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Computing in Accelerator Design and Operation

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PREFACE

Accelerators became long ago a very important research tool in nuclear physics and its industrial and medical applications.

Recently we have observed their impressive development, so well illustrated by the design and construction of very large accelerator systems like the CERN-SPS in Geneva and Fermilab in Batavia. New and still larger accelerators are under study and will be built with international support, for example LEP, once again on the CERN site in Geneva.

During feasibility studies, design and construction, and also during operation, computing plays a very essential role in enabling designers and operators to perform their duties properly. In all these phases of the accelerator life-cycle computers are used very extensively.

It is difficult to state in which of these phases the application of computers is most important. Some people claim that without digital control the usage of accelerators in research would not - at present - be possible. Additionally, physical experiments with particle-accelerator beams cannot be conceived without the decisive role of computers in acquisition and processing of experimental data.

All this means that computers and accelerators are tightly affined to each other. This symbiosis is the essence of progress in both fields.

This explanation makes it obvious that a conference on computing in accelerator design and operation had to be organized. Due to the initiative of one of us (R.Z.) while a member of the Computational Physics Group of the European Physical Society, the board of the CPG decided to convene such a conference under the Europhysics Conference label. The European Physical Society supported this idea vigorously. The sponsoring organizations are acknowledged with gratitude. Without their support and assistance the idea would not have materialized.

The conference was organized around three topical subjects: computing for design applications, for digital control of accelerators and for operational aspects. The subjects of invited lectures as well as the lecturers were carefully selected by the Scientific Advisory Committee. The invited lectures were the only oral presentations in plenary sessions. Each subject was introduced by a 15-20 minutes talk by a leading prominent personality in the field. Invited lectures were given 45 minutes for presentation and discussion. All contributed papers were presented at poster sessions, a format which was positively accepted by the participants. In the framework of the conference two workshops were organized on request. The first was devoted to lattice calculations of accelerator structures, the second to local area network concepts in the field of digital control of accelerators.

It was felt that this conference was necessary to bring together accelerator designers, builders and users, because a common understanding between them is still to be created. Therefore, as an important corollary, both the Scientific Advisory Committee and the participants of the conference endorsed unanimously the idea of organizing such a conference each third year. The Computational Physics Group Board has been approached with this suggestion. Let us hope that the year 1986 will be the year of the next Europhysics Conference in Accelerator Design and Operation.

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Welcome Address by Prof. K.H. Lindenberger, Scientific Director of the Hahn-Meitner Institute, Berlin

Dear Colleagues,

On behalf of the Hahn-Meitner Institute I welcome you heartily to our town. We are pleased and feel honoured that you have chosen Berlin as the place of your conference. By helping to organize this meeting we can, in a certain way, pay back some of the debt which we owe to the community of accelerator builders.

When, more than ten years ago, we started to convert our small Van de Graaff installation into a heavy-ion facility, we had little experience in accelerator technology, especially in how to run such a system with the help of a computer. In this situation we thought it best to ask the professionals for help and we got this help in a really generous way. This talk is not the right opportunity to give a full record of this story, but I would like to mention as an example two outstanding members of your community whose skill, ambition and enthusiasm had great impact on the project and who were essential for its success.

Prof. Hagedoorn from Eindhoven contributed much to the understanding of the orbit-dynamics in our cyclotron. One direct result of this is a programme by which the control computer can center and isochronize the beam. Dr. Susini from CERN was in charge of the design and the construction of the RF-systems of our cyclotron and he did it in such a way that they are really computer-compatible. In the meantime, our accelerator crew has joined your community, and that you meet at our place may be a hint that they now are passing as professionals. But to say it once more: without your assistance we would not have been able to get such a system running with the very good performance that, as we think, we now have at our disposal. I am glad that I can use this opportunity to express our gratitude.

