KiSSAM Simulation Software for Additive Manufacturing

3D simulation of electron beam melting process with adaptive mesh refinement at mesoscale level

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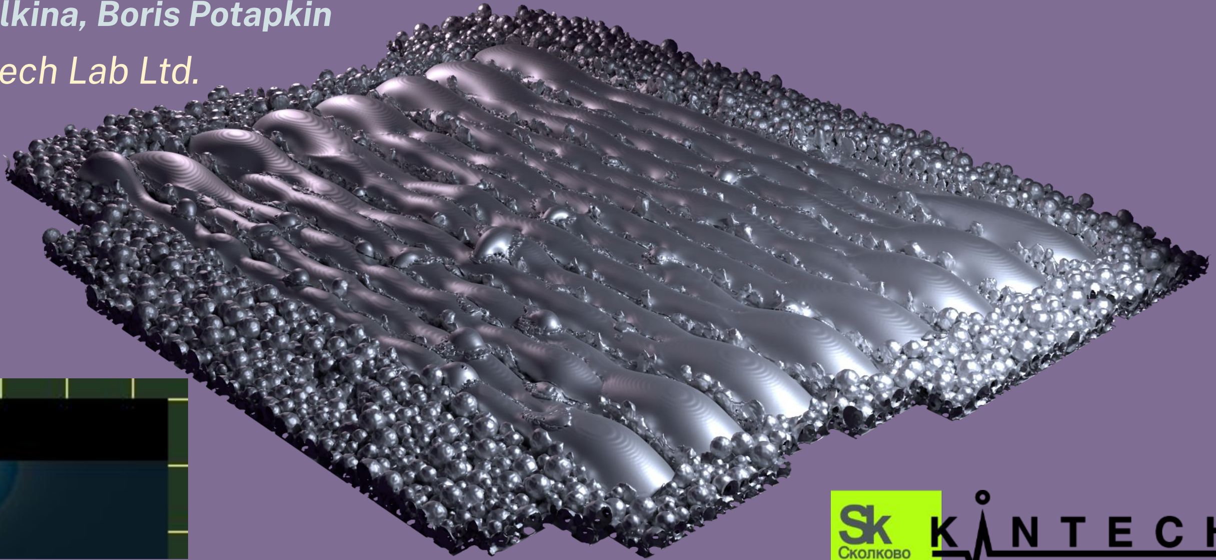
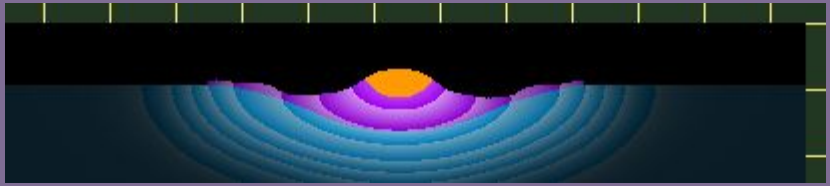


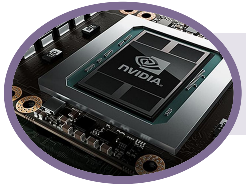


Powder bed fusion processes simulation at mesoscale (melt-pool) level

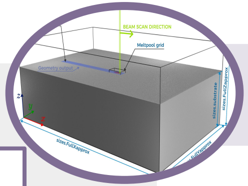
KiSSAM is a high performance software with multiple presets for the purposes of powder bed fusion in additive manufacturing.

Typical performance is 0.5 – 1 hr per 1 ms of scanning time

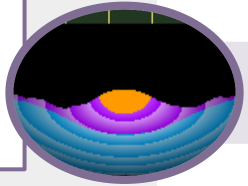
KiSSAM is built around a fluid dynamics code tailored specifically for melt pool modeling.



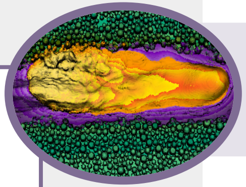
High performance / GPGPU support



Simulation of the full volume of the chamber



In-situ visualization of the modeling process



Mesoscopic level of modeling
Physically based fluid dynamics in the melt pool

SIMULATION FLOW

Unified input file

- Process parameters
- Material parameters
- Powder parameters
- Scenario of experiment

PowDEM solver

- Powder deposition
- Layer generation with a knife movement

KiSSAM solver

- Hydrodynamics
- Phase transition
- Thermodynamics
- Energy deposition
- Energy loss

Output data

- Geometry of a sample
- Temperature history
- Rendered images and cross sections of the meltpool
- Absorbed energy

Scripts for more data

- Track parameters
- Customized cross sections
- Process movie
- Powder cleaner

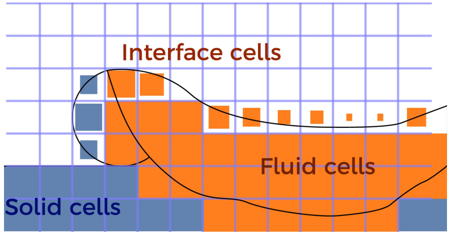
KiSSAM

Underlying physical models in KiSSAM

- Hydrodynamic solver based on Thermal Lattice Boltzmann Method with Volume of Fluid free surface tracking
- Phase transition solid/liquid
- Surface tension and wetting
- Marangoni convection
- Dumping drag force in mushy zone
- Recoil pressure, mass and energy losses due to the strong evaporation from the liquid surface
- Radiation cooling
- Convection cooling
- Evaporated metal and chamber gas flow tracking
- Heat cooling and conduction in the bulk far from the melt-pool
- Ray tracing with multiple reflections (for laser beam) and MC simulation of electron trajectories with elastic and inelastic scattering in metal (for electron beam)
- Sensors and detectors photodiode response simulation
- Grain microstructure simulation at solidification same as CAFE model (*in progress*)
- Powder bed packing DEM solver with knife movement (fork of BlazeDEM project)

Free surface Temperature Lattice Boltzmann Method

Volume of Fluid method for free surface tracking



$$\frac{\partial f}{\partial t} + \vec{v}\frac{\partial f}{\partial \vec{x}} = \Omega(f, f')$$

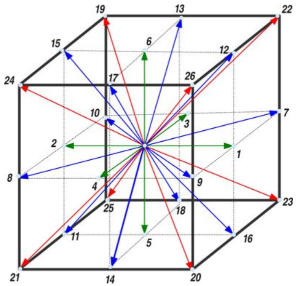
$$f(\vec{x}, \vec{v}, t) \rightarrow f_{ijk}(\vec{x}, t);\ i,\ j,\ k = -1, 0, 1;$$

$$\rho = \int fm\,\mathrm{dv} \qquad \rho = \sum_i f_i$$

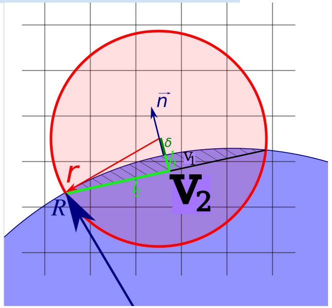
$$\rho\bar{u} = \int fm\bar{v}\,\mathrm{dv} \qquad \rho\bar{u} = \sum_i \bar{e}_i f_i$$

Advanced modern method

- Suitable for massively parallel systems such as GPGPUs
- Liquid surface is explicitly tracked
- Modelling of the interaction with solid
- Describes heat transfer flows (both thermal conductivity and convection)



