DEVELOPMENT OF IRIDIUM CERIUM PHOTOCATHODE FOR THE GENERATION OF HIGH-CHARGE ELECTRON BEAM*

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Abstract

We have been developing a novel photocathode RF gun system with an advanced RF cavity structure and a new photocathode material for the SuperKEKB electron linac. This injector is required to obtain a low emittance and high charge electron beams in order to achieve the highest luminosity in the world. The required beam parameters are 5 nC and 20 mm·mrad from the RF gun. Moreover, 10 nC electron beams for positron production will be also generated by the same RF gun. In order to obtain extremely high charge electron beams, Yb-based laser system is being upgraded for higher power and a high temperature photocathode system for a quantum efficiency (QE) enhancement will be introduced to the new RF gun system. This paper reports on the research and development of the system of high temperature photocathode for QE enhancement to be able to generate high charge electron beams (~10 nC) at the RF gun in SuperKEKB electron linac.

INTRODUCTION

High-charge and low-emittance electron beams are required for the SuperKEKB electron linac to obtain the target luminosity of 8×10^{-35} cm^{-2}·s^{-1}, which would be 40 times higher than the highest luminosity achieved at KEKB. The required electron and positron beam parameters of the SuperKEKB linac are shown in Table 1. The charge of electron bunch must increase up to 5 times higher than that of KEKB, and lower emittance is required under 20 mm·mrad.

Table 1: Required e$^+$/e$^-$ Beam Parameters

	KEKB		SuperKEKB	
	e$^+$	e$^-$	e$^+$	e$^-$
Beam energy [GeV]	3.5	8	4	7
Bunch charge [nC]	(10)**, 1	1	(10)*, 4	5
Emittance [mm·mrad]	2100	300	6	20
Energy spread [%]	< 0.1		< 0.1	

()** : primary electron beam parameters

To achieve these beam parameters, we have developed an advanced photocathode type RF gun which is called the quasi traveling wave side-couple RF gun [1], and a new photocathode material made from iridium and cerium [2].

The quasi traveling wave side-couple RF gun has a strong focusing field to keep the small beam size against the space charge effect in a high charge electron beam. This RF gun has enough performance for generating primary electron beams for positron production according to beam simulation [1].

The iridium cerium (Ir$_5$Ce) photocathode has a reasonably high quantum efficiency (QE = 1.54×10^{-4} @266nm) and a long lifetime (> lanthanum hexaboride : LaB$_6$) [2]. Next, the QE of its photocathode was enhanced nearly 6.5 times by heating at 1000 °C [2]. Moreover, the Ir$_5$Ce photocathode showed a high resistance to poisoning. These great advantages of the new RF gun and the photocathode material made it possible to generate electron beams of 5.0 nC at the RF gun commissioning.

This RF gun system including a Yb laser system is now being upgraded for an accelerator operation in repetition of 25 Hz and the generation of primary electron beam for positron production. To generate higher power ultraviolet laser pulse for photoemission, a cryogenic Yb thin disk amplifier system will be installed to decrease of a thermal lens effect. Furthermore, we have been developing the high temperature photocathode system to enhance the QE for the generation of higher charge electron beams.

PROPERTIES OF IRIDIUM CERIUM PHOTOCATHODE

The iridium cerium compound has a lot of good properties as a photocathode material. For example, it has a low work function of 2.57 eV at 1300 K [3] and a high melting point (1900 ~ 2250 °C [4]). Moreover, the iridium cerium compound shows a good resistance to poisoning and ion bombardment [5], resulting in a long lifetime (> LaB$_6$) [2].

Figure 1 shows the correlation between the QE of the iridium cerium photocathode on the surface temperature [2].
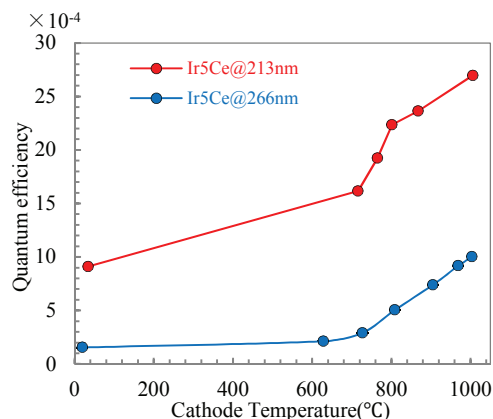

Figure 1: QE of the Ir$_5$Ce photocathode as a function of the surface temperature.

This figure illustrates that the QE of Ir_5Ce photocathode could be increased by adopting a shorter-wavelength pulsed laser, and increasing the cathode temperature. Therefore, it can be concluded that there are three effective methods to get higher charge electron beams by photoemission process from the Ir_5Ce cathode.

