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Simulating Process Subtleties in SEM Imaging

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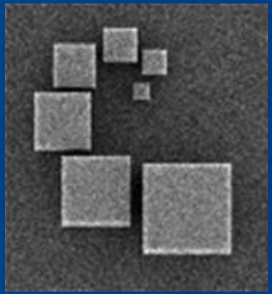


AMAG Consulting, LLC

Established December, 2019

Available via AMAG Consulting:

- Test artifact foundry with AMAG7 reticle
- SEM simulation with AMAG SimuSEM software
- Semiconductor metrology expertise
- Updated industry-wide application-level metrology use-case & gaps analysis
- Specifications & samples usable/adaptable for equipment supplier enablement
- BKM's such as precision, accuracy & matching improvement
- Training in general metrology topics
- Very broad network of contacts

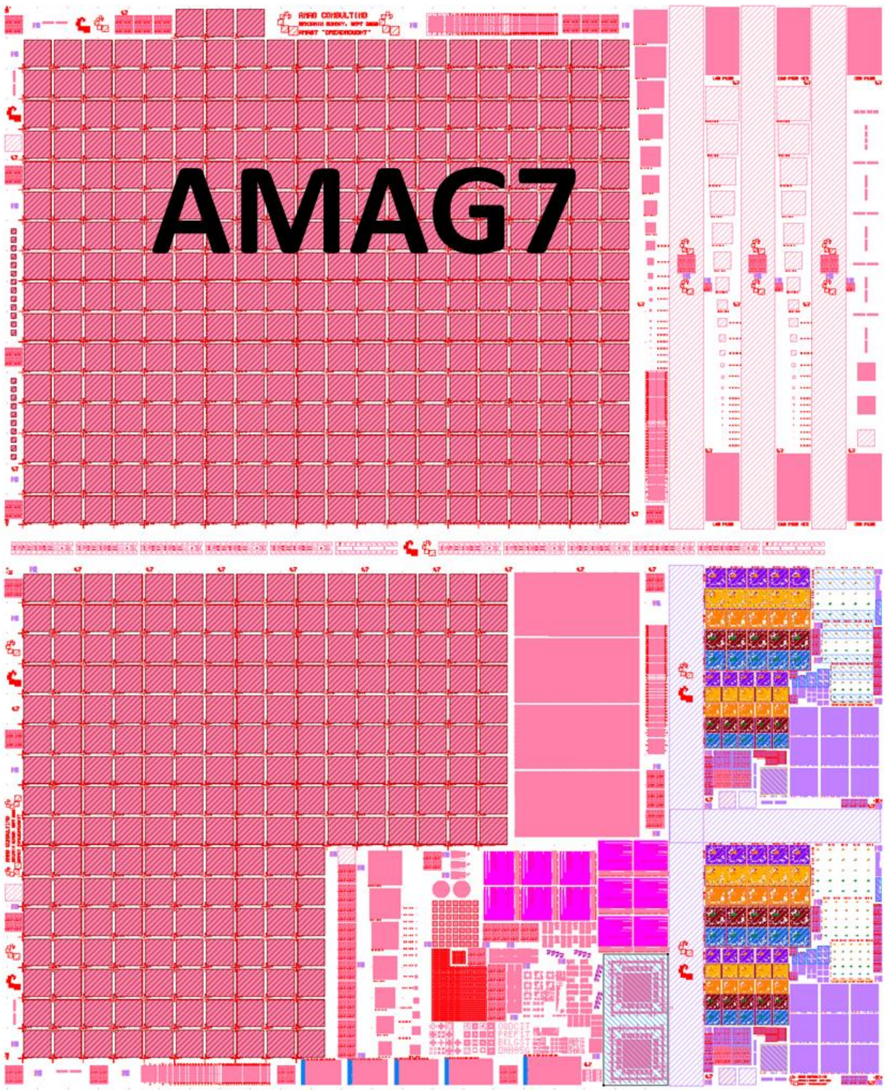
About AMAG:

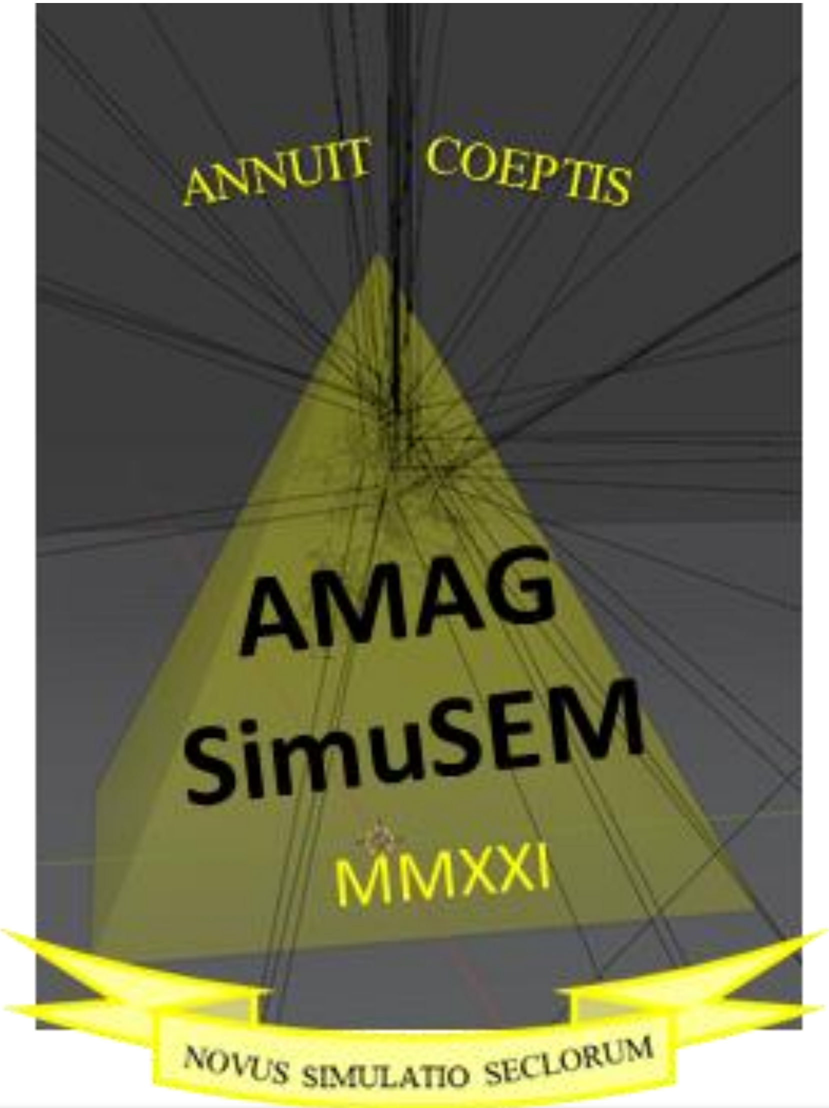
- SEMATECH AMAG (Advanced Metrology Advisory Group) for 20 years was very influential in guiding semiconductor metrology to keep pace with the ITRS roadmap
- Strong collaboration among IC manufacturers, equipment suppliers, laboratories & universities identified critical industry metrology problems and formulated/executed consensus solutions
- AMAG Consulting's Benjamin Bunday was AMAG Chair from 2001-2015, and led the team that developed such AMAG items and can still leverage products of those efforts
- AMAG Consulting offers similar enablement activities in the SEMATECH AMAG tradition

Goal of AMAG Consulting:

- **Leverage & rebuild AMAG assets to enable metrology sector progress.**

AMAG Consulting, LLC
Products



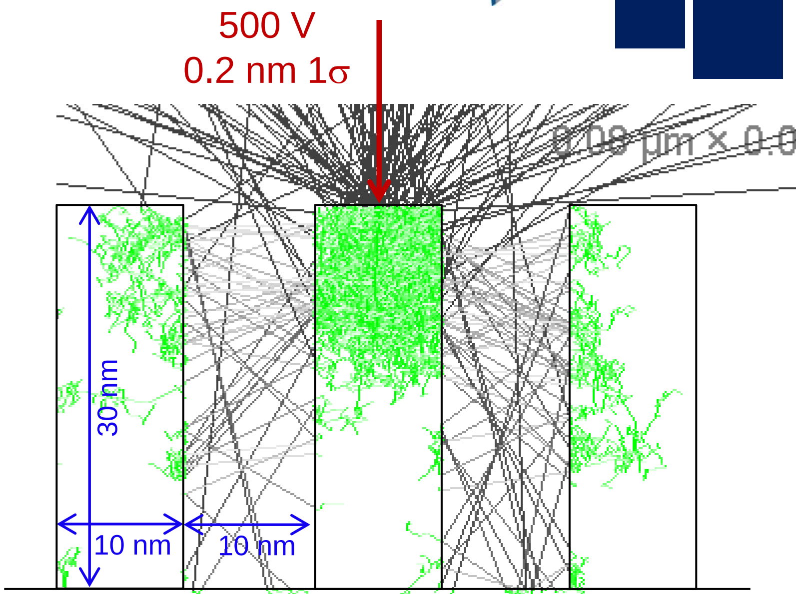


Introduction

- Monte Carlo SEM simulations are necessary but resource hungry, thus usually include few fine details. Perfect smooth idealized structures are the norm.
- Other subtleties of interest include defects, pits, bumps, etch halos, sidewall bowing, craters, scratches or defects on or below the surface, CMP dishing, top corner rounding or footing at the base of a resist line or contact hole, or many other possibilities.
- We know these will add signatures to the simulated image, but it is important to understand how important are they to achieving realistic results.
- In this work, several different cases of such process subtleties will be simulated and compared to results from simulated idealized features, to determine the significance of such details compared to typical noise.
- More complex features can now be modeled using NIST's JMONSEL through a new improved version, AMAG SimuSEM, which essentially completes SEMATECH AMAG's original vision for JMONSEL by adding a powerful GUI, and updates the software to current expectations by greatly improving utility, productivity, flexibility, visualization, accessibility, and achievable complexity of designed features while greatly improving simulation speed and scalability.
- Additionally, the new software allows viewing of all electron trajectories in the 3D environment which allows additional observations on how various process subtleties might affect the SEM signal.

JMONSEL by NIST

- **JMONSEL is a 3-D simulating program**
  - Java MONte Carlo Simulator for Secondary ELectrons
- **Written by John Villarrubia (NIST) for SEMATECH AMAG as 1st principles SEM simulator**
  - Open source, transparently implements best known physical models
- **The program follows electrons as they…**
  - Enter the material
  - Scatter
  - Lose energy
  - Exit the material
  - Are captured by detector
- **By monitoring electrons that exit material and are captured, electron yields found**
  - SEM Line scans (waveforms)
- **User definable targets**
  - Lines, cylinders, spheres, multiplanar shapes, films, substrate
  - Ag, Al, Au, Cu, Diamond, Fe, glassyC, Graphite, Mo, Pt, Ru, SiO2, Si, Ta, TiN, whiteSn, W, PMMA
- **Beam & Scan parameters**
  - Beam energy <5keV (up to 30keV on some materials)
  - Dose (# incident electrons per pixel)
  - Pixel size (set as scan locations at coordinates x,y)
  - Spot size (1sigma of Gaussian-profile)
  - Incident beam angle (could “tilt” if necessary)



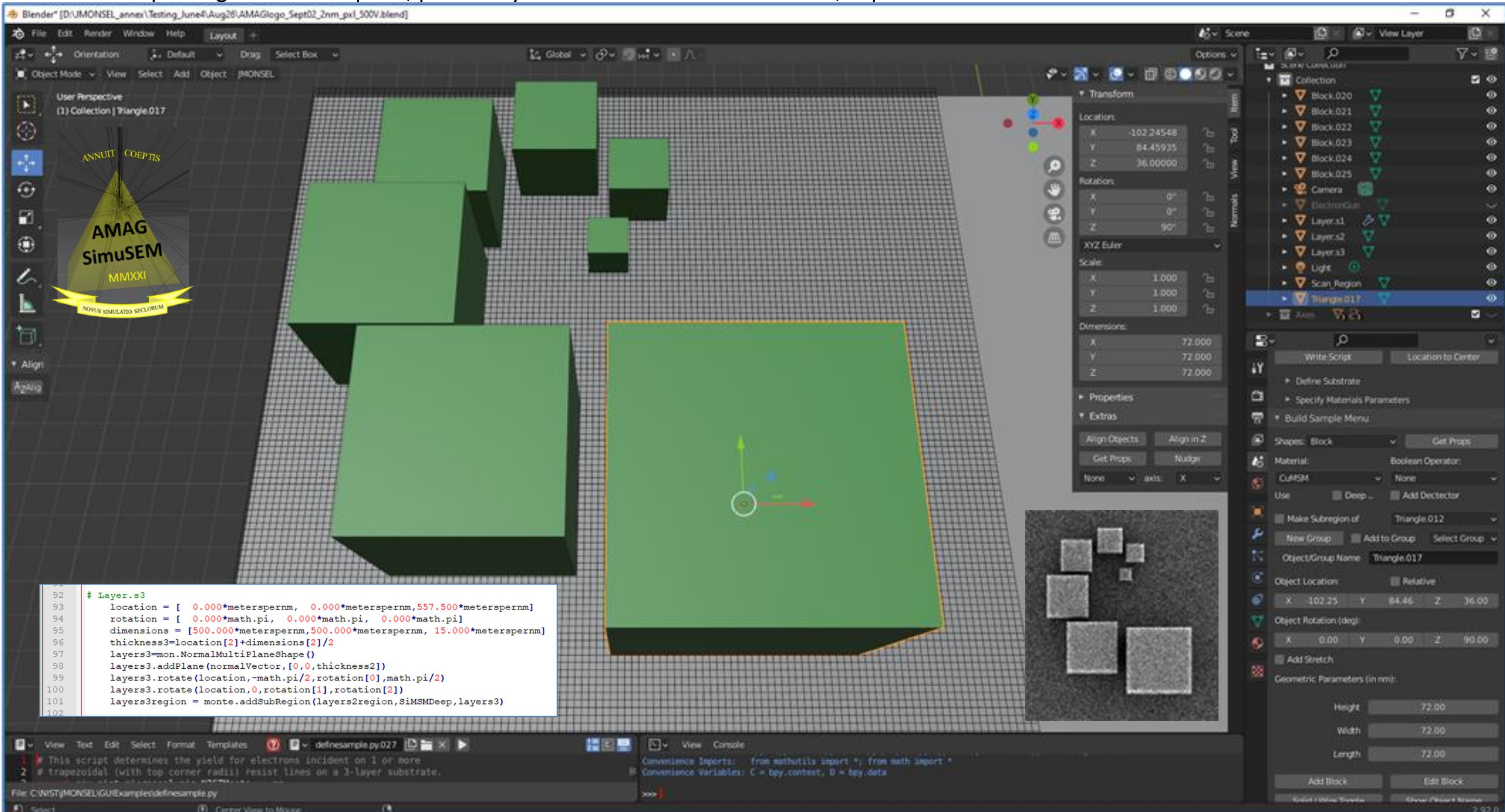
Simulated trajectories,
500 V beam on10 nm line/space

```
# Layer.s3
    location = [  0.000*meterspernm,  0.000*meterspernm,557.500*meterspernm]
    rotation = [  0.000*math.pi,  0.000*math.pi,  0.000*math.pi]
    dimensions = [500.000*meterspernm,500.000*meterspernm, 15.000*meterspernm]
    thickness3=location[2]+dimensions[2]/2
    layers3=mon.NormalMultiPlaneShape()
    layers3.addPlane(normalVector,[0,0,thickness2])
    layers3.rotate(location,-math.pi/2,rotation[0],math.pi/2)
    layers3.rotate(location,0,rotation[1],rotation[2])
    layers3region = monte.addSubRegion(layers2region,SiMSMDeep,layers3)
```

But, coding JMONSEL scripts is challenging and hard to visualize for detailed features.

AMAG SimuSEM / JMONSEL GUI

- AMAG SimuSEM is total overhaul, enhancement & modernization extension to JMONSEL.
- Powerful yet intuitive GUI achieved by building NIST JMONSEL and rigorous sample definition capabilities into 3D Blender interface. Complex samples now possible. Core physics is still original JMONSEL code, although code is speed optimized and enhanced with new & evolving features & outputs.
- Greatly improved utility, productivity, flexibility, visualization, accessibility, & achievable complexity of designed features while improving simulation speed, plus many other refinements & additions, superior results access & visualization.



