White Paper for *Frontiers of Plasma Science Panel*

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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	P
• Plasma self-organization	
• Statistical mechanics of plasmas	

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Oral	
Poster	
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Title:	Plasma as a Coherent Light Source: Basic Properties and Obstacles to Overcome
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- ***Describe the research frontier*** **and importance of the scientific challenge.**

Ever since the invention of lasers in the 1960s, scientists have continued striving for ever higher laser output powers and ever shorter laser pulse lengths. These advances in laser capabilities are commensurate with research advances in a broad spectrum of disciplines ranging from inducing nuclear processes to precision measurement. It is clear that future exploration of the properties of matter over uncharted time scales and at extreme conditions will hinge on further advances in laser technology [1-2].

From the Heisenberg uncertainty principle, the pulse width of an optical short pulse is inversely proportional to its spectral bandwidth. Therefore, the pulse compression can be achieved by spectral broadening, and careful dispersion compensation so the spectral components would be in phase. As the short pulse width is reduced to single cycle, the bandwidth broadening approaches its center frequency, which brings great challenges to the next amplification stage.

Another challenge in ultrafast laser development is to provide a wide range of wavelength tunability, i.e., from far-infrared (terahertz) to near-infrared and to x-rays. As an example, in the past the application of THz pulse has been limited to being used as a probe for materials, because of the weak uJ of energy achieved. Generating a short pulse THz source strong enough to induce dynamic changes of material would enable many new developments for THz photonics and electronics, as well as many new studies for material science. It will also expand the capacity of remote sensing and imaging to long distances.

Comparing to solid-state materials as the lasing and amplification medium, plasma on the other hand with the nonlinear refractive index, the large dispersion of the group velocity over a wide range and the high tolerance for laser power is an ideal candidate medium for lasing at high power and with large wavelength tunabilities.

One of the schemes of plasma base laser that has been successfully demonstrated is through the process of Stimulated Raman Backscattering (SRBS), a resonant interaction is set up in plasma between two counter-propagating electromagnetic waves, known as pump and seed waves. The pump and the seed excite a coherent electromagnetic field, called the plasma Langmuir wave, which can mediate the energy transfer from the long pump pulse into the much shorter seed pulse. The backscattered short seed pulse should undergo simultaneous amplification and compression, and since a plasma is impervious to optical damage, its power can grow to extraordinary levels [3-5]. The SRBS scheme recently has become more attractive, as it has been proven that to achieve the goal of exawatt to zettawatt power, a plasma-based amplifier in the final stage is necessary [6].

Through modeling, a similar new scheme is also set up for THz pulse where a resonant parametric amplification is achieved in a four-wave mixing process. Two co-propagating pumping pulses, with infrared wavelengths, excite a plasma wave. Under resonance condition, which involves the pumping waves, the plasma wave and the THz wave, energy is transferred from the pumping waves into the THz wave mediated via the plasma wave. A preliminary particle-in-cell simulation has verified the amplification of the THz pulse in the scheme. Theoretically a coherent and resonant scheme will provide stronger and shorter THz pulse comparing to the current transient, no-resonant schemes [7, 8], and hence can have broader spectrum of applications.

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

A SRBS plasma laser has been previously studied and demonstrated from experiments [9-10]. However, results from our previous experiments show early saturation in the amplification process that limits the maximum energy conversion efficiency to a few percent and maximum amplified pulse energy to a few millijoules, which restricts the achievable laser power and intensity, and therefore the practical applications of the device.

To overcome the saturation barrier, we developed two schemes. One scheme is setup through detailed study into the dynamics of electrons under the two counter-propagating electro-magnetic fields and its impact on plasma wave to mediate the energy exchange between the two fields. Our studies show that termination of the seed growth begins with the buildup of the spontaneous thermal noise, which originates from thermal plasma density fluctuations and is amplified by the pump pulse. Using the copious amount of data available from the PIC simulations, the influences of the spontaneous thermal noise on plasma and on SRBS amplification are revealed after a systematic examination of the electrons kinetic behaviors and the plasma Langmuir wave spectral behaviors during the three wave interaction [11].

