DESIGN AND STATUS OF EPIC

EPIC Machine Design Study Group of the
Rutherford* and Daresbury† Laboratories, United Kingdom

Presented by G H Rees

Introduction

The origins of EPIC date from the time when a study was undertaken of possible future machines for the national high energy physics laboratories in Britain. The new facilities were to replace the Rutherford and Daresbury accelerators NIMROD and NINA at the end of their useful lives. A few people from the two laboratories evaluated some storage ring machine designs[1], and one such design was described in an internal report[2]. This was based on a proposal made by Pellegrini et al. at the 1971 International Accelerator Conference[3].

The studies were given further impetus in the Autumn of 1972 by visits to the Stanford Linear Accelerator Centre of Professor Flowers, the then chairman of the British Science Research Council and Dr Stafford, director of the Rutherford Laboratory. The thoughts of Professors Panofsky and Richter of SLAC on the physics potential of high energy electron-positron and electron-proton colliding beam systems were communicated to their visitors. Before the end of 1972 an EPIC machine design study group had been established. From the outset it was a combined study between Rutherford and Daresbury Laboratories, for it was appreciated that only by pooling the resources of the two high energy laboratories would it be possible to realise a complex of the size of EPIC.

The first nine months of 1973 were spent obtaining approximate cost estimates for a two ring machine complex, with a number of different options envisaged for the actual construction stages[4]. The complex consisted of a single conventional magnet ring providing electron-positron colliding beams at incident momenta up to 14 GeV/c, together with a second ring housed in the same tunnel which would be capable of accelerating and then storing high energy protons. The second magnet ring was evaluated both for superconducting missing magnet schemes and for conventional magnets. As an electron-proton colliding beam system the peak proton momentum for a full superconducting ring was 200 GeV/c. During the initial design and costing, the study group recognised the machine design uncertainties in predicting the luminosity for the electron-proton colliding beams.

The costings are given in Table 2 of the following section, and were reported at the DESY Storage Ring Symposium of October 1973. At about that time it was decided to concentrate the studies towards a more accurate evaluation of the single ring electron-positron system. The two ring scheme for electron-proton interactions, though now only a long term objective, is still considered an essential feature in the design of the initial ring.

By October 1974 the revised evaluation of the electron-positron ring will be completed. A machine proposal will then be submitted for approval to the Science Research Council, seeking funding to allow completion of a 14 GeV electron-positron storage ring by 1981.

Electron-Positron-Proton Initial Feasibility Study

EPIC has many features in common with the early design of PEP, which was reported[illegible] at the 1973 US Accelerator Conference. A schematic diagram of the proposed EPIC complex is shown in Figure 1. The two ring colliding beam system has four interaction regions, each of which is 17 m maximum in length. The rings are contained in a common tunnel, with the proton ring magnets situated vertically above the magnets of the electron machine. A system of vertical bending magnets brings the separate paths of the electrons and protons into coincidence over the central regions of the long straight sections.

In Figure 2 is shown a proposed lay out of the machine at the Rutherford Laboratory. The use of as much as possible of the existing laboratory facilities has been taken into account. The present linac buildings, the Nimrod magnet hall, main control room and two experimental halls are all planned to be used in the few facility. The 100 MeV electron linac, positron converter and 200 MeV positron linac will be located in the hall that presently houses the Nimrod 15 MeV proton linac. The Nimrod magnet hall will house a debuncher for the 200 MeV positrons together with the linac-booster beam transfer lines. The booster will be sited in its own shielding enclosure, half in and half out of one of the existing experimental halls. Most of the components for the transfer lines from the booster to EPIC will be available from existing experimental hall equipment.

The proposed lay out of the components in an insertion is shown in Figure 3, and typical lattice β-functions in the insertion in Figure 5. The range of the minimum β_H values at the centre of the insertion is 0.4 to 1.2 m in the e-ring and 1.0 to 2.5 m in the p-ring. Corresponding values for β_V are 0.1 m to 0.3 m in the e-ring and 0.4 to 1.0 m in the p-ring. Collinear crossings of the electron and proton beams in the insertions are brought about by vertical bending magnets. The bend angles in the dipoles nearest to the interaction region are 3.7° for the electrons and there is a large associated radiation loss. The choice of such a large bend angle is made to enable the proton-ring high-β quadrupoles to be located as close as possible to the centre of the insertion.

The maximum design luminosity for collisions between 14 GeV/c electrons and 100 GeV/c protons is approximately $5\ 10^{31}$ cm^{-2} sec^{-1}, but with a measure of uncertainty because of the incomplete understanding of the effects of the beam-beam interaction. There is no damping mechanism for the betatron and synchrotron oscillations for the protons, and it remains to establish the maximum allowable space charge forces on the protons in the collision regions of storage rings. Parameters relevant to the initial feasibility study are given in Table 1, where the luminosity estimates correspond to the maximum momentum particles.

