# ACCELERATORS FOR HIGH ENERGY PHYSICS RESEARCH

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ABSTRACT

A brief survey of particle accelerators as research tools for high energy physics is given. The survey includes existing accelerators, as well as those envisioned for the future.

## 1. The Past

Accelerators have been the main tool of high energy physics (HEP) research since the 1930s. The first high energy accelerator is generally considered to be the Cockcroft-Walton electrostatic accelerator of 1932. For 60 years, the equivalent beam energy for HEP research has been increasing exponentially by a factor of 10 every 7 years, as shown by Fig.1, the well-known "Livingston chart".[1] This chart shows the fact that, over the past 60 years, the equivalent beam energy has increased by a remarkable 9 orders of magnitude. Indeed, so far, when one technology ran out of steam, another innovation rose to the occasion, maintaining the exponential growth.

It would be useful to review the latest technology innovation on the Livingston chart, the technology of storage ring colliders,[2] and to learn something from it. The concept of storage ring colliders was suggested long ago by Wideröe in 1943. (He had an interesting idea of colliding a proton beam with a $H^-$ beam.) It was re-introduced by Kerst and O'Neill in 1956 as a proposal.[3,4] Then it took another 15 years and about 5 early storage rings for the technology to mature. This should not be surprising; in developing a new technology, one encounters new problems, and to resolve these problems necessarily takes time and effort. I will return to this point later.

Another remarkable fact over the years is that the cost per GeV of the HEP accelerators has come down drastically, at least for the proton accelerators. This results in the accelerator cost scaling with the beam energy like $E^{1/3}$.[5] From the ISR to the LHC, for example, $E$ increased by a factor close to 1000, but the accelerator cost increased only by a factor of 10. In comparison, the cost per GeV of the electron accelerators has not been reduced as much, and this is the reason why electron storage ring colliders must be replaced by linear colliders. More on this later.

However, even with cost reduction, accelerators have grown from table-top experiments to gigantic projects, so much so that their budgetary impacts require justifications more than ever before. Much more drastic reduction of accelerator cost must be found in a not so distant future. R&D of high energy accelerators has become a critical issue for this reason.

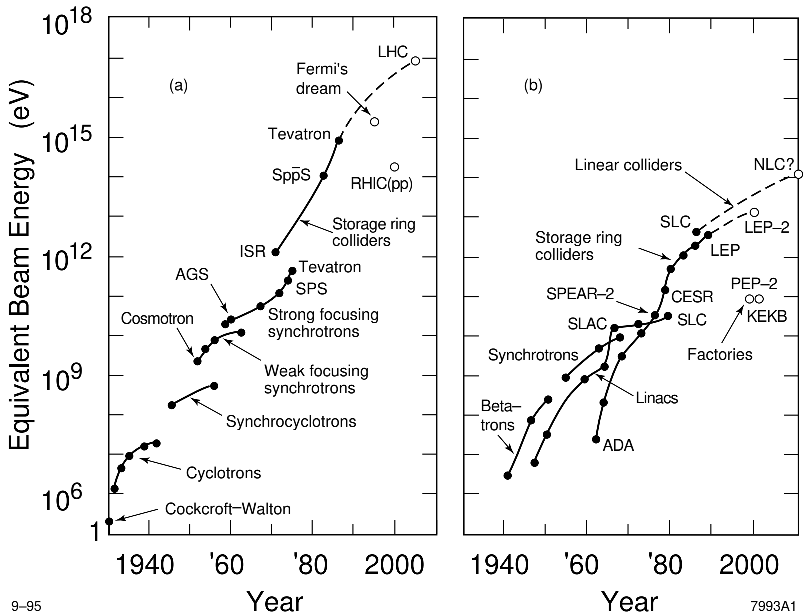


Fig. 1. The equivalent energy of high energy particles is plotted versus time when the accelerator was built. (a) is for proton accelerators and (b) is for electron accelerators. The equivalent energy assumes the beam is hitting stationary proton targets. Each solid dot represents an accelerator which has been built. An open circle is an accelerator not yet in existence. Each solid curve connects accelerators built or designed with a certain technology.

