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Status and Future Directions for Advanced Accelerator Research - Conventional and Non-Conventional Collider Concepts

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ABSTRACT: The relationship between advanced accelerator research and future directions for particle physics is discussed. Comments are made about accelerator research trends in hadron colliders, muon colliders, and e^+e^- linear colliders.

COLLIDERS AND HIGH ENERGY PHYSICS

The mass scale of interest to particle physics is the range of ~ 0.5 to 2 TeV where electroweak symmetry is broken. Experiments at colliders with high enough energy are expected to detect evidence of electroweak symmetry breaking and to shed light on the symmetry breaking mechanism. Is it the classic Higgs phenomena, supersymmetry, strong coupling, or something else? History suggests that discovering the origin of electroweak symmetry breaking will also raise questions about subjects unknown today.

The Large Hadron Collider (LHC) is a technically proven and funded project that could reach high enough energy and luminosity for the study of electroweak symmetry breaking, and the NLC, JLC and TESLA, linear colliders being designed for center-of-mass energies E_{CM} = 0.5 to 1.5 TeV, promise an unrivaled environment for the study of this phenomenon. The sizes and costs of these colliders raise questions that are at the heart of the future of particle physics

1. Are the colliders and detectors needed for the study of electroweak symmetry breaking affordable? The costs of these facilities are modest on the scale of many governmental activities, so the issue is whether our elected representatives decide that high energy physics pursued at this scale is or is not in the national interest. The SSC was started when they decided it was, but that project was terminated when their opinion changed. CERN and the LHC may be facing problems of the same nature with the discussion of budget cuts initiated by the German government.

International collaboration on the design, construction and operation of large colliders is the proposed solution to the high cost of these facilities. The cost per country is reduced, but the involvement and commitment of each country is reduced also. Will one or two large colliders located somewhere in the world meet the needs of the governments that support particle physics, the institutions

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that commit faculty and staff to this scholarly field, and the physicists who perform the research? If these needs are not met, support for and interest in the field could drop precipitously. The discussion of international collaboration has concentrated on the cost reductions without much consideration of these needs and the consequences of not meeting them.

2. Do we have the technology and accelerator physics to move on to the next energy scale? The colliders of today are based on a combination of principles, technologies, and accomplishments that has led to many of the past discoveries in particle physics and has placed the field on the verge of studying the Higgs phenomenon. However, these accomplishments are not enough for the future. We are at the limit of affordability, and an extension of present techniques is not a way to reach the next energy scale.

High energy physics based on an extrapolation of present trends will be a field posing exciting scientific questions but with few opportunities to explore them and with high costs. Reduced opportunities and remoteness from universities, laboratories and nations could reduce institutional and national commitment to particle physics, and the LHC and the next generation of linear collider could be the last major facilities constructed for this science.

This demise of particle physics seems inevitable unless there is a revolutionary change in particle accelerators that reduces costs. This must be a revolution comparable to that which replaced vacuum tubes with integrated circuits and telephone wires with fiber optics and cellular facilities. These are examples of inventions that were so dramatic that new, previously undreamed of ideas became possible. Particle physics must have inventions of comparable impact.

COLLIDERS

Characteristics

Colliders have characteristics that describe the particle physics potential: luminosity, center-of-mass energy, lepton or hadron beams, backgrounds, interactions per crossing, energy spread, collision spot size, etc. Some of these such as luminosity and center-of-mass energy are the raison d'être, and these should be the goal of accelerator development.

Others have major impact on experiments, and accelerator physicists try to make those impacts as favorable as possible. Backgrounds and interactions per crossing are examples. These can be given less emphasis, perhaps even ignored, when revolutionary changes in accelerators are required. Comparable changes in experimentation are going to be necessary also. The choice is as stark as it is for future colliders - work on innovations in experimentation or the survival of particle physics is in question.

Topology

The general topology of a collider has a particle source, accelerator, storage system, and collision system. The two examples given in Table 1 show

Table 1. General Collider Topology and Two Examples

General Topology	SLC	Tevatron
Particle Source	Polarized Gun, Damping Rings	Ion Source, $\bar{p}$ Cooler and Accumulator
Accelerator	SLAC S-Band Linac	Booster, Main Ring, Tevatron
Storage System	------	Tevatron
Collision System	Final Focus	High β Quadrupoles and Interaction Region

that *i)* the SLC has three of four of these systems and *ii)* the functions are combined or closely connected in the Tevatron.