Through simulations, insights are also gained for development of methods to prevent the unfavorable spontaneous noise impacts from being dominant. We proposed breaking a large SRBS plasma laser into a cascade scheme. In the cascaded scheme, a long plasma amplification length was broken down into a cascade of shorter channels –each slightly shorter than the length for gain saturation to occur. Since a shorter plasma channel is equivalent to a shorter propagation time for the pump, and hence a shorter accumulation time for the spontaneous signal. And cascading the amplifiers, is equivalent to obtaining the benefits of a long plasma channel (larger SRBS amplifier) without encountering the deleterious effects of spontaneous noise. Figure 1 shows the schematics and results from 1D and 2D PIC simulations. From PIC simulations, it's verified that the cascade scheme was very efficient to overcome the saturation barrier for SRBS, and the output pulse energy can reach a Joule level with reasonable spot size of ~200 um. This

scheme can also be modified with other pump, seed and plasma regimes. Figure 2 shows a stronger and more compact SRBS cascade setup. We are now in the process of building the experimental setup for the cascaded scheme based on our earlier experimental campaign, which has successfully produced our previous SRBS results (cited by a recent article published on Nature Physics as the best experimental result in the field [12]).

The second scheme to overcome the current SRBS barrier involves pumping and seeding the SRBS scheme with strong pulses beyond the classical wave breaking limit [4, 13, 14]. Figure 3 shows the output pulse at a pump intensity of 5.1×10^{14} W/cm^2 and seed intensity of 2×10^{17} W/cm^2. Interestingly, studies into the pump and seed interaction process shows that the compression of the seed pulse appears that while the seed pulse propagates toward the left, its peak is pushed toward the back of the pulse to the right. From the energy exchange analysis, we found that the energy transfer from the pump to the seed only occurs in the first half of the interaction. In the second half of the interaction, due to the absence of energy transmission from the pump to the seed, we call the compression of the seed in this region self-compression. Furthermore, we also observed the emergence of a moving solition cavity (with the electron/ion distribution peaks at the rims of the hollow) in the wake of the SRBS pulse. Contrary to a static soliton cavity generated in the wake of a strong short pulse in plasma [15, 16], this soliton cavity moves close to the speed of light while slowly expanding its radius.

Since the experimental campaign and success of the second scheme depends on the availability of a strong 2×10^{17} W/cm^2 and short 25fs seed pulse. This seed pulse can be delivered upon the success of the first scheme, or using OPCPA output from other laser facilities [17, 18]. For example, in ref. 17 the generation of a 100 J, ~ 20fs duration, 1250nm seed pulse was reported. We will conduct small scale simulations using the new parameters to test the feasibility.

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

Our proposed plasma based scheme provides new approach for single cycle pulse generation and represents new advancement in decade long research efforts in understanding the rich physics behind the laser-plasma SRBS processes and producing high power ultra-short laser pulses using plasma as the amplification medium. Discoveries in understanding, controlling and overcoming the higher order and nonlinear effects in laser and plasma interaction can be particularly valuable to the plasma physics community in areas related to laser plasma instability (LPI) and inertial confinement fusion (ICF).

New results and regimes can also be uncovered by applying the generated ultrashort, high intensity pulse to the plasma and gas medium. For example, our simulations show that when an 6fs, 1×10^{19} W/cm^2 beam passes through C^+ plasma, carbon ions can be fully ionized and fast electrons are generated with $\gamma\beta$ factor scales up to 60. Interestingly, the fully ionized carbon plasma has a low electron kinetic energy with average electron kinetic energy ~ 25 KeV and 17% electrons has a kinetic energy below 100 eV, which is favorable for the population inversion in X-Ray laser of the recombination scheme [19].

Using plasma as the amplification medium to build plasma based ultrafast lasers provides an interesting and exciting new aspect to the current technology of three phases of lasers: solid-state lasers, gas lasers, and liquid dye lasers. Exploring the full potential and overcoming the obstacles presents a new and fascinating set of theoretical and technological challenges and prospects for which to look forward.

