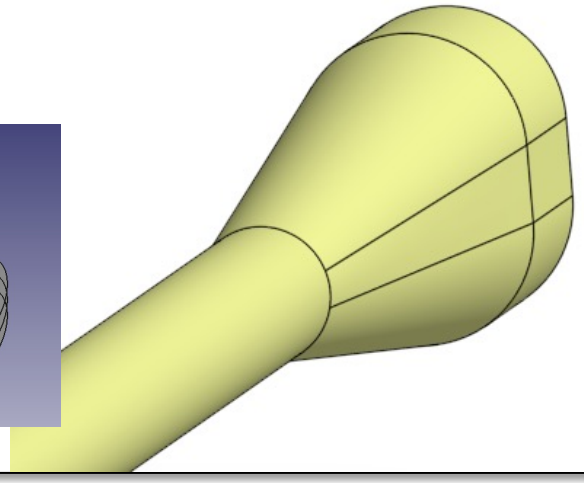


CAD

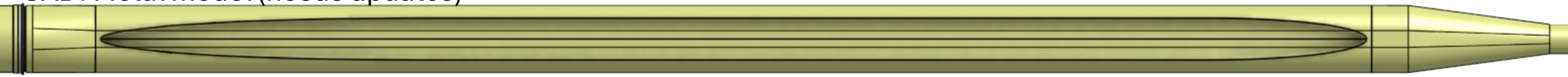
FreeCAD → DD4Hep



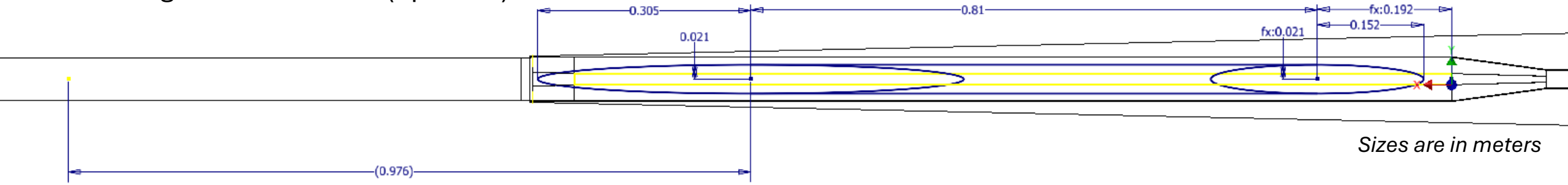


FWD Side Electron Beam Pipe: Hadron Beam Opening

CAD: Metal model (needs updates)

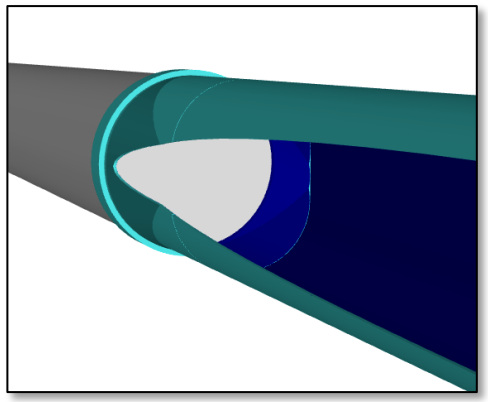


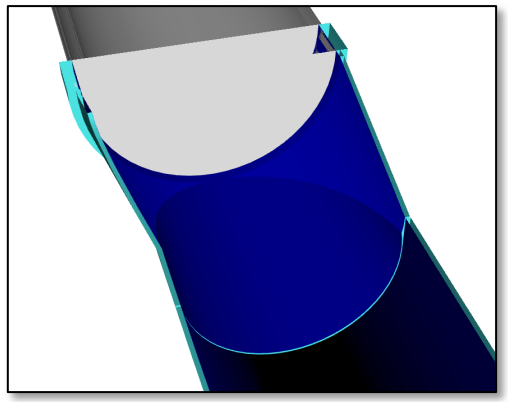
TechDrawing: Vacuum model (updated)