A collider must have most of these systems, and they must work together, complement each other, and the properties of one system can strongly influence other systems. Two examples of that the dominant role of $\bar{p}$ production and cooling in all of the other Tevatron systems, and need for flat beams at the collision point of a linear collider determining many of the parameters of the damping rings and accelerator. While much of this is obvious, it is often ignored in the advanced accelerator community which can become fascinated with an aspect of performance without considering possible functioning as a collider.

OLD AND NEW INVENTIONS

The accelerators and colliders of today are based on:

1) ***Great principles*** of accelerator physics: phase stability, strong focusing, and colliding beam storage rings;
2) ***Dominant technologies***: superconducting magnets, high power RF production, and normal and superconducting RF acceleration;
3) Many other ***substantial accomplishments*** in accelerator physics and technology: non-linear dynamics, collective effects, beam diagnostics, etc.;
4) Years of ***experience*** with operating colliders. This is closely related to the previous element. Overcoming performance limits has often required development of sophisticated theories, experiments, or instrumentation.

A change in the future of high energy physics will require inventions and new ideas of comparable importance to the great principles and dominant technologies. These must encompass both accelerator physics and technology to have the needed impact .

Particle physics is only a small part of science, and these critical ideas may arise in other contexts and have other driving forces including market forces. The accelerator community needs to be aware of developments throughout science and technology and constantly be considering the application of new developments to particle physics. High peak power lasers are a clear example. These devices are being developed for a wide range of scientific and commercial applications, and in the process devices with enormous potential for producing high acceleration gradients are becoming available.

HADRON COLLIDERS

This is the first of three sections that deal with the colliders that could have a role in the future and with issues related to them.

High energy hadron colliders are a proven way to reach the energy scales of interest to high energy physics. Unfortunately the costs of today's technology are prohibitive for thinking about future extrapolations, and the focus of hadron collider development has to be cost reduction.[1] The SSC can be used to understand costs and to identify areas with potentially significant savings. The Appendix shows that the superconducting magnets of the collider ring were almost half of the SSC cost. This is the area where there must be significant savings.

There is extensive experience at the Tevatron, HERA, RHIC, SSC, and LHC with 4 - 8 T $\cos\theta$ magnets. This is the technology determining the present energy frontier. However, since this type of magnet is well developed, it is unlikely to be the basis for the qualitative changes needed in the future. Directions that hold promise for such changes are low-field, superferric magnets and high temperature superconductors.

The low-field superferric magnet[3] addresses many of the costly aspects of higher field magnets. The geometry is simple with a single conductor placed in a low magnetic field region. The principle disadvantage is that the field is low, $B \leq 2T$, because iron is used to shape it. As a result the collider must be large, several hundred km in circumference, and that has consequences for beam stability, stored beam energy, etc.[2] Magnet development together with further work on the consequences of low field should indicate whether this is a viable and cost effective idea.

Table 2 is a comparison of superconductors which shows the high critical magnetic fields and critical temperatures of the high T_c superconductors BSCCO and YBCO. These intrinsic properties make the materials attractive, but the superconductor volume fraction, the mechanical properties, and the production of material must be improved. There will be help from outside high energy physics because of potential commercial applications. In addition to improving the

Table 2. Comparison of Superconductors (Ref. 2)

Property	NbTi	Nb_3Sn	BSCCO-2223	YBCO
Upper Critical Magnetic Field (T)	15	25	~ 100	~ 100
Critical Temperature (K)	9.5	18	110	92
Critical Current Density* (kA/mm^2)	2 - 2.3	1 - 2.4	< 0.9	< 2.4
Superconductor Volume Fraction (%)	40 - 50	35 - 40	35 - 40	~4
Conductor Type	multifila-ment wire	multifila-ment wire	multifila-ment tape	micro-bridge
Mechanical Property	Ductile	Brittle	Brittle	Brittle
Longest Piece Made	~ 10 km	> 1 km	~ 1 km	~ 10 mm

* The magnetic fields and temperatures for the critical current densities are: NbTi - 7 T & 4.2 K or 10 T & 1.8 K; Nb_3Sn - 10 T & 4.2 K; BSCCO - 20 T & 20 K; YBCO - 20 T & 77K.

materials, there need to be ideas about how high T_c superconductors might be used in an accelerator magnet. High field magnets are not attractive at the present time, and the superferric magnet appears to be the only possibility.

