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PRELIMINARY DESIGN OF A DEDICATED SYNCHROTRON RADIATION FACILITY

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Summary

An electron storage ring to be used solely as a synchrotron radiation source has been designed for a maximum energy of 1.5 GeV, expandable to 2 GeV, and a maximum current of 1 A. High field superconducting magnet wigglers to serve as hard radiation ports have been incorporated into the ring to make available a wide range of wavelengths for simultaneous experiments. The regular lattice consists of a series of small achromatic bends forming the arcs. The wiggler magnets are placed in low-β regions in the center of insertions separating these arcs. The arrangement minimizes the electron emittances and yields high source brightness. Other machine parameters are dictated by experimental requirements and apparatus as well as by cost constraints.

Introduction

A substantial user demand exists for synchrotron light sources in the vacuum ultraviolet and x-ray regions. Several scientific research fields need such short wavelength sources for transmission, reflection and absorption spectroscopy.[1] There are synchrotron radiation ports fitted to storage ring SPEAR at SLAC,[2] and the electron synchrotron at NBS is being converted to a storage ring radiation source.[3] One facility, Tantalus I at the Wisconsin Physical Sciences Laboratory, has been operated for several years as a radiation source. The Tantalus I program has demonstrated the ability of a dedicated source to service a large and varied group of experiments, and to adapt the operation to the requirements of the experiments.[4] However, Tantalus I at some 240 MeV will not provide the short wavelength radiation needed for many experiments. It now seems evident that a dedicated facility is needed to extend the available range of both wavelength and source brightness. We describe here an example of electron storage ring design adapted to x-ray and VUV spectroscopy.

Ring Lattice

The spectroscopist working in the region from tenths of an angstrom to 1000 A needs a continuous spectrum and the ability to operate all or most of the optical equipment in high vacuum without windows. These requirements are uniquely satisfied by the electron storage ring. Small source size and high source brightness require low-β sections and large circulating current. Numerous sources and beam pipes would permit multiple operation of experiments and also extended setup of delicate and precise apparatus. Selection of electron energy and magnetic field strength can only be a compromise in a real world. Some workers want very short wavelengths and some want small radii of curvature so that the first optical element can be near the source. One must try to weigh these wants against cost and complexity in construction and operation.

Wavelength of the peak of the radiation spectrum is proportional to $(E^2B)^{-1}$, while RF power to the beam is proportional to E^3B (at a given current). Thus, the spectrum wavelength can be shortened at less expense in RF power by increasing B than by raising E. Only a small angular portion of the required 2π of bend can be brought out for use. These considerations lead to the concept of short sectors of high magnetic field interspersed in sectors of low magnetic field. Figure 1 shows the synchrotron radiation spectrum at electron energies 1.5 and 2 GeV radiating in magnetic fields of 6.13 or 8.2 and 40 kG. A storage ring with a combination of the two field strengths can service x-ray experiments from the high field sectors, and VUV experiments simultaneously from the low field sectors.

One superperiod of an electron storage ring designed for a light source is shown in Fig. 2 and its amplitude functions in Fig. 3. This design has sixfold periodicity, in response to user desires for the bright low-β sources. Twenty-four sources are provided around the ring, and most of these could be fitted with dual beam pipes to supply a total of forty to fifty experimental setups. A similar lattice has been calculated with fourfold periodicity. It has smaller circumference, could be built at lesser expense, and would have fewer sources.

The lattice consists of six arcs matched to six insertions. Each arc consists of two achromatic bends separated by a triplet. In such a lattice the horizontal dispersion function stays below 0.5 m and the horizontal emittance, which is determined by quantum induced betatron oscillations, is kept very small. This design has radial emittance about an order of magnitude smaller than that found in more conventional electron rings of comparable energy, leading to very high beam brightness. Each insertion has two triplets which give a double focus low-β at the center of the insertion. The wiggler at the insertion center comprises a triple superconducting dipole to produce bends of about $+4^\circ$, -8°, $+4^\circ$. Such a triple dipole restores the equilibrium orbit and has only a small effect on the betatron emittance. It can be operated at any ratio to the arc fields, or turned off. Although it is tempting to consider short single high field magnets, such single dipoles must be tracked with the other dipoles and the disadvantages outweigh the saving of RF power. (Less than half of the radiation from the triple dipole can be brought out of the ring and so much of the power is "wasted".) A scheme for supplementing the end dipole of the arc with a short high field magnet was examined and found to be antidamping. If the strong damping is to be maintained, the wiggler must lie at a region of small momentum compaction.

The insertion is matched to the arc at zero X_p (momentum function). Triplets Q4Q5Q6 produce a center β_x of 0.57 m and β_y of 0.35 m with clear space between them of 3.75 m. Two source regions in each half arc have, in BB1, β_x of 1.2 m and β_y of 2.3 m. Multiple regions of small β produce large phase shifts which lead to $\nu_x = 10.8$ and $\nu_y = 6.9$. The strong lenses also make a large negative chromaticity, $d\nu/(dp/p)$, which is -15 in x and -13 in y. This negative chromaticity would cause destructive head-tail instability at very low

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electron current and must be corrected to a positive value with sextupoles. In order to correct in both x and y the sextupoles must be in two classes, one at $\beta_x > \beta_y$ and one at $\beta_x < \beta_y$, and at large as possible values of X_p. Places are found in QF and BB1 which satisfy the requirements with sextupole pole tip fields of a few kilogauss.

