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Compression of Powerful X-Ray Pulses to Attosecond Durations by Stimulated Raman Backscattering in Plasmas

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Motivating Questions

- Can emerging mJ x-ray laser technologies compete with emerging MJ optical laser technologies in producing ultrahigh electromagnetic fields?
- Can expected mJ x-ray output laser pulses be compressed from thousands to just few cycles durations?
- Can these pulses be focused from thousands to just few wavelength size spots?

Vacuum Breakdown Field

- The probability of an electron-positron pair creation from vacuum by a constant field E or plane electromagnetic wave of amplitude E is proportional to (Schwinger, 1951)

$$\exp\,(-\pi E_c/E)\ ,$$

$$E_c = m^2c^3/e\hbar = 1.3\times10^{16}\ \mathrm{V/cm}\ .$$

- The intensity (i.e., power density) of a linearly polarized laser pulse having maximal electric field E_c is

$$I_c = cE_c^2/8\pi = 2.3\times10^{29}\ \mathrm{W/cm^2}\ .$$

Laser energy necessary for the vacuum breakdown

If the critical electric field E_c is to be obtained by means of compression and focusing laser pulses to a spot of linear sizes about the laser wavelength λ , the energy located within such a spot would be

$$\mathcal{E}_c \sim \lambda^3 E_c^2/8\pi \sim \lambda^3\ 8\times10^{18}\ \mathrm{J/cm^3}$$

λ	1 µm	100 nm	10 nm	1nm	1 Å
$\mathcal{E}_c$	8 MJ	8 kJ	8 J	8 mJ	8 µJ

Laser energy $\mathcal{E}$ vs $\mathcal{E}_c$ for the biggest of currently built lasers

Device	NIF or LMJ	LCLS
λ	0.35 µm	0,15 nm
$\mathcal{E}$	2 MJ	2 mJ
$\mathcal{E}_c$	1/3 MJ	1/40 mJ
$\mathcal{E}/\mathcal{E}_c$	6	80

MJ optical or mJ x-ray lasers?

- The energy in either of these emerging laser systems would be, in principle, sufficient for producing vacuum breakdown intensities.
- LCLS (Linac Coherent Light Source) might have some energetic advantages over NIF (National Ignition Facility) or LMJ (Laser Megajoule).
- However, it would be necessary to compress the output laser pulses of either system to several wavelengths and to focus the compressed pulses to spot sizes of no more than several wavelengths.

Expected durations of powerful x-ray pulses

- The currently expected duration of LCLS output pulses is about 200 fs (which is 200000 times larger than the attosecond duration of a 0.3 nm long x-ray laser pulse).
- There are several schemes proposed to reduce the duration of powerful x-ray pulses to 0.3 – 1 fs:

  Saldin, Schneidmiller, Yurkov, *Opt. Com.,* **212,** 377 (2002); **237,** 153 (2004); **239**,161 (2004);
  Reiche, Emma, Pellegrini, *Nucl. Instr. & Meth. in Phys.,* **507A,** 426 (2003);
  Emma, Bane, Cornacchia, Huang, Schlarb, Stupakov, Walz, *PRL*, **92,** 074801 (2004);
  Zholents, Penn, *PRST,* **8**AB**,** 050704 (2005).

- ***Is it possible to compress powerful x-rays pulses to just few asec durations?***

Apertures of powerful x-ray pulses (1)

- The expected diameter of LCLS output pulses ~ 100 μm.

- Available now optical techniques are capable of x-ray focusing to sub 100 nm and even sub 50 nm spot sizes:

