Prospective schemes for next generation X-ray lasers

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Abstract. Two novel schemes for efficient x-ray laser generation from laser-produced plasma and capillary discharge-driven plasmas are described. The combination of nano-structured targets with the high energy ultrashort pulse lasers can result in the generation of laser-produced plasmas that could lead to high brightness sources of incoherent multi-KeV radiation and x-ray lasers of short pulse duration at shorter wavelengths. The generation of 0.5-1 keV x-ray laser radiation from a Ni-like U plasma created using excitation from a Petawatt laser is analyzed. The efficient excitation of capillary discharge plasmas in micro-capillary discharge channels is discussed.

Introduction

In the year of 25th anniversary of first successful demonstration of x-ray lasers (XRL) led by Livermore and Princeton researchers [1-3] and 15th year from the realization of the first discharge-pumped x-ray laser at Colorado State University [4] the interest in improved pumping schemes, and new approaches to x-ray laser development still remains very high. The main challenges include the very steep scaling laws for power and energy demanded by shorter wavelength. As a result the shortest wavelengths achieved so far from a plasma-based x-ray laser were obtained in the fusion source x-ray lasers at 0.3-0.9 keV [5,6]. Laboratory x-ray lasers, which have been mostly limited by pumping power and energy hence will substantially benefit from new approaches to better transform the pump energy into x-rays since the efficiency of this process is many orders of magnitude below their quantum efficiency. The electrical discharge XRLs are typically more wall-efficient and have also advantages in size, repetition rate, energy per pulse, and cost. Unfortunately electrical discharge XRL were not easily scalable to shorter wavelengths, which rises the question of how close are they already to their efficiency limit. We will describe two novel approaches in laser produced plasma and electrical discharge pumped plasma which have the potential of advancing XRLs toward new territories.

Laser- produced plasma x-ray lasers

From the history of the development of XRL we know that numerous initial attempts to obtain lasing produced promising results, but were not reproducible for many years. Early promising results of amplification at 50-70 nm were obtained at P.N.Lebedev Physical Institute in Moscow [7]. Over time further analysis and better understanding showed that the initial gain estimations were too optimistic, and that the pump laser energetics were on the edge of what is necessary. Also, several additional detrimental effects such as refraction were not taken into account [8,9]. The increase of the pump laser parameters from the initial 30 J ,3 ns, used at the Lebedev Physical Institute experiments to 10 kJ 0.5ns in the early LLNL Novette experiments also did not initially help the LLNL efforts to obtain x-ray laser generation. The well known breakthrough at LLNL [1] came after the innovative solution of target design offered by M.Rosen et al. [2] allowed to mitigate the detrimental effect of refraction. This breakthrough design was a real piece of fine technology where the laser target consisted of only several hundreds of Angstrom foil covered with similarly thin layer of Se. It allowed to burn through the foil to create a smooth electron density profile and at the same time heat and ionize the plasma and allow x-ray laser signal amplify over the whole active medium length. The power of most world powerful laser together with unique exploding foil technique and a better theoretical understanding and simulations resulted in the first successful demonstration of a

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laboratory x-ray laser and rapid advances into shorter wavelengths. The history of this area of research also shows that such breakthroughs are happening not very often and new opportunities appear only after major technologies evolve substantially which may takes decades. New relevant technologies in high energy petawatt lasers, stable capillary plasma columns, nanostructure fabrication, and better numerical models and computer capabilities open new opportunities. The requirements for bright x-ray sources has also changed. It became increasingly important to obtain shorter pulse durations and larger energy resulting in higher brightness.

It is known that laser radiation can not penetrate into conducting materials beyond the critical density, which for typical pump lasers with ~1 micron wavelengths is in 10^{21} cm^{-3} range. Typically such plasma is never simultaneously dense and hot, excluding special cases of spherical compressions at the largest laser facilities such as the National Ignition Facility. Additionally the spherical and cylindrical compression methods of obtaining dense and hot plasma are relatively slow, expensive, and not very efficient. Also, the increase in laser power when irradiate plain solid targets does not necessarily result in simultaneously hotter and denser plasmas because its very thin, typically submicron size supercritical layer, quickly expands.

