SLAC – PUB – 3735
July 1985
(M)

LIMITING TECHNOLOGIES FOR PARTICLE BEAMS AND HIGH ENERGY PHYSICS*

WOLFGANG K.H. PANOFSKY

Stanford Linear Accelerator Center
Stanford University, Stanford, California, 94305

Presented at the 1985 SLAC Summer School on
the Physics of High Energy Particle Accelerators,
Stanford, California, July 15-26, 1985

---

* Work supported by the Department of Energy, contract DE – AC03 – 76SF00515.

Since 1930 the energy of accelerators had grown by an order of magnitude roughly every 7 years. Like all exponential growths, be they human population, the size of computers, or anything else, this eventually will have to come to an end. When will this happen to the growth of the energy of particle accelerators and colliders? Fortunately, as the energy of accelerators has grown the cost per unit energy has decreased almost as fast as has the increase in energy. The result is that while the energy has increased so dramatically the cost per new installation has increased only by roughly an order of magnitude since the 1930's (corrected for inflation!), while the number of accelerators operating at the frontier of the field has shrunk. As is shown in the by now familiar Livingston chart (Fig. 1) this dramatic decrease in cost has been achieved largely by a succession of new technologies, in addition to the more moderate gains in efficiency due to improved design, economies of scale, etc. We are therefore facing two questions: (1) Is there good reason scientifically to maintain the exponential growth?, and (2) Are there new technologies in sight which promise continued decreases in unit costs? The answer to the first question is definitely yes; the answer to the second question is maybe.

Preceding speakers today have outlined the reason why collision energies in the 1 TeV range, measured in the center-of-mass frame of the fundamental constituents (quarks and gluons) should be a fertile region. Although high energy physics has scored spectacular successes during the last decade in simplifying our understanding of matter, we are facing the not uncommon consequence that as understanding increases new questions open up. Although the "standard model" unifying the weak and electromagnetic interactions has been an unqualified success in terms of agreement with experiment, it has many unsatisfactory features. There are some 20 arbitrary parameters in the theory. Unification of the theory with the strong interaction is still incomplete. We have discovered three families of quarks and leptons which differ only in mass but apparently not in other fundamental properties. What defines the masses? Will there be further generations or is this aesthetically appealing picture the end? We do not know. In particular we do not understand the mechanism which differentiates the masses of the carriers of the various interactions. Although three families of quarks and leptons seem to be a nice simple number if there were no further generations, the total number of so-called elementary constituents is still disturbingly large if one counts all of them. In fact if one adds up the 18 colored quarks, 6 leptons, the photon, the 3 massive vector bosons which carry the electro-weak force of the standard model, and the 8 gluons which are the transmitters of the strong interaction, together with perhaps 1 graviton which carries the gravitational force, then we obtain a total of 37. This is a lot of particles to be "elementary."

The 1 TeV region for the center-of-mass energy of collisions among fundamental constituents is apt to provide the answer to some but not all of these questions and it surely will open up some new ones again. In particular, work in this energy region is likely to sort out the various alternate models conjectured by theorists for the otherwise unexplained mass differences among some of these particles, or it may uncover other phenomena or explanations which are not on the conjectured list.

Accelerator builders face a fundamental dilemma. Protons are composite particles, while electrons down to dimensions of 10^{-16} cm are still point-like. As a result, the energy of collisions among protons is shared among the quarks and gluons. Therefore, depending on the reaction under study, the energy of protons has to be "derated" by about an order of magnitude relative to electrons in providing the same "reach" into the unknown. Thus electron accelerators of considerably lower energy are equivalent to the corresponding proton acceleerators. On the other hand, electron accelerators at ultra-high energies using known technologies are becoming excessively expensive. But this is not all there is to the electron-proton comparison. The total cross-section in proton-proton collisions is still on the increase, while the cross-section for producing events exhibiting new physical phenomena of interest is expected to decrease as the square of the relevant mass range to be investigated. Therefore, the signal-to-noise ratio for proton-proton colliders for interesting events is degenerating rapidly with energy, while the total event rate continues to increase. As a result the data analysis process applicable to hadron-hadron collider events is a frightening process which has to reject, hopefully successfully, a substantial number of supposedly unneeded features of the primary collision. While this can be accomplished with confidence in designing experiments with reasonably well-defined objectives, the lingering doubt remains that the increasing need for rejecting primary data might also reject unanticipated primary discoveries. Therefore, given the choice, most particle physicists would prefer an electron-positron collider of one-tenth of the particle energy to a corresponding proton-proton collider of roughly comparable luminosity. But does this choice exist? The answer is that in the TeV range it does not within present technologies.