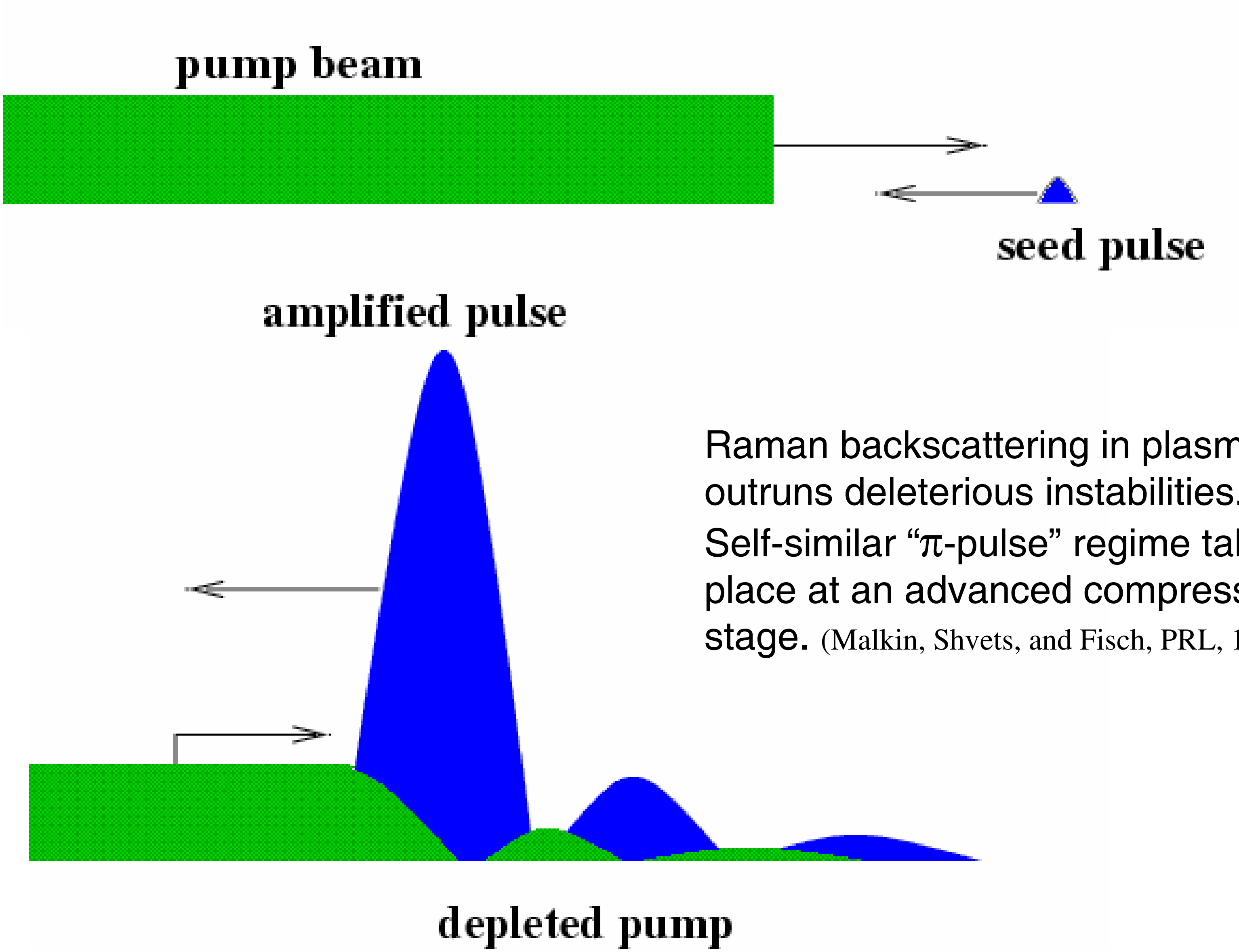
- A. Jarre, C. Fuhse, C. Ollinger, J. Seeger, R. Tucoulou, and T. Salditt, Two-Dimensional Hard X-Ray Beam Compression by Combined Focusing and Waveguide Optics, Phys. Rev. Lett., **94**, 074801 (2005);
- O. Hignette, P. Cloetens, G. Rostaing, P. Bernard, and C. Morawe, Efficient sub 100 nm focusing of hard x rays, Rev. Sci. Instrum. **76**, 063709 (2005);
- Hirokatsu Yumoto et al., Fabrication of elliptically figured mirror for focusing hard x rays to size less than 50 nm, Rev. Sci. Instrum. **76**, 063708 (2005);
- Hidekazu Mimura et al., Hard X-ray diffraction-limited nanofocusing with Kirkpatrick-Baez mirrors, Japanese Journal of Applied Physics, **44**, L539 (2005);
- C. G. Schroer et al., Hard x-ray nanoprobe based on refractive x-ray lenses, Appl. Phys. Lett., **87**, 124103 (2005);
- Wenjun Liu et al., Short focal length Kirkpatrick-Baez mirrors for a hard x-ray nanoprobe, Rev. Sci. Instrum., **76**, 113701 (2005).