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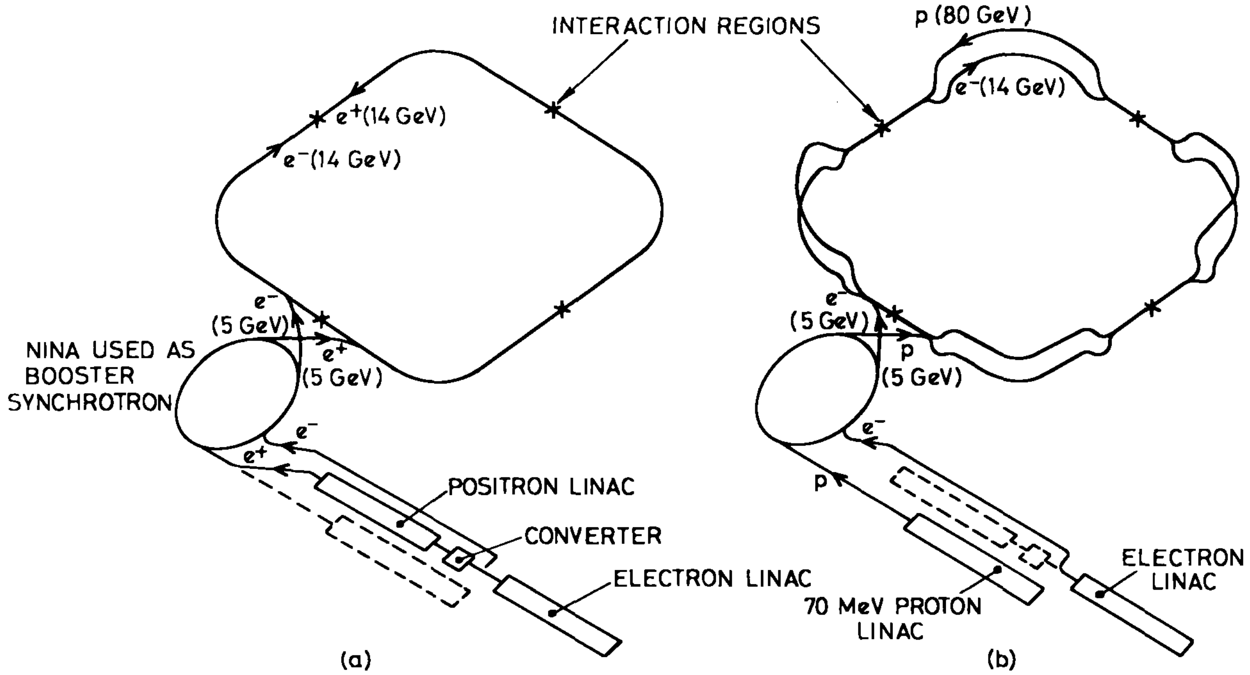
*J R J Bennett, H C Brooks, M H R Donald, D A Gray, M R Harold, J D Lawson, J D Lewin, B G Loach, J R M Maidment, G H Rees, P F Smith and W A Smith

†E A Hughes, N Marks, D E Poole, M W Poole, V P Suller, G Saxon, T Swain, K Tarry and D J Thompson



(a)
EPIC (STAGE 1)

(b)
EPIC (STAGE 2)

