APPLICATION OF LOW-ENERGY, TUNABLE-DELAY ULTRASHORT ELECTRON BUNCH PAIRS FOR IRRADIATION EXPERIMENTS*

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Abstract

On AREAL RF photogun Linac at CANDLE, pairs of time-delayed ultrashort electron bunches are generated by means of temporal shaping of the laser pulses driving the photocathode. The free-space interferometric delay line method used for the laser pulse shaping provides the means for tailoring the beam characteristics such as the charge contrast and relative delay of the bunch pairs in the train. In this paper, the details on generation and characterization of temporally modulated beams are presented along with the description of the set of available control parameters for various applications. The preliminary results of studies of the effects of high-dose rate irradiation on structural and optical properties of transparent thin films and glasses are presented.

INTRODUCTION

Along with a number of key technology applications such as FEL, time-resolved microscopy and advanced acceleration concepts, ultrashort electron beams represent a growing interest as a high-dose rate irradiation tool in clinical radiotherapy, biological and materials research. In a number of experiments including those carried out on AREAL facility, specific radiobiological [1-3] and material modification [4] effects were observed under the electron irradiation with bunches of sub-picosecond duration. This is comparable to or less than the duration of physicochemical reactions of the charged and excited particles in an irradiated medium. One may expect, therefore, that the effects will depend on both duration and the temporal shape of the bunches. The latter may have an especially important role when the induced modifications in the irradiated matter proceed via multi-step excitation and relaxation processes.

The temporal profile of ultrashort electron bunches produced on photogun Linacs can be shaped directly by controlling the optical waveform of the driving laser pulses. A relatively simple method of such shaping is the passive pulse-stacking technique which is based on polarization-selective splitting of pulses and can be implemented either using a set of birefringent crystals [5] or an interferometric delay line (DL) [6]. The DL-based method provides more parametric flexibility and was therefore preferred and implemented on AREAL facility to provide an additional control parameter for irradiation experiments.

Temporally shaped e-bunches will be exploited along with the regular ultrashort-bunches in an ongoing experimental study of irradiation-induced modifications of structural and optical properties of semiconductor CdS films and coatings, which represent a large interest from the point of view of their photo-voltaic, integrated optics, electro-optics and many other applications. In this contribution, we report on the generation, characterization and application of time-separated ultrashort double-bunch beams. The setups and approaches for generation of temporally-shaped e-bunches, along with the main characteristics of the beam and the ranges of variable parameters will be described. Preliminary results of application in irradiation experiments will be presented and discussed.

EXPERIMENTS AND RESULTS

The main characteristics of the AREAL photogun Linac and its laser and electron beam parameters can be found in [1]. The schematic layout of the facility for the current irradiation experiments is presented in Fig. 1. The photoinjector laser (A) provides a train of amplified infrared (IR) pulses which can be split into a pair of pulses with variable time-offset using an interferometric delay line (DL) installed on the IR output (B). The stack of pulses is subsequently converted to UV (258 nm) by the fourth harmonic generation module (FHG) and either directed to the photocathode of the Linac (C) for generation of temporally-shaped e-bunches, or used directly for UV-irradiation experiments.

Laser Pulse Stacking Setup

The optical setup for double-pulse generation (DL in Fig. 1 B) is implemented using a set of mirrors (M) and thin-film polarization beam splitters (BS) with rotating quarter- and half-wave plates (λ/4 and λ/2) which are used for balancing the energy between the split pulses with different (*s*- and *p*-) polarizations. The time-separation between the split pulses is obtained by sending one of the pulses through a variable delay line with a mirror pair (M5, M6) placed on a remotely controlled linear stage. An intensity autocorrelator is used for measurement of both the single laser pulse duration, t_p, and the time delay between the split pulses, t_d.

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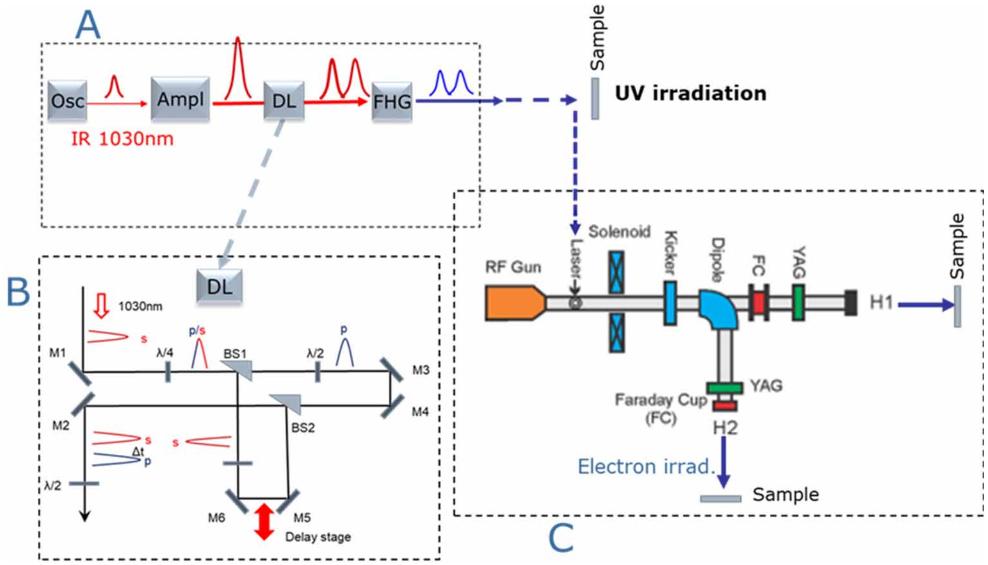