Apertures of powerful x-ray pulses (2)

- There are proposals on focusing x-ray pulses to few nm spot sizes:
- C. Bergemann, H. Keymeulen, and J. F. van der Veen, Focusing X-Ray Beams to Nanometer Dimensions, Phys. Rev. Lett., **91**, 204801 (2003);
- C. G. Schroer et al., Nanofocusing parabolic refractive x-ray lenses, Appl. Phys. Lett., **82**, 1485 (2003);
- C. G. Schroer and B. Lengeler, Focusing Hard X Rays to Nanometer Dimensions by Adiabatically Focusing Lenses, Phys. Rev. Lett., **94**, 054802 (2005).

- However, these focusing techniques handle relatively low intensity (power density) x-rays, and might not be directly applicable to intense LCLS output pulses, for which focusing appears to be more challenging
- See, for instance, D. D. Ryutov, Thermoelastic effects as a way of creating transient renewable reflective optics, Rev. Sci. Instrum., **76**, 023113 (2005).

Pulse Compression by Resonant Raman Backscattering in Plasmas



Raman backscattering in plasmas outruns deleterious instabilities. Self-similar “π-pulse” regime takes place at an advanced compression stage. (Malkin, Shvets, and Fisch, PRL, 1999)

Dynamics of RB pulse compression in plasmas

$$a_t + c a_z = -Vfb\ ,$$

$$f_t = Vab^*$$

$$b_t - cb_z = Vaf^*$$

$$V = \sqrt{\omega_e \omega / 2}$$

(Malkin, Shvets, and Fisch, PRL, 1999)

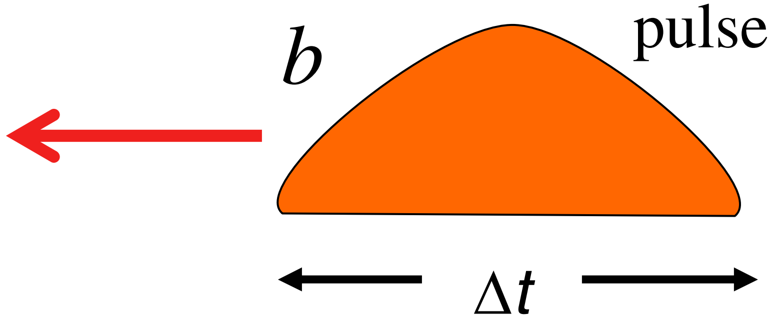
$$a \equiv \frac{eA_{\mathrm{pump}}}{mc^2}, \qquad b \equiv \frac{eA_{\mathrm{pulse}}}{mc^2},$$

f is normalized plasma wave amplitude;