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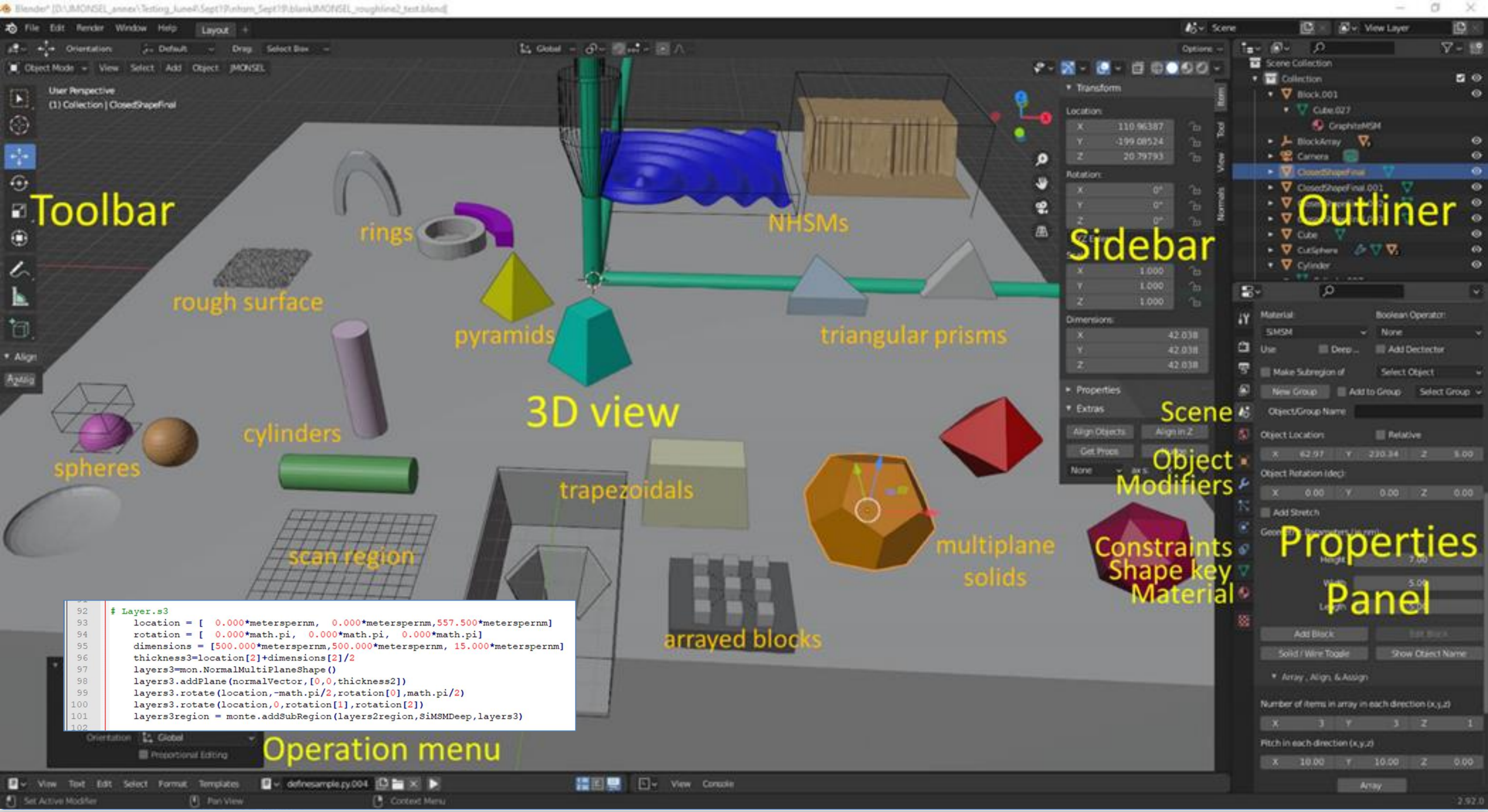
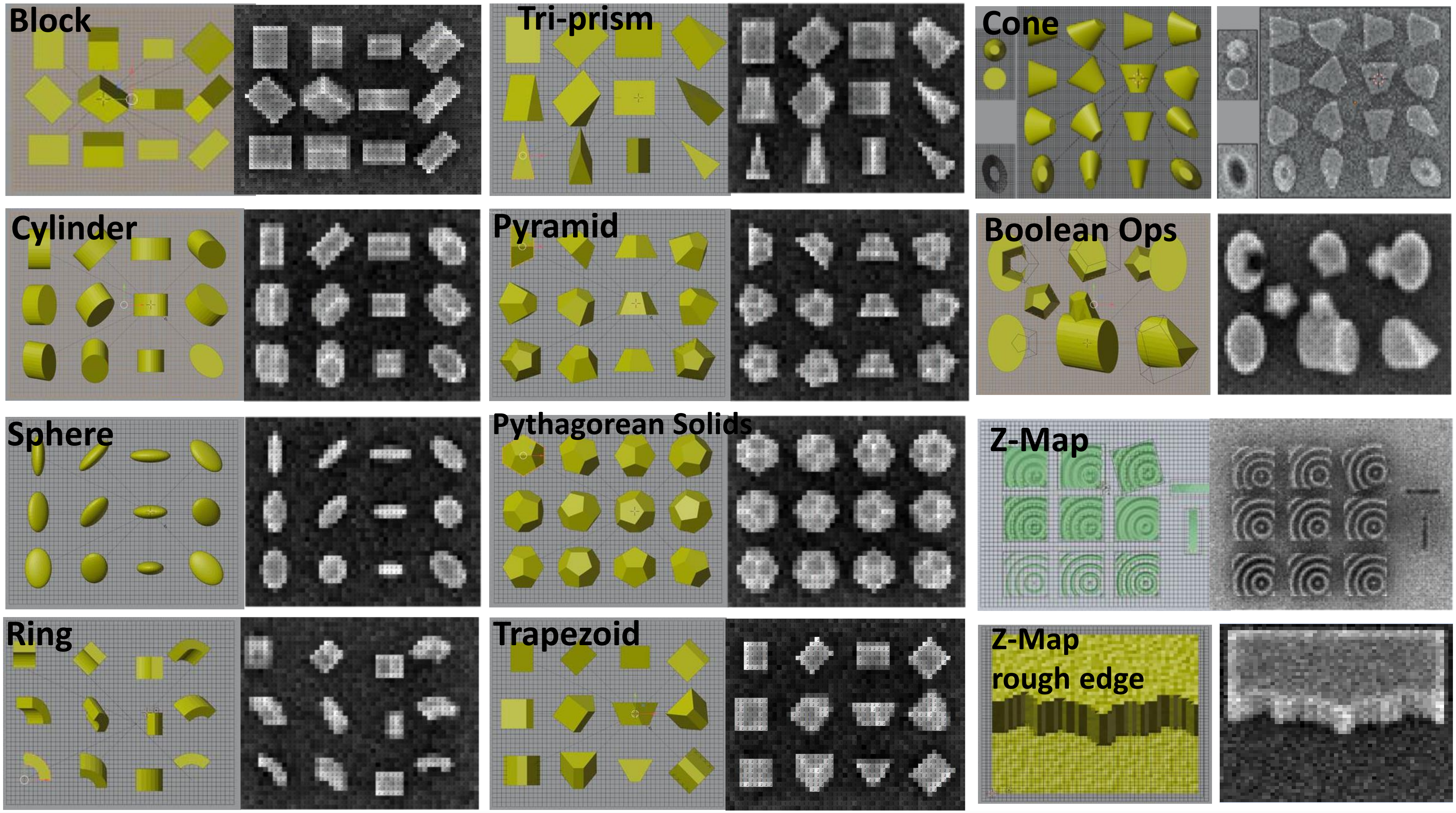


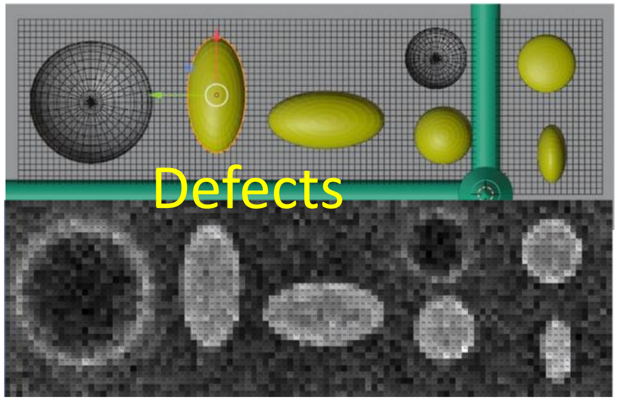
Large variety of proven shape primitives

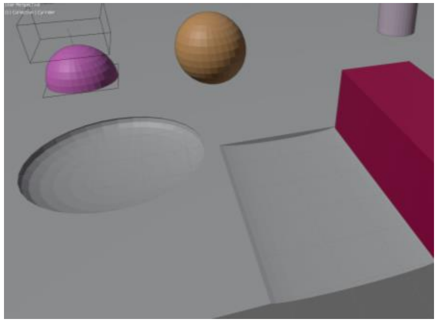
- Many shape primitives now available, and extensively tested for accurate representation.
- Care taken to make sure positions, rotations & stretches translate perfectly to JMONSEL with fidelity to definition.
- Some primitives not shown, and more coming in future.

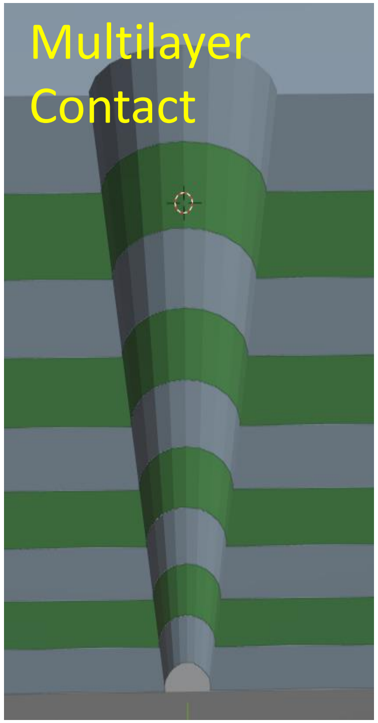


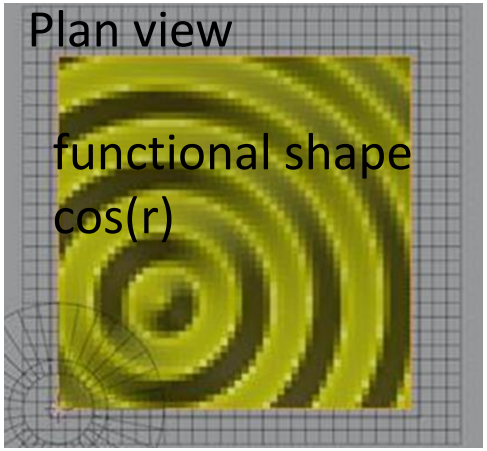
Modelling complexity now possible—examples

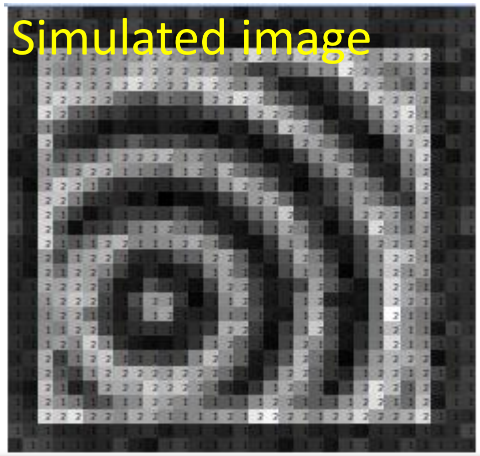
- These improvements allow many complex features to be feasible, and new levels of sample complexity to be designed.

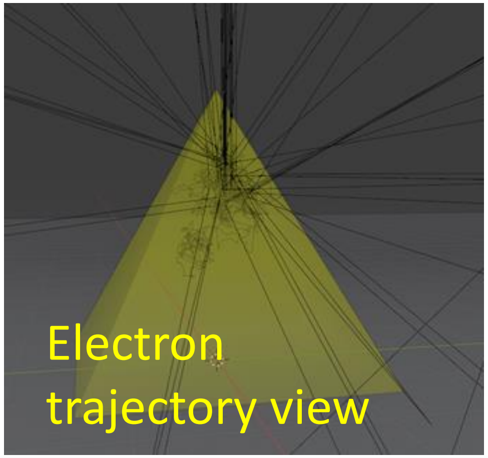








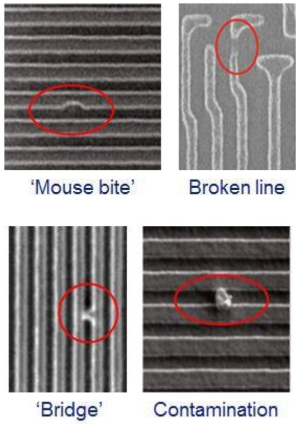




Simulating process subtleties

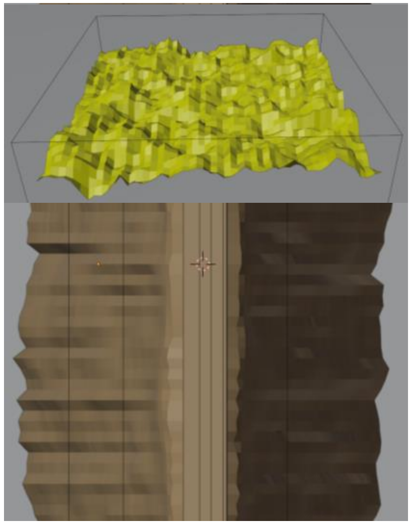
- **Goal: demonstrate ability to simulate process details & subtleties. Evaluate significance in terms of SNR.**
  - Much previous work has been done with JMONSEL and other simulation software, but using more primitive block features.
  - SimuSEM allows more complexity, and here we will explore several cases that were difficult to explore before. Combining features shown allows exploring subtleties, for examples:
  - We explore some of these to demonstrate we now have the means to generate more complex cases to determine the significance of the details.

Realistic defects

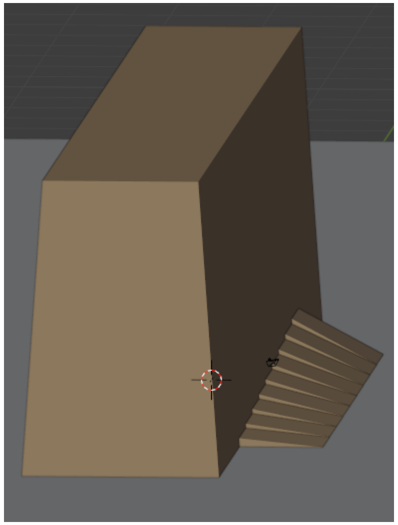


https://medium.com/@ASMLcompany/know-what-you-re-printing-the-story-of-yieldstar-49265489aa1b

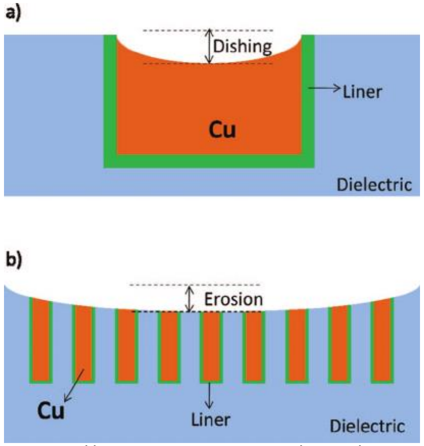
Rough surfaces & facets



Resist footing

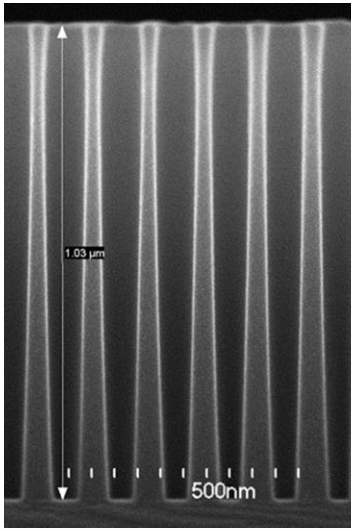


CMP/etch Dishing/haloing



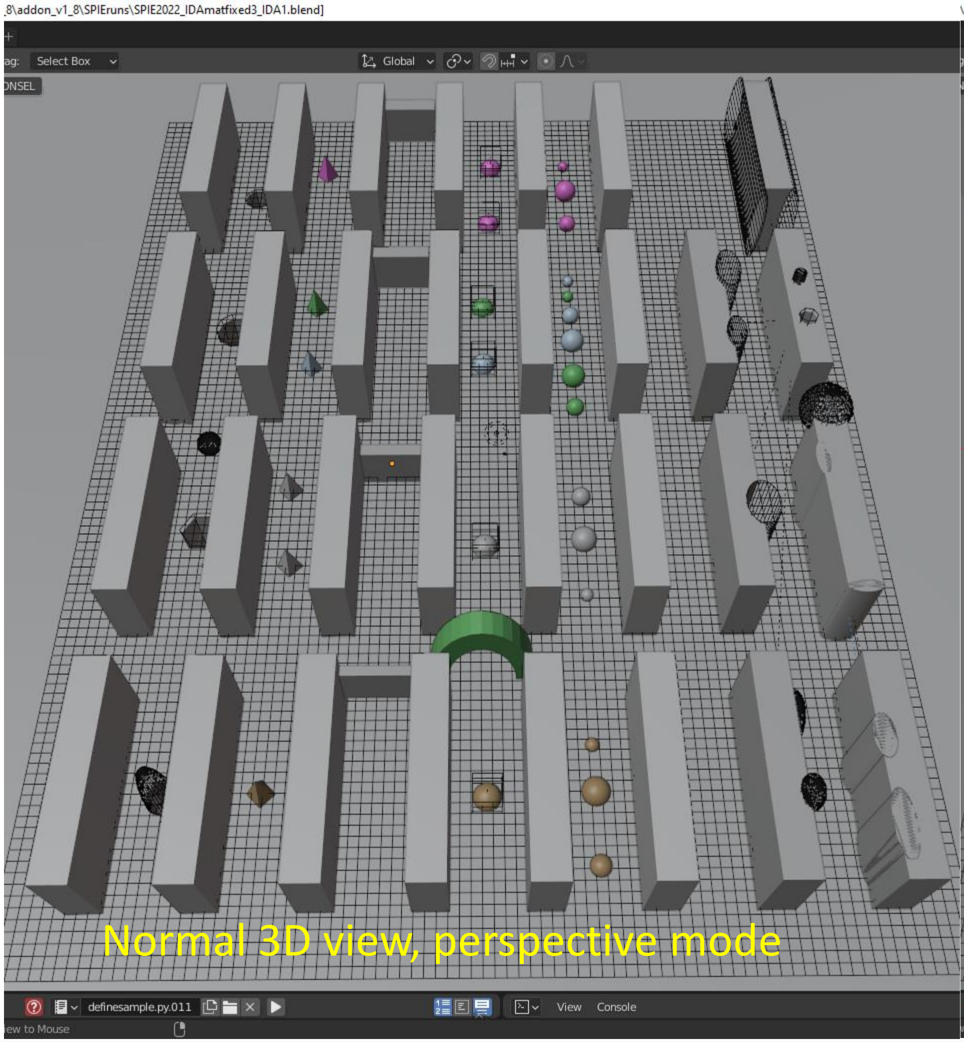
https://www.researchgate.net/figure/Conceptual-framework-showing-dishing-and-erosion-after-barrier-CMP-as-referred-to-in-this_fig2_270602792

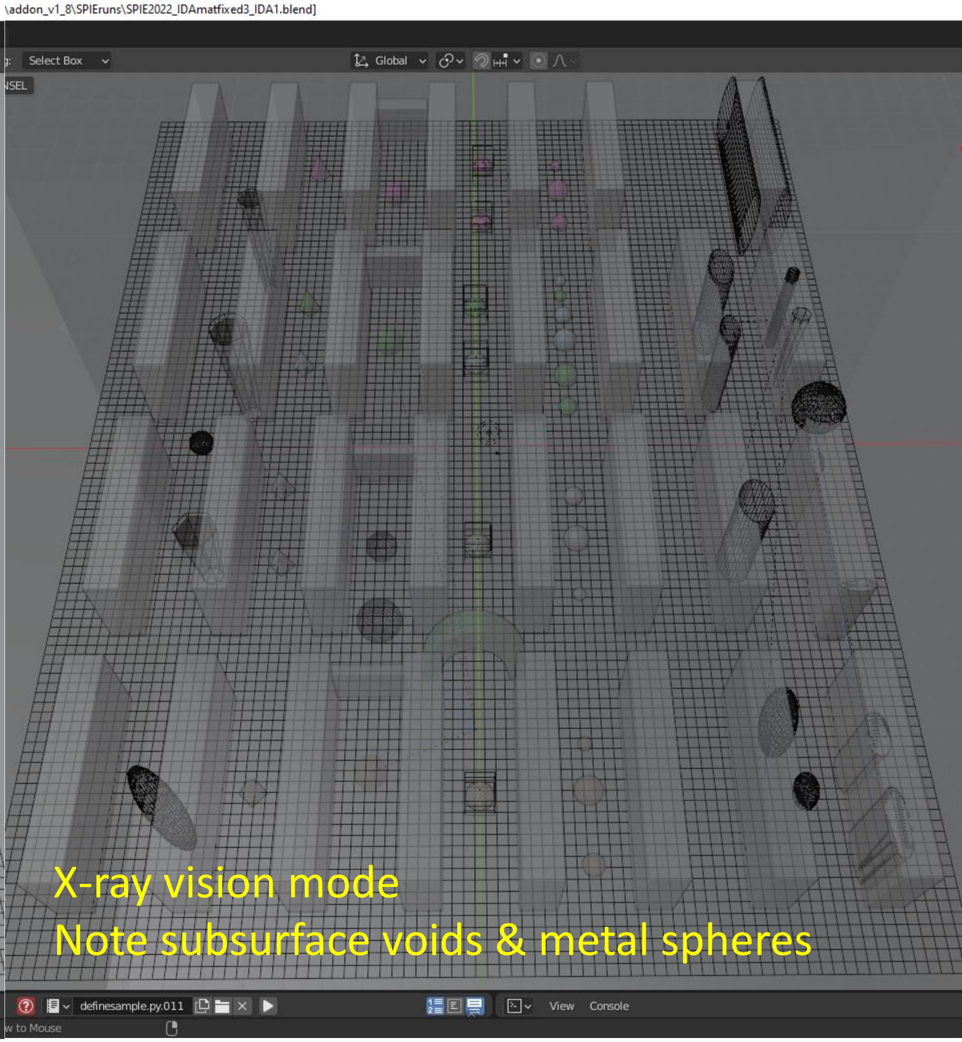
Detailed profile shapes



Intentional Defect Array

- Intentional Defect Array of 10nm wide links at 30nm pitch
- Holes & pits, different particles of different shapes & materials, sub-surface voids/materials, mousebites & undercut links, extensions, etc. All set up within 2 hours.
- 500V, 1000V & 2000V. N=30, 10 frames collected.