At 1.5 GeV the damping time constant of this lattice is 10 ms in both transverse and 5 ms in the longitudinal coordinates. The quantum fluctuation limited beam size with 10% coupling is 0.3 by 0.02 mm at the wiggler. Control of instabilities and avoidance of resonances should permit this small size to be approached. Beam-beam problems are fortunately absent in a single beam light source.

Another consequence of the extremely small transverse beam size is a relatively short Touschek lifetime. At 1.5 GeV and 1 A beam current, it is of the order of 1 hour. Other possible performance limitations can be expected in the form of longitudinal instabilities. However, extrapolation of previous experience gained at CEA[5] with operation in a many-bunch mode indicates that a beam current of one ampere coupled with an injection energy of 650 MeV is feasible. The circumference is 134.5 m and R/c is 2.6. An aperture of the order of 4 × 7 cm will accommodate stacking and will contain large quantum fluctuations in order to obtain beam lives of hours. Initial working energy of 1.5 to 2 GeV is proposed. At these energies the bending magnets, BB, provide 6.1 to 8.2 kG. Simple C dipoles with a 6 cm gap will accommodate the vacuum chamber, bakeout insulation, water-cooled sheet and thin pole face windings. Excitation power is some 300 kW at 1.5 GeV and 530 kW at 2 GeV with reasonable coils. The quadrupoles are more involved. A lattice of this type requires some of the radiation beams to penetrate the outer edge of the quadrupoles, leading to a slot quadrupole analagous to a C magnet. Narrow quadrupoles for beam transport have been built at Brookhaven for several years.[6] These have the sides of the iron yoke omitted, and yet show good field shape. One coil side can be split and the two halves moved above and below the gap to create a slot quadrupole in which the field shape can be corrected by contouring the iron and by adding correcting coils. Q1, Q2, Q4, Q5 and Q6 (Fig. 3) would take this form, and would need pole tip fields no more than 10 kG. However, QF must be combined with a sextupole and would be a 12 slot lens entirely surrounding the orbit. The sextupoles centered in BB1 must also surround the orbit. Thus, some beams are blocked by the sextupole elements but beams can be brought out from the wigglers, from two low-β sources in each arc, and if wanted from one or two high-β sources in each arc. It will be necessary to adjust the working line of such a storage ring. The operating point would be set by the quadrupoles and the chromaticity by the sextupoles. Pole face windings in the dipoles would generate octupole terms and would also produce vertical and horizontal bumps for correction of the central orbit.

Radiofrequency

If all six wigglers are operated at 40 kG, the electrons at 1.5 GeV radiate 160 keV/turn of which 90 keV are radiated in the wigglers. At 2 GeV the electrons radiate 330 keV/turn of which 155 keV are contributed by the 40 kG wigglers. The total RF power, including cavity losses, would approach a half megawatt at an ampere of beam and with at least a half megavolt peak on the cavities. The selection of radiofrequency, and consequently harmonic number, depends strongly on availability of powerful and not too expensive RF generators. A harmonic number of 24 and frequency about 50 MHz permit use of superpower triodes or tetrodes. Three amplifiers would feed three coaxial cavities, each upstream of the wiggler in an insertion. These cavities require fitting of rather large variable gap capacitors to adjust the tuning as a function of heavy beam loading.[7] A harmonic cavity in a fourth insertion could be used to break up bunch-to-bunch oscillations or as a passive cavity to shorten the bunch for single bunch operation. Many experiments need the time structure in the beam, and want bunch lengths no more than a nanosecond. If shorter bunch lengths are necessary a higher radiofrequency would be required. The 200 MHz superpower triodes used on proton linacs could be used, but are very expensive for continuous RF generation. Klystrons can be obtained in the 300-400 MHz range and probably represent the generator of choice for VHF operation. The particular lattice described above has a small momentum compaction factor, 0.0044, which leads to a ν_s of order 10^{-3} at h = 24. Thus, even a higher value of h will not produce strong betatron-synchrotron coupling.

Injection

Injection energy depends upon the amount of current desired in the storage ring. A 240 MeV linac might be available and with direct injection could store at least 100 mA in the ring. However, user demand for intensity indicates a goal of an ampere circulating in the ring and injection of this current leads to an energy of about 650 MeV. A simple booster ring will supply 650 MeV electrons and will use either a linac or a 50 MeV microtron as a preinjector.

An effective and economical booster can be made with combined-function magnets and a corrugated stainless steel vacuum chamber provided one restricts it to use as a booster and does not attempt to use it as a storage ring. An FDO lattice with 35% straight sections and 4 kG field at 650 MeV has a circumference of 52 m. With 12 periods and a ν of 3½, the magnets have a gradient of 4%/cm (about the same as the AGS) and present no new problems in design or fabrication. At 5 Hz, unbiased for simplicity, the magnet loss will be some 35 kW and cooling will be nominal. The peak radiation loss is 2.9 keV/turn and peak accelerating voltage is 3.6 keV/turn. A single RF cavity operating at 10-15 kV will be adequate. Radial betatron motion is radiation antidamped less than 5% during the acceleration.