CERN was an especially important source of information and also of very practical help. So I am very pleased that the opening honorary lecture will be given by Dr. Adams, who was twice responsible for the construction of the large accelerators in Geneva. We all know how brilliantly this job was done, what high technical standards have been achieved and what important experiments can be done with those machines. Here I would like to make a remark on the sideline: I was always very impressed how effective and smooth is the international cooperation in the field of particle physics and accelerator building. I think it would be of great value for all of us if, in other technical and political matters of world-wide impact, the same efficiency of cooperation could be achieved as in particle physics. Once more my special welcome to you, Dr. Adams, here in Berlin.

It is according to the hopes I just mentioned that the chairman of your conference, Prof. Zelazny, comes from Poland, from the Nuclear Research Centre at Swierk. The Hahn-Meitner Institute has a number of scientific contacts with this institute and we are happy that we can cooperate with you, Prof. Zelazny, in running this conference. But, as I mentioned, we have also other contacts to Swierk: the volleyball team of Swierk beat the Hahn-Meitner crew 2:1 when they met at Swierk in 75. Best welcome also to you Prof. Zelazny. I hope the local staff will make life easy for you in your job as a chairman.

I would like to thank the Free University that we can hold the conference in this place. We had to do so because, at our institute, we have no facilities to handle a meeting of this size.

Now nothing is left but to wish you a lively and interesting conference which gives you new ideas for your work at home. But I also hope that beside the work here you will find some time to stroll around Kurfürstendamm, to meet Nefretiti at the Egyptian Museum or to find out what else is going on in our town. After the afternoon session today, however, we would be very pleased if you could visit us at the Hahn-Meitner Institute to have a look at our installations and to join us for a cocktail. Once more, welcome to Berlin and good luck for your conference.

Thank you.

Welcome **Address** by

the chairman of the conference,
Prof. Roman Zelazny, CYFRONET
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Ladies and Gentlemen, Dear Colleagues,

All of you may observe the enormous development of activities in the field of accelerator construction and their application in research, industry and medicine. New accelerators are proposed, are under design and construction, start their operation.

Computers play a very important role in the design, in feasibility studies and in operation of accelerators. They are applied in many interesting and innovative ways: for computer-assisted design, for digital control, for beam administration and particularly in experiments with beams of accelerator particles.

The conference organized under the auspices of the European Physical Society and its Computational Physics Group is devoted to various aspects of computing in accelerator design and operation.

Originally scheduled to be organized in Poland in September 1982, it has been postponed and moved to Berlin. I wish to thank very much the Hahn-Meitner Institute authorities, particularly Prof. Lindenberger and Dr. W. Busse for their willingness to take over the organization of the conference. In a short period of time the local organizers performed a very good job, enabling us to meet today to open this, as I do hope, interesting and important meeting.

Using this chance, I wish to thank not only the Local Organizing Committee headed by Dr. Busse but also other sponsoring organizations: the Deutsche Physikalische Gesellschaft and the Regional Computing Centre of Atomic Energy CYFRONET. It is my special pleasure to thank all members of the Scientific Advisory Committee for their effort concerning the scientific programme of the conference and all invited lecturers for accepting the invitation to deliver the invited talks. Their contributions make the conference an important and interesting event.

Particular thanks are due to Sir John Adams for his acceptance to deliver the honorary lecture at this conference. It seems to me that the community of European physicists shall consider that this homage to his activities in the field of accelerator development is well deserved and that they join the Scientific Advisory Committee's opinion with applause.

I welcome sincerely all the participants. Without you all the conceptual and organizational efforts would be empty. You are the salt of the earth. It is done for you, you will make it finally a success by the contribution of your papers,you make it vivid by discussion and exchange of views and experience. All the organizers have done their duty. The critical mass for a chain reaction necessary to create a peaceful explosion of ideas, concepts, interactions among interesting people has been prepared. Let it go. I declare the Europhysics Conference on "Computing in Accelerator Design and Operation" open.

Thank you very much for your attention.

