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ON SYNCHROTRON RADIATION PRODUCED

PHOTOELECTRONS FROM COPPER

Cu

G.E. Fischer and R.A. Mack

February 28, 1965

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ON SYNCHROTRON RADIATION PRODUCED PHOTOELECTRONS FROM COPPER

ABSTRACT

The absolute quantum efficiency of photoelectron production from copper was measured in a hitherto inaccessible photon energy region using the broad spectrum of polarized synchrotron radiation from the Cambridge Electron Accelerator. The results, believed accurate to within $\pm 10\%$, have application in the design of vacuum systems and beam current monitors for high current storage rings. The measurements were carried out under ultra-high vacuum conditions. Energy distributions of electrons resulting from photon spectra of various characteristic energies are presented. In the regions of photon energy below 50 ev and above 1 kev where data of previous investigators exist qualitative agreement of yield and angular dependence is found.

INTRODUCTION

The lack of laboratory light sources emitting photons in the energy range between 100 and 1000 ev ($100-10 \text{ \AA}^0$) has, in the past, inhibited measurements in this region. However, radiation of this kind is known to originate in stellar bodies, thermonuclear devices and high-energy circular electron accelerators. The motivation for the experiment described below stemmed from the so called "vacuum problem" of high-energy electron storage rings.

In brief, it is believed that the synchrotron radiation¹ from the circulating electrons causes ejection of photoelectrons which in turn release gas from the walls of the vacuum chamber by electrodesorption. In previously reported work² the electrodesorption probability was examined experimentally under environmental conditions similar to those thought to occur in a storage ring. These data were multiplied by the estimated photo-coefficient to yield a value of net gas evolution to be expected in storage ring operation. In the course of this investigation it was found that photo-yields produced by 100 to 1000 ev radiation had not been measured. It was the purpose of the present work, therefore, to establish these yields, their angular dependence and information on the energy distribution

¹J. Swinger, Phys. Rev. 75, 1912 (1949).

²CEAL-1013, "Vacuum Design Problems of High Current Storage Rings," G.E. Fischer and R.A. Mack (Oct. 1964).

of the photoelectrons. In order to compare the results with those of previous investigators in those regions of photon energy where measurements existed^{3,4} we "unfolded" the very broad synchrotron radiation spectrum and obtained absolute quantum efficiencies for various broadly defined energies. The target material chosen was high purity copper which has properties that make it suitable as a high power radiation absorber in a storage ring. Since the quantum efficiency for low energy photons is known to be extremely sensitive to surface contamination,³ the experiment was performed in ultra high vacuum under nearly the same conditions as those that might be expected in a storage ring.

APPARATUS

The layout of the experiment with respect to the Cambridge Electron Accelerator is shown in Figures 1 and 2. Radiation tangent to the equilibrium orbit near the beginning of magnet No. 25, passes out of the machine through a special vacuum chamber and 2" diameter valve into a pipe containing many vertical-aperture limiting stops cooled by helium gas to about 10°K. Liquid helium consumption was about 2 liters/hr. After

³W.C. Walker, N. Waifan, G.L. Weissler, J. Appl. Phys. 26, 1366 (1955).

⁴A.S. Ganeev and I.M. Izrailev, Soviet Phys.-Tech. Phys. 7, 1021 (1963).

FIG. 1

Figure 2 Photograph of Apparatus located in the machine tunnel.
The mirror on top of the U. H. V. system permits obser-
vation of the target through the glass port.

passing through a 4" diameter ultra-high-vacuum valve, a pair of slits and a 72"-long conductance tube, the radiation strikes the target. Several horizontal slit widths from 1-1/2 to 3-1/2 inches and variable slit heights may be chosen by rotating the slotted cylinder by means of a motor driven magnetic coupling. Optical radiation diffusely reflected from the target can be seen at a 80-ft-distant observation station (located at the inner end of a radial access tunnel) by means of a high power telescope.

