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

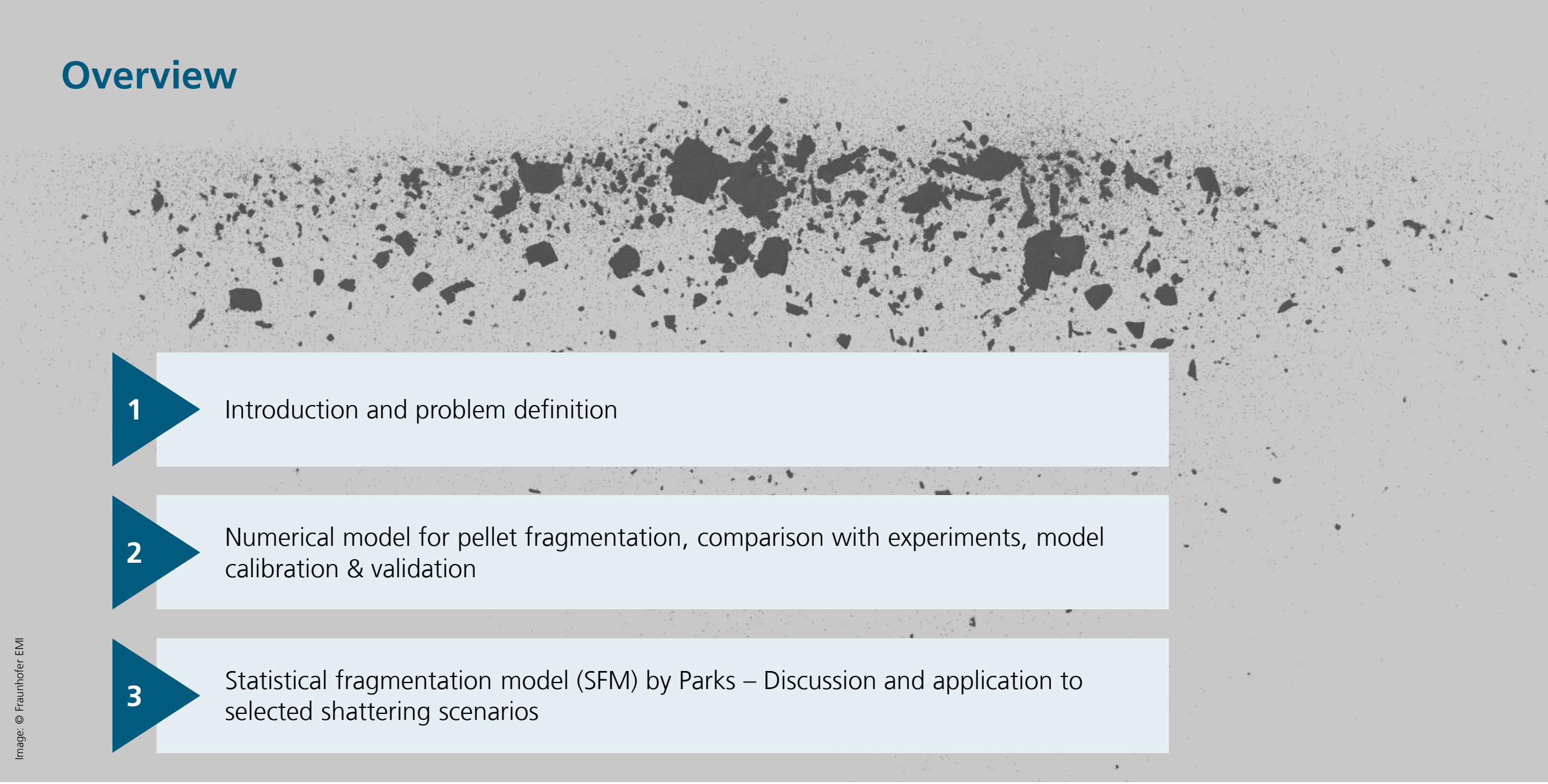
3rd Technical Meeting on Plasma Disruptions and their Mitigation – 4 September 2024, ITER Headquarters

Pellet fragmentation process in the context of the SPI technology for the ITER DMS – Analysis of the fragment characteristics supported by numerical simulations and image diagnostics of shatter tests

Pascal Matura, Stefano Signetti, Stefan Moser, Luis Sandoval, Nathanaël Durr, Erkai Watson, Dilara Gebhardt, Markus Büttner

Work conducted under the contract No. IO/21/CT/4300002337 for ITER Organization

Overview



1. Introduction and problem definition
2. Numerical model for pellet fragmentation, comparison with experiments, model calibration & validation
3. Statistical fragmentation model (SFM) by Parks – Discussion and application to selected shattering scenarios

Image: © Fraunhofer EMI

SPI fragmentation process: problem definition

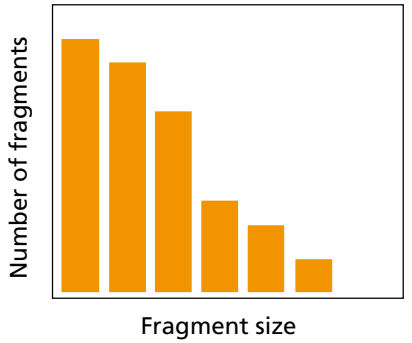
Characteristics & dependencies

Shatter experiments at ASDEX Upgrade

Deuterium pellet, $D = 8$ mm, 12.5°

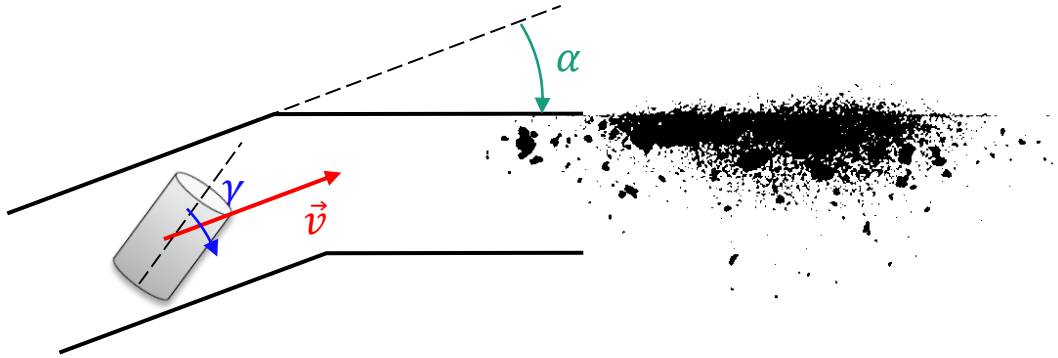
Fragmentation characteristics…

- 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
  - Shatter angle
  - Pellet orientation (tilting)
  - Shatter tube geometry
  - …
- Pellet properties
  - Material (protium, deuterium, neon, …)
  - Geometry (size, shape)
  - Homogeneity (crystallographic structure, defects, thermodynamic properties, …)
  - …



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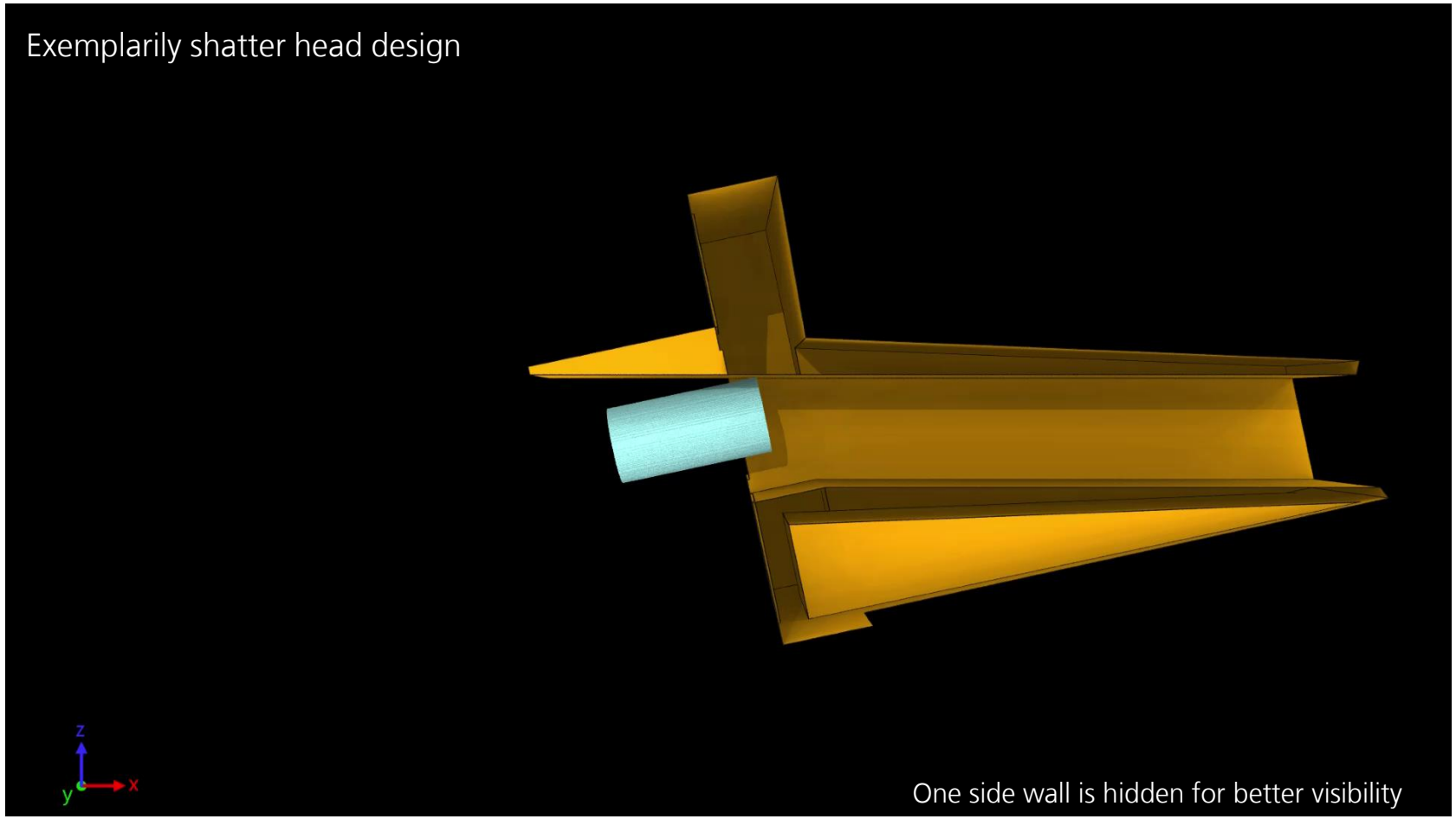
Numerical shattering experiments

EMI's modelling approach based on Discrete Element Method & Peridynamics [1], [2]



Numerical shattering experiments:

- Fragment size distribution
- Fragment velocity distribution

is fully known because of the raw data.

But: Model has to be calibrated and validated

Model details → [1], [2]

2 material parameter involved:

- Bulk Modulus K
- Fracture Strength σ_f

} calibration

[1] Matura, Pascal et al., *Modelling and simulation of the pellet shattering process related to the SPI technology for the ITER DMS*, 2nd Technical Meeting on Plasma Disruptions and their Mitigation, 2022 (https://conferences.iaea.org/event/281/sessions/2515/#20220722)
[2] Signetti, Stefano et al., *Pellet shattering process for the ITER disruption mitigation system – Part I: Development of a discrete element code for modeling the dynamic fragmentation of cryogenic materials,* Proceedings of the 17th Hypervelocity Impact Symposium. Tsukuba, Japan, 8–13 Sept., 2024

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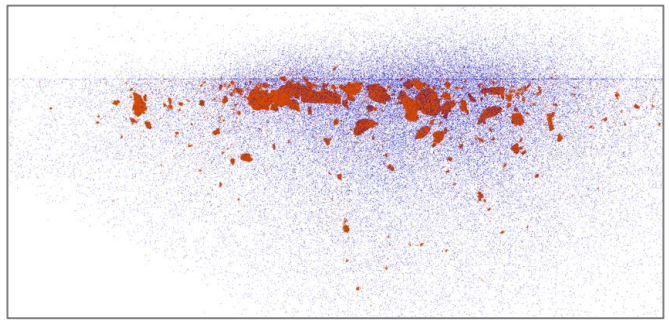
How to compare simulations with experiments?

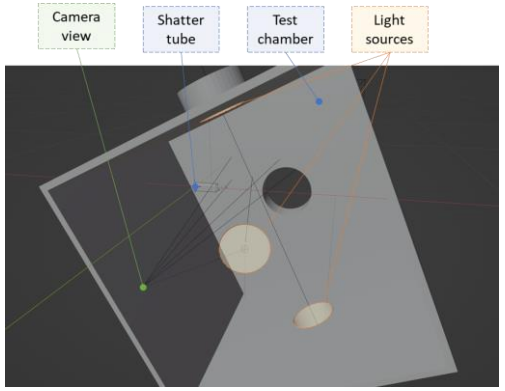
Synthetic diagnostic: Generate photorealistic images from simulation data

- Synthetic diagnostic to…
  …better compare simulation with experiment

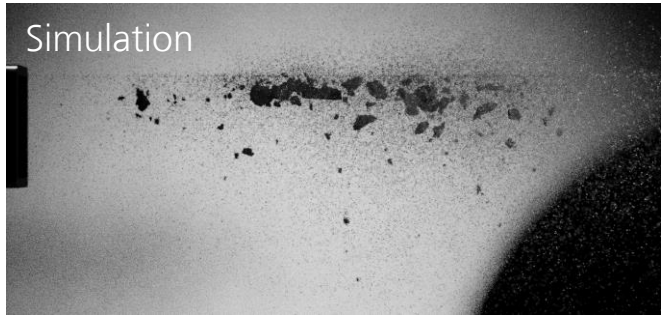
Simulation



Raw simulation data

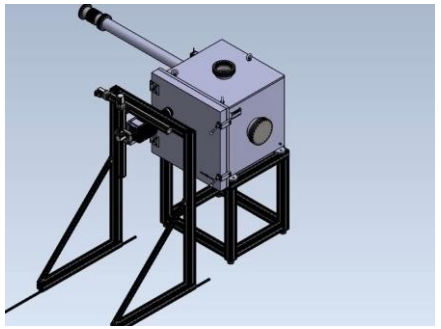


Integrate data into virtual test environment

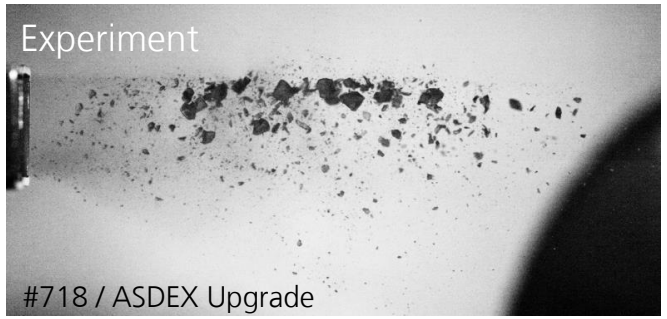


Raytracing etc. ⇕ Comparison

Experiment



CAD data: AUG pellet shattering test setup



Matura, Pascal et al. "Pellet shattering process for the ITER disruption mitigation system – Part II: Synthetic-diagnostics-based testing, calibration, and validation of simulation models." 17th Hypervelocity Impact Symposium. Tsukuba, Japan, 8-13 Sept., 2024

