© 1973 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

ISABELLE e-p OPTION*

R. Chasman
Brookhaven National Laboratory
Upton, New York 11973

G.A. Voss
Deutsches Elektronen Synchrotron
Hamburg, Germany

Summary

During the ISABELLE preliminary design study it became clear from the response of the high energy physics community that the addition of an electron ring to the proposed 200-GeV colliding proton beam facility[1] would be very attractive. It was felt that with the capability of this ring to reach an energy of 15 GeV the already wide range of experimental possibilities of ISABELLE would be greatly extended. Basic design features for such an electron ring have been worked out. Lattice parameters, rf system, injection scheme and characteristics of its interaction with one of the proton rings will be presented. The resulting luminosity was estimated to range from $\approx 10^{33}$ to $\approx 0.5 \times 10^{32}$ cm^{-2} sec^{-1} for c.m. energies from 65 to 109 GeV.

1. Introduction

During the ISABELLE preliminary design study, it became clear from the response of the high energy physics community that the addition of an electron ring as a future option to the proposed 200-GeV colliding proton beam facility would be very attractive. In view of the complementary nature of p-p and e-p reactions, a combined p-p and e-p facility seems to further guarantee important discoveries in particle physics.

Discussions with experimenters led to the conclusion that both electrons and positrons should be available for collisions with protons. For that reason, it seems straightforward to extend the envisioned $e^-(e^+)$-p facility to an e^--e^+ facility as well, at relatively small additional cost.

An electron ring with the capability to reach 15 GeV is felt to be a fair compromise between high energy and practical considerations. Maximum c.m. energies of 109 GeV in e-p collisions and 30 GeV in e^--e^+ collisions will then be achieved.

It is the purpose of this paper to describe basic design features of the ISABELLE electron ring. These were derived, by and large, in a cooperative effort during the ISABELLE Summer Study, which was held at Brookhaven in June 1972 and included participants from the major electron ring facilities in the U.S. and Europe. Lattice parameters, details of the e-p interaction areas, rf system and injection scheme will be presented together with beam and performance parameters.

Most proton ring parameters used in this paper, are those quoted in the ISABELLE Preliminary Design Study report.[1] Some revisions, mostly regarding the straight sections, have taken place after that report was published. These are described in another paper[2] at this conference.

*Work performed under the auspices of the U.S. Atomic Energy Commission.

†Work performed while with the Cambridge Electron Accelerator, Cambridge, Massachusetts.

2. General Design Features

The electron ring will be situated 25 m to the west of and on the same horizontal plane as one of the proton rings. A bypass will take the electrons (positrons) to the west long straight section of the proton ring, which the electrons will intersect twice at an angle of 12 mrad at points separated by 100 m. The general layout is shown in Fig. 1. With minor modifications, the electron ring can also fit inside the proton ring and intersect the east long straight section of that ring. Altogether, four e-p interaction areas will then become available. The preferred location of the electron ring can be decided on later on the basis of the relative importance of more interaction areas versus minimum interference with the operation of the proton rings.

The AGS, which is the proton injector, will also serve as an electron and positron booster. Injection into the electron ring will occur at 4 GeV and the energy at which the electrons are stored in the ring can vary between 4 GeV and 15 GeV.

A 30-GeV proton injector, such as the AGS, permits longitudinal stacking of high intensities in the proton ring, with circulating currents of the order of 15 A. One can therefore operate the e-p rings in a many bunch mode and still obtain very respectable luminosities. Typical proton bunches in ISABELLE are about two orders of magnitude longer than the electron bunches. In order to minimize the tune shift of the protons due to beam-beam interaction, it was suggested by Courant[3] that the electron beam be divided into trains of bunches each having a gross length equal to the length of one proton bunch. The many bunch mode facilitates the design of the electron ring in several respects. Because of its associated reduction in the proton tune shift, a high transition energy can be chosen, leading to small electron emittances and small momentum compaction factor. That, in its turn, results in a relatively low peak rf voltage to contain quantum fluctuations. Furthermore, small transverse electron emittances simplify considerably the design of the e-p interaction regions. No common quadrupoles are needed and the electron and proton rings are completely decoupled from each other.

