White Paper for *Frontiers of Plasma Science Panel*

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Either Oral or Poster	X
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Title:	Plasma physics of hypervelocity impact
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- ***Describe the research frontier and importance of the scientific challenge.***

This section describes the research frontiers as related to warm dense matter (WDM) and high-energy-density plasma (HEDP) conditions produced in hypervelocity (higher than Earth's escape velocity of 11.2 km/s) impact of laser-accelerated solid projectile hitting a solid target. The projectile emulates a micro-meteoroid, a dust particle or a small piece of debris in space. Hypervelocity impact is a widespread phenomenon, which is governed by complicated two- and three-dimensional compressible hydrodynamics and dynamic material properties. Good understanding and accurate modeling of hypervelocity impact in the Mbar pressure range is relevant to a broad range of problems in high-energy density plasma physics and its applications, from the "impact ignition" approach in the inertial confinement fusion [1], to protection of spacecraft against micro-meteoroids, to numerous issues relevant to projectile penetration through various kinds of obstacles including cosmic collisions of meteorites and asteroids with planets [2-4], to astronomy and astrophysics. Better insight into generation of dust particles in hypervelocity collisions of rocky bodies in space is needed to understand the composition and evolution of circumstellar debris disks observed around many stars [5, 6]. Recently it has been proposed [7] to address the recognized hazard represented by the orbital debris for satellites [8] by using a targeted release of a cloud of micro-projectiles for removing the individually untrackable small-scale pieces of debris from orbit.

Progress in all these areas requires the experimental capability for studying the hypervelocity impact of solid macroparticles at velocities exceeding the low-orbit velocity 8 km/s by a factor of 2 or more. Gas guns accelerate solid objects to velocities below ~11 km/s. Magnetically driven hypervelocity launch capability developed at the Sandia Z accelerator [9] makes it possible to accelerate planar aluminum flyer plates up to 45 km/s but this technique is not directly applicable to acceleration of isolated, compact solid objects emulating dust particles, micro-meteoroids or pieces of debris. Electrostatic Van de Graaff accelerators (see [10, 11] and references therein) accelerate macroparticles up to ~100 km/s, but the particle sizes are limited to diameters between 0.1 and 5 μm. Dust particles in space mostly fall into this range but obviously it does not cover larger objects, such as meteoroids, whose impacts produce dust in space, as well as small pieces of debris. To enable experimental studies of hypervelocity impacts involving such larger objects, as well as to develop the techniques of protecting the space assets against such impacts and removing the "space junk" from orbits we need to pursue an innovative approach.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

It is well known that the fastest projectiles are those accelerated by high-energy lasers. The absolute record of the projectile velocity listed in the Guinness Book of Records has been set several years ago at the Naval Research Laboratory, where a thin plastic target was accelerated with the Nike KrF laser to above 1000 km/s [12]. The moderate- and large-scale laser facilities and experimental methods developed for inertial confinement fusion (ICF) and high energy density plasma physics provide an opportunity to advance experimental studies of hypervelocity impact into the relevant parameter range that has not been accessible so far. In our opinion, it can be made by dedicated research and development. Acceleration of laser targets to ~100 km/s is routinely done on all ICF laser facilities. The GEKKO-XII-HIPER laser facility in Japan has been recently used to study cratering at hypervelocity impact of solid spherical or cylindrical projectiles made of aluminum, gold and glass on solid targets [13], as well as size distribution of dust particles produced in such impacts [14]. With laser pulse energy ranging from 1 to 9 kJ, they demonstrated direct ablative acceleration of solid targets with initial diameters 0.1 to 0.4 mm to velocities up to 60 km/s before the impact.