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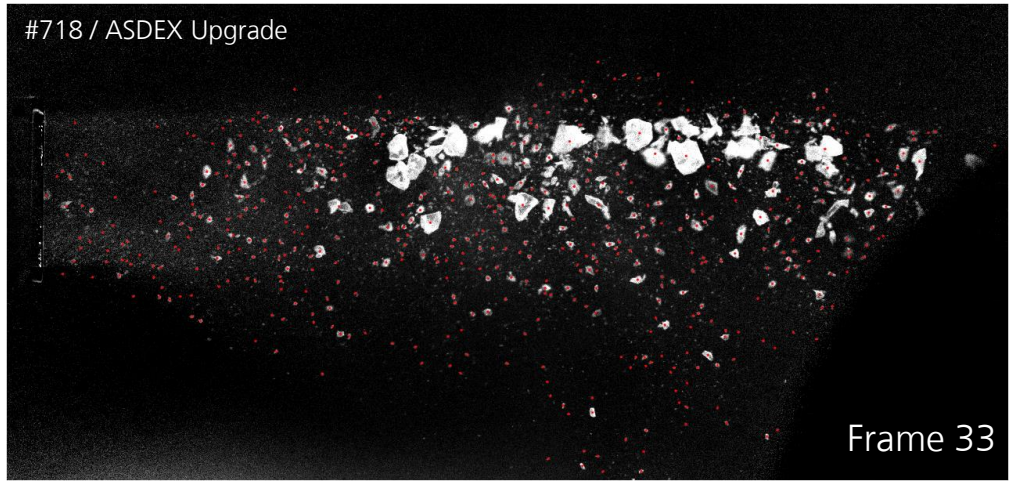
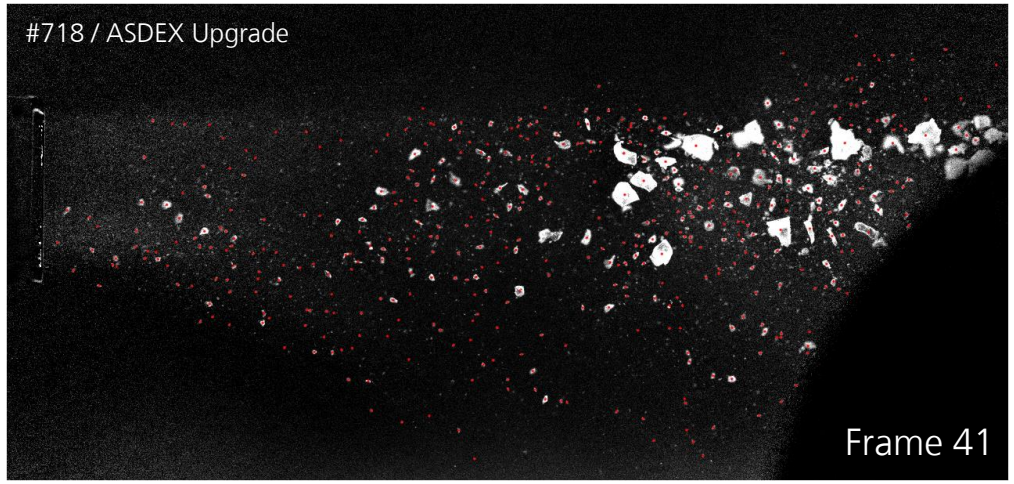
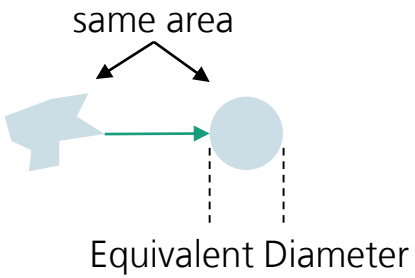
Fragment analyses on 2D image data (experiment & simulation)

Automatic + manual fragment detection and tracking

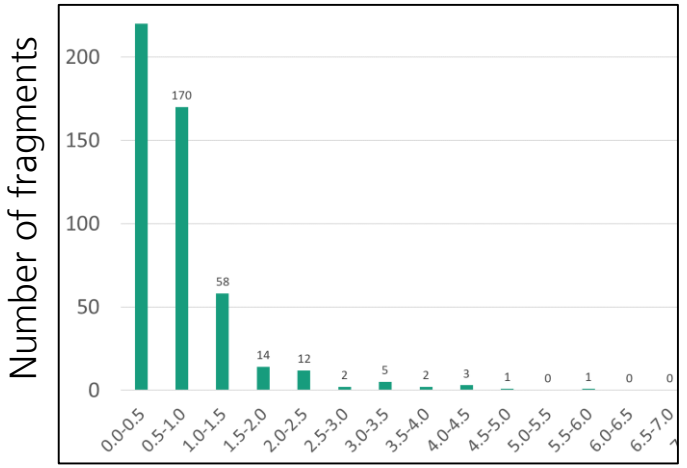




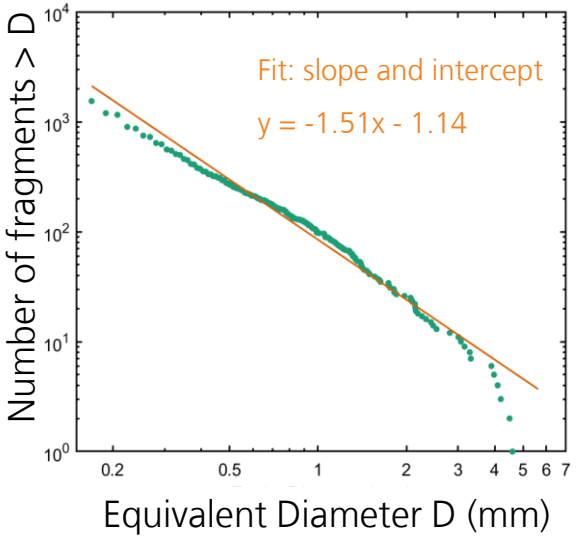
#ID	Area	Diam	Vel	...
0001	0.028	0.19	182.4	
0002	0.145	0.43	145.9	
0003	1.188	1.23	120.1	
...				
1542	25.966	5.75	154.3	



Sorting into bins



or **Cumulative LogLog-plot**



Watson, Erkai et al. "Optical fragment tracking in hypervelocity impact experiments." Acta Astronautica. Vol. 155 (2019): pp. 111–117. DOI: 10.1016/j.actaastro.2018.11.036
Matura, Pascal et al. "Pellet shattering process for the ITER disruption mitigation system – Part II: Synthetic-diagnostics-based testing, calibration, and validation of simulation models." 17th Hypervelocity Impact Symposium. Tsukuba, Japan, 8-13 Sept., 2024

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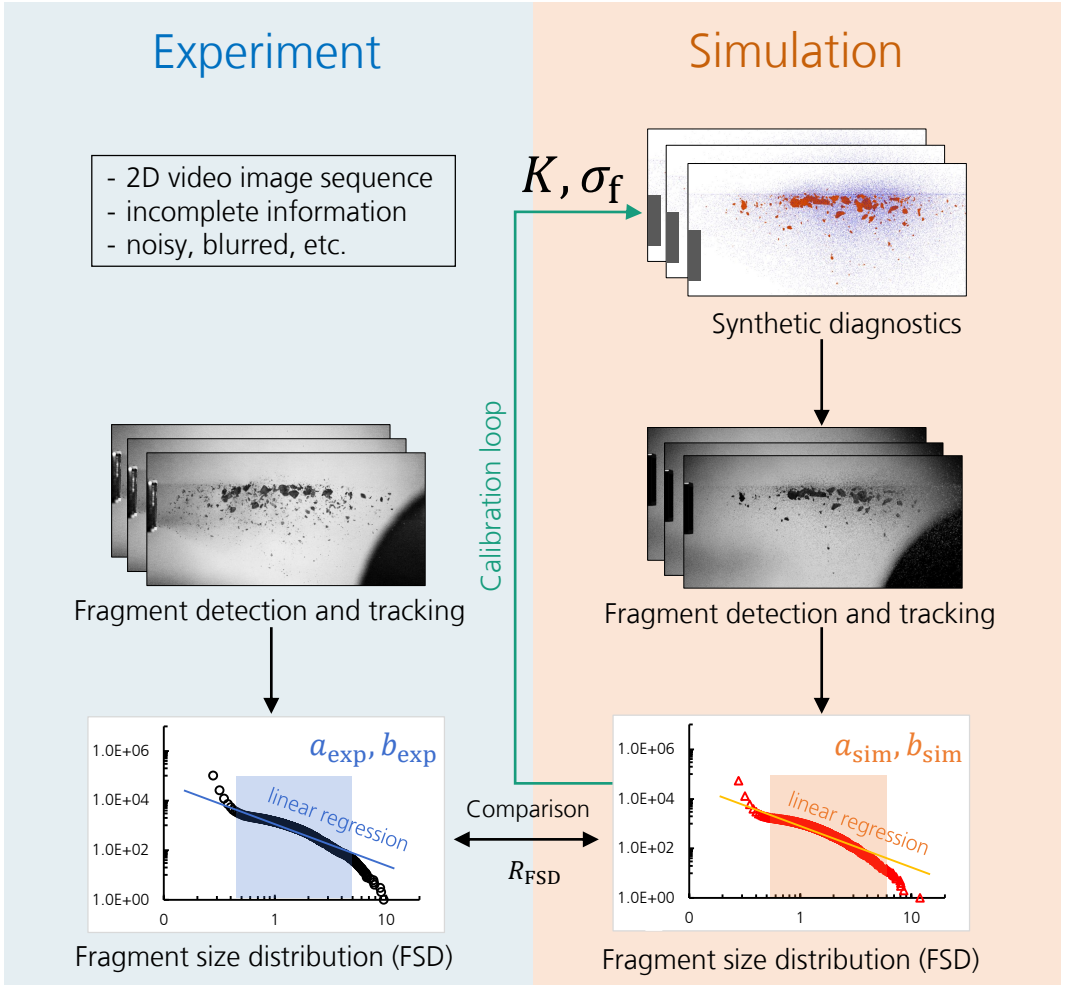
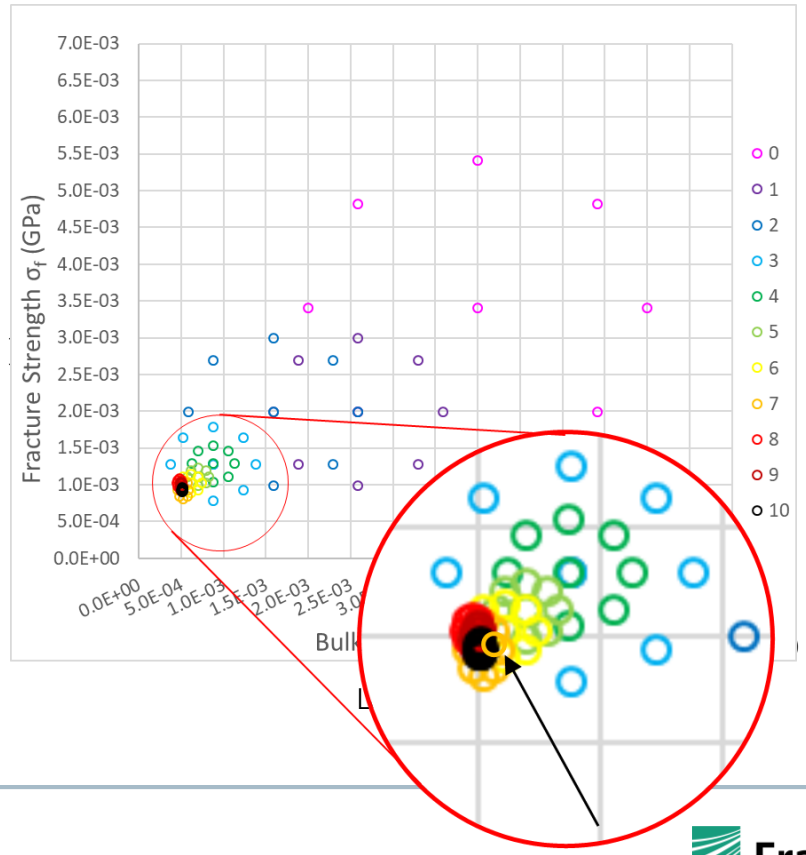
Model calibration and validation

General procedure



Response function R_{FSD}

$$R_{FSD} = \sqrt{\left(\frac{a_{sim} - a_{exp}}{a_{exp}}\right)^2 + \left(\frac{b_{sim} - b_{exp}}{b_{exp}}\right)^2}$$



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Selected AUG calibration and validation cases

Neon and Deuterium

Test ID	Pellet material	Pellet diameter (nominal) D [mm]	L/D [-]	Shatter tube angle [°]	Tilt angle out of plane [°]	Impact velocity v_0 [m/s]	X_R [-]
#700	Neon	8.0	1.10	25.0	0.0	109	33.2
#718	Neon	8.0	1.07	25.0	11.3	156	67.8
#714	Neon	8.0	1.04	25.0	26.6	215	129.5
#1213	Deuterium	8.0	0.65	12.5	23.2	177	3.7
#740	Deuterium	8.0	1.17	25.0	0.0	127	7.2
#1209	Deuterium	8.0	1.19	12.5	24.0	330	12.8
#780	Deuterium	8.0	0.78	25.0	17.9	273	33.2
#811	Deuterium	8.0	0.85	25.0	13.2	391	68.3