Herein we discuss the possibility of combining high energy Petawatt lasers with nanostructure targets to generate 0.5-1 KeV lasers. The generation of x-ray laser radiation from a Ni-like U plasma created using 200-400 J of excitation from a Petawatt laser is analyzed. The new approach described here becomes possible by combining ultra-intense femtosecond lasers, with dense nanotube/nanowire arrays. In this scheme femtosecond pulse laser radiation penetrates into very dense (in average 0.03-0.3 of solid density) targets consisting of vertically oriented nanostructures and deposits energy volumetrically before the interfiber distance collapse. With such geometry it becomes possible to waveguide radiation deep enough (~5-10 micron) inside the dense structure, while maintaining an unprecedented density that surpasses critical density by ~2 orders of magnitude. It consists of a carbon nanotube array covered with a layer of the necessary material. The mechanism of absorption has some similarities to gaseous clusters but is unique in that the nanotube material topology might allow waveguiding of the laser radiation along one dimension before it becomes scattered and absorbed. In comparison, at the same average density, the 5-10 micron pumped depth in this type of structure is an order of magnitude larger than possible with homogeneous 3D structures as clusters, foams airgels, sponges etc. It is also two orders larger than the depth of hot dense super-critical layer of plane solid targets heated by thermal conductivity and radiation. Besides the higher densities, and high absorption this new approach results in longer lifetimes of the dense hot plasma region as compared with regular plain targets.

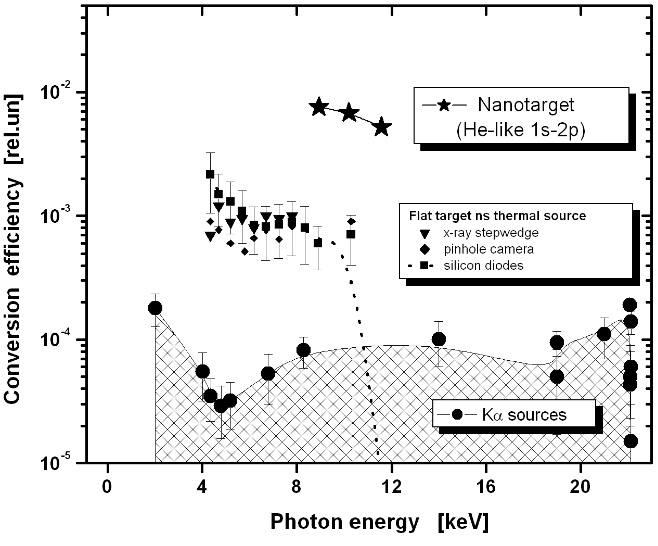

Figure 1. RADEX X-ray conversion efficiency in the He-like 1s-2p line in the femtosecond pulse irradiated vertically aligned nanostructured target as compared with the conversion efficiency for flat targets irradiated by ns laser pulses [10] and numerous Kα sources [11]

In this case the ultrafast optical laser irradiates the target in a so called supersonic heating regime, or volumetrically, not losing density and energy to expansion, similarly to such regimes in low density subcritical foam targets. With the use of current powerful lasers the entire energy will be deposited into a 5-10 micron thick layer of almost solid density material and will form an ultra-hot high-z plasma regime.