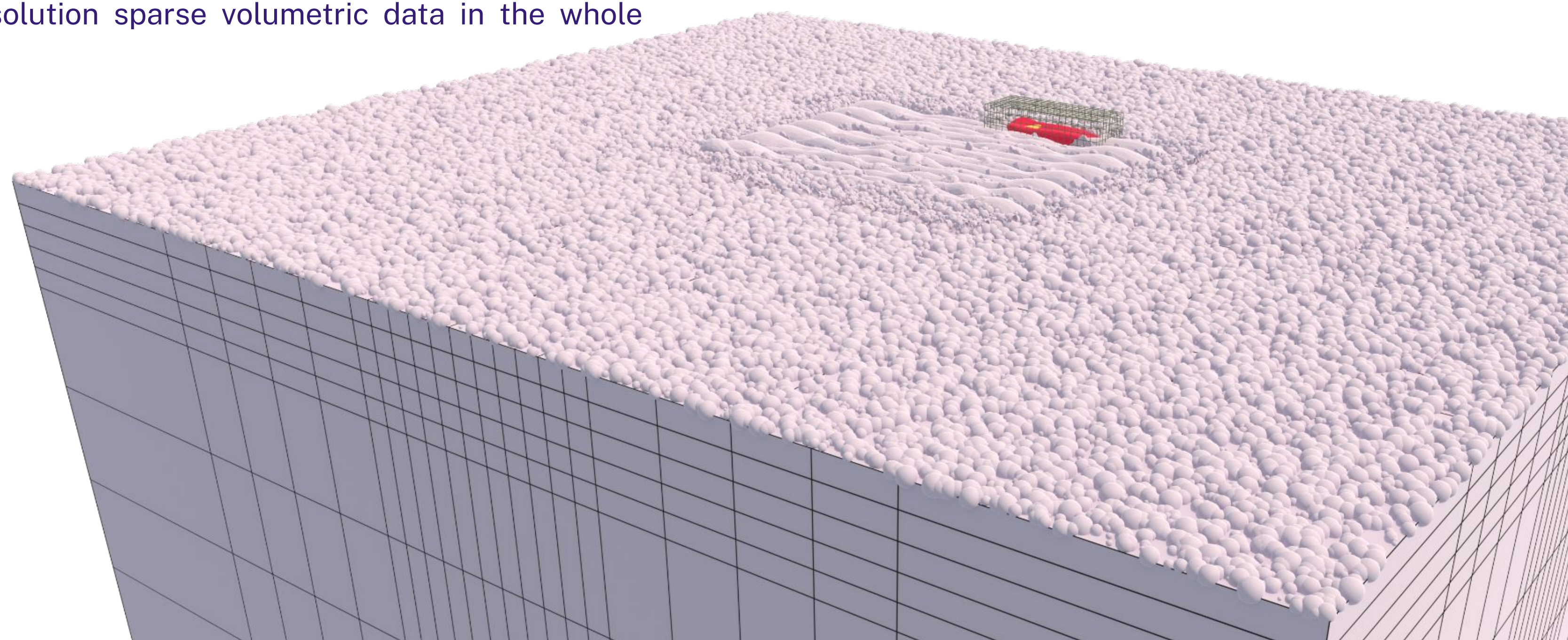
Numerical scheme cell



Curvature calculation scheme

Adaptive Mesh

- Melt pool is fitted by a fine mesh (*3-5 μm* resolution).
- Fluid dynamics is simulated in a small region around the melt pool *(~ 1 mm).*
- Heat transfer is simulated in a large domain *(~ 1 cm)* with adaptive mesh step.
- Geometry of the powder and melted metal is stored as high resolution sparse volumetric data in the whole region.



Electron beam Monte-Carlo ray tracing simulation

Elastic scattering
(approximation of the screened Rutherford scattering):

$$\frac{d\sigma(\theta)}{d\Sigma} = \frac{Z(Z+1)e^4}{p^2v^2}\frac{1}{(1+\cos\theta+2\beta)^2}, \quad \beta = \left(\frac{\hbar Z^{1/3}}{pa_B}\right)^2$$

scattering length: $$\Lambda = \frac{2\beta(1+\beta)p^2v^2A}{2\pi N_A \rho Z(Z+1)e^4}$$

Inelastic scattering
(the differential energy loss (stopping power) due to the electron-electron scattering):

$$\frac{dE}{ds} = -785\frac{\rho Z}{AE}\ln\left(\frac{1.166E}{J}\right)\ [\text{eV}/\text{Å}]$$

Every trajectory consists of straight line segments

segment length: $L_r = -\Lambda \log R_1$

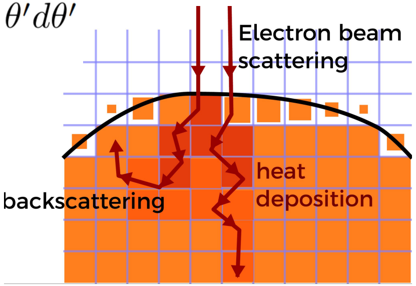
energy deposition per segment: $L_r \frac{dE}{ds}$

polar θ and azimuthal φ angles of collision:

$$R_2 = \frac{\int_0^\theta \frac{d\sigma(\theta')}{d\theta'}\sin\theta' d\theta'}{\int_0^\pi \frac{d\sigma(\theta')}{d\theta'}\sin\theta' d\theta'}$$

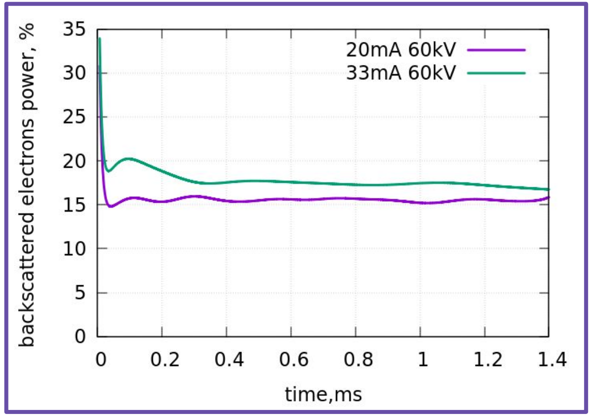
$\varphi = 2\pi R_3$

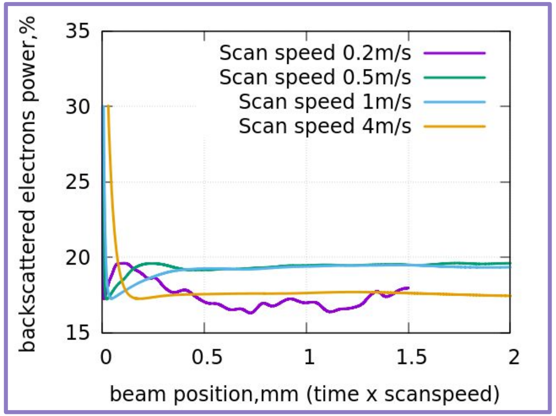
R_1, R_2, R_3 are uniformly distributed random numbers

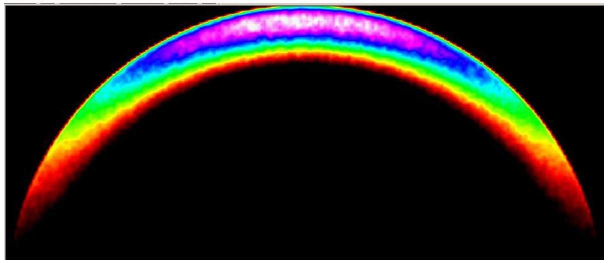


Multiple trajectories are simulated every time step

Power of back-scattered electrons







Absorption profile
in a 70μm Ti sphere for 60 kV beam

Part of backscattered electrons during the simulation of powder melting

Powder simulation using the discrete element method

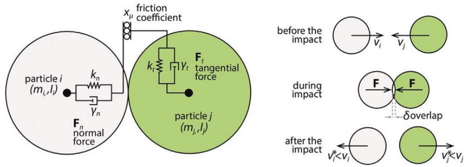
- Powder packing in the PBF process may have significant impact on the quality of the manufactured detail
- Powder dynamics can be simulated using the discrete element method (DEM)
  - numerical method of solving the ODE of dynamics of a system many spherical rigid bodies (particles) with respect to the wall boundaries and moving objects
  - Gravity, friction, elastic forces are taken into account
    - Hertz-Mindlin contact model to calculate the elastic forces acting on each particle
    - Amontons-Coulomb friction law
- The substrate relief is approximated from the previous layer (or some initial substrate relief is assumed)
- Powder particle dynamics is simulated till steady-state solution is obtained
- Particle data is sent to the main simulation module

$$\frac{d^2\boldsymbol{p}_i}{dt^2} = \boldsymbol{f}_i$$

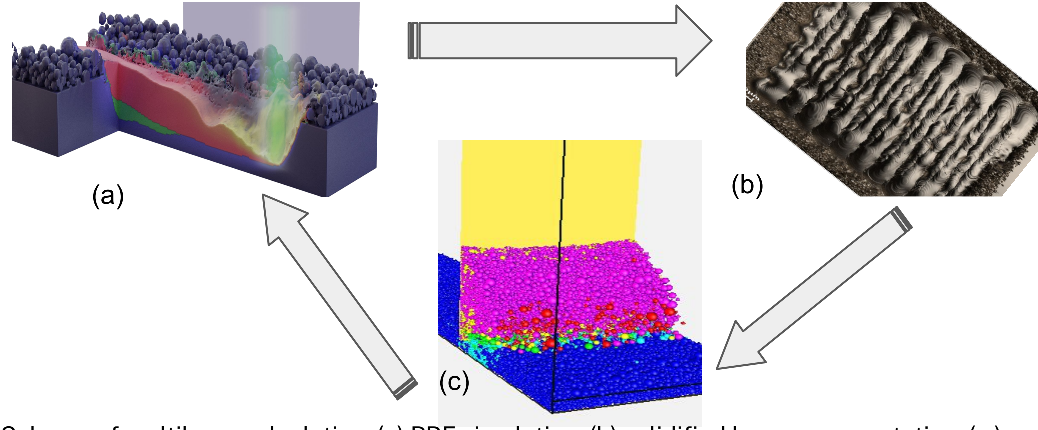
$$\boldsymbol{I}_i \frac{d\boldsymbol{\omega}_i}{dt} + \boldsymbol{\omega} \times \boldsymbol{H} = \boldsymbol{t}_i$$

$$\boldsymbol{f}_i = \sum \boldsymbol{f}_i^s + \sum \boldsymbol{f}_i^b$$

$$\boldsymbol{t}_i = \boldsymbol{r}_i \times \boldsymbol{f}_i^s$$



Scheme of Hertz-Mindlin contact model (picture from [Capozzi et al (2018). Data in Brief. doi:22.10.1016/j.dib.2018.12.061])

