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The output of a laser amplifier with simultaneous amplified spontaneous emission and an injected seed

H. HUANG AND G.J. TALLENTS
Department of Physics, University of York, York, United Kingdom

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Abstract

The minimum irradiance needed to overcome amplified spontaneous emission (ASE) of a seed beam injected into a laser amplifier is evaluated. The treatment is particularly applicable to extreme ultraviolet (EUV) and X-ray laser schemes to inject laser harmonic radiation as a seed into (1) plasma laser amplifiers and (2) free-electron lasers. Simple expressions and calculations are given for the minimum injected irradiance required for amplification of the injected seed beam to exceed ASE from the amplifier, including the effects of gain saturation, assuming one dimensional radiative transfer.

Keywords: Amplified spontaneous emission; Free-electron lasers; Harmonic radiation; Seed beam; X-ray

1. INTRODUCTION

Soft X-ray lasing from laser-plasmas has been a significant achievement for the application of high power infrared lasers (Tallents, 2003), while X-ray free-electron lasers are now an important advancement arising from electron accelerator technology (Ayvazyan, 2006). Applications for such lasers are developing (for example, Edwards *et al.*, 2006, 2007; Kuehl *et al.*, 2007; Neumayer *et al.*, 2005; Purvis *et al.*, 2007; Tallents *et al.*, 2009; Ziaja *et al.*, 2007).

Plasma-based X-ray lasers and free-electron lasers operate without mirrors in amplified spontaneous emission (ASE) mode (Pert, 1994). To improve the spatial uniformity, coherence, and irradiance of both plasma-based X-ray lasers and free-electron lasers, seeding the amplification with an injected pulse from, for example, high infrared laser harmonics has been investigated. Ditmire *et al.* (1995) originally demonstrated the injection and amplification of high harmonics with small gain at 25 nm wavelength in an extreme ultraviolet (EUV) amplifier, while Mocek *et al.* (2005) used an injected seed beam to experimentally investigate the plasma gain dynamics of a gas cell plasma amplifier. Zeitoun *et al.* (2004) and Wang *et al.* (2006) demonstrated injected harmonic amplification to saturation in plasma amplifiers at longer wavelength (33 nm). Earlier plasma-based X-ray laser experiments also showed that two plasma amplifiers could be operated in an injector amplifier arrangement (Carillon *et al.*, 1992; Lewis *et al.*, 1992). Harmonic injection into a free-electron laser has now been demonstrated (Lambert *et al.*, 2008).

Plasma-based X-ray lasers utilize a gain medium pumped transversely by a line focused infrared laser driver pulse (Tallents, 2003), pumped longitudinally by laser irradiation along a gas cell (Mocek *et al.*, 2005), or electrically pumped by a capillary discharge (Rocca, 1999; Wagner *et al.*, 1996). The problems of making a resonator at X-ray laser wavelengths are severe, so only single or double transit amplified spontaneous emission lasers have been employed. With transverse pumping by infrared laser, a pre-pulse is used to produce expanding plasma so that the ground state of the required Ne- or Ni-like ion is abundant in the expanding plasma. A second main pulse heats the pre-plasma causing collisional excitation and the production of a population inversion. The pre-pulse ensures that the density gradients are gentle, so that refraction of the X-ray laser beam is small. It also increases the gain medium volume and increases the pumping laser absorption. Further efficiency of X-ray laser pumping has been achieved using grazing incidence pumping (Keenan *et al.*, 2005). Here a beam is incident into preformed plasma at a grazing angle. The main advantage (Keenan *et al.*, 2005; Tűmmler *et al.*, 2005) of the grazing incident pumping is that the pumping geometry improves laser coupling efficiency into an