Red: used for model **calibration**

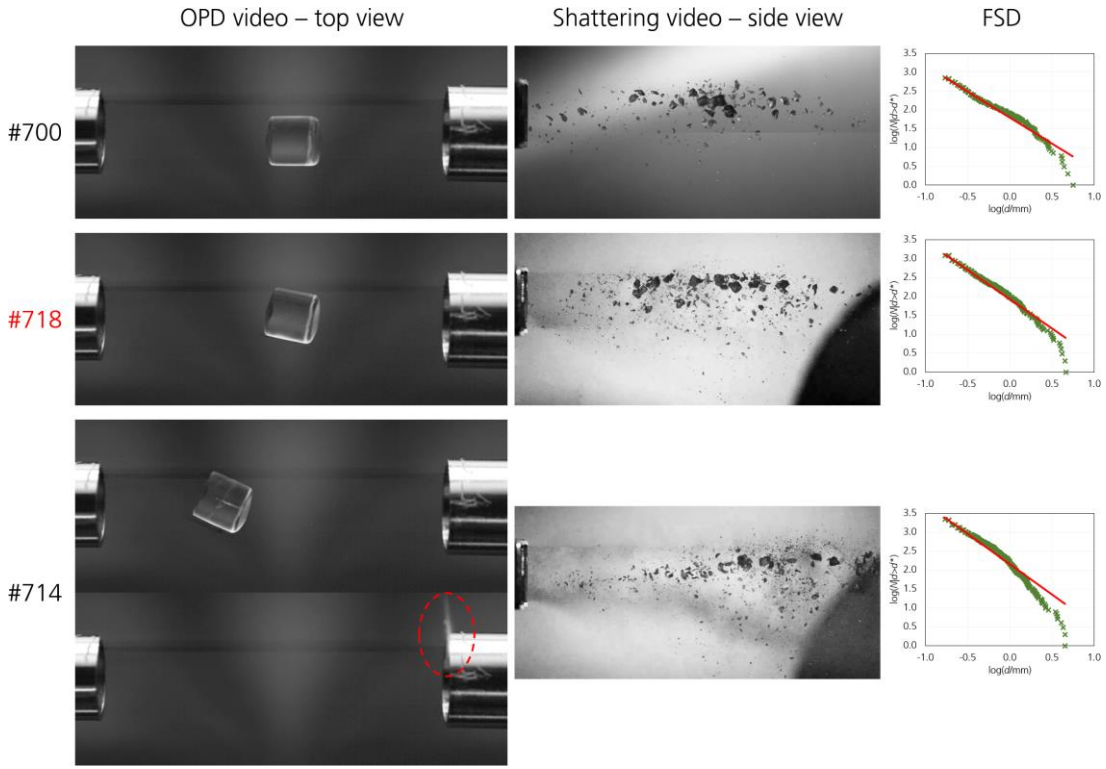
Black: used for model **validation**

X_R: ratio of normal impact kinetic energy to threshold kinetic energy for pellet survivability

ITER pellet
D = 28.5 mm
L = 57 mm

AUG pellet
D = 8 mm
L = 8 mm

Neon shatter tests



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Calibration and Validation for AUG Neon

Calibrated material parameters: $K = 5.438$ MPa – $\sigma_f = 4.749$ MPa

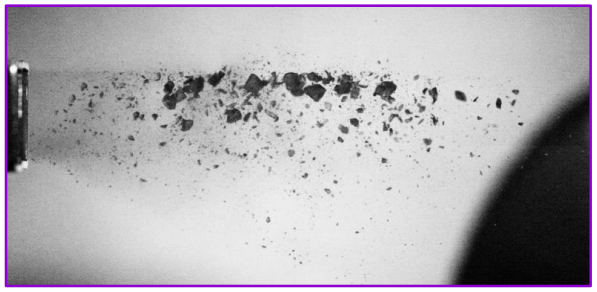
Calibration

Validation

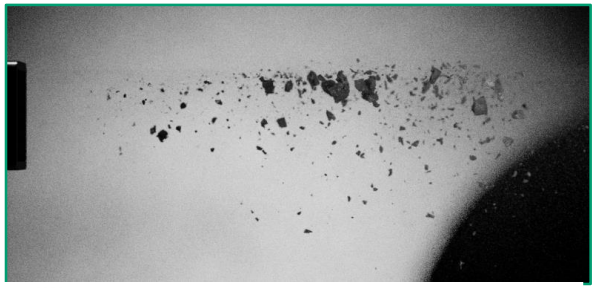
#718 – $X_R = 67.8$

#700 – $X_R = 33.2$

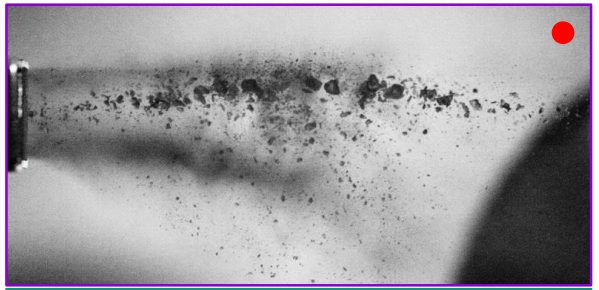
#714 – $X_R = 129.5$

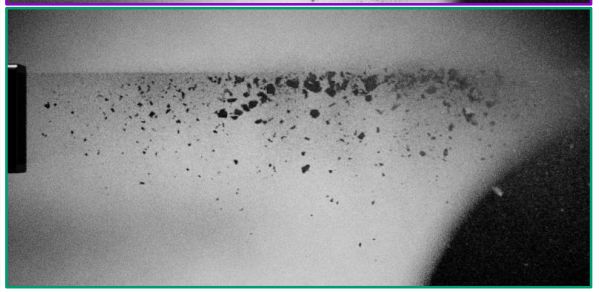


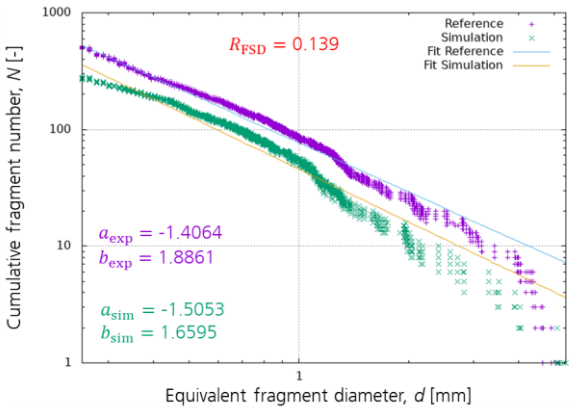
← Experiment →



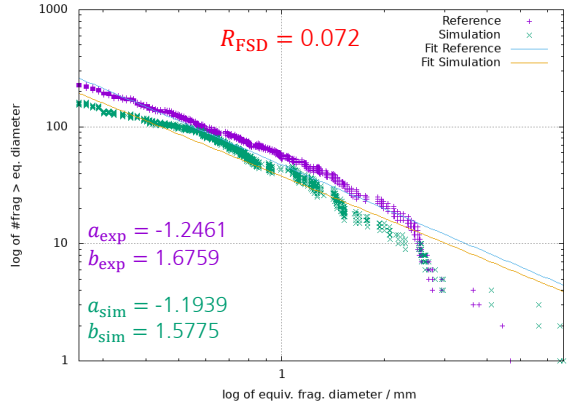
← Simulation →

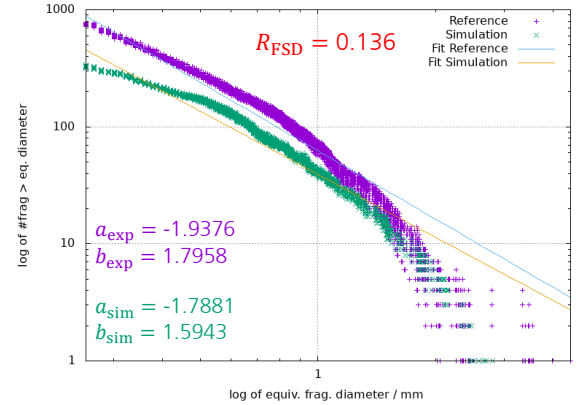






FSDs





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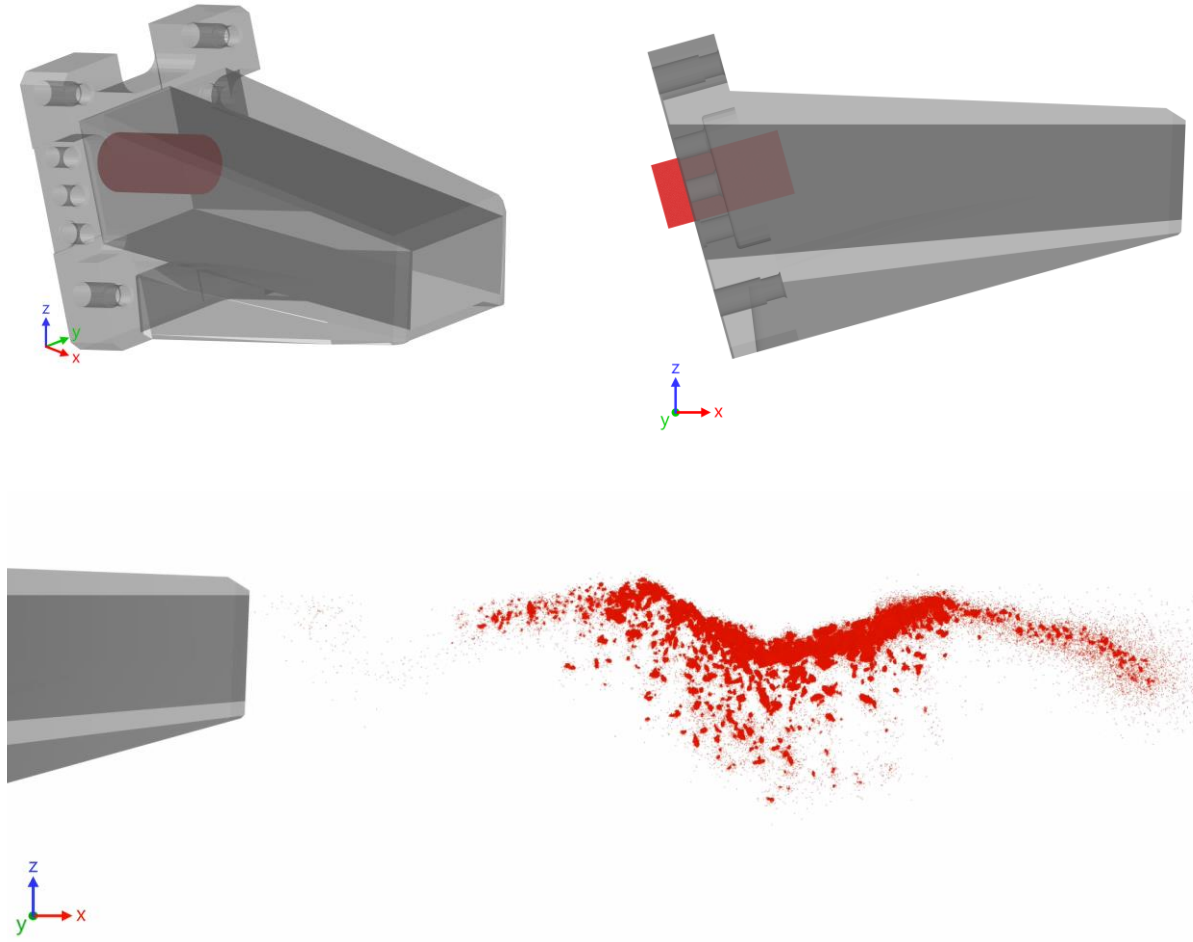
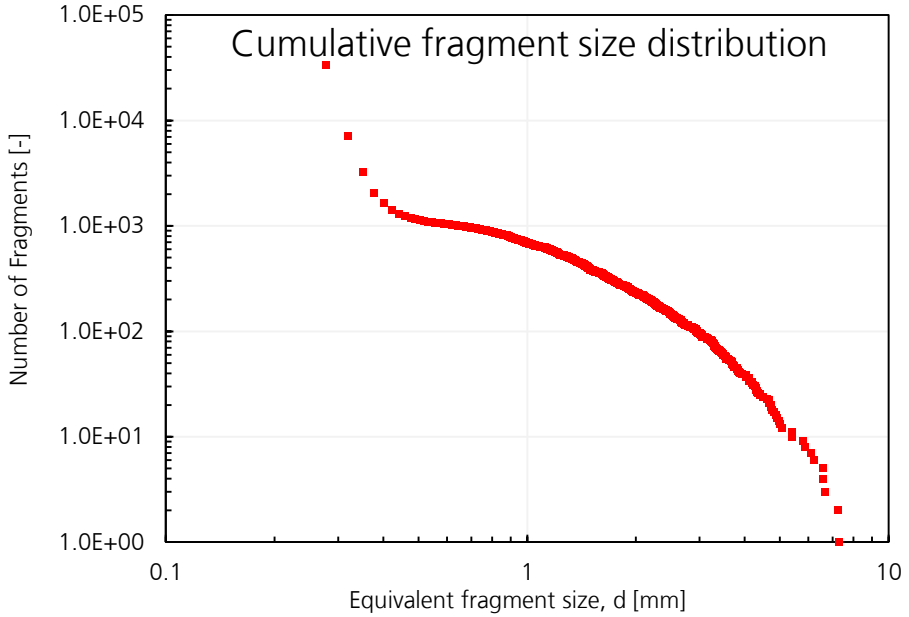
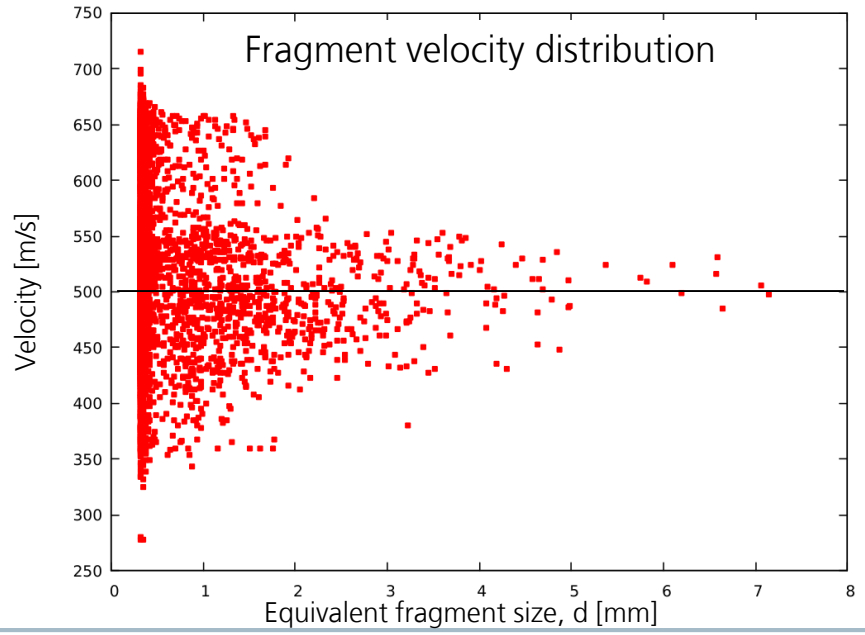
ITER Shatter Head and Pellet

