

FEASIBILITY TEST OF LASER-INDUCED SCHOTTKY-EFFECT-GATED PHOTOCATHODE RF GUN

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Abstract

We propose a laser-induced Schottky-effect-gated photocathode RF gun using Z-polarization of the laser source. This concept of laser-induced Schottky emission can be applied to a photocathode DC gun (even for a polarized electron source). Radial polarized laser propagation modes exist theoretically and were recently generated practically. Focusing a radial polarized beam on the photocathode, the Z-polarization of the laser is generated at the focus point. The generated Z-polarization field can exceed an electrical field of 1 GV/m easily with fundamental wavelength from compact femtosecond Ti:Sa laser systems. According to our calculations (NA=0.15 60-% hollow ratio, inside-out Gaussian beam), the Z-field of 1 GV/m needs 1.3 MW at peak power for the fundamental (790 nm) and 0.32 MW for the second harmonic generation (SHG). In the field of 1 GV/m, the work function of copper cathode reduces ~ 2 eV. The quantum efficiency is pessimistically estimated to be $\sim 10^{-2}$ % at SHG by the Schottky effect associated with the 1 GV/m. This Schottky effect can be used as a gate of the photo-emission process. We report a feasibility study of this new concept of photocathode.

INTRODUCTION

There are three well-known types of electron guns; the thermionic gun, field emission gun, and photocathode gun. They are widely used for many applications. The future light sources based on linear accelerators such X-ray FEL [1,2,3] and ERL [4] required high brightness electron sources. One of the most promising candidates for such an electron source is a photocathode RF gun.

The photocathode RF gun needs a UV-laser source (~ 266 nm) for a long-lived metal cathode like copper and even for a higher quantum efficiency (QE) cathode such as Ce_2Te . At SPring-8 in collaboration with Hamamatsu Photonics K.K. a diamond cathode has been developed as the future transparent cathode candidate [5]. The diamond cathode is a robust and high QE cathode. However, it requires a laser wavelength below 197 nm for acceptable QE. For a robust cathode like copper and diamond, we need UV-laser light due to their high work functions. Consequently, the laser system becomes larger and complex. To make the laser source compact, 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 life time.

One solution to make the work function lower is to apply a high field on the cathode. In the field of 1~2 GV/m, the work function of the copper cathode reduces 2~3 eV. To achieve such a high field (~ 1 GV/m) on the photocathode, the tungsten needle photocathode, the photo-assisted field-emission, was proposed and tested [6]. The dependence of quantum efficiency on a high electric field was investigated using a tungsten needle (radius: $\sim 1\mu\text{m}$) photocathode irradiated by the third harmonic generation (THG) of a Nd:YAG laser (353 nm) whose photon energies were lower than the work function of tungsten. The obtained QE of the needle tip is found to be proportional to the >10 th 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 laser radiation field. We have indirect evidence of such a laser field effect through comparison between normal and oblique incidences to the cathode. It is well known that the oblique incidence obtains higher QE than normal incidence. In the oblique incidence, the more intensive the laser illuminating the cathode, the higher a QE we obtain. It cannot be explained only with Brewster's angle. However, we have to think about multi-photon absorption in the case of intensive laser focusing on the cathode. The oblique incidence makes the laser spot elliptically larger on the cathode. However, we can obtain a higher QE. It indicates that the laser field can assist the Schottky effect on the cathode.

Radial polarized laser propagation modes exist theoretically and were recently generated practically. The radial polarization beam is a superposition of $\pi/2$ phase-shifted TEM_{01} and TEM_{10} mode in the case of a polarisation direction vertical to each other. Focusing a radial 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 azimuth polarized beam on the photocathode results in zero Z-polarization field. Comparing the radial and azimuth polarization with focusing, we conduct a feasibility study of the laser-induced Schottky-effect on the photocathode.

