ACCELERATORS--LIMITATIONS OF TECHNOLOGY AND NOVEL ACCELERATOR IDEAS

A Summary of the Working Group Reports

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Abstract

Hadron colliders and accelerators in the 20 TeV energy range turned out to be the majority interest among active members of the Accelerator Row Group. While other types of accelerator and other energy ranges were discussed, largely on the basis of work done elsewhere, our primary creative activities at this summer study focused on the hadron facility. Examining both the economic and accelerator physics dimensions of such a facility, we were able to give some hope to the idea that a well designed and concentrated R/D program, elaborating much further on technologies we now possess, might bring a 20 TeV facility within our national reach. The central challenges for this R/D program appear to be

1. Achievement of virtual automation of superconducting magnet, accelerator housing and other accelerator component manufacture and installation.

2. Achievement of a thorough understanding of the field vs. cost relation for superconducting magnets.

3. Achievement of a thorough understanding of the luminosity-aperture-energy relation.

Introduction

The special atmosphere, organization and freewheeling style of the Accelerator Section of this DPF Summer Study resulted in a very useful perspective and focus unattainable in a more structured summer study or workshop setting. Participation in the DPF Summer Study in general and the Accelerator Group in particular was largely determined by self-selection rather than by careful prearrangement, the usual procedure for planned accelerator studies. That meant, as it turned out, that the majority of interest was in very large hadron colliders and accelerators. Another interesting contrast with the usual prefocused summer study was our spontaneous interest in making cost considerations primary subjects for study. Another way of saying that is to say that during our first meetings we found that our strongest mutual interest was in exploring the technical and financial prospects for a hadron accelerator complex with 10 to 20 times the beam energies of the Tevatron complex. The bulk of work actually done by the Accelerator Row Group at Snowmass focused on this topic.

Initially we had thought to form five working parties, each addressing itself to one of the following five topics: hadron-hadron colliders, hadron-lepton colliders, lepton-lepton colliders, fixed target accelerators, novel accelerator ideas, each with more-or-less equal emphasis. The self-selection process resulted in drastic modification. In the end, three working groups dealt with hadron machines in some detail, and one small group assembled certain information germane to ep colliders.

The three hadron parties concentrated on a) "low cost" approaches to a 20 TeV collider (Russ Huson, Coordinator); b) $p^{\pm}p$ colliders (Bob Diebold, Coordinator); c) modifications needed to outfit the highest energy proton colliders for fixed target service and high intensity fixed target machines of lower energy (Jim Maclachlan/Gene Fisk, Coordinators). Each of these groups has written a report on their work which is included in these Proceedings. The ep group (Ernest Courant/Yanglai Cho, Coordinators) looked into possible performance figures for various energy range ep machines. Their report is also appended.

The very small e^+e^- group held a number of lively discussions about future possibilities. As most of the material escribed represented work done elsewhere by individuals and not joint work of the group, it was decided not to issue a joint report as part of the Accelerator Row Group but to rely on the report of the Lepton-Hadron Column group for presenting current hopes for future single pass linear colliders and upon individual contributions for the cost-performance relationship for e^+e^- storage ring colliders and other collider concepts.

No special group convened to work on novel accelerator concepts. The seminar series, sponsored by the Accelerator Row Group, did take up this subject. A brief report on the seminars is included later in this summary report.

Procedure Followed by the Accelerator Row Group

At our first plenary session about 40 of us enjoyed a wide-ranging free-for-all discussion of the issues relevant to the machine side of accelerator-based particle physics. It soon became clear that a primary concern of many of us there was to seek an answer to this question: Will the technology which we could reasonably hope to create in the next decade, support the factor of 10 to 20 increase in beam energies which many believe will be necessary for our next step beyond LEP and Tevatron physics? By "support", of course we mean "permit construction of such facilities within practical resource limitations and at useful luminosities."

We "voted" by signing up to work in the various subgroups. The tally showed that the majority of those present were interested in following this question in a hadron accelerator framework. Thus we defined our task and formed the subgroups referred to above. One more plenary work session was held, about halfway through the study, in which the subgroups delivered status reports for the purpose of sharpening up some of the questions which we were trying to attack. Other plenary sessions were held--eight in addition to the two mentioned--and were devoted to informative seminars. The major working sessions were the subgroup meetings or even smaller team meetings which took place almost daily in some cases.

Each coordinator was responsible for formulating a summary of the work of the subgroup for which he was responsible, and for presenting that work, orally, at the final sessions of the DPF Summer Study. The subgroup reports contained in these proceedings closely parallel these summary presentations.

