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A HIGH LUMINOSITY B-$\bar{B}$ FACTORY: A RESEARCH AND DEVELOPMENT PROGRAM

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A Research and Development Program

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1) Introduction

In this paper we discuss a proposal for the construction of a high luminosity, $L \approx 10^{34} cm^{-2} s^{-1}$, electron-positron collider, operating in the energy range of 10 to 15 GeV total center of mass energy. The motivation for such a system is to study the physics of the $B - \bar{B}$ system, in particular the rare decay modes and the CP violation [1].

Our design is based on the following points:

1. unequal beam energies, to produce the B in motion in the laboratory frame;
2. positron recovery and cooling;
3. possibility of positioning the vertex detectors very near to the interaction point (IP);
4. possibility of changing the center of mass energy in the 10 to 15 GeV range, mantaining a high luminosity, to be able to operate effectively at the $\Upsilon(4S)$ resonance or above.
5. a small beam energy spread, less than .1%, to be able to utilize effectively the $\Upsilon(4S)$ resonance.

To satisfy these conditions we propose a scheme utilizing:

a. one 3 to 6 GeV high gradient electron linac, operating at about 16 GHz, with a 5 KHz repetition rate, or an Inverse Free electron Laser;

b. one positron cooling and recovery ring, provided with a bypass, where the IP is located;

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c. a positron converter, low energy positron accumulator, booster synchrotron, to provide the positrons.

This scheme is illustrated in Figure 1.

Other proposals utilizing a linac and a storage ring to obtain electron-positron collisions in the same energy range, have been discussed in the literature [2]. In all these cases the authors have assumed the IP to be in the storage ring itself. while we assume the interaction to occur in a bypass. The main advantage of our approach is to decouple the cooling and recovery function of the ring, from the IP, thus allowing an independent optimization of these different parts. For instance one can reduce the vacuum beam pipe near the interaction point to a very small value without limiting the beam lifetime in the storage ring and increasing the background in the detector.

Using a bypass and utilizing each bunch only every few damping times, one could increase the beam-beam interaction parameter ξ (or equivalently the disruption parameter) to a value larger than that achievable in a storage ring collider, where a collision takes place at each revolution, and thus increase the luminosity per interaction. However in this paper we will use a conservative approach and use a beam-beam interaction parameter near to that normally obtained in a storage ring collider.

The electron beam disruption can be made much larger and we will utilize this possibility to increase the luminosity. To keep to a minimum the positron disruption it is convenient to have the positrons with an energy larger than that of the electrons. In this situation the characteristics of the two beams at the IP are completely asymmetric, with one beam having a large disruption, one thousand or more, and the other with a small or negligible disruption. This case has not been studied in the literature up to now. To estimate what can happen we will use a simple model, with the positron bunch behaving to first approximation as a rigid bunch and the electrons being channeled by the positrons and executing many plasma oscillations within the positron bunch. Although one can reasonably expect that also in this situation the luminosity will be enhanced by the pinch effect, we will again assume for simplicity and to be conservative that there is no enhancement. A self-consistent study of the beam-beam effects in this type of physical situation needs to be done to have a better understanding of the physics of these non-symmetric collisions.

The collision frequency is mainly set by the linac; if one uses a superconducting linac it can be made very high, in the MHz range, while for room temperature linac it is much smaller, in the 0.1 to 5 KHz range. We will partly compensate for this reduction by assuming that in each linac pulse we can accelerate a train of ten bunches, to be collided with a similar train extracted from the storage ring. In this way we can obtain a collision frequency between 1 and 50 KHz.

In this paper we will give only a preliminary estimate of the main parameters of this system, with the purpose of establishing its feasibility. The high luminosity required to study the B physics makes any collider extremely difficult, and pushes the beam characteristics to a region not yet explored. What we propose is no exception and will require a large amount of research and development of beam physics and technology before a more realistic proposal can be made.

2) General considerations

We consider a linear collider with two beams of energies E_1, E_2, (or γ_1 , γ_2). For simplicity we consider only the case of beams with cylindrical symmetry, and rms transverse radius $\sigma_{t,i}$, and length $\sigma_{l,i}$, with i=1 or 2.. We also assume to have N_1 and N_2 particles per bunch.

