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Line Broadening and Pulse Durations in the Context of the Tabletop Ultra-Intense X-Ray Sorce (TUIXS) Project

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Abstract

Presented are predictions that plasma amplified x-ray / extreme ultra-violet (EUV) pulse durations can be reduced dramatically (to below 100 fs). This is through high-harmonic seeding of a suitably engineered plasma. Seeding overcomes gain narrowing by driving the amplifying medium into saturation earlier, and compensates for reduced gain resulting from boosting the lasing transition linewidth through collisional as well as Doppler broadening. Crucially, sufficiently strong seeding renders amplified spontaneous emission (ASE) insignificant, so that the lasing medium gain duration no longer imposes a lower limit on pulse duration. It is concluded that such focussed pulses could reach ultra-high intensities ($\geq 10^{19}$ W cm^{-2}).

The duration of the record shortest plasma-amplified EUV pulse is ~ 2 ps [1] Recently, however, fourth generation light sources have come of age with the development of free-electron lasers (FELs) [2]. These sources are expected to deliver EUV and x-ray radiation with intensities above 10^{19} W cm^{-2} in ultra-short pulses of less than 100 fs duration, but the demand for beamtime is likely to be great for the foreseeable future. Here, the possibility of generating such ultra-intense, ultrashort pulses using plasma-based amplifiers with extremely scaled-down architecture is discussed. The proposed scheme uses a suitably engineered plasma to amplify an initially relatively intense, very large bandwidth ($\Delta\nu/\nu \approx 0.01$) pulse of high harmonic radiation – the 'seed'. Such a scheme has already resulted in saturated amplification of high harmonic seeds using plasma amplifiers generated from gaseous [3] and solid [4] targets. Seeding overcomes gain narrowing by driving the plasma into saturation earlier, preserving more of the linewidth. Seeding also compensates for loss of gain resulting from boosting the linewidth of the lasing transition through collisional as well as Doppler broadening, and, at a sufficiently high level, renders ASE insignificant.

The rate of change of intensity of radiation propagating unidirectionally through plasma gain media when conditions are independent of time can be expressed as [5, 6, 7]

$$\frac{dI(\nu,z)}{dz} = \frac{j_0}{V(\nu_0)}\left[1+\frac{g_0 I(\nu,z)}{j_0}\right]\times\int_0^\infty \frac{S(u)\phi(\nu,u)du}{1+\frac{1}{I_{sat}}\int_0^\infty I(\nu')\phi(\nu',u)d\nu'}. \qquad (1)$$

Here, $I(\nu,z)$ is the intensity at frequency ν at a distance z into the medium, I_{sat} is the saturation intensity, j_0 is the peak emissivity (that at the centre of the line profile) along the direction of propagation and g_0 is the peak small-signal gain. $S(u)$ is the value of the inhomogeneous component of the profile at frequency u and $\phi(\nu,u)$ is the value of the homogeneous component of the profile (both profiles being area normalised) centred on u at ν. $V(\nu_0)$ is the Voigt profile resulting from the convolution of independent homogeneous and inhomogeneous broadening mechanisms. Work by Koch et al [7] measured the intensity and spectral width of a 20.6 nm neon-like selenium laser pulse as a function of distance into the plasma amplifier. They used equation 1 to model the transfer process, and to make comparisons with their experimentally obtained results. The authors justified not considering time explicitly on the grounds that the transit time through the longest plasma target did not exceed the plasma gain duration of ~ 200 ps (i.e. the timescale over which the plasma state across its length was effectively unchanging). Good overall agreement with experiment was obtained. (The same reasoning can be used to justify the use of equation 1 if the plasma is created using a 'modern' transient scheme with travelling wave pumping [8], even if the actual hydrodynamics are time-dependent over the timescale of the transit of the pulse through the amplifier. This is provided that the local plasma conditions ‘seen’ by the pulse do not change as it progresses through the medium.) Although this work was performed quite some time ago, to the best of our knowledge it remains the only test case with which linewidth and, hence, pulse duration predictions under differing plasma conditions can be compared.

Doppler broadening, being inhomogeneous, results in a Gaussian profile; collisional broadening is homogeneous and results in a Lorentzian profile. Inhomogeneous broadening, in the absence of significant homogeneous broadening, causes a re-broadening of the line profile after saturation. Unfortunately, even if the linewidth of the amplifying transition were to re-broaden to its original extent following saturation, it would still not be sufficiently great through Doppler broadening alone to generate ultra-short pulses in the x-ray / EUV regime (this would require *ion* temperatures in excess of 1 keV, and the ions required are not light). This now seems very unlikely, though, as saturation re-broadening has never been observed experimentally in laser-produced plasmas. It has, however, been observed to increase in noble gas laser transitions when the inter-atomic collision frequency is reduced [9, 10]. This suggests that collisional redistribution (of velocity) acts to homogenise the otherwise inhomogeneous Doppler broadening, thus destroying the re-broadening mechanism. Additionally, the presence of even relatively slight homogeneous broadening due to electron-ion collisions appears to be extremely deleterious to re-broadening due to the dominance of the associated Lorentzian distribution in the wings of the profile [11]. To reach the ultra-short, ultra-intense regime, therefore, requires collisional broadening also. Within plasma gain media linear Stark broadening is not present as the levels are degenerate, quadratic Stark broadening is much less significant and the degree of collisional broadening depends almost exclusively on the electron-ion collision frequency as given by the impact approximation (collisional broadening by ions can be neglected).

