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Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut, EMI

Modelling and simulation of the pellet shattering process related to the SPI technology for the ITER DMS,

P. Matura, S. Signetti, S. Moser, L. Sandoval, N. Durr, E. Watson, D. Mert, M. Büttner

Acknowledgement

Funding

The ITER Organization (IO CONTRACT NUMBER – IO/21/CT/430000237)

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ASDEX Upgrade

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Outline

1 Motivation & Overview

2 Modelling Approach

3 How to compare with experiments?

4 First Results of Shattering Simulation

5 Conclusion

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Motivation

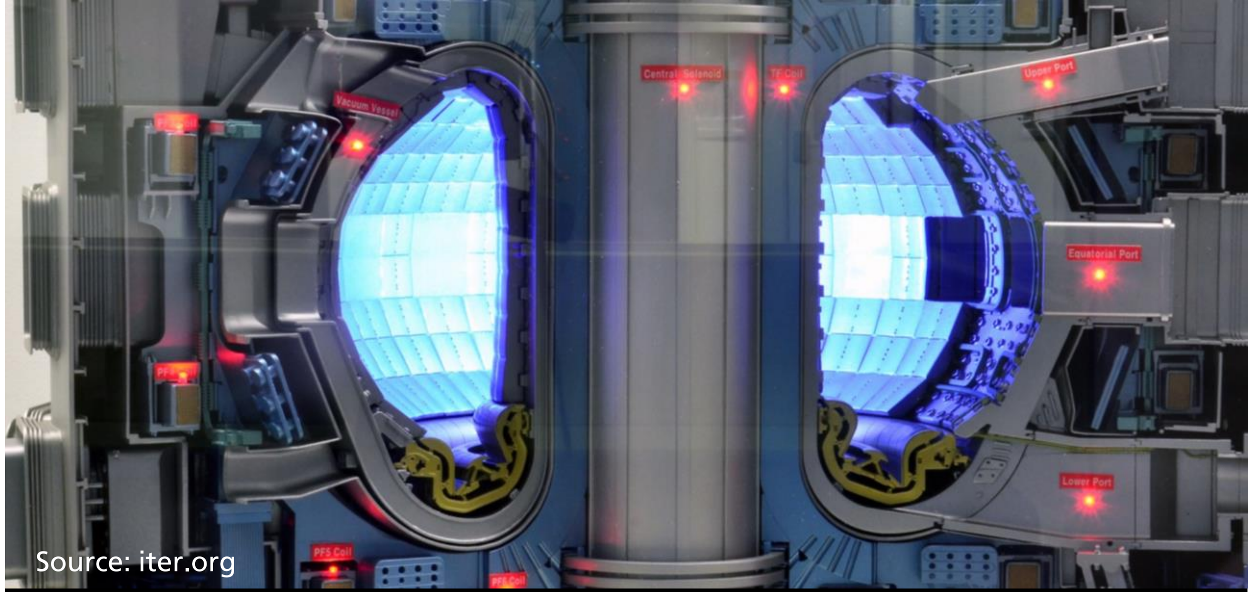
Plasma Instabilities – DMS

- Plasma instabilites can cause sudden loss of energy and induce large forces into machine structures

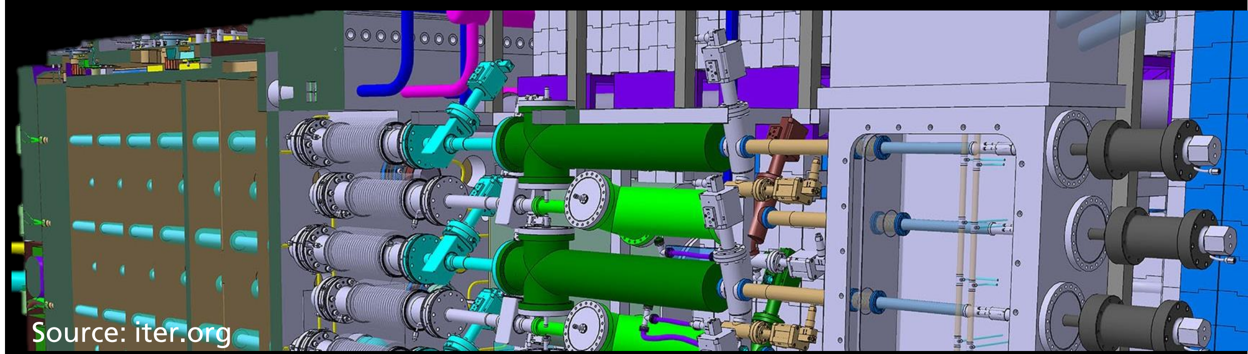
- Protection of machine components is critical

- ITER Disruption Mitigation System (DMS) is based on Shattered Pellet Injection (SPI): Pellets are…

  - … accelerated via gas pressure pulse in a pipe gun barrel
  - … guided in the insection line and finally
  - … intentionally **shattered** before entering the plasma



Source: iter.org



Source: iter.org

Credit: Trey Gebhart / Oak Ridge National Laboratory, U.S. Dept. of Energy

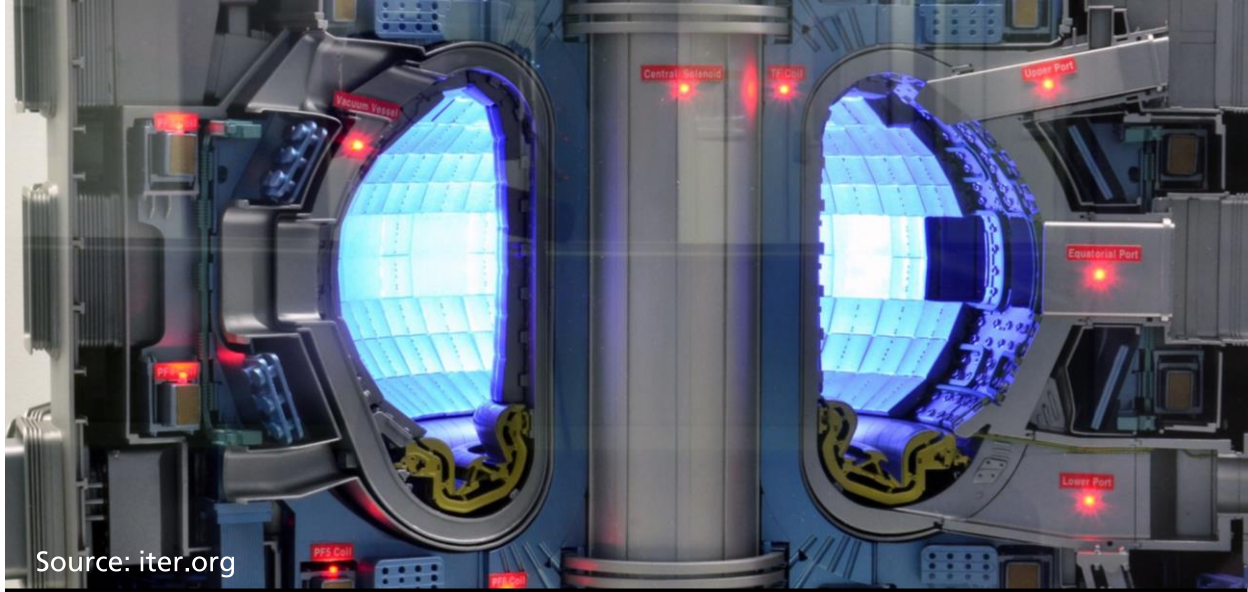
Motivation

Plasma Instabilities – DMS

- Plasma instabilites can cause sudden loss of energy and induce large forces into machine structures
- Protection of machine components is critical
- ITER Disruption Mitigation System (DMS) is based on Shattered Pellet Injection (SPI): Pellets are…
  - … accelerated via gas pressure pulse in a pipe gun barrel
  - … guided in the insertion line and finally
  - … intentionally shattered before entering the plasma

» Physics and engineering **R&D** is required to draw conclusions on the **optimum gas/shard composition** and to **optimise the shattering process towards this optimum**«

ITER Disruption Mitigation Workshop,
ITER HQ, 8 –10 March 2017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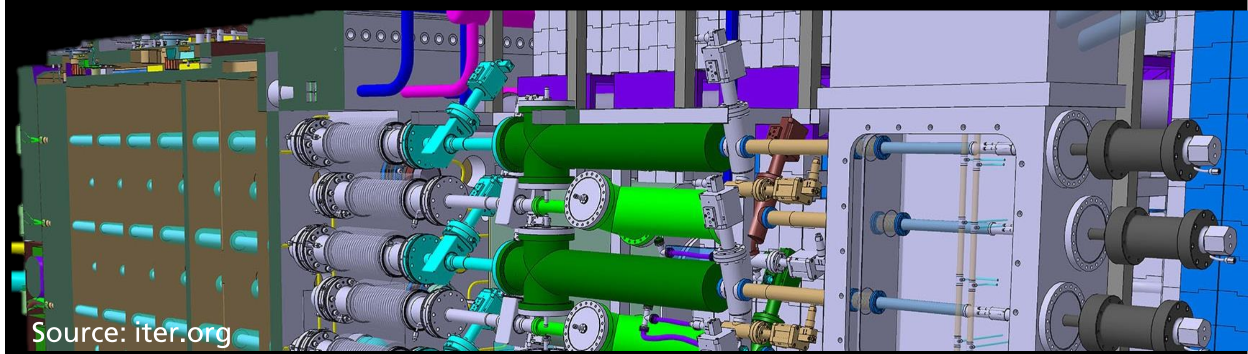

Source: iter.org


Impact of a cryogenic pellet

Credit: Trey Gebhart / Oak Ridge National Laboratory, U.S. Dept. of Energy

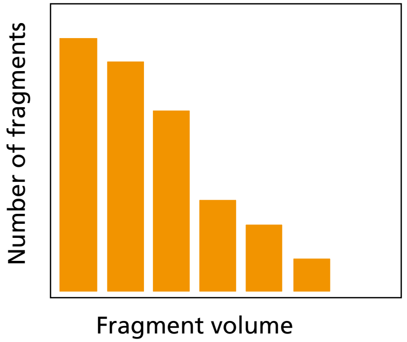
Motivation

Fragmentation Process: Characteristics & Dependencies

Deuterium pellet, ∅ 8 mm, 12.5° (ASDEX Upgrade)

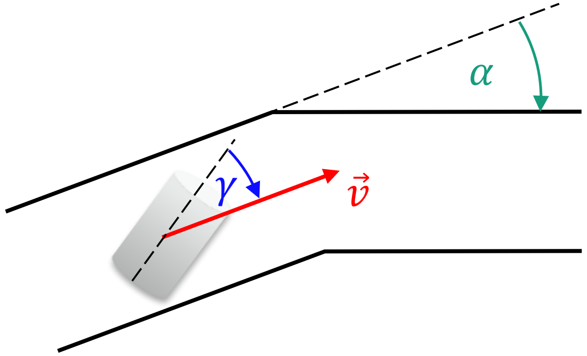
Fragmentation characteristics…

- Size distribution (i.e., volume, mass or equivalent diameter)
- Velocity distribution (i.e., fragment cloud spreading)
- Shapes (i.e., surface-to-volume ratio, aspect ratio, …)