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Address correspondence and reprint requests to: G.J. Tallents, Department of Physics, University of York, York YO10 5DD, United Kingdom. E-mail: gjt5@york.ac.uk

optimum gain region of plasma, using refraction to turn the pumping laser at an electron density below the critical density where gain production is maximized. Plasma-based X-ray lasers have poor transverse spatial uniformity and coherence with for short duration pumping (<10 ps), a typical profile consisting of a complex speckle pattern (Guilbaud *et al.*, 2006) with each speckle associated with amplification of a single spontaneously emitted photon. The longitudinal coherence is close to the Fourier transform limit (Mistry *et al.*, 2006). Seeding of the amplification can allow much more spatially uniform and coherent laser output as long as the amplification of the seeded beam dominates ASE (the subject of this paper). Using Maxwell-Bloch simulations, recent work by Al'miev *et al.* (2007) has shown that short duration, broad bandwidth harmonic radiation injected into a plasma amplifier with a narrow gain bandwidth leads to an amplified output pulse of temporal duration consistent with the gain bandwidth rather than the harmonic bandwidth.

The original concept for a free-electron laser (FEL) was proposed by Madey (1971). Elias (1976) demonstrated that light generated by an electron beam oscillation in a magnetic field can be amplified by stimulated emission. Free-electron lasers use an electron accelerator to produce an electron beam. The electrons arrange themselves into "micro-bunches" and interact with the developing laser electric field so that the laser electric field is coherently additive at each spatial point (Tallents, 2008). Free-electron lasing is achieved with single-pass, high-gain self-amplified spontaneous emission (SASE) (Milton *et al.*, 2001; Ayvazyan *et al.*, 2006). FELs operated in SASE mode have a broad spectral bandwidth ($\nu/\Delta\nu \leq 100$) which means that very short (<1 fs) pulses can be produced, but using the beams for some experiments such as interferometry, where high longitudinal coherence is required, will be difficult. The longitudinal coherence of FELs is significantly improved by seeding the FEL amplifier with moderately spectrally narrow pulses generated by harmonics from optical lasers (Schwettman, 1999; Yu *et al.*, 2000, Lambert *et al.*, 2008). The transverse coherence of FELs is only marginally improved by seeding, as unseeded FELs already have moderately good transverse coherence.

We consider here laser radiation transfer and gain in an amplifier following injection seeding of radiation assuming a single ray path following the ray optic treatment of Pert (1994). The relative strength of amplification of the injected irradiance relative to the ASE irradiance is examined so that the required irradiance of an injected pulse for an amplified injected beam to dominate ASE is estimated.

2. THEORY

When injected light is amplified, the amplifier self-emission is also amplified by ASE. ASE irradiance after integration over frequency and for a uniform amplifier of length L is given by Tallents (2003)

$$\begin{aligned} I_{ASEtot} &= \int I_{ASE}(\upsilon)d\upsilon = I_0 f(0)\int \{\exp[G(\upsilon)L]-1\}d\upsilon \\ &= I_0 f(0)\int \left\{\exp\left[GL\frac{f(\upsilon)}{f(0)}\right]-1\right\}d\upsilon, \end{aligned} \tag{1}$$

where $I_0 f(0) = E(\nu)/G(\nu)$ for $E(\nu)$ the spontaneous emission per unit length, $G(\nu)$ is the gain coefficient at frequency ν and $f(\nu)$ is the small signal gain coefficient line shape function at frequency ν. We assume that $\nu = 0$ is at the gain coefficient peak and that G represents the peak gain coefficient.

The amplified irradiance of an injected beam of peak spectral irradiance I_{Init} into the same laser amplifier can be written as

$$\begin{aligned} I_{Injtot} &= \int I_{Inj}(\upsilon)d\upsilon = I_{Init}\int \frac{g(\upsilon)}{g(0)}\exp\left[GL\frac{f(\upsilon)}{f(0)}\right]d\upsilon \\ &= I_{Init}^{tot}\int g(\upsilon)\exp\left[GL\frac{f(\upsilon)}{f(0)}\right]d\upsilon, \end{aligned} \tag{2}$$

where the initial spectrally integrated injected irradiance is given by

$$\begin{aligned} I_{Init}^{tot} &= I_{Init}\int_{-\infty}^{+\infty}\frac{g(\upsilon)}{g(0)}d\upsilon \\ &= \frac{I_{Init}}{g(0)}, \end{aligned} \tag{3}$$

for $g(\nu)$ is the spectral line profile of the injected beam.

