FIRST OBSERVATION OF PHOTOEMISSION ENHANCEMENT FROM COPPER CATHODE ILLUMINATED BY Z-POLARIZED LASER PULSE

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Abstract

Since 2006, we have been developing a novel photocathode gun gated by the laser-induced Schottky-effect. This new type of gun utilizes laser coherency to aim at a compact femtosecond laser oscillator as an IR laser source using Z-polarization on a metal photocathode. This Z-polarization scheme reduces the laser photon energy to excite the cathode with a longer wavelength by reducing its work function due to the Schottky effect. Before this epoch-making scheme emerged, photocathode guns had never utilized a laser's coherency itself. We applied a hollow laser incidence scheme with a hollow convex lens that is focused after passing the beam through a radial polarizer. Based on our calculations (convex lens: NA=0.15; 60% hollow ratio), a Z-field of 1 GV/m needs 1.26 MW at peak power for the fundamental wavelength (792 nm) of a Ti: Sapphire laser. To confirm photoemission enhancement effects due to a Z-field of a few GV/m compared with copper's conventional photoemission, we used third harmonic generation (THG: 264 nm) as a pilot experiment and generated a Bessel beam with a hollow axicon lens in a vacuum to relax the phase matching condition of the wavefront on the cathode's focus point. We observed the first Z-field emission enhancement with a copper cathode at THG (264 nm). The enhancement factor was 1.4 times at 1.6 GV/m of the averaged Z-field of the central laser spot (Bessel beam) on the cathode surface.

INTRODUCTION

A conventional photocathode RF gun needs a UV-laser source (~260 nm) for robust cathodes like metal copper due to their high work functions that exceed 4 eV. Consequently, the laser system becomes larger and more complex. To make the laser source compact and simple, we need a cathode with a lower work function and high QE. However, such a high QE Negative Electron Affinity (NEA) cathode requires an ultra-high vacuum (< 10^{-8}Pa) and does not have a long lifetime in an RF gun.

One solution to reducing the work function is to apply a high field on the cathode surface. In a field of 1~2 GV/m, the copper cathode's work function is reduced by ~2 eV. To achieve such a high field (~1 GV/m) on the photocathode, a tungsten needle (radius: ~1 μm) photocathode with photo-assisted field-emission was tested [1]. The obtained QE of the needle tip was found to be proportional to the >10th power of the electric field over 500 MV/m and reached 3% of QE at about 800 MV/m. This observed field enhancement of QE is qualitatively explained with a field-emission process that includes the Schottky effect, the tunneling effect, and photoexcitation. However, such a needle cathode tip becomes round and broken in the gun cavity during RF conditioning. The dark current is also very large due to a 100-times longer half-cycle of RF than the pulse duration of the illuminating laser.

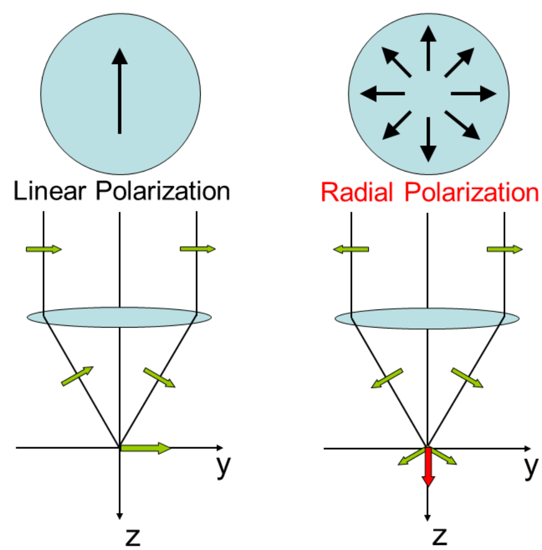

Figure 1: Principle of Z-polarization field on cathode surface generated from radial polarization

