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CRITERIA FOR STEPS TO HIGHER ENERGIES

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I. INTRODUCTION

In discussing or proposing a new generation of high energy accelerators a number of arguments have to be taken into account. Physics motivation should, of course, be the main criteria, but machine technology is important and the development of detectors is getting an increasing weight. Financial boundaries cannot be neglected and political, ecological and sociological issues might also play a certain influence.

II. PHYSICS MOTIVATION

Physics questions are, of course, of major importance in deciding on a new accelerator. Theoretical guidance is needed and different predictions from various theories may be put to experimental test. However, looking back in history, one notices that very often physics questions considered in the proposal for a particular accelerator were not answered by this machine, but on the contrary many machines have discovered new phenomena which were not mentioned at all in the original proposal.

Two machines have certainly accomplished the task for which they were built. The BEVATRON at Berkeley was constructed with the aim to observe the antiproton, and the SPS at CERN was converted into a proton-antiproton collider in order to discover the W and the Z particles. Some examples for phenomena which were found unexpectedly at proton machines are the muon neutrino and the neutral currents at the AGS in Brookhaven and the PS at CERN, the large transverse momentum dependence indicating partons inside the protons at the ISR, the EMC effect at the SPS, the Y particle at Fermilab. The discovery of partons by inelastic electron scattering at SLAC was as unexpected as the discovery of the Charm-quark at the AGS and SPEAR. Gluons have been discovered at PETRA, although they were never mentioned in the original proposals and more recently B-mixing was established at DORIS.

In particular predictions of particle masses are vague or even wrong, which was true for the Charm-, Beauty- and Top-quark, and the exceptions are the W and Z⁰ particles.

Most reliably seemed to be the limits imposed by violation of unitarity. New physics was predicted for weak interactions below the Fermi limit at 250 GeV, and indeed the W and Z⁰ were found well below that limit. For the electroweak interaction such a limit should exist around 1

TeV and one might well expect that the mechanism of symmetry breaking, e.g. the Higgs mass could be below this limit.

In conclusion one might state that the lesson we have learned from the past is that guidelines by theory are important, but that one should not rely entirely on them. Indeed, the most exciting issue is to discover new phenomena not predicted by theory in a newly accessible energy range. Nature is very imaginative and always has surprises at hand.

One should also not forget to test the validity of quantum mechanics and relativity. Going from dimensions of 1 cm to 10^{-8} cm forced us to replace classical physics by quantum mechanics. Now we are exploring dimensions of 10^{-16} cm, and therefore it might not be excluded that quantum mechanics might have to be modified. The same might be true for relativity.

III. MACHINE TECHNOLOGY

Two parameters are essential for the discovery potentiality of an accelerator: maximum energy and luminosity. The technical limitations for these two parameters are different for proton and electron machines.

Proton Machines

The maximum energy of a proton machine is given by the product of radius times magnetic field $E \sim R \cdot B$.

Using superconducting magnets and in particular the new warm superconductors, it might be possible to push B up to field strengths of more than 10 Tesla. At the moment, however, this kind of field seems to be difficult to produce since mechanical stresses become a serious problem. Hence, an increase of the radius of the machine might be inevitable. Apart from the cost this poses no principal technical problem.

A limit to the present design of proton machines might be approached at about 100 TeV, where synchrotron radiation becomes non negligible for beam dynamics. For superconducting magnets and the associated cryogenics synchrotron radiation might pose some problems even at lower energies, but this could be taken care of by a proper design of the magnet structure. Above 100 TeV synchrotron radiation losses will influence the beam dynamics, and the design principles for proton machines will be similar to those of present electron machines. At the Accelerator Conference at Oxford in 1982 Björken considered an admittedly virtual machine of 500 TeV beam energy, with 170 km radius and a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

Possible future technical developments should also have the objective to produce smaller apertures and perhaps a machine which is not in a plane but follows the terrain. This could maybe be achieved by a truly cybernetic accelerator.

In conclusion it seems that proton colliders in the energy range of 40 to 100 TeV per beam are technically feasible and even beyond these energies no principal technical barriers seem to exist.

Electron Machines

In circular electron colliders the maximum energy is not determined by the bending power of the magnetic field, but by synchrotron radiation losses, which increase with the fourth power of the energy. To compensate these energy losses an electric field is necessary which has to be produced by a RF system whose cost will increase with the eighth power of the beam. It is well known that for an optimized machine both the bending radius and the length of the RF accelerating structure has to increase

Fig. 1 Cost of linear and circular electron colliders versus energy (schematically)

with E^2 which implies also that the total cost will increase approximately with E^2 .

The advantage of circular machines, of course, lies in the fact that particles which did not produce a collision at the first encounter meet very often per second thus increasing considerably the chance of a collision. Luminosities therefore can be relatively high.