The luminosity is then given by:

$$L = f\ \frac{N_1 N_2 H}{2\pi(\sigma_{t,1}^2+\sigma_{t,2}^2)} \tag{1}$$

where f is the number of bunch collisions per second. To evaluate the luminosity we must use the constraint introduced by the disruption, using the parameter

$$D_i = \frac{r_e H N_k \sigma_{l,k}}{\gamma_i \sigma_{t,k}^2}\ ,.........i,k=1,2\ \ with\ \ i \neq k \tag{2}$$

The other additional condition is given by the beamstrahlung parameter, describing the average energy loss

$$\delta_i = 8\frac{r_e^3 N_k^2 \gamma_i H}{21\pi^{1/2}\sigma_{l,k}\sigma_{t,k}^2} \tag{3}$$

Using eq. (2) we can rewrite the luminosity as

$$L = \frac{P_1 D_1}{2\pi r_e mc^2 \sigma_{l,2}\ (1+\sigma_{t,1}^2/\sigma_{t,2}^2)} \tag{4}$$

where

$$P_1 = f N_1 \gamma_1 mc^2 \tag{5}$$

is the beam 1 power.

In practical units (5) can be rewritten as

$$L = 7\times10^{24}\frac{P_1(Watt) D_1}{\sigma_{l,2}(cm)\ (1+\sigma_{t,1}^2/\sigma_{t,2}^2)} \tag{6}$$

Let us now assume that beam 1 is the positron beam, and 2 the electron beam. From this equation, and assuming $\sigma_{t,1}$ on the same order as $\sigma_{t,2}$, one can see immediately that to have a large luminosity one can increase the beam power and/or the disruption of the positron beam, and decrease the electron bunch length. This last option leads to an increase in beamstrahlung, according to (3), and to a larger energy spread for the positrons. If we increase the disruption parameter, we can decrease the positron beam power, but we can hardly recover the positron beam.

As an example, let us assume that the two beams have an energy $E_1 = 9GeV$, $E_2 = 3GeV$, $L = 10^{34}cm^{-2}s{-1}$, $\sigma_{t,1} < \sigma_{t,2}$, and $\sigma_{l,2} = 0.1cm$. We then have $P_1 D_1 = 143MWatt$, corresponding to $10^{17}/D_1$ *positrons/second*. To produce these positrons from an electron beam on a target one would need of the order of 100 MW of electron beam, clearly a too expensive proposition. If, on the other hand, we assume a large value of D_1, for instance 10 or larger, to reduce the positron beam power, we eliminate the possibility of positron recovery. If we use a small value, like 1, we can do recovery, but we have a large beam power, which indicates that we need to recover not only the positrons but also their energy. This can be done in the scheme that we are proposing. The alternative of using a much smaller value of the electron bunch length leads to a value of the beamstrahlung parameter, which is incompatible with running at the $\Upsilon(4S)$ resonance.

All of these points will be discussed in more details in the following sections.

To conclude this section, we give in Table 1 a list of the possible parameters for a system

TABLE 1

COLLIDER PARAMETERS

Energy, positrons, GeV	9
Energy, electrons, GeV	3
positrons/bunch	1.6×10^{11}
electrons/bunch	1.6×10^{10}
normalized transverse emittance, positrons, cm rad	3×10^{-4}
normalized transverse emittance, electrons, cm rad	1×10^{-4}
beta at IP, cm	.125
bunch radius, positrons, rms, cm	4.6×10^{-5}
bunch radius, electrons, rms, cm	4.6×10^{-5}
bunch length, positrons, cm	1.0
bunch length, electrons, cm	0.01
Repetition frequency, s^{-1}	5×10^{4}
Beam power, positrons, MW	11.5
Beam power, electrons, MW	0.4
Luminosity, $cm^{-2}s^{-1}$	4.8×10^{33}
Disruption parameter, positrons	1.2
Disruption parameter, electrons	3580
Beamstrahlung parameter, positrons	1×10^{-3}
Beamstrahlung parameter, electrons	3.3×10^{-4}
Center of mass energy spread	6.6×10^{-4}

Notice that to increase the luminosity we have chosen a very small value of the electron bunch length, 0.01 cm. This is much shorter than the positron bunch length, 1.0 cm. The two bunches only start to interact at a distance from the IP equal to a quarter of the positron bunch length, and we have chosen the beta function at the IP equal to this distance.