…are depending on

- Impact parameters
  - Velocity
  - Pellet orientation (tilting)
  - Shatter angle
  - Shatter tube geometry (i.e., cross-section)
  - …
- Pellet properties
  - Geometry (size, shape)
  - Material
  - Homogeneity (crystallographic structure, defects, thermodynamic properties, …)
  - …

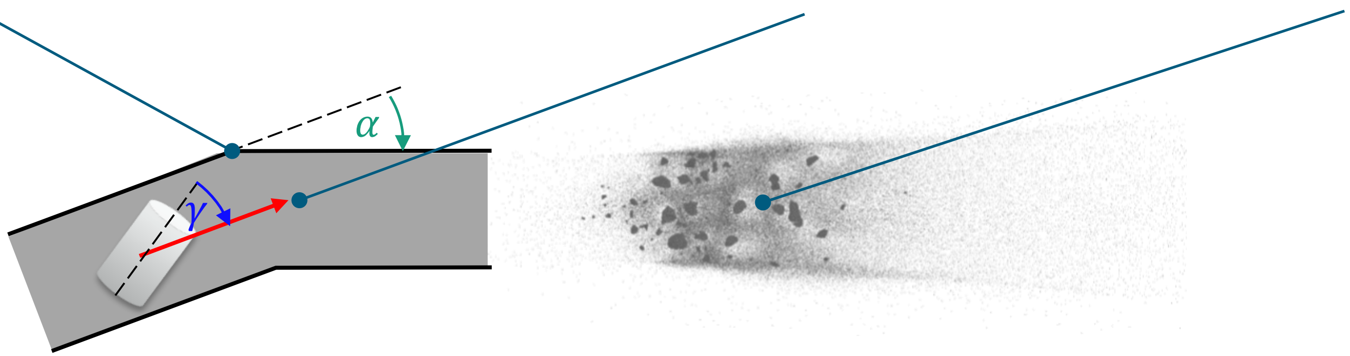


Overview of the Research Project

Pellet Shattering Simulations to Support the ITER DMS Design

IO CONTRACT NUMBER – IO/21/CT/4300002337

- **Goal:** Optimize the shatter unit design and derive guidelines for optimized impact conditions to get the desired fragment characteristics



- **Fraunhofer EMI** is developing numerical models to simulate and analyze the fragmentation process
  - **Task 1: Development stage**
    - Model development, calibration & validation (based on ORNL & ASDEX Upgrade Lab. experiments; later: DMS Support Lab. experiments)
  - **Task 2: Application stage**
    - Simulation studies to optimize the impact process / shatter unit design for ITER DMS pellets

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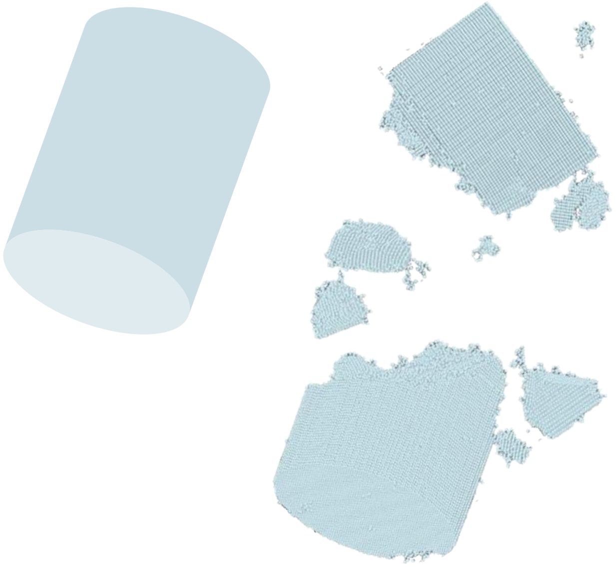
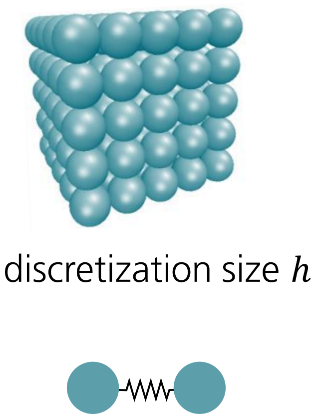
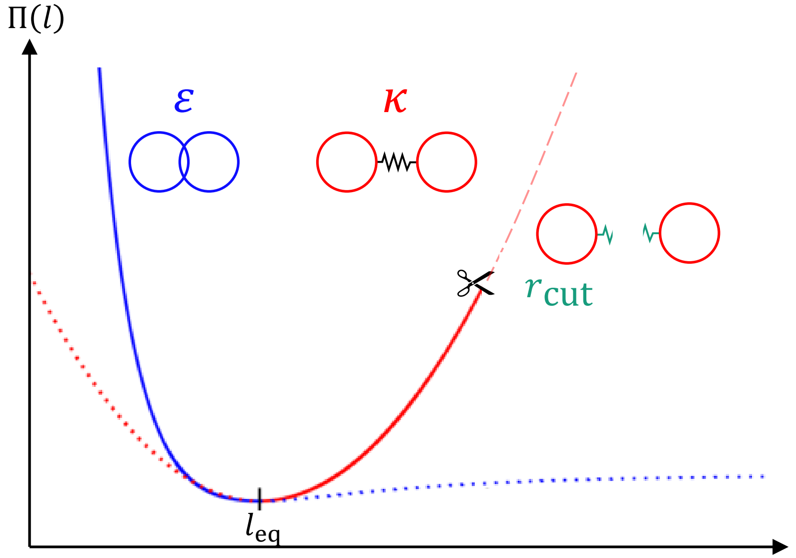
Modelling Approach

Discrete Element Method & Peridynamics

- **Pellets:** Solids made of either neon, hydrogen or deuterium; cylindrical shape
- **Mechanical model:** Isotropic, elastic, brittle material behavoir
  → bulk modulus K, Poisson's ratio ν, fracture strength σ_f
- **Computational model** (EMI's **MD-Cube** software)**:**
  - **Pellet** is represented and **discretized by spheres** linked by bond elements
  - **Constitutive material model** by defining interaction **potentials** for compression and tension with **three parameters** ε, κ, r_{cut}
  - $$\Pi(l) = \begin{cases} \Pi_{\mathrm{LJ}}(l) = 4\varepsilon\left[\left(\frac{\sigma}{l}\right)^{12} - \left(\frac{\sigma}{l}\right)^{6} + \frac{1}{4}\right] & \forall \quad l < l_{\mathrm{eq}} \\ \Pi_{\mathrm{PAR}}(l) = \frac{1}{2}\kappa\left(l - l_{\mathrm{eq}}\right)^2 & \forall \quad l \geq l_{\mathrm{eq}} \end{cases}$$
    LJ = Lennard-Jones
    PAR = Parabolic
  - **Bond failure** initiated by reaching cut-off length r_{cut} in tension
  - **Forces** are calculated by the gradient of the potential $-\nabla\Pi(l) = \boldsymbol{F}_i = m_i \ddot{\boldsymbol{r}}_i$







M.O. Steinhauser, E. Watson. Discrete Particle Methods for Simulating Quasi-Static Loads and Hypervelocity Impact Phenomena. *Int. J Comput. Methods.* 2019.

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Modelling Approach

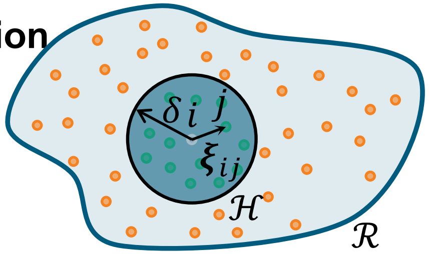
Relation of Constitutive Model Parameters to Classical Theory of Elasticity

Three constitutive model parameter… **…are related to material's bulk modulus K and fracture strength σ_f**

- Spring potential (tension): $\kappa \rightarrow$ $\kappa \sim Kh^5/\delta^4$
- L-J potential (compression): $\varepsilon \rightarrow$ $\varepsilon \sim Kh^6/\delta^4$
- Bond failure (cut-off length): $r_{cut} \rightarrow$ $r_{cut} = r_{cut}(\sigma_f, K, h, \delta)$ h: discretization size

Peridynamics equation of motion

$$\rho \ddot{\mathbf{u}} = \int_{\mathcal{H}} f(x, x')\, dV \approx \sum_j f_j V_j$$



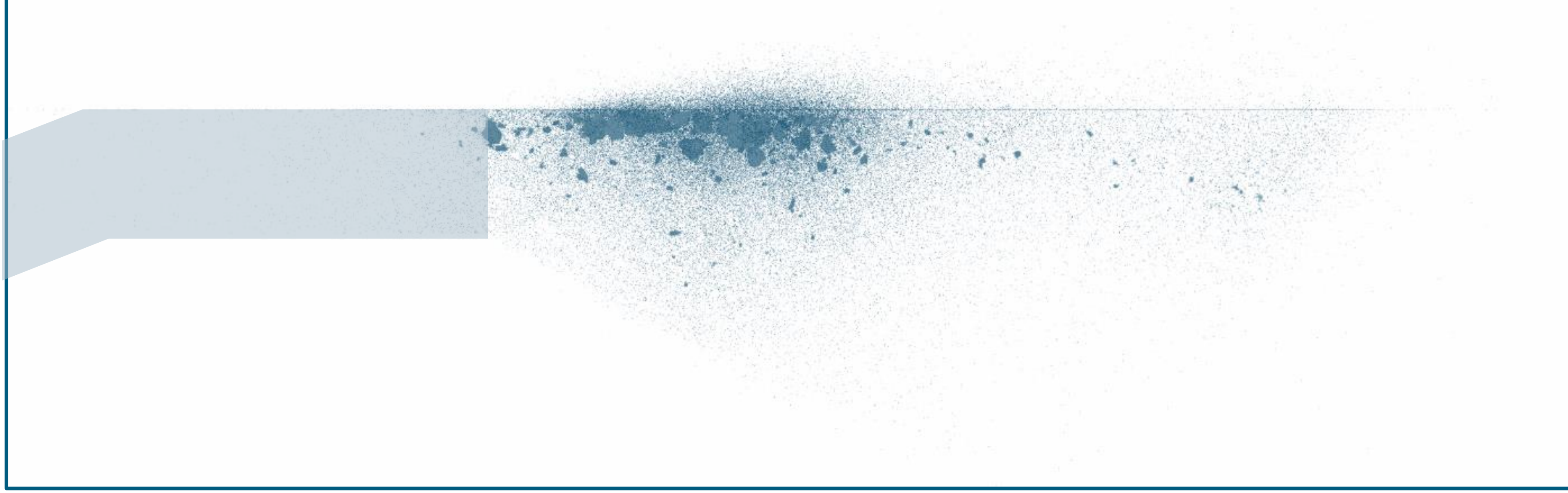
S.A. Silling, E. Askari. A meshfree method based on the peridyinamics model of solid mechanics. *Comput Methods.* 2005.