The SSC is a bold step forward in extending the proton-proton collider technologies using superconducting magnets demonstrated so successfully at Fermilab into the multi-TeV energy range measured in terms of collision energy of the fundamental constituents. This proposal does not involve basically new technology but hopes to extend the energy range of the decreasing unit cost by economies of scale and simply good design. Corresponding matching opportunities for electrons do not exist today.

The reason for this conclusion is known to all of you. Electrons in storage rings emit synchrotron radiation and the rate of energy loss per turn increases as the fourth power of the energy. The cost of storage rings in essence is composed of two terms: (1) proportional to the radius or physical size of the device, and (2) proportional to the fourth power of the energy divided by the orbit radius. If these two terms are matched a quadratic scaling law of cost vs. energy results. Thus it is likely that LEP with a circumference of 27 kilometers will be the last electron-positron collider built along the by-now established storage ring pattern.

For the above reasons it is evident that if the exponential growth in energy for electron collisions and for proton collisions beyond the SSC is to be maintained new technology is needed. We are thus waiting again for the pioneers to devise these new technologies just as the new developments invented by those people we are honoring tomorrow have advanced the accelerator frontiers and have made it possible to maintain the exponential growth. One of the hopefully successful missions of this summer school is to create among the younger generation those who will reduce this expectation into practice.

These are optimistic remarks but even the most inventive people in this audience or elsewhere must in the future deal with certain fundamental limits. If we are to extend electron-positron collisions to higher energies we must abandon storage rings, unless someone makes an invention to suppress synchrotron radiation. Thus the electron-positron collider of the future must be a linear collider in which two linear machines accelerating electrons and positrons are aimed at one another to produce the required rate of interaction.

Such linear colliders lose the primary advantage of storage rings which is the fact that the same electrons and positrons collide repeatedly before eventually being lost due to the finite lifetime of the stored beam. In consequence, as we shall see, useful designs for linear colliders require that both the total beam power required to achieve adequate reaction rates and the density of the particle beams during interaction must become very large.

The reason for this conclusion derives from the unpleasant fact that the total energy of each beam will have to be thrown away after each collision between opposing bunches during which only an exceedingly small fraction of electrons and positrons produce events of interest. The only exception to this situation would arise if energy recovery of the "spent beam" would somehow be possible. This latter possibility has been explored by several physicists, in particular U. Amaldi, by using the spent beam to produce radiofrequency energy in a superconducting linear accelerator; that accelerator thus energized can then be used for accelerating the next bunch. Elementary arguments make it clear that there is hope for such energy recovery only if Q values of superconducting accelerators can be attained which are two orders of magnitude or so larger than those now deemed feasible. Current linear accelerators at room temperature are operating at Q values of the order of 10^4 and use duty cycles of the order of 10^{-5}. Thus if a superconducting accelerator running continuously is to utilize refrigeration power comparable to the rf power fed into conventional accelerators, then we require Q values of $10^4 \times 10^5 \times 10^3 = 10^{12}$, where the last factor of 10^3 is the reciprocal of the efficiency of refrigeration at temperatures usable for superconducting devices. The Q value of 10^{12} is about 10^2 to 10^3 larger than practical values attained to date. In addition, energy recovery in superconducting accelerators has numerous other practical problems which may or may not be more severe than those faced by other devices at room temperature which we will now discuss.

