EUV SOURCE AT HiLASE: THE STATE OF THE ART

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An overview of the Extreme Ultraviolet (EUV) source to be constructed in the frame of the Czech national R&D project HiLASE (High average power pulsed LASErs) is presented. The HiLASE EUV source will be devoted to industrial and medical applications, as well as to fundamental studies (such as the chemistry of polymers). This wide variety of different applications depends on the possibility of targeting different EUV wavelengths (namely 13.5 nm and the water window range, 2.33-4.40 nm), which is insured by the fact that the projected table top EUV source can work on multiple different HiLASE lasers: the cryogenically cooled, Yb:YAG slab high energy laser system and the thin-disk, high repetition rate picosecond laser systems.

HiLASE EUV source is intended as a user oriented device based on a laser plasma source with single stream gas-puff target.

KEYWORDS

EUV, tabletop soft x-ray source, ellipsoidal grazing mirror, laser produced plasma, gas target, water window, EUV lithography

1 INTRODUCTION

EUV table-top systems based on monochromatic beams are efficient devices used in nanolithography and in the micro/nanostructuring of materials, with a wide range of applications spanning from the fabrication of microchips to the construction and improvements of medical devices [Juha 2002, Fiedorowicz 2004, Bartnik 2005, Juha 2005, Bakursky 2010, Bartnik 2010, Wachulak 2018]. Thus, user-oriented facilities with high-power lasers, such as the HiLASE Centre, express a high interest in developing this type of source. For many years, HiLASE Centre has devoted its efforts to improving EUV sources, mainly decreasing plasma instability while working in the high fluence regime. Several years ago, this work began by collaborative works on some of the top class European EUV sources (including e.g. single stream gas-puff target EUV source at Laser-Laboratorium Göttingen, Germany (LLG) and double stream gas-puff target EUV source at Military University of Technology, Poland (MUT)), and by using them for several different applications (e.g. EUV ablation, EUV microscopy or near edge X-ray absorption fine structure (NEXAFS) spectroscopy). Recently, benchmark experiments have been performed at the HiLASE Centre in collaboration with the group of Dr. Mann (LLG), and by using the LLG gas-puff target coupled with the HiLASE picosecond Yb:YAG laser. On the basis of these activities, the effective parameters for the construction of the next generation of EUV plasma sources at the HiLASE Centre are presented.

As stated above, the HiLASE experimental setup targets a wide range of possible applications in industry and in medicine, as well as in pure scientific research, like lithography and surface processing of polymers for fabrication of microchips or medical devices (increasing biocompatibility of plastic prostheses), as well as EUV microscopy with possible biological applications to spectroscopy and material characterization. In order to support precise manufacturing, monochromatic EUV radiation is required [Bakshi 2006], but for spectroscopy, broadband radiation with different optical schemes must not be excluded. Thus, an experimental setup based on the model of LLG EUV source is under construction.

In order to understand the construction requirements for targeting such a wide range of applications, it is necessary to take a step back and look at the general concept of EUV sources and of the methods to deliver a EUV beam to the experiments. With EUV sources, the intermediate focus (IF) is where the EUV light is focused and is defined as the illuminator entrance. One positive, albeit peculiar, property of EUV sources comes directly from this fact: both the exposure tool and its illuminator are independent of the specific characteristics of the EUV source itself. In other words, the characteristics of the EUV light at the IF do not depend on the method of generating the plasma or on its material [Bakshi 2006].

This property is very important for the HiLASE Center as it allows the coupling of the EUV source with more lasers with different kind of properties [Smrz 2017]:

- The cryogenically cooled Yb:YAG slab laser system Perla A-cryo, with 100 mJ energy in pulse, 100 Hz repetition rate and 450 ps pulse duration. With future upgrades, less than 10 picosecond duration and 1 J energy in pulse is expected.
- The so called Perla A120 laser system with 120 mJ pulse energy, 1 kHz repetition rate and 1.4 ns pulse duration, with compressor being currently assembled, targeting few ps pulse duration.
- The thin-disk laser system Perla B20 with less than 20 mJ of energy in pulse, 1 kHz repetition rate and less than 2 ps pulse duration.

All the systems work at 1030 nm wavelength. One advantage of using more laser systems is the possibility to work in more different plasma regimes and therefore having the ability to generate plasma with a wide range of characteristics.

Due to the different properties of the generated plasmas we will be able to produce EUV beams in two different wavelength ranges: 13.5 nm and in the water window range, 2.33-4.40 nm. The first wavelength is particularly suitable for EUV lithography [Bakshi 2006] and for high precision and high volume manufacturing, while the water window range is well known for its various application in biology [Wachulak 2015, Sedlmair 2012] (spanning from imaging to functionalization of materials).