The first method is using higher power pulsed laser pulse. However, it may cause an increase of the laser-induced breakdown at the edge of cathode due to a misalignment of optical axis. The second one is the adoption of a shorter-wavelength pulsed laser. This method also has a difficulty in generating a 5th harmonics laser pulse with high conversion efficiency of more than 10 % under a reasonably high repetition rate by a 3-stage nonlinear crystal configuration. The last one is the heating of photocathode material. In addition to the QE enhancement, this method has a lot of advantages. For example, it is possible to generate a spatial uniform electron beam from the photocathode since impurities on the cathode surface are removed by heating around 1000 °C [2] and the cathode surface is cleaned uniformly. In addition, high temperature photocathode can keep this clean surface during high temperature. Therefore, we decided to introduce the heating system to the RF gun system at the SuperKEKB electron linac.

HEATING SYSTEM

In our project, the iridium cerium photocathode will be used at a temperature which significant thermionic emission does not occur. Accordingly, we have been developing three types of heating system to generate high charge electron beams for SuperKEKB electron injector.

The Backside Electron Beam Heating

In general, the direct, indirect, or radiation heating methods is not suitable for the large cathode to heat to a high temperature due to a difficulty of uniform heating and a low heating efficiency.

The backside electron beam heating is that a main photocathode material is bombarded an accelerated electron beam as a thermal source behind the cathode. The heating power depends on an accelerating electric field and a beam current; it is possible to heat a main photocathode by supplying a high voltage and a relatively low filament heating current compared to the direct, indirect, or radiation heating methods [6]. Therefore, this heating system can be used for a longer term than other heating methods without any maintenance since it is not necessary to heat the filament at high temperature.

Figure 2 shows the novel design of a cathode plug assembly which contains the system of the backside electron beam heating for the RF gun in SuperKEKB electron linac. This new cathode plug has an original cathode holder that hardly generates the position slippage of photocathode from the optimum position by thermal expansion of cathode holder. In addition, this new cathode plug also has a choke structure for RF shielding. We are developing a power supply which contains self-temperature- control function.
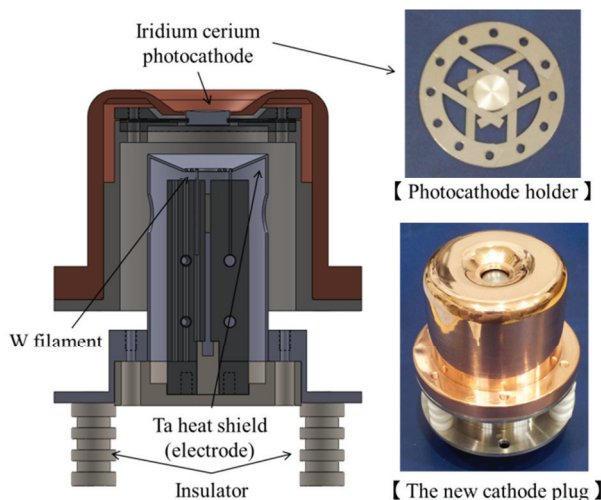

Figure 2: Novel design of a cathode plug.

The CW Laser Heating

The CW laser heating is a method of cathode heating using an energy deposition of photon flux. The direct laser irradiation is so efficient that heating system is equipped without a heating shielding and an electrical circuit in the gun chamber for cathode heating [7]. Moreover, higher-power laser diodes (100 Watt Class) have recently become commercially available at very low cost. Therefore, the characteristics of the CW laser heating system with an Ir_5Ce photocathode have been experimentally investigated in order to observe the practicality of this heating system.

The experimental setup for the demonstration of the CW laser heating is shown in Figure 3. A fiber-coupled laser diode emitting at 940 nm was used to heat the iridium cerium photocathode. The maximum output power of this product is 70 W. A test sample of a backside graphite coated photocathode with an area of 16 mm^2 was supported on a tantalum holder. The surface temperature on photocathode was measured by thermocouple.
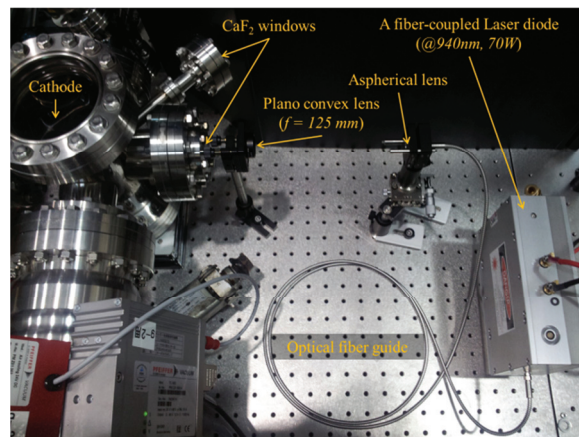

Figure 3: Experimental setup for the laser diode heating.