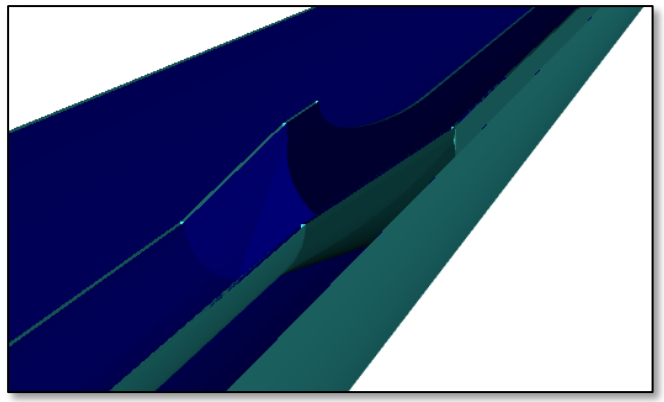


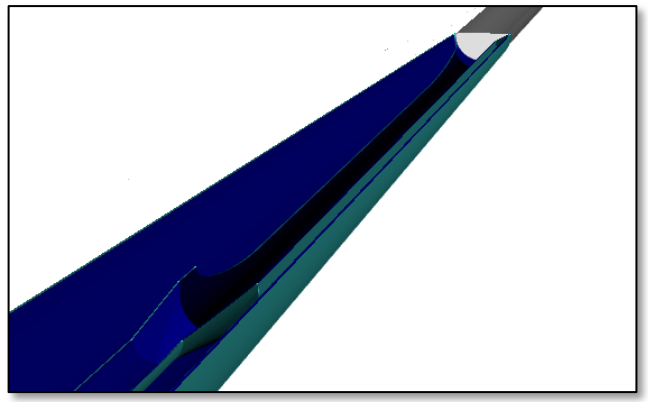
Sizes are in meters

DD4Hep

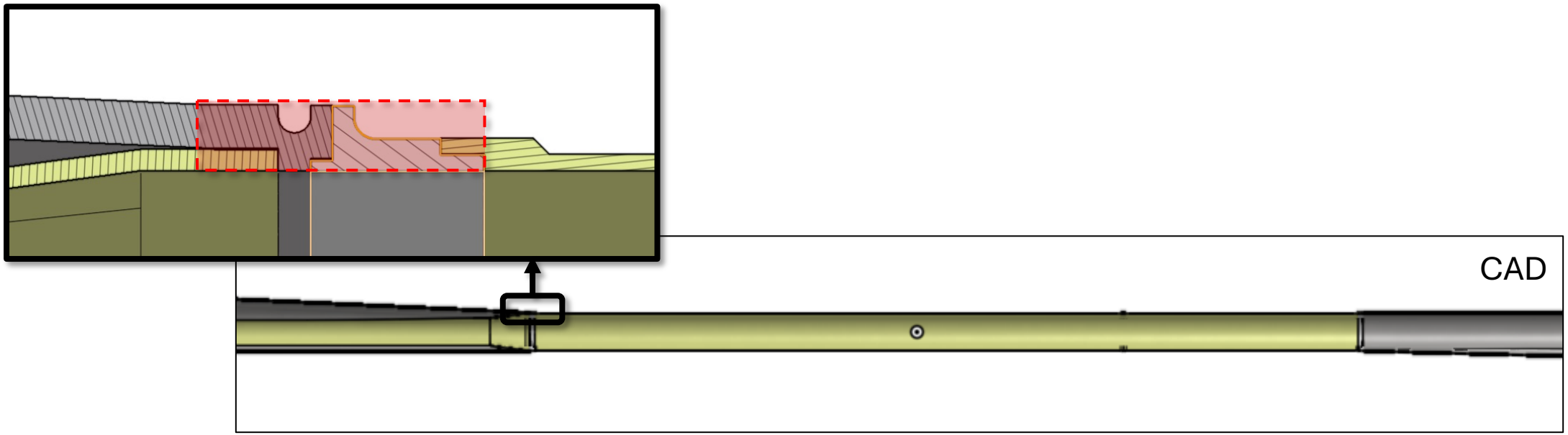


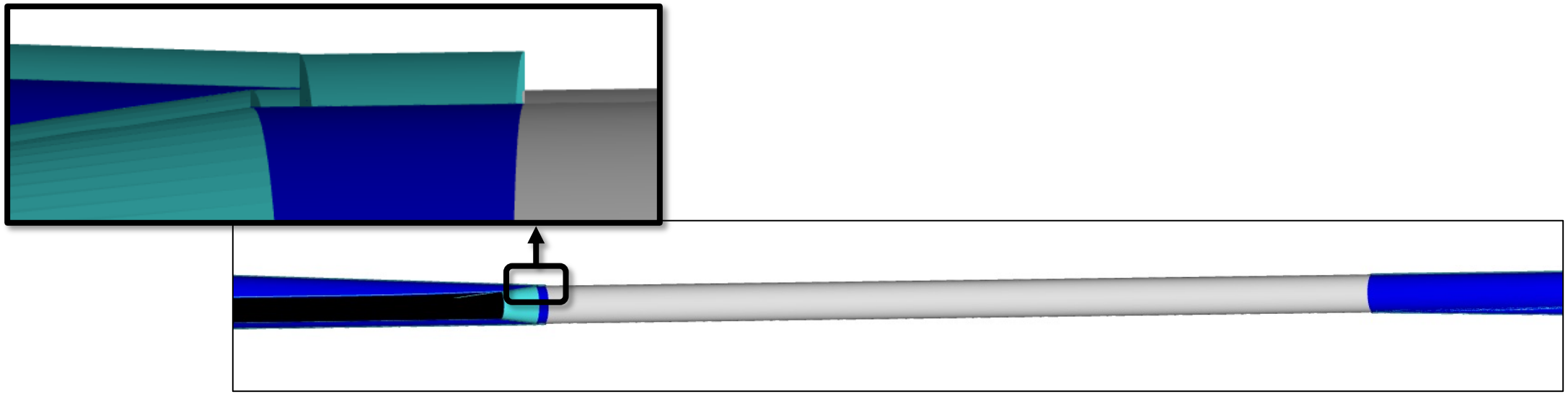






FWD IP Flange



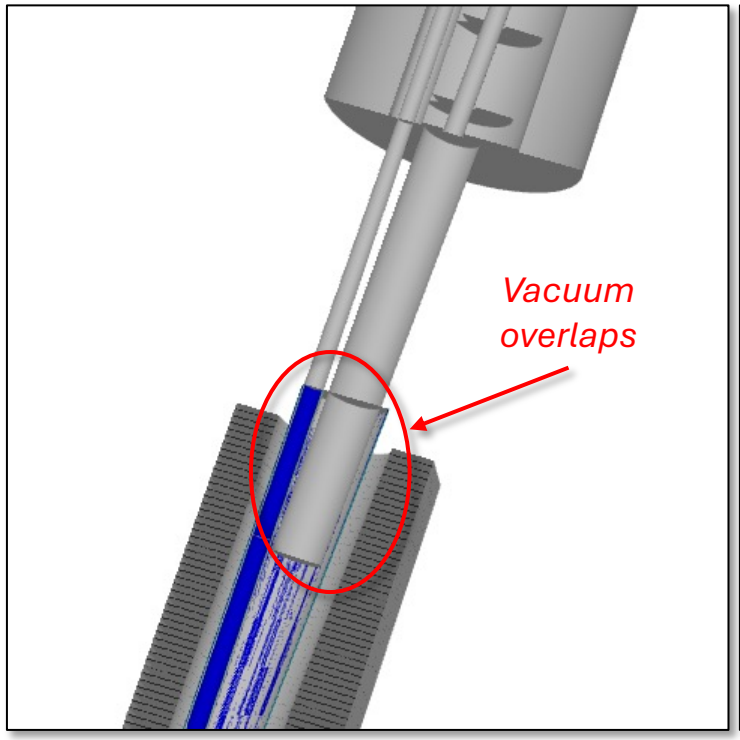


