FIRST EMISSION OF NOVEL PHOTOCATHODE GUN GATED BY LASER-INDUCED SCHOTTKY-EFFECT

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Abstract

A laser-induced Schottky-effect-gated photocathode gun has been in use since 2006. This new type of gun utilizes a laser's coherency to create a compact laser source using Z-polarization of the IR laser on the cathode. This Z-polarization scheme reduces the laser pulse energy by reducing the cathode work function due to the Schottky effect. Before this epoch-making scheme emerged as a concept, photocathode guns had never utilized a laser's coherency. A hollow laser incidence scheme is applied with a hollow convex lens that is focused after passing the beam through a radial polarizer. According to 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). Therefore, we expect that this laser-induced Schottky emission requires just a compact femtosecond laser oscillator. We observed the first emission with a hollow laser incidence scheme (copper cathode illuminated by THG: 264 nm as a pilot experiment). It has a net charge of 21 pC with a 100-fs laser pulse (pulse energy: 2.5 μJ; spot diameter: 200 μm). However, we could not measure a significant difference between radial and azimuthal polarizations with focusing. We will use a hollow axicon lens in a vacuum to make the laser spot larger. The maximum cathode surface field is 97 MV/m. Relaxing the space-charge limit at the cathode, it generates a higher charge to measure the difference. This new scheme of gun will be investigated on several metal photocathode materials by comparing radial and azimuthal polarizations at 264, 396, and 792 nm. This is not only for development of an electron gun, but also to study cathode response and fundamental behaviors of electrons at the cathode. If we cannot observe any Z-field enhancement of electron emission with these laser wavelengths, we will prepare femtosecond laser half-cycle pulses (optical certification) up to mid-IR wavelength to illuminate photocathode metals.

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 over 4 eV. Consequently, the laser system becomes larger and more complex. To make the laser source compact and simple, we need to find a cathode with a lower work function and high QE. However, such a high QE NEA-cathode requires an ultra-high vacuum (< 10^{-8}Pa) and does not have a long lifetime in a gun.

One solution to making the work function lower is to apply a high field on the cathode surface. In the field of 1~2 GV/m, the work function of the copper cathode is reduced by ~2 eV. To achieve such a high field (~1 GV/m) on the photocathode, the 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 it reached up to 3% at about 800 MV/m. This observed field-enhancement of QE is qualitatively explained with a field-emission process including the Schottky effect and photo excitation. However, such a needle cathode tip became round and broken in the cavity during rf conditioning.

Therefore, we started to investigate with a plane-field emitter assisted by a laser radiation field. We utilize recent progress in optical technologies to generate radially polarized laser propagation modes. The radial polarization fundamental mode is a superposition of TEM_{01} and TEM_{10} modes under the condition of a polarization direction in which they are orthogonal to each other. Focusing a radially polarized beam on the photocathode, the Z-polarization of the laser is generated at the focus point. The generated Z-polarization can exceed an electrical field of 1 GV/m easily with fundamental wavelength from compact femtosecond laser systems. On the other hand, focusing an azimuthally polarized beam on the photocathode results in zero Z-fields. Comparing the radial and azimuthal polarizations with focusing, we conduct a feasibility study of the laser-induced Schottky effect on the photocathode. It is also a fundamental study of cathode response in the region of a few femtoseconds. If cathode response is not higher than a laser half-cycle time, the Z-field emission effect cannot be observed because of averaging. With scanning laser wavelength, cathode response time can be measured, if the Z-field emission is observable.

As the first test run, a radially polarized hollow laser is focused with a hollow convex lens in a vacuum to obtain electron emission. The aim of the first test run is observation of the first emission in this new scheme. Comparing the radial and azimuthal polarizations with focusing, we will check the Z-field emission as a significant enhancement of electron emission.

We are preparing a hollow axicon lens for focusing in a vacuum to make the laser spot larger. To relax the space-charge limit at the cathode, the emission current is estimated to be relatively higher. This is the second test run aiming at a higher charge emission to measure polarization dependencies precisely. We report the first emission results and the preparations of the second step.