Deuterium, 28.5 mm, L/D = 2, 500 m/s, 15.5° shattering angle







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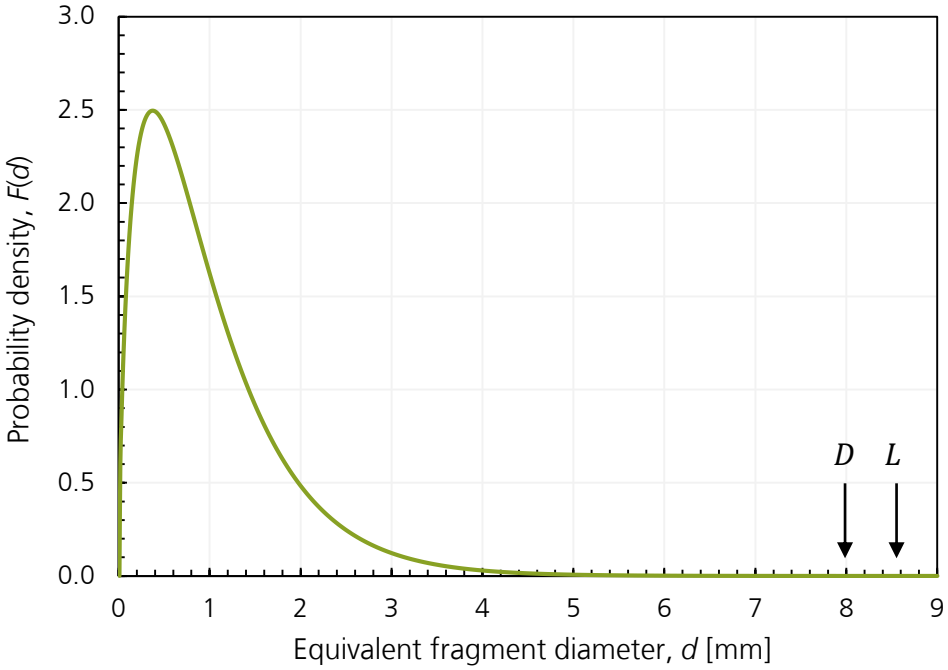
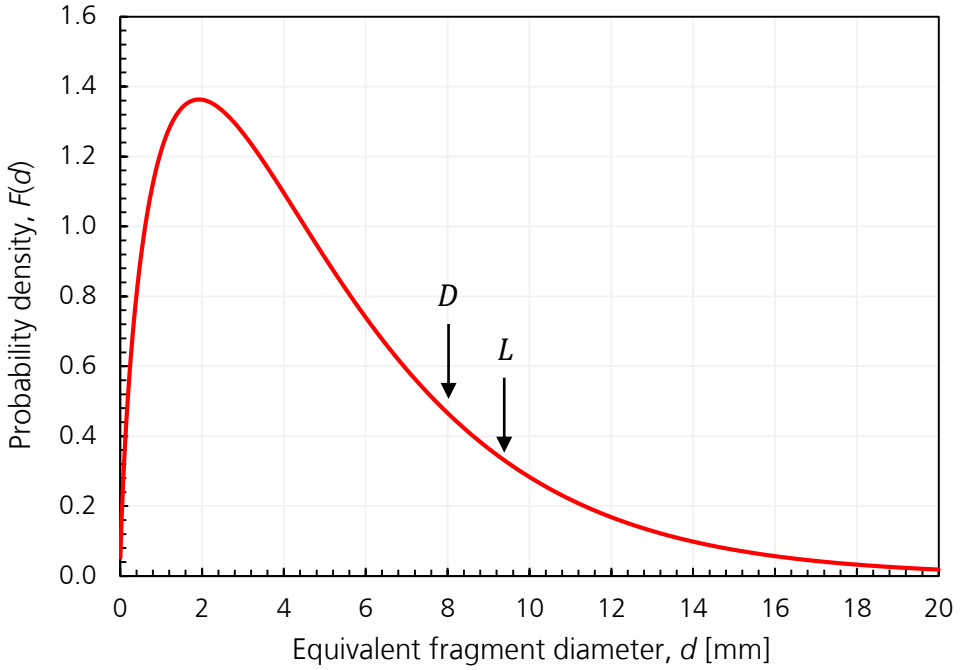
Fragment Size Distribution: Experiments & Statistical Fragmentation Model

Parks' model for selected AUG SPI experiments (calibration cases)

#718 – Neon – $v_{\mathrm{perp}} = 65.9$ m/s – $\theta = 25°$
$D = 8$ mm – $L = 8.56$ mm – $X_{\mathrm{R}} = 67.8$



#740 – Deuterium – $v_{\mathrm{perp}} = 53.7$ m/s – $\theta = 25°$
$D = 8$ mm – $L = 9.35$ mm – $X_{\mathrm{R}} = 7.2$



$$F(d) = X_{\mathrm{R}} \frac{d}{D} K_0 \left(\frac{X_{\mathrm{R}}}{C} \frac{d}{L} \right) \quad \text{with } X_{\mathrm{R}} = \left(\frac{v_{\mathrm{perp}}}{v_{\mathrm{thr}}} \right)^2$$

Threshold velocity when pellet starts breaking

P. Parks. *Modeling dynamic fracture of cryogenic pellets.* General Atomics, San Diego, CA, USA, Report No. GA-A28325, Jun. 2016

Adopted parameters for the modified Parks model as determined from ORNL experiments: T.E. Gebhart, L.R. Baylor, S. J. Meitner. *IEEE T. Plasma Sci.* 48(6):1598-1605, 2020

Fragment Size Distribution: Experiments & Statistical Fragmentation Model

Parks' model for selected AUG SPI experiments (calibration cases)

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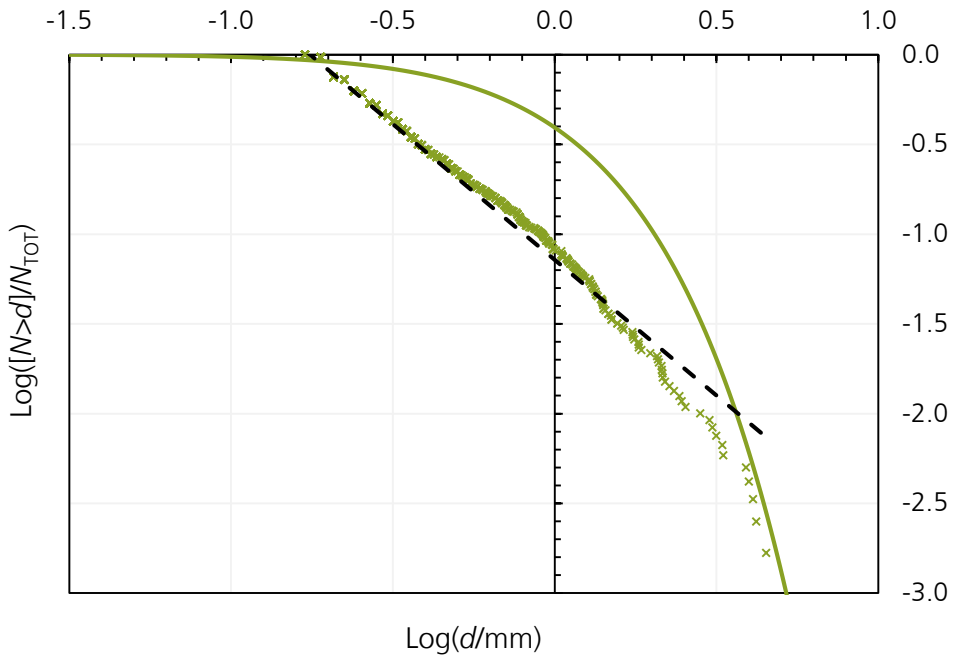
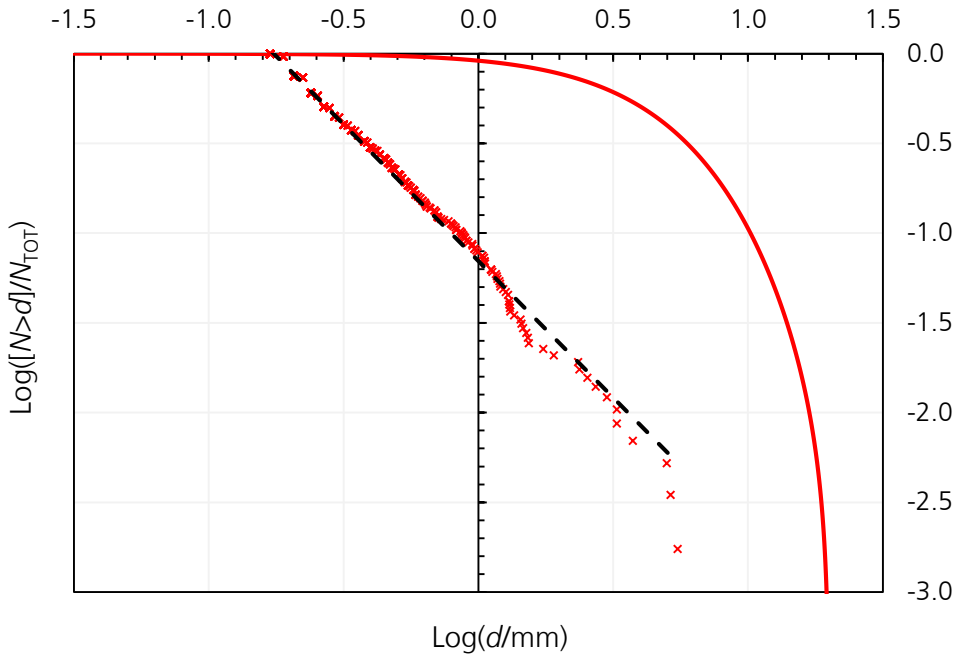


#740 – Deuterium – $v_{\mathrm{perp}} = 53.7$ m/s – $\theta = 25°$ – $X_{\mathrm{R}} = 7.2$



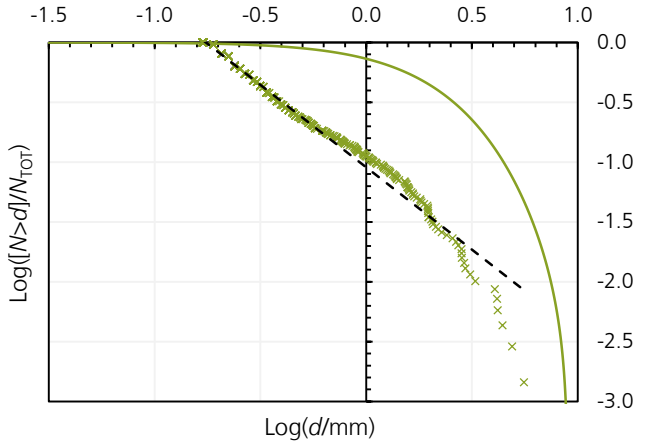
- Experimental data through application of Fraunhofer EMI traking algorithm on experimental videos
- Significant discrepancy in the cumulative FSD (here presented in normalized and Log plots)
- Graphs also show a linear fit with a relationship in the form $\mathrm{Log}(N > d) = a \cdot \mathrm{Log}\,(d) + b$*

*N.L. Johnson et al. *Adv. Space Res.* 28(9):1377-1384, 2001

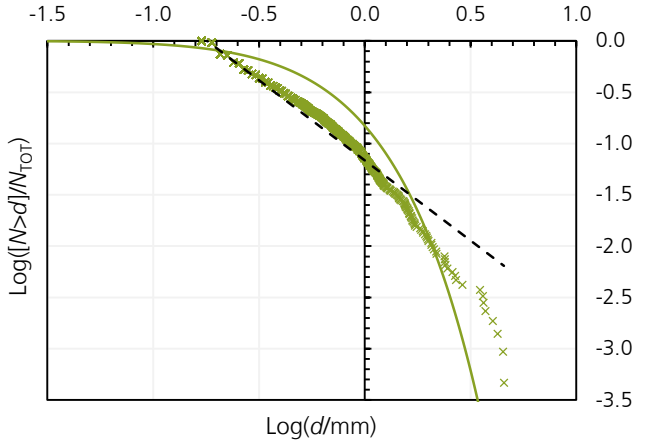
Fragment Size Distribution: Experiments & Statistical Fragmentation Model

Parks' model for selected experiments from ASDEX upgrade (validation cases)

#700 – Ne – v_{perp} = 46.1 m/s – θ = 25° – X_R = 33.2

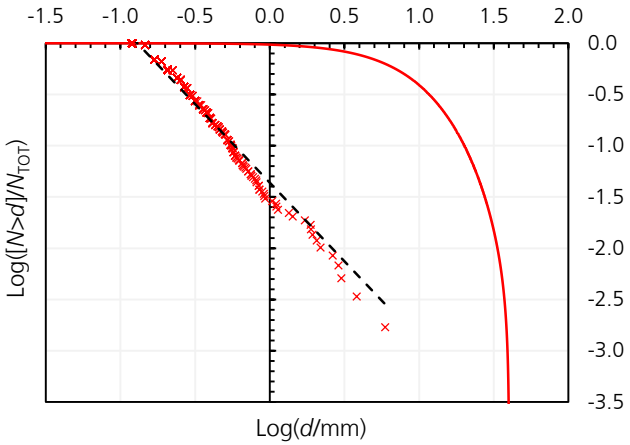


#714 – Ne – v_{perp} = 91.0 m/s – θ = 25° – X_R = 129.5

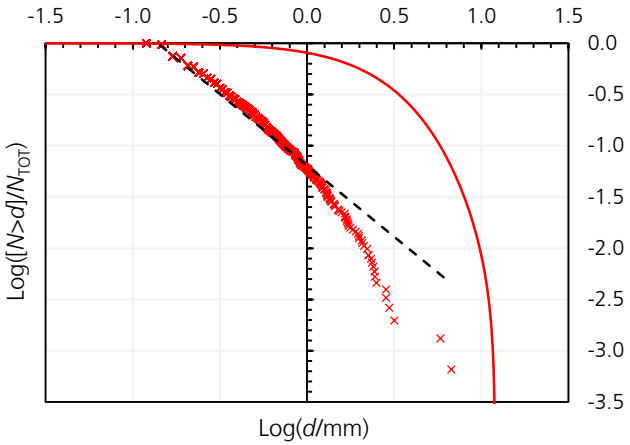


Better agreement for higher X_R

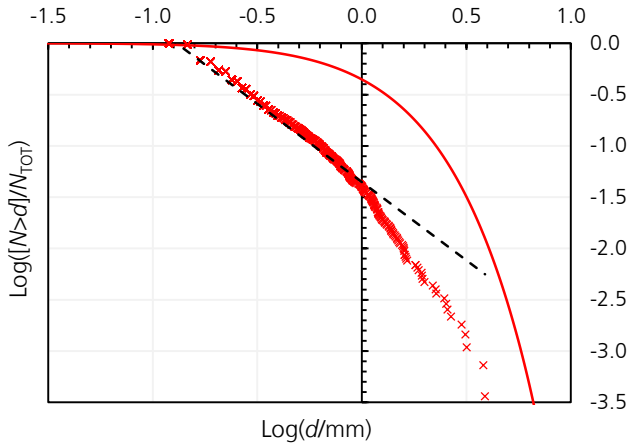
#1213 – D_2 – v_{perp} = 38.3 m/s – θ = 12.5° – X_R = 3.7