Figure 4 shows the dependence of the surface temperature of Ir_5Ce photocathode on the output power from the laser diode. In fact, an input power for cathode heating was reduced to 81.65 % of the output power from the laser diode due to laser absorption on a transmission window and reflection on the surface of graphite coating. This graphite coated photocathode was heated from room temperature to greater than 1000 °C with 20 W output power from the laser diode.
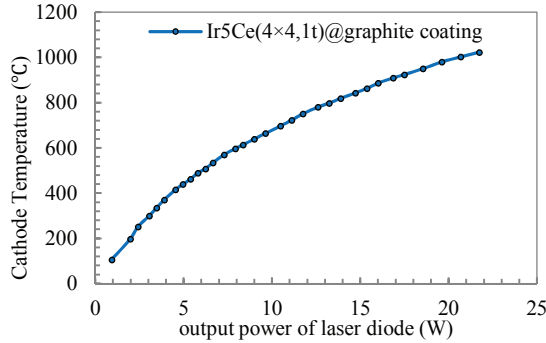

Figure 4: Dependence of the surface temperature of iridium cerium photocathode on the output power from the laser diode.

The Pre-Pulse Laser Heating

The pre-pulse laser heating is a method of a rapid heating process using laser pulse energy deposition. It is expected that the quantum efficiency can be increased instantaneously by an irradiation of laser pre-pulse, and higher charge electron beams will be generated by irradiation of UV laser synchronized with the temperature increase. This method also has merits that a heating system does not need a heating shielding and an electrical circuit in the gun chamber. In addition, it is expected that the generations of dark currents can be less than that in other heating system since a time duration of high temperature is extremely short.

We have calculated a time dependence on the surface temperature using the one-dimensional diffusion equation to model the pre-pulse laser heating by nanosecond laser pulses. The temperature deviation is governed by the diffusion equation, the laser pulse profile, and the boundary conditions, respectively [8] given by

$$\frac{\partial}{\partial t}T(z,t) = \kappa\frac{\partial^2}{\partial z^2}T(z,t) + \frac{\varepsilon}{\rho C_P}\frac{P_0}{\pi r^2}e^{-\frac{(t-t_0)^2}{2\sigma^2}}\delta(z) \quad (1)$$

Boundary Conditions

$$T(z,0) = 0, \qquad \left(\frac{\partial}{\partial z}T(z,t)\right)_{z=0} = 0. \quad (2)$$

where the cathode emissivity ε, specific heat capacity C_p, mass density ρ, and the thermal diffusivity κ. The temperature deviation $T(z, t)$ is a function of depth z from the cathode surface and time t. We assumed that the

profile of the laser pre-pulse is Gaussian envelope with offset t_0 and width σ, P_0 is the peak power of laser pulse and R is the radius of laser spot on the photocathode. We solved the one-dimensional diffusion equation for $T(0, t)$ since the photoelectrons are generated within a few nanometer from the cathode surface.

The temperature increase and normalized laser envelope of a heating pulse as a function of time are shown in Figure 5. We could estimate that Ir_5Ce photocathode can be heated instantaneously from room temperature to greater than 1300 K by irradiation of the fundamental wave of Nd:YAG laser with 10 ns pulse duration and energy density of 0.8 J/cm^2.

The demonstration experiment of the QE enhancement scheme using the pre-pulse laser heating is being conducted by the pulsed laser irradiation from the Q-switch Nd:YAG laser (1064 nm, 10 ns, 10 Hz).
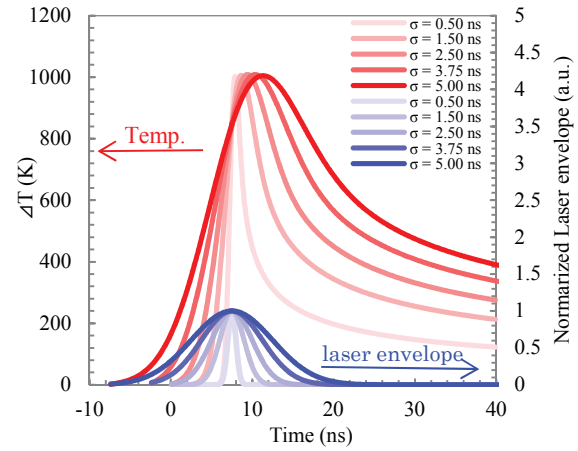

Figure 5: Temperature increase and normalized laser envelope of a heating pulse as a function of time.

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03 Particle Sources and Alternative Acceleration Techniques

T02 Electron Sources