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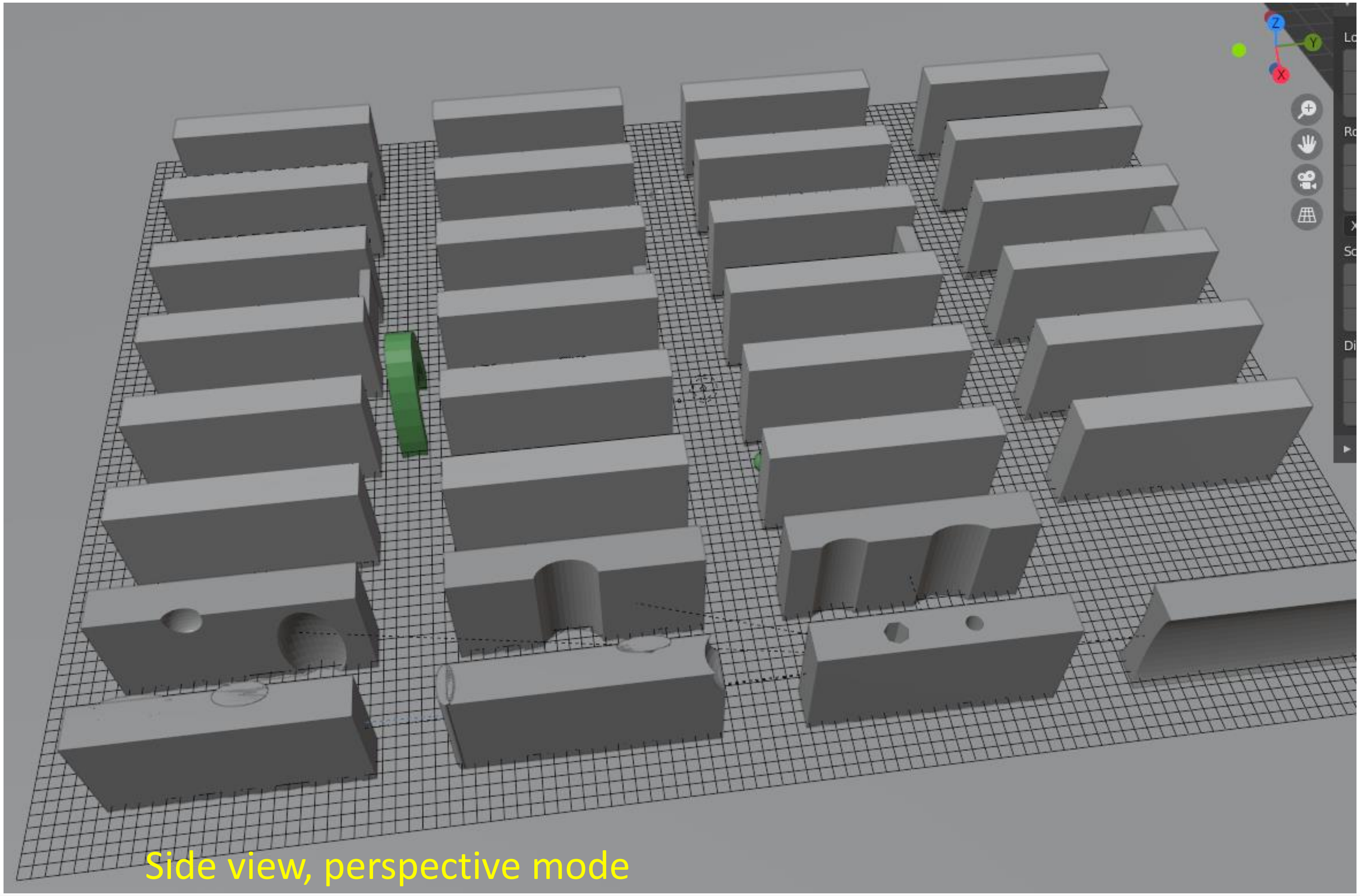
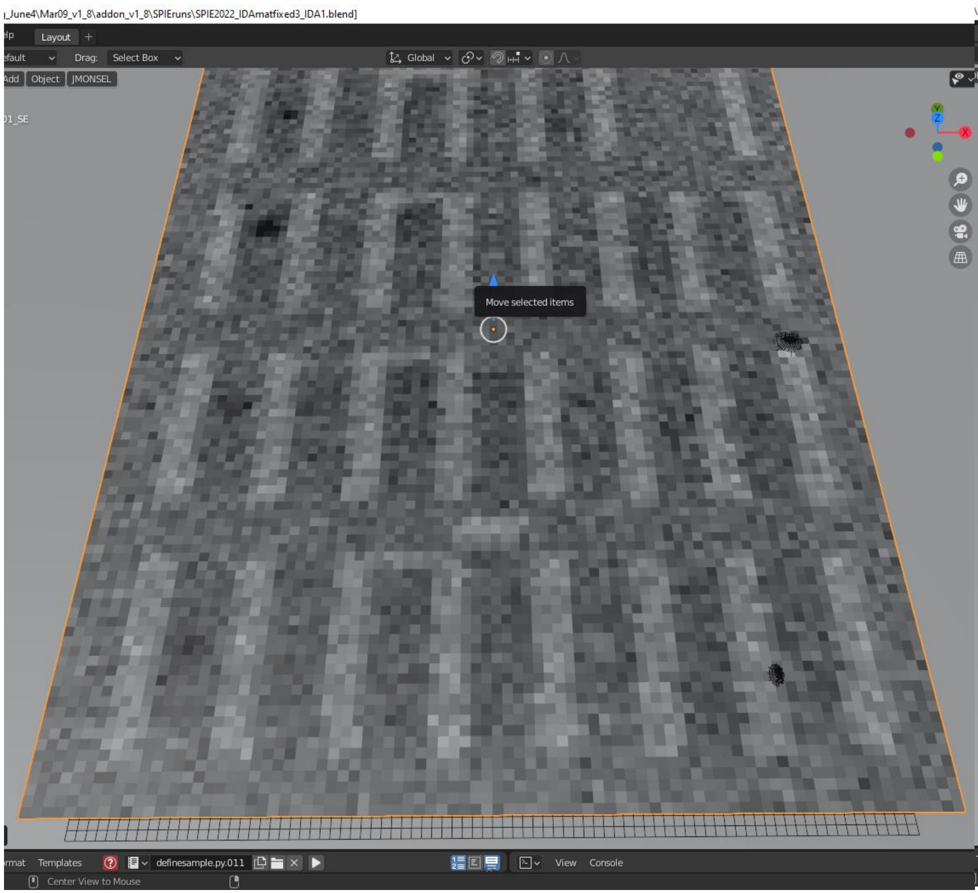
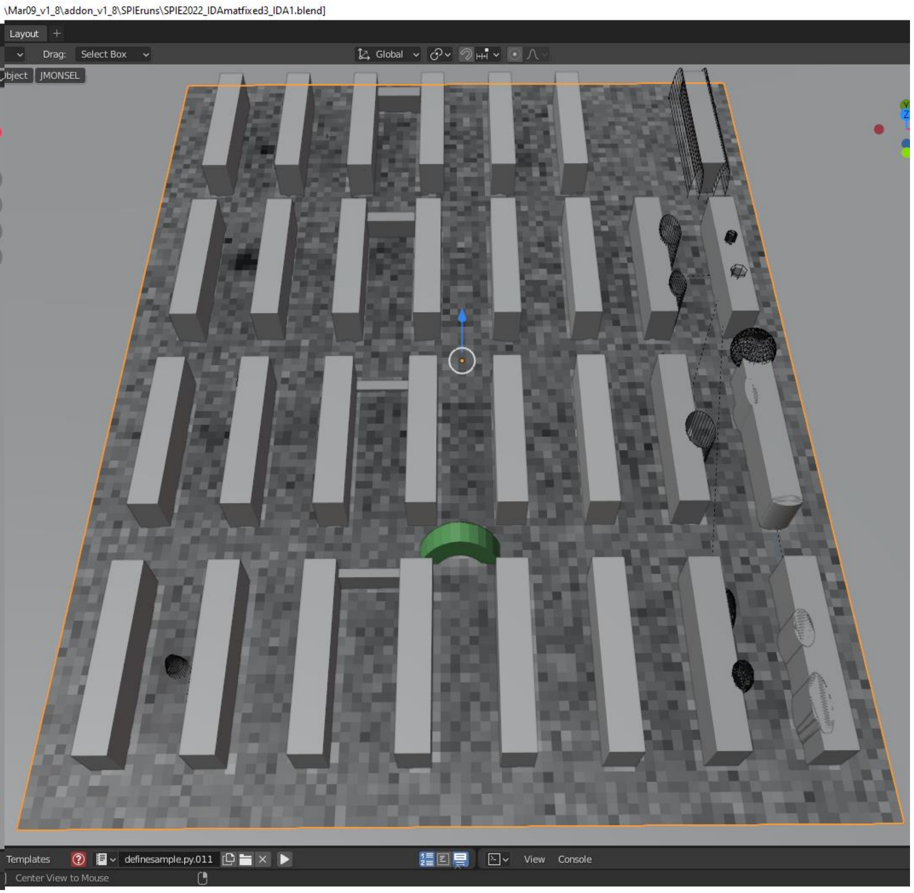


3D Image View

- Image can be viewed in standard conventional topdown mode but also directly in 3D view over exact scan location and topography
- Directly links results to measurand
- Coming soon—Blender enables ray-traced image projected exactly on top of topography in 3D view to see exactly where signal coming from
- Also 3D mesh of signal that can be viewed in same 3D view, will be able to directly correlate to surface z map





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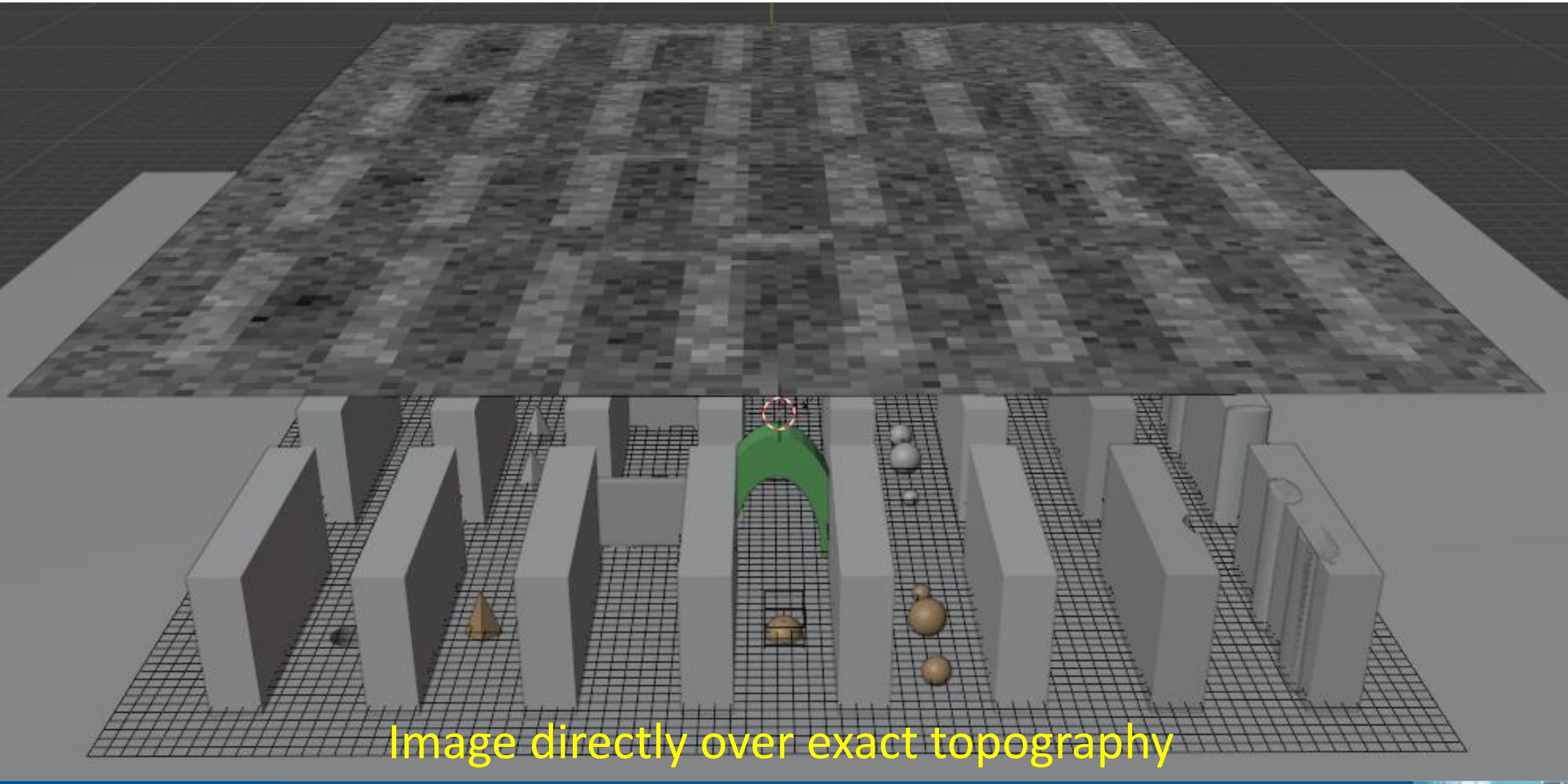

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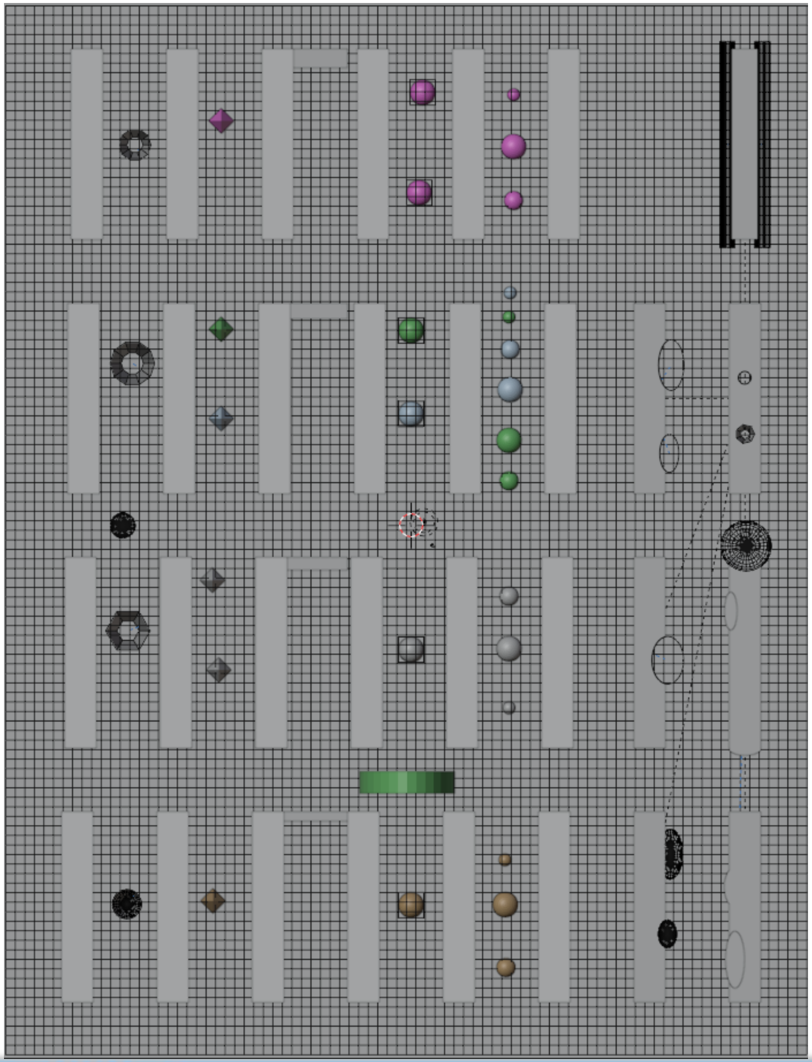