The ultra high vacuum system⁵ consists of a two section bakeable vessel which can be evacuated to pressures in the 10^{-11} torr range by an ion pump operated in conjunction with a titanium sublimator. A glass viewing port may be removed from the top for access. The system is rough-pumped by means of sorption pumps to reduce the possibility of oil contamination. During the experiment, with valves to the machine open and the cryogenic trap cold, the pressure near the target was 3×10^{-9} torr. Of this amount, 1×10^{-9} torr appeared to come from the machine. Mass spectrographic analysis indicated that half of the total pressure was due to residuals from the U.H.V. system (largely CO, H₂ and a little H₂O), the rest from an air leak. There was little evidence of heavy hydrocarbons.

⁵Constructed by Varian Associates, Vacuum Products Div., Palo Alto, California.

The target, a sheet of 0.032 inch thick certified OFHC brand copper,⁶ was mounted so that it could be rotated about a horizontal axis through its center. Water cooling tubes were soldered to its back. The soldering was done in air with pure indium metal. After soldering, the assembly was cleaned with Alkonox and hot water and rinsed in electronic grade alcohol. Before soldering and after cleaning, all parts of the target and cooling lines were glass-ball honed with 0.005-inch-diameter glass balls in a sand blasting machine. It is believed that the surface layer of metal is completely removed by such an operation. The sample was then immediately introduced into the U.H.V. system with no further treatment and was pumped down. The system was not baked before irradiation but was pumped for about three weeks while waiting for accelerator time.

The water cooling lines are brought through the envelope via ceramic seals. Two compensated thermistor probes⁷ having a resistance of about 2000 ohms at room temperature are located in the entrance and exit water streams. Their individual resistances were measured to within one ohm by means of a 200 cps A.C. bridge. Temperature differences between the inlet and outlet water were thus measurable to about 0.01°C. To eliminate

⁶American Climax Inc., Rockefeller Center, New York 20, N.Y.

⁷F.E.I. Iso-Curve Type No. 74502-106, Fenwal Electronics, Framingham, Massachusetts.

drifts in the ambient temperature of the target, a glass lined container full of deionized water at room temperature was kept under constant pressure to act as a source of water. The flow was timed with a 50 ml. burett and stop watch. The thermal time constant of the whole system, excluding a half minute transit time delay, was about 1 minute. An electron bombardment filament was used to check the factory calibration of the thermistors.

The photoelectric current was measured by observing the voltage across the shunt input resistor of a differential amplifier. The target was connected by a 80 foot cable. Figure 3 shows a photograph of the oscilloscope screen. The depression on the lower trace is proportional to the time average of the beam current in the machine for the particular acceleration cycle in question. Surrounding the target is a screen grid of fine tungsten wires spaced about 3/8-inch apart. This grid can be biased to 4 kv and is used either to assist the photoelectrons in leaving the target or to suppress them. Notice that the onset of the photoelectric current in Figure 3 is not coincident with the time of injection. One calculates that, with the magnetic field of the machine set to accelerate electrons to a maximum energy of 3.0 Gev, it takes respectively 2.05 and 4.75 milliseconds from the time of minimum field to accelerate electrons to 0.400 and 1.82 Gev, at which time the

Figure No. 3

Appearance of oscilloscope screen during a single acceleration cycle of the synchrotron. Upper photograph : screen voltage set to assist electrons leaving the target. Lower photograph : screen voltage set suppress the emission of electrons of energy less than 500 electron volts. Time scale : 1 millisecc/ cm. Gain of lower picture : 25 X gain of upper picture.

resulting photons have a critical energy of 5 and 500 volts respectively; that is sufficient energy to overcome the photoelectric work function of copper (Fig. 3a) and the superimposed bias (Fig. 3b).