MUON COLLIDERS

There are two premises leading to the interest in muon colliders for ultra-high energies. The first is that lepton-lepton collisions are necessary because the radiation damage to detectors at hadron colliders will be unacceptable, and the second is that beam-beam effects are a critical flaw of linear e^+e^- colliders. These are strong criticisms of hadron and linear e^+e^- colliders, and they deserve being addressed. Possible answers could include *i)* novel experimental techniques, *ii)* changes to the linear collider paradigm, and *iii)* the muon collider.

The muon collider consists of a high intensity proton synchrotron, a muon production system, ionization cooling stages, accelerators capable of bringing the beams to collision energy rapidly, and a collider ring.[4] A system approach has been taken to the design of a muon collider with all of the elements of the general topology of Table 1 being considered at the same time. Since each of the major component systems has significant technological and/or beam dynamics issues, this approach optimizes the collider concept and focuses research on critical issues.

Some people believe that since a complete collider concept is being discussed, the muon collider has moved from the realm of advanced accelerator research to that of project oriented research. This is not the case. The muon collider poses research questions in many fundamental areas of accelerator physics and technology. Beam current limits in proton synchrotrons and ionization cooling are two examples. The muon collider provides a context for the study of this accelerator physics just as an e^+e^- linear collider and a hadron collider provide ones for research in high gradient acceleration and high T_c superconductors, respectively.

ELECTRON-POSITRON LINEAR COLLIDERS

There is no complete concept for a 5 - 10 TeV e^+e^- linear collider, but there are several issues of clear importance.

Limitations of the Beam-Beam Interaction

The expressions for luminosity, L, beam power, P_B, and the number of beamstrahlung photons per incident particle, n_γ, can be combined to give

$$L \approx \frac{1}{8\pi\alpha r_e} \frac{P_B n_\gamma}{E\sigma_y} \ . \tag{1}$$

The beam energy is denoted by E, and the vertical beam size, σ_y, is assumed much smaller than the horizontal beam size, σ_x. The other quantities in the equation are: α = fine structure constant; and r_e = electron classical radius. This equation shows the well-known trade-offs between beam power, vertical spot size and beamstrahlung. The factor n_γ in the numerator is taken as a measure of backgrounds produced by the beam-beam interaction. Increasing the collision point electromagnetic fields increases beamstrahlung and luminosity. If there is a limit on beamstrahlung from detector backgrounds, there is a limit on luminosity.

This expression is valid when the collision point electromagnetic fields are much less than the critical magnetic field, $B_C = 4.4\times10^{13}$ G. When the fields are comparable to B_C, phenomena such as coherent pair production increase backgrounds dramatically.[5] The parameter Y,

$$Y = \frac{\gamma B}{B_C} \approx \frac{r_e^2 \gamma N}{\alpha \sigma_z (\sigma_x + \sigma_y)} \qquad (2)$$

($\gamma = E/mc^2$; B = collision point magnetic field; N = number of particles per bunch; σ_z = bunch length), is usually kept $Y < 0.3$ in linear collider designs. This becomes increasingly difficult at high energies because of *i)* the direct proportionality to γ, *ii)* high gradient structures have short wavelengths and the bunch length must be a small fraction of the wavelength, and *iii)* the need for small σ_y together with limits on σ_x/σ_y from beam optics.[6] If $Y < 0.3$ is necessary, this could be the critical flaw of e^+e^- linear colliders mentioned earlier in the muon collider section. However, there are several possible ways to deal with the limitations of the beam-beam interaction within the linear collider concept.