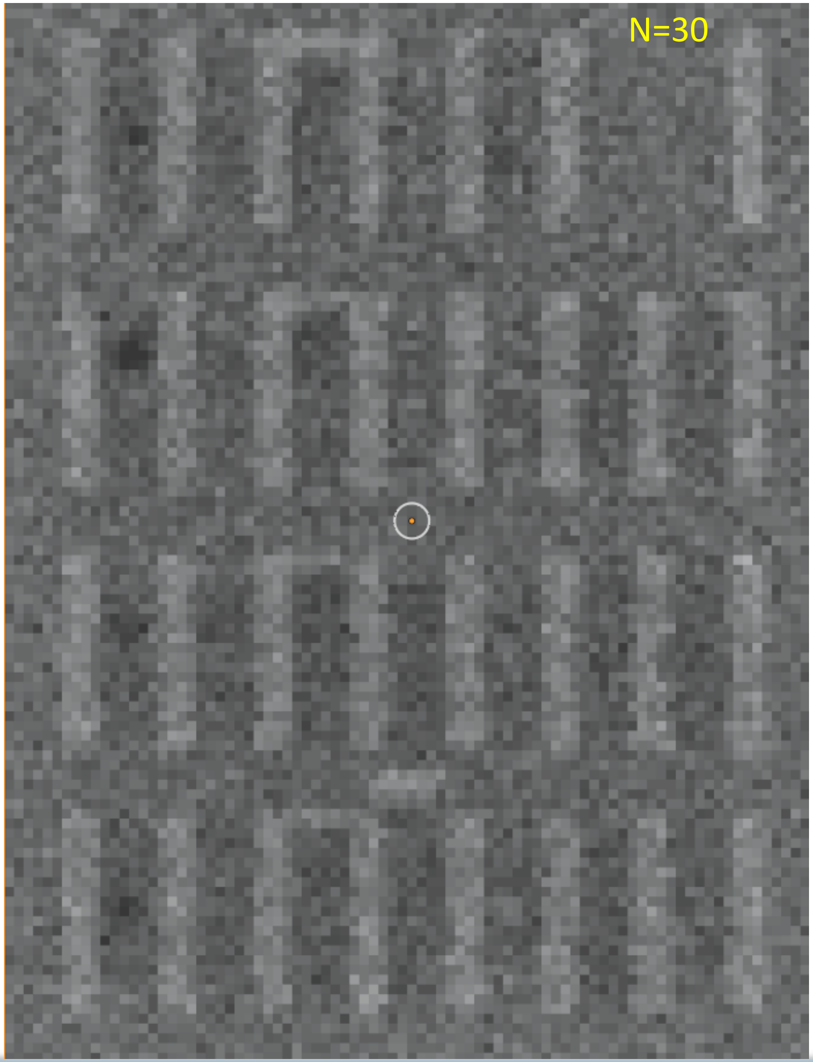

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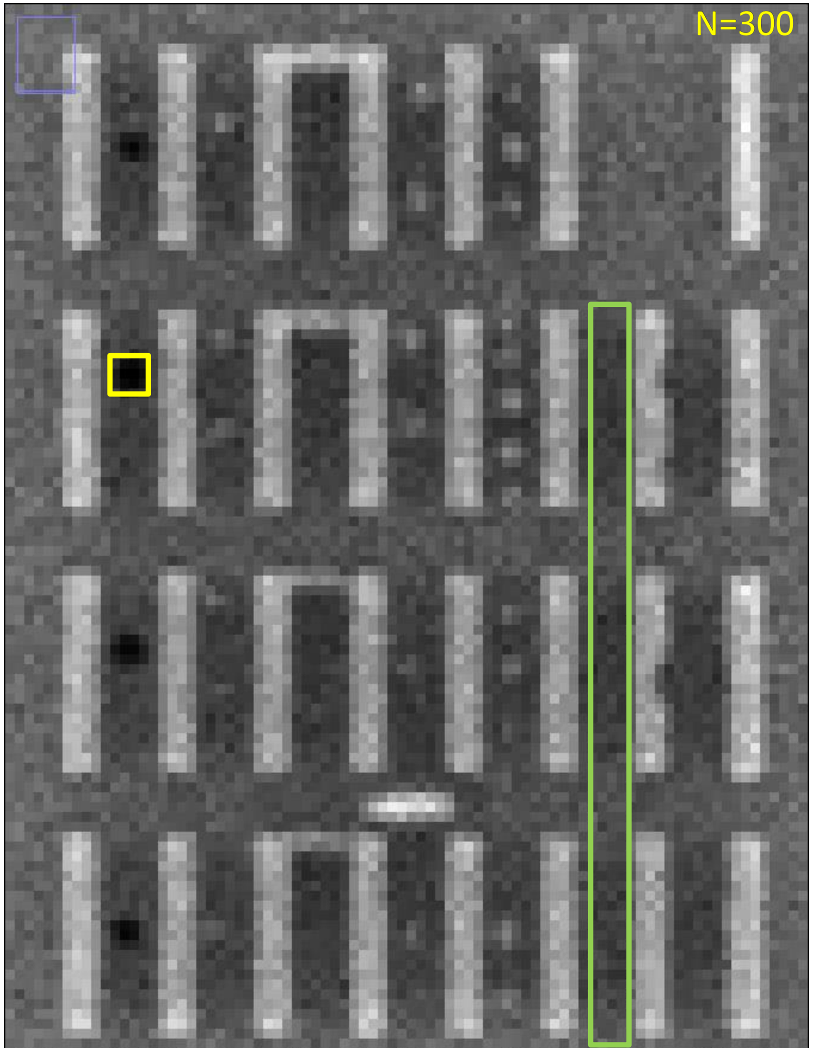

Defect	Defect Type	DeltaSigma SE 500V	DeltaSigma SE 1000V	DeltaSigma SE 2000V	DeltaSigma BSE 500V	DeltaSigma BSE 1000V	DeltaSigma BSE 2000V
A1	Hole small	3.74	2.73	1.65	3.29	3.36	2.95
A2	Hole med	5.00	3.45	2.53	3.88	4.04	3.89
A3	Crater	0.91	0.16	0.02	1.18	0.65	0.04
A4	Hole med	4.19	2.99	1.84	3.49	3.56	2.76
A5	Hole sphere	3.39	2.80	1.93	2.93	3.21	2.80
B1	W pyramid	1.11	1.64	1.36	0.43	1.31	1.89
B2	Cu pyramid	0.55	1.56	1.36	0.02	0.63	1.10
B3	SiO2 pyramid	0.23	0.06	0.04	1.62	0.63	0.30
B4	Si pyramid	0.25	0.11	0.60	0.23	0.01	0.07
B5	Si pyramid	0.67	0.09	0.17	1.07	0.95	0.11
B6	PMMA pyramid	0.04	0.21	0.16	0.96	0.92	0.42
C1	buried W sphere	1.45	0.33	0.91	1.65	0.06	3.30
C2	buried Cu sphere	1.69	0.55	0.19	1.89	0.25	1.16
C3	buried void small	1.91	1.46	0.81	1.48	2.04	1.63
C4	buried void med	1.43	1.44	1.00	1.30	1.97	1.64
C5	buried PMMA sphere	1.58	1.76	0.35	1.67	1.93	1.18
D1	W hemisphere	1.60	2.54	1.12	0.34	1.74	2.13
D2	W hemisphere	1.23	2.01	1.96	0.34	1.50	2.51
D3	Cu hemisphere	1.33	2.10	1.55	0.68	1.20	1.18
D4	SiO2 hemisphere	0.77	0.34	0.12	1.61	0.82	0.42
D5	Si hemisphere	0.44	0.00	0.10	0.94	0.52	0.15
D6	PMMA hemisphere	0.11	0.19	0.03	1.52	1.16	0.36
E1	W sphere smallest	0.08	0.37	0.23	0.63	0.43	0.80
E2	W sphere med	1.62	2.91	2.48	0.65	1.93	3.89
E3	W sphere small	0.42	0.80	1.15	0.77	1.01	1.33
E4	SiO2 sphere smallest	1.25	0.55	0.37	0.49	0.65	0.04
E5	Cu sphere smallest	1.15	1.07	0.57	0.10	0.38	0.03
E6	SiO2 sphere small	0.70	0.34	0.83	0.40	0.68	0.07
E7	SiO2 sphere med	1.58	1.25	0.83	1.27	0.49	0.09
E8	Cu sphere med	1.35	3.14	2.76	0.63	1.84	2.52
E9	Cu sphere small	0.84	1.81	1.60	0.68	0.75	1.22
E10	Si sphere smallest	0.07	0.16	0.21	1.19	1.15	0.04
E11	Si sphere med	0.25	0.54	0.52	0.68	0.01	0.65
E12	Si sphere small	0.39	0.40	0.47	0.98	1.03	0.21
E13	PMMA sphere smallest	0.69	0.18	0.14	1.13	0.99	0.15
E14	PMMA sphere med	1.46	1.11	0.86	1.17	0.54	0.34
E15	PMMA sphere small	1.28	0.43	0.54	0.11	0.01	0.10
F1	Line med mousebite	0.35	0.80	0.52	0.44	0.56	0.37
F2	Line small mousebite	0.33	0.38	0.49	0.21	0.12	0.37
F3	Line big mousebite	1.39	1.59	1.46	1.17	1.45	1.36
F4	Line sidewall crater	0.04	0.21	0.00	0.30	0.16	0.00
F5	Line top corner nic	0.18	0.02	0.12	0.03	0.12	0.16
G1	Line bowed sidewalls	2.96	1.72	0.92	2.05	1.79	0.41
G2	Line hole	1.17	0.63	0.64	0.68	1.00	0.35
G3	Line hole	0.75	0.61	0.46	0.51	0.75	0.53
G4	LineEnd nic	1.68	1.17	0.94	1.01	1.07	0.66
G5	Line bump small	1.47	1.41	1.34	0.92	1.71	1.19
G6	LineEnd extension	1.67	1.80	1.33	1.09	1.48	1.20
G7	Line bump small	1.19	1.61	1.27	1.04	1.73	1.24
G8	Line bump med	1.82	1.96	1.65	1.23	2.35	1.22

Intentional Defect Array results

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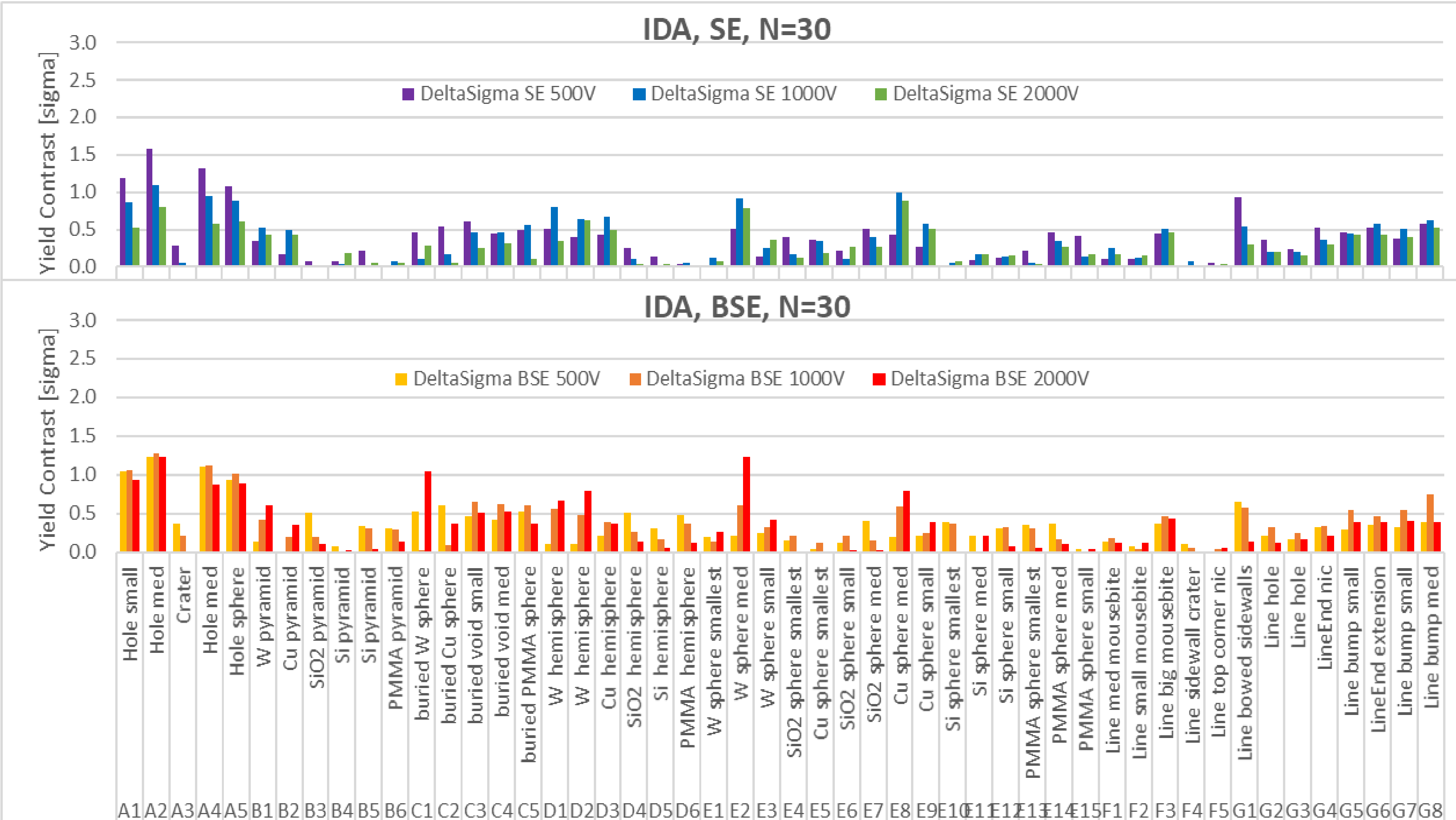

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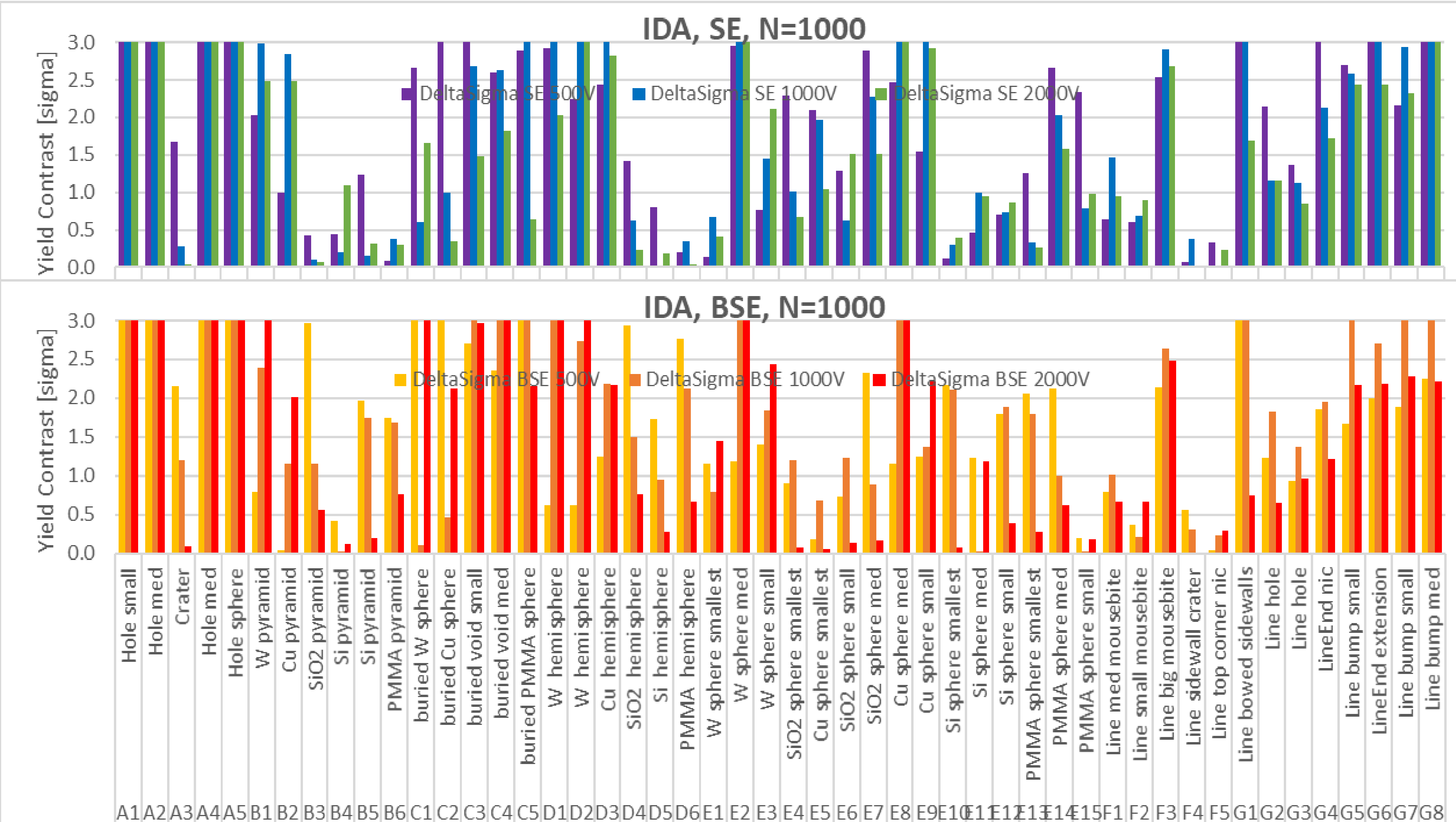
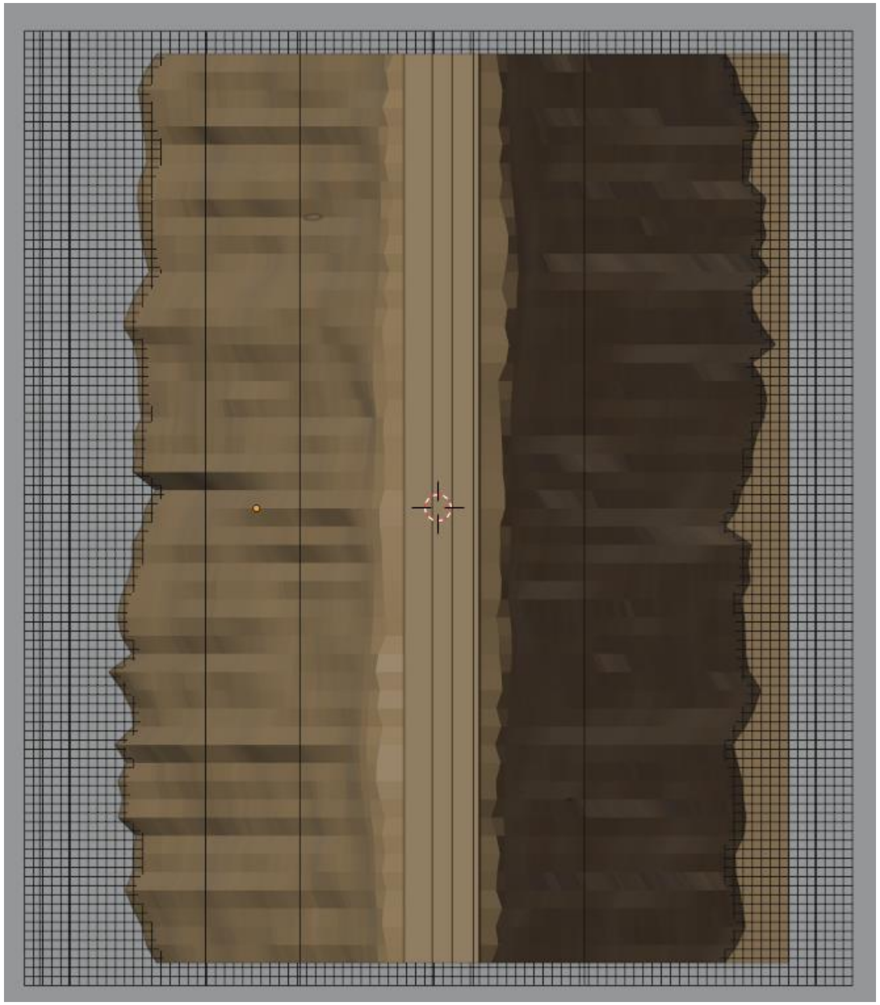
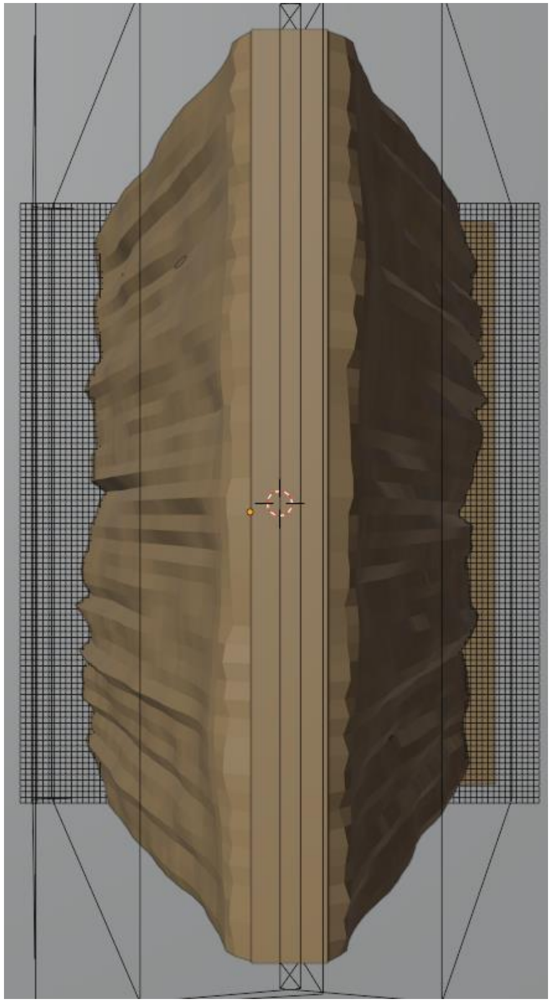
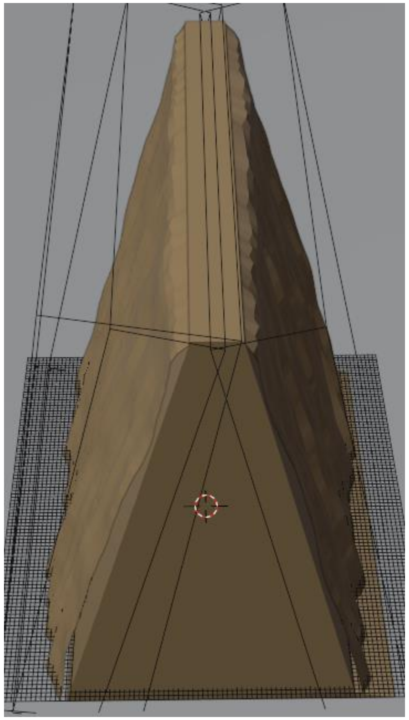


