White Paper for *Frontiers of Plasma Science Panel*

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Title:	Plasma photonics for ICF and HED experiments
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PLASMA PHOTONICS FOR ICF AND HED EXPERIMENTS

Introduction

New laser facilities such as the National Ignition Facility (NIF) are opening a new era for inertial confinement fusion (ICF) and high energy density (HED) science. The unprecedented laser fluxes and the extreme conditions under which matter is driven open new avenues of laser-matter interaction physics in regimes never reached before. At the same time, these facilities present formidable technological challenges due to the complexity of operating lasers with an extreme degree of precision at such high fluxes, and the constraints associated with optics damage.

"Plasma photonics", i.e. the science of light manipulation using plasmas, could offer radically novel solutions to some of the existing challenges related to high power laser design or ICF and HED experiments. In fact, it has already played an unexpected but crucial role in ignition experiments on the NIF: the novel scheme of implosion symmetry tuning via light redirection using self-induced plasma gratings, first proposed by us [1,2], turned out to be indispensable for achieving symmetric implosions on the NIF [3,4], and has been used on almost every NIF shot since 2009. That technique was later

extended by introducing a third wavelength capability on NIF [5], in order to fine-tune the light propagation direction inside the targets and avoid the regions most prone to backscatter instabilities. That new capability first allowed us to improve the laser-target coupling, as was demonstrated in Ref. [6], but is now primarily used to fine-tune higher-order azimuthal asymmetry modes of the imploded nuclear fuel pellet inside the hohlraum [7].

A better understanding of laser-plasma interactions (LPI) for such applications is not only necessary to the success of on-going ICF and HED experiments on the NIF but it could also offer radically new opportunities for light manipulation at high intensity that could be used directly *in situ*, i.e. inside the targets, or even in the laser architecture by designing plasma-based systems that could be operated at intensities over a million times higher than traditional (crystal-based) optical systems.

Proposed approach

LPI studies in the context of ICF have traditionally focused on their detrimental aspects for fusion experiments: backscatter losses, asymmetries, preheat from suprathermal electrons, etc. Most of the efforts have concentrated on developing relevant limitation and mitigation strategies (non-linear saturation mechanisms, optical smoothing etc.). Studying plasma photonics for ICF & HED requires a new perspective on LPI, from treating it as a problem to using it as a tool to design new optical systems. We are currently pursuing several avenues: i) we are exploring the fundamental physics of light manipulation using plasmas, and proposing new conceptual designs for plasma-based systems reproducing what is done in state of the art optical components; ii) we are investigating the applicability of these plasma photonics elements and their robustness in laboratory experiments.

We believe much progress can be made by merging the concepts and the theoretical formalisms of plasma physics and non-linear optics. We have successfully applied that approach recently by investigating how wave-mixing could in theory be used to control the polarization of light in plasmas [8]; that study led us to propose new conceptual designs for a “plasma polarizer” and a “plasma waveplate”, as illustrated in Fig. 1. An experimental campaign aimed at demonstrating these concepts just took place at the Jupiter Laser Facility at LLNL; the experiment was extremely successful and the results will soon be submitted to a high profile scientific journal.

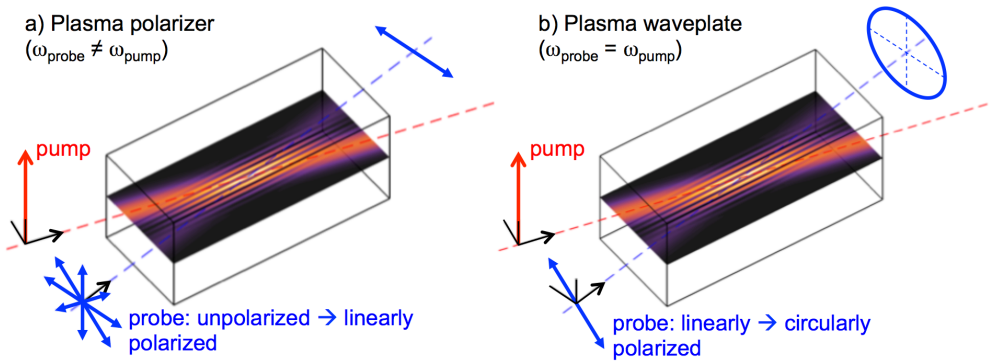

Figure 1 (from Ref. [8]): a) Plasma polarizer: by using an auxiliary "pump" laser beam, an initially unpolarized "probe" beam becomes linearly polarized after propagating through a plasma. b) Plasma waveplate: the pump laser can also induce birefringence in the plasma; the probe beam can have its polarization switched from linear to circular ("quarter-waveplate", as shown) – or if the pump intensity is doubled, becomes linear again but rotated 90° ("half-waveplate").

The manipulation of the real and imaginary parts of the plasma refractive index via optical wave mixing effectively introduces optical resonance in the "laser + plasma" optical system. We are currently investigating novel applications of such systems for advanced light manipulation at ultra-high energies, using two- and four-wave mixing schemes.

The other aspect we envision to be critical is the robustness and reproducibility of such systems. Unlike "traditional" ICF-LPI where non-linearities are almost always present and at the core of most studies, a robust plasma-photonics system is most likely one where all the plasma waves remain in a controllable, linear regime like the plasma gratings used in NIF's ICF experiments. While the shot-to-shot reproducibility of energy redirection in NIF experiments has been remarkable (achieving symmetry control to the few percent level, which translates into a sub-percent variation of energy transfer between beams shot-to-shot), the predictability using our modeling tools has become increasingly difficult. Multi-beam effects are a great challenge, as the simultaneous presence of hundreds of plasma waves can for example trigger kinetic effects and affect local plasma properties due to weak turbulence, while each plasma wave remains in a linear regime [9,10].

Conclusion

In summary, plasmas photonics could have an enormous influence on the development of the next generation of laser facilities and a dramatic impact on the science experiments carried out at these facilities, such as ICF or HED, by allowing manipulation of light directly inside the target. Some of the light-matter interaction concepts involved are at the forefront of physics research. With the current emergence of new laser facilities around the world and the new era of ICF and HED science on facilities like NIF, we believe there is now a unique opportunity to push this new field forward and dedicate more effort to it.

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