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SYNCHROTRON RADIATION AT THE CAMBRIDGE ELECTRON ACCELERATOR*

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Introduction

The Cambridge Electron Accelerator (CEA) has operated from 1962 to 1970 as an electron synchrotron, accelerating 20 mA of electrons to 6 GeV at 60 Hz and producing external bremsstrahlung and electron beams for a broad high energy physics program. It has now been converted to an e^+e^- storage ring colliding beam machine[1] and has recently completed an experiment[2] at $E_{cm} = 2 + 2$ GeV. A final experiment at $E_{cm} = 2.5 + 2.5$ GeV is in progress, after which the colliding beam physics program will be terminated because higher luminosity is available from the storage ring SPEAR.

In parallel with the high energy physics program, a parasitic program using synchrotron radiation has been pursued. A special room has been constructed by Harvard University, and a fully-instrumented beam run was completed in April 1972. The beam run was designed initially to meet the requirements of a unique scanning x-ray microscope[3] which is now in routine operation. Five experimental groups share the three ports on this run and many more proposals have been received in anticipation of an expanded facility.

The CEA is a most potent source of synchrotron radiation. Large stored electron currents (55 mA has been achieved and 100 mA is expected) and high stored beam energy (3.5 GeV has been achieved and 5.0 GeV is possible with minor improvements) produce a large flux of ultra-violet and x-radiation.

A proposal to operate the CEA as a National Laboratory dedicated to the use of synchrotron radiation for research in physics, chemistry, biology, and medical diagnostics, is now under consideration by the NSF. This proposal projects the installation of many additional beam runs and "wiggler" magnets in the target area, a 35-ft x 130-ft fully-equipped experimental hall. Flux densities on the experimenters' target are high because beam runs are short (8 ft to 30 ft). Shielding will be installed to permit safe occupancy near experimental equipment during storage conditions and very likely during injection.

This paper discusses the basic features of synchrotron radiation (with particular reference to the CEA), its enhancement by the use of wiggler magnets, the present performance and future capability of the CEA in storage and cycling modes of operation, special pulsing and modulation techniques, the features of the present beam run, and plans for future beam runs and shielding to permit occupancy of the target area.

Features of Synchrotron Radiation

An electron of energy $E = \gamma m_e c^2$ moving with a radius of curvature R in a magnetic field B, emits synchrotron radiation. The mean angular spread of high-energy photon emission with respect to the electron direction is $\sim 1/\gamma$. The power radiated by one electron with energy E, travelling with $v \approx c$ perpendicular to a magnetic field B, is: (all equations in MKS units unless otherwise stated)

$$P = \frac{2}{3}\frac{r_e e^2 c^3}{m_e c^2}\gamma^2 B^2 \; ; \qquad r_e = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{m_e c^2} \tag{1}$$

Multiplying equation (1) by R/c, where R=E/eBc gives the energy loss per radian of arc as

$$\Delta E/\text{radian} = \frac{2}{3} r_e e c B \gamma^3$$

For a current $i_a = e\,dN/dt$, the power radiated per radian is $dN/dt \times \Delta E/\text{radian}$:

$$P/\text{radian} = \frac{2}{3} r_e c i_a B \gamma^3$$

$$= 0.424\left(\frac{B}{\text{kG}}\right)\left(\frac{E}{\text{GeV}}\right)^3\left(\frac{i_a}{\text{A}}\right)\frac{\text{kW}}{\text{radian}} \tag{2}$$

This energy is radiated as a continuum (see Fig. 1) characterized by the critical energy

$$\varepsilon_c = \frac{3}{2}\frac{e^2\gamma^3}{\alpha R} = \frac{3}{2}\frac{e^3 c}{\alpha m_e c^2}B\gamma^2$$

