# Recent developments in plasma x-ray lasers

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Plasma X-ray lasers (XRL) are sources of bright, highly coherent and directed short wavelength electromagnetic fields. They are a flavour of lasers with active media based on population inversion in ionised gases. While they were developed since early eighties of twentieth century at large-scale research facilities, they were gradually improved to fit in small-scale university labs. The two major challenges where x-ray lasers try to provide suitable answers are related to brightness and spectral range. Recent developments on control for the plasma dynamics in terms of temperature and ionization state significantly improved the capabilities of the plasma XRL.

## 1. Context

The first work on the amplified spontaneous emission of light was made in 1917 by Albert Einstein. Based on his theoretical seminal work, the laser was subsequently demonstrated in the beginning of the sixties of the twentieth century. The laser became a solution looking for a problem.

Ever since, tremendous effort was put for the developments of lasers with wavelength bands across the entire electromagnetic range, more average output power and peak pulse energy, shorter pulse duration and lower cost.

The plasma x-ray lasers (XRL) are based on gain generation in multiple ionized plasmas. Ne-like, Ni-like and Pd-like ions in laser produced plasmas on solid, foil and gaseous targets are chosen to build the active media. Electrons heated by the pump laser are colliding with the ions, inducing ionization, excitation and, through further depopulation mechanisms, population inversion. Depending on the specific level structure of the ions in the plasma, amplified spontaneous emission can be produced at wavelengths from above 30nm (Ne-like ions) to lower than 4 nm (Ni-like ions). This optical range is particularly difficult in terms of optical components availability. Mirrors for this spectral region have poor reflectivity. Hence, no cavity is implemented for the XRLs in most of the cases and the plasma is columnar, in order to favour the directed amplification of the spontaneous emission of the plasma.

The history of the XRLs is driven by the interplay of the plasma properties and the ways to control them. In the following section, several specific breakthroughs are briefly presented. For more detail see [1], an extended early x-ray lasers review.

## 2. Highlights

The early x-ray lasers (e.g. [2]) were using laser induced plasmas as active media. The pump laser energies were reaching up to tens of kJ in energy cumulated from several laser pulses with durations in the half-of-nanosecond range. A plasma gradient smoothing technique based on the use of multiple pulses was proposed in [3] to enhance the pump laser absorption in the plasma. With the introduction of a prepulse, the plasma scale length was controlled in a proper way. The plasma in the XRL pumped with half-of-nanosecond long laser pulses was reaching a quasi-steady state (QSS) regime over periods of time in the range of 100ps. A lot of energy was used for the pumping, that was compensating for the huge loss of energy because of the plasma cooling.

The pulse duration in the range of half-of-nanosecond were long in comparison with the cooling time scale. A lot of the pumped energy was lost through conduction in the target and through adiabatic expansion of the plasma in vacuum. The solution came with the advance of the ultrashort pulse lasers; the main pump laser pulse was reduced to few picosecond duration and thus the heating of the plasma was a 100 times shorter [4]. As a consequence, the plasma cooling significantly reduced during the period where population inversion appears, less than 10 ps, typically in this configuration. The scheme was labelled with the term transient collisionally excited (TCE) XRL.

The main advantage of the TCE versus the QSS XRL was the hundred times reduction in the pump energy requirements to total values around 10J. This moved the XRL from national scale facilities to middle-size laser facilities and increased the repetition rate of operation to few shots per hour. Subsequently, a number of improved results were obtained for Ni-like XRL [5], with wavelength down to 6 nm when Dy was used as target element.

The XRL pumping was based on a half-of-nanosecond long pump pulse for pre-ionization of the plasma and for control of the plasma scale length (also known as pre-pulse) and on a few ps long pulse to induce electrons heating for collisional excitation and subsequently population inversion followed by plasma lasing effect. Both the long and the short pulses were sent close to normal incidence on the target.

However, absorption of the pump laser in the plasma strongly depends on the incidence angle. While at normal incidence, for a laser in the visible range and near infrared, the absorption takes place close to the critical density, at above $10^{21}$ electrons/cm$^3$, the laser is absorbed at lower electron densities when the beam is sent on the target at large incidence angle (grazing angle). This property was correlated with the observation that in the TCE scheme, the gain appears most of the cases in the regions with densities of about $10^{20}$ electrons/cm$^3$. A modified TCE scheme was proposed, using a long pulse and a GRazing Incidence short Pump pulse (GRIP) [6,7]. The consequence of the GRIP was again a reduction in the pumping energy needs, to values about 1 J and an augmentation of the repetition rate of the XRL to 10Hz. Also, wavelengths from 18.9nm [8] down to 10.9nm were demonstrated [9], together with outstanding peak brilliance [10].