Therefore, we started to investigate with a plane-field emitter gated by a laser radiation field by exploiting recent progress in optical technologies to generate radially polarized laser modes. The fundamental mode of radial or azimuthal polarization is the superposition of TEM_{01} and TEM_{10} modes as orthogonal linear polarizations. By focusing a radially polarized laser beam on the photocathode (Fig. 1), the laser's electric field is generated in the laser propagating direction (Z-direction) at the focus point. The generated Z-polarized laser field (Z-field) easily exceeds an electrical field of 1 GV/m with fundamental wavelength from compact femtosecond laser systems. On the other hand, focusing an azimuthally polarized beam on the photocathode results in the zero Z-fields. Comparing the radial and azimuthal polarizations by focusing on metal cathodes, we conducted a feasibility study of Z-field effects on the photocathode [2]. This is also a fundamental study of cathode response and emission mechanisms with a cylindrical vector beam in the femtosecond region.

In our first test run, we focused a radially polarized hollow laser with a hollow convex spherical lens in a vacuum to enhance the electron emission. After comparing the radial and azimuthal polarizations by focusing, we could not observe any significant enhancement differences of electron emission [3]. In our second test run, we prepared a hollow axicon lens that was especially designed to tolerate the constructive phase condition of the wavefront to generate a Z-field in the depth of focus on the cathode. We report the first observation and analysis of the emission enhancements due to the laser Z-field effects on the copper photocathodes by varying from radial to azimuthal polarizations of the incident laser pulses.

PRINCIPLE OF Z-POLARIZATION GUN

Principle of Z-polarization Generation

If the Schottky or tunnelling effect due to the Z-field is dominated, we expect that electrons will emit from the outermost surface of the metal cathode and be extracted with the external electric field of the RF cavity.

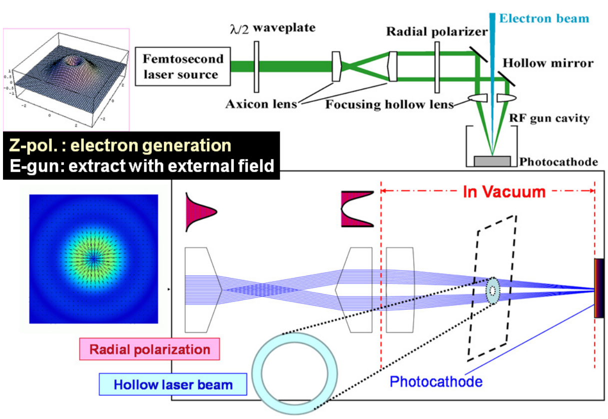

Figure 2: Schematic drawing of Z-polarization gun with novel laser illumination system of hollow laser beam incidence

To effectively utilize Z-polarization, we must develop special hollow optics. A schematic drawing of a Z-polarization gun with the optical systems of hollow laser beam incidence [2] is shown in Fig. 2. The original hollow incidence scheme was designed with a hollow spherical convex lens in a vacuum that focuses the laser pulse that passed through a radial polarizer. The Z-field is proportional to the square of the numerical aperture (NA). To make NA as large as possible, we designed a final focusing lens in a vacuum and a hollow laser beam generator with an axicon lens pair that transforms the Gaussian profile (intensity distribution) from the inside out (anti-Gaussian profile).

UV Radial Polarization Converter for Big Hollow Laser Beam

The radial polarization fundamental mode is generated from a combination of Hermite-Gaussian (HG) modes TEM_{01} and TEM_{10} [4]. Therefore, we chose a simple divided waveplate (see details in ref. [3]) to generate radial polarization from a conventional linearly polarized beam.