Rough Line Segment

- Adding an NHSM to sidewall of trapezoidal line allows new complex realistic photoresist features to be represented. Automatic generator in development, including user-input PSD.
- UL & LR edge minima show narrow ridges along edge in y direction closer into profile scatter less and base gets difficult to see, closer to noise limit.
- The right edge had a 2nm high foot added to see effect of thin foot in PMMA. It is undetectable.







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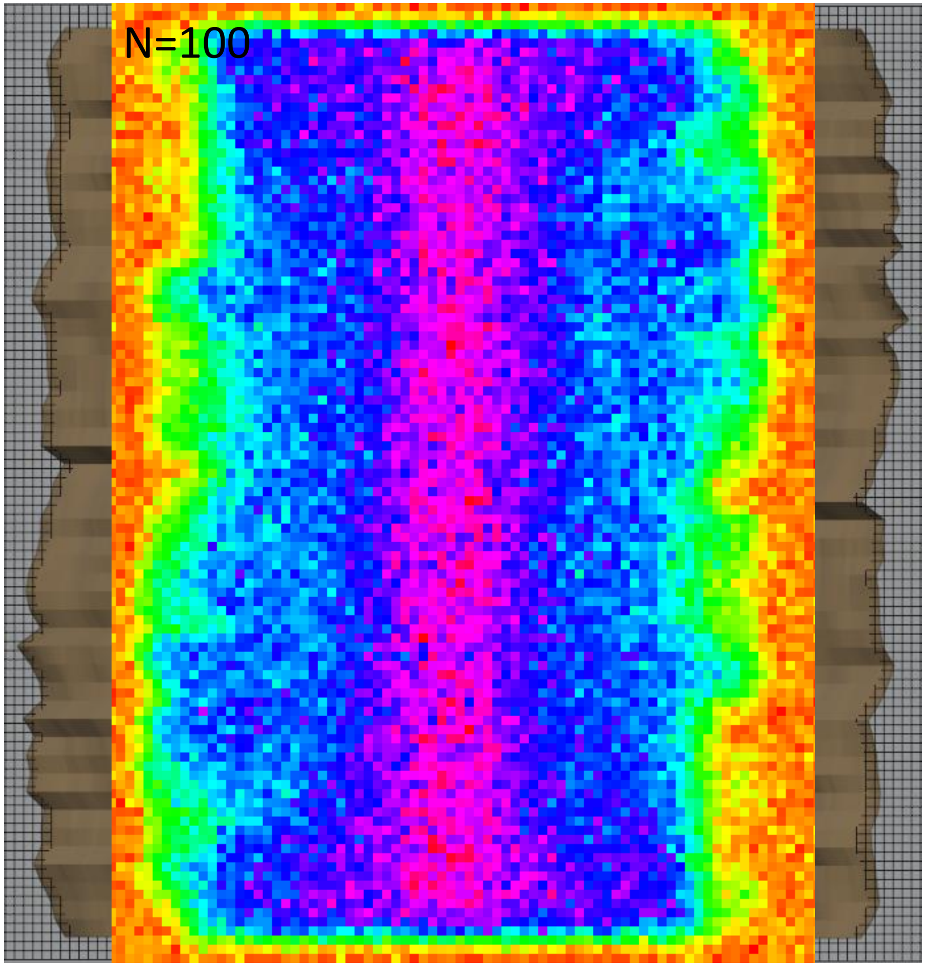
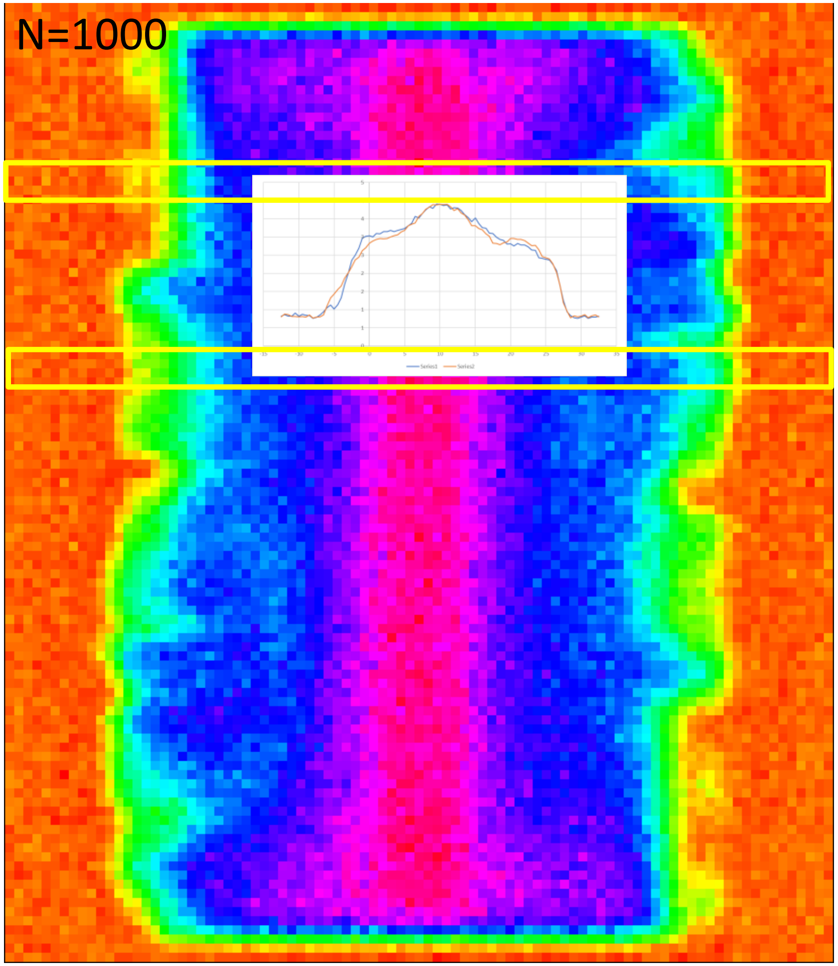
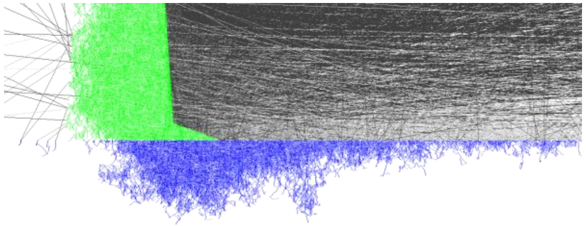
- The right edge had a 2nm high foot added to see effect of thin foot in PMMA. It is undetectable.

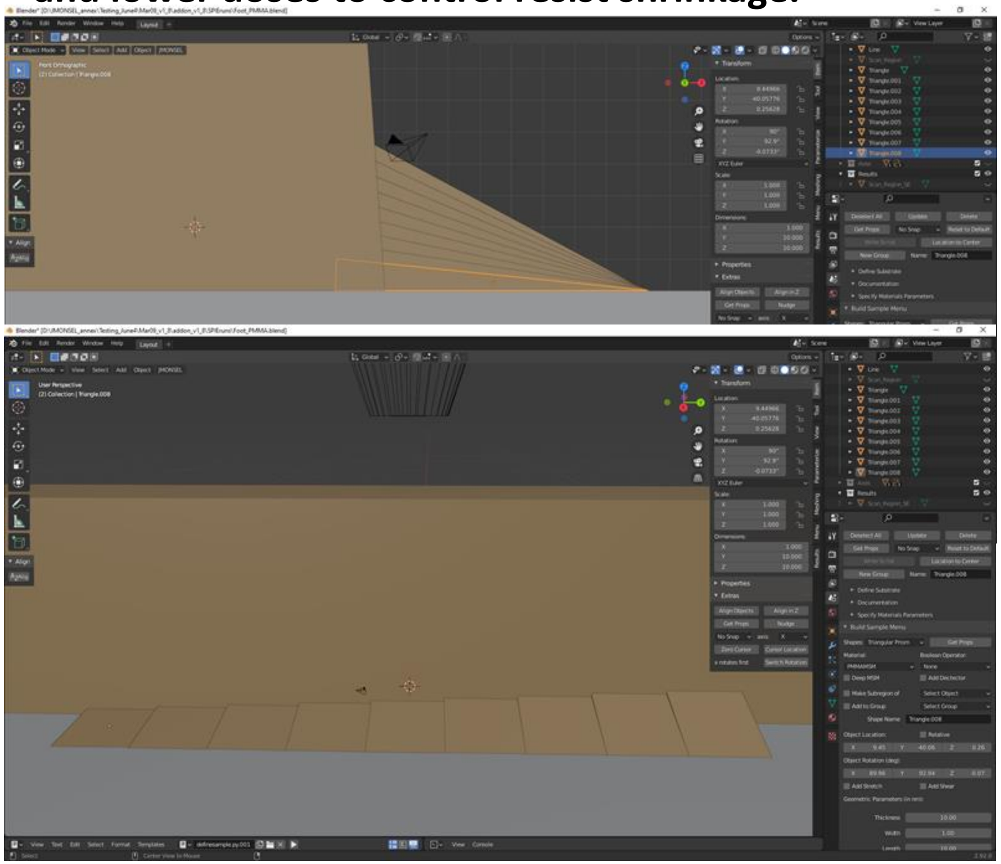


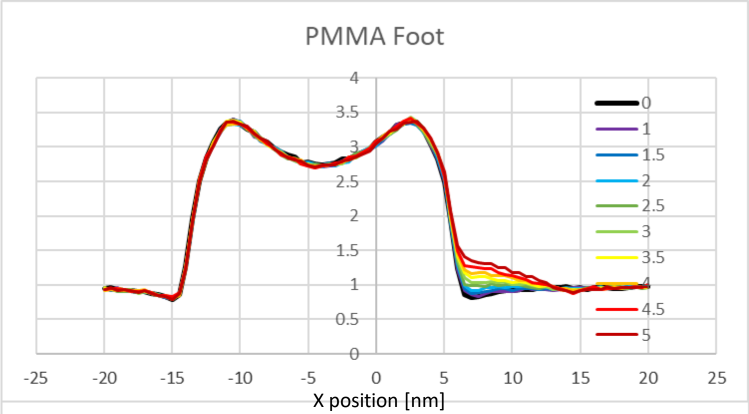


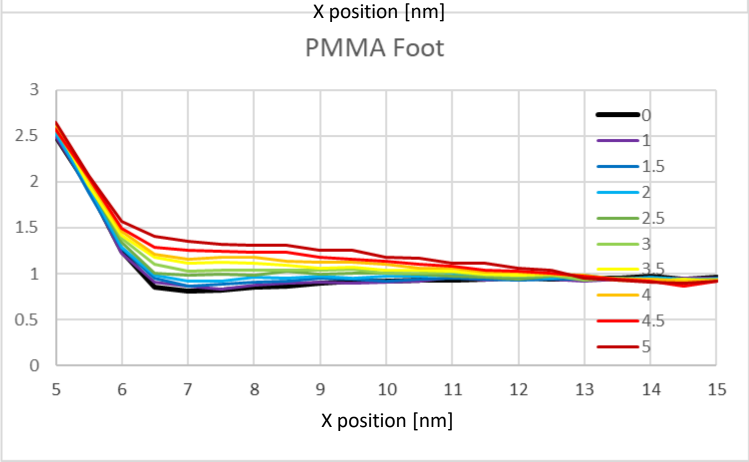
Foot of PMMA profile



- Varied foot in 0.5nm increments.
- Noise at N=100 is sigma=0.12.
- SE signal difference between different steps well within 1sigma of noise
  - Difficult to distinguish below 3nm foot height; signals very flat.
- Many often assume 2nm foot—model-based solution possible if enough pixel density and signal. However, resist foot seems very difficult to detect, especially along with edge roughness and lower doses to control resist shrinkage.

