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A 60x60 GeV^2 Electron-Positron Storage And Colliding Device. An Alternative To The Several Hundred GeV Proton-Proton Projects.

by

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Introduction

During the 1975 ISABELLE Summer Study held at Brookhaven National Laboratory we had the opportunity of exchanging opinions with some of the high-energy physics experimentalists. The topics, of course, were mainly physics with proton-proton storage rings at several hundred GeV, but the question that was raised was whether one would prefer to do experiments with different kinds of particles, for instance electrons and positrons. The most relevant field one would concentrate in the future is likely the investigation of where electromagnetic and weak interactions lead to each other, namely the search of the intermediate bosons and associates. Many experimentalists expressed the opinion that this kind of research is made complicated in a proton-proton storage ring by the non-elementary structure of the protons. The experiments would be easier if the protons are still the target but electrons are used to hit them. In this case one makes use of the very simple structure of the electrons to dig inside the distribution of a proton. This idea had a follow-up and many new projects (PEP, ISABELLE, LSR, POPAE) include the option of electron-proton crossings.

Nevertheless, with e-p experiments one has to cope with some problems. The electron energy should be of 10-20 GeV, usually not available where a high-energy proton beam is. The energy of the electrons and that of the protons are an order of magnitude apart and this makes the e-p scattering kinematics asymmetric though this may not be a bad situation for some of the experiments. Finally, some experiments may be intended to use the electrons to look for the constituants of the protons, but in many more other experiments the structure of the protons is still a nuisance when searching for the intermediate bosons.

Thus one, moving to the next step, could be better off if the search is done with electron-positron scattering. The idea is not new and there are, indeed, many projects of this sort around the world all in the range from 10 to 15 GeV (PEP, EPIC, PETRA, SUPERADONE, TRISTAN). Actually two of these projects (PEP and PETRA) have received, or have a good change to receive, governmental approval for construction. In particular, PETRA has been designed with the capability to reach a 19x19 GeV^2 energy. Nevertheless, all these projects will not have the capability of finding the intermediate bosons. For this purpose according to some more recent estimates, one needs an energy of 60x60 GeV^2. A storage and colliding ring device of this energy for electrons and positrons requires of course, special examination. This is the purpose of this paper. We found that such a device is quite feasible, provided enough real estate is available (some 5 km across). The main concern is, of course, the RF power, but it is possible to limit the power consumption to 60 MW which is about the power consumption of a laboratory like Fermilab. Also the cost of this machine is about the cost of a proton-proton machine like POPAE or ISABELLE, and the design concepts and requirements are much easier to understand and to satisfy than in a several hundred GeV proton machine.

In conclusion, of course the experimentalists have to decide which machine better suits their research needs, but we believe that the electron-positron colliding device at 60 GeV energy presents a very valid and suitable alternative to ISABELLE or POPAE or LSR or ...

The authors wish to thank Carlo Rubbia for stimulating the research of which this paper is the outcome. A similar note has already appeared as a CERN-NP internal report[1] with an introduction and conclusion by Carlo Rubbia.

A feasibility study of a super $e^{\pm}$ storage ring can be found also in Ref. 2.

Most of the formulae used in the following were taken from Ref. 3.

We have profited very much from discussions with Don Edwards and Luke Mo.

1. General Description, Size

Because of the high energy and the large amount of synchrotron radiation a large size of the magnetic ring is obviously required. Nevertheless, the top value of the magnetic field is determined by the values of the field and the energy at injection. We shall consider here an injection energy of 20 GeV, high enough to supply an appreciable damping time and an injection field of 400 Gauss. A lower value of the field does not seem to us technically practical. Also a fast cycling injector at 20 GeV seems to us relatively easy to design and not exceptionally expensive.

By scaling, then, the top field value at 60 GeV would be of 1.2 kG with a bending radius of ρ = 1667 m. The total bending circumference is $2\pi\rho$ = 10,472 m. We increase the regular bending part of the machine by 20% to make space for quadrupoles and drift sections, and in addition we add straight sections for a total amount of 2000 m, which we believe would be adequate for the RF system and the experimental insertions. The total circumference would then be $2\pi R = 2\pi \times 2{,}318$ m = 14,566 m.

The shape that one would give, then, to the machine could be the one shown in Fig. 1, which has symmetry 4 with four straight sections each 500 m long and four 90° circular arcs with a radius of exactly 2 km.

