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THE NEXT GENERATION OF ELECTRON-POSITRON COLLIDING BEAM MACHINES*

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BUDKER MEMORIAL LECTURE

DEDICATION

The development of the colliding beams technique for high energy physics began slightly more than 20 years ago with the work of three groups of physicists - one in the United States, one in the USSR and one in Italy. These pioneering groups were the Princeton/Stanford collaboration in the U.S. (W. C. Barber, B. Gittleman, G. K. O'Neill, and B. Richter); the Novosibirsk group in the USSR (G. I. Budker and his colleagues); and the Frascati group in Italy (F. Amman, B. Tushek and colleagues). From those first small machines, as our understanding of the behavior of the intense stored beams evolved, have come even larger colliding beam facilities. The success of the technique is indicated by the fact that all new machines now under construction are colliding beam machines.

Professor Budker played an important role in these developments. I first met him in 1965 and continued to see him every few years thereafter. My first impression remained my impression throughout — he was a man with enormous vitality, great charm, and originality. His death in 1977 was a loss to the accelerator physics community and to high energy physics. Were he still alive, he too would be thinking about working on the next generation of machines, and so I dedicate these remarks to his memory.

I. INTRODUCTION

The contribution of electron-positron colliding beam experiments to high-energy physics in the 1970's has been prodigious. From the research done with the two highest-energy e^+e^- machines of the present generation of these devices, have come such things as the discovery and illumination of the properties of the psi family, charmed particles, a new heavy lepton, non-ambigious evidence for hadronic jets, etc. The rapid pace of new developments in physics from such machines comes about for two reasons. First, the electron-positron annihilation process at present energies is particularly simple and well understood, making the problem of determining the quantum numbers and properties of new particles particularly simple. Second, in electron-positron annihilation all final states are on a relatively equal footing, and small production cross sections are compensated for by a lack of confusing background. For example, the rate of production of charmed particles at the SPEAR storage ring at SLAC and the DORIS storage ring at DESY is 3 or 4 orders of magnitude less than the rate of production at FNAL and the SPS. Yet these particles were first found at the storage rings where the background cross sections are comparable to the signal cross section, and have not yet been observed directly by their hadronic decays at the proton machines where the background cross sections are 4 orders of magnitude larger than the signal cross sections.

The next step for the electron-positron machines is being taken now. The machines PEP at SLAC and PETRA at DESY will soon be operating at 35-40 GeV c.m. to explore new regions of energy. This talk is not concerned with these great new research tools but with the generation of machines beyond these. I believe that studies of electron-positron annihilation at much higher energies than presently planned have a great deal to teach us not only about particle structure and dynamics but also about the nature of the weak interaction. In the rest of this talk, I will discuss some of the physics which can be done with such machines with a view toward getting an idea of the minimum required energy for the new generation of colliding beam devices, and will then discuss some of the parameters of the machines which I think we ought to be building.

II. PHYSICS

A choice of energy for a new machine always involves a great deal of guess work. It is easy to say "make it big" but the question "how big?" is clearly of great importance from the point of view of costs and technical complexity. Since the cost of a machine increases rapidly with its energy and the costs of new machines have become so large, we must try and choose the energy of the next step to be sufficiently high for physics but not so high that it will take us forever to raise the money necessary to build it. As always, we turn to present theoretical ideas to get a rough idea of what we might see with electron-positron machines at higher energy and thus to determine a "threshold" for the energy of a new machine.

Figure 1 takes us on a imaginary trip to very high energies in e^+e^- annihilation. In it I have plotted what we might find for R - the ratio of the cross section for meson and new lepton production - vs. the square of the center-of-mass energy(s). We start in the region up to $s \approx 9$ with the co-called "old physics" involving u, d, and s quarks and the production of ordinary and strange mesons and baryons. This is the realm of the machines Adone at Frascati, DCI at Orsay, and VEPP2 at Novosibirsk.

In the region around s = 10, the production of the narrow psi resonances signals the opening of channels involving c quarks and charmed particles. There is a sharp step in R and a rich structure of charmed particle resonances around the threshold. In addition, the evidence is now overwhelming for the production of a heavy lepton (τ) with a mass of about 1.8 GeV. The region of s from 10 to 50 is the realm of SPEAR and of DORIS.

As the energy continues to increase we move toward the edge of the known. Lederman and co-workers at FNAL have found evidence of the production of 3 new psi-like particles that they have named the upsilon family. In a technical tour de force, the accelerator physicists at DESY have stretched the energy of the DORIS e^+e^- ring to the utmost and have observed the lowest mass member of this family, confirming that it is indeed a very narrow resonance and that it most probably involves a bound state of a new quark-antiquark combination each with charge 1/3 (b quark).

We now move beyond the known into speculation. If there is indeed a b quark, there should be b particles produced at around s = 100, and we will probably find a structure of b particle resonances similar to the charmed particle resonances seen at s of about 10. The rise in R will be only 6% if the b quark is indeed charge 1/3. The region of b particles will be covered by new machines now under construction - CESR at Cornell and VEPP4 at Novosibirsk.