FIG.1. SCHEMATIC DIAGRAM OF EPIC (STAGE 1) FOR e^+e^- COLLISIONS AND EPIC (STAGE 2) FOR $e\,p$ COLLISIONS

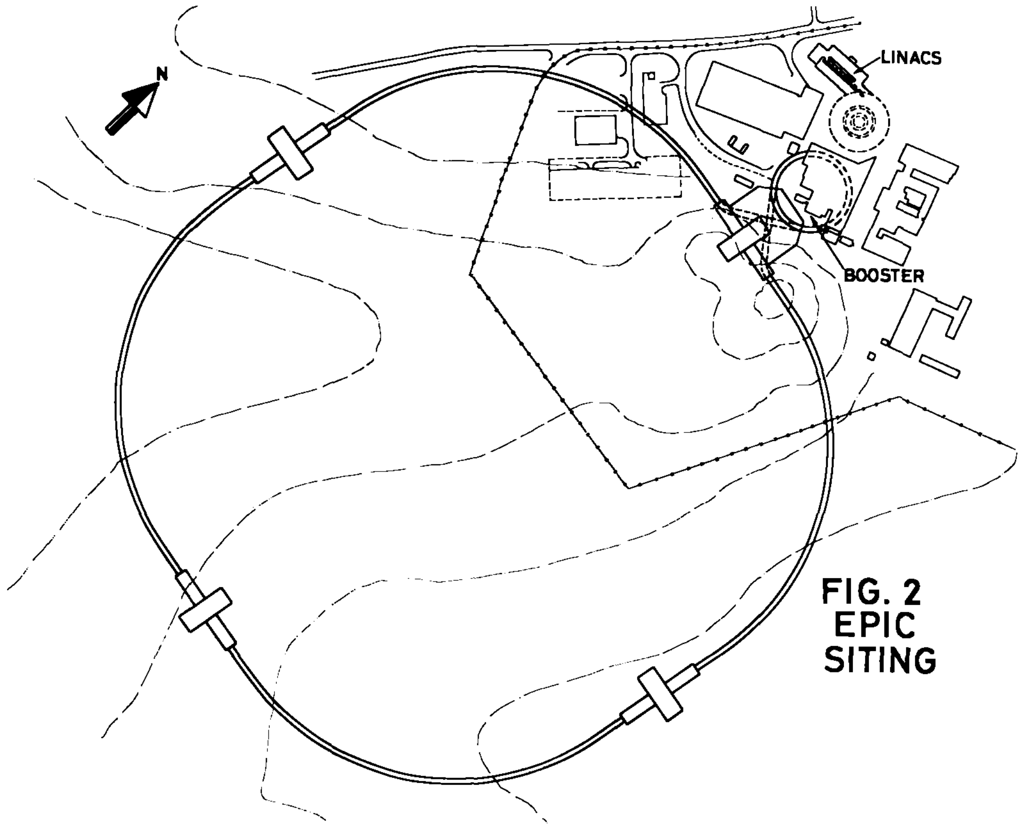


FIG. 2
EPIC
SITING

TABLE 1 - Selected Parameters
(Half-Full S/c Ring for Protons)

Ring circumference (metres)	2122.3
No. of Interaction Regions	4
Interaction region lengths (metres)	17.0
Long st. section lengths (metres)	141.4
No. of normal magnet cells	56
No. of dispersion matching sections	8
Machine tunes, Q	15.1-19.4

	e-ring		p-ring
Maximum momentum (GeV/c)	14		100
Bending radius (metres)	168.1		74.5
Peak RF Voltage (Megavolts)	42.8		4.0
Peak radiated power (Megawatts)	2.5		0.0
No. of bunches/ beam for e⁻p	8		8
No. of particles/ bunch for e⁻p	$5\ 10^{11}$		$7.5\ 10^{11}$
e⁻p Luminosity ($cm^{-2}\ sec^{-1}$/Xn.)		$\sim 5\ 10^{31}$	
No. of bunches/ beam for $e^+ - e^-$	2		
No. of particles/ bunch for $e^+ - e^-$	$5\text{-}8\ 10^{11}$		
$e^+ - e^-$ Luminosity ($cm^{-2}\ sec^{-1}$/Xn.)		$\sim 5\ 10^{31}$	

Preliminary investigation has shown that the vertical bending units may be used as spectrometer magnets for the detection of proton fragments which emerge from the electron-proton interactions at small angles. It is possible to place detection systems behind the common vertical dipoles which are downstream of the collision region for the proton ring. The shaded area of Figure 4 is an acceptance plot for the small angle fragments. The region marked (A) is related to an additional detector array installed normal to the beams at the location (A) of Figure 3. Similarly, (B) is realised by the use of a long septum magnet and further detectors at the corresponding point (B) in this figure. The use of machine components as spectrometer magnets is a feature missing from the PEP[5] and ISABELLE[7] e-p proposals.

A powerful RF accelerating system compensates for the synchrotron radiation energy losses of the electrons (and positrons). This leads to very short bunch lengths. For electron-positron collisions there are two bunches in each beam so that separation of the beams prior to collision is necessary only at the intersection regions. In the case of an electron-proton system there is the choice of using either bunched or unbunched proton beams. Provided that the problem of satisfactory bunch compression can be obtained and sustained for protons there are many advantages for the bunched option. The most important of these is the reduction in the total number of protons, easing the shielding requirements and the protection problems for superconducting magnet rings. In the EPIC design the choice is made of eight proton bunches together with eight electron bunches. The scheme for the required proton bunch compression is described in reference 2, and a method for separating the electrons and protons in the intersection region in reference 8.

Synchronisation is an essential feature of the collisions between bunched electron and proton beams. The increase of proton velocity with energy requires compensating path lengths in the particle orbits. Schemes considered for EPIC include: radial steering of the proton beam together with a number of different vertical 'dog-leg' insertions in the electron ring[9], continuously variable 'dog-leg' insertions[10] and moving the proton high-β quadrupoles to allow the electron energy to be changed at a given proton energy. Synchronisation becomes progressively more difficult at the lower proton energies and in the EPIC feasibility study the lowest proton momentum is restricted to 55 GeV/c.

A modified form of the Daresbury accelerator, NINA, will serve as a booster for EPIC. The combined function magnets are adequate for accelerating particles to a peak momentum of 5 GeV/c. The NINA repetition rate will be reduced from 53 Hz to 4 Hz, and an additional RF system will be installed. During the feasibility study it was considered that the booster could serve as an injector for electrons, positrons and protons. To this end, the gamma transition of the lattice was arranged to assist with proton bunch compression. Now there are reservations that the protons can be accelerated successfully in the presence of the electron RF systems. If a separate booster is developed for protons, it might also cater for deuterons. There is a strong physics case for studying electron-deuteron collisions[11] in EPIC in conjunction with electron-proton studies. However, the entire question of whether or not to use bunched proton beams must be reassessed if there is the additional requirement of providing deuteron beams.

