A 2 GeV 1A ELECTRON STORAGE RING DEDICATED TO THE PRODUCTION OF SYNCHROTRON RADIATION

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Summary

An electron storage ring is being designed to replace the 5 GeV electron synchrotron NINA as a source of synchrotron radiation. The new machine will be used solely for this purpose and its design is being optimized to the needs of the experimenters. The characteristic wavelength of the radiation will be 4 Å and the flux at that wavelength about 3 x 10^{13} photons/s/mr (horizontal) in 0.1% bandwidth. Design considerations include long beam lifetime, small source size and large available solid angle for most beam lines. Assuming a bending field of 1.2 T the beam in the storage ring will have an energy of 2 GeV and the design value of the circulating current will be 1 A. The mean radius will be about 15 m and there will be at least 10 beam lines. Superconducting wavelength shifters or "wigglers" can be incorporated to extend the usable spectrum on two beam lines to 0.1 Å. The new machine will fit into the existing buildings at Daresbury.

Introduction

At the present time, the 5 GeV electron synchrotron NINA provides two synchrotron radiation beam lines supporting nine experiments. These are parasitic on the high energy physics programme, which is expected to cease in about four years' time. To continue to provide a synchrotron radiation facility it is estimated that a purpose-built dedicated source will not only be more suitable but will be cheaper to operate than a high energy synchrotron, saving the capital cost after about five years of operation. Studies have therefore been carried out to determine the requirements and feasibility of such a machine and a detailed design is now emerging.

Specification

A considerable proportion of experiments use radiation down to 1 Å (0.1 nm) in wavelength, and a few such as scattering experiments and radiometry require wavelengths down to 0.1 Å or less.

For reasons of intensity, duty cycle, beam stability, and access, the source should clearly be a storage ring, and it has therefore been designed for a characteristic wavelength (λ_c) of about 4 Å, with the understanding that wavelength shifters[1,2] (or "wigglers") will be inserted in two straight sections to provide shorter wavelengths.

High intensity is most important for many experiments and is necessary to justify the facility. This design will provide 3 x 10^{13} photons/s/mr (horizontal) in 0.1% bandwidth at 4 Å wavelength and 5 x 10^{13} at the spectrum peak (10 Å). With a 1.2 T bending field and a 2 GeV beam this will require a circulating current of 1A. Other user requirements are: small beam cross section at the tangent points ($\sim$ 2 mm^2); lifetime of stored beam at least 8 hours; facility to circulate only one bunch, for time-resolved measurements in the nanosecond region (at reduced mean intensity); and space for at least 10 beam lines of up to 40 mr horizontal aperture and with good access whilst a beam is circulating (but not necessarily whilst filling).

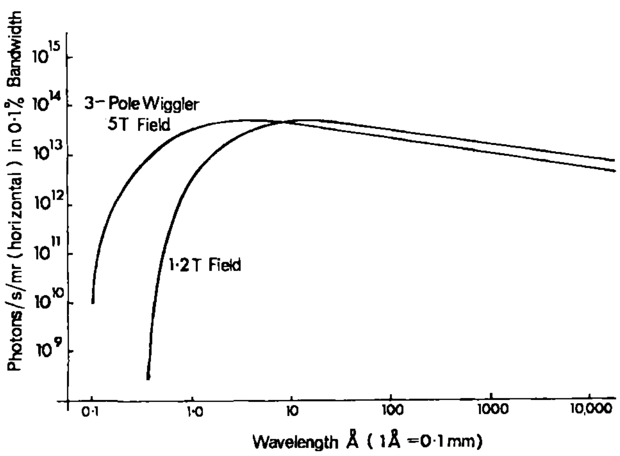

Fig.1 shows the spectra[3] for the two types of beam line.

Some Machine Design Features

Choice of energy and field

Unlike an accelerator or storage ring used for high energy physics, in a synchrotron radiation source it is the characteristic wavelength λ_c rather than the energy which is a prime parameter. The number of photons/s/mr (horizontal) in 0.1% bandwidth at a wavelength λ is given by[3] $N = F(\lambda/\lambda_c)$ x beam energy (GeV) x beam current (A), where F is an algebraic function involving no other machine parameters, and $\lambda_c = 18.6/BE^2$ where B is the bending field (T) and E is the energy (GeV).

