

IPW-3 TFG2 Results Overview

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Collins Aerospace

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IPW-3 TFG2 results overview

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09/22/2026

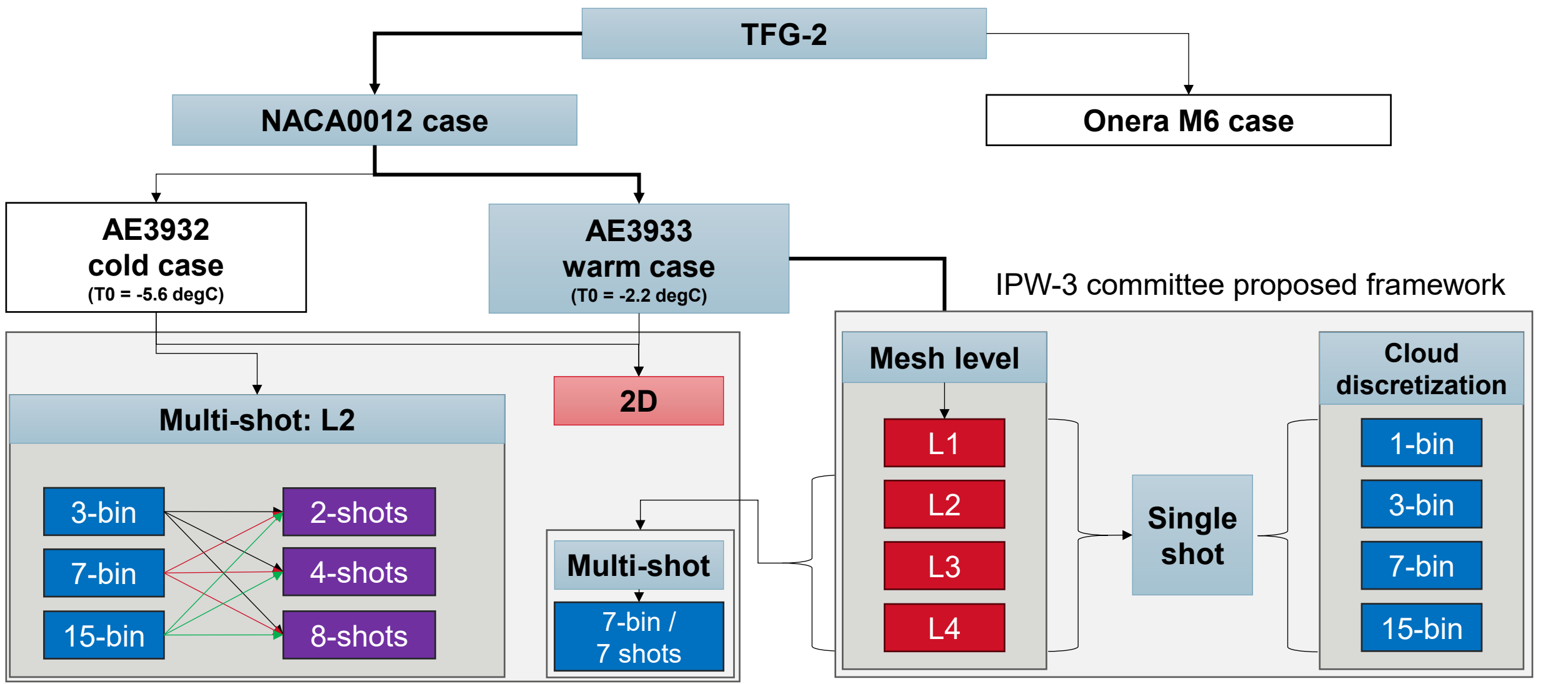


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Agenda

1. Modeling overview
2. Results overview
3. Remarks and observations
4. Conclusion and future direction
5. Q&A

Modeling overview



Modeling overview

Aerodynamic setup

- Ansys Fluent 2025R2, double precision solver
- Physics models
 - Ideal Gas air
 - Adjusted, constant thermal conductivity & viscosity to ref. temperature
 - K-omega SST turbulence model
 - Production & K-L limiters + viscous work
- Boundary Conditions
 - Mass-flow @ inlet, pressure @ outlet
 - 1% turbulence intensity, 3.8mm turbulence length scale
 - Adiabatic walls with roughness on wing:
 - 0mm for CoP,
 - 0.5mm for single-shot icing simulation / 1st multi-shot step (then variable roughness from ICE3D Beading model)
 - No correction to pressure loss due to viscous walls, reference Mach number < 0.01 at a given probe location
- Numerics:
 - Coupled pressure-velocity scheme, CFL=10
 - 2nd order upwind for pressure
 - QUICK scheme elsewhere (Quadratic Upstream Interpolation for Convective Kinematics)
 - Fixed 2000 iterations, convergence typically stalls earlier, i.e. continuity ~ 1e-5 normalized value

Modeling overview

Droplet trajectory setup

- DROP3D 2025R2 solver (Fensap-Ice package)
- Physics models
 - Standard, small droplet regime physics setup
 - Water – extended Reynolds
 - Particle thermal equation
- Boundary Conditions
 - Droplets entering at reference velocity, 1-way coupled, LWC = 0.55 g/m³
- Standard numerical setup:
 - Streamline upwind discretization scheme
 - CFL = 15
 - 400 iterations per shot, 1e-9 change in total beta convergence (based on moving average from 20 iterations)

Modeling overview

Ice accretion setup

- ICE3D 2025R2 solver (Fensap-Ice package)
- Physics models
 - Extended Icing Data (EID) for HTC calculation on adiabatic walls
 - Beading model for multishot roughness development
 - Temperature recovery factor = 0.9
- Boundary Conditions
 - Ice accretion computation on wing only
 - Sliding condition at the tunnel floor / ceiling
- Auto T-S, 420s single shot duration or 60s-time interval for multishot approach

Mesh deformation

- ALE displacement with 10 morphing iterations

Numerical methodology

Model / Method	NACA0012	ONERAM6
CFD Model	RANS	
Turbulence Model	SST-K ω	
HTC Method	Adiabatic wall + EID	
Droplet Formulation	Eulerian	
Droplet Drag Model	Extended Reynolds	
SLD Effects	None	
Thermodynamic Model	SWIM	
Ice Density Model	Variable – Impact ice density	
Roughness Height	0.5mm single shot / beading model multishot	
Geometry Evolution	ALE mesh morphing	
Ice Accretion Steps	Single-shot / Multishot (1-min intervals)	

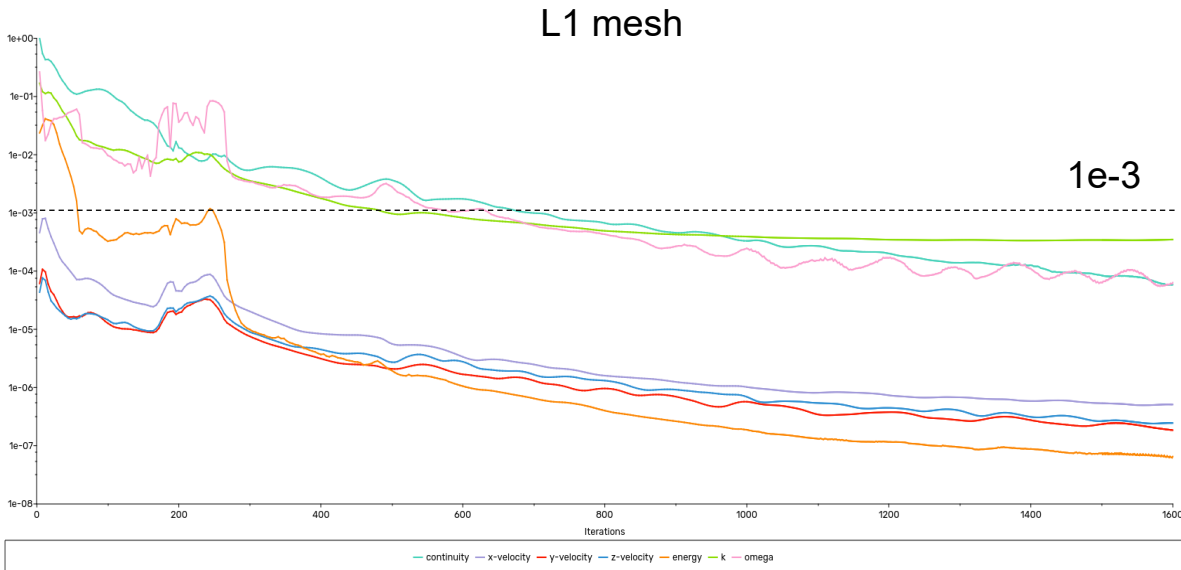
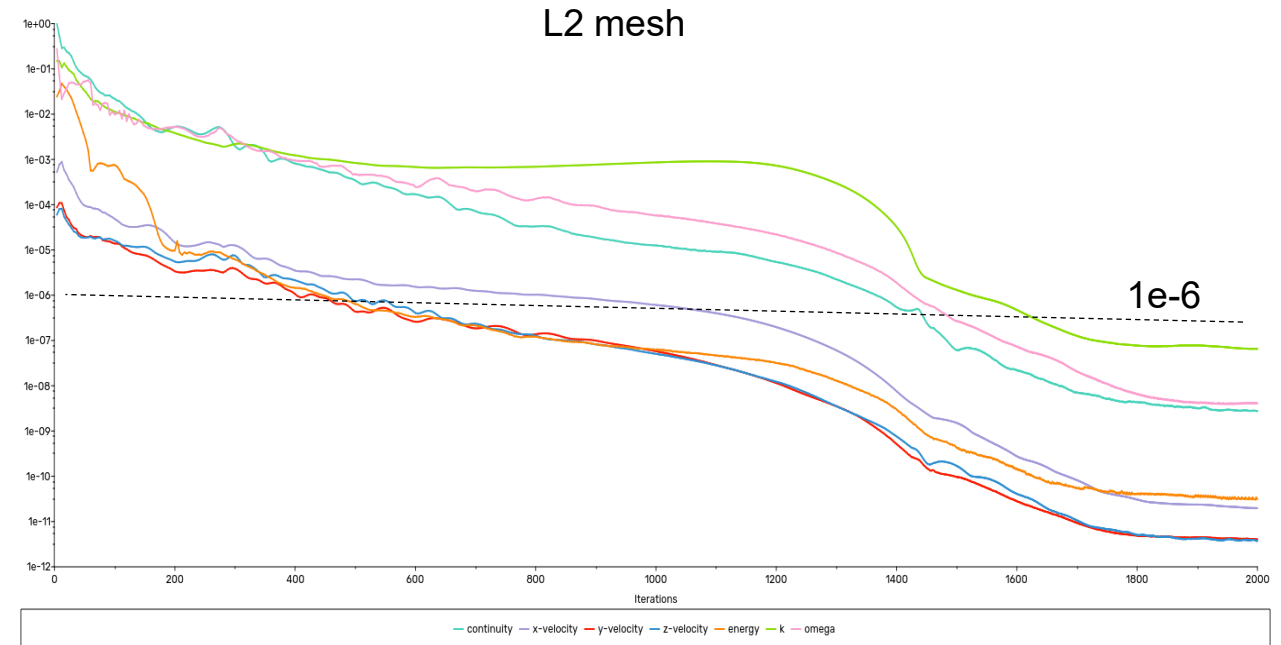
AE3933 conditions

$M_{ref} = 0.3127$
 $U_{ref} \text{ [m/s]} = 102.19$
 $AOA \text{ [deg]} = 4$
 $T_{s,ref} \text{ [K]} = 265.8$
 $T_{0,ref} \text{ [K]} = 271.0$
 $\rho_{ref} \text{ [kg/m}^3\text{]} = 1.2000$
 $P_{ref} \text{ [Pa]} = 91554$
 $P_{0,ref} \text{ [Pa]} = 97974$

$a_{ref} \text{ [m/s]} = 326.83$
 $\mu_{ref} \text{ [kg/m-sec]} = 1.6794\text{E-}05$
 $Re_{L,ref} \text{ [/m]} = 7.3016\text{E}6$
 $Re_{c,ref} = 3.8947\text{E}6$
 $LWC = 0.55$
 $MVD = 20\mu\text{m}$
 $\text{Time} = 7 \text{ minutes}$