Constitutive Model Parameter $(\varepsilon, \kappa, r_{cut}) \leftrightarrow (K, \sigma_f)$ Material Parameter

Modelling Approach
Example Simulation

Simulation

Neon pellet, ∅ 8 mm, L 8.56 mm, 156 m/s, 25° (Reference test #718 / ASDEX Upgrade)



Material parameter used: K = 9.8 MPa, σ_f = 6.45 MPa

Discretization h = 0.096 mm → ~ 500.000 particles

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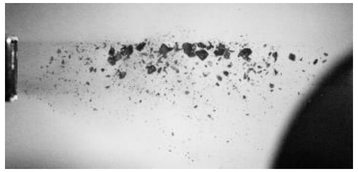
How to compare Simulation with Experiment?

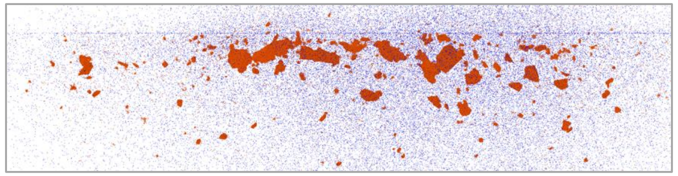
Experiment

- Setup known (shatter head design / shatter angle)
- Pellet properties
  - Shape / size
- Impact conditions
  - Velocity
  - Pellet orientation (certain degree of uncertainty)
  - Impact location (certain degree of uncertainty)
- Data source for fragmentation characteristics
  - High-speed video recordings (→ set of 2D images)


Simulation

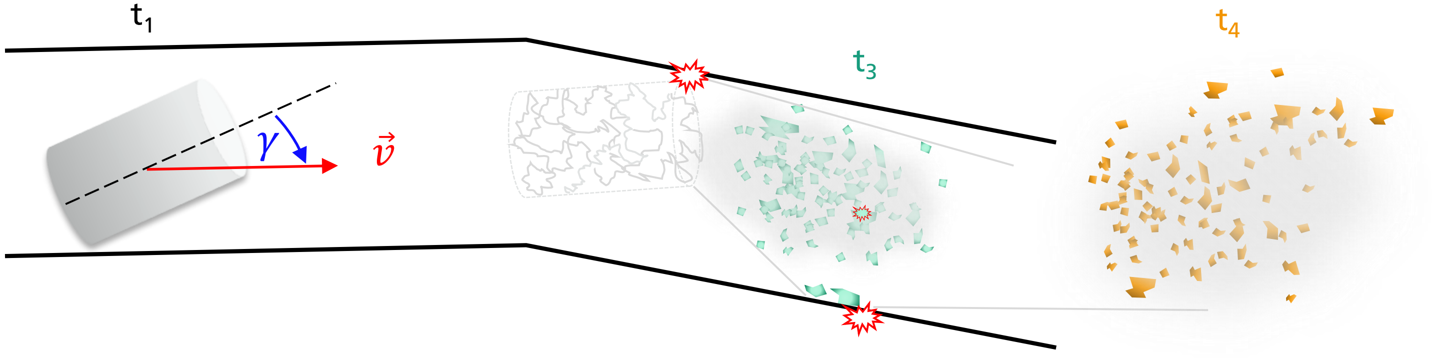
- Setup as in the experiment
- Pellet properties
  - Shape / size (idealized); constitutive material behavior must be defined
- Impact conditions
  - Velocity as in the experiment
  - Pellet orientation must be defined
  - Impact location must be defined
- Data source for fragmentation characteristics
  - **Full 3D data** for all timesteps available
  - **2D images** from all perspectives for all timesteps

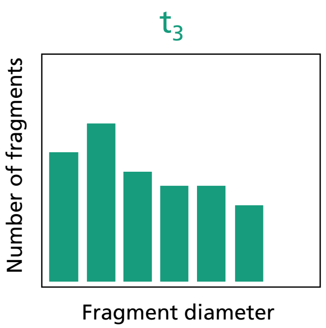


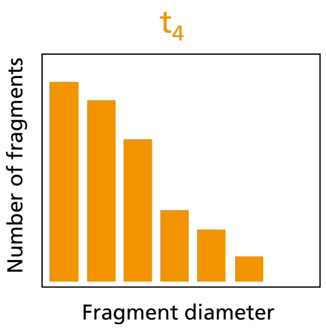
How to compare Simulation with Experiment?

Information Gap between Experiment and Simulation

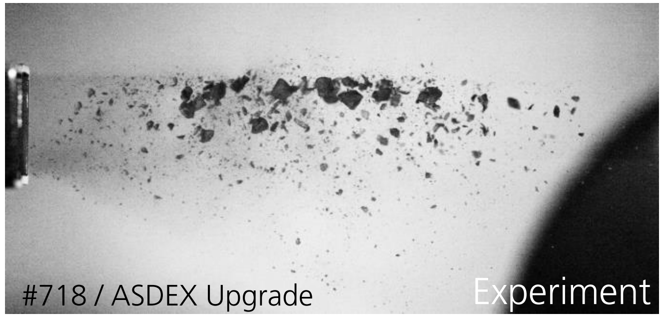
- Simulation: **Full information** on the time-resolved fragmentation process available

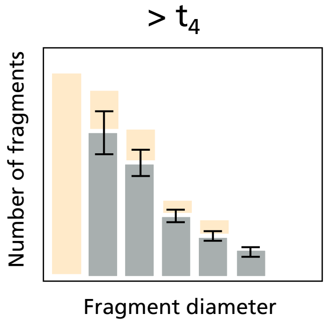






- Experiment: Only **incomplete information** available





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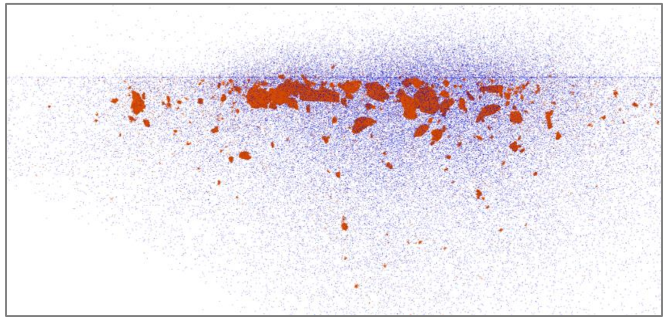
How to compare Simulation with Experiment?