Since new particle families seem to appear at each decade in s (the strange particle family opens at s = 1), I guess that the t quark, the charge 2/3 partner of the b which most theoretical models require, will appear at around s = 1000. It will probably appear first with a few narrow resonances and then about a 20% step in R. We may also find t-particle resonances, and why not another heavy lepton as well to complicate life for my theoretical friends. This region around s = 1000 will be the hunting ground of the PEP and PETRA rings.

At still higher energies we come to the region where the weak interaction begins to compete with and then to dominate the electromagnetic interaction. At around s = 10,000, gauge theories would predict the appearance of the Z^o resonances, the carrier of the weak neutral current. At higher energies yet (a few x 10^4 GeV^2), the threshold for charged-vector-boson production will be reached. This high energy region is that which we wish to explore with the next generation of electron-positron machines.

Let us look in a little more detail at the expected phenomenology of the electromagnetic and weak interactions in this high energy regime to see if there are any well defined thresholds to use in determining minimum energy of the next generation machines. Figure 2 shows the rates expected for production of point-like particles - (mu-pair production) in a large e^+e^- machine with a luminosity of 10^{32} cm^{-2} sec^{-1}. The curve shows, as a function of center-of-mass energy, the electromagnetic one-photon annihilation process and two models of the weak interaction (no interference between electromagnetic and weak interactions is included). The Weinberg/Salam model gives a huge resonance peak in the cross section, the location of which depends on the mass of the Z^o. The predicted Z^o

mass has been slowly increasing with time and now seems to be about 100 GeV ($\sin^2\theta_W \approx 0.2$).

The curve labelled "Fermi" is that expected for an infinite Z^0 mass and a neutral current strength as determined in neutrino experiments [$G_0{}^2$ about 12% of G^2(Fermi)].

Figure 2 defines a minimum energy for the next generation machine in the range of 120 to 150 GeV. Around this energy the weak interaction dominates the electromagnetic interaction, independent of gauge theories or, if gauge theories are correct independent of the value of the Z^0 mass.

A second threshold can be defined in terms of particular models. This threshold is the energy required for the production of pairs of charged W mesons - the carriers of the charged current weak interaction. Figure 3 shows the production rate vs. energy of W pairs in the Weinberg/Salam model. With the caution that these curves are strongly theory dependent, we can see that a second threshold energy exists greater than about 200 GeV in the center of mass.

I conclude that the weak interaction as we understand it today gives only one model independent threshold to set the energy of a new e^+e^- machine and that threshold corresponds to a c.m. energy of 120-150 GeV. We have insufficient information at present to identify the next weak interaction threshold, but it would be desirable to design a new machine such that its energy could be increased to the 200 GeV region to cover what present theories predict for charged bosons. A machine of ~ 150 GeV gives an increase of 15-20 in s over that available with PEP and PETRA. If past experience is a guide we might expect some surprises in hadron physics as well as a more fundamental knowledge of the weak interactions.

I will next look at the design of an e^+e^- machine guided by four rules.

1. The minimum energy is 120-150 GeV
2. More is better than less.
3. Sooner is better than later
4. Low cost is better than high cost

III. SCALING LAWS FOR e^+e^- RINGS

The energy scaling laws for any machine are determined by choosing the machines parameters at a given energy to minimize the cost for a given technology and performance. In contrast to proton machines, in high-energy electron storage rings or electron synchrotrons the cost of rf power (required to make up for the energy loss of the particles by synchrotron radiation) becomes a major part of the total cost of the facility. The interplay of the cost of rf (voltage per turn $\propto E^4/R$) and the cost of magnet, housing, etc. (roughly proportional to radius) determines the size of the machine. I will briefly review below the optimization technique [for details see B. Richter, Nuc. Instr.& Meth. 136, 147 (1976)].

The basic equation governing the design of an electron-positron machine is

$$\mathcal{L} \times 10^{32} = 1.23 \times 10^{33} \frac{\Delta\nu^* P_B(\mathrm{MW})\,\rho(\mathrm{m})}{E_B^3(\mathrm{GeV})\ \beta_y^*(\mathrm{m})}, \qquad (1)$$

where $\mathcal{L}$ is the desired luminosity at each collision point (reaction rate per unit cross section in units of $\mathrm{cm}^{-2}\mathrm{sec}^{-1}$), E_B is the energy of one beam in the ring, P_B is the rf power required to make up for synchrotron radiation losses in both beams, ρ is the bending radius, $\Delta\nu^*$ is related to the focusing effect of one beam on particles in the other beam at a collision point, and β_y^* is a property of the guide field. Clearly, β_y^* should be made as small as possible, and I will take it to be 0.1 m. The lower bound on β_y^* arises because it cannot be made smaller than the length of the bunch in the storage ring (5 to 6 cm) nor can it be reduced significantly below 0.1 m without shortening excessively the free space for experiments in the interaction region.

The parameter $\Delta\nu^*$ is the linear tune shift at each interaction point. On the basis of experience with many different kinds of electron storage rings at many different energies, this quantity is independent of the design of the machine and has a maximum value of approximately 0.06 ($\Delta\nu$ for proton rings is thought to be much smaller, approximately 0.005).