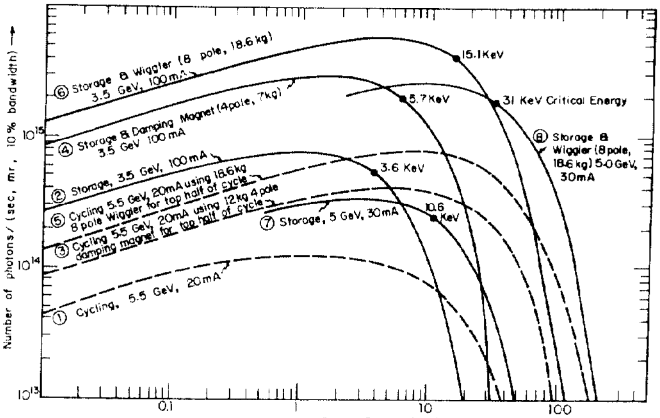
$$= 0.0670\left(\frac{B}{\text{kG}}\right)\left(\frac{E}{\text{GeV}}\right)^2 \text{keV} \tag{3}$$

where α is the fine structure constant $e^2/\hbar c$.

The number of photons emitted per second, per 10% energy bandwidth, per milliradian of angle in the plane of the orbit, integrated over the narrow range of angles out of the horizontal plane, is given by:

$$\frac{dI}{d\varepsilon} = 5.28 \times 10^{15}\left(\frac{i_a}{\text{A}}\right)\left(\frac{E}{\text{GeV}}\right) g\left(\frac{\varepsilon}{\varepsilon_c}\right)$$

where $g(\varepsilon/\varepsilon_c)$ is a function which has been tabulated and plotted.[4] It has a broad maximum with a value of ~ 0.4 at $\varepsilon/\varepsilon_c \simeq 0.4$ and decreases as $(\varepsilon/\varepsilon_c)^{1/3}$ below that energy.



Spectral photon distribution of synchrotron radiation from CEA. Curves ① ② ③ ④ indicate present capabilities with existing damping magnets. Curves ⑤ ⑥ show capabilities that will result when a new wiggler magnet is built and installed. Curves ⑦ ⑧ show capabilities that will result when a 5.0 GeV beam is stored.

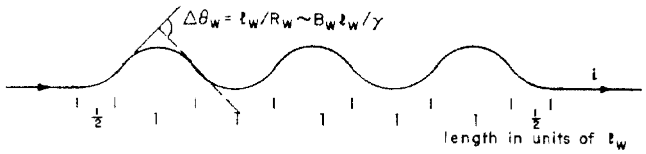
Figure 1.

Because of the very small natural emission angle of the photons, the horizontal angular divergence of a synchrotron radiation beam is usually fixed by the arc subtended by the defining slit. The vertical angular width is usually determined by the vertical angular divergence of the electron beam itself and/or the natural emission angle. The "source size" is given by the projected size of the electron beam where the radiation originates.

The radiation is linearly polarized with its electric vector in the orbital plane for photons emitted in this plane and slightly elliptically polarized for photons leaving the plane.

Wiggler Magnets

As experimenters require shorter wavelength and higher-intensity synchrotron radiation beams the use of local regions of independently controlled high magnetic fields to generate the photon beams becomes highly desirable. The local magnetic field, B_w, can be made much larger than the ring magnetic field, B_a, and n such local regions or sectors, alternating in polarity (so as to produce no net displacement or deviation), each of length l_w, can be put in series to form a wiggler as sketched in Fig. 2 where the sidewise deflection is exaggerated for clarity.



Electron path through a wiggler magnet

Figure 2.

How does a photon beam produced in such a wiggler compare to that produced in a standard ring magnet? From equations (2) and (3) in the previous section we obtain the following:

(1) The γ of the electrons remains, of course, determined by the ring magnetic field B_a;

(2) The critical energy ($\varepsilon_c \sim B\gamma^2$) is increased through the use of B_w by a factor B_w/B_a;

(3) The total power radiated per milliradian ($P \sim i_a B\gamma^3$ per sector) is increased through the use of n sectors of B_w by a factor nB_w/B_a.

In addition to its enhancement of the spectrum of synchrotron radiation, a wiggler may be used to produce beams with special emittance characteristics. For instance, the very small vertical angle of emittance ($\sim 1/\gamma$) of synchrotron radiation can be increased by a factor of ~ 10 or more by a wiggler with horizontal magnetic field. Independently controlled vertical and horizontal fields, alternating in the same wiggler, can be used to illuminate flexibly a rectangular area with dimensions independently variable from ~ 0.2 in. to ~ 10 in. and located say 100 ft from the source. This may be particularly useful for medical purposes.