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Figures:

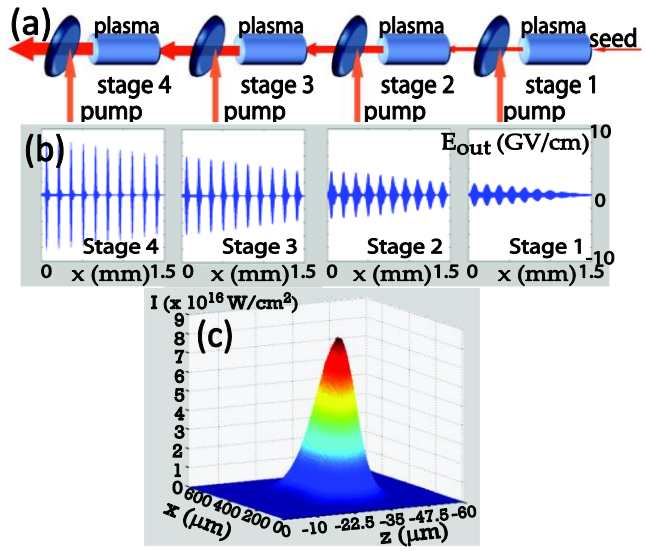

FIG. 1: (a) A cascaded four-stage SRBS amplifier: from right to left are stages 1, 2, 3 and 4, respectively. For each stage, $n_e = 1.5\times10^{19}/\text{cm}^3$, $l_{\text{plasma}} = 1.5$mm, $I_p = 1.8\times10^{14}$ W/cm^2, $\tau_p = 10$ps, $\lambda_p = 800$nm and $\lambda_s = 882$nm. (b)1D PIC simulation illustrating the unsaturated growth of the seed pulse. (c) 2D PIC simulations.

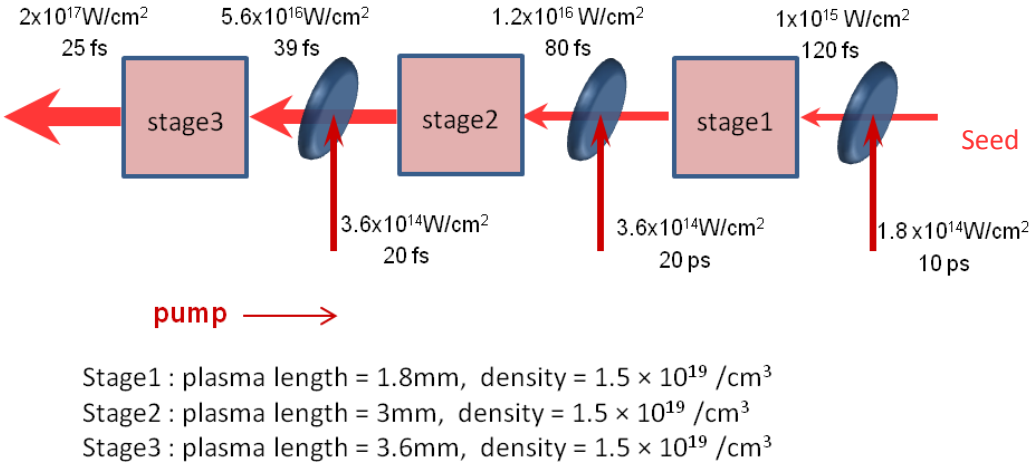

Figure2: Schematics and PIC simulation of a stronger and more compact cascaded SRBS laser amplifier.

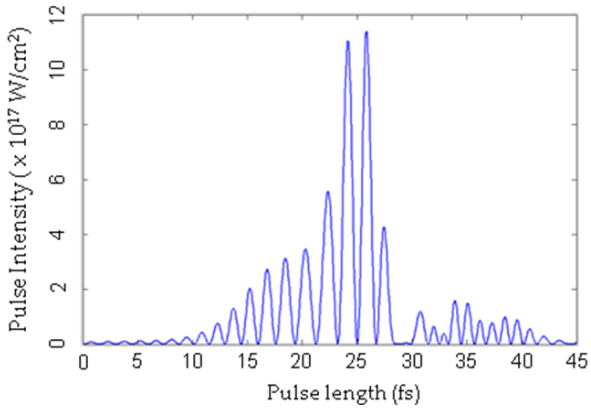

Figure3: The output SRBS pulse when seed $I_{in} = 2\times10^{17}$ W/cm^2, $\tau_{in} = 25$fs; $l_{plasma} = 4.5$mm, $n_e = 1.5\times10^{19}$/cm3, $T_{e0} = 5$eV; and $I_{pump} = 5.1\times10^{14}$ W/cm^2, $\tau_{pump} = 25$ps.