Momentum Predictability and Heat Accumulation in Laser-based Space Debris Removal

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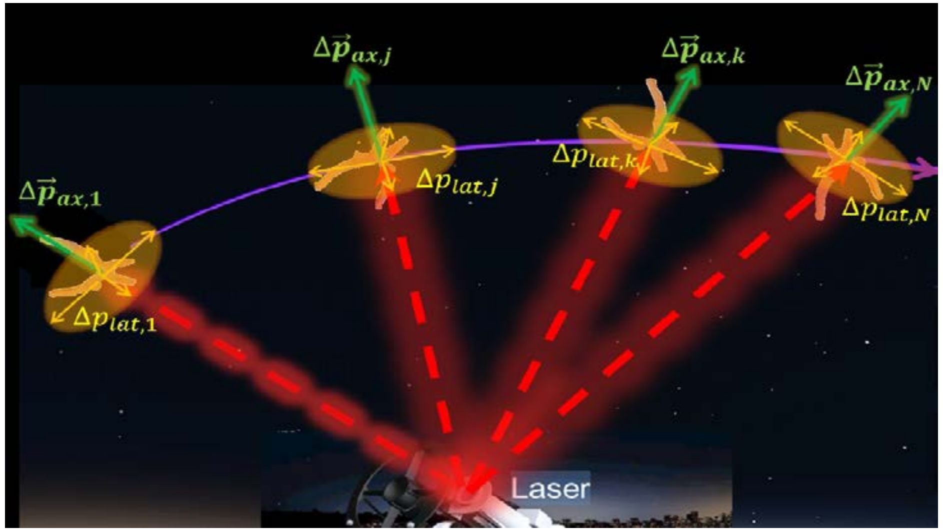
International High Power Laser Ablation Symposium HPLA 2018
Tuesday, March 27

Motivation

Momentum Scatter

- Irregularly shaped targets
- Random target orientation
- Unknown target material



Impulse components in repetitive laser irradiation

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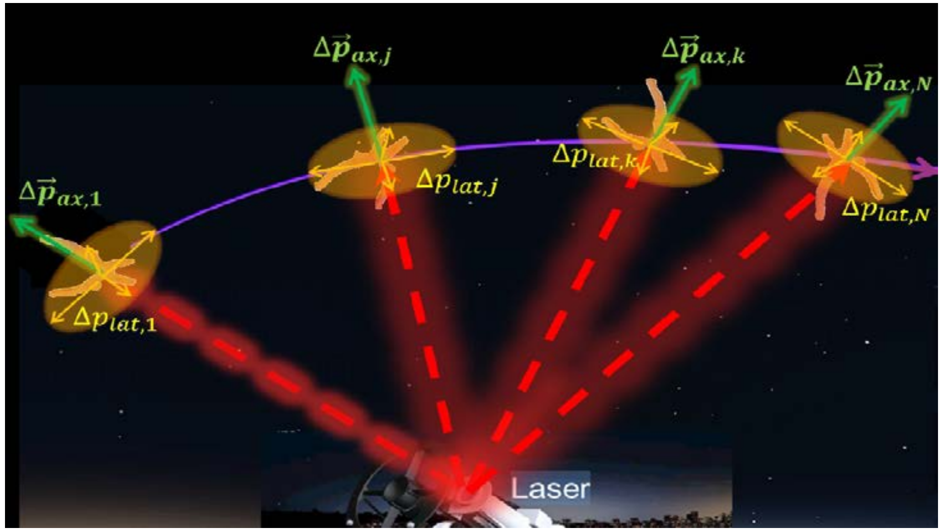
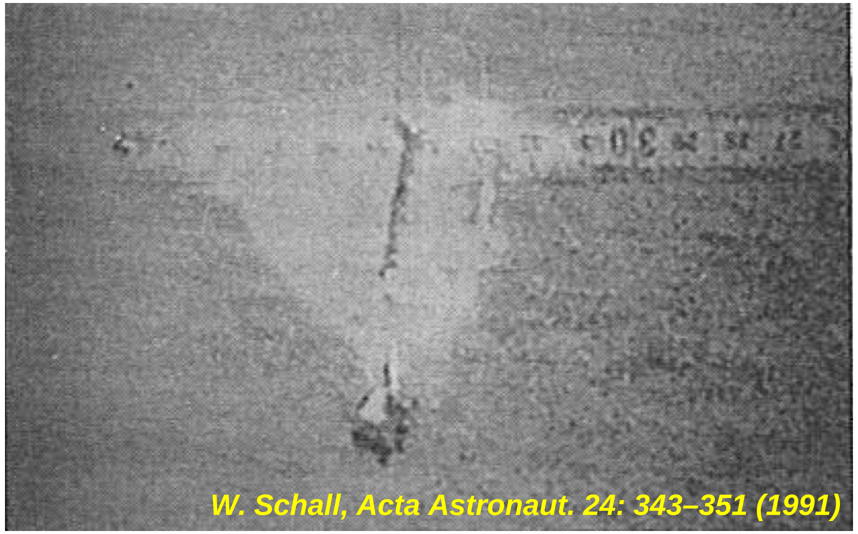


Impulse components in repetitive laser irradiation

Heat Accumulation

- Thermal stress
- Droplet ejection
- Target Melting


W. Schall, Acta Astronaut. 24: 343–351 (1991)

Molten aluminum target after repetitive laser irradiation

Thermal constraints …

Heat Accumulation in Laser Ablation

- Residual heat for metals: $\eta_{res} = \frac{Q_{heat}}{E_L} \approx 15 \ldots 25\ \%$

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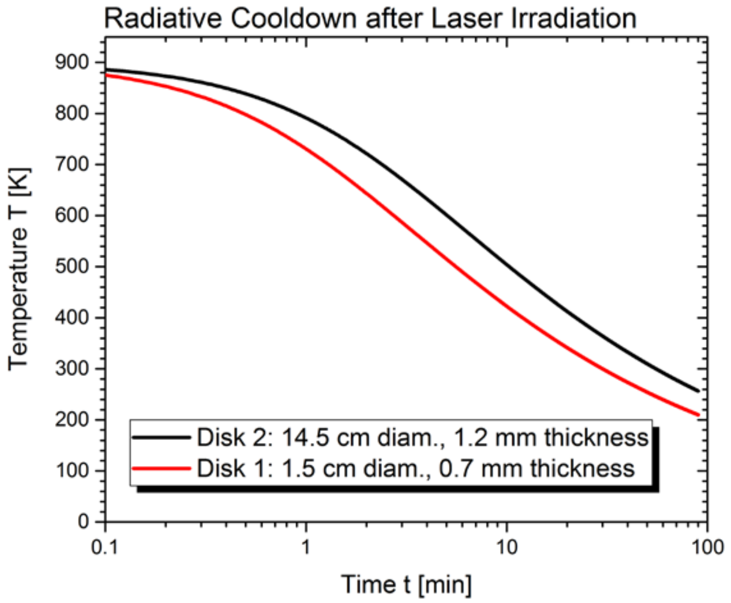

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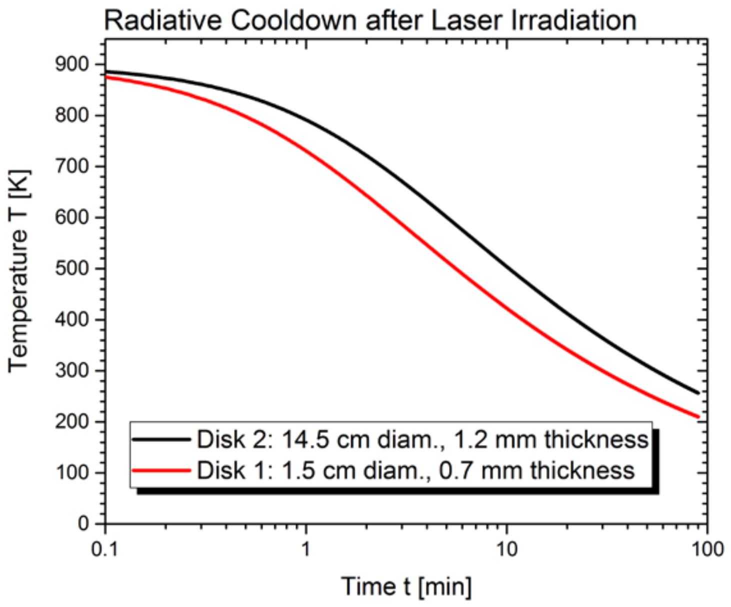

Thermo-Mechanical Coupling Coefficient c_{tm}

- *How much momentum can be transferred, taking into account for the residual heat?*

$$c_{tm} = \frac{\Delta p}{Q_{heat}} \left(= \frac{\Delta p}{\eta_{res} E_L} = \frac{c_m}{\eta_{res}} \right)$$

Scharring et al., AIAA Journal (DOI: 10.2514/1.J056718)

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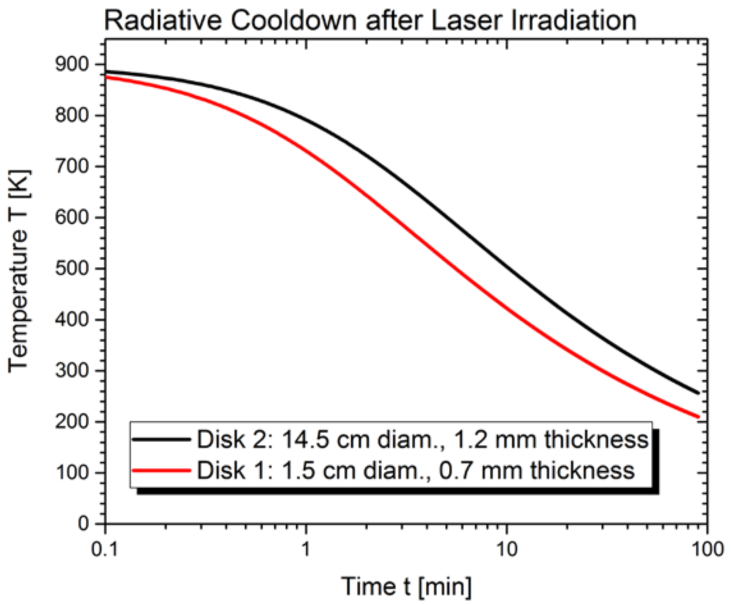

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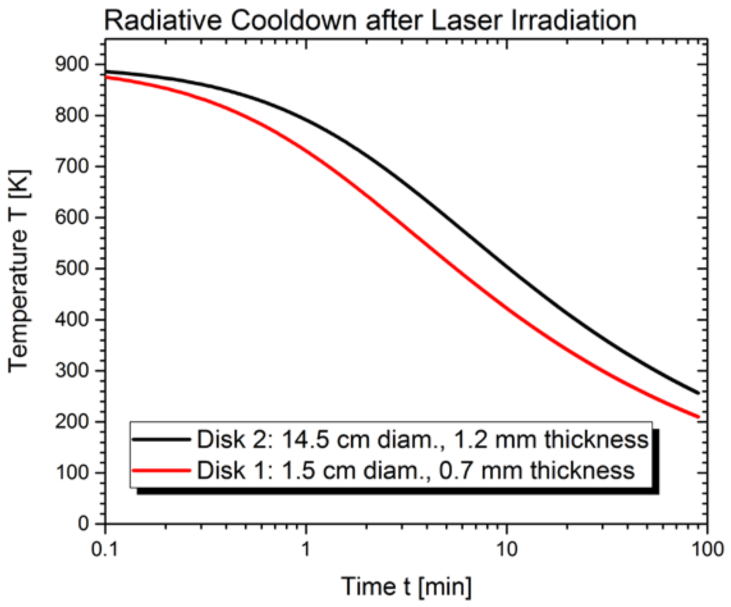

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$$\Delta p_{max} = c_{tm} \cdot c_p \cdot m \cdot (T_m - T_0)$$

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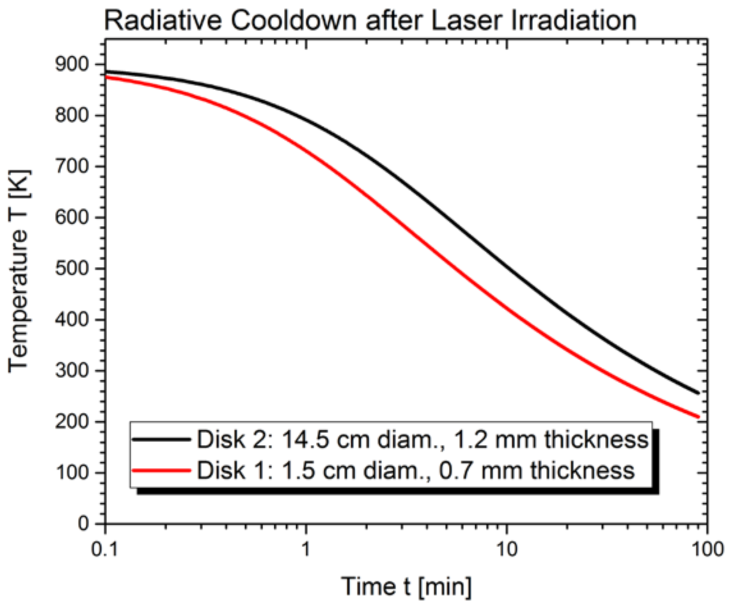

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- Maximum velocity increment:

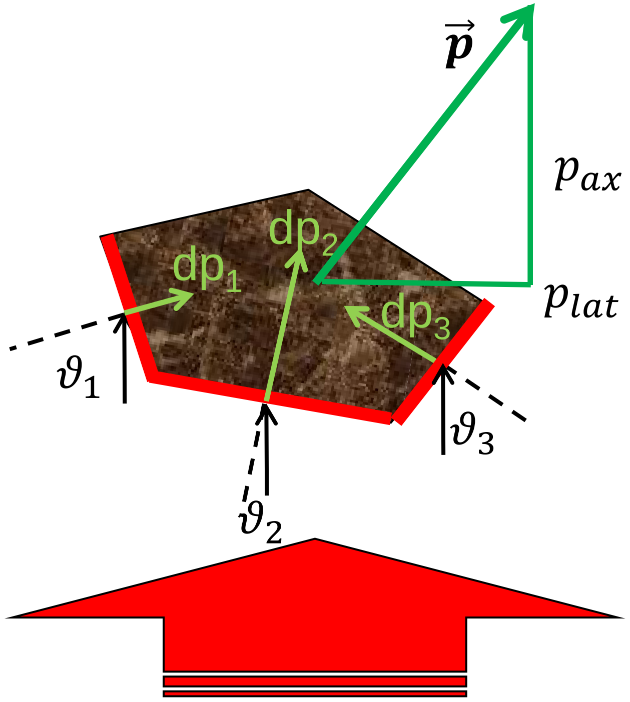
$$\Delta v_{max} = \frac{c_m}{\eta_{res}} \cdot c_p \cdot (T_m - T_0)$$

DLR

… and Momentum Prediction

Area-matrix concept $\vec{p} = c_m \Phi_L \vec{\boldsymbol{k}} \cdot \underline{\boldsymbol{G}}$

Liedahl et al., Adv. Space Res. 52(5): 895 – 915 (2013)



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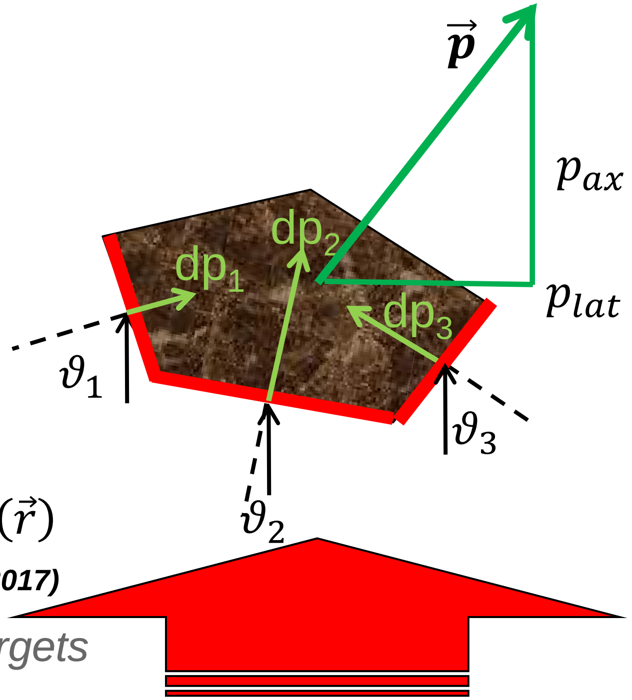

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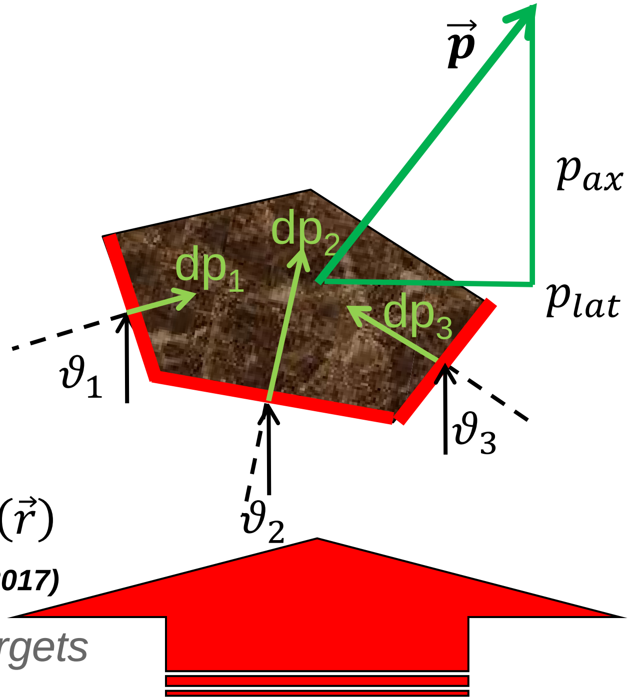

Discretization of **Laser** $\Phi = \Phi(\vec{r})$

Raytracing of Gaussian beam profile: Nvidia Optix, GPU

Discretization of **Matter**

Finite surface elements (obj files)

Discretization of **Interaction**

Parameter dependencies of $c_m(\Phi), \eta_{res}(\Phi)$

Programming language: C++

Python wrapper for API: Monte Carlo studies, Orbital propagation

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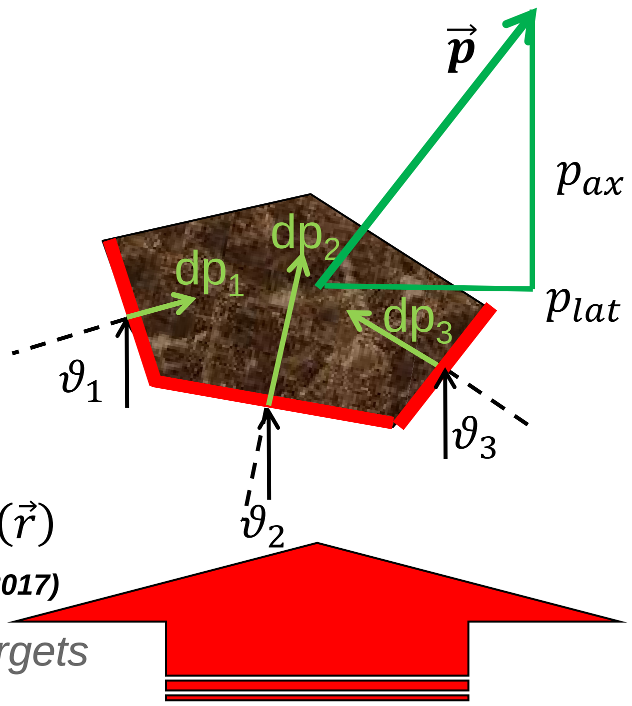

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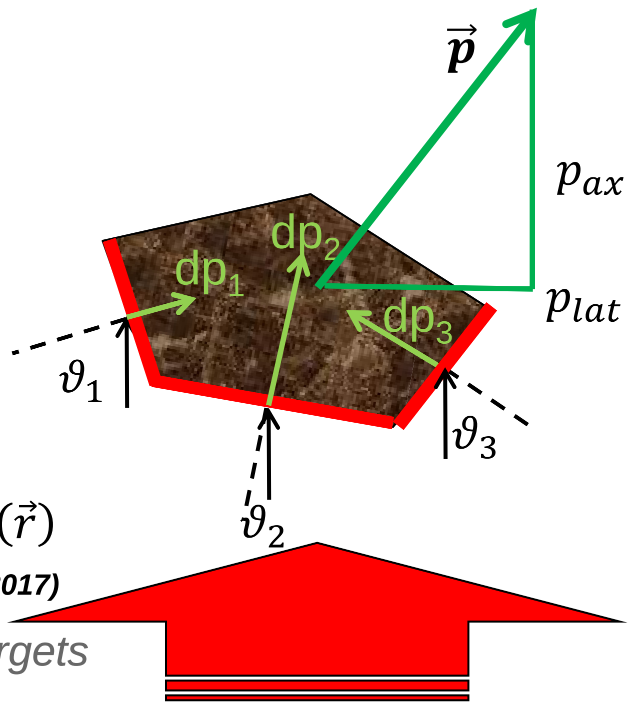

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$c_m(\Phi(\vec{r}))$
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Local momentum density on the surface of an irregularly shaped target.
Cow model courtesy of NVidia.

