Momentum Enhancement β Measurement of Basalt-based Rubble Pile Simulants Impacted by Aluminum Spheres at over 5 km/s

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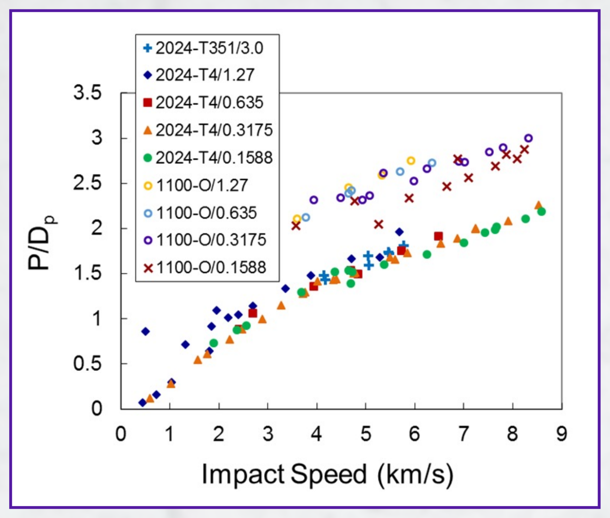
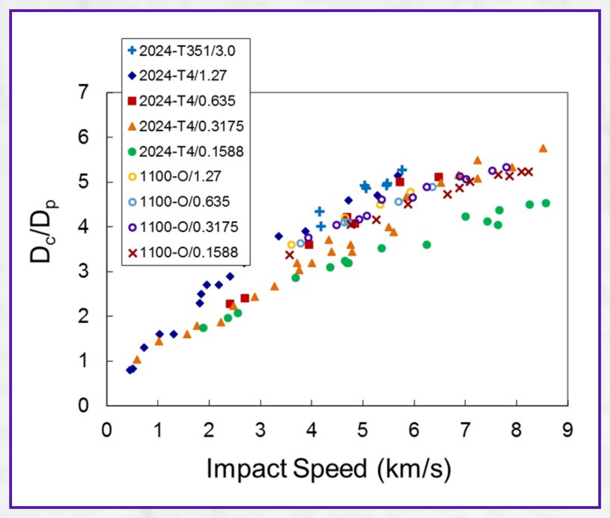
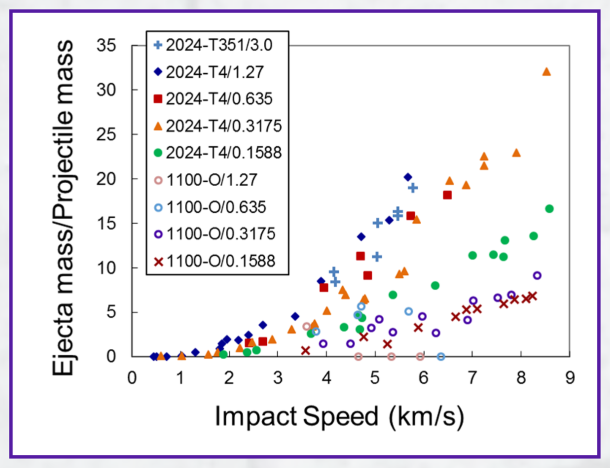
Historical Work on Momentum Enhancement Showing Size Scaling and Impactor Density Scaling

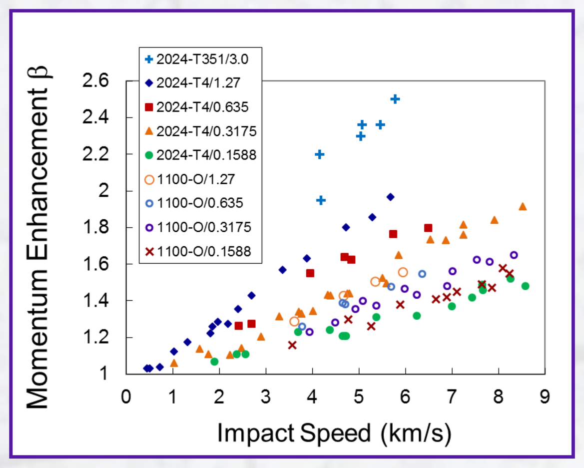
- We performed impacts into granite, aluminum, concrete, sandstone, pumice, to quantify the size scaling behavior and the role of the impactor density.
- We also performed computations studying the various features of momentum enhancement.



