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CALCULATIONS AS TO HOW LARGE A DOSE-RATE OF
SYNCHROTRON RADIATION WOULD BE RECEIVED BY A
PERSON STANDING CLOSE TO THE CEA RING OR BYPASS
WHEN THERE IS A 5-MA-AVE 3-GeV BEAM STORED THERE

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March 30, 1972

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Calculations as to How Large a Dose-Rate of
Synchrotron Radiation Would Be Received by a
Person Standing Close to the CEA Ring or Bypass
When There Is a 5-mA-ave 3-GeV Beam Stored There

Summary

Ring The vacuum chambers of the synchrotron ring proper include three stainless steel windows that have thicknesses of 10, 30, and 60 mils. Normally, these windows are not used and are kept covered by 1/8-inch-thick stainless-steel clip-on cover plates. Consider the synchrotron radiation incident on the thinnest window when there is a 5-mA-ave 3-GeV beam in storage. Calculations show that if a person were to stand at such a position, 10 ft. from the window, that his eye was in the path of the synchrotron radiation that emerges through window and cover, his eye would receive only a very small dose-rate: < 1 mrem/sec. If for some reason the window cover were absent, the dose-rate would be large: ~ 0.5 rem/sec.

Bypass Two of the four 3-mil-thick stainless steel windows of the bypass are normally covered by 1-inch-thick lead plates

leg

and the other two are normally left uncovered in order to minimize the amount of mass lying between bypass interaction region and bypass on-axis luminosity monitors. The 2-ft-long region between uncovered window and monitor is partially enclosed by massive equipment, and it would be difficult for a person to get his head into this region. Calculations show that if, somehow, a person were situated so that one eye was in the path of the synchrotron radiation emerging from an uncovered window with a 5-mA-ave 3-GeV beam in storage, this eye would receive a dose rate of $\sim 10,000$ rem/sec. Interposing the 1-inch-thick lead plate would reduce the rate to < 1 mrem/hr. (Interposing merely a 1/8-inch-thick stainless steel plate would not be adequate: the dose-rate would still be large: ~ 10 rem/sec.)

Appendix 1 discusses the 2.5-GeV case, which yields dose-rates that, typically, are one order of magnitude less.

Acknowledgment

I am indebted to many persons, including R. A. Mack and K. W. Robinson for advice given several years ago, and to A. Hofmann and J. Shapiro for advice given in recent weeks.

PART 1. Introduction

Because, at the CEA e^-e^+ colliding beam facility, Bypass Group persons and Operations Division persons occasionally enter the Circular Tunnel and Target Area (in accordance with certain "stored-beam special access" safety regulations) while beams are in storage there, it is desirable to estimate the maximum synchrotron-radiation dose-rates that these persons might encounter if they worked near certain stainless steel (ss) windows in the vacuum chambers of the synchrotron ring and bypass and if the window covers were, for some reason, absent. (The danger from a sudden dumping of the high-energy beam requires consideration also, but is outside the scope of this report.)

Such stored-beam special access has been -- and still is -- considered safe inasmuch as:

There is practically no synchrotron radiation at locations radially inward from the orbit.

The major part of the synchrotron radiation is sufficiently soft (sufficiently small photon energy) as to be stopped by the walls of vacuum chambers and straight section tanks, and by simple covers fitted to the windows.

Such localized emission of high-energy component of synchrotron radiation as does occur tends to occur along lines tangent to the orbit, and the men in question have been instructed to (a) remain at radially inward locations or (b) keep all parts of the body well below the horizontal plane that contains the tangents.

PART 2. Synchrotron Radiation from Beam in Ring

A. Spectral Energy Distribution

Figure 1 shows, in log-log format, the spectral energy distribution of the synchrotron radiation emitted by a 3-GeV electron in the CEA synchrotron ring proper. The ordinate is radiated power per eV of bandwidth and the abscissa is photon energy. The data are from R. A. Mack's Report CEAL-1027 and his 4/30/69 memorandum on the same subject. This format is excellently suited to providing, in a single curve, high relative precision over a wide (3-decade) range of ordinate and wide (4-decade) range of abscissa. The peak of the curve is at ~ 0.5 KeV.