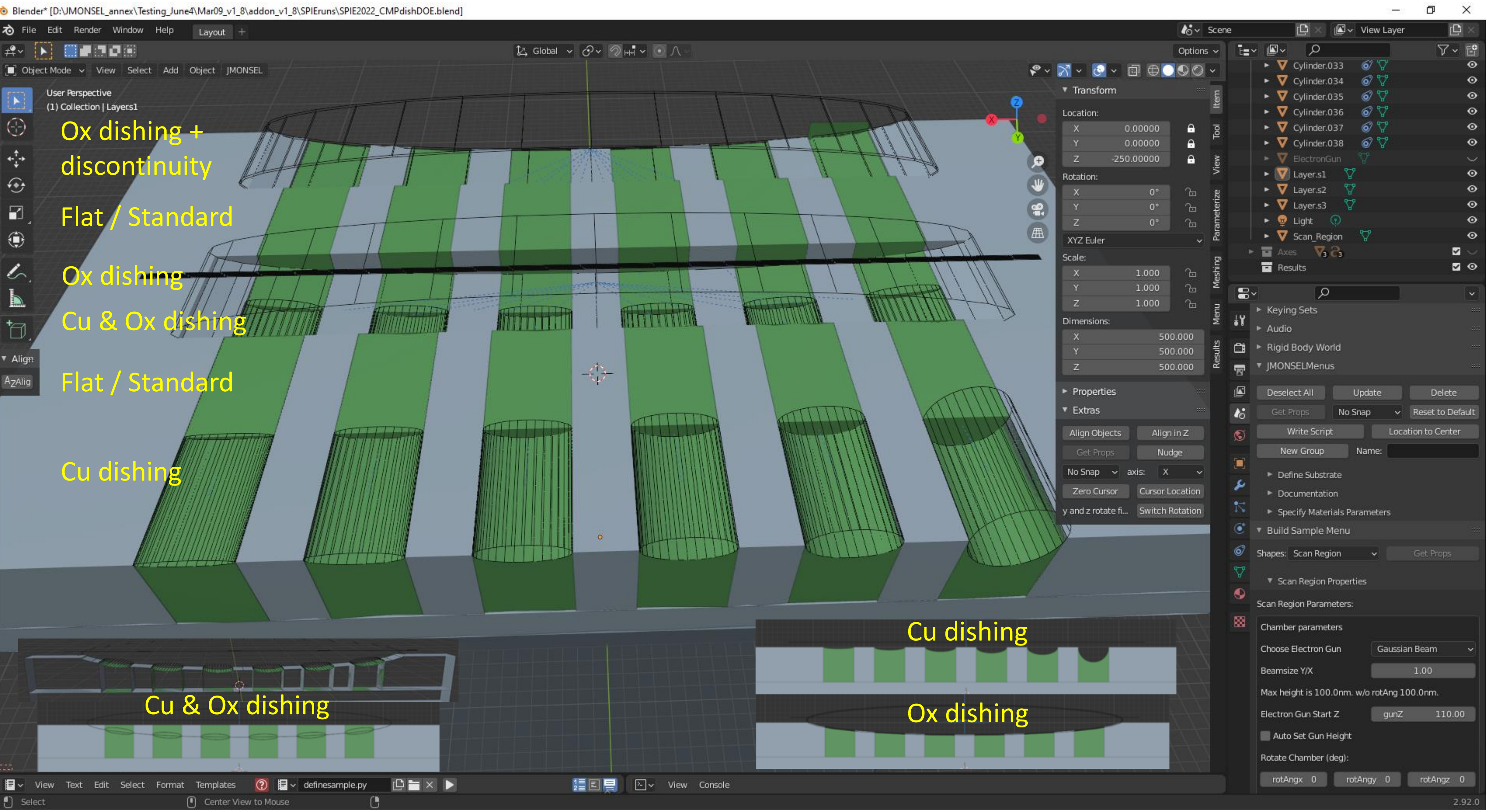






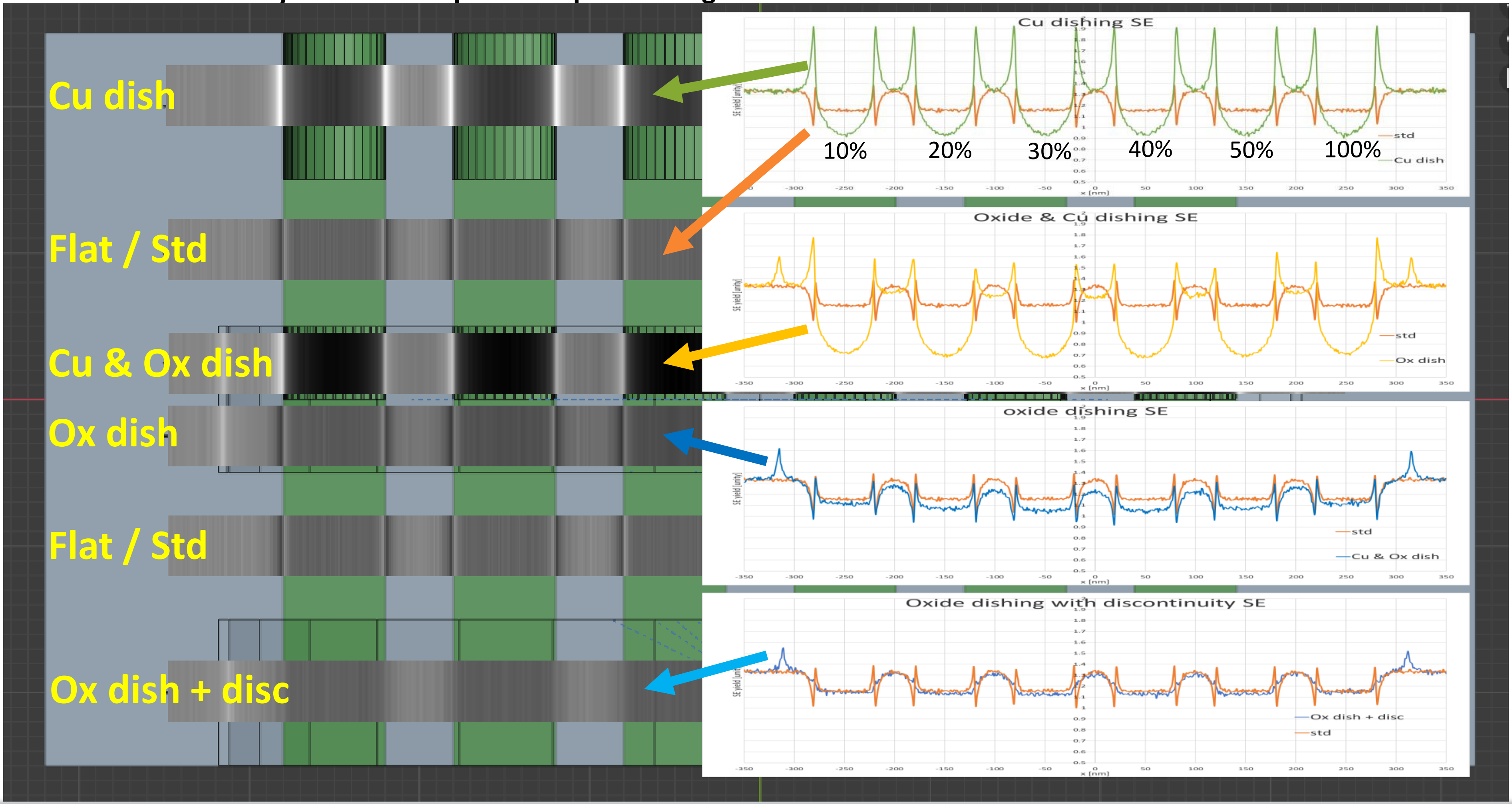
Cu CMP dishing

- **Modeled grating-wide oxide dishing both with & without Cu dishing**
- **Also flat control features to compare signals**



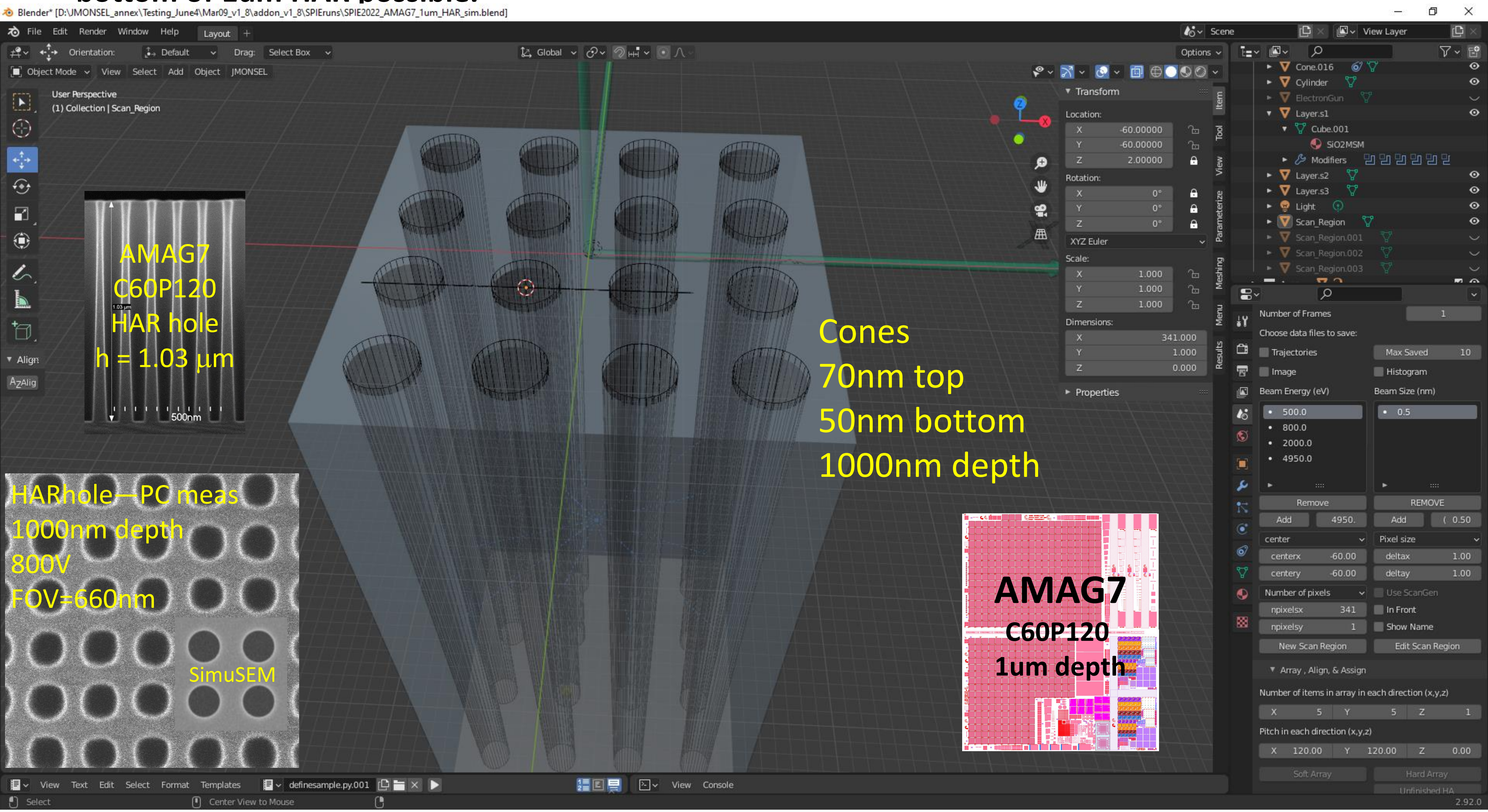
Cu CMP dishing

- Large signatures with Cu dishing (well above noise), although seems not much variation depending on how much dishing in range tested, and if so, beneath noise. Future work—test range under 10%.
- Oxide dishing, less sensitive, although peaks emerge at grating edges if present. MB solution promising.
- When oxide and Cu dishing present, large changes in contrast. A model-based solution likely possible, more exploration needed.
- The discontinuity seems to surpress the peak at edge of Cu.



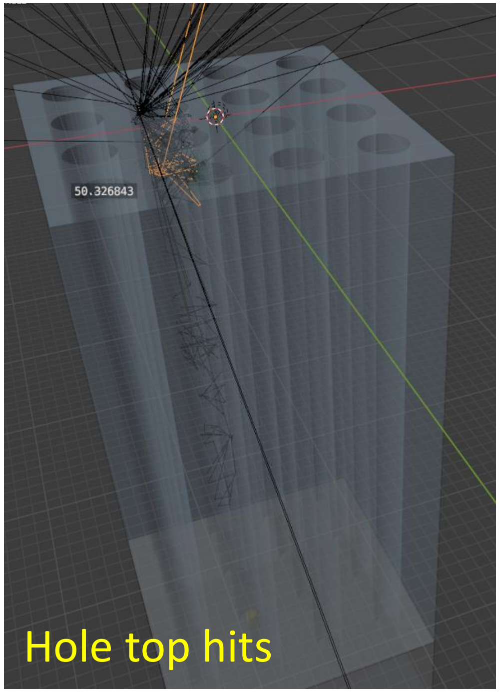
AMAG SimuSEM & AMAG7 HAR holes

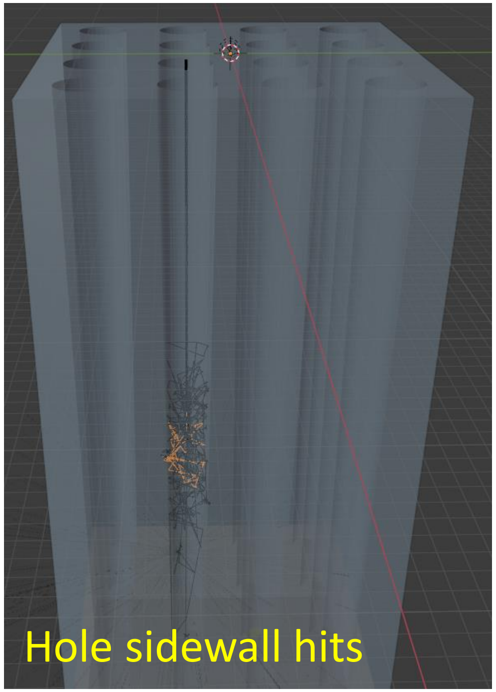
- AMAG SimuSEM used to study measurements of 1um deep AMAG7 HARholes.
- DOE of beam energies along hole radius to seek signal from known edge at hole bottom.
- The results will agree with what has been observed experimentally, that ~10000V makes seeing bottom of 1um HAR possible.

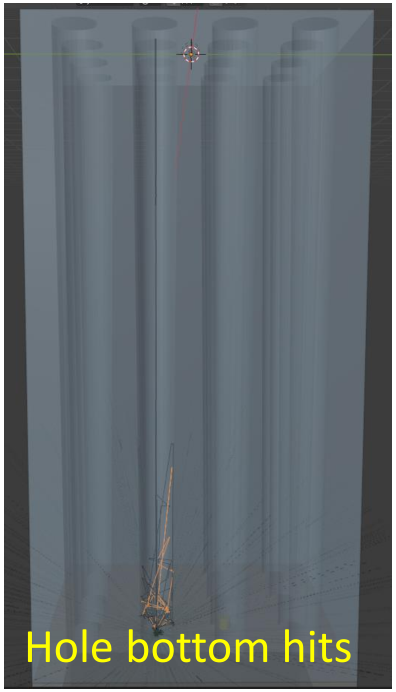


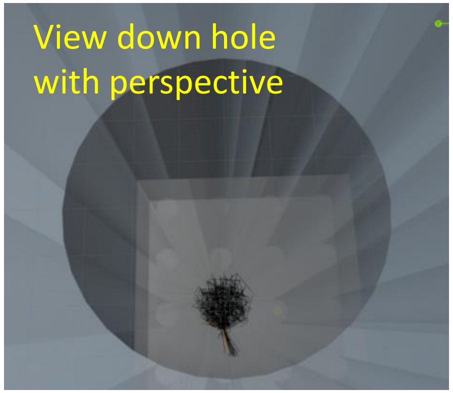
HAR hole signal (1 um depth)

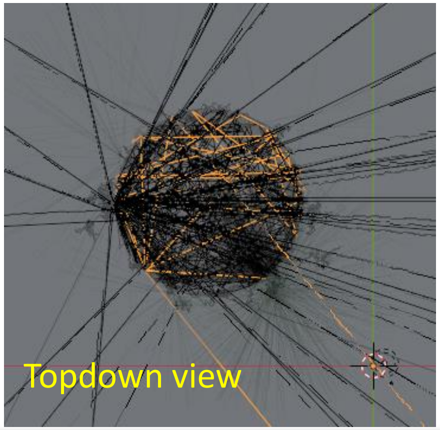
- **Views of trajectories can be viewed for qualitative understanding of what scattering is important from given features at different locations.**

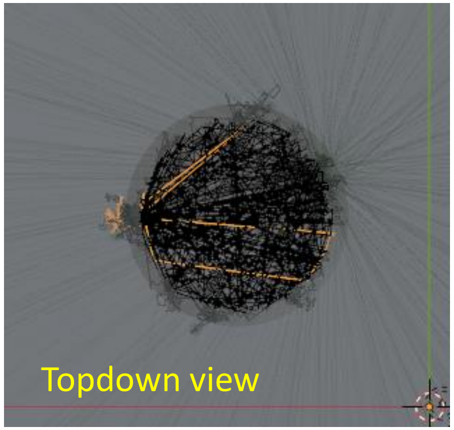


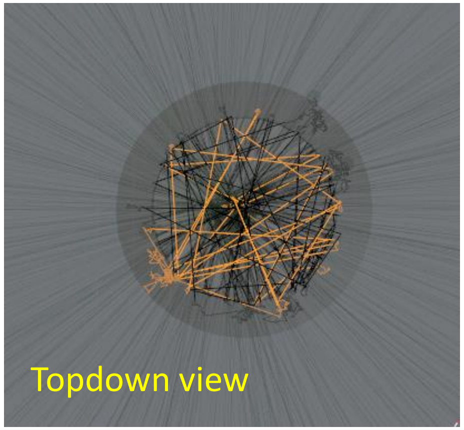


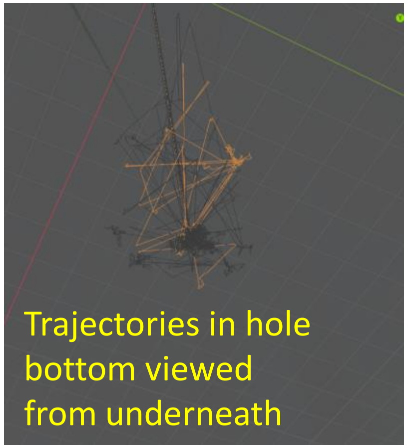








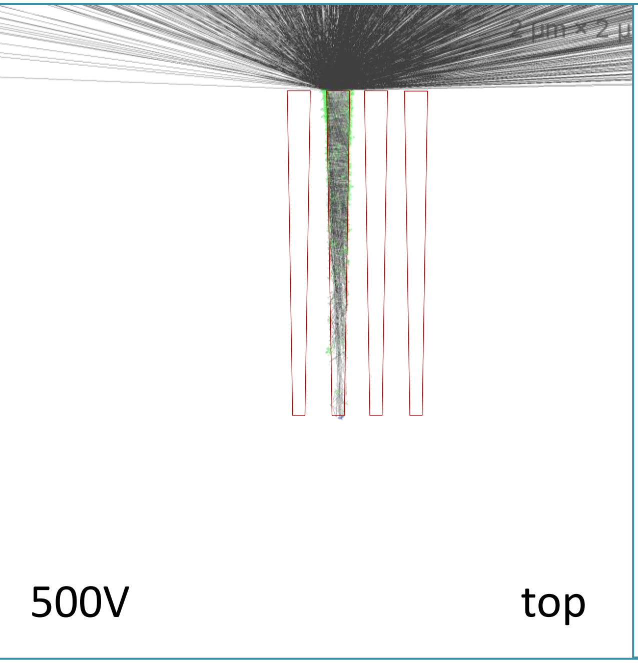


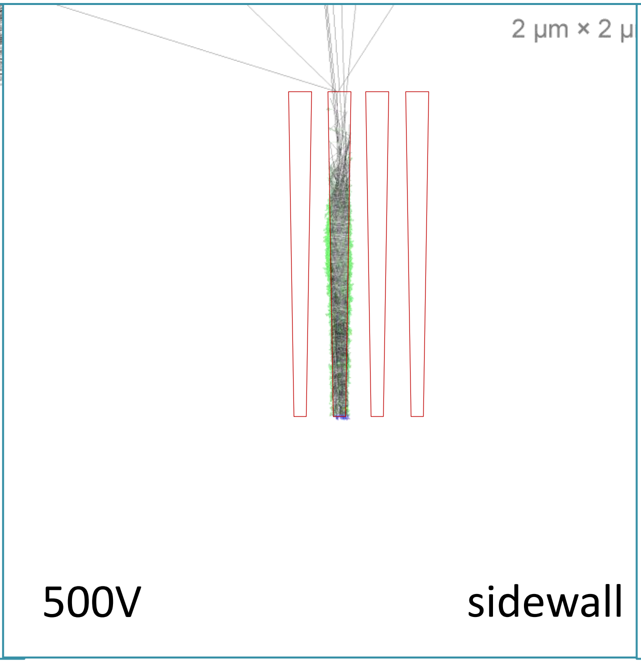


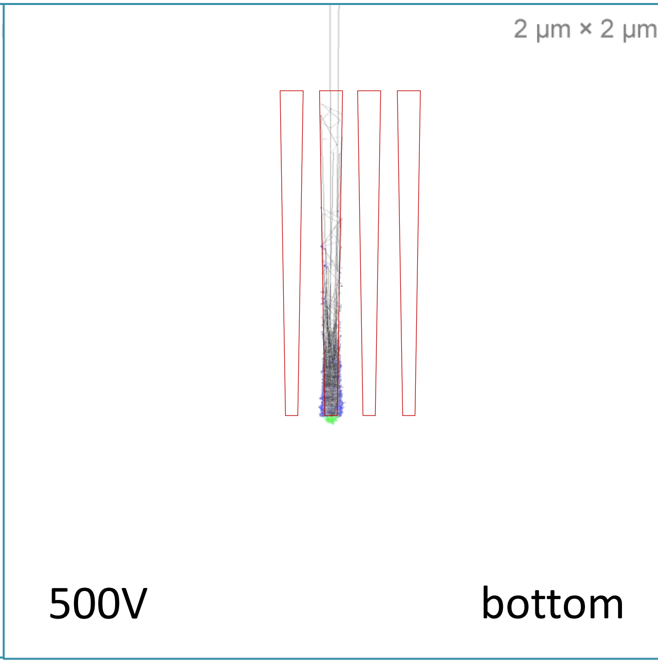
HAR hole signal (1 um depth)

- **SimuSEM predicts better BSE signal ≥10kV with for HAR holes of this depth, as reported in literature.**
- **Trajectory views tell much. More signal but significant tertiary scattering events, so noisy. 10kV-15kV not so many but at higher energies they get very prevalent. Entire sample "bathing" in electrons. Energy filtering should be of benefit. LLBSE.**