Monte Carlo Study Design: Baseline Setup

Parameters

- Laser: CLEANSPACE concept
  B. Esmiller et al., Appl. Opt. 53(31): I45-I54 (2014)
  - Pulse energy: $E_L = 25\ kJ$
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- Beam Discretization:
  - 0.1 mm resolution

- Monte Carlo:
  - Random target orientation
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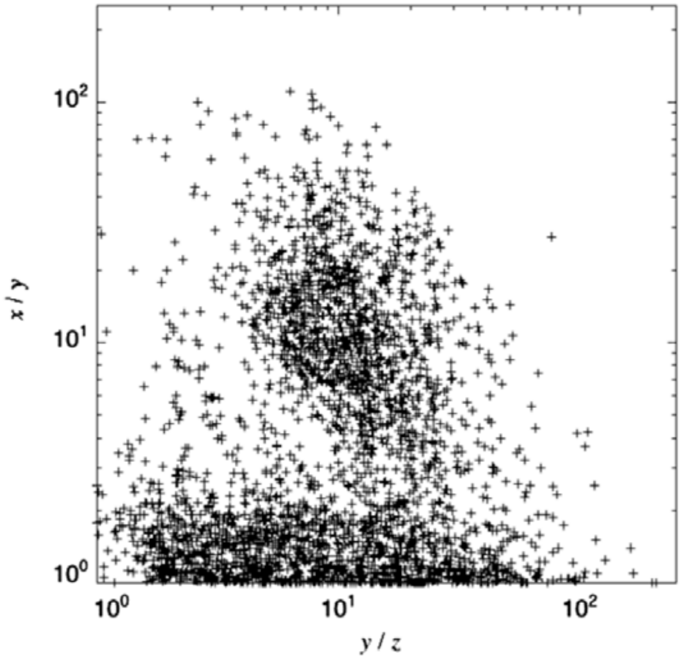

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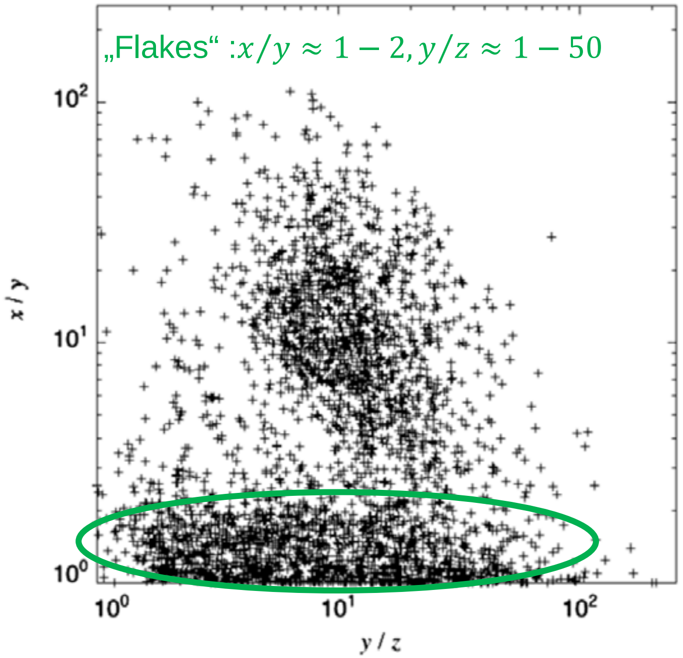

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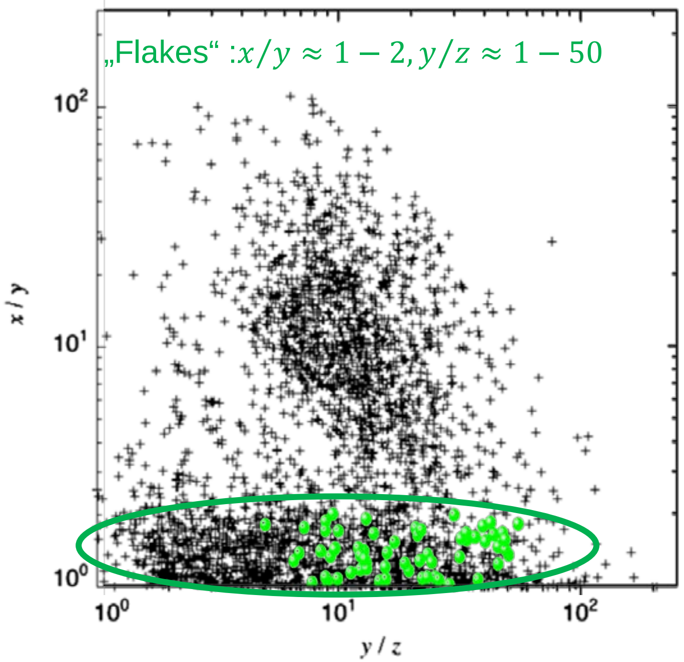
Targets

- 100, randomly generated
- Flake-like ellipsoids
- Material: aluminium



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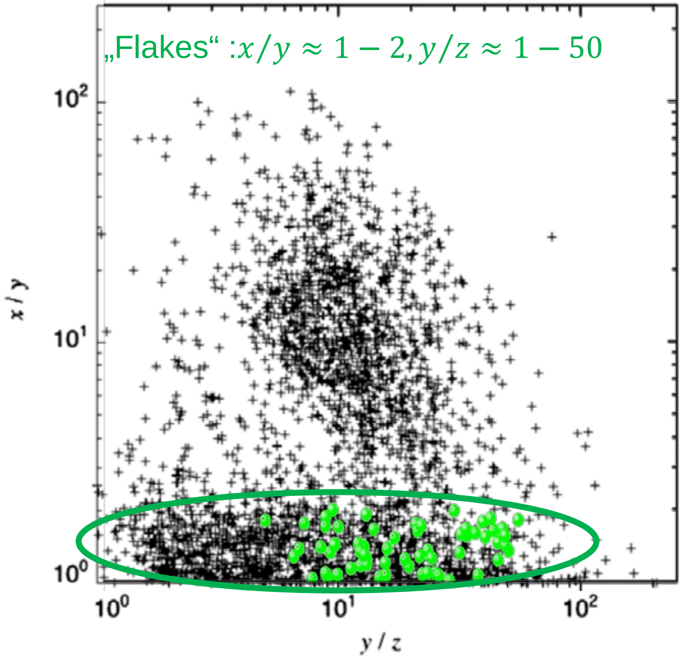

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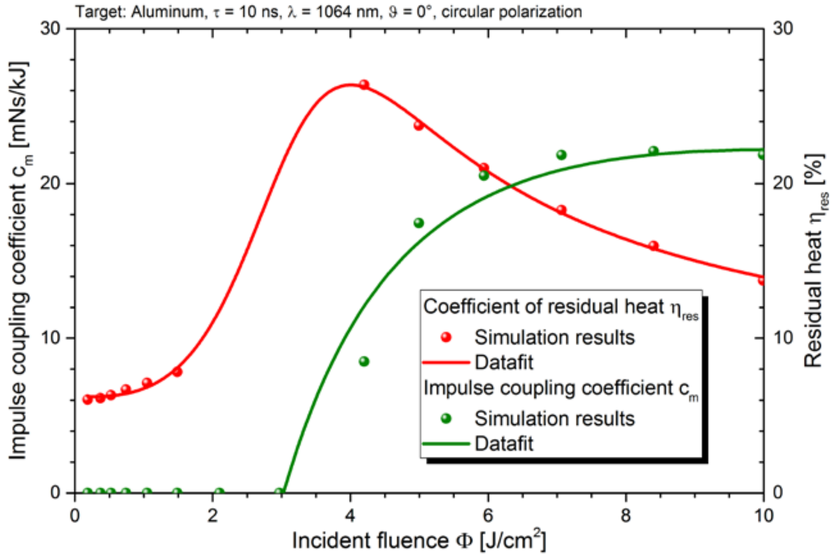
Laser-matter Interaction

- Results from HD simulations (Polly-2T*)
- Datafit parameters → Expedit simulation



****Polly-2T code courtesy of M. Povarnitsyn, RAS Moscow.***

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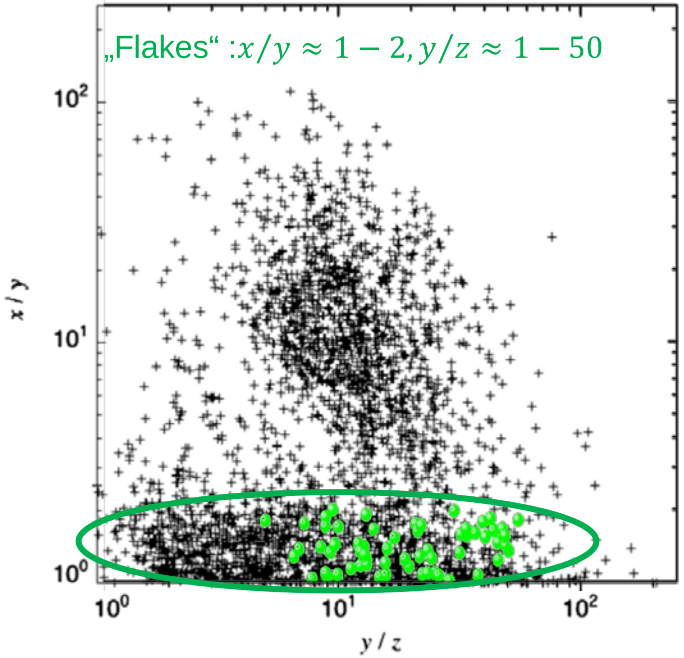

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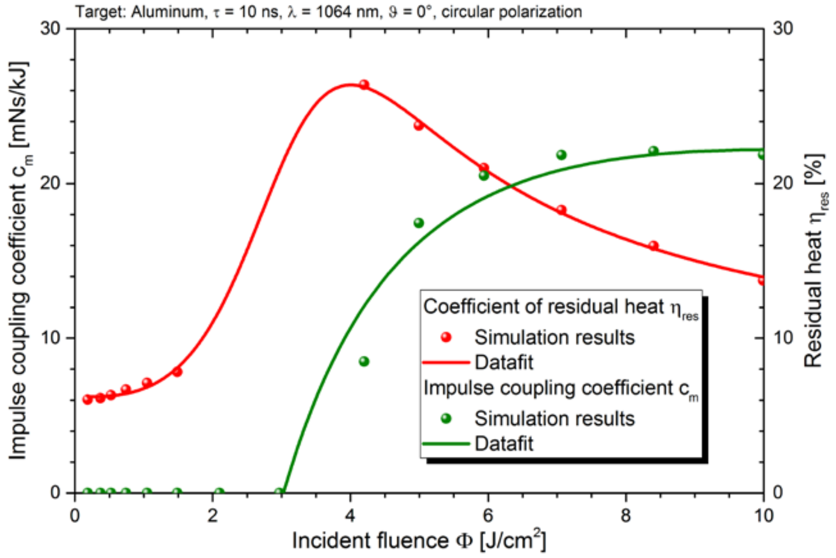
$$c_m[mNs/kJ](\Phi) \underset{(\Phi>\Phi_0)}{\approx} \frac{\Phi-\Phi_0}{a+(\Phi-\Phi_0)} \cdot b \cdot 12.46 \cdot A^{7/16} \cdot \left(\frac{\sqrt{\tau}}{\lambda \cdot \Phi[\mathrm{J/cm^2}]}\right)^c$$

$$\eta_{res}(\Phi) \approx \frac{a_0 + a_1 \cdot \Phi + a_2 \cdot \Phi^2}{1 + a_3 \cdot \Phi + a_4 \cdot \Phi^2 + a_5 \cdot \Phi^3}$$



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Monte Carlo Study: Random Target Orientation

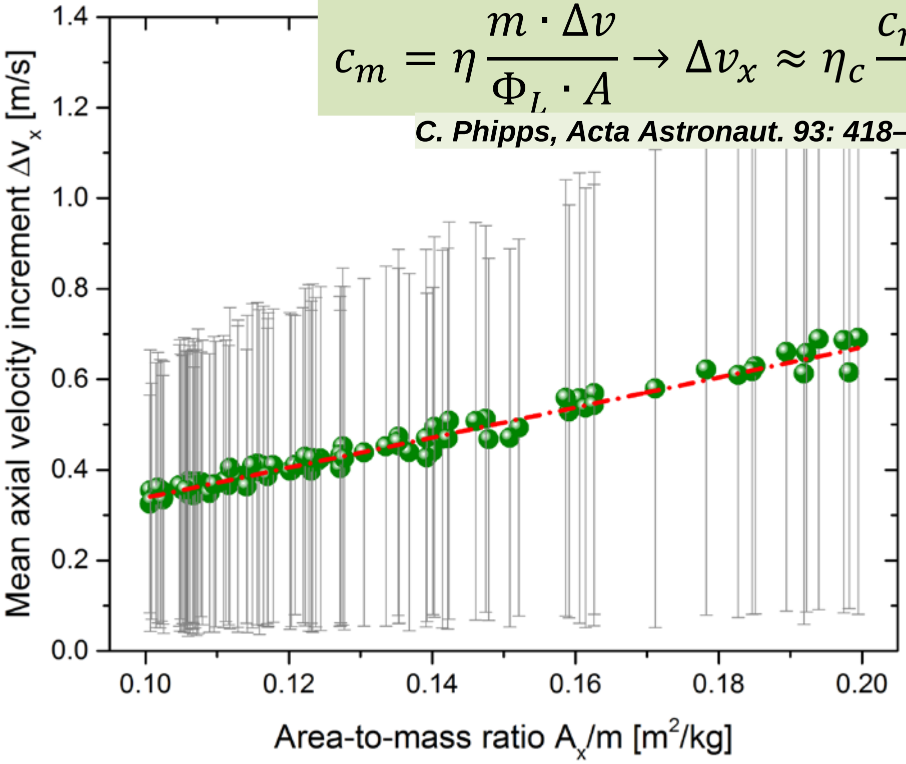
Simulation setup (3 DOF)

- Target CMS = beam center
- Random target orientation
- Gaussian laser spot profile

Velocity Increment Δv

$$c_m = \eta \frac{m \cdot \Delta v}{\Phi_L \cdot A} \rightarrow \Delta v_x \approx \eta_c \frac{c_m \Phi_L A_x}{m}$$

C. Phipps, Acta Astronaut. 93: 418–429 (2014)



→ **Consideration of large momentum scatter necessary**
→ **Collision analysis for conceivable trajectories required**

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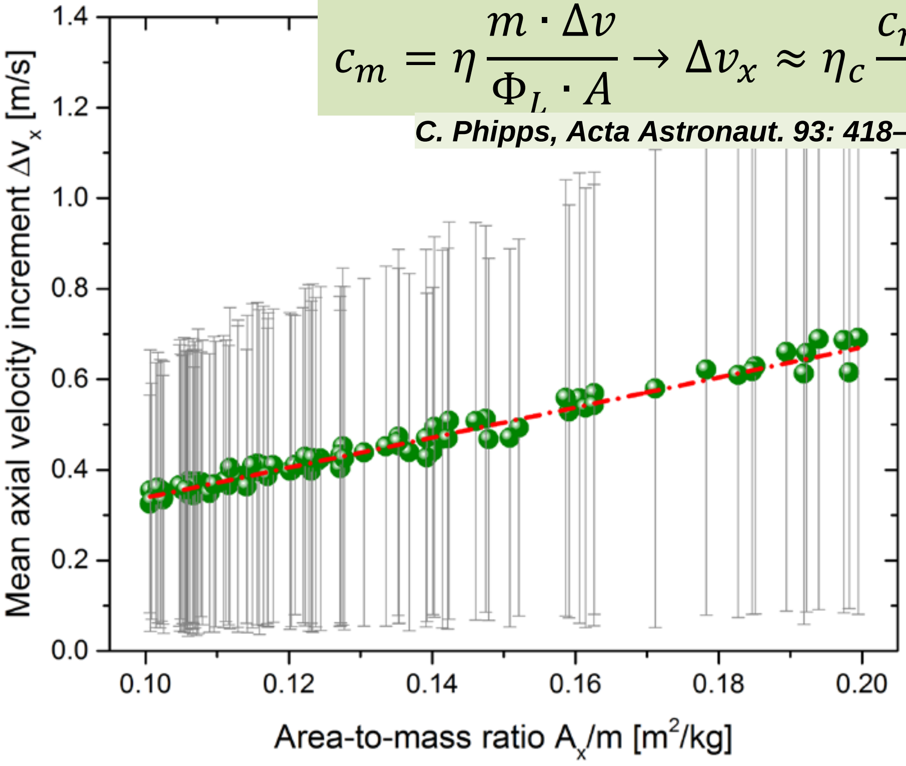
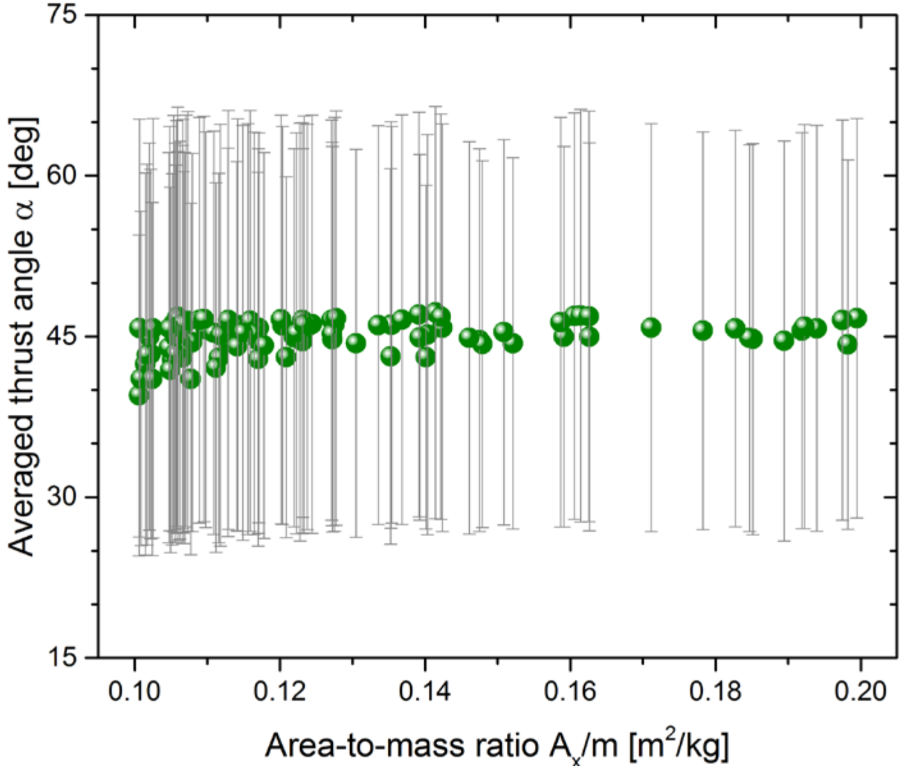


Mean thrust angle



→ **Consideration of large momentum scatter necessary**
→ **Collision analysis for conceivable trajectories required**