Since wigglers may be designed to produce no significant disturbance to the beam (other than the extraction of energy) several wigglers may be used in the same ring, each providing independent control over the spectral and emittance properties of the synchrotron radiation beam for a particular user.

Thus an ideal synchrotron radiation facility would employ such wigglers to generate intense photon beams at specific useful locations, while minimizing rf and magnet power requirements in the ring itself. The power that goes into synchrotron radiation from the ring magnets varies as $i_a\gamma^4/R_a^2$, and the ring magnet power requirement varies as γ^2/R_a. Since large values of i_a and γ also maximize wiggler-produced synchrotron radiation, the only parameter which can be adjusted to reduce the ring magnet and ring rf power requirements is R_a. Clearly the largest value of R_a minimizes the power requirement. Thus, although a compact installation of small R_a possesses obvious construction cost advantages, it has relatively higher power requirements, and an increased R_a may reduce the overall cost. In addition, minimization of the synchrotron radiation produced, other than at chosen locations for wiggler magnets, reduces outgassing effects and helps to keep a low gas pressure and a long beam lifetime.

Because of the substantial benefits of wigglers, as described above, we plan to make immediate use of operating wiggler magnets while designing magnets of even stronger field and larger number of poles. The existing wiggler magnets are the CEA damping magnets with n = 4, B_w = 7 kG and $l_w = 3\frac{2}{16}$ in. These magnets are used to redistribute synchrotron radiation damping among the three modes of oscillation (synchrotron oscillations, horizontal and vertical betatron oscillations) such that all modes are damped (in the normal alternating gradient structure of the CEA the horizontal betatron oscillations are radiation antidamped). Since the damping strength is determined by the product $B \times \partial B/\partial r$ (whereas wiggler strength is determined by B_w and the number of poles, n), damping magnets have nonuniform fields, which introduce changes in ν values and chromaticity. If not compensated this can result in resonances, beam size enlargement, and reduced lifetime. Compensation is now provided by special quadrupole and sextupole magnets, with the result that the damping magnets are in routine use and cause no problems.

As is shown in Fig. 1, the photon beam from the damping magnets has a critical energy greater than that of the photon beam from the ring magnets by a factor of 7 kG / 4.4 kG = 1.58, and a radiated power / mrad greater by a factor of 4 x 7 / 4.4 = 6.32.

By comparison, a new design of wiggler magnet (not needed for damping), in which the field is designed to be as high and uniform as possible, is a simple device and the insertion of these into the CEA lattice is straightforward. Because the bending radius of the CEA is large (86 ft), the guide field is low (4.4 kG at 3.5 GeV) and the enhancement provided by a wiggler is particularly large.

The mechanical tolerances to which a wiggler must be built, in order that orbit distortions, changes in tune and chromaticity, etc. are negligible or easily correctable, have been evaluated[5] and are readily met. Designs have been made[5] for a powered wiggler with n = 8, B_w = 18 kG, l_w = 1.5 in., and also a novel permanent magnet wiggler with n = 8, B_w = 9 kG, l_w = 1.5 in. Both have a gap height of 0.8 in.

Mode of Operation - Capability and Performance

At present CEA can operate in two modes:

(1) Storage Mode: 100 mA of electrons at energies up to 3.5 GeV with lifetime of 1 hour or

more. Thus far the maximum current stored has been 55 mA, filling 55% of the orbit, at 2.65 GeV (limited by present restrictions due to colliding beam requirements).

(2) Cycling Mode: 20 mA of electrons with energies up to 5.5 GeV with 60 Hz repetition rate (has been achieved).

See Fig. 1 for spectral distributions. The main parameters of storage and cycling modes are given in Tables 1 and 2.