A homogeneously broadened gain profile $G(\nu)$ is related to the small signal gain coefficient at line center g_0 by

$$G(\upsilon) = G\frac{f(\upsilon)}{f(0)} = \frac{g_0}{1+\dfrac{I_{av}}{I_s}}\frac{f(\upsilon)}{f(0)}, \tag{4}$$

where I_s is the saturation irradiance and I_{av} is the average irradiance. The average irradiance I_{av}, considering both ASE and the amplified injected beam, is given by

$$\begin{aligned} I_{av} &= \int \frac{f(\upsilon)}{f(0)}[I_{ASE}(\upsilon)+I_{Inj}(\upsilon)]d\upsilon \\ &= I_{av}^{ASE}+I_{av}^{Inj}. \end{aligned} \tag{5}$$

3. INJECTED AMPLIFICATION AND ASE

The ratio of the irradiance at output due to amplification of the injected beam to that due to ASE is given by

$$R_{Inj/ASE} = \frac{I_{Inj}(\upsilon)}{I_{ASE}(\upsilon)} = \frac{I_{Init}^{tot}g(\upsilon)\exp\left[GL\dfrac{f(\upsilon)}{f(0)}\right]}{I_0 f(0)\exp\left[GL\dfrac{f(\upsilon)}{f(0)}-1\right]}. \tag{6}$$

We can approximate

$$R_{Inj/ASE} \approx \frac{I_{Init}^{tot} g(\upsilon)}{I_0 f(0)}, \tag{7}$$

for large gain length product GL. The average irradiance can thus be rewritten as

$$\begin{aligned} I_{av} &= \int \left\{ \left[\frac{f(\upsilon)}{f(0)} I_{ASE}(\upsilon) \right] (1 + R_{Inj/ASE}) \right\} d\upsilon. \\ &= I_{av}^{ASE}(1+S), \end{aligned} \tag{8}$$

where

$$\begin{aligned} S &= \frac{I_{Init}^{tot}}{I_0 f(0)} \frac{\int g(\upsilon) I_{ASE}(\upsilon) d\upsilon}{I_{av}^{ASE}} \\ &= \frac{I_{Init}^{tot}}{I_0 f(0)} \frac{\int \left\{ f(\upsilon) g(\upsilon) \exp\left[GL \frac{f(\upsilon)}{f(0)} - 1 \right] \right\} d\upsilon}{\int \left\{ f(\upsilon) \exp\left[GL \frac{f(\upsilon)}{f(0)} \right] - 1 \right\} d\upsilon} = \frac{I_{Init}^{tot}}{I_0} S'. \end{aligned} \tag{9}$$

Noting the relationship between I_ν and I_s in Eq. (4), the effect of saturation on the amplification of the injected and ASE beams can be taken into account by adjusting the saturation irradiance in the formula determined by Pert (1994) and Casperson (1977). We can write for the relationship between the actual gain coefficient G and the small signal gain coefficient (Pert, 1994)

$$\left(1 - \frac{I_0}{I_s'}\right) GL + \frac{I_{tot}}{I_s'} = g_0 L, \tag{10}$$

where $I_{tot} = I_{Injtot} + I_{ASEtot}$ for a single directional X-ray laser output. Here the effective saturation irradiance I_s' is related to the actual saturation irradiance I_s by

$$I_s' = \frac{I_s}{1+S}. \tag{11}$$

Eq. (10) then becomes

$$GL + \left(\frac{I_{tot}}{I_s} - \frac{I_0}{I_s} GL \right)(1+S) = g_0 L. \tag{12}$$