If energy recovery is proven infeasible, then we have to face the power consumption inherent in throwing the interacting bunches away after collisions. We can write an equation which directly relates the luminosity L of interaction as related to the frequency f of collision, and the cross section A of the interacting beams:

$$L = fN^2/A \tag{1}$$

where N is the number of particles per bunch. If we assume that the beam is circular in cross-section and has an invariant emittance ϵ_n, and if the opposing bunches are focused into collision with a focusing parameter β, then the average power P_B of each of the colliding beams is given by:

$$P_B = m_o f N \gamma \qquad \text{and} \qquad L = fN\gamma^2/4\pi\epsilon_n\beta \tag{2}$$

The number of particles which we can handle per bunch is limited by the energy spread produced due to the beamsstrahlung of the electrons or positrons during collision. The very factors, in particular the density of interaction, which enhance luminosity also increase the electromagnetic radiation experienced by an opposing particle. One might assume that this beamsstrahlung can be calculated by the applicable classical forumlas. However, using the ordinary expressions for synchrotron radiation, we find that the frequency spectrum of the emitted radiation extends up to the cube of the cyclotron frequency of the emitting particle in the electromagnetic field of the opposing bunch; in other words, the upper limit of the energy spectrum in general grows faster than the energy of the colliding particles themselves. Once the top energy of the radiated photons exceeds that of the primary beam the classical calculation is no longer valid; as a practical matter the spectrum is cut off at an energy equal to that of the primary beam. If we assume that the parameters of an electron-positron collider are of interest for the next generation machines only if such a quantum mechanical cutoff in the synchrotron radiation spectrum is required, then we can write formulas relating the parameters of interest to the physicists to the parameters which the machine builder would consider limiting in design.

The physicist has to specify three basic parameters;

(a) the required beam energy

(b) the luminosity

(c) the tolerable energy spread δ_q produced in the interaction.

The latter is particularly important should there be resonances in the new energy range to be investigated. This importance is somewhat moderated by the fact that if there are resonances the cross sections would be larger at such a resonance and one could therefore afford to decrease the luminosity at the resonance in order to achieve a narrower energy width. With the exception of this unlikely situation reasonably broad energy spreads - say in the 50-30% range - could be tolerable. However it is unavoidable that within current quantum-mechanical wisdom the required luminosities would have to go up with the square of the energy in order to give reasonable rates for events of interest. A luminosity of at least $10^{33} cm^{-2} sec^{-1}$ in the 1 TeV range and $10^{34} cm^{-2} sec^{-1}$ in the 3 TeV range appear essential if event rates of interest of the order of 10^2 to 10^3 per year are to be anticipated.

In addition to these preliminary experimental parameters there are also secondary requirements of concern to the physicists. Background due to beam gas interactions or radiation from upstream or downstream focusing devices must be held at tolerable limits. From the point of view of event reconstruction one would like to limit severely the expected number of events per bunch crossing. In addition, one would like to make it possible to place detectors very close to the interaction point in order to be able to detect short-lived decays. If possible the accelerating mechanism should preserve polarization so that events originating from states of specified angular momentum can be isolated. However, for these considerations let me assume that the primary factors, luminosity, energy and energy width are all that define the usefulness of a machine.

A problem is that at present it is not fully clear which machine parameters are controlling the economics of the overall machine. Average beam power combined with the finite efficiency of generating the beam is clearly a very important and probably the most important parameter. In other words, a linear collider at super high energy must operate heavily loaded.

Let me make a remark on the somewhat arcane "voodoo" economics in which the accelerator physicist defines the construction cost for a machine. In the past the government has been persuaded to supply appropriate adequate construction funds to build a new facility. With the exception of inflation all such monies are directly applied to the relevant construction cost. In contrast, when a public utility builds a power plant the money needed may be as large as three times the actual cost of construction due to the cost of raising the necessary capital and the accumulating interest rate during the construction period. Therefore, considering the large power probably required for an accelerator of the future, one might even entertain the notion that a power plant might be part of the projected construction cost. This, of course, is not a saving in real economic terms.

The attainable accelerating gradient and therefore the economically (or politically!) practical length of a machine may or may not be a constraining factor. Because of the high power costs the efficiency of extracting the stored energy in the accelerating dcevices by the beam is important. Since the total amount of energy per bunch is limited by the energy spread produced in the beam-beam interaction attainment of such extraction efficiency can become more difficult if the accelerating gradients are very large and therefore the energy stored in the accelerating structure is correspondingly increased. Therefore the shortest accelerator is not necessarily the most economical accelerator overall, although it is obviously much more attractive aesthetically and reduces the total impact of the installation.