The first is to *ignore it*. This may be wishful thinking, but perhaps it isn't. High field Quantum Electrodynamics with $Y \sim 1$ has been studied experimentally in laser - electron beam interactions,[8] but there is no experience with beam-beam related backgrounds in a linear collider. Real life will be different than the Monte Carlos studied to date which have considered backgrounds in an extrapolation of today's high energy collider detectors. A compelling multi-TeV linear collider concept will spark creativity in the experimental physics community, and innovative approaches to experimentation could emerge.

The second approach to the limitations of the beam-beam interaction are to *avoid them* with a different collision paradigm. One possibility is photon-photon rather than e^+e^- collisions.[9] There are no issues of beamstrahlung or coherent pair production in a photon-photon collider, and the dominant problem is the configuration near the collision point. Accelerated electrons have to be converted to photons by Compton scattering with an intense laser, and this conversion point must be close to the collision point for high luminosity.

The other possibility of a different collision paradigm is plasma[10] or beam compensation where fields at the collision point are reduced by neutralization. There would be substantial backgrounds from interactions in a plasma if one were used to neutralize the collision. The creativity of experimentalists would be required to deal with them. Compensation with beams would require overlapping electron and positron beams. Efficient generation and control of such beams together with the stability of the compensated configuration are all problems to be solved. There are ideas for this.[11]

Harnessing the Potential of the Laser

High peak power lasers are a breakthrough technology, and exploiting their enormous potential for particle acceleration is one of the major challenges for accelerator physics research. They have found use already for the generation of low emittance beams in laser driven RF guns, and they could have a role in generation of power at high frequencies.[12] However, the primary interest has to be with the high gradients possible in a laser driven accelerator.

Different laser driven accelerators have been studied both theoretically and experimentally. Far field accelerators (of which the Inverse Free Electron Laser (IFEL) is the most prominent) couple to the transverse electric field of the laser by giving particles a transverse component of motion. This motion generates synchrotron radiation which limits the beam energy. Far field accelerators could find application as injectors or bunchers, but the energy limit makes them relatively uninteresting for high energy physics.

There have been many ideas for direct acceleration of a beam with a laser by using structures to give a longitudinal component to the laser field. Structures with features comparable to the laser wavelength are similar to RF driven linacs. Lithographic techniques could be used for fabrication, but there will be stringent limitations on accelerated charge from wakefields. These limitations are so severe that interest in this type of structure has dropped substantially. Current interest is focused on structures with the features in at least one dimension large compared to the laser wavelength. Crossed laser beams[13] and a structure similar to the open optical waveguide are being considered.[14] Both promise gradients ~ 1 GeV/m with substantially lower wakefields than optical renditions of RF linacs.

The highest acceleration gradients achieved to date have been with laser driven plasma accelerators. Plasma waves can be excited resonantly in the laser beatwave accelerator or by the excitation of a wakefield with a short, high intensity laser. The laser pulse is self-modulated when the pulse is long compared to the plasma wavelength. Gradients of ~ 100 GeV/m have been observed in the latter configuration.[15] This type of result has attracted widespread interest, and the field of laser driven plasma accelerators is moving on to achieving this acceleration over long distances, staging of multiple accelerators, and beam quality and stability. When these have been successfully addressed the plasma accelerator will attract the interest of the mainstream accelerator community.

Short Wavelength & High Gradient Limits of Metallic Structures

The SLC has an RF wavelength of 10.5 cm and an accelerating gradient of G ~ 20 MeV/m. While there is a variety of RF technologies being considered for a next generation of linear collider, the tendency is towards shorter wavelengths and higher gradients. A 5 - 10 TeV collider could be possible by going even further in this direction to mm wavelengths and GeV/m gradients.

The arguments for this include energy efficiency, which for a fixed gradient and number of particles is proportional to λ^{-2}, and the dependence of gradient on wavelength. The dominant phenomena limiting gradient at 1 - 10 cm wavelengths are *i)* capture and acceleration of dark current and *ii)* RF breakdown. Dark current capture depends on wavelength as $1/\lambda$.[16] Loew and Wang[17] have measured RF breakdown at a fixed pulse length of 1 μs and different frequencies. They find that the breakdown gradient is proportional to $\lambda^{-1/2}$. Correcting for reduced pulse length at shorter wavelengths, Wilson estimates that the gradient limit from RF breakdown is proportional to $\lambda^{7/8}$.[16] These are empirical results, and, while further research is needed to clarify underlying mechanisms, they argue for short wavelengths.