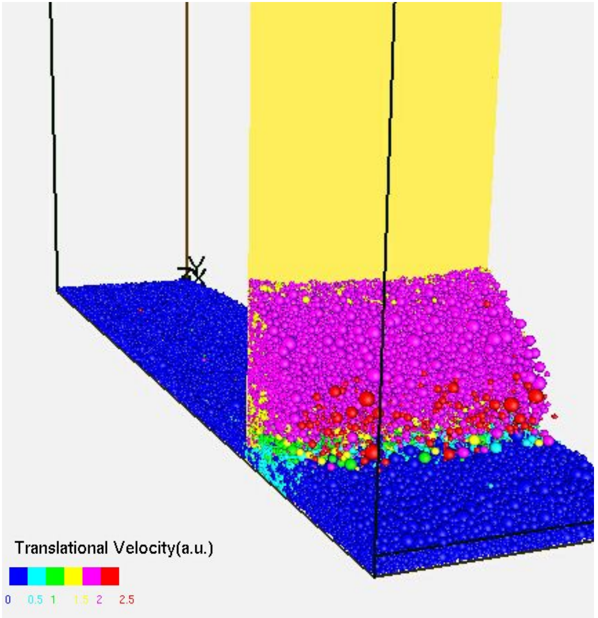


Scheme of multilayer calculation: (a) PBF simulation, (b) solidified layer representation, (c) powder generation for the next layer. Lines mean data dependencies

Fast GPU DEM solver

Nicolin Govender, Daniel N. Wilke, Schalk Kok. Blaze-DEMGPU: Modular high performance DEM framework for the GPU architecture, SoftwareX, V. 5, 2016, P. 62-66, https://doi.org/10.1016/j.softx.2016.04.004

- The solver is developed based on Blaze-DEMGPU open source DEM code core
  - Blaze-DEMGPU algorithms and data structures improved
  - Some bugs fixed
- Code is optimised and extended for the PBF powder generation
  - Initial setup of a particle “cloud” with a given size distribution
  - Substrate reader from the STL format
    - Python scripts for STL substrate decimation based on the vtk library routines are developed
  - Verlet algorithm for substrate discrete elements i.e. triangles of its fast GPU implementation
  - A moving blade for the powder alignment is introduced
- Code has performance more than 10^{10} discrete elements per second
- 5mm x 5mm layer can be simulated in ~ 1–2 hours using the particles with mean size 40 μm



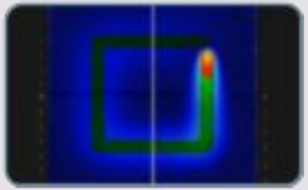
Simulation of powder packing 6mm x 1mm x 80 μm. Yellow is a moving blade. Powder particles are colored by their velocity magnitude. Simulation time ~ 30 mins.

High Performance Computing

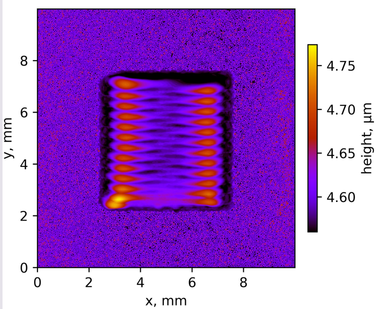
KiSSAM is a high performance software with multiple presets for the purposes of powder bed fusion in additive manufacturing.

Typical performance is 0.5 – 1 hr per 1 ms of scanning time

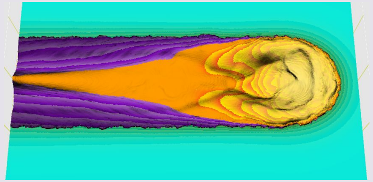
Here are some sample setups modeled on a single GeForce RTX 3090 24 GB GPGPU and total simulation times.