Level	1	2	3	4
Nodes	60,450,029	27,308,300	11,234,674	5,947,691

Convergence assessment



AERO Solution

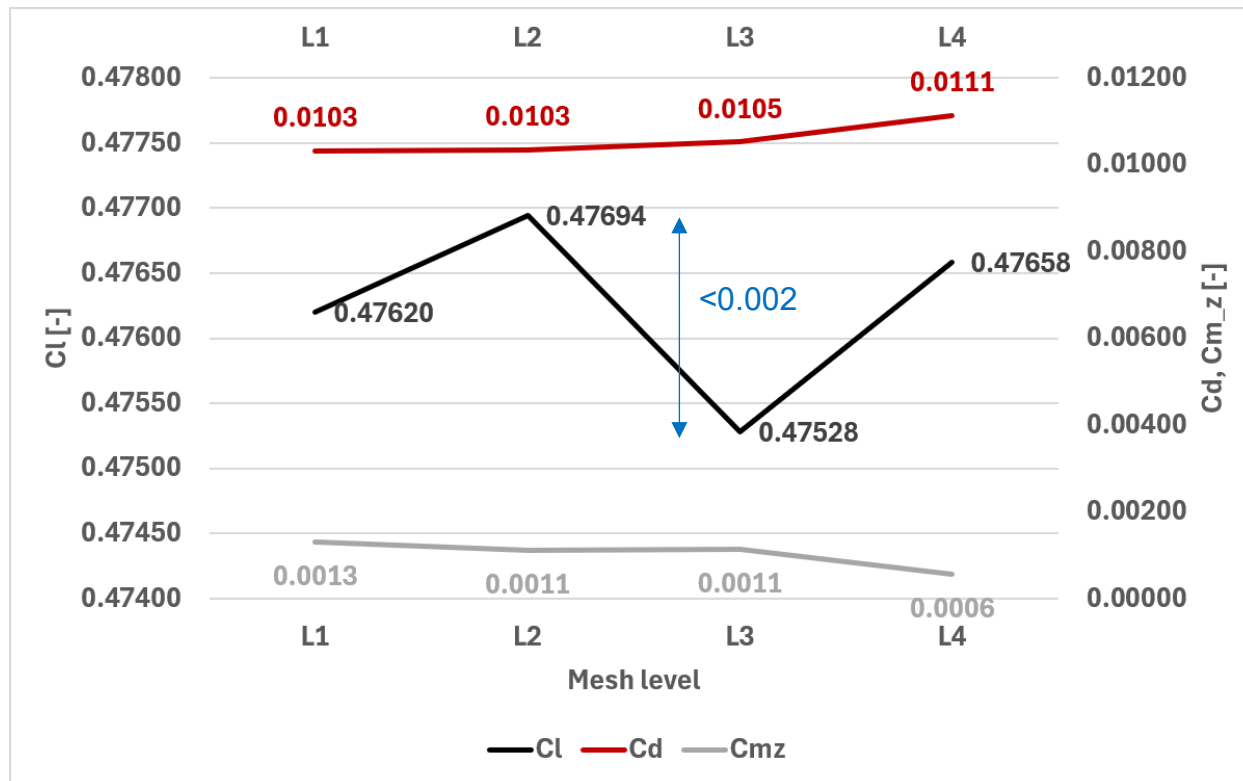
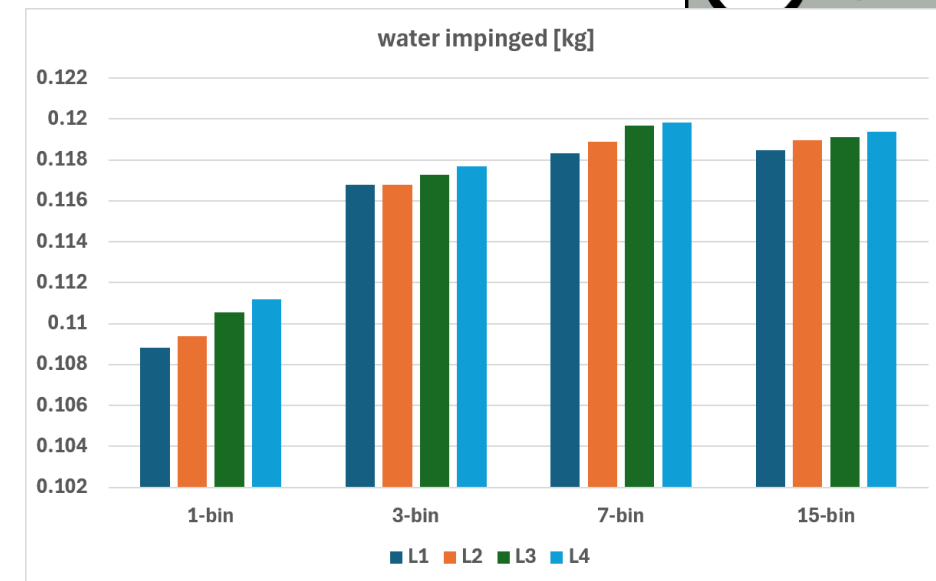
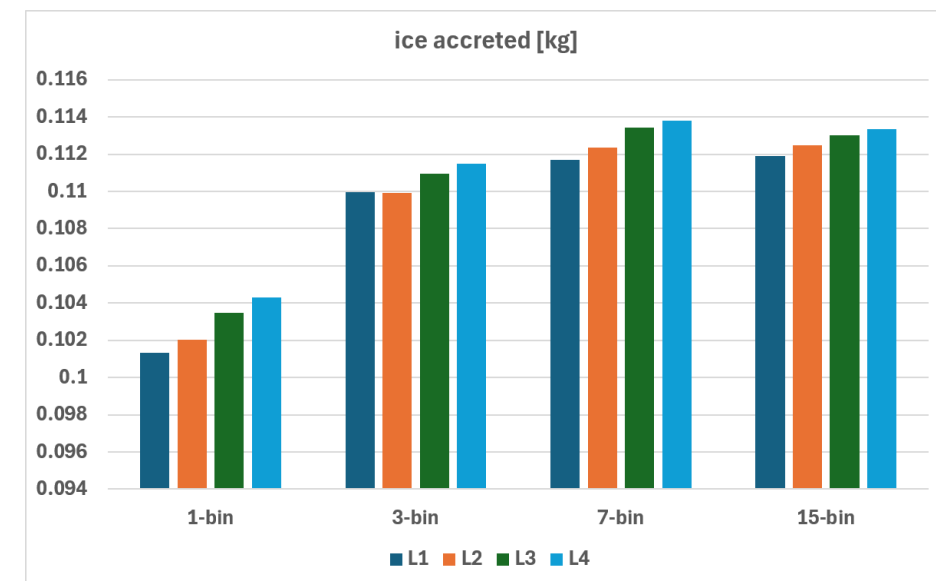
Quantity monitors:

- Cl, Cd, Cm monitors remains constant to 4th decimal place
- Mach number at probe point remains constant to 4th decimal place
- Gauge pressure at probe point remains constant to 1st decimal place

DROP Solution

- Change in total beta drops below 1e-9 for 20 iterations moving average
 - Except for the smallest drops ~6um where typically oscillates ~1e-7 – 1e-8
 - But this bin contributes 5.7% to LWC, while 0.035% of total collected water mass

Integrated values comparison

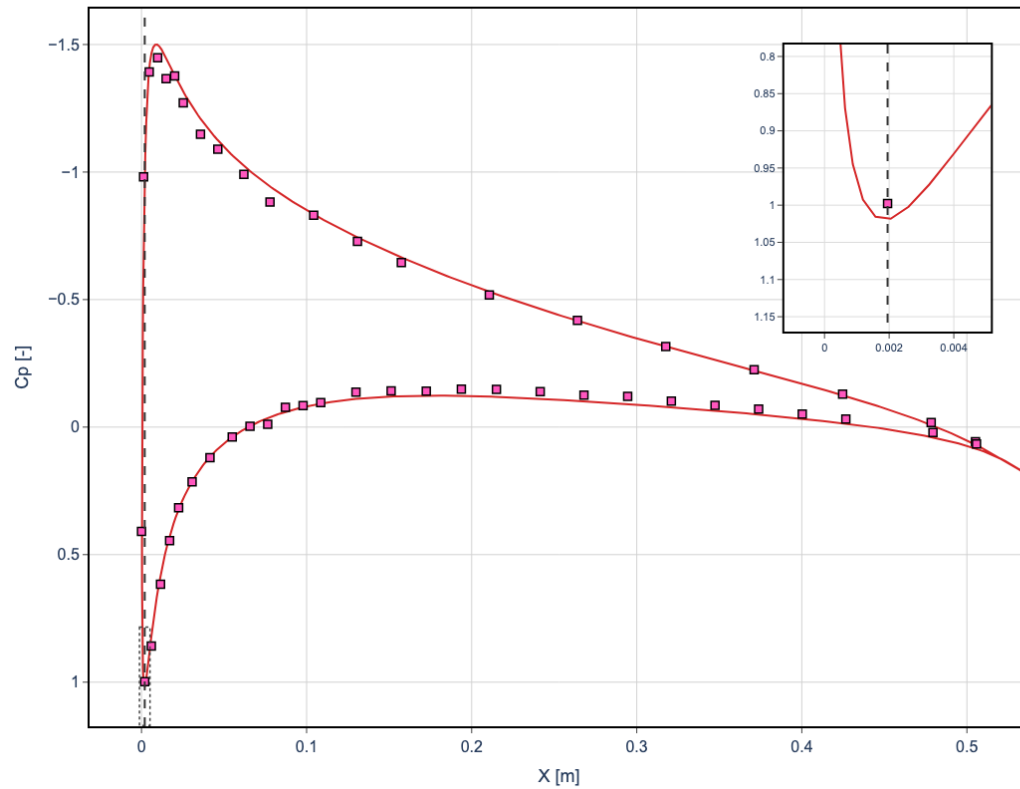


* Mass of water evaporated: 6.5 – 7.5 [g]

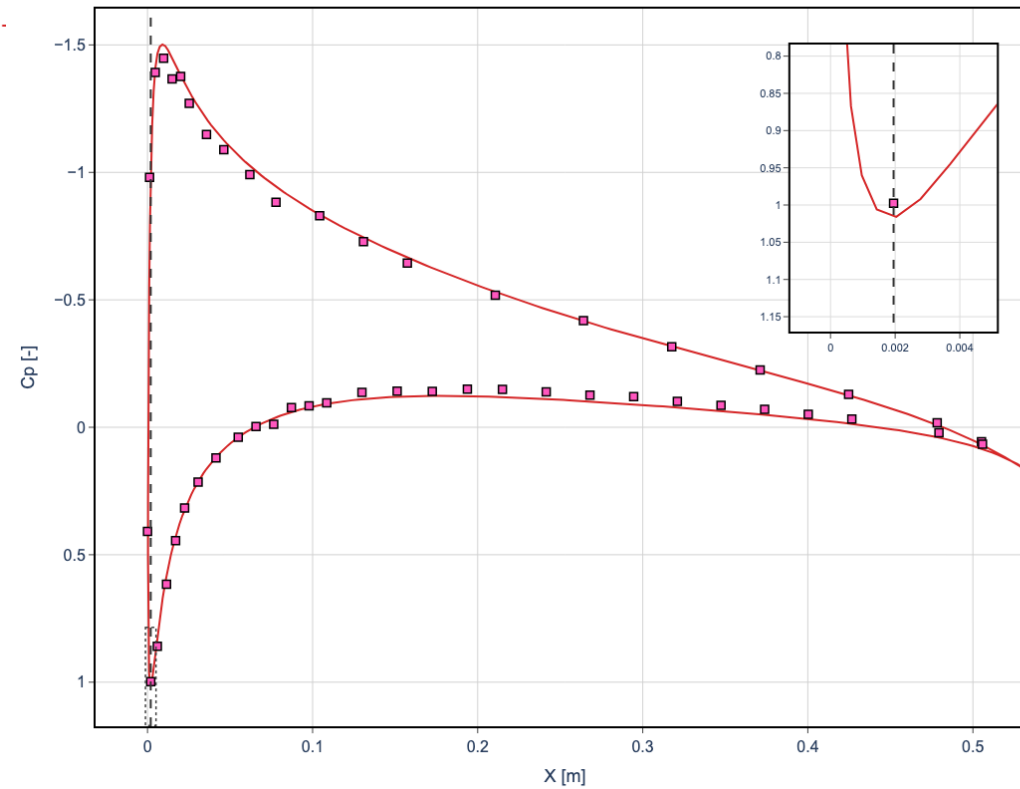
Cp comparison

L1 vs L2

Cp vs X | L1 | Y = 0.9144 m | All roughness heights



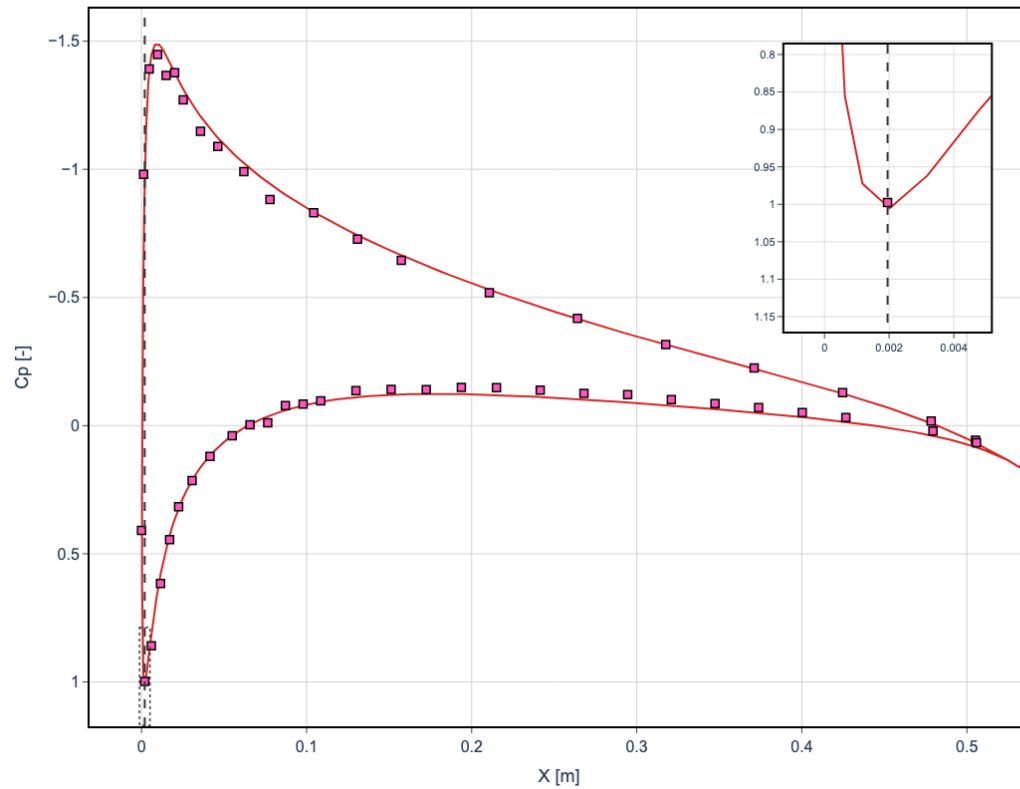
Cp vs X | L2 | Y = 0.9144 m | All roughness heights