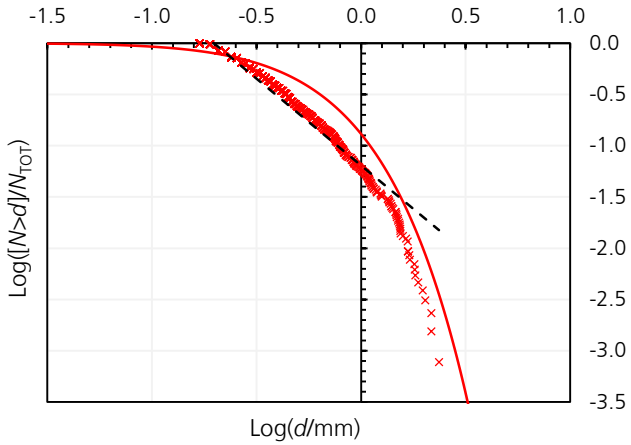
#1209 – D_2 – v_{perp} = 71.5 m/s – θ = 12.5° – X_R = 12.8



#780 – D_2 – v_{perp} = 115.3 m/s – θ = 25° – X_R = 33.2



#811 – D_2 – v_{perp} = 165.3 m/s – θ = 25° – X_R = 68.3

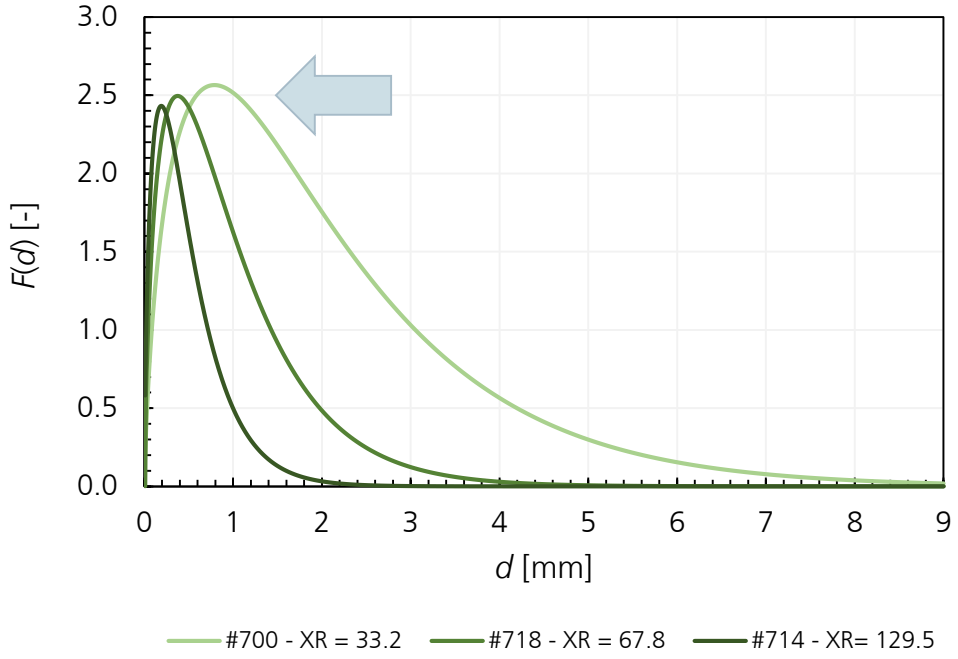


Fragment Size Distribution: Experiments & Statistical Fragmentation Model

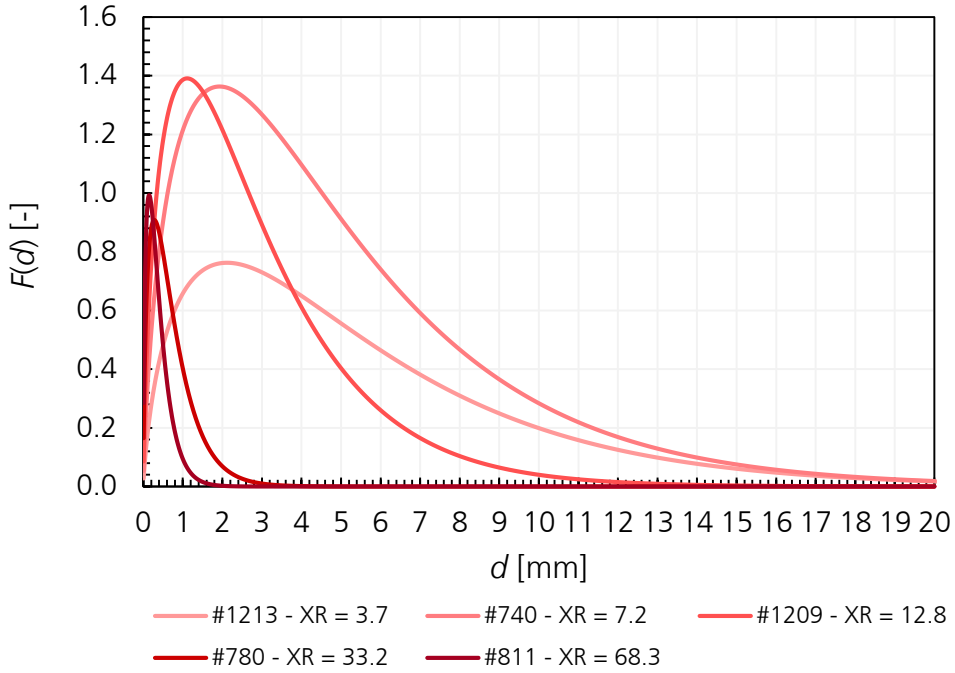
Parks' model for selected AUG SPI experiments – General considerations

$$F(d) = X_{\mathrm{R}} \frac{d}{D} K_0 \left(\frac{X_{\mathrm{R}}}{C} \frac{d}{L} \right)$$

Neon pellets



Deuterium pellets



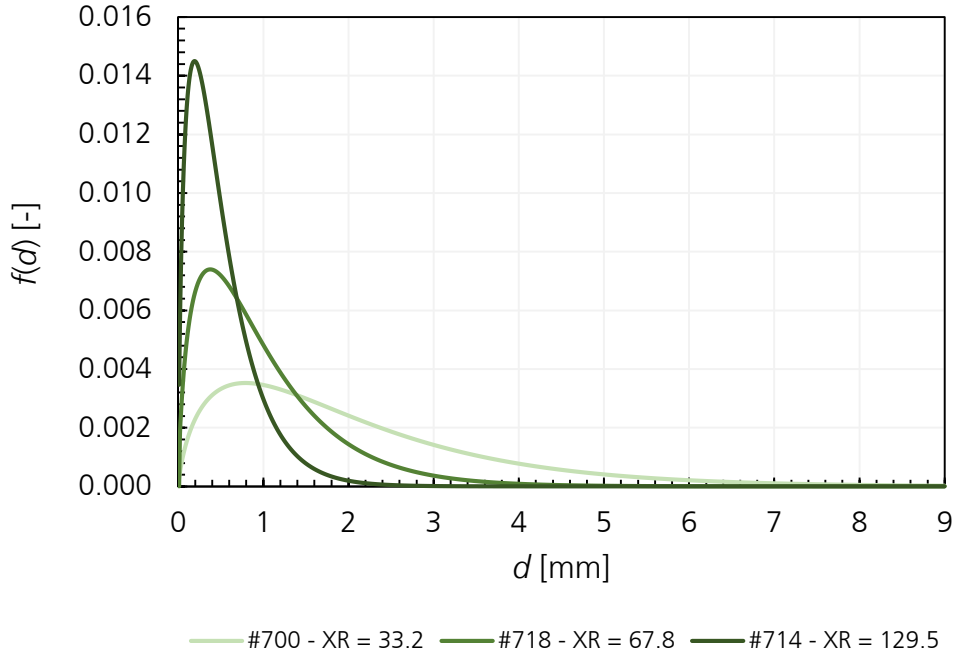
- The Parks equation as adapted by Gebhart et al. is not a normal distribution, namely $\int_0^\infty F(d) = \int_0^\infty X_{\mathrm{R}} \frac{d}{D} K_0 \left(\frac{X_{\mathrm{R}}}{C} \frac{d}{L} \right) \neq 1$
- For a given material, the absolute peak value is a function of L/D only → X_{R} only changes the width of the FSD
- First, a normalization is required in order to better compare different shattering scenarios

Fragment Size Distribution: Experiments & Statistical Fragmentation Model

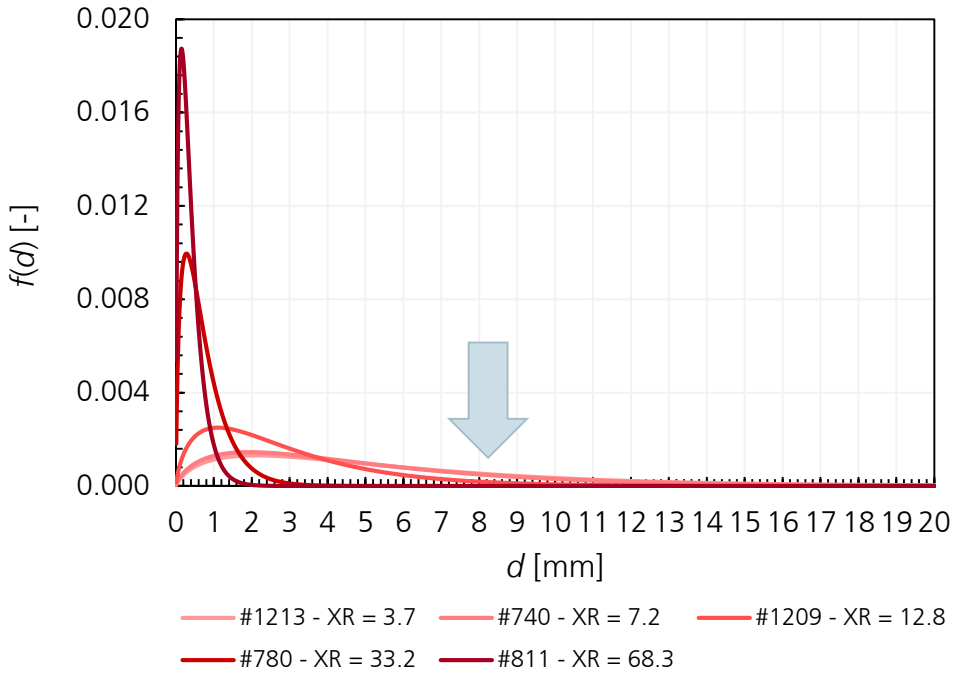
Parks' model for selected AUG SPI experiments – General considerations

$$F(d) = X_{\mathrm{R}} \frac{d}{D} K_0 \left(\frac{X_{\mathrm{R}}}{C} \frac{d}{L} \right)$$

Neon pellets



Deuterium pellets

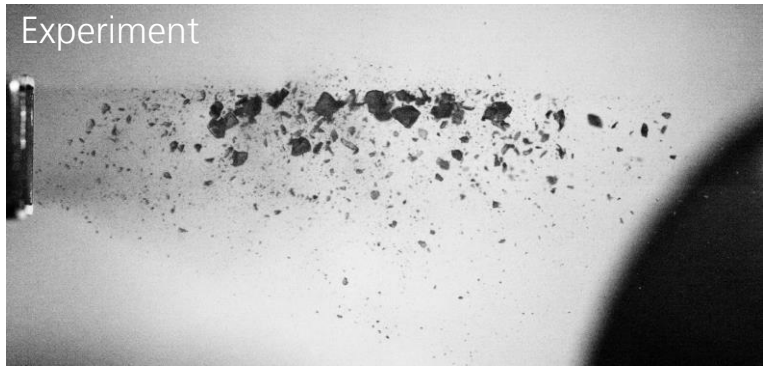


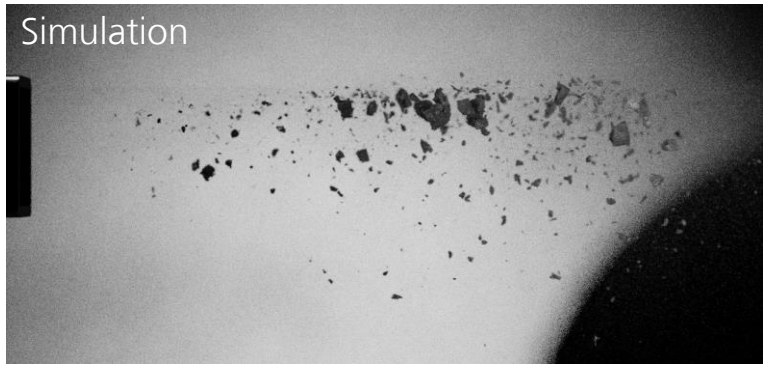
- After the normalization, some FSDs still provide a significant probability for fragments larger than the pellet size
- Assuming that treshold velocities, and thus X_{R}, can be relatively well determined, we focus on the free fitting parameter C

