White Paper for *Frontiers of Plasma Science Panel*

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Title:	Toward Compact Synchrotron Light Source Based on Extended Interaction of Laser-Plasma Accelerated Electrons with Backscattered Raman Radiation
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- ***Raman backscattering of ultrashort laser pulses as potential source of coherent X-rays*.**

Raman backscatter (RBS) has been well developed and studied for electromagnetic radiation at moderate powers. However, recent breakthroughs in laser technology made possible laser-plasma interaction experiments with laser field intensities comparable or even higher than inter-atomic fields. More recent experiments on RBS [1] demonstrated that a considerable revision of the previously used weakly nonlinear theory is required to explain new experimental results. Today's theory and experiments of high intensity RBS are very limited, while computer simulations [2, 3] indicate that RBS might play a significant role in an ultrashort laser pulse evolution in plasma and wakefield excitation.

Previous attempts to generate X-rays in all optical experimental configurations were based on two counter-propagating laser beams. The first beam was used to generate high energy electrons, while the second intersected these electrons in collinear or off-axis geometry. Aligning a counter-propagating laser beam to an electron beam is very difficult and the generation length of the x-rays is limited by the overlapping distance (usually measured in micrometers) of the electron beam and counter-propagating laser beam. As a result the flux of Compton backscattered X-rays was limited.

The energy in the RBS radiation can be a significant fraction (10% or more) of the original laser pulse [4]. If the plasma is cold, i.e., the thermal motion of the free plasma electrons is not relativistic, the growth rate of this stimulated RBS radiation is maximized in the backward direction such that the scattering produces a counter-propagating beam of backscattered photons which also is co-linear with the original beam. This naturally occurring process of self-aligning can be used for extended generation of X-rays in laser-plasma accelerators. In such configuration a single laser pulse can be used to produce both

the electron beam and the counter-propagating radiation for the extended Compton scattering generation of X-rays.

The backscattering of the laser radiation is a continuous process, and the accelerated electrons can interact with the backscattered radiation over an interaction distance that traverses the entire length of the plasma, typically a few millimeters to a few centimeters long. This extended interaction distance can result in an X-ray production that is increased by many orders of magnitude over other methods of X-ray production. In addition, if the intensity of the backscattered radiation is sufficiently high and the interaction distance is long, self-amplification of the X-rays, achieving exponential gain, is possible. In this case the exponential gain in the X-ray radiation amplitude is a consequence of the periodic bunching of the electrons at the X-ray wavelength and the X-ray emitted under such conditions would become coherent. This mechanism is similar to the coherent radiation mechanism in a Free Electron Laser, but it occurs in compact laser-plasma acceleration structure.

- ***Technical approach, challenges and new research tools and capabilities required for coherent X-ray generation.***

The objective of this white paper is to study a new mechanism of monochromatic X-ray generation using Raman backscattering of an intense, ultrashort laser pulse in a novel Compton back-scattering configuration. The novelty of the approach is presented in two respects: 1) the high energy electron beam and the counter-propagating photon radiation are both self-generated by an ultrashort laser pulse in plasma and interact over extended distance, and 2) the source can generate short pulses of hard x-rays that are polarized, coherent and tunable.

For example, for 40 MeV electrons having peak current of 100 kA interacting with backscattered photons having a power of 0.2 TW, the X-ray emission will self-amplify to more than e times (exponential gain) the original intensity in an interaction distance, called e-folding distance, of only 100 micrometers. By increasing the interaction distance, e.g., by increasing the width of the plasma to several e-folding distances, the intensity of the output X-ray can be increased by several orders of magnitude.

In order to have narrow energy spread on the Compton scattered x-rays, stable, monoenergetic, high brightness electron beams are needed. Recent advances in laser-plasma acceleration [5-7] were able to produce quasi-monoenergetic electrons beams, but in most cases such beams have demonstrated a lack of stability. Furthermore, today's understanding of detailed processes involved in laser-plasma acceleration is based mostly on computer simulations. Conventional experimental diagnostics on LWFA are in general based on remote and indirect measurements of the laser-plasma interaction region.

For a viable RBS-based laser-driven X-ray source to be realized, the scientific issues that need to be solved are 1) effects of the plasma density profile on the threshold for generating the back-scattered photons through processes such as the RBS instability, 2) effects of laser shape and pre-pulse on RBS and LWFA and how they can be controlled, 3) the efficiency and saturation levels of the RBS, 4) phase front uniformity of the RBS radiation, and 5) effects of plasma cavitation on the X-ray spectral and angular distribution.

Recent developments make NRL uniquely suited to carry out this research: 1) the recent experimental generation of stable, bright, and highly repeatable electron beams, 2) the development of unique electro-optical shock diagnostics [8, 9] and shock wave controlled plasma jets [10-12], 3) a novel and robust laser pulse shaping technique was recently studied by our theory group and confirmed experimentally in our laboratory [13], 4) backscatter laser wakefield diagnostics that were recently added to the electron accelerator system and initial results indicating strong back reflection of the laser pulse, and 5) theoretical studies of laser retroreflection for Compton backscattering X-ray generation [14]. With these developments and the strong collaboration between theory, modeling, and unique experimental

capabilities, the Plasma Physics Division is poised for an innovative study of the necessary plasma conditions in the novel self-generation of monochromatic x-rays via Compton scattering.

- ***Impact of compact synchrotron X-ray sources on plasma science and related disciplines and potential for societal benefit***.

Tunable, monochromatic, polarized sources of x-ray produced by synchrotron devices have wide ranging applications in a number of areas such as medical and biological imaging, archaeology, drug discovery and others. However, synchrotron devices are big and expensive. More compact devices using a laser beam as the undulating media with a conventional electron beam from a radio-frequency linear accelerator (RF linac) have been studied at NRL since the 1990's [15, 16]. RF linac's are massive, and aligning a counter-propagating laser beam to an electron beam is also quite difficult and cumbersome, hence, the need for a compact, monochromatic x-ray source remains unfulfilled.

The Compton Backscattered X-Ray light sources will have a strong potential impact on the plasma science and related disciplines. If successful it can replace very large (area of a city block) and expensive (billion dollars or more) conventional synchrotron light source facilities by table-top, cost-efficient single beam lines. Potential applications of such compact light sources range from detection of nuclear materials, to advanced armor components, to medical applications. Such a compact system can be installed in university size laboratories or even hospitals, providing new and presently impossible capabilities.

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