The ratio R_{out} of the spectrally integrated irradiance due to the injected beam to that due to ASE is given by

$$\begin{aligned} R_{out} &= \frac{I_{Injtot}}{I_{ASEtot}} = \frac{\int I_{Inj}(\upsilon) d\upsilon}{\int I_{ASE} d\upsilon} \\ &= \frac{I_{Init}^{tot} \int \left\{ g(\upsilon) \exp\left[GL \frac{f(\upsilon)}{f(0)} \right] \right\} d\upsilon}{I_0 f(0) \int \left\{ \exp\left[GL \frac{f(\upsilon)}{f(0)} \right] - 1 \right\} d\upsilon} = \frac{I_{Init}^{tot}}{I_0} R_{out}'. \end{aligned} \tag{13}$$

Assuming Gaussian line profile shapes $f(\upsilon)$ and $g(\upsilon)$ for the gain coefficient and injected beam initial profile respectively and that the profiles $f(\upsilon)$ and $g(\upsilon)$ are centered on the same frequency, we can expand the exponentials as Taylor series in the formulae for R_{out}' and S' and integrate term-by-term. We obtain that

$$R_{out}' = \frac{\sum_{n=0}^{\infty} \frac{[GL]^n}{n!} \frac{1}{\sqrt{1+nr^2}}}{\sum_{n=1}^{\infty} \frac{[GL]^n}{\sqrt{n} n!}}, \tag{14}$$

for $r = \Delta\upsilon_{Inj}/\Delta\upsilon_p$, the ratio of the width of the injected beam spectral profile to the gain coefficient spectral width. Values of R_{out}' are plotted in Figure 1.

To take account of saturation effects, we need to evaluate S' (see Eq. (9)). As for R_{out}', we obtain

$$S_{out}' = r \frac{\sum_{n=0}^{\infty} \frac{[GL]^n}{n!} \frac{1}{\sqrt{n+1+r^{-2}}}}{\sum_{n=1}^{\infty} \frac{[GL]^n}{n!} \frac{1}{\sqrt{n+1}}}. \tag{15}$$

Values of S_{out}' are plotted on Figure 2. The values of $S = (I_{Init}^{tot}/I_0)\, S_{out}'$ are used to account for saturation effects using Eqs (9) and (12). We see that for large r (as may be expected for harmonic injection) that saturation will occur at a lower amplified irradiance of the injected beam as S_{out}' can be larger.

4. NUMERICAL RESULTS

An example of the output irradiance variation of an injected amplified pulse and ASE calculated using the above equations with $I_{Init}^{tot} = I_0$ for a relatively spectrally broad injected pulse is shown in Figure 3. The effect of the slow increase of the injected pulse irradiance at short lengths L as observed by Wang *et al.* (2006) is clearly seen. The

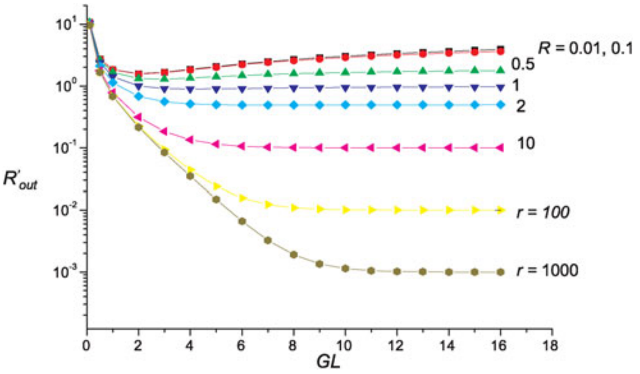

Fig. 1. (Color online) The reduced ratio of the irradiance at output due to amplification of the injected beam to that due to ASE as a function of the actual gain length product. Results are for different ratios $r = 0.01$, 0.1…(as labeled) of the spectral width of the injected beam to the gain coefficient.