Defining a new parameter δ equal to the beam energy in units of 100 GeV, Equation 1 can be rewritten as

$$P_B(\mathrm{MW})\ \rho\ (\mathrm{km}) = 136\,\mathcal{L}\delta^3. \qquad (2)$$

The physics research objectives of the machine specify δ and $\mathcal{L}$. The machine design is generally determined by P_B and ρ , and their product is constrained by Equation 2.

We next require a procedure to determine the values of P_B and ρ to minimize the cost of the project. Since we are interested in scaling laws, I ignore subtleties of interest to the machine builders, such as the difference between the bending radius and the gross radius; and of interest to the economists, such as the discount rate. The cost of the machine can then be divided into five parts. First there is the cost of the main ring, including such things as magnets, vacuum chambers, supports, power supplies, tunnels, cooling, instrumentation and control, cables, etc. (k_1 million dollars per kilometer). Second is the cost of rf power, including such things as klystrons, power supplies, waveguides, coolings, AC switch gear, controls, etc. (k_2 million dollars per megawatt). Third, there is the cost of the accelerating structure, including such things as cavities, stands, tuners, cooling, controls, housing, etc. (k_3 million dollars per kilometer). Fourth, there is the cost of operating power (k_4 million dollars per 10 megawatt-years). Fifth, there is the cost of the laboratory and the experimental program, including such things as roads, workshops, office building, experimental halls, apparatus, etc. (this item depends on the scope of the experimental program and not on details of the machine design; hence, it is left out of the optimization procedure given below).

The cost of the machine including 10 years of operating power can then be written as

$$C = 2\pi\ k_1\ R + (P_B + P_D)\ k_2 + L\ k_3 + [k_4(P_B + P_D)/\varepsilon] \qquad (3)$$

where R is the machine radius in kilometers, P_D is the power dissipated in the accelerating structure in megawatts, L is the length of the accelerating structure in kilometers, and ε is the efficiency of converting input power to rf power. Equation 3 can be reduced to a function of two variables R and P_D by the use of Equation 2 and the relations

$$P_D = V^2/LZ \quad , \tag{4a}$$

$$V \propto \delta^4/\rho \quad , \tag{4b}$$

$$L = \frac{1.04 \times 10^5 \delta^8}{P_D R^2 Z} \quad . \tag{4c}$$

Equation 4a relates the power dissipation to the cavity voltage, cavity length, and cavity shunt impedance; Equation 4b relates the voltage to the beam energy and machine radius; Equation 4a and 4b together imply Equation 4c.

The cost minimum is found by setting to zero the partial derivatives of the cost equation with respect to R and P_D. The result is a radius scaling law for a machine of minimum cost including 10 years operating power of the form

$$R = (a\delta^3 + b\delta^4)^{\frac{1}{2}}.$$

For a machine in the energy range required for weak interaction studies, the δ^4 term dominates and the radius and cost are proportional to the square of the energy. Using values of the constants that come from experience with construction of the PEP storage ring at SLAC (a power cost of 3 cents/KW-hr, $k_1 = 12.8$, $k_2 = 0.6$, $k_3 = 80$, $k_4 = 1.8$), and extrapolating the power conversion efficiency to 0.75, the optimum radius as a function of energy is shown in Figure 4. A 70 x 70 GeV machine has a radius of approximately 2.7 kilometers. There is, of course, much more to the design of the machine than specifying the radius, but once the radius is set the other parameters follow fairly naturally.

The minimum in the cost curve is fairly flat as illustrated in Fig. 5, which shows the construction, ten-year power, and total costs for two examples -- one at 120 GeV in the center of mass and one at 200 GeV in the center of mass. (Note that the capital cost given here includes only the machine with personnel cost included. Power costs are those to operate the rf system. The radius is that of the circular arcs of the machine, and not the gross radius. Costs are in 1976 dollars, including EDI and contingency.) The minimum in the Capital Cost curve is always at a smaller radius than the minimum in the total cost. Large changes in radius can be made with only small changes in the total cost of the facility.

IV. SOME MACHINE VARIANTS AND THE VIRTUES OF EXPANDABILITY

I now turn to a discussion of some examples of machines, including some at other-than-optimum radii. Table I shows the parameters and costs (excluding laboratory development costs) of machines with center-of-mass energies of 100 GeV, which I believe to be below the proper energy, but which those with great faith in present gauge theories believe to be sufficient to produce Z^o's; 140 GeV, which is in the middle of my "threshold" range; and 200 GeV which is around the region of second threshold defined above. I have included non-optimum machines in this table, in a spirit of humility (non-high energy physicists may be forgiven for possibly believing that any group that can conceive of spending the kind of dollars shown in Table I doesn't know the meaning of the concept of "humility"), for we do not know Nature with as much certainty as we often pretend. Nature usually surprises us and we must accept the possibility that what we build will be just below the most interesting region. It is prudent to design a machine which is expandable in energy, if building in the energy expansion capability does not increase the cost of the project by a large factor.

