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Secondary Electron Emission at the SNS Storage Ring Collimator

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I. Summary

1. Secondary electron (SE) production is briefly reviewed. If the collimator of the SNS storage ring allows proton beam scraping to take place, the electron yield might be quite large.

2. At the AGS Booster, by steering the Au^{31+} ion beam into the electrostatic inflector, beam scraping effect on SE production is studied.

3. The results of this experiment can be translated into the situation of proton beam scraping at the SNS collimator. It seems sufficient to support a new look of the SNS ring collimator design.

II. Secondary Electron Production

In secondary electron emission, the electronic stopping (Coulomb collision) is dominant if the projectile velocity is larger than the Bohr velocity $2.18 \times 10^8\ cm/s$ ($\beta = 0.0073$). If the primary ion, proton, or electron have the same velocity, the kinetics of the collision is very similar [1,2]. The Seiler model shows that the peak SE production energy of projectile is around $E_k \approx 0.9\ MeV/u$ ($\beta = 0.044$). Also according to this model, the SE production rate at the SNS, $E_k \approx 1\ GeV/u$ ($\beta = 0.875$), is about 10% of the peak yield.

Since the electronic stopping power of the target is approximately proportional to q^2, where q is the charge state of the projectile, it was believed that the SE yield Y also has a q^2 dependance [5,6]. However, experimental results have shown that it is more likely a $q^{1.7}$ dependance [7].

Probably the most profound factor in SE emission is the projectile scraping effect. Only the excited electrons near the surface have a chance to escape, and a major part of stopping power of a grazing projectile is deposited on the surface. In [3], this dependance is estimated as a factor of $(cos\theta)^{-n}$, where a perpendicular incident implies $\theta = 0$, and a range of the index $0.8 \leq n \leq 1.5$ is indicated. The complication of this mechanism, both theoretically and experimentally, in fact prohibits any accurate account on this factor.

Following an experimental observation, in [8], it was calculated that $Y \approx 200$ for a grazing proton at the PSR of LANL ($\beta = 0.841$). The electrons collected there seem in agreement with this yield.

If the collimator of the SNS storage ring allows proton beam scraping to take place, the electron yield will probably be around 200. Note that this yield is about 1000 times higher than the yield that has been theoretically and experimentally confirmed, without the scraping effect.

To be more confident with the necessity to eliminate proton beam scraping on the surface of the collimator, an experiment was performed at the AGS Booster to study the beam scraping effect on the SE production.

III. Experiment at the AGS Booster

By horizontally steering the Au^{31+} ion beam into the electrostatic inflector, which guides the ion beam from the Tandem transfer line into the Booster orbit, a situation of beam scraping on the inflector surface at different angles is created. Since the projectile energy and charge state effects on the SE production are known, this scraping study could be a useful reference for the SNS collimator electron production.

The inflector has a horizontal aperture of 17 mm, and is usually charged at 24 KV. The capacitance at the inflector is about 300 pf, and the charging resistance is 1 $M\Omega$. The anode of the inflector is grounded, therefore, the cathode carries a voltage of -24 KV. By steering the ion beam into the cathode, the electrons there may escape from the surface, then these electrons are expelled by the cathode. By observing the cathode voltage, therefore, the secondary electron emission can be estimated. This is illustrated in Fig. 1.

The gold ions from the Tandem to Booster transfer line (TtB) carry a positive charge of 31, and the kinetic energy of $E_k \approx 0.9$ MeV/u ($\beta = 0.044$), which happens to be the peak production energy of SE.

In a normal running condition, the TtB line horizontal dipole 29TDH2 upstream the inflector was set at -0.55 A. The beam full width half magnitude (FWHM) size was 4 mm. It is believed that during 670 μs multiturn injection period, beam scraping at either the anode or the cathode causes a voltage drop at the inflector. This voltage drop is almost invisible at low intensity, and it is about 300 V at the high intensity. After stacking, the inflector voltage is recovered by the charging current. The high intensity of gold beam injection usually implies more than 3×10^9 ions per pulse.

