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Generation and Application of X−ray Pulses on a Terawatt Laser System

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Abstract. Currently, the Kurchatov Laser−Synchrotron Complex is conducting research on the interaction of powerful femtosecond laser radiation with matter. The purpose of these studies is to develop new techniques and approaches for the characterization of high−temperature plasma, X−rays and particle acceleration, which can be the basis for the work planned within the framework of the synchrotron−neutron project. Laser−driven X−ray production, electron acceleration, nuclear fusion, ultrafast structural dynamics of nanoparticles in intense laser fields remains an active research topic, aimed at generating advanced controllable sources.

1. Introduction

The main directions are the development and creation on the basis of existing and planned Russian synchrotron sources of modern materials science stations capable of working on fundamental and applied studies of matter with femtosecond, and in the future with attosecond time resolution, according to the "pump–probe" scheme with femtosecond laser pumping and X−ray probing. For time−resolved studies of a non−stationary state of matter X−ray pulses of femto− and atto−second duration are requested.

Instant X−ray photography helps to avoid diffraction pattern blur due to movement/ rotation of (bio) molecules.

Such pulses can be obtained by converting a high−power laser radiation; the part laser radiation can simultaneously create a non−stationary, extreme state of matter. This enables pump−probe X−ray study with fs temporal resolution. Using a 200 TW laser system, we are developing several approaches for femto− and picosecond X−ray studies at the Laser−Synchrotron Complex at the NRC "Kurchatov Institute".

Our activity in laser−plasma hard x−ray generation and particle acceleration includes: femtosecond laser system and infrastructure [1], electron acceleration in clusters with super intense chirped fs pulses [2], X−ray generation from remote atmospheric laser filament [3], broadband X−ray generation in clusters with relativistic fs laser pulses [4], efficient ultrashort X−rays production by fs laser in vacuum free regime [5]. We use three approaches to obtain X−ray pulses for time−resolved studies:

2. Results

2.1. Laser−plasma hard X−ray source

The first approach is the generation of laser−plasma induced characteristic X−ray radiation. This generation occurs due to three processes (see Fig. 1): 1− tunneling ionization by strong laser field, 2− acceleration of electrons on time scale of the optical cycle and 3−phase−dependent re−entrance into the target [6].

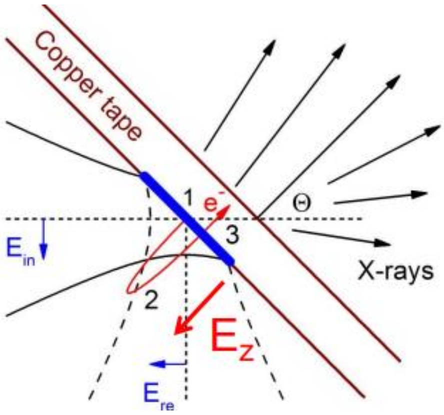

Fig. 1. Scheme of laser−plasma generation of X−ray radiation [6].

With high enough intensity of laser radiation, K−alpha photons (6−8 keV depending on the metal) are generated on the metal surface, with a duration of 50−500 fs, determined by the laser pulse and the target thickness. Among other things, we were able to obtain remote generation of X−rays using the delivery of laser radiation in the form of a filament, despite the relatively low intensity of the laser field in this case [3].