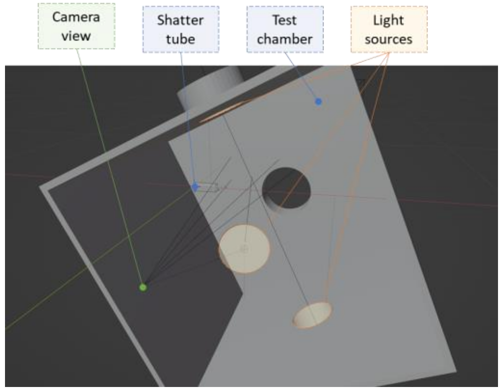
Synthetic Diagnostic

- Synthetic diagnostic to…
  - …better compare simulation with experiment

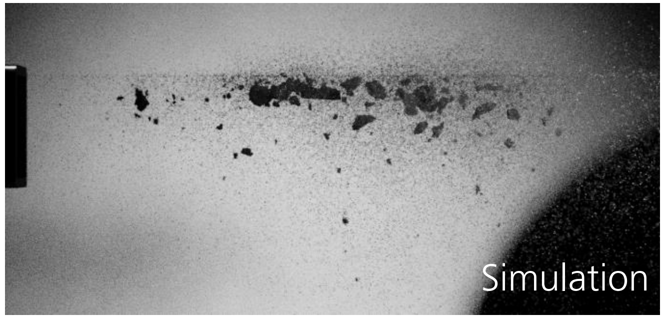
Simulation



Raw simulation data

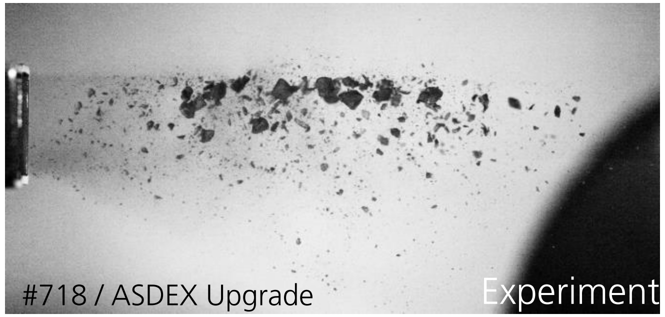


Integrate data into virtual test environment



Raytracing etc. Comparison

Experiment



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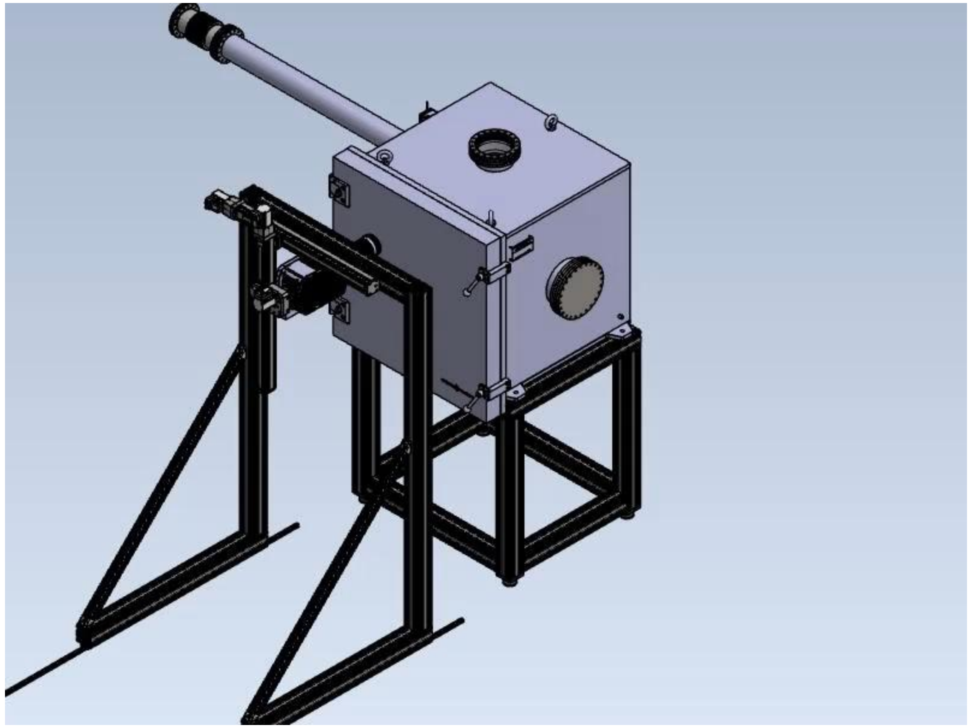
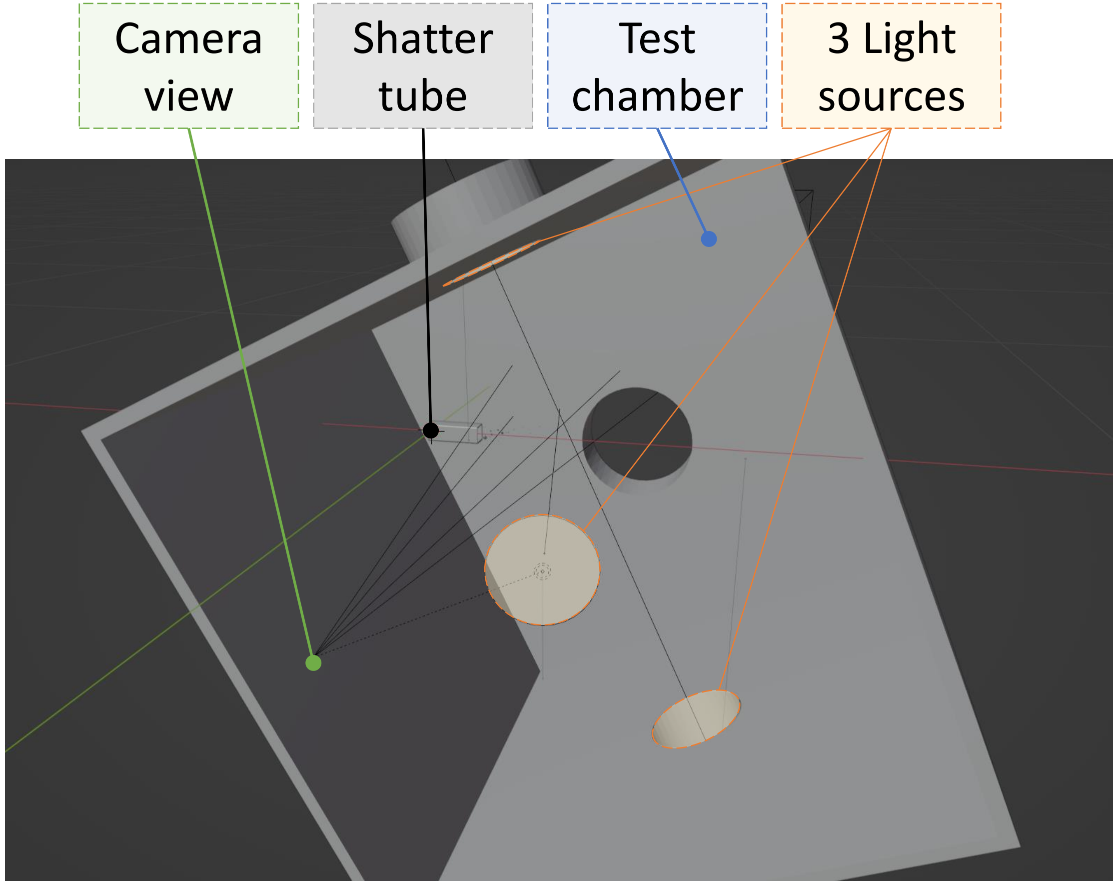
Synthetic Diagnostics

Setup of virtual test environment

CAD data from ASDEX Upgrade pellet shattering test setup



Test setup as blender model



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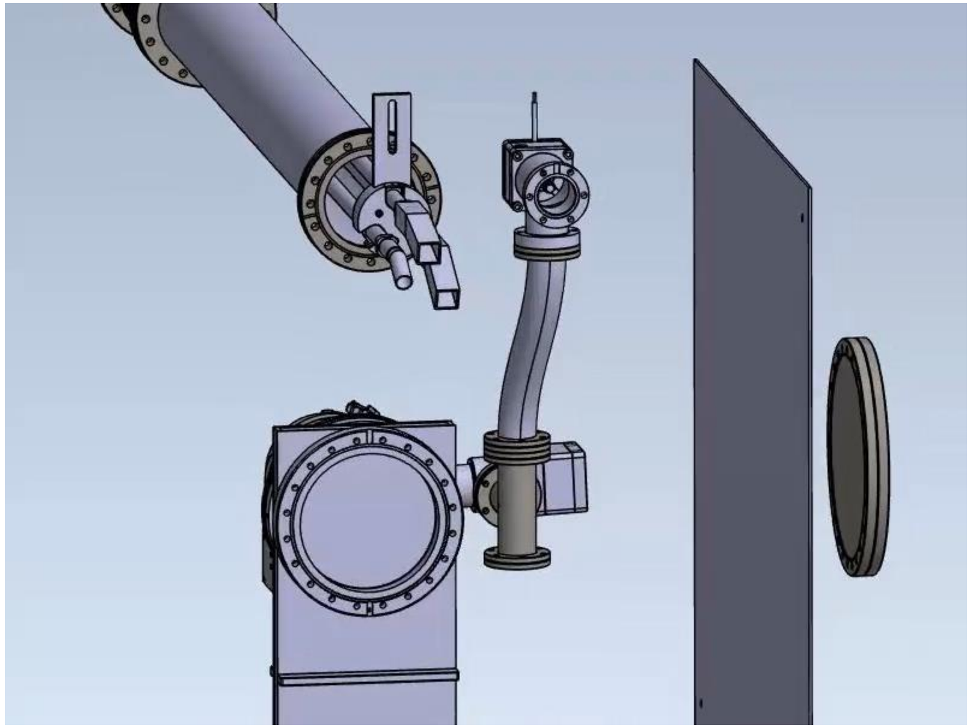
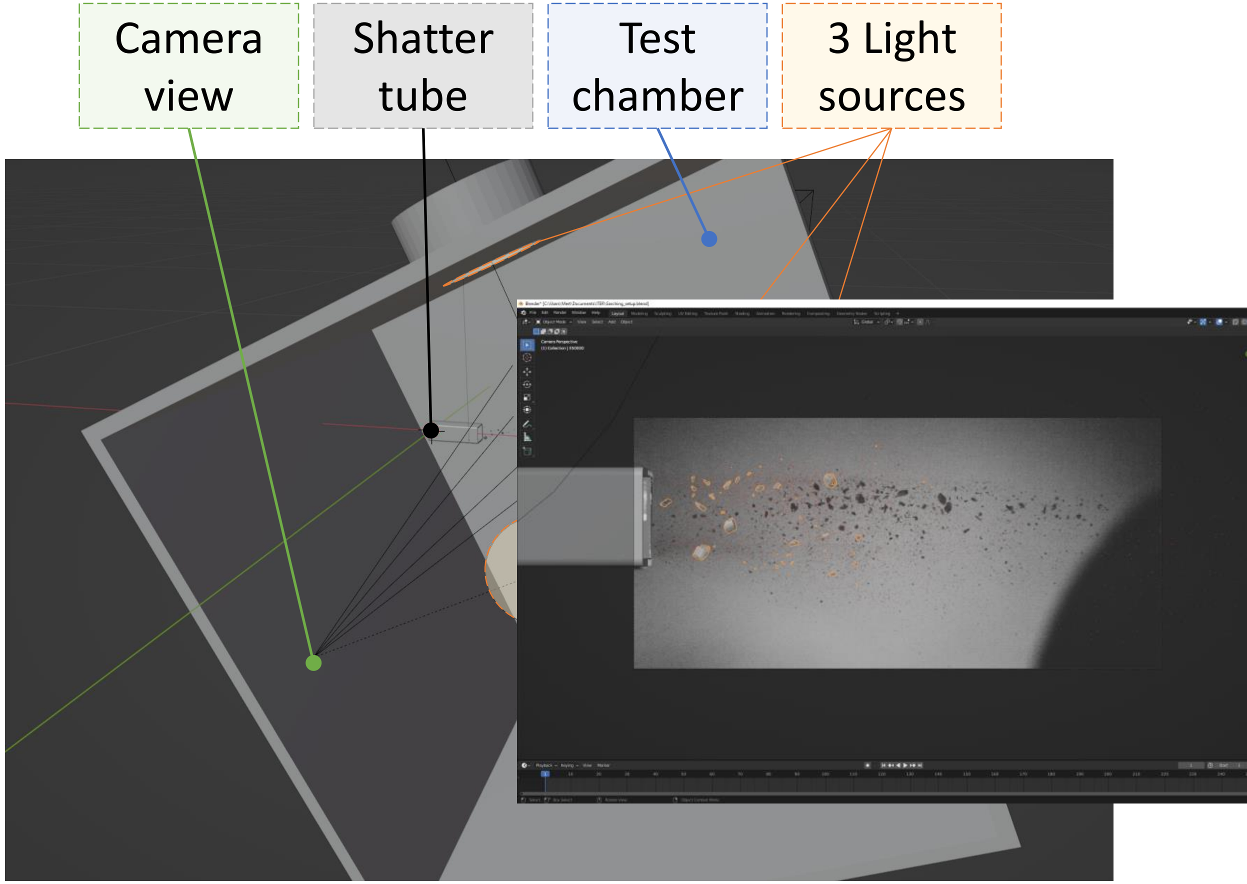
Synthetic Diagnostics

Setup of virtual test environment

CAD data from ASDEX Upgrade pellet shattering test setup



Test setup as blender model



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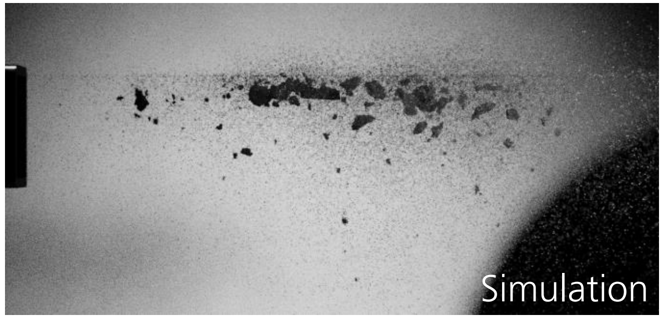
How to compare Simulation with Experiment?

