Toward Compact Synchrotron Light Source Based on Extended Interaction of Laser-Plasma Accelerated Electrons with Backscattered Raman Radiation

Plasma Physics Division

Frontiers of Plasma Science Panel

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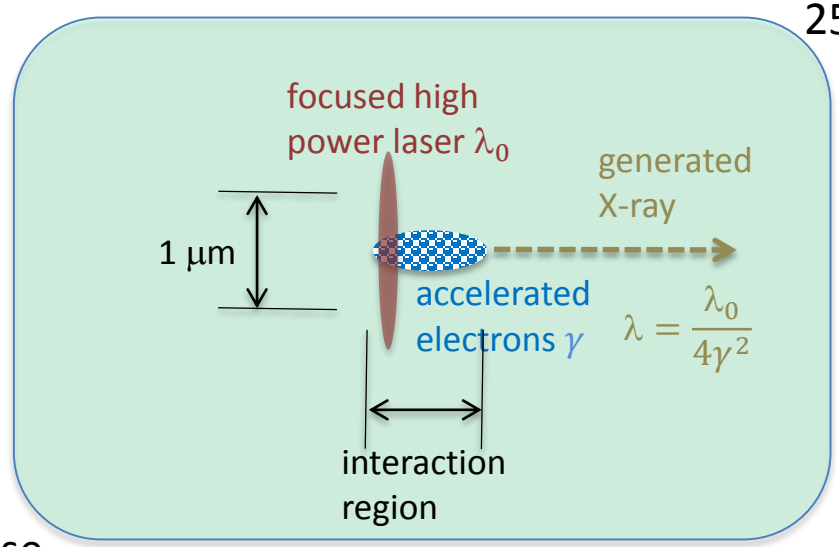
Limitations of Conventional Counter-Propagating Compton Scattering Scheme

X-rays are generated by Compton scattering of laser from high energy electrons

Experiment on University of Nebraska 100 TW Diocles laser generated 250 MeV electron beam



Interaction region is limited (diffraction length, overlap)

Using off-axis geometry of Compton scattering 1 MeV γ-rays were generated

Requires very precise spatial (up to 1μm) and temporal (up to a few femtoseconds) alignment

Total number of γ-rays was 10^8 per shot

S. Chen *et al.*, PRL 110, 155003 (2013)

Advantages and Uniqueness of Proposed All Optical Single Beam Scheme

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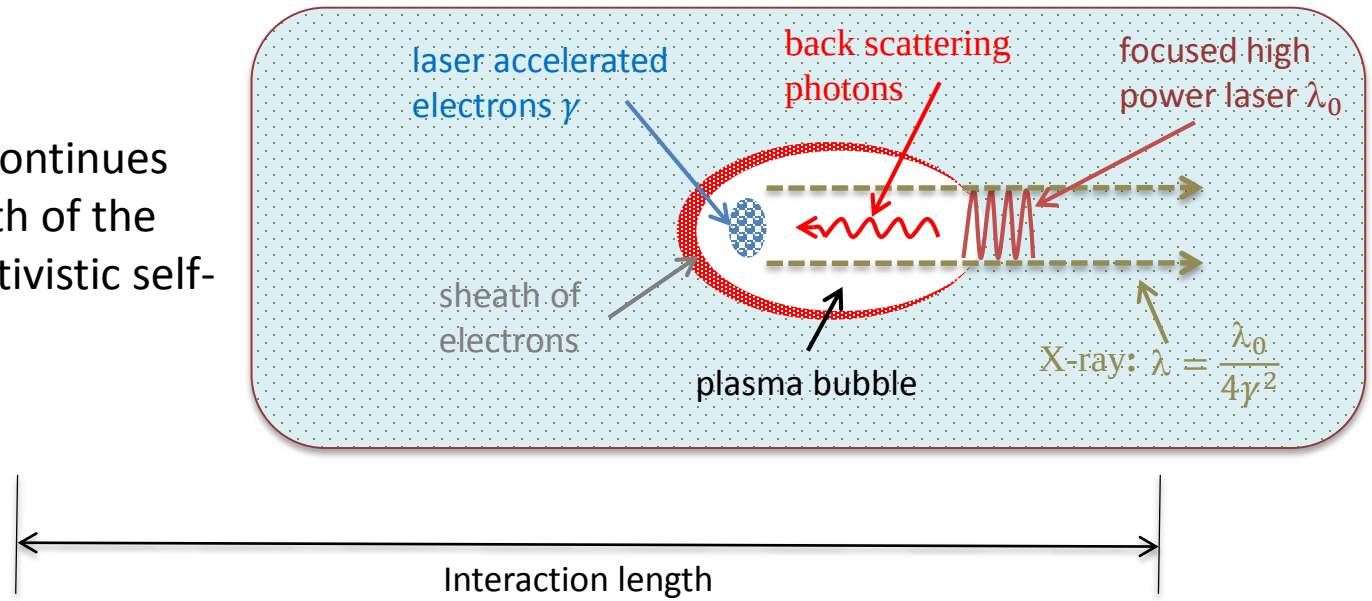
Electron beam and counter-propagating photons are generated by the same laser beam in plasma