By setting the DH2 current at -3.76 A, -3.96 A, and -4.16 A, the detected inflector voltage variation is shown in Fig.2. For convenience, the voltage has been offset by -24 KV. We observe that at the end of injection period, the inflector cathode voltage is raised by 2 KV, 8.6 KV, and 7 KV, respectively. In other words, the cathode voltage becomes -22 KV, -15.4 KV, and -17 KV at the end of stacking, respectively.

A simple model is used to explain the results. A constant voltage source, at $V_1 = -24$ KV, charges the inflector through $R = 1$ $M\Omega$. The inflector itself is represented by a capacitance of $C = 300$ pf, and its voltage is V_2. The ion beam generated SE production is modeled as a current source I. At the beginning of stacking, we have $V_1 = V_2 = -24$ KV, and $I = 0$. Once the ion beam is steered into the cathode, $I \neq 0$, and the inflector cathode voltage rises, which in turn induces the charging current through R. At the end of the stacking, once again $I = 0$. The inflector cathode voltage is recovered by the charging current. The following equation can be used to describe this model.

$$V_2 = V_{2,0} + \frac{1}{C}\int\left(\frac{V_1 - V_2}{R} - I\right)dt \qquad (1)$$

where $V_{2,0} = -24$ KV is the static cathode voltage. Using the detected V_2, we try to find I, which is then used to get the SE yield. This is,

$$I(t) = \frac{V_1 - V_2}{R} - C\frac{dV_2}{dt} \qquad (2)$$

By fitting to V_2, we found that both the rising and falling of this voltage are exponential, the time constant of the rising is $\tau_{rise} = 2 \times 10^{-4}$ sec., and the falling $\tau_{fall} = 3 \times 10^{-4}$ sec. This is shown in Fig.3, where the amplitude of V_2 is normalized to unity. The falling time constant confirms that $R = 1$ $M\Omega$ and $C = 300$ pf,

$$\tau_{fall} = RC = 10^6 \times 300 \times 10^{-12} = 3 \times 10^{-4}\,\text{sec}. \qquad (3)$$

On the other hand, the fit of the rising voltage, during the stacking period, requires I to be time dependent.

Take the case that the DH2 current of -3.96 A as an example. The current I is calculated using (2) and the measured V_2. The result is shown in Fig.4. At the beginning of stacking, this current is 13.3 mA, and at the end of stacking, it is reduced to 9 mA. This is not a surprise. However, a reliable explanation of this is difficult to reach. Among possible reasons, the most noticeable ones are:

1. Electrostatic potential that deflects the projectile. In our case, the inflector voltage has been dropped significantly during stacking. In fact, shortly after the beginning of stacking, most ions in the beam have been completely deflected and hit the anode.

2. Electron-depletion effect. At 13.3 mA, the electrons escape at a rate of 8.3×10^{16} per second. Depending on the thickness of the electron exciting layer, depletion might take place.

To estimate the SE yield due to beam scraping, therefore, the peak current of 13.3 mA can be used.

A nontrivial question is how many scraping ions are responsible for these secondary electrons. Assuming that the DH2 current -0.55 A places the beam in the center of the inflector aperture, and the current -4 A steers the beam center into the cathode. This gives rise to 3.45 A, which steer the beam horizontally by half the inflector aperture, 8.5 mm. It is shown in Fig.2 that at the DH2 current of -3.76 A, the cathode voltage is raised by 2 KV at the end of stacking. Decreasing the current by 0.2 A, the cathode voltage is raised by 8.6 KV, and another 0.2 A, it is 7 KV. DH2 current of 0.2 A implies a 0.5 mm beam horizontal position shift. In comparison, we note that the beam FWHM size was 4 mm, and $\sigma = 4/2.355 = 1.7$ mm.

Let us take 20% of the beam per pulse to be responsible for the scraping effect in producing SE. This is $3 \times 10^9 \times 0.2 = 6 \times 10^8$ ions. Thus, we have the SE yield per lost gold ion,

$$Y_1 = \frac{13.3 \times 10^{-3} \times 670 \times 10^{-6}}{1.6 \times 10^{-19} \times 6 \times 10^8} = 9.3 \times 10^4 \tag{4}$$

To translate this yield into the SNS situation, we take the SE production rate at 1 GeV as 10% of that in the experiment. Also we assume a projectile charge state dependance as $q^{1.7} = 31^{1.7} = 343$. Then, the SE yield shown in (4) is,

$$Y_2 = \frac{Y_1}{10 \times 343} = 27 \tag{5}$$

This yield is smaller than the one estimated in [8], however, it is much larger than the one observed in experiments, without scrapping effect. For instance, see [9]. Note also that the early estimate of the SNS collimator SE yield was 0.25 to 2, depending on the collimator edge angle [10].

