3.3 XUV Interferometry using X-ray Lasers

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XUV interferometry is a unique tool for accurate metrology based on phase modification. X-ray lasers are very bright and short-duration sources that give opportunity to make interferometry of fast-evolving phenomena, such as dense plasmas or surface deformations due to external fields. In particular, picosecond resolution has been obtained by using transient collisional X-ray lasers produced by CPA infrared lasers.

Keywords: X-ray laser, XUV interferometry, grazing incidence and multilayer optics, nanoscale diagnostics, high-density plasmas, surfaces under high electric field.

1. Introduction

After the first demonstration of X-ray laser (XRL) feasibility in 1984 [1], a major question was, besides lowering of the pumping energy and improvement their optical properties, the development of XRL applications. Indeed, creation and studies of XRLs needed large scale pumping devices; demonstration of the practical interest of these bright and brief soft X-ray sources was then necessary to justify persistent efforts devoted to XRLs progress. From this point of view, interferometry takes a special place because interference patterns can be decoded to give complete information on the electromagnetic wave that caused them, including phase as well as intensity. Moreover, XUV interferometry gives more accurate information than similar technique in the visible and near UV range:

- Spatial resolution: the phase difference φ is related to the path difference δ and the wavelength λ by the relation $\varphi = \delta\ /\ ;\lambda$then, resolution may be up to 20 times better at $\lambda = 20$ nm than with the third or fourth harmonics of infrared lasers, which was typically used for interferometric diagnostics [2,3].
- Higher electron - density range in plasmas: XUV probe beams are less refracted and less absorbed by inverse Bremsstrahlung than conventional optical beams and give access to higher density regimes; the critical density region of Nd-glass laser-produced plasmas (10^{21} – 10^{22} cm^{-3}) may be investigated by XUV interferometry, which is not possible with the 4th harmonics of Nd-glass lasers.
- No interaction with probed surfaces under grazing incidence: the electromagnetic field of optical lasers is able to produce parasitic field emission from metallic surfaces under high electric field. That is not the case for XRLs, because refraction index is smaller than 1 in the XUV range; then, the probe beam under grazing incidence is totally reflected by the surface and does not interact with the probed medium.

Brightness of the most of X-ray lasers is large enough for recording interference patterns in single-shot exposures. Then temporal resolution may be as short as the XRL pulse duration. Temporal resolution reaches the picosecond range in the case of the so-called "transient collisional XRLs", driven by ~ one ps-pulse in a plasma previously produced by nanosecond pulse, [4, 5].

2. Techniques of XUV interferometry.

Interference patterns are produced by combination of two mutually coherent waves, one being used as a reference whereas the other may be perturbed by a sample. Both waves come generally from the division of a

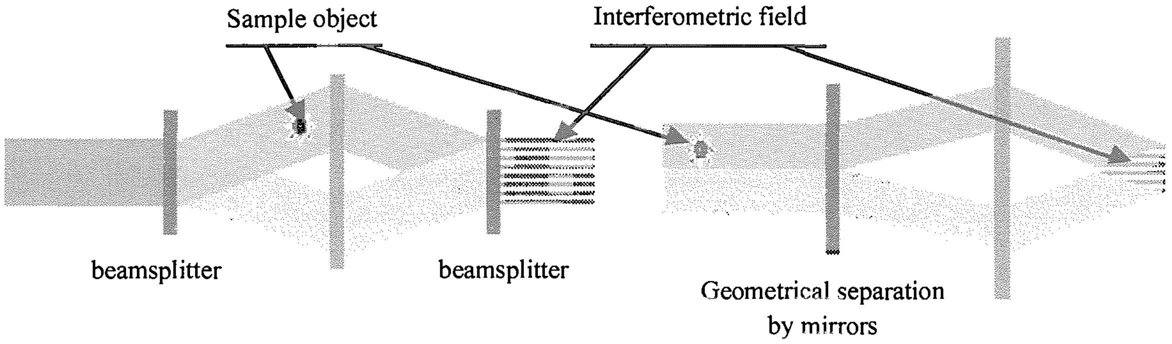


***Figure 1** : Schematic of interferometry by amplitude division (left) and wavefront division (right).*

single one, which ensures their mutual coherence. As shown in figure 1, one can produce the two waves either by amplitude division (left) or wavefront division (right).