For the plasma of their experiment, Koch et al [7] determined the electron density to be ~ 4 x 10^{20} cm^{-3}, the electron temperature to be ~ 900 eV and the ion temperature to be ~ 400 eV. This ion temperature corresponds to 36 mÅ of Doppler broadening, and the impact approximation used in the present work predicts a collisional broadening contribution of ~ 24 mÅ under these conditions. The authors explain that values for g_0, ε_0 and I_s, were obtained iteratively until a best fit to a plot of intensity versus distance using equation 1 was identified. They were estimated to be 5.5 cm^{-1}, 1.5 x 10^{-9} W cm^{-3} Hz^{-1} and 1.7 x 10^{-4} W cm^{-2} Hz^{-1}, respectively. Also given are the rates of population and depopulation of the lasing levels for their conditions. Using these, g_0 and I_s have been re-calculated for the *revised* conditions of twice the electron density and half the electron and ion temperatures to be ~ 60% of and 4.5 times the original values, respectively. ε_0 has not been recalculated as results are only given for the revised conditions with seeding at a sufficiently high level as to render it insignificant. *The collisional broadening contribution to lasing transition linewidth is now actually predicted to be twice as great as that due to the Doppler effect under the original conditions*. The resulting linewidth and intensity predictions for the propagating pulse are shown in figures 1 and 2, respectively. Even a seed of $0.1I_s$ under the revised conditions generates a pulse of ~ 100 fs duration with a final integrated intensity of ~ 2.5 x 10^{11} W cm^{-2}. This results in an intensity of ~ 10^{16} W cm^{-2} if focussed to 50 μm; if focussed to 1.5 μm, an intensity of ~ 10^{19} W cm^{-2} results.

Relying on collisional as well as Doppler broadening to produce ever-shorter pulses *is* unorthodox, but it is predicated on results indicating that the plasma can still function as an amplifying medium under the required conditions, and that seeding at a sufficiently (though no longer unfeasibly) high level can compensate for resulting gain reduction. All the seeding levels considered here are so great as to render ASE insignificant and linewidth predictions in some cases correspond to sub-100 fs pulses. It is noteworthy that the gain inferred by Koch et al of 5.5 cm^{-1} is much less than that achievable routinely today using transient pumping schemes. This suggests that ultra-high intensity pulses – of the order of 10^{19} W cm^{-2} – could be attainable following focussing to within the diffraction limit using this technique with much reduced plasma amplifier lengths (despite the associated reduction in I_s).

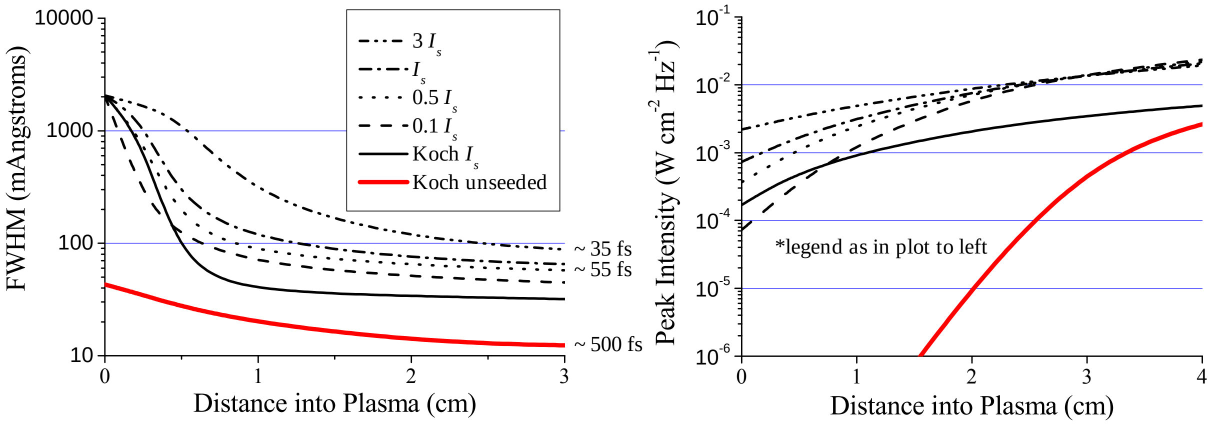

Figure 1 (left) Predicted full width at half maximum of a 20.6 nm laser pulse versus distance into a Ne-like Se plasma under differing plasma conditions. The unbroken lines show predictions under the original Koch conditions (see text) and the broken lines show those under the revised conditions (again, see text). In each case, the seeding level is given in terms of the saturation intensity, I_s. Figure 2 (right) Corresponding intensities.

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