Synthetic Diagnostic

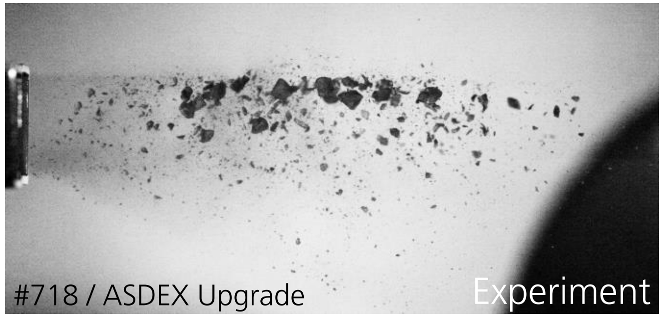
- Synthetic diagnostic to…
  - …extract fragment characteristics based on 2D views

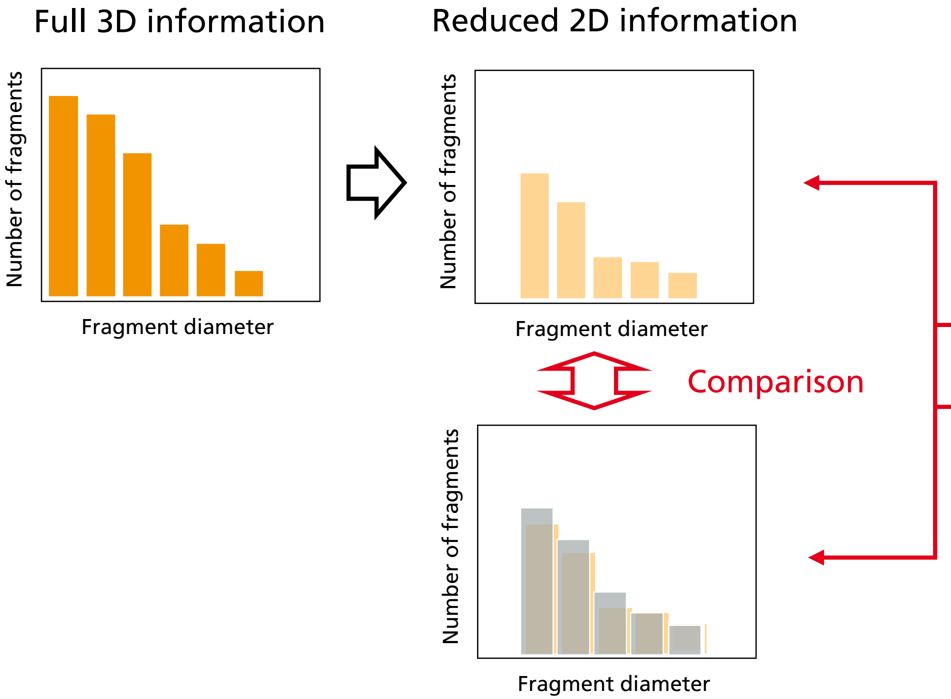
Simulation



Comparison (visual / post-processed data)

Experiment

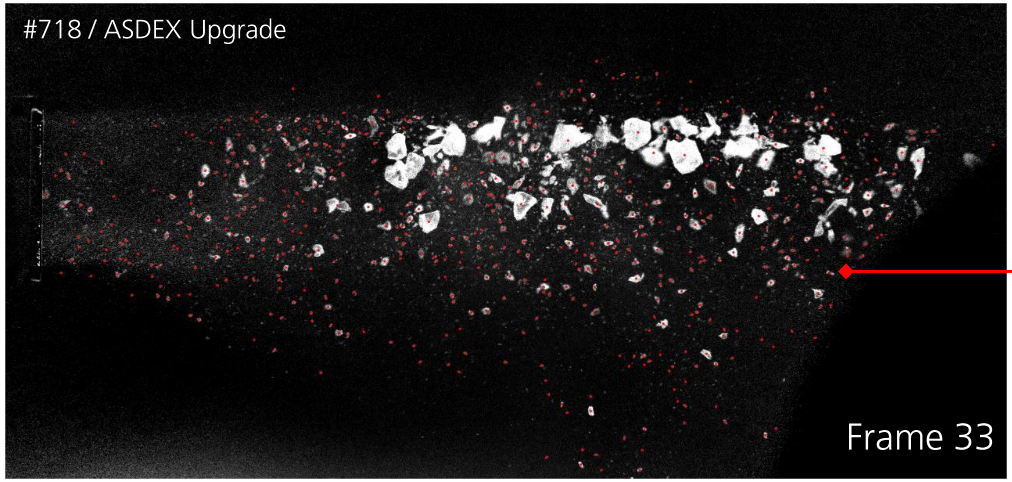


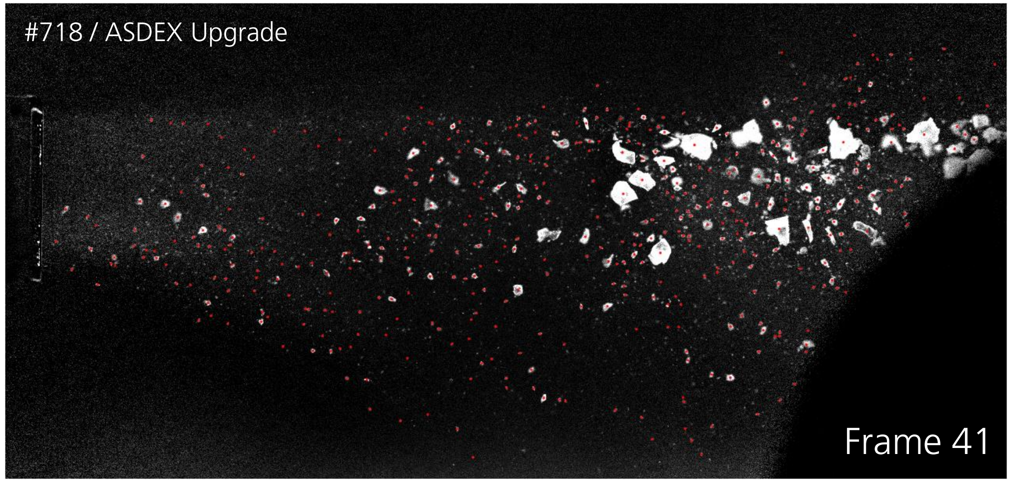


- Calibration
- Validation
- Optimize view

How to compare Simulation with Experiment?

Fragment Analyses: Automatic Fragment Detection and Tracking on synthetic and experiment Images



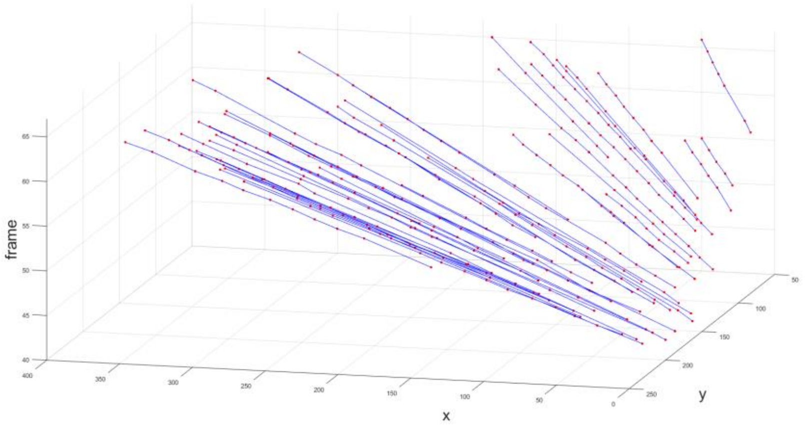


Fragment detection (on every single frame):

- Foreground / background separation (top hat filtering etc.)
- Appling a watershed algorithm for segmenting overlapping blobs
- Determining centroid and areas (Otsu method) of detected blobs

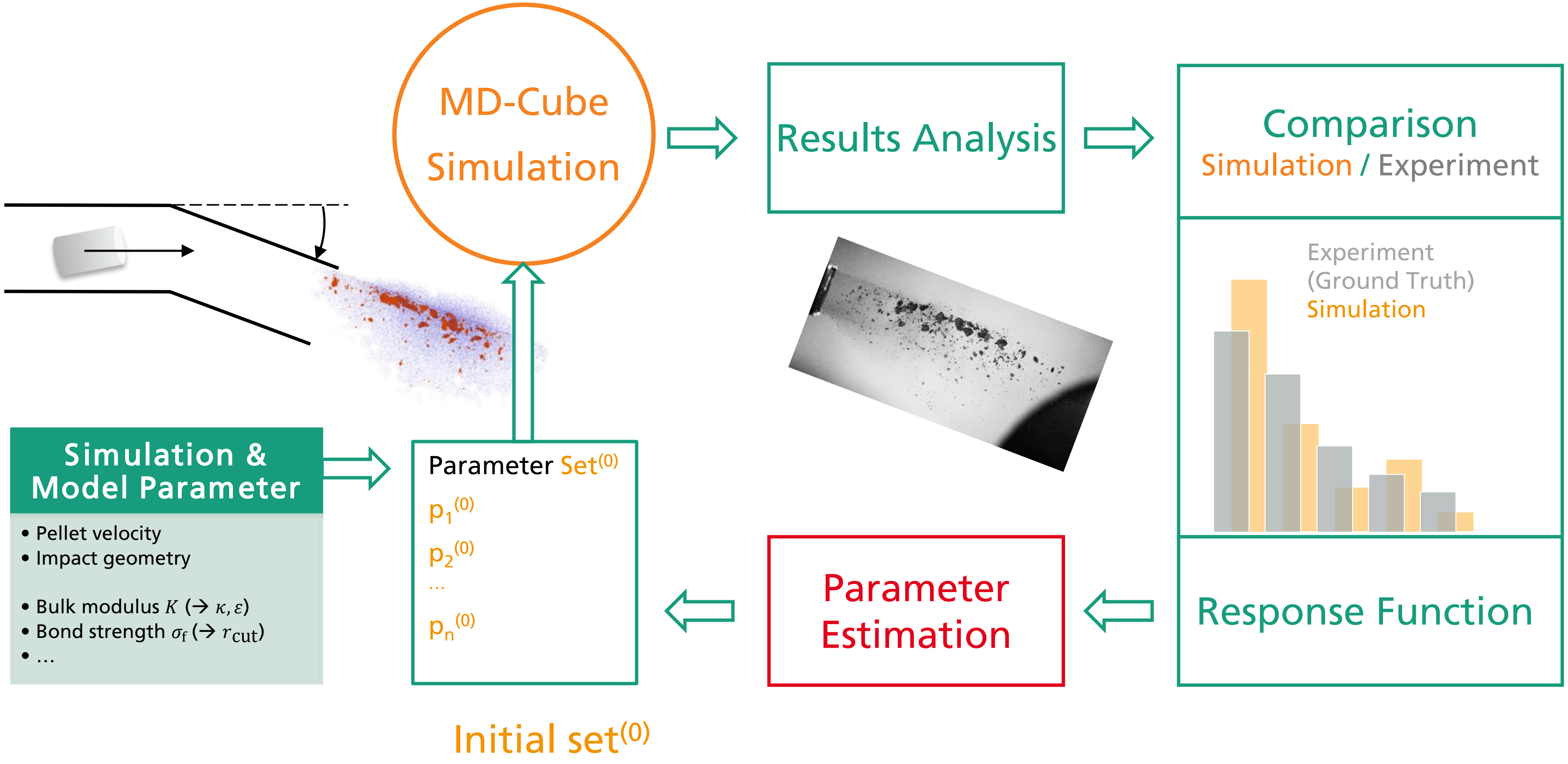
- Output:
  List of fragment centroids (x, y), time (frame number), and area (pixels)

Fragment tracking (combining data from all frames):

