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STANDARD WIGGLER MAGNETS *

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ABSTRACT

Interest in Wiggler magnets (a close sequence of transverse fields with alternating polarity) to extend and enhance the spectrum of synchrotron radiation from electron storage rings has increased significantly during the past few years. In this paper we consider standard wigglers i.e. wigglers in which interference effects on the spectrum of synchrotron radiation are not important. In standard wigglers the spectrum of synchrotron radiation has the same general shape as the spectrum from ring bending magnets. However, the critical energy of the wiggler spectrum may be different. The critical energy of the wiggler spectrum is given by

$$\varepsilon_{CW} = \varepsilon_{CB} \frac{B_W}{B_B}$$

where ε_{CB} is the critical energy from the bending magnets and B_W and B_B are the magnetic field strengths of the wiggler magnet and bending magnets respectively. Since most electron storage rings operate with relatively low bending magnet fields ($B_B \lesssim 12$ KG), even a modest wiggler magnet field ($\lesssim 18$ KG) can significantly increase the critical energy. Such magnets are planned for ADONE and SPEAR. Higher field (30-50 KG) superconducting magnets are planned at Brookhaven, Daresbury, and Novosibirsk to produce even larger increase in the critical energy. For some standard wigglers a further enhancement of the spectrum is produced due to the superposition of the radiation from the individual poles. Wiggler designs are discussed as well as the effect of wigglers on the synchrotron radiation spectrum and on the operation of storage rings.

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I. INTRODUCTION

In this paper we review the use of wiggler magnets in straight sections of electron storage rings primarily to provide a synchrotron radiation spectrum with a critical energy that may be controlled independently of the ring bending magnets. The structures of concern will in general have a few poles (3-9) of alternating polarity transverse magnetic field and may be referred to as standard wigglers to distinguish them from structures with many poles in which interference effects are important (e.g., undulators and free electron lasers).

Although the idea of a standard wiggler is an old one[1], such devices have not yet been used as synchrotron radiation sources. However, standard wiggler structures have been successfully used for other purposes in high energy storage rings at the Cambridge Electron Accelerator (C.E.A.), USA, and at Frascati, Italy. At the C.E.A. a pair of wiggler damping magnets[2] were used to redistribute damping rates to enable beam storage in the alternating gradient structure of the C.E.A. ring. Each damping magnet wiggler consisted of 3 central full poles and 2 end half poles (4 equivalent full poles - a two wavelength structure) operating at a peak field of about 8 KG. The beam actually traversed a point in the fringe field of the magnet chosen to maximize the product B·dB/dr to provide maximum damping.

At Frascati the M.E.A. magnet[3] is used for a colliding beam experiment in the storage ring ADONE. The magnet consists of a central pole and 2 end poles (a structure with one wavelength) and operates at 3.0 KG.

At Wisconsin a 3 pole, one wavelength wiggler magnet[4] has been built to extend the synchrotron radiation spectrum from the 240 MeV storage ring Tantalus I. In order to obtain the maximum hardening of the spectrum (compared to the 12 KG bending magnets) the device was designed to produce a 25 KG field with a vertical magnet gap of 5 mm. In brief trials with the device serious degredation of the beam lifetime was encountered, presumably due to the small vertical aperture for the circulating beam (~ 3 mm).

More recently at Novosibirsk, USSR[5], a damping magnet wiggler has begun operation at low energy. This 8 pole structure is necessary to permit storage of electrons in the VEPP-4 storage ring, which was originally designed as a proton anti-proton colliding beam ring. At full 7 GeV electron beam energy this magnet will operate at 8 KG. In Erevan, USSR[6], trials of a 3 pole 18 KG wiggler magnet are in progress on the 4.5 GeV synchrotron Arus.

Interest in utilizing standard wigglers as synchrotron radiation sources is increasing rapidly throughout the world and it is very likely that such a device will soon be inserted into a storage ring and used as a synchrotron radiation source. Conventional (i.e., non-superconducting) 16-18 KG standard wiggler magnets are now being planned as synchrotron radiation sources in the ADONE[7] (1.5 GeV) and SPEAR[8] (4 GeV) storage rings within the next two years. Superconducting 35-50 KG wigglers are being considered for use in the VEPP-3 colliding beam storage ring and in new dedicated synchrotron radiation storage rings now in construction at Daresbury[9] (2 GeV) and Brookhaven[10] (2.5 GeV). In addition, conventional standard wiggler magnets with fields up to 19 KG are included in the lattice of the 18 GeV PEP colliding beam storage ring in order to control beam size and damping time[11].