Summary of the Subgroup Findings

As a starting point in technical considerations, we leaned heavily on the reports of the two recent ICFA workshops[1,2] on "Possibilities and Limitations of Accelerators and Detectors", the first of which took place at FNAL in 1978, the second taking place in 1979 at Les Diaberets near CERN. The accomplishments of these seminal workshops were extended in some areas by further technical work along some of the lines begun there and considerably broadened by the inclusion of cost considerations.

As there was great overlap in both membership and interests of the various subgroups, the division lines between the foci of their efforts are somewhat blurry and arbitrary. Nevertheless the thrust of their efforts was distinct enough to make categorization by subgroup name useful for this summary.

Hadron Colliders (Bob Diebold, Coordinator)

This subgroup took the lead in examining some of the important accelerator physics issues which bear on the possibilities for 20 TeV class pp and $\bar{p}$p colliders and in trying to understand the cost consequences of "straightforward" extrapolation of current technology from 1 TeV class hadron machines. Shared with the "Low Cost Approaches" group was an attempt to find a cost optimum value for the design magnetic field at peak energy.

In carrying out their objectives, model 20 TeV accelerators based on yet to be developed 10T magnets disposed in one and two ring configurations with bunched and unbunched beams were considered. Such machines would have circumferences of 55-60 km. For each type of machine a complex of issues such as interrelation of space and time separation of beams with aperture needed, injection energy, stability, interaction region design, etc., must be considered. Most of these matters are dealt with to some extent in the group report. Particular attention was given the problem of separation and collision of multi-bunch beams and the influence of the long-range beam-beam interaction in collisions of continuous beams crossing at an angle[3]. One of the interesting features of a 20 TeV proton machine with 10T magnets is the concomitant synchrotron radiation leading to emittance damping times of 6 hours and power emissions in the tens of kW range. Whether this radiation will be more than a minor perturbation is not clear. It was pointed out[4] that as $\varepsilon_c \sim 400$ eV at 20 TeV, 10T, one could use the phenomenon of "total reflection" to pipe the SR down the beam tube to a warm absorber.

From these considerations and others touched on in the group report, tentative conclusions are that in a single ring $\bar{p}$p machine with bunched beams one might achieve

$$10^{31} \leq \mathcal{L} \leq \text{few} \times 10^{31}\ \text{cm}^{-2}\text{sec}^{-1}$$

if the mean number of interactions per bunch crossing, $\langle n \rangle$, were restricted to ~ 1. In this case a $\bar{p}$ filling time of 3-4 hours ($N_{\bar{p}}(\text{tot}) \sim 3.5 \times 10^{12}$) might be achieved. If higher $\langle n \rangle = 25$ were allowed, higher luminosity might be achived. ($\mathcal{L} \propto \langle n \rangle$). For example, if $\langle n \rangle = 25$ were allowed, then one might hope for

$$\mathcal{L} \sim 3 \times 10^{32}\ \text{cm}^{-2}\text{sec}^{-1},$$

at the cost of increasing filling time to 18 hours.

At the cost of adding another ring, (PP), one could get to higher luminosities, still using bunched beams to minimize stored energy in the beam and filling problems. In this case, if one accepted $\langle n \rangle = 10$,

$$\mathcal{L}_{pp(\text{bunched})} \simeq 10^{33}\text{cm}^{-2}\text{sec}^{-1},\ N_p(\text{tot/beam}) \simeq 10^{14}.$$

With dc beams, 100% detection dutycycle, one might expect

$$\mathcal{L}_{pp(dc)} \simeq 10^{33},\ N_p = 4 \times 10^{14}/\text{beam}$$

at the expense of filling time and stored beam energy, 3×10^9 Joules in the latter case.

Questions of single beam stability were examined briefly[5] and may be of particular concern in small aperture, low field machines of high design luminosity.

To establish a cost benchmark this group attempted to extrapolate from known FNAL costs on a very conservative basis. Their result was that a 20 TeV beam energy collider, built by extending present "conventional" technology with superconducting magnets, would come to something of the order of (2 to 3) x 10^9\$. Considerable detail concerning thier cost scaling is given in the report.

This conclusion gives a rather firmer basis to the common wisdom that extension of our present methods to a 20 TeV machine would be extravagant to say the least.

With this goad, the "Low Cost Approaches" group received even further inspiration to try harder.

Low Cost Approach to Collider Facilities (Russ Huson, Coordinator)

As indicated in the title, the primary focus of this group was on study of cost structure of large collider facilities and what means might be developed to cut costs dramatically. The division of this group report from that discussed above is somewhat arbitrary due to the great overlap in personnel and interests. The strictly accelerator physics considerations mentioned above apply equally here.