Unique is the fact that with 10^{18}-10^{19} W/cm^2 it will be possible to reach 20 keV temperatures. Important is that even with such temperatures, due to high density and Z, the electron elastic collision time is very small and on the order of 1 fs. As a result the electrons, even fast electrons < 100 keV, thermalize quickly and the plasma remains classical and can be reliably modeled. The long lifetime of such plasma will allow to rapidly ionize atoms to high Z~ 50-70 in ~1 ps. This kind of hot high density plasma can find numerous applications in high energy density physics. For example, the relatively long lifetime, high temperature, high density, and high Z can result in very bright and efficient thermal point source of line and continuum multi-keV radiation. Simulations show that up to 16 keV this source emits line radiation one to two orders more efficiently that plain targets or any K-alpha sources (Fig.1). The tail of the spectral distribution of continuum bremsstrahlung and photorecombination radiation spectra from high-Z plasma can reach 100 keV competing in integrated intensity with K-alpha sources.

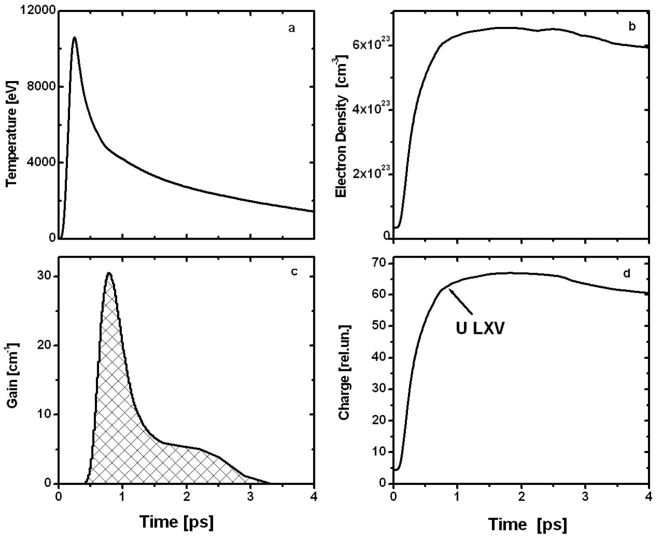

Figure 2. RADEX modeling results: the temperature, density, ion charge and transient gain obtained on 4d-4p transitions of 64 times ionized Uranium at 2.1nm in a plasma heated by a 200-400 J of femtosecond laser. Gain up to 10-20 cm^{-1} is computed on the 0.8nm and 1.7nm 3p-4p transitions

Of more interesting for x-ray lasers is its favorable scaling into higher Z, that other types of targets do not provide due to the low critical density of optical lasers. The high temperatures, electron densities and high degree of ionization of this novel approach could brings new possibilities for higher brightness, and substantially shorter pulse duration and high photon energy. Fig.2 shows the example of a RADEX calculations of temperature, density, gain and Z for an Uranium plasma heated with 200-400 J of optical pumping energy. It can be noticed that the very high density and ionization charges in just 1-2 ps reaching Z~65. The gain in Fig.2c is shown for typical Ni-like ions 4d-4p J=0-1 transitions. There exist several other transition with acceptable gain for SASE or numerous others for generator-amplifier schemes. The high electron density assures short gain duration, in this case ~400fs, that after amplification with gain-length product gl ~16 the laser pulse will be shortened by the factor $(gl)^{1/2}$ reaching 100fs. This design delivers also energy and brightness parameters competing with ones of XFEL in 0.03-1 keV photon range

Discharge-based x-ray lasers

Electric current discharges are typically associated with the concept that they are extremely efficient. Although this is in general true in the sense that eventually most of initial stored electrical energy will be transformed into the thermal energy, what is important for x-ray lasers is how large is the electron temperature and density that can be *simultaneously* achieved during the discharge. For example, for lasing using the collisional excitation scheme for each Z there exist an optimal set of temperatures and densities. Since without special pulse shaping arrangements these high temperatures and densities are typically reached during the first half cycle of the current pulse it is of interest to analyze what fraction of the stored energy can been dissipated into plasma heating during this time.