Figure 1: Schematic layout of the AREAL facility for irradiation experiments. (A) laser system, (B) delay line for laser pulse-pair generation, (C) electron beamline.

The spatial overlap of the transverse profiles of the two beams on the photocathode is monitored using a camera-based optical setup which provides a virtual image of the laser beams on the photocathode and is installed before the gun entrance window. Precise alignment allows to maintain the full overlap of the beam spots over a range of optical path variation corresponding to time delays from 0 to more than 100 ps. This is larger than the range of time-equivalents of emission phases of the 3 GHz RF gun. The minimum time-offset between the pulses in pairs which is exploited for generation of temporally shaped (or double) e-bunches, however, is 850 fs (i.e., larger than the shortest pulse duration, 550 fs), since larger temporal overlap leads to laser polarization instabilities with the current DL setup. The energy ratio of the laser pulses in a doublet can be varied from 1:1 up to 1:300 which allows to effectively shape the generated e-bunches with desirable charge distribution.

Generation of E-Bunch Pairs

Figure 2 represents an example of a double electron bunch generated with a doublet of drive laser pulses with 20 ps time offset.

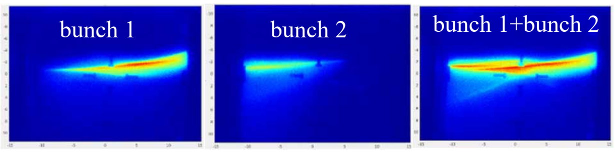

Figure 2: Energy-spectrometer images of single and double e-bunches (gun phase is 75 deg).

The images are taken on the YAG screen of the energy spectrometer and correspond to the optimized (on-crest) gun phase for the leading bunch. The laser and electron pulse parameters are presented in Table 1. The time offset between the leading and trailing bunches derived from the difference of the respective on-crest gun phases agrees with the autocorrelation measurements to within the RF-phase accuracy (±1 deg).

Table 1: Parameters of Laser and Electron Double-Pulses

Parameter	**Pulse 1**	**Pulse 2**
Laser		
Pulse duration	550 fs	550 fs
Repetition rate	20 Hz	20Hz
Time delay	--	20 ps
Pulse energies	16.1 μJ	16.3 μJ
E-beam		
Energy, on crest	2 MeV	2 MeV
On-crest rel. gun phases	75 deg.	96 deg.
Charge, on crest	83 pC	72 pC
Charge, at phase 75 deg.	83 pC	48 pC

In order to test the alignment and stability of the delay line, a Schottky scan (charge vs. injection phase) was performed in which the pulse delay is varied instead of the RF phase. For a pair of driving pulses with nearly the same energy (see Table 1), Fig. 3 represents the measured non-zero emission curves with fixed- and variable-path pulses, respectively, by RF-phase and delay variation.

A Schottky scan at a fixed (pre-defined) gun RF-phase can be used also as a fast method for finding and optimization of parameters of a bunch pair (such as time-offset, charge ratio and off-crest energy) for tailoring the shape of the resulting e-bunch.

It should be noted from Fig. 3 and Table 1 that, near the optimized RF-phase for a pair of pulses with the same timing, the emission is smaller for a higher-energy driving pulse. A possible reason of such an irregularity is the combined effect of different characteristics of the driving laser pulses: 1) positioning (misalignment), 2) slight ellipticity of the UV-converted beams and polarization-dependence of the photoemission, 3) difference of the spot sizes (i.e., effective areas) of the divergent ($M^2 \sim 1.3$) beams due to the optical path difference. These effects are the subject of ongoing studies.