In all this calculations we have also assumed the enhancement factor, H, to be one. We believe this to be a reasonable assumption, because of the small value of the positron disruption parameter. On the contrary the electron disruption parameter is very large. In this situation the positron bunch will act as a channel in which electrons propagate and are focused. If we use, for simplicity, the model of a uniform positron beam to calculate the force on the electron, we can calculate the characteristics of the electron motion [2]. The oscillation frequency is given by the beam plasma frequency, and is related to the disruption parameter by

$$\omega_p = 2D \ (c/\sigma_{l,1}) \tag{7}$$

The number of oscillations during the crossing is given by

$$N_{osc} = \frac{\sqrt{2D}}{2\pi} \tag{8}$$

With the numbers of Table 1, we have $N_{osc} \approx 13$, and $\omega_p \approx 7\times10^{12} s^{-1}$.

For the positron beam the disruption effect can be considered equivalent to a beam-beam tune shift given by

$$\xi = \frac{\beta}{\sigma_{l,2}}\frac{D_1}{4\pi} \tag{9}$$

With the values of Table 1 we obtain $\xi \approx 1$.

3) The Cooling-Recovery Ring

The Cooler-Recovery Ring (CRR) must provide low emittance bunches of positrons at a high repetition rate. The bunches are extracted and sent in the bypass where they collide with the electrons at the IP. After the collision the positrons are sent back into the CRR where radiation damping will bring them back to the initial condition after a few damping time. We make the assumption that the effects of the interaction on the bunch, like disruption and beamstrahlung, are such that only a small fraction of the positrons, say less than 1%, are lost during the cycle described above.

The CRR is designed to provide;

a. fast cooling (short damping time);

b. short bunches, to reduce the electron beam disruption;

c. high peak current (for large luminosity);

d. small emittance.

To design the ring we have assumed a FODO type magnetic structure with or without the addition of wigglers. We have also considered two options:

1. a ring energy of 9 GeV, producing a beam which can be used directly for the collider;
2. a lower energy ring, say 2 to 3 GeV, with acceleration to the final energy taking place in the bypass, followed by the interaction with the other beam, and then by decelaration to the ring energy.

In both cases we base the ring design on the work of Bassetti at al.[3]. The ring is designed as a series of FODO achromat cells, made of four 90 degrees phase advance cells, terminated at each end by a dispersion suppressor. In the zero dispersion straight sections one can insert wigglers, RF cavities and other components. For such a lattice the emittance can be written as

$$\varepsilon = p\varepsilon_0 + (1-p)\varepsilon_w \tag{10}$$

where ε_{zero} and ε_w are the contributions to the emittance from the arcs and the wiggler magnets, and

$$p = \frac{\rho_w}{\rho_w + \eta\rho} \tag{11}$$

In this formula ρ_w and ρ are the bending radii in the arcs and wigglers, and

$$\eta = \frac{L_w}{2\pi\rho_w} \qquad (12)$$

with l_w being the total wiggler length.

The emittance due to the wiggler can be written as

$$\varepsilon_w = 3.06\times10^{-8} E^2 \beta_w \frac{\lambda_w^2}{\rho_w^3} \qquad \textit{with E in GeV} \qquad (13)$$

and that due to the arcs as

$$\varepsilon_0 = 3.83\times10^{-13}\, \gamma^2 (\frac{\pi}{N_p})^3 f_{latt} \qquad (14)$$

In (13) and (14) λ_w is the wiggler period, β_w is the beta function in the wiggler magnet, assumed roughly constant, and N_p is the number of achromat blocks in the ring, and f_{latt} is a lattice form factor which in our case can be assumed to be $f_{latt} = 0.115$.

The radiated energy and the momentum compaction also have a contribution from the arcs and from the wigglers. The corresponding expression are given in ref. [3].

To determine the beam characteristics we must also consider and estimate the main collective effects which can limit the beam current and its emittance. For a small emittance ring the main collective effects is the microwave instability, limiting the peak current and energy spread; for a longitudinal coupling impedance $\frac{Z}{n}$, this can be written as

$$I_p = \frac{2\pi\alpha E \sigma_E^2}{\frac{Z}{n}} \qquad (15)$$

To estimate the coupling impedance we use the Spear scaling

$$\frac{Z}{n} = [\frac{Z}{n}]_{co} (\frac{\sigma_l}{b})^{1.68} \qquad (16)$$

where $[Z/n]_{co}$ is the impedance at the vacuum pipe cutoff frequency.