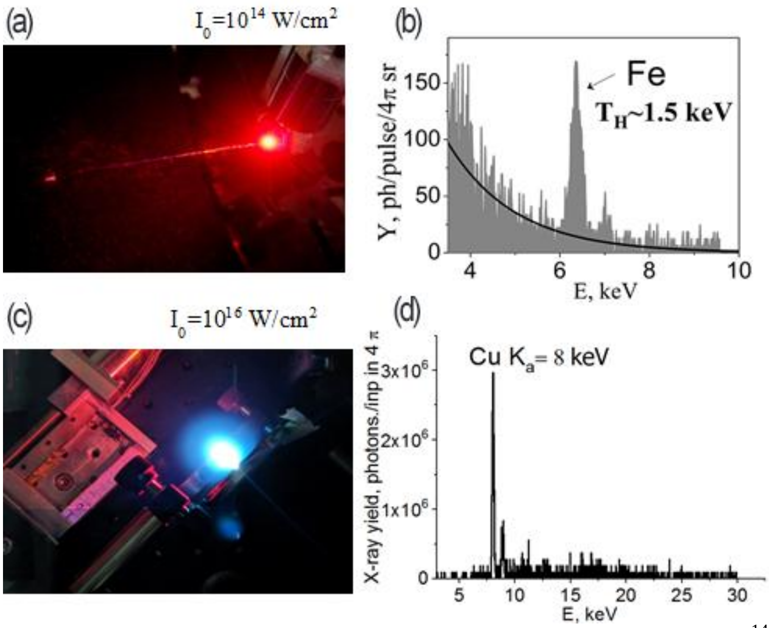

Fig. 2. Photo of a torch on a target when exposed to low (a) and high (c) laser intensities 10^{14} and 10^{16} W/cm^2 accordingly. X−ray spectrum for low (b) and high (d) laser intensities.

By optimizing the energy and duration of the laser pulse, the focusing geometry, the pressure of the surrounding gas, we obtain sufficient brightness of this type of X−ray radiation for diffractometry. The dependence of the output of the K_α line on the intensity is shown, for example, Fig. 3, in our range of intensities, the X−ray output grows with an intensity approximately as I^2.

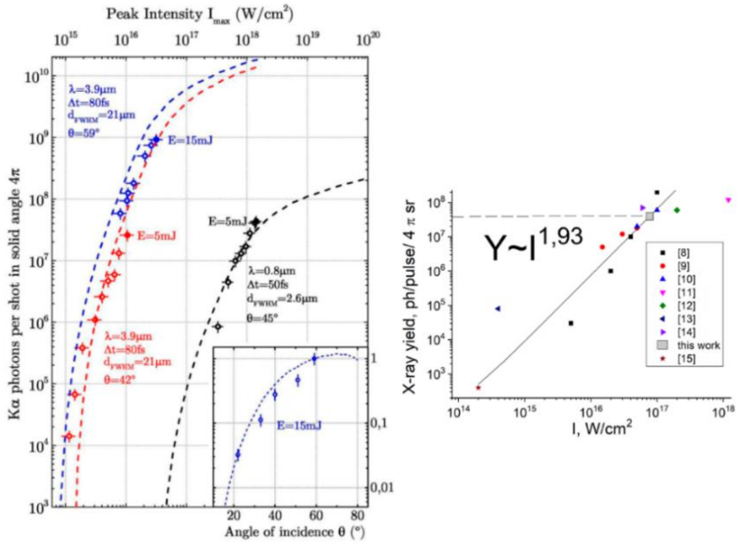

Fig. 3. Generated X−ray Kα flux as a function of the laser−peak intensity. a) Comparison of experiment (symbols) with theory (dashed lines) for a 20 μm thick Cu band illuminated under different angles of incidence. For the mid−infrared (blue circles, λ = 3.9 μm, Δt = 80 fs, θ = 59°; red triangles, same parameters but θ = 42°) and near−infrared pulses (black circles, λ = 0.8 μm, Δt = 50 fs, θ = 45°) [7]. b) Data from refs [8–15] obtained under vacuum conditions and our data in data in He atmosphere [16].

On Fig. 3 the benefit on using long wavelength radiation in also demonstrated. X−ray yield is higher for mid−infrared laser source. In a helium and air atmosphere, the main limitation for the X−ray yield is ionization and the associated losses of energy and focusing sharpness [5,16].

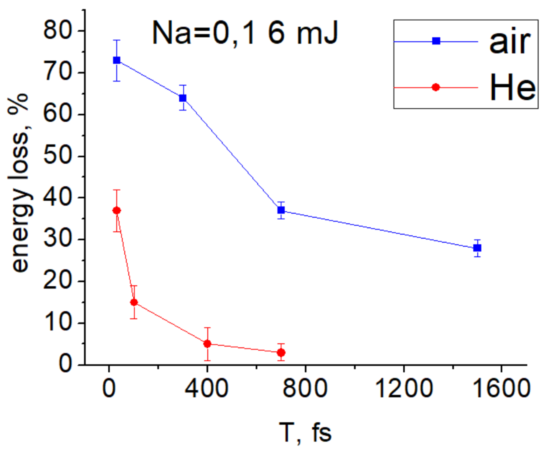

Fig. 4. Loss of energy transmitted through the waist of a focused (NA = 0.1) beam as a function of the duration of a laser pulse for two gases − air and helium. Incoming pulse energy 6 mJ [5].

