White Paper for *Frontiers of Plasma Science Panel*

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Indicate the primary area this white paper addresses by placing "P" in right column.
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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	S
• Interactions of plasmas and waves	S
• Plasma self-organization	
• Statistical mechanics of plasmas	P

Indicate type of presentation desired at Town Hall Meeting.

Oral	X
Poster	
Either Oral or Poster	
Will not attend	

Title:	Absorption of multi-petawatt laser light by dense materials for fundamental physics probes and next-generation laboratory astrophysics
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- ***Describe the research frontier* and importance of the scientific challenge.**

Absorption, the conversion of laser energy into particle energy, is the crucial first step in all high power laser interactions with matter. Developing a comprehensive understanding of absorption dynamics is therefore a fundamentally important problem for laser-driven plasma physics, and applications based thereupon, ranging from compact relativistic particle accelerators[1], to fast ignition inertial confinement fusion[2], to laboratory astrophysics[3].

Petawatt lasers, having powers $>10^{15}$ W and intensities $> 10^{18}$ W cm^{-2} at 1μm wavelength, are the most powerful light sources on Earth. Using these lasers to illuminate optically-thick materials creates extreme states of plasmas, with temperatures exceeding ten million degrees Celsius and pressures exceeding one billion earth atmospheres. Key metrics for petawatt laser-based applications relate to absorption, yet conditions in this regime are so strongly nonlinear that it is often impossible to know the fraction of absorbed light f, and even the range of f has been unknown.

While many important aspects of absorption remain topics of active research, it has recently been shown that f exhibits a theoretical minimum and maximum in petawatt-scale interactions [4]. Thus, it is clear that a key research frontier involves absorption dynamics beyond the petawatt-scale, and indeed, the search

for limits on *f* therein. Such limits become particularly topical as the laser field increases towards the scale of the Schwinger, or quantum critical, field.

In multi-petawatt laser interactions with optically-thick materials, it is believed that copious numbers of electron-positron pairs are created via quantum electrodynamical (QED) processes taking place in the laser fields[5]. Pairs take on further importance in broader contexts as they are believed to be essential constituents in numerous high-energy astrophysical events such as pulsar winds, blazar jets, and gamma-ray burst outflows. They also are also intimately connected to the fundamental nature of light and its conversion into matter. At extreme electric field strengths, near the quantum critical field ~ 10^{18} V m^{-1} , no matter is necessary to generate positrons: the electric field of the laser is sufficiently strong to rip apart the vacuum itself and trigger a cascade of formerly virtual electron-positron pairs[6]. This Schwinger mechanism is believed to form the ultimate upper limit on light which can exist in the universe. Recent work has predicted that a Schwinger-like electron-positron cascade can occur at much lower laser intensities, ~ 10^{23}-10^{24} W cm^{-2}, corresponding to a ~ 10 petawatt class laser system[5]. These regimes are relevant to near term and proposed laser facilities such as ELI and LCLS-II at the SLAC National Accelerator Laboratory.

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

The high energy density conditions in petawatt laser interactions with optically-thick materials are driven at the microscopic scale by dense currents of relativistic electrons (~ 10^{11} A cm^{-2}), oscillating violently in the intense laser fields (> 10^{10} V cm^{-1}). Here the laser power is sufficiently high that free electrons oscillating in the laser fields become relativistic, enabling efficient collisionless mechanisms of absorption. Facilitating absorption studies in this regime, recently a formalism for intense laser light interacting with dense matter that is analogous to the Rankine-Hugoniot relations for shock waves has been developed[4]**.** The model overcomes difficulties of particle nonlinearity by creating a kinematic basis on which to formulate the interaction. A geometry centered at the laser-matter interface is used, taking advantage of the laser decay into an evanescent wave over a relativistic collisionless skin depth in the optically-thick target. Here, Rankine-Hugoniot-like conservation laws must be satisfied by the forward-going evanescent light wave, backward-going reflected wave, and forward-drifting highly-relativistic electrons and moderately-relativistic ions accelerated by the laser. By representing the complex motion of individual particles with ensemble properties such as density and momentum, accounting for the relativistically-correct laser-solid physics, the absorption model realizes an essentially four body kinematics situation. These kinematics exhibit restrictions in terms of values the ensemble properties of electrons and ions can take on. Since acceleration of electrons and acceleration of ions are modes of absorption of laser light, these kinematic restrictions are transformed into useful upper and lower bounds on absorption. Close agreement with a broad range of published experimental and simulation data has confirmed that the absorption theory is distilling fundamental aspects of the nonlinear dynamical physics, as is shown in Fig. 1.

Hence, it is clear that key steps in advancing this research frontier will involve incorporating into such absorption models the high frequency radiation and electron-positron pairs that play key roles in the multi-petawatt regime. Importantly, this optically-thick situation is likely to be the first setup realized in the laboratory using a multi-petawatt laser. That is due to the fact that low density and matterless interactions[7-9] will require multiple multi-petawatt laser pulses: in order to create substantial quantities of high frequency radiation and anti-matter, the accelerated electron center of mass frame should coincide closely with the laboratory frame[5]**.**

Numerical simulations will also play a crucial role in carrying out aspects of this research program. The "QED-PIC" code EPOCH[10] has been used to study multi-petawatt laser physics, exhibiting many

successes[11,12], and it is important that support for its development is continued into the future. The development of codes employing different approaches to integrating QED processes into the particle-in-cell (PIC) model, to establish suitable benchmarking protocols, is further essential.