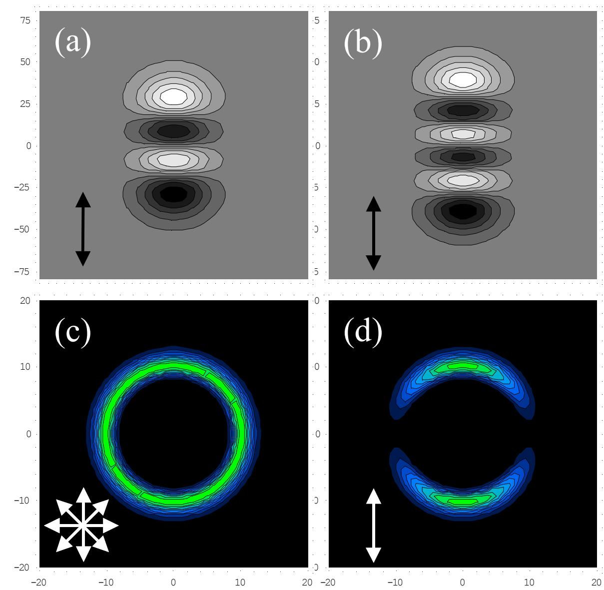

Figure 3: Electric field distribution of Hermite-Gaussian (HG) beam: (a) TEM_{03} and (b) TEM_{05}. Intensity distribution of radially polarized hollow beam expressed by superposition of higher order modes of HG (c), and its vertically polarized component (d). Arrows indicate polarization orientation.

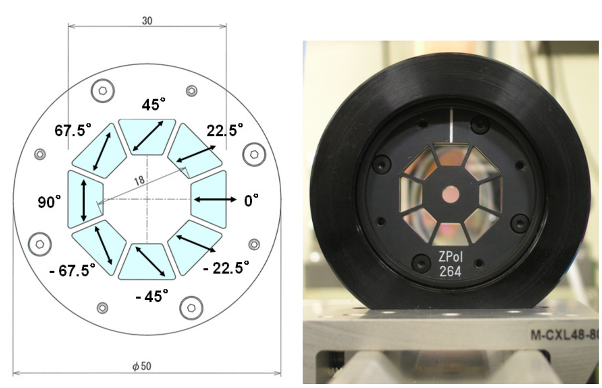

Figure 4: Eight-segment zero-order half waveplate (designed for femtosecond laser incidence; optical-contact) for a hollow beam @ 264 nm: eight-segment waveplate for a hollow beam (right) and orientations of optical axes in each segment (left).

However, a higher order mode of radial polarization is required to make NA larger. For instance, a higher order mode of radially polarized hollow beam is generated

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from a combination of higher HG modes: TEM_{03}, TEM_{30}, TEM_{05}, and TEM_{50} (Fig. 3). We designed an eight-segment half waveplate especially for a hollow beam (Fig. 4).

FEASIBILITY TEST OF Z-FIELD GUN

Experimental Concept and Setup

We performed experiments in a single-cell RF gun generated laser Z-field at the cathode. For this feasibility test, we chose a combination with a copper cathode illuminated by Ti:Sa THG (264 nm) to compare with the emission at the conventional photocathode RF gun with normal laser incidence. Switching from radial to azimuthal polarizations of incident laser pulse, we measured the difference of the bunch charge of photoemission with a Faraday cup downstream.

The hollow laser incidence with the axicon lens is shown in Fig. 5. It is more complicated than a spherical convex lens to focus at the cathode surface, because the focal length depends on the outer and inner diameters of the incident hollow laser beam. The hollow, copper lens protection ring restricts the inner diameter of the hollow laser beam whose outer diameter is 20 mm. On the other hand, the entrance of the RF gun works as an aperture with a 20-mm diameter to restrict the hollow laser beam's outer diameter. The distance between these two optical obstacles with the inner and outer permissible diameter of 20 mm defines the focal length of this laser incidence system. Due to our single cell RF gun cavity, the working distance between the gun's entrance and cathode is rather short: 88 mm. The hollow laser's outer diameter must be 26~27 mm. In this case, the focal length is between 114.4~118.8 mm. The NA of this final focusing system is around 0.11.