PRINCIPLE OF Z-POLARIZATION GUN

Principle of Z-polarization Generation

Focusing a radially polarized laser beam on the photocathode as shown in Fig. 1, the electric field of the laser is generated in the laser propagating direction (Z-direction) at the focus point. The Z-field oscillates with a periodic time of ~2.6 fs at the fundamental Ti:Sa laser (~790 nm). Roughly estimating in the case of a metal cathode, laser radiations (wavelength: λ) enter the cathode surface to a depth of ~λ/20, and photocathode response is less than 10 fs. If the Schottky-effect-induced Z-field is large enough, we expect that electrons will make oscillations with the Z-field frequency on the outermost surface of the metal cathode and will be extracted with the external electric field of the RF cavity. Note that photocathode response should be higher than a laser half-cycle time.

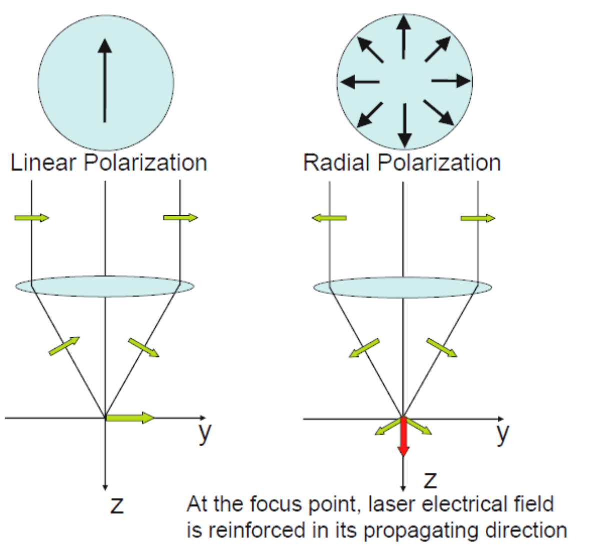

Figure 1: Principle of Z-polarization field on the cathode surface generated from radial polarization

To utilize the Z-polarization effectively, development of special hollow optics is required. A schematic drawing of a Z-polarization gun with optical systems of a hollow laser beam incidence [2] is shown in Fig. 2. The hollow laser incidence scheme is applied with a hollow convex lens in a vacuum that is focused after passing the beam through a radial polarizer. The Z-field is proportional to the square of the numerical aperture (NA). The laser diameter before the final focusing lens should be as large as possible, and the focus length should be as short as possible. 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. The axicon pair transforms the Gaussian profile from the inside out (so-called hollow beam).

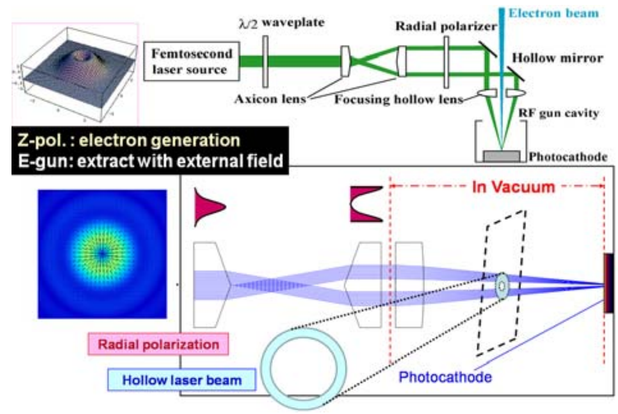

Figure 2: Schematic drawing of Z-polarization gun with optical configuration of hollow laser beam incidence

Radial Polarization Beam Generator

The radial polarization fundamental mode is generated from a combination of Hermite-Gaussian (HG) modes TEM_{01} and TEM_{10} [3]. Therefore, we chose a simple divided waveplate (see details in ref. [2]) to generate the radial polarization from a conventional linearly polarized beam. However, a higher mode of hollow radial beam is required to make NA larger. For instance, a higher mode of radially polarized hollow beam is generated from a combination of higher HG modes TEM_{03}, TEM_{30}, TEM_{05}, and TEM_{50} as shown in Fig. 4. We designed a zero-order eight-segment wave-plate especially for a hollow beam as shown in Fig. 3