PRINCIPLE OF Z-POLARIZATION

Principle of Z-polarization generation

Focusing a radial polarized beam on the photocathode as shown in Figure 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 into the cathode surface with a depth of $\sim\lambda/20$, and photocathode response is <10 fs. If the Schottky-effect-induced Z-field is large enough, we expected that electrons would make oscillations with the Z-field frequency on the outermost surface of the metal cathode and are extracted with the external electric field of the RF cavity. Note that the perfect back reflection on the cathode with normal incidence cancels out the Z-field generated by laser radiation.

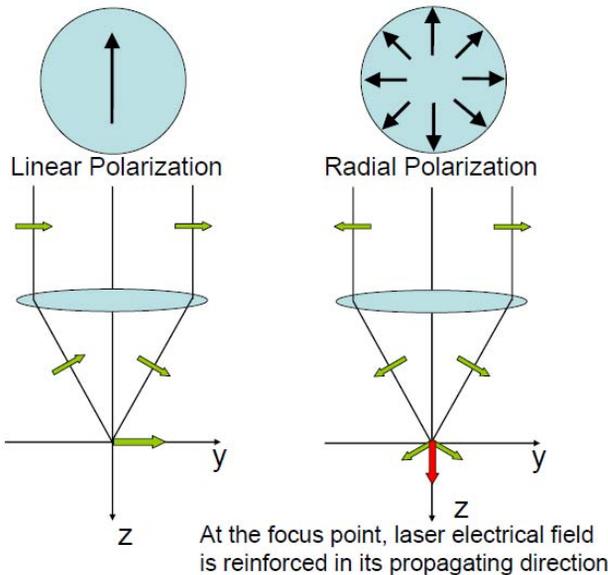


Figure 1: Principle of Z-polarization field on the cathode generated from radial polarization

Reflection ratio of cathode candidates

In order to generate the electrical field in the perpendicular direction on a metal cathode, we have to select a combination of metal cathode material and laser wavelength. Comparison among laser wavelength dependencies of reflectivity with different mirror-finished metal surfaces is shown in Figure 2. Reliable candidates for the combinations are silver with the THG of Yb:fibre laser (~350 nm), copper with the SHG of Ti:Sa laser (~395 nm), and aluminium with the fundamental of Ti:Sa laser (~790 nm). The reflection ratio of the first combination is ~10 %, the second ~30 %, the last ~75%. For the first test run, we chose the second combination with copper illuminated by the Ti:Sa SHG.

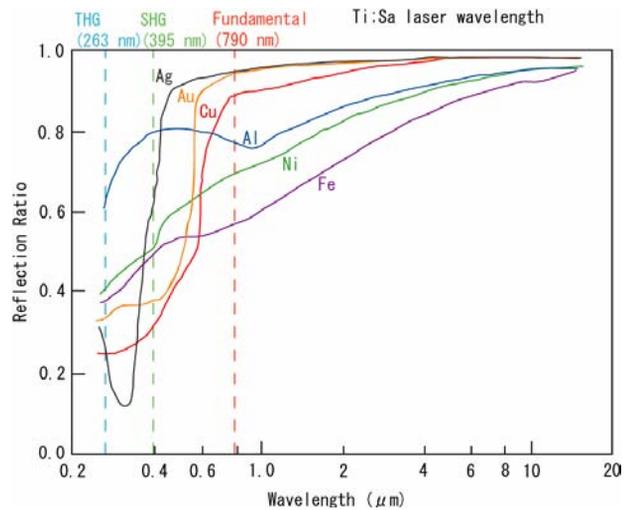


Figure 2: Laser wavelength dependencies of reflection ratio with different mirror-finished metal surfaces

