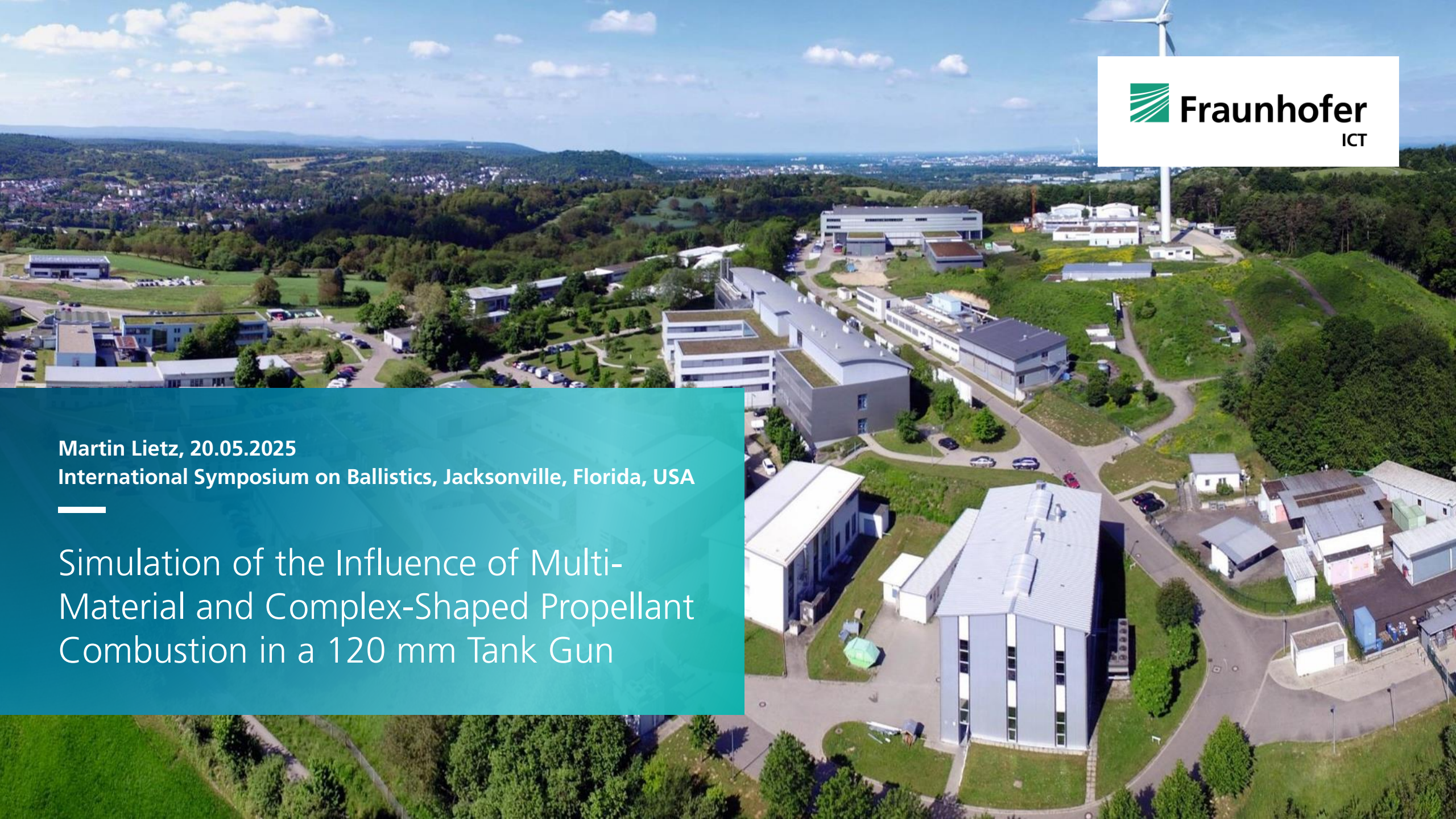


Fraunhofer ICT

Martin Lietz, 20.05.2025

International Symposium on Ballistics, Jacksonville, Florida, USA

Simulation of the Influence of Multi-Material and Complex-Shaped Propellant Combustion in a 120 mm Tank Gun

