11 Collimated and Ultrafast X-Ray Beams from Laser–Plasma Interactions

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Summary. We show that different schemes can be now followed to produce collimated X-ray radiation using laser systems. By focusing intense femtosecond laser light onto a gas jet, electrons of the plasma can be manipulated to generate ultrafast (femtosecond) X-ray radiation in the forward direction along the laser axis. In this chapter we discuss nonlinear Thomson scattering, betatron emission and Compton scattering. In years to come, the rapid development of laser technology will provide more intense laser systems. We can expect to see the creation of bright X-ray beams with a high degree of collimation (<1 mrad divergence), as well as even shorter pulse durations, down to attosecond time scales. Such sources will provide multidisciplinary scientific communities with unique tools to probe and excite matter.

11.1 Introduction

Aside from the first instant of the interaction of the laser with the matter, the X-ray radiation self-emitted from laser-produced plasmas provides an efficient diagnostic of processes that occur within such plasmas. Over the past ten years, the advent of short-duration laser systems and the progress made in the development of short-pulse X-ray sources have led to such systems being applied to multidisciplinary fields in order to probe matter.

Today, there is a strong need for increasingly short X-ray pulses that can be used to obtain ultrafast snapshots of the evolution of matter [1–4] and to study new states of matter that arise under intense X-ray irradiation. This has opened new areas of research and resulted in tremendous applications in various areas of science, including condensed matter physics, plasma physics, chemistry, biology, and engineering. Laser–plasma sources (atomic line emission) and accelerator-based technologies can now provide X-ray pulses of durations down to 100 fs, and a number of workshops, conferences and summer schools have been organized on these topics [5–9]. X-Ray Free-Electron Lasers (XFEL) at DESY (Hamburg, Germany) [1] and LCLS (Stanford, USA) [2], both of which will be capable of delivering short-pulse X-rays, are currently under development. In Japan, the Japan Science and Technology Agency has selected the field of ultrafast transitions as a priority program in condensed matter physics, and this program started in April 2004.
Laser-based X-ray sources have played a significant role in previous research in this field ever since the pioneering experiments conducted in 1997 using this technique [10]. This initial work was followed by extended experiments [11–17]. On the other hand, accelerator-based approaches have more recently provided the first results at the femtosecond time scale [18]. Despite this, their compactness and relatively inexpensive infrastructures as well as their perfect synchronization down to the femtosecond timescale with the process under study represent key advantages of the laser-based schemes.

However, their relatively small X-ray flux and/or spectral bandwidth severely hinders the efficient and broad experimental application of existing X-ray sources. In particular, few schemes that convert femtosecond visible laser light to femtosecond X-rays have been demonstrated. The principles of these sources were established more than ten years ago. Among them, the K\(\alpha\) X-ray source relies on inner shell electronic relaxation following excitation by electrons accelerated at moderate energies (a few tens of keV) during a laser–plasma experiment [19,20]. Its principle is analogous to the standard “X-ray tube”, with the difference that the duration of the electron bunch occurs on the femtosecond timescale thanks to the short duration of the laser pulse compared to thermionic emission (which occurs in the tube). This type of radiation has already shown its potential by enabling the first experiments in ultrafast X-ray science to be performed [10].

However, there are some important points that should be made about this existing source. First, the X-ray flux available for ultrafast experiments is severely limited due to the full divergence of the X-ray radiation [4]. This prevents the efficient development of applications. Second, the X-ray flux cannot be scaled-up due to the physics of the laser–matter interaction. Finally, the source is highly monochromatic and fairly tunable, which prevents any X-ray absorption applications.

Novel laser-based strategies must therefore be created to address these bottlenecks. The goal is to produce beams of X-ray radiation similar to the ones available at synchrotrons or the beams that the free-electron lasers will provide, but with the additional unique properties of the laser pulses being ultrafast (femtosecond time scale), and the laser system being more compact and cheaper in order to ensure high dissemination among the scientific community. In this article we will present three X-ray sources arising from the manipulation of electrons in laser-produced plasma electrostatic fields and in laser fields: nonlinear Thomson scattering, betatron radiation, and Compton scattering.

### 11.2 X-Rays from Nonlinear Thomson Scattering

#### 11.2.1 Brief History

Among several schemes used to produce femtosecond or subfemtosecond pulses in the X-ray region (Fourier synthesis, the use of two short perpendicularly polarized pulses, high-order harmonics from a nonlinear medium