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FUTURE HIGH ENERGY ACCELERATORS

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Introduction

I feel very honoured to be asked to give the opening talk at this conference on computing in accelerator design and operation. The subject of my talk is future high-energy particle accelerators and colliders, that is to say machines that may be built after those that are now in operation or under construction. The reason for this choice of subject is that I believe that these future machines will make even heavier demands on computing than the present ones, especially on computer control systems. I realise that this is not a very original thought since it only follows the trend which has been evident in recent years. Nevertheless, we are a still a long way from the cybernetic machine proposed many years ago by scientists at the Radio Technical Institute in Moscow but I believe future machines will push us much further in this direction.

The needs of the research

In presenting this subject to you I thought that I should start by saying something about the needs of the research in the years ahead, since it is these needs which should determine what kind of accelerators and colliders are built in the future. These research needs are usually determined by theoretical predictions so one may ask the question, what does theory predict?

The most depressing prediction is that nothing much will happen after the W and Z particle energy range of about 0.1 TeV until one reaches energies which are well beyond any accelerator or collider that can be conceived today. In other words, there stretches before us a featureless desert whose further boundary is way beyond our reach. This view is based on two assumptions. Firstly that there are no new gauge forces except the know SU(3), SU(2) and U(1) operating between the presently accessible energy range and some very much higher energy level and secondly that no new particles will occur in this energy range which upset the value of the Weinberg angle , $\sin^2 \theta_W = 3/8$. With these two assumptions and the known quarks and leptons, the renormalization group extrapolation shows that the effective couplings of the three gauge forces converge to the same value at the same upper energy level and that this level has the very high value of 10^{11} TeV. Beyond that energy level there is another at about 10^{16} TeV which comes from the supergravity ideas and the possibility of unifying gravity with the other forces. Thus the desert stretches from 0.1 TeV out to at least 10^{11} TeV. This prediction is not, of course, very encouraging to experimentalists and machine builders nor is it very much use in fixing the characteristics of future machines, at least not until we know how to get to 10^{11} TeV. In fact, it led Abdus Salam to entitle a talk which he gave last year on this subject at the International Particle Physics Conference "The impending demise of high energy accelerators" and I am indebted to that talk for the explanation of the desert syndrome which I have just given you. Incidently, he concluded his talk with the advice - "Do not ask theorists which energy to aim at for future machines. Aim at the highest possible".

A more useful prediction, at least for machine builders, is that there may be flowers blooming this side of the desert which with a great effort we might be able to reach. This view is based on the observation that the present so called standard model based on the unified electroweak theory of Glashow, Weinberg and Salam and the QCD theory of strong interactions cannot be the final answer. For example, it does not predict the numbers of families of quarks and leptons or their masses or their mass ratios. Also there is the all important symmetry breaking which causes the gauge bosons that mediate between the weak interactions, the W particles, to acquire very large masses whereas those that mediate between the electromagnetic interactions, the photons, are massless. The "deus ex machina" is said to be the Higgs mechanism with its scalar Higgs particle. Unfortunately, nothing seems more elusive than the Higgs particle. Is it a particle or a set of particles or - and I quote - "an approximation of dynamical effects which manifest themselves at energies a few times the inverse square root of the Fermi weak interaction coupling constant", i.e. roughly 1 TeV ? Clearly the search for and study of the Higgs particle or its equivalent is of the highest interest and priority and fortunately the energy range in this case could conceivably be reached by particle colliders in the forseeable future.

The machine energies required to explore the Higgs sector depend on whether the machine is a proton collider or an electron collider. A rule of thumb is that an electron-positron collider of one sixth to one tenth the centre of mass energy of a hadron collider will explore the same general domain of hard processes or heavy particle production. So, if the Higgs sector has a mass scale of about 1 TeV, the future electron-positron collider should give about 2 TeV in the centre of mass system and a proton-proton collider about 20 TeV.

This seems for the moment the best guide we can get from theory concerning future machines but before turning to these machines, I should point out that past predictions about the future needs of the research show a marked lack of correlation between the reasons given for building the machines and the important discoveries they made.

