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Traveling Wave Pumping of Ultra-Short Pulse X-ray Lasers

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ABSTRACT

Pumping of proposed inner-shell photo-ionized (ISPI) x-ray lasers places stringent requirements on the optical pump source. We investigate these requirements for an example x-ray laser (XRL) in Carbon lasing on the 2p-1s transition at 45 Å. Competing with this lasing transition is the very fast Auger decay rate out of the upper lasing state, such that the x-ray laser would self-terminate on a femto-second time scale. XRL gain may be demonstrated if pump energy is delivered in a time short when compared to the Auger rate. The fast self-termination also demands that we sequentially pump the length of the x-ray laser at the group velocity of the x-ray laser. This is the classical traveling wave requirement. It imposes a condition on the pumping source that the phase angle of the pump laser be precisely de-coupled from the pulse front angle. At high light intensities, this must be performed with a vacuum grating delay line.

We will also include a discussion of issues related to pump energy delivery, i.e. pulse-front curvature, temporal blurring and pulse fidelity. An all-reflective optical system with low aberration is investigated to see if it fulfills the requirements.
It is expected that these designs together with new high energy (>1J) ultra-short pulse (< 40 fs.) pump lasers now under construction, may fulfill our pump energy conditions and produce a tabletop x-ray laser.

Keywords: ultra-short pulse, x-ray laser, reflective optics

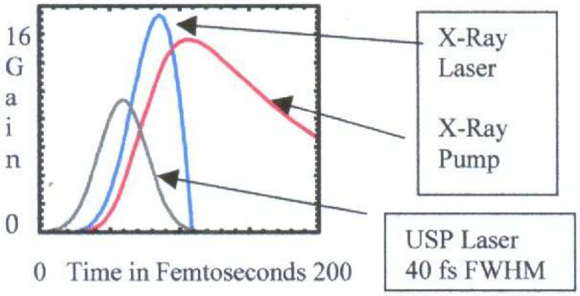
1. INTRODUCTION

The use of traveling optical waves as a method of delivery of optical energy to various media is not new to laser science (1-6). Bor extensively investigated and used this technique as a method of producing 1 pico-second optical pulses before CPA came on the scene. Indeed, the field of collisional x-ray lasers has seen the implementation of traveling wave pumping (TWP) to enhance XRL performance (7,8). Moreno has noted that TWP may be beneficial whenever the pump time divided by the target length is less than 33 ps/cm (8).

There is a class of x-ray lasers yet unrealized where traveling wave pumping is a strict requirement if gain is to be demonstrated. First proposed by Duguay and Rentzepis (9) and further developed by Kapteyn (10) and most recently by Moon (13), inner-shell photo-ionized x-ray lasers (ISPI) operating on K-α transitions of low Z elements seemed an attractive way to efficiently pump an XRL in the sub 50 Å regime. As first discussed these new schemes still needed sub 50 fs and greater than 10 J in an optical pulse to drive the transition. Prompted by recent advances (11) in powerful ultra-short pulse lasers (USP) a preliminary investigation into traveling wave optical systems is now warranted. We begin by examining the physical dynamics of an example inner-shell photo-ionized x-ray laser at 45 Å in Carbon to derive the traveling wave optical system parameters.

2. INNER-SHELL TRANSITIONS

The physical characteristics of a traveling wave optical pump system are largely determined by the physics of the x-ray laser transition. For our example, we will use a 10 μm × 10mm line focus. To pump the 45 Å 2p-1s carbon line requires an ultra-short pulse filtered broad-bandwidth x-ray pump source to preferentially ionize just the inner-shell 1s electrons. It must also have a very rapid rise time, faster than the upper state lifetime of carbon, which suffers from a fast radiative decay as well as a competing fast Auger decay. Additionally, as inner-shell electrons are ejected from the atom cores, they contribute to collisional ionization and subsequent depopulation of the lower laser state of other atoms. Thus, we require that the rise time of the pulsed x-ray source be less than 80 fs (Gain of 0 for > 80 fs.). Pulsed x-rays from USP laser irradiated plasmas have been thought a good candidate to drive ISPI x-ray lasers (12). Summarizing this scheme is a LASNEX XRL gain calculation in carbon of a USP laser at 1.0 × 10^17 W/cm^2 incident on a 200 Å thick gold target, where the prompt back-side x-ray emission from a gold foil is used to pump the carbon lasant material (13).



Notice that this time constraint is true for every incremental length of the lasing volume. Thus, we find that a 10 mm. long XRL with group velocity of c (index of refraction n~1.000) needs to be strictly linearly pumped in 33 ps. +/- 40 fs.