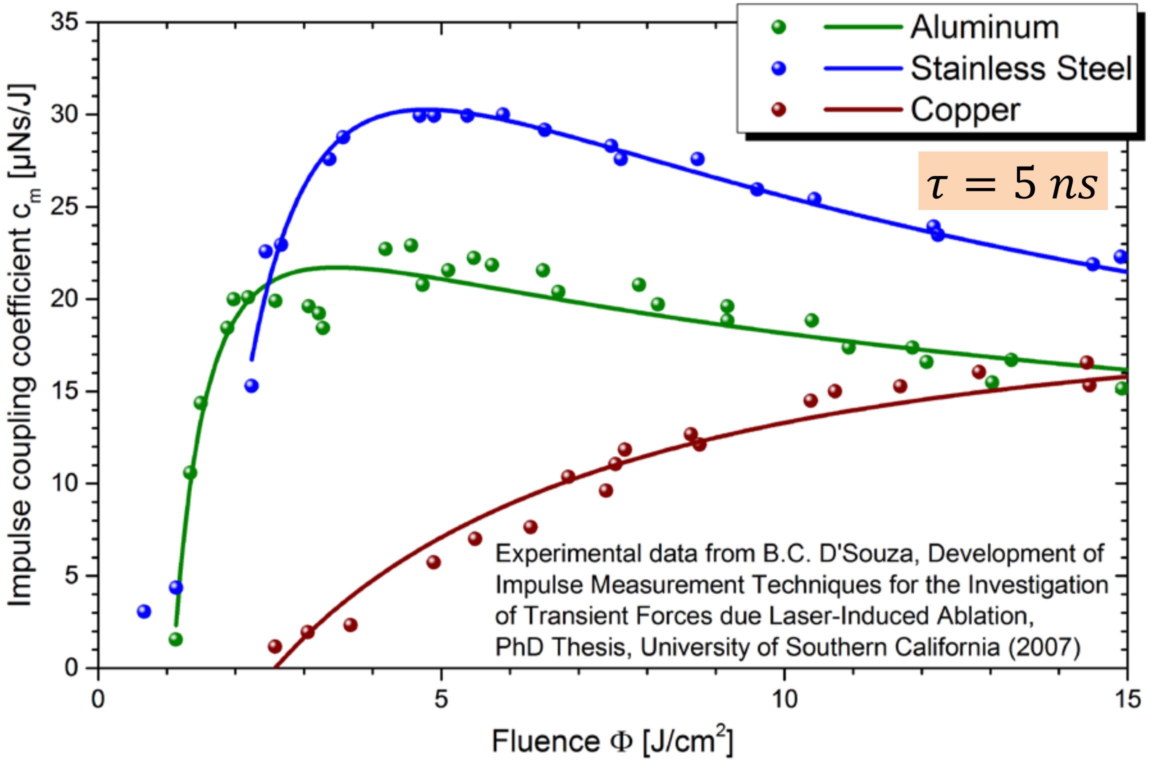
→ **Large thrust angle yields significant losses in Δv_x.**
→ **Lateral momentum might cancel out in multi-pulse irradiation.**

Various Target Materials

Simulation setup (3 DOF)

- Target CMS = beam center
- Random target orientation
- ***Target material: Al, Steel, Cu***

Impulse Coupling Characteristics $c_m(\Phi)$



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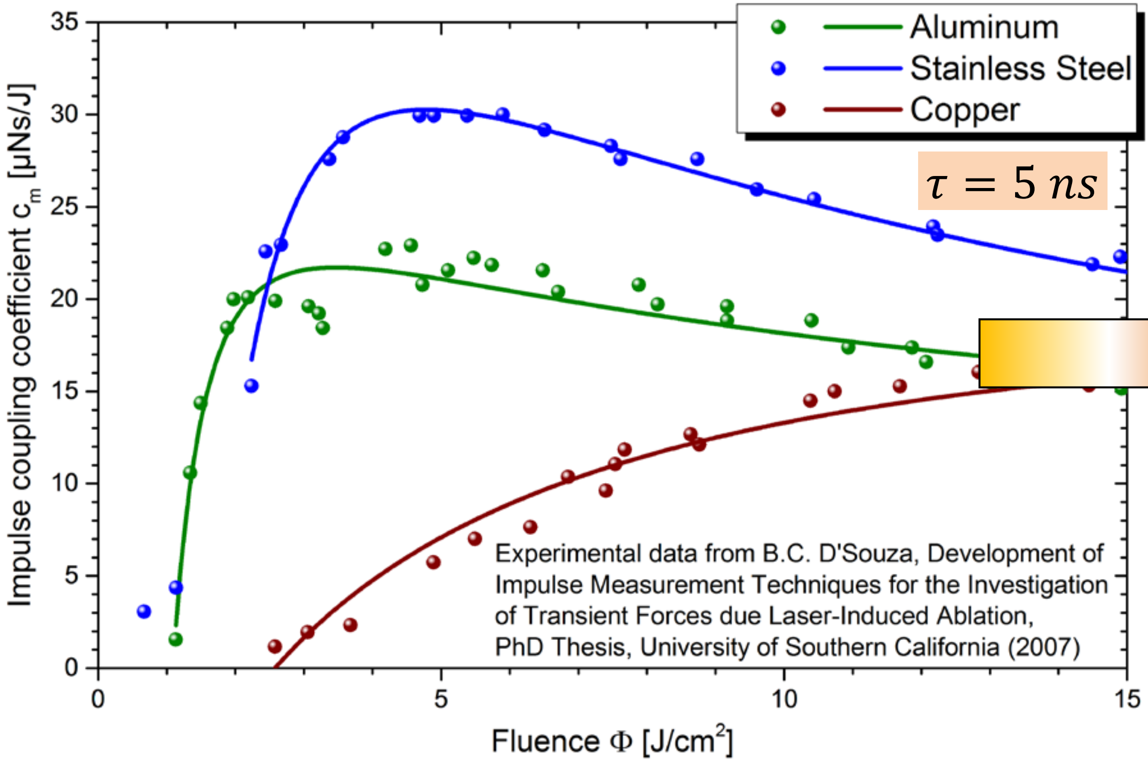
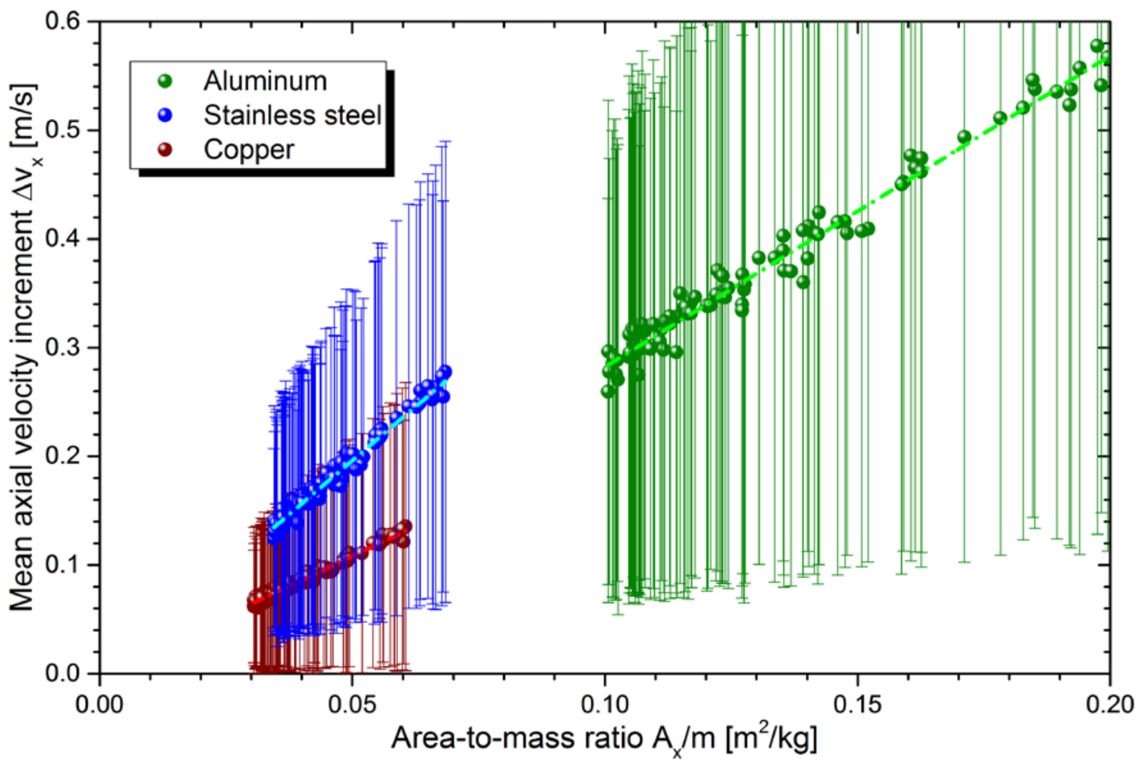


Velocity Increment Δv



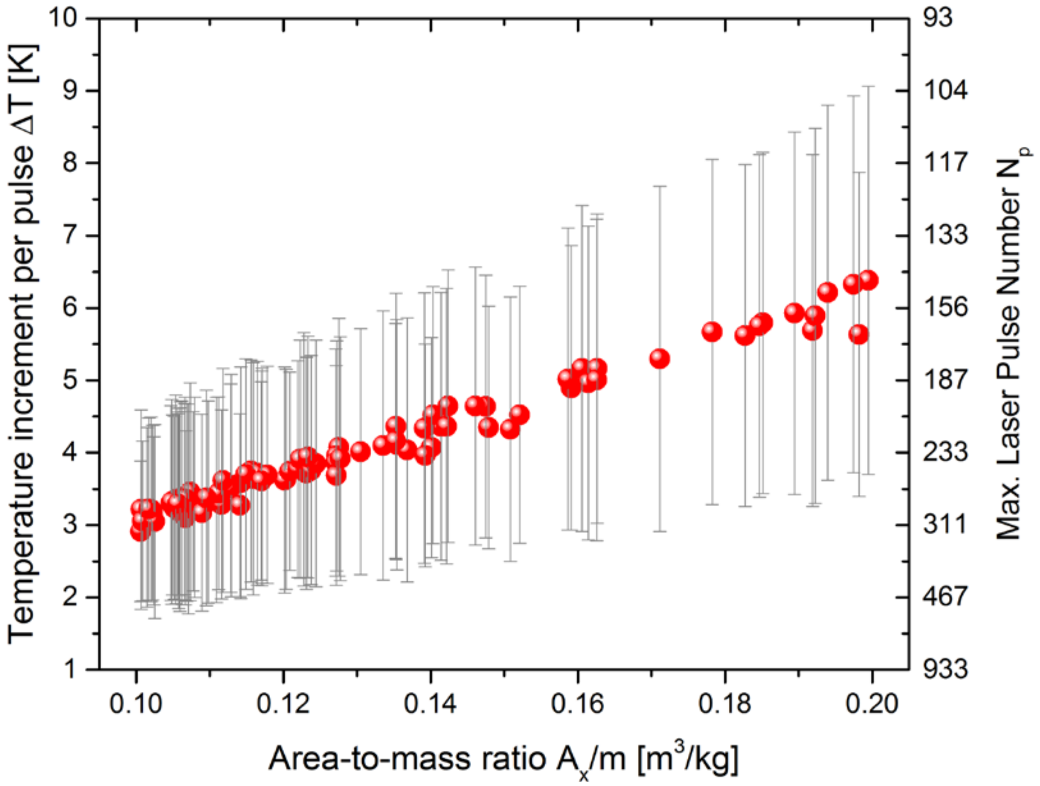
$\rightarrow$ **Remote material reconnaissance advisable for precise orbit modification**

Thermo-Mechanical Coupling

Simulation setup (3 DOF)

- Target CMS = beam center
- Random target orientation
- Target: Aluminum

Heating



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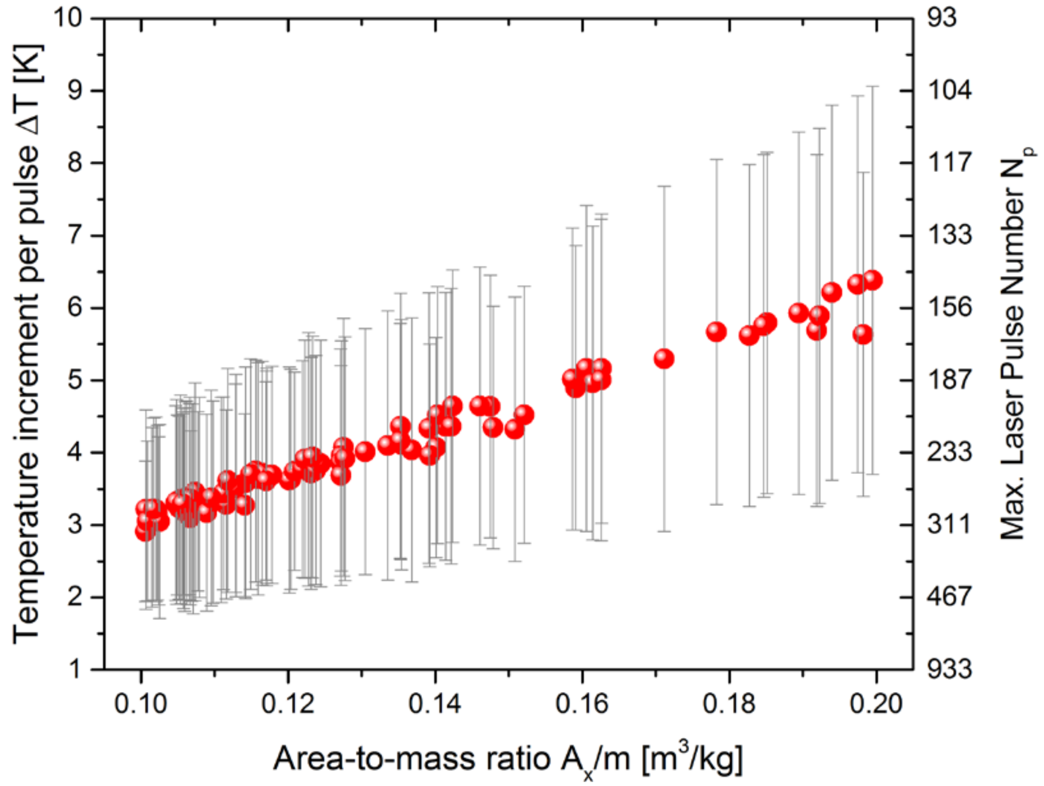
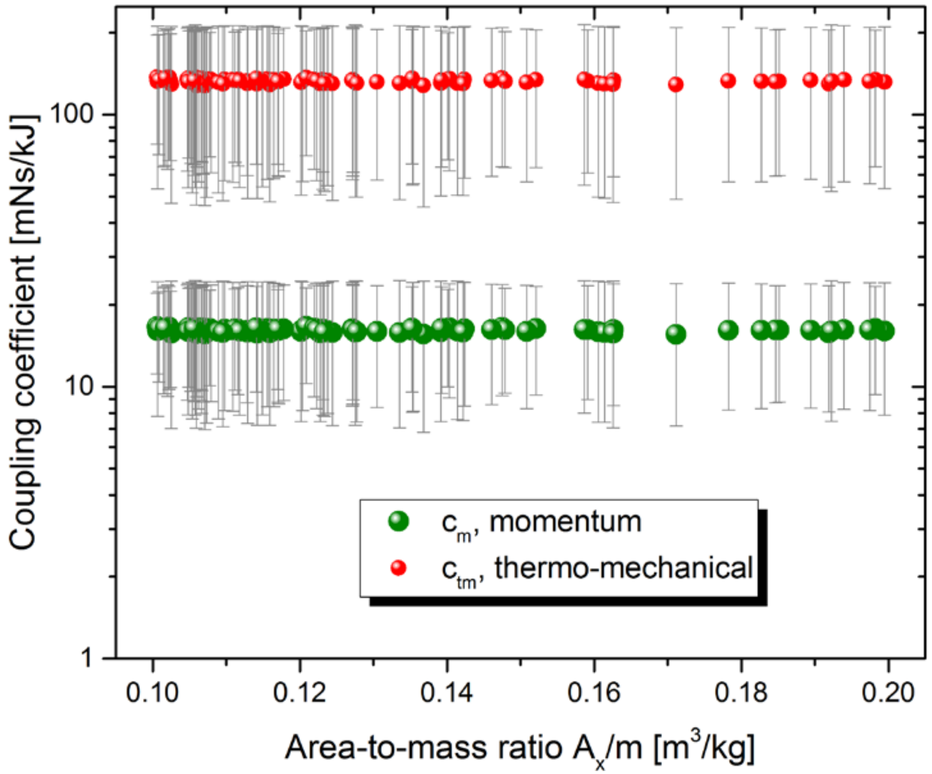


(Thermo-)mechanical Coupling



→ **Safe Debris Removal requires strong limitation laser pulse number.**

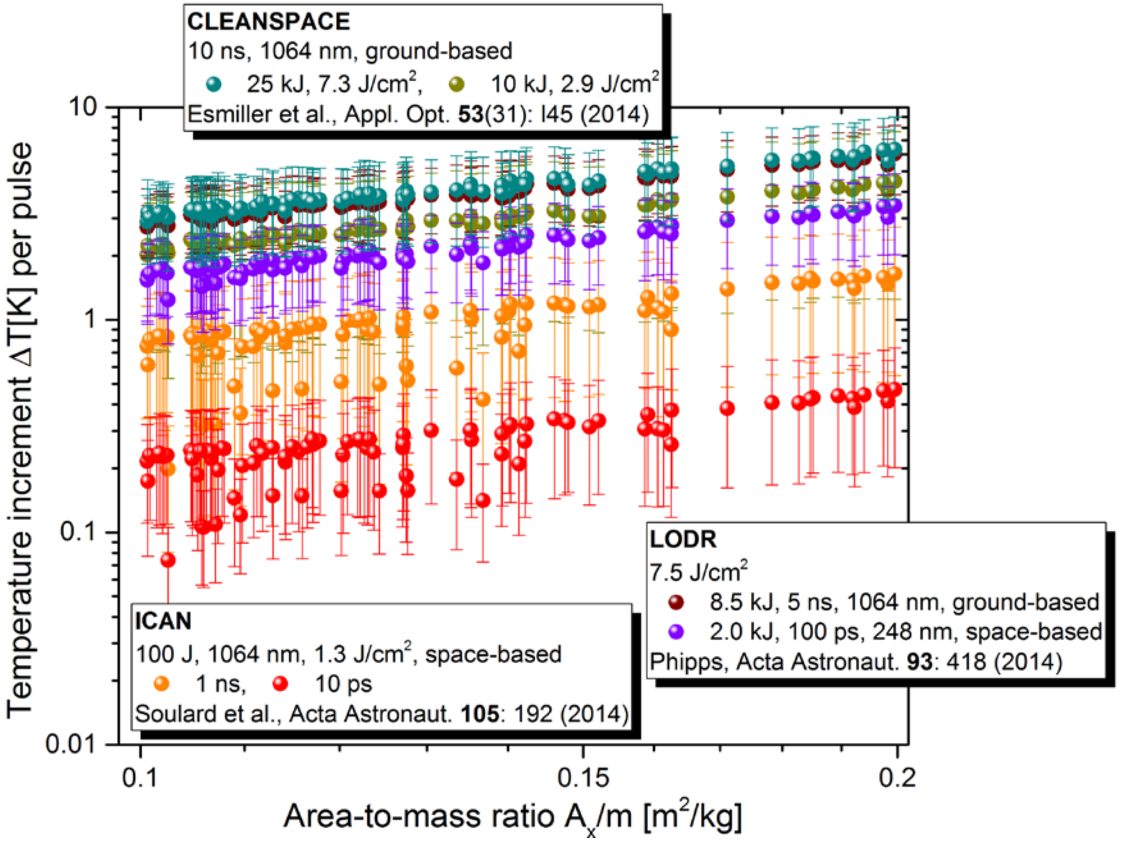
→ ***CLEANSPACE, Al: max. 100 laser pulses during one transit***

Various Laser Configurations

Simulation setup

- Various laser configurations
- $c_m(\Phi), \eta_{res}(\Phi)$ ***from simulations***
- Target: ***Aluminum***