## 2. Accelerators in Operation and Their Upgrades

Figure 2 shows the major high energy accelerators around the world. Here let me mention that an accelerator is built as a versatile instrument. After it is built, it invariably continues to be improved and upgraded, yielding increasing performances with time. For a collider, this is reflected in an increasing luminosity. In fact, one is led to conclude that the "design" luminosity of a collider is only a set goal at the time of the design, and it is sometimes not *whether* but *when* the design luminosity would be achieved — especially when talking about new technologies.

Figures 3(a), (b) and (c) show the luminosity evolution of the Fermilab Tevatron, the SLC, and the Cornell CESR.[6,7,8] These accelerators respectively represent the three leading technologies of the present colliders: proton storage ring collider, electron storage ring collider and electron linear collider.

Table 1. Accelerators being built.

| | LHC | LEP-2 | RHIC | KEKB | PEP-2 | DAΦNE |
|---|---|---|---|---|---|---|
| particle type | pp | $e^+e^-$ | ions, pp | $e^+e^-$ | $e^+e^-$ | $e^+e^-$ |
| beam energy (GeV) | 14000 | 96.5 | 250 (pp) | 3.5+8 | 3.1+9 | 0.51 |
| circumference (km) | 27 | 27 | 3.8 | 3.0 | 2.2 | 0.098 |
| design $\mathcal{L}$ ($10^{33}$cm$^{-2}$s$^{-1}$) | 10 | 0.08 | 0.01 | 10 | 3 | 0.5 |
| expected completion | 2004-2008 | 1997 | 1999 | 1998 | 1997 | 1996 |

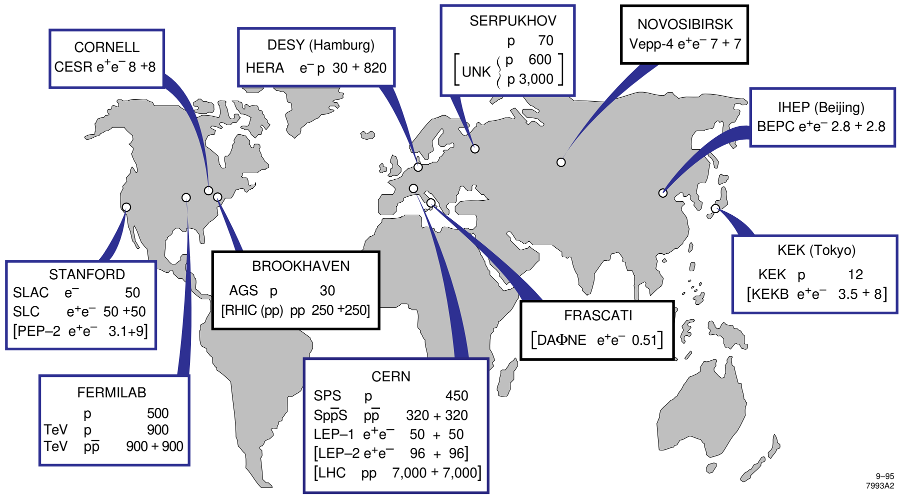


Fig. 2. The major high energy accelerators around the world. Each entry gives the name, the particle type, and the beam energies (in GeV), of the accelerator. In square brackets are accelerators presently under construction.

The SLAC Linear Collider (SLC) is the first and only electron linear collider ever built so far. Its design luminosity was $6 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, while the luminosity reached so far is $0.8 \times 10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (with the added feature of 80% polarization of the electron beam). The linear collider technology is a difficult one. In fact, one of the reasons to build the SLC was to develop this technology, and indeed SLC has been an indispensable source for learning. For example, the discrepancy between the design and the achieved luminosities is mainly due to the worse-than-expected difficulty to keep the beams rock steady and sharply focused while trying to increase the beam intensity, and this has been one of the lessons learned with the SLC.

## 3. Accelerators Being Built

The present state of HEP accelerators seems reasonably healthy, as indicated by the fact that a spectrum of accelerators are being built worldwide [see Table 1].