Standard wigglers will extend the spectral range of relatively low energy storage rings (≲ 2 GeV) into the important range of photon energies ≳ 10 KeV. They will also provide such hard X-ray flux for symbiotic synchrotron radiation research programs on higher energy colliding beam rings when they operate at lower than peak electron energy.

Designs for standard wigglers and analyses of their effects on storage ring operation have been made or are now in progress at several laboratories throughout the world including Amsterdam (The Netherlands), Brookhaven (USA), Daresbury (United Kingdom), Frascati (Italy), KEK (Japan), Novosibirsk (USSR), Pakhra (USSR), Stanford (USA), and Wisconsin (USA). Information about many of these efforts is contained in internal laboratory reports (which may be obtained from the individual laboratories) and also in the Proceedings of a recent Wiggler Workshop[12].

It is fairly clear from the analyses that have been made and also from the experience with wigglers that their effect on storage ring operation can be minimized and compensated to the extent that their routine use as synchrotron radiation sources will pose no problems. This will open new research possibilities because of the higher intensity and independent control of the spectrum offered by wigglers.

In this paper we review the basic design features of standard wiggler magnets, their effects on the synchrotron radiation spectrum and their expected effects on storage ring performance, with particular examples from the studies that have been done at several laboratories.

II. EFFECT OF A STANDARD WIGGLER MAGNET ON THE SYNCHROTRON RADIATION SPECTRUM

The synchrotron radiation spectrum is characterized by the critical energy ε_c, or critical wavelength λ_c, given by

$$\varepsilon_c(\mathrm{KeV}) = 2.218 \frac{E^3}{\rho} = .06651\ BE^2$$

$$\lambda_c(\text{Å}) = 5.59 \frac{\rho}{E^3} = \frac{186.4}{B\ E^2}$$

where E is the electron energy in GeV, ρ is the local bending radius in meters, B is the local magnetic field in kilogauss. The primary effect of a standard wiggler magnet on the synchrotron radiation spectrum is its effect on the critical energy through its dependence on the local magnetic field in the wiggler. In general the desire is to harden the spectrum of synchrotron radiation through the use of wigglers with magnetic fields higher than the field in the storage ring bending magnets. It may also sometimes be desirable to operate wiggler magnets at fields lower than the bending magnets to produce spectra with lower critical energy. This could be useful to reduce the X-ray flux in ultra-violet beam lines or to minimize the intensity of harmonics from crystal monochromators in X-ray beam lines.

Table 1 gives the critical energy of the synchrotron radiation spectrum from hypothetical standard wigglers and from the bending magnets of several rings. The list is not meant to be complete but only to give a range of examples. At full energy most rings operate with bending magnet fields of about 12 KG. Thus an 18 KG wiggler would increase the critical energy by about a factor 1.5 and a 45 KG superconducting wiggler would give an increase of about a factor 4.

Rings dedicated only to synchrotron radiation research are likely to operate at, or close to, their highest energy. Colliding beam rings, however, often operate at less than peak energy. Synchrotron radiation programs that operate symbiotically on these colliding beam rings have reduced flux, particularly at the higher photon energies, during these periods of low energy operation of the ring. In these cases wiggler magnets can be particularly effective in increasing the critical energy by a large factor because the ring bending magnets operate at reduced field for low energy operation of the ring.

For example, as shown in table I, when SPEAR operates at 2 GeV the field in the bending magnets is only 5.3 KG and the critical energy of the spectrum from the bending magnets is 1.4 KeV. An 18 KG wiggler increases the critical energy by a factor of 3.4 up to 4.8 KeV. Furthermore, a wiggler with many short poles can produce a very small amplitude of oscillation in the electron path, comparable to the beam transverse dimension. The results in an enhancement of the entire spectrum by a factor equal to the number of wiggler poles. This enhancement is particularly useful for experiments that can accept radiation from a 1-2 m long distributed source as opposed to the usual bending magnet case where only a few centimeters of arc act as the source. Such a wiggler provides an enormous increase in synchrotron radiation flux particularly in the 5-20 KeV region (see Fig. 1) making it possible to perform experiments in this photon energy range that would be difficult or impossible using the flux from the bending magnets at 2 GeV. Because this photon energy region (5-20 KeV) is of great interest to a wide range of experiments in X-ray diffraction, adsorption, fluorescence and scattering, even a modest 18 KG wiggler would have a dramatic effect on the research capabilities of SPEAR when it operates around 2 GeV.

To gain this advantage in SPEAR and also in other colliding beam rings with symbiotic synchrotron radiation research programs (DORIS, ADONE, DCI), the wiggler must be compatible with colliding beam operation and in particular it must not reduce the lumniosity (event rate) of collisions. This places special requirements which are discussed in section IV.