Single Pulse Characteristics



Various Laser Configurations

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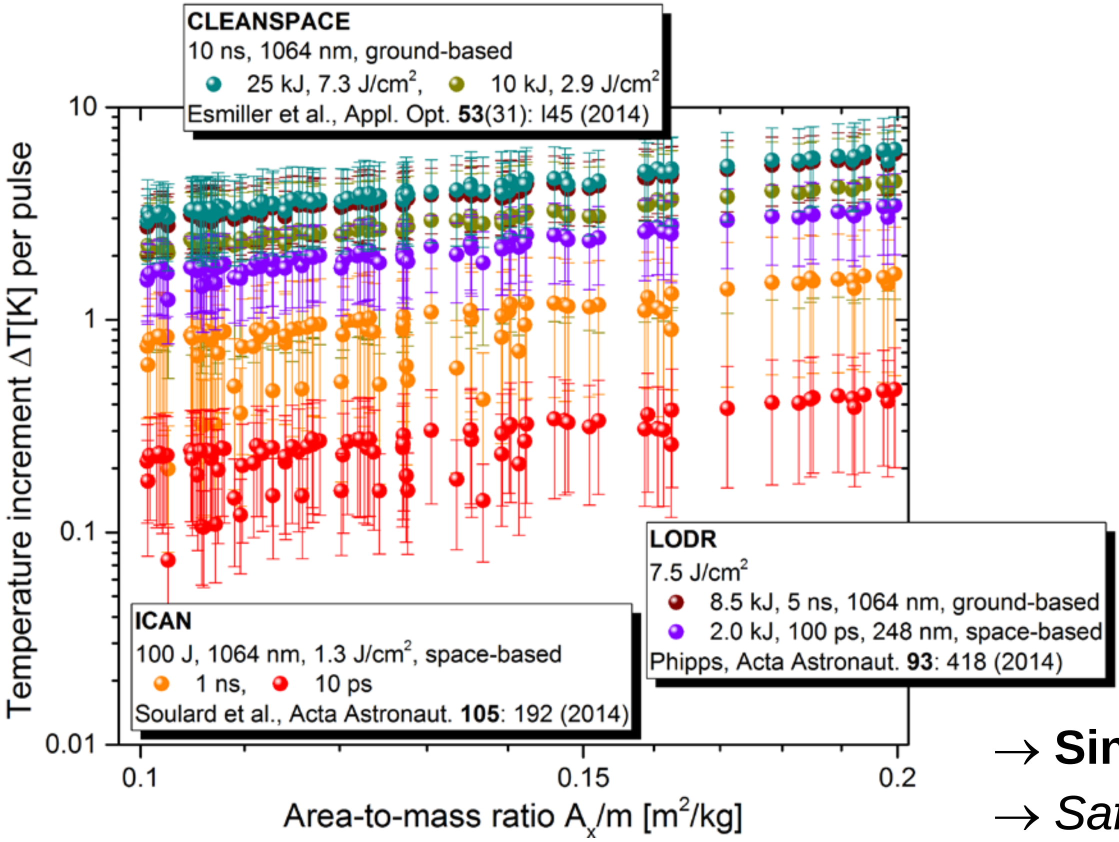
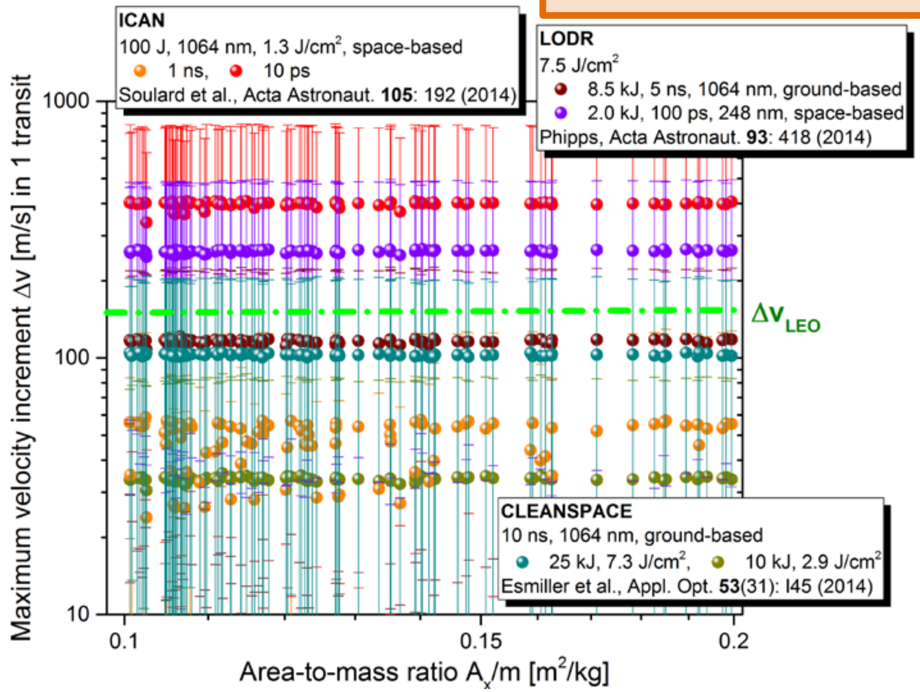
$$\Delta v_{max} = \frac{c_m}{\eta_{res}} \cdot c_p \cdot (T_m - T_0)$$

Single Pulse Characteristics



Multi-pulse Limitations

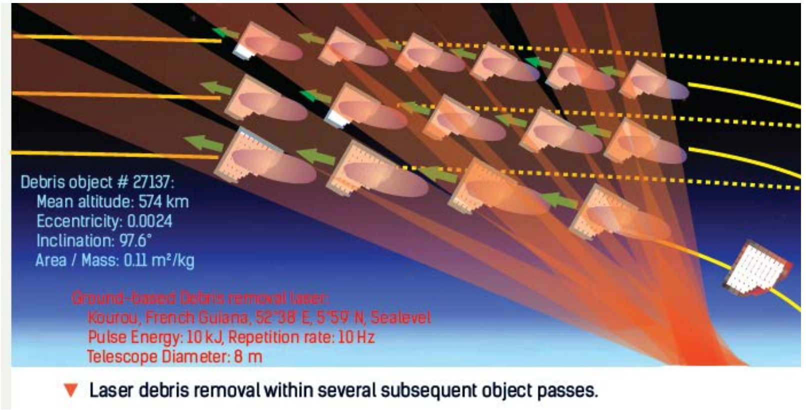


→ **Single transit removal might work for rather short pulses.**

→ *Safety margins for initial temperature and melting needed*

→ *Accumulation of mechnical stress in ultrashort pulse trains?*

Conclusions



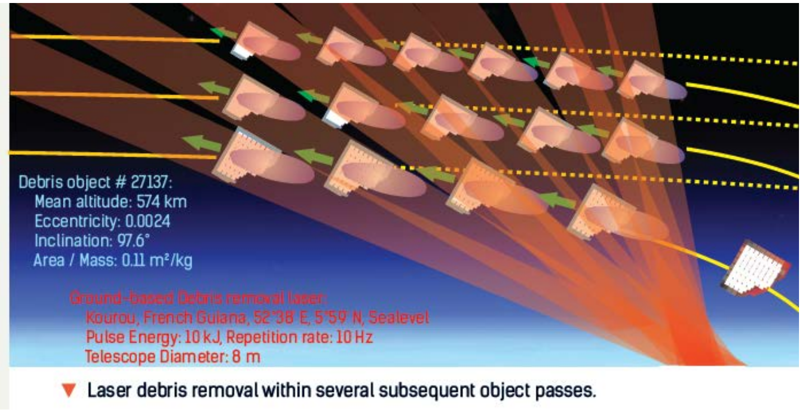
B. Esmiller et al., HPLA-BEP 2014

Momentum Predictability

- Discretization of Area Matrix approach with CUDA-parallelized C++ code *Expedit* on GPU
- Large scatter in Δv
- Material reconnaissance for Δv prediction
- Pulse number limitation within one transit:
  $\rightarrow$ Moderate absolute prediction error in Δv
  $\rightarrow$ lower Rep-rates / average power needed

DLR

Conclusions



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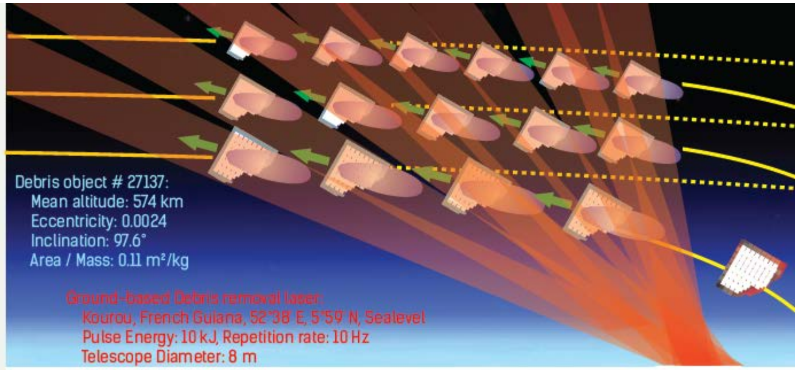
Outlook

$\rightarrow$ Poster Session: R.-A. Lorbeer et al., Laser-Based Space Debris Removal – Laser-Induced Momentum Generation on True Scale Debris-Like Targets

Conclusions



▼ Laser debris removal within several subsequent object passes.

B. Esmiller et al., HPLA-BEP 2014

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Heat Accumulation

- Discretized Add-on to *Expedit* based on HD simulation data
- Temperature increment per pulse: up to $\Delta T \approx 5K$
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  $\rightarrow$ Avoidance of target melting
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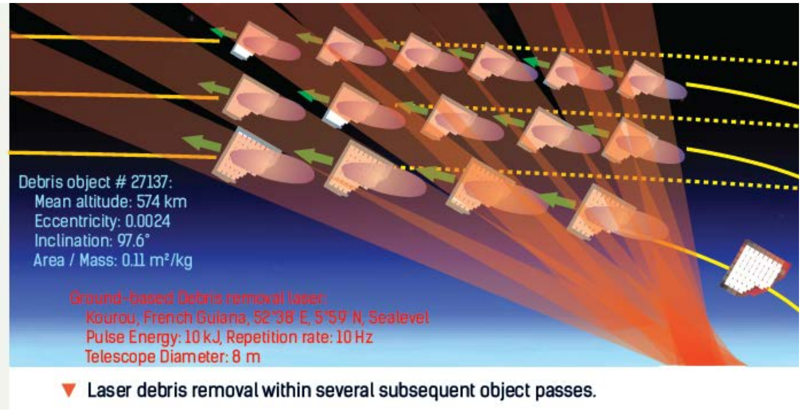

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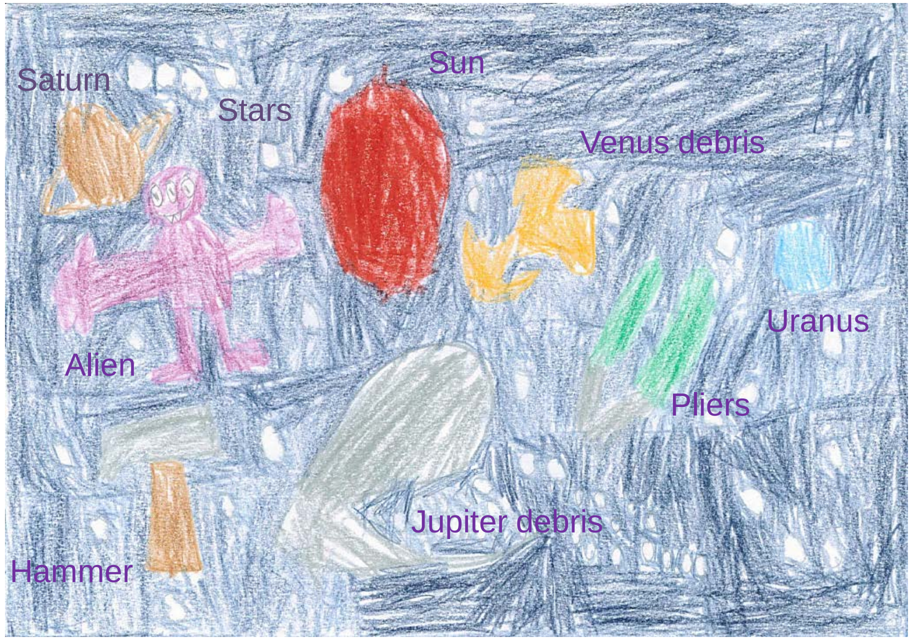
Outlook

- ***Experimental data*** needed on:

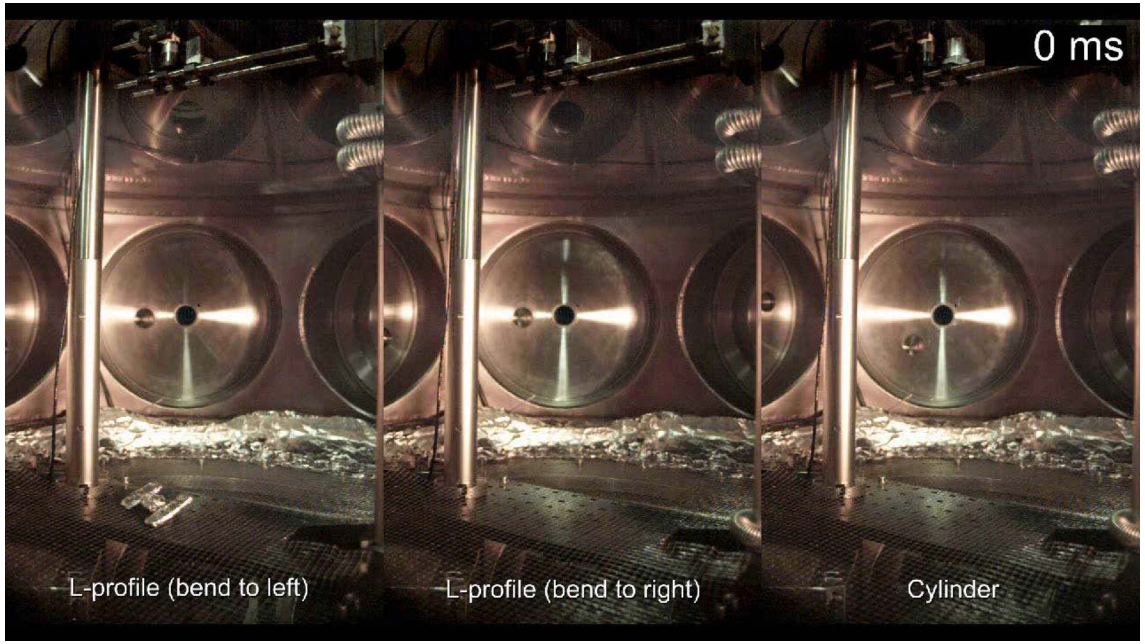
$c_m(\Phi, T)$: temperature-dependent momentum coupling

$\eta_{res}(\Phi, T)$: heat (and stress) accumulation

Thank you for your kind attention



„Space debris,“ Finnegan, 7 years



Drop experiments with irregularly shaped targets → Poster Session

Q&A Backup Slides

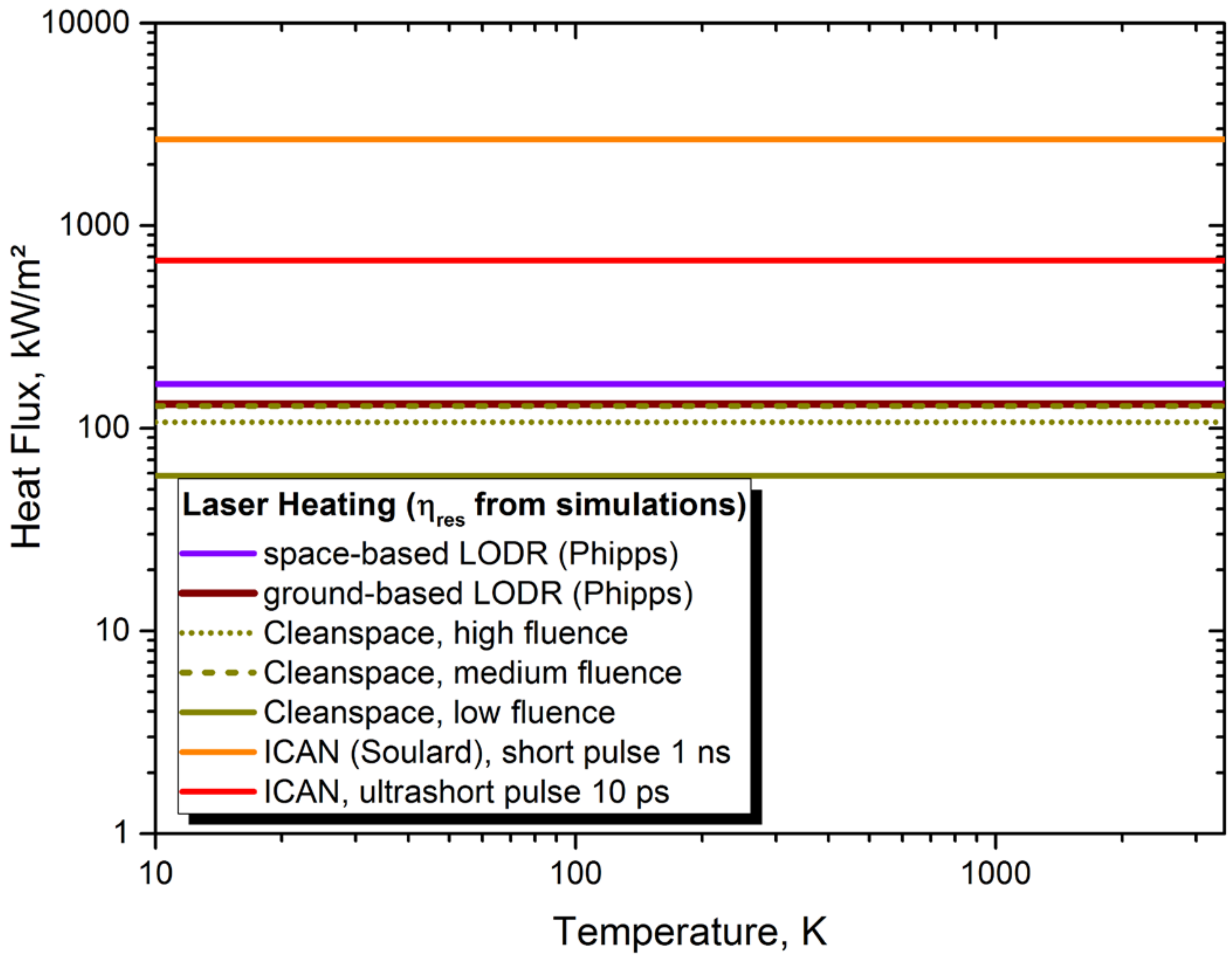
DLR

Literature Data on Residual Heat in Laser Ablation

τ	λ [µm]	f_{rep}	Mat.	η_{res} [%]	Ref.
1-6 µs	10.6	(1 pulse)	Al	**10 – 40**	Autric, Proc. SPIE **3343**: 354 (HPLA I, 1998)
120 ns	1.064	(1 pulse)	Al	**35**	Lenk et al., Appl. Surf. Sce. **109/110**: 419 (1997)
45 ns	0.69	(1 pulse)	Al	**10 – 25**	Vorobyev et al., Appl. Phys. A **82**: 357 (2006)
6 ps	1.03	300 kHz	Steel	**12.6**	Weber et al., Opt. Express **25**(4): 3966 (2017)
65 fs	0.8	(1 pulse)	Ti	**20 – 60**	Vorobyev et al., J. Phys.: Conf. Ser. **59**: 418 (2007)
65 fs	0.8	(1 pulse)	Zn	**10 – 40**	Vorobyev et al., Opt. Express **14**(26): 13113 (2006)
60 fs	0.8	1 kHz	Cu, Al	**10 – 40**	Vorobyev et al., Appl. Phys. Lett. **86**: 011916 (2005)
60 fs	0.8	(1 pulse)	Al	**15 – 35**	Vorobyev et al., Appl. Phys. A **82**: 357 (2006)

Removal Laser Configurations: Heat Accumulation

Laser heating is:

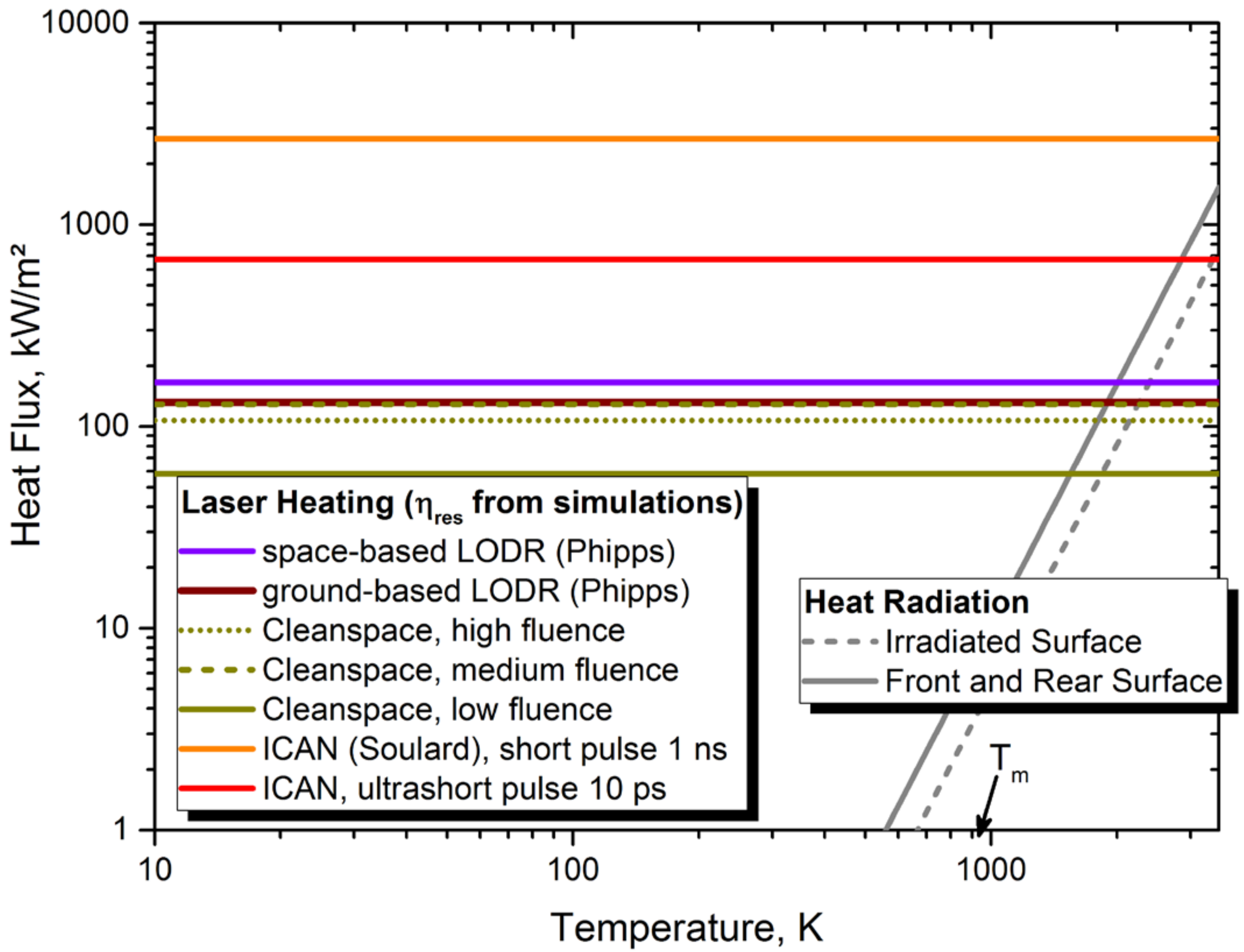


Scharring et al., AIAA Journal (accepted manuscript)

Removal Laser Configurations: Heat Accumulation

Laser heating is:

- at least 3 orders of magnitude faster than heat re-radiation



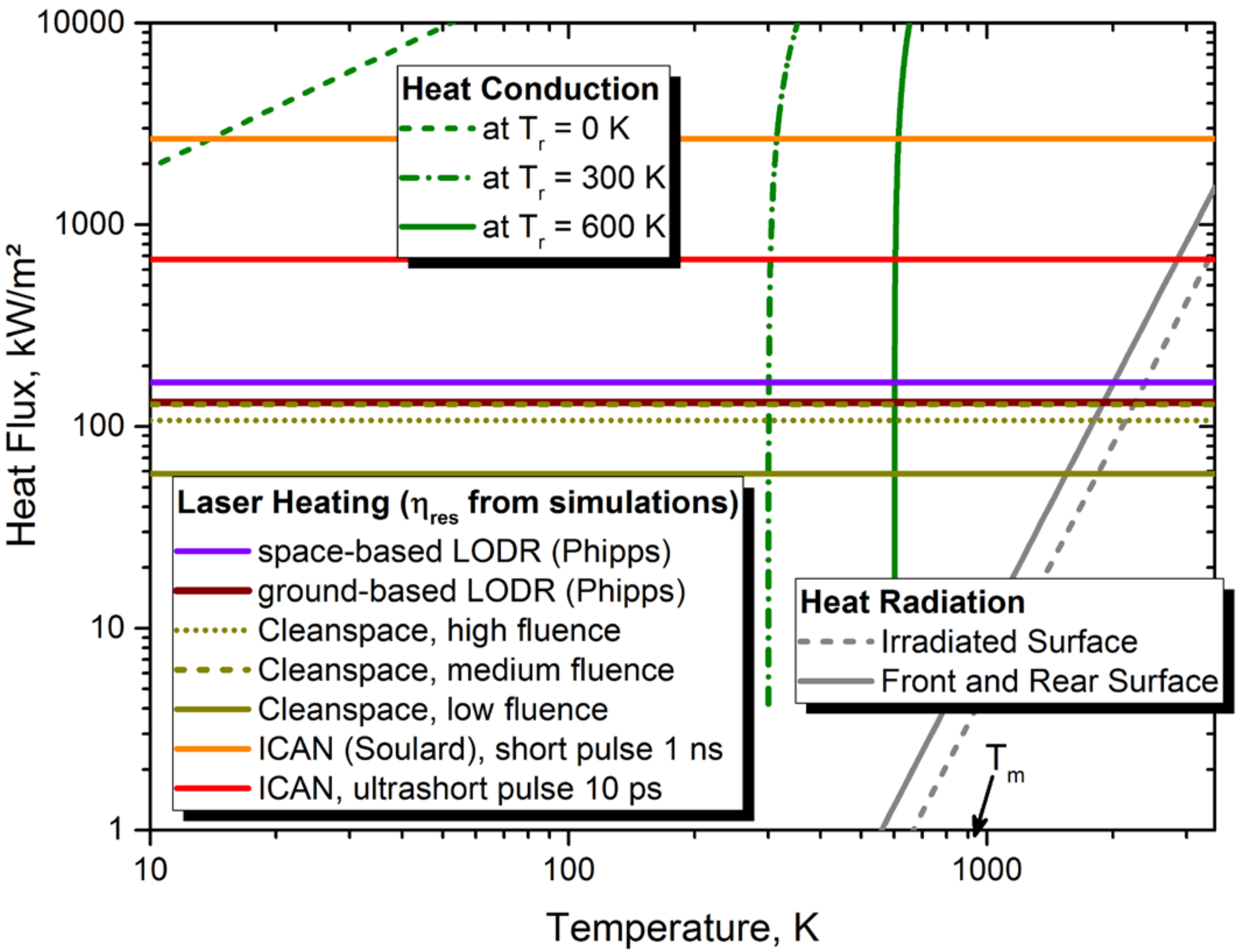
Scharring et al., AIAA Journal (accepted manuscript)

Removal Laser Configurations: Heat Accumulation

Laser heating is:

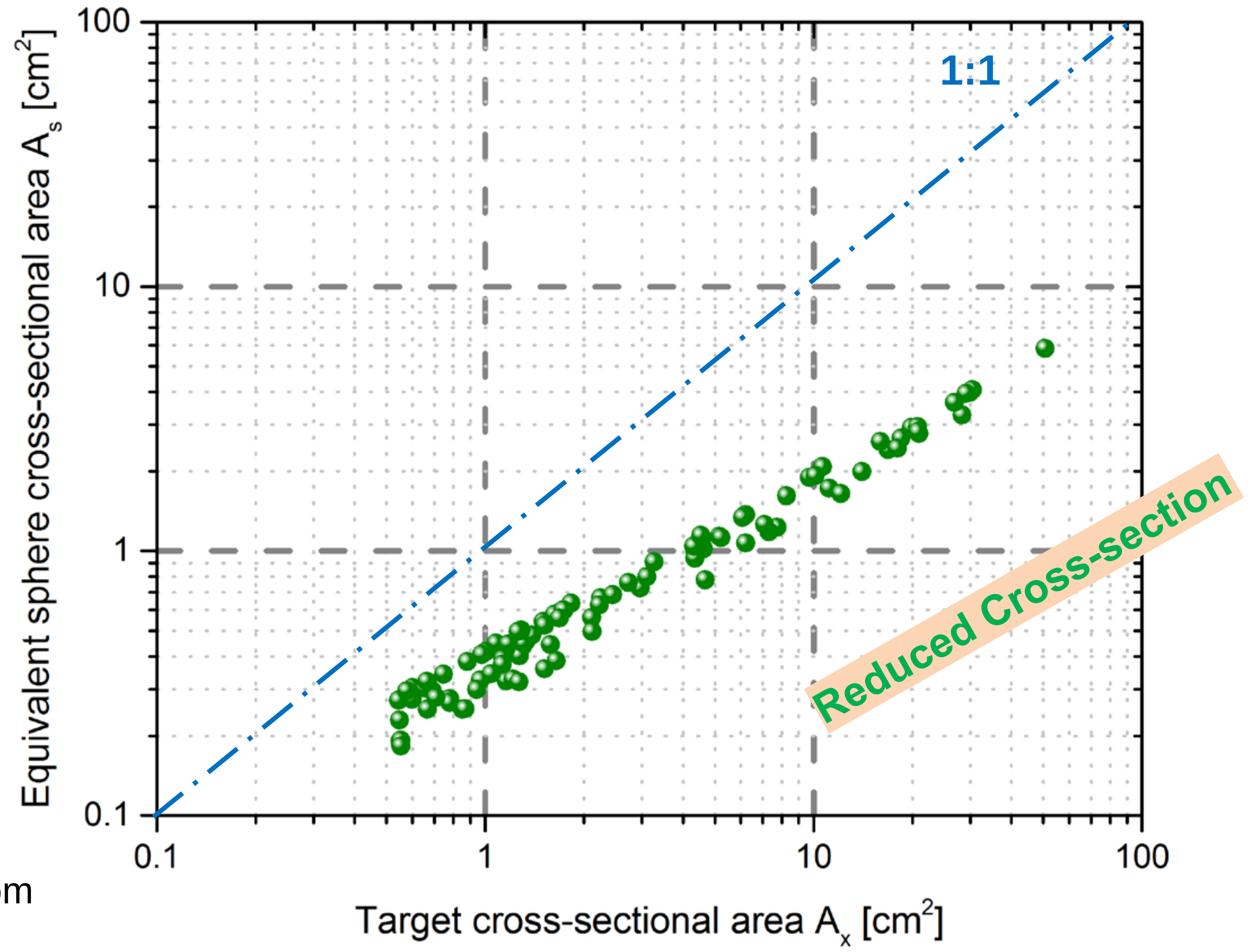
- at least 3 orders of magnitude faster than heat re-radiation
- much slower than heat conduction (for significant T-gradients)

Simulations for Al sample targets



Scharring et al., AIAA Journal (accepted manuscript)

Target Melting: Space Debris Compactor



Ellipsoid Sample Targets from Monte Carlo Simulations

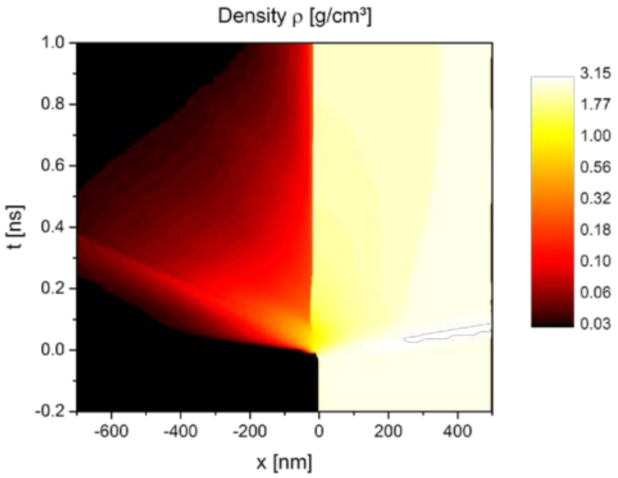
Residual Heat and Mechanical Stress in Short and Ultrashort-Pulse Ablation

Short pulses:

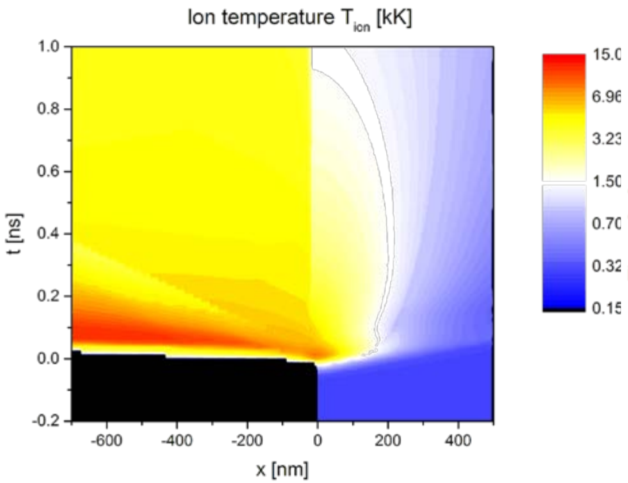
Example $\tau = 50\ ps, \Phi = 1.49\ \frac{J}{cm^2}$

- Large residual heat
- Moderate pressure waves

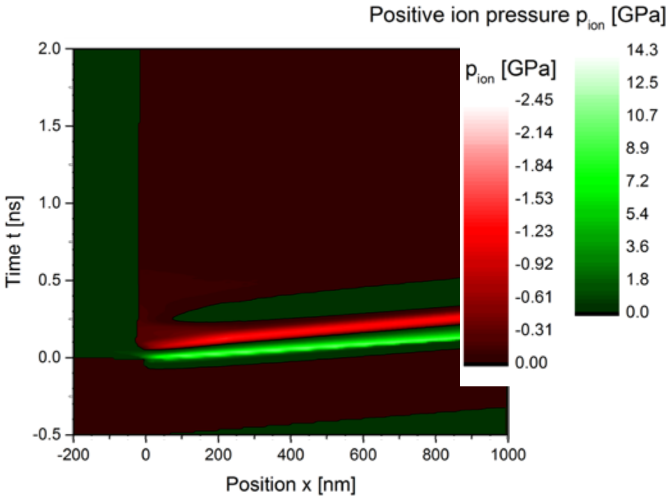
Density



Temperature



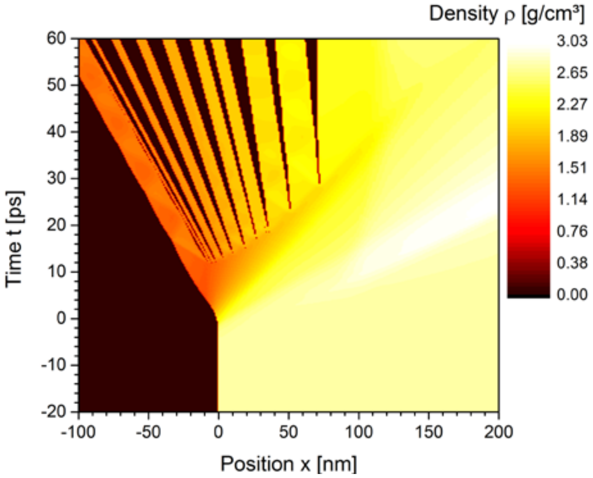
Pressure

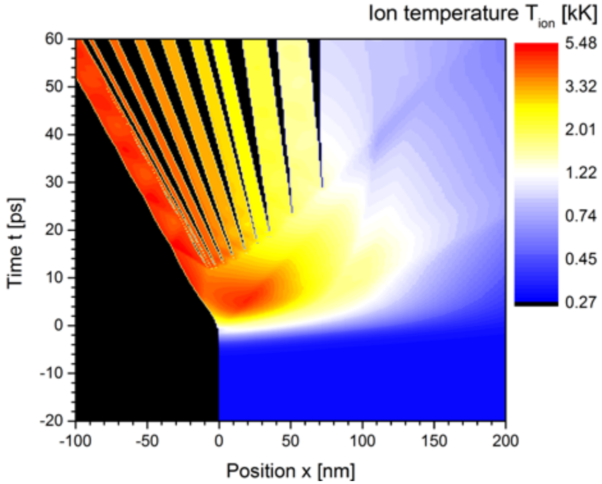


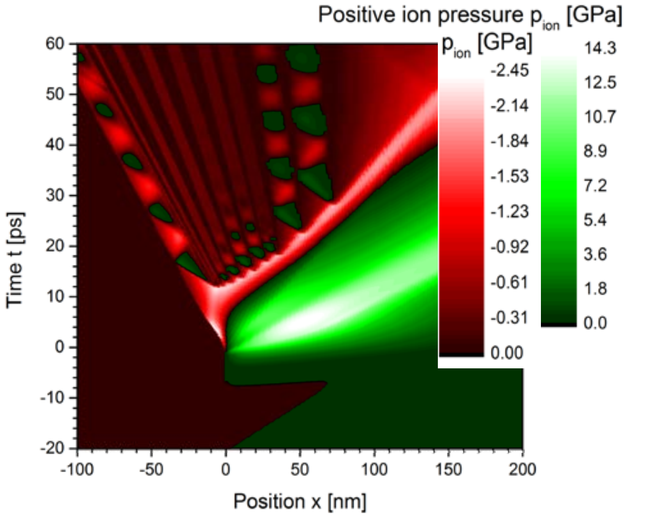
Ultrashort pulses

Example: $\tau = 5\ ps, \Phi = 0.74\ \frac{J}{cm^2}$

- Low residual heat
- Strong pressure waves



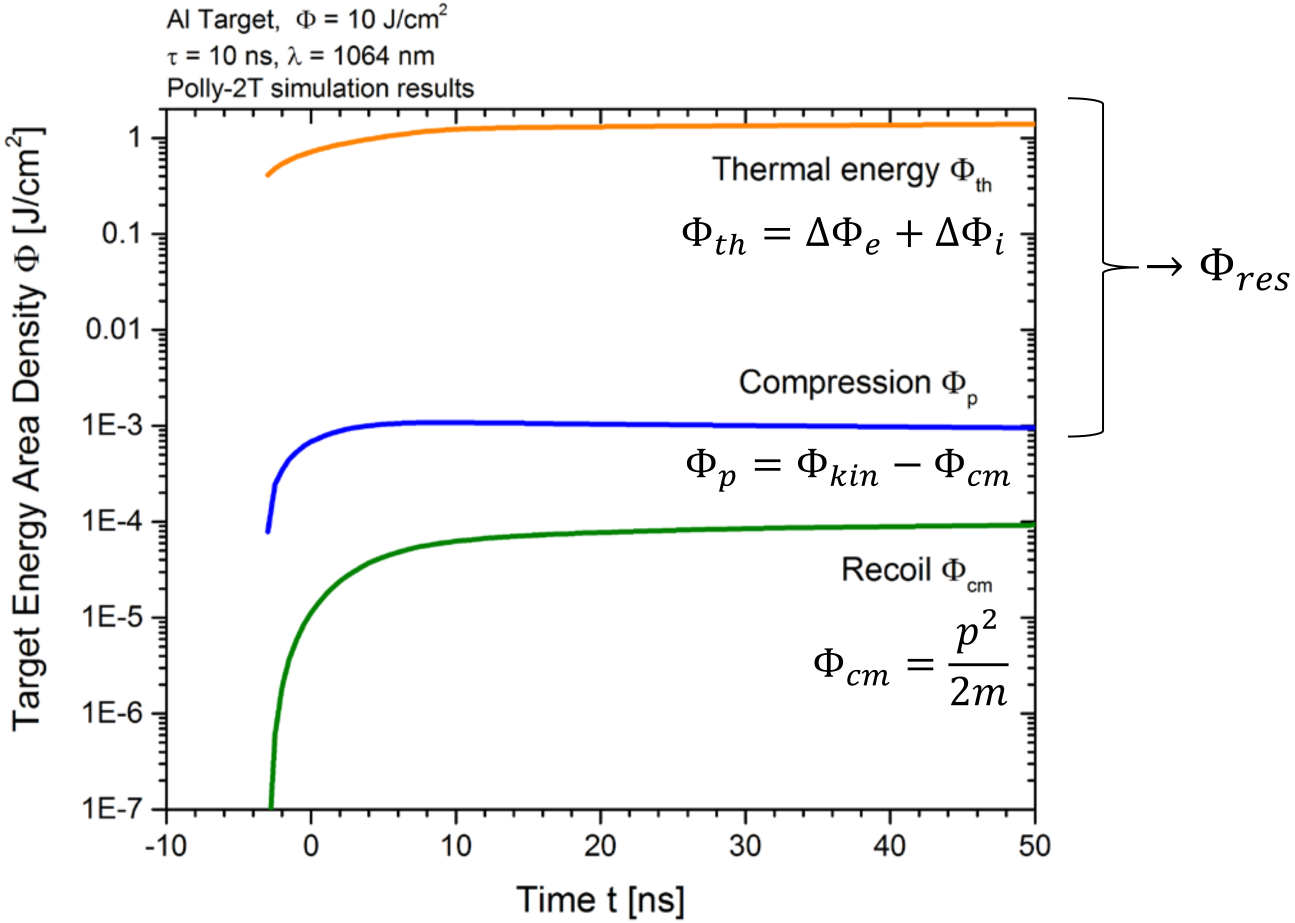




Hydrodynamic simulations with Polly-2T ,
code kindly provided by Mikhail Povarnitsyn,
JIHT RAS Moscow