LEP-1 is an existing accelerator. <u>LEP−2</u> is an energy upgrade (in contrast to a luminosity upgrade) of LEP-1.[9] As the room temperature rf cavities of LEP-1 are progressively replaced by superconducting ones, the LEP energy is expected to reach 70 GeV by the end of 1995, 80.5 GeV in early 1996, 93.5 GeV when all cavities are replaced, and when extra rf cavities (both superconducting and room temperature) are added, to reach 96.5 GeV some time in 1997. The expected LEP-2 luminosity is $7 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The <u>LHC</u> is a p-p storage ring collider to be installed in the existing LEP tunnel.[10] Its superconducting magnets, with a field strength of 8.4 Tesla, require a significant extension from the SSC magnets and are the single most demanding technical item. The present plan is that if sufficient foreign contributions (500 million Swiss francs)

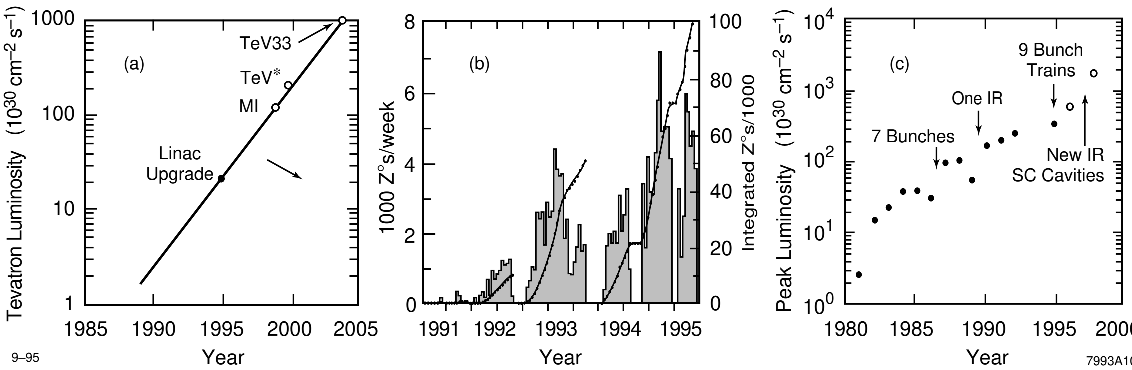


Fig. 3. Luminosity versus time for (a) Tevatron, (b) SLC and (c) CESR. Solid circles are history. Open circles are the expected luminosities in the near future if the upgrades are carried out. The Tevatron design luminosity was $10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The SLC luminosity is measured in units of the number of $Z_0$ particles produced per week (histogram). The integrated luminosity is also plotted for the SLC (solid squares). The luminosity efforts at CESR constitute a learning ground for the realization of a new breed of accelerators called factories.

are available, LHC will be completed in 2004. Otherwise, the plan is to build 2/3 of magnets to reach 4.7 TeV in 2004, and then to complete the remaining 1/3 by 2008.

One important new breed of modern accelerators is the factories, which are high performance accelerators of modest energies. The cost of these factories is not excessive, but the technology requirements are high. No factories have been built yet, but there are presently two B-meson factories and one Φ factory (DAΦNE)[11] being constructed. The luminosity goals of the B factories are higher than that of CESR, the present luminosity record holder, by a factor of 10 or more. This is achievable only if the $e^+$ and $e^-$ beams are stored in two separate rings.

One B factory under construction is the KEKB in Japan.[12] In order to study the CP-violation decay states more effectively, the energies of the two beams are chosen to be asymmetric: 3.5 GeV for $e^+$ and 8 GeV for $e^-$. To produce the high luminosity, unprecedented high beam currents must be stored. All technical difficulties — from the collective instabilities to beam-beam effects — of conventional storage ring colliders become much more pronounced in factories.

The other B factory is PEP-2 at SLAC.[13] It has 3.1 GeV $e^+$ and 9 GeV $e^-$ beams. The two B factory designs differ in their optimization, which is profoundly affected by their respective choices of areas of technology efforts. It would be most interesting to learn which ends up producing more B mesons and why.