This notion of expandability is not new to the world of high-energy accelerators. Examples of expandable machines are FNAL and the CERN SPS which were expanded in energy by 25% to 50% over their initial design values even before they were completed. The SLAC Linac and the Cornell Synchrotron were increased in energy by 25% after completion by the addition of more rf power. FNAL will double its energy by the application of a new technology to magnets -- superconductivity. The SPEAR Storage Ring increased its energy by 50% by replacing the rf system and a few power supplies. There are many other examples. The common feature of all these examples is that the possibility of expansion was foreseen by the designers and incorporated at little cost into the basic design of the machine. We should include expandability in the design of a new e^+e^- machine.

Turning again to Table I, the first two columns show the cost of a 100-GeV machine built at the optimum and at a larger-than-optimum radius. At the larger radius, the machine costs increase while the operating costs decrease such that the total, including ten years' operating power, is up by only 15%. The third and fourth columns of Table I show the costs of an optimum 140-GeV machine and a large-radius 140 GeV machine. Again, the trade-off between power and capital costs is such that the larger machine costs, over a ten-year period, about 20% more than the smaller version at the same energy. The last two columns show a 200-GeV machine at its optimum radius and at a smaller-than-optimum radius. Again, the smaller radius costs about 20% more than the larger, although, in this case, it is 20% of a very large figure.

My conclusion from this table is that the 200-GeV machine is too costly to build with conventional rf and with the resources of any one region of the high energy physics world. The optimum 100-GeV machine is a bad choice, for its energy is marginal, giving only enough energy to reach what is now thought to be the Z^o threshold (a threshold which has increased significantly in the past few years).

The machines of columns two, three, and six of Table I are almost the same machine, except for the installed rf system. Magnet costs are not significantly different for the three machines since the amount of iron in these low-field magnets is determined more by structural requirements than by iron saturation. It seems clear to me that the most reasonable course would be to build a machine of roughly 3-km bending radius and equip this machine with enough rf initially to get above what is now thought to be the first threshold -- the Z^o mass. Thus, we get a machine of the minimum desirable energy at a cost not significantly larger than that for the optimum machine of the chosen energy and, at the same time, allow the possibility of a major expansion in energy in the future.

V. NEW TECHNOLOGY FOR STORAGE RINGS

The most interesting new technologies on the horizon for electron-positron storage rings are new rf technologies. It is the cost of power which drives the radius of these machines to large values and most of the power with conventional rf is used to heat the cavity walls (P_d in Table I).

Two types of new technology are being pursued at laboratories around the world. The first of these is rf superconductivity, which cuts the power dissipated in the cavities dramatically by increasing the cavity shunt impedance by a factor of 10^4 or 10^5. The second is what I call transient rf schemes, which do not have voltage on the cavities during the entire time between beam passages. Either superconductivity or transient schemes can, in principle, sharply decrease the rf power which does not go to the beams. The importance of these new technologies will depend entirely upon their costs, as compared to conventional rf. If the costs are lower than those of conventional rf, then the costs of the machine of a given energy can be reduced or, alternatively, a machine of a given radius can be driven to a much higher energy. It is this second alternative which I find most interesting.

Regardless of whether or not the Z^0 exists, there will be strong pressures to go to higher energies in the e^+e^- system. If the Z^0 is found, then the next threshold, $W^{\pm}$ pair production, will be an important region for work. If no Z^0 is found, we will need higher energies either to get a clue to the mass of the carrier of the weak interactions or to try and understand the form of the weak interactions. These new technologies may allow the expansion of the energy of a given machine at considerably lower cost than the old technologies. However, we will not know if these new technologies are practical or what they cost for several years.

For an expandable machine there is no point in waiting for these new technologies in the hope of some great economic benefit. The "big 100" GeV machine outlined in Table I has a small fraction of its capital costs (10% to 15%) devoted to conventional rf. New rf technology cannot give a significant economic benefit here. The great benefit of these new technologies may come in increasing the energy of the machine to 150 or 200 GeV in the center of mass.

The new technologies may significantly reduce the cost of a 100-GeV optimized machine, but such a machine cannot be expanded to as high an energy as a larger radius machine, for not only money but quantum-fluctuation-driven energy spread, rf power to the beam, etc., limit the maximum energy of a given e^+e^- storage ring.

VI. CONCLUSIONS

The physics results which can be obtained from an e^+e^- storage ring operating in the energy regime where yields are dominated by weak interactions will be crucial to understanding the weak interaction and its relation to the electromagnetic interaction. There is a threshold energy for the next generation e^+e^- machine some place around 120 GeV in the center of mass. My view of the proper strategy is to build a machine with greater-than-optimum radius than that required for this threshold energy and plan from the beginning on expanding the energy of the machine at a later date -- the magnitude of the expansion to depend on the physics results obtained in the initial operating range. The energy expansion can be accomplished with the addition of conventional rf or new technology rf. There is no point in waiting for new technology for there is no significant cost-saving to be obtained in the first phase of operation.

We should begin as soon as possible for we need the answers that can be obtained from experiments on such a machine to understand the relation of the weak to the electromagnetic force and thus to reduce the number of apparently independent force laws in nature.

TABLE I

Some parameters for machines of various c.m. energies and radii. Costs are in millions of 1976 dollars, and are based on PEP unit costs. The rf systems are conventional.