3. TRAVELING WAVE OPTICS

We may now define the optical parameters of the TWP optical system. The optical energy of an USP laser must be linearly delivered at an intensity of 1.0×10^{17} W/cm^2 over a 10 μm wide line for 10 mm. From above we find the temporal distortion of the optical system must be limited to less than 80 fs./33 ps. or ~ .0025 to drive laser gain over the length of the laser volume. Also attendant is the vertical spatial distortion that naturally must be limited to +/- 5 μm over 10 mm. or ~ .0005 over the laser length.

These are not unreasonable distortion figures for normal optical systems. However when a high power USP laser is required, (with its ~ 50-100 nm. bandwidth), all-reflective optical surfaces must be used to eliminate both the chromatic distortions that lead to pulse temporal broadening (14) and distortions due to the intensity induced nonlinear index of refraction or B-integral. Of the various traditional methods to tilt optical pulses by angular dispersion i.e. prisms, Fabry-Perot interferometers and gratings (7,15) only the diffraction grating operating in vacuo succeeds as a dispersive element. Problematically, the use of an all-reflective optical system constrains both the number and orientation of the surfaces used to minimize optical aberrations.

The treatment of femto-second optical pulses propagating through dispersive elements may be rigorously analyzed by path delay methods, where the frequency dependent action of diffraction gratings is completely described by geometrical optics (16). In previous experiments utilizing TWP, the pulse tilt angle and target tilt angle alone was sufficient to achieve synchronism across the target plane. This relied on the quasi-monochromatic nature of the lasers used in the TWP schemes. Here we require the use of large bandwidth (100 nm.) USP lasers, where the angular dispersion of the grating leads immediately to temporal broadening of the laser pulse. Our problem then is to tilt a USP laser pulse without disturbing its propagating 0 GVD. There are two methods available which satisfy the distortion requirements above. If a positively chirped pulse is incident on a grating, the grating will impart a negative chirp to the pulse resulting in a 0 GVD plane at some distance from the grating. This 0 GVD plane may be relay imaged to the target plane. Since relay imaging maintains the optical path length of the marginal rays, then the target plane is also a 0 GVD plane (17). For practical reasons of alignment and adjustment, we propose the following scheme. Illuminate a grating with the USP laser and disperse the light. Every point on the grating intersects the propagating 0 GVD of the laser pulse. An idealized optical system relay images this 0 GVD plane (grating) to the target plane. Note that to preserve optical path lengths the 0 GVD target plane must be parallel to the grating plane. (Fig.2)

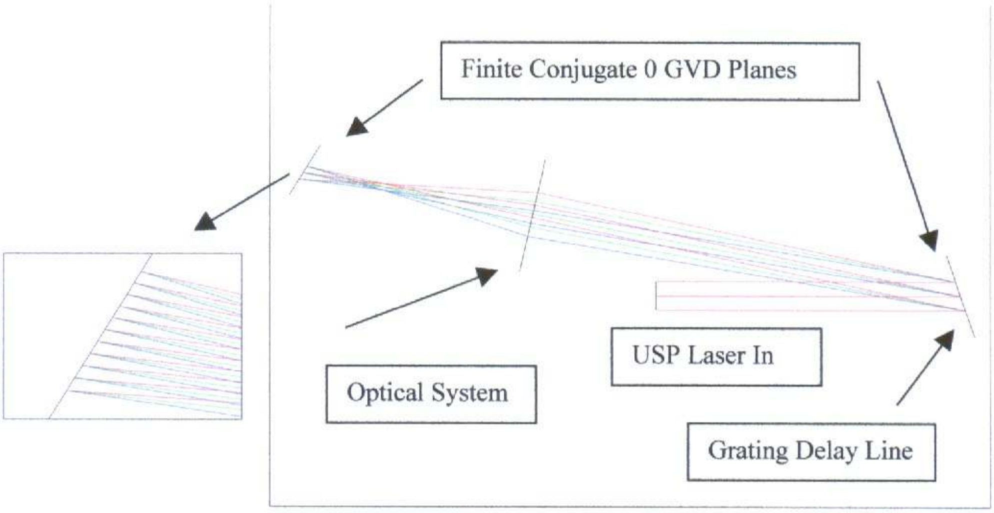


Figure 2. Schematic of 0 GVD Relay Imaging.

The inset above is a simplified view of the image plane. This image plane is indeed parallel to the object plane in ray space however recall that imaging telescopes invert the image with respect to the object. Note that the frequency dependence of the rays implies different optical paths. Additionally as noted in (17) above there are limitations to TWP with a grating delay line. Since the group velocity index (η) of x-rays in the target is 1, the delay required across the target is simply the target length. The delay (D) created at the grating surface is D = (grating length)$*$Sin[θ_i], where θ_i is the incident angle. Though we set the amount of delay by adjusting the incident angle that the USP makes with the grating, there is no incident grating angle that satisfies this amount of delay for the case where (grating length) = (target length), since Sin[θ_i] = 1 implies θ_i = 90`. This is clearly unworkable so we must resort to a 2-D demagnification of the object plane to achieve the necessary target line length while preserving the optical delay.