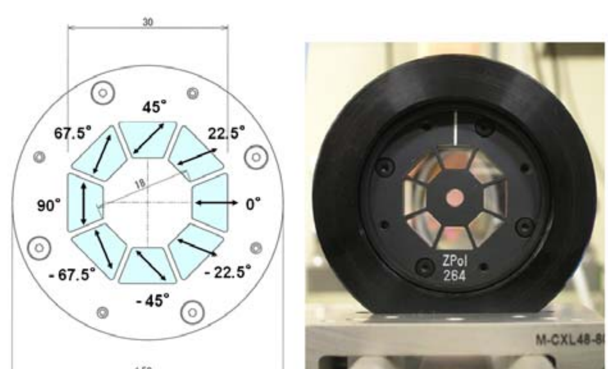

Figure 3: Eight-segment zero-order waveplate (designed for femtosecond laser incidence; optical-contact) manufactured by Nanophoton Corporation for a hollow beam @ 264 nm: the photo of an eight-segment waveplate for a hollow beam (right) and the direction arrangement of optical axes in each segment (left) are shown.

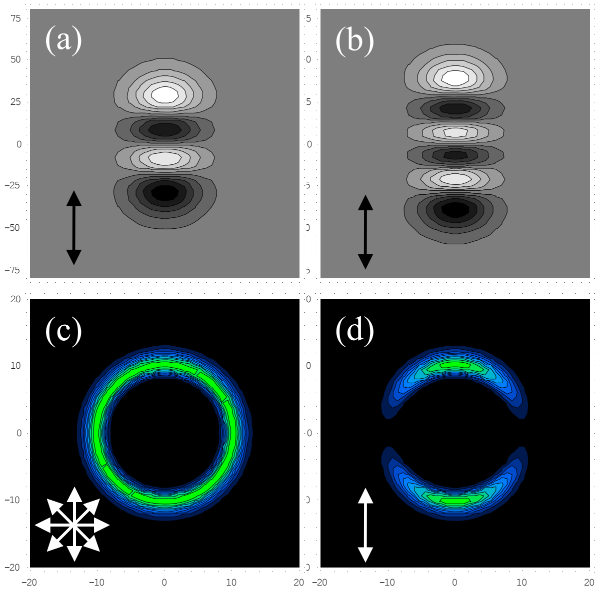

Figure 4: Electric field distribution of Hermite-Gaussian (HG) beam: (a) TEM_{03} and (b) TEM_{05}. Intensity distribution of radially polarized hollow beam expressed by sum of high-order modes of HG (c), and its vertically polarized component (d). The arrows in the images indicate the direction of polarization.

To generate the electrical field in the perpendicular direction on a metal, we have to select a combination of metal cathode material and laser wavelength. Comparison among laser wavelength dependencies of reflectivity on our seven metal cathode surfaces is shown in Fig. 5. If the laser is reflected perfectly at the metal surface, the Z-field will be cancelled out. Also, the metal cathode response should be taken into account in combinations with laser wavelength.

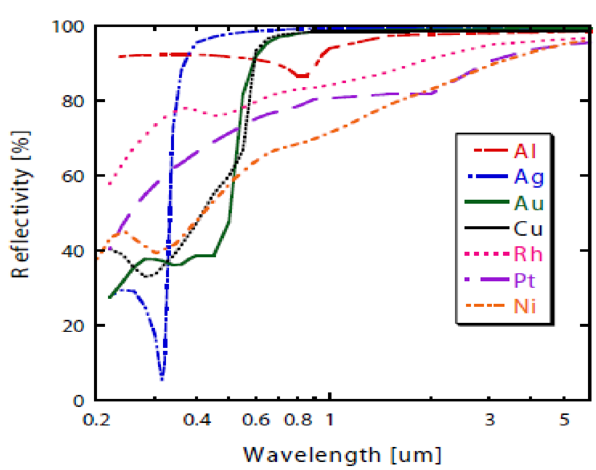

Figure 5: Wavelength dependencies of reflection ratio with metal cathode candidates' surfaces

Therefore, we prepared generators of a hollow beam with a radial polarization at wavelengths of 264, 396, 792, and 1,064 nm. The current optical set-up for the Z-polarization RF gun (pill-box type) is shown in Fig. 6.