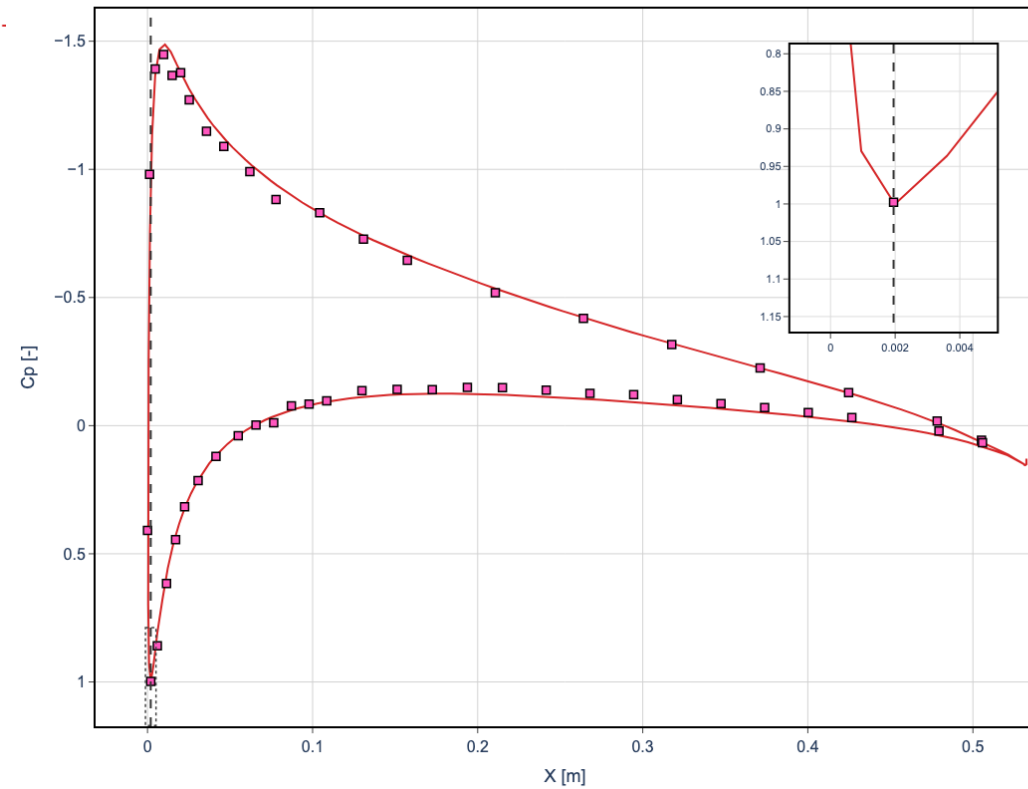
Cp comparison

L3 vs L4

Cp vs X | L3 | Y = 0.9144 m | All roughness heights



Cp vs X | L4 | Y = 0.9144 m | All roughness heights

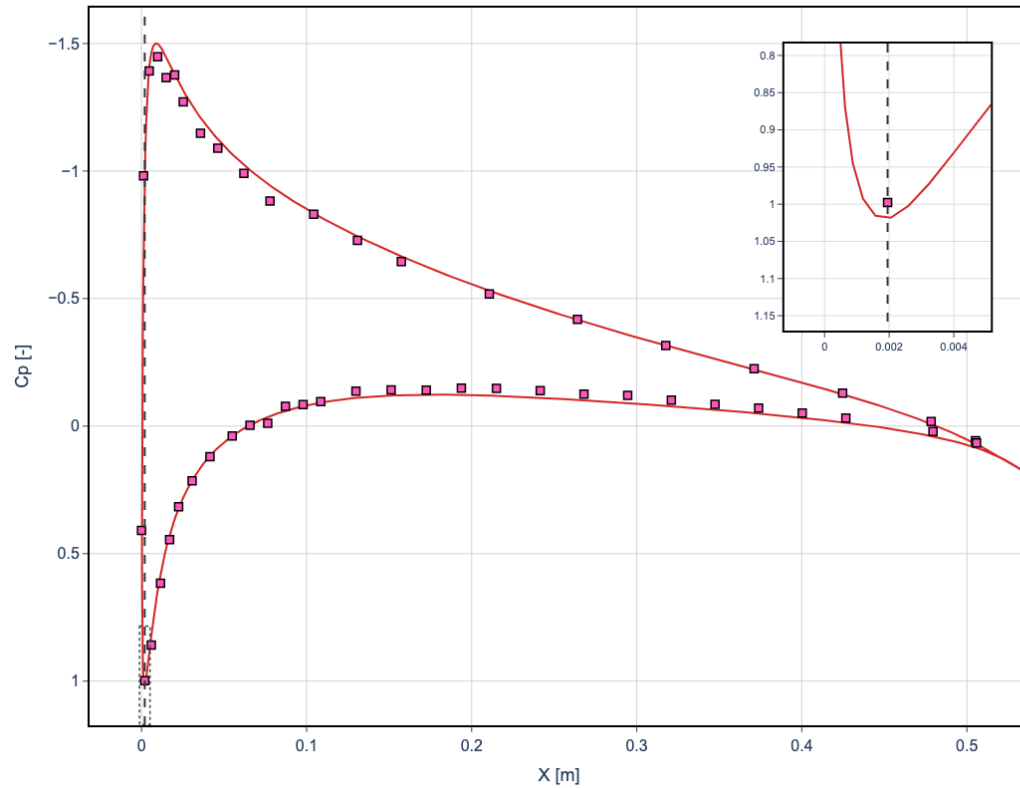


— 008 | Roughness height = 0.5 mm
 ■ Experimental Cp average

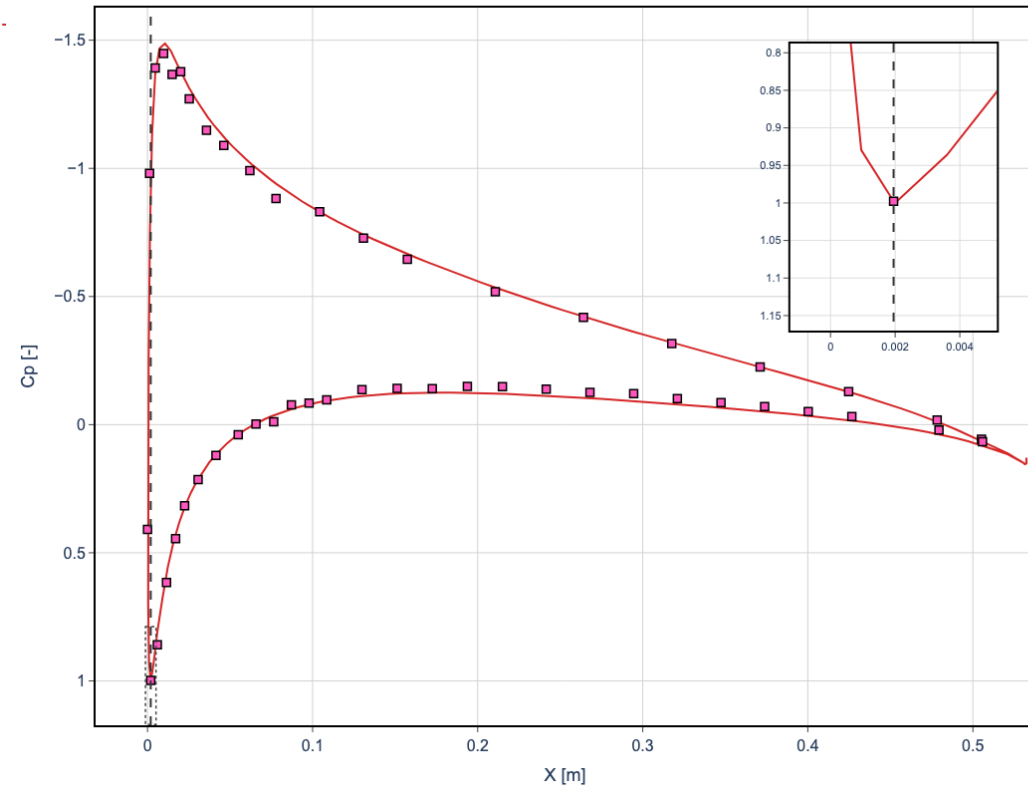
Cp comparison

L1 vs L4

Cp vs X | L1 | Y = 0.9144 m | All roughness heights



Cp vs X | L4 | Y = 0.9144 m | All roughness heights

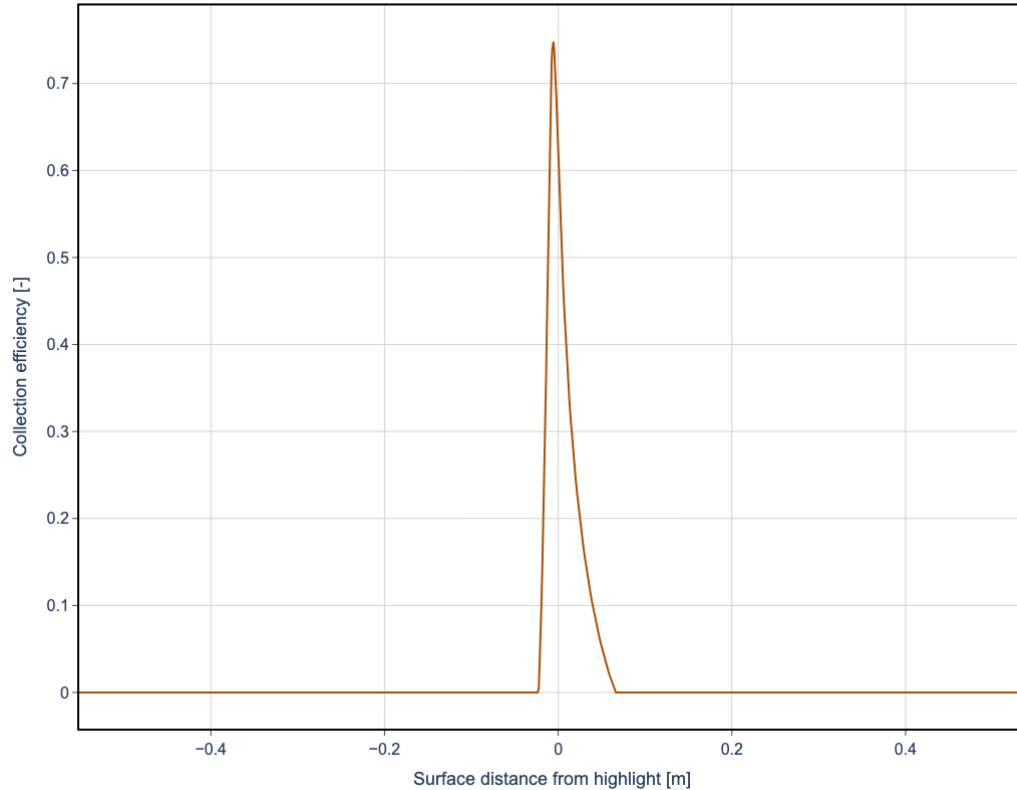


— 008 | Roughness height = 0.5 mm
 ■ Experimental Cp average

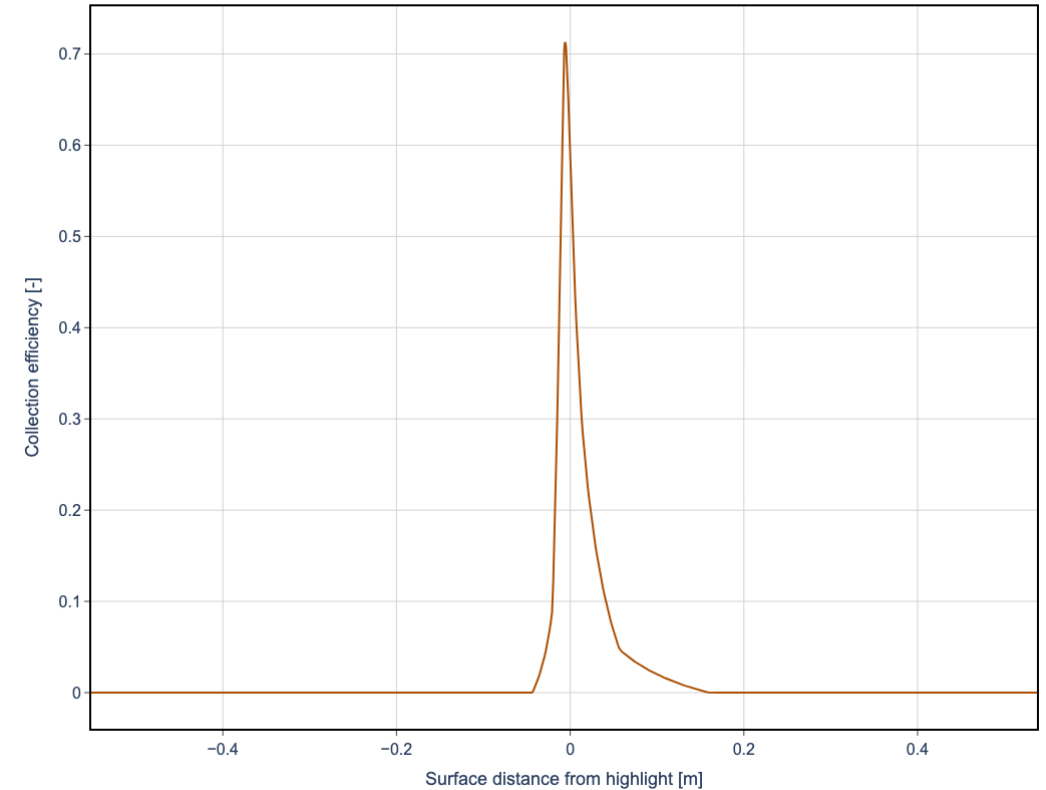
Beta distribution

Effect of cloud discretization for L1 mesh

Collection Efficiency vs s | BINS01 | L1 | Y = 0.9144 m | All roughness heights



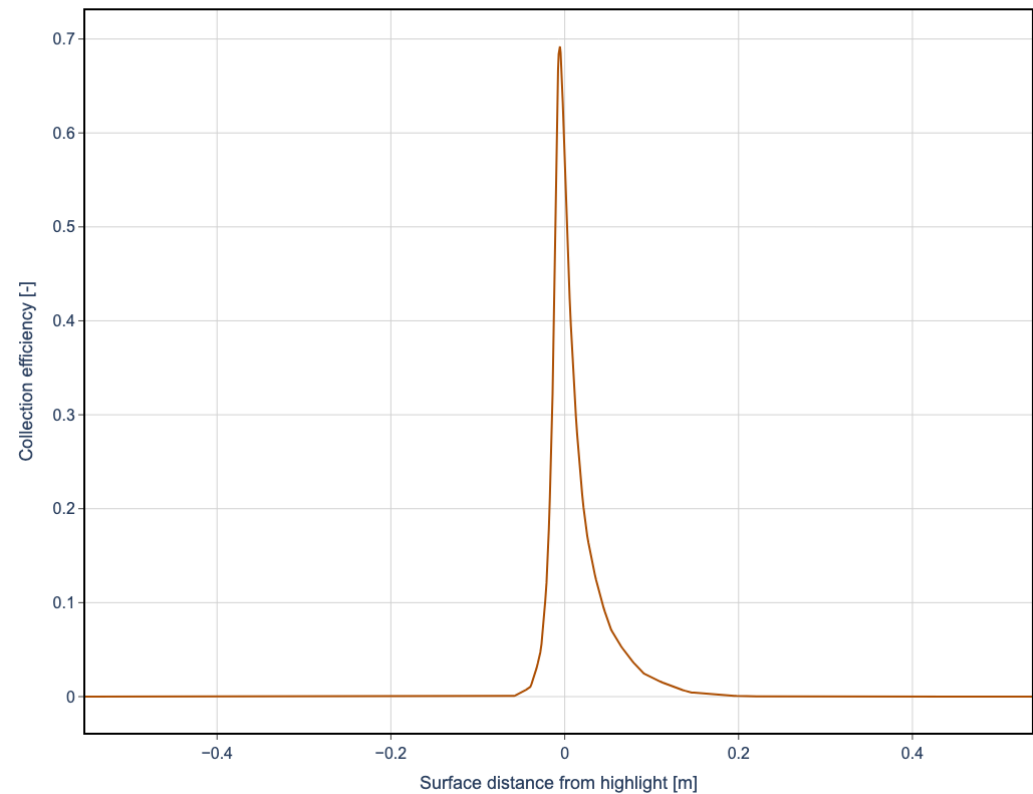