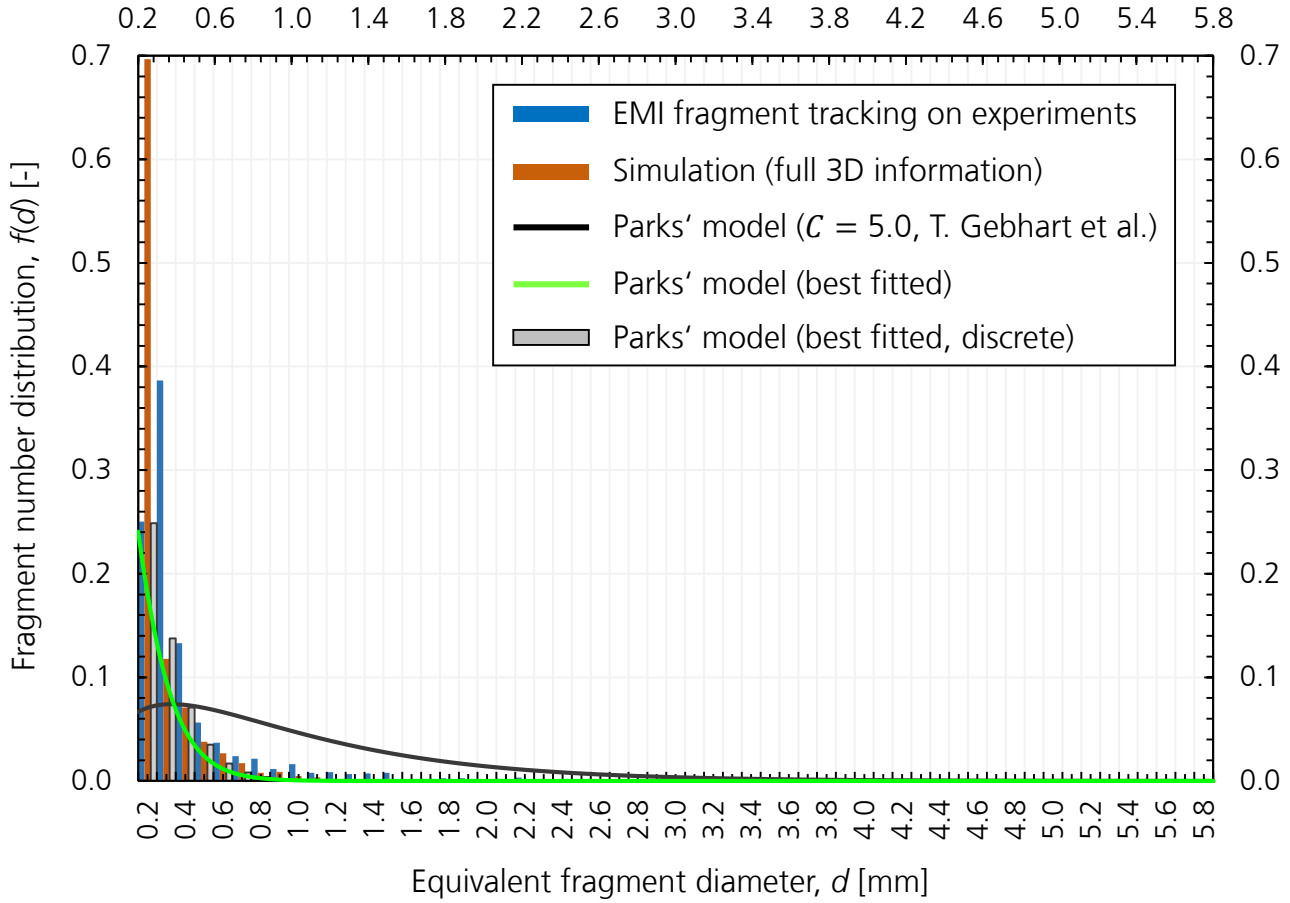
Fragment Size Distribution: Experiments & Statistical Fragmentation Model

Parks' model for selected AUG SPI experiments

#718 – Neon (calibration case)
$\theta = 25°$
$v_{\mathrm{perp}} = 65.9$ m/s
$X_{\mathrm{R}} = 67.8$







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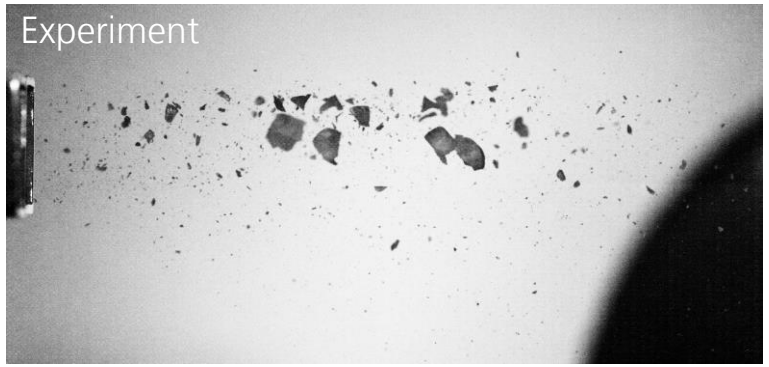
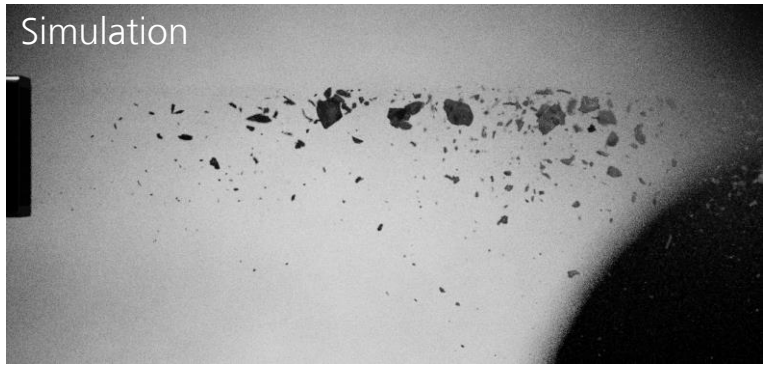
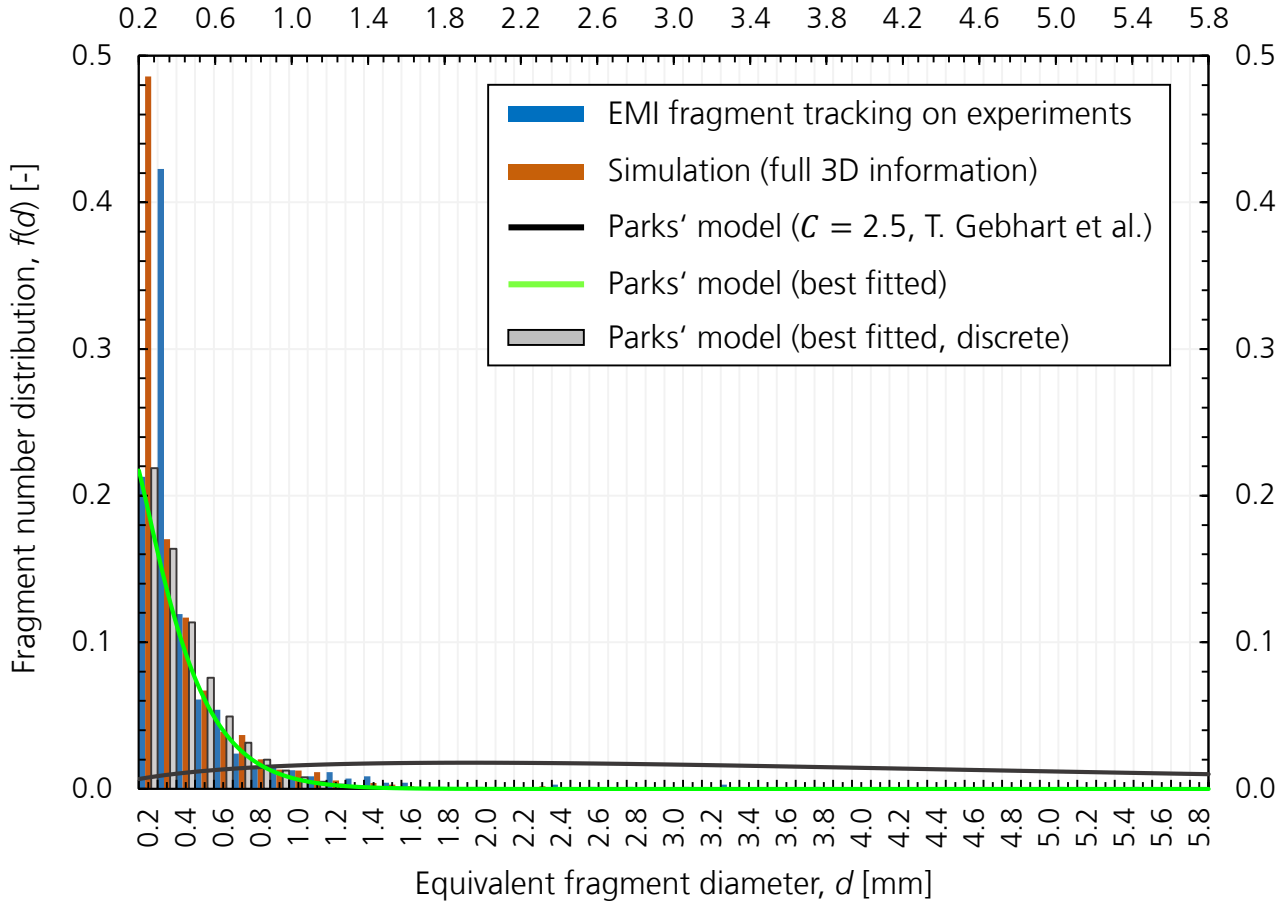
Fragment Size Distribution: Experiments & Statistical Fragmentation Model

Parks' model for selected AUG SPI experiments

#740 – Deuterium (calibration case)
$\theta = 25°$
$v_{\mathrm{perp}} = 53.7$ m/s
$X_{\mathrm{R}} = 7.2$







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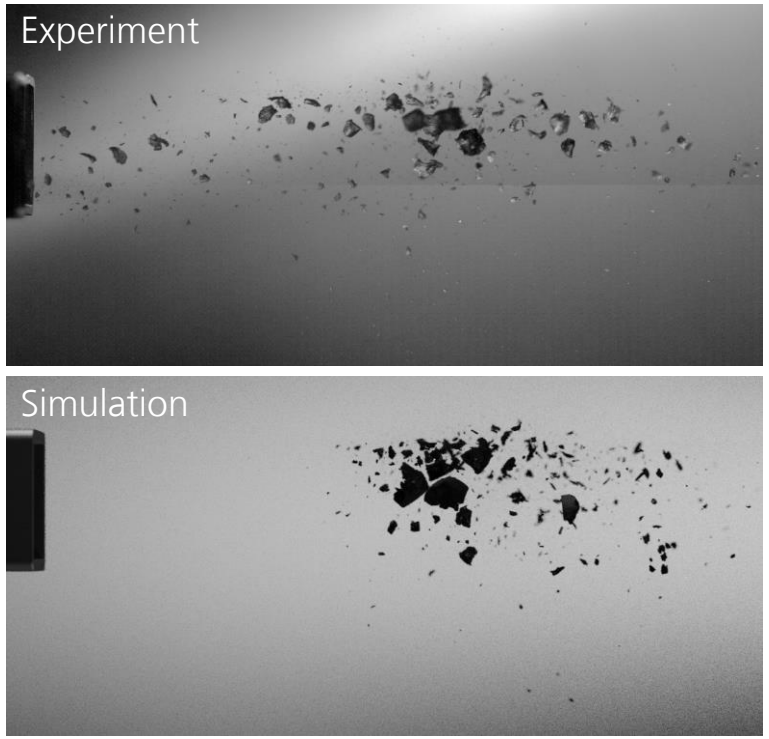
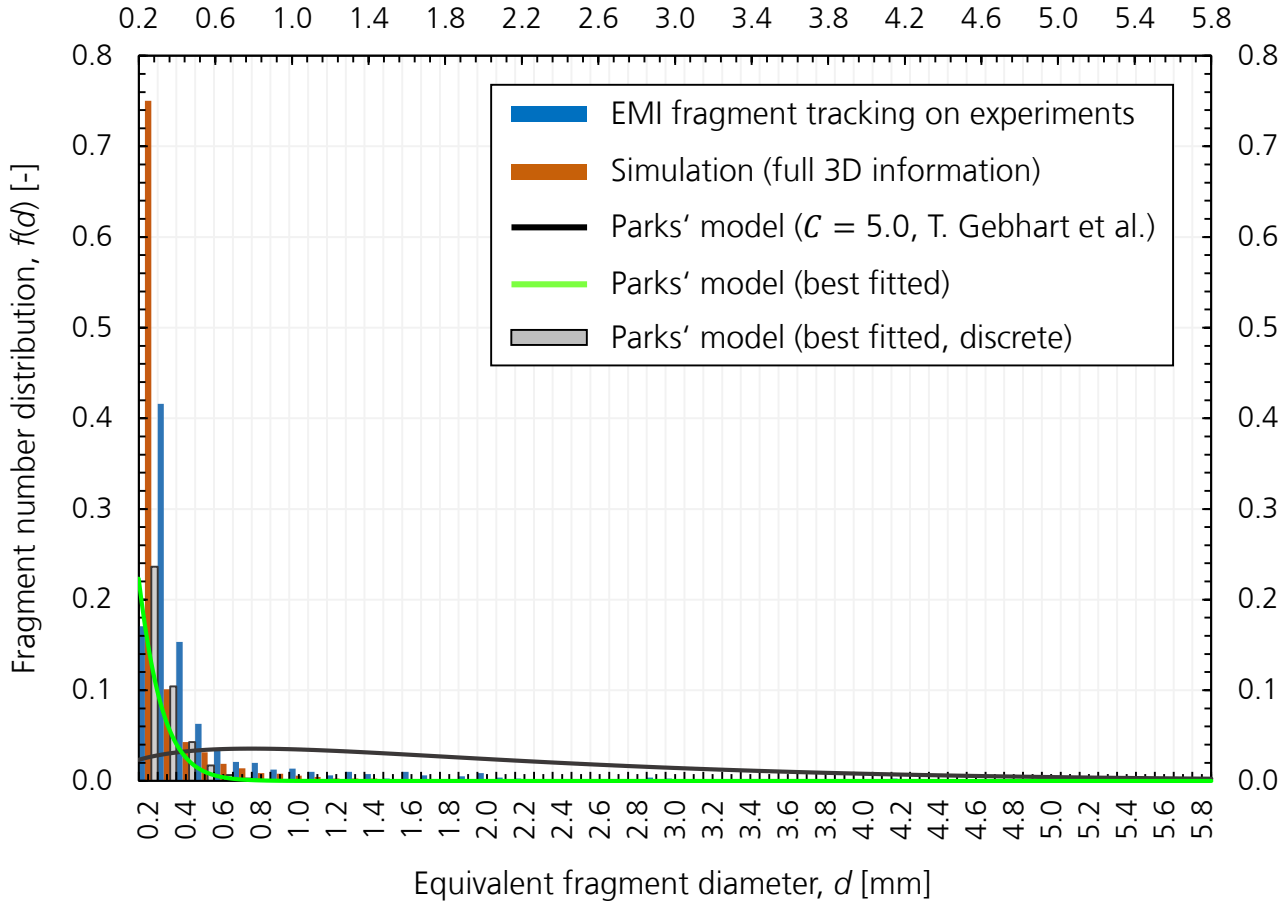
Fragment Size Distribution: Experiments & Statistical Fragmentation Model

Parks' model for selected AUG SPI experiments

#700 – Neon (validation case)
$\theta = 25°$
$v_{\mathrm{perp}} = 46.1$ m/s
$X_{\mathrm{R}} = 33.2$