For the first test run, we chose the combination with a copper cathode illuminated by Ti:Sa THG (264 nm) to compare with the emission at the conventional photocathode RF gun.

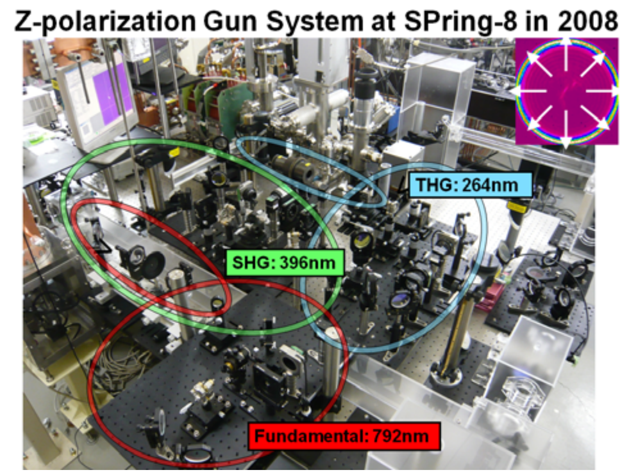

Figure 6: Optical setup to generate radially polarized hollow laser beam at 263, 396, 790 nm. To generate a femtosecond laser pulse at the cathode, a negative-chirped laser pulse is generated at the laser source with an AO-modulator (DAZZLER HR-800, FASTLITE) to be compensated with the material dispersions.

Final Focusing Optical Lenses in Vacuum

We prepared two types of final focusing lenses with a central hole. The central hole is covered with a 3-mm-thick copper ring to protect lens glasses from electron bombardments. One is a conventional convex lens for low charge generation. The other is an axicon lens for a relatively higher charge generation (relaxation of space-charge limited emission current). The laser diameters and profiles with both lens types are shown in Figs. 7-8.

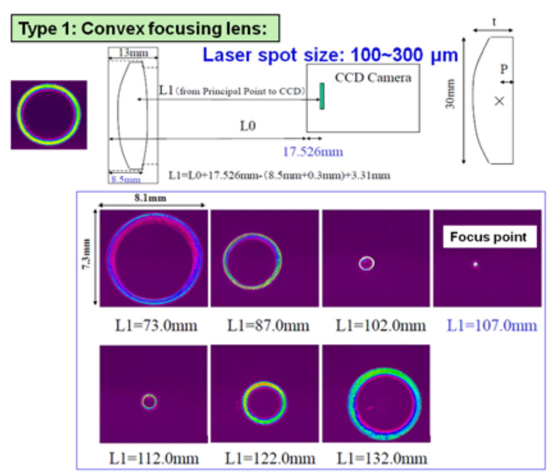

Figure 7: Focus test with convex lens with hollow beam

The outer diameter of the incident hollow laser beam was 27.2 mm (ring width: ~1 mm) at a wavelength of 546 nm (an He-Ne green laser was chosen as a standard wavelength to test optics). At the focus (minimum) point, diameters were 200 µm with the convex lens and, 800 μm with the axicon lens. In focusing a hollow beam with an axicon lens, the focus (minimum) spot diameter is theoretically the ring width of the incident hollow beam in geometrical optics. In the case of Gaussian beam incidence, half of the incident beam diameter is the focus spot diameter. However, in reality, diffraction effect, intensity distribution, and incident beam divergence should be taken into account to estimate laser spot focus (minimum) size at the cathode.