Collection Efficiency vs s | BINS03 | L1 | Y = 0.9144 m | All roughness heights



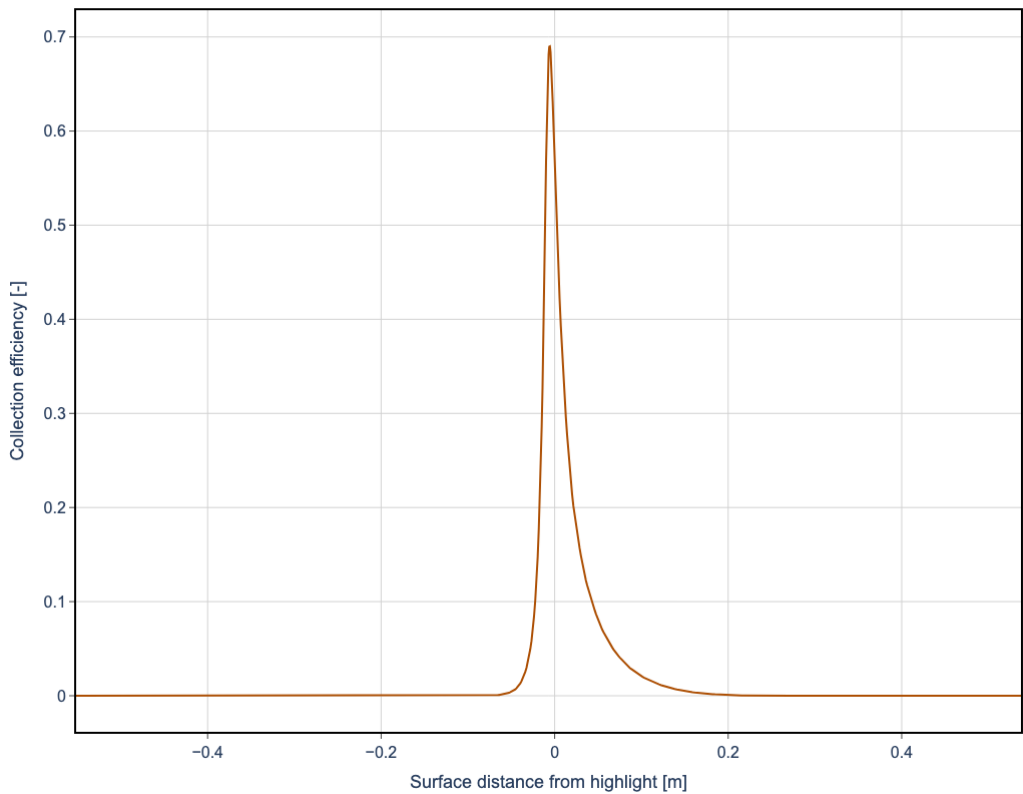
Beta distribution

Effect of cloud discretization for L1 mesh

Collection Efficiency vs s | BINS07 | L1 | Y = 0.9144 m | All roughness heights



Collection Efficiency vs s | BINS15 | L1 | Y = 0.9144 m | All roughness heights

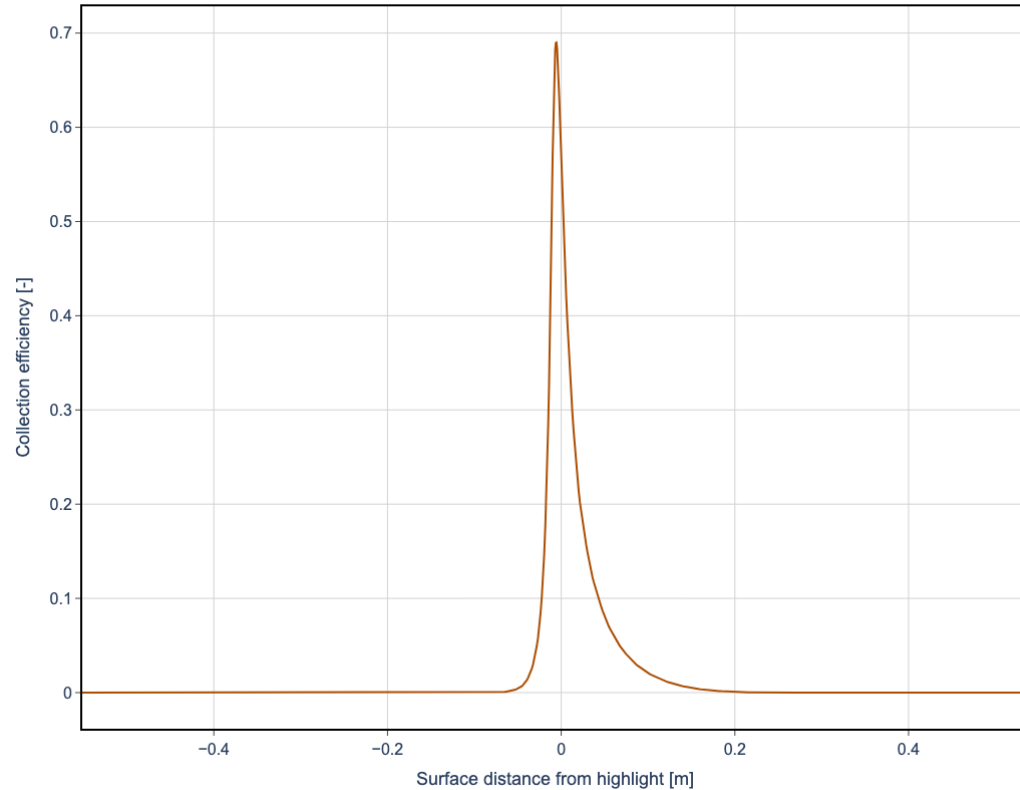


Between 7-bin distribution and 15-bin distribution there is virtually no difference (as for a single shot framework)

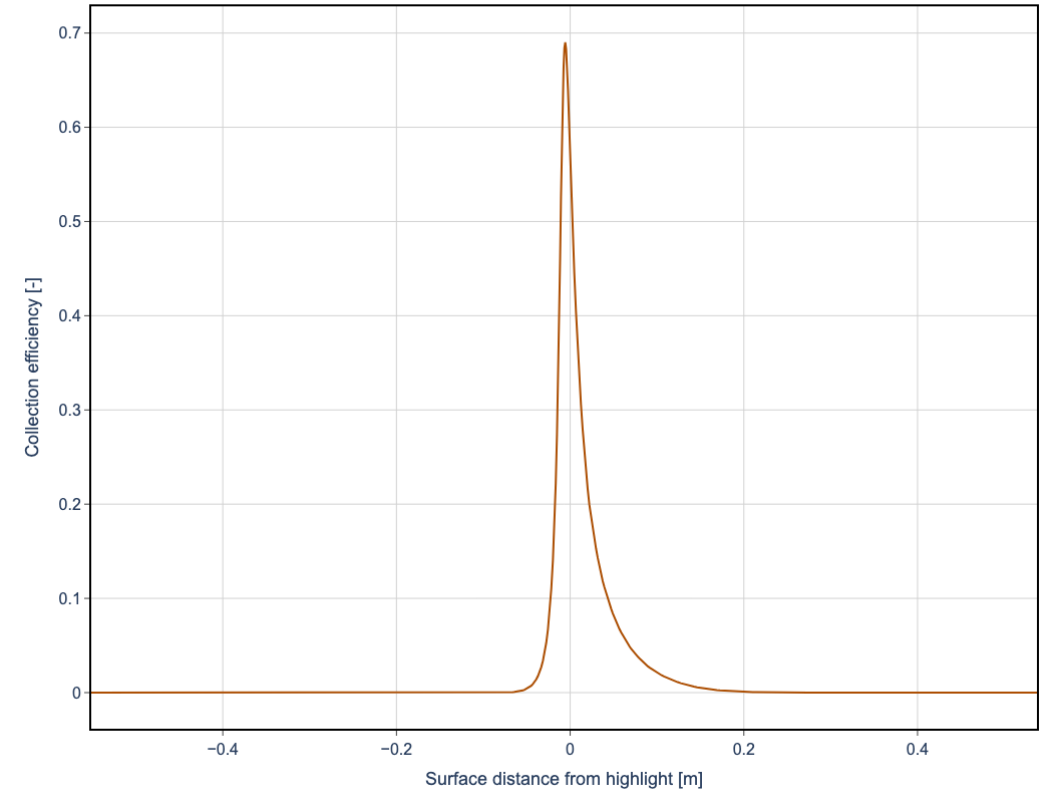
Beta distribution

Effect of mesh resolution on the example of 15-bin cloud discretization

Collection Efficiency vs s | BINS15 | L1 | Y = 0.9144 m | All roughness heights



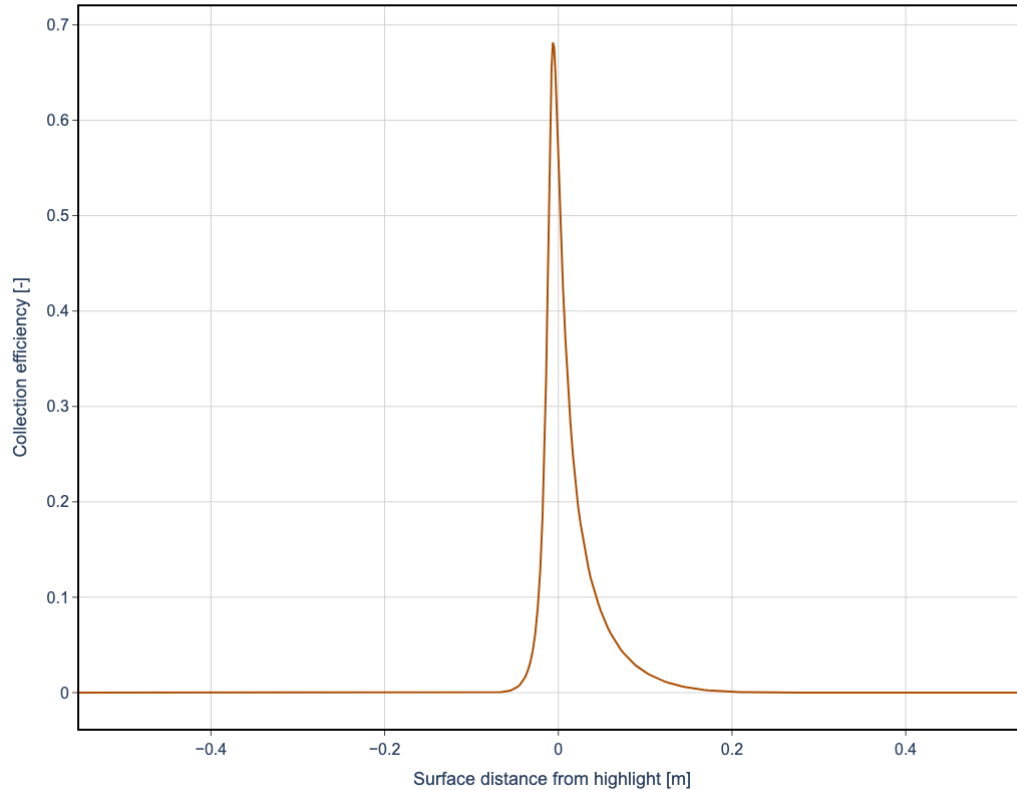
Collection Efficiency vs s | BINS15 | L2 | Y = 0.9144 m | All roughness heights