The laser pulse creates a plasma bubble that traps and accelerates the background plasma electrons

The backscattered radiation collides with the accelerated electron bunches and Doppler upshifted to X-ray frequencies

X-ray generation is continues over the entire length of the plasma through relativistic self-guiding



With high electron beam current and long interaction length, self-amplification of the X-rays is possible

Expected X-Ray Characteristics

High brightness	source is ≈1 μm in diameter
Polarized	same as laser polarization
Near monochromatic (?)	≈1% bandwidth
Tunable photon energy $\lambda = \frac{\lambda_0}{4\gamma^2}$	40 MeV electrons → 30 keV X-rays, 100 MeV electrons → 180 keV X-rays
Well-collimated	half angle $=1/\gamma$ (γ = 80 for 40 MeV → 12 mrad)
Compact	table-top size
Ultra-short X-Ray	length of electron bunch (~fs)
Potentially coherent	self amplified spontaneous emission (50 e-folds)

The repetition rate is limited by the laser. New laser technologies promise the possibility of tens of kHz lasers with average power of up to tens of kW.

Such laser system will generate 10 mW – 1W average power x-rays (polarized!), comparable with conventional synchrotron light sources* (per user line)!

*Brookhaven NSLS-II provides 10-200 keV X-rays

Applications of Compact, Tunable, Polarized X-Ray Sources

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- Material, chemical and nano science:
  - magnetic materials
  - molecular electronics
  - high-temperature superconductors
  - …
- High energy physics: source of monochromatic X-ray for generation of **polarized** positrons
- New diagnostics for laser-plasma accelerators
- Research tool for study X-ray lasing

Brookhaven National Synchrotron Light Source II

$912 million to design and build.

Why we don't see these X-Rays?

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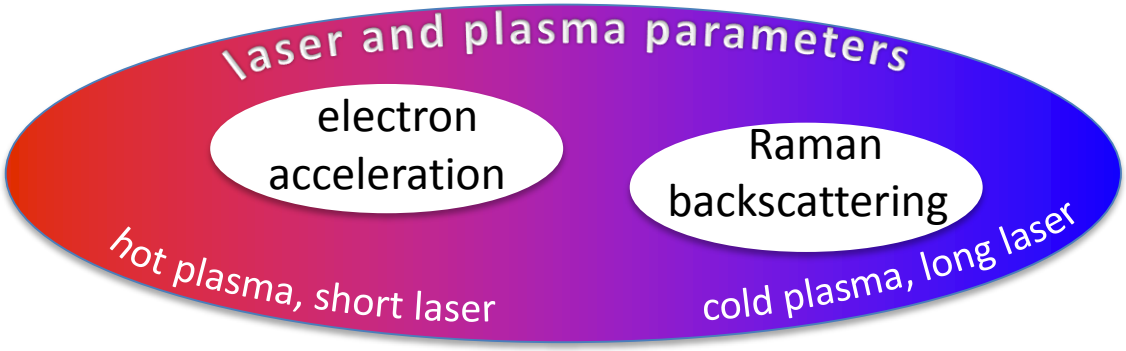
Raman Backscattering (BRS) and electron acceleration require different plasma and laser parameters:



Achieve **coherent X-ray** in high gain amplification regime

- High current and low emittance electron beam
- High backscattered intensity

} simultaneously

Natural Alignment of Raman Backscattering and its Limitations

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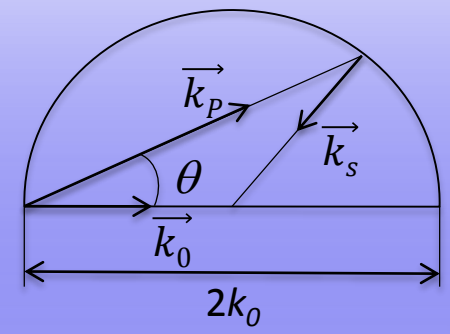
RBS is a 3 wave mixing instability process.

Laser pump wave (k_0, ω_0), Plasma wave (k_P, ω_P), and Scattered wave (k_S, ω_S) satisfy phase matching and dispersion relations:

$$k_S = k_0 - k_P, \quad \omega_S = \omega_0 - \omega_P, \quad \omega_0^2 = \omega_P^2 + c^2 k_0^2$$

For long laser pulse ($\tau >> \omega_P^{-1}$), up to 10% of the laser can be scattered.



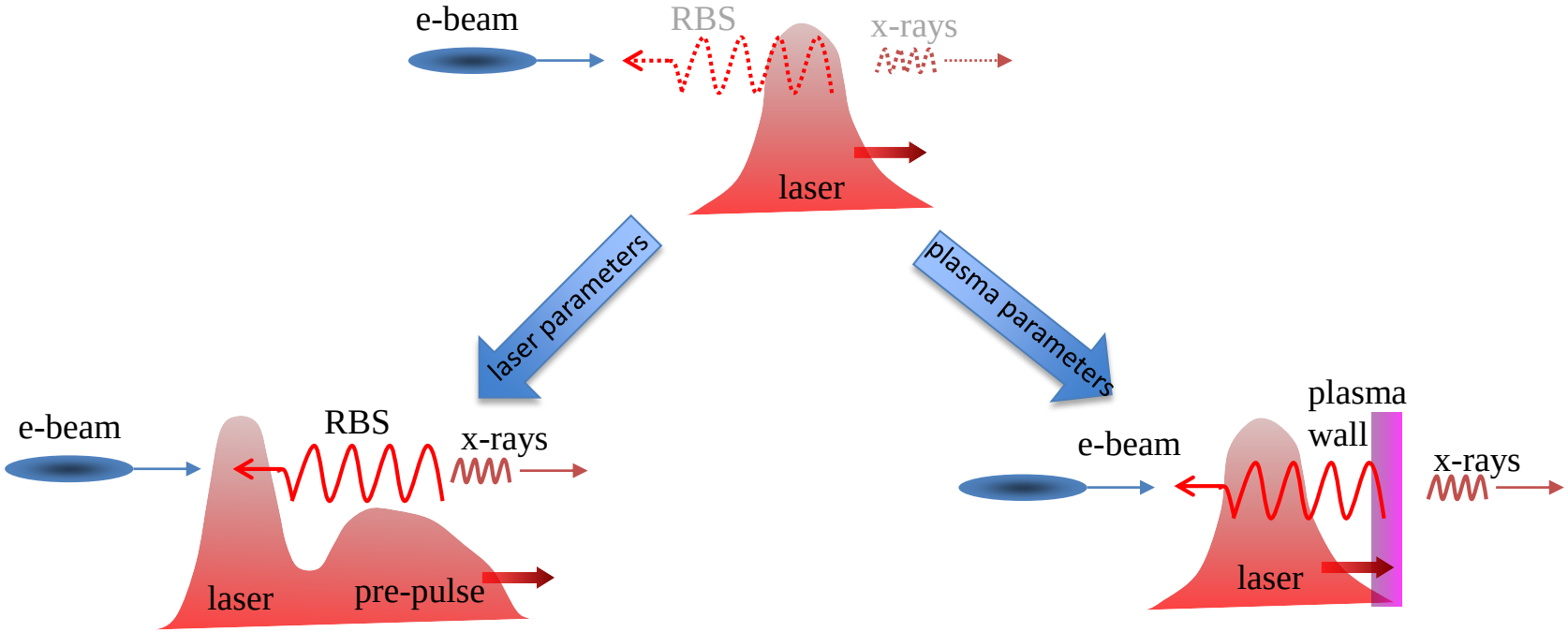
Growth rate $\Gamma \sim cos^2(\theta)$ provides the **natural alignment**.