Having said all this we can write a number of basic equations which define the various derived quantities for accelerator design in terms of the specified physical parameters. Since in the multi-TeV region the quantum mechanical cutoff of the synchrotron radiation spectrum will enter into the picture I am giving these equations only in that region.

$$N = \frac{4\pi}{(1.63)^3\alpha^4}\left(\frac{\delta_q^3}{D}\right) \tag{3}$$

$$A = \frac{4\pi}{(1.63)^3\alpha^4}\left(\frac{P_b\delta_q^3}{EDL}\right) \tag{4}$$

$$f = \frac{(1.63)^3\alpha^4}{4\pi}\left(\frac{P_bD}{E\delta_q^3}\right) \tag{5}$$

$$\sigma_z = \frac{1}{4\pi}\left(\frac{P_bD}{r_em_ec^2L}\right) \tag{6}$$

In these equations D is the "disruption" parameter which is the ratio of the bunch length at interaction to the focal length produced by the electromagnetic focusing effect in the beam-beam interaction. This number cannot be very large because if it were each particle would undergo oscillations within the bunch of the opposing particle, and eventually these oscillations would become unstable. For moderate values of D this mutual focusing effect is beneficial in that it increases the average beam density and therefore the luminosity.

The above equations are written for beams of circular cross sections. Additional advantages can be obtained using "flat beams" because then for a given beam density the total disruptive beam-beam interaction and the beamsstrahlung effects are reduced. If for the time being we ignore this possibility and also ignore the enhancement produced by the beam-beam interaction (which at most can become a factor of 6), we can combine the above equations by eliminating the D factor and write a simple expression for the beam power as follows:

$$P_b = 5\left(\frac{L}{10^{30}}\right)\left[\frac{\epsilon_n \beta \sigma_z}{\delta_q^3}\right]^{1/2} \tag{7}$$

Here the power is measured in megawatts and luminosity in $cm^{-2}sec^{-1}$. The quantity ϵ_n is the invariant emittance, that is $\gamma r r'$, and β is the usual focusing parameter and σ_z is the bunch length, all measured in centimeters. Note that the required luminosity would have to increase as the square of the energy.

Note that this equation is totally independent of the <u>means</u> which are employed to produce beams and bring them into collision. Such acceleration would be achieved by traditional rf structures or some new, for instance laser, devices.

It is interesting to plug numbers into this equation under the assumption that accelerator performance was no better than that employed in the design of the SLAC SLC, but assuming that we would be producing 5 TeV per beam, rather than 50 GeV per beam as is the case for the SLC. If we assume that the luminosity is to scale by the square of the energy from the design luminosity of $6 \times 10^{30} cm^{-2}sec^{-1}$ of the SLC, the invariant emittance ϵ_n is $3 \times 10^{-3} cm$, and the β value 1 cm, and if we assume a permissible energy spread δ_q of 30%, then we require a beam power well in excess of 10^4 Megawatts. This is clearly impractical and therefore one has to go considerably beyond SLC parameters if the linear collider idea without energy recovery is to become practical in the TeV range. Since the SLC is considered to be a "daring" machine by many, such a further extrapolation is clearly not an immediate prospect and thus the time scale at which the SSC (which is based on existing technology) and such a super linear collider can be achieved are many years apart.

In order to go beyond the SLC performance the following steps come to mind:

1. make the beam non-circular,
2. reduce the normalized (invariant) emittance,
3. reduce the bunch length.
4. reduce the β value in the interaction region.

A non-circular beam with aspect ratio R in principle introduces a factor $2/(1+R)$ into the power equation. This is not a very steep dependence and there are limits to the practicality of focusing an asymmetric beam to the required small dimensions considering the extreme complexity of the final focus system when designed to handle beams of finite energy spread.

Reducing the normalized emittance ϵ_n is in practice a matter of designing a damping ring to "cool" the radial temperature of the electrons and positrons to an extent greater than that projected for the SLC. Increasing the brightness of the primary gun is not of major relevance to achieve reduction of the normalized emittance since the phase volume of the positrons is determined by the electromagnetic shower process in the positron converter and not by the driving beam.

The ultimate performance of damping rings has not been thoroughly studied but an improvement in ϵ_n by perhaps 2 orders of magnitude appears feasible. One should note, however, that if the particle energy is increased beyond the SLC and if the normalized emittance is decreased, then both of these factors decrease the actual beam diameters at the interaction point below the 1.2 micrometers now projected for the SLC. If we reduce the normalized emittance by

2 orders of magnitude and increase energy by 2 orders of magnitude, then the beam diameter is decreased by about 100 and the beam area by a factor of 10^4. We are talking about beams of radius of perhaps 10 angstrom units. Although beams of such dimensions have proven practical in scanning electron microscopes, the question how to design final focusing systems with sufficient freedom from aberrations, sufficient focusing strength, and mechanical stability has not even been considered.