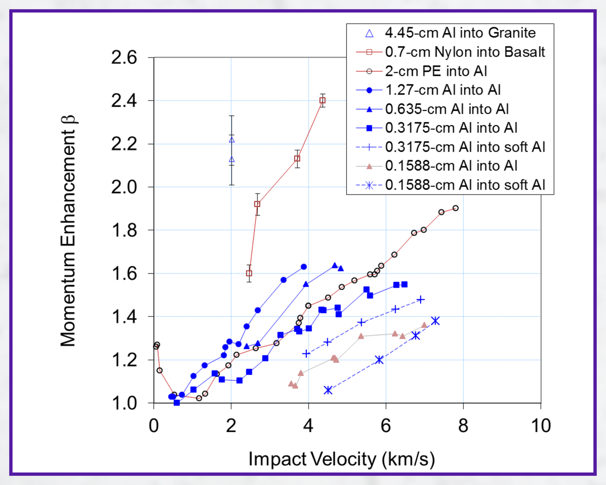


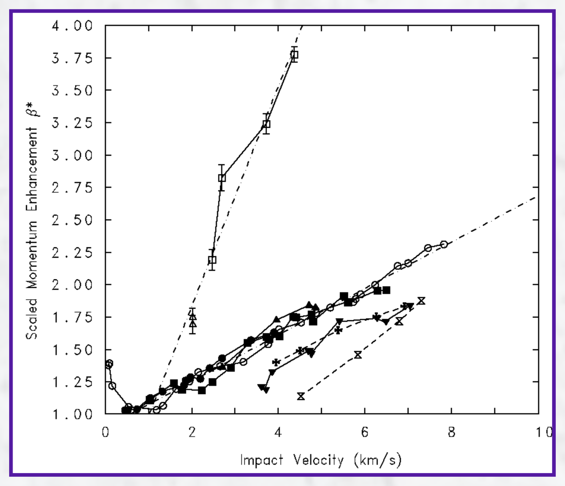
Through impact experiments with various sized impactors, these two figures show the size scaling behavior of Al 2024-T351/T4 (a relatively strong, brittle aluminum alloy) and Al 1100-O (pure aluminum) in terms of crater depth and crater diameter. The crater depth P and the crater diameter D_c are normalized by the impactor diameter D_p. There is little size dependence in the crater depth and a small amount of impactor size dependence for crater diameter.