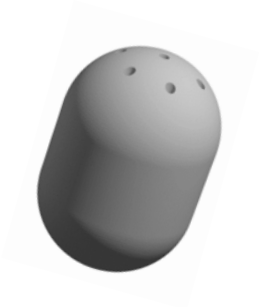
Motivation

Necessity for Increasing the Perform… Systems

Dutch Panzerhaubitze 2000 firing in Afghanistan (Source); Licenz: CC0 1.0

Motivation

Necessity for Increasing the Performance of Gun Systems



Longer barrel length

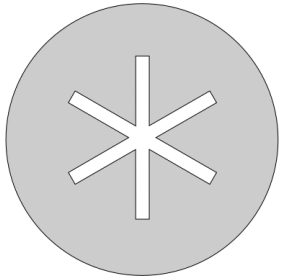
Higher permitted maximum pressure

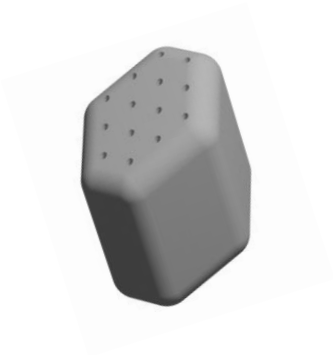
Efficiency

Energy

Propellant composition with higher force

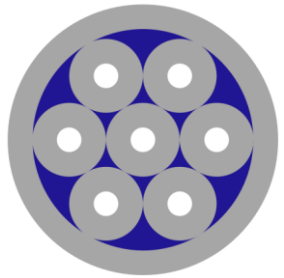
Larger combustion chamber





Progressive propellant design

Increase loading density



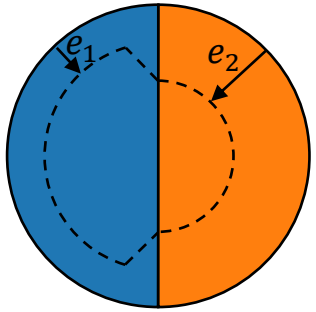
Co-extrusion and additive manufacturing processes offer new opportunities for multi-material and complex-shaped gun propellant grains

Methodology

Interior Ballistic Simulation Process

Define Gun Propellant Geometry → **Estimate Loading Density** → **Pressure Evolution Simulation**

Pressure Evolution Simulation →
- **Mean Pressure**
- **Breech Pressure**
- **Base Pressure**
- **Bullet Travel**
- **Bullet Velocity**
- **Gas Temperature**
- **…**



- Simulation is based on STANAG 4367
- The burn rate is a local property for multi-material propellant grains

$$\frac{dz}{dt} \neq \frac{S_0}{V_0} \cdot \varphi(e) \cdot r(p)$$

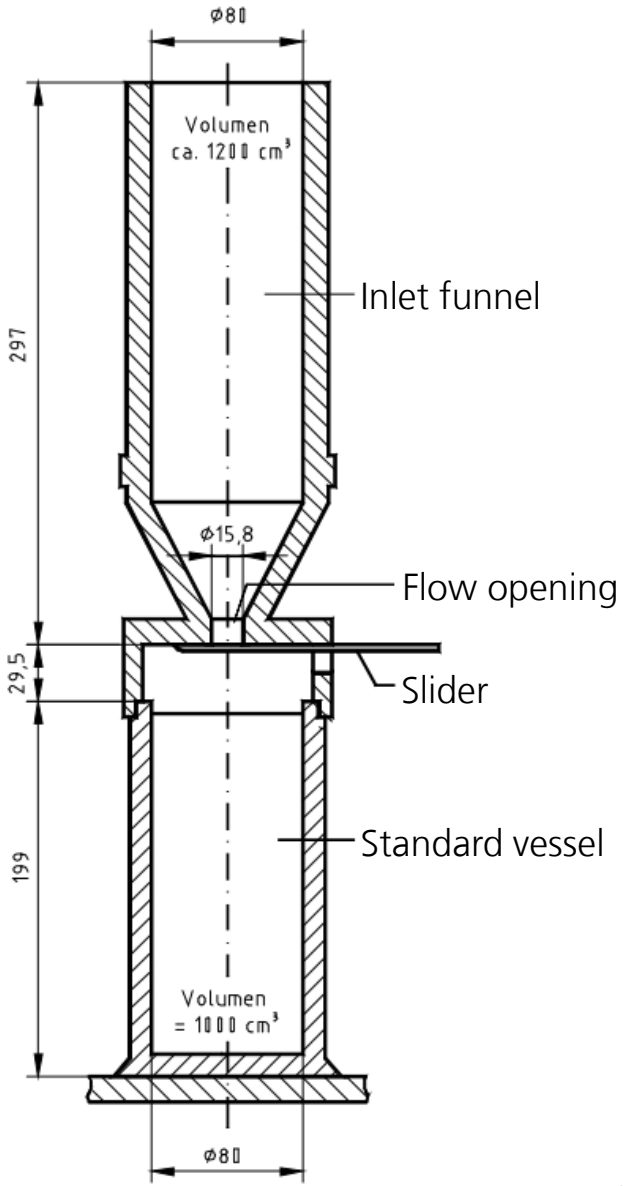
- Surface regression and pressure evolution have to be coupled in each time step

Methodology

Loading Density Determination

Experimental determination

- German regulation: TL 1376-0600 T500
- A standard vessel of 1L with a funnel is used
- Drawbacks
  - Not practical for large propellant grains
  - Each grain geometry has to be fabricated
  - The real weapon system, e.g., cartridge or projectile base isn't considered
  - Process parameters like shaking and vibration aren't specified