If the dipole magnetic field is increased, the radiation spectrum can be kept constant by decreasing the particle energy, which results in a reduction in the bending radius and integrated field length of the magnets, though it is also necessary to increase the circulating beam current. The reduction in integrated field length decreases both the capital and running costs of the magnets, and it has been found[4] that the combined costs are a minimum when a dipole field of about 1.7 T is chosen. Above this value saturation effects dominate the magnet design and cause the costs to increase sharply. However the loss of aperture, also due to pole saturation, at fields above 1.4 T cannot be tolerated in an electron storage ring, and the final choice of field will be in the region of 1.2 to 1.3 T. At such levels the loss of aperture is small, and the total magnet cost is only 6% above optimum. The higher energy and lower circulating current benefit the r.f. system through reduction of beam loading and provide better high energy flux from a given wiggler magnet. For 1.2 T the energy will be 2 GeV and the bending radius 5.55 m.

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The magnet lattice

Having chosen the energy and bending radius, the magnet lattice must be selected. A separated function design is essential in a storage ring to provide radial damping. An 8-cell FBODBO lattice (F, D = quadrupoles, B = dipole, O = straight) was chosen for the following reasons:-

it gives good access to the synchrotron radiation,

it has adequate length and numbers of straight sections,

it has economy of components,

it provides ease of chromaticity correction,

it requires reasonable quadrupole field gradients,

the triplet lattice is anti-damping to electrons with relatively small energy deviations.

The requirement for 2.3 m of clear space in each straight section, after allowance for sextupoles, then fixed the mean radius.

There will be 16 sextupole magnets, individually energized, for chromaticity control and for local sextupole field correction. Other correction elements include skew quadrupoles and an octupole magnet.

Stability considerations restrict the Q-values to less than 3.5 Within this region the structure resonances centred on $Q_V = Q_R = 2^2/_3$ (i.e. p = 8) dominate the diagram and need to be avoided. The regions centred on $Q_V = Q_R = 2\frac{1}{4}$ and $3\frac{1}{4}$ are reasonably free of lower order resonances and in the injection process allow the maximum flexibility in kicker timing. As $2\frac{1}{4}$ is much further from the stability limit it is preferred for the storage ring to operate in the region $2\frac{1}{4} < Q_V, Q_R < 2\frac{1}{2}$. However, the cross-sectional dimensions of the damped beam, which are determined by the quantum excitations resulting from synchrotron radiation emission, and therefore increase with energy, are smaller for a given lattice when operated at higher Q_R values. For this reason the storage ring will be operated at the highest feasible Q_R value. The storage ring will have the capability of operating at any point within the stable area in the Q-diagram so that subject to injection limitations the tune can be changed to find the optimum working point.

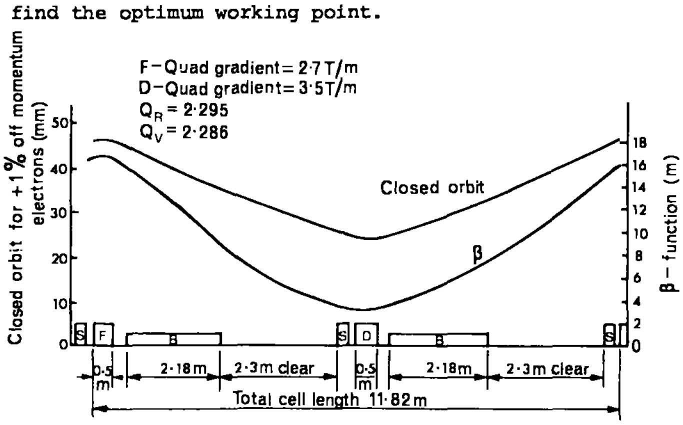

Fig.2. Storage ring lattice

The lattice parameters assuming $Q_V \sim Q_R \sim 2.25$ are shown in fig.2.

The sixteen dipole bending magnets have a magnetic length of 2.18 m and are of a 'C core' design. Whilst this design has a smaller good field aperture and is more susceptible to saturation effects than the 'H' or 'window frame' designs, it is required in order to allow the connection of a large number of beam lines including those from "wigglers". The magnets will be built from thick laminations rather than machined from solid blocks. This not only allows complete shuffling of the steel but also eliminates the small eddy currents which occur in a solid magnet when rise times of the order of a few minutes are used.

The sixteen quadrupoles will also be laminated and there will be separate power supplies for the dipoles and for the focusing and defocusing magnets so as to control the radial and vertical Q values separately.

Injector

In order to accumulate a high circulating current it is essential to inject many pulses into the storage ring. The injection energy must therefore be high enough for radial damping of betatron oscillations to take place between injection pulses. An energy of 600 MeV has been chosen, giving a damping time constant of 400 ms and an adequate Touschek lifetime of 50 mins.