CALCULATION OF PHOTON FLUX AND RADIATED POWER

The theory of radiation from an electron in a circular orbit is given by Swinger¹ and has been calculated for specific machines by Tombouliau and Hartman,⁸ Tombouliau and Bedo,⁹ and Haensel.¹⁰ The number of photons/sec, radiated into all angles, with energy E in the interval dE (ev) per circulating electron can be written

$$\frac{d^2N(E)}{dE dt} = \frac{4.381 \times 10^{12} \times g(r)}{\gamma^2(r)} \quad \text{where} \quad \gamma^2(r) = \left(\frac{E}{m_0 c^2} \right)^2, \quad r = \left(\frac{E}{E_c} \right),$$

and $g(r)$ is a universal spectral function expressed in terms of the "characteristic" or "critical" energy

$$E_c = 2.2 \times 10^3 \times \frac{E^3 \text{ (GeV)}}{R_{\text{magnetic in meters}}} \text{ eV.}$$

This function is similar to the function $G(y)$ in Equation 6, Reference 8, which contains an integral of the modified Bessel

⁸D.H. Tombouliau, P.L. Hartman, Phys. Rev. 102, 1423 (1956).

⁹D.H. Tombouliau, D.E. Bedo, J. Appl. Phys. 29, 804 (1958).

¹⁰R. Haensel, DESY Hamburg, Report No. A2, 101 (1963).

function. For convenience $g(r)$ is plotted in Fig. 4a. Fig. 4b shows a plot of the photon spectrum at various instants during the acceleration cycle when the CEA is operated at 3 GeV. Arrows next to the curves point out the critical energies at the various times indicated. One can see that the effect of raising the critical energy is largely to add photons at the high-energy end of the spectrum, leaving the low-energy end unchanged. The low energy asymptote can be seen to have an $\left(\frac{E}{E_c}\right)^{-2/3}$ dependence.

Figure 5 shows plots of incremental spectra derived by taking differences between the total spectra pertinent to a succession of instants during the acceleration cycle. The energy intervals are indicated at the bottom of Fig. 4. These differential spectra represent an unfolding of the synchrotron radiation, being the incremental photon flux produced between successive instants. Table I lists the numerical values. A check on the numerical integration for the total energy radiated up to 8 milliseconds agrees with the analytic integration to within 2%. Photons of energy less than the work function of copper were not used in the subsequent analysis. The geometry of the experiment was such that nearly all photons of energy exceeding 100 ev were captured on the target. Some corrections were applied between 5 and 100 ev for loss on the vertical slits.

FIG. 4_a

FIG. 4b

TABLE 1 3 GEV DIFFERENTIAL SPECTRA

Additional Number (in millions) of Photons per second per circulating electron
value in () corrected for cut-off and loss on vertical slits

		2 - 2.5	2.5 - 3	3 - 4	4 - 5	5 - 6	6 - 8	Time interval (ms)	Total Energy in Interval/sec
		.348-.597	.597-.843	.843-1.39	1.39-1.95	1.95-2.45	2.45-2.988	energy of machine electron GeV	
		4.74-17.9	17.9-50.2	50.2-226	226-626	626-1236	1236-2240	range of critical energy (eV)	
Energy Interval eV	Central Energy of Interval								
1 - 2.15	1.5	(0) 3.82	(0) 2.55	(0) .93	0			7.3	11
2.15-4.63	3.2	(0) 7.32	(0) 3.98	(0) 2.49	(0) .49	0		14.29	46
4.63-10.0	7.0	(6.1)12.0	(2.4)6.4	(1.2) 4.28	(.43) 2.14	0		24.82	173
10.0-21.5		(9.9)13.8	(6.5)11.0	(4.6) 9.85	(1.3) 3.48	(.4) 1.15		39.29	590
21.5-46.3	32	(6.8)7.63	(13.9)17.1	(12.2) 17.4	(4.44)7.45	(1.4)2.49		52.07	1660
46.3-100	70	(1.04)1.07	(12.4)13.1	(25.5) 28.6	(11.0)13.4	(4.18)5.35	(1.2) 1.6	63.12	4415
100-215	150	.023	3.8	34.4	23.2	10.4	6.9	78.70	11800
215-463	320		.17	22.1	36.1	18.6	12.4	89.37	28550
463-1000	700			5.9	32.6	31.0	24.1	93.60	65600
1K-2.15K	1500			.23	14.3	32.5	35.2	82.23	123100
2.15K-4.63K	3200				1.24	12.4	34.3	47.94	153200
4.63K-10.0K	7000					.80	10.4	11.20	78400
10.0K-21.5K	15000						.29	.29	8400
		(23.8)45.7	(39.1)58.1	(106) 126	(124) 134	(112) 115	(125)125	604.3	