The lattice design of EPIC is influenced by the need to provide an electron-positron radial beam size that satisfies luminosity requirements. It has been found that, to provide adequate values in the e-ring of gamma transition and radial beam size, it is necessary to provide a number of combined function magnets in a predominantly separated-function lattice. In each superperiod, two such units are included amongst the sixty bending magnets. This lattice feature is shown in Figure 6, together with the horizontal dispersion matching sections.

An important consideration for the electron-proton colliding beams is the choice of the radial to vertical beam aspect ratio at the interaction region. The ratio is chosen at four to one. If a choice had been made of a smaller ratio, the vertical magnet apertures would have been undesirably large, particularly as the conventional ring in the feasibility design had to cater for the possibility of storing 80 GeV/c protons in addition to 14 GeV/c electrons. This feature allowed for a possible proton-proton colliding beam option. The effect of horizontal-vertical space charge coupling between the electron and proton beams has not been assessed, but it is realised that this could affect the luminosity estimates. At electron energies below 14 GeV, the natural beam size may be too small, and two possible schemes have been considered to

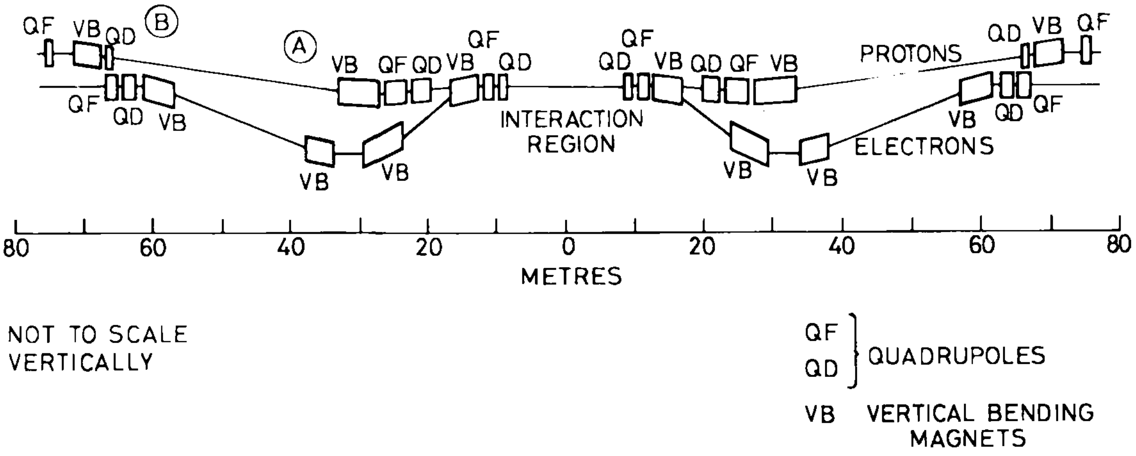


FIG. 3. e-p INTERACTION REGION GEOMETRY

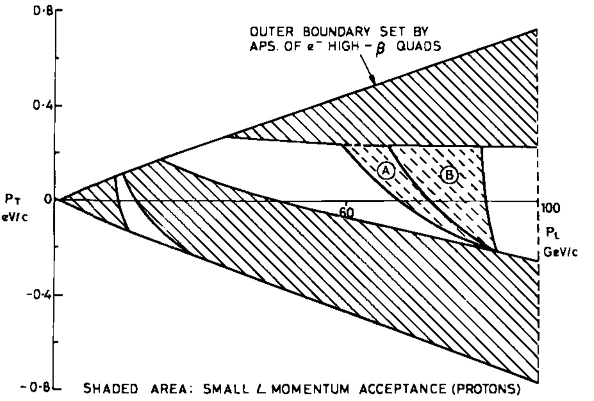


FIG. 4.