The need of beam splitters available in the XUV range is a major difficulty of amplitude division. Mo:Si multilayer mirrors can be routinely fabricated with high reflectivity, especially in the wavelength range around 13 nm. However, multilayers for beam splitters must be deposited on very thin membranes, typically less than 100 nm, for preventing large absorption of transmitted light (cf. Fig. 2, left part). The most difficult question is to keep the multilayer uniformly plane, i.e., to avoid stress during deposition process, in order that beam splitters do not introduce wavefront deformations. In addition, such structures are very fragile, and their lifetime is short, in particular when hot plasma is produced in one arm of the interferometer. In spite of complications due to multilayer beam-splitters, a skewed Mach-Zehnder interferometer (shaped as a parallelogram instead of a rectangle) has been realised at the Lawrence Livermore National Laboratory (LLNL) [6]. It was operating at 15.5 nm by using collisionally pumped neon-like yttrium XRL as the probe source. Recently, a Michelson interferometer operating at 13.9 nm has been designed by LIXAM and Laboratoire Charles Fabry (LCFIO) [7].

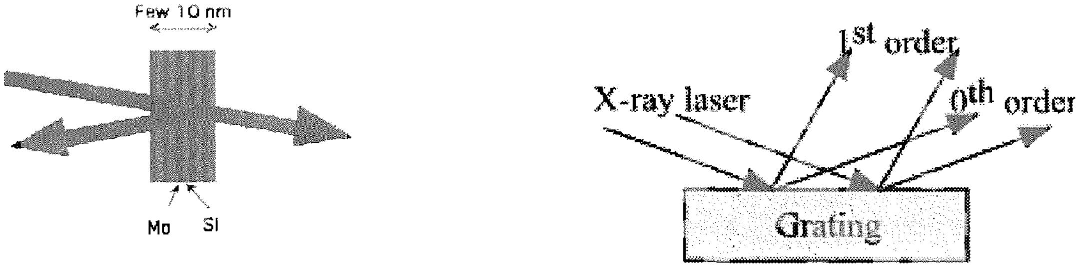


***Figure 2**: Amplitude division techniques. Multilayer beam splitter (left), diffraction grating (right)*

An alternative way for amplitude division is the use of diffraction gratings: two different diffraction orders follow two different ways, which constitutes amplitude division of the XRL beam (Fig.2, right). This scheme requires only to design properly the ruling and blaze angle of gratings, in order to privilege two orders of interference, namely the zero and the first order. Rocca and his colleagues at Colorado State University have built a Mach-Zehnder interferometer based on gratings under grazing incidence [8]. One can also conceive similar interferometer based on transmission gratings; however a first attempt by the group of Queen's University of Belfast at the Rutherford Appleton Laboratory has not been successful yet [9].

Wavefront division technique is more versatile because it is independent on wavelength owing to mirrors under grazing incidence. On the other hand, it is based on spatial coherence. Intrinsic spatial coherence width of XRLs at the plasma edge is generally very small, in the range of a few micrometers; spatial coherence is built in the propagation of XRL beam. At about 3 meters from the emitting plasma, coherence width is large of 0.5 to 1 mm. This limits sample size that can be probed by wavefront division interferometry. Fortunately, XRLs are bright