If an initial simple initial assessment we will consider the typical LCR circuit equations with load parameters that do not change in time. The table below shows these parameters together with the voltage, peak current, first half-cycle pulse duration, stored energy, energy dissipated during first half cycle and efficiency of this deposition, for the case of capillary discharges with three different diameters ranging from 3cm to 0.03cm. The discharge parameters were selected based on approximate analytical scaling to yield similar plasma parameters at the peak of compression. The selection was subsequently adjusted using RADEX simulations to make ensure that the final temperature and density are approximately the same in all cases.

	3cm	**0.3 cm**	**0.03 cm**
C, F	1.4 x10^{-7}	3 x10^{-9}	1.8 x10^{-10}
L, H	1 x10^{-7}	1.2 x10^{-7}	1.5 x10^{-7}
R, Ohm	3.4 x10^{-3}	3 x10^{-1}	3 x10^{1}
U, V	2 x10^{5}	3 x10^{5}	1.5 x10^{5}
Pulse duration, ns	430	75	17
Stored energy, J	2800	135	2.03
Deposited energy, J	25	16	1.94
Efficiency	<1%	12%	95%

As we can see the efficiency of dissipation of stored energy during first half cycle of the current is very different for these three cases. The current shapes (see Fig.3) are also substantially different. On one hand the 3 cm discharge has a sinusoidal current that very slowly decays over many cycles. On the other, the 0.03 cm discharge has an asymmetric current pulse that is rapidly attenuated by the high plasma resistance. We see that in case of 0.03 cm capillary the high resistance leads to a much better first half cycle heating efficiency. The current pulse is mostly defined here by the (RC)$^{-1}$ characteristic time as opposed to the dominant of the (LC)$^{-1/2}$ characteristics in 0.3cm and in 3 cm cases, and most of the stored energy directly transformed by Joule dissipation into plasma thermal energy.

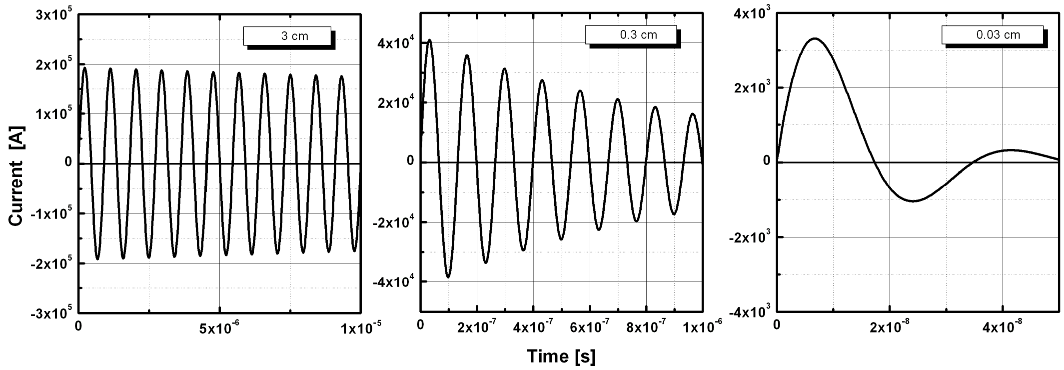

Figure 3.Electric current shapes for the cases set in Table 1

We have to note that the energy dissipated in the larger diameter discharges is spread over a much larger volume then in case of small capillary (similarity laws require smaller initial densities for larger size capillaries). In capillary soft x-ray laser only the rapidly compressed and heated at the time of collapse central 100-200 micron part of plasma is important. For a typical Ar capillary discharge soft x-ray laser this useful region of the plasma contains only ~1 J of thermal and ionization energy. That means that off the noted 135 J of stored energy in 0.3cm less than 1 % of the energy is eventually transformed into useful active medium plasma, and even much less in larger size case. In contrast, in the case of the 0.03cm micro capillary plasma this fraction is almost 25-50%.

Here we logically come with a concept which if confirmed in the experiments may eclipse previous fast capillary discharges in efficiency. Due to the smaller currents this ultrafast microcapillary discharge can be made very compact. Also important is the fact that the thermal and radiation load on the surface is approximately the same than in the case of the larger diameter capillaries used in the existing soft x-ray lasers, with some potential for further improvement.