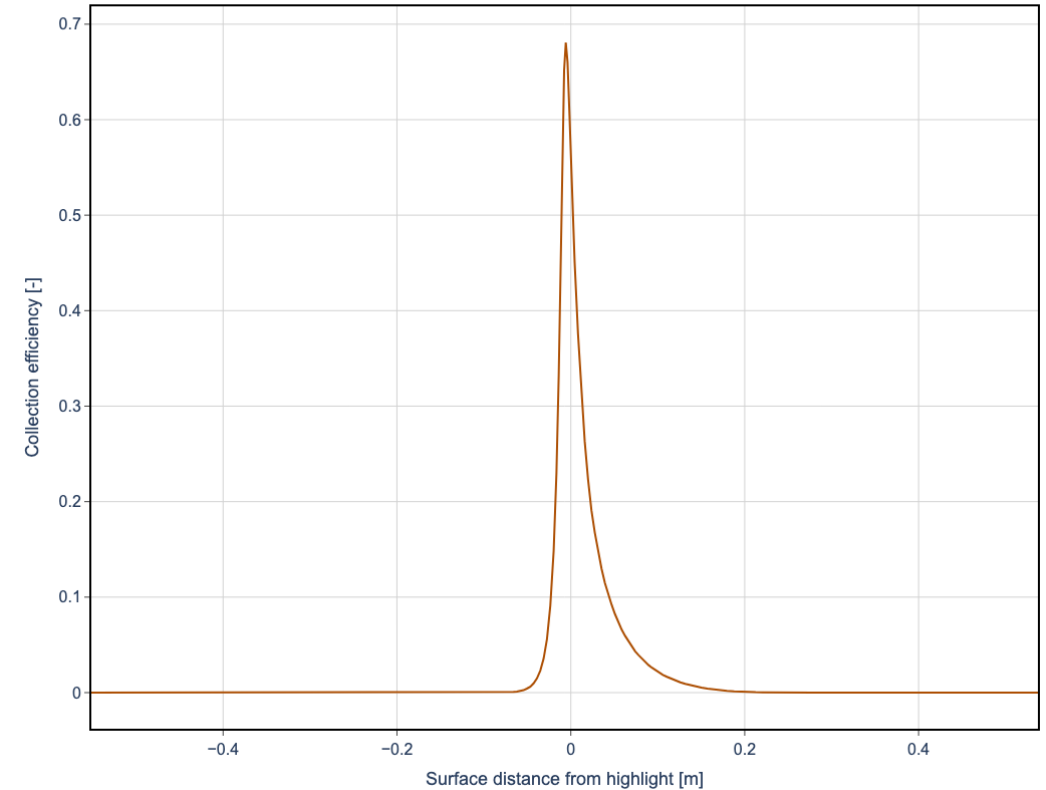
Beta distribution

Effect of mesh resolution on the example of 15-bin cloud discretization

Collection Efficiency vs s | BINS15 | L3 | Y = 0.9144 m | All roughness heights



Collection Efficiency vs s | BINS15 | L4 | Y = 0.9144 m | All roughness heights



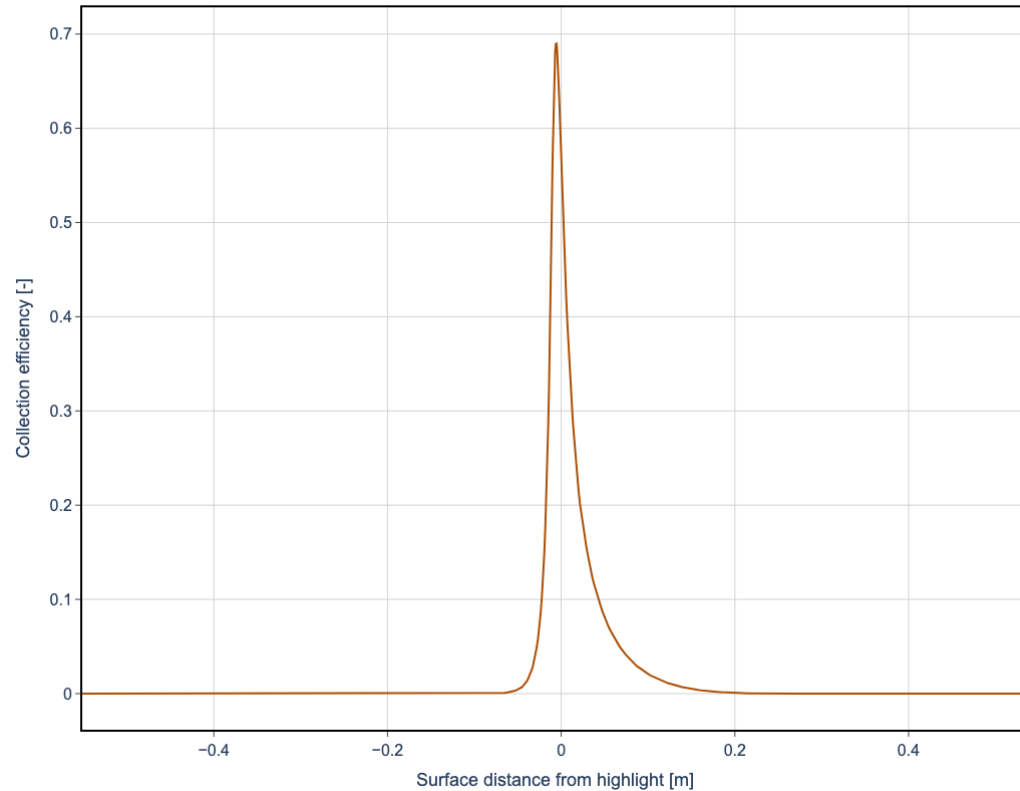
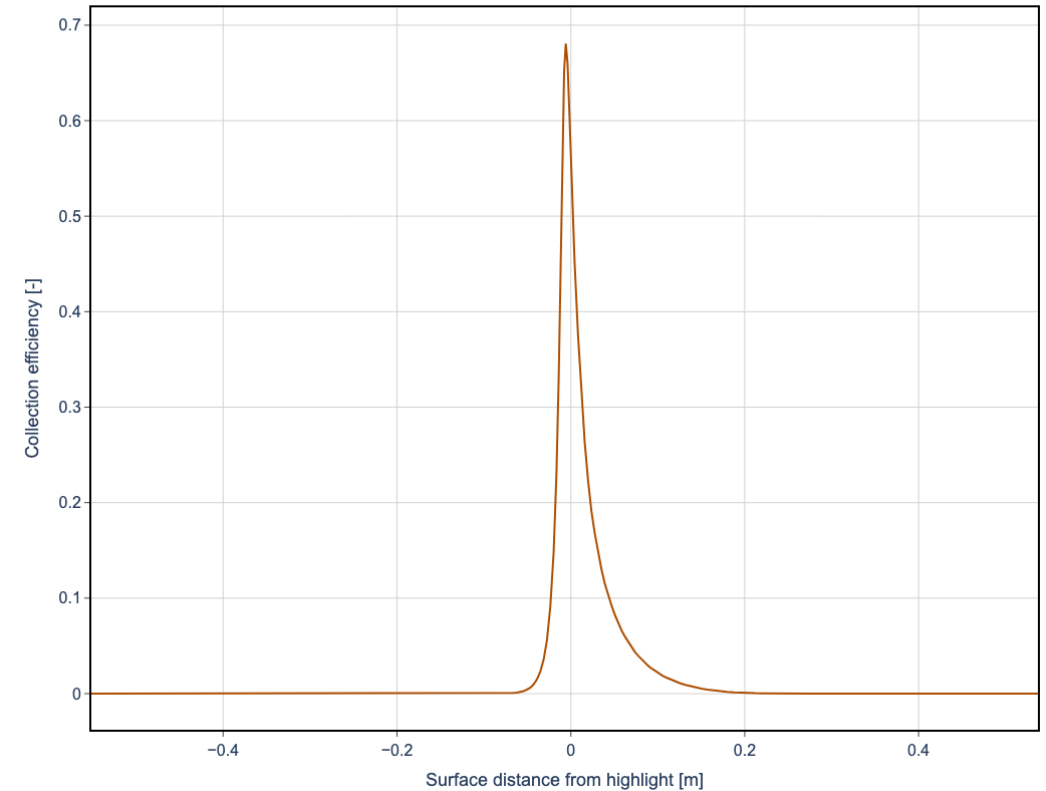
Beta distribution

Effect of mesh resolution on the example of 15-bin cloud discretization

Collection Efficiency vs s | BINS15 | L1 | Y = 0.9144 m | All roughness heights

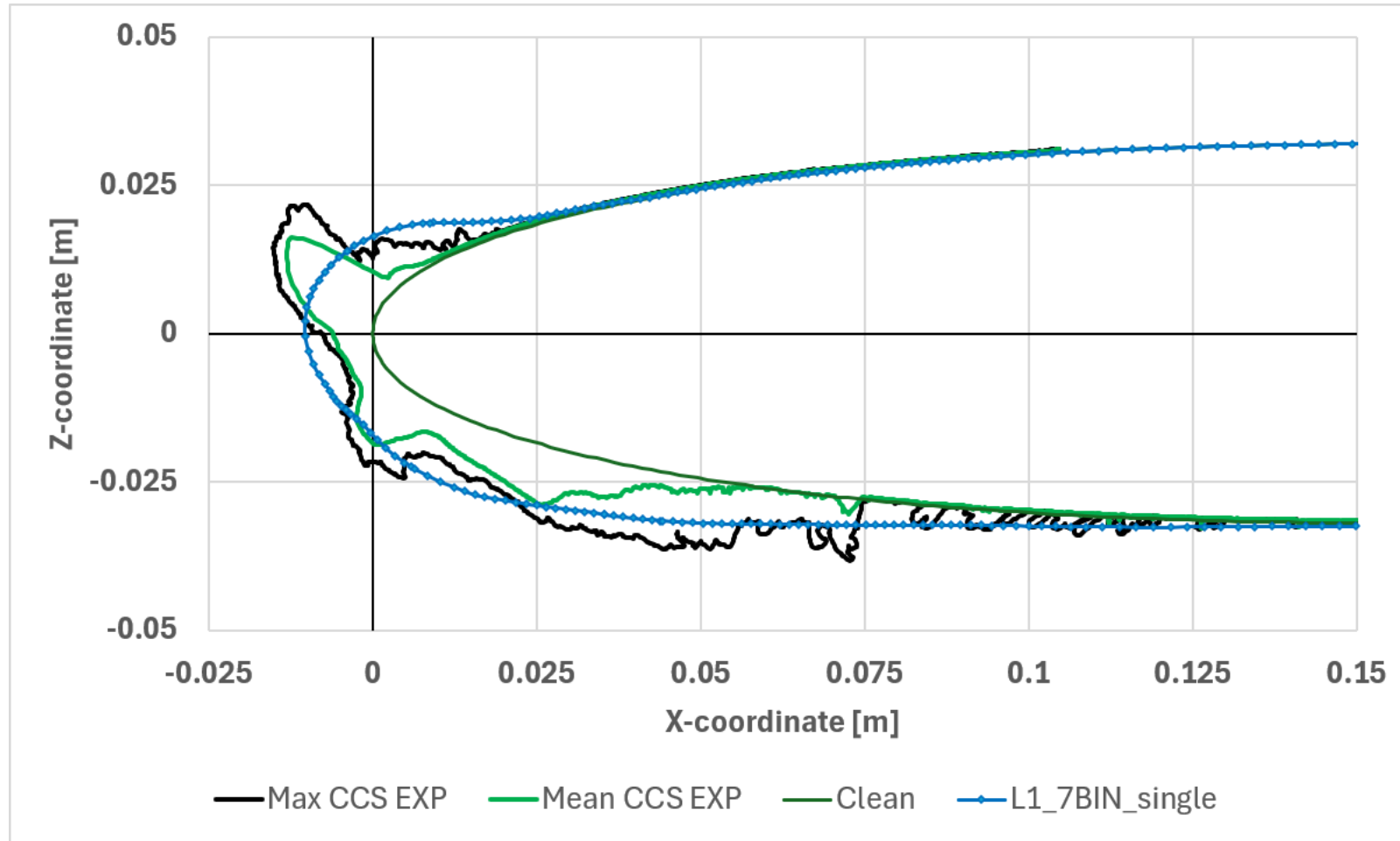
L1 vs L4

Collection Efficiency vs s | BINS15 | L4 | Y = 0.9144 m | All roughness heights

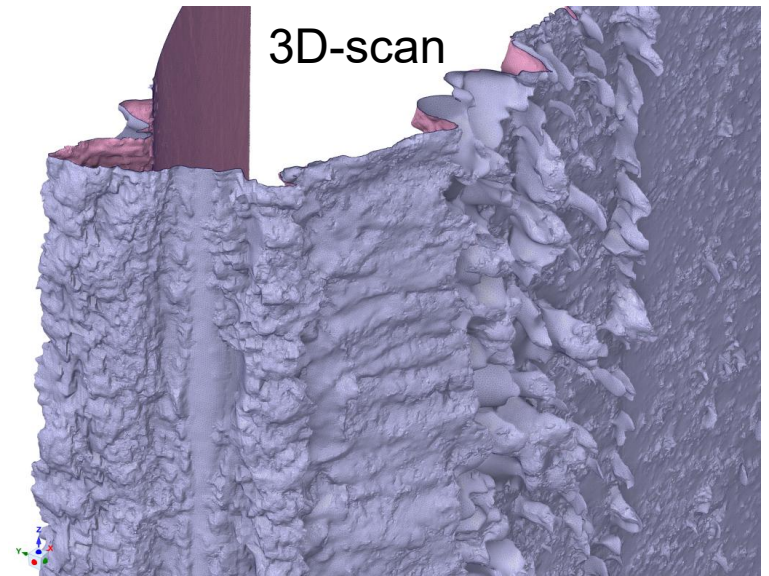


All grid levels produced very similar β distribution, even L1 vs L4 meshes show negligible difference