The energy loss per particle per turn would be of 8.5 MeV at 20 GeV and of 688 MeV at 60 GeV. The revolution frequency is f = 20.6 kHz; the revolution time is T = 48.6 μs. From this we derive the energy damping time which is τ = 113 ms at 20 GeV and τ = 4.2 ms at 60 GeV. This time is reasonably small, also at low energy, so that one can consider an injection rate of 10 pulses/sec, and this should be also the repetition cycle of the injector synchrotron.

Positrons can be produced by sending the electrons from a high intensity linear accelerator at several hundred MeV energy on a target in front of the injector synchrotron. Either electrons or positrons are then accelerated in the synchrotron at moderate intensity to the final value of 20 GeV. Then they would be stacked in the common storage ring. Stacking will be performed at the low energy of 20 GeV and the two beams would be kept separated at the crossing points. Once the stack is completed, the two beams are accelerated by the common RF system to any energy between 20 GeV and 60 GeV. The separation device turned off, the two beams are made to collide with each other.

2. Luminosity, Tune Shift and Intensity

The basic formulae are those for the luminosity and the beam-beam tune shift. In the case of head-on collision and $\sigma_y^* < \sigma_x^*$, the largest tune-shift occurs on the vertical plane, and the important parameter is the beta-value β^* at the crossing point. We assume that $\beta_x^* \sim \beta_y^*$.

One has

$$L = \frac{B f N_B \gamma \, \Delta\nu}{2 r_e \, \beta^*}$$

and

$$\Delta\nu = \frac{N_B r_e \, \beta^*}{2\pi\gamma\sigma_x^* \sigma_y^*}$$

where N_B is the number of particles per bunch, B is the number of bunches in a beam (not necessarily equal to the RF harmonic number h),

$\gamma = 1.174 \times 10^5$ and $r_e = 2.8 \times 10^{-13}$ cm. We are assuming the two beams are identical, namely made of the same number of bunches and of the same intensity.

We take $L = 10^{32}$ cm^{-2} s^{-1} and $\Delta\nu = 0.05$. Also we chose a small value for β^* to keep the beam intensity low. The value of $\beta^* = 20$ cm is reasonable as it has already been adopted for other machines (SPEAR, PEP). One obtains

$$BN_B = 9.26 \times 10^{12}$$

which corresponds to an average current of 30.5 mA. To keep the filling time short, one requires a high intensity injector synchrotron. If the number of electrons per pulse is 10^{12} one needs only ten pulses to build up the electron beam. But, assuming an efficiency of 0.1% for positron production one then needs ten thousand pulses to get the stack of positrons. At the rate of ten pulses per second, both rings would be filled up in about half of an hour.

3. Beam Size

For the following calculations we assume that the radiation repartition factors are $J_e = 2$ and $J_x = J_y = 1$. Also it is a good approximation to replace the momentum compaction factor α with $1/\nu^2$, where ν is the number of betatron oscillations per revolution.

One has for the energy spread

$$\left(\frac{\sigma_E}{E}\right)^2 = \frac{3.84\times10^{-13}\ \gamma^2}{2\ \rho_{(m)}}$$

from which $\sigma_E/E = 1.26 \times 10^{-3}$.

The machine can be made of regular cells each 60 m long and each with a 90° phase advance (which is by now considered as a standard cell). In this case there would be about 243 cells and the betatron tune is $\nu = 60.7$.

The horizontal rms emittance is given by

$$\frac{\sigma_x^2}{\beta_x} \approx 2\frac{\alpha R}{\nu_x}\left(\frac{\sigma_E}{E}\right)^2$$

which in our case gives 3.3×10^{-8} m.

If we let the two modes to have a full coupling so that, say, $\sigma_y^* \sim \sigma_x^*$ we have

$$\begin{aligned} B\, \sigma_x^* \sigma_y^* / \beta_x &= B\, \sigma_x^{*2} / \beta_x \\ &= \tfrac{1}{2} \times 3.3 \times 10^{-8}\ B\ \mathrm{m}\ ^{(*)} \\ &= B N_B\, r_e / 2\pi\, \gamma\, \Delta\nu \\ &= 7.0 \times 10^{-7}\ \mathrm{m} \end{aligned}$$

which results in the number of bunches $B \sim 40$. The average value of β is $\bar{\beta} = 40$ m, thus the average beam width (2 x rms) is, including a 50% due to the energy distribution, 1.6 mm and the average beam height (2 x rms, no vertical dispersion) is 1.1 mm. At the crossing point $\sigma_x^* = 0.08$ mm.