$\omega = 2\pi c/\lambda$ is laser frequency,

ω_e is electron plasma frequency,

$$\omega >> \omega_e$$



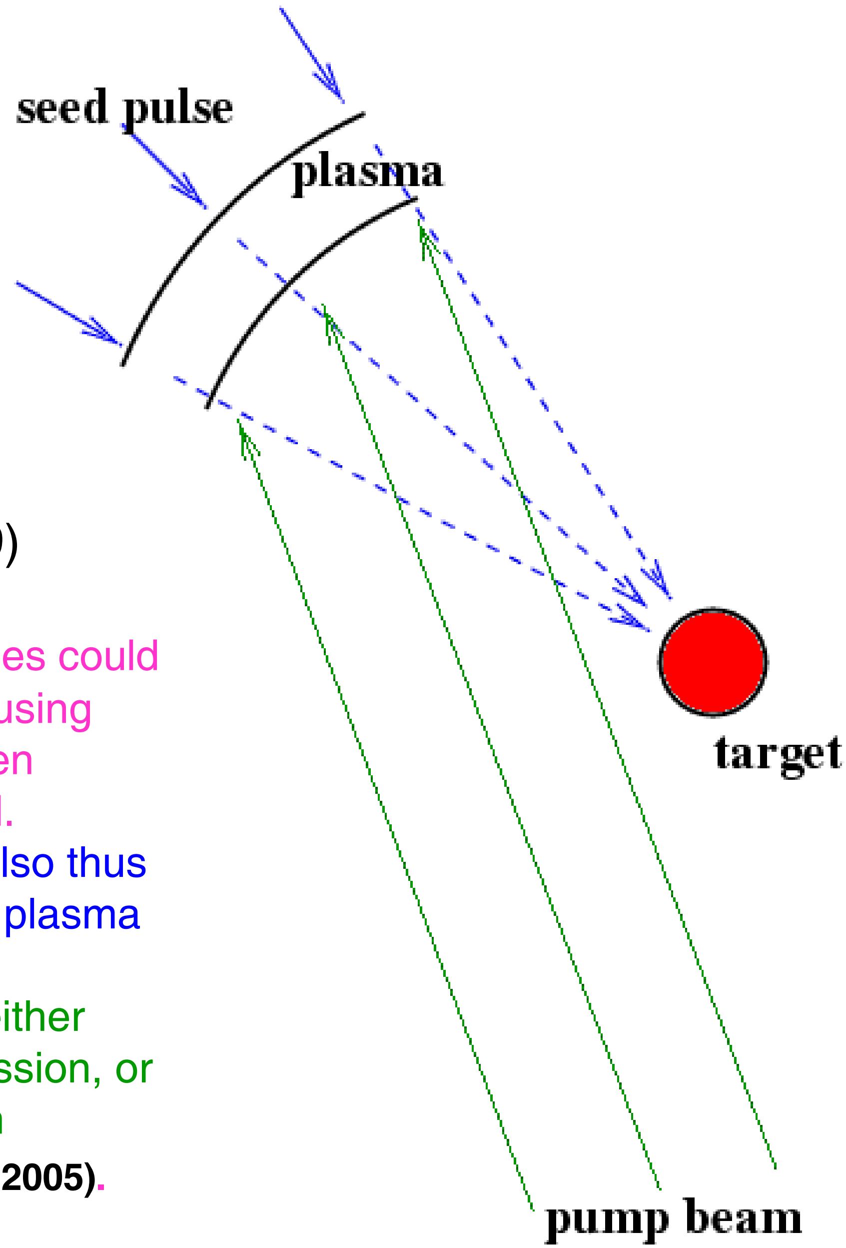
Self-similar advanced nonlinear regime at $z \approx ct$:

$b \sim t$; $\Delta t \sim 1/t$; $b^2 \Delta t \sim t$

Pulse Focusing by Resonant Raman Backscattering in Plasmas

(Malkin, Shvets and Fisch, PRL, 1999)

- The problem of focusing intense laser pulses could thus be reduced to a simpler problem of focusing less intense seed pulses which consume then intense pumps while remaining well-focused.
- "Beam-cleaning" of noisy pump pulses is also thus accomplished, while the entropy is taken by plasma waves.
- The pulse focusing can be accomplished either simultaneously with the longitudinal compression, or as an extra step of a RB pulse processing in plasmas **(Malkin and Fisch, Phys. of Plasmas, 2005)**.



Which output could be theoretically possible, if RB compression works for X-rays?

By means of a RB in plasmas, laser pulses could be compressed to durations about the electron plasma wave period

$$t_o \sim \frac{2\pi}{\omega_e}, \qquad \omega_e \equiv \left(\frac{4\pi n_e e^2}{m}\right)^{1/2},$$

n_e is the electron concentration.

$$n_e = 10^{26}\mathrm{cm}^{-3} => t_o \sim 10 \text{ asec.}$$

Longitudinal compression of a 2 mJ pulse to 10 asec would produce the power

$$P \sim \varepsilon / t_o \sim 200\,\mathrm{TW}.$$

The intensity of such pulse focused to a spot of diameter 0.5 nm would be

$$I_f \sim 8 \times 10^{28}\mathrm{W}/\mathrm{cm}^2.$$

It is not clear, however, if the RB mechanism can be practiced in the x-ray regime.