Shockwave thermalization

Short Pulses, Example: 10 ns



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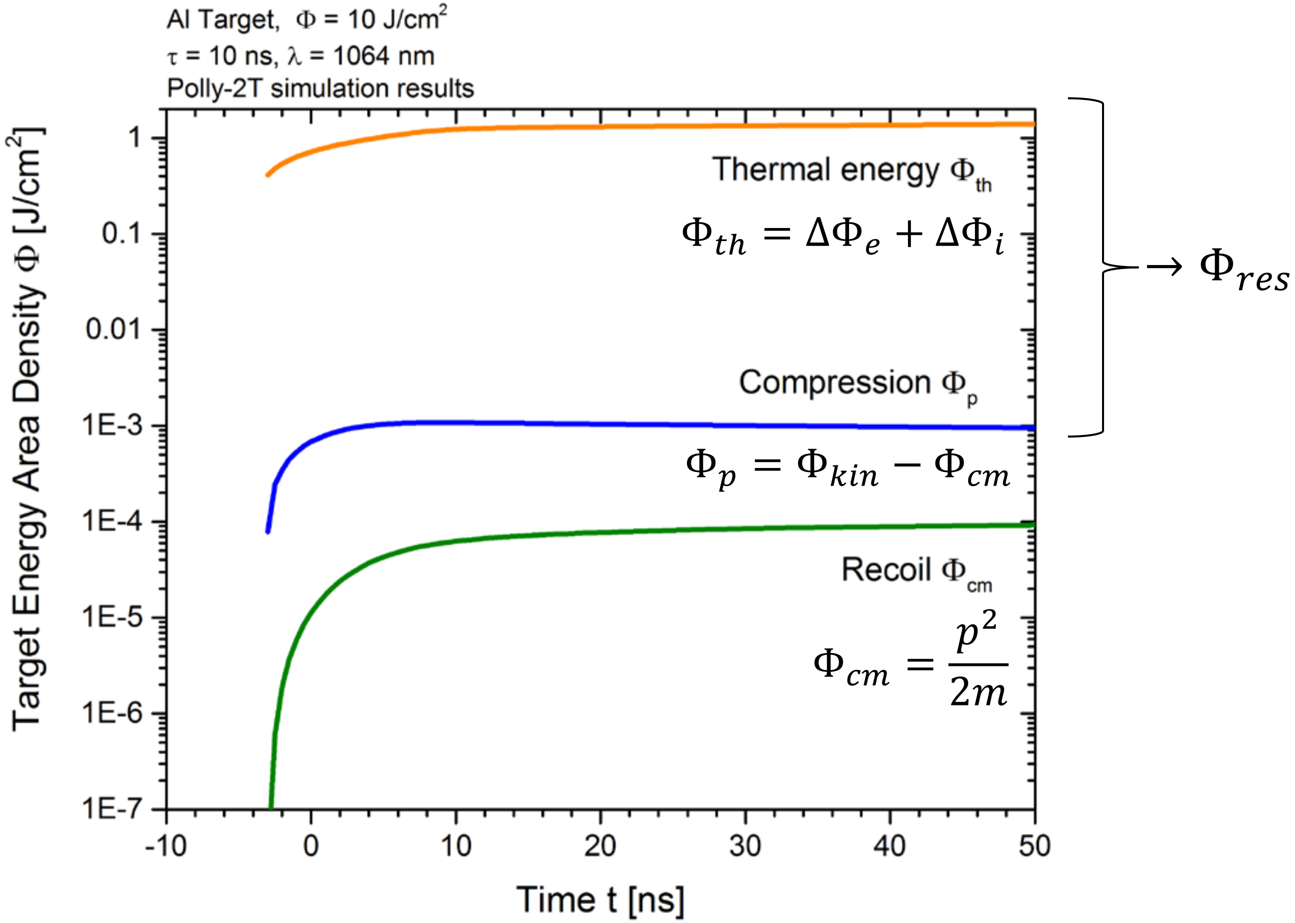
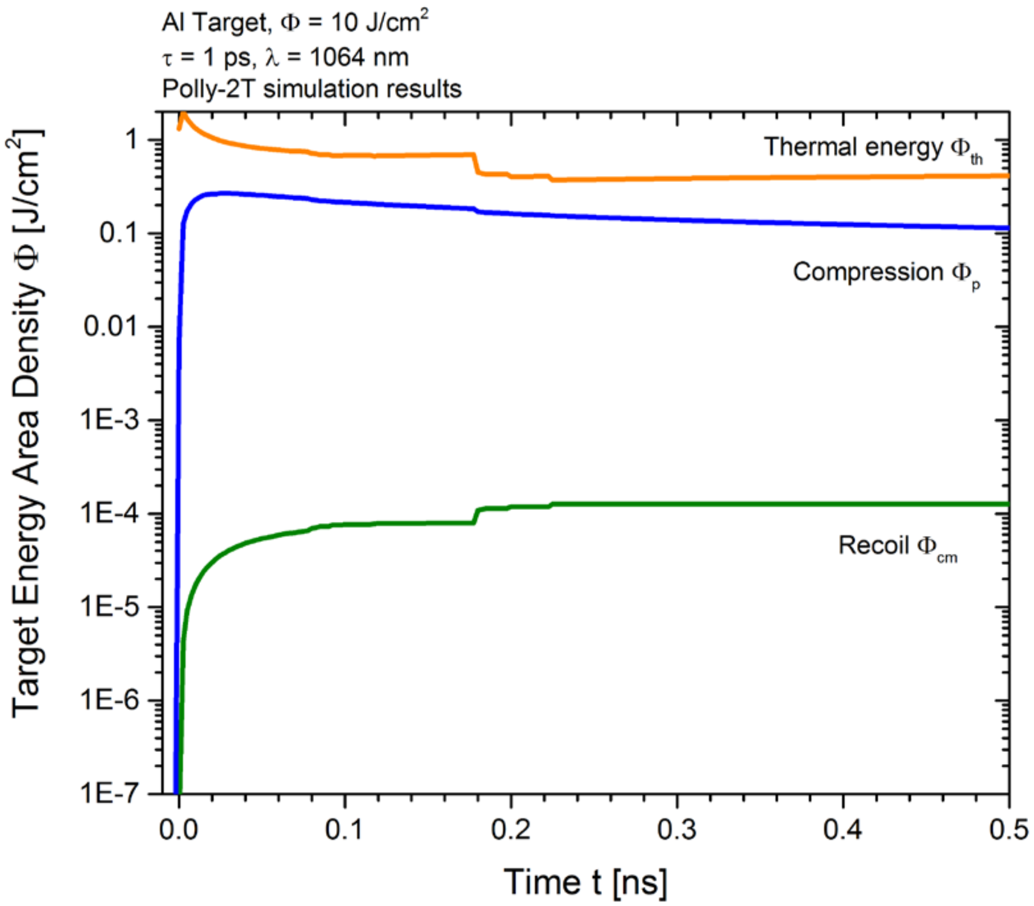
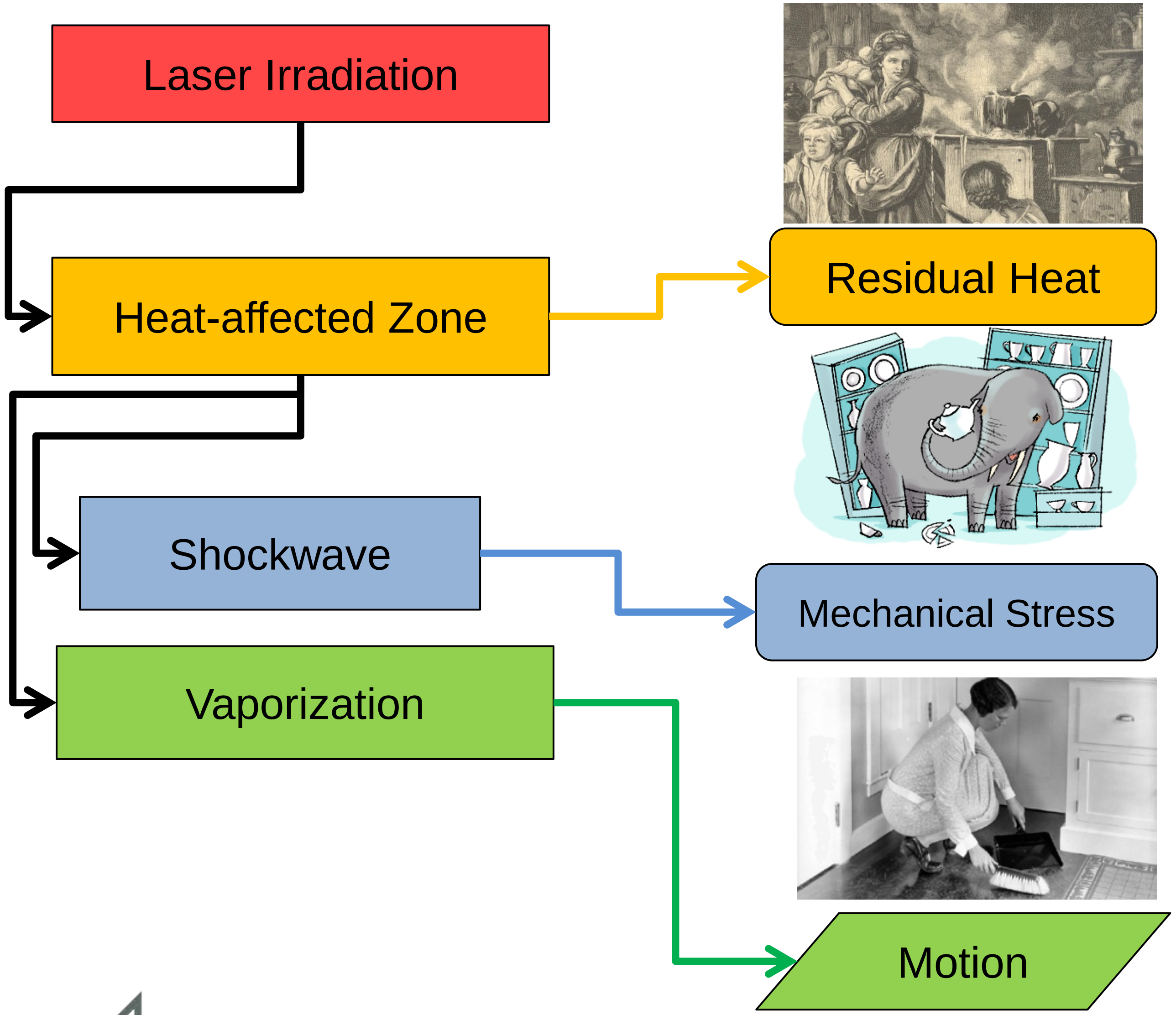


Ultrashort Pulses, Example: 1 ps



Side Effect: Ablative Recoil



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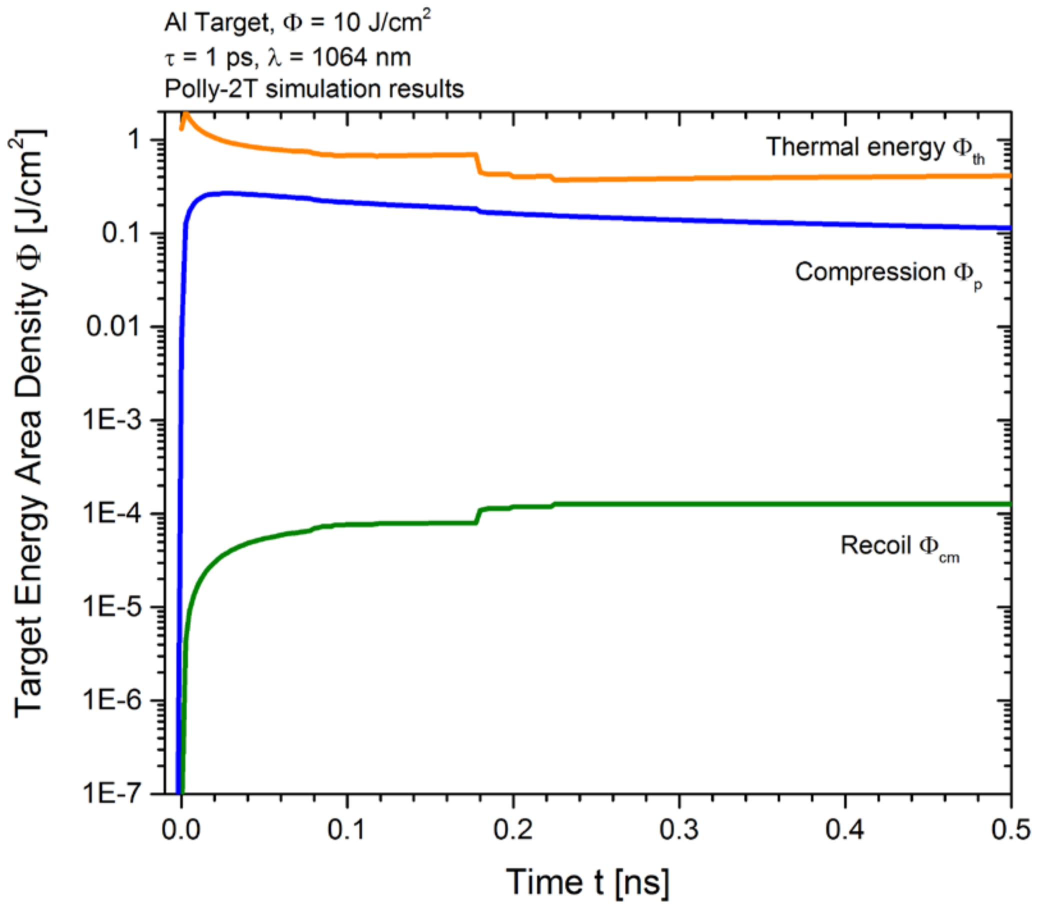
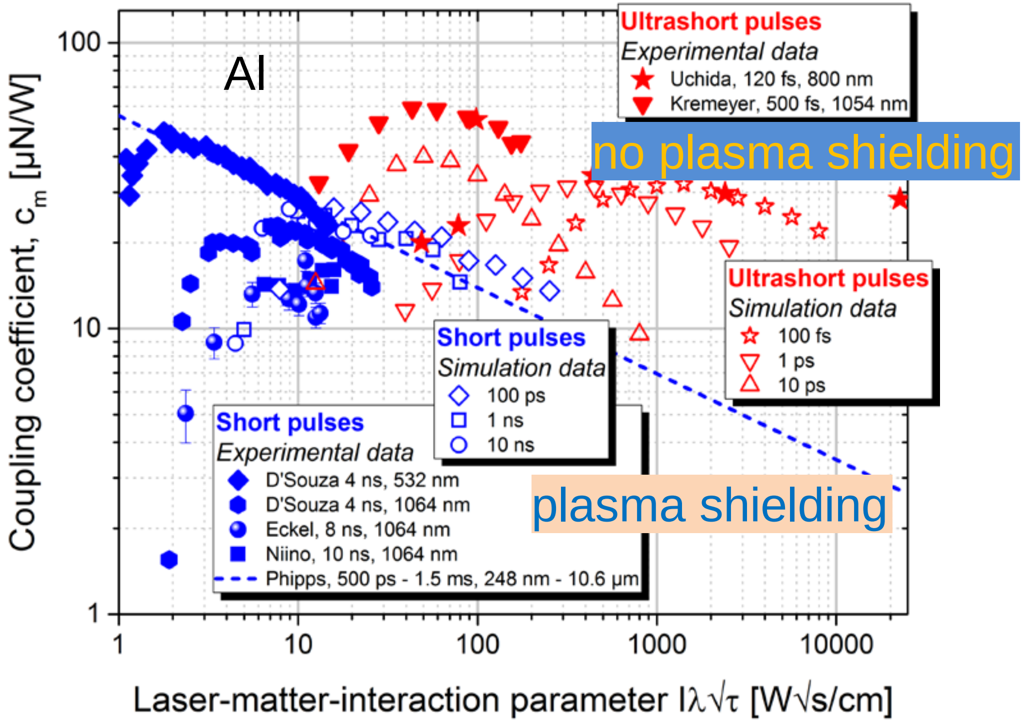


HD Simulations on Momentum Coupling
Experimental Validation

Wide Range



D'Souza, B. C., PhD Thesis, University of Southern California, 2007
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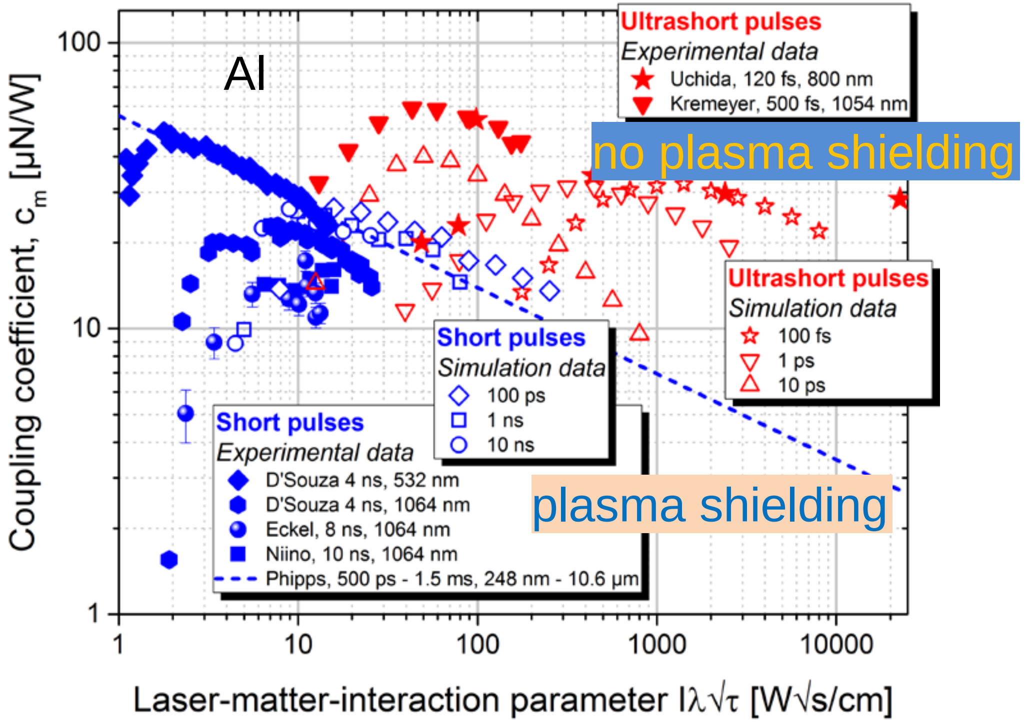

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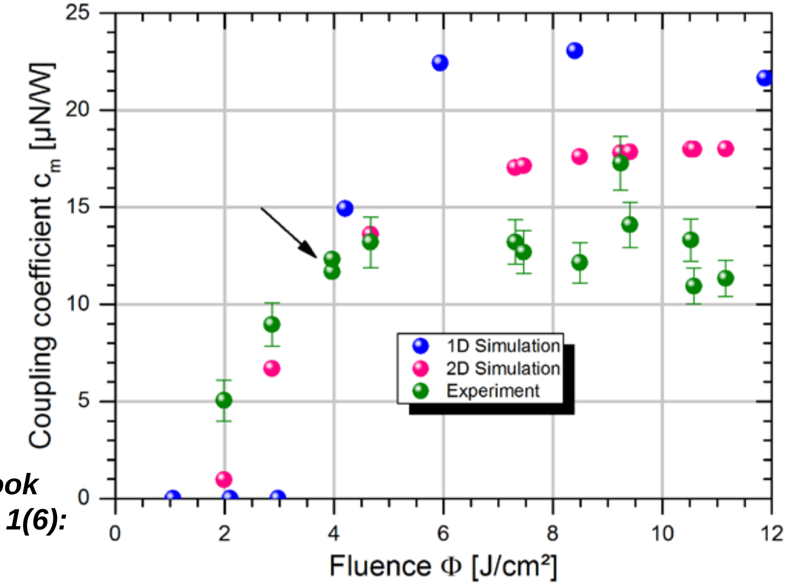
Short Pulses