For linear accelerators the cost increases obviously proportional to the maximum energy apart from a small base constant cost. If the cost is plotted as function of the energy, one finds a cross-over point for the cost of a linear collider with that of a circular machine (Fig. 1). If one uses copper cavities in a circular machine this cross-over is somewhere between 200 and 300 GeV, whereas it is higher when one uses superconducting cavities. Many technical problems have to be solved before a linear collider could be constructed.

Fig. 2 Livingston plot for fixed target proton accelerators

Fig. 3 Livingston plot for proton colliders

The obvious disadvantage of a linear accelerator is that the particles have only one chance to produce a collision. Therefore, high beam currents are required. The production of a well defined beam focus with dimensions between microns and angstroms and the prevention of a disruption of the beams might be the most difficult task to solve.

A machine with an energy of about 500 GeV per beam might seem to be realistic in the not too distant future. A linear collider with beam energies in the TeV range would have to be a later step.

Energy versus Time

In the famous Livingston-plot the maximum energy achieved with accelerators is plotted as function of time. In figures 2, 3 and 4 this plot is given separately for proton colliders, proton fixed target machines, and e^+e^- storage rings. For proton colliders (Fig. 3) one can notice an increase of energy by a factor of about ten every ten years, and this trend could continue in the future with projects like LHC, SSC and ELOISATRON for two more powers of ten. For fixed target proton machines (Fig. 2) one sees a certain flattening off. e^+e^- storage rings (Fig. 4) have achieved an energy increase by a factor of 7 to 8 about every 10 years. This trend could be continued beyond LEP 200 with colliding linear accelerators.

IV. DETECTOR TECHNOLOGY

As is well known, point like cross sections fall with $1/E^2$ although some enhancement due to resonances or the opening-up of thresholds like WW or ZZ increase the cross section (Fig. 5). Also the cross section for Jet production decreases rapidly (Fig. 6). If one wants to observe hard collisions, it will be inevitable to increase the luminosity. In the ideal case the luminosity should increase with E^2 in order to obtain a certain number of events.

If one plots the luminosities either achieved or planned for different machines (Fig. 7) one notices that by no means did the luminosity increase proportional to E^2 .

Fig. 4 Livingston plot for electron colliders

But even if the luminosities foreseen for LHC and SSC of the order of 10^{33} or $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ can be achieved, detectors will have a hard time to cope with the large counting rates and high multiplicities. In addition it might be necessary to introduce single bunch crossing luminosities of $10^{28} \text{ cm}^{-2} \text{ s}^{-1}$ which result in many hundred events per crossings.

As a result the development of new detection techniques might be a more difficult and more challenging task than the development of accelerators. Completely new ideas and techniques are needed. Maybe one will

Fig. 5 Pointlike cross section

Fig. 6 Jet production cross section

have to give up tracking of individual particles, and even the detection of muons behind thick absorbers might become difficult. Detector development is therefore as important as new accelerator technologies.

V. FINANCIAL BOUNDARIES

The highest energies one can achieve are not only limited by technical problems, but also by the available financial means. Hence, a big effort has been made in the past to reduce the size and with it the cost of accelerators. A characteristic parameter which determines to a large

Table 1 Energy gradient for proton accelerators

Energy/length = gradient

Proton synchrotrons

Name	Energy GeV	Gradient GeV/km	Magnet	Year
Bevatron	6.1	51	Fe	1954
PS, AGS	26, 31	40	Fe	1959
SPS, NAL	500	70	Fe	1976/72
Tevatron	1000	160	4.4 T	1986
UNK	3 TeV	140	6 T?	1992?
SSC	20 TeV	240	6.6 T	
LHC	9 TeV	330	10 T	

Table 2 Energy gradient for linear electron accelerators

Electron machines

Linear accelerators

Name	Energy GeV	Gradient GeV/km	Year
LBL	1.2 (2.3)	5.2	1959
SLAC	22	7.3	1966
KEK	2.5	7.8	1981
SLC	50	17	1987

extent the cost efficiency of an accelerator is its maximum energy divided by its length (its circumference for a circular accelerator). This gradient is shown in Table 1 for successive generations of proton machines. One can notice that going from the BEVATRON to the LHC, a factor of 7 has been gained for the gradient. This is to a large extent due to the transition from iron to superconducting magnets.

In Table 2 the gradient for electron linear accelerators is shown. They reflect the development from 1959 to 1987 during which time an improvement factor of more than 3 was achieved.

For circular electron machines it is rather the quantity E^2/length which is characterizing the efficiency of the accelerator since for such machines the radius goes approximately with the square of the maximum energy. Table 3 shows that an improvement factor of about 15 was obtained going from ADONE to LEP 200.