One framework used by this group to give coherence to their efforts was a comparison of the cost of a facility based on 2½T, "superferric" magnets (circumference ∿200 km), with one based on 10T magnets (circumference ∿50 km). A "superferric" magnet is one in which iron pole pieces are largely responsible for setting the magnetic potential contours and the currents which are the sources of the field flow in superconducting wires to minimize the cross-sectional area of conductor needed as well as the power requirement. The price per unit length for superferric magnets is supposed to be relatively favorable owing to the ease with which iron structures can be manufactured automatically and precisely and the looser conductor placement tolerances resulting in lower assembly cost. The degree to which this statement is correct is a matter of debate among experts. If a 10T accelerator grade magnet can be built, it will be more expensive per unit length than the 2.5T superferric magnet. The reason for the comparison is to see whether the presumed cost savings for the 2.5T magnet can compensate--or more than compensate--for the extra length of tunnel and other accelerator components concomitant to this approach. Conversely, it is interesting to see whether the extra expense per unit length of 10T magnets might be compensated--or more than compensated--by the savings in tunnel and other components and labor which accrue to the small circumference, high field design.

To complete an estimate for overall facility cost including these two contrasting magnet types, one needs a picture of what the facility would look like and how it is to be erected. This seminal vision was publicly presented early on in the Summer Study by one of our great prophets.[6] Central to the concept is the idea of on-site, semi-automatic manufacture of components and sub-assemblies and their installation in a housing of small cross section which could be laid continuously in a shallow trench much as a long pipeline is installed. Access to the housing by humans would not be necessary--or perhaps even possible--as the final adjustments and repairs would be carried out by robots taking their cues from a central mission control. More than one ring or type of accelerator might be installed in the same housing.

Incorporation of these elements into a useful cost estimate is a formidable task, given the inherent uncertainties in forecasting the results of the mass of detailed R/D implied by this picture. Nevertheless this brave group made a valiant attempt to do so. Their conclusion was that, detailed accelerator physics considerations bearing on performance aside, the net cost of the complete 20 TeV hadron machine facility would be about the same for both magnet types (2.5T, 10T) and would perhaps come to about 1.5×10^9\$ when using these advanced manufacturing and installation methods.

Some work was directed at the question of whether these two examples might be extreme and whether there might be a cost minimum for some intermediate field[7] value and/or some other configuration, e.g., two beam channels in one yoke. There was a rather strong feeling on the part of some individuals that there are significant gains to be made along these lines. Further study is certainly worthwhile.

Other topics explored by this group were siting and interaction area layout. Circular colliders to date have had interaction areas disposed symmetrically about the ring. With the prospect of tens of km radii for a collider, communication problems become impressive. For this reason the idea of developing adjacent serial or parallel interaction areas was put forward. Further work is required to see if this most attractive idea is feasible.

The obvious economies of putting such a large facility on a naturally flat site were discussed to some extent. Several potential sites in the Southwest, having the requisite flatness, were mentioned. Other siting ideas will doubtless emerge in due course.

Fixed Target Group (Jim Maclachlan/Gene Fisk, Coordinators)

Two areas of interest emerged in this subgroup: required modifications permitting very large hadron colliders to serve beams to fixed target areas and possibilities for a very intense fixed target accelerator of moderate (i.e., less than 32 GeV) beam energy. Most details of work in the latter category are included in a separate report[8] describing the LAMPF II proposal. The reader is directed to this report and that of the fixed target column group for further details.

Possibilities for using the big hadron collider for fixed target work were studied first by the ICFA workshops[1,2] and many technical details are contained therein. Considerations of cost and power led our group to think on a somewhat more modest scale in terms of beam power. The purely accelerator aspects of this usage of the machine do not appear formidable but without a detailed design of the collider one cannot be sure. The experts seem to agree that a workable solution can be found and that the accelerator modifications themselves will not be terribly costly. The majority of the investment would be in the beam lines, shielding, and to some extent target areas. Some cost estimates are given in the report of the Fixed Target Proton Column Group (Lee Pondrom, Coordinator).

ep Colliders (Ernest Courant/Yanglai Cho, Coordinators)

The small ep accelerator group performed a very useful service in assembling in their report a useful group of formulae for luminosity and tune shift covering the various different configurations which are often discussed. In addition, they pulled together calculations of performance expectations for three different cases of 20 GeV e, 400 GeV p and four cases of ep with the 20 TeV p beam colliding with an e storage ring or linac. They concluded that in the 20×400 case, one might reasonably hope to achieve $\mathcal{L} \gtrsim 6\times10^{31}$ cm^{-2}sec^{-1} while in a 100 GeV × 20 TeV case one could hope to achieve $\mathcal{L} \gtrsim 10^{32}$ cm^{-2}sec^{-1} for quite reasonable beam parameters.

Interestingly, they found that bremsstrahlung is not likely to be a problem at these energies and luminosities.