	Optimum 100	Big 100	Opt 140	Big 140	Opt 200	Small 200
ρ (km)	1.4	2.7	2.7	5.4	5.4	2.7
P_B (MW)	12.0	6.0	17.0	9.0	25.0	50.0
P_D (MW)	17.0	9.0	34.0	17.0	70.0	140.0
L_{cav} (km)	0.6	0.3	1.2	0.6	2.5	5.1
Capital $	180.0	250.0	345.0	500.0	700.0	740.0
10 yr. Power $	70.0	36.0	122.0	60.0	225.0	400.0

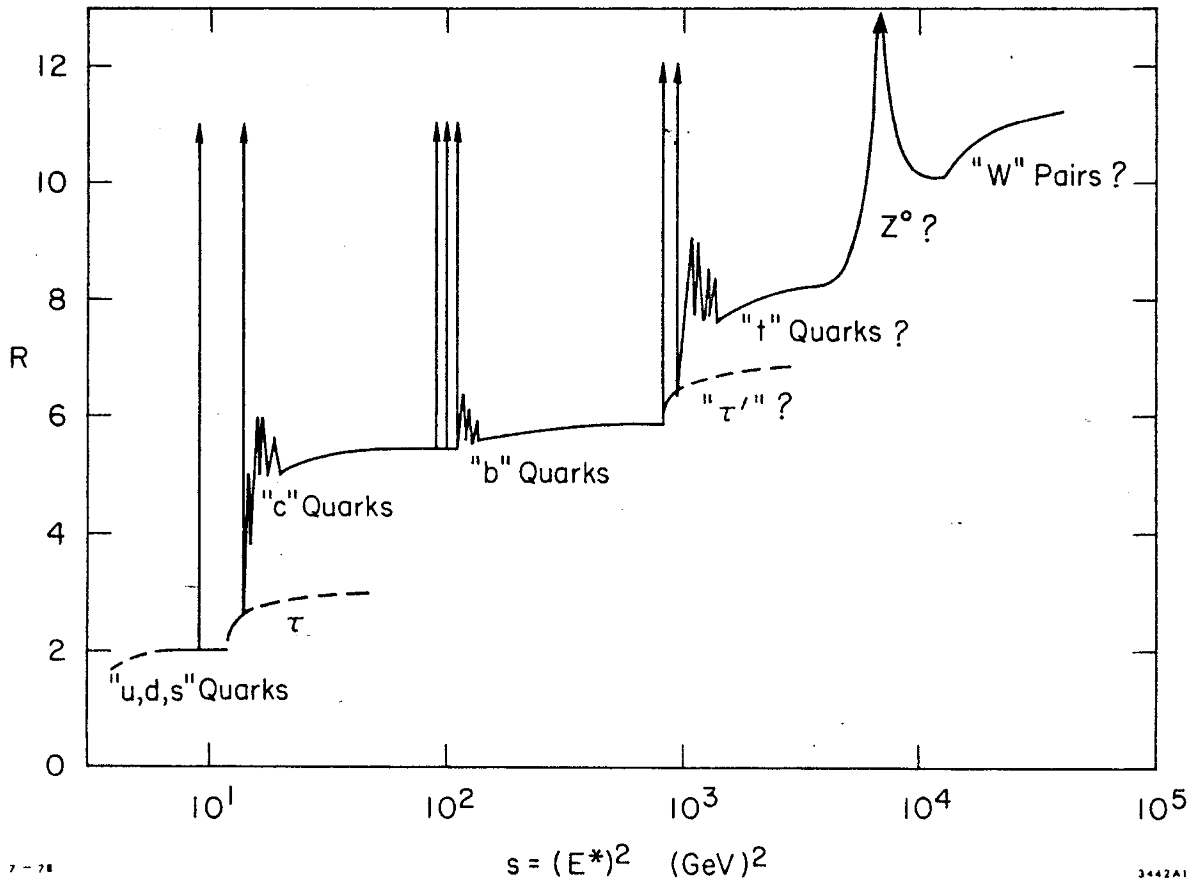

Fig. 1--The ratio (R) of the total cross section for the production of particles heavier than the μ meson to μ meson pair production vs. s, the square of the center-of-mass energy. The region including the three large peaks at around s=100 has been explored and the indicated features seen. The rest is from my imagination.