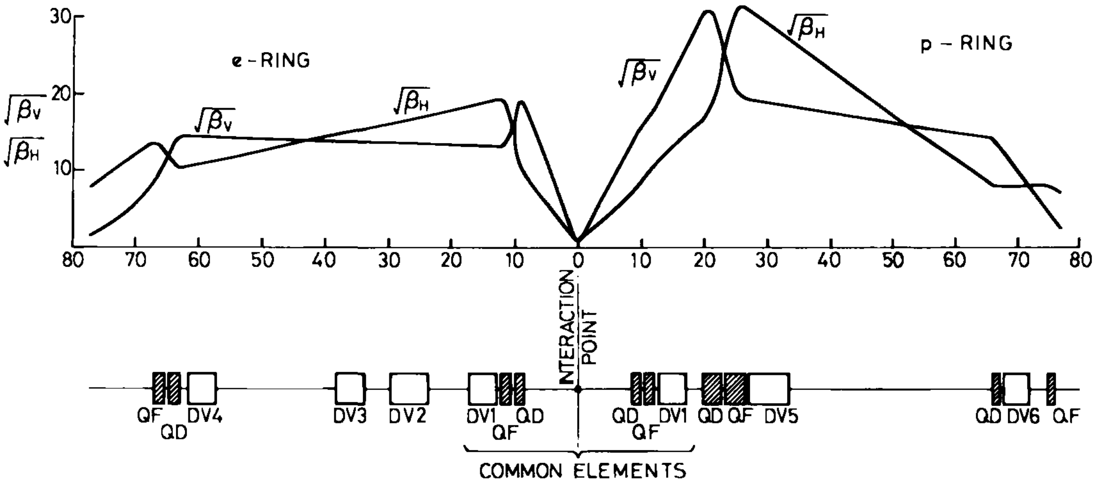


FIG.5. e-p INSERTION (N.B. BOTH RINGS ARE SYMMETRICAL ABOUT THE INTERACTION POINT)

overcome this effect. These include reducing the Q values of the machine and a further adjustment in the radial damping. If satisfactory enhancement is introduced, the luminosity will scale approximately as the product of the energies of the incident particles.

The approximate costings of the various options of the feasibility study are given in Table 2.

TABLE 2 - 1973 Cost Estimates of EPIC Options

Option	Rings	Cost
14 GeV e^+ - e^- Ring	Conventional (C)	£19.6M
14 GeV e^- - 80 GeV p	C + C	£35.1M
14 GeV e^- - 100 GeV p	C + Half-Full S/c	£43.7M
14 GeV e^- - 200 GeV p	C + Full S/c	£56.5M

Revised Design of Electron-Positron Ring

The ring circumference has been extended by 3% to provide increased straight section lengths. This will ease the design of a future proton ring in the event that it is built with all conventional magnet units.

The dipole magnets now proposed for the single ring are low field units, and costing is proceeding on the basis of using C-magnets. The open end of the C will face radially inwards to simplify the design of the vacuum system.

The magnet lattice has a high chromaticity as a consequence of the high β-values in the long insertions. The full range of the beam momentum spread is also large to ensure an adequate beam lifetime. To correct for the chromaticity, provision is made in the lattice to include sextupoles near to every quadrupole. Studies of the distribution and strengths of these sextupoles are still continuing and are proving to be a major design problem. Present studies treat the problem in linear approximation, but subsequent studies will include tracking over many machine revolutions.

As in the feasibility study the space between the high-β quadrupoles, which is completely free for experimental equipment, is set at 17 m. This may be revised if necessary as the insertion is longer than is required for the design of the electron-positron ring alone. However, there are restrictions on the maximum allowed β-values in the insertion, and the premium to be paid for increasing the central region is a decrease in the luminosity.

The variable damping feature has been mentioned in the previous section. Referring to Figure 6, the modified damping is introduced by combined-function focussing units, indicated DI/QF. On either side of these units are quadrupoles which may be adjusted to vary the local dispersion while still preserving the dispersion matching. Details of the scheme are given in reference 12. The damping time constant of the horizontal betatron oscillations of the electrons and positrons is given by:

$$T_x = [\, J_x P_\gamma / 2E \,]^{-1}$$

where P_γ is the average rate of synchrotron radiation energy loss, E is the energy of the circulating electrons or positrons and J_x, the partition coefficient, is a function of the magnet lattice. The horizontal beam size varies inversely as the square root of the coefficient, J_x. In a separated-function magnet lattice J_x is approximately equal to 1, while in the EPIC electron-positron ring it is adjusted to be approximately 0.4.

The beam aspect ratio at the interaction region is now under review. Recent studies of the beam-beam interaction for e^+ - e^- collisions indicate that a larger ratio than the previously considered value of four to one might be acceptable. These studies are reported in a subsequent section. The possible advantage for EPIC in increasing the beam aspect ratio is that the maximum horizontal β-value could then be decreased.

The revised ring parameters are given in Table 3. The luminosity will scale as E^2, provided satisfactory beam sizes are obtained by adjustments of machine tune and damping.

TABLE 3 - EPIC Electron-Positron Ring

Ring circumference (m)	2191.6
Long st. section lengths (m)	154.3
Maximum momentum (GeV/c)	14
Injection momentum (GeV/c)	4.8
Range of machine tunes, Q	15.1-19.4
Bending radius (m)	171.9
Max. energy loss/turn (MeV)	19.8
Peak RF Voltage (MV)	30.0
No. of bunches/beam	2
Max. no. of particles/bunch	$8\ 10^{11}$
Peak synch. rad'n. power (MW)	1.39
Rms. mom. spread at 14 GeV/c	$8\ 10^{-4}$
Rms. bunch length (cm)	1.8
Rms. bet. amp. (cm) at β_x = 42 m	0.33
Max. luminosity (cm^{-2} sec^{-1}/Xn.)	$\sim 5\ 10^{31}$

Injection Scheme for Electrons and Positrons

The specification for the total filling time of the EPIC ring is 15 minutes for two bunches of electrons and two bunches of positrons, with the maximum number of particles per bunch set at $8\ 10^{11}$. At the injection momentum of 4.8 GeV/c, the damping time constant of the radial betatron motion is approximately 0.6 sec, so that the maximum rate for filling an individual EPIC bunch is of the order of once per second. Accordingly, if individual bunches are filled in sequence, the repetition rate of the booster injector must be approximately 4 Hz, and the number of particles per booster pulse must be at least 10^9.