There are currently two main techniques used for generation of high power EUV radiation in a small laboratory but not a large scale facility [Bakshi 2006]: Laser produced plasma (LPP) and gas discharge produced plasma (DPP). The HiLASE EUV source will be a LPP source and it is important to remark that by considering only plasma sources, the applications area is not restricted. Indeed, several materials (N_2, Xe, Sn, etc.), or a mixture of them [Bakshi 2006, Bartnik 2010, Duda 2018], can be used for plasma production. This means that there are many potential candidate target materials and consequentially the EUV source can be used for high-volume manufacturing (HVM) as well as for scientific research. It is important to note that these targets can be either liquid, gas or solid. Solid target provides most intense EUV light, but has intrinsic problem with debris production. Further, it must be put on a roto-translational stage, moving in helix, so that the laser ablates fresh areas of the target during the whole experiment. This movement creates some plasma instability, depending on the non-uniformity in the particular solid target surface ablated and/or in some discontinuity of the motion itself. Liquid targets are used together with CO_2 lasers in HVM systems, but are unsuitable for driving lasers at 1 µm wavelength due to limited absorption [Bakshi 2006]. In this work, a single stream gas-puff target has been selected. The reason for this choice is that gas target enables sufficiently high flux [Fiedorowicz 2004, Bakursky 2010, Bartnik 2010], without any instability caused by motion stage, while requiring minimum effort to align it, which is advantageous for a EUV source working with multiple driving lasers.

Plasma based EUV sources require a spectral filter in order to achieve spectral purity as plasma emits light in a wide-range spectrum, from EUV to IR. The spectral filter for LPP must be optimized according to the targeted EUV wavelength.

In order to collect and focus EUV light radiating from a plasma, a collector is used. Many types of collectors are available and new types are currently being developed [Bakshi 2006]. Among them, multilayer mirrors [Jiang 2001] are particularly promising. A multilayer mirror is a device that reflects extreme ultraviolet radiation over a specific wavelength range that is determined by the composition of the mirror layers. The mechanism which determines the wavelength selectivity is the same as dielectric mirrors in the visible range: Bragg reflection [Apfel 1982]. This acts as a spectral purity filter, which is basically an anti-reflection layer for ultraviolet (UV) radiation and its presence increases the EUV/UV-reflectivity ratio of the multilayer mirror. The spectral purity filter includes a non-diffracting graded-index anti-reflection layer able to reduce the reflectivity in the second wavelength range [Bakshi 2006]. These properties, together with a compact design, minimize vibration in vacuum and, consequentially, stability with respect to other EUV optics such as Schwarzschild objective.

2 EUV SOURCE

To obtain a monochromatic, high flux EUV radiation, the basic experimental setup, shown in Fig. 1, has been projected, constructed and implemented based on the model of LLG.

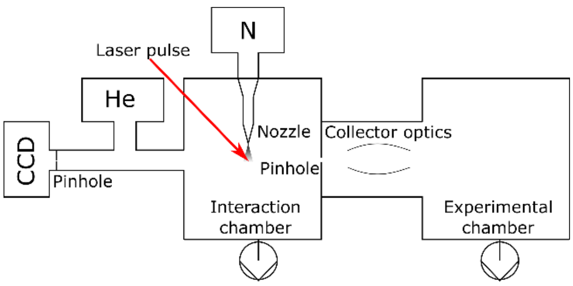

Figure 1. Experimental setup. CCD (charge coupled device) serves for plasma diagnostics. He is helium tank, N is nitrogen tank. Plasma is generated at the output of the nozzle in the interaction chamber, with He background. Experimental vacuum chamber is prepared for user experiments.

In order to analyze critical points in the system design and achieve stable plasma in the interaction chamber, with predictable EUV emission, various measurements and calculations have been conducted in collaboration with group of Dr. Mann from LLG.

The dimensional analysis of the nozzle characteristics and of the expected plasma position has been calculated by the LLG group. Two regimes were calculated: gas injected into vacuum and gas injected into He background. Scheme is presented in Fig. 2.

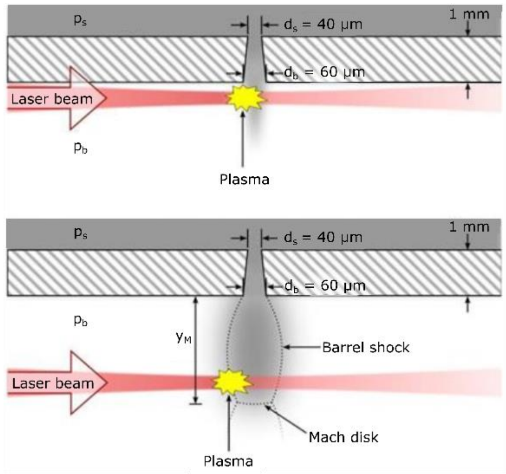

Figure 2. Model of the gas puff target in two different operation modes: N_2 gas jet in vacuum – top; N_2 gas jet with He background – bottom.