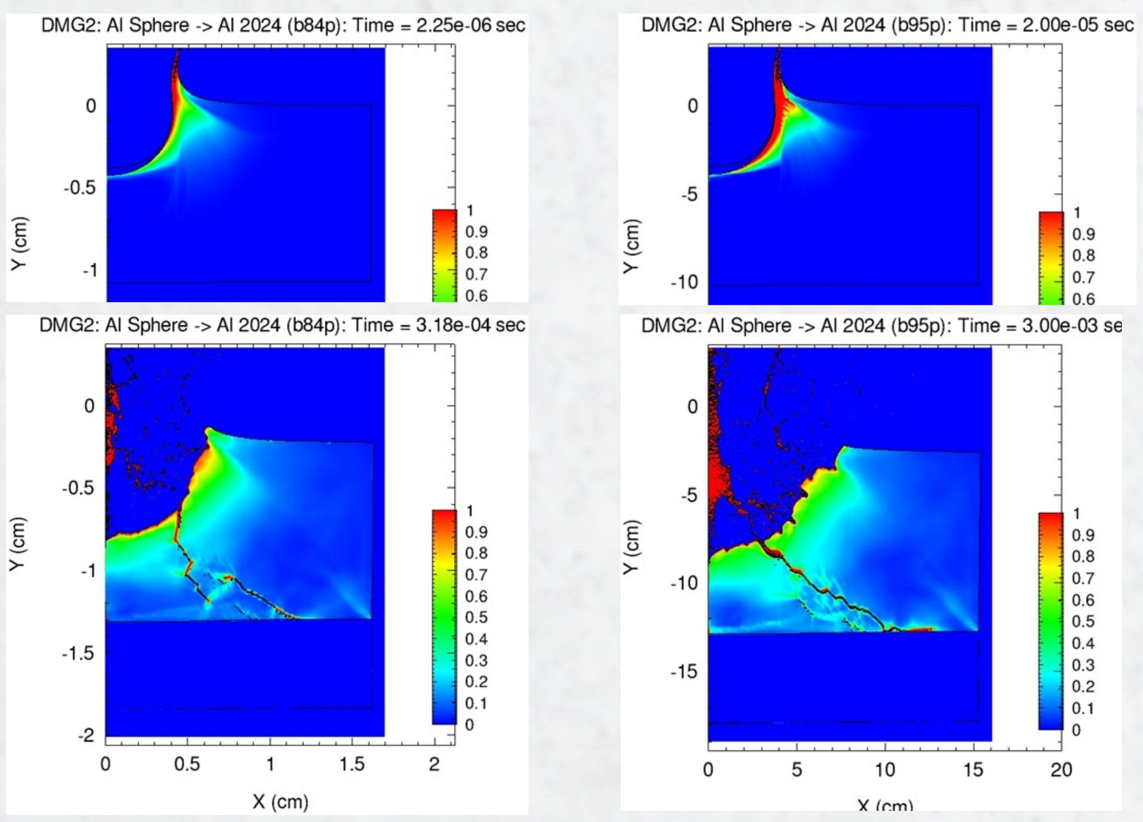
Through impact experiments with various sized impactors, these two figures show the size scaling behavior of Al 2024-T351/T4 and Al 1100-O in target mass loss through ejecta and momentum enhancement β. Both these experimental results are strongly dependent on impactor size.





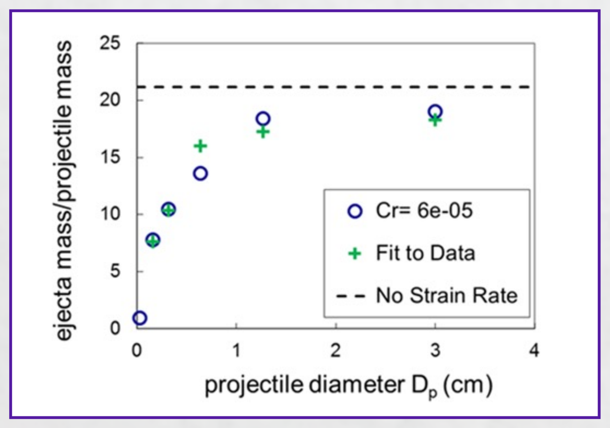
These charts show the size and impactor density scaling for granite, basalt, and aluminum targets and polyethylene, nylon, and aluminum targets. The second chart shows that the following equation can collapse the data, thus quantifying the size and impactor density scaling,

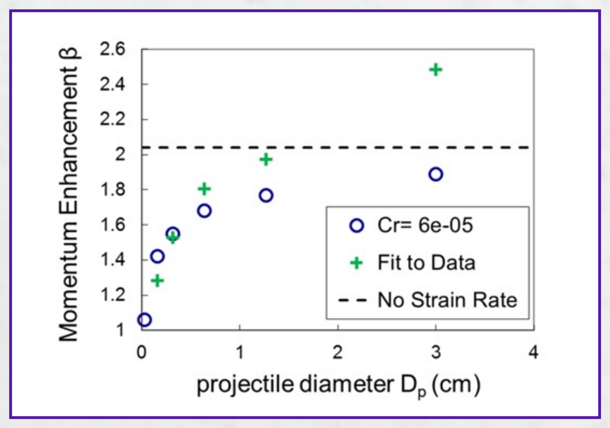
$$\beta - 1 = \left(\frac{\min(\rho_i, \rho_t)}{\min(\rho_0, \rho_t)}\right)^a \left(\frac{D_i}{D_0}\right)^b (\beta_0 - 1).$$



Left images are with a 0.3175-cm-diameter impactor; right images with a 3-cm-diameter impactor.