The many bunch mode does lead to long range beam-beam interaction.[4] However, it was recently pointed out by Voss[5] that for the geometry of the ISABELLE e-p interaction area, the long range contribution to the nonlinear effects is almost negligible compared to that of the crossing region itself, while only the rather irrelevant linear parts are of the same order of magnitude. Therefore it is assumed in the following that the beam-beam interaction is proportional to that part of the tune shift which is due to the crossing region.

Proton emittances are those quoted in the ISABELLE Preliminary Design Study report. To maximize the e-p luminosity, it is assumed that the proposed interchange of horizontal and vertical phase space, between the AGS and ISABELLE, does not take place. Recent studies

connected with the required ISABELLE vacuum system calls for an increase in the diameter of the vacuum chamber. Under these conditions, the aperture requirements are satisfied even without such a phase-space interchange.

The electron emittances are determined by quantum fluctuations of the synchrotron radiation.

3. Lattice

A. General Description

The electron ring is designed in close resemblance with the proton rings. It consists of four 90° arcs separated by four matched straight sections. The two long straight sections are experimental insertions for future e^--e^+ collisions, while the two short ones are designed to accommodate the rf system. All straight sections have zero dispersion, which is accomplished in adjacent momentum matching sections. Each arc consists of 10 regular cells, one matched insertion and two momentum matching sections. The 60 m long matched insertion is removed by one cell from the momentum matching section of the adjacent experimental insertion. It has a 10 m free space in its center to be used for injection or fast protective extraction, depending on its location in the ring. The electron bypass will connect to two of these insertions. The bypass consists of a similar, but slightly longer matched insertion and one regular cell followed by the momentum matching section of the e-p experimental insertion. If the electron ring is situated inside the proton ring, a second bypass will be added on the other side of that ring. Further theoretical studies on the seriousness of a slight perturbation in twofold periodicity of the electron ring, will show if it is necessary to add a second bypass even in case the two rings lie side by side.

The basic electron ring lattice parameters are shown in Table I.

B. e-p Experimental Insertion

The design of the e-p experimental insertion was guided by the following considerations.

A 10 m long free space on each side of the crossing points is required by the experimentalists. Very low values for the β-function have to be achieved at the crossing points to obtain high luminosity. However, the β-function cannot be arbitrarily low at these points if excessively high values are to be avoided at the quadrupoles nearest to them. $\beta \leq 1000$ m was adopted in the ISABELLE Preliminary Design Study in order to avoid broad linear structure resonances and to set reasonable magnet tolerances. The same upper limit for β was adopted for the electron ring. Additional conditions for maximum luminosity are $\beta_y^e < \beta_y^p$, $\beta_y^e < \beta_x^e$ and $\beta_y^p < \beta_x^p$ at the crossing points, having to do with the relative sizes of electron and proton transverse emittances. If the β-function is smaller or comparable to the interaction length, it will vary over the crossing region and the average value there will be the determining factor for the luminosity. For the case considered here maximum luminosity is obtained if β_y^e at the crossing point equals half the interaction length, which is w_p/α, w_p being the proton beam half-width and α half the crossing angle. This determines α for a given value of β_y^e at the crossing point.