B. Total Power

Figure 2, employing linear abscissa and ordinate scales, has the merit of facilitating estimation of total power within a given range of photon energy. One simply measures the area under the curve. Rough inspection indicates the total area pertinent to a 3-GeV electron to be ~ 5 to 10×10^{-8} watt.

Recalling that the CEA nominal current of some years ago was 21 mA ave and consisted of 10^{11} electrons (per CEAL-1000), and noting that a 5-mA-ave current consists of $(10^{11})(5/21) = 2.38 \times 10^{10}$ electrons, one finds that the power radiated by a 5-mA ave current of 3-GeV electrons is:
 $(2.38 \times 10^{10})(5 \text{ to } 10 \times 10^{-8} \text{ watt}) = 1 \text{ to } 2 \text{ kw.}$

A more accurate figure may be obtained by employing the pertinent equation from CEAL-1027 (for a ring that contains no field-free regions) and then correcting for the presence of

Fig. 1. Spectral Energy Distribution of Synchrotron Radiation from the CEA at Indicated Machine Energy. Ordinate is instantaneous rate of emission of electromagnetic power (in a 1-ev-wide band of photon energy) by one electron in actual orbit -- averaged over one turn. Data per R.A.Mack; see his Rpt. CEAL-1027 and his 4/30/69 memo. Plotted by W.A.S. 5/1/69

↑ 2
Power
(10^{-11} watt)

Fig. 2. Linear plot of spectral energy distribution in synchrotron radiation from one electron at 3-GeV, in CEA ring. Ordinate is power in 1-ev bandwidth at the indicated photon energy. Abscissa is photon energy.

Plotted 2/4/72 by W. A. Shurcliff from data from R. Mack's Report CEAL-1027 and his 4/30/69 memo, and Shurcliff's (corrected) log-log graph of that data. Plotted here on linear scale, per K. W. Robinson's suggestion. Symbols $\boxed{50}$, $\boxed{10}$, etc., indicate photon-energies beyond which 50%, 10%, etc., of the power lies.

such regions in the CEA ring. If current I , energy E , and radius-of-curvature R are expressed in mA, GeV, and m, the equation is:

$$\text{Power} = 88.46 \left(\frac{IE^4}{R} \right) w.$$

The radius of curvature of path segments within the bending magnets of the CEA ring is 86 ft. (per CEAL-100, p. 3.9), i.e., 26.26 m. Thus the power radiated by a 5-mA-ave 3-GeV beam in an ideal orbit of this curvature is:

$$\text{Power} = 88.46 \left(\frac{(5)(3^4)}{26.26} \right) w = 1.34 \text{ kw.}$$

At the CEA, about 70% of the circumference of the orbit is between the poles of bending magnets and has the above-mentioned radius of curvature. About 30% of the circumference is in field-free straight sections. Thus the duty factor of synchrotron radiation is $\sim 70\%$, relative to an ideal orbit. Accordingly, the actual power output by the beam in question, in the CEA ring, is $(0.70)(1.34 \text{ kw}) = \sim 1.0 \text{ kw}$.

C. Photon Energies Beyond Which Just 50%, 10%, 1%, and 0.1% of the Power Lies

These energies are easily calculated once one knows the critical energy E_c , which is the photon energy beyond which 50% of the power lies. The equation giving E_c appears on p. 3 of CEAL-1027. If, as before, beam energy E and radius of curvature R are expressed in GeV and m, the expression becomes:

$$E_c = 2218 \left(\frac{E^3}{R} \right) \text{ eV.}$$

If the energy is 3 GeV and the radius of curvature is 26.26 m,

$$E_c = 2218 \left(\frac{3^3}{26.26} \right) \text{ eV} = 2300 \text{ eV or } 2.3 \text{ KeV.}$$

To find the photon energy beyond which just 10% of the power lies, one refers to column 3 of p.7 of CEAL-1027 and observes that the energy in question is $2.85 (E_c)$, i.e., is $2.85 (2.3 \text{ KeV}) = 6.5 \text{ KeV}$. Likewise one finds that the photon energies beyond which just 1% and 0.1% of the power lies are 12.5 KeV and 18 KeV.