T. D. Lee in a recent talk at Brookhaven listed the twenty most outstanding discoveries made using accelerators and colliders during the last 35 years starting with pion production at the 184 inch cyclotron at Berkeley in the late 1940's and ending with the intermediate vector bosons at the SPS collider at CERN this year. He pointed out that only two of these twenty landmark discoveries, the anti-nucleons at the Berkeley Bevatron and the intermediate vector bosons at the CERN collider were anticipated at the time the relevant machines were approved. Another remarkable feature he found was that the major discoveries arrived very regularly over the 35 years - almost one every two years. It seems that Nature reveals her secrets unexpectedly but rather regularly, but she does not read machine prospectuses.

After these cautionary remarks I will now pass on to the machines themselves.

Future accelerators and colliders

Two machines have emerged in recent years as possible candidates for the accelerators and colliders of the future. The first is a hadron collider, either proton-proton or proton-antiproton, which might also be used as a fixed target machine and the second is a linear electron-positron collider. Both of these machines were studied in some depth at two workshops organized by the International Committee for Future Accelerators (ICFA) in 1978 and 1979. More recently, the hadron collider, under the name of the Desertron, or Superconducting Super Collider (SSC), has been taken up enthusiastically in the USA. There was a Summer Study on particle physics and future facilities held at Snowmass in Colorado in July 1982.This was followed by a Technical Workshop on a 20 TeV hadron collider held at Cornell University in March 1983 and by a Workshop on hadron collider detectors held at Berkeley in April 1983.

From all these studies and workshops, the general conclusion emerges that a hadron collider with a centre of mass energy of about 20 to 40 TeV is technically feasible, that it would cost about 2 billion dollars and maybe more, and that detectors could be designed to measure the events produced in the collisions at these high energies and extract the relevant data. To reduce the machine cost down to 2 billion dollars it is thought that 3 or 4 years of design and development work will be needed on its components before construction can start. There is less agreement on how long all this would take assuming, of course, that the U.S. government is willing to agree to such a large and expensive project. Estimates range from 9 years to 15 years. In other words, if approval is given to this venture in 1984, the collider might be operating at the earliest in 1993 or at the latest in 1998; let us say sometime in the second half of the 1990's.

Let me now say something about this machine. Since it is assumed that new particles or sets of particles beyond the W will have smaller production cross-sections following roughly the $s^{1/2}$ law, the highest machine luminosity seems to be desirable and this can best be achieved by a proton-proton collider, i.e. an intersecting ring machine like the ISR or CBA in which luminosities approaching 10^{33} per cm^2 per second are thought possible.

The magnet system for this machine will have to use superconducting coils to reduce its electrical power consumption to an acceptable level. Three magnet systems were studied at the Cornell Workshop, the first used bending magnetic fields of 2-3 Tesla, the second 5-6 Tesla and the third 8-10 Tesla. The first would use iron to shape the field and superconducting coils to save power. The second would be based on Tevatron or CBA technology using NiTi conductor at 4.5° K. For the third, 8 Tesla could be reach with NiTi conductor by operating at 2°K, but 10 Tesla would need Nb_3Sn conductor. A 3 Tesla machine for 20 TeV beam energy would be about 160 km in circumference, a 5 Tesla machine 100 km and an 8 Tesla machine about 60 km. For comparison, the largest machine now under construction is LEP which is 27 km in circumference. This future machine is therefore several times the size of LEP. Curiously enough rough estimates of the total cost of the machine made at Cornell showed little difference whichever bending field level is chosen as can be seen in Table 1.

Table 1

Estimated Machine Costs (Million Dollars) [20 + 20 TeV.pp]

	3 Tesla	5 Tesla	8 Tesla
Fixed costs [1]	540 ± 80	540 ± 80	540 ± 80
Enclosure, etc. [2]	300 ± 120	190 ± 70	130 ± 50
Magnets [3]	450 ± 150	710 ± 240	780 ± 260
Accelerator components [4]	350 ± 80	280 ± 60	230 ± 50
TOTAL	1640 ± 320	1720 ± 360	1680 ± 360

[1] Fixed costs include the site infrastructure (but not the cost of the site) the injector machines, experimental areas and the magnet factory.