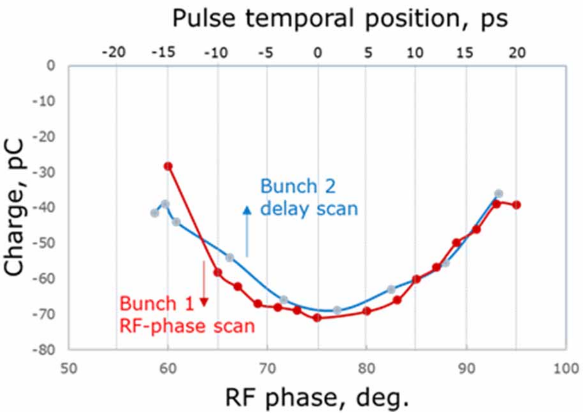

Figure 3: Comparison of Schottky scans with gun RF-phase and laser pulse delay variation for the fixed and delayed bunches, respectively.

Application for Irradiation of Thin Films

The double-bunch beams with parameters given in Table 1 were exploited in the ongoing experimental studies of the effect of ultrashort-bunch irradiation on structural and optical properties of the CdS thin films thermally deposited on glass substrates. The irradiated sample is an 1820 nm-thick CdS film thermally deposited on an area of 24 mm × 75 mm of a 1 mm-thick soda-lime substrate.

In order to evaluate the role of the temporal shape of ultrashort bunches in irradiation-induced modifications, different areas of the sample were irradiated with the same dose by single- and double-bunch beams. The double-bunch parameters are those presented in Table 1, whereas for single-bunch irradiations, only the drive pulse of the fixed arm of the DL was used. In the latter case, the laser pulse energy was increased in order to obtain the same total charge per shot (155 pC) in the on-crest regime and the same cumulative dose (2×10^{13} el/cm^2). The sample and an uncoated reference substrate were irradiated in air on the station H1 (see Fig. 1) simultaneously, placed on a distance from the titanium extraction window where the beam diameter is ~18 mm. The sample and the reference are positioned side-by-side, so that equal areas are irradiated, and the non-irradiated areas served as references.

Preliminary results of structural (SEM) and optical studies of irradiated and non-irradiated samples are presented in Fig. 4 and Fig. 5, respectively. The irradiation by both single- and double-bunch beams does not lead to significant modifications of the surface structure (Fig. 4) and optical properties (Fig. 5, orange) of the films. In contrast, the optical transmission of the substrates decreases significantly due to the higher absorbed dose and large concentration of colour centers in the glass.

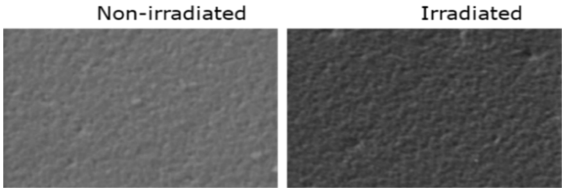

Figure 4: SEM images of non-irradiated and irradiated surfaces of CdS thin films.

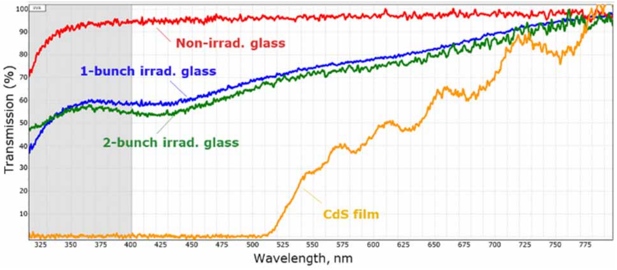

Figure 5: Optical transmission spectra of non-irradiated and irradiated samples of glass and CdS thin film.

Moreover, single- and double-bunch irradiations result in a difference of the spectral dependence of UV transmission (grey region on Fig. 5) of the glass which may be associated with the specifics of dynamics of the defects formation in the two cases. Nevertheless, higher estimated irradiation doses (>10^{14} el/cm^2) will be needed in the following studies for reliable qualitative and quantitative studies of the effects of the ultrashort bunches on the properties of films and substrates.

CONCLUSION

In addition, using the interferometric delay-line method for stacking of driving laser pulses, ultrashort electron bunch pairs with tuneable time-offset were generated on AREAL Linac for applications in irradiation experiments. The time-offset and the energy ratio of the pulses in the stack can be precisely varied in wide ranges for efficient and reproducible shaping of the electron bunches. A 20 ps time-offset double-bunch beam was exploited in ongoing irradiation experiments on CdS films deposited on glass substrates. The preliminary results have shown that low-dose irradiation with low-energy (~2 MeV) bunches induced only slight modifications of structural and optical properties of the film, whereas the optical transmission of the glass substrate decrease significantly due to the large absorbed doses. The effect of the irradiation dose rate on the film properties and the role of the e-bunch shape are expected to be more pronounced at high irradiation doses (>10^{14} el/cm^2) which is the subject of the following experimental studies.

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