To convert these photon-energy values to the corresponding wavelengths, one may employ the conversion relation presented in "Handbook of Chemistry and Physics", 37 Ed., p.3086:

Wavelength in units of 10^{-8} cm (i.e., in Angstrom units (A)) is equal to 12400 divided by the photon energy in units of eV.

One finds that the wavelengths corresponding to 2.3, 6.5, 12.5, and 18 KeV are 5.4, 1.9, 0.99, and 0.69 A respectively.

To find a rough value of the 0.01% photon-energy, one may extrapolate the series of 10%, 1%, 0.1% photon energies (namely 6.5 KeV, 12.5 KeV, and 18 KeV) to obtain about 22 to 24 KeV. To err on the safe side, I use the value 22 KeV. (One cannot obtain an accurate value of the photon energy in question from Report CEAL-1027 because of certain approximations made there for high values of energy; see p. 13 of that report).

D. Containment by Standard Vacuum Chambers and Straight-- Section Tanks

The radially outer walls of vacuum chambers are 0.4 inch thick and are of alumina (Al_2O_3). Noting that the synchrotron radiation strikes the walls at a small ($\sim 4^\circ$) grazing angle,

one would expect only negligible amounts of such radiation to emerge from those chambers. Likewise one would expect only negligible amounts to emerge from the (stainless-steel) straight section tanks and the (copper) rf cavities.

E. Descriptions of Windows on Vacuum Chambers in Ring

The vacuum chambers of the ring include three windows, i.e., three ports that are normal to the direction of the synchrotron radiation and have been made thin in order to have high transmittance for multi-GeV beams. Such windows are on Vacuum Chambers 2, 4, and 26. Each window is ~ 4 in. from the orbit; see Fig. 3.

Each window is of Type 304 stainless steel. The thicknesses of the Vacuum Chamber 2, 4, and 26 windows are 10, 30, and 60 mils.

The window of Vacuum Chamber 2 is used as such on rare occasions only -- in connection with the calibration of special detectors (for NAL, e.g.) by an external multi-GeV beam. The windows of Vacuum Chambers 4 and 26 are not used as such.

Fig. 3. Window in vacuum chamber of ring.

F. The Pseudo-Windows of the Ring

There are four pseudo-windows, situated on Vacuum Chambers 2, 4, 26, and 28. Each pseudo-window consists of a piece of stainless steel forming the end of an extra-wide portion of the chamber. Drawings indicate that the pseudo-window is 1/8 inch thick and is of Type 304 stainless steel. (This piece of metal is not intended to be a window; but, being normal to the direction of the synchrotron radiation incident, it acts as a window with respect to synchrotron radiation photons having energies exceeding about 60 KeV (as is shown in Table 2). However, the total transmitted power (with 5-mA-ave 3-GeV beam in orbit) is so small as to produce a dose of no more than about 1 mrem/sec, as shown in Section 2L. Thus the pseudo-windows will not be considered further in this report.

G. Chemical Composition of Type 304 Stainless Steel

This alloy contains (by weight) about 70% iron, 20% chromium, and 10% nickel, according to an Allegheny-Ludlum Steel Co. handbook. The atomic numbers of these elements are 26, 24, and 28 respectively. The specific gravity of the alloy is 8.0.

H. Transmittance of Windows

To compute the transmittance T of a stainless steel window with respect to perpendicularly-incident x-rays of a given photon energy (or wavelength), one employs the relation:

$$T = e^{-\mu x}$$

where μ is the linear absorption coefficient (cm^{-1}) at the photon energy in question and x is the thickness of the metal piece (cm).

Pertinent absorption coefficients may be found in "Handbook of Chemistry and Physics", 49 Ed., 1968, p. E-133. The values presented are values of (μ/ρ) , where ρ is the (dimensionless) specific gravity of the material in question.

At photon energies of 10 KeV or greater, the absorption coefficient of nickel is about 10% greater than that of iron, and the absorption coefficient of chromium is about 10% less than that of iron. Accordingly (and inasmuch as both of these elements are but minor constituents of the alloy), when dealing with photons of energy exceeding 10 KeV I shall regard the alloy as consisting entirely of iron.