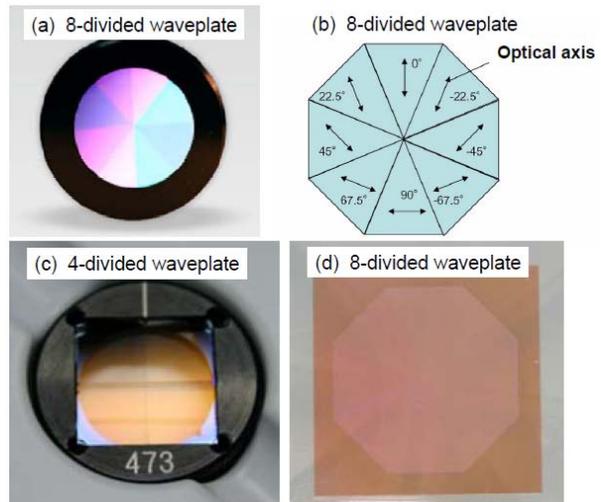


Figure 3: Several divided waveplates manufactured by Nanophoton Corporation: (a), (b) 8-divided waveplate and the direction arrangement of optical axes in each segment, (c) 4-divided waveplate with assembling 4 cuts of waveplate, (d) 8-divided waveplate with growing photonic crystal as a function of waveplate in each segment on single base plate.

Radial polarization beam generator

The radial polarization fundamental mode is generated from a combination of Hermite-Gaussian mode TEM_{01} and TEM_{10} [7]. However, directly lasing with TEM_{01} mode is not practically simple. Therefore, we chose a simple divided waveplate as shown in Figure 3 to generate the radial polarization from a conventional linearly polarized beam. We investigated the divided number dependency of Z-field at the focus point generated with the divided waveplate. The intensity distributions of Z-polarization intensity $|E|^2$ generated with waveplates with different division numbers of are shown in Figure 4. In the case of more than eight divisions, it shows no significant difference from the Z-field intensity generated from ideal radial polarization.

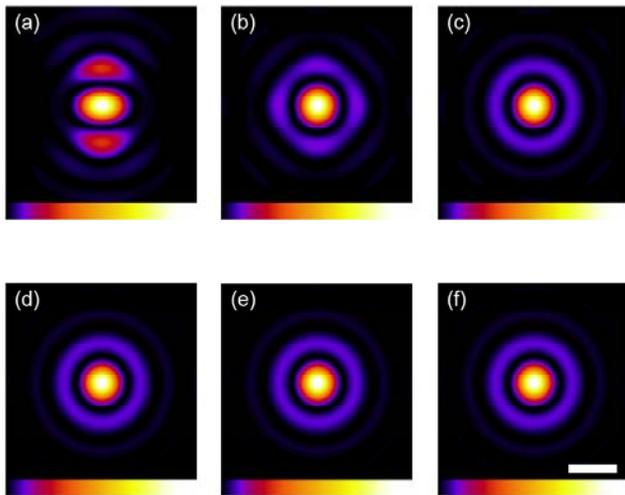


Figure 4: Using divided waveplates, the intensity distribution of Z-polarization intensity $|E_z|^2$: (a) 2-divided, (b) 4-divided, (c) 8-divided, (d) 16-divided, (e) 32-divided, (f) perfect radial polarization (n : infinity). White scale bar in (f) is $7.5\mu\text{m}$ @790 nm, $\text{NA}=0.1$ (Flattop).

Z-polarization ratio with divided waveplate

The divided number dependence of the radial polarization ratio to ideal radial polarization is shown in Figure 5 regarding the simulation results of Z-polarization at the focus point compared with analytical under- and over- estimation of the radial polarization ratio at the focus point.

In the case of the 8-divided waveplate, the radial polarization ratio to ideal radial polarization is 95% as with the simulation results of Z-field at the focus point.

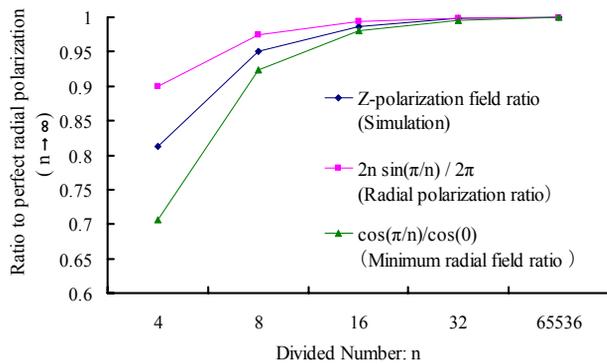


Figure 5: The divided number dependence of radial polarization ratio to ideal radial polarization

Z-polarization electric field dependency of optical characteristics and parameters

To maximize the Z-polarization field, the optical parameters should be optimized. The Z-field is reciprocal proportional to the square of the laser wavelength. This indicates that the SHG can generate a four-time stronger field than the fundamental at the focus point. Utilizing the SHG is totally efficient in Z-field generation, because the SHG conversion efficiency reaches up to 50%. The numerical aperture (NA) is characteristic of the final

focusing optics. The Z-polarization field is proportional to NA raised to fourth power. The laser diameter before the final focusing lens should be as large as possible. The focus length should be as short as possible.