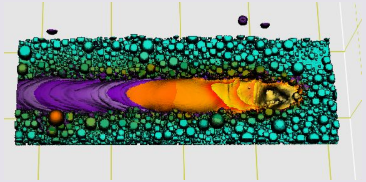
Contours
~ 4h



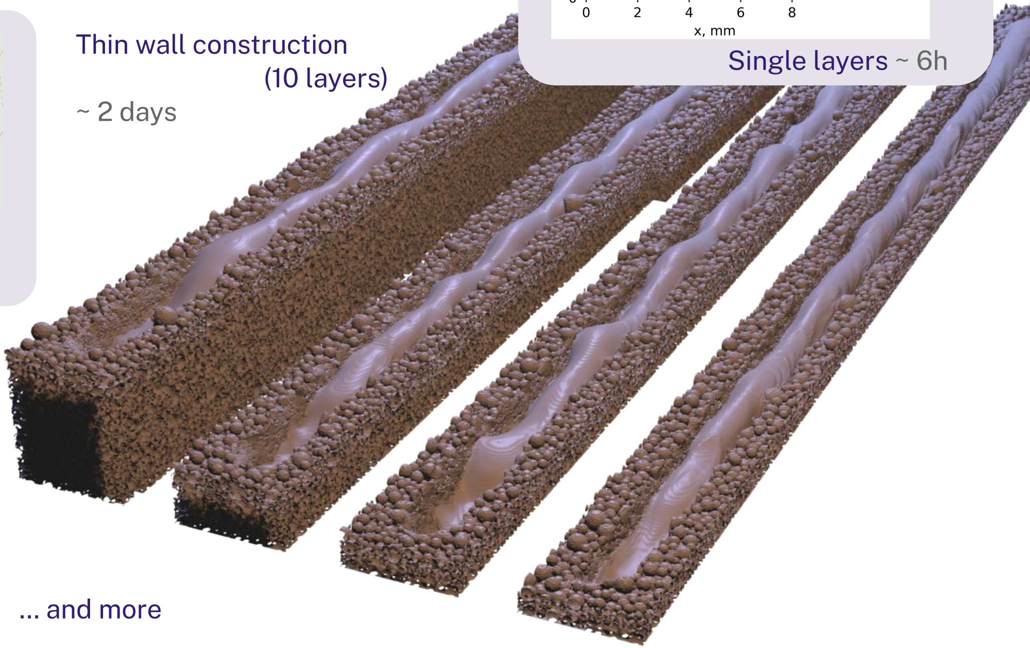
Single layers ~ 6h



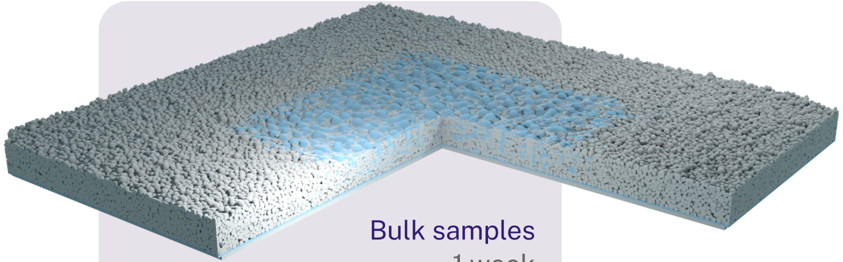
Single tracks on a plate
~ 1h



Single tracks on powder
~ 1h



Thin wall construction
(10 layers)
~ 2 days

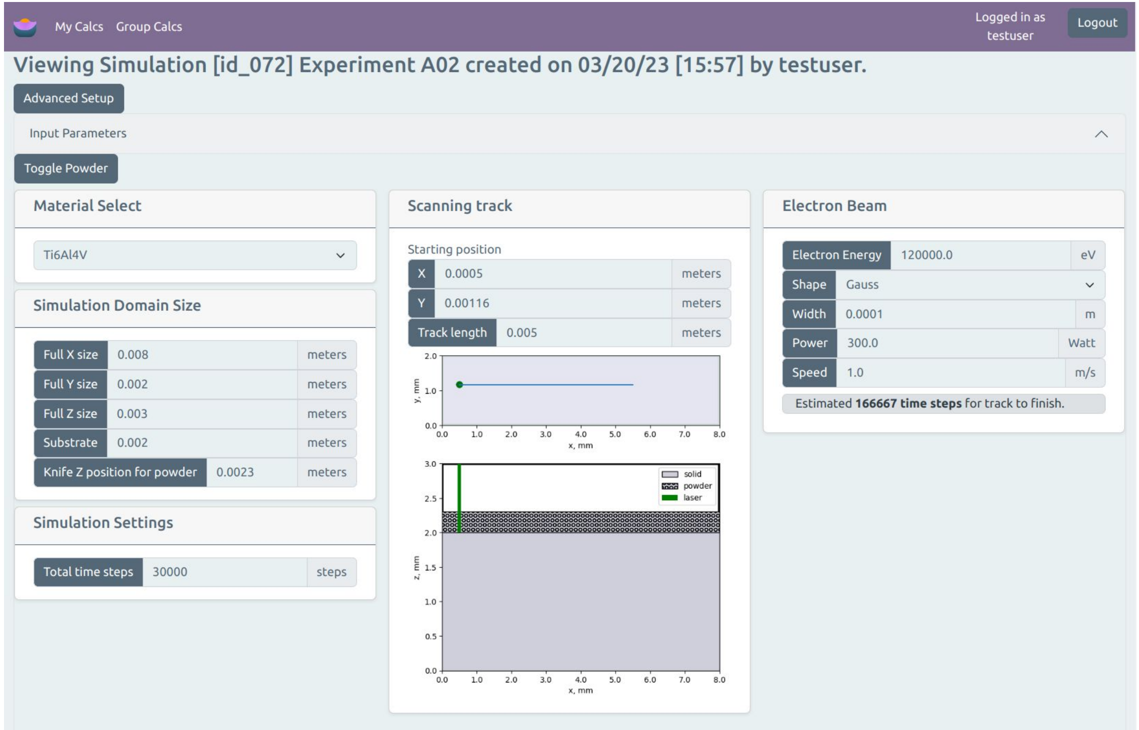


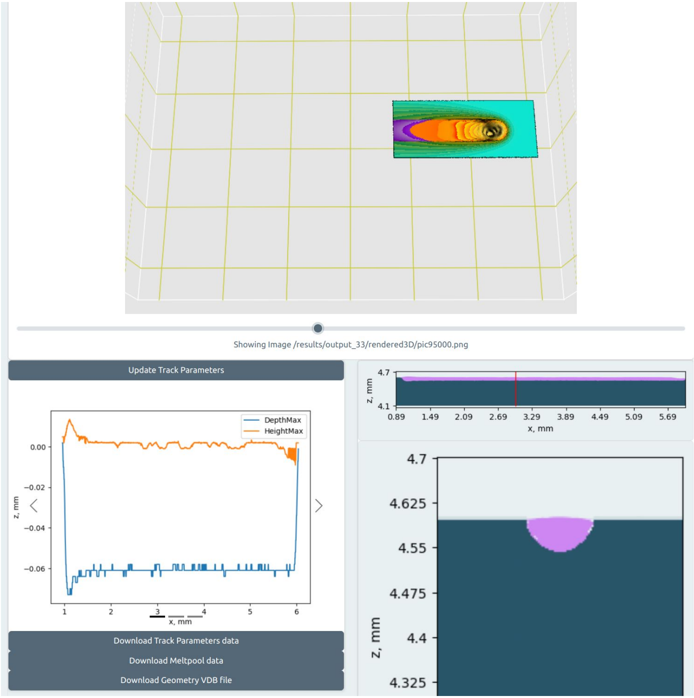
Bulk samples
~ 1 week

... and more

KiSSAM on web cloud

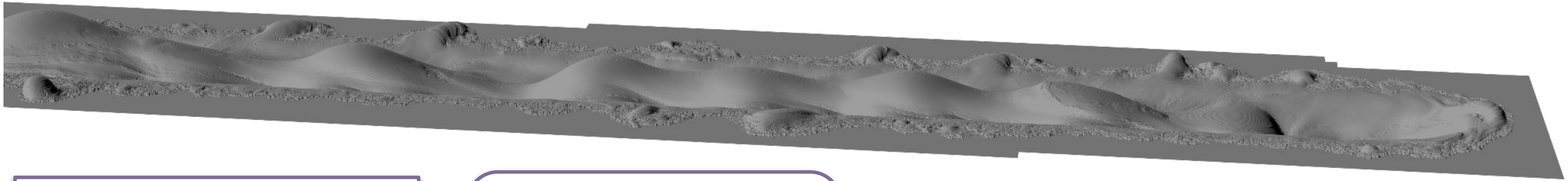
www.kissam.cloud

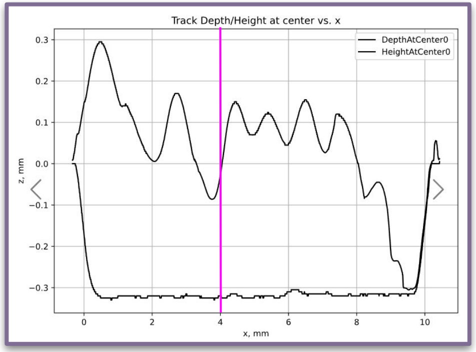


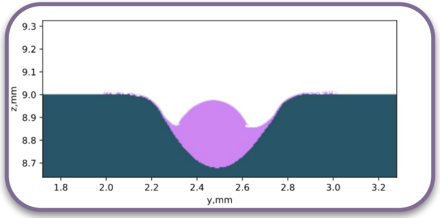


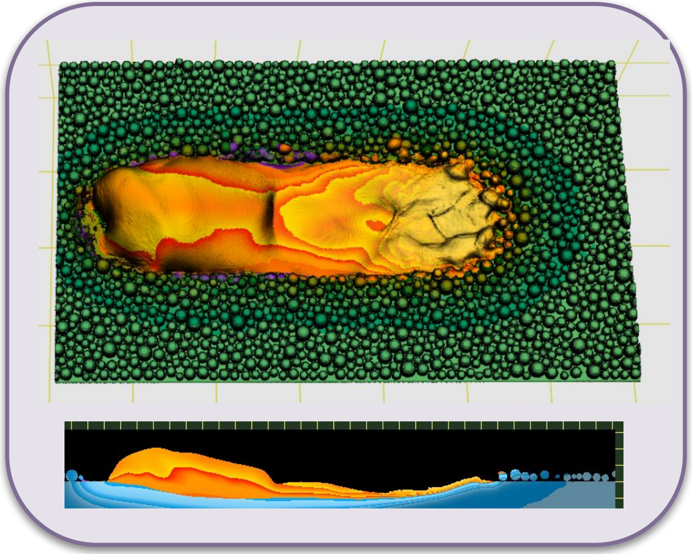
Simulation examples

Single track on plate
???? P=**1500**W Speed=**1.0** m/s