A simple extrapolation of the mechanism from the visible light regime, examined earlier, is not sufficient, because competing effects (inverse bremsstrahlung of the pump, Landau damping of the plasma wave, heating of plasma, etc) might narrow and even close the window in parameter space for efficient RB operation.

What follows clarifies this basic issue.

Inverse Bremsstrahlung Effect

A necessary condition for efficient RB is the smallness of the laser energy absorption due to electron-ion collisions in plasma, the so-called ``inverse bremsstrahlung''. The inverse bremsstrahlung rate can be evaluated as

$$\nu_{ib} = \nu_{ei}\omega_e^2/\omega^2,$$

where ν_{ei} is the rate of electron-ion collisions in plasma

The pulse energy loss upon traversing a plasma of length L should be small

$$q_{ib} = \nu_{ib}L/c \ll 1 \ .$$

For a plasma of length L, the pump laser pulse length should be $2L$
(in order for the counterpropagating seed to meet the pump front upon the seed entering the plasma, and for the pump to end upon the seed exiting the plasma).

The pump duration $t_{pmp} = 2L/c$ should satisfy the condition

$$q_{ib} = \nu_{ib}\, t_{\mathrm{pmp}}/2 \ll 1 \ .$$

Efficiency coefficient and pump duration

A slice of the pump traverses, in average, distance *L/2* before meeting the growing seed pulse (and being consumed by it), so that the average fraction of pump energy spent for the inverse bremsstrahlung is $q_{ib}/2$, for the energy uniformly dissipated.

The laser pump energy fraction transferred to Langmuir waves constitutes

$$q_L = \omega_e / \omega \ .$$

The efficiency of laser energy conversion from the pump to a shorter growing seed pulse (longitudinal compression)

$$q_{ef} \leq 1 - q_L - q_{ib}/2.$$

To produce an output pulse of fluence w, the pump fluence w/q_{ef} is needed. Then, the pump of intensity (power density) I should have the duration

$$\mathrm{t_{pmp}} = w/(q_{ef} I) \ .$$

Output Fluence

- Assuming that the Langmuir wave, mediating energy transfer from the pump to the growing seed pulse, is not damped within the growing seed pulse duration (transient RB) at least at the final stage of compression, π-pulse regime is established.
- In the π-pulse regime, the pulse duration is inversely proportional to the pulse fluence .
- In order for the output pulse to be compressed to a duration about the electron plasma wave period, the fluence is needed

$$w = \frac{q_w}{\lambda}\left(\frac{mc^2}{e}\right)^2 \approx 0.3\,\frac{q_w}{\lambda}\,\frac{\mathrm{J}}{\mathrm{cm}}\ ,$$

where $q_w \sim 1$ is a slowly varying function of the system parameters.

Pump Intensity at Langmuir Wavebreaking Threshold

The pump pulse intensity should not significantly exceed the threshold for breaking of the mediating Langmuir wave in the transient RB regime,

$$I_{\rm thr} = n_e m c^3 q_L / 16 \ ,$$

since both the laser coupling and RB efficiency decrease for intensities too far beyond the threshold. Thus, in efficient RB regimes

$$I = q_I \, I_{\rm thr} \ , \qquad\qquad q_I \lesssim 1 \ .$$

Inverse Bremsstrahlung Smallness Condition

Substitution of the above formulas for fluence and intensity into the formula for pump duration leads to the following condition for Inverse Bremsstrahlung smallness:

$$q_{ib} = \frac{16 q_w \nu_{ei}}{q_{ef} q_I \omega_e} \ll 1 \ .$$

Interestingly, this condition does not contain explicitly the laser parameters. It also implies that the Langmuir wave collisional damping

$$\nu_{Lei} \approx \nu_{ei}/4$$

is negligible within the pumped pulse duration of order of the plasma period,

$$\nu_{Lei} t_o \sim \frac{\pi \nu_{ei}}{2\omega_e} \ll 1 \ .$$

Avoiding Excessive Landau Damping of Langmuir Wave Mediating the Energy Transfer

For the RB regime to be essentially transient, Landau damping of Langmuir wave mediating the energy transfer from the pump to the growing seed pulse should be negligible within the output pulse duration.

Larger Landau damping may reduce the Langmuir wave amplitude and, hence, the coupling of pump and seed lasers, which would increase the duration of output pulse (at the same input parameters).