The important role that the development of multi-petawatt laser facilities in the near term will play is evident. It is further desirable that a multi-petawatt capability be fielded as part of the LCLS-II upgrade that is scheduled to take place at the SLAC National Accelerator Laboratory. The possibility to couple the high power laser to a high brightness 4th generation light source opens important capabilities in areas such as X-ray Thomson scattering plasma diagnostics[13].

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

This frontier research program seeks to develop an understanding of absorption dynamics in the interval from the petawatt scale – the most powerful light sources on earth today – to the Schwinger scale – the most extreme conditions in the universe.

It thus forms a plasma science-based opportunity to address fundamental questions about the conversion of light energy to matter energy, and about limits on light power in the universe.

Furthermore, progressing this research program seems very likely to open the way to novel fundamental physics studies and laser-based probes of the nonlinear properties of the vacuum[14]. Finally, since the creation of prolific electron-positron pairs is predicted in its course, understanding and ultimately controlling absorption dynamics at these scales seems very likely to open a path to next-generation laboratory astrophysics platforms.

References (Maximum 1 page)

[1] Daido, H. et al. (2012). *Reports on Progress in Physics. Physical Society (Great Britain)*, *75*(5), 056401.
[2] Tabak, M. et al. (1994). *Physics of Plasmas*, *1*(May), 1626–1634.
[3] Huntington, C. M. et al. (2015). *Nature Physics*, (January), 1–13.
[4] Levy, M. C. et al. (2014). *Nature Communications*, *5*(May), 1–6. doi:10.1038/ncomms5149
[5] Bell, A., & Kirk, J. (2008). *Physical Review Letters*, *101*(20), 200403.
[6] Schwinger, J. (1951). *Physical Review*, *82*(5), 664–679.
[7] Fedotov, A. et al. (2010). *Physical Review Letters*, *105*(8), 1–4.
[8] Bulanov, S. et al. (2010). *Physical Review Letters*, *105*(22), 1–4.
[9] Nerush, E. et al. (2011). *Physical Review Letters*, 106(3), 19–22.
[10] Ridgers, C. P. et al. (2014). *Journal of Computational Physics*, *260*, 273–285.
[11] Ridgers, C. et al. (2012). *Physical Review Letters*, *108*(16), 1–5.
[12] Brady, C. S. et al (2012). *Physical Review Letters*, *109*(24), 245006.
[13] Glenzer, S., & Redmer, R. (2009). *Reviews of Modern Physics*, *81*(4), 1625–1663.
[14] King, B. et al. (2010). *Nature Photonics*. doi:10.1038/nphoton.2009.261.
[15] Davies, J. R. (2009). Plasma Physics and Controlled Fusion, 51(1), 014006.

Figures (maximum 1 page)

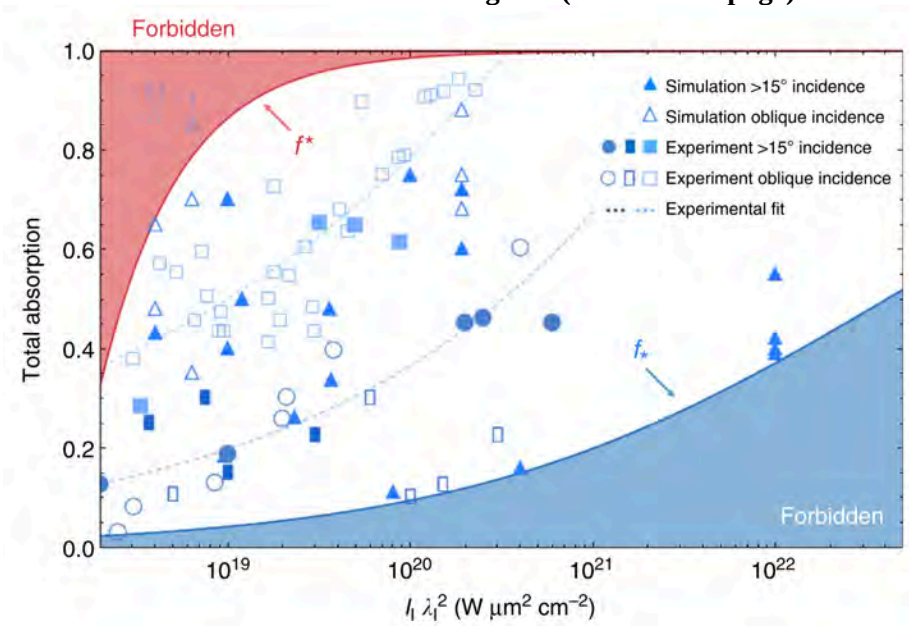

Fig. 1. *Theoretical limits on absorption at the petawatt laser power-scale, and comparison to published absorption data[4]*. The upper limit on absorption f^* is depicted in red and the lower limit f_* in blue, with forbidden regions indicated using shading. These bounds are shown to forbid high absorption values at low laser power and low absorption values at high laser power. The complete absorption data set compiled in ref. [15] is reproduced here, spanning experimental and simulation data published over the past two decades, across a variety of laser and plasma conditions. The research program outlined in this whitepaper will extend our understanding of absorption dynamics from from the petawatt scale shown in this plot – the most powerful light sources on earth today – to the Schwinger scale – the most extreme conditions in the universe.