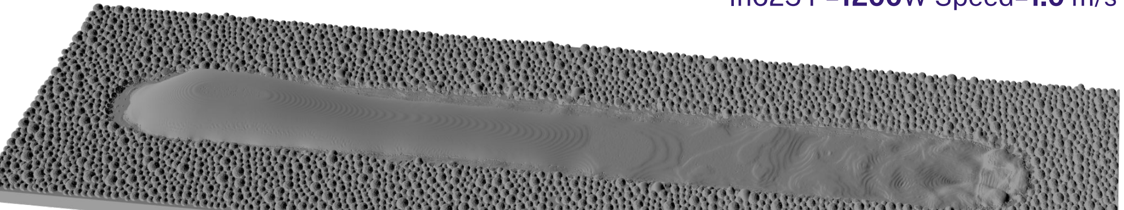




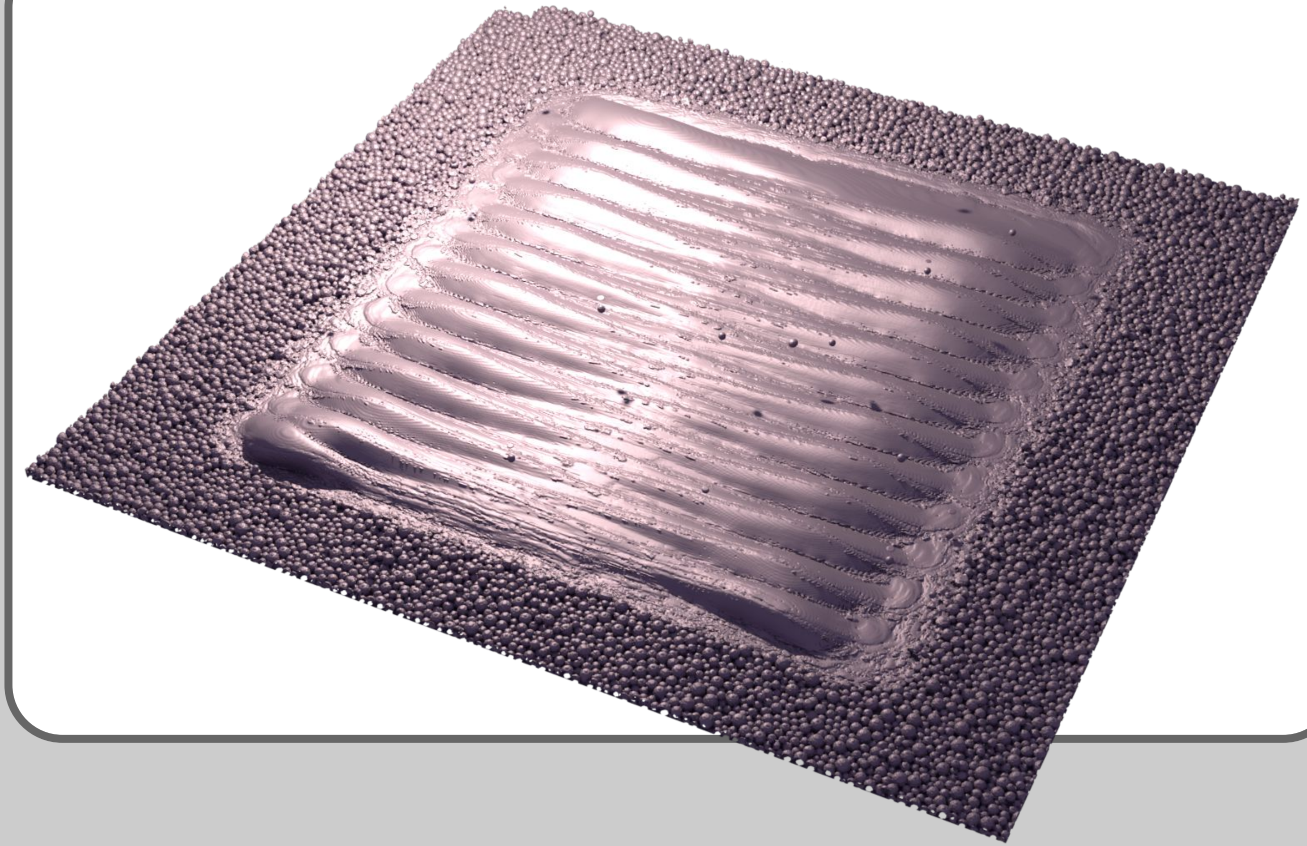




Single track on powder
In625 P=**1200**W Speed=**1.0** m/s

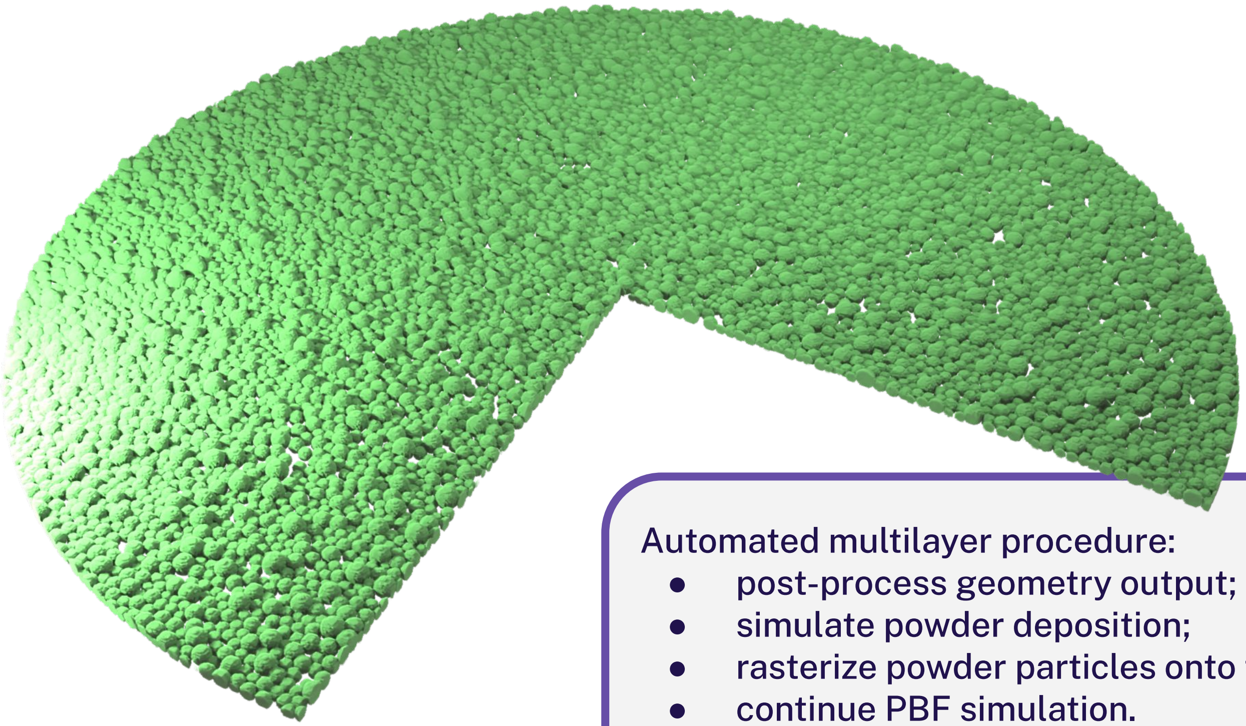


Simulation examples



Hatched layer
Ti6Al4V
Power =1680.0 W
Speed = 4.27 m/s

Simulation examples



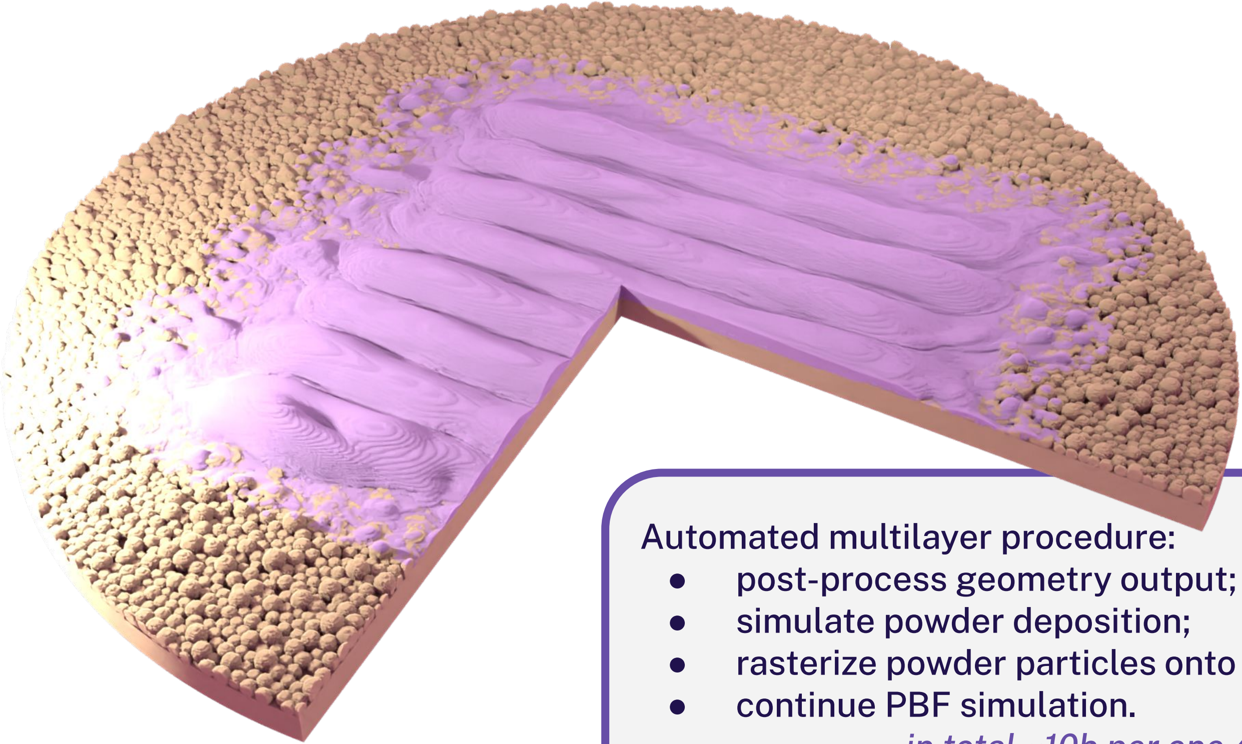
Bulk sample
Ti6Al4V
Power = 2208 W
Speed = 5.854 m/s

Automated multilayer procedure:

- post-process geometry output;
- simulate powder deposition;
- rasterize powder particles onto fine mesh;
- continue PBF simulation.

in total ~10h per one 4mm^2 layer.

Simulation examples



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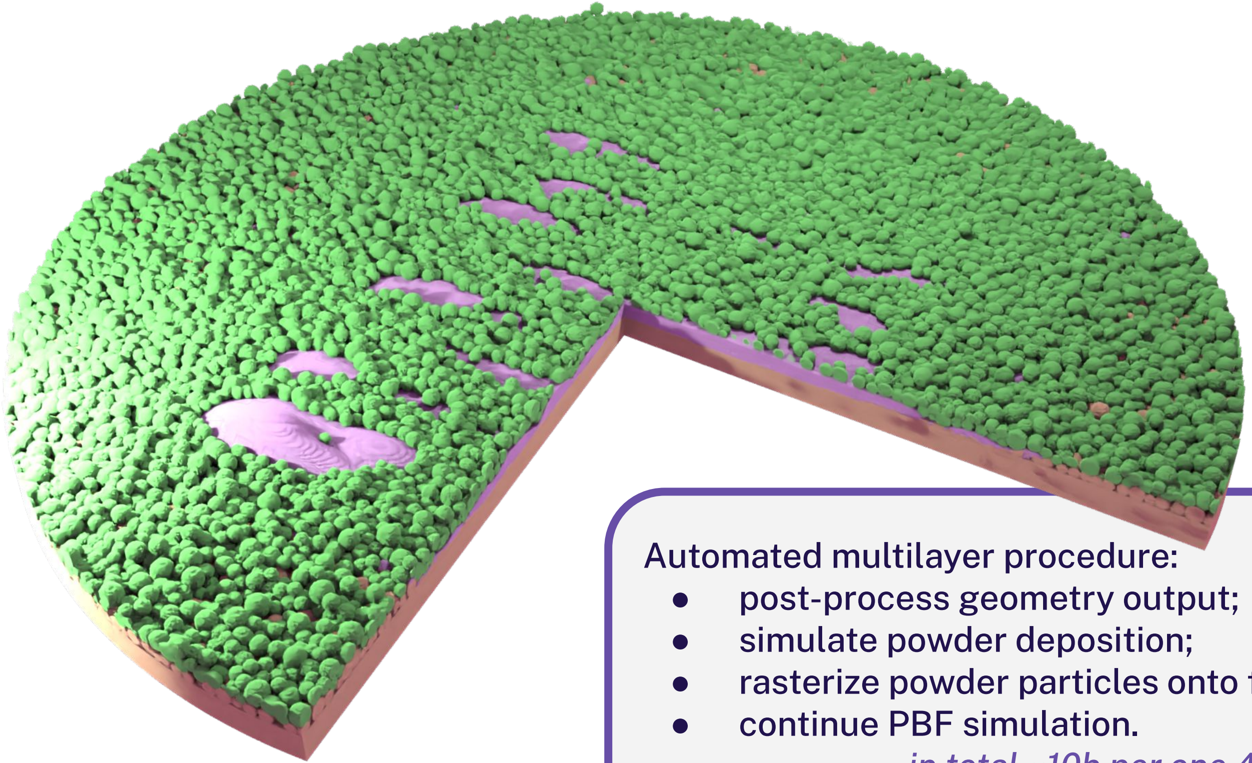