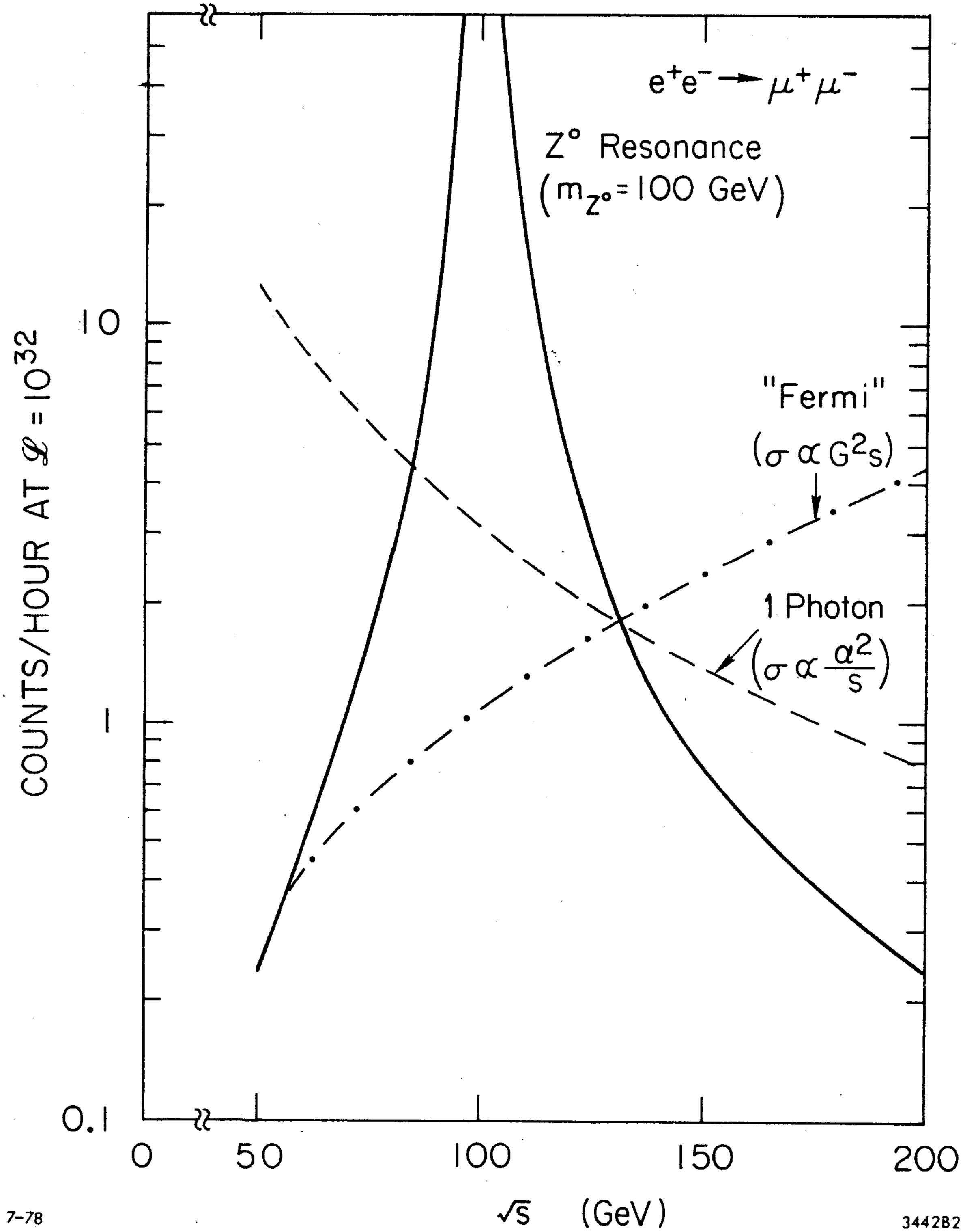

Fig. 2--Counts per hour for μ-pair production at a luminosity of $10^{32} cm^{-2} sec^{-1}$ vs. center-of-mass energy. The "1-photon" curve give the contribution from the electromagnetic interaction only. The "Z^o" current weak interaction is mediated by a Z^o of mass 100 GeV and $\sin^2\theta_W = 0.25$. The curve labeled "Fermi" gives the rate for a weak interaction with no Z^o.