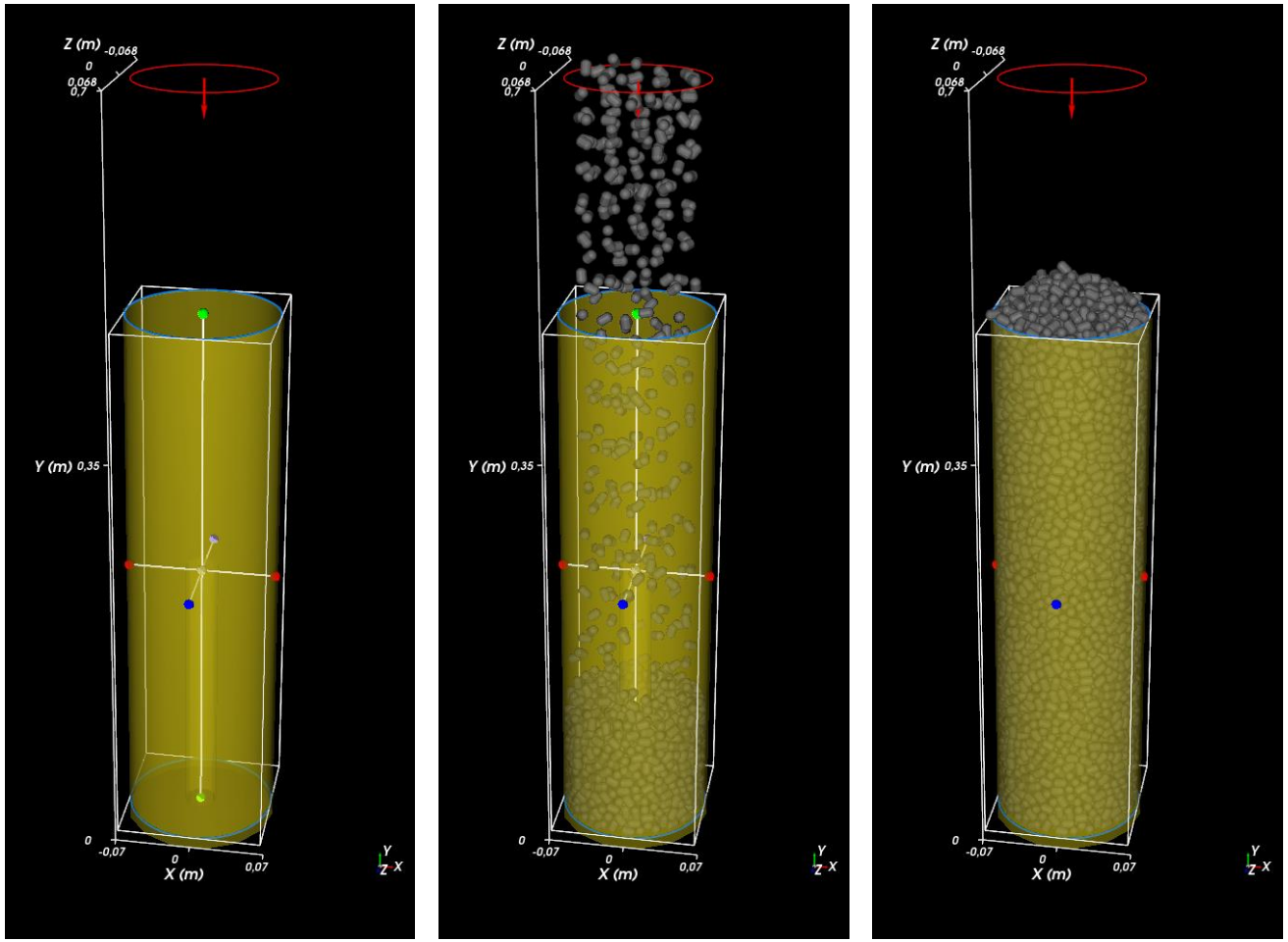
Dimensions are in millimeter

Methodology

Loading Density Determination

Simulation-based determination

- Cartridge and grain geometry could be designed without limitation using CAD software
- Simulation is based on discrete element method (DEM)
  - Friction could be considered
  - Process parameter like shaking and vibration could be considered
- Propellant grains fall from the inlet in a random orientation
- Only grains inside the control volume are counted
- The loading density is calculated by the mean value of several simulation trials



Methodology

Surface Regression of Multi-Material Propellant Grains

What are our requirements for the method?