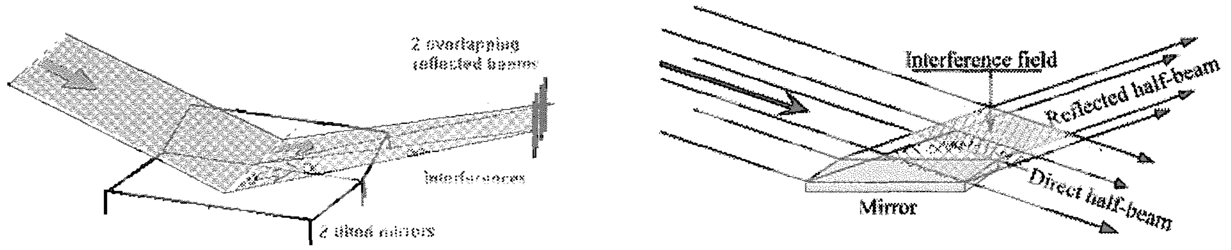


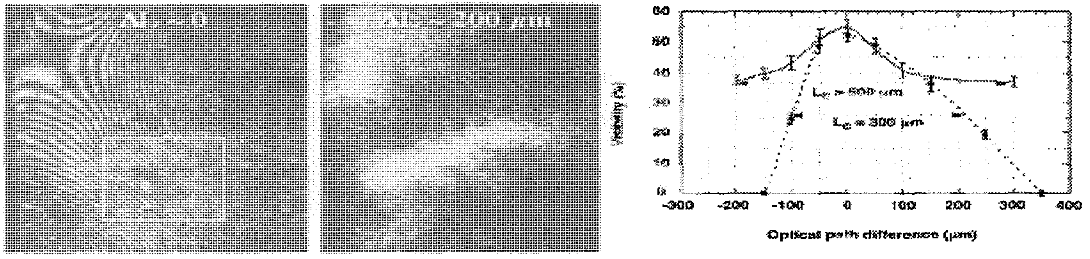
Figure 3 : interferometry under grazing incidence. Fresnel (left) and Lloyd (right).

enough to give a large intensity at such distance in order to record interferograms in single shots. Fig. 3 shows schematically both Fresnel [10,11] and Lloyd [4] systems used for wavefront division interferometry with XRLs.

3. Science with X-ray lasers and XUV interferometers.

XUV interferometry with XRLs has been used until now for probing (i) XRLs themselves from fringe contrast measurements, (ii) dense plasmas and (iii) surfaces perturbed by high electric field.

One can evaluate the coherence width of a beam from fringe visibility by using wave front division interferometers. At LIXAM, we have measured also the line width and the coherence length (temporal coherence) of a Ni-like silver laser with a Michelson interferometer. Figure 4 gives an example of two interference patterns corresponding to two similar XRL beams for an optical path difference of ~ 0 (a) and 200 μm (b). Coherence length is determined from variations of fringe visibility in function of the path difference (c). One can see that the beam-splitter foil is not flat, and only a small part of the beam can be used for interferometric measurements; on the other hand, coherence is not constant over the entire beam.



(a) (b) (c)

Figure 4 : Coherence length measurement of a Ni-like silver XRL driven by a 130 ps laser pulse. Interference patterns for equal paths of the two arms of the Michelson (a) and for 200-μm-path difference (b). (c) Fringe visibility versus path difference; one can deduce the coherence length, which varies with position in the beam.

Dense plasma probing has been the first application considered for XUV interferometry, in conjunction with imaging systems, resulting in XUV microholography. With the LLNL interferometer at 15.5 nm, density of 2 10^{21} cm^{-3} has been detected at 25 μm from the initial target surface [6]. The Rocca's group has probed capillary discharge plasmas [12] and exploding wires plasmas [13] by using the Ne-like argon laser at 46.9 nm produced in capillary discharge plasmas. With a Ni-like Pd laser at 14.7 nm driven by the COMET laser, they realised picosecond interferometry [14]. The probed densities are in the range of a few 10^{20} cm^{-3}, which is much lower than the limit density due to refraction. This is due to geometrical aberration of the optical device and/or large pixel size on the detector, which can reduce drastically the resolution of the imaging system. Aberration-free imaging mirrors, realised with ion-etching technique, are now able to improve resolution up to the diffraction limit [15].

Plasma probing is far from the only application of XUV interferometry. In collaboration with the LCFIO and the CEA-DSM, we have developed at LIXAM a Fresnel interferometer aimed to probe optically polished surface [11]: one half of the surface is used as reference while the other may introduce phase difference. Both half-beams are then recombined in the interference field. We have applied this technique to niobium surfaces under high electric field, analogous to surfaces of superconductive accelerating cavities of future particle accelerators [16]. Field emission and other electric perturbations may heat the surface, which does not remain superconductive. That limits the useable electric field under the nominal value. In situ probing by XUV interferometry should be able to give a better understanding of deleterious phenomena and to find solutions to increase the field up to its nominal value. The left part of Fig. 5 shows the experimental device used recently at PALS [17. The E-field is peaked on one half of the niobium cathode. The right part shows two patterns recorded for 0- and 50 MV/m and the relative surface maps. The cathode surface is bent in the direction parallel to the field lines, with a peak-to-valley gap of 30 nm.