The injection method is a conventional multi-turn system using a septum magnet and a fast localized orbit bump produced by two fast kickers. The exact rate at which injection can take place is determined by the acceptance aperture of the storage ring, the emittance of the 600 MeV beam and the radial Q value at injection. These parameters are not yet finalized, but so far it appears that injection can be at a rate of up to 6 Hz when Q_R is in the vicinity of $2\frac{1}{4}$.

The 600 MeV electrons for injection into the storage ring will be provided by a linear accelerator in the range 10-15 MeV followed by a booster synchrotron. This will have a mean radius one third that of the storage ring. Extraction and transfer to the storage ring will take place over three turns though it is not considered necessary for each injected pulse to fill the storage ring uniformly.

Extraction from the booster will be by a simple shaving technique with a fast orbit bump and a septum magnet. With a circulating current of 20 mA in the booster this will lead to electrons being accumulated in the storage ring at between 1 and 5 mA per pulse, and at a transfer rate of 5 Hz the 1000 mA stored beam will be reached in $\sim$ 3 minutes.

Alternatively efficient single-turn extraction using an integer resonance system could be developed.

The booster synchrotron is a combined function machine of the FODO type to provide maximum length of useful straight section. It too will contain 8 unit cells and the field on the equilibrium orbit will be 0.785 T. Each magnet will bend through an angle of $22\frac{1}{2}^{\circ}$ and will be curved. The bending radius is 2.546 m and the gaps in the central orbit between the individual laminated blocks reduced by inserting profiled, laminated steel packets, bonded to the nearest magnet block.

The repetition rate of the booster will be 10 Hz, but injection into the storage ring can be at any submultiple by appropriate pulsing of the gun. At 10 Hz it is calculated that both the dipole and sextupole fields due to eddy currents in the corrugated stainless steel vacuum vessel (wall thickness 0.2 mm) will be acceptably small.

The radio-frequency system

Since the beam loss due to synchrotron radiation at 2 GeV, 1A is 255 kW the r.f. system forms a major part of the storage ring equipment. Factors to be taken into account in the design of such a system are i) quantum lifetimes with implications in the choice of cavity voltage in the storage mode; and ii) stability of operating conditions with heavy beam loading. It is also necessary to limit the synchrotron oscillation frequency, particularly at injection.

The radiated beam power will be increased by about 10% if two "wigglers" are added (without reducing the beam current). The total power requirement will therefore be around 400 kW. It is judged prudent not to exceed 50 kW per cavity window, so that there will be 8 separate single cell cavities. In order to maintain the low shunt impedance (10-15 MΩ) required from stability and beam loading considerations at an acceptable peak voltage, the unconventional technique of fabricating the cavities from stainless steel will be adopted, although this increases the difficulty of achieving a high coupling factor to the feeder waveguide. The cavity frequency is not finally decided but will be either 428 MHz or 499 MHz depending mainly on economic considerations relating to r.f. power sources.

For resistive matching the coupling β is $1 + P_b/P_c$ where P_b is the radiated power and P_c is the power dissipated in the cavities. Reactive compensation of the beam loading induced voltage is obtained by detuning the cavity by an amount

$$\Delta f = \frac{f_o I_o \cos \phi_s \, ZT^2 \ell}{2Q_o V_{ep}} = \frac{f_o P_b \cot \phi_s}{2Q_o P_c}$$

where I_o is the mean beam current, V_{ep} is the effective peak cavity voltage, $ZT^2\ell$ is the total transit time corrected shunt impedance and ϕ_s is the phase angle of the beam relative to the voltage zero.

Ideally the beam loaded cavity should present a match to the amplifier at all energies and beam currents. This can only be achieved if both the cavity tuning and the coupling factor are varied and it is hoped to go some way towards achieving this. It is necessary to work with a system stable in the presence of coherent synchrotron oscillations. To ensure this the 'stability factor' δ must be less than unity. For the resistively matched system $\delta = 1/(1 + 2P_c/P_b)$ which is always less than one if there are cavity losses. If the beam loaded cavity is not resistive then the more general expression for stability is

$$1 + \tan^2 \psi - \frac{I_o \tan \psi \, ZT^2 \ell}{(1 + \beta) V_{ep} \cos \phi_s} > 0$$

where ψ is the detuning angle. It may be noted that stability is aided by over coupling (high β) and by detuning to a higher frequency (high tan ψ) than would give exact compensation.

At injection (600 MeV) the beam builds up in small increments to 1A. The beam power is low so stability is easy to achieve. However the beam induced voltage is high and a large cavity detuning must be used. To keep this to a reasonable amount a high cavity voltage must also be employed, with due regard, however, to the frequency and amplitude of the synchrotron oscillations.