The magnet length is 1.4 m, about the maximum advisable because the sagitta is 4½ cm, and the straight sections are about 1.5 m long. Phase shift of 97° per period permits placement of bump coils or kickers at quarter wavelength intervals. Injection into the booster would be the well-known multiturn method using septum and bump coils. Extraction would use a fast kicker. Stacking in the main ring would be in transverse phase space by taking advantage of the radiation damping. The damping time constant of the ring is 0.15 s at 650 MeV, and since three booster pulses would be stacked end to end to fill the ring circumference, adequate damping can be obtained without interim acceleration in the ring.

Other Considerations

An ultravacuum is necessary in the ring. Operation at SPEAR has shown the utility of an extruded aluminum chamber with integral water cooling channel to absorb the radiation energy and with distributed titanium pumps for collecting the gas from radiation and electron bombardment. The entire chamber should be surrounded by insulated heaters for bakeout and the system must connect to many discrete vacuum pumps in addition to the distributed pumps. There must be careful attention to geometry and cooling just downstream from the wiggler dewar. With small angles of "wiggle" the synchrotron radiation will strike beyond the end of the dewar. However, 75 cm downstream from the wiggler a one ampere beam at 2 GeV will deposit more than 500 W/cm^2 on the wall of a straight pipe chamber.

The shielding needs to be minimized so that experimenters can work alongside the machine (excepting during filling) and can set up optical equipment in relatively clear space. Experiments conducted at CEA[8] indicate that a lead plug in the magnet gap and lead shields outside the straight sections will protect personnel from the stored beam. Although such shields will hold the radiation dose from a beam dump to a just tolerable value, they must be backed up by an almost foolproof triggered beam dump in a thick shield hut.

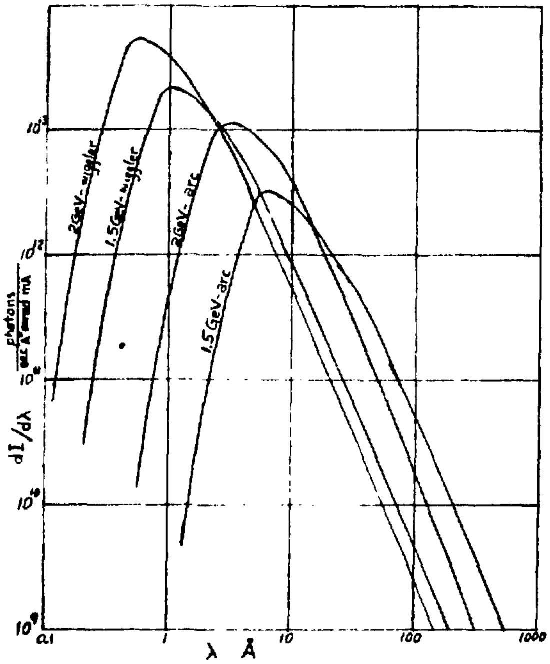

Fig. 1. Synchrotron radiation spectra.

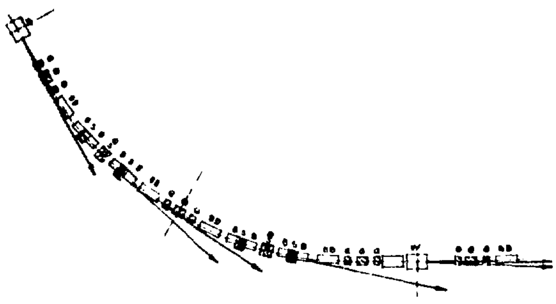

Fig. 2. Schematic of one superperiod.

This preliminary design illustrates the great flexibility of alternating gradient focusing for adaptation to specialized purposes. Furthermore, one can now confidently propose the use of superconductors for incorporation of high magnetic fields in storage rings.

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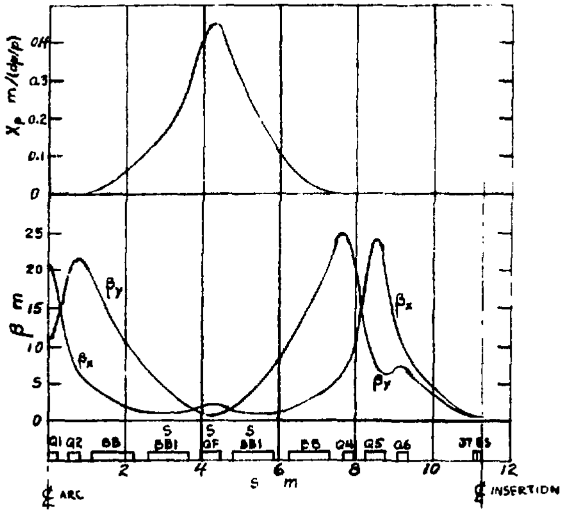

Fig. 3. Amplitude functions.