4. RF System

The power radiated by a 60-GeV beam of 30.5 mA is 21 MW. Taking into account a power loss in the RF system itself of about 30% of what should be delivered one arrives to an average input

(*) In the case of full coupling the natural rms emittance is reduced by a factor 2.

power of about 55 MW. The power required to accelerate from 20 GeV to 60 GeV should not exceed 1 MW and does not represent a problem.

One would obviously take a high frequency for the RF system since the high voltage and power envolved. Our choice is f_{RF} = 476 MH (CEA RF frequency). This would correspond to the harmonic number h = 23,120 of which, as we said in the previous section, only 40 would be filled by the beam (h = 40 x 578).

The last number in turns would give a size to the injector synchrotron. Since this should supply the stack in 10 pulses, it can eject 4 bunches at a time. By taking the same RF frequency the size of the injector can be 1/10 of the storage ring size, namely have a radius of 231.8 m which is an adequate size for a 20 GeV electron beam (see Fig. 1). The RF power required to run the injector should not exceed 5 MW, so that the total RF power required for the entire system is around 60 MW.

The RF peak voltage can be set to 1,000 MV/turn which corresponds to a synchronous phase

$$\phi_s = \text{arc sin} \frac{688}{1,000} = 43.5°$$

a very reasonable number.

Finally, if the entire RF system has to be accommodated within a total length of 1 km one requires about 1 MV/m which should not be difficult to attain at the frequency of 476 MHz. Also the radiation loss spread all over the vacuum chamber is about 3 kW/m, certainly a large quantity but not difficult to cope with (PEP has the same amount of loss per unit of length).

5. Bunch Length - Quantum Lifetime

The rms bunch length (in unit of time) is calculated according to the formula

$$\sigma_\tau{}^2 = \frac{C_q}{C}\,\frac{R}{J_E\rho}\,\frac{\alpha\gamma^2}{f_{RF}}\,\frac{E}{V}$$

where

$$C_q = 3.84 \times 10^{-13}$$

$$C = 3 \times 10^8 \text{ m/s}$$

$$f_{RF} = 476 \text{ MHz}$$

$$V = 1 \text{ GeV} .$$

At 60 GeV one obtains $\sigma_\tau = 0.02$ ns to be compared to $\sigma_\tau = 0.004$ ns at 20 GeV. At the same time the bucket length is $\tau_B \sim 1$ ns. From these numbers we can calculate the quantum lifetime which is given by

$$\tau_q = \frac{\tau_E}{2}\,\frac{e^\xi}{\xi} \qquad , \qquad \xi = \frac{J_E E}{\alpha h E_1} F(q)$$

where $\tau_E = 4.2$ ms, $E_1 = 1.08 \times 10^8$ eV and in our case $F(q) \sim 0.6$. We obtain ($\xi \approx 100$)

$$\tau_q \approx 1.6 \times 10^{35} \text{ hours}$$

which is a very long time. A shorter and still safe lifetime can be obtained with less RF voltage.

We like to call the attention to the fact that the beam peak current is close to 1000 A, a very large number indeed, and one could expect collective effects that would endanger the beam stability. On the other hand it is possible, in our case, to increase the number of bunches by a factor 10, in such a way the beam-beam tune shift remains unchanged and the peak current is of a more reasonable amount of 100 A, by allowing only partial coupling between the horizontal and vertical mode of oscillation.

6. Scaling of the Luminosity with the Energy

In the previous sections we have set the luminosity of 10^{32} cm^{-2}. s^{-1} to occur at the energy of 60 GeV. Obviously, the luminosity will change with the energy. First of all the beam-beam tune-shift goes like γ^{-3}, thus, in order to keep the same value at any energy, the number of particles per bunch N_B has to change like γ^3. Second the radiation power goes like γ^4, thus if one wants to make full use of the available RF power at any energy, the total number of particles BN_B can go like γ^{-4}. In conclusion, the luminosity decreases with the third power of the energy, provided the number of bunches changes like γ^{-7}. One has, for instance, B = 5,120 and L = 8×10^{32} cm^{-2}. s^{-1} at 30 GeV, with $\Delta\nu$ = 0.05 and the RF power of 55 MW. At the same energy, a luminosity of 10^{32} cm^{-2} s^{-1} can be achieved again with 5,120 bunches and reducing the intensity of each beam by a factor $\sqrt{8}$. This would correspond to a tune shift of 0.018 and to a total RF power of 10 MW.

Observe, finally, that in principle there is no reason to stop at 60 GeV. There is still a lot of luminosity at higher energies; also when the two main constraines on the beam-beam tune shift and on the RF power are kept the same. For instance, with the same scaling law one has a luminosity of 10^{31} cm^{-2} s^{-1} at the energy of 130 GeV and of 10^{30} cm^{-2} s^{-1} at 280 GeV.