Comparing the absolute cost of different accelerator generations is difficult since the ways of presenting the budget are quite different in different laboratories. I tried to estimate the total cost of the accelerator including its infrastructure, but without experiments and the infrastructure for experiments. The result for fixed target proton machines is shown in Fig. 8. If one takes the cost per GeV one notices that going from the BEVATRON to the Fermilab or SPS machine one has gained about a factor of 20. In Fig. 9. the corresponding figures are shown for hadron colliders where an impressive gain of about a factor of 100 can be noticed comparing the cost per GeV of these different machines.

Table 3 Energy gradient for circular electron accelerators

Circular machines

Name	E /beam	E^2/length	Year
Adone	1.5	22.5	1969
Spear Doris	5	18	1972
Petra PEP	23	230	1977
LEP200	100	332	1989

Much effort is usually spent to reduce the price for the machine components themselves like magnets, RF accelerating cavities, controls etc. However, very often the importance of civil engineering and infrastructure like power distribution are neglected. Indeed, considering different projects I found that on the average about 45% of the project cost went into civil engineering and infrastructure (Fig. 10). As a consequence, a comparable effort should be made to reduce these costs, whereas a reduction of the cost of the accelerator components alone will not suffice.

Fig. 8 Cost of fixed target machine
(without experiments and experimental infrastructure)
a) total cost b) cost/GeV

Fig. 9 Cost of hadron colliders
(without experiments and experimental infrastructure)
a) total cost b) cost/GeV

VI. ECOLOGICAL, SOCIOLOGICAL AND POLITICAL ASPECTS

The interference with the environment becomes an ever more important topic. Nowadays even deserts belong to the best protected regions. I believe, therefore, that the construction of tunnels for large accelerators by the cut and fill method will not be possible in the future. The largest part of the accelerator will have to be housed in underground tunnels. This unfortunately makes civil engineering more expensive.

Working conditions and safety regulations for people working for the construction of the accelerator but also operating it later become more rigorous. Such problems are in particular important for machines using liquid helium or experiments employing explosive gases. Ventilation systems and safety protections become a non negligible part of the project cost.

Fig. 10 Cost of civil engineering and infrastructure relative to total project cost

Sometimes the length of time to construct an accelerator and to prepare the experiments is considered as a major sociological difficulty. However, I believe that these periods have not essentially changed over the last two decades. It still takes five to six years from the first discussion of a project to its authorisation and about the same time for the construction of the machine. For students, of course, it seems very hard to bridge such long times without producing physics. However, it should be accepted that developing accelerators and detectors implies as interesting physics as the analysis of data.

The size of collaborations involving several hundred people is sometimes considered as a natural barrier for future developments. This poses certainly a sociological problem, and requires the development of new sociological structures. Of course, inside such a large group not everybody can interact with everybody, but a certain distribution of responsibilities must evolve. The experience with present large collaborations shows that even in these large groups excellent young people have a very good chance to distinguish themselves, get to be known and make a career.

With very large and costly machines, such as those considered for the next generation of accelerators, a duplication in different parts in the world is of course excluded. Already the present generation of accelerators under construction corresponds quite well to a complementary world-wide programme. This, however, was not achieved in any systematic way, and I believe that coordinating bodies, where a world-wide programme can be discussed both by physicists and politicians are missing. It is my strong opinion that an extension of international collaboration, which works already so well for experiments (planning and financing) will have to be extended to accelerators and should replace nationalistic "accelerator races".

VII. CONCLUDING REMARKS

Taking all these arguments into account for the planning and the decision on future accelerators is, of course, difficult and the weight

Fig. 11 Energy ratios of successive proton accelerator generations

of the different arguments will change according to the project and the country. A different approach therefore might be simply to look back into the past to see which steps were taken and how successful they had been from the physics point of view.

For proton fixed target machines the energy steps for different machines are shown in Fig. 11. As one notices, the steps were about a factor of 3 and these steps seemed to be reasonable, since the task of building the accelerator could be handled, the funding could be obtained, and also programmes related to the detectors and the analysis could be coped with and last not least, good physics was produced. If one looks at proton colliders, there was a big step of a factor 10 between the SPS collider and the ISR. The TEVATRON provides another factor 3 with respect to the SPS collider. With respect to the TEVATRON a hadron collider in the LEP tunnel would give another factor close to ten, whereas the SSC would present a step of a factor of 20. Compared to the experience in the past this appears to be a very large step. Of course, one might find this fact attractive, since it presents an interesting challenge. However, my opinion is that a step from TEVATRON to a hadron collider in the LEP tunnel of about a factor 10 would be more reasonable, followed by another step to a collider with an energy above 40 GeV per beam. Such a procedure would seem justified not only because of the global arguments given here, but also based on the arguments given above concerning the physics, detector technology and accelerator technology. Such a machine could either be an upgraded SSC or the ELOISATRON.