Extensive computations and the placement of a sophisticated material model into the impact physics code CTH have shown that we can, with a material model that includes a finite slip to failure distance of a shear plane, reproduce the ejecta mass, but we have so far not been able to match the momentum enhancement computationally. These axisymmetric computations have 60 computational cells across the impactor radius, and computations up to 240 cells across the impactor radius have been performed.

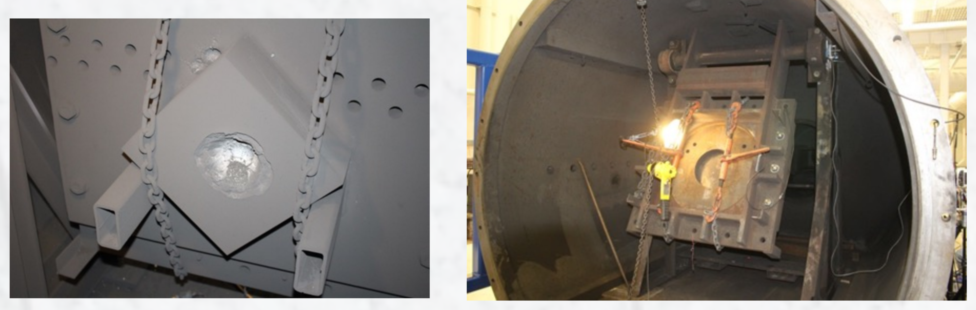




3-cm-diameter aluminum sphere impacts at 5.77 km/s into Al 2024-T351/T4 for a range of projectile sizes (green crosses). CTH computations with sophisticated failure model (blue circles) with 60 cells across the radius of the impactor. These plots show the impactor size dependence and the challenge of reproducing the momentum enhancement β data.

Launching 3-cm-diameter Aluminum Spheres over 5 km/s into Rock and Metal and Measuring Momentum Enhancement

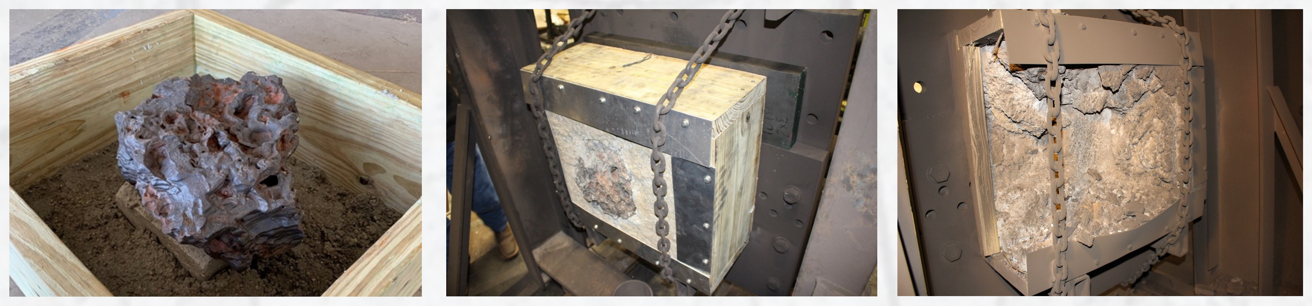
- Prior to the DART spacecraft impact into Dimorphos, our group performed impact experiments into metal and rock structures measuring momentum enhancement. Iron rich targets were motivated by the asteroid Psyche. A collection of stones was motivated to mimic a rubble pile for DART.
- Our two-stage light gas gun arrangement is horizontal and we measure momentum enhancement through the swing of a target pendulum. The target that was a collection of stones required cement to hold them in place.
- The measured momentum enhancement β with this assembly of stones was 3.4 for an impact of a 3-cm-diameter aluminum sphere at 5.44 km/s.