Seminar Series

To help interested physicists become aware of some of the ferment brewing in the novel accelerator idea arena, we held a series of eight seminars led by Summer Study attendees:

1. Beam Cooling Ideas, Dave Cline

Dave reviewed progress in the use of e beams for p cooling and emphasized the benefits that could accrue to high energy machines if performance in this area could be improved (contributions to these Proceedings).

2. The Grating Accelerator, Bob Palmer

By use of a high power laser pulse incident on a grating structure in a certain way, it appears theoretically that effective gradients of some GV/m may be possible (see Proceedings of LANL Laser Accelerator Workshop, 1982).

3. The Linac Boosted Storage Ring, Maury Tigner

In this concept high current beams of particles are accelerated to the collision point in superconducting linacs and decelerated to recover their kinetic energy. Continuous circulation through low energy storage rings preserves the particles and damps out the collision induced phase space growth by electron beam cooling in the case of protons and radiation damping in the case of electrons and positrons (report in process).

4. LAMPF II, H. Thiessen

This high current proton accelerator for up to 32 GeV may have interest for both particle and nuclear and solid state physicists (contribution to these Proceedings).

5. Accelerators for Up to 1000 TeV, Bill Wenzel

Bill Wenzel presented us with his vision of how automated production could be used to build really big accelerators (contribution to these Proceedings).

6. The Beat Wave Accelerator, Andy Sessler

Andy presented a tutorial explanation of the accelerator proposed first by Tajima and Dawson. In this device a laser beam is used to organize dense clumps of charge in a background plasma. The fields from these charge density modulations can be made to have traveling components with $v_p \sim c$ and can in principle produce effective accelerating gradients in the GV/m range (see Proceedings of the LANL Laser Accelerator Workshop, 1982).

7. Single Pass Linear Colliders, Helmut Wiedemann

In this session, hopes for the future of e^+e^- pulsed linear colliders were presented. If substantial developments in charge accelerated per bunch, in emittance control, beam focusing and in pulsed microwave source development are accomplished, one might hope for luminosities in the 10^{33} $cm^{-2}sec^{-1}$ range at hundreds of GeV or even TeV energies for reasonable ac power input (contribution to these Proceedings).

8. Free Electron Laser and Inverse Free Electron Laser, Claudio Pellegrini

If a focused laser beam propagates perpendicular to an alternating magnetic field produced either by dc magnets or a microwave beam, an electron beam can be made to give up energy to the laser beam (FEL) or receive energy from that beam (inverse FEL) depending upon the phase relationships. One might hope to accelerate electron beams to several hundred GeV at effective gradients of hundreds of MV/m in this way. Conversely, one might produce peak powers of up to 1 GW in the wavelength band less than 1 cm (see Proceedings of 1982 Accelerator Summer School of SLAC).

Summary Remarks

Our primary creative activity at the Summer Study was rather specialized and centered on considerations pertaining to the kind of hadron accelerator we will need to attack particle physics beyond LEP and Tevatron energies. We tried hard to grapple with the economic dimensions of the problem, as well as with the purely accelerator issues, involved. It would be easy to find fault with our attempt to make useful cost estimates, a notoriously slippery business, often best left to the experts working in a calm atmosphere. However, the resulting cost numbers are enormous, showing that we're dealing with a problem too important to be left to the experts. Without a wide community appreciation of what we're up against, we may fail to find a timely solution that permits our science to go forward with reasonable expectations for new discovery. These Proceedings are an account of the first community-wide effort to appreciate the challenge. One particularly important result of this study was the bringing together of a truly representative collection of particle physicists and accelerator specialists from all of the U.S. institutions playing significant roles in particle physics. They set to work with a will to compare design methods and cross-calibrate their cost assessment methods. Much work remains to be done but this was an important early step.

It is clear that we are desperately in need of new, dramatically more cost effective, accelerating methods for future facilities. The results of this summer study give a hint that a well-designed R/D program to squeeze the last drop out of the technologies we have may suffice to give us the accelerators we'll need for the next big step. Along these lines we need to pursue extensive automation in all phases of accelerator manufacture and assembly and to zero in on the question of optimum magnetic field and superconducting magnet design. Success with higher fields would pay dividends in terms of easing siting requirements, reduction in number of circulating charges required for a given luminosity, improvements in beam stability and perhaps in benefits due to the cooling of protons by synchrotron radiation. Also urgently needed is a reliable theoretical means for stability assessment at the design stage.

References

1. Proceedings of the Workshop on Possibilities and Limitations of Accelerators and Detectors, FNAL 1979.
2. Proceedings of the 2nd ICFA Workshop on Possibilities and Limitations of Accelerators and Detectors, CERN 1979.
3. L. Smith, these Proceedings.
4. L. Jones, these Proceedings.
5. L. Teng, these Proceedings.
6. R.R. Wilson, these Proceedings.
7. C. Taylor, these Proceedings.
8. H. Thiessen, these Proceedings.