On accelerating to 2 GeV the radiated power increases. It is proposed to vary the voltage, the coupling and the detuning during acceleration and fig.3 shows a suitable programme.

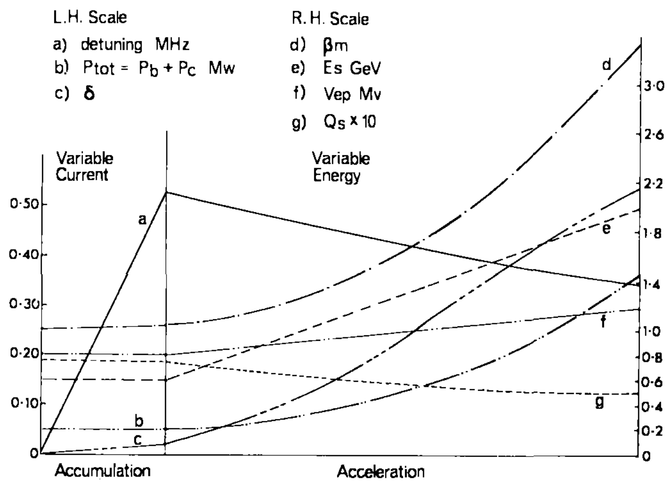

Fig.3. R.f. parameters

Other Design Features

Vacuum. The high value of radiated power in the storage ring (255 kW excluding wiggler losses) dictates a well-cooled vacuum chamber. Because of the large number of branches, ease of fabrication of complex shapes is essential and stainless steel will be used. Because of lifetime considerations, the emphasis will be on a clean bakeable vacuum system, giving a pressure of 10^{-9} torr at full beam current. There will be differential pumping between the storage ring and each experimental beam line, and in the transfer path from the booster synchrotron. There will be distributed ion-pumping in the dipole magnets giving at least 1000 ℓ/s pumping speed per dipole.

Radiation. Personnel safety presents a problem in that the users must be able to set up equipment whilst a beam is circulating, and be in close proximity to their equipment whilst data-taking. Radiation levels around a storage ring are inherently low except whilst filling, at which time the building will be evacuated. By using scrapers and an emergency beam dump it can be arranged that most of the beam is lost in pre-determined areas which are adequately shielded. The remainder of the ring will have a modest shield wall of lead, iron or concrete, and the vacuum chamber will be designed to prevent high energy photons from going down the beam lines to experiments.

Single Bunch Operation. This will be required by experimenters interested in measurement of lifetimes of excited states. It will provide 300 ns between pulses. It will require a low frequency chopper to inject a short burst of pulses into the synchrotron, followed by a higher frequency device (∿ 35 MHz) to reduce this to a single bunch. Using a suitable synchronizer to trigger the extraction system, a single bunch will be stacked in the storage ring.

Controls. The whole machine complex will be controlled through a network of computers. At the lowest level, three minicomputers, one each for linac, booster synchrotron and storage ring, will be interfaced to the plant via CAMAC. All local controls will operate via these to permit independent testing of the three accelerators. These minicomputers will be connected via parallel data links to a more powerful machine forming the central control facility. This machine will contain the main database for the system, and will support two identical control consoles, aided by a fourth minicomputer. It will also be linked to an on-line task in the Daresbury central computer, an IBM 370/165, which will make very powerful computation facilities available on-line for accelerator physics work.

The Wavelength Shifter or "Wiggler"

To accommodate the small number of users who require radiation between 0.1 Å and 0.8 Å it is intended to insert "wiggler" magnets[1,2] into straight sections in the storage ring lattice. In view of the development of superconducting technology it is certainly feasible to provide a sufficiently high field over the full aperture. The use of large numbers of poles in these magnets to enhance the radiation intensity is undesirable because of the large increase in r.f. power required. Use of a small number of poles with the highest fields practicable is to be preferred, as this benefits the user at short wavelengths most economically. It is therefore intended initially to use only three poles in each wiggler magnet and to design for a peak field of 5 T. Recent improvements in superconducting coil design indicate that fields in excess of 6 T may eventually be realised, and this will enhance the intensity at 0.1 Å by an order of magnitude. Design work on a superconducting wiggler magnet is proceeding at the Rutherford Laboratory of the Science Research Council. These magnets will be full aperture so as not to affect injection or beam lifetime, but will only be energized after the beam has been stored and accelerated.