- Local definition of the burn rate
- Complex geometries and material structures
- Slivering should be treated naturally
- Stabile numerical schemes

The level set method (LSM)

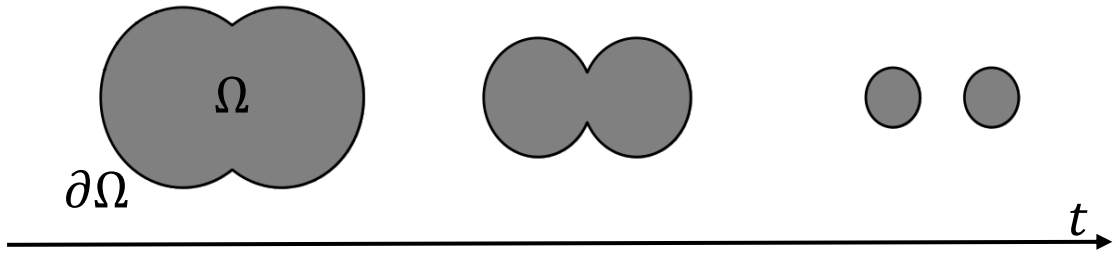
- The boundary $\partial\Omega$ of geometry Ω is given by the zero-level set of the implicit function $\phi(\boldsymbol{x}, t)$:

$$\partial\Omega = \{\boldsymbol{x} \mid \phi(\boldsymbol{x}, t) = 0\} \qquad \forall\, t \geq 0$$

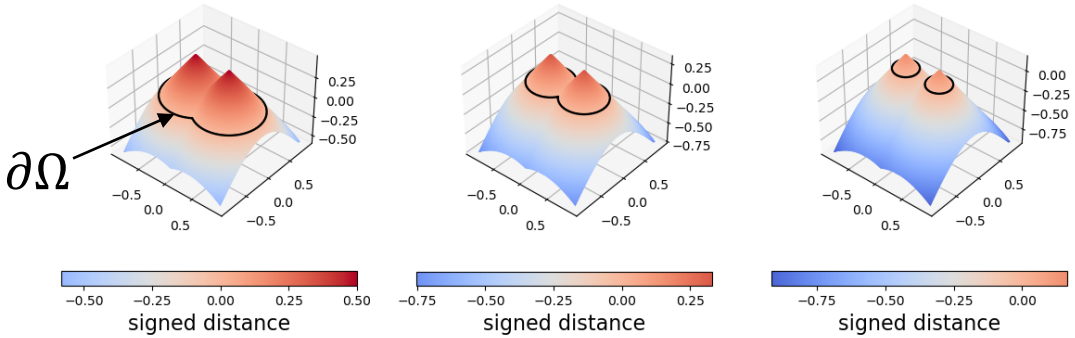
- The signed distance function (SDF) is a common choice for $\phi(\boldsymbol{x}, t)$
- Temporal evolution could be computed by the equation of motion of Gomes and Faugeras

$$\partial_t \phi(\boldsymbol{x}, t) = v(\boldsymbol{x}, p(t)) \cdot \left(\boldsymbol{x} - \phi(\boldsymbol{x}, t) \cdot \nabla\phi(\boldsymbol{x}, t)\right)$$

2D Geometry



Signed Distance Function



Methodology

Pressure Evolution according to STANAG 4367

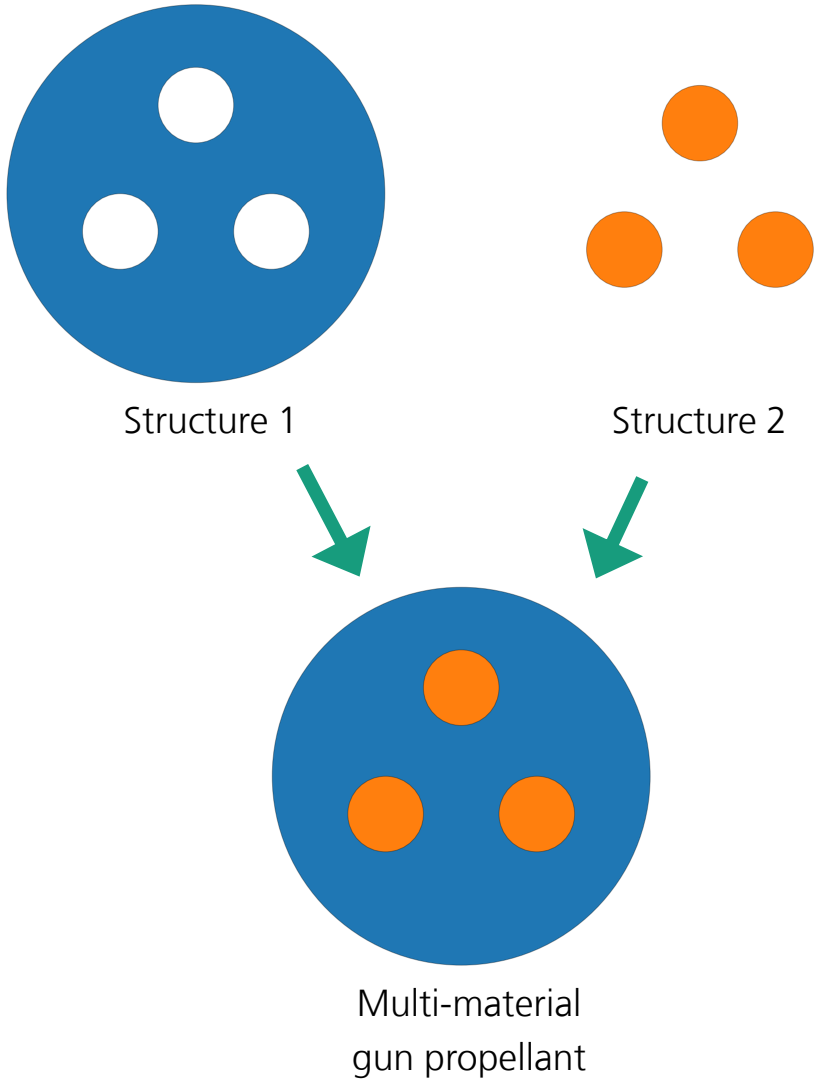
- Each equation containing the mass fraction and/or thermodynamic parameters has to be modified:

$$\frac{z(t) \cdot m \cdot F}{T_{\mathrm{ex}}} \quad \Rightarrow \quad \sum_{\sigma \in S} \frac{z_\sigma(t) \cdot m_\sigma \cdot F_\sigma}{T_{\mathrm{ex},\sigma}}$$

- The sum runs over all structures of the propellant grain (blue and orange)
- Each structure is represented by its own static SDF
- The burned fraction of structure σ is given by:

$$z_\sigma(t) = 1 - \frac{V_\sigma(t)}{V_\sigma(0)}$$

- The volume $V_\sigma(t)$ is estimated via Monte-Carlo Integration
- The thermo-chemistry is computed using the ICT Thermodynamic Code



Simulation

Complex-Shaped Gun Propellant in 120 mm Tank Gun

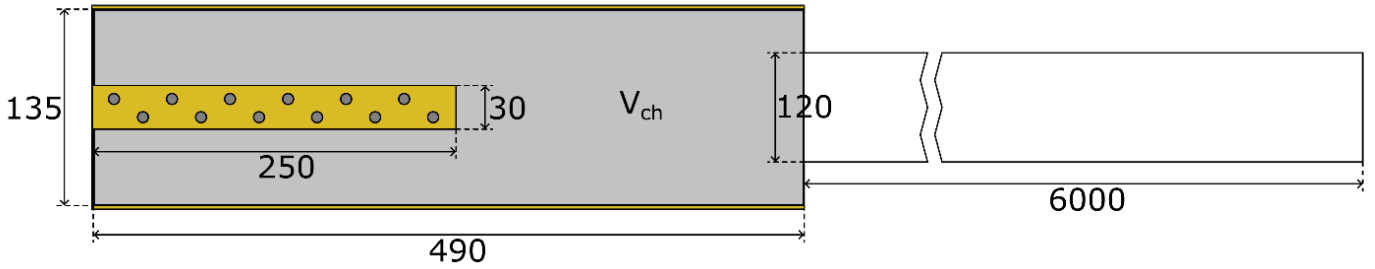
Input simulation parameters

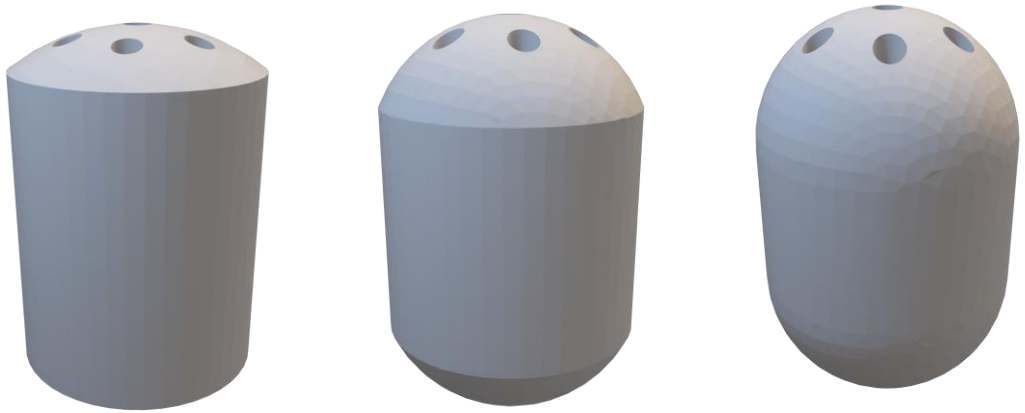
Generic 120mm tank gun

- Cylindrical combustion chamber ($Ø = 135\ \mathrm{mm}$, $L = 490\ \mathrm{mm}$)
- Cylindrical igniter tube ($Ø = 30\ \mathrm{mm}$, $L = 250\ \mathrm{mm}$)
- Effective chamber volume $V_{\mathrm{ch}} = 6837\ \mathrm{cm}^3$
- Smoothed barrel of caliber $120\ \mathrm{mm}$
- Barrel length: $6\ \mathrm{m}$
- Bullet mass: $11.5\ \mathrm{kg}$
- Constant friction pressure: $10\ \mathrm{MPa}$
- Recoil mass: $13\ \mathrm{kg}$