## 4. Foreseeable Future

There are some accelerators being designed using extrapolations of present-day technologies. These are not approved projects, but are candidates for the foreseeable future. Examples of accelerators in this category are: a TeV electron linear collider, a proton storage ring collider with $E > 30$ TeV,[14] a TeV $\mu^+\mu^-$ collider,[15] and a $\gamma$-$\gamma$

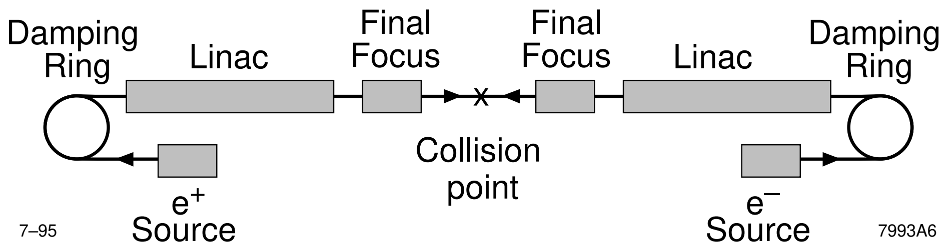

Fig. 4. Schematic layout of a linear collider design.

collider[16]. Below I will mention only the case of a linear collider.[a]

Electron storage ring colliders suffer from making too much synchrotron radiation, which forbids sharp bending of the beam. (For example, although 1.8 T magnets are routine, the bending magnetic field for LEP is only 0.135 T.) The consequence is that the size, and thus the cost, of electron storage ring colliders scales quadratically with beam energy, making it an inefficient accelerator design. This is why, as mentioned earlier, the cost per GeV of electron accelerators has not been coming down. The technology that replaces the storage ring colliders is the linear collider.

The original concept of a linear collider was proposed by Tigner in 1965.[17] Then SLC was built in 1986. We learned a lot from the SLC operations, but there remains a lot more to learn, particularly because the SLC does not address all the envisioned issues of the next linear collider. On the other hand, the next linear collider is the big prize for HEP research, which explains why there are several serious competitive R&D efforts going on world-wide:

NLC (Next Linear Collider) at SLAC,[18]
CLIC (Compact Linear Collider) at CERN,[19]
JLC (Japan Linear Collider) at KEK
TESLA (TeV Superconducting Linear Accelerator) at DESY,[20]
SBLC (S-band Linear Collider) at DESY,[21]
VLEPP at Novosibirsk

The schematic layout of a linear collider is shown in Fig.4.

The parameters of different designs listed above span a wide spectrum (including the bottom line luminosity).[22] Most use beams with multiple bunches, one (VLEPP) uses single high-intensity bunches. One (TESLA) uses superconducting rf structures, others use room temperatured ones. One (CLIC) uses a two-beam arrangement for the rf power source, others use the more conventional klystron approach. The choice of rf frequency ranges from 1.3 to 30 GHz, while the vertical beam spot size at the collision point ranges from 3 to 65 nm. The spread of parameters reflects the spread of the degree of conservatism, as well as the difficult judgments as to which technologies to be identified as the R&D goals prior to the construction of the collider.

To address the various difficult technical areas identified by each design, each

[a]An extended version of this survey is submitted for publication elsewhere.

laboratory is constructing test facilities, which are mid-sized projects in their own rights. These new test facilities are necessary before the next linear collider can be confidently built. Hopefully one learns from these facilities soon as to which technology is the best.

In the factory family, I should mention the one being considered at the IHEP, Beijing. Like the B factories, a tau-charm ($\tau$/c) factory is a technically difficult machine, and has to be approached with corresponding care. What is being done presently at IHEP is a feasibility study. If successful, the hope is to follow it by an R&D study. Results of these two studies, together with the experience of actual performance of the two B factories (available in 1999), should constitute a good technical basis for making a decision at that time. As an ex-SSC refugee, I hasten to add my understanding that a solid financial evaluation — not considered in my report here — is at least equally important.