TABLE 1

Beam Parameters in Storage Mode

Energy	1.0 - 3.5 GeV*	
Current		
Rf Limit†	∿ 300 mA at 3.5 GeV	
Instability Limit	> 100 mA	
Achieved	55 mA with 55% orbit fill	
Lifetime	> 1 hour	
Beam Size at 3.5 GeV (full width at 1/e height)		
Location	Vertical	Horizontal
"Odd" Junction	0.06 mm	5.0 mm
"Even" Junction	0.14	2.1
Straight Section	0.10	3.5
Critical Energy at 3.5 GeV		
Source		
Ring Magnets (4.43 kG)		3.6 keV
Damping Magnet (7.0 kG)		5.7 keV
Proposed Wiggler Magnet (18.6 kG)		15.1 keV

*All systems except the damping system are capable of operating in storage mode at energies up to 5.0 GeV. Additional damping magnets are required for 5.0-GeV operation.

†Rf limits are calculated for our present transmitter (210 kW) and 16 rf cavities ($R_s = 10^8\ \Omega$). The rf current limit in storage at 5.0 GeV is ∿ 30 mA.

TABLE 2

Beam Parameters in Cycling Mode

Peak Energy	1.0 - 5.5 GeV	
Minimum Energy	120 - 280 MeV	
Current	< 5.0 GeV	5.5 GeV
Rf Limit	> 200 mA	∿ 30 mA
Instability Limit	> 100 mA	> 100 mA
Achieved	30 mA	20 mA
Peak Critical Energy at 5.5 GeV Operation		
Source		
Ring Magnets (7.0 kG)		14.0 keV
Damping Magnets (12.0 kG)		24.0 keV
Proposed Wiggler Magnet (18.6 kG)		37.2 keV

We expect that the main demand of users of synchrotron radiation will be for operation in storage mode. In this mode the synchrotron radiation has constant critical energy and its intensity decays smoothly with a lifetime of ≳ 1 hour. In the cycling mode both critical energy and photon intensity vary continuously during each period of 1/60 second. Additional intensity variations are minimized by keeping almost all of the beam throughout the acceleration and deceleration portions of the cycle and maintaining a fairly constant average current with multicycle injection. The only advantage of cycling mode is the existence of a band of very high energy x-rays (Fig. 1).

Storage Mode

The CEA has a unique system of beam storage. See Fig. 3 for the operation cycle.

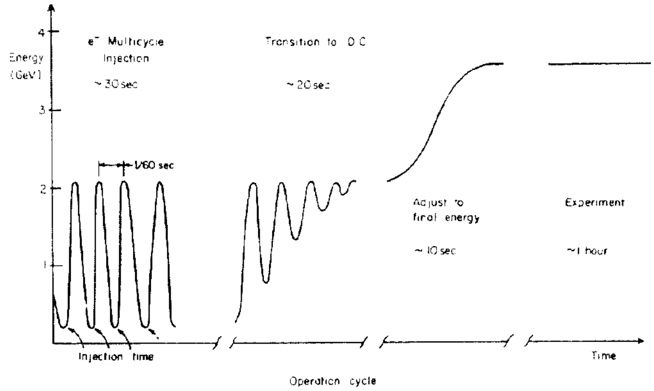


Figure 3.

While the ring magnets cycle at 60 Hz between field values corresponding to 240 MeV and 2.1 GeV, 260-MeV electrons are injected at the appropriate times. Radiation damping at the top of the cycle reduces the phase space of the radial betatron motion and permits off-axis injection of additional current at the next minimum. The electrons originate in a 5-stage Varian linac. When the desired circulating beam intensity is reached (the maximum value is determined by single-bunch phase instability), the ac component of the magnetic field is turned off slowly in such a way that the peak energy remains at approximately 2.1 GeV. The dc field is then slowly raised (or lowered) to the desired final value. During this whole cycle, currents in the damping magnets and sextupole coils are programmed to insure stability of the electron current. The entire process of filling and changing the magnet excitation from ac to dc at the desired level takes ∿ 1 minute. The multicycle injection scheme, by adding up many linac pulses, results in a uniform, reliable filling of the ring, largely independent of the linac output pulse amplitude.