This loss can be reduced by increasing the pulse width at constant energy. In this case, the intensity decreases, the power density is maintained (taking into account the decrease in losses, it even increases), as a result, it is possible to increase the X−ray yield, since for it the power density is more important than the intensity.

For pump−probe experiments, X−rays are refocused onto the sample with a specially developed polycapillary lens. However, such X−ray radiation is non−directional and incoherent. For additional information about the processes occurring at the target surface, along with X−rays, we register the spectra of the visible range.

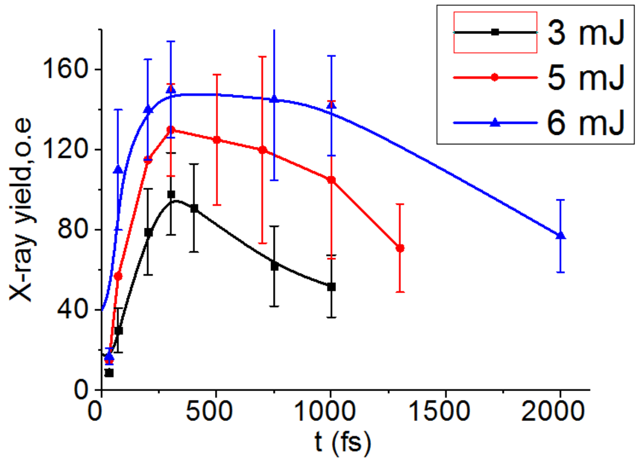

Fig. 5. X−ray output versus laser pulse duration for a helium atmosphere [5].

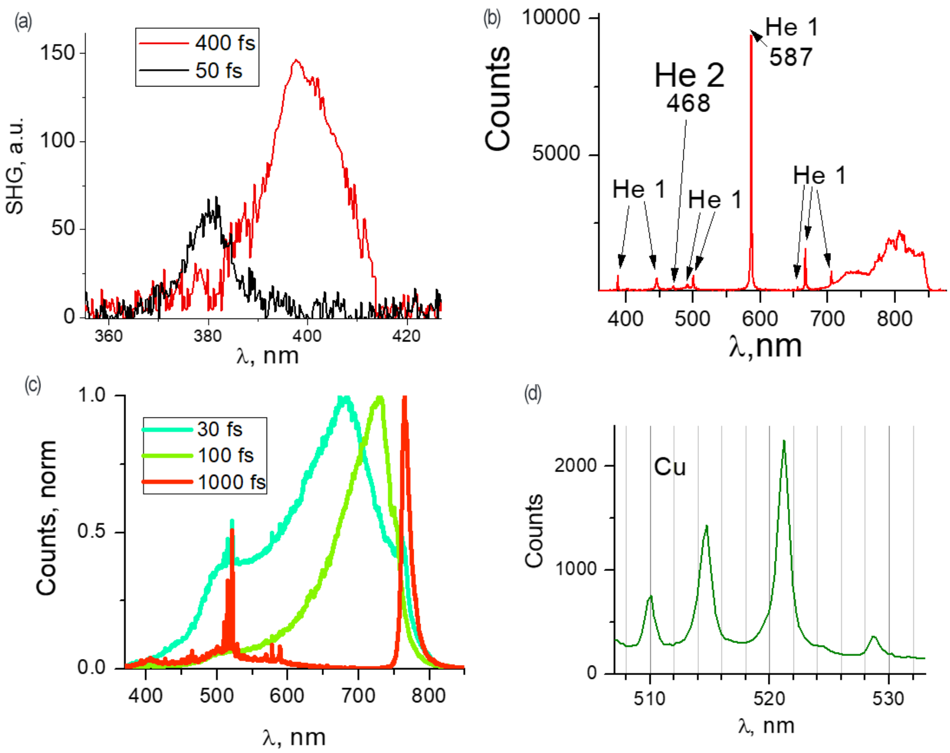

Fig. 6. Spectra of the second harmonic (a) and pumping (b) at different pulse durations. (c) LIBS lines of helium in the absence of a target and 30 fs pumping (the absence of nitrogen lines (air)), (d) LIBS lines of a copper target.

From these spectra can be seen: Fig. 6 (a) the intensity on the target surface − by the magnitude of the second harmonic; (b) Gas composition near the surface (absence of air, predominance of helium, second degree of ionization); (c) supercontinuum generation (in an ionized gas); (d) Composition of the target (LIBS of the copper line) and the intensity on it (the relative magnitude of these lines).