The demagnification and spectral dispersion of our optical system introduces both pulse curvature and an array of spectrally separated pulse tilts to the beam. This confuses the traditional meaning of pulse tilt angle and in fact, it looses its utility for our application. However, if each point in the image plane is the finite conjugate of its object plane point, then by Fermat's Principle not only do we preserve pulse temporal fidelity across the image plane, we also relay the optical delay from the grating to the target. (Fig. 3)

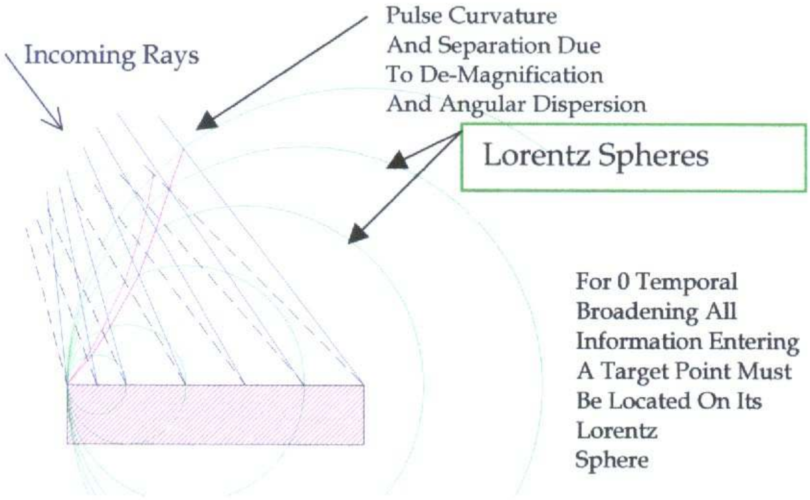


Figure 3. Pulse Curvature and Chromatic Separation

A preliminary look into the performance of a simple finite conjugate reflective optical system with regard to temporal and spatial distortions mentioned earlier may now be attempted. In principle, our system needs to accurately perform stigmatic point to point imaging over a limited field of view with low coma, while maintaining very low distortion. An optical system corrected for these aberrations is said to be anastigmatic and aplanatic. First, some corrections are in order. Remember we are interested in a line focus at the target plane, yet we are imaging a plane grating surface. In actuality we desire to image the grating onto the target in the x-z plane only, and in the y-z plane we wish to image an infinite conjugate point onto the target that together results in a line focus geometry. An inverted Schwarzschild microscope geometry may be modified to accommodate our needs. By replacing the concentric spherical surfaces with concentric cylindrical (aspherical) surfaces, imaging power for the finite conjugate y-z plane is provided. Insertion of a third surface just prior to the target plane may be deformed to provide power for the infinite conjugate x-z plane. Methods of correcting the optical aberrations in the y-z plane are similar to those to correct Schwarzschild microscopes or multi-mirror relay systems. Using these parameters (18,19), the following geometry with a magnification of 1/3 is produced. (Fig 4.) Though it may not be obvious, without the third mirror, this system has the advantage of being symmetric about the y-z optical axis. In addition, gratings can be used to first order and in efficient diffraction configurations.

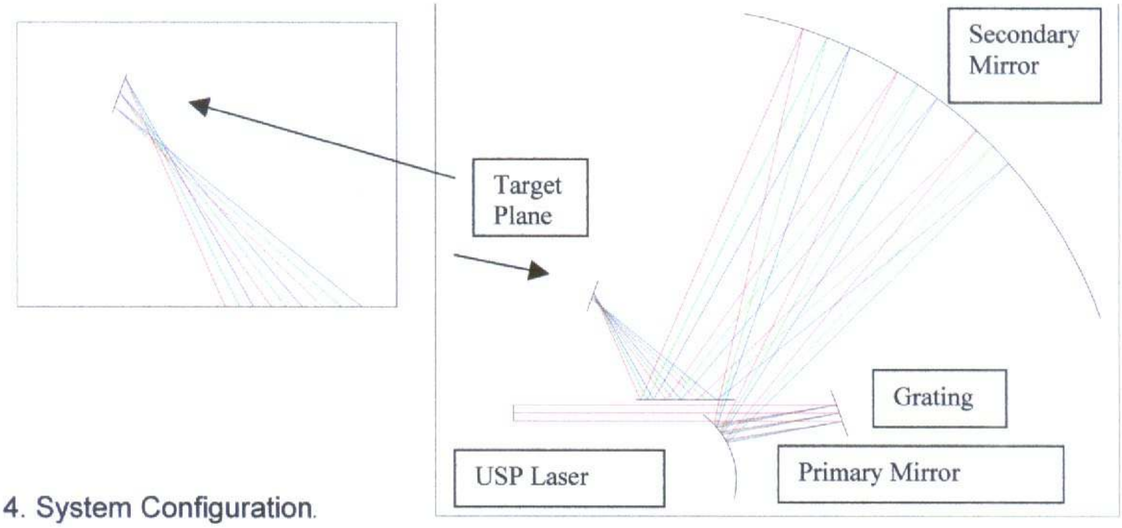


Figure 4. System Configuration.