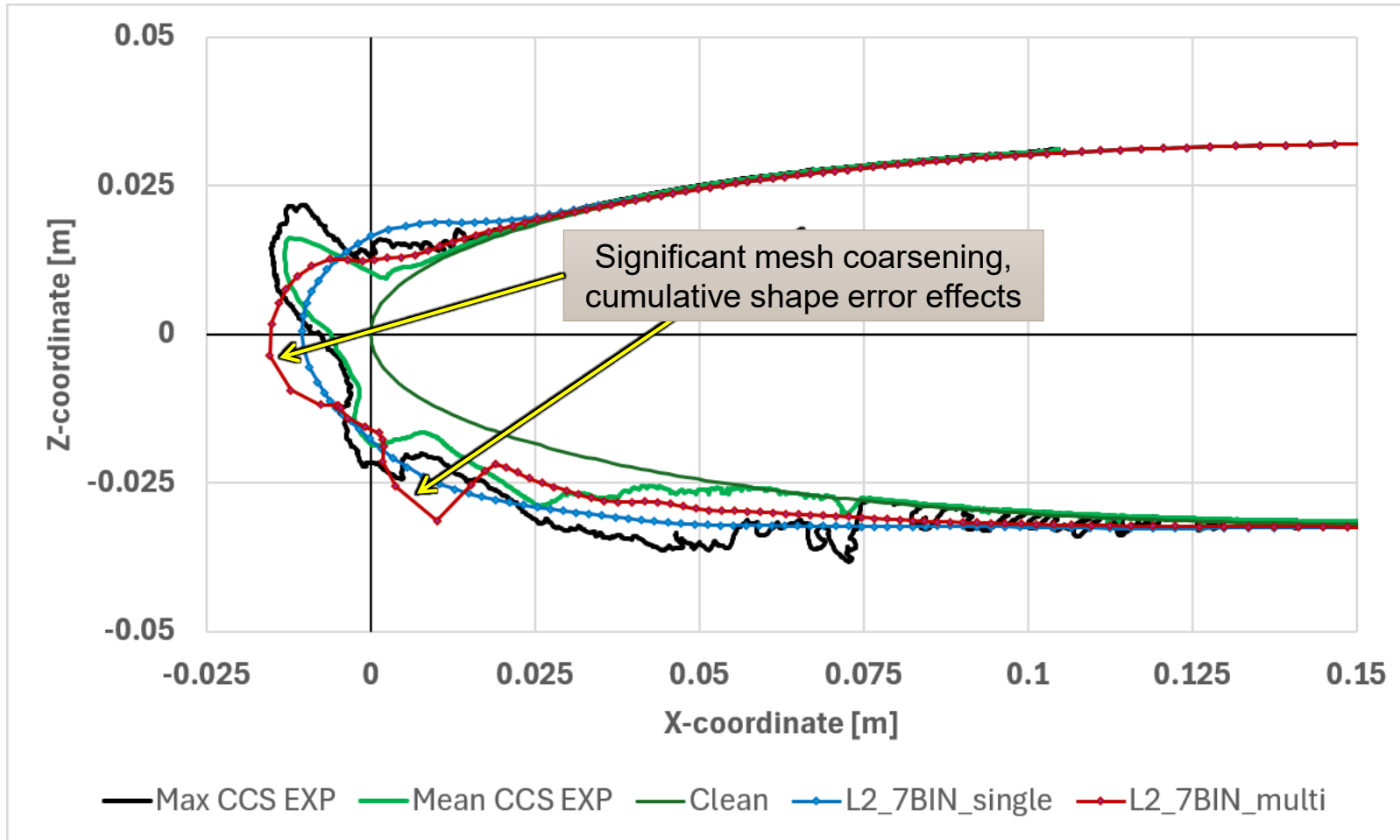
Ice shape comparison



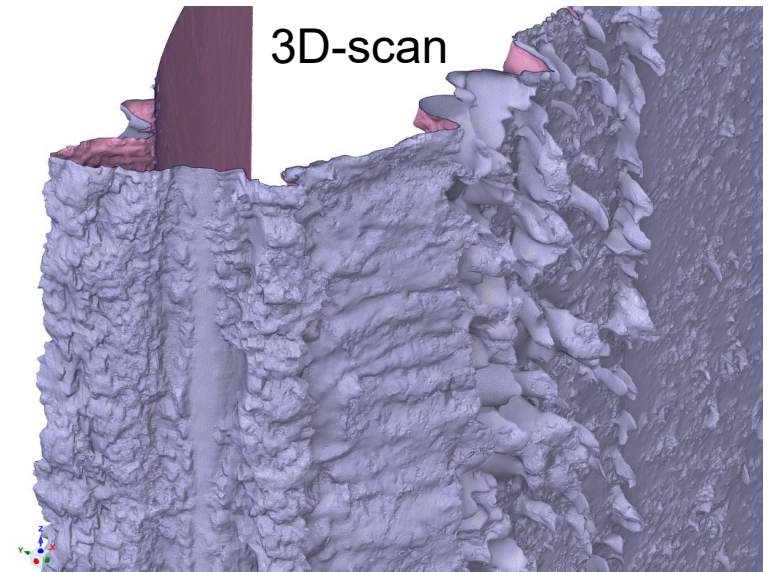
- **L1 mesh**
- Only single shot results
 - Multishot produce self intersecting surface after 5th shot (5 min)
- 7-bin distribution used for multishot
 - Based on single shot sensitivity study we see minor influence between 7 and 15 bin (on single shot results!)



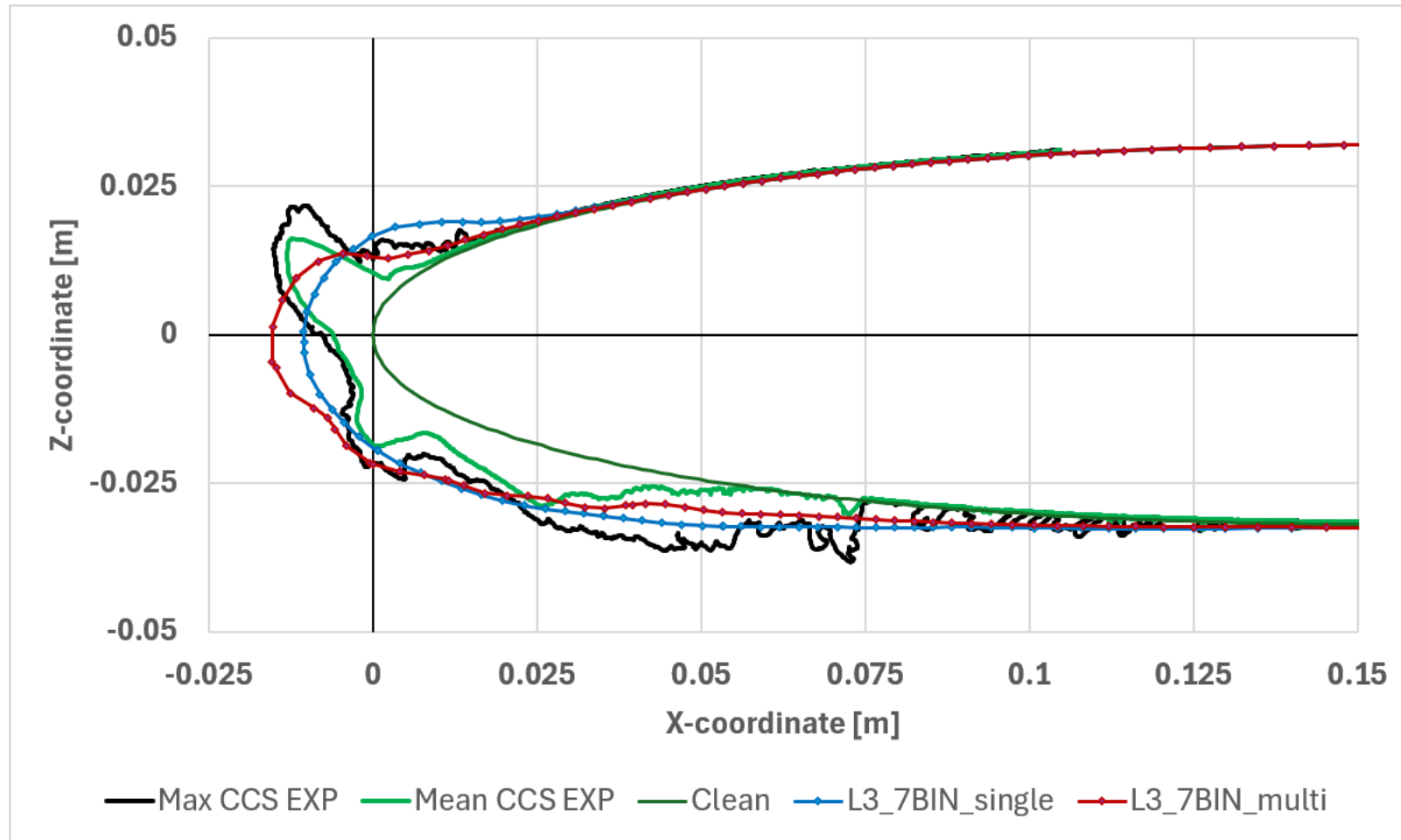
Ice shape comparison



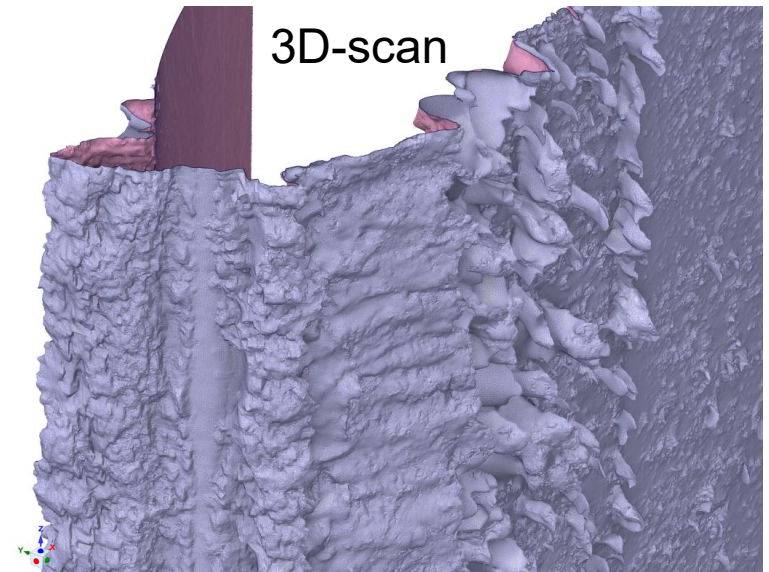
- **L2 mesh**
- 7-bin distribution used for multishot
 - Based on single shot sensitivity study we see minor influence between 7 and 15 bin (on single shot results!)