It is easily shown that, at photon energies of 2 to 5 KeV, correspondingly, the coefficients of the three elements involved are sufficiently similar that one may regard the alloy as consisting solely of iron.

At photon energies below 2 KeV each of these materials, even if present as films as thin as 3 mils, has essentially zero transmittance.

The K-edge of the absorption spectrum of iron is at 7 KeV, and accordingly at slightly smaller photon energies (near 6.5 KeV) the absorption coefficient is much less than at, say, 7.5 KeV. The step-wise drop amounts to a factor of 10.

Because the absorption by iron near 6.5 KeV is low, the (high i.e., one-order-of-magnitude greater) absorption by chromium here is important. To an important extent, the absorption by chromium ($\sim 5 \times 10^2 \text{ cm}^{-1}$) compensates for the dearth of absorption by iron (54 cm^{-1}). The effective absorption coefficient has the intermediate value of $\sim 1.2 \times 10^2 \text{ cm}^{-1}$. (I will omit the derivation of this number, because, as indicated in the following tables, the absorption is so great that employment of an exact value is unnecessary.)

Table 1 presents the pertinent values of (μ/ρ) , and also the values of μ . In addition it presents the values of (μx) for window thicknesses of 10 mils (0.025 cm.), 30 mils (0.076 cm.), 60 mils (0.15 cm.), and 1/8 inch (0.3 cm.). It presents also the transmittances of the windows at the key photon energies mentioned.

Here is a sample calculation for 10-mil (0.025 cm.) window and a 18 KeV photon energy:

$$T = e^{-\mu x} = e^{-280(0.025)} = e^{-7.0} = 10^{-7.0(0.4343)} = 10^{-3}$$

1. Amount of Synchrotron Radiation Striking Window in Ring

The 1.0 kw of synchrotron radiation produced by the 3-GeV 5-mA-ave beam in the synchrotron ring (see Section 2B) is produced throughout the great majority of the orbit, specifically, throughout all 360° of direction change. The 3-cm-dia. window, mounted normal to the incident radiation, is located ~ 4 inch

TABLE 1

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Absorption Coefficients and Transmittances Pertinent
to Synchrotron Radiation from 3 GeV Beam in Ring

Photon Energy (KeV)	$(\mu/\rho)_{Fe}$ (cm^{-1})	$(\mu/\rho)_{SS}$ (cm^{-1})	μ^*_{SS} (cm^{-1})	TRANSMITTANCE (pure no.) of ss film of Thickness			
				10 mil (0.025cm)	30 mil (0.075cm)	60 mil (0.15cm)	1/8 inch (0.3cm)
2.3 (5.4A) "50% point"	10^3	$\sim 10^3$	$\sim 10^4$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-10}$
6.5 (1.9A) "10% point"	---	$1.2 \times 10^{2**}$	1×10^3	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-10}$
~ 7 (1.7A) Leakage band							
12.5 (0.99A) "1% point"	96	96	770	10^{-8}	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-10}$
18 (0.69A) "0.1% point"	35	35	280	10^{-3}	10^{-9}	$< 10^{-10}$	$< 10^{-10}$
~ 22 (0.50A) "0.01% point"	14	14	110	0.06	$\sim 10^{-3.6}$	$\sim 10^{-7}$	$< 10^{-10}$

* Obtained by multiplying data in previous column by 8, the specific gravity of stainless steel.

** Because the "10% point" photon energy (6.5 KeV) is very close to the leakage band energy (7 KeV), and because the width of this band is appreciable (such as 0.2 or 0.4 KeV), and because readily available data, in this range, for Fe and Cr are sufficiently meagre as to require interpolation, I have used the identical value of (μ/ρ) for 6.5 KeV and 7 KeV.

Source of absorption coefficient data: Handbook of Chemistry and Physics, 49 Ed. 1968, p. E-133.

from the orbit (see Fig. 3) and receives radiation that originates ~ 3 m upstream. Thus the window width subtends, at the point of origin of the radiation, $\arcsin(3 \text{ cm}/3\text{m})$ or $\arcsin 0.01$ (about 0.6°). This represents $(0.6)/360 = 0.17\%$ of the full circle. The height of the window provides 100% acceptance; that is, practically no radiation passes above it or below it. One concludes that the amount of radiation incident on the window is $(1.0 \text{ kw})(0.17\%) \approx 2 \text{ watts}$.