A synchrotron radiation spectrum of unusually high energy will be provided by standard wiggler magnets in the 18 GeV colliding beam storage ring PEP now under construction at SLAC. These wigglers[11] will be used to control beam size and damping rates when PEP operates below 14 GeV. For example the PEP wigglers will have a field of 17 KG at 12 GeV producing a spectrum with a critical energy of 163 KeV.

High field standard wiggler magnets will produce very high power densities posing severe design problems on exit chambers, beam lines, and beryllium windows. The power per milliradian varies directly with the magnetic field and with the number of equivalent full poles of the wiggler. For example the SPEAR wiggler described in table 3 would produce, at 2 GeV, a power per milliradian about 34 times higher than the bending magnets.

Table 1

The effects of 18 and 45 KG wiggler magnets on the critical energy in particular storage rings.

		Bending Magnets		Wiggler Magnets	
Machine	E (GeV)	B (KG)	ϵ_c(KeV)	B (KG)	ϵ_c(KeV)
Aladdin (USA)	.75	12.3	.46	18	.67
				45	1.7
Adone (Italy)	1.5	10.0	1.5	18	2.7
				45	6.8
SRS (U.K.)	2.0	12.0	3.2	18	4.8
				45	12.0
Photon Factory (Japan)	2.5	10.0	4.2	18	7.5
				45	18.7
SPEAR (USA)	2	5.3	1.4	18	4.8
				45	11.9
	4	10.5	11.2	18	19.2
				45	48.0

III. DESIGNS FOR STANDARD WIGGLER MAGNETS

The design considerations for standard wiggler magnets have been discussed by several authors[3,4,7-15]. A basic requirement on a wiggler is that it produce no net displacement or deflection of the electron beam; so that turning it on or changing its excitation level does not significantly perturb the electron orbit. A structure with reflection symmetry about its transverse midplane and a vanishing field integral along the electron trajectory satisfies these requirements.

The vertical aperture that must be preserved for the circulating beam is an important design parameter affecting the peak field attainable with a given length of an individual pole. For example in SPEAR and ADONE full vertical aperture requirements are now about 3 cm (except for the low-beta interaction regions of SPEAR where ~ 1 cm is required) resulting in pole lengths (in the beam direction) of $\gtrsim$ 10 cm. In low emittance dedicated machines full vertical aperture requirements of 1 cm or less are planned for wiggler locations.

Several standard wiggler magnet designs have been made, along with some analysis of their effects on storage ring operation. For example table 2 lists design parameters for an 18 KG standard wiggler for SPEAR. A sketch of this wiggler is given in figure 2. A similar 18 KG wiggler designed for ADONE is shown in figure 3. Superconducting wigglers with fields of 40-50 KG have been designed for the Brookhaven and Daresbury dedicated storage rings now under construction. The Daresbury design is shown in figure 4.

IV. EFFECTS OF STANDARD WIGGLERS ON THE PERFORMANCE OF STORAGE RINGS

A. Dedicated Synchrotron Light Facilities.

In a dedicated facility the lattice may be designed specifically to accommodate wigglers in an optimum manner. Some design and operational considerations are listed below. Numerical examples for a dedicated facility and two parasitic cases are given in Tables 3 and 4.

1. Linear Beam Optics.

The standard wiggler design, based on rectangular magnets, is horizontally neutral optically, provided only that the end poles are adjusted to exactly cancel the net deflection. This is because the edge focussing exactly cancels the geometric focussing of the bends. The circumference and momentum compaction are perturbed slightly, requiring minor adjustment of the rf. In the vertical, the edge focussing is cumulative and the optical equivalent is a thick lens. See Table 3 for typical wiggler optical properties.

2. Matching.

The vertical focussing of the wiggler will cause a tune change and a mismatch of the betatron function. These effects may be minimized by locating the wiggler at a low $-\beta$ point in the ring. The tune change may be corrected by retuning the ring. The betatron mismatch, in addition to perturbing beam sizes around the ring, will open linear stopbands. One way to match approximately is to choose a focussing configuration such that the β_v of the ring at the wiggler location matches the natural β of the wiggler thick-lens equivalent. Better operational flexibility would be obtained by independent adjustment of local pairs of quadrupoles in the lattice. Two such pairs would in principle be required to match β_v and β_h, and a third pair would be required if the dispersion η_h were non-zero at the wiggler insertion. In practice it may be possible to compromise some of these constraints and get by with fewer matching quadrupoles. Table 4 shows effects of a particular wiggler on optics and beam parameters with and without matching.

3. Effects on Beam Parameters.

Besides the additional energy loss in synchrotron radiation, the high-field wiggler magnets tend to increase the excitation of longitudinal and horizontal oscillations, and to increase the damping rates for longitudinal, horizontal, and vertical motions[11].