For hot plasma $\Gamma = \frac{\omega_p a_0}{2\gamma^{5/4}}\sqrt{\frac{\omega_0}{\omega_p}}$, where $\gamma = \sqrt{1 + a_0{}^2}$, $a_0 = \frac{eE_0}{m\omega_0 c}$,.

Limitations:

- Γ is saturated for $a_0 \geq 1$. Fully nonlinear treatment required.
- For $\tau \approx \omega_p^{-1}$ (best for electron acceleration), only 1 e-fold of RBS growth.
- Experimental and theoretical studies of ultra-short and high power lasers RBS are complicated and up day very limited.

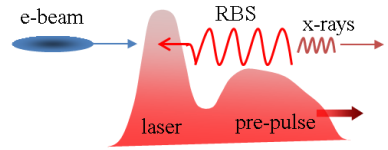
Enhancement of Backscattered Radiation by Modification of Laser and Plasma Parameters



Generate long pre-pulse in front of the main pulse

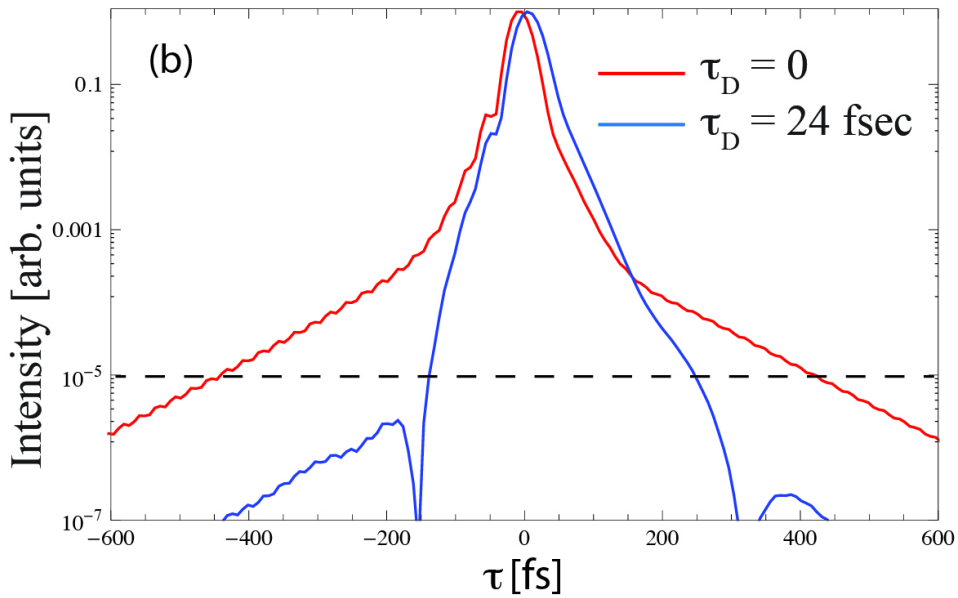
Use laser generated shock-waves to reflect part of the laser pulse

Laser Beam Modification for Efficient Raman Backscattering



Beam control system* developed at NRL allows independent manipulation of intensity for the main laser pulse and pre-pulse.
For example: 0.5 ps pre-pulse, following by 50 fs main pulse.

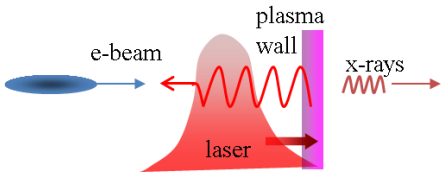
Issue:
Electron acceleration is affected by pre-ionization of gas#.



