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	
• Interactions of plasmas and waves	P
• Plasma self-organization	S
• Statistical mechanics of plasmas	S

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	X
Poster	
Either Oral or Poster	
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Title:	High Intensity Laser Matter Interaction
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- ***The research frontier*** **and importance of the scientific challenge.**

Nowadays with the fast growth of laser technology, lasers are one of the most powerful sources of electromagnetic (EM) radiation under laboratory conditions.. PW-class lasers, such as at the BELLA facility at LBNL or the proposed lasers at the European Extreme Light Infrastructure laser facilities, can in principle be focused down to intensities approaching or in excess of 10^{22} W/cm^2 [1, 2]. There are proposed projects to generate pulses with intensity up to $10^{25\text{-}26}$ W/cm^2 [3]. Such PW-class (and beyond) laser systems [4] can be used to accelerate ions to relativistic energies, generate sources of high frequency coherent radiation, model the processes typical for relativistic astrophysics, study the interaction of particles with EM fields in the radiation dominated and quantum regimes, which completely change the nature of interaction, and, maybe, probe the properties of the vacuum. The latter two processes are from the domain of nonlinear quantum electrodynamics (nQED) where high intensity laser pulses would allow for the study of the unexplored regime of interaction of charged particles with ultra-intense radiation. As will be discussed in the approach section, plasma physics is at the crossroads of all this physics and will enable the exploration of ultra-intense laser-particle interactions by providing energetic particle beams and radiation source.

The interaction of high intensity EM pulses with either underdense or solid density plasmas uncovers a vast range of phenomena, among them relativistic flying mirrors (RFM) [5]. RFM are thin electron or electron- ion sheets in the case of solid targets and electron density modulations in the case of underdense targets accelerated to velocities close to the vacuum light speed by high intensity laser pulses. The

reflection of an EM wave from these RFMs leads to the change of the frequency and energy of the wave according to the double Doppler effect. The scientific area emerging in the counter-propagation setup promises the development of sources of X-rays in the attosecond regime, the expected intensity may reach the level at which the nQED effects will manifest themselves. In the co-propagation setup the energy of the laser pulse is transferred to the RFM energy, which can be used to accelerate ions.

High intensity laser-matter interaction also enters regimes of interest for astrophysics: shock waves and collimated plasma jets are created, instabilities play an important role in plasma evolution, and the equation of state of matter under extreme conditions can be studied. Further, the laser plasma may reach the radiation dominated regime. Very strong magnetic fields generated during the laser plasma interaction may in principle be configured in a way to model magnetic reconnection phenomena.

Finally, ultra-high intensity electromagnetic (EM) fields can significantly modify the interactions of particles and EM fields, giving rise to the phenomena that are not encountered either in classical or perturbative quantum theory of these interactions [6]. One can imagine a cube of theories, which has three orthogonal axes marked by c, $\hbar$, and a (see Fig. 1). These three axes correspond to relativistic, quantum, and high intensity effects. Each vertex of the cube corresponds to a physical theory: $(0, 0, 0)$ is nonrelativistic mechanics, $(c, 0, 0)$ is special relativity, and $(0, \hbar, 0)$ is quantum mechanics. The theory that has both quantum and relativistic effects included is the quantum field theory, $(c, \hbar, 0)$. The classical electrodynamics corresponds to the vertex $(c, 0, a)$ and atomic, molecular, and optical physics to $(0, \hbar, a)$. If the high intensity effects are included in the framework of the quantum field theory, then the corresponding vertex $(c, \hbar, a)$ corresponds to the high intensity particle physics. Thus the high intensity EM fields add a new dimension to the processes occurring in quantum field theory, significantly changing the physics of the interactions.

In the radiation dominated regime the energy emitted by charged particles during the interaction with high intensity EM fields is of the order of the energy gain from these fields. The quantum nature of the interaction reveals itself when the emitted photon takes away a significant part of the electron or positron energy, or when the production of new particles becomes possible. These regimes of interaction are closely related to non-perturbative quantum field theory and the behavior of matter in extreme conditions. There are many open questions both from the point of view of theory and experiment, which high intensity laser matter interactions may address, such as the thresholds of the applicability of currently used theoretical models. Most theoretical approaches use the approximations of the external field and plane waves for the high intensity EM pulses. However, these approximations do not take into account the backreaction of nQED processes on EM fields and the finite size effects, which are very important for the tightly focused laser pulses. Closely related to the backreaction and finite size effects is the problem if there exists an ultimate limit for the attainable laser intensity. Also manifestations of the physics beyond the Standard Model may potentially be observed in high intensity laser matter interactions. Moreover these interactions may serve as testbeds for future detector techniques and model the interactions at future colliders.

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

There has been a significant interest lately in studying the configuration of charged particle interaction with high intensity EM field. Here, photon emission by electrons or positrons (Compton effect) and photon decay into an electron-positron pair (Breit-Wheeler process) occurr subsequently in the EM field of two colliding laser pulses. This will give rise to a complex multistage process - EM-avalanche type discharges at intensities of about 10^{25} W/cm^2 [7] (see Fig. 2a). This type of process will lead to the exponential growth of the number of electrons, positrons, and photons, which may impose a fundamental limit on the maximum attainable laser intensity as well as advance our understanding of the backreaction of nQED processes on the properties of strong EM fields.