In the usual case where the wiggler fields are large compared to the standard bending magnet fields, the longitudinal excitation is enhanced more than the damping rate, so that the longitudinal emittance (energy spread, bunch length) increases. Because of this as well as the additional energy loss, the rf voltage may need to be increased in order to maintain the quantum lifetime.

The horizontal excitation, however, depends quadratically on the local dispersion function so that if the wiggler is placed at a point where η_h nominally vanishes, the wiggler adds virtually no horizontal excitation. Then, because of the enhanced damping rate the horizontal emittance may be decreased very substantially. This increases the brightness at all the synchrotron light ports - a valuable property of wigglers which of course should be exploited in the design of dedicated facilities.

4. Injection and ramping.

During injection it would be desirable to be able to leave the wigglers on; first, in order to take advantage of the increased damping and, second, to avoid ramping of the wigglers which could be very time-consuming for both superconducting and highly saturated normal magnets. These advantages would be especially valuable during the "topping up" mode of operation in which additional beam is injected periodically without changing the focussing configuration, to replenish beam loss. This "topping up" operation, which is possible whenever injection is at the operating energy, has proved very useful at SPEAR (even in the absence of wigglers).

The capability for ramping the wiggler strengths after beam is stored may be required in some experiments. Such ramping requires following a carefully determined path in machine parameter space in order to avoid resonances and instabilities. This could best be handled through computer control.

5. Nonlinearity.

The wiggler fields are strongly non-linear away from the symmetry plane. However, these nonlinearities are periodic and tend to average out over a wiggler period[14,16]. Computer ray-tracing has shown that non-linear tune spread is quite small for typical beam heights and reasonable wiggler designs.

Orbit errors can introduce tune errors and horizontal-vertical coupling due to the nonlinear wiggler fields. These effects are estimated to be not very serious but in any event they can be minimized by locating the wiggler at a point where the betatron functions are symmetric and small in average value, and by good closed orbit control.

It is perhaps worth noting that the end fields of the ring bending magnets introduce the same sort of nonlinearities. Thus as long as the linear tune increment from the bending magnets is larger than that from the wigglers - as is in the case in several proposed wiggler designs - it is unlikely that the wiggler nonlinearities will be noticeable compared to the standard bends.

6. Non-periodicity.

Ideally, from the beam dynamics point of view, the wigglers should be installed with the same periodicity and symmetry as the storage ring lattice. In practice, wigglers at different insertions in the ring might be absent or running at different fields. Linear stopbands could be controlled by betatron function matching. However, nonlinear elements (e.g., the sextupoles, required for chromaticity correction) would be aperiodic with respect to the betatron functions and phases, and certain nonlinear stopbands could become serious.

7. Vertical emittance.

Vertical dispersion resulting from closed orbit errors can excite vertical emittance, especially in the strong fields of the wiggler magnets. For example, vertical dispersions on the order of 0.1m are routinely measured in SPEAR, even when the vertical orbit errors are fairly good. This vertical emittance is independent of coupling, and cannot be removed by rotated quadrupoles. Thus, very good orbit control, with particular attention to vertical dispersion, will be required in order to attain minimum vertical emittance.

B. Parasitic Wigglers in $e^+ - e^-$ Storage Rings

The synchrotron light capabilities of operating $e^+ - e^-$ storage rings could be greatly enhanced by parasitic wigglers. In this case, all the problems mentioned above for dedicated facilities are still relevant. We may also list a few additional comments.

1. Non-periodicity.

The strongly nonlinear beam-beam forces impose an additional constraint; not only should the betatron functions be equal at all the interaction points, but also it is thought that betatron phases between adjacent interaction points should be equal[17]. Again, it would be desirable to install wigglers with the same periodicity and symmetry as the ring. If this is not possible, it might be necessary to perturb some of the quadrupoles in different sectors of the ring differently in order to effectively obtain the required interaction point symmetry. Problems with aperiodicity with respect to the sextupoles might still remain.

2. Non-optimum location of wiggler.

In general it will not be possible to locate a parasitic wiggler where the machine functions are ideal; namely, low betas and zero dispersion functions. Large betas tend to worsen the tune changes and the beta function mismatches. Non-zero dispersion means that the wiggler will contribute significantly to horizontal excitation and is likely to increase the emittance.