The scheme proposed to inject a full booster beam pulse into a single EPIC bunch is the following. The booster accelerates eight bunches, which are subsequently ejected bunch-by-bunch, one after every revolution period of the main ring. There is an interchange of the radial and vertical beam emittances in the transfer line, followed by radial multi-turn injection into EPIC. A requirement for this scheme is that the circumference of the booster is related to that of EPIC by the ratio 8/(2n+1), where n is an integer. The chosen value of n is 35.

The straight sections of NINA are increased in length when it is used as a booster for EPIC. The harmonic number, h, of the existing RF system is thus altered, and the ring size is adjusted to make the new value of h equal 336, a number which is

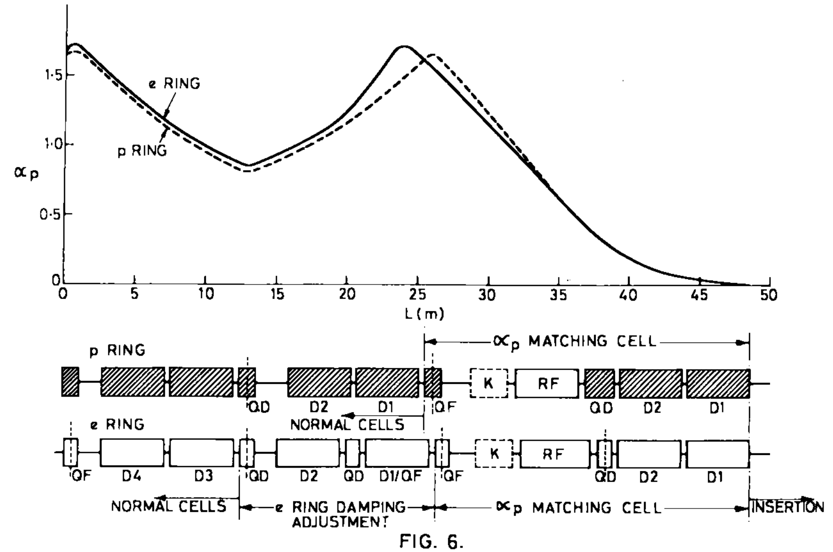


FIG. 6.
e⁻-p RINGS - αp MATCHING SECTIONS - e RING DAMPING ADJUSTMENT

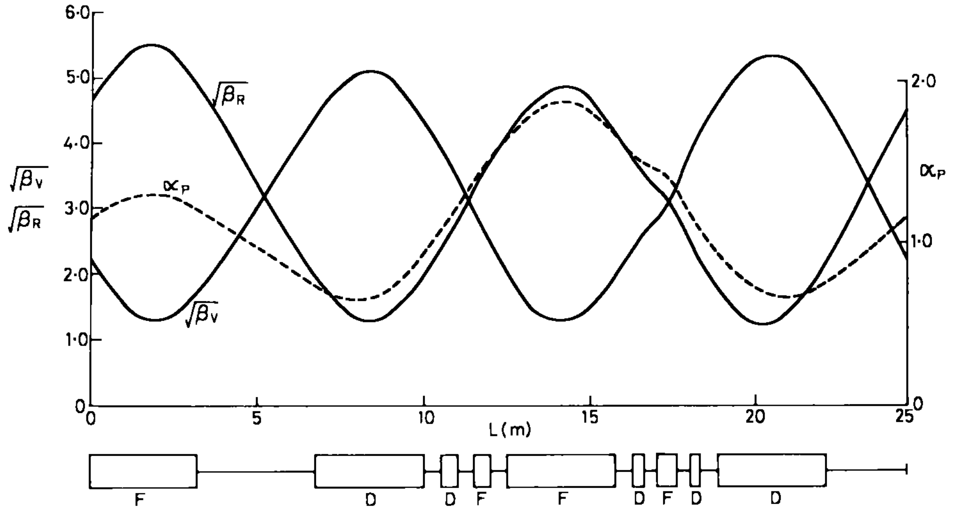


FIG. 7. NINA BOOSTER-NORMAL PERIOD

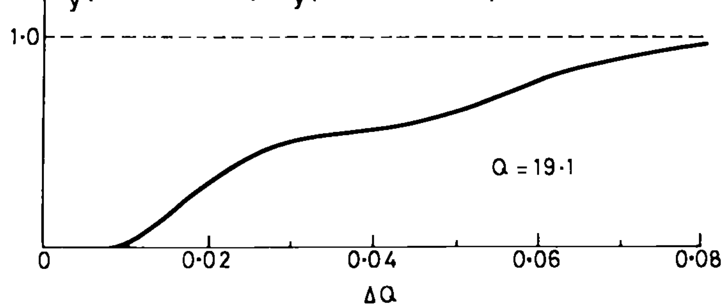


FIG. 8. BEAM-BEAM HORIZONTAL-VERTICAL COUPLING IN EPIC

divisible by 8. A second RF system is installed, with h = 48, to assist in initial trapping and bunch compression.