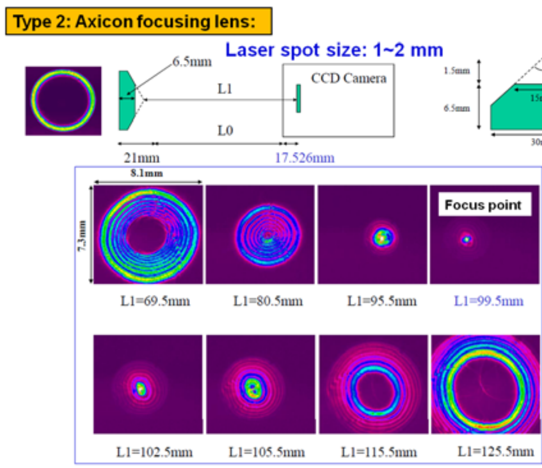

Figure 8: Focus test with axicon lens with hollow beam

FEASIBILITY TEST RESULTS

In the first test run, radially polarized THG was focused on a copper cathode with the convex lens (NA=0.15, 60% hollow ratio R_{ratio}, inside-out Gaussian beam) to maximize the Z-field. The maximum cathode surface field was 97 MV/m. In this feasibility test setup shown in Fig. 8, we set a hollow beam with an outer diameter R0 of 30 mm and an inner R1 of 18 mm (R_{ratio}=R1/R0=60%). We observed the emission with 100-fs and 1-ps THG pulses. The net charges were 21 pC with 100-fs laser pulse (pulse energy: 2.5 μJ; spot diameter: 200 μm), and 11 pC with 1-ps laser (1.7 μJ; 200 μm), respectively. We could not observe significant differences between radial and azimuthal polarizations.

SUMMARY AND DISCUSSION

We reported recent progress with our Z-polarization RF gun and its feasibility test. Focusing radially polarized 100-fs and 1-ps THG pulses on the copper cathode, we observed the first emission of this new concept of photocathode. The net charges were 21 pC with the 100-fs laser pulse and 11 pC with the 1-ps laser. The emission current seems to be larger than the space-charge limited emission current.

We could not observe significant emission differences between radial and azimuthal polarizations because of dark currents. We would require ten times more emission current to measure the fine difference between them. We make clear the feasibility with an axicon-focusing lens. The hollow laser incidence with the axicon lens is shown in Fig. 9. It is rather complicated to focus at the cathode surface because focal length depends on the outer and inner diameters of the incident hollow laser beam. The lens protection ring made of copper works as a restriction of the inner diameter of a hollow laser beam with its outer diameter of 20 mm. On the other hand, the entrance of the RF gun works as an aperture with a diameter of 20 mm to restrict the outer diameter of the hollow laser beam. The distance between these two optical obstacles with the equivalent permission diameter of 20 mm defines the focal length of this laser incidence system. Thanks to our single cell RF gun cavity, the working distance between the entrance and cathode of the gun is a rather short 88 mm. The outer diameter of the hollow laser should 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 0.1. A flattop laser beam as a reliable spacial profile is generated at the focus (minimum) point.

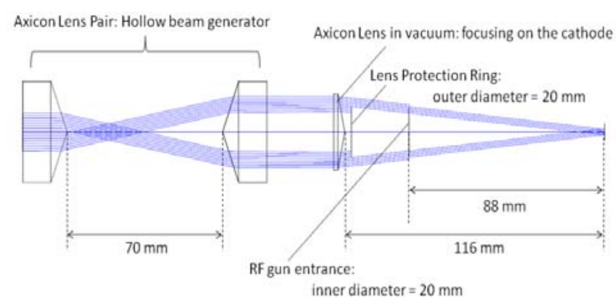

Figure 9: Optical configuration of Z-field RF gun with final focusing of axicon lens

Comparing the radial and azimuthal polarizations with focusing, we are using a hollow axicon lens in a vacuum for larger laser spot size on the metal cathode candidates. To relax the space-charge limit at the cathode, the emission current is estimated to be relatively higher. This will be the second test run aiming at a higher charge emission to measure polarization dependencies precisely. It is not only for development of a new type of electron gun, but also to study cathode response and fundamental behaviors of electron emission at the cathode. If we cannot observe any Z-field enhancement of electron emission with these laser wavelengths, we are going to decrease the femtosecond laser frequency down to the mid-IR wavelength region to illuminate photocathode metals. A half-cycle of the mid-IR laser pulse achieved in the 10-fs region is surely greater than the response time estimated to react with electrons on the metal cathode surface.

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