The problem with direct laser or x-ray acceleration is that a radiation-driven target is in a contact with the hot corona plasma of keV temperature, it absorbs a broad spectrum of x rays emitted by the corona, it is strongly shocked when the radiation drive is turned on. Its acceleration is a result of ablation of a part of its mass turned into a plasma. At the end of acceleration, the mass of the projectile is less than its initial mass, and its thermodynamic state is uncertain – partly solid, partly molten solid, partly WDM/dense plasma. It is not obvious that a hypervelocity impact of such partly softened projectile would result in cratering and dust production similar to an impact of a solid body of the same material and mass. And it is difficult to directly compare the momentum transferred to the impacted body with the initial momentum of the projectile, whose velocity can be directly measured, as in [12-14], but the mass is uncertain.

We propose to advance this approach further to achieve a better control over the thermodynamic state and mass of the accelerated solid projectile. For that, we propose to develop a laser plasma gun in which a projectile is softly driven by the expansion of laser-accelerated and compressed material. This method was first suggested in early 1990s [15]. More recently, a similar experiment on shockless compression and acceleration on the Omega laser was reported [16]. In this experiment, the laser irradiated a foam slab, accelerating it to a high velocity of ~100 km/s. The accelerated foam was heated to ~10 eV in the process of acceleration and is allowed to expand before it impacts the Al foil. The reduced ram pressure of the "pillow impactor" acts for a longer time, while the momentum transfer to the foil is about the same as for a foil directly accelerated by the laser [15]. The greater the initial separation between the foam and the foil, the lower is the peak pressure accelerating the foil, and the longer it lasts. This distance can be chosen such that the pressure remains below 0.5 Mbar so that the accelerated foil does not liquefy upon release. In a recent experiment [17], a solid Al flyer plate is accelerated to 5 km/s by gently pushing it with expanding polyimide target that was directly irradiated by a 300-J pulse of Janus laser at LLNL. Acceleration of a grain, as schematically shown in Fig. 1 does not require the flyer to be a flat, largely uniform planar object, as the equation-of-state measurements, like those of [17], do. Our estimates indicate that small solid targets, like those used in the experiments [13, 14] can be maintained in solid state in the process of acceleration by such mechanism for velocities up to ~50 km/s. On a 2-kJ Nike laser one can work with target dimensions of 30 to 50 μm. Once the acceleration in solid state has been demonstrated on a smaller facility, it would open an opportunity for large-scale experiments on Omega and NIF laser facilities, to increase both the dimensions and the velocities of the projectiles.

Among many experiments that development of the experimental platform described above would make possible, the following two appear to be of special interest. The first one, pertaining to the basic physics of hypervelocity impact, is: How strong is the impact, for given mass, velocity, and material of the solid impactor, on the one hand, and material of the solid impacted surface, on the other? Obviously, the strength of any punch is determined by the momentum transferred to the impactee normalized to the momentum of the impactor. If the impacting projectile sticks to the target, the transferred momentum is unity. In the case of ricochet, if the projectile is elastically reflected from the target, the transferred momentum increases to two. In the hypervelocity range of interest to us, strongly shocked impactee material, fragmented, molten and vaporized, is ejected normal to the impacted surface, thereby increasing momentum transfer, potentially by a large factor. For example, an estimate based on the well-researched data [18] on the meteorite impact that produced the Arizona crater, Fig. 2, indicates momentum amplification by a factor of 18. One can say that a body impacting at hypervelocity punches "above its weight." If this conjecture is confirmed for solid objects of sub-mm dimensions, it will make possible de-orbiting of small debris that cannot be done by any other means.

Another issue of immediate practical interest is the electromagnetic pulse, EMP, produced by the hypervelocity impact. High velocity of the impact implies that the projectile material becomes partially ionized at the impact, turning into dense plasma. As the plasma expands outwards the collision rate will reduce allowing free electron oscillation around the plasma frequency in the sheath region, which leads to EMP emission [19]. This process is schematically shown in Fig. 1. The frequency spectrum of the EMP depends on the plasma density in the ejecta front. If the impacted object is a satellite, then the EMP can interfere with its sensors, leading to temporary or permanent "blindness" depending on its magnitude. Therefore, for developing countermeasure it is important to quantify material specific EMP effects. This is another reason for developing the experimental capability discussed above.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.***

The proposed work will provide another direct link of ICF/HEDP plasma science to laboratory astrophysics, equation-of-state studies and material science and broaden the range of applications addressed with the National Laser User Facilities. If the experiments with measuring the momentum amplification in hypervelocity collisions yield the results close to our preliminary estimates, this work will open the way for removal of small-scale, individually untrackable pieces of orbital debris [7], which represent a large and growing hazard [8] not addressed by any other method proposed so far. It will enable experimental studies of hypervelocity-impact-induced EMP [19] that will help protecting both civilian and military assets in space from micro-meteorites, space debris and adversary actions in space.