3. Possible enhancement of $e^+ - e^-$ luminosity.

Although an increased emittance reduces synchrotron light brightness, it can in principle enhance the $e^+ - e^-$ luminosity. This is because the storable current (I) at the beam-beam tune-shift limit (assuming no limitation from aperture or rf power) is proportional to the emittance (ϵ) while luminosity is proportional to I^2/ϵ or ϵ. Referring to Table 4, we see that a luminosity increase in the order of a factor of 2 might be a reasonable expectation at low energy. This advantage can be realized if the matching and periodicity constraints, mentioned above, are satisfied reasonably well. Then the wiggler could truly make synchrotron radiation research a symbiotic rather than a parasitic operation. Incidentally, the increase in stored current would largely offset the loss in synchrotron radiation source point brightness due to the increased emittance.

Acknowledgement

Comments by J. McE. Paterson are gratefully acknowledged.

TABLE 2 - Parameters of a Standard Wiggler for SPEAR[8] (See Figure 2)

λ (length of two pole pairs)	38 cm
Gap	4 cm
Pole Length (in beam direction)	10.75 cm
Pole Width	26 cm
Coil turns per pole	35
Coil height x width	7 x 4.125 cm^2
Gap Field	19,000 gauss
Ampere Turns per Pole	41540
Conductor	Copper
Conductor Cross Section	.8636 x .6604 cm^2 with .4318 cm dia. coolant hole
Net Conductor Area	.4187 cm^2
Conductor length per coil	30.18 m
Conductor weight per pole	11.36 kg
Current density	2835 A/cm^2
Water Cooling Required	.22 ℓ/sec-coil
Pressure drop	74,000 kgs/m^2
Electrical resistance per coil	0.0138 ohms
Coil Terminal Voltage	16.38 volts
Current	1187 A
Power per coil	19.44 KW

For a 5 λ magnet (i.e. 10 equivalent poles)

Overall length	209 cm
Overall width	64 cm
Overall height	32 cm
Steel weight	1,600 kg
Copper weight (22 coils)	250 kg

TABLE 3 - Specifications and Optical Parameters of Standard Wigglers Being Considered at BNL[10], SPEAR[18], and ADONE[7]

	Brookhaven (NSLS)	SPEAR	ADONE
Number of wiggle periods, N	1	$5^{(a)}$	3
Wiggler period, λ_w(m)	0.7	0.364	0.654
Peak Field, B_o(KG)	$40^{(b)}$	18	18
Typical beam energy, E (GeV)	2.0	2.0	1.5
Path Length change, $\Delta L/L_o$	$\sim 10^{-5}$	$\sim 10^{-6}$	$\sim 10^{-5}$
Momentum compaction change, $\Delta\alpha/\alpha$	3×10^{-3}	3×10^{-5}	4×10^{-4}
Vertical thick lens parameters$^{(c)}$			
$\Theta_w/2\pi$	0.05	0.06	0.10
β_w(m)	1.98	5.0	3.2
Unperturbed beta, β_{vo}(m)	0.35	3.1	3.1
Vertical tune change$^{(d)}$ $\delta\nu_v$	0.005	0.018	0.04

Notes

(a) A three wave-length wiggler is now being considered for SPEAR.

(b) Superconducting.

(c) The vertical thick-lens matrix is expressed as

$$\begin{bmatrix} \cos\Theta_w & \beta_w \sin\Theta_w \\ -\sin\Theta_w/\beta_w & \cos\Theta_w \end{bmatrix}$$

(d) Assuming one wiggler insertion and no matching.

TABLE 4 - Effects of the SPEAR wiggler described in Table 3 on beam properties in SPEAR at 1.5 GeV. In the "matched" case β_v and η_h are matched by varying the two nearest pairs of quadrupoles in the ring. The two values of beta function error refer to the two interaction points; the wiggler is not at a symmetry point.

	No Matching	β_v and η_h Matched
Tune change		
$\delta\nu_h$	0	-0.001
$\delta\nu_v$	0.027	0.072
Beta function error at Interaction Points		
$\delta\beta_h^*/\beta_h^*$	0	+3% -1%
$\delta\beta_v^*/\beta_v^*$	+3% -12%	0
Emittance increase		
ϵ/ϵ_o	1.83	1.93
Damping time reduction		
τ_x/τ_{xo}	0.80	0.80

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Figure Captions

Figure 1	Examples of the effects of standard wigglers on the spectrum from SPEAR and the Daresbury SRS, both operating at 2 GeV.
Figure 2	A five wavelength standard wiggler magnet design for SPEAR[6]; 11 poles are shown but the two end poles are operated to produce half the bending of the central poles.
Figure 3	A three wavelength standard wiggler magnet design for ADONE[5].
Figure 4	A superconducting standard wiggler magnet design with one wavelength for the Daresbury SRS[7].