Though the intensity needed for the EM avalanche to develop is beyond reach of the available laser facilities (it would require 10 – 100 PW laser systems), the complex physics of multistage cascade-type processes can be accessed in the interaction of high energy electron beams with high intensity laser pulses. The intrinsic flexibility of the laser wakefield acceleration allows for the production of electron beams with the energy from several MeV to several GeV [8], which colliding with a high intensity PW-class laser pulse would allow to study a wide range of parameters from Thompson scattering to multiphoton Compton process and multiphoton Breit-Wheeler electron-positron pair production. This all optical setup for the study of nQED processes would be an ideal environment to look into detail at the parameter space of the Standard Model not covered experimentally before (see Fig. 2b). It would allow the study of the production of electron-positron jets and high energy gamma-rays and their interaction with high intensity EM fields [9].

The configuration of a counterpropagating 46-GeV electron beam and a 10^{18} W/ cm^2 laser pulse was used in the E144 experiment at SLAC [10]. The relatively low laser intensity resulted in a long mean free path of electrons and photons with respect to either radiation or pair production and thus led to a small number of events observed. By contrast, today the achievable peak laser intensity is of the order of 10^{22} W/ cm^2 , GeV electron beams are routinely produced by laser-plasma accelerators [8,11]. Thus combining a 10-GeV electron beam with a 10^{22} W/cm^2 laser pulse (which would require a facility with two PW-class laser systems) will bring us much further into the experimentally uncharted domain of high intensity particle physics.

The above mentioned all optical setup is beneficial for the study of RFM operation. The first pulse drives the mirror either in a form of a breaking plasma wave in the case of an underdense plasma or in a form of a dense electron or electron-ion sheet in the case of a solid density foils. The second pulse is reflected by the mirror to generate high frequency EM pulse. A PW-class laser pulse is required to effectively drive the RFM. The two pulse setup, but with a co-propagating configuration, may be utilized for the study of magnetic reconnection.

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

The study of the high intensity laser-matter interactions is an important area of fundamental physics. It opens a new regime of EM field interaction with matter in the parameter regime not available before. This regime would allow one to study the effects of strong field physics important for high energy physics studies in a more controlled and less noisy environment. Moreover, such interactions are an ideal test bed for new detectors and detection techniques and can model the interactions at the next generation of lepton colliders. The extreme conditions of matter under the action of intense laser pulses may allow modeling of some relativistic astrophysical effects. All these studies may also lead to a number of applications with a potential societal benefit. The most important might be the generation of sources of high frequency radiation ranging from X-rays to gamma-rays.

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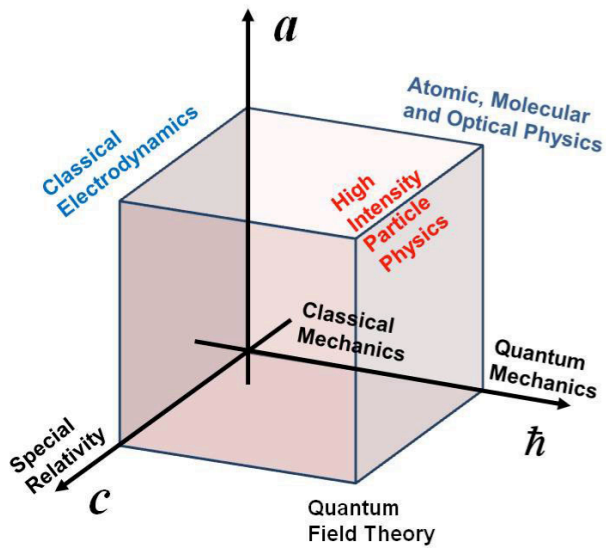

Fig. 1: The cube of theories.

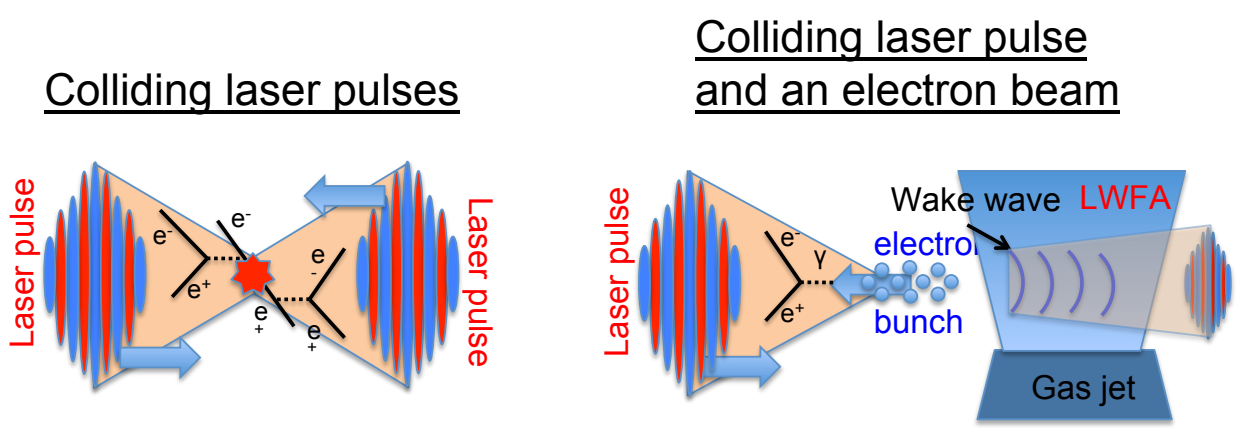

Fig. 2: The principle schemes of experiments on high intensity particle physics.