2.2. High optical harmonics generation

The second approach makes it possible to obtain directional and coherent soft X−ray radiation of significantly shorter duration. The approach is based on the generation of a train of high optical harmonics from a laser pulse of relativistic intensity in a gas jet or upon ablation of the target surface. For Ti:Sa laser radiation and solid–state targets, it is now possible to broaden the spectrum of such radiation to wavelengths less than 10 nm.

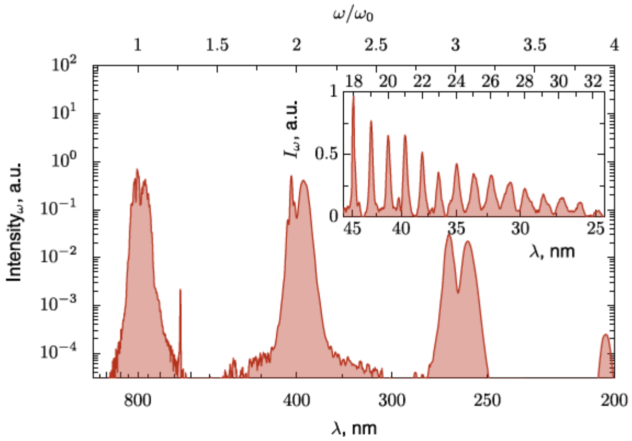

Fig. 7. Experimentally measured spectral intensity of light reflected from a plasma mirror for a 25–fs driving pulse at 5×10^{19} W/cm^2. Inset, relativistic extreme ultraviolet harmonic spectrum [17].

Again, the process of generating high–order harmonics is more efficient for radiation at long wavelengths [18]. After spectral filtering, such pulses can reach attosecond duration. In this case, the spectrum extends from the visible range to hundreds of eV.

2.3. Synchronization with the synchrotron source

In the third approach the laser oscillator is carefully synchronized to the repetition rate of synchrotron bunches, amplified laser pulses give a giant energy input into the sample under study, the induced changes in the structure are observed by diffraction of synchrotron, bright and collimated probe radiation, with a time resolution of 100 ps. The delay between laser and synchrotron pulses is scanned.

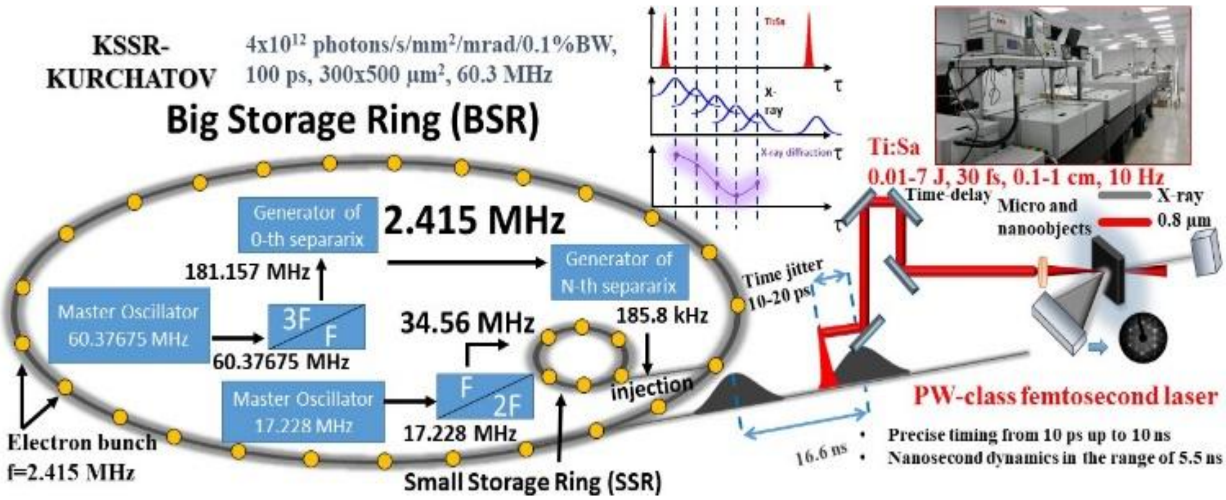

Fig. 8. Synchronization of different systems of Synchrotron Radiation Source in Kurchatov National Research Center (NRC) [1].