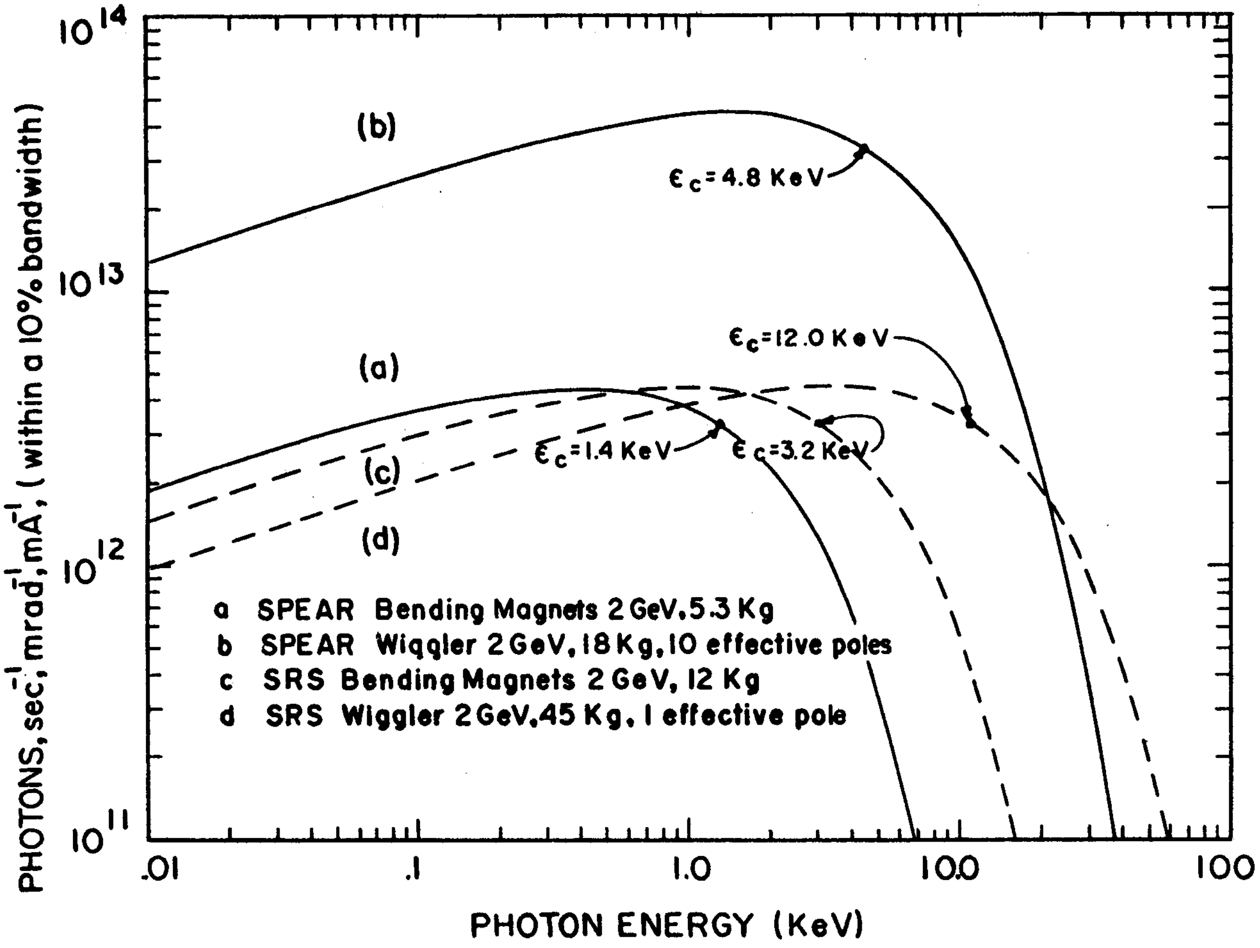
PHOTONS, sec⁻¹, mrad⁻¹, mA⁻¹, (within a 10% bandwidth)
10^14
10^13
10^12
10^11
(b)
ϵc = 4.8 KeV
ϵc = 12.0 KeV
(a)
ϵc = 1.4 KeV
ϵc = 3.2 KeV
(c)
(d)
a SPEAR Bending Magnets 2 GeV, 5.3 Kg
b SPEAR Wiggler 2 GeV, 18 Kg, 10 effective poles
c SRS Bending Magnets 2 GeV, 12 Kg
d SRS Wiggler 2 GeV, 45 Kg, 1 effective pole
.01
.1
1.0
10.0
100
PHOTON ENERGY (KeV)