The main improvement with respect to the gas jet system used in LLG will be the use of a mixture of N_2 and Xe gases, with He as a background.

When He background is used, high gas density can be found farther from the jet. Thus, plasma can be generated at larger distance from the orifice, which will result in slower degradation of the experimental equipment. This can be seen in Fig. 2.

The idea about using gas mixture as a target is following: Xe is well known for producing the highest intensity of EUV radiation, considering a gas target, but it is also expensive. By using two gases there are two advantages: decreasing the price, compared to using Xe only, while increasing the efficiency of the source with respect to the use of one other gas (e.g. N_2). The efficiency of a mixed gas based target was already demonstrated by a top class EUV group at MUT [Fiedorowicz 2004, Bartnik 2005, Bartnik 2010]. In particular, it has been demonstrated that adding a small amount of Xe to the N_2 gas source is an efficient technique to improve plasma parameters, almost to the level obtained by using Xe alone, and thus to acquire more intense EUV beam. Downside to this technique is a loss of monochromaticity (considering water-window region), which can be compensated by spectral filtering optics.

3 SELECTION OF THE EUV COLLECTING OPTIC

The original setup at LLG was based on Schwarzschild two-mirror optics. However, in this work, ellipsoidal optics have been used to insure compactness, decrease vibrations, making the system easier to be aligned and moved while increasing EUV focus quality on target.

EUV beam conditioning requirements are: increasing flux, improving spectral purity and controlling divergence. However, it is necessary to consider that, in most of the cases, these three properties cannot be tuned independently. So, the optimization of any optical system requires the trade-off for the best application with the currently available technology.

No single optical system is capable of meeting all the requirements of every application. On the other hand, multilayer optical systems has been demonstrated [Bartnik 2006] to be a good candidate for many X-ray diffraction applications. In some cases, it is sufficient to use them alone, in other cases, combination with other optical elements (e.g. pinhole, slits or crystal optics) is required.

Beams aligned by multilayer optics are monochromatic, because the optics serves as a band-pass filter [Bakshi 2006]. The multilayer's performance can be estimated in a fairly good approximation by treating reflectivity as a function of the incident angle, otherwise known as the rocking curve. Two parameters are sufficient to characterize the performance: peak reflectivity and full width at half maximum (FWHM) of the rocking curve. A wide rocking curve is the most distinctive characteristic of a multilayer.

Different coating materials can be used for changing the rocking curve width, and the optimized rocking curve width for EUV focusing optics has been obtained by means of a gold coating, as was shown in previous experiments [Fiedorowicz 2004, Bartnik 2005, Vashenko 2006, Muller 2014].

To fulfill precise alignment and high flux requirements, and to minimize debris, non-imaging transmission ellipsoidal optics has been selected. It is important to remark that this optical system is not a focusing optics; it a point-to-point imaging so that a stigmatic image can be fulfilled. The advantage of such a system is that it offers the possibility to control the focused beam easier.

This result can be understood by deriving the shape of the meridian of the surface capable of stigmatic imaging, according to [Rosicky 2012]. Generally, this surface is described by a 4^{th} order equation; such optical element is complicated to manufacture. When the optics is ellipsoidal and in the air or vacuum, the surface equation can be reduced to the 2^{nd} order equation of ellipsis, which is easier to deal with in manufacturing process. The ellipsoidal mirror can be considered as a standalone imaging element and is similar to a positive lens.

After optimizing the mirror parameters for a plasma with a diameter of the order of 50 μm (Fig. 3), a grazing incidence mirror axisymmetrical ellipsoidal collector manufactured by Rigaku was selected. Its collection angle is 0.8 sr at grazing angles of 14.5–16.5 degrees. The reflecting surface is coated with a gold layer having a RMS roughness of 1 nm. The reflection coefficient increases monotonically from 0% to 50% in a 6–10 nm wavelength range.

This system has been chosen for the first arrangement of the HiLASE EUV table top laser-plasma source because of its high performance in terms of focalization and, consequently, capability for the system to obtain high fluence already shown in Göttingen systems as reported by [Muller 2014] and in Warsaw systems reported by [Bartnik 2011].