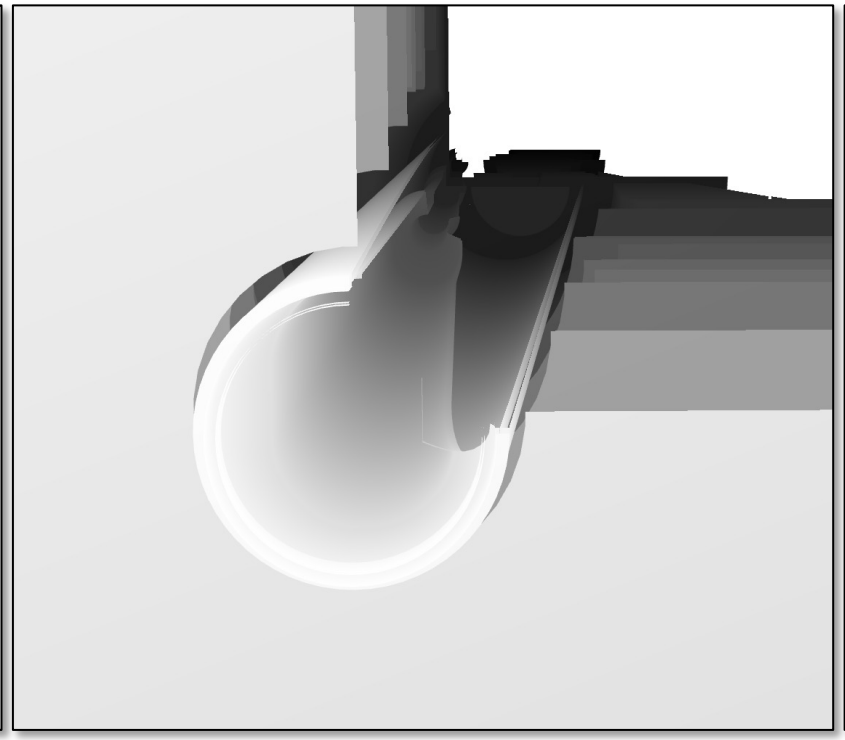
ePIC and Beampipe Overlap: DD4Hep

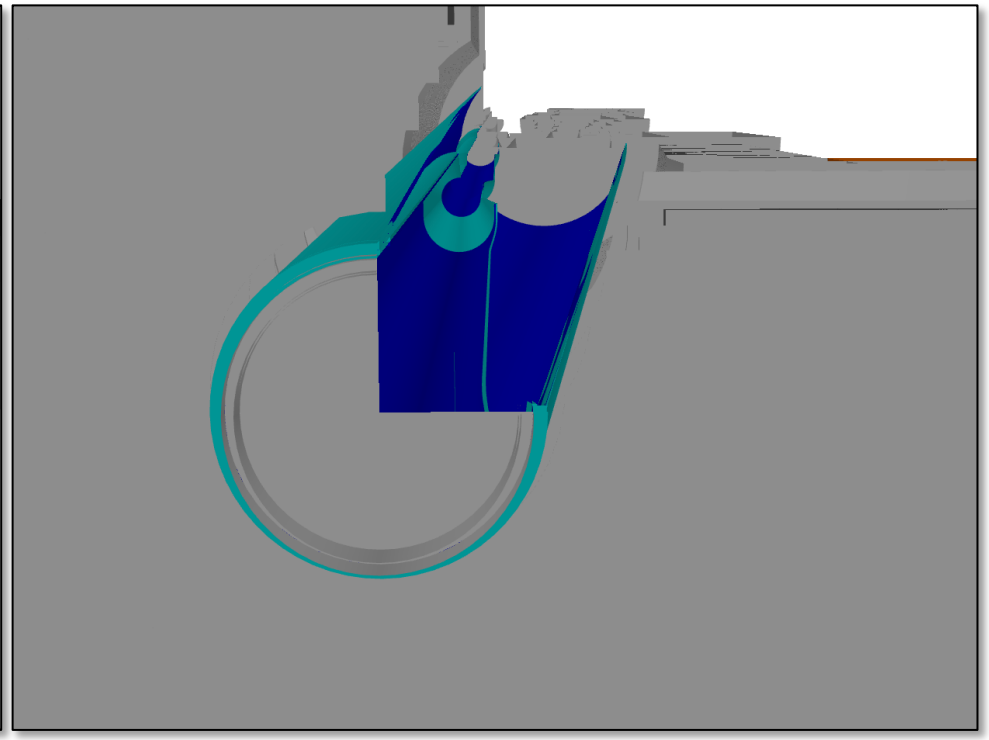
```
Check overlaps:     [==========] 5385290 [100.00 %]
Info in <TGeoNodeMatrix::CheckOverlaps>: Number of illegal overlaps/extrusions : 0


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

- There are no overlaps with materials.
- Some overlaps are detected with vacuum, which can be easily fixed.







ePIC and Beampipe Overlap: DD4Hep

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