IV. Conclusion

The experiment performed at the AGS Booster, using Au^{31+} ion beam to scrape on the electrostatic inflector, has shown the importance of the scraping effect on the secondary electron production. The result of this experiment seems sufficient to support a new look at the SNS ring collimator design [11].

V. Acknowledgment

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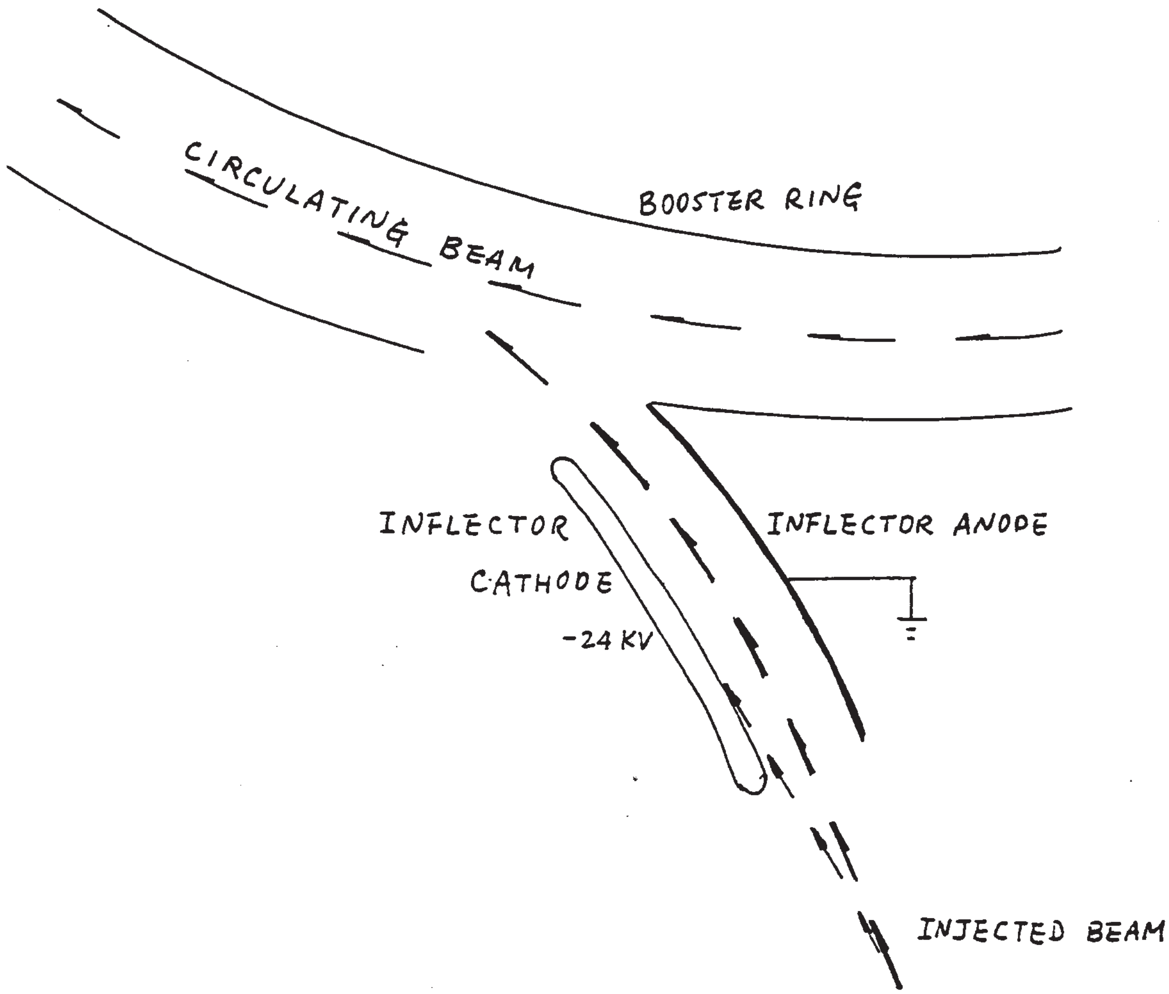