At very high frequencies this impedance becomes very small, and one has to take into account another contribution, the so called vacuum impedance

$$[\frac{Z}{n}]_{FS} = 300 \frac{b}{R} (1+\eta) \qquad (17)$$

peaking at a frequency near $\omega_v = c (\frac{R}{b^3})^{1/2}$. For frequencies larger than ω_1 the impedance decreases like $\omega^{-2/3}$.

In addition to the microwave instability, we must also consider the limit introduced by the fast head-tail effect

$$I_p < \frac{4\pi \nu_\beta \nu_s E}{Z_T} \qquad (18)$$

where Z_T is the transverse coupling impedance. To evaluate this we use the approximate formula $Z_T = 2\,(R/b)^2 [Z/n]$.

The transverse emittance can be influenced by the Intrabeam scattering effect. For the two rings that we are considering this effect is, however, small and to a first approximation can be neglected.

The main characteristics of the rings are given in Table 2, for the 9 GeV ring, and Table 3 for a 2.2 GeV ring. This last ring is the same one described by Bassetti at al., for the Frascati 5 to 10 GeV linear collider.

TABLE 2

COOLER-RECOVERY RING CHARACTERISTICS

Energy, GeV	9
Magnetic structure	FODO
Bending radius, m	33.6
Bending field, T	0.89
Number of dipoles	704
Dipole length, m	0.3
Average radius, m	67.2
Circumference, m	422
Phase advance per cell, rad	1.99
Bending angle per cell, rad	0.0178
Betatron tune	112
Normalized emittance, mm mrad	3
Momentum compaction	5×10^{-5}
Energy loss/turn, MeV	17.5
Betatron damping time, ms	1.4
RF frequency, GHz	3
Harmonic number	4240
RF voltage, MV	270
Synchrotron tune	0.033
Energy spread, zero current	1×10^{-3}
Bunch length, zero current, mm	0.13
Positrons/bunch	1.5×10^{11}
Coupling impedance, Z/n, Ω	0.1
Energy spread, full current	1×10^{-3}
Bunch length, full current, mm	0.13

TABLE 3

COOLER-RECOVERY RING CHARACTERISTICS

Energy, GeV	2.2
Magnetic structure	FODO
Bending radius, m	22.9
Bending field, T	0.32
Number of dipoles	96
Dipole length, m	1.5
Average radius, m	114
Circumference, m	717
Wiggler period, cm	25
Wiggler field, T	1.7
Total wiggler length, m	335
Phase advance per cell, rad	1.57
Bending angle per cell, rad	0.131
Betatron tune	11.6
Normalized emittance, mm mrad	3
Momentum compaction	2.8×10^{-3}
Energy loss/turn, MeV	6
Betatron damping time, ms	1.7
RF frequency, GHz	0.5
Harmonic number	1200
RF voltage, MV	20
Synchrotron tune	0.07
Energy spread, at zero current	9×10^{-4}
Bunch length, at zero current, mm	4.1
Positrons/bunch	1.6×10^{11}
Coupling Impedance, Ω	0.2
Energy spread, at full current	1.8×10^{-3}
Bunch length, at full current, mm	5.6

he two rings described in Tables 2 and 3 are only possible examples of accelerators that would provide the positron beam needed for the colliders, and more work would be needed to optimize the choice of the CRR. In all cases, these CRRs require the study of many accelerator physics issues, from the dynamic aperture, to the coupled bunch instabilities, to the low Z/n value, to the efficiency of positron recovery.

4) Linac and Collision Frequency.

The electron linac is assumed to be a high gradient, high frequency, high repetition rate system. It could be based on the relativistic klystron work being done at Livermore, SLAC and Berkeley, and run at a frequency of about 18 GHz, and an accelerating field of about 200 MV/m.

The electron beam is formed in a high brightness RF electron gun, similar to those being developed at Los Alamos and Brookhaven National Laboratories. We assume that it can produce a bunch with a normalized transverse emittance $\varepsilon_N = 10^{-6}\ m\ rad$, a longitudinal emittance $\varepsilon_L = 0.02\ m$, and a charge per bunch of up to 10^{11} particles.