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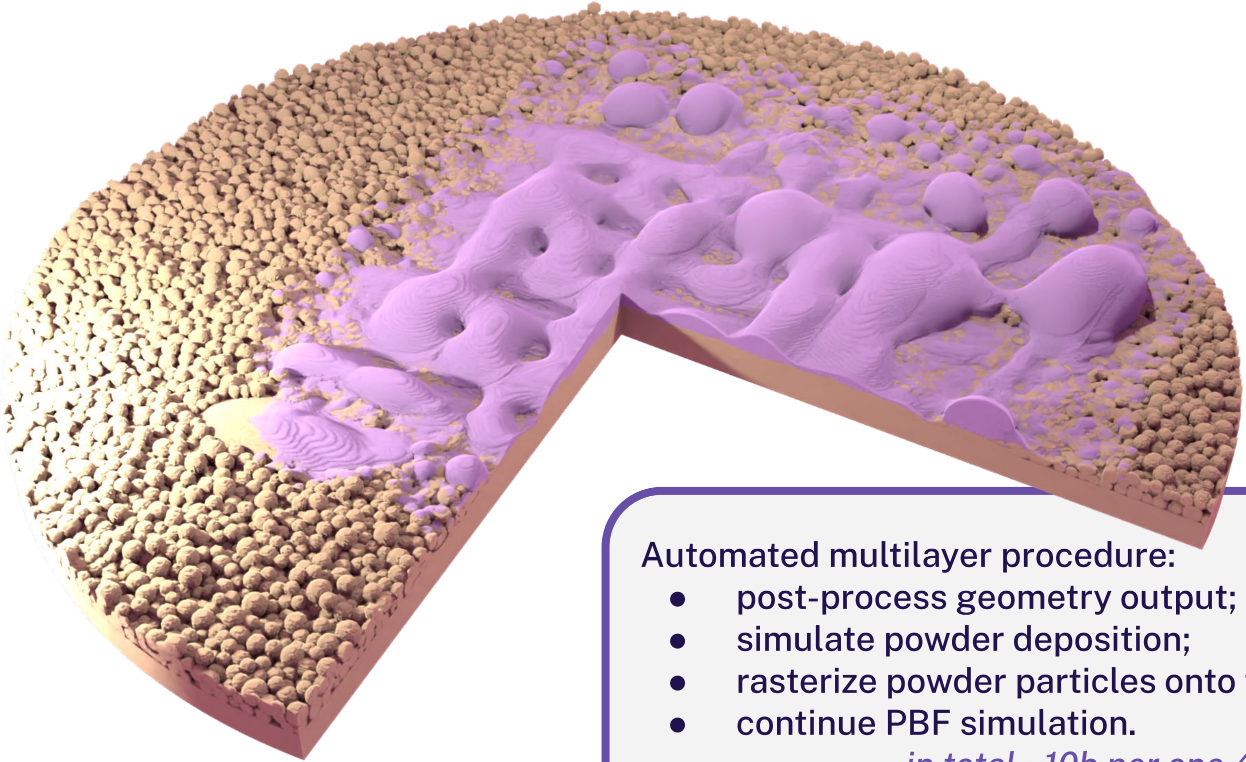

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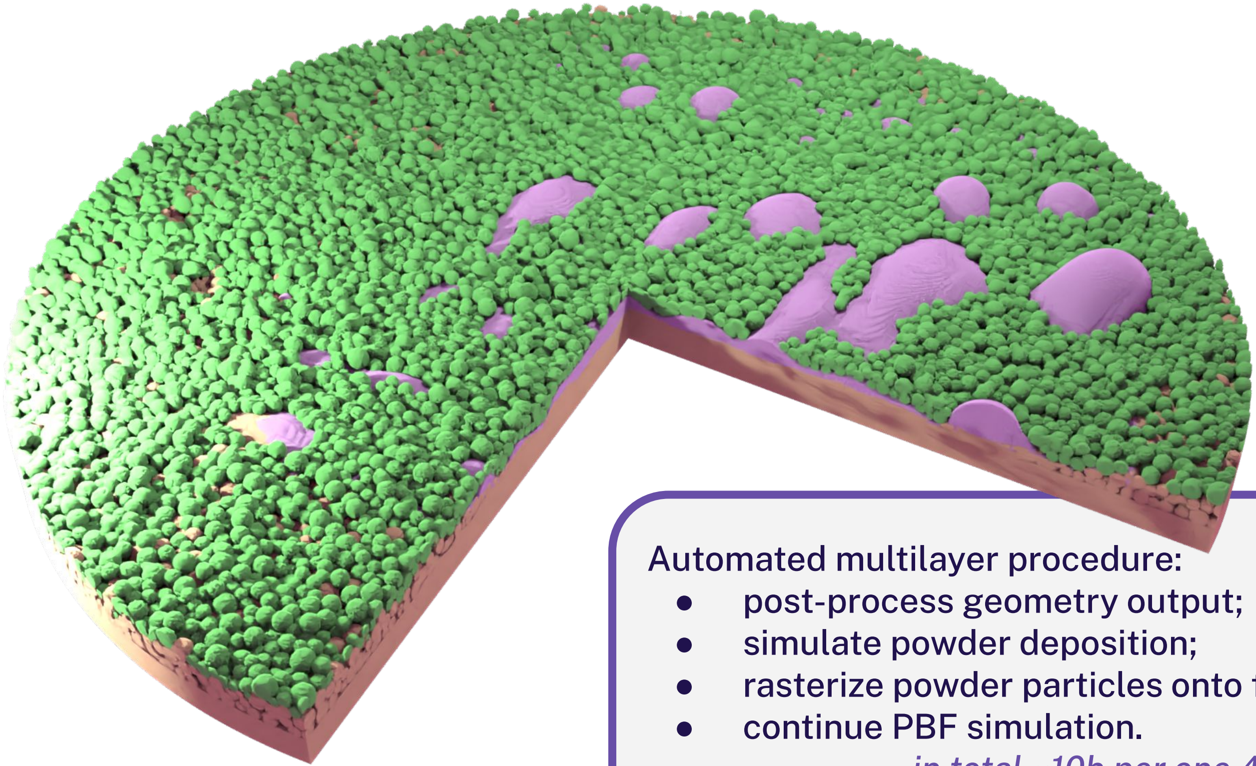

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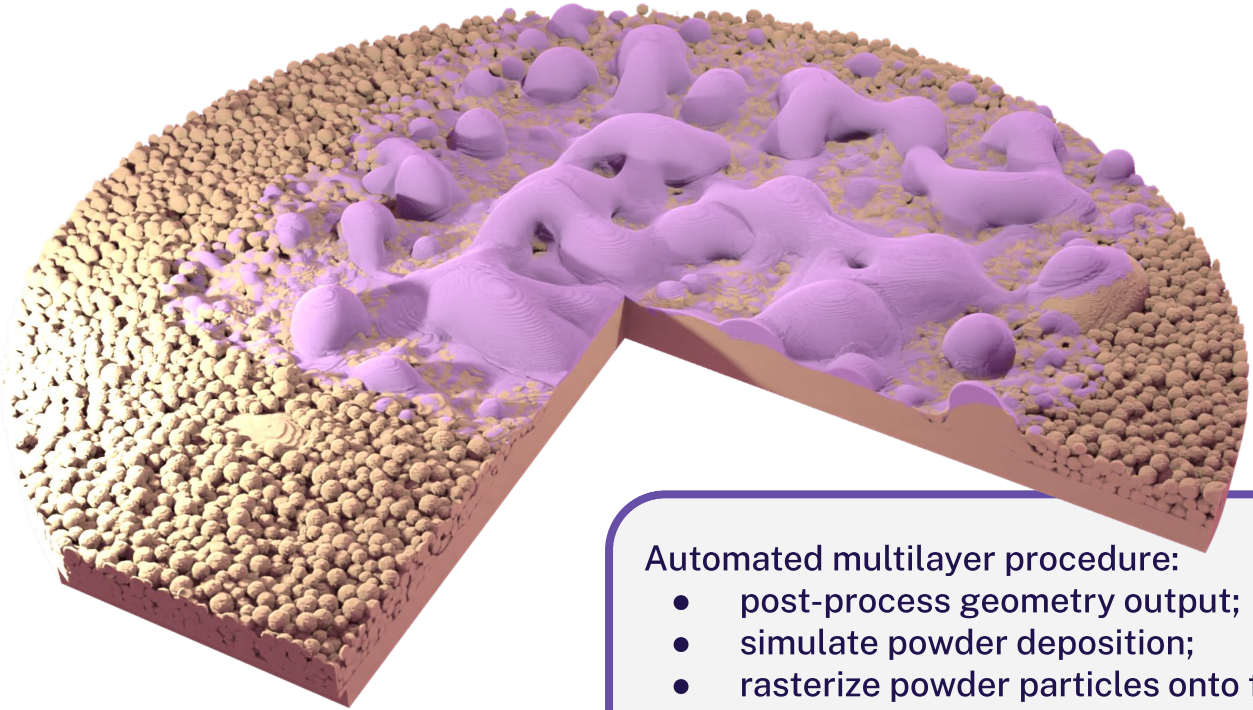