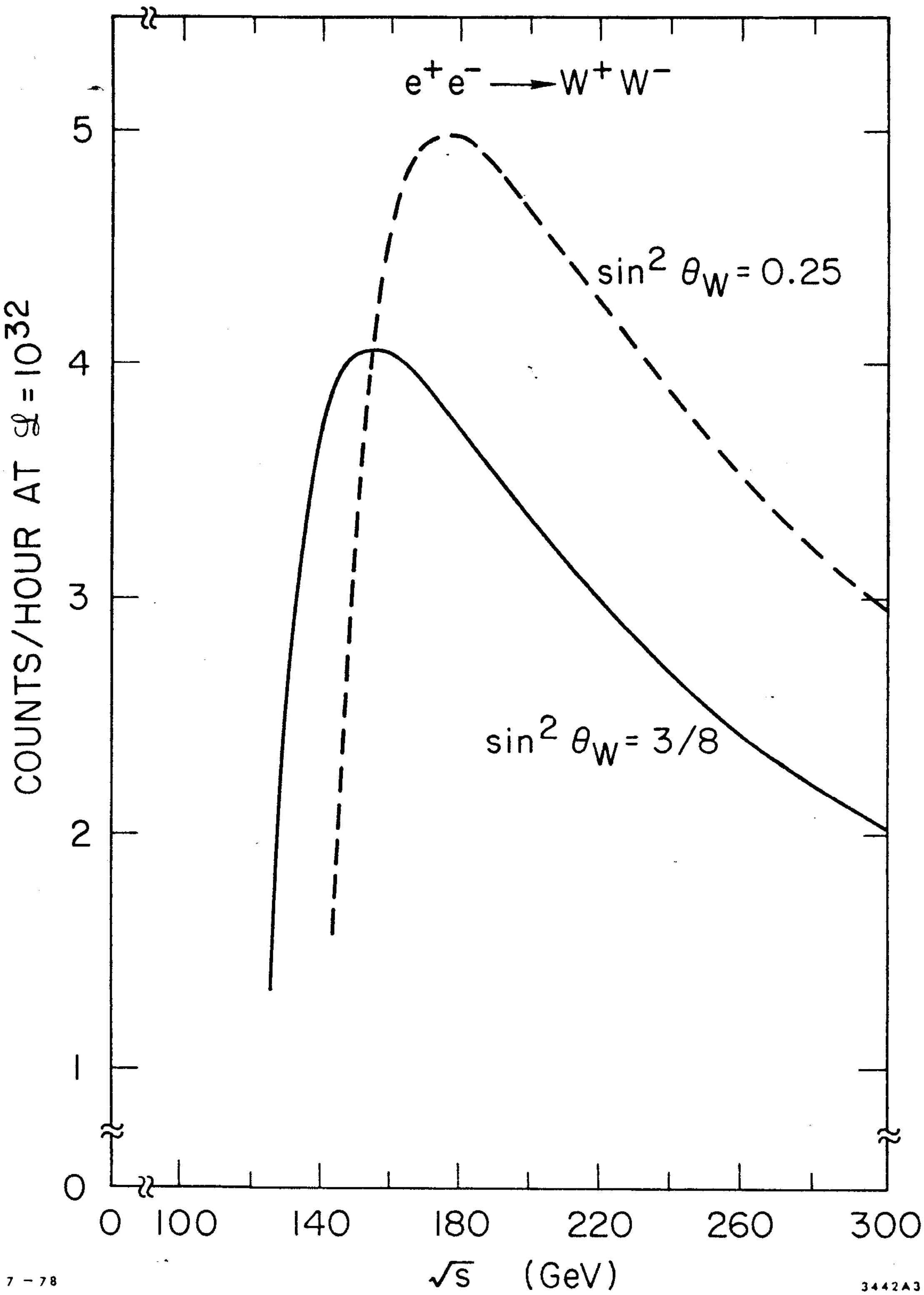

FIG.3--The $W^{\pm}$ pair production rate vs. center-of-mass energy for two values of the Weinberg angle.