J. Amount Emerging from a 10-mil Window

About 0.01% of this power (about 2×10^{-4} watts) lies at photon energies of $\geq 22 \text{ KeV}$ (see Section 2C). The transmittance at this photon energy is 0.06 (per Table 1) and is greater at greater photon energy. Let us assume the representative value to be 0.1. Then the total power (at 22 KeV or greater photon energy) emerging from the window is $\sim (0.1)(2 \times 10^{-4} \text{ watt}) = 2 \times 10^{-5} \text{ watt}$.

One might expect some power in the leakage band near 7 KeV to emerge. But Table 1 shows that the transmittance here is extremely low ($<10^{-10}$), thanks to the fact that the chromium content of the material "plugs the leak." Also, no appreciable amount of power emerges at other photon energies below about 22 KeV. Thus the total amount of power emerging is $\sim 2 \times 10^{-5} \text{ watt}$.

(The thicker windows transmit amounts of power that are lower by several orders of magnitude.)

K. Dose-Rate That Such Emerging Power Could Produce

If a man's hand were placed in contact with the window, the irradiated portion of the hand would have a mass of ~ 1 g, as the following argument indicates. It may be shown from CEAL-1027 (per A. Hofmann) that the FWHH vertical spread of 1 A radiation produced by a 3-GeV beam in the ring is $\sim 1/3$ milliradian. Thus the height of the affected portion of an object close to the window would be $(1/3 \text{ milliradian})(3 \text{ m}) = 0.1 \text{ cm}$. The window width is 3 cm., and accordingly the area of the affected portion of the object would be $(0.1)(3 \text{ cm}) = 1/3 \text{ cm}^2$. Some of the radiation would penetrate several cm. into the body; if the average penetration were 3 cm., the total volume affected would be $(1/3 \text{ cm}^2)(3 \text{ cm}) = 1 \text{ cm}^3$, and the mass of such portion would be ~ 1 g.

If there were no cover over the 10-mil window, and if the 2×10^{-5} watt of synchrotron radiation emerging struck a 1-g portion of a man's hand that was in contact with the window, the dose rate to this portion would be:

$(2 \times 10^{-5} \text{ joule/sec})(10^7 \text{ erg/joule})(10^{-2} \text{ rad/erg}) = 2 \text{ rad/sec}$.
The RBE is ~ 1.0 , and accordingly the biological dose rate would be $\sim 2 \text{ rem/sec}$.

Because the window is situated in a relatively inaccessible region (between magnet coils that are only 3 1/2 inch apart), a man would be unable to place his trunk or head (or eye) near the window and in the emerging beam of synchrotron radiation. To intercept the beam with his eye he would have to be 3 or 2 m farther

downstream, and the dose rate would be less by a factor of ~ 4 because of the increased spread of the beam (and, to a much lesser extent, because of absorption by the air.) Thus the maximum dose to the eye would be of the order of 0.5 rem/sec.

(The dose-rate that could exist beyond a thicker window, i.e., a 30- or 60-mil window, would be less by several orders of magnitude.)

L. Transmittance of Cover

The data of Table 1 show that the transmittance of a standard cover for a window in the ring (1/8-inch Type 304 stainless steel cover) is less than 10^{-10} at all photon energies below 22 KeV. At 28 KeV the transmittance is 10^{-7} .

Thus no significant amount of radiation (< 1 mrem/sec) would emerge from a synchrotron ring window that was covered by such device -- when a 5-mA-ave 3-GeV beam was in storage.

PART 3 Synchrotron Radiation from Beam in Bypass

A. Introduction

To estimate the synchrotron-radiation dose produced by a beam in the bypass is especially necessary inasmuch as:

1. It is often necessary to have two of the bypass windows free of covers, as covers would interfere with measurement of luminosity.
2. The bypass bending magnets produce greater curvative of beam path than the magnets of the ring produce, and accordingly produce a spectrum of radiation that is shifted toward higher photon energies (to which stainless steel is more transparent).
3. The bypass windows are thinner than those in the ring.