[2] Enclosure costs include the machine tunnel, access roads, service buildings and power distribution.

[3] Magnet costs include all magnet elements and their cryogenic systems.

[4] Accelerator components costs include the refrigerators, vacuum, RF, controls, injection and abort systems, power suppliers, robots, etc., and installation costs.

One of the tasks during the initial development period of this machine will be to chose between these three magnet systems. Another even more important task is to see whether the present cost estimates are realistic since if one compares them with superconducting magnet machines like the Tevatron or CBA, one sees that large reductions have been made in the unit costs of the components to get the total machine cost down below 2 billion dollars.

The size of these reductions can be seen from estimates made by R.B. Palmer for a 5 Tesla 20 + 20 TeV pp collider based on the latest Fermilab cost data for Tevatron magnets. He arrived at total cost of 6.6 billion dollars compared with the 1.7 of Table 1 and cost reduction factors for magnets and tunnels ranging between 4 to 6. Achieving such large cost reduction factors will not be easy. Even the alternating gradient focusing principle, when it was introduced in 1953, only reduced total machine costs by a factor of 2.

Different ways are proposed to make these cost reductions, for example, using a very small magnet aperture giving a good field region of about 20 - 30 mm diameter and getting the beam once round the machine by coaxing it sector by sector round the 100 km circumference; installing the bending magnets of each ring side by side in the same cryostat to reduce heat losses and save refrigerator power; using very small cross section tunnels, in the limit only sufficient for the machine but not for human beings; and using modern techniques to reduce production costs of machine components.

Let me now turn to the other future machine, the linear electron-positron collider. At the ICFA Workshops of 1978 and 1979, a tentative design was made for such a machine to give 700 GeV in the centre of mass system. A linear machine was chosen since limiting synchrotron radiation losses in circular electron machines with beam energies above about 250 GeV gives machine circumferences which are prohibitively large. Two solutions were studied, a linear collider using room temperature RF cavities and one using superconducting RF cavities. On balance the room temperature solution looked more feasible although it required a peak RF power of the order of 10^6 MW for driving the cavities. Since then the Novosibirsk and SLAC laboratories have continued with these studies. At SLAC the construction is going ahead of a machine called SLC using the existing 30 GeV electron linac upgraded to give 50 GeV. Both electrons and positrons will be accelerated in this linac and at the end of it the electrons will travel round one semi-circular arc to meet head on the positrons which travel around a second arc. To reach the desired luminosity of 6×10^{30} per cm^2 per second the two beams, or rather bunches of particles, have to be focused down to a diameter of about 1 or 2 microns. High precision and stability are necessary in space and time to ensure that such small diameter bunches actually hit each other at the collision point. This machine, which is planned to come into operation in 1987 will give the first opportunity to study experimentally the problems likely to be encountered in linear colliders particularly the disruptive effect which one bunch has on the other when they collide.

In addition to this experimental machine a tentative study has recently been made of a linear electron-positron collider to give 2 TeV in the centre of mass system based on existing technology. Some of the parameters of such a machine are given in the next table.

Table 2

1 + 1 TeV electron-positron linear collider

RF frequency	2856 MHz (S band)
Length	2 x 50 km
RF gradient	20 MV/m
Repetition rate	185 Hz
Bunches per pulse	12
Bunch length	2 mm
No of particles per bunch	$1.4 \cdot 10^{10}$
No of klystrons	2 x 3500
Peak klystron power	330 MW
Average klystron power	23 kW
Total peak RF power	$2.4 \cdot 10^6$ MW
Total average RF power	160 MW

The total length of this machine, 100 km, is about the same as the circumferential length of the 20 TeV hadron collider and a very rough estimate of its cost suggests a figure about twice as large.