Fig.1. *Illustration of the Scraping of Ion Beam on the Inflector*

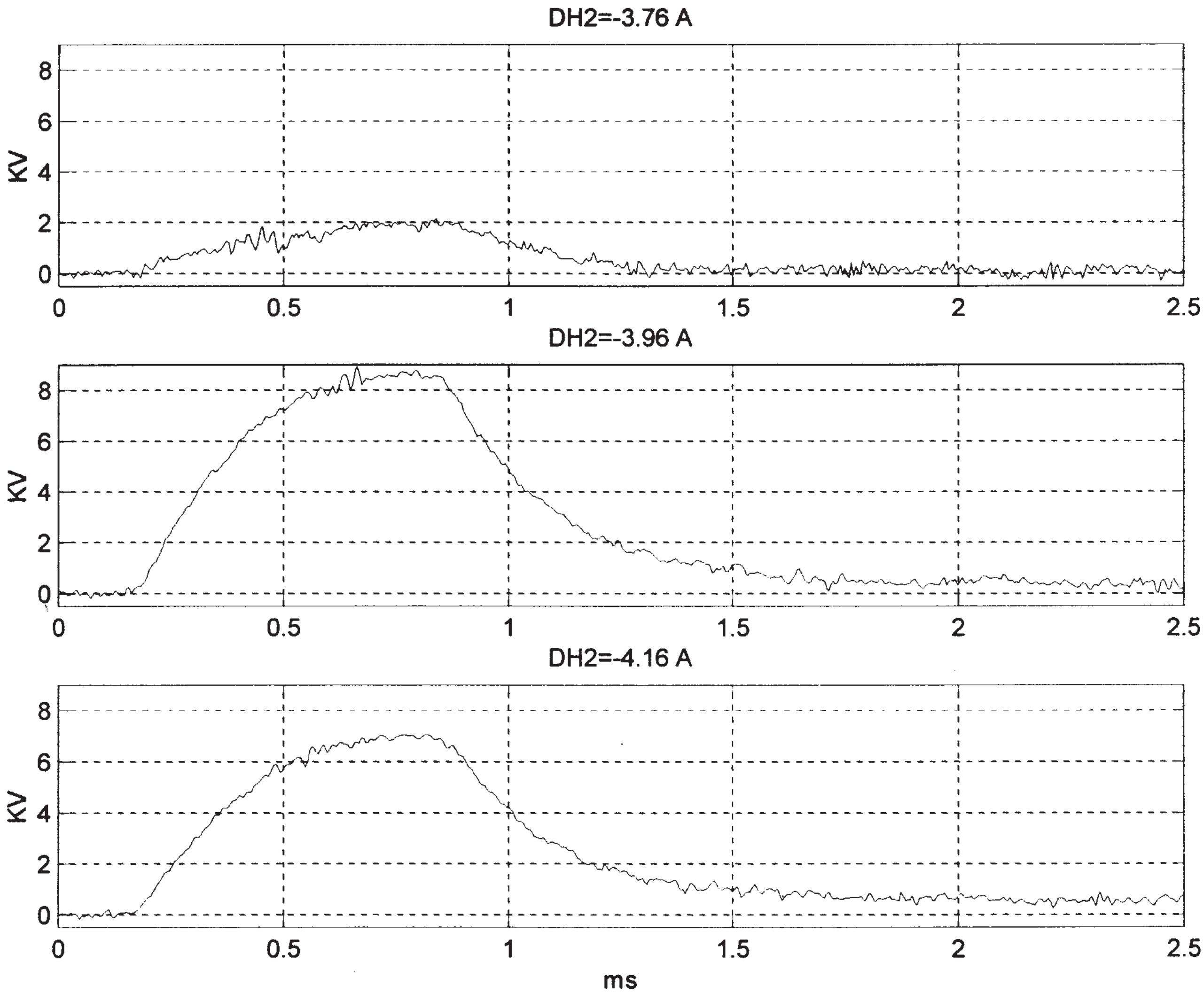

Fig.2. *Beam Scraping Induced Voltage on the Inflector*