The longitudinal dimension σ_z could also be shrunk from the 1 millimeter value of the SLC, let us say to 1 micron. All these factors combined would bring the average beam power into the few megawatt range. This might, perhaps, permit a practical design, provided the efficiency from the wall plug to the beam is not too small. Note, however, that the beam density would become of the order of $10^{27} electrons/cm^3$ (!) very much larger than ordinary macroscopic densities.

A similar problem arises in respect to the accelerating structure. If we assume that a damping ring can produce normalized emittances well below those projected for the SLC we are facing an increased problem of growth of this emittance in the actual accelerating and final focusing structures.

Many different kinds of accelerating structures and methods have been proposed and are under intensive study. Time does not permit me to discuss these here. Some of these are plasma devices in which a laser beam or laser beams interfering with one another produce waves in a plasma which, in turn, accelerate the particles. Such devices appear attractive because of the potentially high gradient they might produce. However, I am personally pessimistic about their utility in this case because of two factors: (1) the overall efficiency of transfer of power source to the beam, and (2) the fundamental difficulty in controlling the exact micro-detail of the plasma to avoid growth in the emittance of the beam. Other accelerating methods use either the electric fields of lasers or microwave energy to produce acceleration.

The most predictable performance would involve "conventional" rf structures which, however, must be fed by power sources not as yet developed. All such sources are in effect tranformers from low voltage, high current devices to the high energy, low current beam to be produced for collision purposes. The "conventional" electron linac uses a multiplicity of such high current beams in the klystron tubes feeding the machine. The most challenging of such transformers are in essence two beam devices. In one design a hollow beam of high intensity is transmitted at the edge of a conventional rf structure where the magnetic field is large and the electric field is small. The beam to be accelerated passes at the axis where the electric field is high and the magnetic field is zero. In another version a many kilo-ampere beam is produced in an induction accelerator and rf energy is extracted periodically either by a free electron laser, that is by use of a wiggler, or with conventional rf cavities if the primary high current beam is bunched. The energy loss corresponding to the extracted rf is replenished by re-acceleration with induction cores. The microwave power is then fed from the extraction points to the high energy accelerator. Such two beam devices have an inherently high efficiency.

The problem with all such devices deals with wake field effects, in particular in respect to transverse deflecting modes. Any medium which supports the required longitudinal accelerating fields will also support transverse modes, and therefore the required alignment tolerances will become extraordinarily severe if, as indicated above, emittances much smaller than those projected for the SLC are to be employed. Since the optimization of parameters suitable for this purpose points to wave length much shorter than the customary S-band range, this situation would be aggravated.

Reducing the β value below 1 cm, or as far as that goes even to attain 1 cm for beam energies as high as 5 TeV, is an unsolved problem. An exciting possibility is to employ 2 bunches, one to produce the focusing field to contract the second bunch which is the one to yield the desired collision intensities. Such first order lenses produced by placing charge into the beam are potentially a great deal more powerful than existing external focusing lenses such as superconducting quadrupoles. Note that in the above formula (Eq. 7) giving the average power the luminosity increase produced by the beam-beam interaction of the colliding beams has not been explicitly included.

The situation can be summarized as follows: the construction of ultra-high energy electron-positron colliders does not involve foreseeable problems which cannot be solved without violating basic physical principles. However, in order to produce the high luminosity required for reasonable data rates at high energies, preferably all three quantities, that is invariant emittance, the bunch length, and the β value in the above equation (7) would each have to be reduced by roughly at least 2 orders of magnitude in order to reduce beam powers to what appear to be practical values. This, in turn, requires development of new power sources, the development of new final focus methods, unprecedented alignment techniques, possibly requiring continuous servo-loops, and unprecedented stability and freedom from noise of basic power supplies. All this will require not only development but also invention. You accelerator physicists in this audience are facing a severe but exciting challenge.