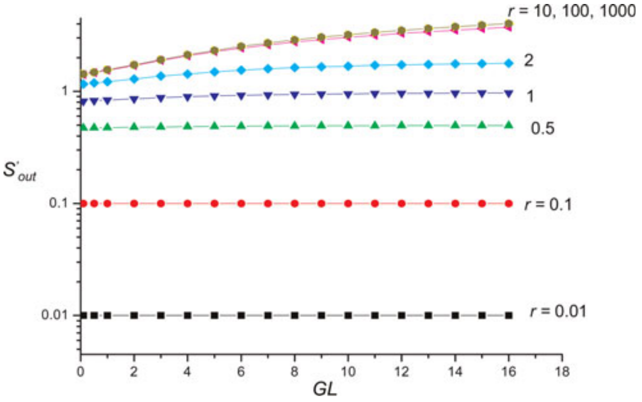

Fig. 2. (Color online) The parameter S'_{out} relating the saturation behaviors of a plasma amplifier with and without an injected seed beam as a function of the gain length product for different values of $r = 0.01, 0.1\ldots$ (as labeled) of the spectral width of the injected beam to the gain coefficient width.

spectrally broad injected pulse spectrally narrows with increasing length at short lengths without significant increase of the spectrally integrated irradiance. For the example shown in Figure 3, ASE dominates the amplified injected pulse. Saturation of the ASE beam has a simultaneous saturation effect on the amplified injected beam at $g_0L \approx 15$.

The injected laser pulse normally needs to have irradiance $I^{tot}_{Init} \gg I_0$ for the amplified injected beam to dominate ASE output (see the discussion below). The initial spontaneous emission irradiance can be written for a Gaussian shaped gain coefficient line profile as (Tallents, 2003)

$$\begin{aligned} I_0 &= \frac{E(\upsilon)}{G(\upsilon)f(0)} \\ &= \frac{\Omega}{4\pi}\frac{8\pi h\upsilon}{\lambda^2}\frac{1}{f(0)}\frac{1}{1-\frac{g_u}{g_l}\frac{n_l}{n_u}} \\ &\cong \frac{\Omega}{4\pi}\frac{8\pi h\upsilon}{\lambda^2}\frac{\sqrt{\pi}\Delta\upsilon_G}{\sqrt{4\ln 2}}, \end{aligned} \tag{16}$$

where Ω is the solid angle for which spontaneous photons can be amplified. Values of I_0 are plotted in Figure 4.

We can estimate the injected pulse energy E_{Init} from a harmonic or other source required for amplification of the injected pulse to dominate over ASE. We require

$$\frac{I^{tot}_{Init}}{I_0}R'_{out} > 1, \tag{17}$$

and hence from Figure 1, require $I^{tot}_{Init} > I_0 r$ as $R'_{out} \approx 1/r$ at large GL and large r. Assuming the amplification process is constant when present and ASE only occurs for the gain coefficient characteristic duration τ_p, the injected pulse energy required for a time-integrated measurement to observe more output from the amplified injected pulse than from ASE is given by

$$E_{Init} = I^{tot}_{Init}\tau_{Inj}A > I_0 r A \tau_p, \tag{18}$$

where A is the amplifying cross-section area and τ_{Inj} is the injected pulse duration after amplification (see Al'miev *et al.*, 2007). For typical laser-pumped plasma amplification with amplifying cross-section area $A = 10^{-4}\,\mathrm{cm}^2$, $\tau_p = 10\,\mathrm{ps}$, relative spectral bandwidth of the injected beam to the gain coefficient $r = \Delta\upsilon_{Inj}/\Delta\upsilon_p = 100$ and spontaneous emission irradiance $I_0 = 10^3\,\mathrm{Wcm}^{-2}$ (see Fig. 4), we obtain $E_{Init} > 0.1$ nJ. Harmonic output, for example, can be readily produced with $E_{Init} > 0.1$ nJ (McNeil, 2007), so our results confirm that it is feasible to seed plasma amplifiers with harmonic output without a significant ASE contribution to the total laser output.