The operation of an SR source with electron bunches is characterized by various methods for determining separatrices. The frequency multiplicity of radio–frequency resonators to the electron revolution frequency in the BSR is 75 (the so–called harmonic number). Thus, there are wide possibilities for creating chains of bunches: with a uniform distribution of bunches over the ring in an amount (1, 3, 5, 15, 25, 75); with asymmetric and uneven distribution of bunches over separatrices (including with empty separatrices between two sequences).

In our case, to work with the laser synchronization circuit at its standard frequency of 60.3 MHz, we have a deal with the asymmetrical filling of 25 bunches around the big ring, achieving the maximum amplitude of the electron current spectrum at the 25−th harmonic of the revolution frequency, i.e., 2.41507*25 = 60.37675 MHz [1]. Optimization of the synchronization circuit requires obtaining the narrowest amplitude−frequency characteristics of electron current near the operating harmonic − in our case, the 25th harmonic of the revolution frequency. It requires additional efforts to obtain a uniform electron filling of every third separatrix while avoiding “spurious” charges in the “empty” separatrices.

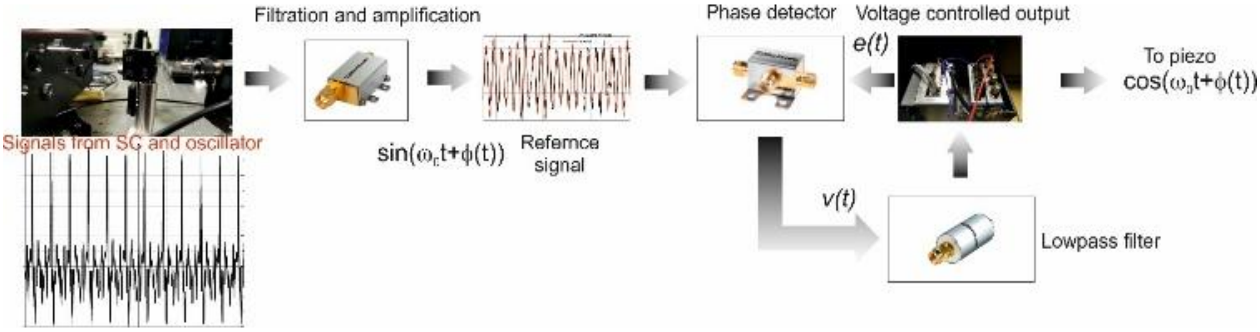

Fig. 9. Block diagram of phase locked loop (PLL) system implemented inside the Kurchatov National Research Center (NRC) [1].

3. Conclusions

Finally, advantages and disadvantages on laser−plasma X−rays from giga− and tera−watt femtosecond laser pulses are compared with the prospects of the high harmonics and synchrotron methods being developed – Table 1.

Table 1. Comparison of three types of pulsed X−ray sources

	Duration	Range, keV	Brightness	Directivity
Generation of characteristic X−rays	−100 fs	4−17	+/−	−
Generation of high harmonics and coherent X−rays	−500 ac	0.01−0.1	−	+
Synchronization with synchrotron source	−100 ps	0 – 100	+	+

In experiments in forevacuum (0.2 mbar), focusing NA = 0.12, energy 50 mJ, 30 fs laser pulse on metal targets [19], an intensity of $0.5*10^{17}$ W/cm^2 and a flux of X−ray radiation of $0.5*10^8$ photon/(steradian*sec).

An out−of−vacuum approach is proposed for efficient laser generation of X−ray radiation, which consists in a combination of the process of blowing helium, which has a high ionization potential and allows minimizing the number of induced electrons, and the stretching (chirping) mode of laser pulses to optimize the delivery of energy to the region of interaction of laser radiation with matter. With a laser energy of 6 mJ and a pulse duration of 300−500 fs, the X−ray output reaches a maximum of $2.5*10^7$ photons/pulse at 2π steradian, which meets the requirements for the required flux from the source for applications. It is a new regime of generation of intense, femtosecond X−ray pulses.

Using bright line X−ray source, the diffraction experiments with Si target have been performed. We apply the scheme to highlight a high−contrast copper line in the broadband X−ray spectrum using crystalline silicon (111). The diffracted X−ray at the sample situated at Bragg angle is recorded with high (100:1) contrast respect to background.

For applications with shorter (<5 fs) X−ray pulses, it is more promising to use the method of generating high optical harmonics. For studies on ps and more time scales — radiation from a synchrotron source together with laser pulses.

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