Fig. 4. Main components of the CEA Bypass. The symbols Q, BM, ABM, LM, IR stand for quadrupole magnet, bending magnet, auxiliary bending magnet, luminosity monitor and interaction region. The four windows are W_A , W_B , $W_{A'}$, $W_{B'}$.

B. The Bypass Windows

Figure 4 shows the locations of the four bypass windows, each of which is of 3-mil-thick Type 304 stainless steel, per Dwg. C-23-V-35. Each is 10 cm. in diameter and is located ~ 2.5 m from the locus of origin of synchrotron radiation that strikes the window.

C. Asymmetry of Irradiation of Bypass Windows

As is apparent from Figure 5, the irradiation across disk-shaped Window W_A is far from uniform. The window is situated perpendicular to, and concentric with, the extended axis of the long straight path-segment from Auxiliary Bending Magnet 1 to Bending Magnet 1. There is a segment of the (curved) particle-path in Bending Magnet 1 that aims at the radially inner half of the window and accordingly much synchrotron strikes this half of the window. But there is no segment of particle-path that aims at the radially outer half of the window; accordingly practically no radiation strikes this half.

Fig. 5. Diagram (greatly exaggerated) showing the location of the 10-cm-dia Window W_A relative to the pertinent horizontal fan of synchrotron radiation.

Our task is to compute the dose rate that applies to an object in contact with (or close to) the radially inner portion of the window. (The dose-rate at the radially outer half is ~ 0 .) This same remark applies to the corresponding window W_A' .

Both portions of Window W_A (likewise W_{B1}) are irradiated, but with somewhat dissimilar intensities because of the two (not-equally-distant) loci-of-origin of the radiation.

D. Radius of Curvature of Path in Bypass Bending Magnet

Each half (upstream or downstream) of a bypass bending magnet has a magnetic length of 40 inches and a field strength such as to deflect an orbiting particle by 0.1 radian; see Fig. 6; also Dwg. D-23M-3. Thus the radius of curvature of the path here is $(40 \text{ inch})/(0.1) = 400 \text{ inches}$. This is to be compared with the radius of curvature of 1032 inches in a half-magnet of the synchrotron ring: the curvature in the bypass magnet is 2.5 times as great.

Fig. 6. Bending Magnet of Bypass.

E. Total Power per 0.6° of Arc Length in Bypass

The synchrotron-radiation power produced by an electron of given energy traveling in a truly circular synchrotron varies as (curvature)², per CEAL-1027. Curvature enters once because of greater intrinsic emissivity, and it enters again because the orbital frequency varies as curvature.

The CEA bypass bending-magnet trains occupy only a small (< 10%) fraction of the orbit circumference, and the bypass itself lengthens the path by a negligible amount (~ 1%). Accordingly the orbital frequency remains essentially unchanged when the beam is switched into the bypass.

Thus the power output per degree or orbit bending in a path-segment in a bypass bending magnet is related to the corresponding output in a ring bending magnet by the factor (curvature)¹, not (curvature)².

Referring to the ring result (PART 2), where the total power was found to be 1.0 kw, and the power incident on a window subtending 0.6° (thus receiving radiation from a 0.6° arc of orbit) was 2 watt, one concludes that a window of similar subtense in the bypass (having 2.5 times the curvature) would receive (2.5)(2 watt) = 5 watt (assuming, still, a 3-GeV 5-mA-ave beam).

F. Spectral Energy Distribution of Synchrotron Radiation Produced in the Bypass

Because the critical energy of a beam of given energy varies as the first power of curvature, per CEAL-1027, the critical

energy of the bypass synchrotron radiation is 2.5 times that originating in the ring, i.e., is $(2.5)(2.3 \text{ KeV}) = 5.7 \text{ KeV}$. One finds that the 50%, 10%, 1%, 0.1% points occur at about 5.7, 17, 31, 44, $\sim 55 \text{ KeV}$ respectively.

The pertinent spectral curve would be identical to that shown in Figure 1 and labeled "3-GeV" but shifted to the right by a factor of 2.5 in photon energy. (The curve would lie within 1/16-inch of the curve there labeled 4-GeV, in the graph region to the right of the vertical line corresponding to 20 KeV.)