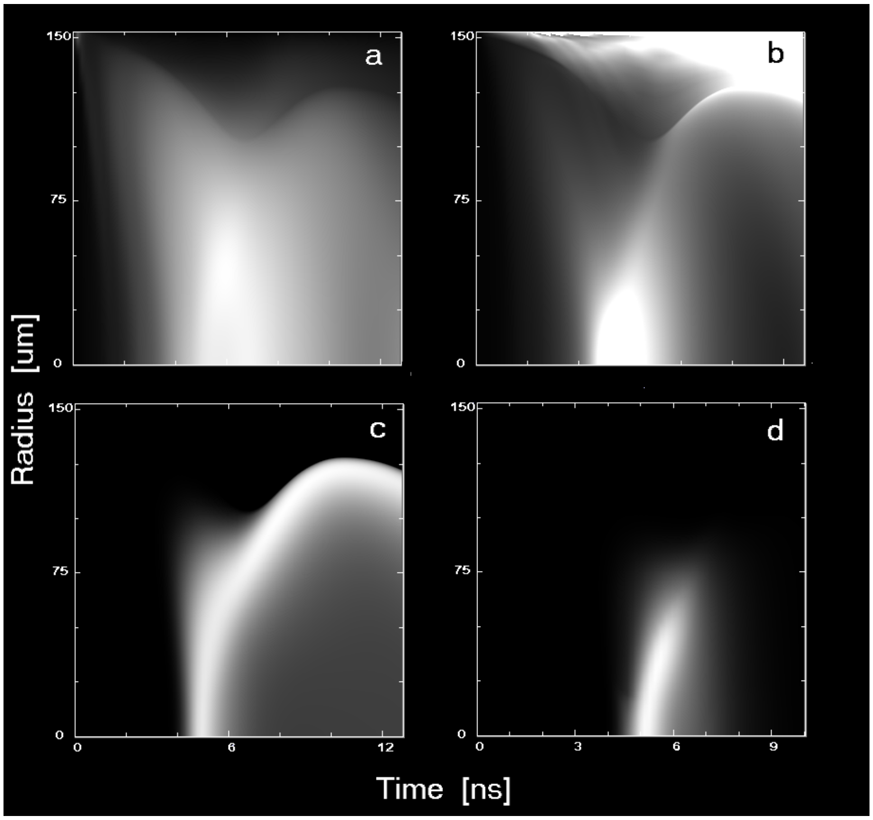

Figure 4. RADEX modeling of ultrafast Ar 300 micron microcapillary discharge with the 3.9 kA peak current. The surface plots a to d are electron temperature, electron density, relative abundance of Ne-like Ar IX ions and gain on 3p-3s J=0-1 transition of Ar IX. The normalized gray scale is linear from black (0) to white (1) with maximum a) 75 eV, b) 1.e19 cm^{-3}*, c) 0.9 and d) 3.5 cm*$^{-1}$ *respectively*

Figure 4 shows the results of RADEX simulations of hydrodynamics (a and b) and atomic kinetics (c and d) for such microcapillary driven by a ~ 4 kA current pulse. We selected and optimized the initial and boundary conditions such that the plasma parameters obtained resemble those we typically find in the conventional 3-4mm diameter capillary Ar soft x-ray laser driven by 20-40 kA electric current with the pulse duration 50-70ns on the base [4].

This new approach for creating soft x-ray lasers has numerous other advantages. One of which of course is its scalability and potential for operation at shorter wavelengths. With currents pulses of ~30kA peak amplitude it might becomes possible to obtain electron temperatures of the order of 0.5 keV. For comparison, in our previous works we used a high current 200 kA discharge in 3.3 mm capillaries to reach temperatures ~250 eV in Cd metal vapor [12] and Ar gas [13].

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