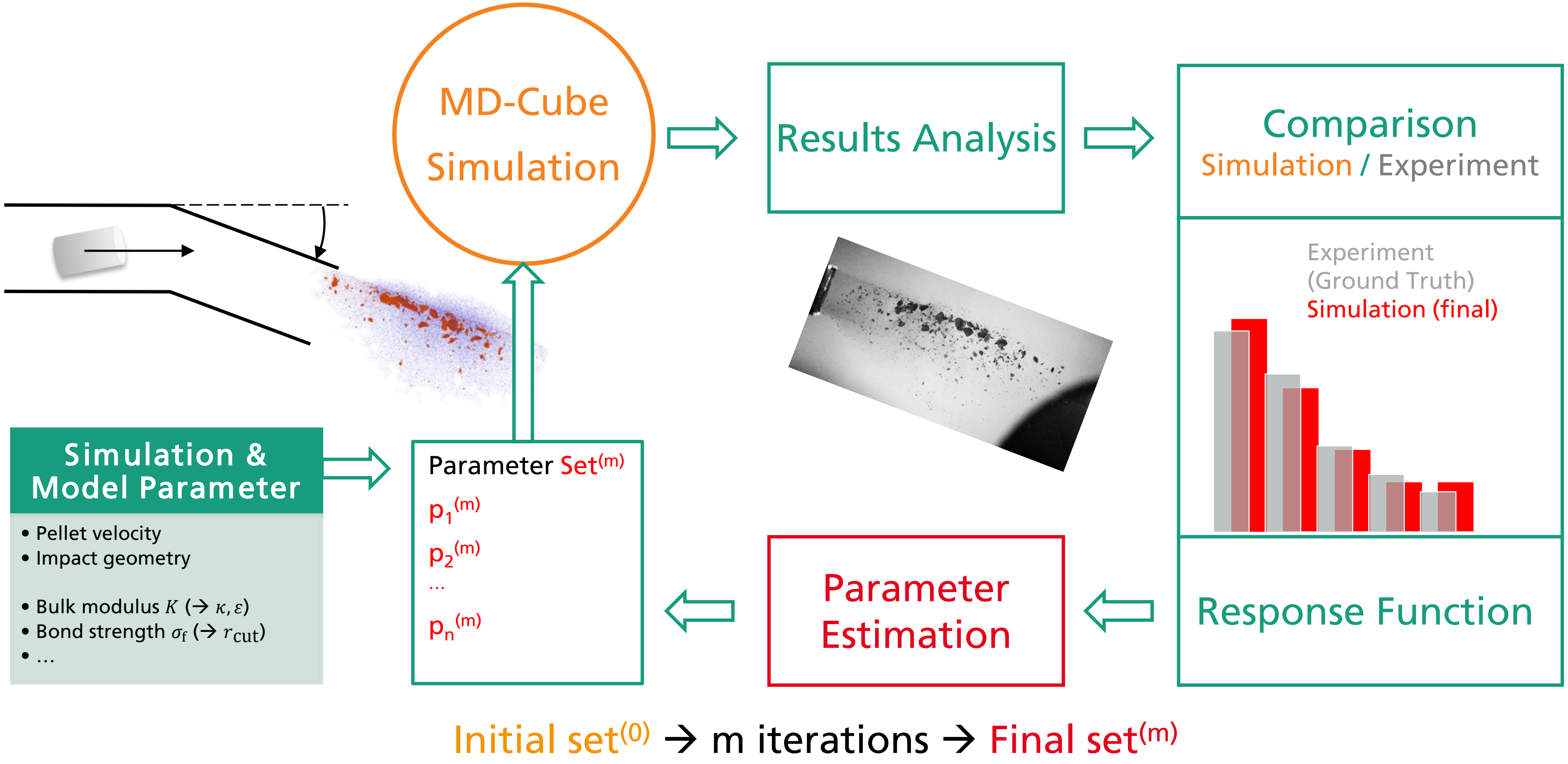


Linking fragments detected in separate frames into trajectories (Random Sample Consensus)

Model Calibration Cycle



Model Calibration Cycle



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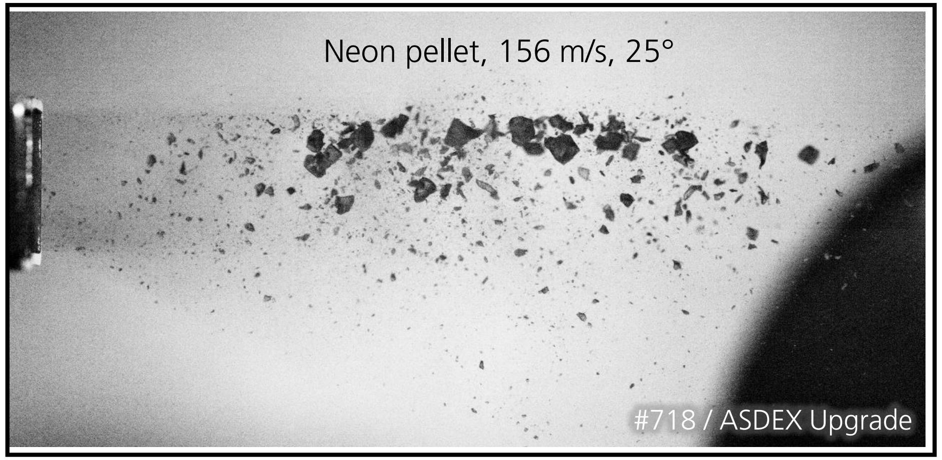
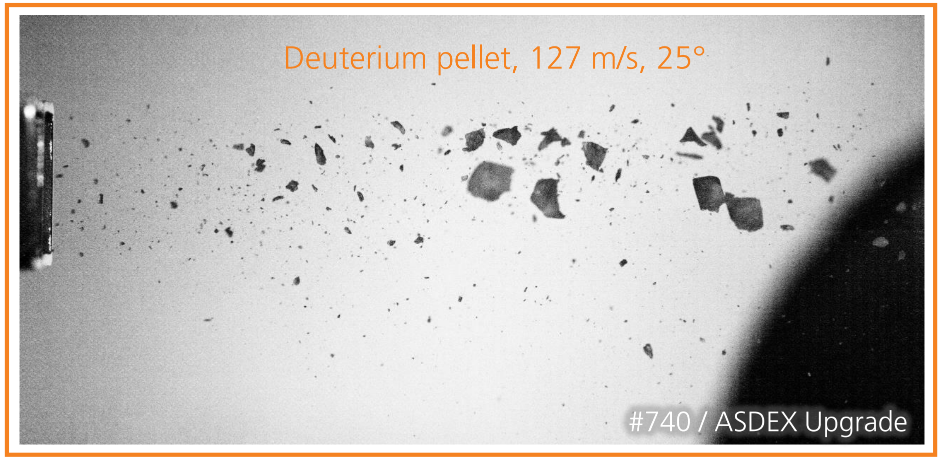
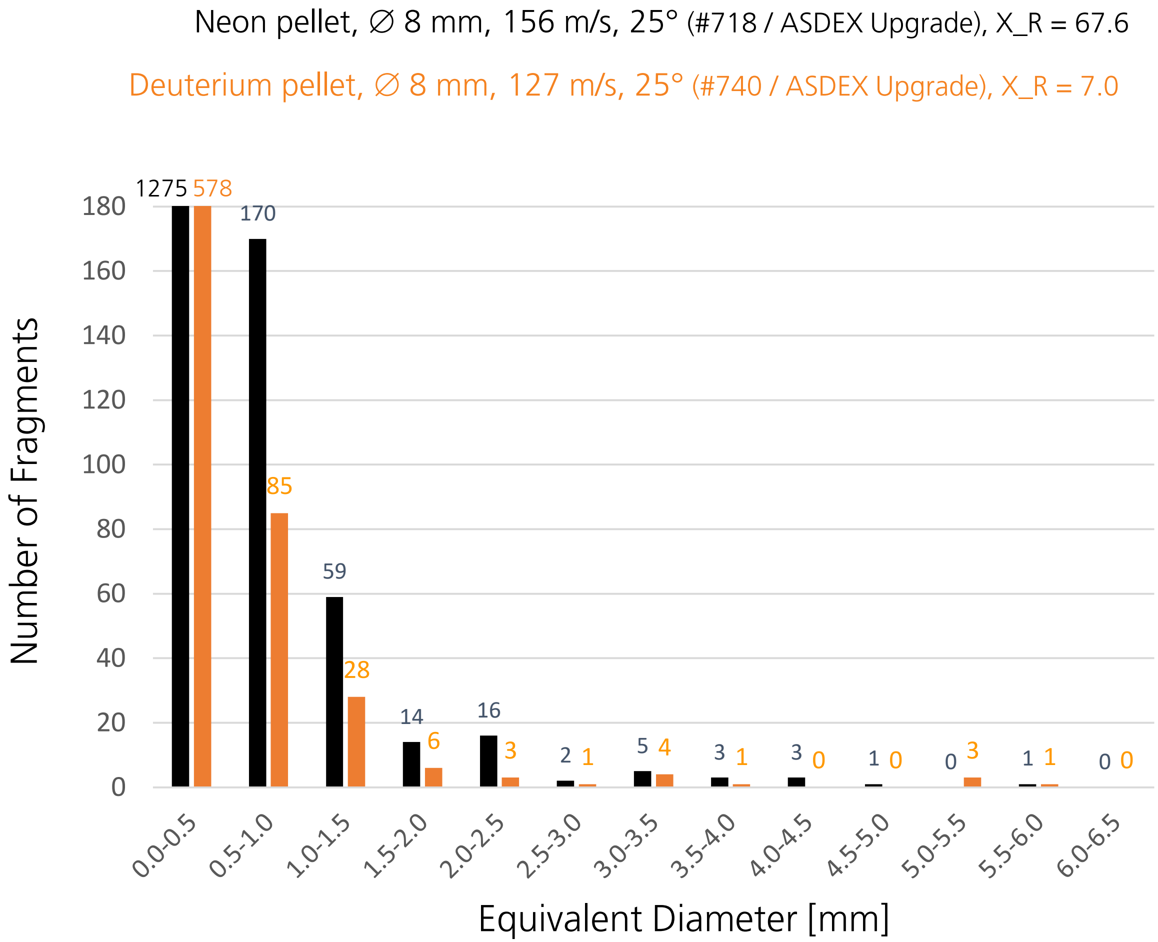
Current Results: Fragment Analyses of ASDEX Upgrade Tests