To make NA as large as possible, we designed a hollow laser beam generator with an axicon lens pair. The Z-field dependency of the hollow laser beam ratio is shown in Figure 6 in the case of the Gaussian beam incidence to the axicon lens pair. In our feasibility test set-up shown in Figure 7, the diameter of the electron beam is roughly 18 mm. Considering the vacuum duct inner diameter, realistically $R_0=30$ mm and $R_1=18$ mm. In the case of $R_{\text{ratio}}=R_1/R_0=60\%$, the hollow beam makes a 10 times higher Z-field on the photo cathode than Gaussian beam incidence without an axicon lens pair.

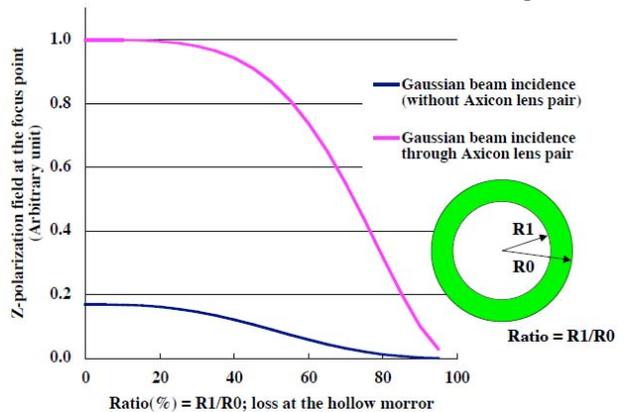


Figure 6: Z-polarization field dependency of hollow laser beam ratio (Gaussian beam incidence to axicon lens pair)

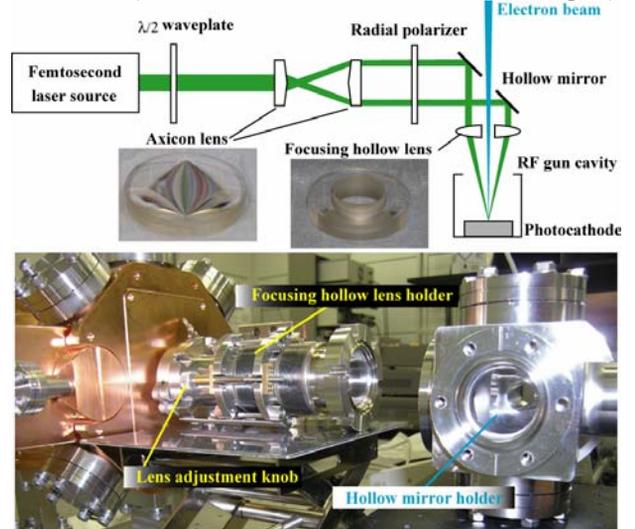


Figure 7: Experiment set-up for Z-polarization RF gun with hollow laser beam incidence optics

TYPE OF LASER INCIDENCE TO CATHODE

It is possible to make several configurations of normal incidence to the cathode. Making NA larger, backward illumination with the transparent cathode can make a short working distance (see (a) in Figure 8). For normal incidence to the conventional reflective cathode, it is necessary to use hollow laser beam incidence as shown

in Figure 7. The hollow inside-out Gaussian laser beam is generated by an axicon lens pair, and then reflected at the hollow mirror for normal incidence and finally focused to the photocathode with a hollow lens in a vacuum. This Schottky effect can be used separately as a gate of the photo-emission process. It is possible to separate the Schottky-gate laser pulse and photo-excitation source as shown in (b) in Figure 8. In the case of a polarized electron source with GaAs, the fundamental is used as a photo-excitation source, the SHG as a gate pulse. However, we have to take into account the time response of the cathode. Several improvements of response time down to 2 ps for GaAs were performed [8]. If the diffusion model is in good agreement in this case, making the cathode even thinner, it is possible to make the response time less than 1ps.