The position of the stored electron beam is exceedingly stable. In an alternating gradient machine such as the CEA, the beam position is dependent only on the frequency of the accelerating voltage which is stable to 1 part in 10^8, giving a theoretical radial position stability of $< 10^{-4}$ cm. In confirmation of this, the users of the CEA synchrotron radiation have not detected any shifts in beam shape or position.

Cycling Mode

This mode differs from the conventional synchrotron operation only in that the beam is no longer extracted or steered onto a target at the peak energy. Instead, electrons remain in orbit indefinitely, their energy varying sinusoidally from 240 MeV to the top energy, which can be varied from 1 to 5.5 GeV.

The synchrotron radiation spectrum thus varies at 60 Hz. However, the electron beam spends 20% of its time in a magnetic field $B > 0.9\ B_{max}$. The beam size (and thus the synchrotron radiation source size) varies throughout the cycle.

Wiggler magnets can be used just as well in the cycling mode as in the storage mode by pulsing the wiggler at the top of the cycle or by moving the beam at the bottom of the cycle so that the high field of the wiggler magnet does not perturb the injection process and the low energy beam.

Special Pulsing and Modulation Techniques

Because of the unusually high frequency (475 MHz) of the accelerating voltage of the CEA, the rf bunch structure is quite sharp. Thus the synchrotron radiation is produced in bursts, 0.1 ns or less in duration, separated by 2 ns. Any consecutive number of these bunches from 1 to 360 may now be filled and to first order the total beam intensity is proportional to the number of bunches filled. Installing a gridded gun in the linac injection will make it possible to fill any or all of these bunches in any pattern desired by an experimenter. The orbital period is 760 nsec.

Also many sets of high voltage electrostatic plates exist inside the CEA vacuum system. By connecting pairs of these plates, separated by 180° in vertical betatron phase angle, to existing high voltage pulsers, individual synchrotron radiation beams can be directed towards or away from collimator openings. Thus for example, a particular user could direct synchrotron radiation into his apparatus for say 50 ns with a repetition rate of say 10 Hz, while other users select a different program or steady radiation.

Finally, a fast-ejection system is installed in the CEA that can be used to deflect the beam into an external channel within one orbital period. This external beam could be passed through a long superconducting wiggler which could extract much of the total beam energy (∿ 150 J) in an intense burst of synchrotron radiation lasting from 0.1 to 600 ns depending on how many rf bunches were filled.

Beam Runs

Present Beam Run

The existing beam run is shown in Fig. 4. Planning for this run began in 1968 with the expectation that experiments would be parasitic on colliding beam experiments. Hence the run is long (80 ft) and leads into a separate room, well-shielded from the ring tunnel.

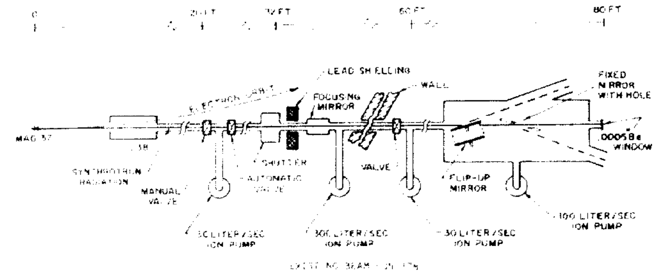


Figure 4.

This run is a fully-instrumented, interlocked, bakeable, high-vacuum run complete with ion gauges, pumps, a shutter, an automatic valve (interlocked to close if a pressure rise is detected by gauges or pumps), leak-detector and fore pump connections, a remotely-movable focusing mirror, a flip-up mirror, and a beam splitter mirror with a central hole. Thus the run can accommodate 3 sets of experimental apparatus (one x-ray and two UV) two of which can operate simultaneously.

The focusing mirror is a totally externally-reflecting ellipsoidal quartz mirror[3] which collects radiation from about 10 inches of curved orbit of a ring-bending magnet (or about 10 mrad), reflects it upwards by 1°, and focuses it to a spot about 80 ft from the source and 7 in. above the median plane. This displacement from the median plane permits the installation of lead shielding to block high energy radiation from the machine and makes occupancy in the experimental area safe during all phases of synchrotron operation.