The initial error measurements that need to be found for our system are the optical path difference (OPD) and optical distortion (OD). The OPD is the measured distance from the grating to the target for an array of conjugate points. A poor OPD directly leads to re-chirping of the compressed pulse and temporal broadening. The OD is similar to the familiar pincushion or barrel distortion of photographic images and here it is a measure of the synchronism between the traveling wave pump pulse and propagating x-ray laser pulse. Here, it is measured as the sum of the differences of $X_{\text{theory}} - X_{\text{calc}}$. These are presented in figure 5 below.

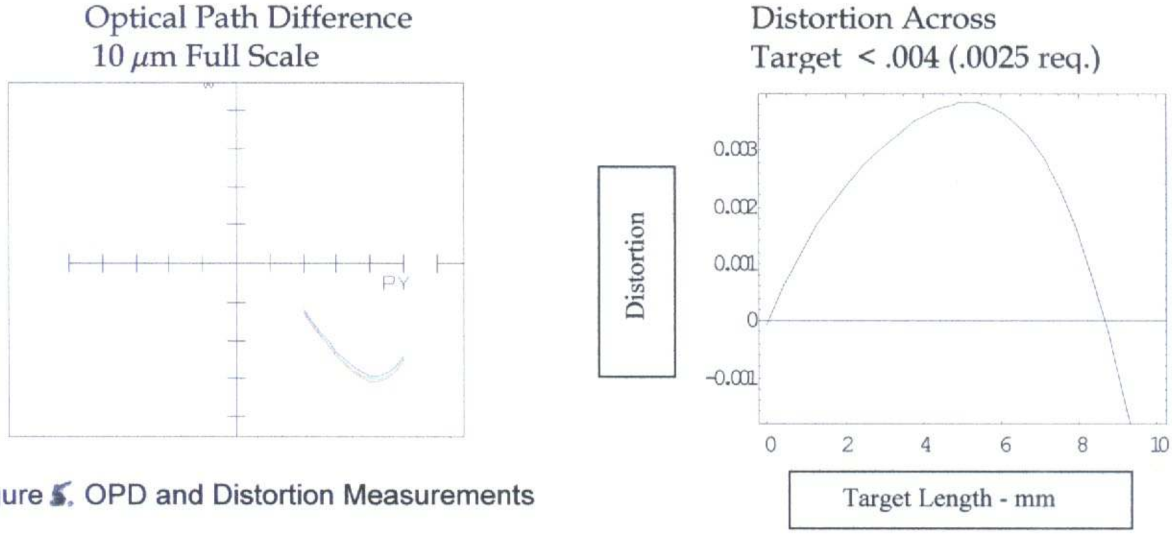


Figure 5. OPD and Distortion Measurements

The OPD plot shows that while we have a 2-3 μm OPD field curvature over the target length (~2-3 waves) the spectral path differences are less than 1 μm implying that our system has a minimum of temporal broadening. The distortion across the target is generally less than .004. Unfortunately, we need distortions of less than .0025 to maintain gain over the length of the x-ray laser. This distortion is not unexpected in a two mirror corrected system. Generally, the correction of distortion, field curvature, astigmatism and spherical aberration requires a minimum of three optical surfaces (18). So far, we have not addressed power in the x-z plane off the third mirror. This will be a highly aspherical off-axis low f/# optic to produce the 10 μm line focus and it is expected that it may participate in the reduction of the residual system distortion as we progress in our optical design.

SUMMARY

We have begun a preliminary investigation into the optical performance of an all-reflective traveling wave pumped x-ray laser system. The traditional traveling wave pulse tilt analysis was abandoned in favor of stigmatic imaging of the temporal delay off a diffraction grating. We derived a measurable set of optical performance characteristics required to pump an ISPI x-ray laser. We then modeled a 2-D variant of an inverted Schwarzschild microscope and imaged a grating delay line onto an x-ray laser target surface. The modeled system demonstrated excellent temporal pulse fidelity. However, the current model exhibited a small amount of field curvature that leads to some de-focus plus an amount of distortion that is 2 × greater than required. Future work will include the minimization of these residual aberrations and completion of final aspherical optic geometry.

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