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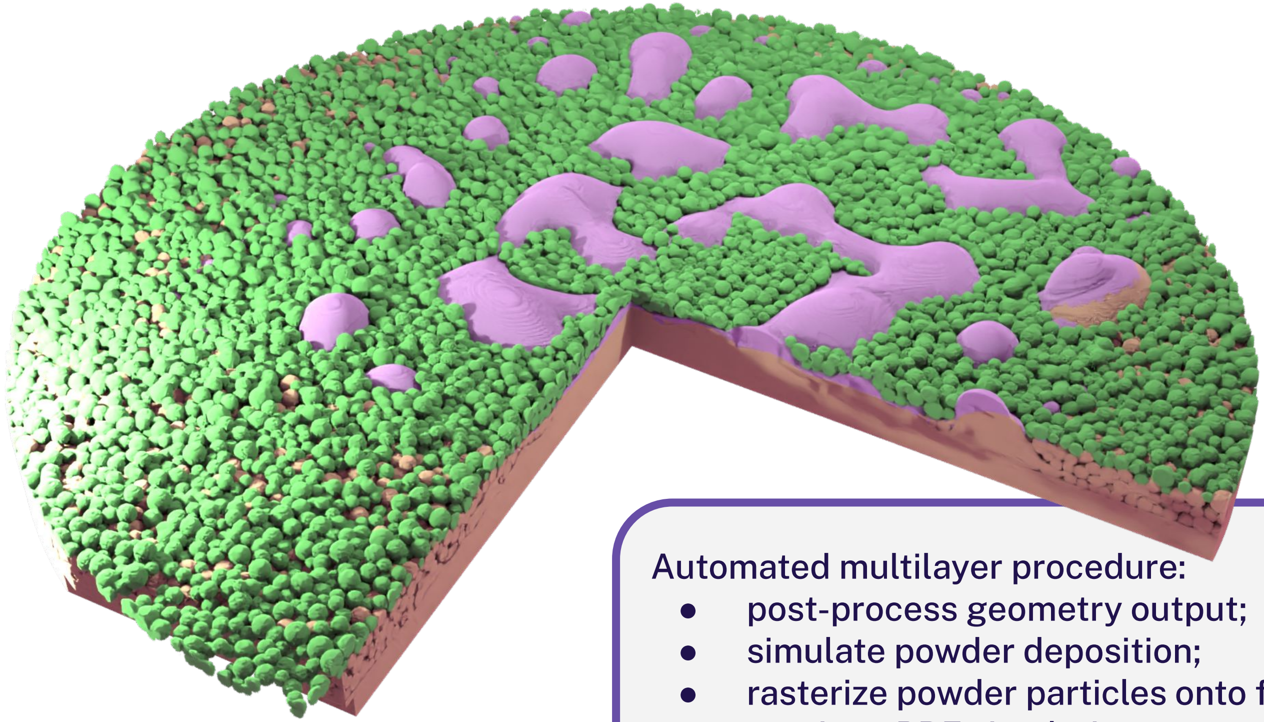

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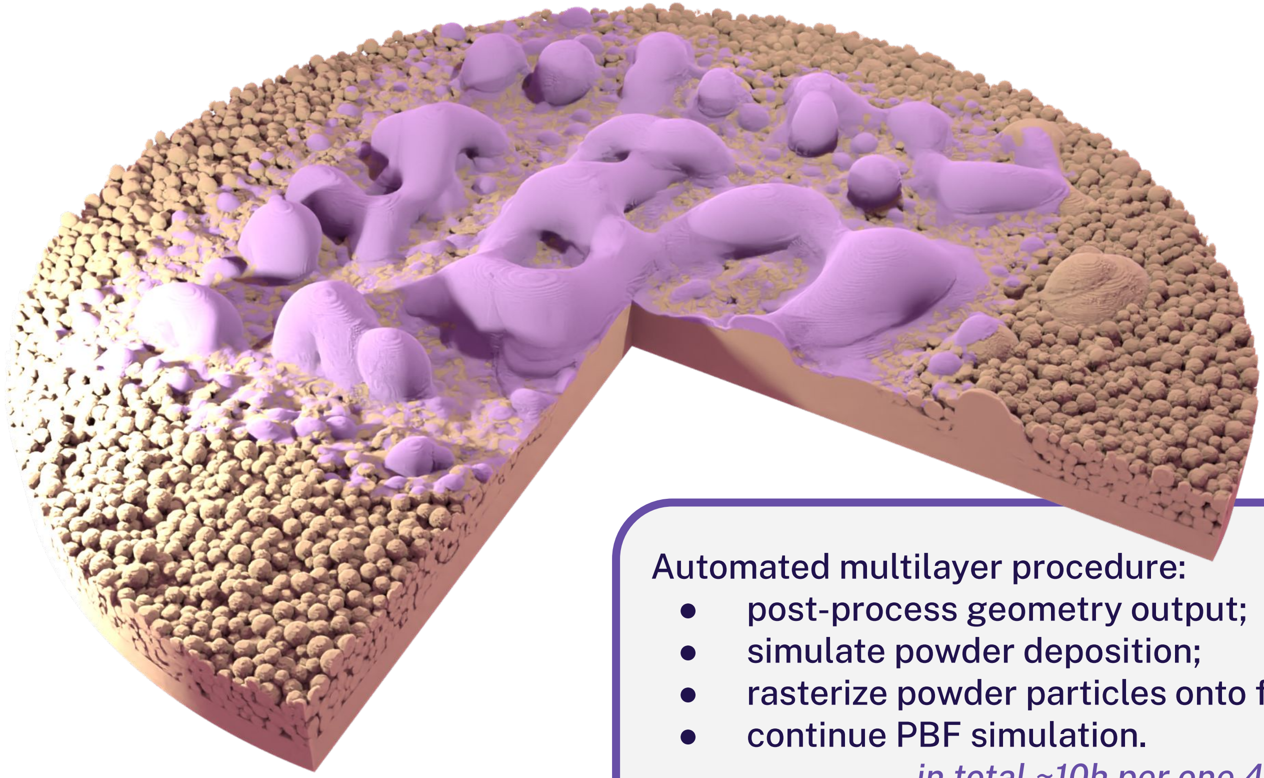

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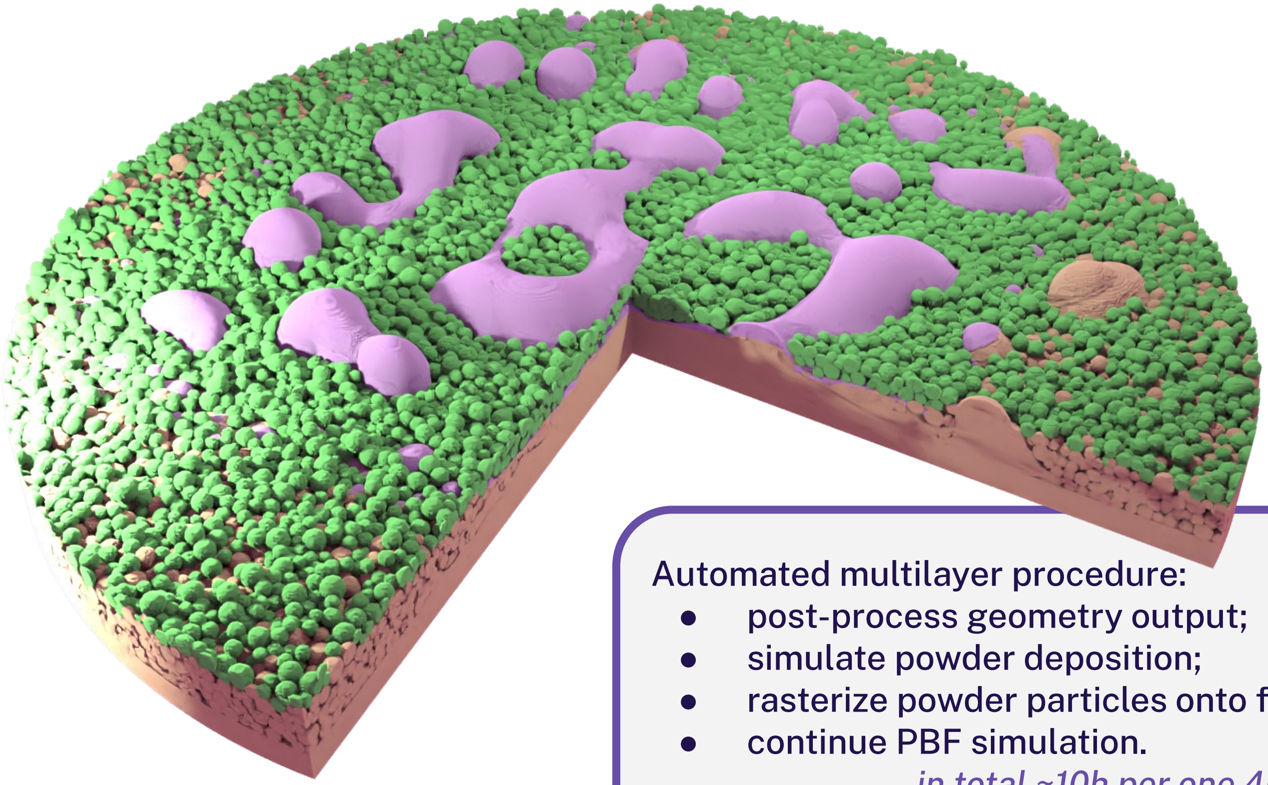