The size of the focused spot is about the same as that of the circulating beam (< 1 mm high, 2 - 5 mm wide) thus producing about a 500-fold increase in x-ray flux density over an unfocused beam. The resulting x-ray beam is probably the most intense soft x-ray beam ever made. It is limited to energies of ≲ 4 keV because reflection from the focusing mirror at 1/2° grazing angle of incidence falls rapidly at higher energies. At 3.5 GeV with 100 mA stored, this beam would contain $\sim 10^{16}$ UV and soft x-radiation photons/second.

The beam is readily visible as blue air fluorescence (Fig. 5) after emerging through a 0.001" Be window even at lower stored beam current and energy.

Figure 5

Visible Air Fluorescence caused by intense x-ray beam emerging from .001-inch Be window.

Additional Beam Runs

We plan to install up to 15 beam runs in an enlarged section of our ring tunnel (35 ft wide, 150 ft long, 12 ft high) part of which is shown in Fig. 6.

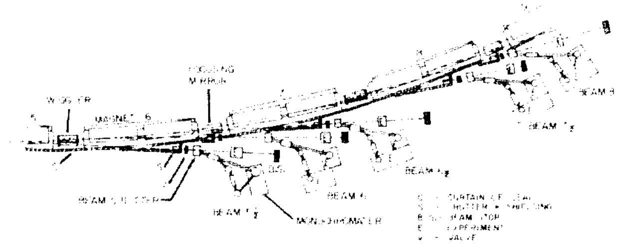


Figure 6.

This section of the ring tunnel is already a fully-equipped experimental hall complete with overhead crane, and electrical, vacuum, water, and compressed-air services.

If these new runs are kept short, the complexity and cost of the beam run hardware are small, and if the experiment uses photon energies so high (greater than ∿ 5 keV) that focusing is difficult or impossible, the gain in radiant flux per square millimeter of user apparatus is large. Our standard runs will be 18 ft to 30 ft from the point of origin of the radiation to the user apparatus, with special runs being as short as 8 ft.

If the apparatus is close-in to the accelerator, it is important that the experimenters be allowed to work at these close-in locations, under storage conditions, to eliminate the need for remote controls.

Radiation measurements at the CEA[6] show that a 4-in-thick circumferential lead shield placed in the median plane attenuates radiation doses by about a factor of 1000, thus permitting safe occupancy under stored beam conditions even in the unlikely event of a "worst-case" accident, i.e. the local abrupt loss of 100 mA of electrons stored at 3.5 GeV. With such a shield (Fig. 7) the highest dose level in the above "worst-case" accident would be ∿ 375 mrem (sum of neutron plus beta-gamma doses) over ∿ 20 square inches of a person's body and the average whole-body dose would be one to two orders of magnitude lower. Observations made during normal injection and filling of the storage ring showed that dose rates of ∿ 50 mr/hr were present. Thus it should be possible to allow occupancy even during brief (∿ 30-second) controlled injection periods, since injection occurs only about once an hour.

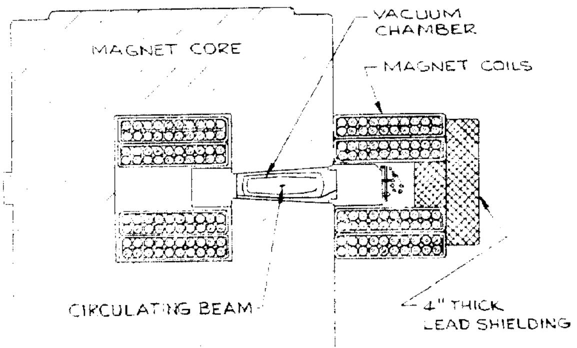


Figure 7. Cross-Section of Ring Magnet Showing Placement of Lead Shield Curtain.

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Paul Horowitz and John Howell are largely responsible for the present beam run. Their work on the scanning x-ray microscope[3] and also the work of Dean Eastman and John Freeouf on electron energy levels[7] have shown the great potential of the CEA as a source of synchrotron radiation.

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