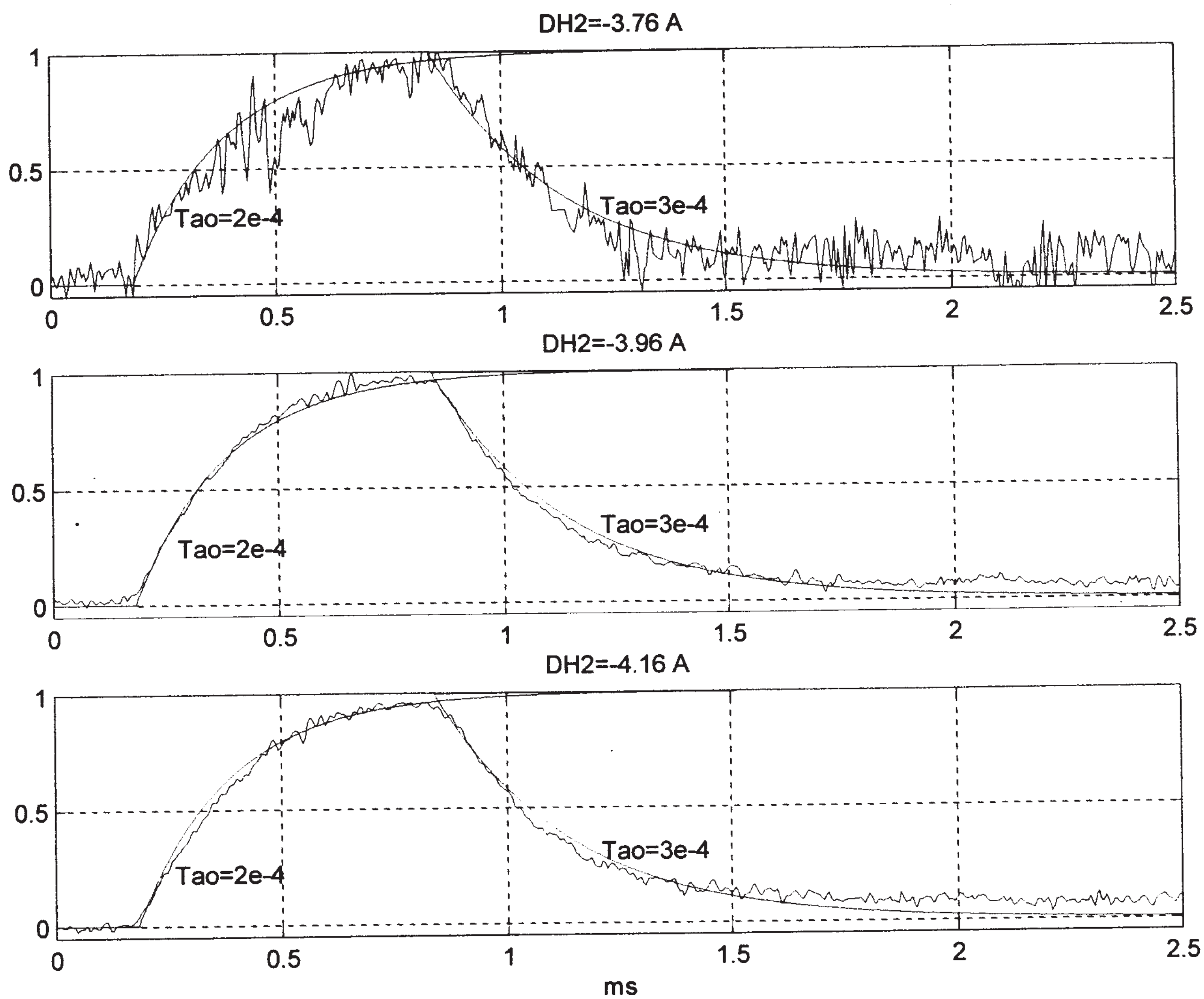

Fig.3. *Time Constants of the Rising and Falling Voltage on the Inflector Cathode*