1 Neon and 1 Deuterium Test for Model Calibration







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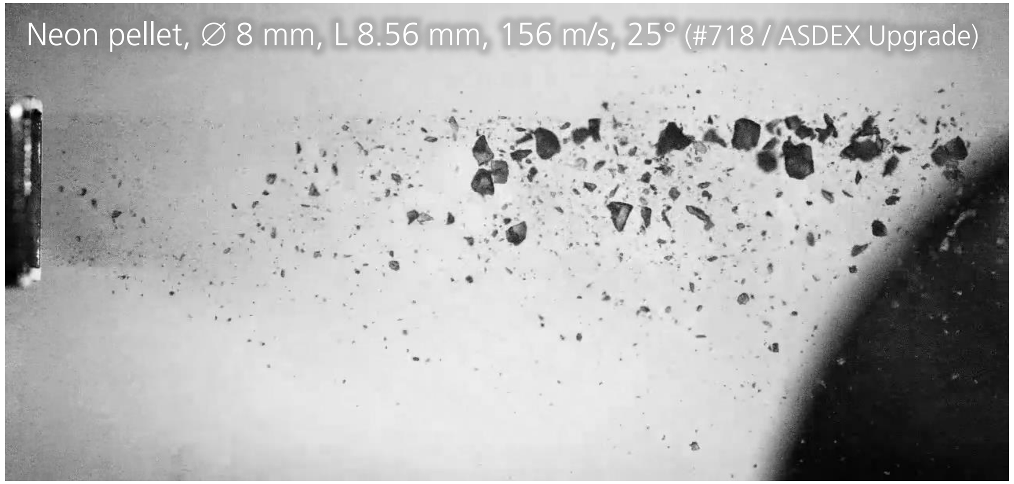
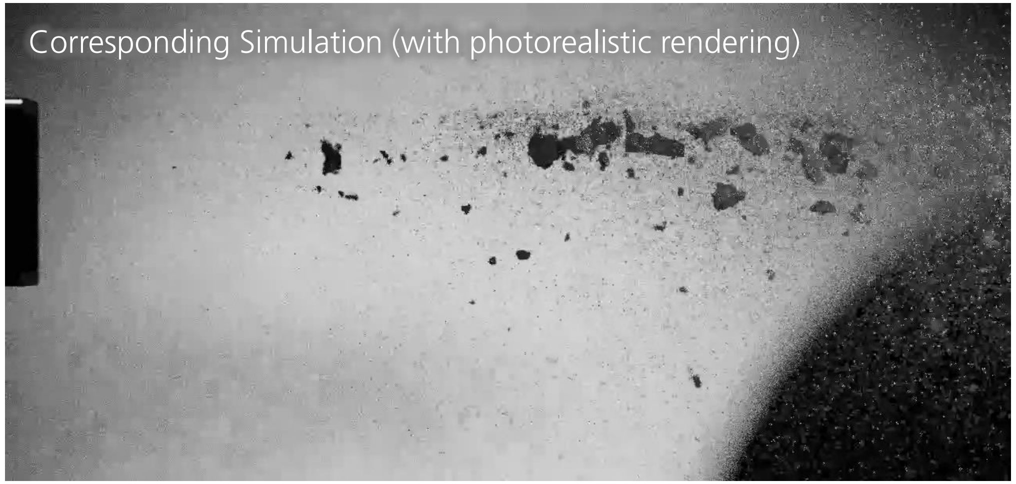
Current Results: Model Calibration for Neon (ASDEX Upgrade)

Ongoing Parameter Optimization

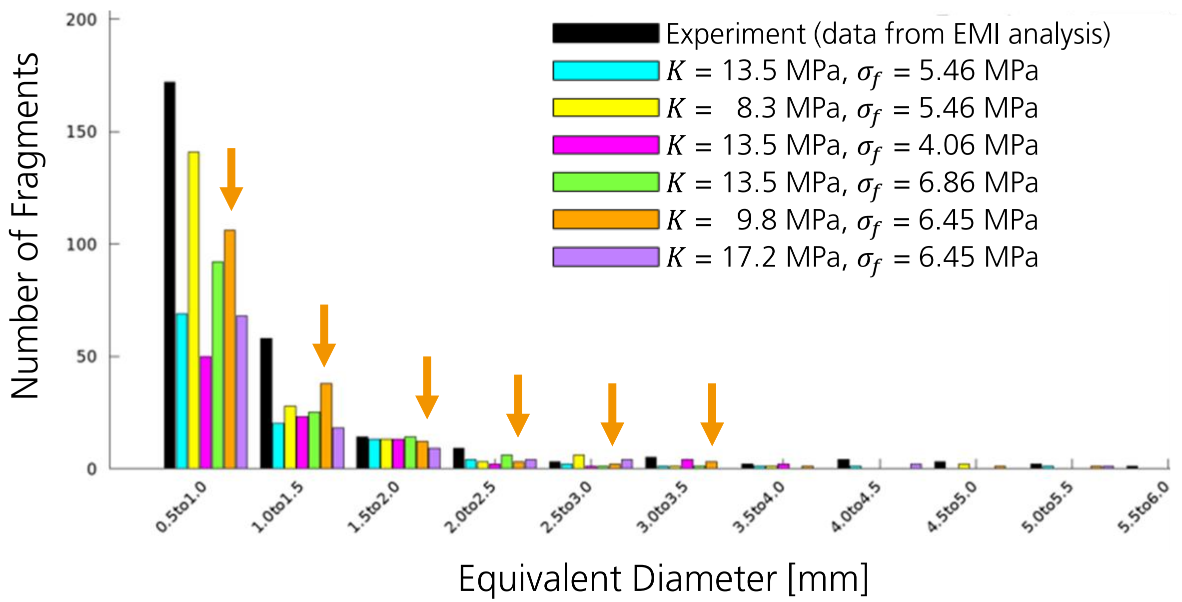




Not yet fully optimized material parameters:

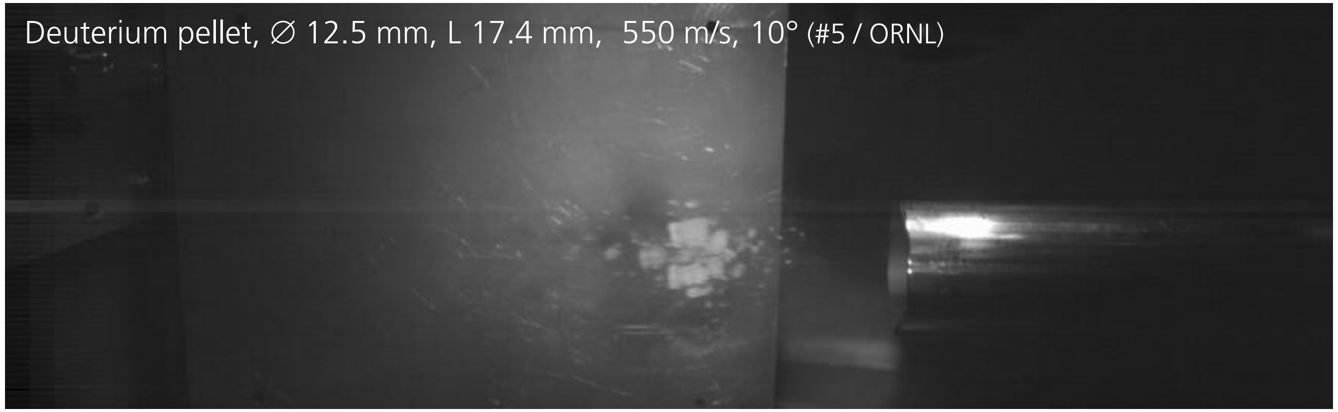
K = 9.8 MPa, σ_f = 6.45 MPa

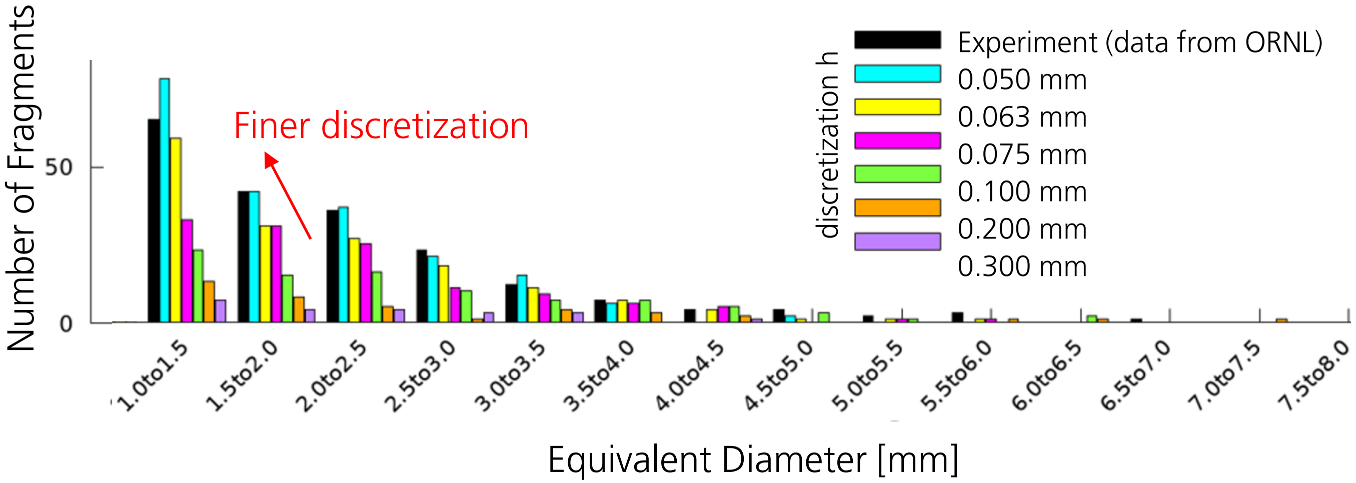
Discretization h = 0.096 mm



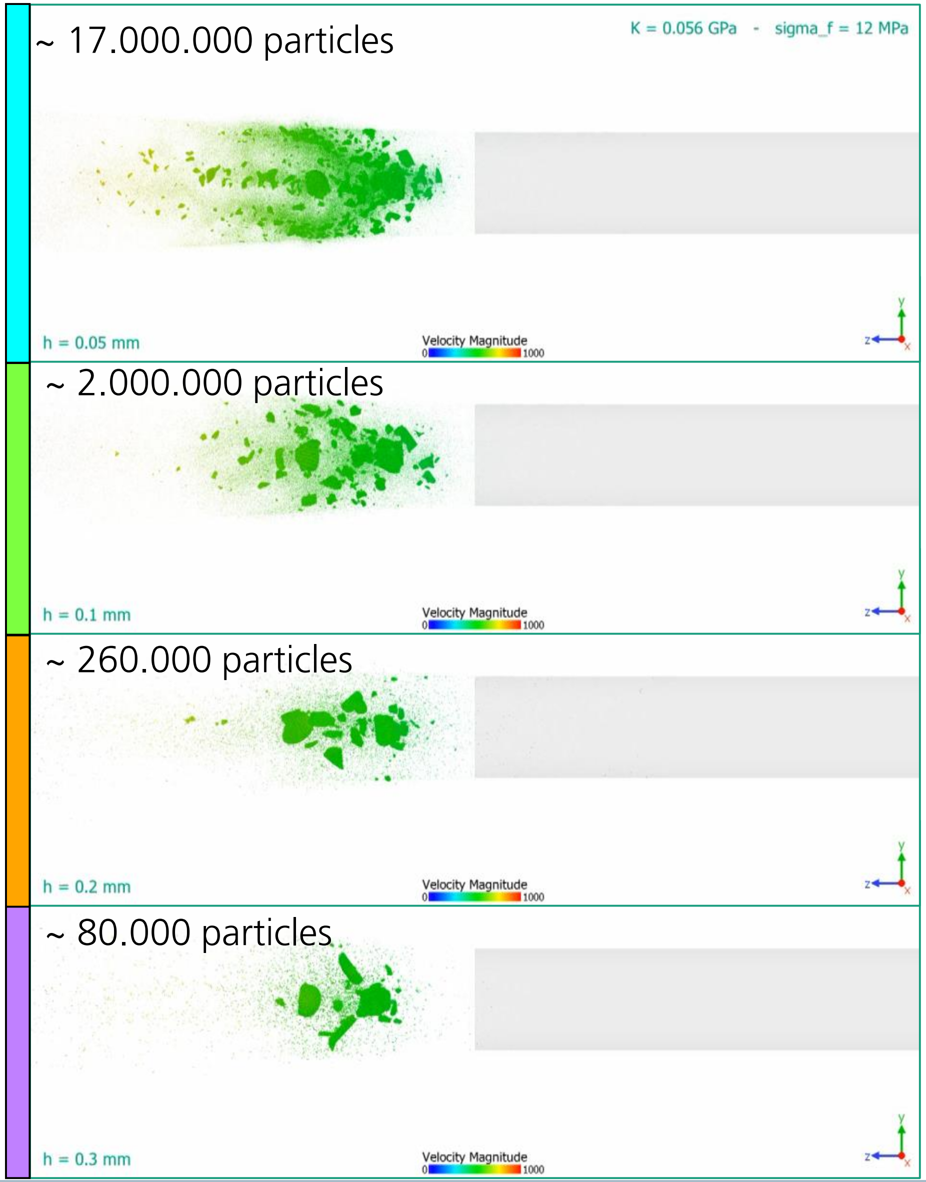
Current Results: ORNL Test (Deuterium)

