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XIV CONFERENCE ON HIGH ENERGY ACCELERATORS TSUKUBA, JAPAN

SUMMARY REMARKS

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Wolfgang K. H. Panofsky

These brief remarks cannot be a summary of this conference. This would require "pulse compression" by a factor of nearly 100 which greatly exceeds the ability of this speaker and even exceeds the microwave power pulse compression results reported at this conference. Therefore I will only make some general observations on the status of the field, based on the input to this conference.

The exponential growth of collision energies available for research in high energy physics has been nourished by a succession of technologies. As the potential of each technology has become saturated the evolution of new approaches has supported the continued exponential growth in collision energy which has since the 1930's exceeded one decade in energy for each two decades of years. We are now approaching another such watershed where a certain class of technologies is approaching its limits and where we are praying that new ideas followed by dedicated research and development will sustain the growth of the past and enable us to reach goals where results essential to increased understanding of particle physics will be obtained.

During the past sessions we have heard status reports from across the world on machines just entering research operations, in particular LEP at CERN, the SLC at Stanford, and the BEPC in China. We have also heard reports on machines which are not as yet quite ready for operations such as HERA and then UNK, and those which are in the design or initial engineering phases such as the SSC, LHC, and VLEPP to be built at Serpukhov. Then we have heard about machines such as the Tevatron, the AGS and TRISTAN which have been producing data successfully for some time but where upgrading plans are in progress.

All these machines with the exception of the SLC and VLEPP are electron or proton synchrotrons, most of which ramp into storage ring operations. The further growth of such devices is approaching limits, sooner for electron machines than for proton machines. In the case of electron machines this limit, set by optimizing the design to balance synchrotron radiation costs with costs proportional to the length of the installation, results in the well-known quadratic scaling law which probably will make LEP the highest energy of the electron-positron storage rings. I am saying "highest energy," not the "last electron positron ring," because plans for lower energy high luminosity rings such as B-factories and the Tau-Charm factory are being strongly pushed and have considerable merit.

On the proton side of the house we are also finding that synchrotron radiation is no longer a negligible consideration; the SSC is projected to have about 9 kilowatts synchrotron radiation loss per beam which has to be dissipated at liquid helium temperature. If the energy of proton colliders were to be pushed beyond that of the SSC then this will become a very serious limitation. Moreover the signal-to-background ratio for proton colliders degenerates as the square of the energy, and for a useful proton colliding beam storage ring in the "beyond the SSC" energy range the number of nuclear events per crossing becomes a very large number, contributing even further to the fundamental difficulties in detection. Thus for extending the energy for either electrons or protons of higher energy we will predictably depend on new technology. Some of these approaches have been discussed extensively at this conference. Most solutions rest on some form of linear collider, since some, but by no means all, of the limitations mentioned before are associated with the use of storage rings.

However, linear colliders face limits of their own. Fundamentally the use of a linear collider decreases the rate of collisions between particle bunches by 3-4 orders of magnitude relative to storage rings. Moreover, as energy is increased the required luminosity to do useful physics must increase approximately quadratically; I note from the summary presented e.g. by Skrinski that such an increase in luminosity has historically in fact not been achieved in the past. This is shown in the accompanying figure. To compensate for these requirements the density of interaction per colliding bunch has to increase dramatically with energy. Moreover, in a linear collider the total energy of each bunch is discarded after each collision, while in circular colliders of the past only a few percent of the energy of each bunch is lost between collisions. For these reasons required beam powers for linear colliders will become larger by perhaps 2 orders of magnitude above such powers experienced in the past, even for comparable energies. This, in turn, implies that power efficiency from power source to beam becomes a major consideration, which has not previously been so.

One session of this conference was dedicated to what I call esoteric means of accelerating beams for linear colliders. By esoteric I mean devices other than the conventional microwave linear accelerator methods. Impressive progress has been made on studies of these devices and experimental demonstrations have shown that wake-field acceleration and plasma wave acceleration mechanism is real. Yet there is a wide gap between such demonstrations and a conviction that such methods can attain the practical goals required for overall power efficiency and control of the quality of accelerated beams. Thus there is a general consensus that the next generation of particle linear colliders will be based on "conventional" microwave accelerating structures, although the requirements which apply to such structures will be considerably more severe than has been the case in the past. The severity of such requirements is principally a matter of dimensional control. The requirements for such dimensional control stems from two needs: limitation of growth of higher order modes and preservation of the invariant radial phase space during the accelerating process. We have heard useful discussions on how these requirements result not only in a need to isolate structures from vibrations in the range of a few Hertz but also lead to unprecedented alignment tolerances to assure the required precision of overlap between the electromagnetic center of the accelerating structure, the focusing system, and the beam position indicators.