To avoid excessive Landau damping, it is necessary to have the phase velocity of the Langmuir wave,

$$v_{\mathrm{ph}} \approx c\, q_L/2,$$

exceeding significantly the thermal electron velocity $\sqrt{T_e/m}$.

This is possible for not too high electron plasma temperatures T_e,

$$T_e \ll mc^2 q_L^2/4 \equiv T_M .$$

Restriction from below on electron plasma temperature

On the other hand, the electron plasma temperature should be large enough to suppress the inverse bremsstrahlung of the x-ray pulses, as seen from the condition

$$q_{ib} = \frac{16 q_w \nu_{ei}}{q_{ef} q_I \omega_e} \ll 1 \; .$$

The rate of electron-ion collisions in this condition could be evaluated for a nearly ideal and classical plasma with singly charged ions as

$$\nu_{ei} \approx \frac{4}{3}\sqrt{\frac{2\pi}{m}}\,\frac{\Lambda n_e e^4}{T_e^{3/2}} \; ,$$

where Λ is the Coulomb logarithm.

The Shortest Laser Wavelength (1)

By substituting this ν_{ei} and

$$T_e \equiv q_T \, T_M \qquad\qquad (q_T \ll 1)$$

into the formula for q_{ib}, it can be rewritten in the form

$$q_{ib} = \frac{256\sqrt{2\pi}\,\Lambda\, q_w}{3\, q_T^{3/2} q_{ef}\, q_I\, q_L^2} \frac{r_e}{\lambda} \ll 1 \ ,$$

where

$$r_e \equiv \frac{e^2}{mc^2} = 2.818 \text{ fm}\,.$$

Taking into account physical ranges of parameters (q_L < 1/2, q_T << 1, etc), this condition could possibly be satisfied just for laser wavelengths λ larger than angstrom.

Plasma heating via the inverse bremsstrahlung

There is yet another requirement associated with the plasma heating via the inverse bremsstrahlung of laser energy.

Under conditions when the electron cooling by thermo-conductivity and ions are negligible, the inverse bremsstrahlung increases the electron plasma temperature by

$$\delta T_e = \nu_{ib} t_h I / (C_e n_e c)$$

where t_h is the time of heating, and C_e=3/2 is the specific heat per electron. The largest heating occurs at the edge where the pump enters the plasma. There, $t_h = 2L/c$ and

$$\delta T_e = \frac{2 q_{ib} I}{C_e n_e c} \, .$$

By using the above formulas, this temperature increase can be presented in the form

$$\delta T_e = T_M \frac{q_{ib} q_I}{2 q_L C_e} \, .$$

The Shortest Laser Wavelength (2)

Since $\delta T_e \leq T_e$, it follows

$$q_{ib} \leq 2 q_L C_e q_T / q_I \;.$$

When the right hand side is much smaller than unity (which is true for not too small q_I), this condition is stricter than the first one. Then, the shortest allowed laser wavelength is somewhat longer and is given by

$$\frac{256\sqrt{2\pi}\,\Lambda\, q_w}{9\, q_T^{5/2} q_{ef} q_L^3} \frac{r_e}{\lambda} \ll 1 \;.$$

Laser energy per electron and Fermi energy

Laser pump energy per plasma electron can be evaluated as

$$T_P = \frac{2I}{n_e c} = mc^2 q_I q_L / 8 \ .$$

Electron plasmas can be treated as nearly classical at temperatures exceeding the electron Fermi energy,

$$T_e \gg F = \frac{\pi^2 \hbar^2}{2m} \left(\frac{3n_e}{\pi} \right)^{2/3} \ .$$

Linear Raman backscattering rate

Generally speaking, care should be taken to prevent premature Raman backscattering of the pump by noise, since the pulse compression length may exceed significantly the linear RB e-folding length given by

$$\Gamma_R = \sqrt{\frac{q_I}{2} \frac{\omega_e^2}{4\omega}} \; .$$

Interestingly, the parasitic Raman instability may be significantly suppressed by collisional and Landau damping of the thermal Langmuir waves, while the useful RB survives in a narrow domain trailing the short seed, where ultimately the output pulse is built.