Fig. 1

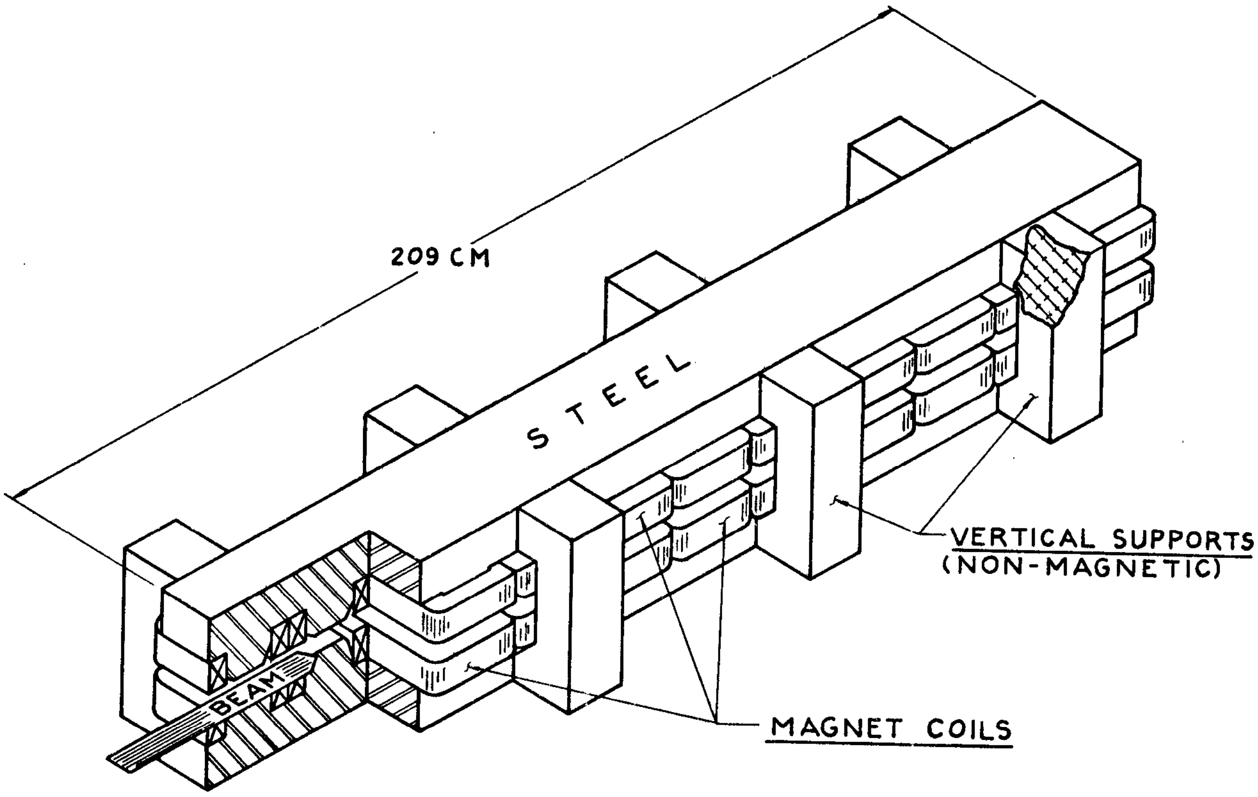
209 CM
STEEL
BEAM
VERTICAL SUPPORTS
(NON-MAGNETIC)
MAGNET COILS

Fig. 2

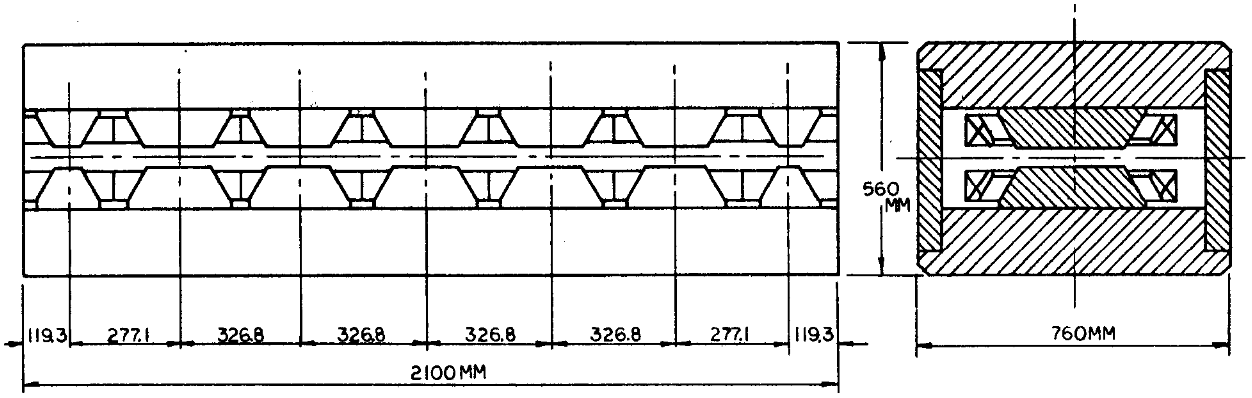

Fig. 3

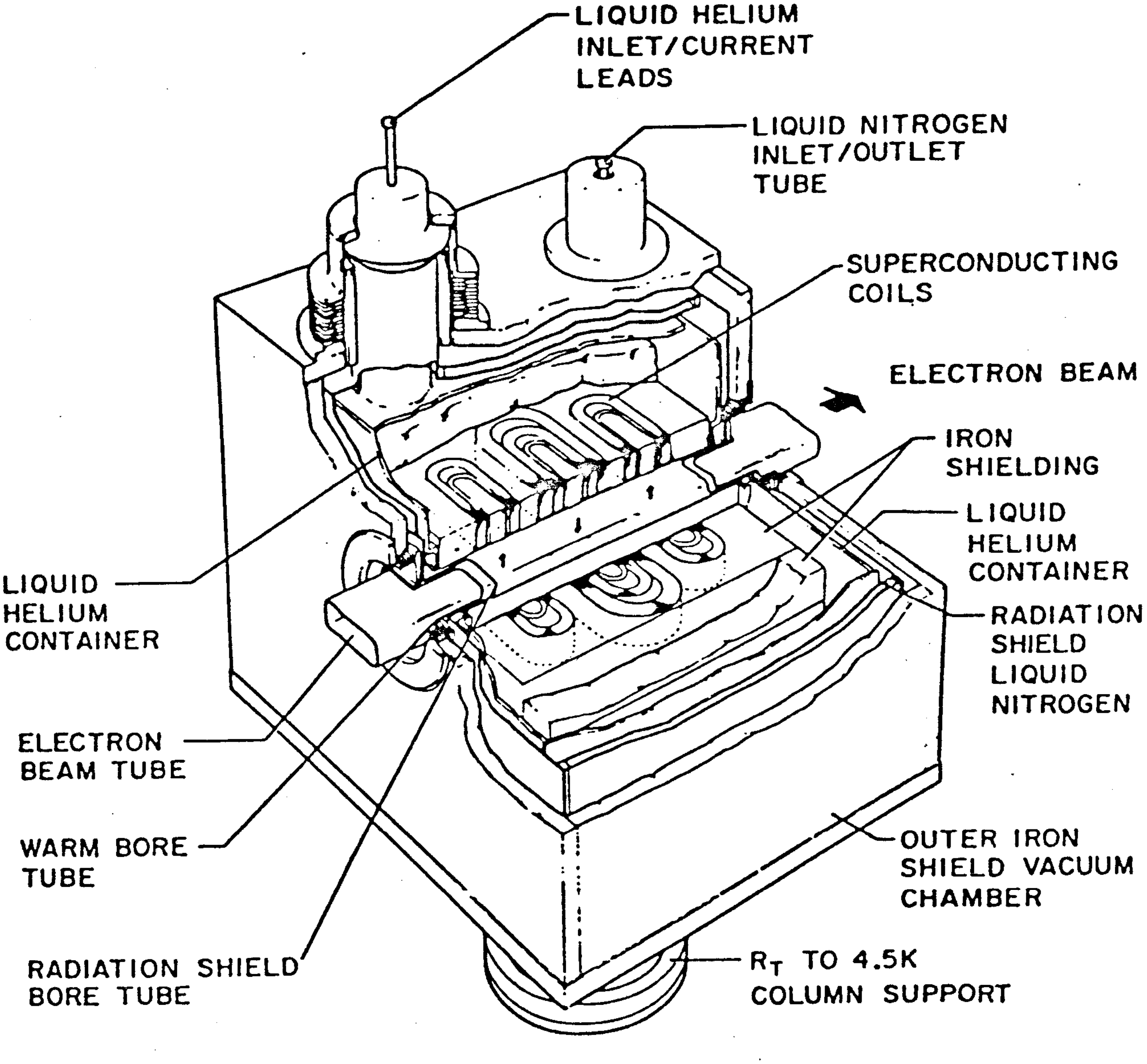
LIQUID HELIUM INLET/CURRENT LEADS
LIQUID NITROGEN INLET/OUTLET TUBE
SUPERCONDUCTING COILS
ELECTRON BEAM
IRON SHIELDING
LIQUID HELIUM CONTAINER
RADIATION SHIELD LIQUID NITROGEN
LIQUID HELIUM CONTAINER
ELECTRON BEAM TUBE
WARM BORE TUBE
RADIATION SHIELD BORE TUBE
OUTER IRON SHIELD VACUUM CHAMBER
R_T TO 4.5K COLUMN SUPPORT

Fig. 4