The question remains as to how rapidly one can expect electron-positron linear colliders to progress well beyond the energy now attained at the SLC, and attainable at LEP. The answer to this question has both economic and fundamental technical feasibility dimensions. Economically we would like to understand the scaling laws of all relevant parameters, and then the cost factors associated with each parameter. Technically we would like to understand at what point the required parameters exceed the state of the art. Some cost factors have been examined and references to them have been made in the parameterization of linear colliders. Unfortunately cost estimates can easily be associated only with major construction items such as power sources, modulators, tunnel construction costs, manufacturing costs of microwave structures, etc.

There are still many candidates for power sources in the running; some of these hold promise to eliminate the need for pulse modulators which historically have been the most expensive single component in linear accelerators. But some of the power sources may have difficulties meetings phase and amplitude stability requirements. What is even more difficult to do without detailed designs is to identify the cost of the increased standards of precision and quality which are required for higher energy linear colliders. The required invariant emittance for linear colliders decreases very rapidly with energy. This, in turn, means increasing demands on the damping rings as well as on the tolerances of the accelerator structures. The overall parameterization involves a complex interaction between pulse repetition rate, limits on beam power, energy broadening due to radiative beam-beam interaction, choice of wave length, aspect ratio of the final beam, and the performance of the final focus system. Some of these limitations are quite "hard," for instance the total power consumption is limited in practice, the quadratic increase of luminosity with energy is based on firm physical principles, and the radiative broadening due to beam interaction must be limited to preserve the utility of the machine for physics. Other considerations such as permitted length of the machine and the maximum aspect ratio in the final beam which is permissible are not necessarily fixed.

In particular I would maintain that the conventional assumptions about choice of wave length are not as yet on a firm basis. Conventional wisdom is that the wave length is based primarily on a contest between power economy and maximum sustainable gradient, on the one hand, and moderation of wake-field effects and manufacturing problems, on the other. Yet the factors pushing towards shorter wave length which have made most designers chose a wavelength between 1 and 3 cm. are in my view not firmly based. The maximum gradient is not the most economical gradient: both the peak and average power requirements of the energy storage per pulse increase linearly with gradient. Therefore, although very long machines are clearly unappealing, the maximum gradient is not necessarily the right economic answer.

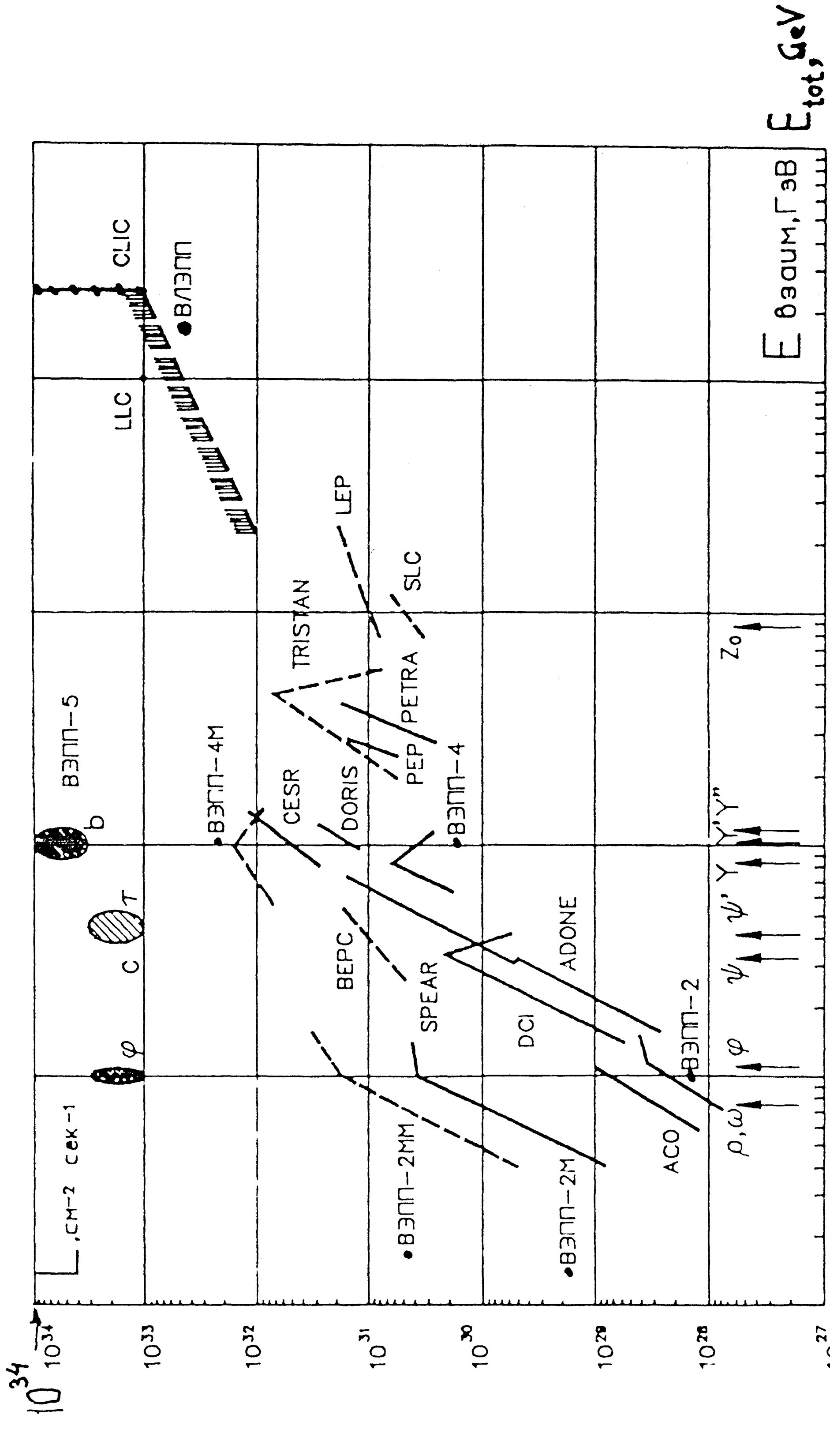
Then the matter of power economy depends strongly on whether one is talking about single or multiple bunch operation per RF pulse. If multiple bunch operations is achieved – and there are very good reasons to attempt to do so – then a large fraction of the stored energy can be converted into beam. Under those circumstances the average rf power consumption is more dominated by the required average beam power than by the product of pulse repetition rate times energy storage in the accelerating structure. Therefore the scaling of average line power with choice of radiofrequency wave length could become much less steep than is conventionally presumed.