7. Costs

Table I gives a rather rough estimate of the costs.

The estimate for the curved portion of the tunnel has been scaled out from the cost of the main-ring tunnel. The length is doubled but the cross section (width and height) can be appreciably reduced because one can take advantage of the very simplicity of the magnetic ring.

The two straight sections for the RF should have probably a cross-section similar to that of the main-ring long straight sections and supplied with RF buildings on top. The figure shown is again scaled out from the main-ring tunnel and buildings cost.

The cost for the two experimental areas is taken by blowing up a factor 20% on the cost of the RF sections. The figures for magnets, magnets power supply and vacuum are taken 20% to 30% less than the proportional estimate for the PEP design. Probably, in our case, the magnets can have a smaller cross-section. The cost of the RF scales exactly with the cost of the RF system for PEP.

Finally we took for the injector synchrotron cost about 1/3 of the cost for PEP.

8. Location

We do not really know which location is more suitable for the construction of this machine. But we remind that Fermilab owns already a valuable piece of equipment: a 300 MeV Linac for electrons inherited from CEA. Also we have drawn the outline of the machine on the Fermilab site in Fig. 2.

References

1. C. Pellegrini et al,: "Comments on the Desirability and Feasibility Study for e^+e^- Colliding Rings with L ≈ 10^{32} cm^{-2} s^{-1} and E_{cm} = 120 GeV", CERN, NP Internal Report 75-11, 26-9-75.

2. E. Keil, Proceedings of the IXth International Conference on High-Energy Accelerators, Stanford, May 1974, p. 660

3. M. Sands, SLAC-121, Nov. 1970

Table I

Cost for the 60x60 GeV^2 $e^{\pm}$ storage ring

Curved Section of Tunnel		M$	40
RF Long Straight Sections and RF Buildings (2x4M$)			8
Experimental Areas (2x5M$)			10
Magnets and Magnet Power Supply			40
Vacuum			42
RF			38
Injector Synchrotron			18
	Total	M$	196
ED and I (20%)			39
Contingency 15% on Conventional Facilities			9
Contingency 20% on Technical Components			27
	Total	M$	271