Gun propellant geometry

- 7PF-Cylinder and 7PF-Sphero-Cylinder
- Constant grain diameter ($9\ \mathrm{mm}$), grain length ($14\ \mathrm{mm}$), and perforation diameter ($1\ \mathrm{mm}$)
- Variation of spherical cap height ($1.5\ \mathrm{mm}$, $3.0\ \mathrm{mm}$, $4.5\ \mathrm{mm}$)



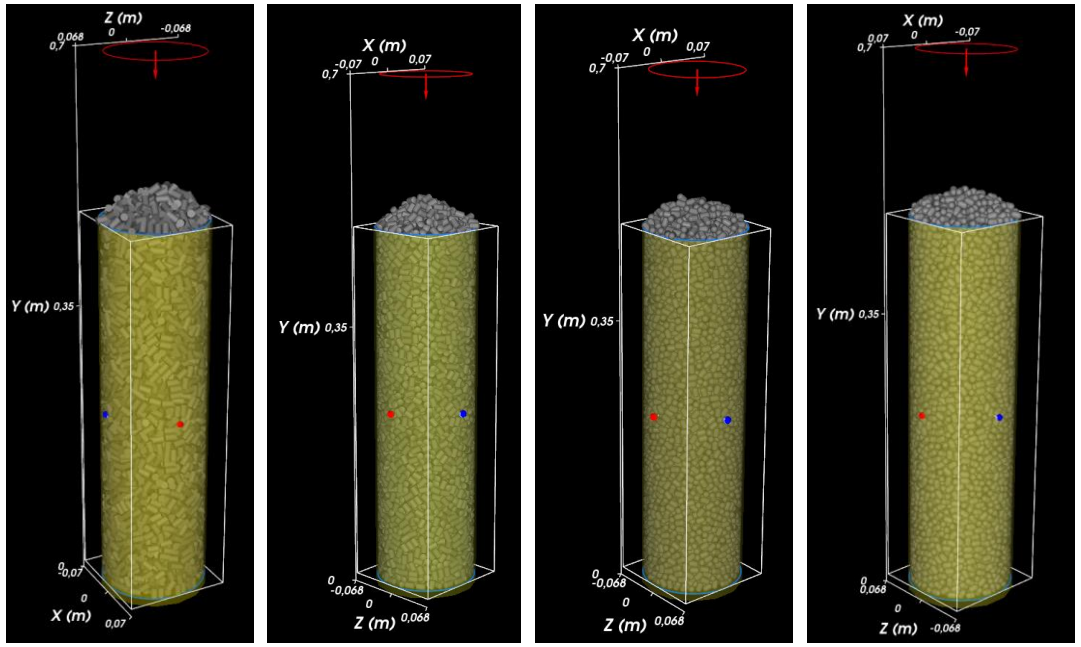


Simulation

Complex-Shaped Gun Propellant in 120 mm Tank Gun

Loading density simulation

- The simulation is performed using grains without perforations, due to performance (convex geometry)
  - Perforations are subtracted later!
- 10 simulation trials per geometry
- Propellant density: $1.56\ \mathrm{g/cm^3}$



Spherical Cap Height	Number of Grains	Grain Volume	Loading Density	Propellant Mass
0.0 mm	4650 ± 5	$813.67\ \mathrm{mm^3}$	$86.33 \pm 0.09\ \%$	$5903 \pm 6\ \mathrm{g}$
1.5 mm	5540 ± 6	$722.38\ \mathrm{mm^3}$	$91.32 \pm 0.09\ \%$	$6243 \pm 7\ \mathrm{g}$
3.0 mm	6163 ± 5	$657.68\ \mathrm{mm^3}$	$92.49 \pm 0.08\ \%$	$6323 \pm 5\ \mathrm{g}$
4.5 mm	6430 ± 3	$630.02\ \mathrm{mm^3}$	$92.43 \pm 0.05\ \%$	$6319 \pm 3\ \mathrm{g}$