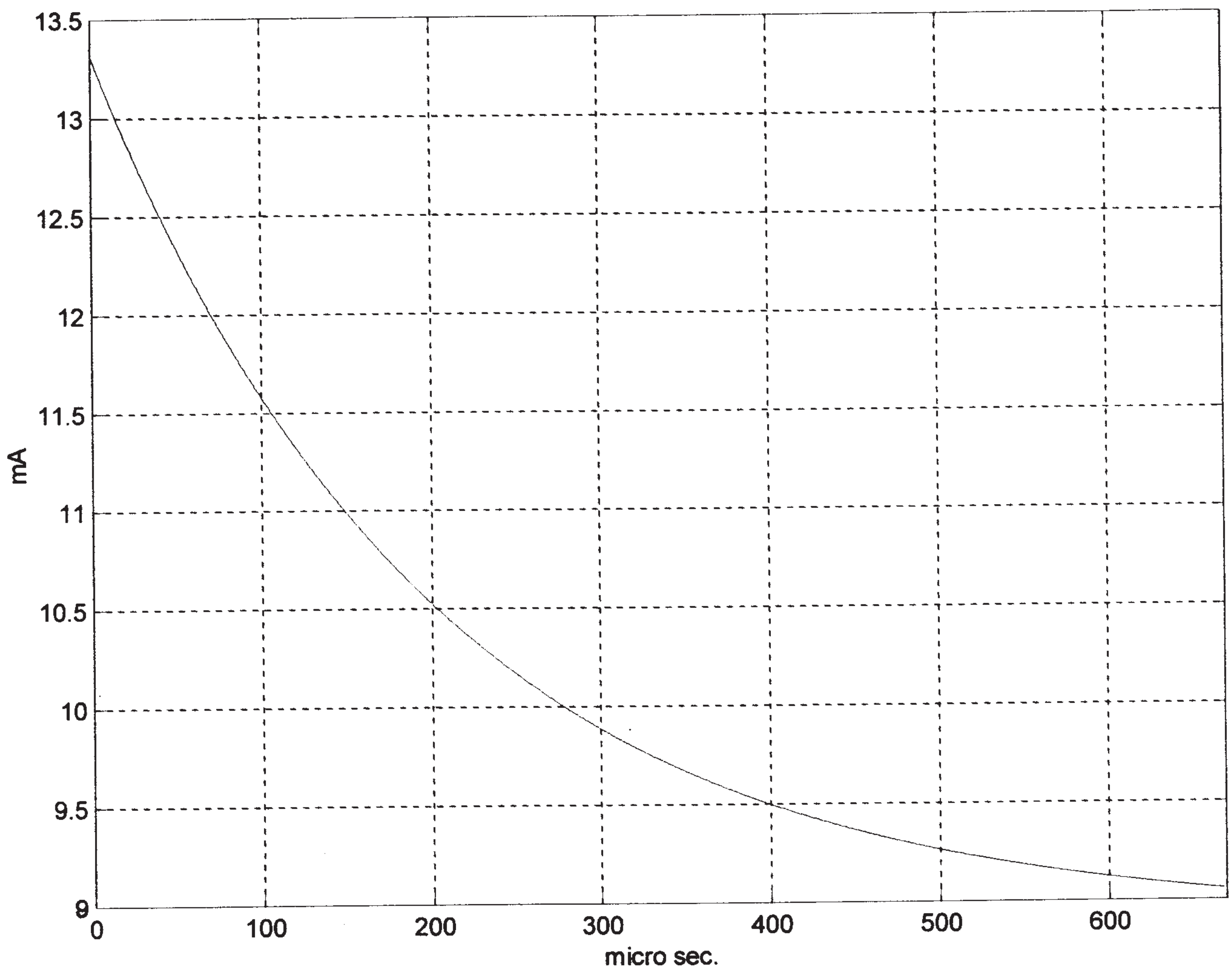

Fig.4. *Equivalent Current due to the Beam Scraping*