A further gain in overall capture efficiency is obtained by modulating the gun of the proposed 100 MeV electron linac injector[13]. Modulation at 9.71 MHz, with 10 nanosecond pulse lengths, leads to the filling of the required 8 booster bunches. This proposal is important for obtaining the required fluxes of injected positrons. If the average current in the electron linac is set at 400 mA for positron production, the peak current during the 10 ns pulses becomes 4A. The electron energy at the positron converter will be modulated by more than 10% during the pulse, but the output energy of the subsequent 200 MeV positron linac can be correctly stabilised.

It is planned to reduce the momentum spread of the 200 MeV positrons by means of a debuncher and correcting cavity. A scheme is under study which is similar to the one installed at the 300 MeV electron linac of Mainz University[14]. Studies of trapping in the booster indicate that the input momentum spread should be approximately $\pm\ 3.5\ 10^{-3}$.

The proposed modifications for NINA include a new magnet power supply, the second RF system, new injection and fast extraction systems and the introduction of quadrupole doublets and combined function triplets into the magnet lattice. The lattice design is shown in Figure 7. The doublets introduce a range of Q-tuning, while the triplets provide damping of the horizontal betatron motion of the electrons and positrons. The damping magnets have a D-profile and are arranged to form a triplet of zero total bend by the use of a reversed field in the central unit.

The magnetic field in the booster has a reduced rate of rise at injection, an intermediate flat at a field level corresponding to 2.25 GeV/c and a flat top of approximately 20 ms duration. Trapping, and acceleration to 2.25 GeV/c are undertaken by the lower frequency RF system. During the intermediate flat, the beam damps in phase sufficiently to be captured by the high voltage, high frequency RF system, which then completes acceleration to 4.8 GeV/c. The beam phase is adjusted during the flat top for synchronisation with the EPIC main ring.

Electron-Positron RF System

Design is proceeding on the basis of a peak energy gain per turn in EPIC of 30 MeV, developed in 42 m of accelerating structure. At 14 GeV/c the energy loss per turn in synchrotron radiation is 19.8 MeV. The RF over-voltage provides a beam lifetime of 10^5 s for loss out of the phase stable region due to quantum fluctuation effects.

Beam loading of the RF cavities by the two electron and two positron bunches is being analysed in a manner similar to that proposed by Keil[15]. The tightly bunched beams excite the RF cavities not only at the fundamental resonant mode but also at the higher cavity modes. This is a consequence of having appreciable harmonic components of beam current up to quite high frequencies, together with a close spacing of the harmonics. The amplitude of the harmonics varies as $e^{-(\omega\Delta)^2/2}$, where Δ is the rms bunch duration. The spacing of the harmonics is at twice the bunch repetition frequency. Beam-cavity and beam-equipment interactions will affect the equilibrium bunch lengths and the synchrotron motion, and these effects remain to be determined.

The design of the RF system is thus provisional, and there may be future changes in the choice of RF harmonic number and type of accelerating structure. The present choice of harmonic number is 2944, corresponding to an RF frequency of 402.7 MHz. The proposed standing wave accelerating structure is of the type developed at Los Alamos for LAMPF, but at approximately half the frequency. The inner aperture of the proposed cavity is of diameter 12 cm. The re-entrant nose cones are adjusted to optimise the transit-time corrected shunt impedance (approximately 30 MΩ/m). As discussed in reference 16 there is mechanical complexity in Los Alamos type structures at 400 MHz. The addition of the side-mounted cavities, that give the resonant coupling and $\pi/2$ mode operation, is complicated by the cavity size.

There will be four RF buildings, one associated with each superperiod of the machine. These buildings will provide access for installing and removing ring components. The installed RF power at each building will be approximately 1 MW, CW. The accelerating structure adjacent to an RF building will be subdivided into two sections of approximate length 5 m. The number of feeder points for the 5 m sections will be determined by power characteristics of windows. In the event that the peak energy of the storage ring is subsequently increased, further RF buildings and accelerating structures will be installed.

Normal Cells

Each of the four superperiods contains 14 normal cells which are of a separated-function FODO design of length 24.8 m. Each half-cell contains two dipoles, a quadrupole, a sextupole, a correction dipole and a beam monitor.

The dipoles for the electron-positron ring are 4.5 m long while the quadrupoles are 1.0 m. There is a spacing of 0.4 m between the two dipoles of a half-cell. One section of vacuum chamber extends through the two dipoles, and a shorter section threads through the quadrupole, sextupole and correction dipole. Two pumping ports are included in the longer section, while the shorter section has a length of bellows and a beam monitor. An aluminium chamber is proposed as in the SPEAR design, with the necessary cooling channel along the length of the outer wall. There will be distributed pumps within the vacuum chamber in the dipoles.