A number of various other approaches based on TCE GRIP approach were further investigated, such as the use of grazing prepulse [11] for generating gain closer to the critical density, shaped and multiple prepulses for preplasma control [12-15].

On the other side, in order to improve on the optical properties of the emitted x-rays, in particular the coherence properties, seeded x-ray lasers were developed [16-18]. Phase-Coherent, Injection-Seeded, Table-Top Soft-X-Ray Lasers at 18.9 nm and 13.9 nm were reported [17] and their gain recovery lifetime was studied [18]. In these schemes that intend to provide control over the coherence properties, the essential idea is to avoid the amplified spontaneous emission of the plasma through complete depletion of the active media by the seeding pulse. However, ultrashort pulses generated through high order harmonics have short durations and large bandwidth, in comparison with the gain lifetime and bandwidth, so part of random ASE is generated by plasma on top of the amplified seed pulse.

## 3. Recent developments

As there are many plasma parameters involved, it appeared that the XRL optimization needs one more knob to turn. The easiest way to introduce such a knob is by introduction of an additional pump pulse, one long (1L) pulse or one short (1S) pulse.

Various attempts were made for 2L1S XRL configurations [13, 14] and for 2S XRL configurations [12], and improvement was observed. 1L2S was also theoretically studied in [19], and significant improvement was predicted following adequate optimization of the pump parameters. However, two short pulses with variable delay seemed a complex endeavor until the introduction of a method for multiple short pulses generation directly in the optical stretcher of the chirp pulse amplification (CPA) chain of the pump laser [20,21]. The method was subsequently implemented at the TEWALAS facility in Magurele, Romania to demonstrate the first 1L2S XRL [22]. The main result confirmed the simulations in [19]. Moreover, saturated emission of the plasma XRL was reported using only a total of 200mJ pump energy, a fivefold reduction in the pumping energy when compared with similar GRIP XRL emitting at 13.9nm.

Scalability of the method was cross-checked in several subsequent experiments, with different pump energies [23,24] and demonstrating enhancement in the output of high-average-power, 100-Hz-repetition-rate, tabletop soft-x-ray lasers at sub-15-nm wavelengths [25].

As a side note, it is worth mentioning that the methods developed for the generation of multiple pulses that I proposed in [20] and in [24] were also used in some further plasma related subjects such as phase measurement in long chirped laser pulses with spectral phase jumps using plasma mirror [26] and THz radiation generation [27].

The 1L2S pumping method has a very important advantage when compared with the previous ways of XRL emission optimization. Namely, it allows to fine tune the plasma parameters with picosecond resolution, through proper control of the delays and durations of the two short pulses. This is important, as ionization and excitation are processes which take place at the picosecond time scale. The first laser pulse controls the plasma ionization dynamics, the second short pulse defines very accurately the moment when the plasma heats up to generate the highest collisional excitation rate, hence the highest gain.

Also, it can be conjected that the gain lifetime could be slightly tuned using the 1L2S method, based on the optical properties control of the plasma, partly discussed in [28]. This can provide an interesting path for harmonics seeded plasma XRL, both in line with the developments involving ultrashort seed pulse [17] and also in the case of CPA XRL systems [29] by matching the gain lifetime with the seed pulse duration.

## 4. Outlook

The recent developments of the 1L2S XRL are promising in all the major XRL development directions.

The first one is the demonstration of lab sources with peak brightness and average brightness comparable with the one from synchrotrons. Here, the 1L2S 100 Hz XRL brings the decisive advantage in the near future [25]. Compton scattering experiments using plasma XRL could be considered at ELI-NP facility to be built in Romania [30,31] using the 100Hz, 0.4J, 2ps green laser drivers of the gamma beam system (GBS) and the corresponding 700MeV electron beam.

The second one is related to the development of coherent sources in the water window spectral range. For this 1L2S method scalability has to be investigated at facilities such as CETAL PW, now under commissioning at INFLPR, Romania.

The third one is related to optimization of seeded amplifiers for the efficient extraction of the energy from the amplifiers. Preliminary results show that the 1L2S scheme is able to control both the spatial mode and the gain lifetime of the plasma amplifier, to a certain extent.

## 5. References


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