S. Scharring et al., IAA Book Series on Small Satellites 1(6): 27 – 34 (2016)

HD Simulations on Momentum Coupling

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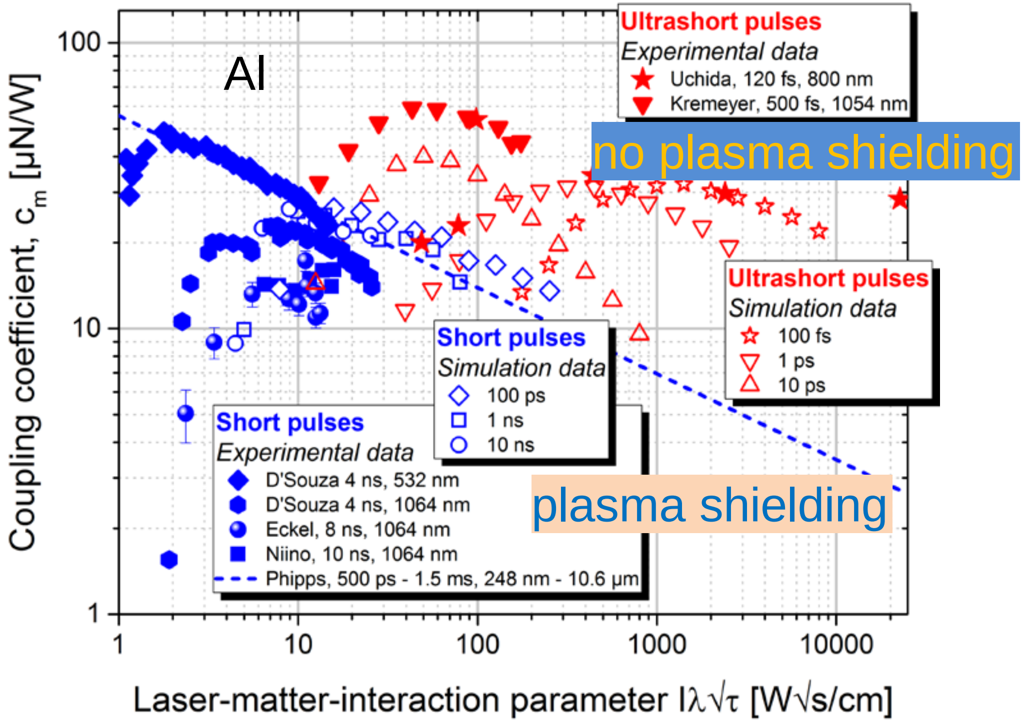

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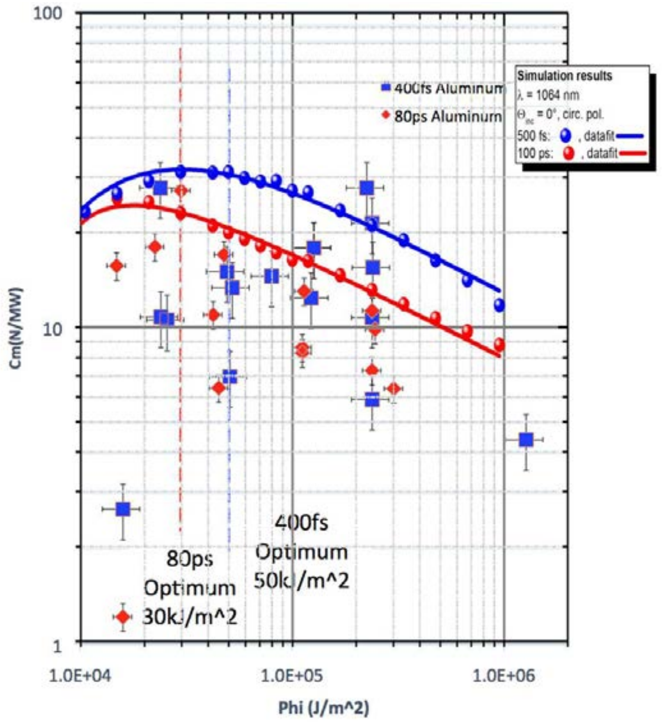
Ultrashort Pulses



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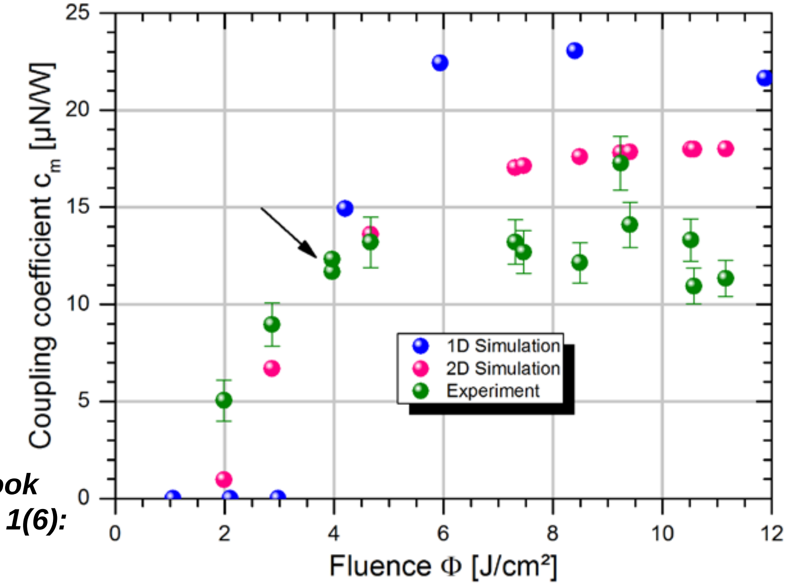

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DLR

$$c_{tm} = \frac{\Delta p}{Q_{Heat}} = \frac{\text{Thrust}}{\text{Heating Power}}$$

Thermo-mechanical Coupling

$$\Delta v_{max} = \frac{c_m}{\eta_{res}} \cdot c_p \cdot (T_m - T_0) = c_{tm} \cdot c_p \cdot (T_m - T_0)$$

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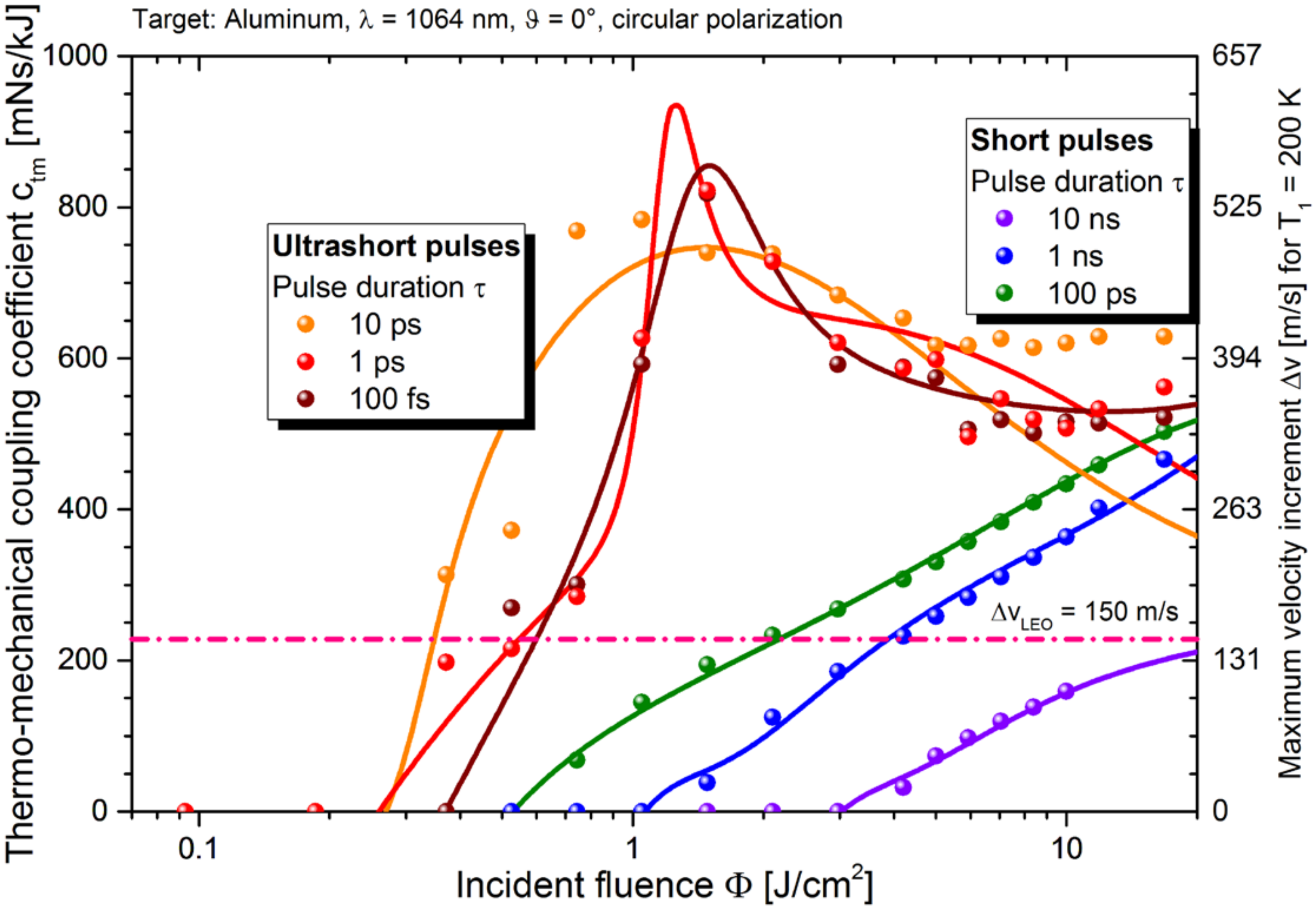
$$\Delta v_{max} = \frac{c_m}{\eta_{res}} \cdot c_p \cdot (T_m - T_0) = c_{tm} \cdot c_p \cdot (T_m - T_0)$$

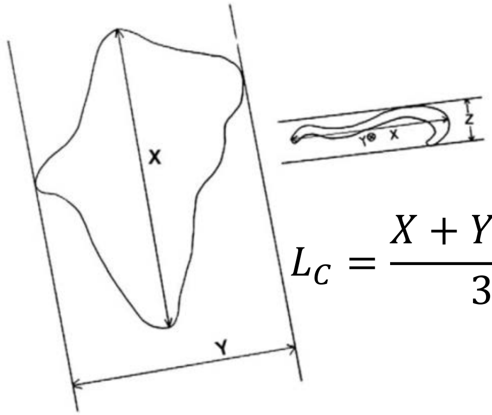
Pulse Length Dependency

- Short Pulses:
  - Unfavourable thermo-mech. coupling
  - Acceptable at larger fluences
- Ultrashort Pulses:
  - Advantageous thermo-mech. coupling
  - Even at moderate fluences



Space Debris – Properties

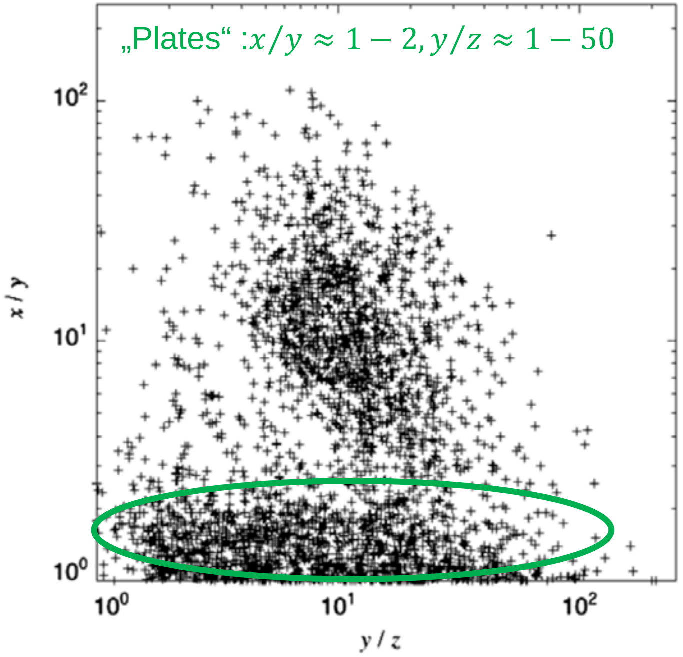
- Characteristic length L_c



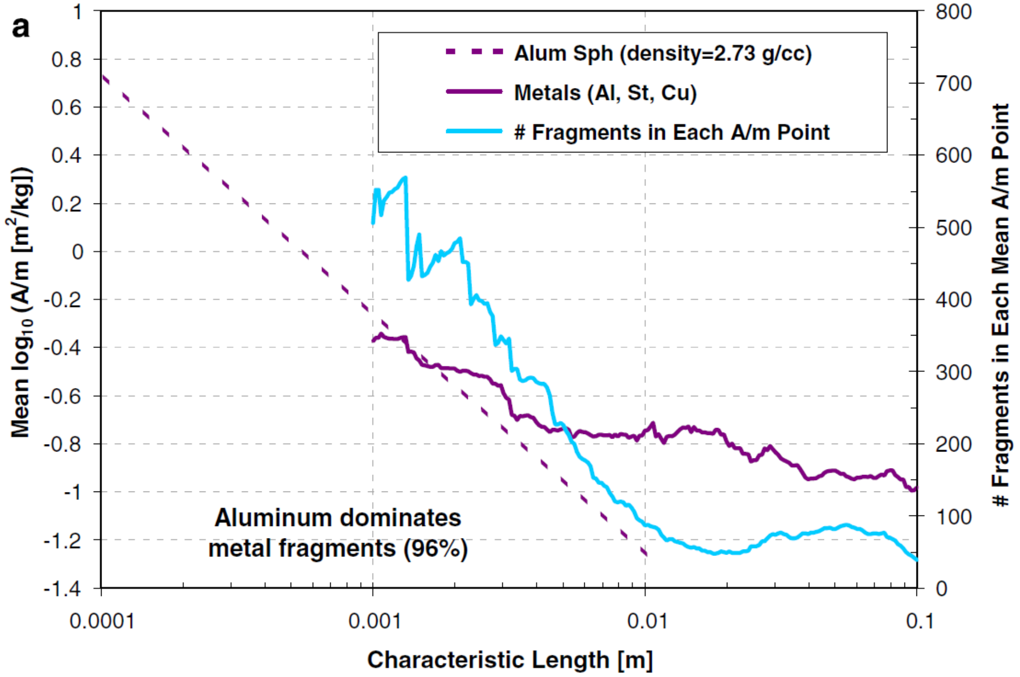
$$L_C = \frac{X+Y+Z}{3}$$

Fig. 6. Sketch of NASA orthogonal 'Projection Dimensions' in Krisko et al. (2008).

Hanada et al., Adv. Space Res. 44(5): 558 – 567 (2009)



T. Hanada et al., ibid



P.H. Krisko et al., Adv. Space Res. 41: 1138 – 1146 (2008)

DLR

Space Debris – Properties

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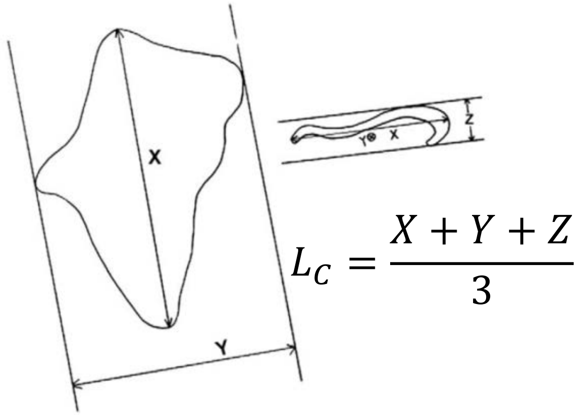
- Cross-sectional area A_x



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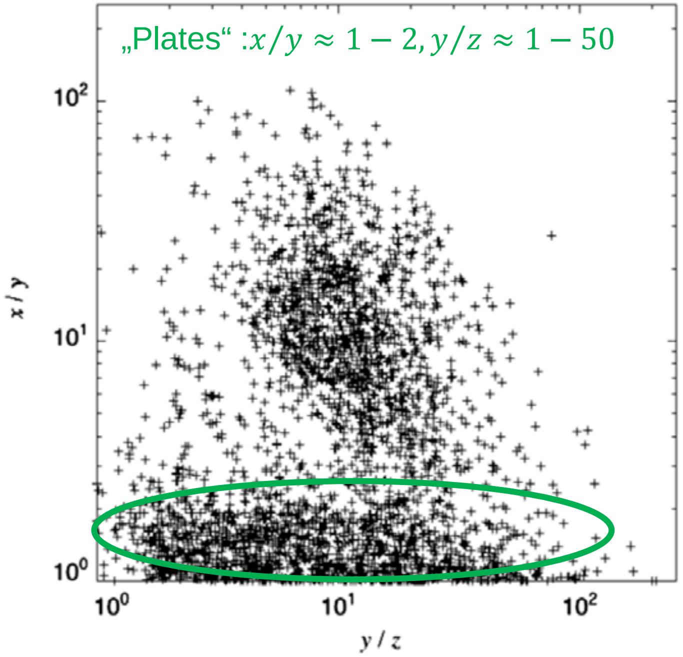

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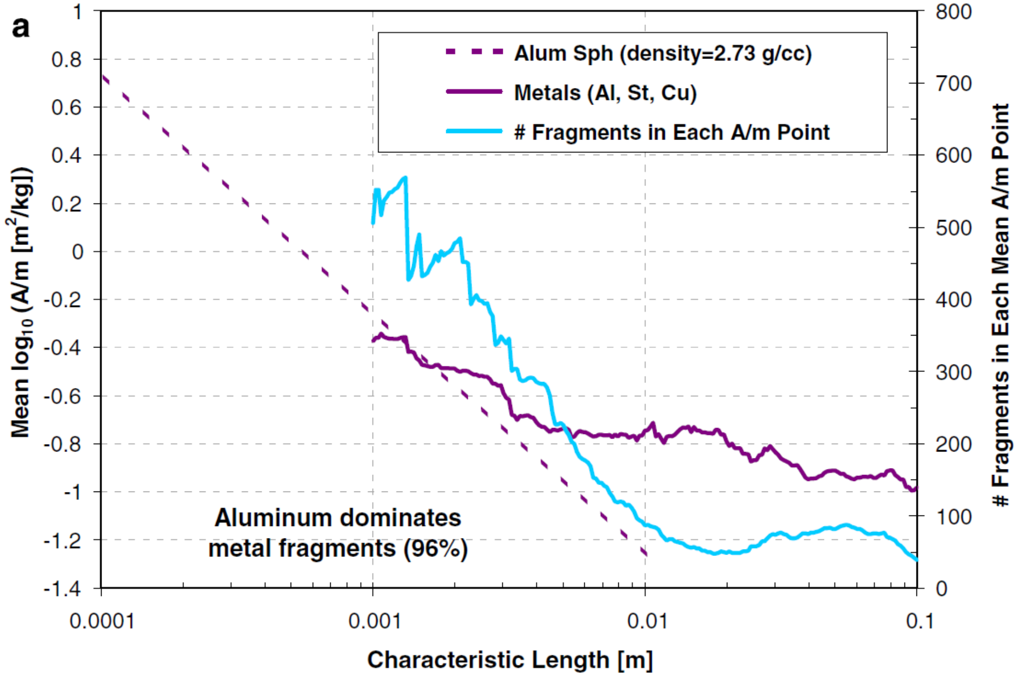

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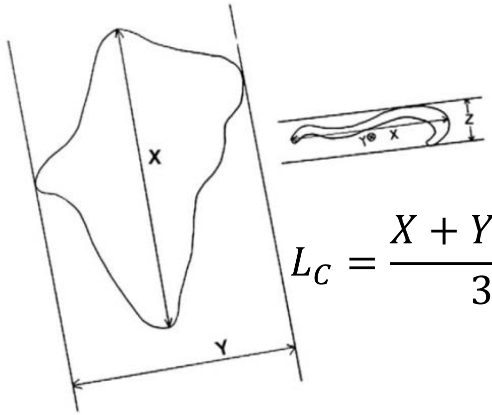
- Material: mainly aluminum