To evaluate the repetition rate we assume that in the CRR and in the linac we have trains of ten bunches separated by $1/3\ ns$,for a total train length of 3 ns. The linac repetition rate is assumed to be 5kHz, thus providing up to 50,000 electron bunches per second for the collider.

The collision geometry is based on colliding at an angle in the horizontal plane so that the electron and positron bunches only interact one by one, and one is not using multiple collisions.

The storage ring also has to provide 50,000 bunches per second. Assuming that we extract or inject trains of ten bunches, and that this trains must be separated by about 10 m for extraction, we can store about 38 trains for ring 1 (9 GeV), and 65 for ring 2 (2.2 GeV). The possible repetition rate for train is $f_{train} = 1/5\tau_x$, and for N_T trains we have $f = 10N_T/5\tau_x$, giving $f \approx 10^5, s^{-1}$, for ring 1, and $f \approx 7.6\times10^4, s^{-1}$ for ring 2. We see that in both cases we exceed the linac capability.

The average ring current producing a rep rate of 50,000 Hz is .35 A for ring 1, and 0.46 A for ring 2.

In the case of the 2.2 GeV ring we need to accelerate and decelarate the positrons; this can be done using the same type of linac used for the electrons. The electron beam power is $P_2 = fEN_2 = 0.24MW$. The positron beam power needed for acceleration from 2.2 to 9 GeV if we use the ring 2 option, is $P_1 = 6.8\times10^9 fN_1 = 8.7MW$. Although one could recover this energy from the decelerating linac to improve the overall energy balance, the option using the 9 GeV ring is clearly the most convenient.

5) The Bypass and Collision Characteristics.

To match the positron beam characteristics, to those required in TABLE 1, we need to perform some beam manipulation in the bypass region, increasing the bunch length and reducing its energy spread. For ring 1 we can increase the bunch length to 0.5 cm, reducing the energy spread to a value smaller than the beamstrahlung parameter. For ring two we can make use of the acceleration from 2.2 to 9 GeV, and again exchange bunch length for energy spread to meet the same condition.

The bypass can be designed as a system with unitary transformation matrix between the exit and entrance point of the ring, and a transformation with elements

$$m_{11} = -(\frac{\beta_1}{\beta_0})^{1/2}, \quad m_{12} = 0$$

$$m_{12} = 0, \quad m_{22} = -(\frac{\beta_0}{\beta_1})^{1/2}$$

where β_0 is the beta function value at the ring exit and entrance points, assumed equal, and β_1 is the value at the IP. We also assume that α=0 at the the ring points and the IP.

This solution has the advantage of producing a small beam size at the IP, and minimizing the effect of the beam-beam interaction on the positrons, thus making easier their recovery.

Since a disruption value of one, corresponds to a beam-beam tune shift of about one, only slightly larger than the usual value for a ring collider, the positron recovery efficiency is expected to be very large. The positron production, using 3 GeV electrons, is of the order of $0.5\frac{e^-}{e^+}$; with the number of Table 1 this is equivalent to a production of about 10^{13} positrons per second, sufficient to compensate a rather large loss. It is clear that also this problem needs a more detailed calculation.

6) R&D Program

The system outlined in this paper seems to offer an interesting and promising approach to a $\overline{B-B}$ collider. It offers the high luminosity and reduced energy spread to fully exploit the Y(4*S*) resonance, to produce greater than $10^8 B-\bar{B}$ events per year. Thus it would really be a $B-\bar{B}$ Factory as specified in this workshop [2].

In order to realize this machine, there are several crucial R&D questions, as:

(1) can the high gradient linac operate at 5 KHz?

(2) Can the disruption parameter of the positron beam be kept at the required level?

(3) Can the CRR complex be simplified to reduce the cost?

As in all proposal for a $B-\bar{B}$ Factory, the extreme requirements for luminosity and energy spread are pushing the system in a new and unexplored range of parameters. This points to the need of a consistent R&D program to study questions like the beam-beam interaction for non symmetric beams, the efficiency of positron recovery, the design of low coupling impedance storage rings, the damping of coupled bunch instability in high average current rings, the wake field effects in high frequency linacs, and many more. Most of these questions are of interest to all $\overline{B-B}$ factories design and also for future higher energy electron-positron collider, making an R&D program on this approach of general usefulness.