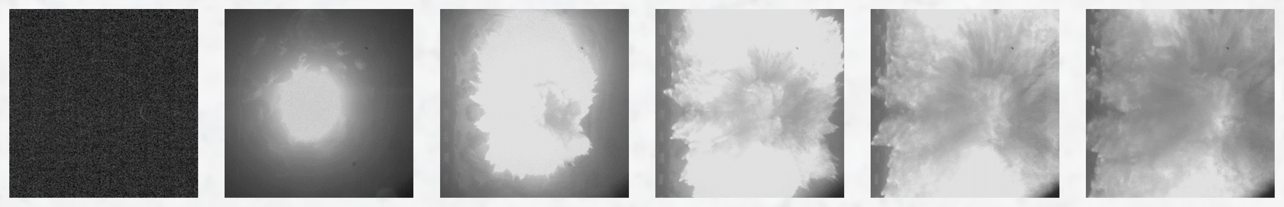
Impact tests at SwRI: SwRI's large two-stage light gas gun, 3 cm Al Projectile and sabot, Al 2024-T351 target attached to ballistic pendulum in evacuated target tank

- The target is mounted on a pendulum where the swing is measured mechanically.
- Swing of the pendulum and pendulum mass distribution information provides momentum transferred to pendulum.

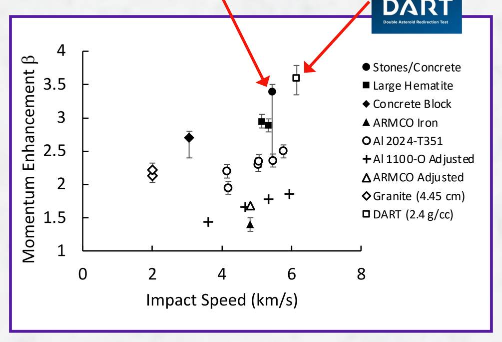
ARMCO iron (pure iron) target struck at 4.81 km/s (LGG-248)

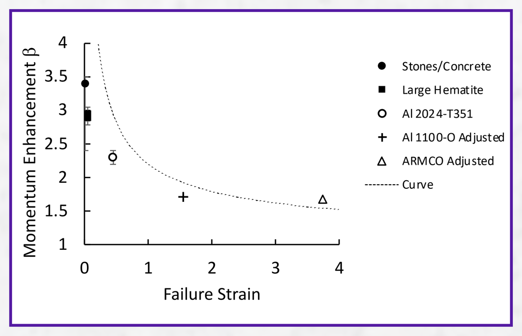


Targets included large hematite rocks in concrete. This hematite rock impacted at 5.33 km/s (LGG-252).



Stones/Concrete Target (LGG-251), 5.44 km/s0.29 microsecond exposure, 12.65 microseconds frame to frame. Result was $\beta = 3.4^{+0.1}_{-1.0}$





- (left) Measured momentum enhancements with 3 cm diameter aluminum sphere impactors. Solid marker data points are from 2021 experimental series (reported at HVIS 2022). The collection of stones data point is β = 3.4. The granite data points used a 4.45 cm diameter aluminum sphere impactor launched from a 50-mm powder gun (reported at HVIS 2012). The adjusted ARMCO iron point is an estimate of β if the impactor had been made of iron, not aluminum. The adjusted Al 1100-O points are 1.27 cm impactors scaled up to 3 cm impactors. The DART result (β = 3.6) assumes 2.4 g/cm³ density for Dimorphos.
- (right) Momentum enhancement βs vs. target failure strain (ductility) for 3 cm diameter aluminum sphere impactors at roughly 5 km/s impact speed. The curve is based on CTH computations at 8 km/s of impacts into aluminum with the strength model of Al 2024-T351 with varying failure strain.