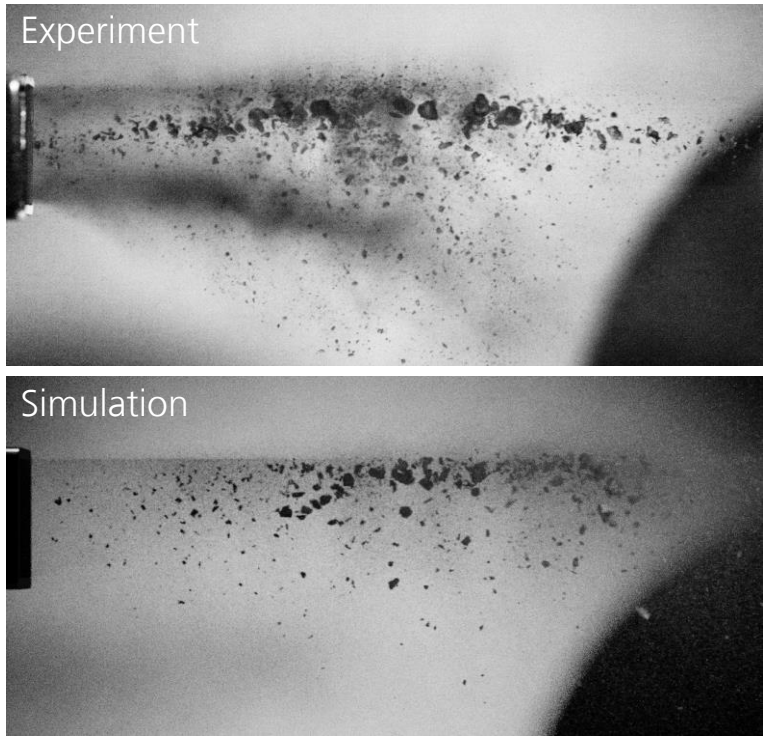


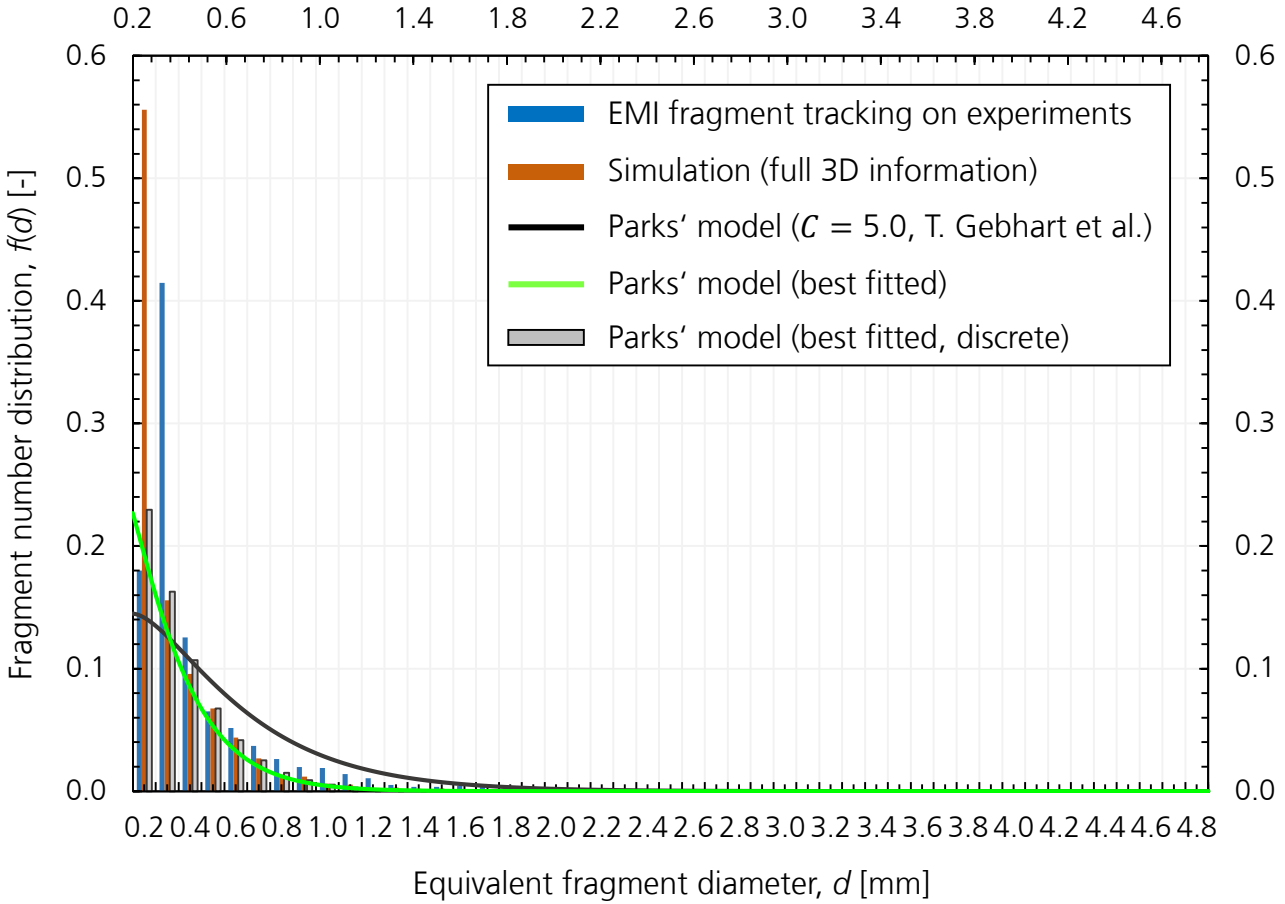


Fragment Size Distribution: Experiments & Statistical Fragmentation Model

Parks' model for selected AUG SPI experiments

#714 – Neon (validation case)
$\theta = 25°$
$v_{\mathrm{perp}} = 91.0$ m/s
$X_{\mathrm{R}} = 129.5$

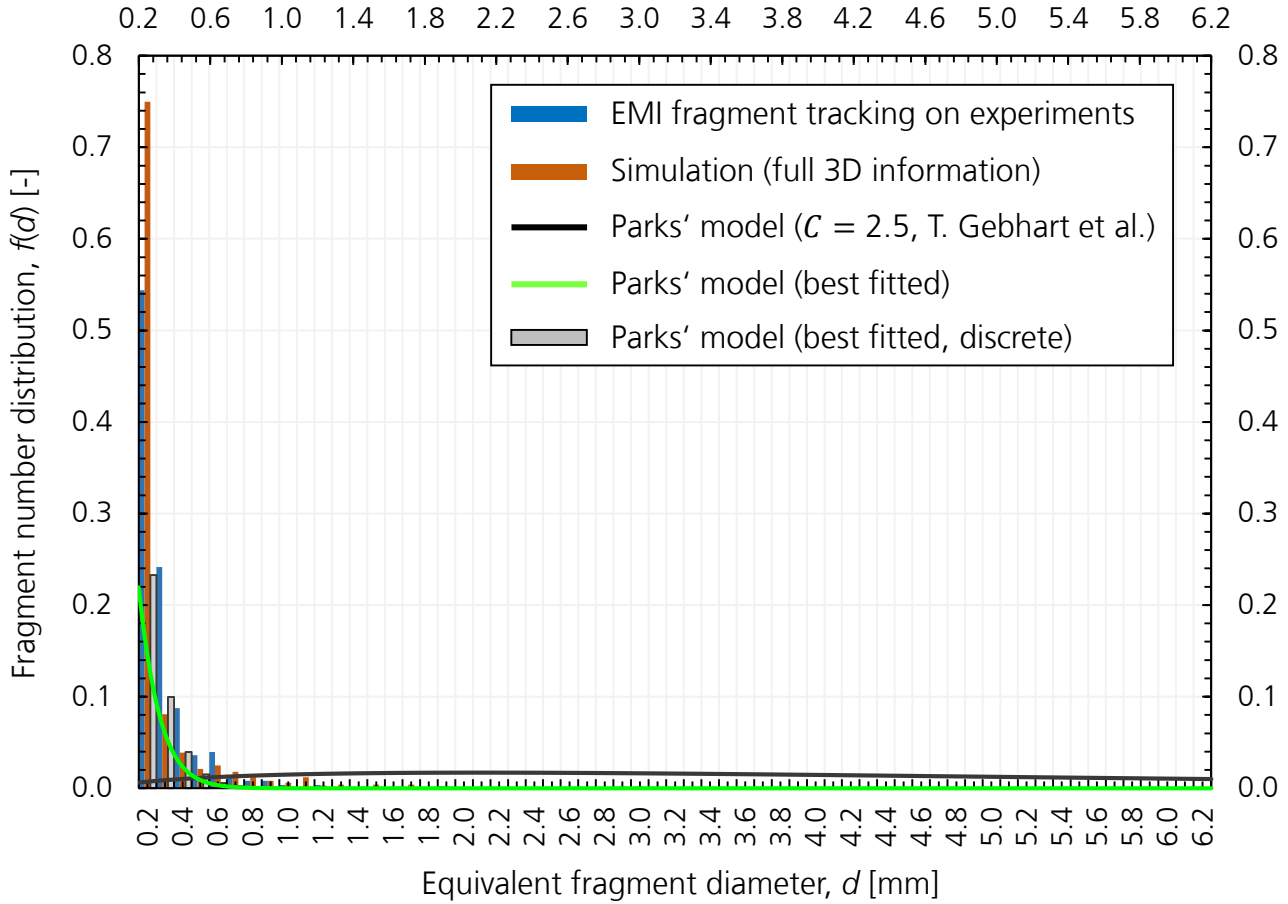




Fragment Size Distribution: Experiments & Statistical Fragmentation Model

Parks' model for selected AUG SPI experiments

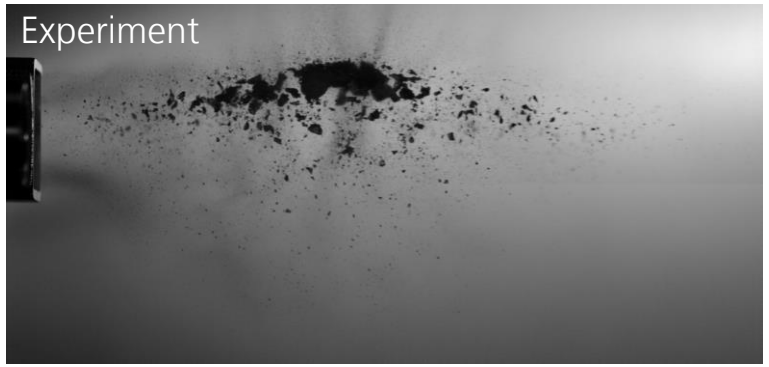
#1213 – Deuterium (validation case)
$\theta = 12.5°$
$v_{\mathrm{perp}} = 38.3$ m/s
$X_{\mathrm{R}} = 3.7$

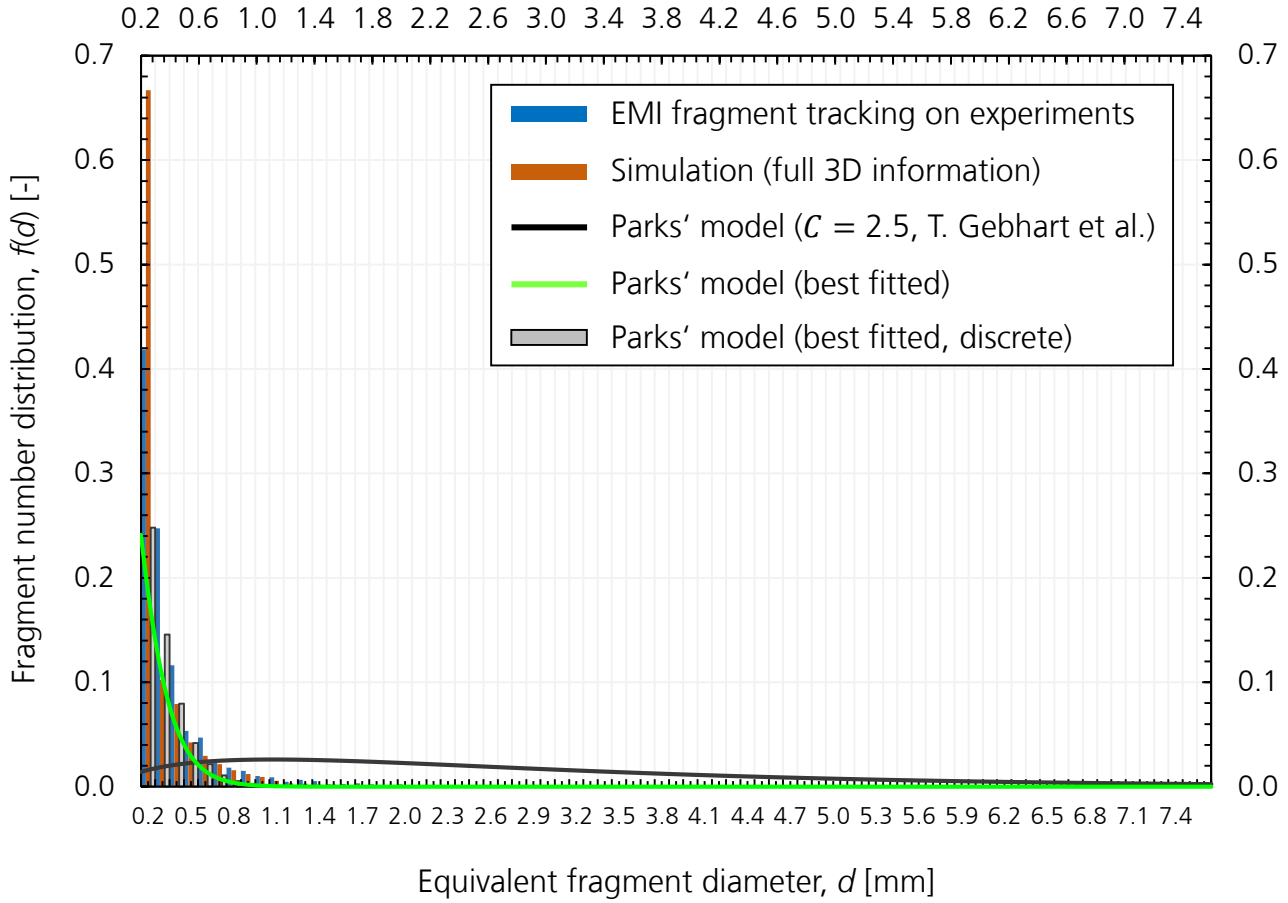


Fragment Size Distribution: Experiments & Statistical Fragmentation Model

Parks' model for selected AUG SPI experiments

#1209 – Deuterium (validation case)
$\theta = 12.5°$
$v_{\mathrm{perp}} = 71.5$ m/s
$X_{\mathrm{R}} = 12.8$