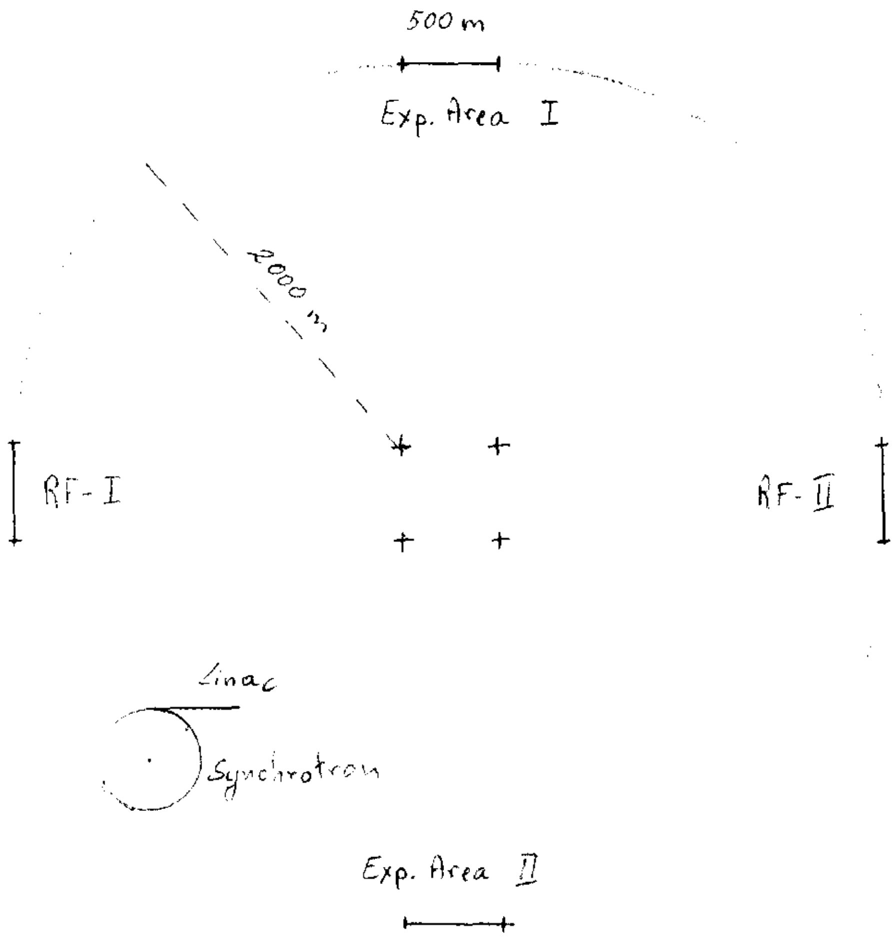

Fig. 1

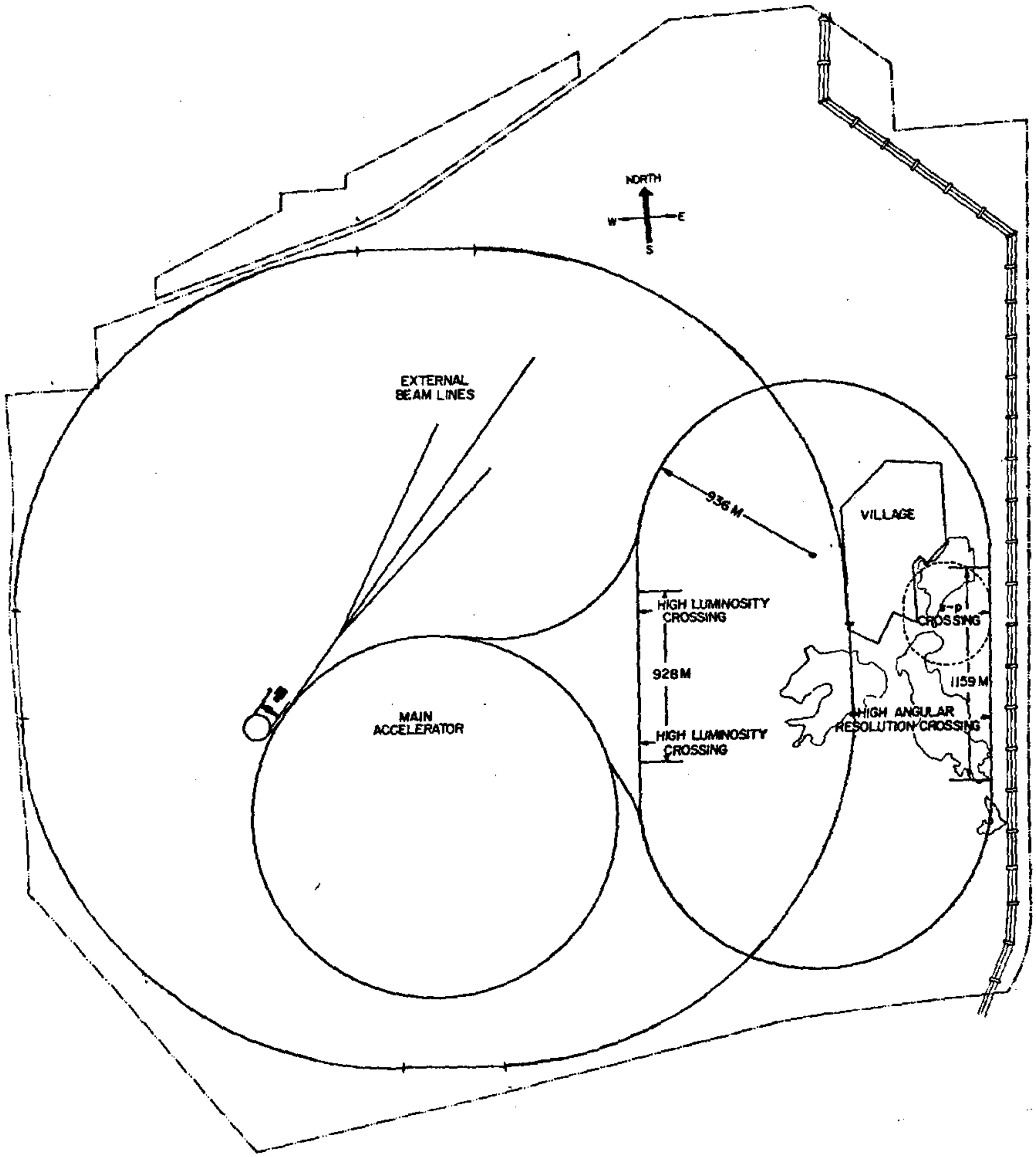

Fig. 2. POPAE and e$^{\pm}$ - Ring at Fermilab