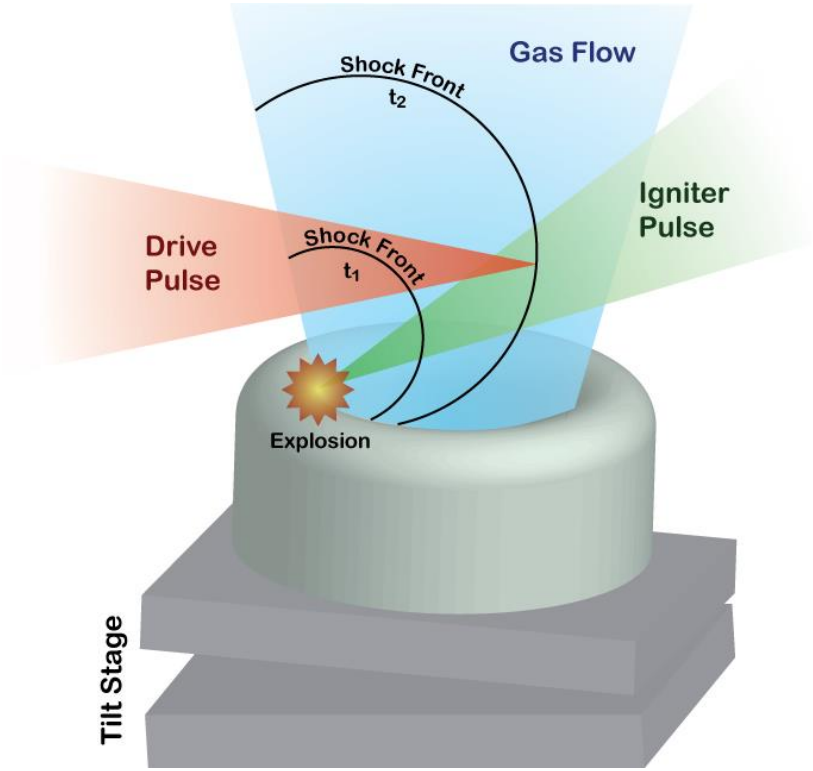
Example of pre-pulse modification by the beam control system

*D. Kaganovich, J.R. Penano, M. H. Helle, D. F. Gordon, B. Hafizi, and A. Ting, "Origin and control of the sub-picosecond pedestal in femtosecond laser systems," Optics Letters, **38**, 3635 (2013), "Enhancement of laser contrast in chirped-pulse amplification systems," Navy invention disclosure #102638, (August, 2013)
#D. Kaganovich, D.F. Gordon, and A. Ting, "Observation of large-angle quasi-monoenergetic electrons from a laser wakefield," Phys. Rev. Lett. **100**, 215002 (2008)

Modification of the Plasma Density



- Shock wave moves the gas across the gas jet.
- Can create variety of plasma density profiles as function of time, distance from the nozzle and strength of the shock wave.
- Shock wave creates sharp density gradient that can be used to reflect part of the laser radiation.



D. Kaganovich, M.H. Helle, D.F. Gordon, A. Ting, "Measurements and simulations of shock wave generated plasma-vacuum interface," Physics of Plasmas **18**, 120701 (2011)
D. Kaganovich, D. F. Gordon, M. H. Helle, and A. Ting, Shaping gas jet plasma density prole by laser generated shock waves", Journal of Applied Physics 116, 013304 (2014).

Proposed Direction of Studying

- Development of fully nonlinear theory of RBS for arbitrary laser intensity. Modeling laser-plasma interaction including ionization effects on electron acceleration.
- Identify experimentally the best mechanism for the backscattering radiation generation.
  - Upgrade the electro-optical shock diagnostic and study effects of plasma bubble on RBS.
  - Modify laser and plasma parameters for the optimum RBS generation.
  - Differentiate various X-ray generating processes inside the acceleration bubble.
- Build Compact Synchrotron Light Source.

NRL has all necessary infrastructure to conduct the study.