A schematic of the e-p interaction areas is shown in Fig. 2 together with the horizontal beam profiles. The much smaller vertical profiles have been left out. Figure 3 shows the β and X_p (momentum dispersion) functions in the region. At the end of the momentum matching section, the electron beam emerges at the desired crossing angle with respect to the proton beam. Both beams are brought to a narrow focus (low β-region) at the crossing point by two sets of doublets, DE1, DE2, and DP1, DP2 for electrons and protons respectively. DE2 and DP2 are 10 and 20 m away from the crossing point. At the place of DE2, the proton beam is sufficiently far removed from the electron beam that it can pass unaffected through a hole in the iron cores of the electron quadrupole magnets. The electron beam just clears the proton doublet DP2. The beams are again brought to focus at the center of the insertion by the doublets DE3 and DP3. DE3 and DE2 are symmetric with respect to the crossing point and the same holds for DP2 and DP3. Two bending magnets placed symmetrically about the electron insertion center accomplish the necessary bend for the second intersection. The additional electron triplet, TE1, keeps the dispersion function zero in the intersection region and in most of the electron insertion. Both electron and proton insertions are symmetric about their centers.

Because the proton beam is larger at energies below 200 GeV, the strength of the proton lenses in the experimental insertion will have to be changed during stacking and acceleration. The β-function at the crossing point has to be increased in order to reduce the proton beam size at the quadrupoles nearby.

Beam and lattice parameters in the interaction region are listed in Table II.

4. RF System

The electron ring rf system is designed[5] to store 100 mA rf current at 15 GeV. At this energy, the radiation loss per turn is 25 MeV. A rf frequency of 400 MHz is chosen as an optimal value considering minimum zero current excitation power and favorable geometries of the rf cavities. The peak voltage required at this frequency to contain greater fluctuations is 38 mV. Chains of π-mode coupled cavities with a shunt impedance of 25 MΩ/m are suggested. They would be a scaled down version of the 800 MHz cavities used in the electron linac at Los Alamos. It will be necessary to distribute 270 cavities over 100 m. They will be divided into 6 groups, each of which will be fed by a 500 kW klystron. In each of the two rf straight sections, there are three 18 m long free spaces to accommodate the six groups of rf cavities. The X_p function is zero in these spaces and the maximum value of the β-function is 70 m.

There will be 2.5 MW of power going into the beam and 0.5 MW into the cavities. When the electron ring is operated at energies below 15 GeV, the current will be increased to a limit set by the available rf power or by the proton tune shift to obtain higher luminosity. This will be done by lowering the shunt impedance of the rf system.

5. Injection Scheme

The AGS will serve as an electron (positron) booster so that maximum advantage can be taken of radiation damping during the electron ring filling process.

The AGS rf system can accelerate electrons up to 4 GeV. At this energy, the damping times are of the order of 0.5 sec. The AGS can be cycled at 10 pulses/sec for acceleration up to 4 GeV. It takes 3 AGS pulses to fill the electron ring and hence radiation damping will cause considerable reduction in the betatron and synchrotron oscillation amplitudes between consecutive injection turns.

The AGS, being an alternating gradient and not a separated function machine, will be radially antidamping

for electrons. However, an estimate shows that this increases the radial width of the beam by about 35% only so that no special damping system is required. Using a typical 200 MeV electron linac, the AGS can trap and accelerate 10 mA. Taking into account the transfer to and rebunching inside the storage ring an electron injection rate of 25 mA/sec can be obtained. For positrons, the injection will be considerably slower due to lower positron currents in the linac. Both electrons and positron injection rates can be increased by chopping the linac frequency at the rf frequency of the storage ring and by adding an accelerator cavity of that frequency to the AGS.

In connection with the injection scheme, it should be pointed out that the trains of electron bunches, mentioned earlier in this paper, will be formed either in the AGS or in the storage ring itself, depending on the final choice of the rf frequency of the proton rings. If this frequency equals the AGS frequency, the proper electron trains can be formed in the AGS. Otherwise, this will have to be done in the electron storage ring.

6. Luminosities and Tune Shifts

The luminosity for e-p collisions in each interaction region is given by[3]

$$L = \frac{2N_e N_p}{\pi w_p \ell_p \alpha} f_e B_e$$

where N_e is number of electrons per bunch
N_p is number of protons per bunch
w_p is twice the rms width of the proton beam at the crossing point
ℓ_p is twice the rms length of the proton bunch
B_e is number of electron bunches
f_e is the electron ring revolution frequency.