Landau damping for Maxwellian electrons

The linear Landau damping rate for Maxwellian electron distribution is

$$\Gamma_{\mathrm{Lnd}} = \frac{\omega_e \sqrt{\pi}}{(2q_T)^{3/2}} \exp\left(-\frac{1}{2q_T}\right) \ .$$

The condition for RB be transient within the output pulse duration $t_o \sim \dfrac{2\pi}{\omega_e}$,

$$1 \gg \Gamma_{\mathrm{Lnd}} t_o = \frac{\pi^{3/2}}{\sqrt{2} q_T^{3/2}} \exp\left(-\frac{1}{2q_T}\right),$$

could be satisfied just for $q_T < 0.1$.

However, nonlinear saturation of Landau damping can allow transient RB at larger q_T and, respectively, smaller λ.

Laser front duration and cross section

Note that for a highly efficient RB, the seed pulse front should be short enough, namely, as short as the desired duration of compressed output pulse $t_o \sim 2\pi/\omega_e.$

Note also the RB length L must be shorter than diffraction lengths of lasers L_D. A laser pulse of given fluence and energy can be accommodated within the cross section $S = \varepsilon/w,$

so that the respective diffraction length is $$L_D \approx \frac{S}{\lambda} \approx \frac{3\varepsilon}{q_w}\frac{\mathrm{cm}}{\mathrm{J}} \;.$$

Interestingly, it does not depend explicitly of laser wavelength.

The transverse thermo-conductivity is small for

$$S \gg \frac{24T_e}{mc^2}\frac{L^2}{1 + 2\nu_{ei}L/c} \;.$$

Numerical examples of system parameters for $q_I = q_w = 1$ and $q_{ef} = 0.5$. Nonlinear saturation of Langmuir wave Landau damping is needed, all other applicability conditions are satisfied.

Name	Value 1	Value 2	Units
Laser wavelength λ	7	15	$\AA$
Laser frequency ω	2.69	1.26	10^{18} sec^{-1}
Single photon energy $\hbar\omega$	1.77	0.83	keV
Laser pump pulse energy ε	2	2	mJ
$\varepsilon/\varepsilon_c$	0.75	0.08	
Electron plasma concentration n_e	1	0.3	10^{26}cm^{-3}
Electron plasma frequency ω_e	5.64	3.09	10^{17} sec^{-1}
Pump energy fraction going to Langmuir waves $q_L = \omega_e/\omega$	0.21	0.25	
Electron Fermi energy F	0.79	0.35	keV
Laser pump energy per plasma electron T_P	13.4	16	keV
Electron energy T_M corresponding to Langmuir wave phase velocity	5.6	7.7	keV
Electron plasma temperature T_e	2.8	2.6	keV
Plasma edge electrons heating by the pump inverse bremsstrahlung $\delta\, T_e$	2.0	1.8	keV
Electron-ion collision time ν_{ei}^{-1}	0.25	0.6	fsec
Langmuir wave collisional damping time ν_{Lei}^{-1}	1	2.4	fsec
Inverse bremsstrahlung time ν_{ib}^{-1}	5.8	10	fsec
Laser pump pulse duration $t_{\rm pmp}$	2.6	3.4	fsec
Pump energy fraction lost for the inverse bremsstrahlung $q_{ib}/2$	0.11	0.086	
Thermal electron free flight time across the pump pulse diameter	16	24	fsec
Pump pulse diffraction time	460	450	fsec
The pump pulse diameter D	350	510	nm
Laser pump intensity I	3.2	1.1	10^{21}W/cm^2
Linear BRA growth rate Γ_R	2	1.3	10^{16} sec^{-1}
Time of linear Landau damping of Langmuir wave	2.7	4	asec
BRA output duration t_o	11	20	asec
BRA output power P	90	50	TW
Intensity of BRA output focused to spot of diameter $\lambda/2$	9	1	10^{28}W/cm^2

Conclusions

- The short wavelength theoretical limit is found for compression and focusing of powerful x-ray pulses by Raman backscattering in plasmas.
- The shortest wavelength appears to be about 1 nm, at which mJ x-ray pulses might be, in principle compressed and focused to intensities sufficient for the vacuum breakdown.