Instantaneous energy radiated by
an electron at 8.0 msec. is 4.75×10^{11} eV./sec.

FIG 5

The accelerator magnet lattice contains regions of zero magnetic field. In computing radiation loss, one must take care in converting the number of electrons in the orbit into circulating current since not all electrons radiate at any given instant. For clarification a numerical example is given. The average orbit radius of the CEA is set by the radio frequency which is typically 475.70 Mc/s. Since the system works on the 360th harmonic, the revolution frequency is 1.325 Mc/s, which corresponds, since the particles are completely relativistic, to an average radius of 36.06 meters. If there are 10^{11} particles in the orbit, the circulating current is $\frac{10^{11} \times 1.325 \times 10^6}{6.281 \times 10^{15}} = 21.1$ milliamperes. This is the number of milliamperes measured by the pickup electrodes. The magnetic radius, however, is 26.62 meters so that only $\frac{26.62}{36.05}$ of all electrons in the orbit contribute to radiation at any instant.

The fraction of the so-calculated number of electrons that are effective in producing radiation that impinges on the target is then $\frac{d}{2\pi D}$ where d is the horizontal extent of the illuminated target and D is its distance from the tangent point on the orbit.

Formula I.11 of Reference 1 gives the energy radiated per electron per turn as $\frac{88.46 (E_{\text{Bev}})^4}{R_{\text{mag. in m.}}} \text{ kev.}$ Since this is

the number of kilovolts per turn one can simply multiply by the circulating current to derive the instantaneous power in kw that goes into radiation. This power is, of course, unchanged whether one considers a machine having straight section and 10^{11} particles with a revolution frequency of 1.32 megacycles or a reduced machine having no straight sections with fewer radiating particles but which revolve at higher frequency.

To first order, the magnetic field of the CEA varies as $B = B_{av}(1 - 1.018 \cos 2\pi ft)$, so that one may approximate the energy of the particles by $E(t) = E_m \sin^2 \left(\frac{\pi t}{2T} \right)$. If the radiated power varies as $E(t)^4$ then the ratio of the average to peak power will be $\frac{1}{T} \int_0^T \sin^8 \frac{\pi t}{2T} dt = \frac{2}{\pi} \int_0^{\pi/2} \sin^8 u du = \frac{105}{384}$

However, the beam is normally spilled at the top of the cycle and therefore can radiate for only half the time; consequently, the duty factor is $\frac{105}{768} = 0.137$. For example, a 4 ma beam with maximum energy of 5.0 Gev produces a total of 1.155 kw of which 1.77 watts impinge on the target.

CALIBRATION OF APPARATUS

Aside from the usual calibrations of amplifier gain and oscilloscope sensitivity, it was necessary to ascertain that measurements of photon flux were indeed absolute. Two conceptually separate approaches were taken and agreement between

these methods constitutes the basis for believing the flux to be known within $\pm 7\%$.

a) Calorimetric Method

As described above the target was equipped with cooling lines. We were able to measure the difference between the input and exit temperatures to about 0.01°C . The temperature of the input water was permitted to come to within a fraction of a degree of room temperature before use. A tungsten filament heated to emit electrons was turned on and, after the surrounding vacuum vessel had come to equilibrium, the thermal power radiated to the target was balanced out. Then, knowing the flow-rate of the water and knowing the bombarding voltage and current (typically one kilovolt and three milliamperes, respectively) we were able to compute the temperature rise. It agreed with the manufacturers calibration to within 10%. For the rather small temperature rises involved (i.e., about 1°C), the necessary radiation corrections were small.