The effect of beam-beam interaction limits the permissible proton and electron densities. The strength of this effect is traditionally described by its associated linear tune shift, $\Delta\nu$, for which an upper limit of 0.025 has been assigned, based on both electron ring experience and numerical computations. Experience with proton rings is limited to that of the ISR where $\Delta\nu = 3 \times 10^{-4}$ and where no growth effects from beam-beam interaction have been observed.

For the geometry and beam parameters of the ISABELLE e-p interaction region, the electron and proton tune shift, $\Delta\nu$, are given by the following expressions:

$$\Delta\nu_e = \frac{2e^2}{\pi E_e} \frac{N_p}{h_p \ell_p \alpha} 2\beta_e^y$$

$$\Delta\nu_p = \frac{2e^2}{\pi E_p} \frac{N_e}{h_e \ell_e \alpha} \beta_p^y$$

where E_e is the electron energy
E_p is the proton energy
ℓ_e is twice the rms length of each electron bunch
β_e^y is the electron vertical β-function at the crossing point
β_p^y is the proton vertical β-function at the crossing point.

With the parameters listed in Table II $\Delta\nu_e = 0.025$ at $E_e = 15$ GeV. For electron energies E_e below 15 GeV N_p will have to be adjusted to $2 \times 10^{13} \times E_e/15$ in order to keep $\Delta\nu_e = 0.025$. Number of available electrons per bunch, N_e, will vary with the electron energy E_e for given rf power. Keeping in mind that the energy loss per turn increases with the fourth power of the electron energy, one can write $N_e(E_e) = N_e(15)(15/E_e)^4$. The height of the electron beam is proportional to E_e, provided that the coupling coefficient between horizontal and vertical betatron oscillations is kept constant with energy. Given $N_e(E_e)$ and $h_e(E_e)$ one can calculate $\Delta\nu_p$ as a function of electron energy and gets $\Delta\nu_p \geq 0.025$ for $E_e \leq 5.5$ GeV. In order to keep $\Delta\nu_p = 0.025$ for $E_e \leq 5.5$ GeV, N_e will have to be varied linearly with E_e, resulting in electron intensities below those available on the basis of rf power.

Using the expressions for $N_e(E_e)$ and $N_p(E_e)$, the luminosity can be calculated as function of electron energy and is shown together with $\Delta\nu_e$ and $\Delta\nu_p$ in Fig. 4.

For an unbunched ISABELLE proton beam N_p/ℓ_p has to be replaced N_p^t/C_p where N_p^t is the total number of protons in the ring and C_p its circumference. Assuming that N_p^t is the same as in the bunched case, luminosities will be reduced in the high energy region, keeping all other parameters constant. However, $\Delta\nu_e$ will now be smaller than 0.025. One can then vary the crossing angle as function of electron energy to keep $\Delta\nu_e = 0.025$ and get luminosities comparable to those obtained with bunched protons. Obviously, the interaction region geometry will have to be modified in this case.

7. Summary

A preliminary design for the ISABELLE electron-proton option has been presented. The system consists of an electron ring and a proton ring with 2000 and 2400 m circumferences, intersecting horizontally twice (or possibly four times) at an angle of 12 mrad. The rings are run in a many bunch mode, in which each of the 36 proton bunches collide with one of 30 trains, each of which contains 32 electron bunches.

The proton ring operates at a fixed energy of 200 GeV while the electron energy can be varied between 4 and 15 GeV. Center-of-mass energies vary between 56 and 109 GeV.

With an available power of 3 MW in the electron ring rf system, a maximum luminosity of 1.13×10^{33} cm^{-2} sec^{-1} is obtained for an electron energy of 5.5 GeV corresponding to 66 GeV in the c.m. system. At 15 GeV electron energy (109 GeV c.m. energy), the luminosity is 0.56×10^{32} cm^{-2} sec^{-1} with a proton tune shift, due to beam-beam interaction of 1.2×10^{-3}.