4 Source performance

To test the performance of the EUV source, its stability and the applicability of the HiLASE lasers, Perla B20 laser system was used for the first measurements and considerations. The laser was operated at pulse energies between 5 mJ and 12 mJ, with 2 ps pulse duration and 1 kHz repetition rate.

To obtain a stable, easily detectable plasma, the pressure in the source chamber should be as high as possible. Maximum pressure of the target gas allowed by the gas bottle of 70 bar, was used. An example of the resulting plasma, is visualized in Fig. 3.

After experimenting and changing various laser parameters, considering the plasma stability during these measurements, we arrived at several conclusions.

Using frequency as high as 1 kHz does not seems to degrade the plasma quality and stability. This was not previously tested, as the sources in LLG and MUT typically use 10 Hz to 100 Hz Nd:YAG lasers with ns pulse duration. High repetition rate used in our experiments did not allow for pulsed operation of the gas jet.

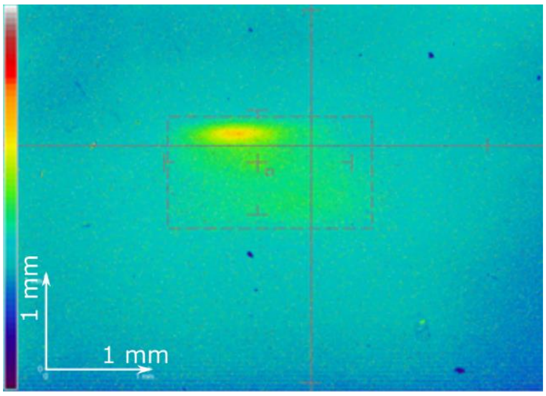

Figure 3. Image of a plasma acquired at 70 bar pressure, 11 mJ energy in pulse, 30 s exposure time, averaging 10 times, without any spectral filter.

It was found, that using a continuous gas jet does not induce gas turbulence, even under high pressure of 70 bar, and the plasma is sufficiently bright. However, the continuous operation of gas jet causes the working gas to accumulate in the interaction chamber, as the scroll pump has only limited throughput. Thus the absorption of the EUV radiation increases and the overall efficiency is somewhat lowered.

Shorter pulse durations, in the order of few picoseconds, allow for much higher intensity at the target. With spot size approximately 30 μm, we reached intensity in the order of 10^{15} W/cm^2. Small spot size and resulting small source size is advantageous for spectroscopic measurements. However, intensity has to be increased further, which will be done in the future by increasing pulse energy, or even by changing the driving laser. Intensity can be also increased by tighter focusing, when the beam size is expanded before focusing optics to obtain smaller spot size. This will increase the photon energy, but the number of available photons will be limited because of source size being too small. Thus, increasing driving laser energy is preferred. Another advantage of ps laser pulses is higher conversion efficiency and, when using broadband sources, shifting the peak value of spectral intensity towards shorter wavelengths.

For practical reasons such as safety and increased stability, the nitrogen should be backed by lower pressure, approximately 35 bars. When the pressure is lowered, the driving laser energy has to be increased proportionally, at least doubled to obtain required plasma parameters.

Overall, the experiment with the Perla B20 laser system was beneficial for deciding on the next steps and helped with formulating driving laser parameters needed for targeted applications.

5 Conclusion

For water window imaging with nitrogen gas puff target and narrowband radiation, sub-2 ps laser pulse with at least 50 mJ energy is required to sufficiently heat up the plasma. Similar parameters are needed for NEXAFS spectroscopy using krypton gas as broadband water window radiation source. For this purpose, Perla A120 laser will be used in the future, when the work on the compressor is finished.

In water window spectral region, there is another very promising application: polymer ablation. Ablation of polymers was already investigated in the 11 nm and 13.5 nm EUV range, but the phenomenon is not yet fully understood. Studying polymer ablation in new spectral region, which will be allowed by our new high-brightness source, could help to explain the process and improve the quality and quantity of possible applications of laser-processed polymers.

For EUV lithography, the preferable wavelength is 13.5 nm generated with nitrogen gas mixed with xenon. Since the wavelength is longer, the driving laser pulses can be longer. However, to generate sufficiently hot and dense plasma, energy in pulse has to be increased. This will be allowed by the Perla A-cryo laser system.

In conclusion, we have researched current compact EUV sources used around the world and we combined various ideas into our own source. We have found the dependencies of plasma parameters on driving laser parameters, and we have verified, that laser with high repetition rate and pulse with picosecond duration can improve the efficiency and brightness of the EUV source in two distinct wavelength ranges, while not making the stability of the source worse. Multiple HiLASE driving lasers, which are already built or are in a development stage, can be used to create table-top EUV source with different plasma characteristic and particular driving laser can be chosen based on desired application.

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