All parameters for large linear colliders which are now being analyzed throughout the world in Siberia, Japan, CERN, and the U.S. represent a very large jump from SLC experience. How large a jump is technically or economically reasonable is a matter of judgment. I suggest that at this time it would be extremely difficult to evolve a design for an energy even as low as 400 or 500 GeV collision energy in less than a few years. At this time a timetable for a machine in the multi-TeV range, that is of energy reach comparable to the SSC, is essentially impossible to establish.

All these remarks indicate that the total worldwide research and development effort dedicated to electron-positron linear colliders must be increased if the opportunities for high energy physics using electrons and positrons are to catch up in terms of energy reach with those offered by the highest energy proton colliders such as the SSC and the LHC. I would like to emphasize, however, that both the electron and proton frontiers must be covered. The detection problems with protons are so severe, and the net of discovery which investigations with proton machines provide is so coarse that electron-positron collides at the highest energies practically attainable will remain indispensible tools of high energy physics.

My previous remarks covered only the highest energy frontier, in line with the title of this conference. However, rightfully many important applications of high energy accelerator technology, in particular in respect to high brightness photon sources, have been discussed, and here advances during the last few years have been truly remarkable. There have also been extensive discussions of "factories," that is ϕ factories, Tau-Charm factories and B factories using electron-positron colliders and K factories using hadron colliders of high repetition rate. These plans reflect the fact that the luminosity of electron-positron colliders at sub-frontier energies have been inadequate to answer well-identified problems in particle physics. Moreover, in the surge to reach higher energies the evolution of colliders has not even provided luminosities which have maintained pace with the requirement of unitarity which demands luminosity increasing proportional with the square of the energy. Thus the high luminosity or "high precision" frontier, quite separate from the energy frontier, needs increased attention. However, this need stemming from particle physics notwithstanding, I have the strong impression that accelerator research and development is insufficient worldwide. Both in this field as well as in respect to the high energy linear collider issues already mentioned, we continue to uncover new phenomena which may set unsuspected limits to performance. Let me mention here only such phenomena as electron-positron pair formation in the coherent field of opposing bunches and energy losses in the beam-beam interaction derived from transverse particle deflections. I note that such phenomena, whether serious or not, have only gained attention very recently. We must be prepared for more surprises. Until research and development has been sufficiently thorough it is going to be extraordinarily difficult to submit credible proposals either for the high luminosity "factories" or higher energy colliders.

Notwithstanding these somewhat pessimistic remarks I would like to emphasize that progress in many technical areas, as witnessed by the reports at this conference, has been truly extraoardinary. The SLC is a pioneering effort in accelerator physics. LEP has come on the air with a remarkably short commissioning period, although it will take a bit of time to reach design luminosity. The BEPC is operating almost precisely to specifications. TRISTAN has been spectacularly productive and has incorporated the world's largest superconducting RF system. New esoteric acceleration methods have been demonstrated experimentally. For all these and other reasons the community of accelerator physicists has a great deal to be proud of and I salute them.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