Top hits | **Sidewall hits** | **Bottom hits**

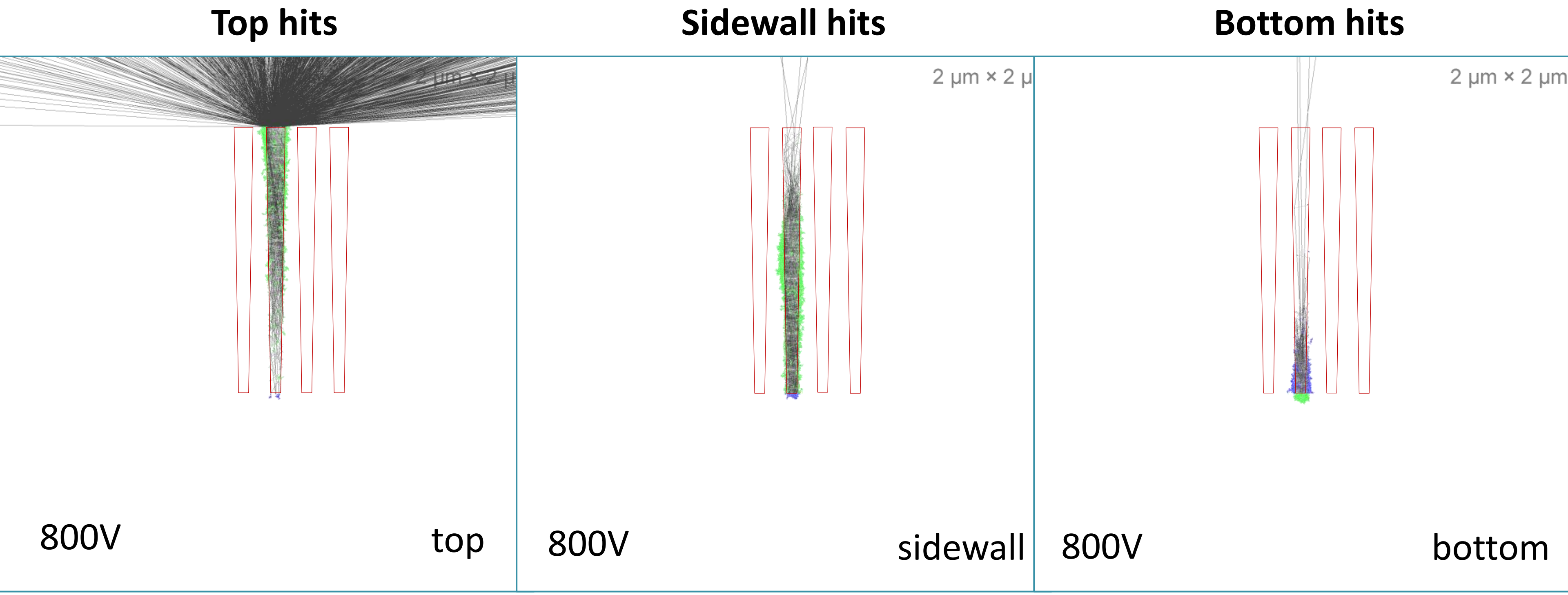






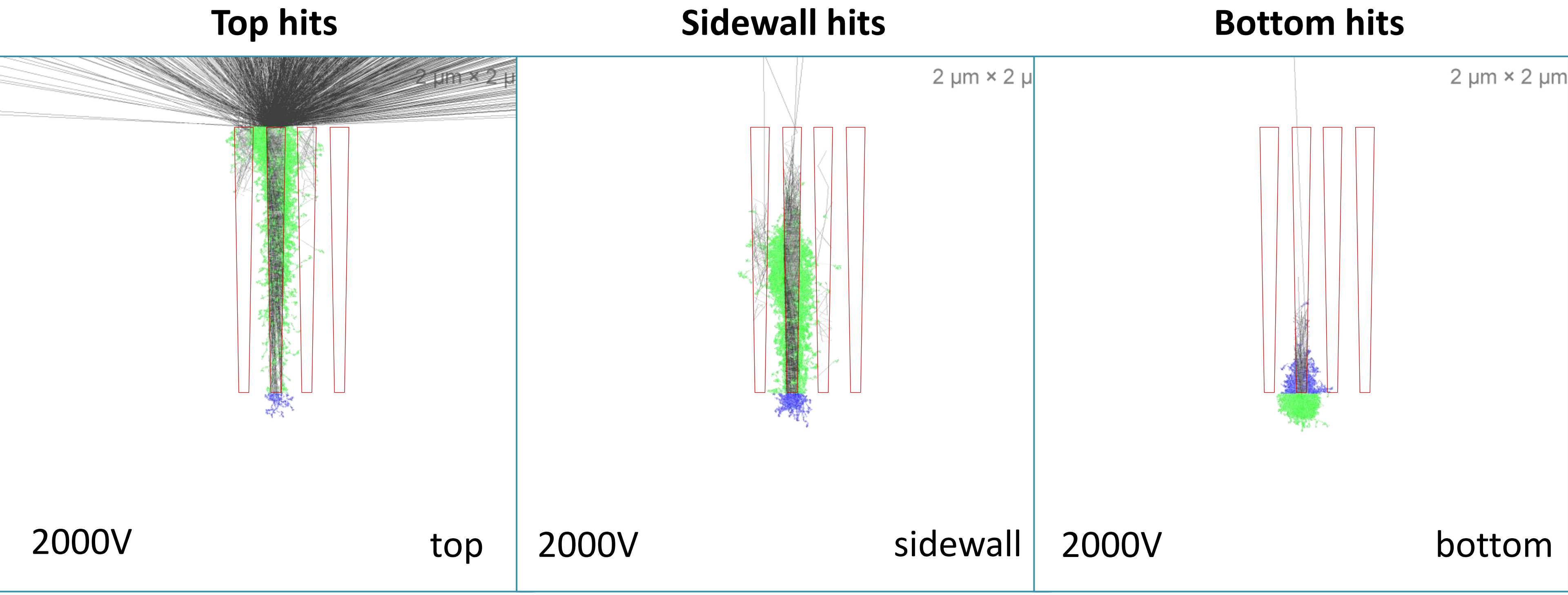
HAR hole signal (1 um depth)

- **800 V beam**



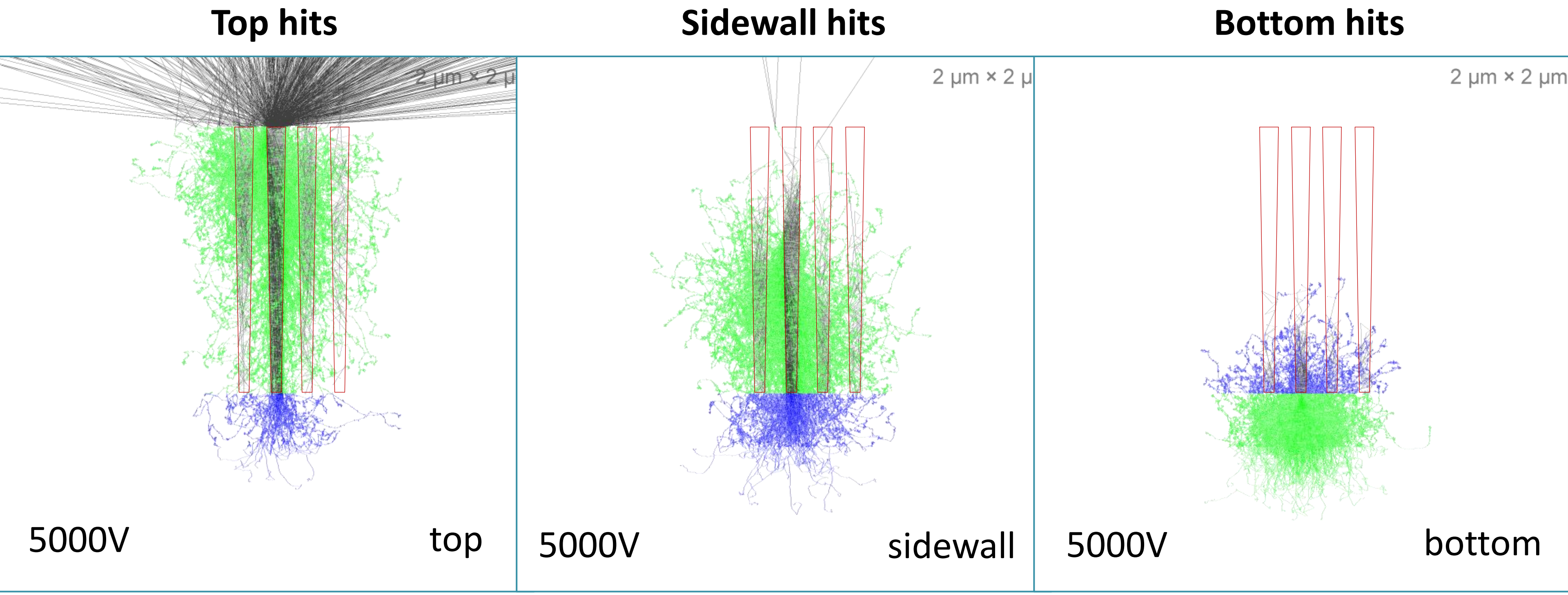
HAR hole signal (1 um depth)

- **2 kV beam**



HAR hole signal (1 um depth)

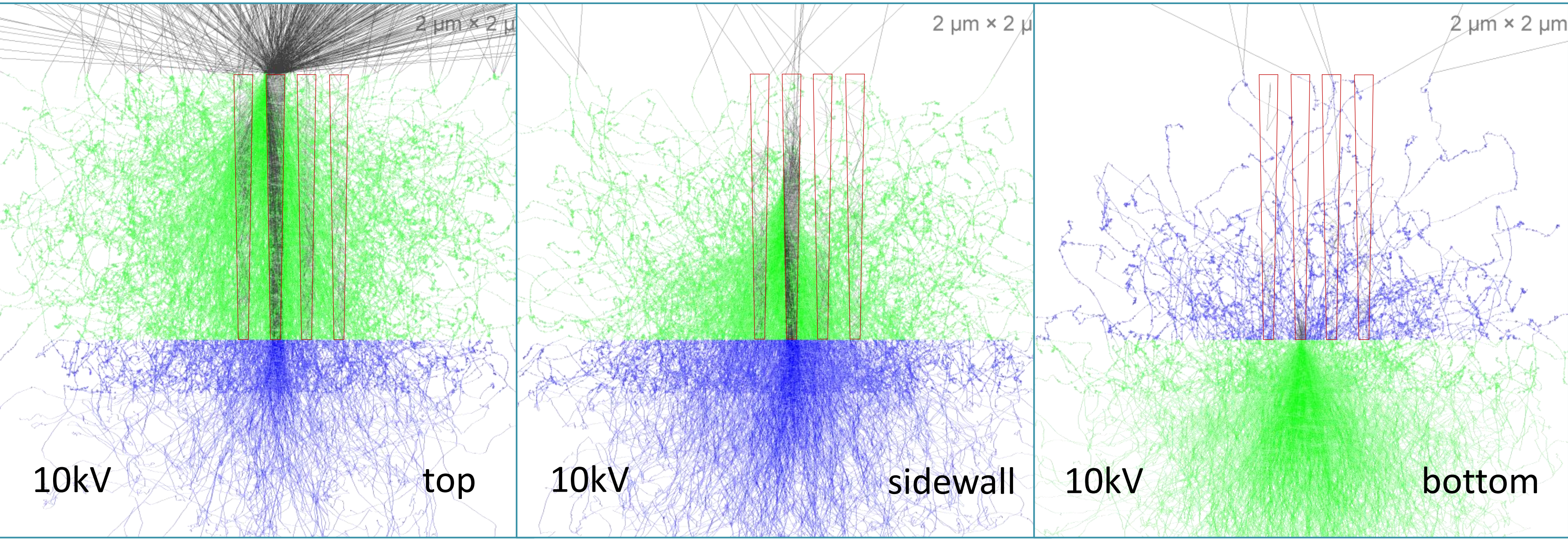
- **5 kV beam**



HAR hole signal (1 um depth)

- **10 kV beam**

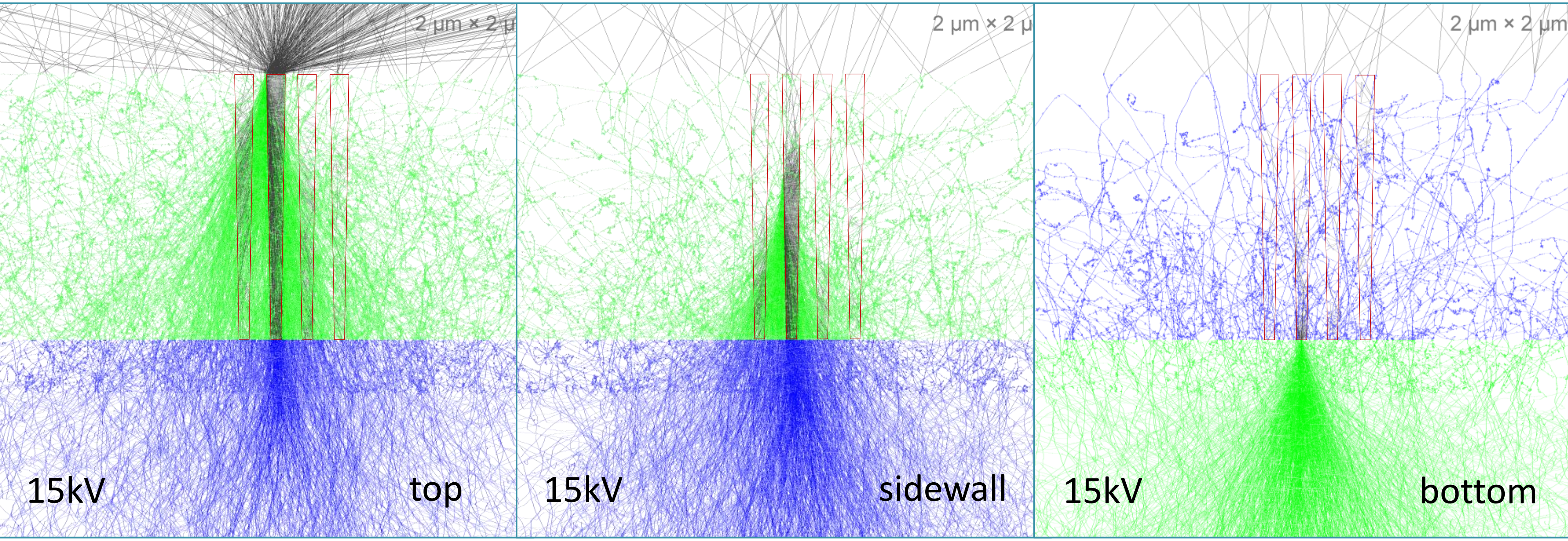
Top hits **Sidewall hits** **Bottom hits**



HAR hole signal (1 um depth)

- **15 kV beam**

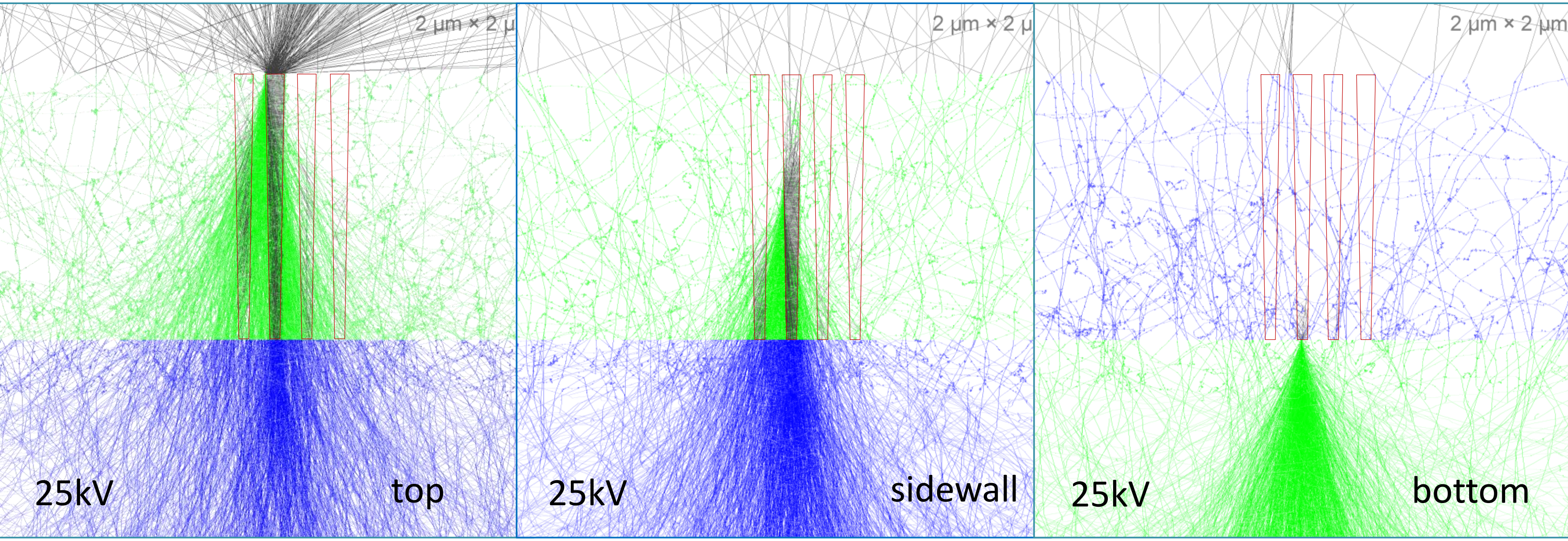
Top hits **Sidewall hits** **Bottom hits**



HAR hole signal (1 um depth)

