Josh Yoskowitz
Photogun Magnetic Field Idea

1 Purpose

Ion backbombardment is one of the main causes of photocathode QE degradation. Residual gas within the accelerator can be ionized by the electron beam and then accelerated toward the photocathode. If the ions have sufficient kinetic energy, they can damage the photocathode and thus decrease its QE.

Since the photogun is designed to have the electron beam go in a straight line from the photocathode, any ions formed are accelerated straight back towards the photocathode. However, if the electron beam trajectory is curved due to a perpendicular, uniform magnetic field, any ions that are accelerated towards the photocathode will be deflected at larger bending radii, since the ions are much more massive than the electrons. Thus, one plausible design for hindering ion backbombardment is to have a uniform magnetic field that is perpendicular to the electron beam.

2 Theory

A particle with charge q in a uniform magnetic field $\vec{B}$ will experience a magnetic force $\vec{F}_B$ given by

$$\vec{F}_B = q\vec{v} \times \vec{B} \tag{1}$$

If the particle's velocity $\vec{v}$ is perpendicular to $\vec{B}$, then the particle will move in a circle. The force that keeps a particle moving in a circle is the centripetal force $\vec{F}_c$ given by

$$\left|\vec{F}_c\right| = \frac{mv^2}{r} \tag{2}$$

Equating (1) and (2) yields

$$\begin{aligned} \left|\vec{F}_B\right| &= \left|\vec{F}_c\right| \\ |q|\, vB &= \frac{mv^2}{r} \\ r_L &= \frac{mv_\perp}{|q|\, B} \qquad (3) \end{aligned}$$

Equation (3) yields an expression for r_L, which is known as the Larmor radius for a charged particle in a uniform magnetic field perpendicular to its velocity $v_\perp$. This equation holds for non-relativistic particles. For relativistic particles, we add the Lorentz factor γ:

$$r_L = \frac{\gamma m v_\perp}{|q|\, B} \tag{4}$$

Note that we have neglected any other possible forces, such as the force due to the beam potential. We'll assume that this force is negligible compared to the magnetic force. Further work is needed to determine whether or not this is a valid approximation.

3 Some example calculations

Assume that the bending radius of the electron beam is 1.000 m and the gun voltage is 200.0 kV. The kinetic energy is given by

$$\begin{aligned} E &= (\gamma - 1)\, mc^2 \\ \gamma &= \left(1 - \beta^2\right)^{-\frac{1}{2}} \\ \beta &= \frac{v_\perp}{c} \end{aligned}$$

We can solve the energy equation for $v_\perp$:

$$\gamma = \frac{E}{mc^2} + 1$$
$$1 - \beta^2 = \left(\frac{1}{\frac{E}{mc^2} + 1}\right)^2$$
$$v_\perp = c\sqrt{1 - \left(\frac{1}{\frac{E}{mc^2} + 1}\right)^2}$$

In this case, the electrons have energy 200 keV and their rest mass is approximately 511 keV. Thus, the electrons have a velocity of 2.084×10^8 $\frac{\text{m}}{\text{s}}$. The required magnetic field is found by solving equation (4) for B:

$$B = \frac{|q|\, r_L}{\gamma m v_\perp}$$

With $|q| = e = 1.602 \times 10^{-19}$ C, the required magnetic field is 1.185×10^{-3} T. For the same magnetic field, any ions present will have a larger bending radius than the electrons due to their higher mass. Below are calculated values of bending radii for a hydrogen gas ion a carbon monoxide ion with the values for an electron for comparision.

Name	m (kg)	γ	$v_\perp$ $\left(\frac{\text{m}}{\text{s}}\right)$	r_L (m)
Electron (e^-)	9.1094×10^{-31}	1.391	2.084×10^8	1.000
Hydrogen gas $\left(H_2^+\right)$	3.3462×10^{-27}	1.0002722	6.993×10^6	123.3
Carbon Monoxide (CO^+)	4.6512×10^{-26}	1.000007665	1.174×10^6	287.6

Table 1: Calculated parameters for various particles and molecules bending in a uniform magnetic field

Of course, other ions may be present such as N_2^+, O_2^+, CH_4^+, etc. However, we can clearly see that all of them will have much larger bending radii than the electron due to their relatively large mass and would not be able to reach the photocathode in a perpendicular magnetic field.