## 5. Far Future

As mentioned, the present day technologies are running out of steam. Even the linear collider technology will most likely run out of steam after the NLC with a center-of-mass energy of 0.5-1.5 TeV. (The project costs become comparable to the annual worldwide HEP expenditure, about 2 billion US dollars.) In view of this, the accelerator R&D in the last decade has been concentrated in two areas: one is the NLC-related activities mentioned earlier, the other aims for a yet-unidentified new technology of the far future. In contrast to the NLC activities, these futuristic activities are understandably far less focused. One may envision the procedure to take three stages: first, one has to demonstrate the concept by proof-of-principle experiments (the "research" stage); next, one needs to wisely choose one concept and device test facilities of this concept (the "development" stage); and finally, the "construction" stage. We are presently somewhere in the first stage.

There are no lack of ideas. On the contrary, there have been a wide spectrum of ingenious ideas, covering from lasers to plasmas, from structures to crystals. They are at different levels of development, some are just concepts, some are in the middle of proof-of-principle experiments, and some have apparently been abandoned. So far, however, the efforts have not yet left the sense of developing a "gene pool". Below is an incomplete list of this pool:[23]

plasma beat wave accelerator
plasma wake field accelerator, beam-generated
plasma wake field accelerator, laser-generated
plasma soliton accelerator
plasma lens focusing
laser-switch radial-transmissionline accelerator
wake-field radial-transmissionline accelerator

wake-field electron accelerator with proton driver
acceleration at laser focus in free space
laser grating accelerator
laser dielectric medium accelerator
inverse Cerenkov accelerator
inverse free electron laser accelerator for electrons
inverse free electron laser accelerator for protons in a modulated crystal
cyclotron resonance laser accelerator
collective implosion accelerator
acceleration by electron plasma wave in metal
laser acceleration along crystal channel
acceleration by stimulated emission of radiation

How do these genes become an accelerator — like trying to breed dinosaurs from their DNA's in the movie *Jurassic Park* — is yet to be seen.

## 6. Summary

(1) The present status of high energy accelerators is reasonably healthy. Demise of the SSC was serious, but was partly recovered by the approval of the LHC. Several worthwhile projects are ongoing: two B factories, LHC, HERA, and upgrades at CESR and Tevatron.

(2) The near future seems fine. With active R&D efforts, the next linear collider seems technically within reach.

(3) LHC, LEP and NLC are likely to be the last accelerators in their respective technologies (proton storage ring collider, electron storage ring collider and the electron linear collider). These technologies are running out of steam. Factories and cosmic rays might serve as alternative routes in some cases.

(4) Advanced accelerator R&D is a must in order to assure a far future of high energy physics. The R&D has been started, but we have yet a long way to go. Opportunities and challenges are ahead of us.

A possible view of the future accelerator landscape from 1995 can perhaps be shown as Fig.5.

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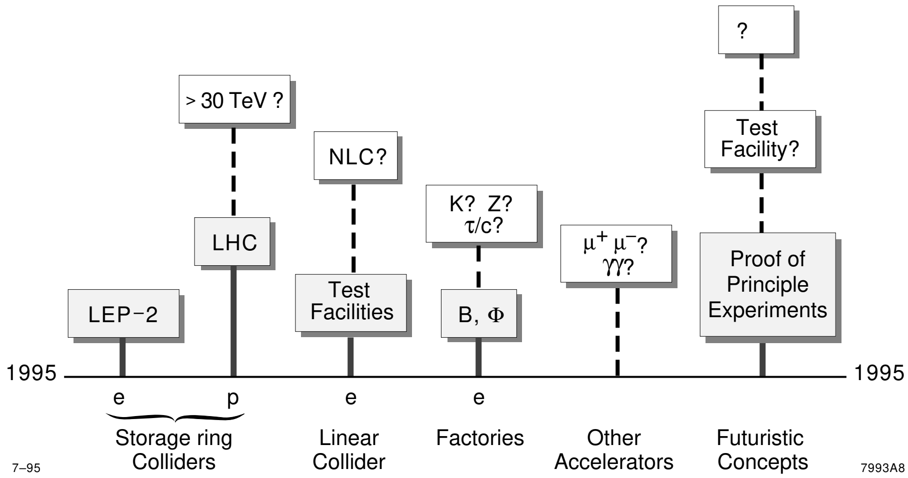


Fig. 5. A "tourist map" of the accelerator landscape in the future, as viewed in 1995. Hopefully some of the dashed lines will become realities.


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