One of the problems of linear colliders is that there is only one region where the two beams meet head on. To run as many experiments as with a circular hadron collider which has several interaction areas around its circumference, the experiments of a linear collider have to be placed side by side and the linac beams switched to each experiment in turn on a pulse to pulse basis. Since the beams consist of bunches 2 mm long and a few tenths of microns in diameter, colliding the bunches at the correct place inside each experiment does not seem so easy.

I can hardly leave this part of my talk without mentioning the pressing need for new ideas for accelerating particles in order to reduce the size and cost of the accelerators and colliders. The two future machines which I have just described really are monsters; 100 km in circumference or length and costing several billion dollars each. It is by no means certain that governments or even groups of governments will be willing to finance such machines and we may be forced to find cheaper solutions or stop building very high energy accelerators. Let me try to explain what these new ideas should be aiming to achieve.

To reduce the size of future machines higher accelerating gradients are needed, the accelerating gradient being defined as the maximum particle energy of the machine divided by its length or circumference. Electron linacs are now approaching gradients of 20 MeV/m although short test cavities have reached voltage gradients of up to 150 MV/m. In the case of proton synchrotrons the accelerating gradient as I have defined it is set by the maximum bending magnetic field. A 5 Tesla machine achieves 150 MeV/m and a 10 Tesla machine would achieve 300 MeV/m. Therefore the new ideas of accelerating particles if they are to enable smaller machines to be built should aim at accelerating gradients of several 100 MeV/m and preferably at a few GeV/m. Since at a few 100 MeV/m it becomes impossible to maintain the necessary voltage gradients between metal surfaces, the accelerating field has then to be established in a medium such as a plasma column or an intense electron beam. Some of the new ideas aim in this direction, for example the beat wave accelerator in which two laser beams running along a plasma column have a frequency difference equal to the plasma frequency and by beating together set up intense localised charge concentrations and hence very high field gradients which can then be used to accelerate particles. Several GeV/m are promised by this scheme at least theoretically. However, these new ideas are still in their infancy and even if they are found promising experimentally, it will take many years to develop them into an accelerating system for a machine to give several TeV beam energy.

Also they must at least hold out the promise of less cost per GeV. A shorter but more expensive machine is not a solution to this problem.

Future machines and computers

I would like to end now with a few remarks about the implications of future machines to computing and so try to link my talk with the subject of this conference.

There are, as everyone knows, five distinct but overlapping phases of machine building. These are the design phase, the construction phase, the installation phase, the commissioning phase and finally the operating phase. I notice that this conference only covers computing for the design and operating phases. I would like to suggest that for future machines the other three phases will also need a great deal of computing.

Let me illustrate this point by taking first the construction phase. Until bright new ideas actually succeed in reducing the size and cost of future particle colliders, we are faced with machines which will be of the order of 100 km in circumference or length. These machines will contain thousands of components of a limited number of types - magnets, RF cavities and power units, vacuum pumps and so on. These components will have to be cheaply mass produced to very tight tolerances. Up to now machine builders and industrial firms have used manufacturing technologies which, although achieving the desired products to the required tolerances, are relatively primitive compared with the methods now employed in the most advanced mass production industry. In the case of superconducting magnet production, Fermilab and Brookhaven have set up their own factories on site but the Tevatron and the CBA are very small machines compared with a future 20 + 20 TeV hadron collider. To manufacture the magnets of the latter in the same time as it took for the Tevatron one would need 20 Fermilab factories working in parallel. It seems therefore that much more automation in production perhaps using robotic systems under computer control will be needed for future machines. This will also allow a closer quality control which can then be integrated into the production process rather than be superimposed as periodic inspection as has been the case up to now. This same technology will be required for all the other machine components which will be needed in their thousands.

Turning now to the assembly stage, the problem is to install thousands of components in the correct order via a limited number of access points in a tunnel 100 km in circumference or length and to align them to a very high accuracy. If all this is to be done in a reasonable time, like two or three years, it will require superb logistic organization and a great deal of automation. There is first the