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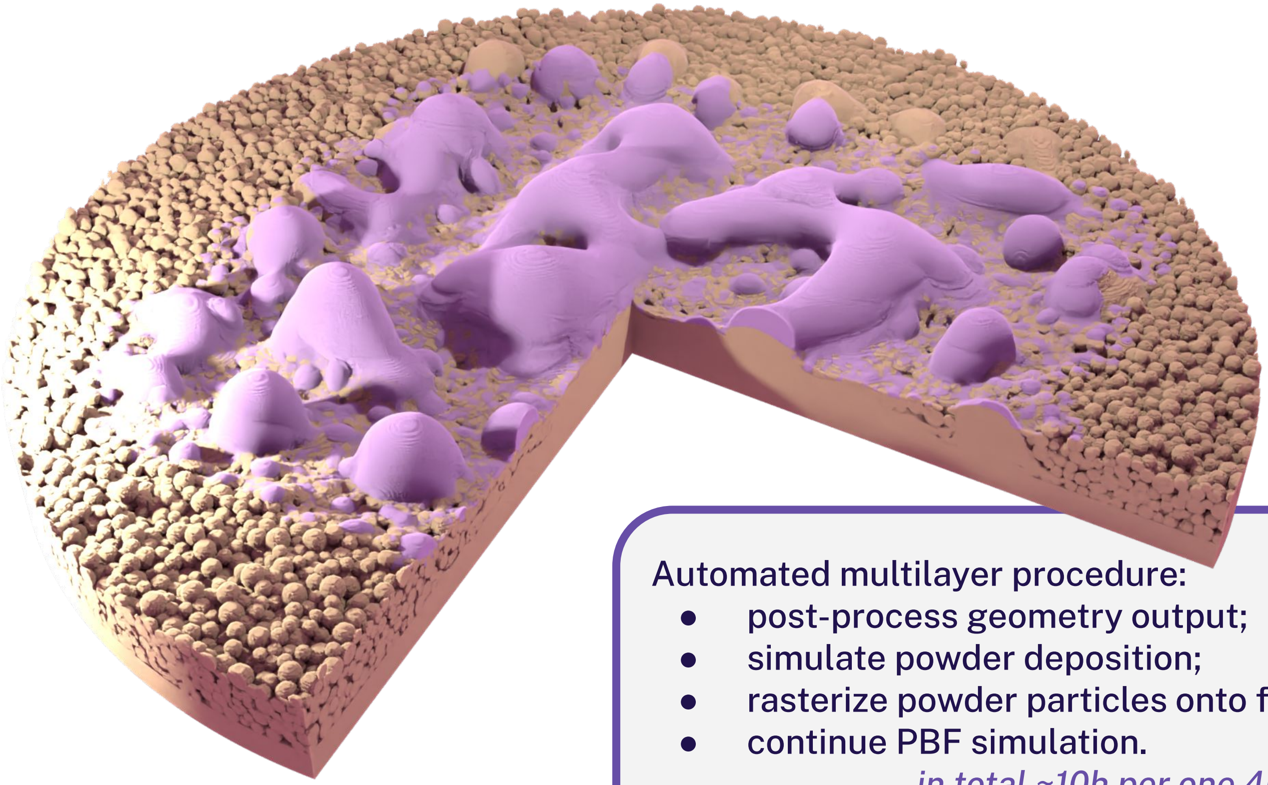

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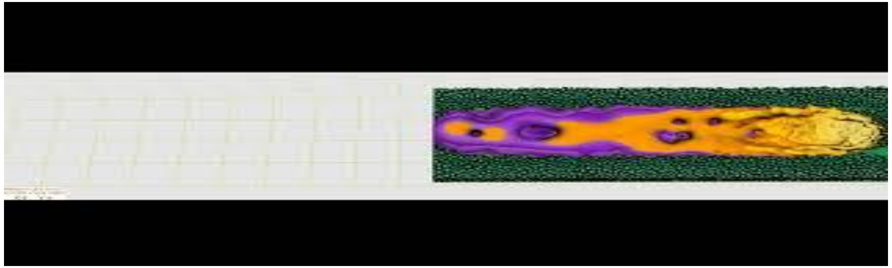
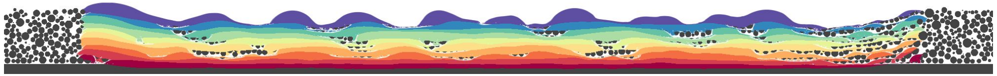
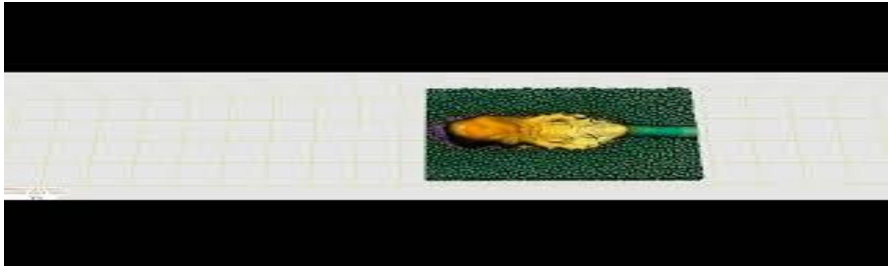
Thin wall

Left column: longitudinal cross-section of the wall. Right: video of the melt pool dynamics during the EB-PBF process for all the layers.

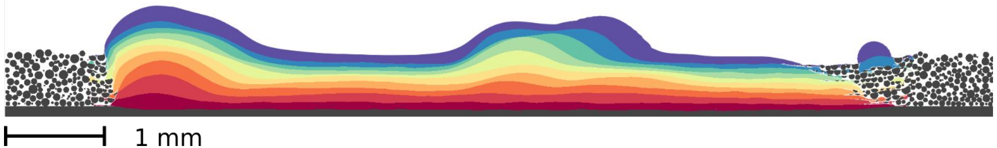


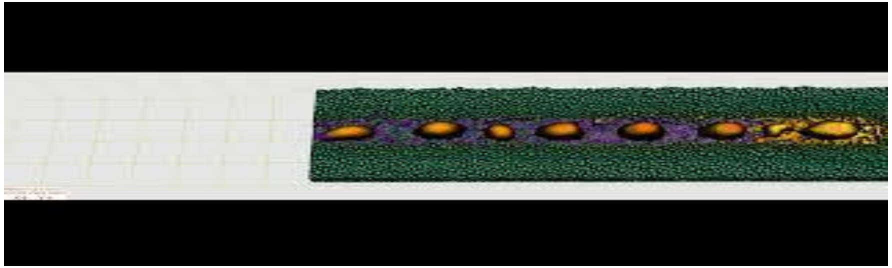
Powder too strong wetting (θ_{pow} = 10°) leads to the melt pool spill, wall widening and decreasing the melt depth causing.



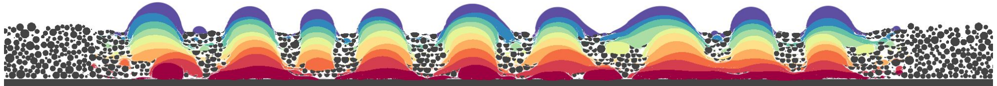


Changing the wetting (θ_{pow} = 90°) leads to more narrow and deeper melt pool and resulting wall low porosity but also hills formation. Same hills appear in the experimental data.





Example of the thin wall manufacturing failure due to the melt pool balling.



Conclusion

KiSSAM is GPU-based software for additive manufacturing simulations of melt-pool scale.
The code allows to:

- Identify scanning regime defects: balling, keyholing, etc.
- Inspect melted sample morphology: roughness, porosity.
- Virtually build overhangs, thin walls, fine structures.
- Get temperature history, portion of absorbed energy.

On a desktop workstation with at least one high-end GPU, it is possible to:

- Simulate in full 3D
- Resolve small powder particles, sintering and pores on a fine mesh
- Perform multi-layer simulations
- Get detailed process maps (hundreds of experiments) in a few days

For code usage please contact via e-mail:
info@kintechlab.com (Kintech Lab Ltd.)

www.kissam.cloud

Related papers

- Zakirov, A., Belousov, S., Bogdanova, M., Korneev, B., Stepanov, A., Perepelkina, A., ... & Potapkin, B. (2020). Predictive modeling of laser and electron beam powder bed fusion additive manufacturing of metals at the mesoscale. *Additive Manufacturing*, *35*, 101236
- Nakapkin, D. S., Zakirov, A. V., Belousov, S. A., Bogdanova, M. V., Korneev, B. A., Stepanov, A. E., ... & Meshkov, A. (2019). Finding optimal parameter ranges for laser powder bed fusion with predictive modeling at mesoscale. In *Sim-AM 2019: II International Conference on Simulation for Additive Manufacturing* (pp. 297-308). CIMNE.
- EBAM-2023 poster *KiSSAM 3D simulation of electron beam melting process with adaptive mesh refinement at mesoscale level*

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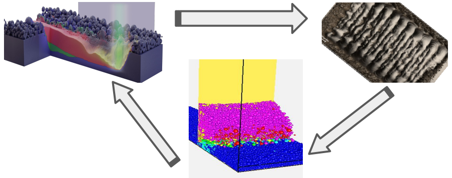
Morphology during multilayer melting

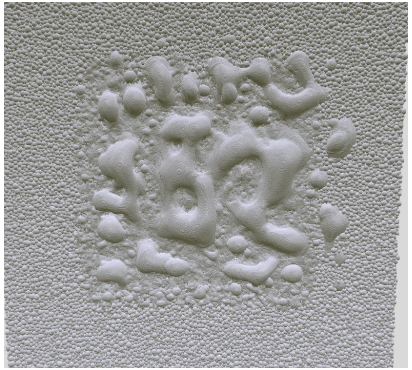


1st layer

2nd layer

3rd layer

4th layer



5th layer