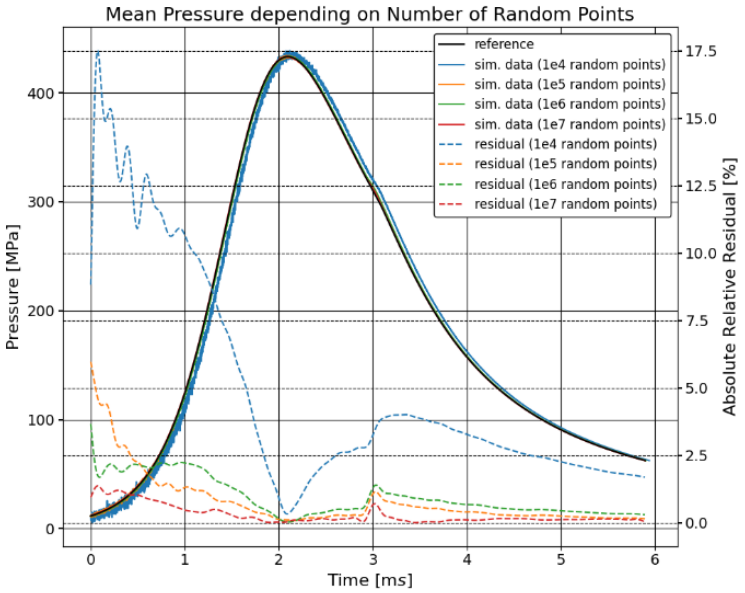
Simulation

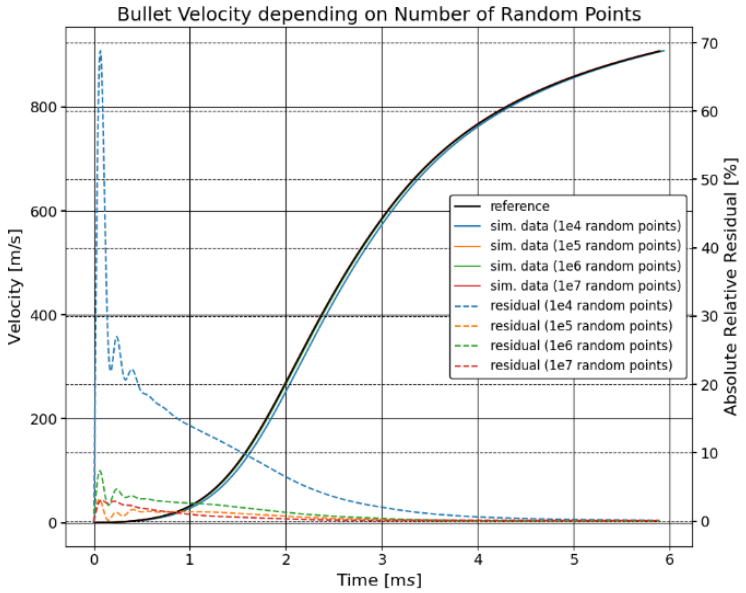
Complex-Shaped Gun Propellant in 120 mm Tank Gun

Dependency on Monte Carlo Integration

- Geometry: 7PF-Cylinder
- Radial grid resolution: $79\ \mu m$
- Axial grid resolution: $118\ \mu m$
- Variation of the number of random points from 10^4 to 10^7
- Burn parameters: $\alpha = 0.95, \beta = 0.15\ mm/s$

➔ The absolute relative deviation is less than 2.5 % (mean pressure) or less than 5 % (bullet velocity) for 10^6 and more random points.