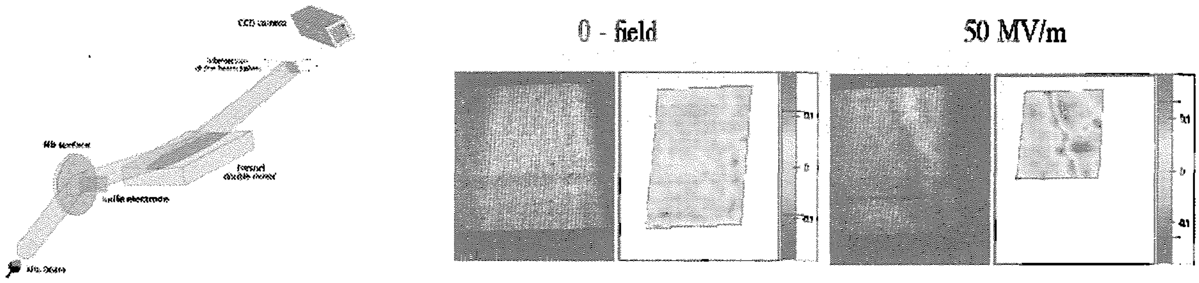


Figure 5: *interferometry of an optically polished niobium surface (see text).*

4. Conclusion.

XUV interferometry using XRLs is a very promising technique to probe not only plasmas and surfaces, but also gases and thin samples under various conditions. A small amount of results has been recorded presently owing to the too few XRL facilities available. Most of these experiments have been made on giant high-power lasers such as NOVA, RAL, GEKKO XII, LULI, and PALS, which cannot give enough XRL shots to perform complete analysis. New small size or tabletop machines, purely devoted to XRL studies and applications, will give opportunity to make comprehensive studies and not only feasibility tests. Capillary discharge at Colorado State University as well as CPA XRL facilities at LLNL and APR are now able to make complete studies by XUV interferometry. In France, we are making "LASERIX", a high repetition rate CPA facility purely devoted to XRL progress and development of applications. LASERIX will deliver up to six XRL shots per minute in a wavelength range comprised between 10 and 40 nm.

References

[1] D. Matthews et al., Phys. Rev. Lett. **54** (1985)110-113
[2] D.T. Atwood et al, Phys. Rev. Lett. **40** (1978) 184
[3] B. Rus et al., Phys. Rev. A **56** (1997) 4229
[4] B. Rus et al, in X-ray Lasers 2002, edited by J.J. Rocca et al, AIP (2002) p. 522
[5] R.F. Smith et al, Phys. Rev. Lett. **89** (2002) 065004
[6] L.B. Da Silva et al., Phys. Rev. Lett. **74** (1995) 3991-3994
[7] S. Hubert et al, J. de Physique. IV **82** (2001) 515
[8] J. Filevich et al., Optics Lett. **25** (2000) 356
[9] S. Topping et al., Central Laser Facility Report 2001/2002, p. 53
[10] F. Polack et al, Rev. Sci. Inst., **66** (1995) 2180
[11] F. Albert et al, Optics Commun. **142** (1997) 184
[12] J.J. Rocca et al., Proceedings of the SPIE **4065** (2000) 173
[13] J. Jankowska et al., in X-ray Lasers 2002, edited by J.J. Rocca et al, AIP (2002) p. 498
[14] J. Dunn et al., in X-ray Lasers 2002, edited by J.J. Rocca et al, AIP (2002) p. 484
[15] R. Mercier et al., Rev. Sci. Instrum. **72** (2001) 1559
[16] Ph. Zeitoun et al., Nucl Instrum and Methods A, **416** (1998) 189
[17] T. Mocek et al., in X-ray Lasers 2002, edited by J.J. Rocca et al, AIP (2002) p.