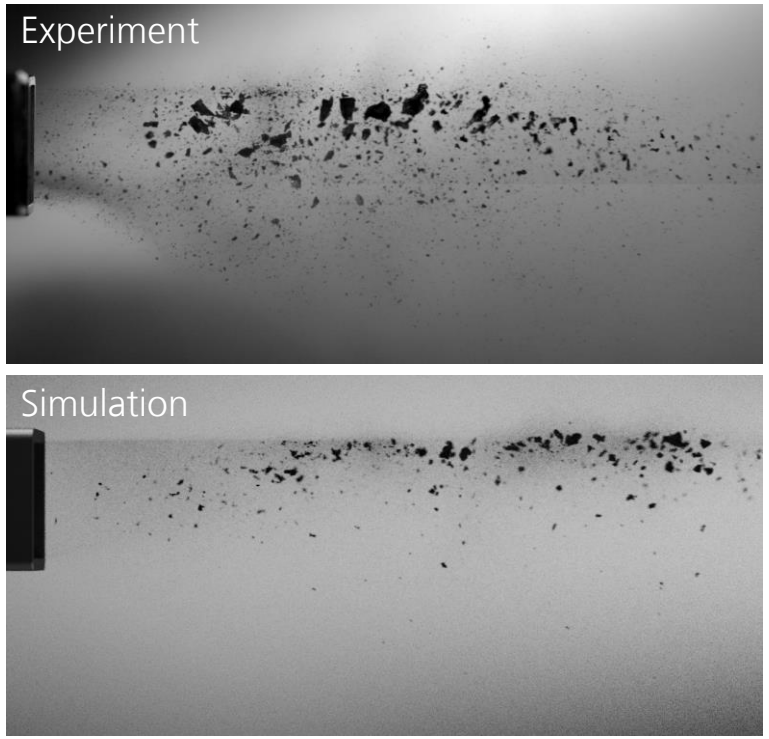


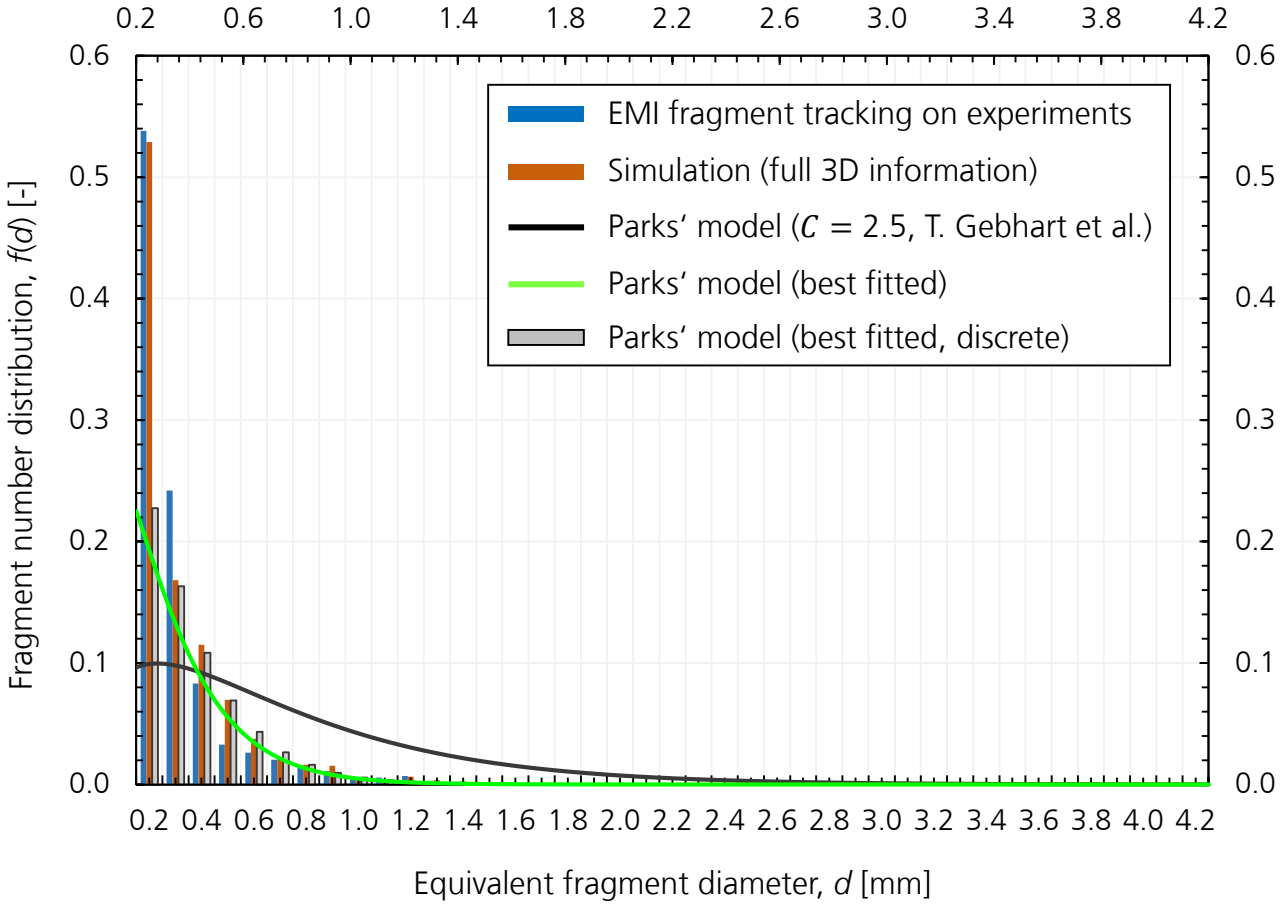


Fragment Size Distribution: Experiments & Statistical Fragmentation Model

Parks' model for selected AUG SPI experiments

#780 – Deuterium (validation case)
$\theta = 25°$
$v_{\mathrm{perp}} = 115.3$ m/s
$X_{\mathrm{R}} = 33.2$

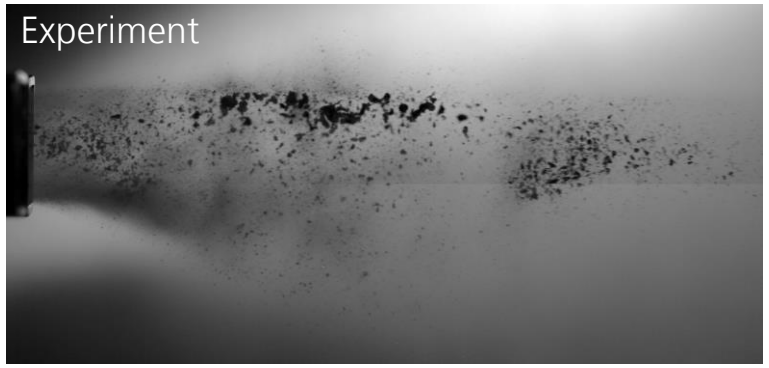


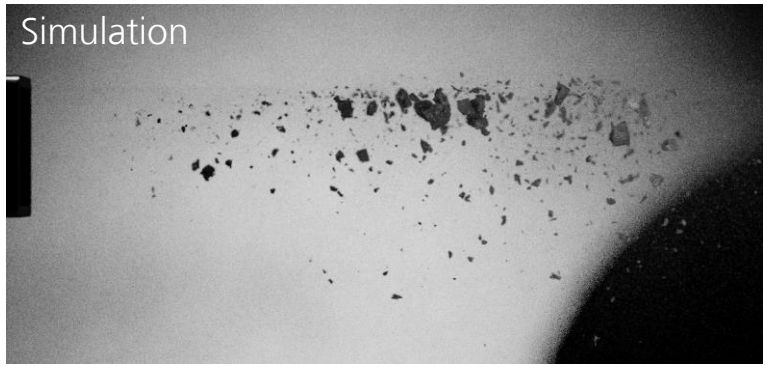


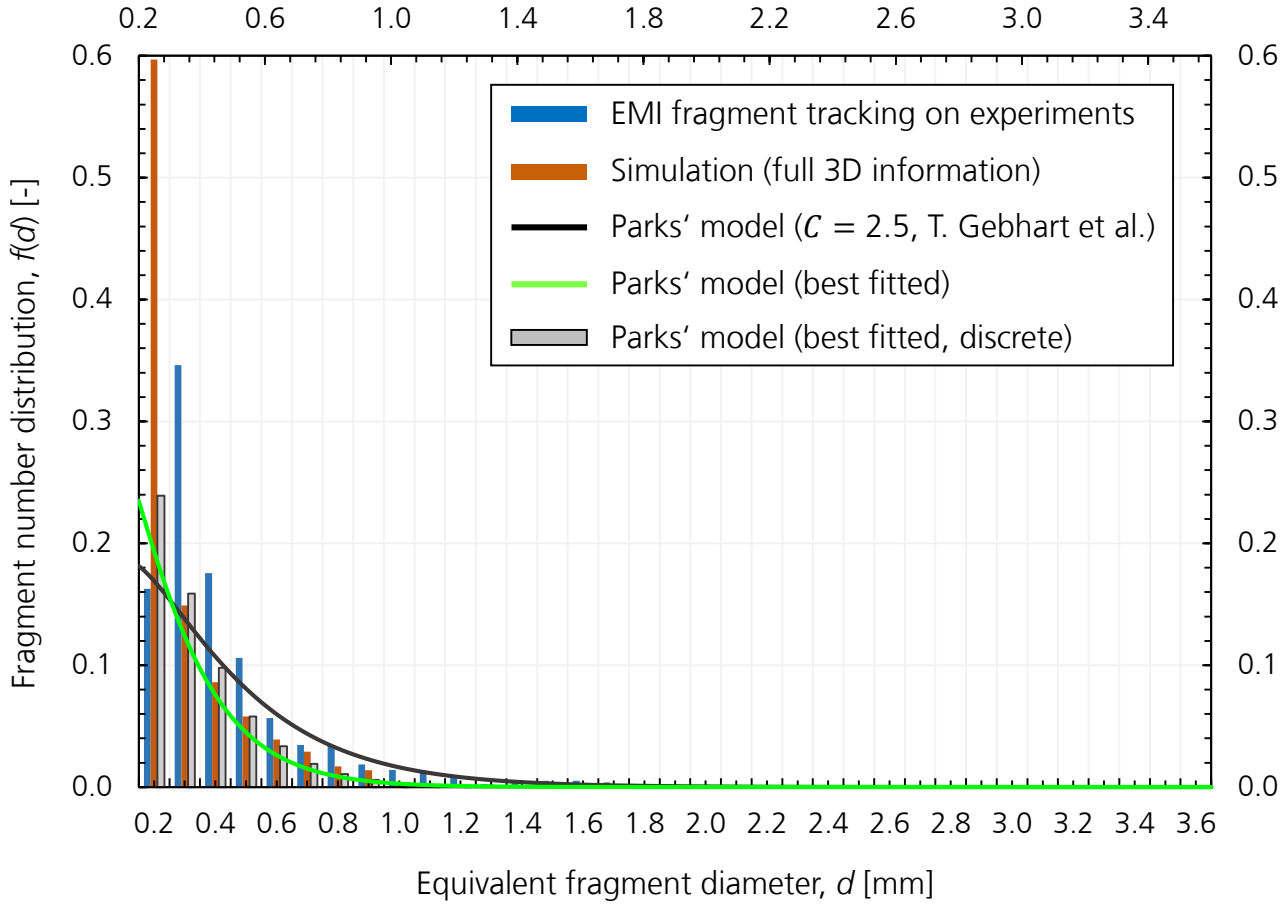
Fragment Size Distribution: Experiments & Statistical Fragmentation Model

Parks' model for selected AUG SPI experiments

#811 – Deuterium (validation case)
$\theta = 25°$
$v_{\mathrm{perp}} = 165.3$ m/s
$X_{\mathrm{R}} = 68.3$







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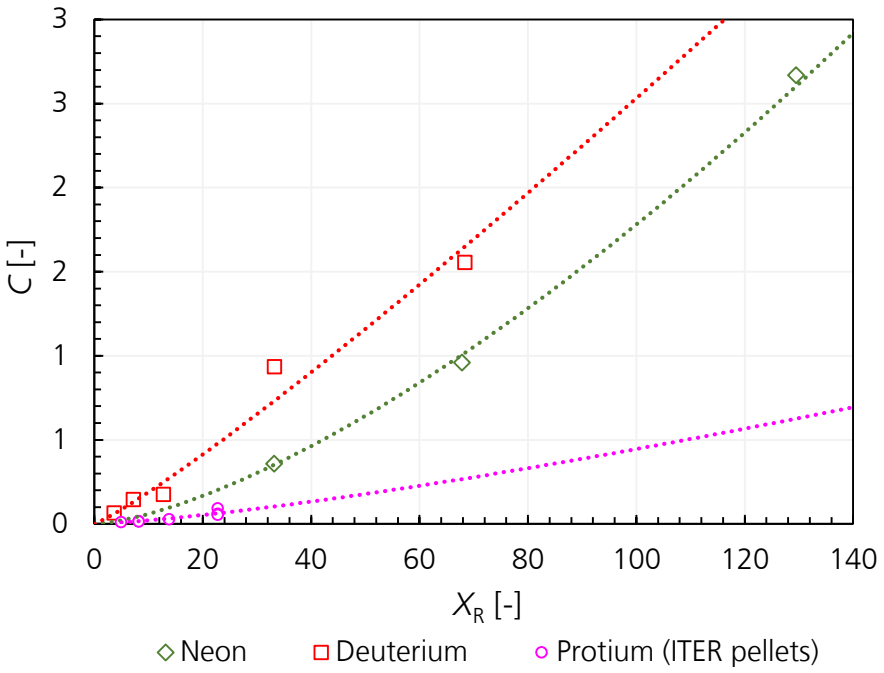
Application of the SFM by Parks to the pellet shattering problem

Conclusion and remarks



- In the adaptation of the Parks model by Gebhart et al., the parameter C shall not be assumed as a constant for a given material.
- Results on ASDEX experiments (8 mm pellets) would suggest a monotonic dependence on X_{R}.
- The extrapolation of our results appears to be compatible with the estimate of C by Gebhart et al. (12.5 mm pellets, L/D =1.5).
- Size-scale dependence of C still needs to be assessed (→28.5 mm ITER).
- Is also v_{thr}, and thus X_{R}, size-scale dependent?
- No v_{thr} and C values available for protium (in progress).

*T.E. Gebhart, L.R. Baylor, S. J. Meitner. *IEEE T. Plasma Sci.* 48(6):1598-1605, 2020

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