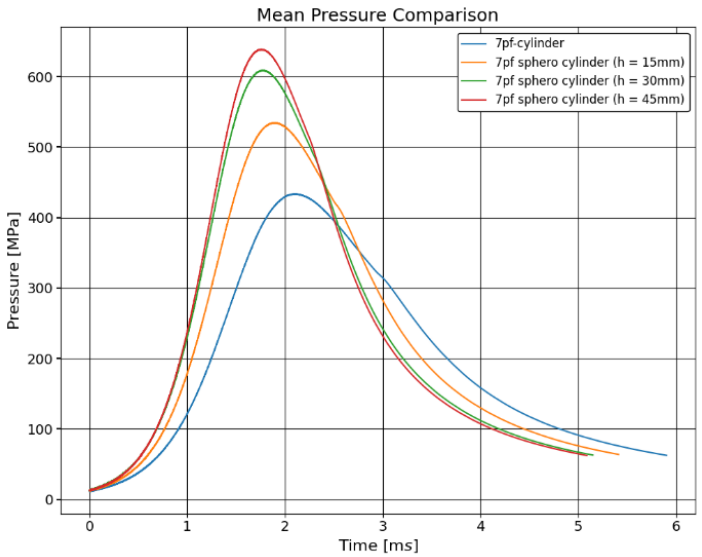


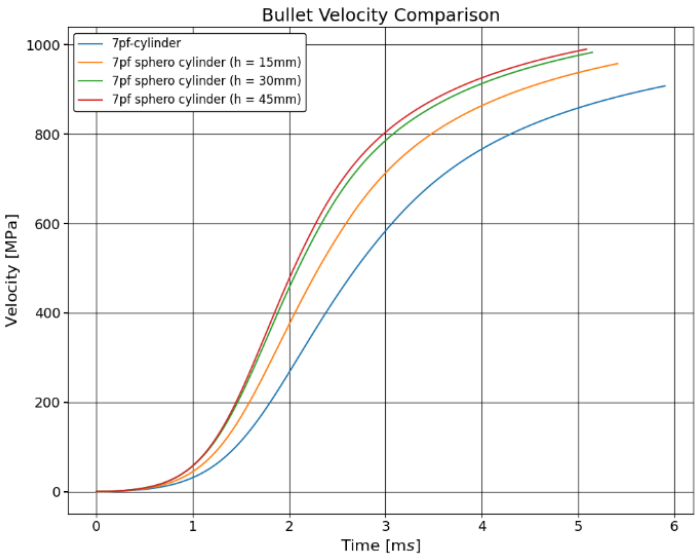
Simulation

Complex-Shaped Gun Propellant in 120 mm Tank Gun

Simulation setup info

- Radial grid resolution: $79\ \mu m$
- Axial grid resolution: $118\ \mu m$
- MCI: 10^6 random points
- Burn parameters: $\alpha = 0.95, \beta = 0.15\ mm/s$





Simulation result info

Spherical cap height	Max. pressure	Time to max. pressure	Muzzle velocity
0.0 mm	434 MPa	2.09 ms	908 m/s
1.5 mm	535 MPa	1.90 ms	958 m/s
3.0 mm	609 MPa	1.79 ms	983 m/s
4.5 mm	639 MPa	1.76 ms	990 m/s

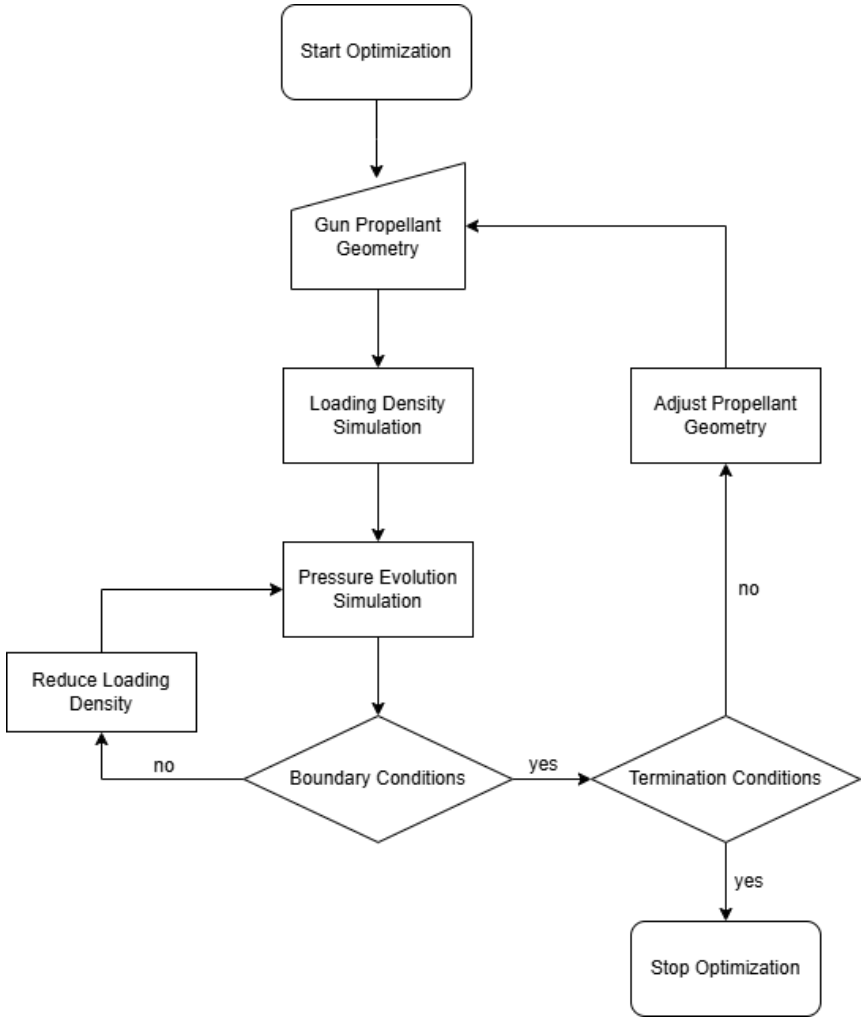
Conclusion and Further Work

Conclusion

- Co-extrusion or additive manufacturing processes offer new opportunities for the gun propellant design to increase performance
- The real loading density and combustion have to be simulated to investigate the full potential of new grain designs
- The surface regression and pressure evolution have to be coupled in each time step for multi-material gun propellants
- New geometries have the potential to optimize the gun system

Further work

- Investigate the influence of multi-material and complex-shaped gun propellants, e.g., with perforations filled with a faster burning propellant composition



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