After this calibration, synchrotron radiation from a 5 Gev electron beam was allowed to strike the target (the radiation was controlled by opening and closing the rotation slit). The apparatus and slits had previously been aligned to be within 0.030" of the median plane of the accelerator. Checks on the vertical orbit distortions, by means of displacement coils in the machine, indicated the fortunate result that within the

pertinent portion of the orbit (magnets 23 to 31), distortions considerably smaller than average were present. Displacements of 0.010" were noted. With the rotating slit open and high negative bias maintained on the target to suppress emission of electrons, a power of 1.74 watts was measured when the average beam current was 4.0 milliamperes. The beam was steady to about 10% during the measurements, which take several minutes; such variation is the primary limitation on the accuracy of the calibration.

For a 5 Gev electron beam nearly all the radiated power is contained in a vertical angular spread of ± 0.1 milliradian. To this must be added a contribution from the vertical betatron oscillations of about another ± 0.1 milliradian. If added in quadrature this implies that most of the power strikes the target within a vertical height of 0.10 inch. The power was measured as a function of slit opening and found to fall off for slit opening smaller than 0.12 inch. This indicates that the slit was well centered in the plane of the radiation and one should expect minimal spectral distortions with a wide open slit. Since the radiation is known to come from the beginning of a vertically defocussing machine magnet, it will appear to converge leaving the machine. No appreciable changes in solid angle that the target subtends should therefore result at the start of the acceleration cycle at which time the betatron amplitudes are larger. Some corrections were applied to

the low-energy data to make allowance for spectral distortions arising from the fact that low energy photons have wider angular distributions.

b) Flux Calculation

From an accurate knowledge of the beam energy¹¹ and the measured geometry of the apparatus, one may use the theory¹ to calculate the power incident on the target. The beam-current pick-up coil¹² used during the experiment was removed together with its amplifier from the machine and recalibrated in the laboratory. It is believed to be correct to 1%. The calculated power at 5.0 Gev and 4.0 milliamperes, and with the previously mentioned duty cycle factor, was 1.77 watts. Agreement between this number and the calorimetrically determined value is quite satisfactory.

RESULTS AND DISCUSSION

For storage ring design purposes one wishes to know the number of photoelectrons produced and their energy for a given characteristic energy of synchrotron radiation. This information is contained in Fig. 6. One may choose E_c and quickly extract the number of electrons in the energy region of interest. It was discovered that small stray magnetic fields from the machine

¹¹CEAL Report No. 1015, Herman Winick (Feb. 1965).

¹²CEA Report No. 89, L. Holcomb, D. Porat, K. Robinson (June 1962).

FIG. 6

influenced the emission of low energy electrons from the target during the later parts of the acceleration cycle. For this reason bias curves near zero volts are not shown. In addition, the target, when emitting large currents, will bias itself positive by about a volt. Space charge effects are considered negligible. It was found that a screen bias of +80 volts was sufficient to attract all the electrons from the target but the -10 volt curve might in fact be closer to -20 volts because of these effects for the higher critical energies. The higher bias curves are not affected.

To place a value on the photoefficiency, we unfolded the synchrotron radiation spectrum in the manner described; the results are shown in Fig. 7. A representative spectrum is indicated also. One can see that the yield falls off when the photon energy exceeds the energy of the L shells of copper (about one kilovolt), but the resolution is too poor to show this. The yields in this region are higher than those of Reference 4, but this also might be due to the resolution problem. The error bars in Fig. 7 represent variations in the measurements of oscilloscope photographs; they do not take into account the possible $\pm 7\%$ systematic error in absolute flux, an error that would affect all points the same way.