Installation

The layout (fig.4) has been chosen with three things in mind - to provide for many experiments with good access, to allow the maximum amount of installation to proceed prior to the cessation of high-energy physics using NINA, and to minimise civil engineering work. All these points result in the storage ring being placed approximately centrally in the "Inner Hall" of the NINA building. At least one quarter of the ring can be constructed without interfering with the operation of NINA. Reduction of the high energy physics experimental areas from five to three will release sufficient space to build the injector (perhaps without all its shielding), and at the same time other space will become available for controls and for some of the ancillary plant before NINA closes down.

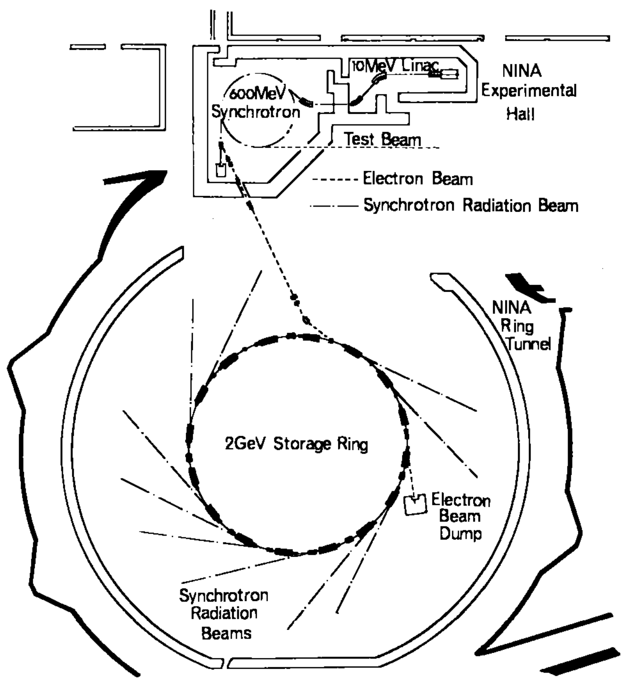

Fig.4. Layout

Parameter List

Injector

Energy	10-15 MeV
Energy spread (maximum)	± 0.5%
Emittance (maximum)	10^{-5} m-r
Current (within above limits)	20 mA

Booster Synchrotron

Peak energy	600 MeV
Current	20 mA (∿ 10^{10} e^-/pulse)
Peak magnetic field on orbit	0.785 T
Bending radius	2.546 m
Mean orbit radius	5.02 m
Betatron Q-value, both planes	2.25
Period structure	FODŌ (Comb. Func. Lattice)
No. of periods	8
Field index in F-sector	-5.2
Field index in D-sector	6.2
Field gradient in F	2.04% per cm
Field gradient in D	2.44% per cm
Magnetic length of sector magnet	1.0 m
Aperture	120x35 mm (approx.)
Repetition rate	10 Hz
R.f. frequency	428 MHz or 499 MHz
R.f. power	< 1 kW peak

Storage Ring

Energy	2 GeV
Characteristic wavelength	3.88 Å
Maximum current	1 A (∿ 2 x 10^{12} e^- stored)
Beam lifetime at maximum current	8 hours
Peak magnetic field	1.2 T
Bending radius	5.55 m
Mean orbit radius	15.05 m
Betatron Q-value (either plane)	2.0 - 3.5
Peak quadrupole gradient	4.5 T/m
Period structure	FBODBO (Sep. Func. Lattice)
No. of periods	8
Dipole magnetic length	2.18 m
Quadrupole magnetic length	0.5 m
No. of sextupoles/period	2
Clear length of straight section	2.3 m (approx.)
Good field aperture	150x40 mm (approx.)
Maximum pressure with 1A beam	10^{-9} torr
Vacuum chamber aperture	200 x 45 mm
Distributed pumping capacity/dipole	1000 l/s
Radiation damping time, 600 MeV	440 ms (radial betatron)
Touschek lifetime, at 600 MeV	50 min
Radiation loss from normal dipoles, at 2 GeV	255 keV/turn
R.f. frequency	428 MHz or 499 MHz
Total r.f. power	∿ 400 kW
No. of cavities	8
Cavity material	Stainless steel
Cavity shunt impedance (transit time corrected)	1.25 to 2.0 MΩ
Q_s	∿ 0.05

Programme

The official design study of the dedicated Synchrotron Radiation Source will be complete by the end of 1974. It is expected to show that the capital cost will be about £2M (1973 prices). Approval for construction will then be sought, and if the present ideas for the NINA programme turn out to be correct, the SRS will come into operation during 1979.

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