G. Transmittance of Window

Table 2 presents the pertinent absorption coefficients of stainless steel and lists the transmittances of a 3-mil stainless steel window.

H. Power Emerging from 3-Mil Window of 0.6° Subtense

Referring to Table 2 and its row of data for 31-KeV radiation (the "1% point"), one estimates that the effective transmittance for such 1% of the power is ~ 0.7 . Thus the transmitted power at energies exceeding 31 KeV is:

$$(5 \text{ watt})(0.01)(0.7) = 0.04 \text{ watt.}$$

Referring to the rows of data for 17 and 31 KeV one estimates that the effective transmittance for the next (10% - 1%) or 9% increment in power is ~ 0.15 . Thus the transmitted power at energies from 17 to 31 KeV is:

$$(5 \text{ watt})(0.09)(0.15) = 0.07 \text{ watt}$$

Referring to the rows for 5.7, 7, and 17 KeV, one estimates

Absorption Coefficients and Transmittances Pertinent to
Synchrotron Radiation from 3-GeV Beam in Bypass

Photon Energy (KeV)	$(\mu/\rho)_{Fe}$ (cm^{-1})	$(\mu/\rho)_{SS}$ (cm^{-1})	μ_{SS} (cm^{-1})	TRANSMITTANCE (pure no.)	
				3-mil (0.0076 cm) SS window	1/8-inch SS cover
5.7 (2.2A) "50% point"	$\sim 10^3$	$\sim 10^3$	$\sim 10^4$	$< 10^{-10}$	$< 10^{-10}$
~ 7 (1.7A) Leakage band	---	1.2×10^2	1×10^3	3×10^{-4}	$< 10^{-10}$
17 (0.73A) "10% point"	42	42	340	0.08	$< 10^{-10}$
31 (0.40A) "1% point"	7.2	7.2	58	0.6	4×10^{-8}
44 (0.28A) "0.1% point"	3.0	3.0	24	0.85	3×10^{-4}
~ 55 (0.23A) "0.01% point"	1.6	1.6	13	0.9	0.02

that the effective transmittance for the next (50% - 10%) or 40% increment in power is 0.005. Thus the transmitted power at energies from 5.7 to 17 KeV is:

$$(5 \text{ watt})(0.40)(0.005) = 0.01 \text{ watt.}$$

At energies less than 5.7 KeV, the transmittance is so close to zero ($<10^{-10}$) that the transmitted power is negligible. Thus the total transmitted power is:

$$0.04 + 0.07 + 0.01 = \text{approx. } 0.1 \text{ watt.}$$

I. Dose Rate That Such Power Could Produce

If this 0.1 watt of radiation were absorbed in a 1-g. portion of a man's hand or eye, the dose-rate would be:

$$(0.1 \text{ joule/sec})(10^7 \text{ erg/joule})(10^{-2} \text{ rad/erg}) = \sim 10^4 \text{ rad/sec or } \underline{\text{about } 10^4 \text{ rem/sec.}}$$

Because this result (the most important one of this report) is believed to be accurate only within 1/2 order of magnitude, we shall ignore the facts that (1) the source-to-window distance here ($\sim 2 \frac{1}{2}$ m) is less than that of PART 2 (3 m), (2) the width of irradiated portion of window here (5 cm) is greater than that of PART 2 (3 cm.), and (3) the radiation, being of higher photon energy, will be deposited in a greater depth of material in the man's body.

J. Effectiveness of 1/8-Inch Stainless Steel Cover

Inspection of the Table 2 data on a 1/8-inch-thick stainless steel window-cover shows that such a cover would transmit no appreciable amount of power below a photon energy of 44 KeV. But at 55 KeV, estimated to be the "0.01% point", the transmittance

of the cover is 0.02; the effective transmittance at 55 KeV and higher may be close to 0.05. Thus one estimates the power transmitted by a 0.6°-subtense-portion of the cover to be:

$$(5 \text{ watt})(0.01\%)(0.05) = 3 \times 10^{-5} \text{ watt.}$$

The power transmitted in the photon-energy range just below 44 KeV may be estimated to be 1 or 2 times this amount.