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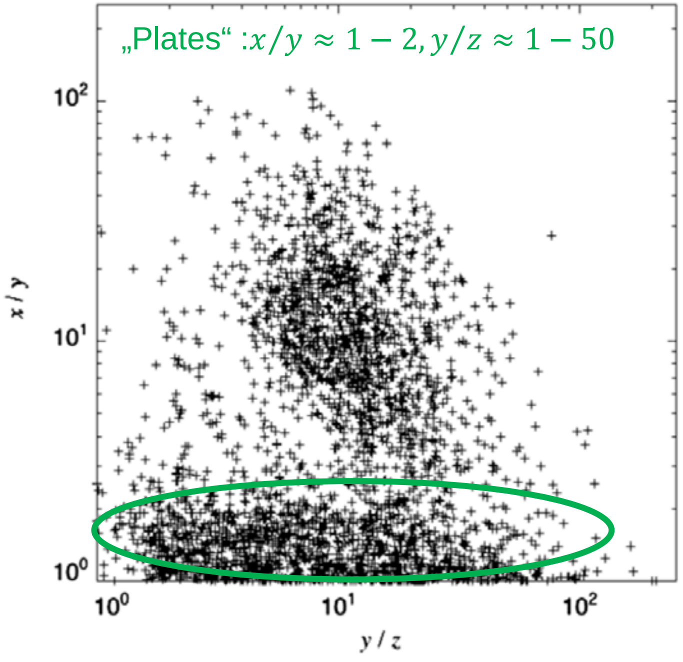
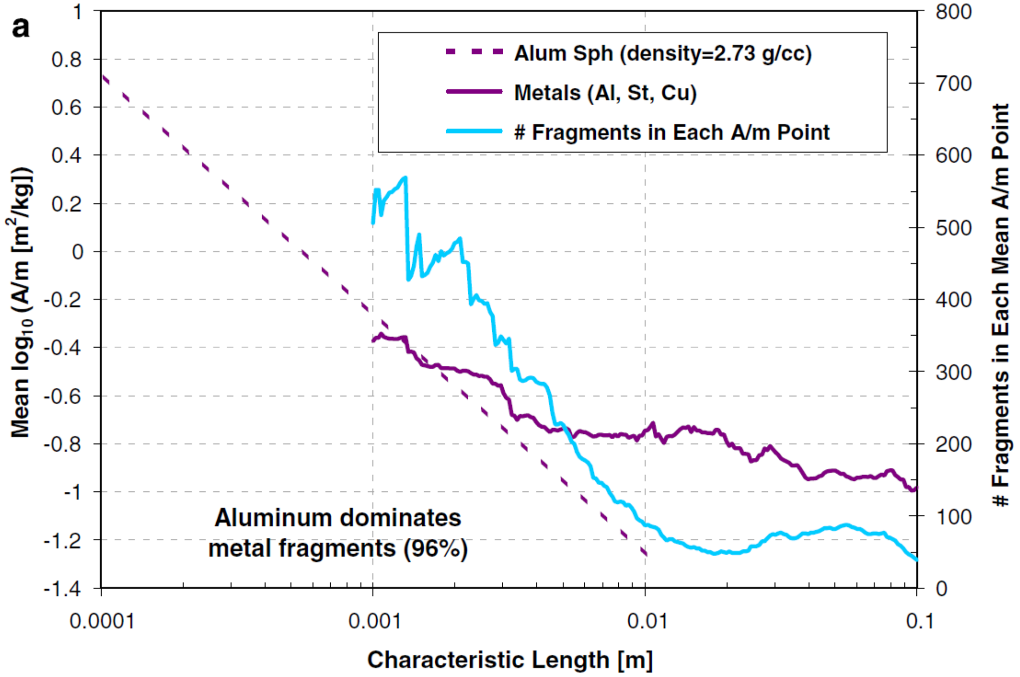


T. Hanada et al., ibid



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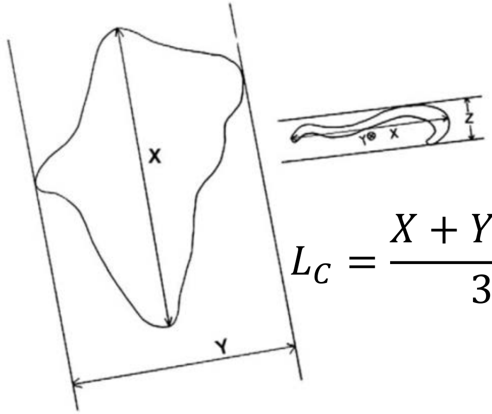
- Area-to-mass ratio: A_x/m
- Material: mainly aluminum
- Typical shape: flakes



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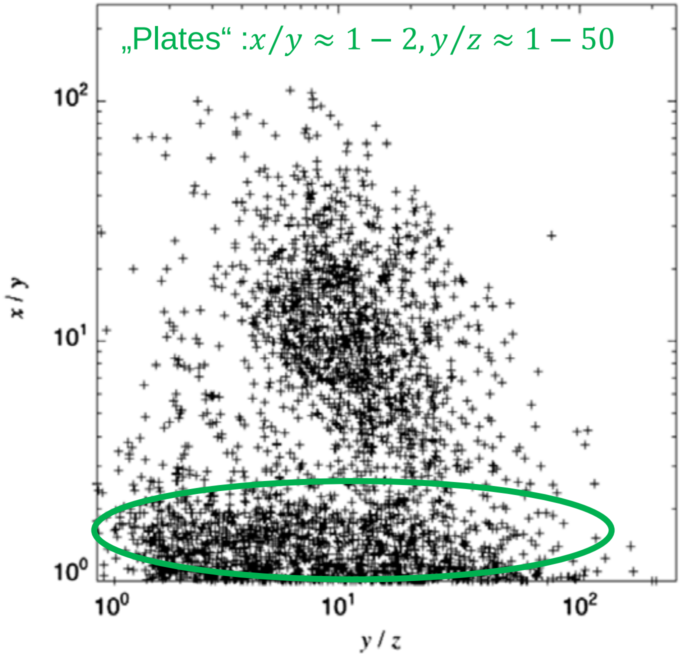

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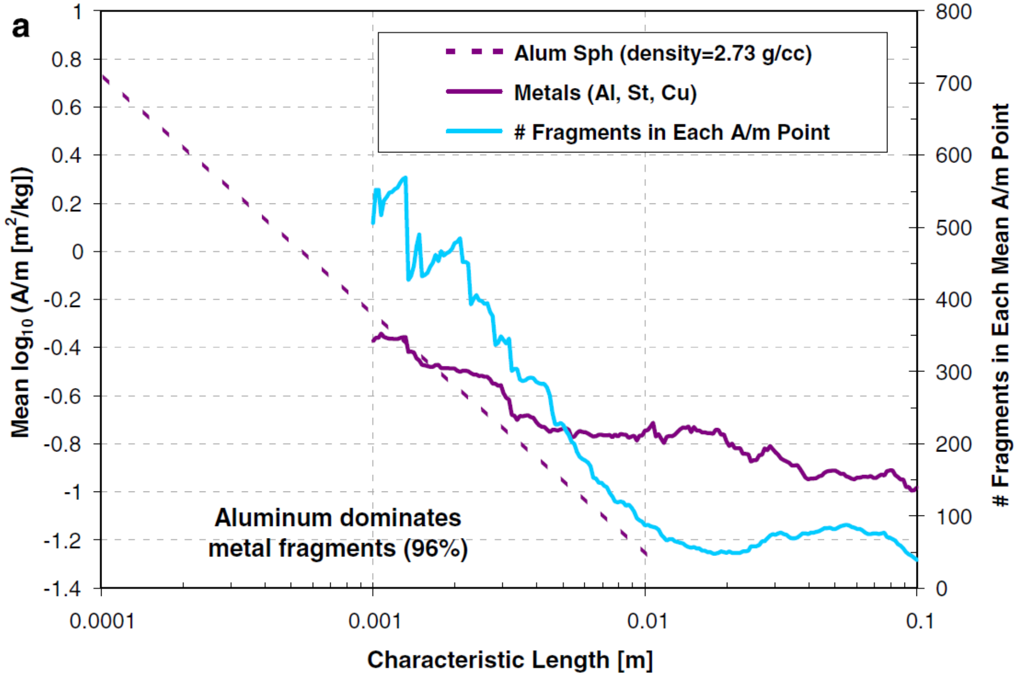

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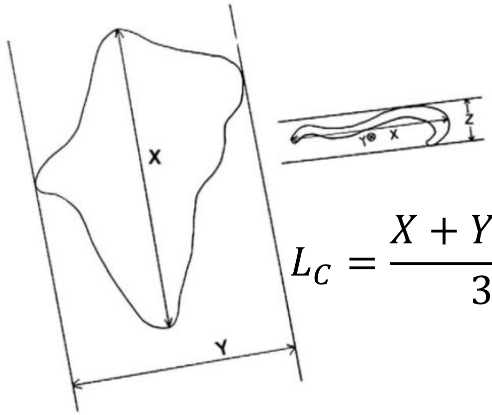
$$A_x = 0.5556945 \cdot L_c[m]^{2.0047077} | L_c \geq 1.67\ mm$$

NASA standard breakup model, in Hanada, ibid.



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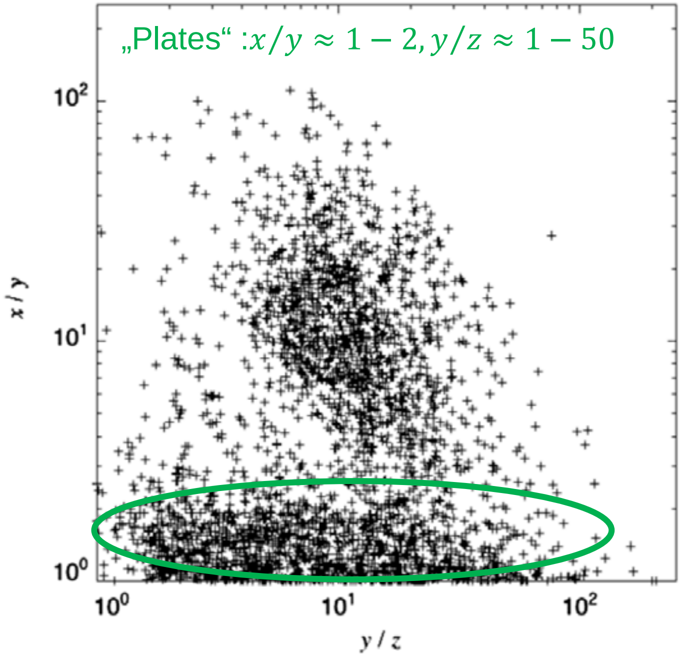
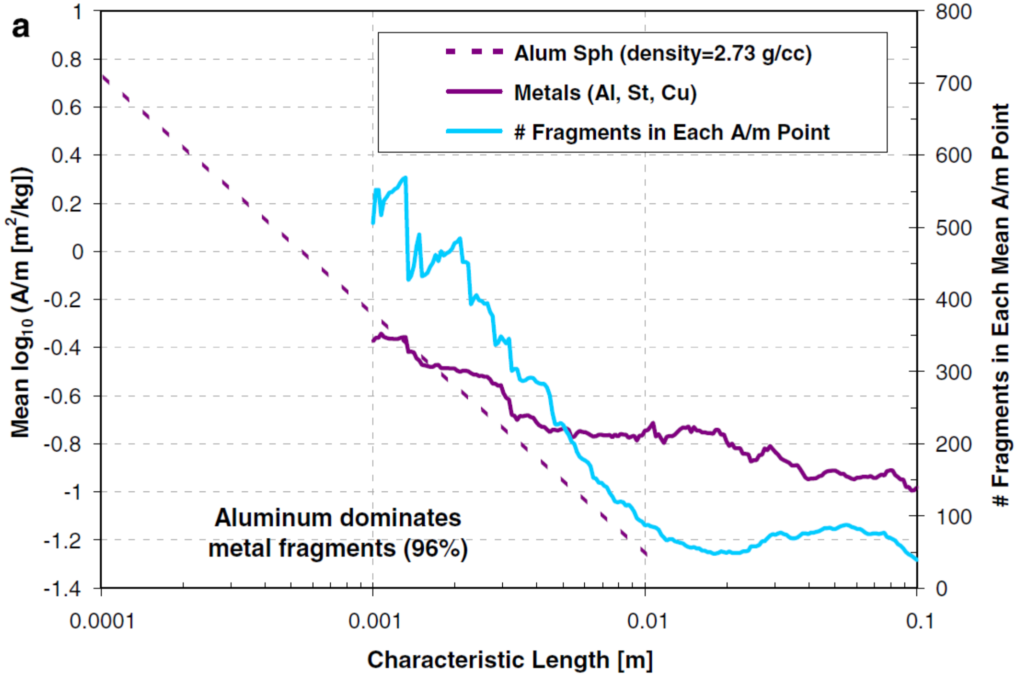


T. Hanada et al., ibid

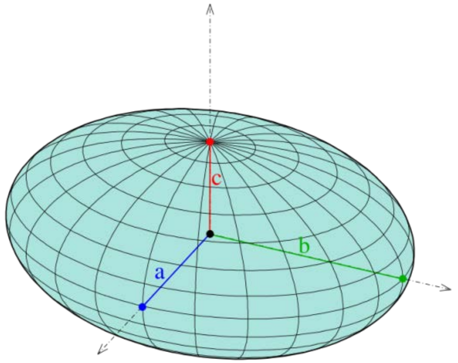


P.H. Krisko et al., Adv. Space Res. 41: 1138 – 1146 (2008)

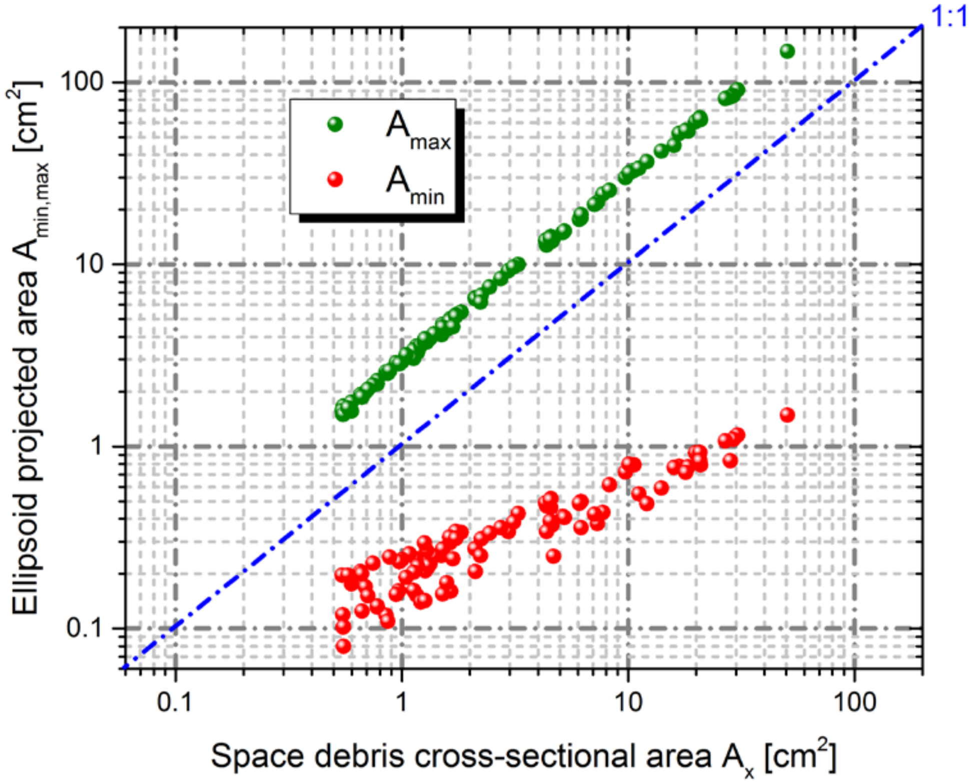
Laser cross-section area vs. area-to-mass ratio

Laser cross-sectional area (projections)

- Maximum: $A_{max} = \pi ab$
- Minimum: $A_{min} = \pi bc$



from: https://commons.wikimedia.org/wiki/File:Ellipsoide.svg



Space debris cross-sectional area

$$A_x = 0.5556945 \cdot L_c[m]^{2.0047077} | L_c \geq 1.67\ mm$$

with characteristic length $L_C = \frac{X+Y+Z}{3}$

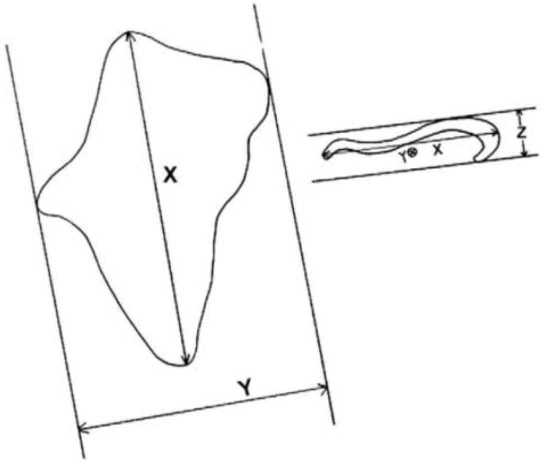


Fig. 6. Sketch of NASA orthogonal 'Projection Dimensions' in Krisko et al. (2008).

NASA standard breakup model, in T. Hanada et al., Adv. Space Res. 44(5): 558 – 567 (2009)

Analytical treatment of momentum scatter for a 1D plate

Target position in a Gaussian beam

- Optimum position:

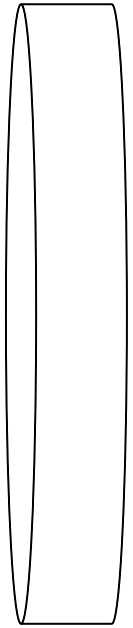
$$r = 0 \rightarrow \Phi(r) = 2\langle\Phi\rangle, \Delta v \approx 2\,\frac{c_m \cdot A \cdot \Phi}{m}$$

- Worst position:

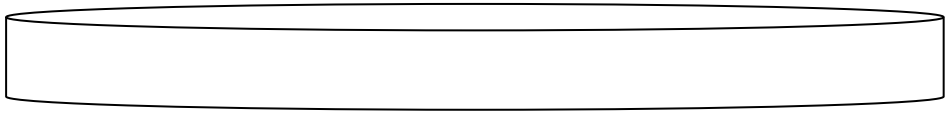
$$\mathrm{r} \gg \sigma: \Phi(r) < \Phi_0, \Delta v \approx 0$$

Mean target orientation

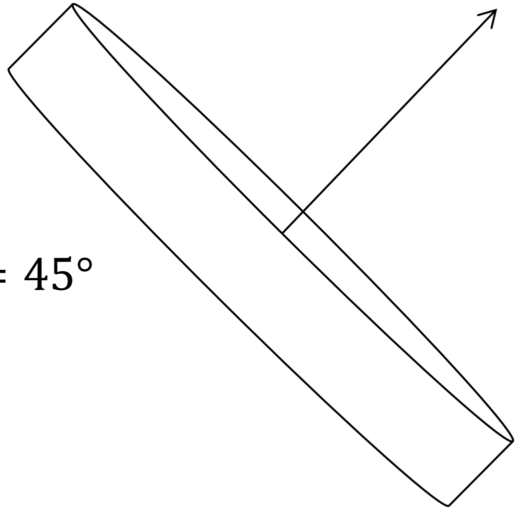
- Optimum orientation: $\Delta v \rightarrow \frac{c_m \cdot A \cdot \Phi}{m}$



- Worst orientation: $\Delta v \rightarrow 0$



- Average orientation: $\alpha = 45°$



Expedit Upgrade: Temperature-Sensitive Modeling of Repetitive Debris Irradiation

→ Interaction of thermo-mechanical coupling and debris temperature

→ $c_m(\Phi, T), \eta_{res}(\Phi, T)$ experimental data needed!

→ Approximation $c_m(\Phi, T_{init}) = c_m\left(\Phi + c_p \varrho d (T_{init} - T_0), T_0\right)$

→ Intra-pulse radiative cooldown

→ Temperature-dependent material parameters: $c_p(T), \varrho(T), \varepsilon(T)$