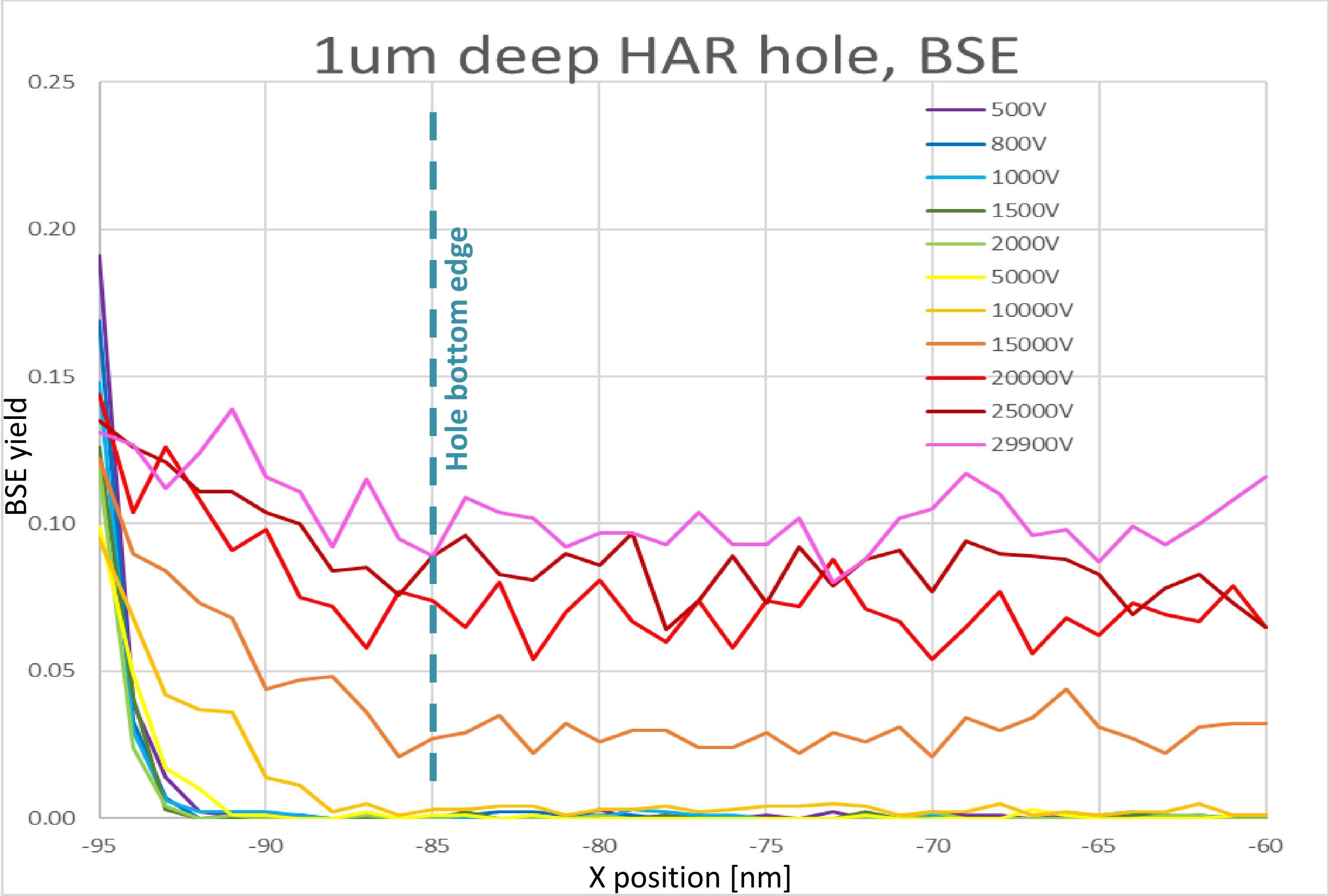
- **25 kV beam**

Top hits **Sidewall hits** **Bottom hits**



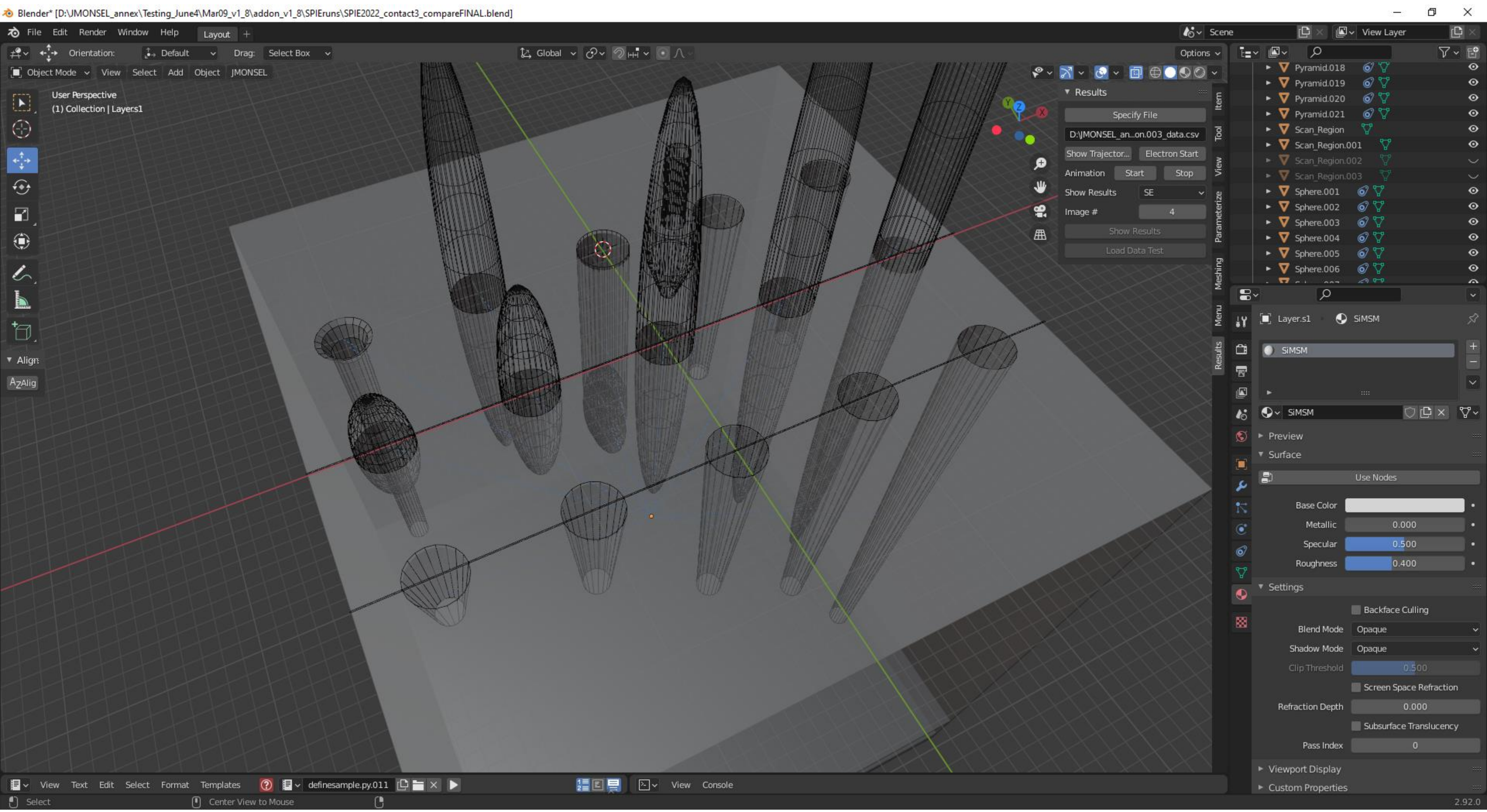
HAR hole signal (1 um depth)

- **15kV shows response at x=86nm, correct edge is at 85nm. 10kV close also, also maybe 20kV. Will require good statistics for detecting such a dim edge, but signal does exist.**



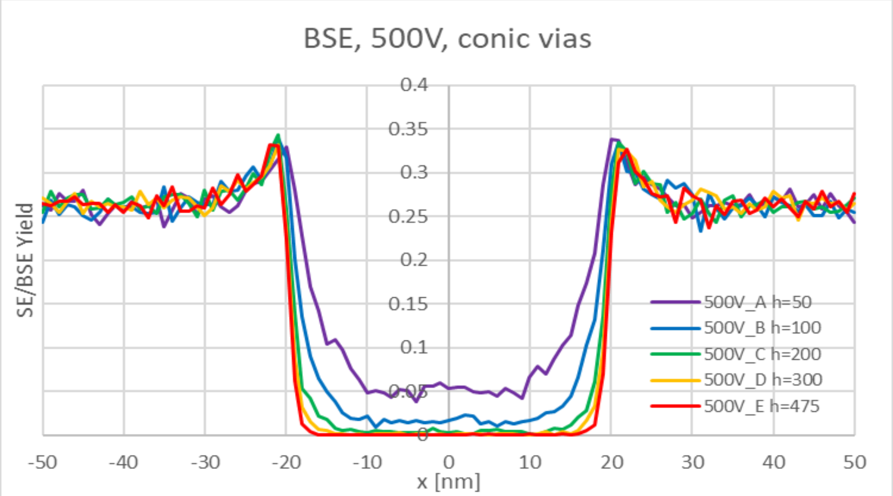
Contact hole profile

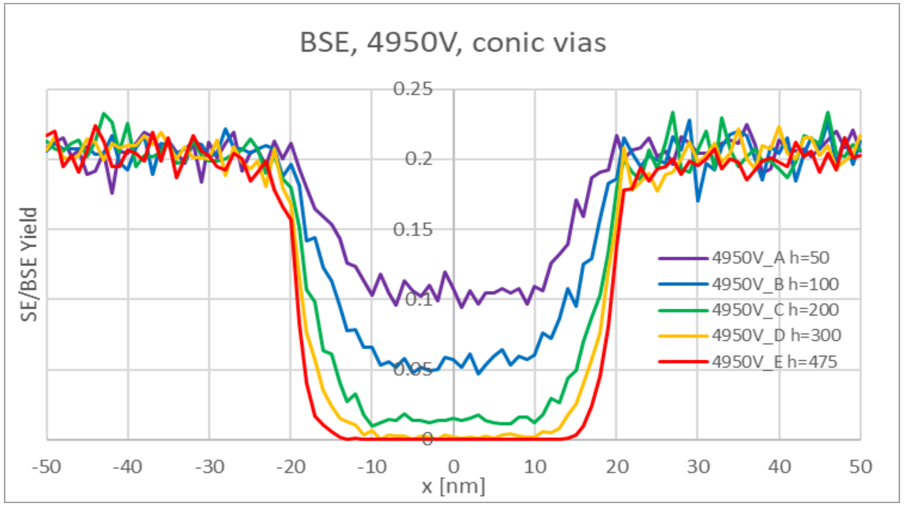
- Conic vias are typical. Here, Top = 40nm, Bottom = 20nm, h = 50nm, 100nm, 200nm, 300nm, 475nm.
- Can also mimic bowed profiles with closing bottoms with spheroid. Same dimensions as conic holes.
- Or, fabricate more complex profiles with TCR, foot, more bowing, or bent vias (future work).

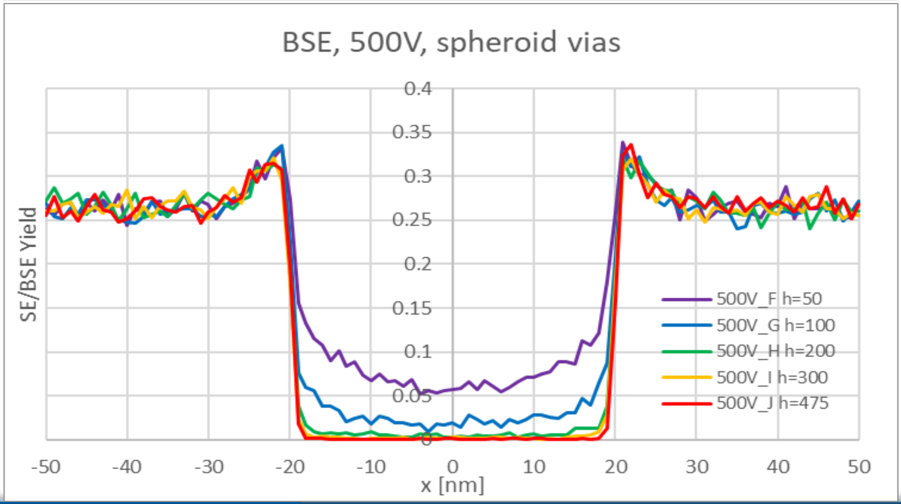


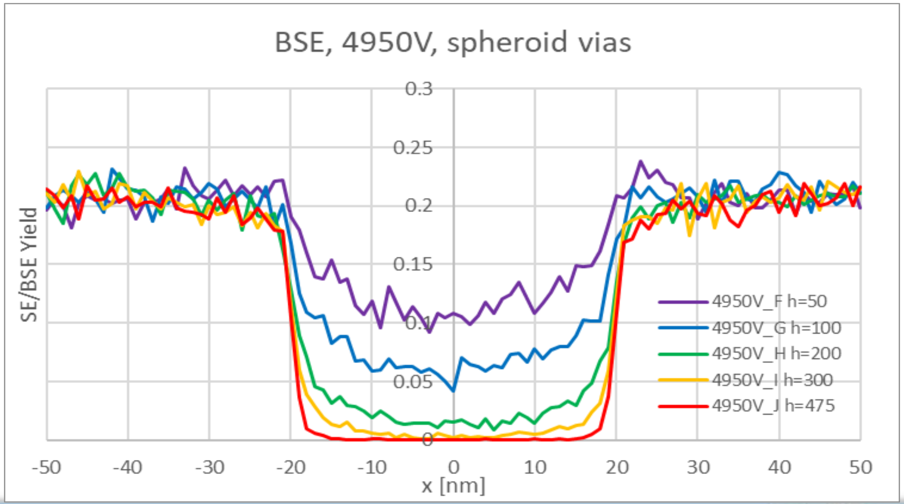
Conic vs Spheroid Contacts

- **Conic vias show 20nm bottom to waveform down to ~300nm depth at 5000V using BSE signal. Future work will be done to look at higher energies in same way. At 500V, can only see bottom down to depth ~100nm.**
- **Spheroidal holes show the curved bottom as expected. Noise likely too large to discern much more than basic shape unless very high dose, but more exploration of conditions can be done. But the signal difference for spheroid vs conic for deeper holes is subtle but likely detectable from noise.**









Conclusions

- More complex features can now be modeled using AMAG SimuSEM, which uses JMONSEL's physics but through a powerful GUI, greatly improving utility, productivity, flexibility, visualization, accessibility, and achievable complexity of designed features with greatly increased speed.
- SimuSEM was applied to cases of industry interest with more complexity than in past:
  - Intricate Intentional Defect Array designs demonstrated ability to predict response to large variety of SNR signatures in same test, with defect types previously impossible.
  - Rough resist lines can be simulated more realistically than in past, with ability to explore where signal is scattered, to understand how the profile, roughness and foot interact to define apparent meandering line edge.
  - Photoresist footing was explored, showed foot <3nm very difficult to detect in photoresist.
  - 1um deep HAR via's trajectories & BSE signals showed bottom edge location most detectible in the 10kV-20kV range, consistent with reported experimental results. Most likely improved with LLBSE filtering.
  - Conic vs spheroidal via shapes were explored and were discernible vs noise.
- SimuSEM demonstrated ability to systematically define and evaluate SEM performance on very small details to allow careful DOE work to be done on such cases, which is important for:
  - Model Based Metrology development
  - Hybrid metrology comparisons involving SEM
  - HV-SEM/OVL exploration
  - SEM imaging condition optimization
  - Limits, Gaps Analysis & Feasibility studies
  - Faux image generation for AI training
  - Calibration of analytical models
  - Fundamental understanding of signal generation in tough cases
- Over the next year, we expect to add rigorous meshing solutions to allow user-defined roughness, new sample definition and image analysis & comparison features, charging capability, and more.

Acknowledgements

- AMAG Consulting thanks Dr. John S. Villarrubia of NIST, creator of JMONSEL.
- Also Andrew Sher of Sher Legal, David Klotzkin of SUNY Binghamton & Adam Plager of Quick Software Solutions.

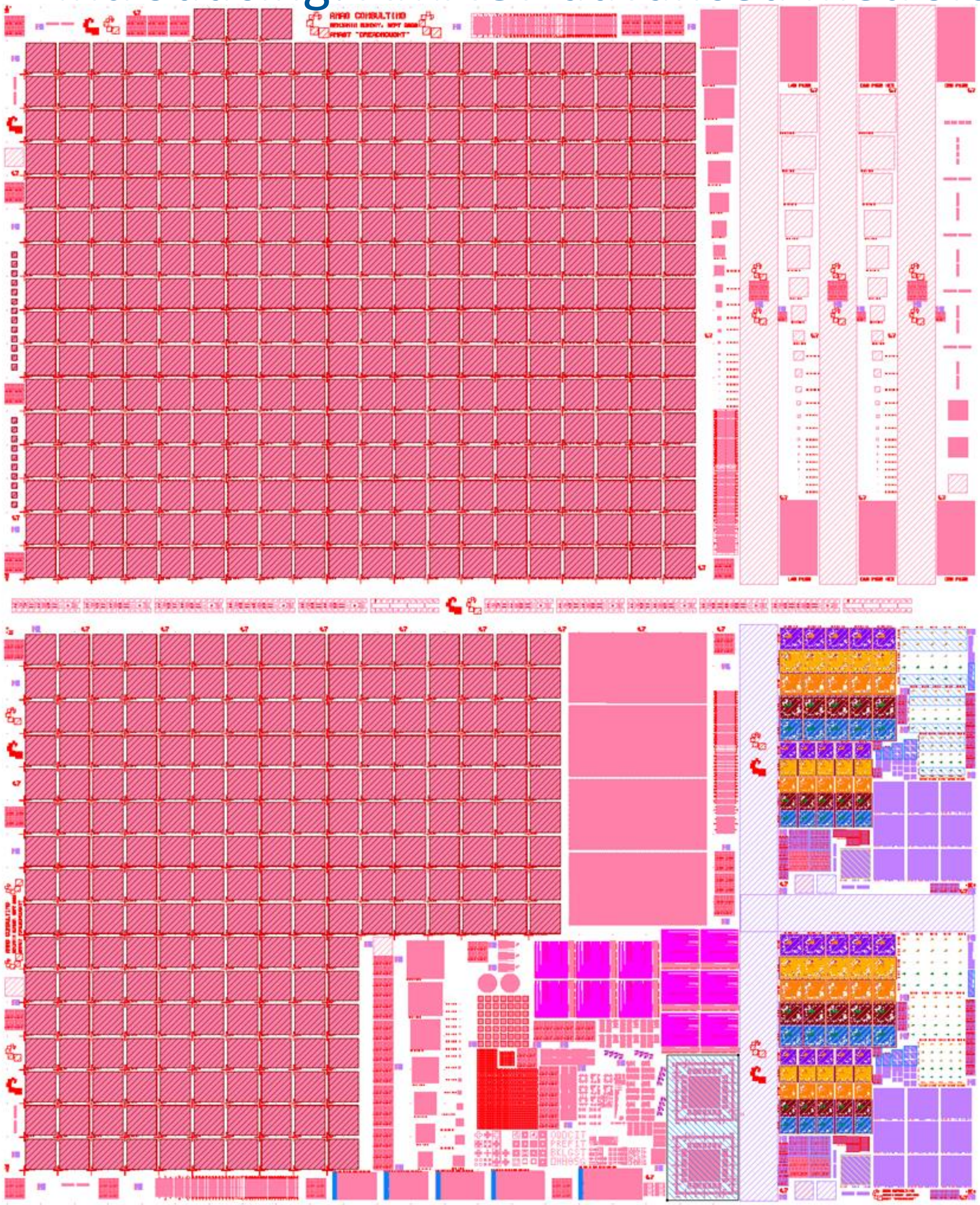
Product: AMAG7 HARhole, available from AMAG Consulting, LLC

Thank you for your Attention!

Note image cropped on right.

Introducing: AMAG7 advanced metrology reticle

Backup



- iArF litho test reticle for challenging metrology test sample creation
- AMAG7 is culmination of the development of test reticles from past SEMATECH AMAG reticles, with updated and improved elements, useful as a very versatile patterning platform for short-loop metrology test wafers for many applications
- Reticle usable with many processes at various foundries allowing for many different products with very flexible form factor
- Flexible design means reticle should stay pertinent for many years as with past AMAG reticles
- Content fine-tuned and executed for ease of use by the metrologist
- 547x 0.8mm gratings of many types, large enough for any CD-SAXS tool to utilize, allowing full collaboration with these new tools
- 2 level overlay module includes 10x 2-level gratings including FinFETs, via-in-trench, etc.
- Large pads of random polygon pseudo-logic for large FOV instrument tests
- Exposed full field on wafer will be 28x33mm die.

Backup