Thus the total power transmitted is of the order of 10^{-4} watt.

If this power were incident on a 1-g portion of a man's body, the dose rate here would be:

$$(10^{-4} \text{ joule/sec})(10^7 \text{ erg/joule})(10^{-2} \text{ rad/erg}) = \\ 10 \text{ rad/sec} \approx 10 \text{ rem/sec.}$$

Because this rate is large, such covers are not used. Instead, one-inch-thick lead covers -- discussed below -- are used.

K. Effectiveness of a One-Inch-Thick Lead Cover

At photon energies near 55 KeV the absorption coefficient μ/ρ of lead is five times that of iron, and the coefficient μ is 7 times that of iron.

Starting in February 1972, we provided one-inch-thick lead covers for two of the bypass windows (those that receive synchrotron radiation from the bypass oblique legs that run to the synchrotron ring.) The transmittance of 55 KeV photons by such a cover is $\sim 10^{-100}$, and the power transmitted (with 5-mA-ave 5-GeV beam in orbit) would produce a dose rate $< 1 \text{ mrem/hr}$, i.e.,

substantially zero.

No covers are used at Windows W_B and W_B' , because of the need to minimize the amount of mass between the interaction region and the on-axis luminosity monitors. The two-foot-long region between uncovered window and monitor is partially enclosed by massive equipment, and it would be difficult for a person to get his head into this region. Regulations prohibit his inserting any part of his body in this region while beams are in storage.

L. Dose-Rate from Radiation Emerging Through Walls of Bending-Magnet Vacuum Chambers, Etc.

The thickness of the wall of the (stainless steel) vacuum chambers in the bypass bending magnets is 1/4 inch, per Dwg. S-23-V-1. From the drawings of the vacuum chambers and of the orbit, I find that, typically, the glancing angle of synchrotron radiation on bypass vacuum chamber walls is 12 to 14 deg. Thus the pathlength in stainless steel of synchrotron radiation emerging from the wall at such angle is ~ 1 inch. The pertinent transmittances may be shown to be $\sim 10^{-10}$ at 60 KeV (0.2 A) and 6×10^{-3} at 120 KeV (0.1 A), and one might expect the dose-rate from the emerging radiation to be of the order of a few mrem/sec.

M. Do the Auxiliary Bending Magnets Pose Any Threat?

Near each end of the bypass there is an auxiliary bending magnet. Such a magnet produces a curvature of beam path that is about the same as that produced by a bypass bending magnet (same within $\pm 10\%$) (per information received from Mr. H. Meiras). Thus

an auxiliary bending magnet could produce a comparable danger -- were it not for the fact that there are no windows nearby and any synchrotron radiation that emerges can do so only after having passed through the beam pipe wall at a grazing angle of $\leq 5^\circ$. However, one might expect dose-rates of a fraction of a rem/sec. at various nearby locations.

APPENDIX 1

Remarks Concerning Beams of Other Energies

Beam Energy of 2.5 GeV

(1) Window in Ring:

A 2.5-GeV beam energy is of present importance, as we now occasionally produce such beams. (The energies used most frequently in recent months have been 2.0 and 2.5 GeV.)

Relative to the 3-GeV case, the critical energy of the 2.5-GeV case is lower by the factor $\left(\frac{2.5 \text{ GeV}}{3.0 \text{ GeV}}\right)^3 = 0.58$.

To obtain the spectral energy distribution curve that applies to the ring, one may use the "3-GeV" curve of Fig. 1 and slide it to the left by a factor of $(1.00 - 0.58) = 0.42$ in frequency. From such a curve, one finds that, in the photon energy range where a given window has appreciable transmittance, the power at any specified photon energy is almost exactly one order of magnitude less than in the 3-GeV case.

Accordingly, the pertinent dose rates, likewise, will be about one order of magnitude less.

(2) Window in Bypass:

Here, too, the spectral energy distribution curve is shifted to the left and the power at any specified (pertinent) photon energy is less by an order of magnitude. Accordingly, the dose rates, likewise, will be about one order of magnitude less.

Beam Energy of 3.5 GeV

Here one would expect dose rates to be about an order of magnitude greater than in the 3-GeV case.

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