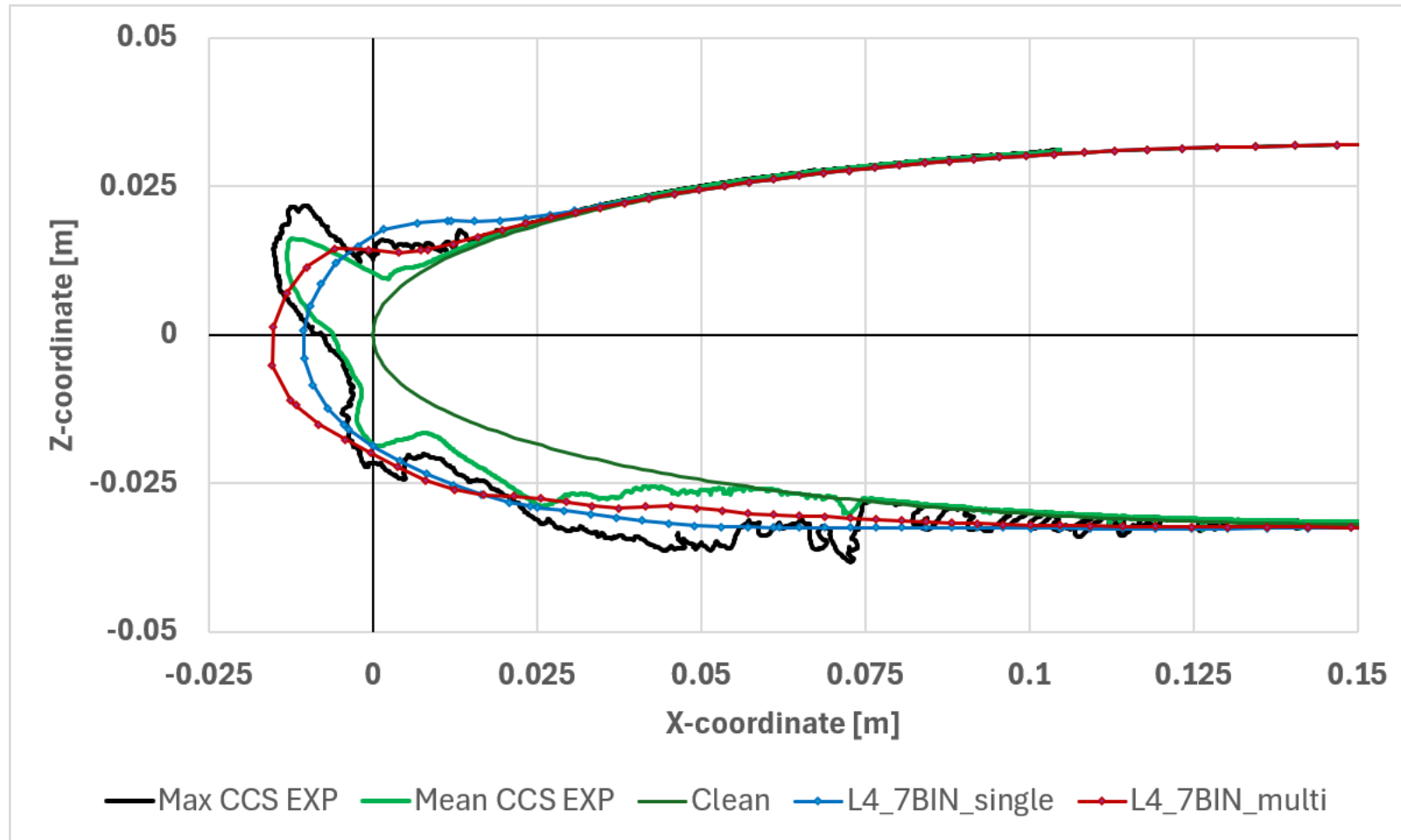
Ice shape comparison



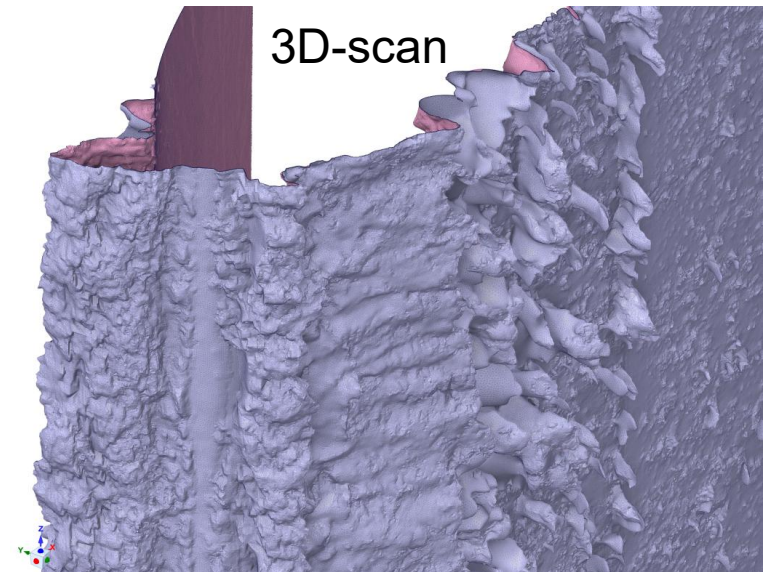
- **L3 mesh**
- 7-bin distribution used for multishot
 - Based on single shot sensitivity study we see minor influence between 7 and 15 bin (on single shot results!)



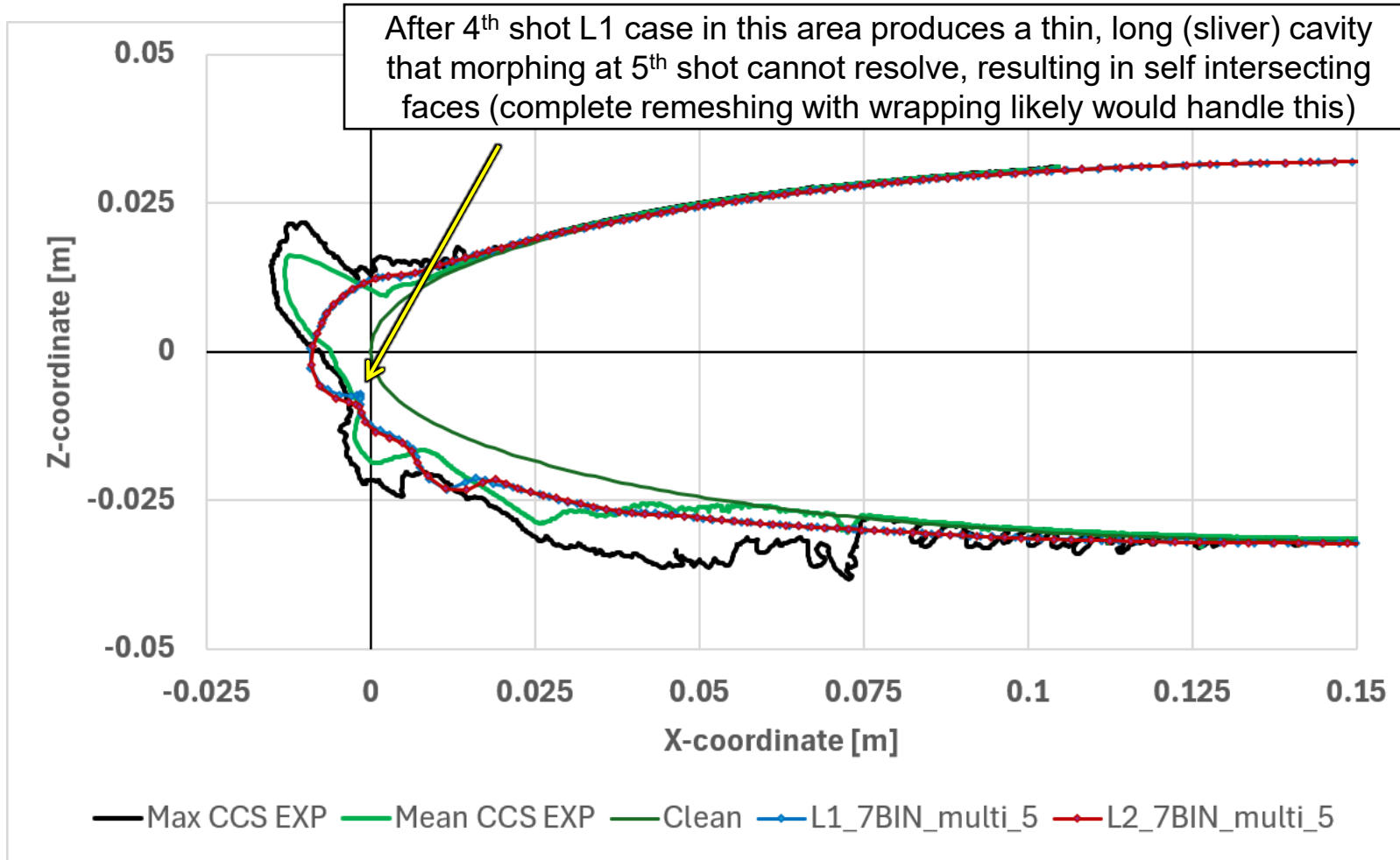
Ice shape comparison



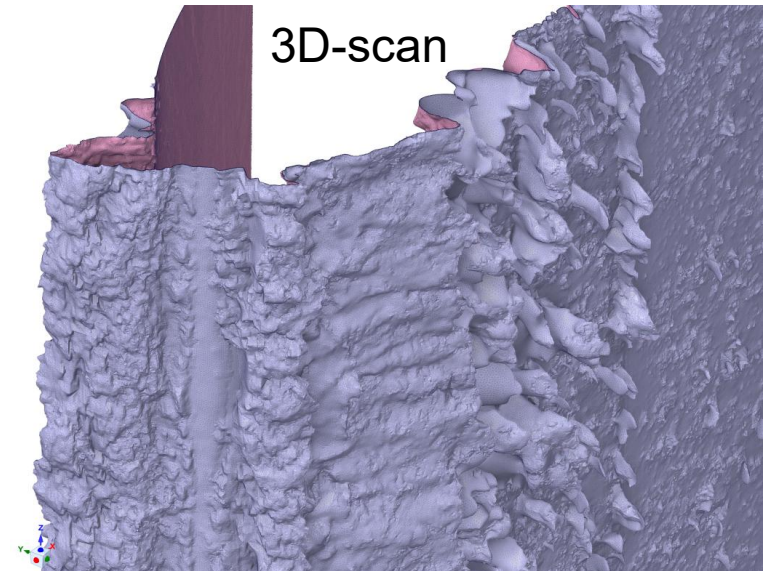
- **L4 mesh**
- 7-bin distribution used for multishot
 - Based on single shot sensitivity study we see minor influence between 7 and 15 bin (on single shot results!)



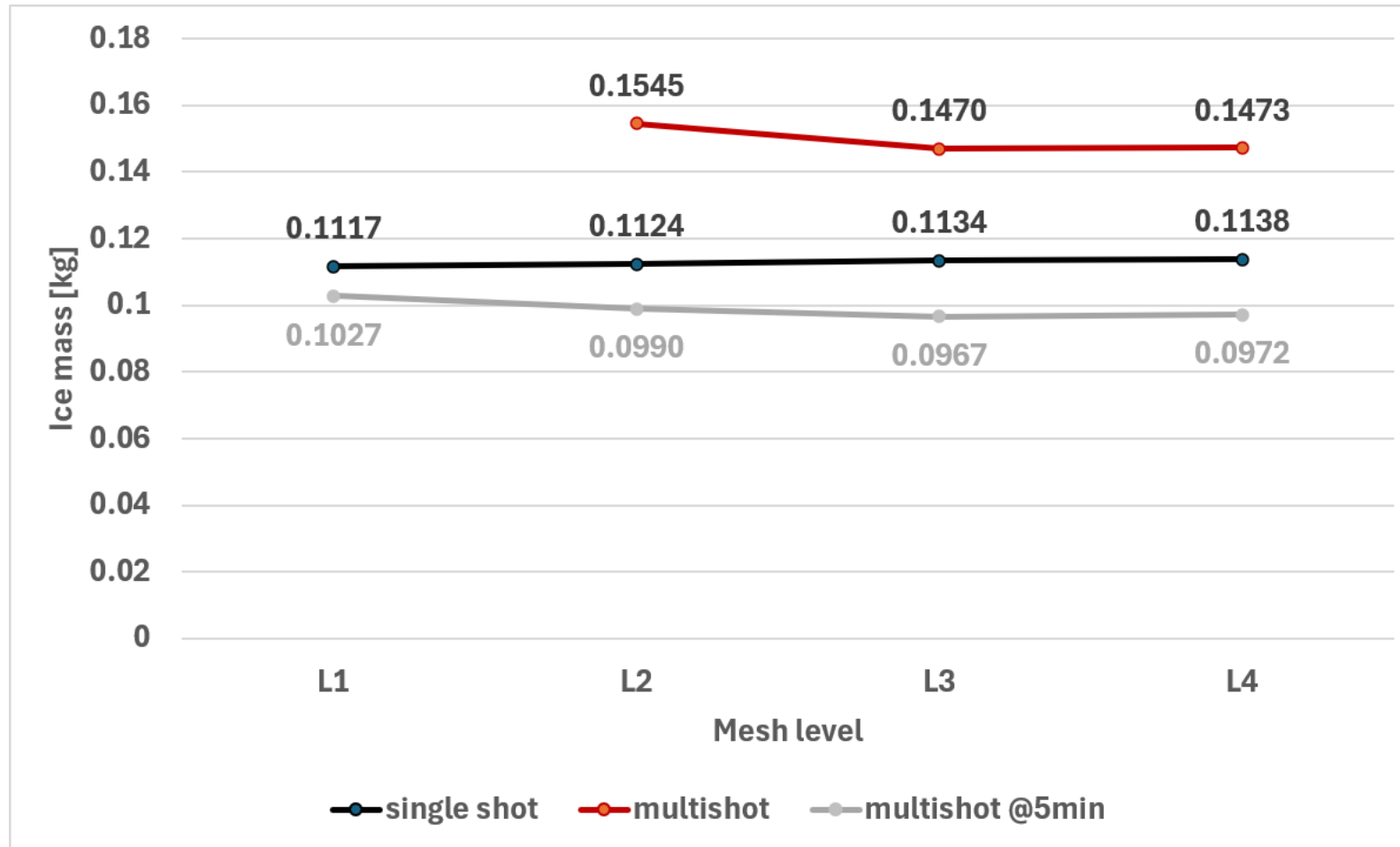
Ice shape comparison



- L1 & L2 mesh after 5 shots (5min)
- 7-bin distribution used for multishot
 - Based on single shot sensitivity study we see minor influence between 7 and 15 bin (on single shot results!)



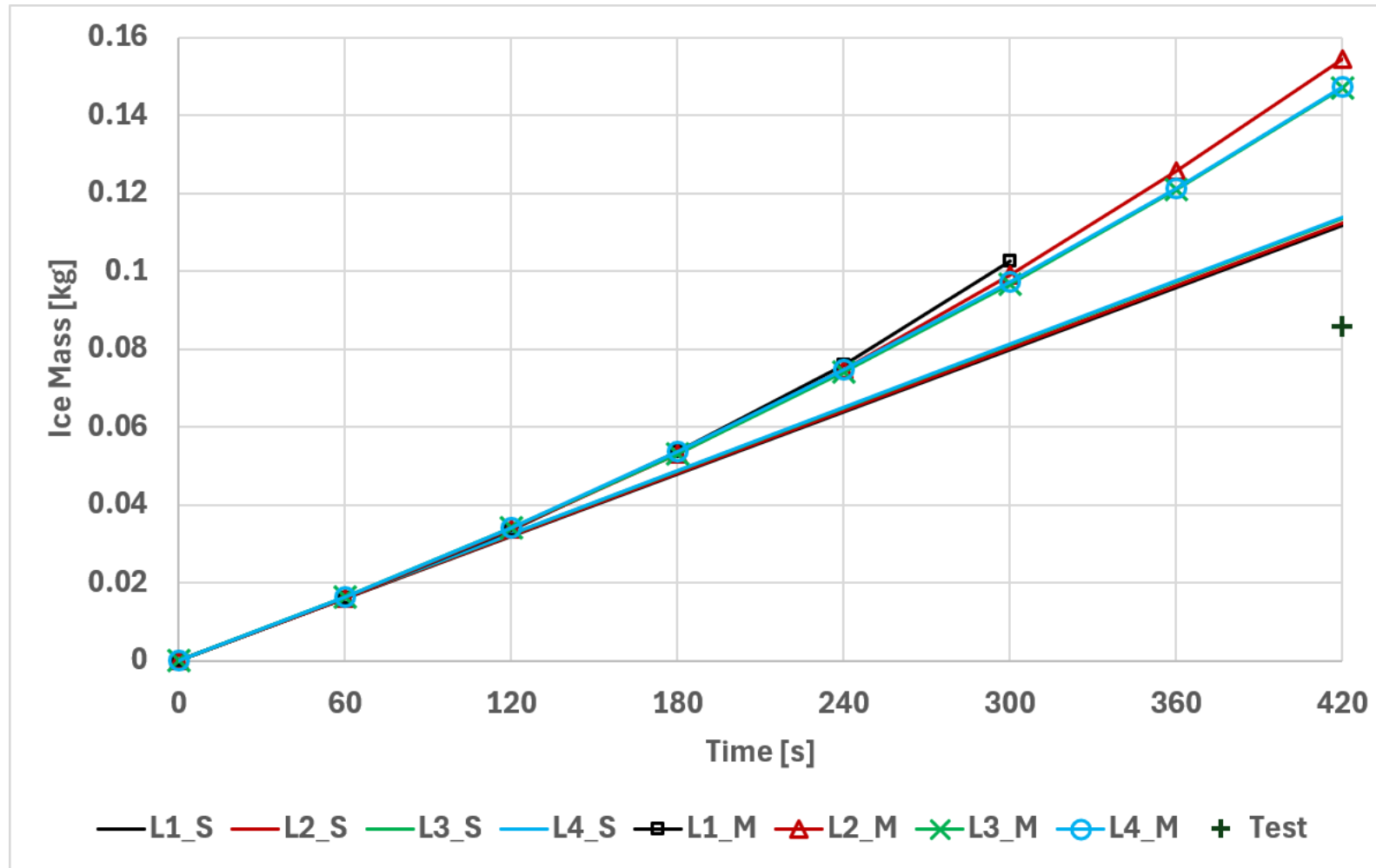
Ice mass comparison



Accumulated ice mass comparison with respect to mesh level

- Reference test value is 0.0859 [kg]
- L3 and L4 meshes predict ~29% more ice mass compared to single shot
- L2 mesh predicts ~37% more ice mass compared to single shot
- For L1 mesh only partial data exists and shows that increasing ice mass trend is maintained
 - Using simple extrapolation, we could expect ~45% more ice mass predicted with L1 multishot compared to L1 single shot analysis