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Figures

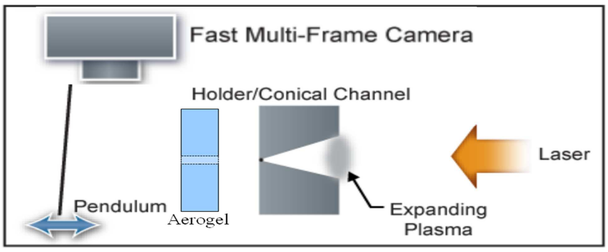

Figure 1. – Sketch of measurement: A laser pulse accelerates and heats a thin foil which expands into a reverse nozzle channel, generating pressure to accelerate a tungsten grain at the nozzle tip. The expanding foil carries momentum to the grain while protecting the grain from laser irradiation, thereby reducing the heat and shock on the grain. The grain velocity is measured by a fast multi-frame camera, and momentum is calculated from the product of the velocity and the mass. The momentum transferred to a surface impacted by the grain is measured by a ballistic pendulum.

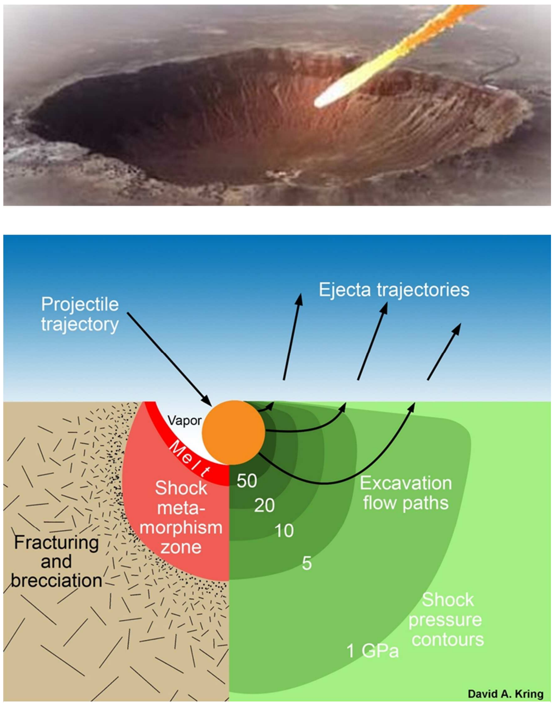

Figure 2. – (a) Arizona crater (b) A sketch of the impactor/impactee collision.

http://www.lpi.usra.edu/nlsi/education/hsResearch/crateringLab/lab/part1/background/

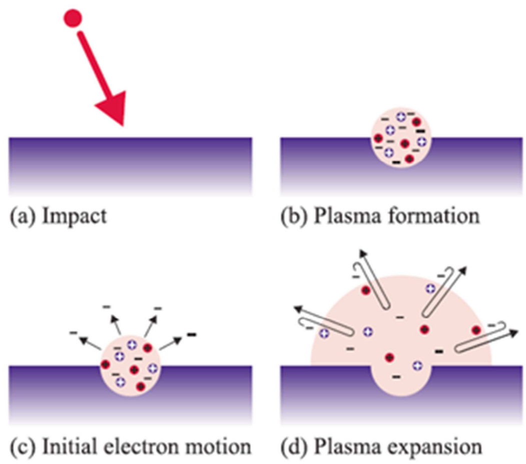

Figure 3. – Schematic of the plasma formation and expansion process [19].