The results shown in Fig. 7 are those obtained after the target had been bombarded for about 3 hours with 1.7 watts of

synchrotron radiation. The pressure in the vessel was 3×10^{-9} torr, and a fresh coat of copper had just been evaporated onto the target face. It was not possible to detect a measurable difference before and after evaporation. A coat of copper had been evaporated in a test run 3 weeks earlier and the vessel was kept at 1.5×10^{-9} torr during this waiting interval.

Figure 8 shows the dependence of total yield on angle of incidence of the photon. For photon energies larger than 30 to 100 volts, the quantity $K \sin \theta$ is seen to be quite constant -- in agreement with the results of Rumsh, Lukirskii and Schemelev.¹³ At lower energies this angular dependence is seen to fail, in agreement with the results of Hintereger et al.¹⁴ and Samson.¹⁵ This is not surprising since the secant law is based on the simple picture that electrons come to the surface from an "effective depth". At low energies, where the surface roughness (particularly of a sand blasted surface) is comparable to the effective depth, the model should break down. Unfortunately, the 10 degree yield was not obtainable. The low energy yield is in good agreement with that of Reference 3 for clean surfaces.

¹³M.A. Rumsh, A.P. Lukirskii, V.N. Schemelev, Soviet Phys.-Doklady 135, 1231 (1960).

¹⁴L. Herous, J.E. Manson, H.E. Hintereger, J. Opt. Soc. Am. 55, 103 (1965).

¹⁵J.A.R. Samson, R.B. Cairns, Rev. Sci. Instr. 36, 19 (1965)

FIG.8

The yields shown are per incident photon and no correction has been applied for the reflectivity of the sample. It should be noted that the results presented are valid for photons that are highly polarized in the horizontal plane. This is the plane of the accelerator and also contains the axis of rotation of the target. While the degree of polarization is a function of wavelength and the angle made with this plane, an integration over all angles and wavelengths yields a ratio of horizontal to vertical polarization power of 7 to 1.¹⁶ 100% polarization for all wavelengths exists for radiation at 0 degrees with respect to the horizontal plane. A small effect of polarization on the photoyield has been noted by Rumsh and Schemelev.¹⁷

To dramatize the role that secondary electrons play in the high energy photoelectric process, we have plotted in Fig. 9 the energy spectrum of emitted electrons for various characteristic energies. One may see that a large number of electrons have energies below 100 ev. This fact confirms the conclusions drawn by Rumsh and Schemelev¹⁸ and by Nakhodkin and Melnik.¹⁹ An examination of Fig. 6 shows the ever-increasing role that the higher energy photons play. Above L shell energies, these effects will fall off.

¹⁶K.W. Robinson, Private communication.

¹⁷M.A. Rumsh and V.N. Schemelev, Soviet, Phys.-Solid State 4, 1503 (1963).

¹⁸M.A. Rumsh, V.N. Schemelev, Soviet Phys.-Solid State 5, 46 (1963).

¹⁹N.G. Nakhodkin, P.V. Melnik, Soviet Phys.-Solid State 5, 1779 (1964).

FIG. 9

CONCLUSIONS

1. The information presented above may be used in conjunction with electrodesorption data to calculate the gas load due to synchrotron radiation in a high-current storage ring. In a previous article² an analysis was made on the basis of the then available photoelectric data. For comparison, Fig. 6 may be extrapolated to a characteristic energy $E_c = 3.9$ kev (i.e., for a 3 Bev storage ring of the proposed size) and the yield corrected to 10° angle of incidence using Fig. 8. For a one ampere stored current 2×10^{12} electrons are effective. The results of this computation are shown in Table II.

TABLE II

Comparison of Previous and Present Photoyield Data

Number of Electrons/sec with Energy Greater than V Volts		
V Volts	Previous Estimate	Calc. from this Experiment
0	194×10^{18}	200×10^{18}
20	96	64
100	49	40
1000	4.3	7.2

From Table II one may see that no substantial changes in gas load are therefore expected.

2. It appears from this experiment that a measurement of the photoyield or photo-power permits an accurate and simple determination counter rotating beam currents in a storage ring.

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