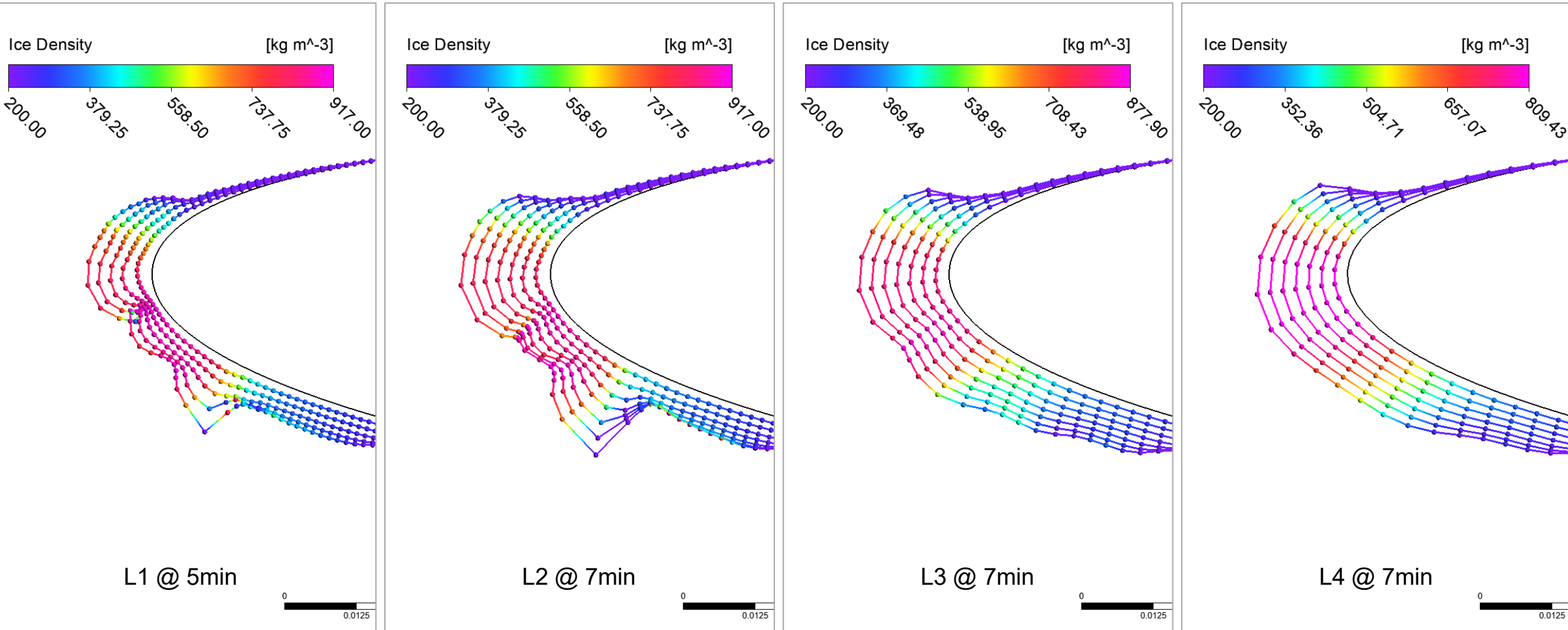
Ice mass comparison



Ice mass development with respect to time

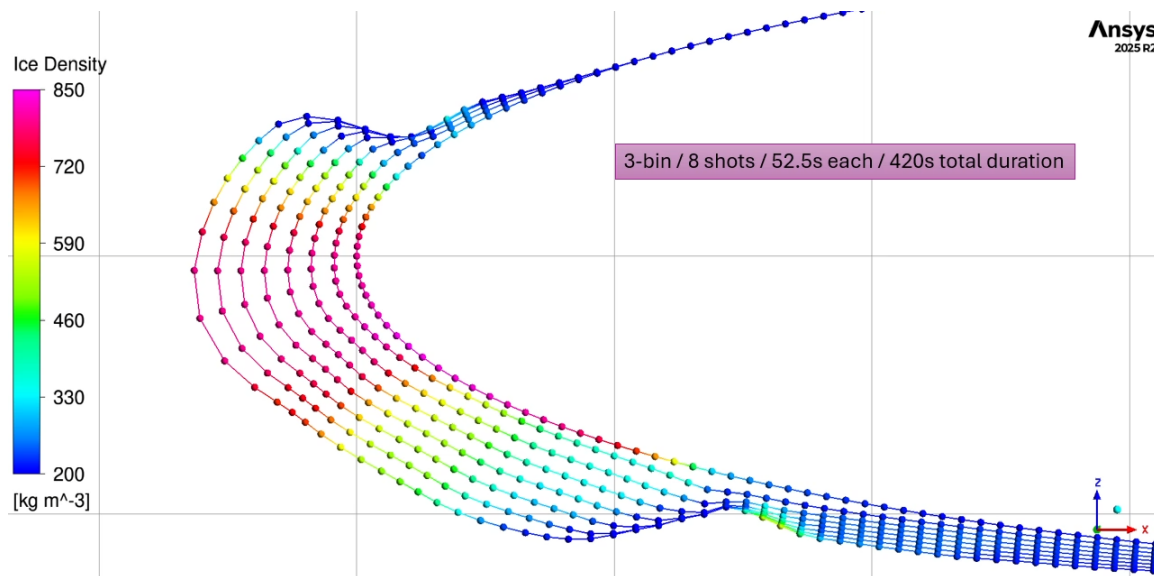
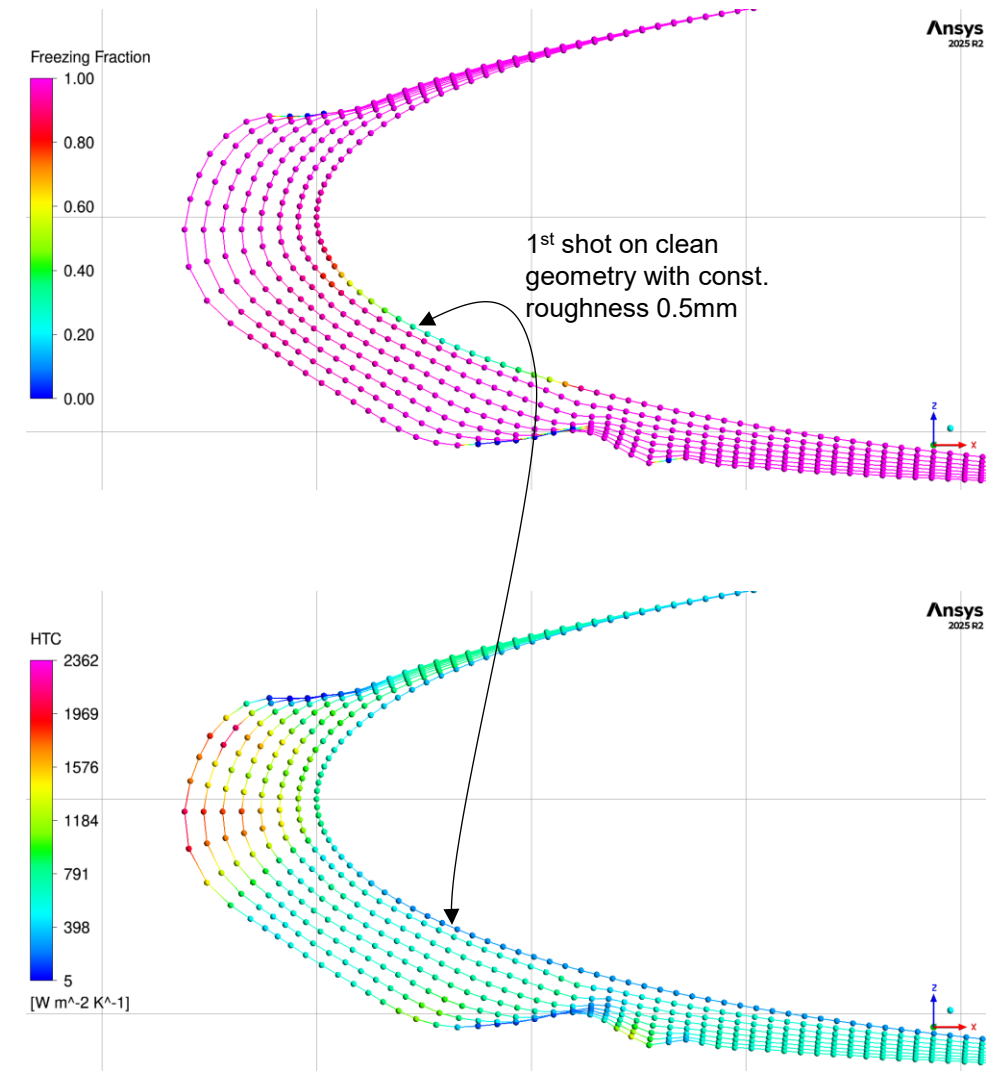
- Reference test value is 0.0859 [kg]
- Single shot simulation yields almost identical ice mass between mesh levels and overpredicting by ~31.3%
- L3 and L4 meshes in multishot simulation predict virtually the same ice mass
- L1 and L2 meshes predict the same ice mass up to 4th shot then rate of mass accumulation increases
 - More detailed 3D ice features yield to more water catch?

Multishot ice shape development



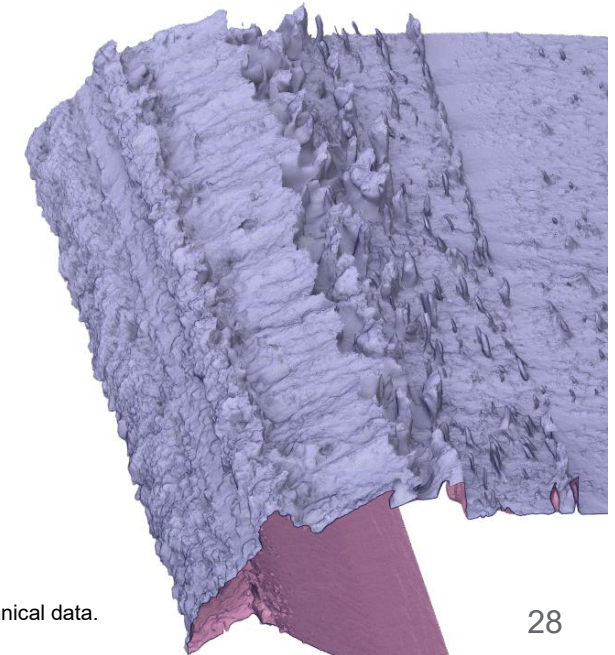
Other remarks and observations

- Ice mass convergence study and ice shape convergence study in multi-shot framework, where varying parameter is number of bins, suggests minor effect of predictions using more than 7 bins
 - This statement is assuming small droplets physics
- Morphing method produces coarse elements very quickly, thus curvatures become under-resolved / aliased
- Roughness evolution quickly amplifies predicted HTC, increasing as a result freezing fraction if possible



Conclusion and future direction

1. Experimental ice mass is significantly lower than simulated one for warm conditions (AE3933)
 1. Splashing of larger drops, not being modeled? (10% of drops > 60um)
 2. Overpredicted HTC due to roughness value / roughness evolution yielding higher FF?
 3. LWC uncertainty? (<10%)
 4. Thermal non-equilibrium of the droplets leaving spray bars, traveling downstream, resulting in lowered FF?
 5. Ice shedding during experiment in warm conditions, resulting in lowered ice mass at the end of experiment?
 6. Other explanation either on numerical or experimental side?
2. Morphing method was quickly coarsening curved surfaces which has a cumulative effect
 1. Full remeshing or hybrid, morphing – node redistribution method might help
3. Simulated ice horns in multishot framework are shifted
 1. Initial roughness / roughness evolution / HTC evolution / shear stresses / impact ice density model leading to water film freezing too quickly / too late, thus shifting horns?
 2. Finer multishot resolution (shot duration) combined with efficient handling of geometry evolution?
 3. Again, the coarsening effect of the mesh being morphed aliased the predicted shape and had cumulative effect?



Q&A



Thank you

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