REFERENCES

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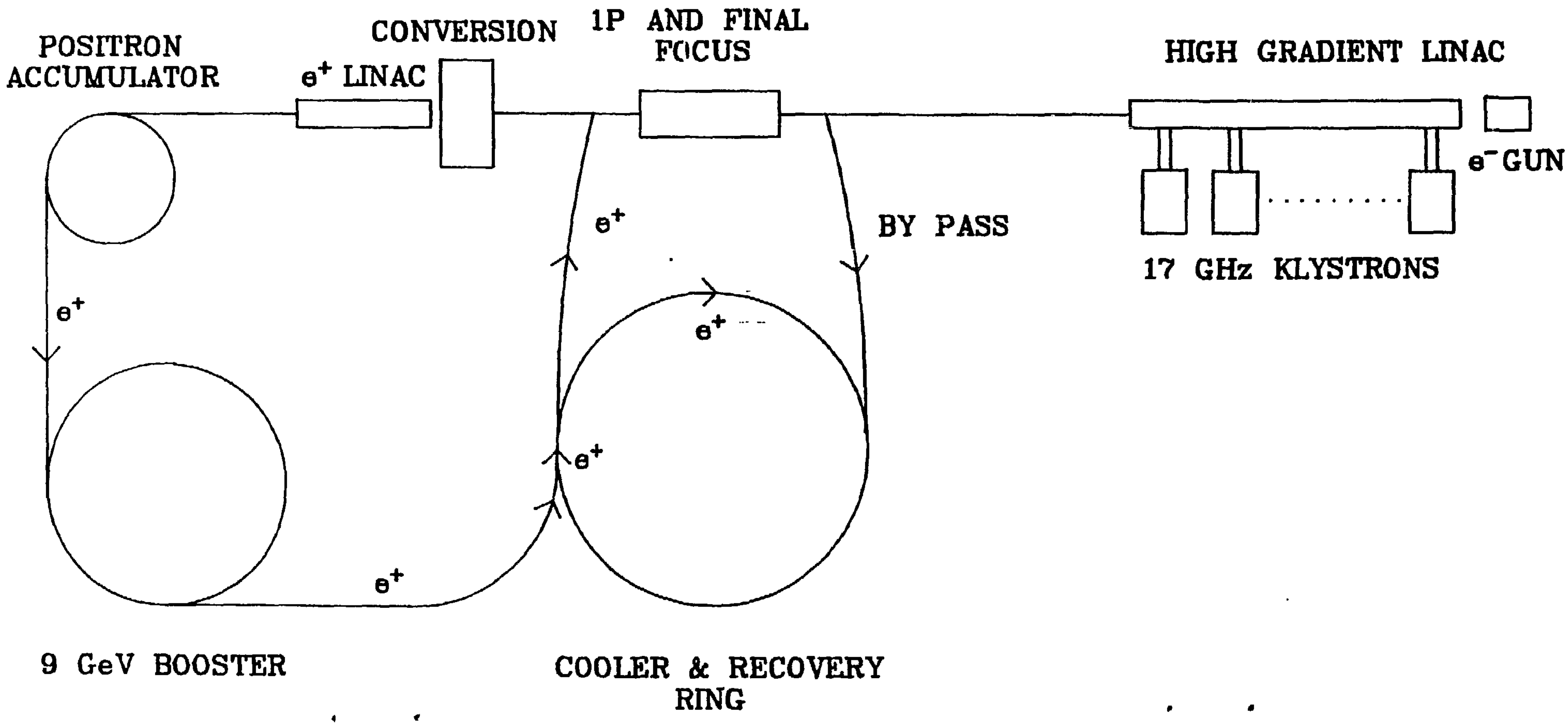
POSITRON ACCUMULATOR
CONVERSION
e^+ LINAC
1P AND FINAL FOCUS
HIGH GRADIENT LINAC
e^- GUN
e^+
BY PASS
17 GHz KLYSTRONS
e^+
e^+
e^+
e^+
9 GeV BOOSTER
COOLER & RECOVERY RING