For an unbunched proton beam, similar luminosities can be obtained, provided that the interaction geometry is modified to allow a variation of the crossing angle with electron energy.

Possible collective longitudinal instabilities in the electron ring connected with the many bunch mode, will have to be investigated.

Acknowledgments

The authors are indebted to many participants in the ISABELLE summer study for taking part in much of the work that preceded this paper. In particular, they thank Drs. M. Allen, E.D. Courant, J.M. Patterson, G. Rees and K. Steffen for their contributions, and Dr. M. Month for valuable discussions. Special thanks are due to Dr. J.P. Blewett who initiated the design work on the ISABELLE e-p option.

References

1. ISABELLE Preliminary Design Study, BNL 16716 (1972).
2. R. Chasman, E.D. Courant, M. Month and A. van Steenbergen, IEEE Trans. Nucl. Sci. NS-20, No. 3 1973 (to be published).
3. E.D. Courant, CRISP 72-79, BNL 17277 (1972).
4. E. Keil, C. Pelligrini and A.M. Sessler, CRISP 72-34 (1972). See also E. Keil, CERN/ISR-TH/72-33 (1972).
5. G.A. Voss, CRISP 72-79 (1972).
6. M. Allen and G. Rees, CRISP 72-68 (1972).

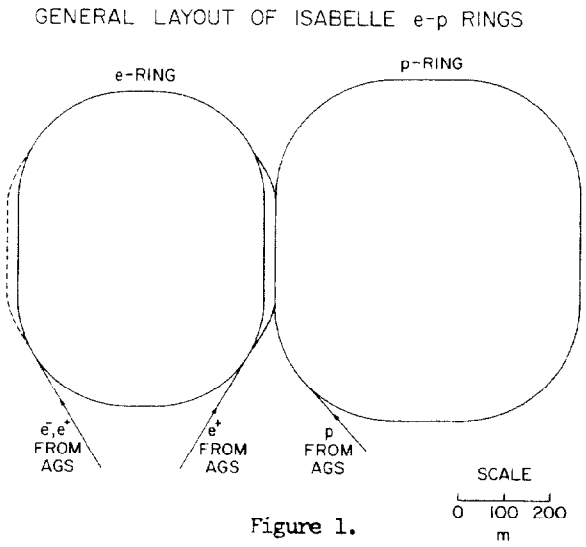


Figure 1.

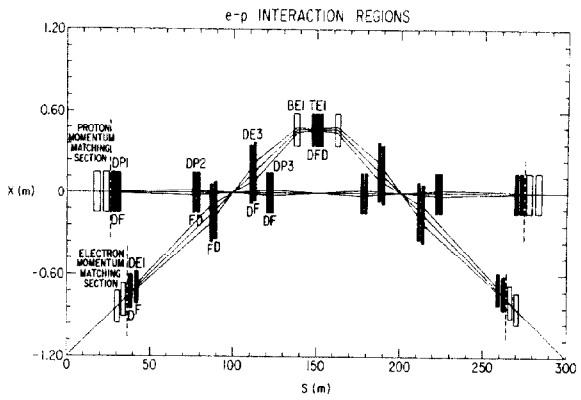


Figure 2.

TABLE I

LATTICE PARAMETERS

Type of Lattice	Separated Function
Average Radius	318 m
Average Radius of Circular Arcs	232 m
Magnetic Radius	180 m
Number of Regular Cells	40
Type of Cell	FBDB
Betatron Phase Advance Per Cell	
Horizontal	1.63 rad
Vertical	1.57 rad
Magnetic Field in Cells	2.77 kG
Quadrupole Gradient in Cells	~ 1 kG/cm
Cell Length	25 m
Number of Insertions	8
Number of Momentum Matching Sections	8
Number of Superperiods	2
Length of Experimental Insertion*	225 m
Length of rf Insertion*	58 m
Length of Injection, Extraction Insertion	59.4 m
Transition γ	19
Cell β-function	
maximum	42 m
minimum	6.6 m
Cell-Off-momentum Function	
maximum	1.65 m
minimum	0.8 m
Effective Beam Sizes (at 15 GeV)	
Cell F x x y	2.51 x 0.20 cm x cm
Cell D x x y	1.10 x 0.51 cm x cm

*Excludes momentum matching section.