There are several disadvantages of short wavelengths. Longitudinal and transverse wakefields scale as $1/\lambda$ and $1/\lambda^3$, respectively. New ideas for aligning and stabilizing accelerating structures and beams are needed. Recent work on structure alignment based on detecting RF induced in deflecting modes may provide a basis.[18] There is a possible gradient limitation from pulsed heating. This is thought to scale as $1/\lambda^{1/8}$,[11] but the experimental information about pulsed heating in RF systems is contradictory. An experiment studying pulsed heating in RF systems is planned.[19] Structures and filling times get shorter with shorter wavelength, and the peak power per meter depends on gradient and wavelength as $G^2\lambda^{1/3}$.[16] The consequences are that new RF power sources and pulse compression techniques are sure to be required. These problems must be solved for short wavelength, high gradient RF to be viable.

CONCLUDING REMARK: ACCELERATOR IR&D

The future of high energy physics and successful accelerator ***Invention, Research and Development (IR&D)*** are one and the same. The last three sections have discussed and commented on some of the current directions for advanced accelerator research in hadron, muon, and linear colliders for future generations of high energy physics colliders. Most of the ideas are not the revolutionary ones that are needed. However, my hope is that the combination of motivated, intelligent people and a supportive atmosphere will produce the critical insight that is so badly needed.

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APPENDIX: SSC COST ANALYSIS

While a detailed SSC cost analysis is complicated because project evolution and schedule changes had large impacts the cost,[20] the "Site Specific Conceptual Design" can be used to show relative costs. From Tables A-1 and A-2 one sees that 52% of the Total Project Cost (TPC) was in the accelerator system with the collider accounting for 42% of the TPC. When it is assumed that project management, contingency, R&D, and administrative and technical support should be apportioned according to system costs rather than appearing as separate items in the budget these percentages become 75% and 61%.

The accelerator systems (not including the magnets), superconducting magnets, and conventional systems of the collider are 17%, 44% and 10% of the TPC, respectively. Almost one-half of the cost is associated with the collider ring superconducting magnets.

Table A-1. SSC Site Specific Conceptual Design Costs* [21]

Category	**SCDR Costs FY90$**
Construction	
1.0 Technical Systems	2,986,400,000
2.0 Conventional Systems	1,051,500,000
3.0 Project Management	48,700,000
Contingency	753,000,000
Construction Subtotal (TEC)	*4,839,600,000*
Other Program Costs	
4.0 R&D, Pre-Operations, Administrative and Technical Support	975,900,000
5.0 Experimental Systems	752,100,000
Other Subtotal	*1,728,000,000*
Total Project Cost (TPC)	***6,567,600,000***

* These numbers correspond to a proposed actual year cost of $7,836,600,000 which was increased to $8,249,000,000 after reviews by the Department of Energy.

Table A-2. SSC Accelerator Technical and Conventional Systems[22] (1)

System	Accelerator Systems (2)	Conventional Systems	System Cost (3)		% of TPC (3)	
Linac	37	3	40	(58)	0.6	(0.9)
LEB	42	5	47	(68)	0.7	(1.0)
MEB	113	35	147	(212)	2.2	(3.2)
HEB	326	74	400	(576)	6.1	(8.8)
Injector	*518*	*117*	*635*	*(915)*	*9.7*	*(13.9)*
Collider	2,304	464	2,768	(3987)	42.1	(60.7)
Accelerators	*2,822*	*581*	*3,403*	*(4901)*	*51.8*	*(74.6)*

Notes: 1. Costs in FY90 M$. 2. Including superconducting magnets which are $1,668M$ of the collider cost. 3. The numbers in ()'s indicate costs and percentages with project management, contingency, R&D etc. allocated in proportion; (cost) = cost ¥ [1 + (48.7+753.0+975.9)/(2986.4 + 1051.5)].