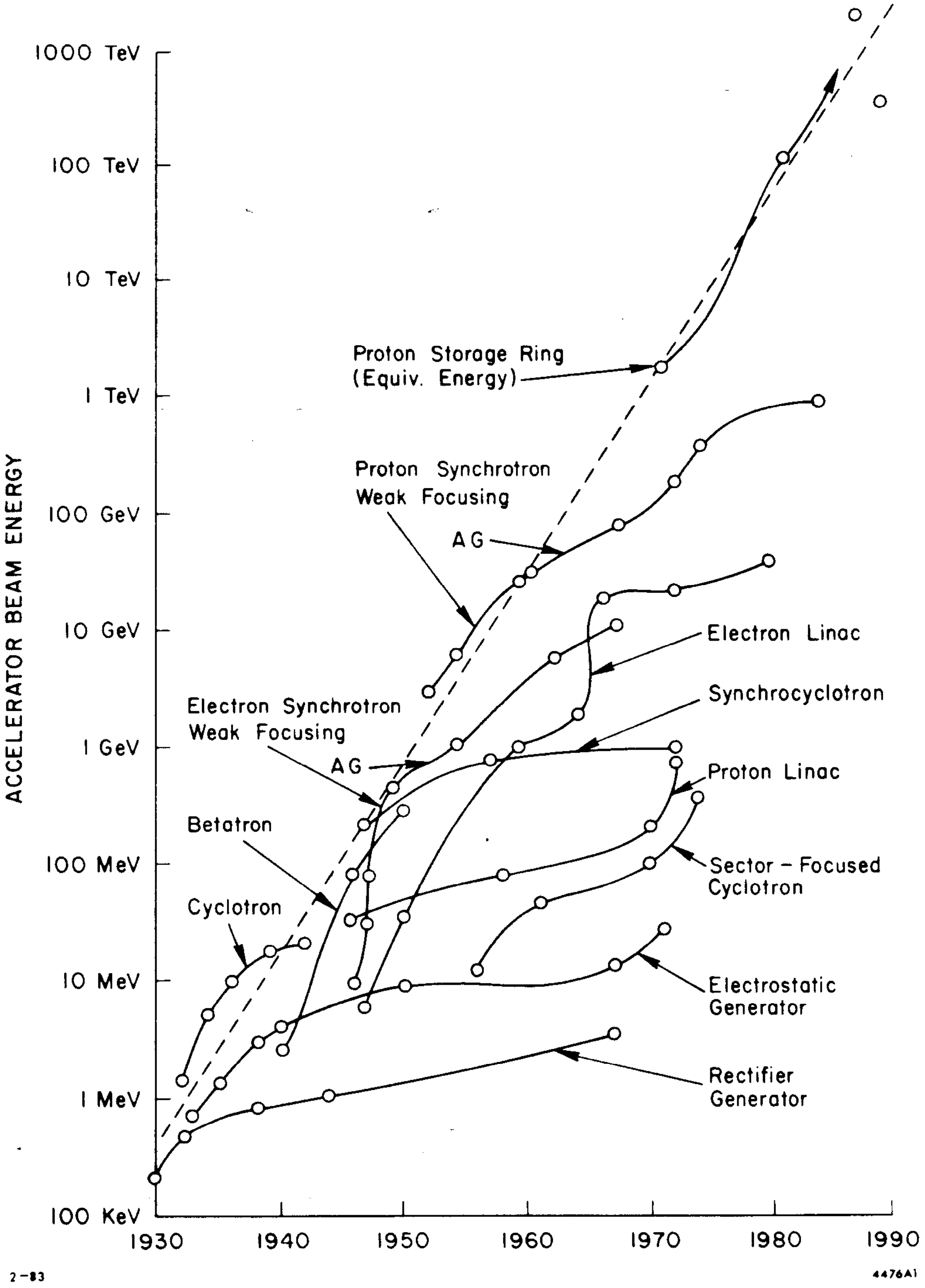
1000 TeV
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
100 KeV
ACCELERATOR BEAM ENERGY
1930
1940
1950
1960
1970
1980
1990
Proton Storage Ring
(Equiv. Energy)
Proton Synchrotron
Weak Focusing
AG
Electron Linac
Synchrocyclotron
Electron Synchrotron
Weak Focusing
AG
Proton Linac
Betatron
Sector – Focused
Cyclotron
Cyclotron
Electrostatic
Generator
Rectifier
Generator
2-83
4476A1

Fig. 1