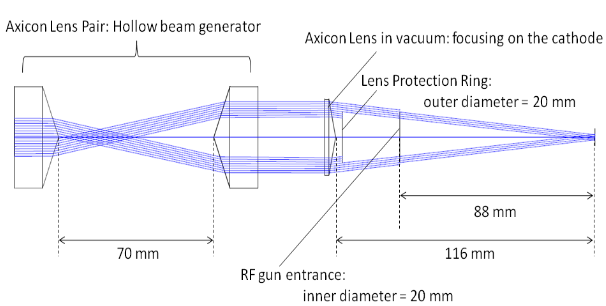

Figure 5: Optical configuration of Z-field RF gun with final focusing of axicon lens

Experimental Result

We focused a radially polarized THG on a copper cathode with an axicon lens (NA=0.11) to generate the Z-field. The maximum cathode surface of the RF gun field was 84 MV/m. We observed the first Z-field emission enhancement with a copper cathode at THG (264 nm) with a pulse duration of 100 fs (Fig. 6). The enhancement factor was 1.4 times at 1.6 GV/m of the Z-field of the averaged peak laser spot on the cathode surface (pulse energy: 25 µJ; central peak spot diameter: 30 µm). During polarization dependency measurements with switching from radial to azimuth, the dark currents were measured individually to observe whether breakdown occurred. We could not observe any significant increase of dark currents.

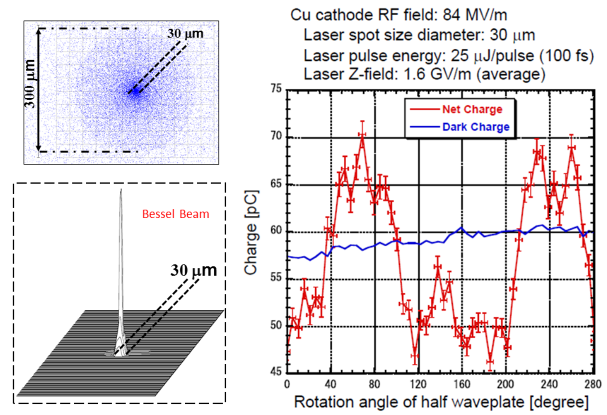

Figure 6: Experimental result of Z-field enhancement with final focusing by axicon lens, varying from radial to azimuthal polarizations of incident laser pulses.

SUMMARY AND DISCUSSION

We reported the first observation on Z-field enhancement in an RF gun cavity and demonstrated a feasible condition of the Z-polarization gun we proposed in 2006. Focusing radially polarized 100-fs THG pulses on the copper cathode with an axicon lens, we observed an enhancement factor of 1.4 at 1.6 GV/m of the Z-field on the cathode surface. This result clarifies the photoemission differences between a Z-field gun (Z-field: 1~2 GV/m) and the conventional photocathode gun with normal incidence (zero Z-field).

The net charge of the Z-field enhancement was 15 pC. As shown in Fig. 6, some significant spike strictures were observed. They can be the results of the Z-field phase mismatching among higher order transverse modes.

We expected the electrons to be mitted just from the outermost atomic layer within the cathode's central laser spot. Based on our calculation with the WKB approximation under the experimental condition, the effective reduction of work function was 1.4 eV.

Next, we are going to prepare backward illumination with half-cycle laser pulses (optical certification) in mid-IR to generate a Z-field on a spin-polarized photocathode without utilizing the NEA surface [2].

REFERENCES

[1] T. Inoue, et al., *JJAP*, **41**, 12, (2002) 7402.
[2] H. Tomizawa, et al., *Proc. of FEL 2007*, Novosibirsk, Russia (2007) 382.
[3] H. Tomizawa, et al., *Proc. of FEL 2010*, Malmo, Sweden (2010) 640.
[4] S. C. Tidwell, et al., *Applied Optics*, **29**, 15, (1990) 2234.