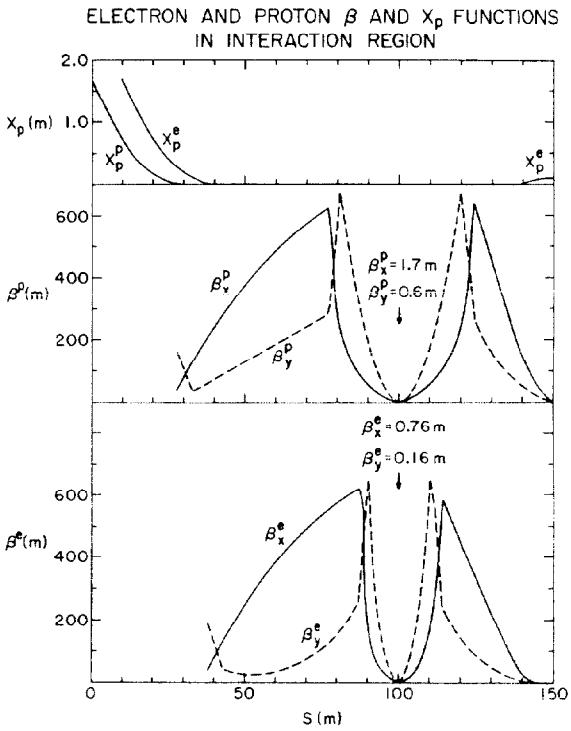


Figure 3.

TABLE II

PERFORMANCE PARAMETERS FOR e-p COLLISIONS AT MAXIMUM ELECTRON ENERGY

	Proton	Electron
Energy	200 GeV	15 GeV
Total Number of Particles	7.2×10^{14}	4.2×10^{12}
Number of Bunches	36	960 (divided into 30 trains
Number of Particles per Bunch	2×10^{13}	4.4×10^{9}
Transverse rms Emittances		
Horizontal	0.135×10^{-6} π m-rad	0.159×10^{-6} π m-rad
Vertical	0.0175×10^{-6} π m-rad	0.018×10^{-6} π m-rad
Crossing Angle (horizontal)	12 mrad	
Free Drift space	± 10 m	
Dispersion Function	0.0 m	0.0 m
Beta function at Crossing Point		
Horizontal	1.7 m	0.76 m
Vertical	0.6 m	0.16 m
rms Momentum Spread	1.5×10^{-3}	1.0×10^{-3}
rms Beam Sizes at Crossing Point		
Horizontal	0.048 cm	0.035 cm
Vertical	0.010 cm	0.0055 cm
Longitudinal	6 m	3.75 cm

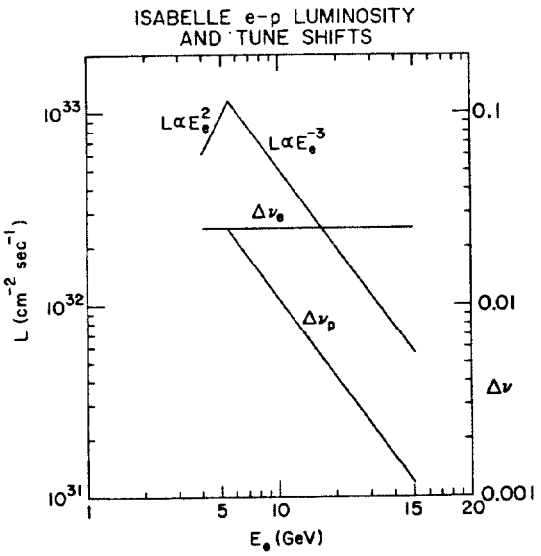


Figure 4.