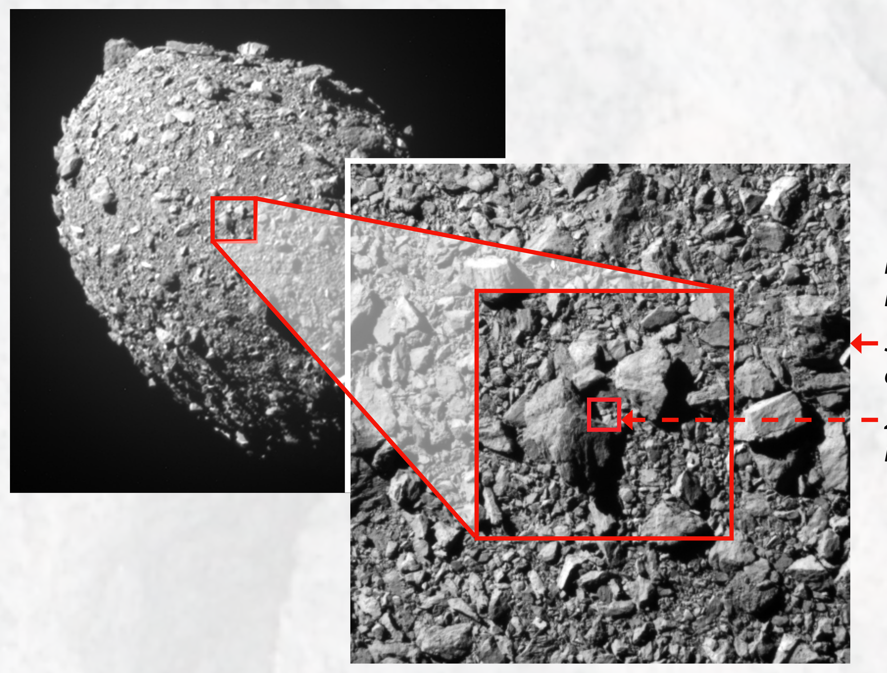
These charts show the results of 3-cm-diameter aluminum sphere impact experiments with targets of

- ARMCO iron (pure iron)
- Al 1100-O (pure aluminum, adjusted for 1.27 cm data to 3-cm with scaling law with b = 0.25)
- ARMCO iron (pure iron, adjusted for aluminum impact to show results of iron impact, a = 0.5)
- Al 2024-T351 (stronger, more brittle aluminum alloy)
- Concrete stepping stone bock
- Large hematite rocks
- Collection of stones

- Granite (with larger impactor, 4.45 cm)
- DART spacecraft impact into Dimorphos on September 26, 2022

Crushed Basalt Targets with Different Size Distributions of Rock (Experiments Performed December 2022)

- With the approach of the DART spacecraft to Dimoprhos, photographs were taken before impact which showed the surface morphology. Examination of the photographs of the Dimorphos surface allowed us to propose simulants for the asteroid to perform additional impact experiments to study momentum enhancement due to hypervelocity impact on the simulated surfaces.
- Within the DART community, nearly all computations are being performed with basalt as a surrogate for the Dimorphos surface material. Because of this, it is relevant to pursue building targets of basalt since 1) basalt is viewed by many as an appropriate analog to the asteroid material and 2) basalt is being used by DART Investigation Team members and others in their computations.
- We based our targets to simulate asteroids, and Dimorphos in particular, to the extent possible, on crushed basalt. The use of basalt-based targets will allow the results to be directly comparable to computations performed by DART Impact Modeling Working Group.



Last Complete Image of Dimorphos from DART

31 meters across (100 ft), 12 km out, 2 seconds before impact

2 meters across, the size of the DART spacecraft main body

- Five experiments were performed in December 2022 with targets made of crushed basalt of a variety of sizes.
- The specific targets were over 200 kg and were 60 x 60 x 30 cm.
- The targets were held in a vertical pendulum, and so it was necessary to hold the basalt with a binder.
- We used grout mixed with sand, trying to make it relatively weak.
  - Typically the target weight was 2/3rd rock, 1/3rd binder.
  - For "S" targets it was all the small basalt
  - For the "S, M" target it was roughly half small, half medium crushed basalt
  - For the "S, M, L" targets it was roughly 1/3rd of each constituent size.
- Shots were between 5.25 and 5.50 km/s.