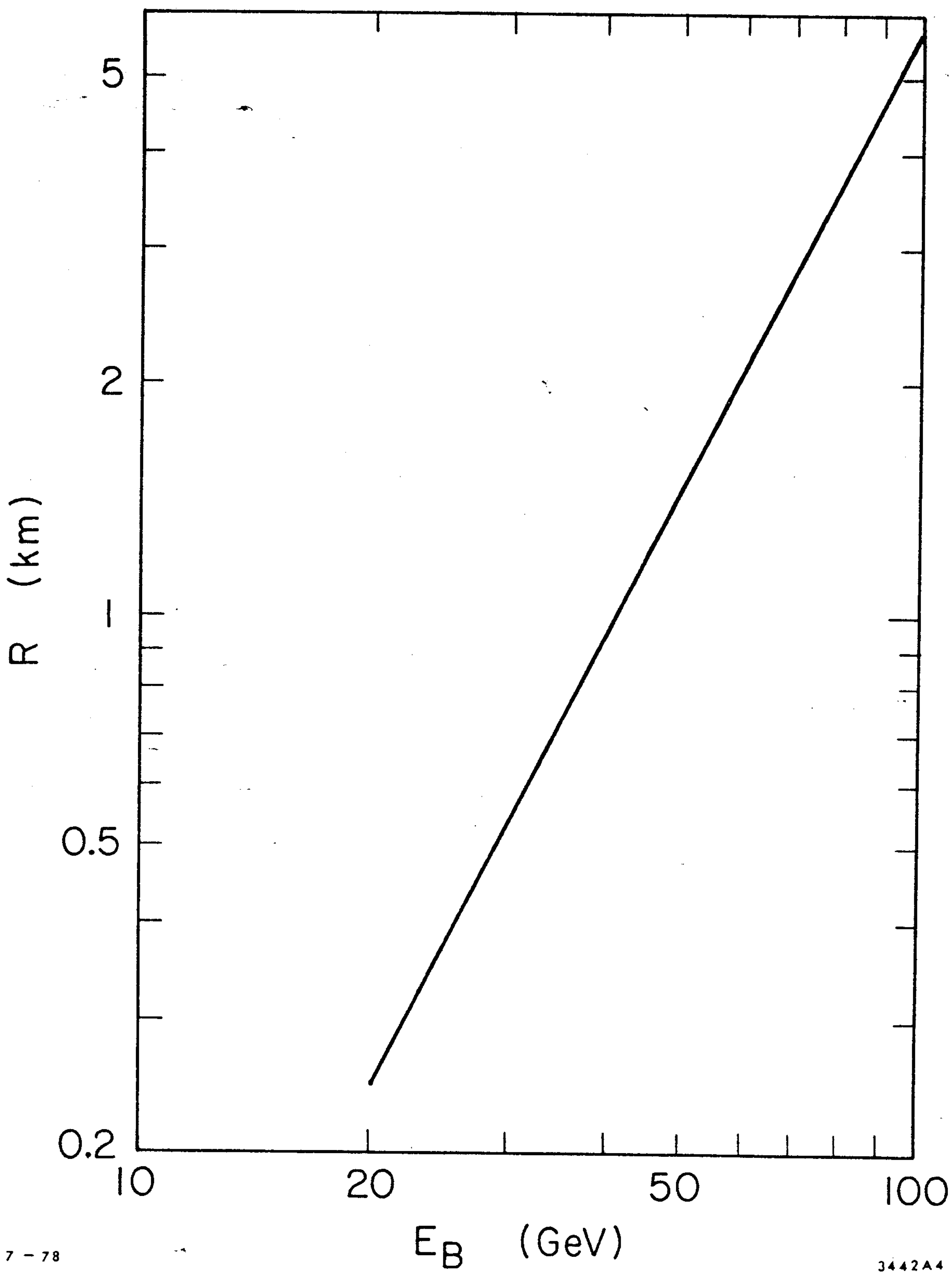

FIG.4--The cost optimized bend radius vs. beam energy of an e^+e^- storage ring using conventional rf technology and "PEP" unit costs.

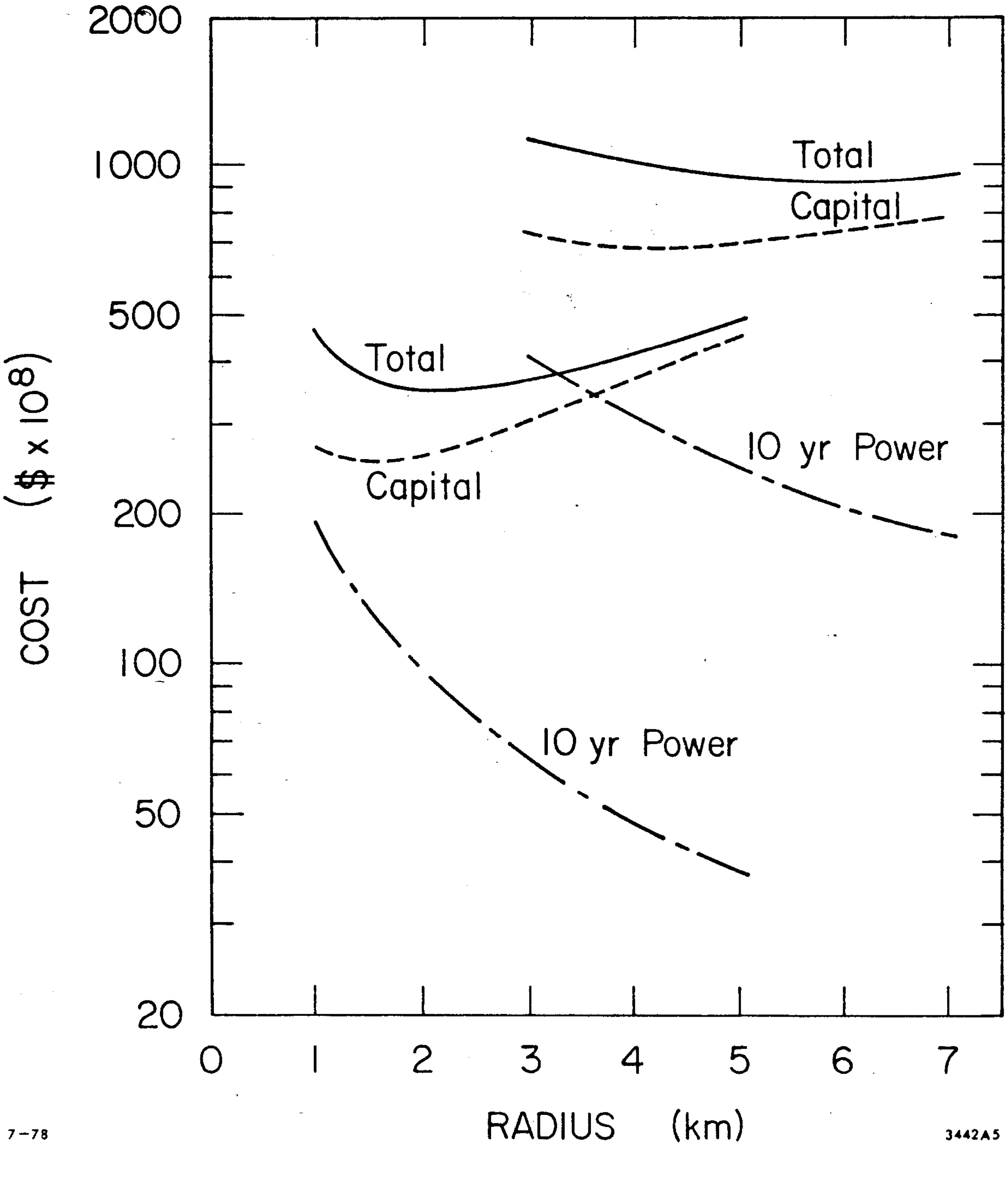

FIG.5--Cost vs. radius of a 60 and a 100 GeV per beam machine. Costs are based on PEP unit costs in 1976 dollars and do not include office building lab space, etc.