Insertions

No vertical bending magnets are required in the insertions of the electron-positron ring. The quadrupoles are arranged as in the electron-proton configuration. Each half of an insertion has a pair of high-β quadrupoles together with a pair of matching quadrupoles. These doublets generate the low-β values at the centre of the insertion and provide betatron motions which are matched to those in the normal cells.

In one of the long insertions there are two injection systems, one for the electrons and one for the positrons. Each system has an injection septum magnet together with upstream and downstream fast kicker magnets.

Other elements contained in the long insertions are the RF systems, electrostatic beam separation plates, correction dipoles, sextupoles, octupoles and skew quadrupoles. The insertion sextupoles will be distributed relative to the chromaticity correction sextupoles so as to minimise third order resonances.

Beam-Beam Computer Simulation

A computer program has been developed that evaluates the motion of a weak beam in the presence of a strong beam for the case of electron-positron beam-beam interactions. The dimensions of the strong beam are assumed fixed, with Gaussian distributions in the two transverse phase planes. Representative particles of the weak-beam are introduced with the same radial distribution as the strong beam but with small initial vertical motions.

The program tracks particles of the weak beam through successive superperiods of the storage ring, assuming no magnet imperfections in the lattice components. For each superperiod transit, estimates are obtained for the radiation damping, the fluctuations of the quantum excitations and the linear and non-linear forces of the beam-beam interaction. Random number generators are used to derive the quantum excitation terms. A number of different approximations have been used for the beam-beam space charge forces, but all have given essentially the same results. The possibility is now being considered of extending the program to include the added effects of imperfections in the ring magnets.

Initial tracking studies have been made for EPIC Q values of 19.1. Results are given in Figure 8 for a radial to vertical beam aspect ratio in the strong beam of four to one. The horizontal axis of the graph is the parameter ζ, which is approximately equal to the tune shift per interaction, ΔQ. The radial size of the weak beam remains unchanged, but the vertical dimension grows to reach that of the strong beam for $\Delta Q = 0.08$. Luminosity estimates for EPIC assume ΔQ values of 0.04.

A second set of results has been obtained for the same Q values but with a different beam aspect ratio for the strong beam. The aspect ratio at the collision region has been changed to 16:1 by doubling the radial dimension and halving the vertical. Though σ_y (strong), the rms beam height of the strong beam, is halved, it is found that σ_y (weak) again approaches the value of σ_y (strong) when ΔQ reaches 0.08. It is of interest to note that the beam-beam limits of operating storage rings occur at ΔQ values of this magnitude.

Results have also been obtained for EPIC Q values of 18.1. At this tune, the effect of the linear term in the space charge force is equivalent to reducing the minimum β-function at the point of collision. The simulation becomes approximate and the results difficult to interpret. Preliminary results indicate a reduced vertical growth of the weak beam at the interaction point, but an appreciable vertical size at the high-β quadrupoles.

Summary

The present status of the EPIC machine design has been outlined in this report. By October 1974 an improved cost estimate will be obtained for a 14 GeV electron-positron storage ring. The physics case for EPIC and a machine proposal will then be submitted to the Science Research Council, seeking funds to allow the ring to be built by 1981.

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DISCUSSION

Phil Morton (SLAC): What is included in your cost estimate—salaries and so forth, or what?

Grahame Rees (Rutherford): No, never include salaries.

Matthew Allen (SLAC): The shunt impedance figures for the cavities seem awfully high. Are you sure of that number?

Rees: We assumed copper cavities, not aluminum cavities, and these were values obtained from Los Alamos type computer programs.

Allen: Losses in the coupling slots will reduce the value below the computed values.

Rees: Perhaps we have been a bit conservative in power estimates because of the large amount we've allowed for power dissipated in the higher modes—we've allowed as much as for the fundamental mode. I agree, we might have to evaluate this.

Ednor Rowe (University of Wisconsin): What fraction of the power loss due to synchrotron radiation occurs in the dog legs in the interaction region?

Rees: About 30 - 40% at top energy.

Ernest Michaelis (CERN): Do you plan to vary the proton energy or is it fixed?

Rees: The usual way we thought to change energy would be to keep the ratio of electron and proton momenta constant so that the particles always come out of the vertical bending magnets at the same angle. We also thought it desirable to change the energies of the beams independently. This would be quite difficult in our design because one then has to change the position of the proton quadrupoles. But since the displacements required aren't large, this could be set up before a run at a given energy.

Melvin Month (BNL): You said that the synchrotron frequency goes up to a dangerous level if the tune drops below 15. Could you explain that statement?

Rees: Synchrotron frequencies are reaching 10% of the revolution frequency which has always been considered an undesirably high value. So we will have to look seriously at betatron-synchrotron coupling at modes higher than this.