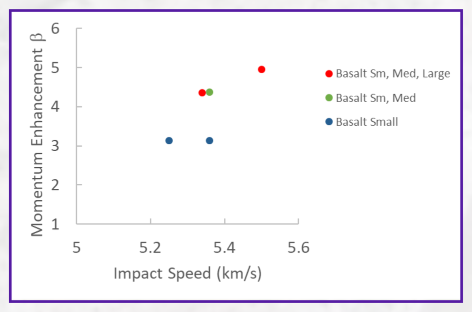
Figure shows 3-cm-diameter aluminum impactor and the three sizes of crushed basalt used in the study.

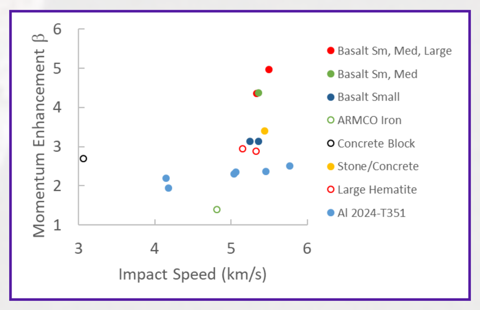
Small basalt rock target hanging in pendulum with CAD model (LGG-403, Small, 5.25 km/s)

Result of 3-cm-aluminum sphere impact into small basalt target (LGG-403, Small, 5.25 km/s)

Small, medium, large distribution basalt rock target before and after impact (LGG-407 Small, Medium, Large, 5.50 km/s)

		km/s	beta
LGG-403	S	5.25	3.14
LGG-406	S	5.36	3.14
LGG-404	S,M	5.36	4.37
LGG-405	S.M,L	5.34	4.36
LGG_407	S,M,L	5.50	4.96





- Preliminary results from December 2022 experiments (internal review, error bars, and significant figures still in process).
- Experiments clearly show that the size distribution of the basalt rocks affects the momentum enhancement.
- These results show that Dimorphos rock distribution can have a large effect on the momentum enhancement β.
- These results provide a baseline case for computational comparison.

References

- Crushed basalt work still in progress and will be submitted to a journal. Will be presented at LPSC (#2622), the Planetary Defense Conference in Vienna (April 2023) and ACM in Flagstaff (June 2023).
- Impact into rock assembly was published right before the DART impact in PSJ:
  - "Momentum Enhancement from a 3 cm Diameter Aluminum Sphere Striking a Small Boulder Assembly at 5.4 km s−1," J. D. Walker, S. Chocron, D. J. Grosch, S. Marchi, A. M. Alexander, Planetary Science Journal 3 215, 2022. https://doi.org/10.3847/PSJ/ac854f.
- Additional rock and iron impacts in graph were presented at the Hypervelocity Impact Symposium (HVIS 2022) and have been submitted to IJIE for the special special HVIS issue:
  - "Momentum Enhancement from 3-cm-diameter Sphere Impacts at over 5 km/s into Iron and Rock," J. D. Walker, S. Chocron, D. J. Grosch, S. Marchi, and A. Alexander, Hypervelocity Impact Symposium, Alexandria, VA, Sept. 19 – 22, 2022, submitted to International Journal of Impact Engineering.
- Aluminum data in graph was presented at the HVIS 2019 and appeared in the IJIE special issue for that conference:
  - "Size Scaling of Hypervelocity-impact Ejecta Mass and Momentum Enhancement: Experiments and a Nonlocal-shear-band-motivated Strain-rate-dependent Failure Model," J. D. Walker, S. Chocron, D. J. Grosch, Int. J. Impact Engng 135 (2020) 103388:1-14 DOI: 10.1016/j.ijimpeng.2019.103388.