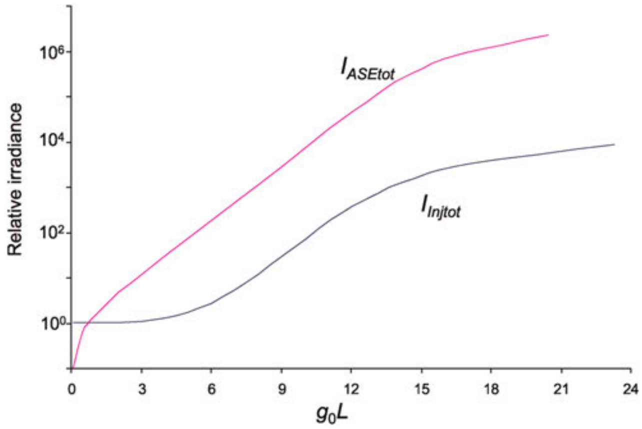

Fig. 3. (Color online) Relative spectrally integrated irradiance due to ASE (I_{ASEtot}) and the amplification of an injected pulse (I_{Injtot}) as a function of small signal gain coefficient length product. The ratio r of injected beam spectral bandwidth to the gain coefficient bandwidth is taken to be 100 here. It is also assumed for this plot that the injected pulse irradiance $I^{tot}_{Init} = I_0$ where I_0 is a measure of the irradiance of spontaneous emission (see text and figure 4). Saturation effects are modeled assuming a saturation irradiance such that $I_s/I_0 = 10^6$.

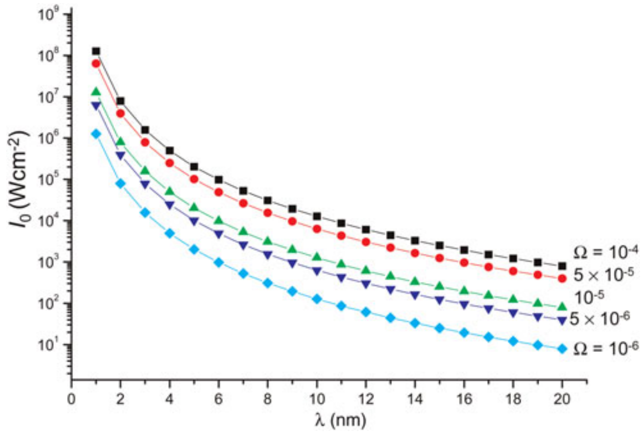

Fig. 4. (Color online) Spontaneous emission irradiance I_0 as a function of wavelength λ at particular solid angles Ω (in steradian) for emission and gain spectral bandwidth $\Delta\upsilon_G = 10^{-4}\,c/\lambda$.

5. CONCLUSION

The relative irradiance of an amplified injected beam and ASE output from a laser amplifier has been examined. It has been shown that the spectrally integrated injected beam irradiance I_{Init}^{tot} needs to exceed the value of spontaneous emission irradiance I_0 (see equation (16)) by a ratio R'_{out}. For larger gain length products $G(0)L$, the R'_{out} values lie in the range $10^{-4} - 10$ depending on the relative spectral widths r of the injected beam and amplifier gain coefficient. We can see that where the injected spectral width greatly exceeds the gain coefficient spectral bandwidth (at larger $r = \Delta\upsilon_{Inj}/\Delta\upsilon_p$), $R_{out} \propto (I_{Init}^{tot}/I_0)(1/r) = (I_{Init}^{tot}/I_0)(\Delta\upsilon_p/\Delta\upsilon_{Inj})$, while $R_{out} \propto (I_{Init}^{tot}/I_0)$, if the injected spectral width is much less than the gain coefficient bandwidth.

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