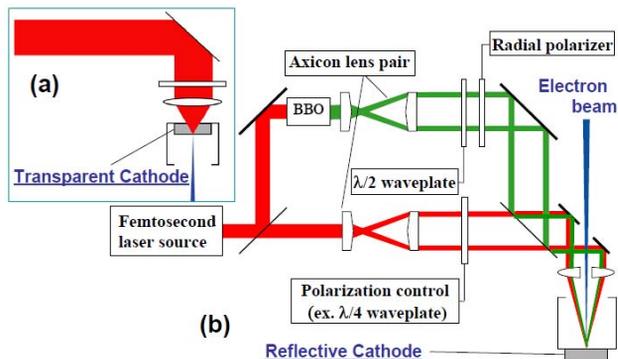


Figure 8: Z-field gun set-ups for different type cathodes

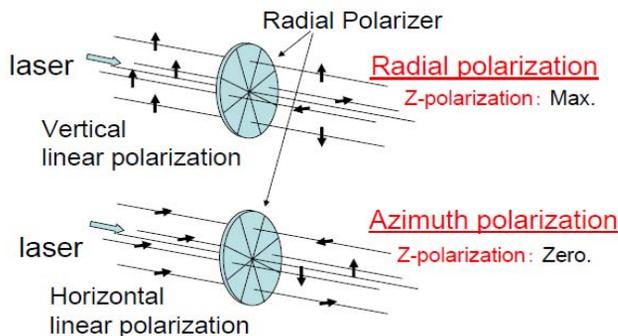


Figure 9: Concept of feasibility test for Schottky effect due to Z-polarization at focus point with the comparison of Z-fields between radial and azimuth polarization

FEASIBILITY TEST PLAN

Up to now, we have only discussed focusing radial polarization to maximize the Z-field on the photocathode. On the other hand, focusing an azimuth polarized beam makes Z-polarization zero. We conducted a feasibility study of the laser-induced Schottky-effect on the photocathode with the comparison between radial and azimuth polarization shown in Figure 9. In this experiment, the linear polarization of the incidence laser switches only from vertical to horizontal. In this method, we can check just the Z-field effect separated from the multi-photon process. Comparing the photo-emission

process with these polarizations, we make clear the feasibility of this new concept of photocathode.

SUMMARY AND DISCUSSION

We discussed a new concept of photocathode with Z-polarization and showed the method for its feasibility test. Focusing a radial 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 the fundamental from compact femtosecond Ti:Sa laser systems. According to our calculations (NA=0.15, 60-% hollow ratio, inside-out Gaussian beam), the Z-field of 1 GV/m needs 1.3 MW at peak power for the fundamental (790 nm) and 0.32 MW for the SHG (395 nm). In the field of 1 GV/m, the work function of the copper cathode reduces ~2 eV.

In our design of the Schottky-effect-gated photocathode, the fundamental is used as a gate pulse and the SHG as a laser source for the photo-excitation with the copper cathode. (In the case of the polarized electron source with GaAs, the circular polarized fundamental wave is used as a photo-excitation source, the SHG as a gate pulse.) The same single laser pulse can also gate its emission by itself. To maintain normal incidence on the cathode, we developed a new type of hollow beam incidence system for cathode illumination with an achromatic axicon lens pair.

In the first feasibility test run, we are preparing a Z-polarizer (8-divided waveplate) for the SHG to generate radial and azimuth polarizations. Comparing the photo-emission process with these polarizations, we make clear the feasibility of this new concept of photocathode.

Using femtosecond laser pulses for photocathode RF guns, a pancake bunch can be created that will evolve automatically into a uniformly filled 3D ellipsoid [9]. This scenario is needed to reduce laser pulse intensity, to avoid damage of the cathode. The Z-polarization RF gun can be fit to this scenario. Next, we will test this scenario to generate a low-emittance beam with our Z-field gun.

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