Optimized Parameters, Influence of Discretization





Optimized Material Parameters: K = 0.056 GPa, σ_f = 12 MPa



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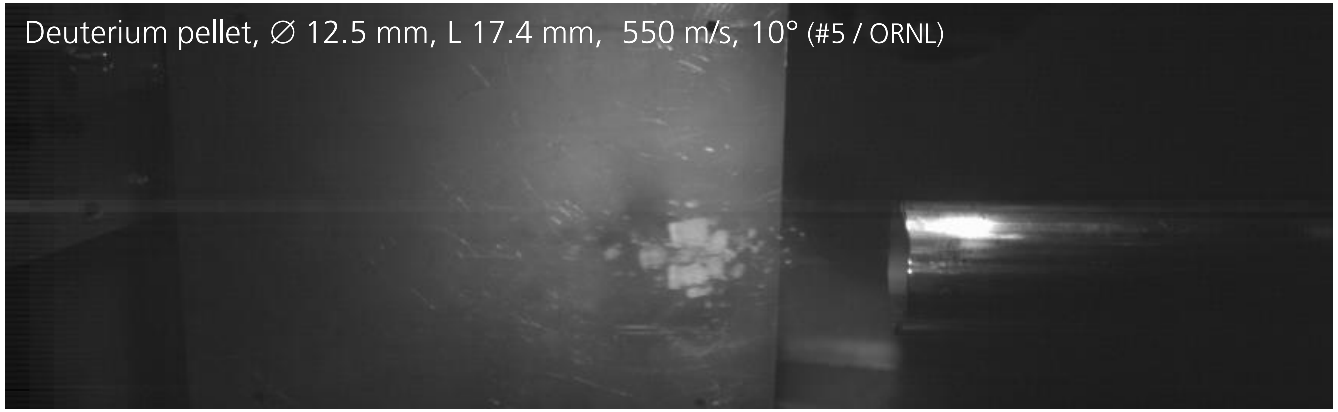
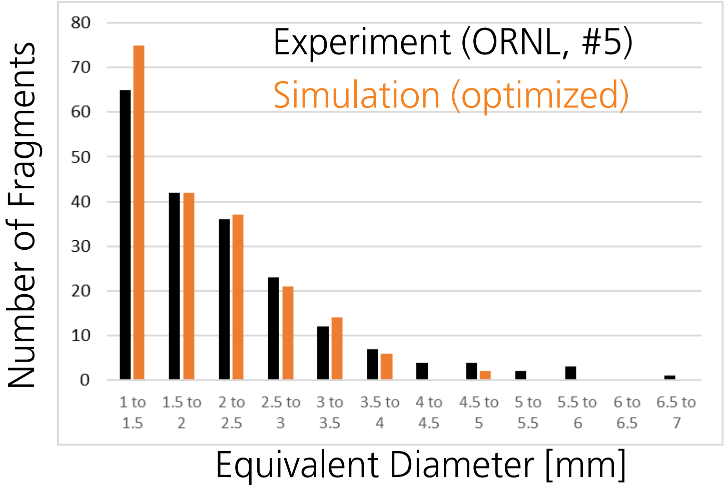
Current Results: ORNL Test (Deuterium)

Optimized Parameters, Influence of Discretization





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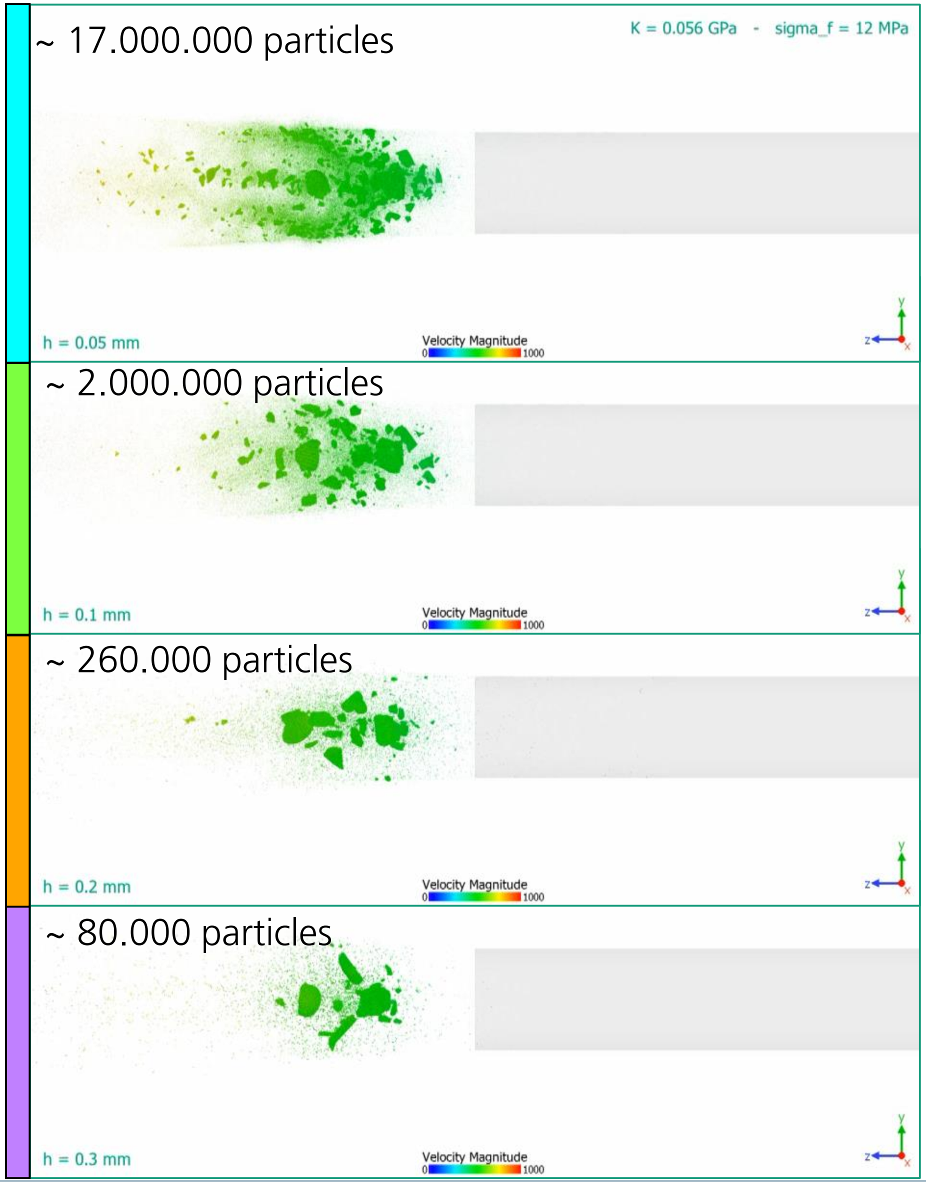

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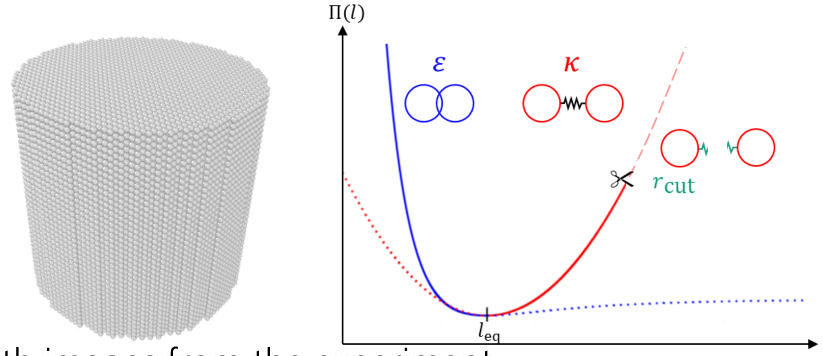
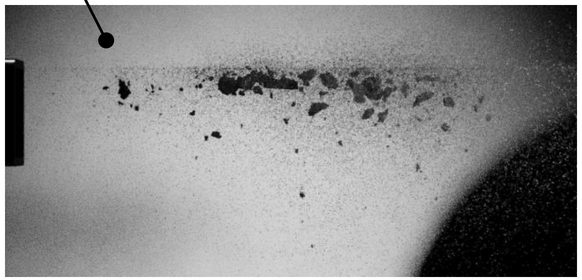
Conclusion

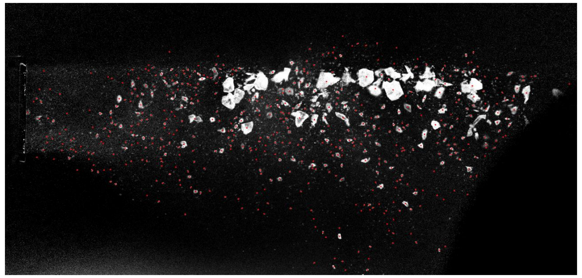
EMI's MD-Cube software



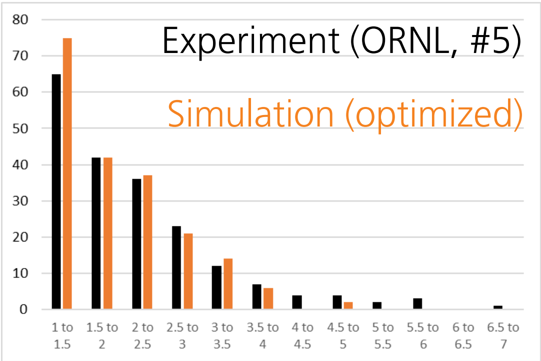
- **Computational framework** for investigating the pellet shattering process established.

- **Synthetic diagnostic procedure** developed to generate photorealistic images comparable with images from the experiment.





- (Automated) **fragment tracking** algorithms adapted to typical properties of the experimental/synthetic images. **Fragment tracking** is applied to both the synthetic diagnostic and the experimental images for a **fair comparison.**



- **Model calibration** for several shatter experiments performed (2 ORNL tests) and ongoing (ASDEX Upgrade).

- **Next steps**: Complete calibration, start **validation** & to perform **simulations of ITER shattering setup**.

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